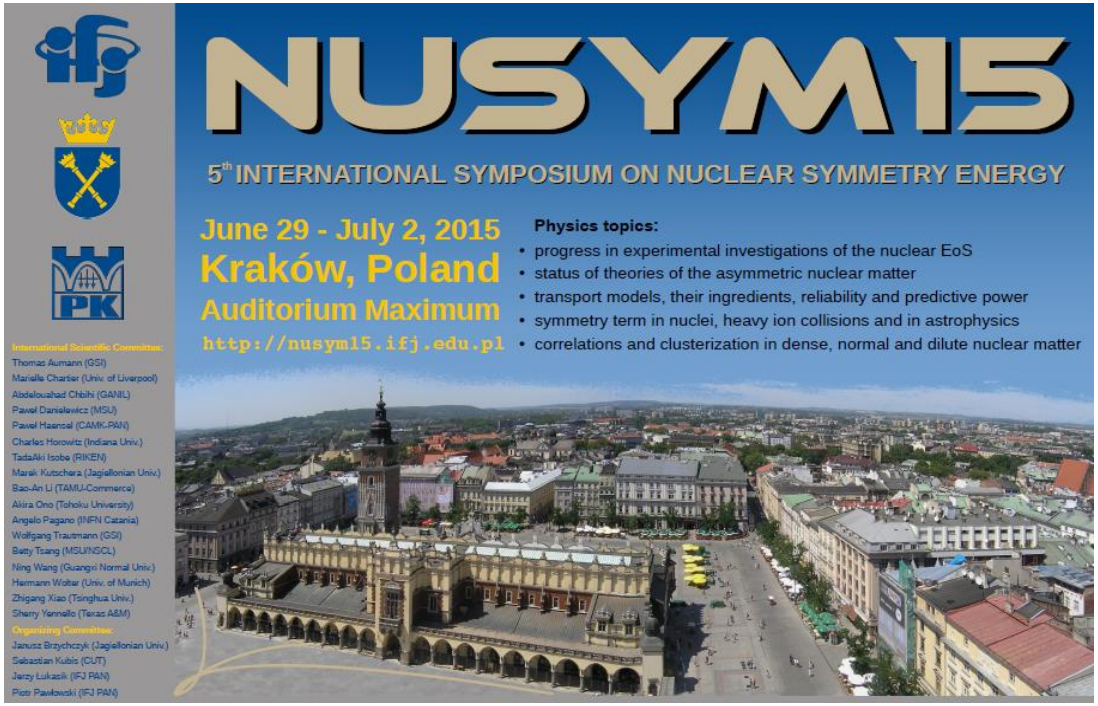


The ASY-EOS experiment at GSI: investigating symmetry energy at supra-saturation densities

P. Russotto*

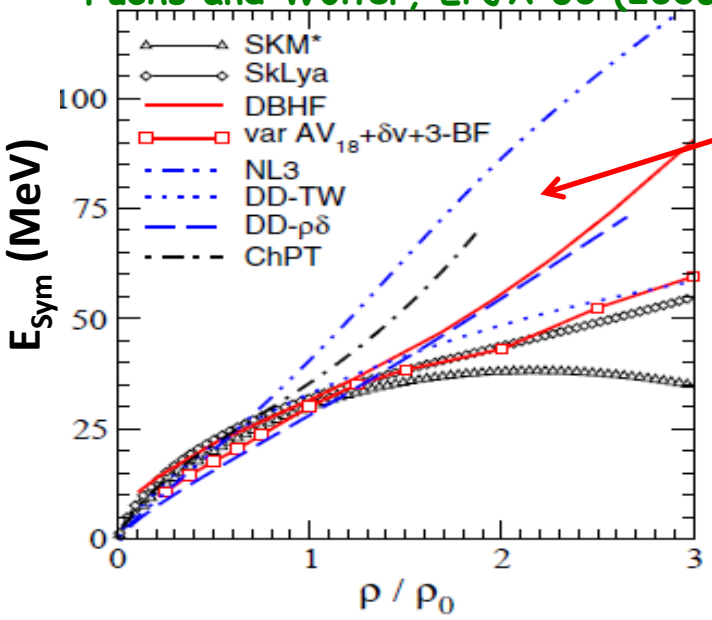
for ASY-EOS collaboration

*INFN-Sez. di Catania, Italy

6/30/2015 6:39 PM

High density Symmetry Energy: uncertain and poor constrained

Fuchs and Wolter, EPJA 30 (2006)



High density…so important!

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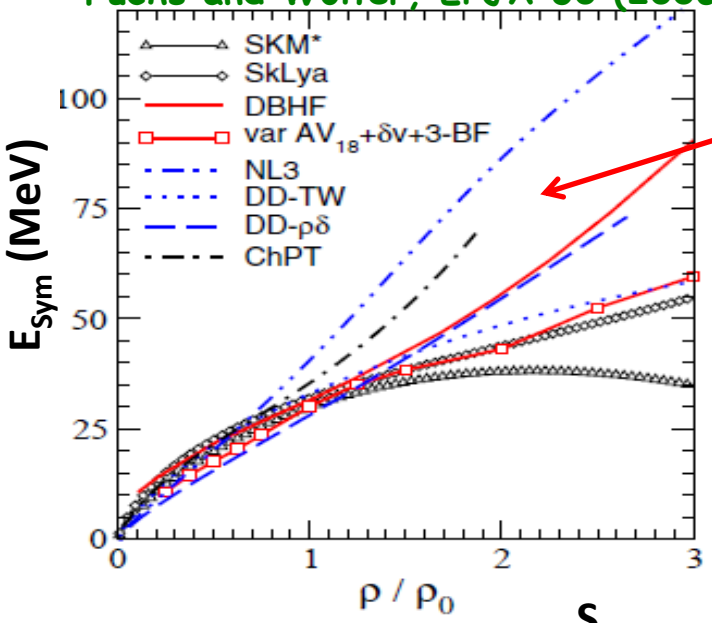


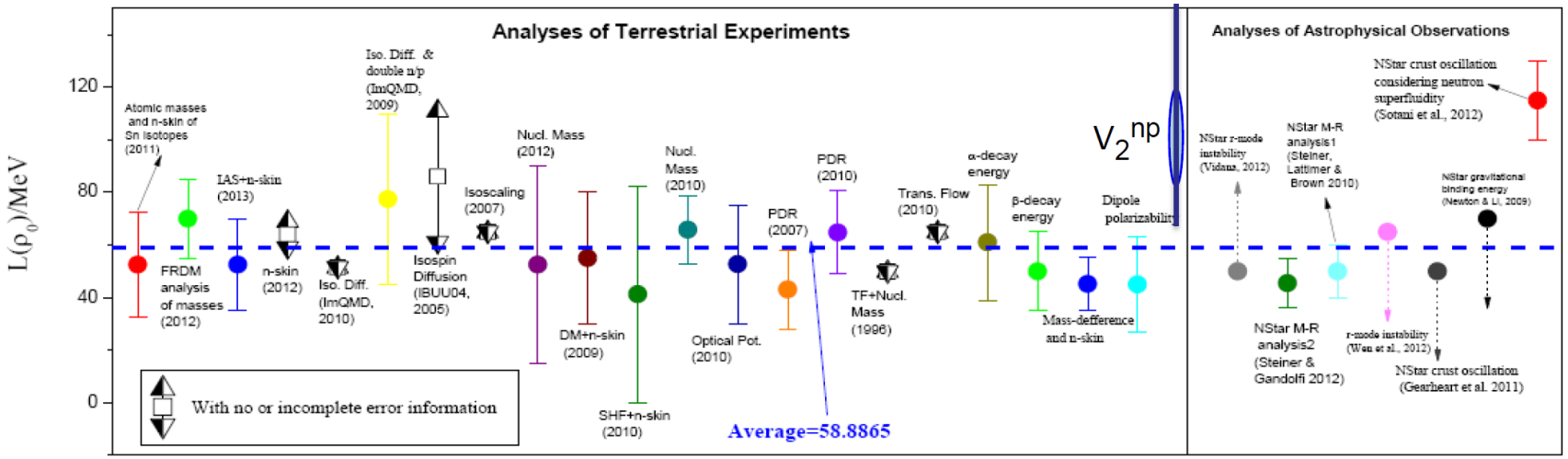
High density…so important!

B.A. Li NuSym13 summary talk

	S_0	L
average of the means	31.55415	58.88646
standard deviation	0.915867	16.52645

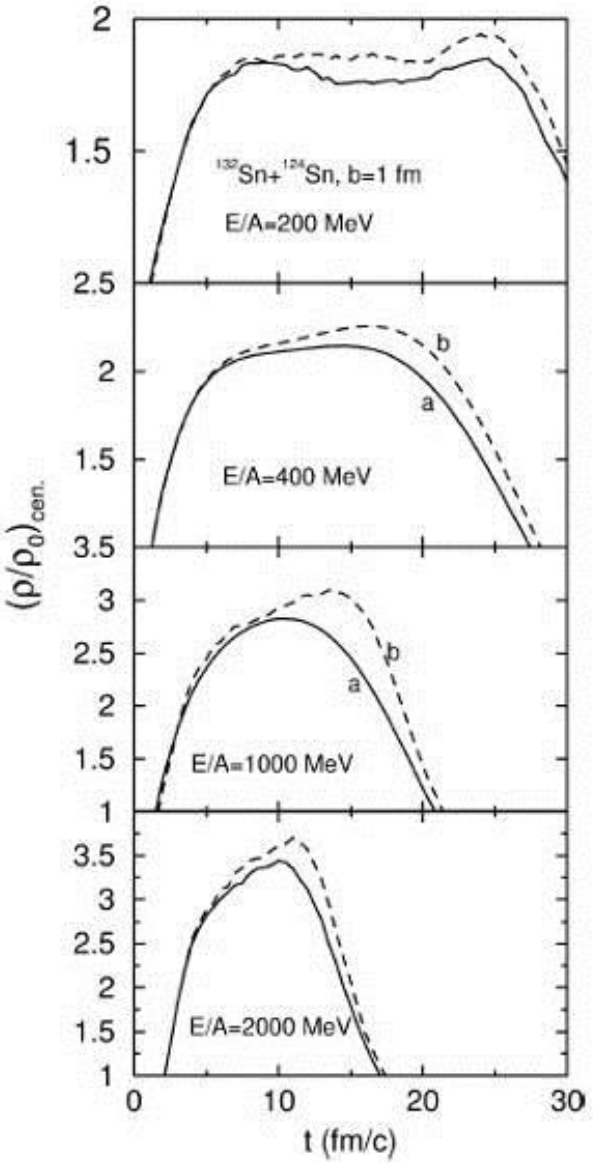
Terrestrial laboratories

- Several constraints (quite consistent among them) around and below ρ_0
- Few constraints above ρ_0



High density symmetry energy in relativistic heavy ion collisions

Which densities can be explored in the early stage of the reaction ?



Bao-An Li, NPA 708 (2002)

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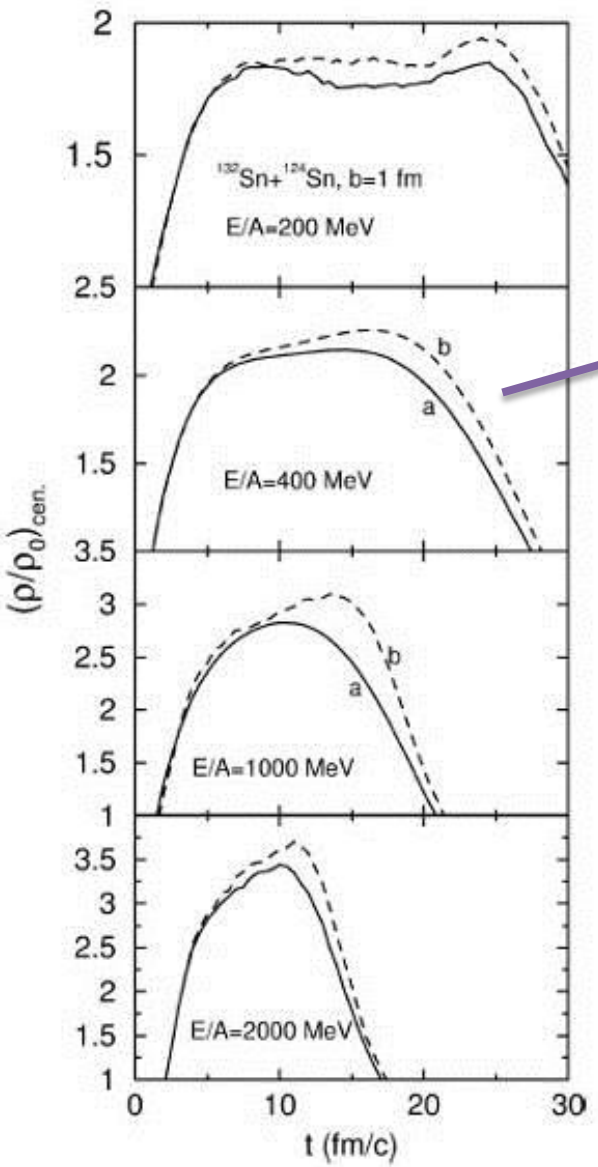

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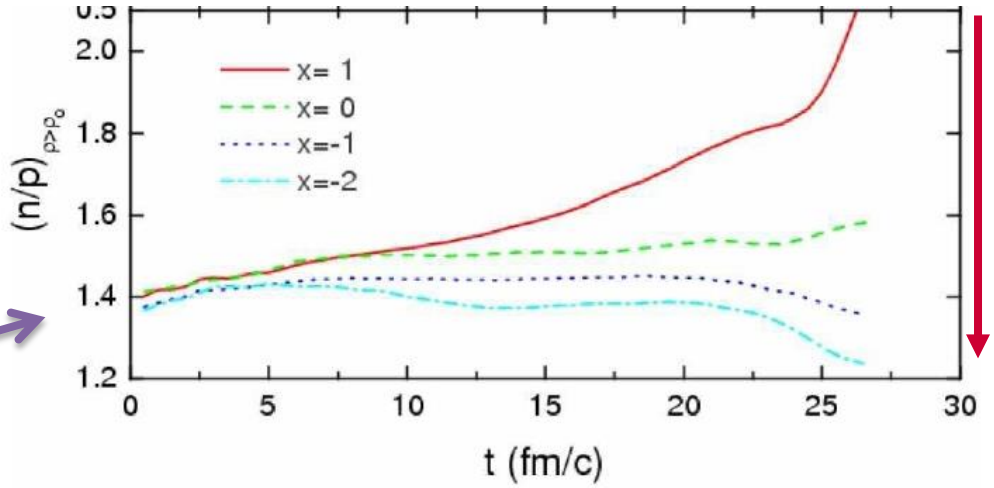
B.A. Li et al., PRC71 (2005)



- N/Z of high density regions sensitive to $E_{sym}(\rho)$
- High $\rho>\rho_0$: asy-stiff more repulsive on neutrons

High density symmetry energy in relativistic heavy ion collisions

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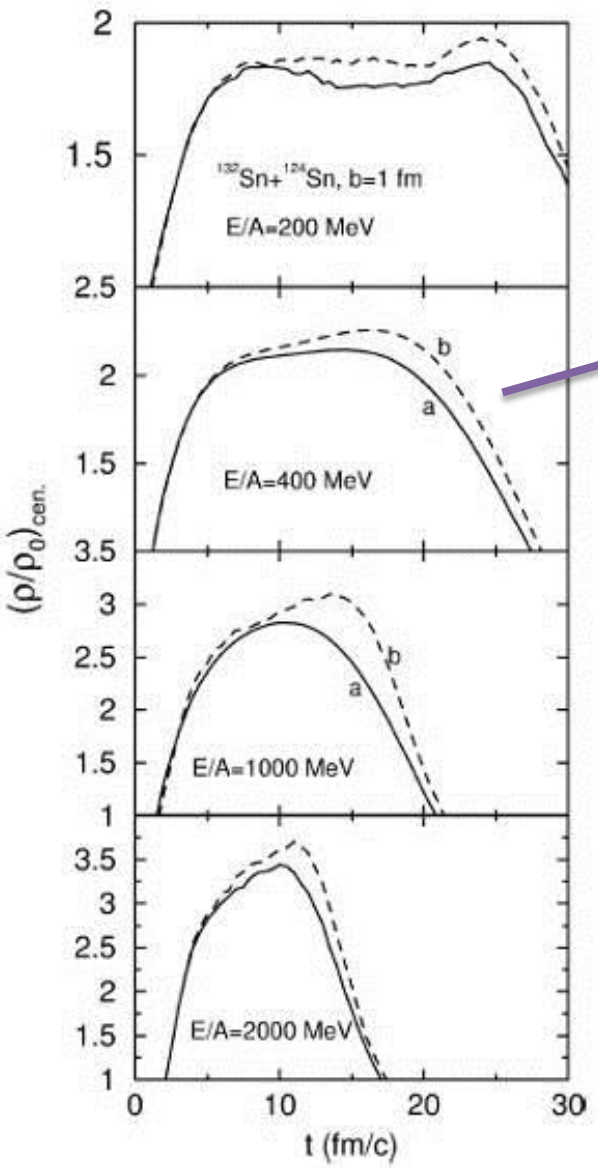

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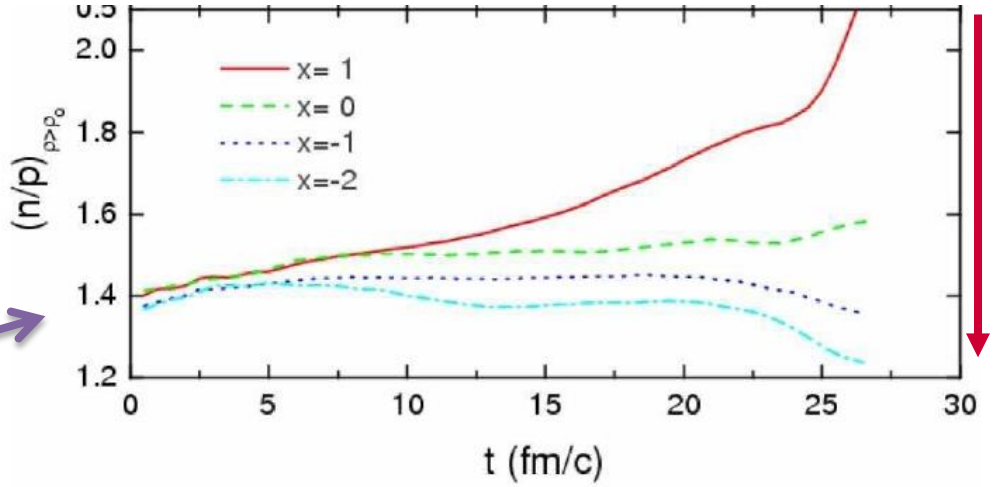

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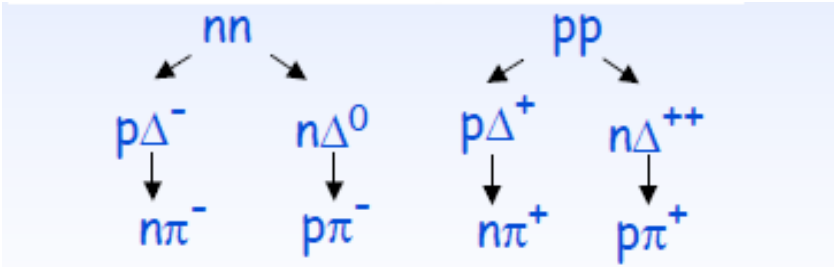


NN collisions in high density regions

π^-/π^+ reflecting the $(N/Z)_{dense}$

π^-/π^+ sensitive to $E_{sym}(\rho)$ at high ρ

See talks about pions

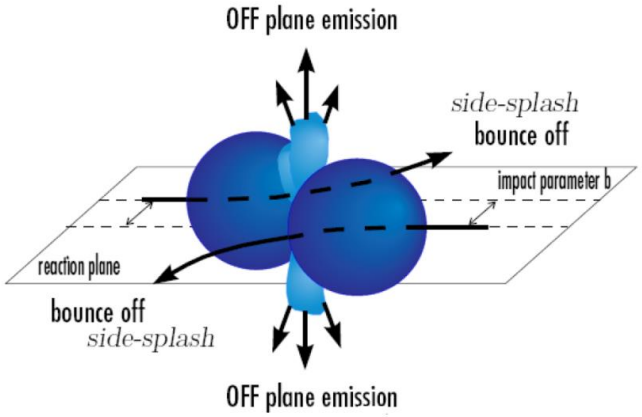
High densities: flows

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

Y = rapidity
pt = transverse momentum

$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

Elliptic flow: competition between in plane (V2>0) and out-of-plane ejection (V2<0)



Qingfeng Li, J. Phys. G31 1359-1374 (2005)
P.Russotto et al., Phys. Lett. B 697 (2011)

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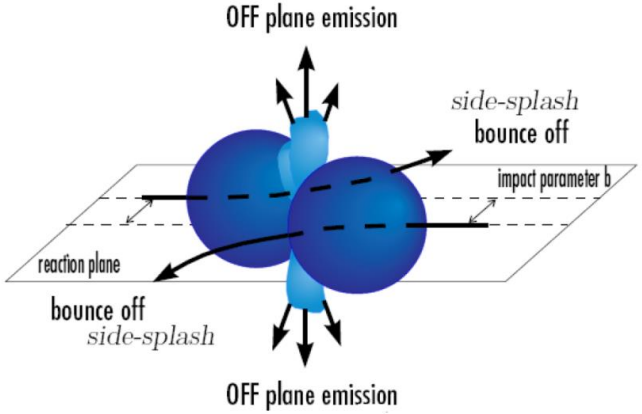
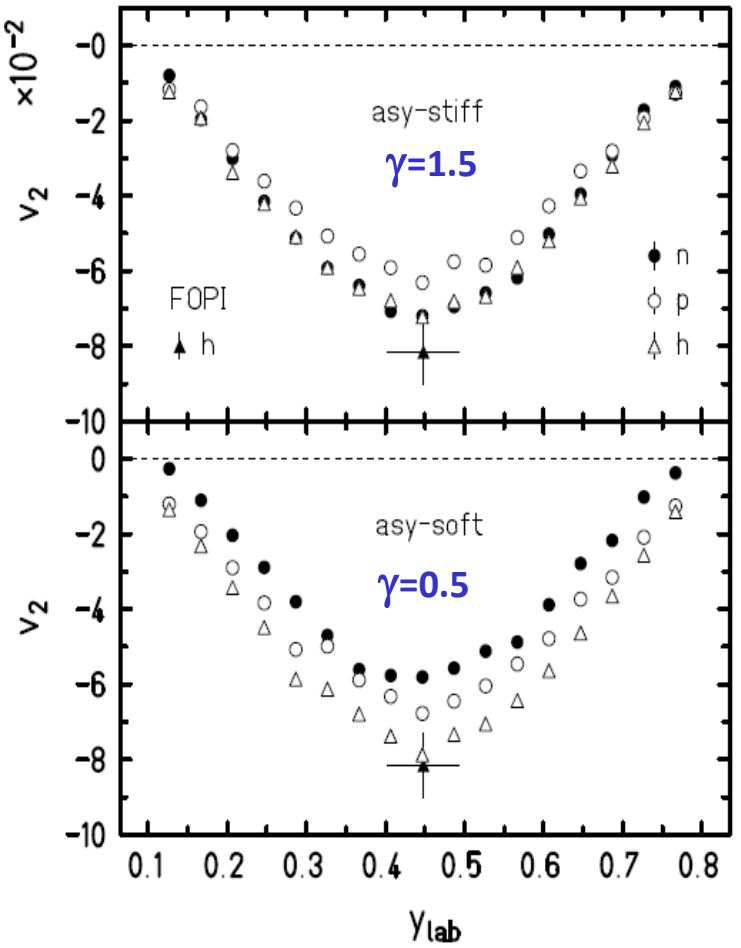


$$E_{sym}=E_{sym}^{pot}+E_{sym}^{kin}$$
$$=22\ \text{MeV}\cdot(\rho/\rho_0)^{\gamma}+12\ \text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

UrQMD :Au+Au @ 400 AMeV
5.5<b<7.5 fm



Qingfeng Li, J. Phys. G31 1359-1374 (2005)
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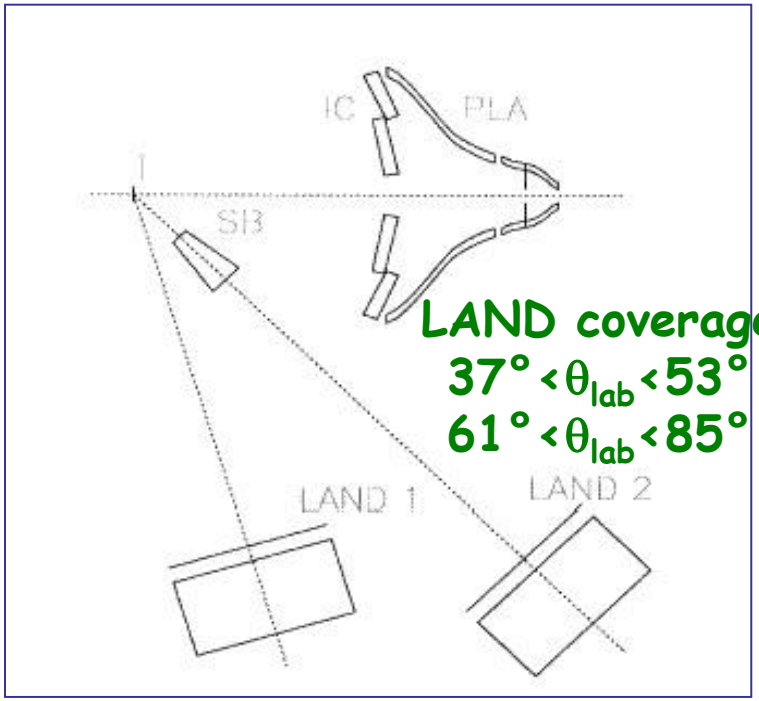
FOPI/LAND experiment on neutron squeeze out (1991)



LAND coverage
$37° < \theta_{lab} < 53°$
$61° < \theta_{lab} < 85°$

Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

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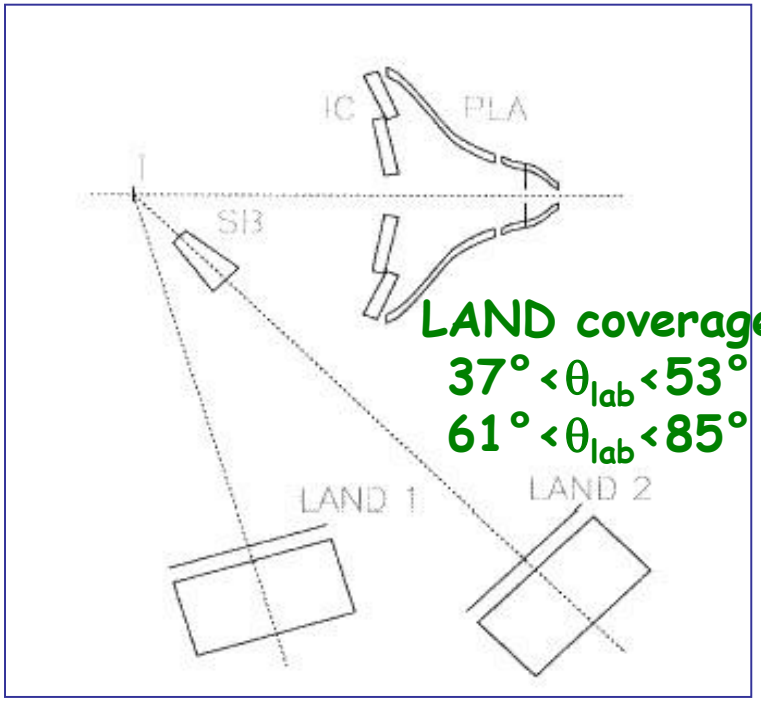

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Au+Au 400 A MeV
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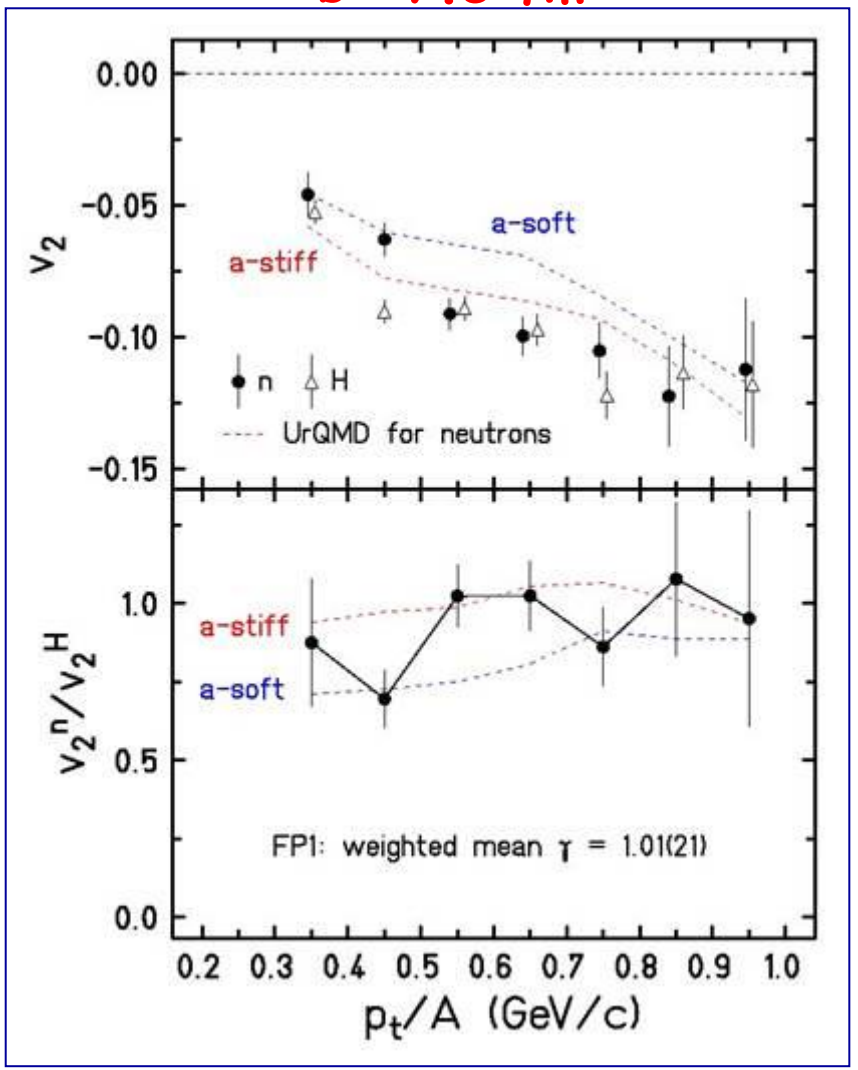

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
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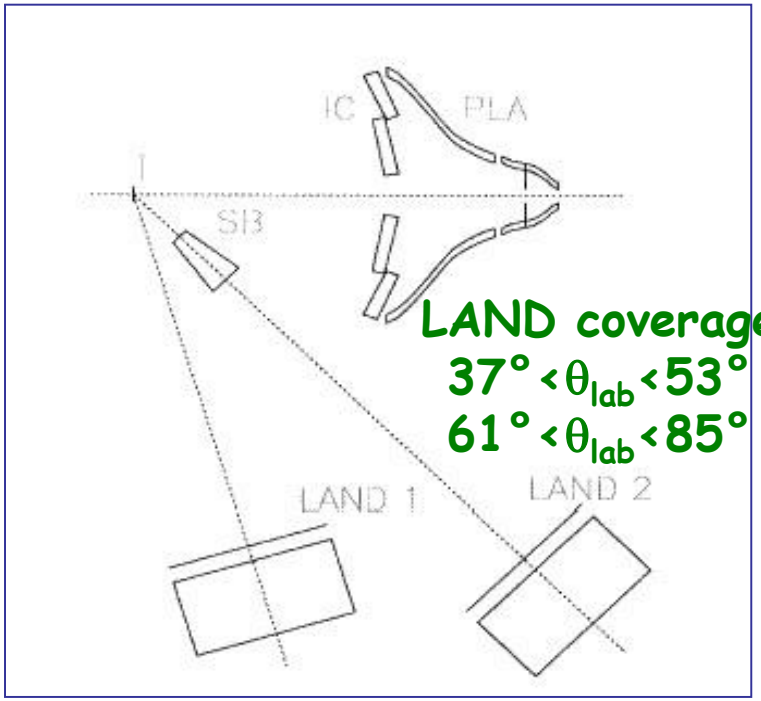

LAND coverage
$37° < \theta_{lab} < 53°$
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$\gamma = 0.9 \pm 0.4$
$L = 83 \pm 26$

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22MeV \cdot (\rho/\rho_0)^{\gamma} + 12MeV \cdot (\rho/\rho_0)^{2/3}$$

Au+Au 400 A MeV
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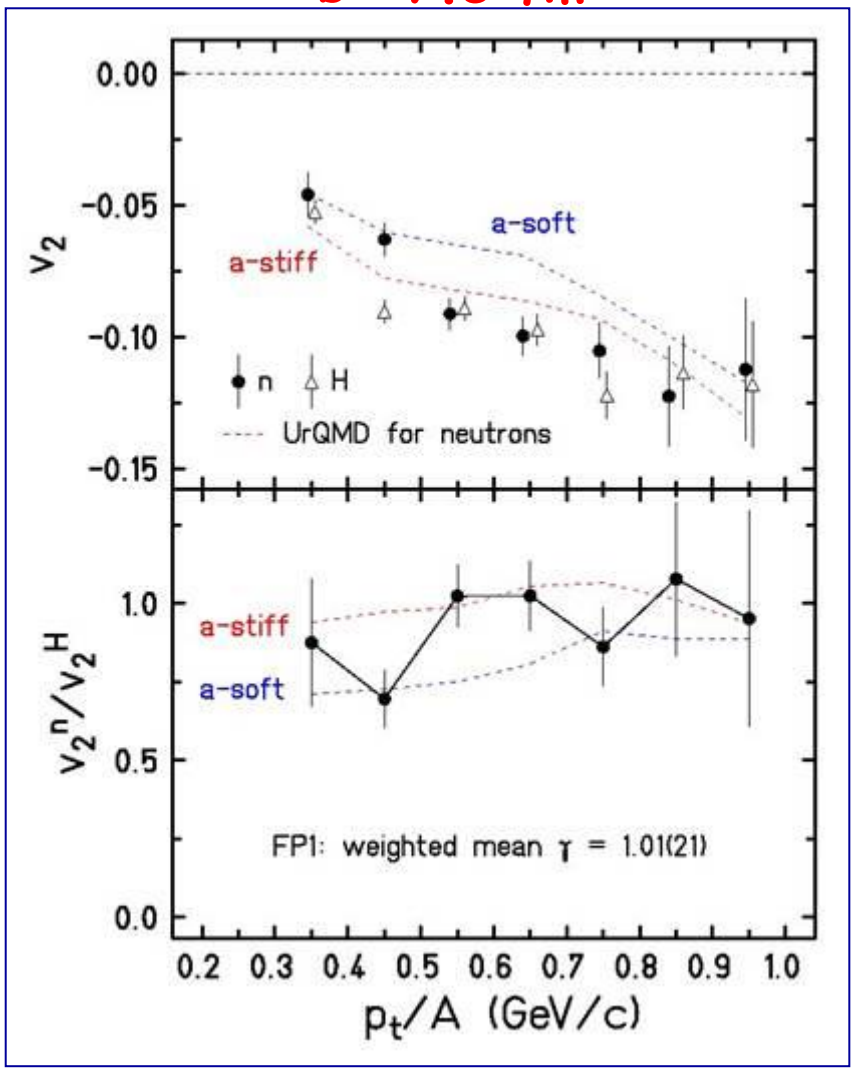


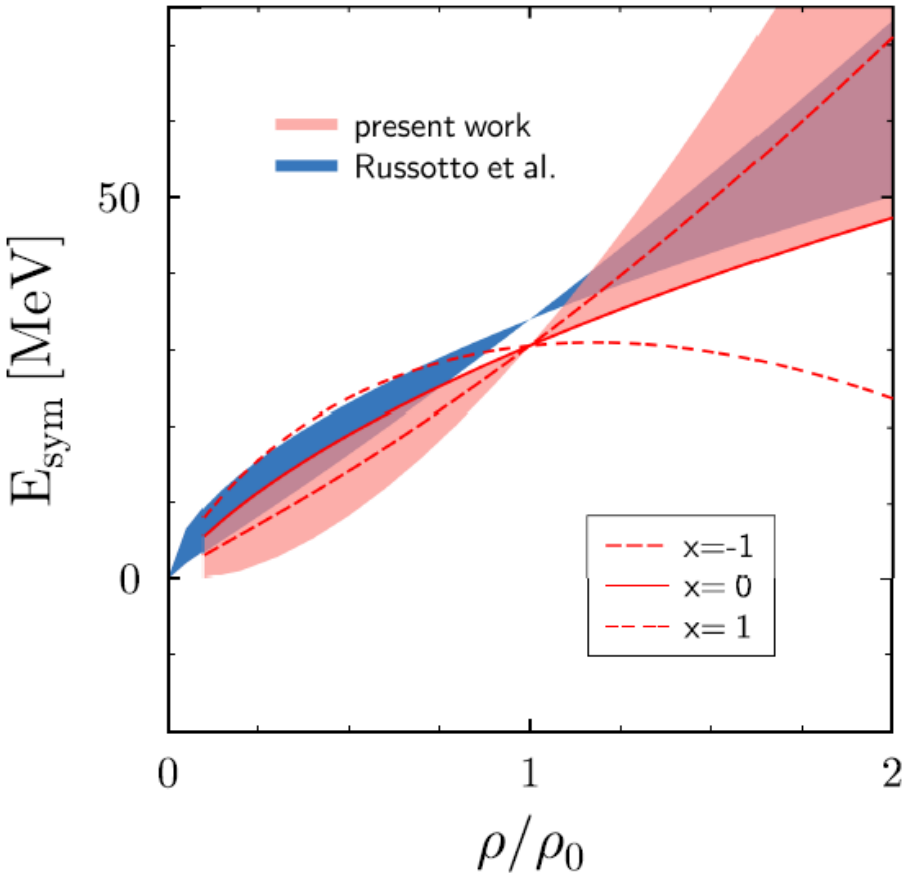
Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

Results with Tübingen QMD

UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS
momentum independent power-law
parameterization of the symmetry energy

Tübingen-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets
momentum dependent (Gogny inspired)
parameterization of the symmetry energy

M.D. Cozma, PLB 700, 139 (2011);
arXiv:1102.2728



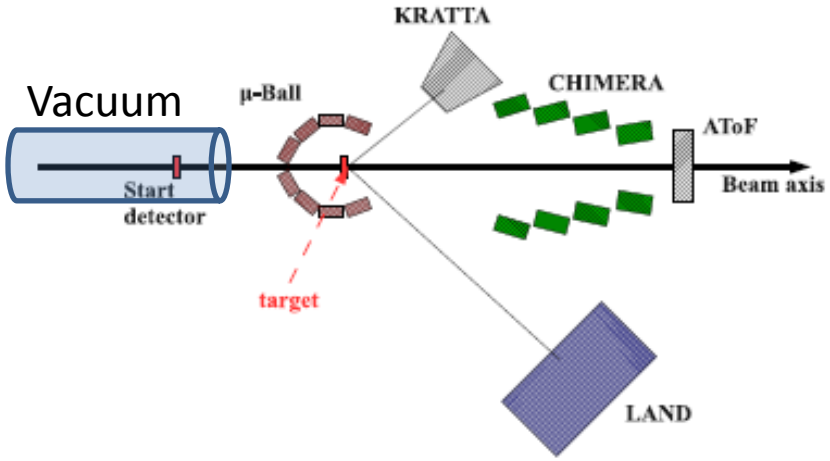
M.D. Cozma et al., Towards a model-independent constraint of the high-density dependence of the symmetry energy

arXiv:1305.5417 [nucl-th] PRC88 044912 (2013)

x = -1.0±1.0

ASY-EOS S394 experiment @ GSI Darmstadt (May 2011)

Au+Au, ^{96}Zr+^{96}Zr , ^{96}Ru+^{96}Ru @ 400 AMev



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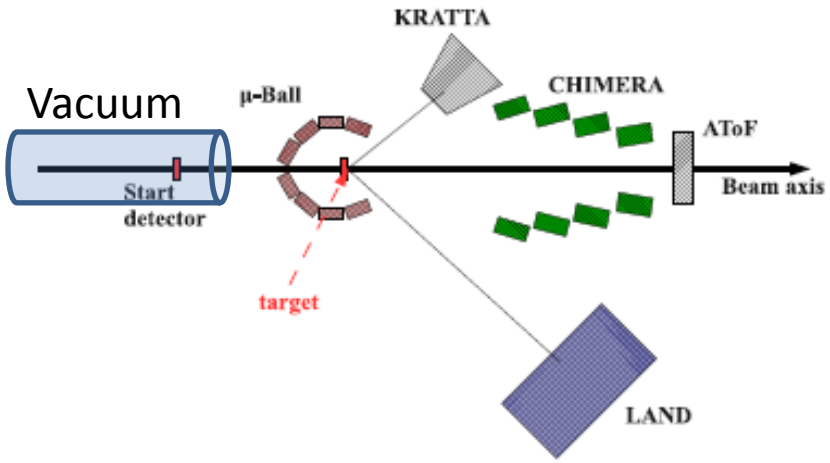

TOFWALL: **96 plastic bars; ToF, ΔE, X-Y position. Trigger, impact parameter and reaction plane determination**

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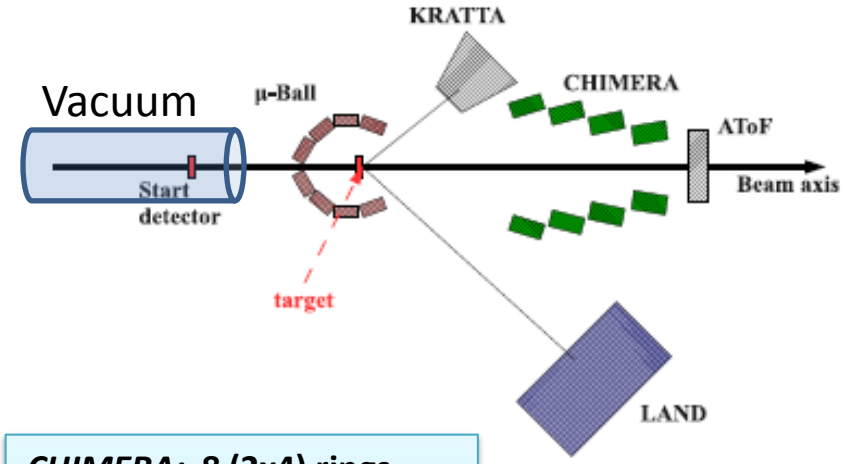

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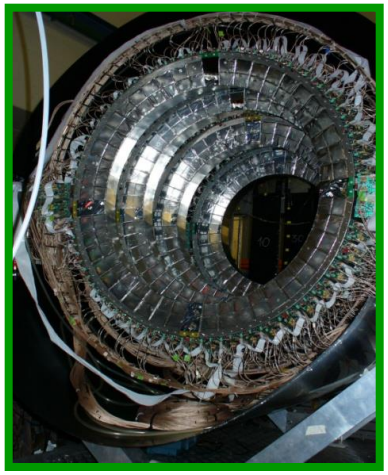

CHIMERA: **8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. Multiplicity, Z, A, Energy: impact parameter and reaction plane determination**

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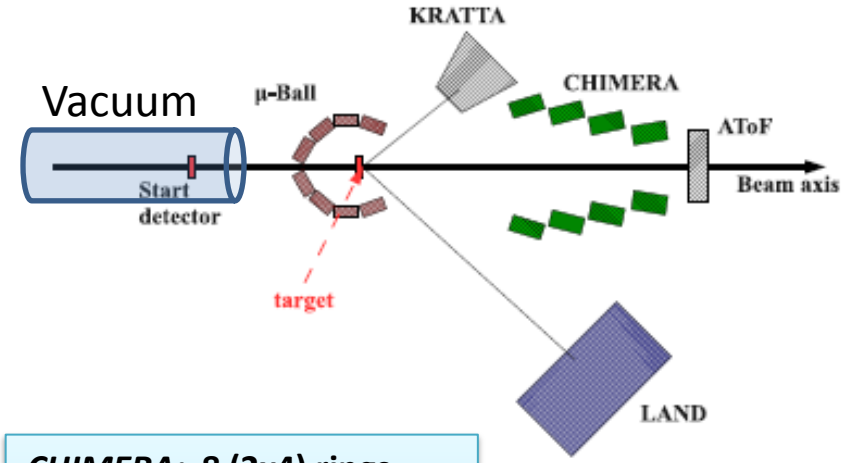

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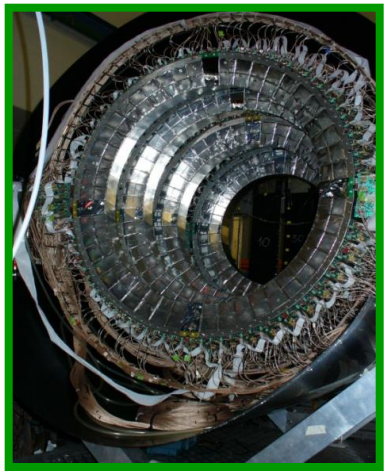

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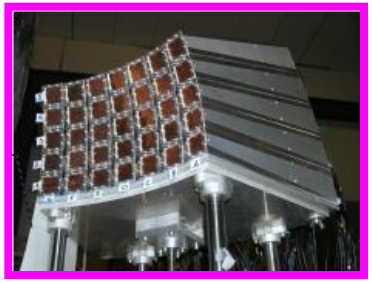
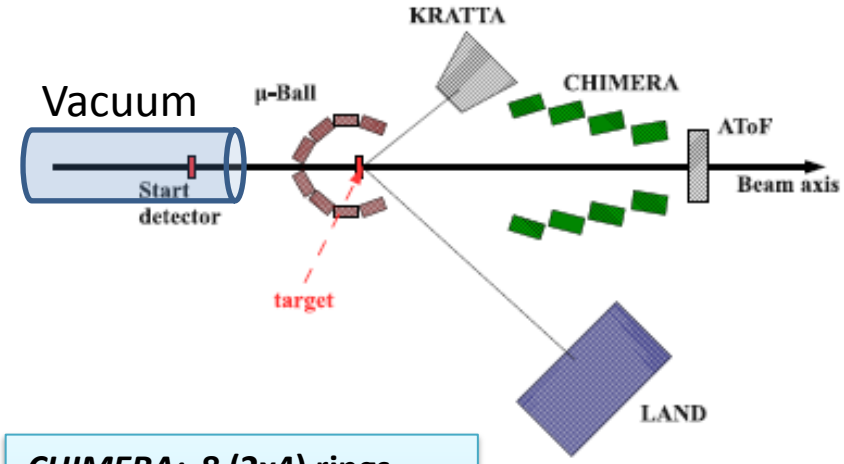


KraTTA: 35 (5x7) triple telescopes (Si-CsI-CsI) placed at 21°<Θ<60° with digital readout . Light particles and IMFs emitted at midrapidity



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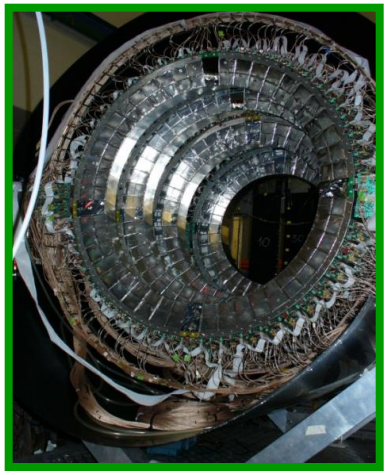

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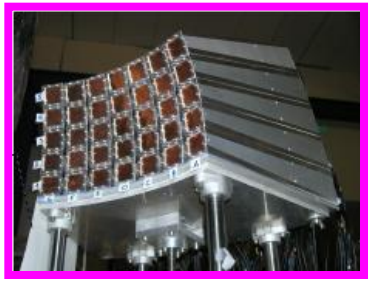

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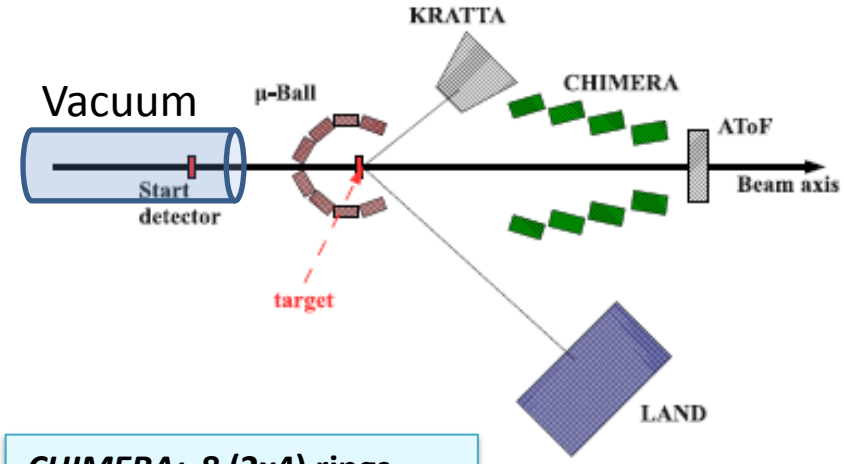

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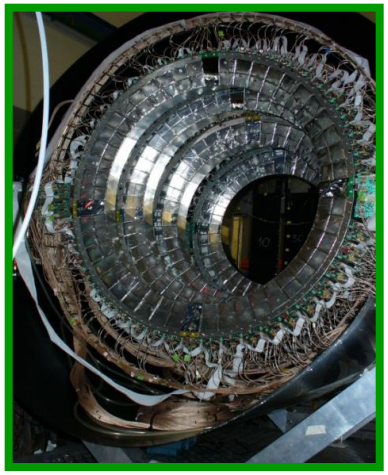

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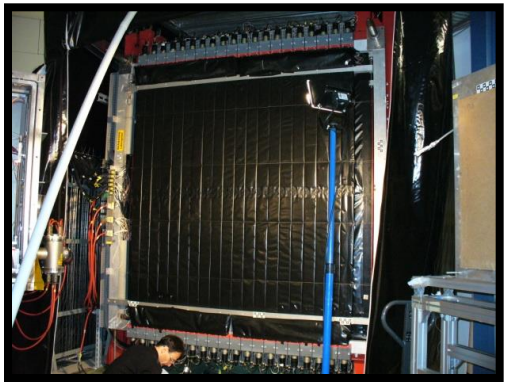

LAND: Large Area Neutron Detector . Plastic scintillators sandwiched with Fe 2x2x1 m^3 plus plastic veto wall. New Taquila front-end electronics. Neutrons and Hydrogen detection. Flow measurements

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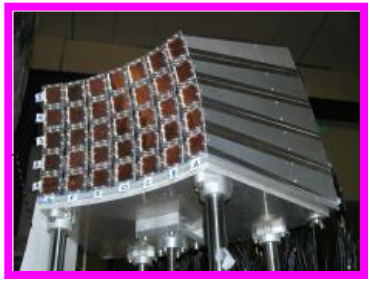

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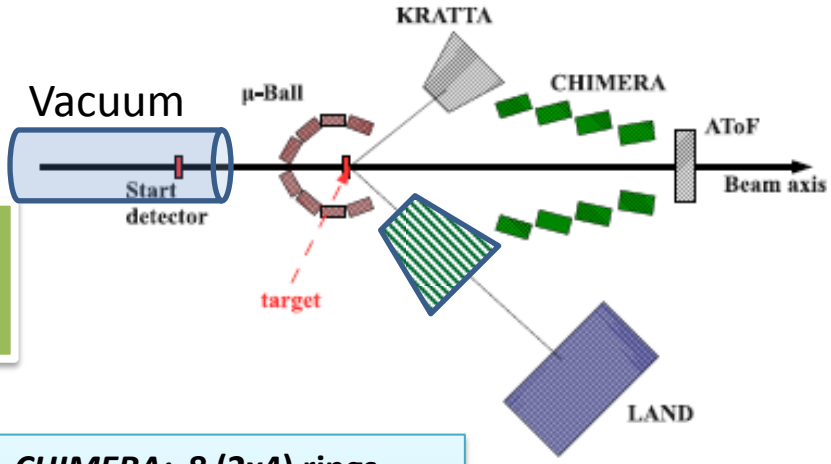
Shadow bar: evaluation of background neutrons in LAND



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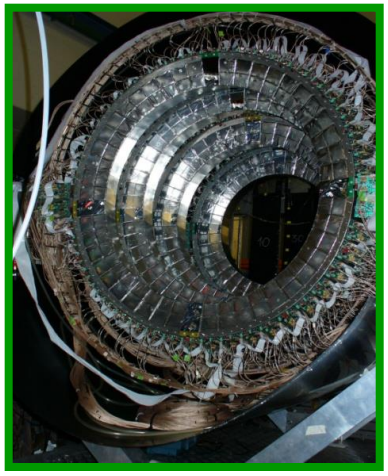

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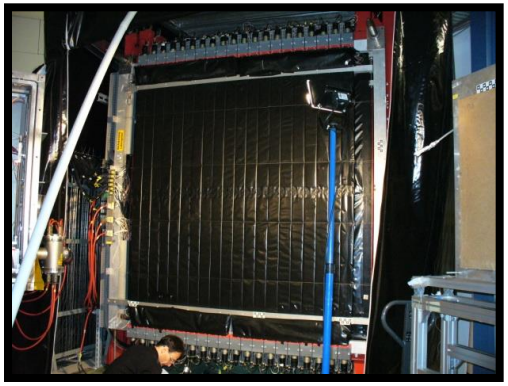

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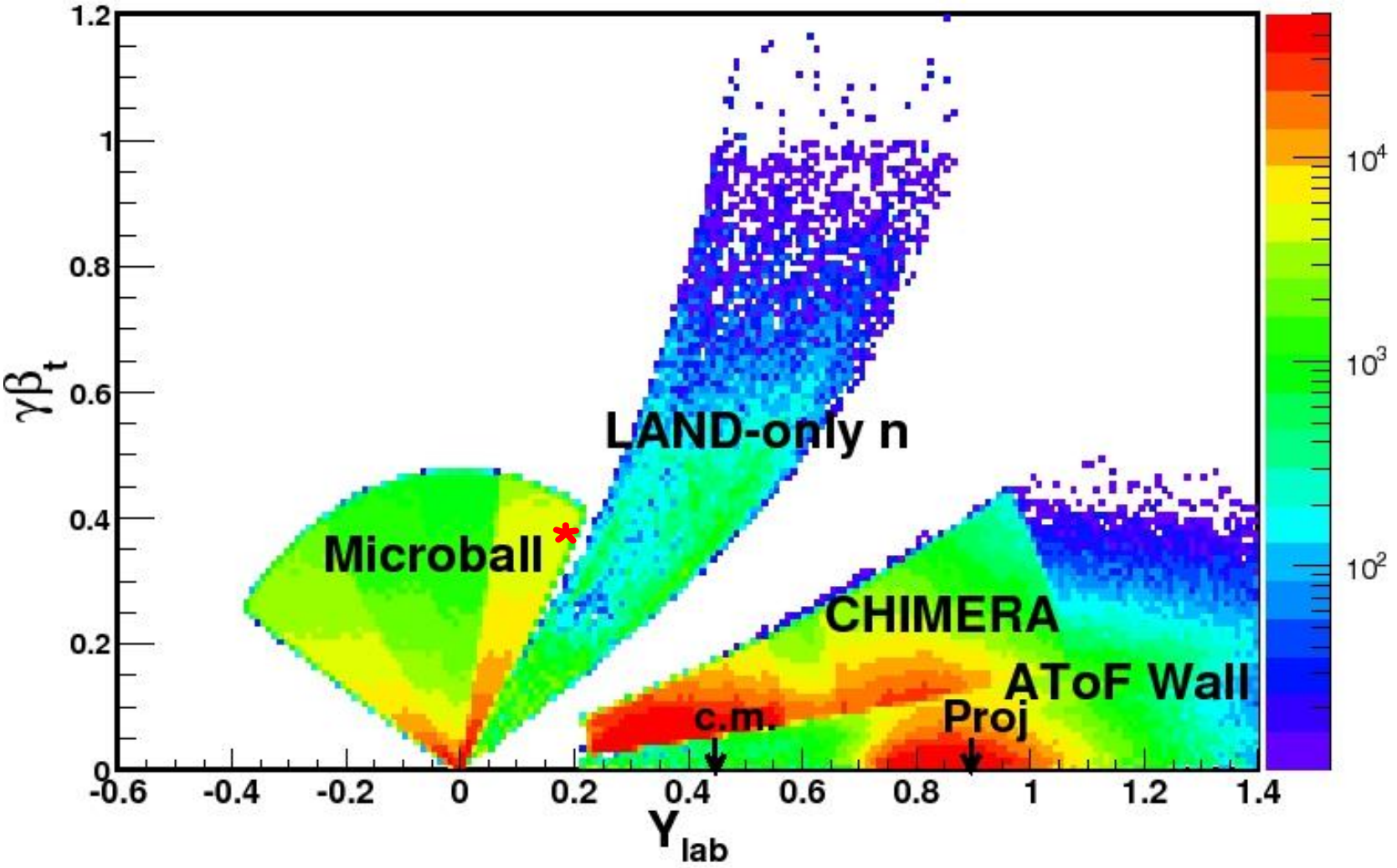
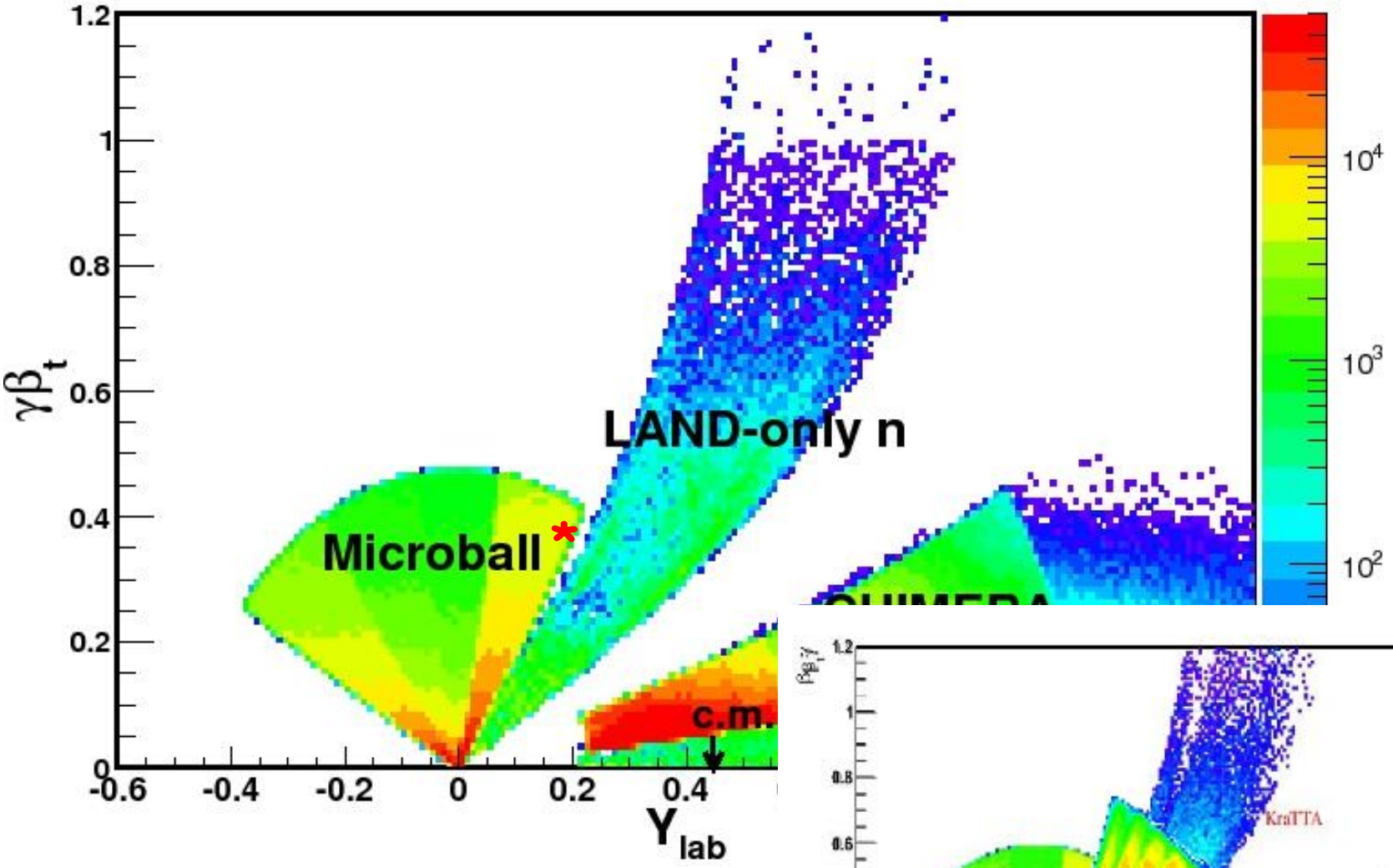
Au+Au @ 400 A.MeV: Some kinematics

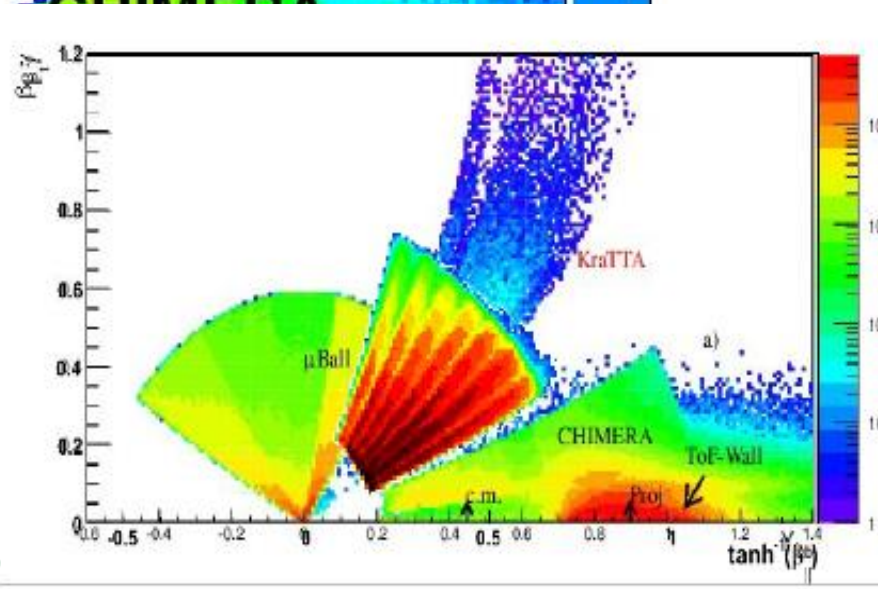


* Random uniform distribution EKin<100 Mev

P. Russotto et al., EPJA 50, 38 2014.
P. Russotto et al., Procs. of INPC2013, EPJ Web of Conf.
P. Russotto et al., Journal of Phys. Conf. Series 420, 012092, (2013)

Au+Au @ 400 A.MeV: Some kinematics

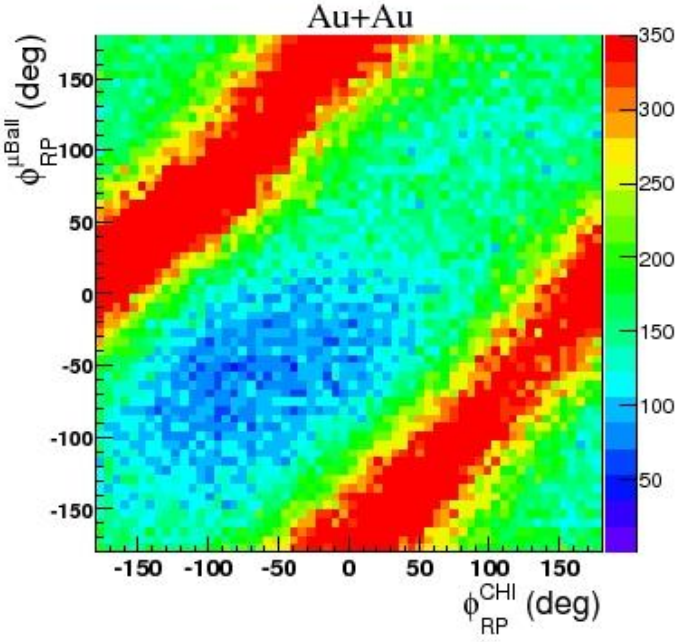


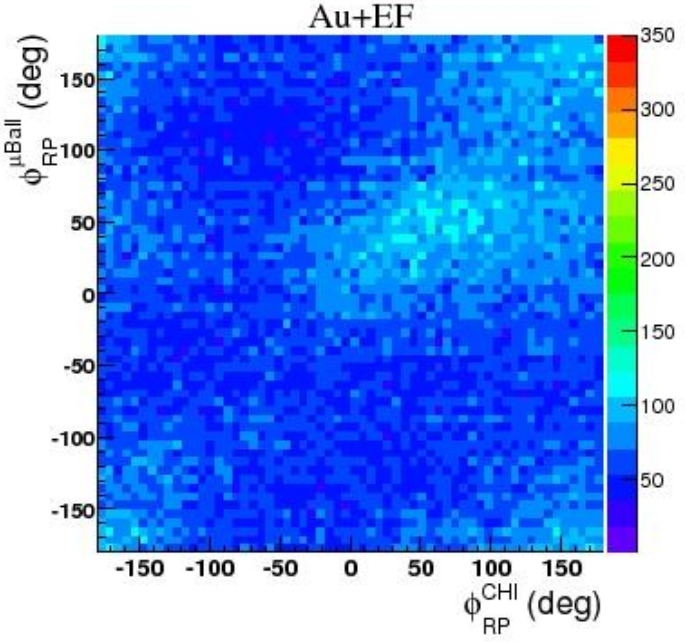


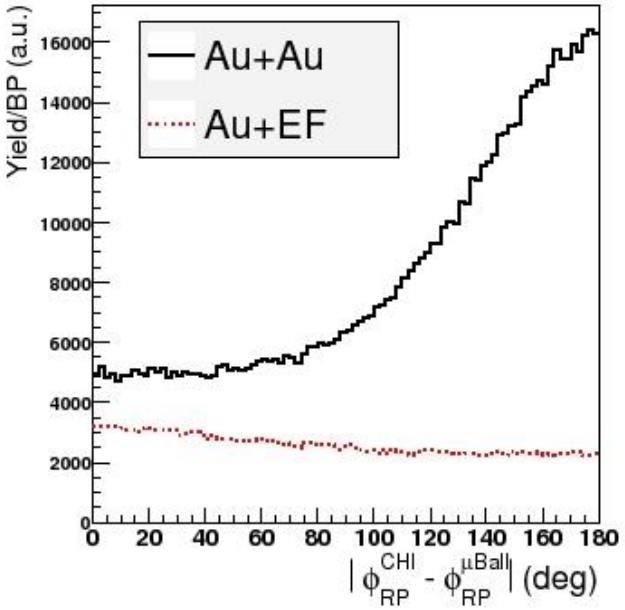
* Random uniform distribution EKin<1C

P. Russotto et al., EPJA 50, 38 2014.
P. Russotto et al., Procs. of INPC2013, EPJ Web of Conf.
P. Russotto et al., Journal of Phys. Conf. Series 420, 012092, (2013)

Au+Au @ 400 A.MeV: Background rejection







CHIMERA $M(Y_{cm}>0.1) \geq 4$

$$\vec{Q} = \sum_{i=1}^{M} w_i Z_i \gamma \vec{\beta}_t^{\,i} \qquad w_i = \begin{cases} 1 & \text{for } Y_{cm}>0.1 \\ 0 & \text{for } Y_{cm}<0.1 \end{cases}$$

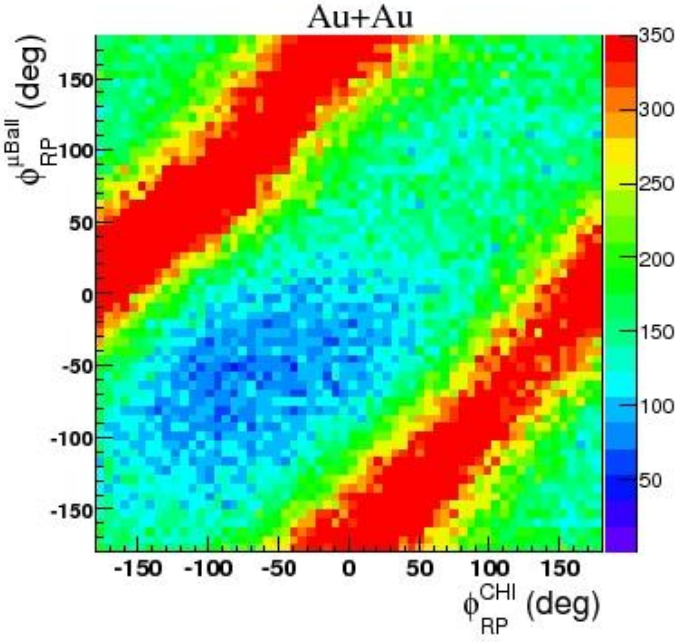
μBall $M \geq 2$

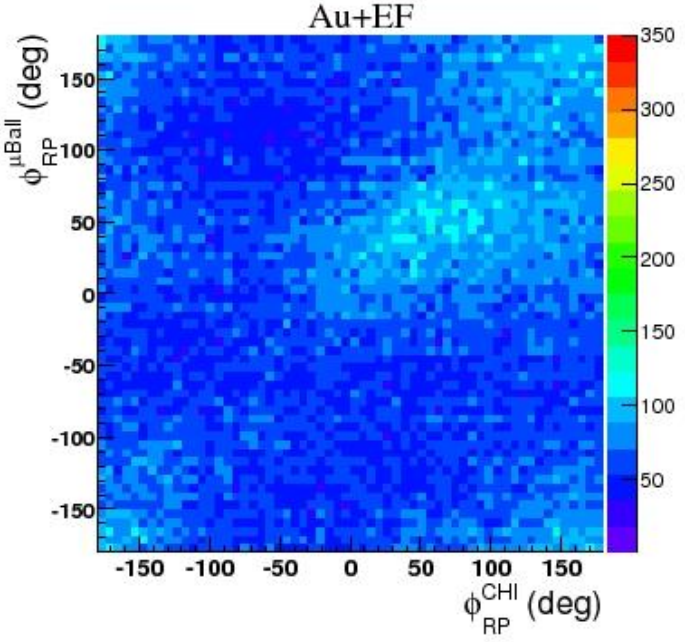
$$\vec{Q} = \sum_{i=1}^{M} \hat{r}_t^{\,i}$$

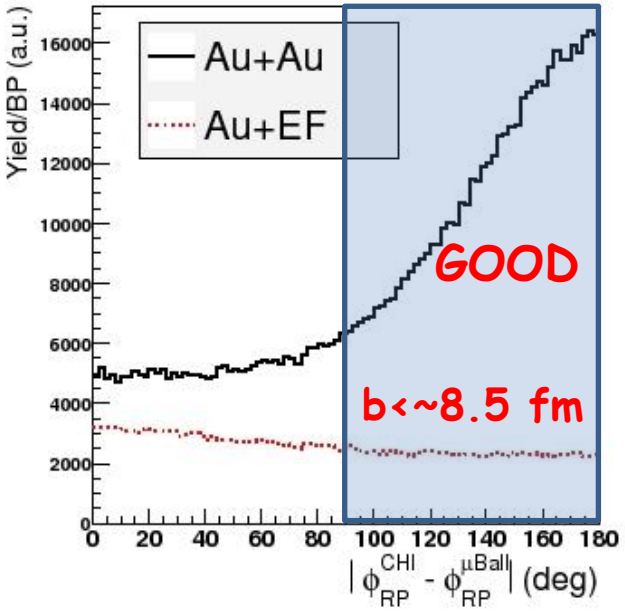
ad. from P. Danielewicz et al., PLB 1985

From MI28022014

Au+Au @ 400 A.MeV: Background rejection







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μBall $M \geq 2$

$$\vec{Q} = \sum_{i=1}^{M} \hat{r}_t^{\,i}$$

ad. from P. Danielewicz et al., PLB 1985

From MI28022014

Comparing ASY-EOS with FOPI: rapidity dep. of charged particles

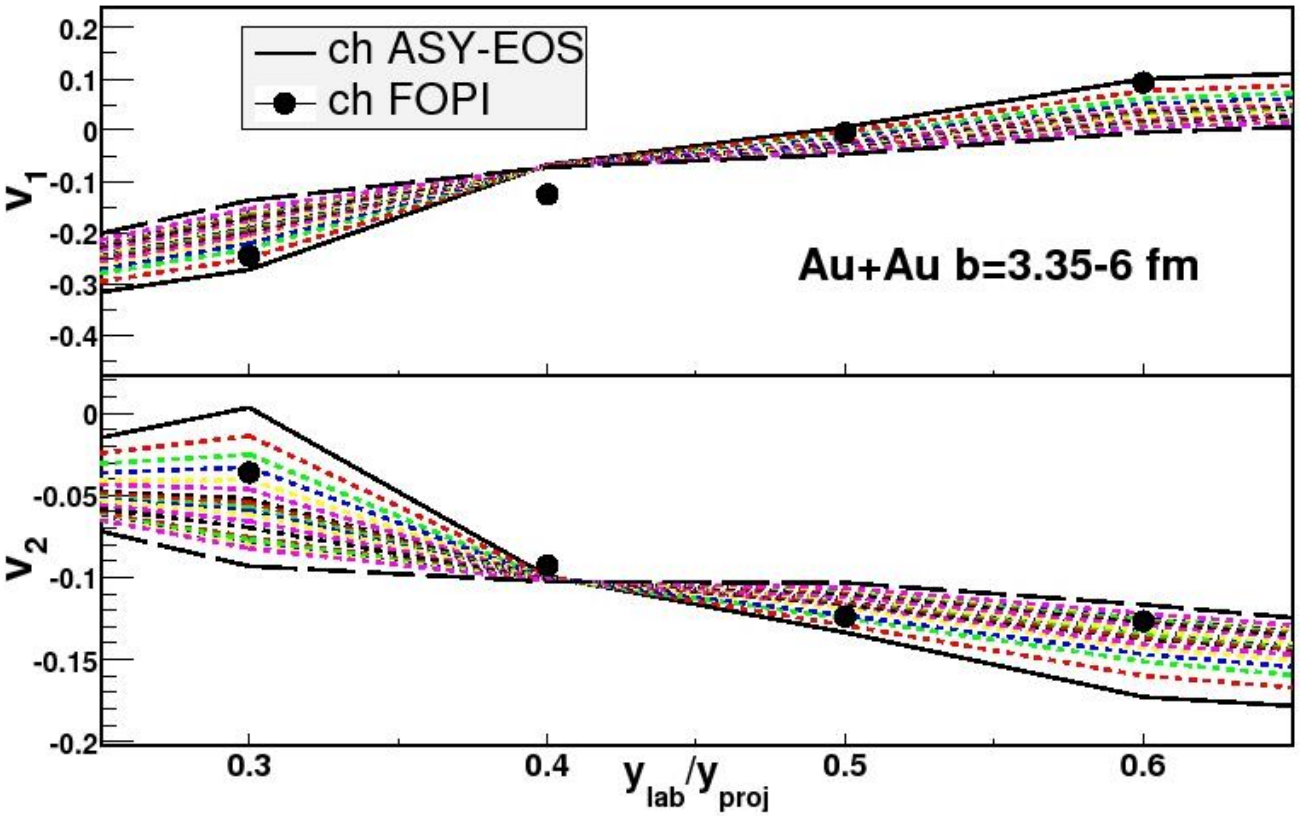
Main uncertainty due to timing problems in LAND:
ToF ±25 ns

Au+Au @ 400 A.MeV

3.35<b<6 fm (c2)

θ_{lab} cut as LAND in ASY-EOS exp

Courtesy of W. Reisdorf

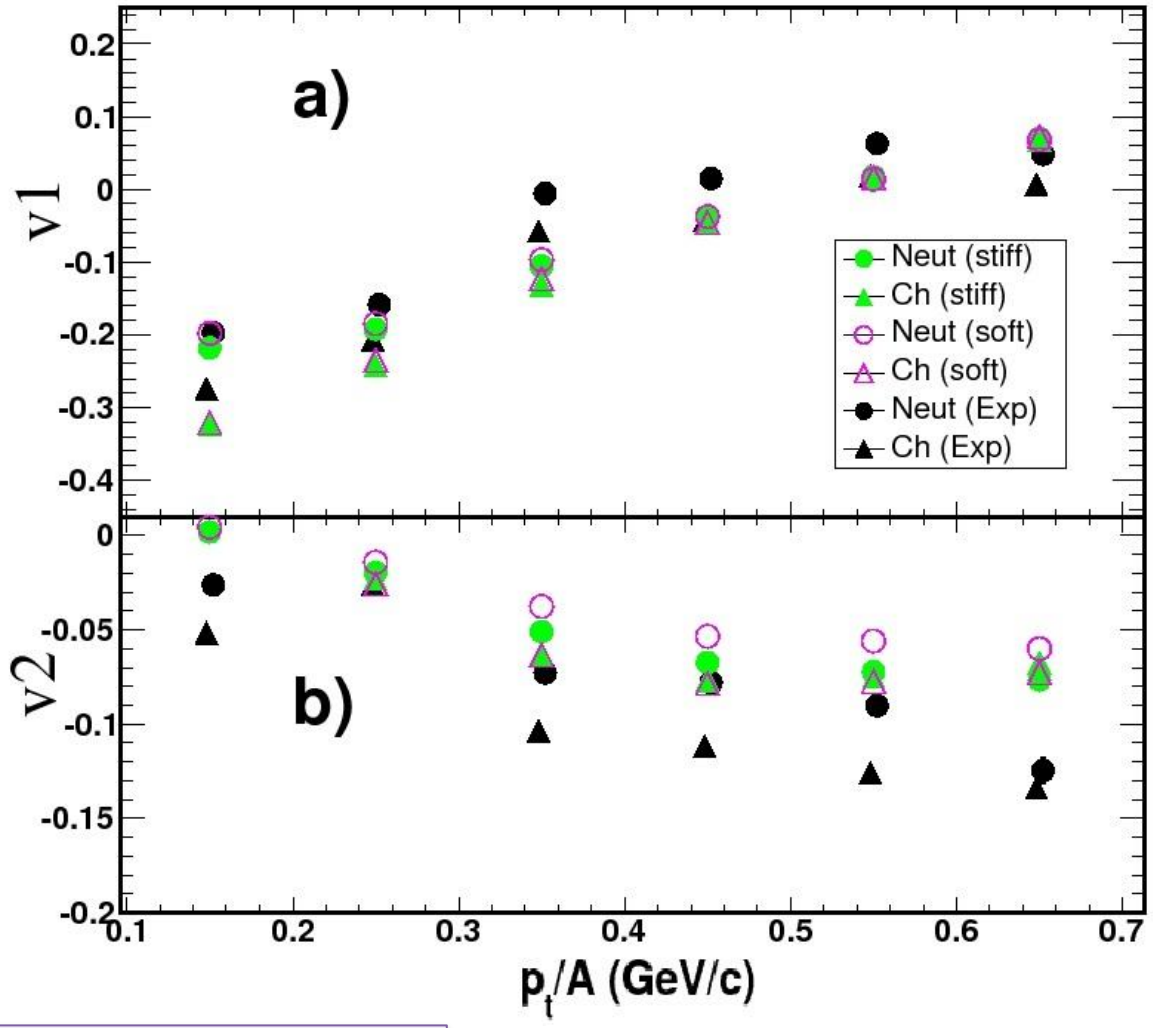


Comparison with UrQMD

Au+Au @ 400 AMeV b<7.5 fm

Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

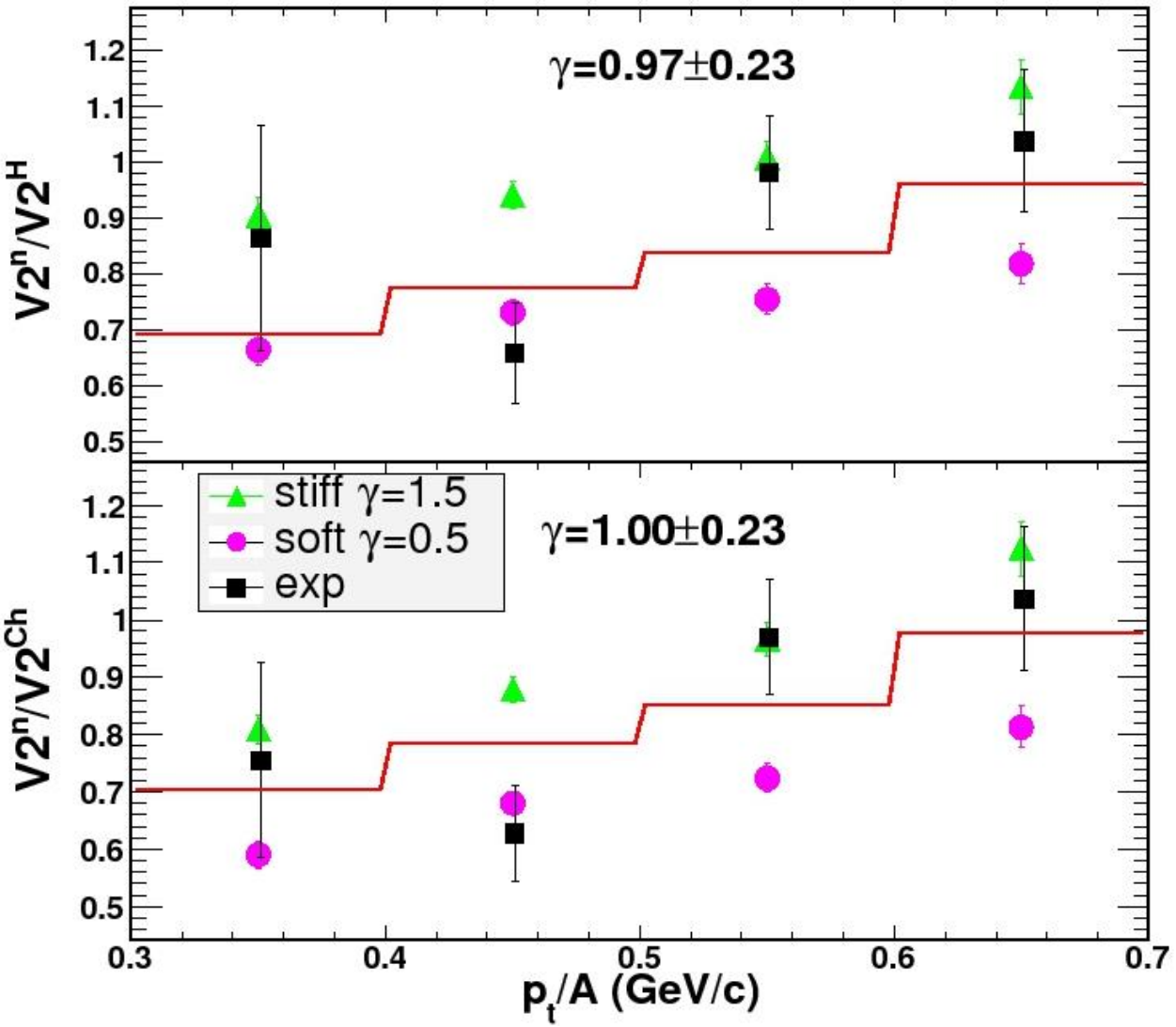
Charged Particles:
(Au+Au)-(Au+EF)



Only charged particles!!!

V2n/V2H vs V2n/V2ch

Au+Au @ 400 AMeV b<7.5 fm
but
FOPI-LAND data compared with UrQMD

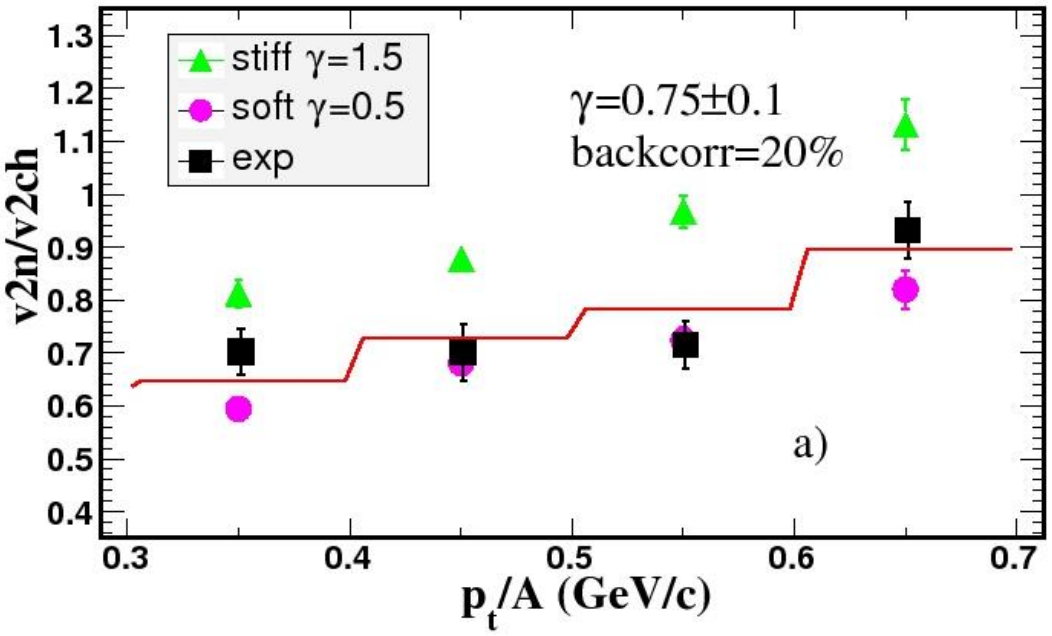


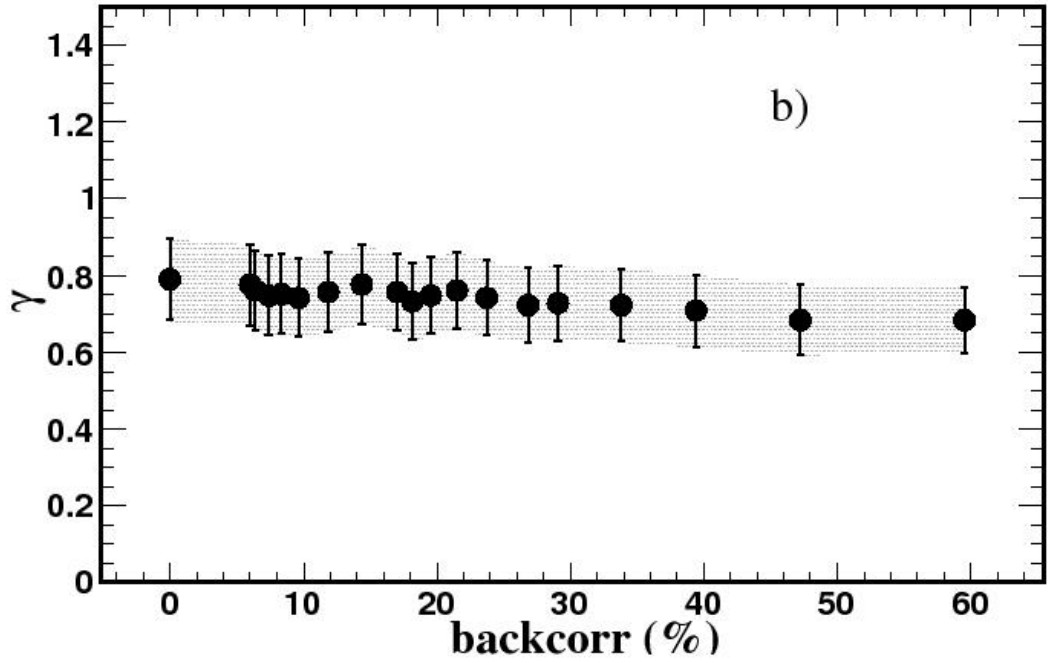
Gamma extrapolation I

Au+Au @ 400 AMeV
b<7.5 fm

Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

Charged Particles:
(Au+Au)-(Au+EF)





Gamma extrapolation II

Au+Au @ 400 AMeV
b<7.5 fm

Neutrons:
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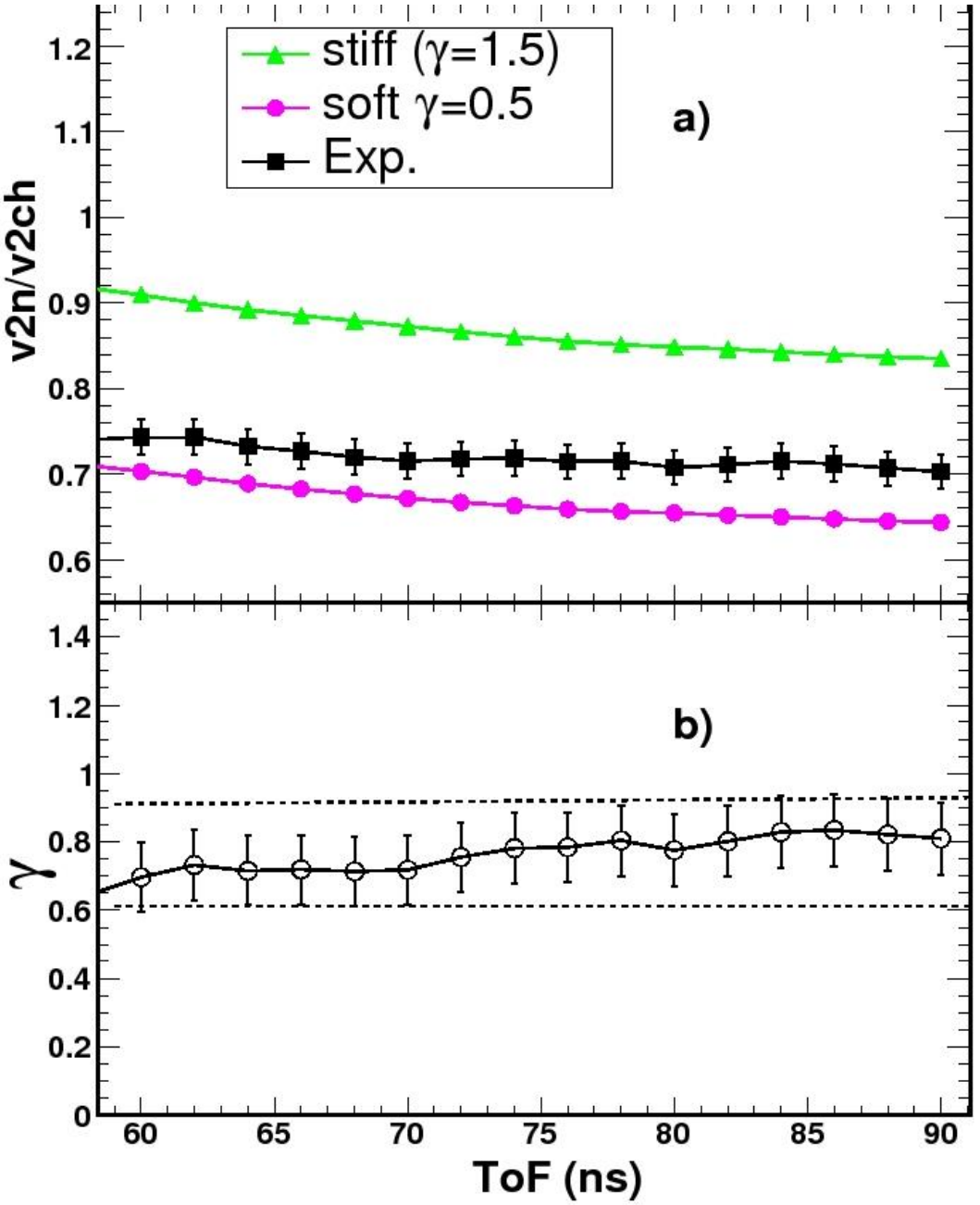
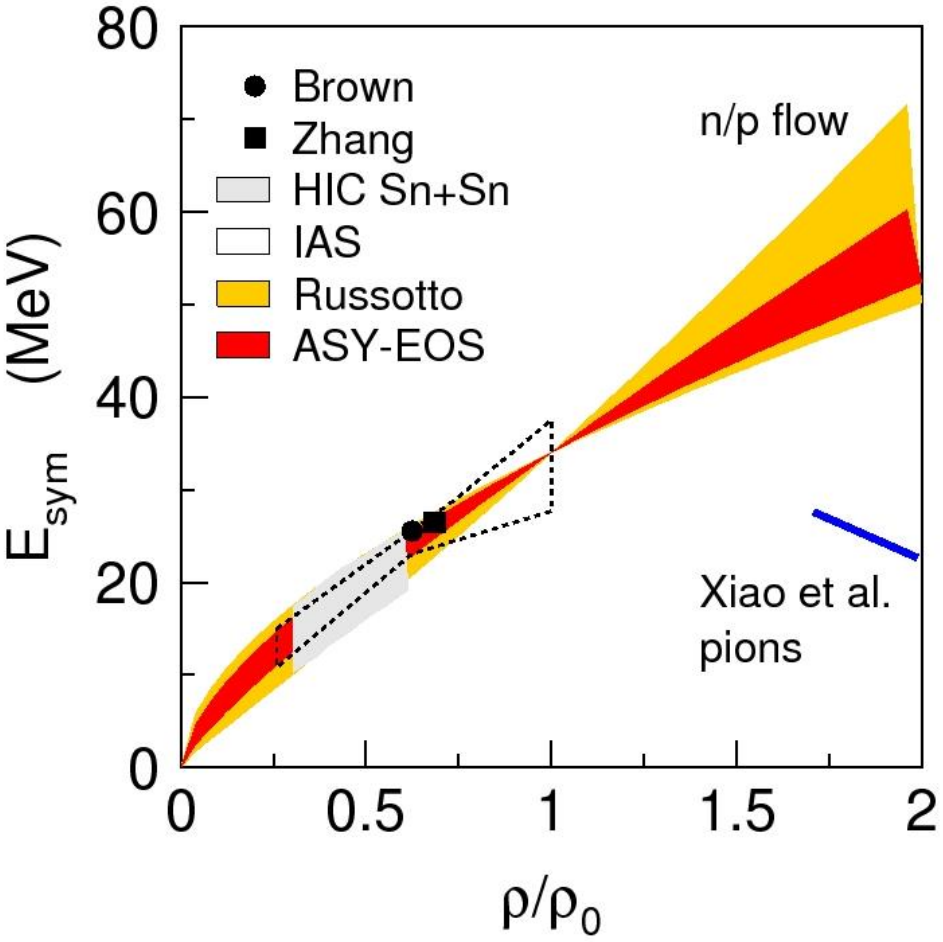
-(Au+EF)+(Au+EF with SB)

Charged Particles:
(Au+Au)-(Au+EF)



Our (probably) final result…

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \ldots,$$



Adapted from "roadmap" paper, C. Horowitz et al, J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001

HIC: (mainly Isospin diffusion for Sn+Sn) M.B. Tsang et al., PRC 86, 015803 (2012)

neutron skin thickness, binding energies,….: B.A. Brown, PRL 111, 232502 (2013); Zhang and Chen, Phys. Lett. B 726 (2013).

FOPI DATA : P.Russotto et al., Phys. Lett. B 697 (2011)

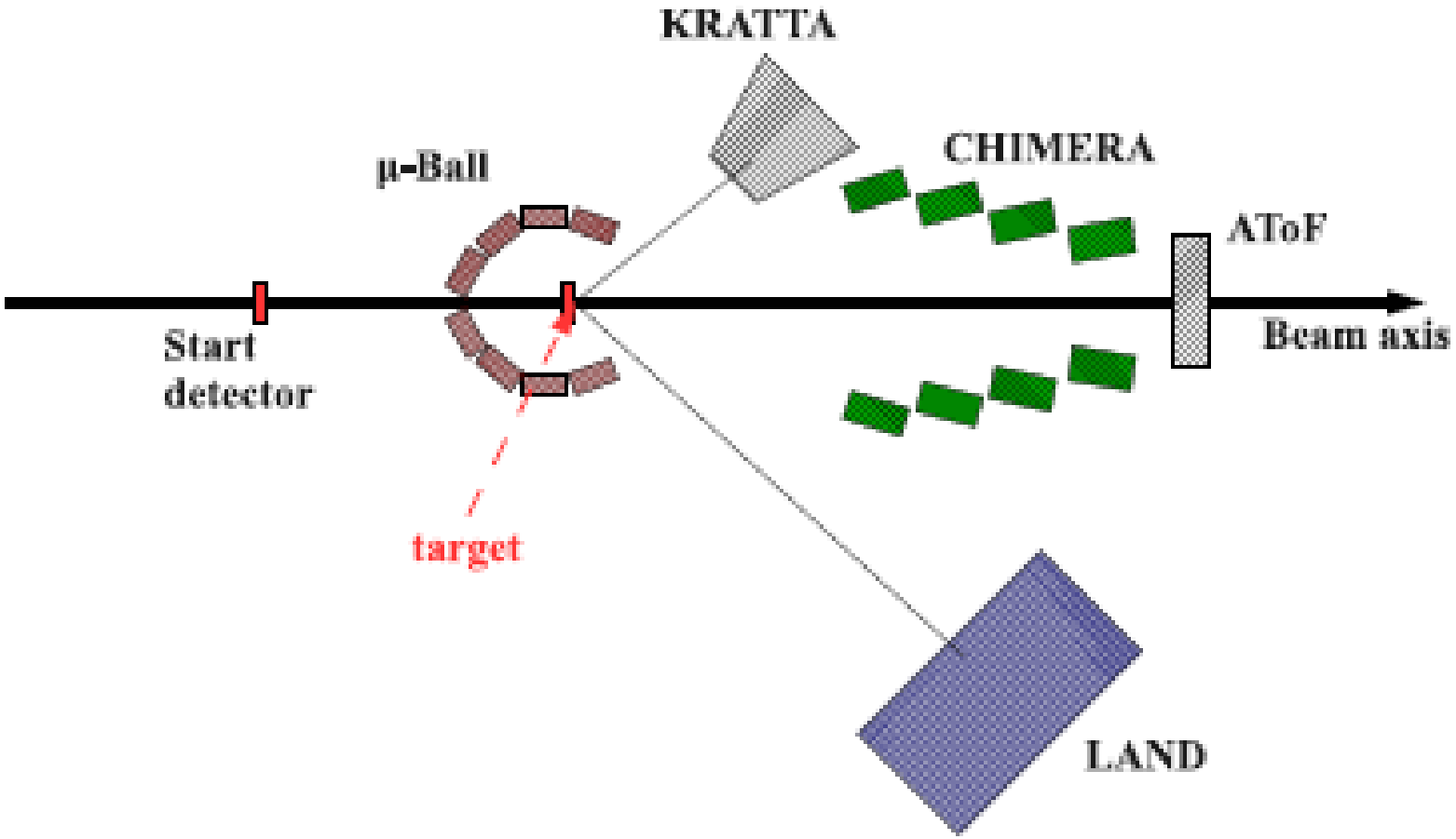
$\gamma = 0.9 \pm 0.4$; L=83±26

ASYEOS DATA: THIS WORK

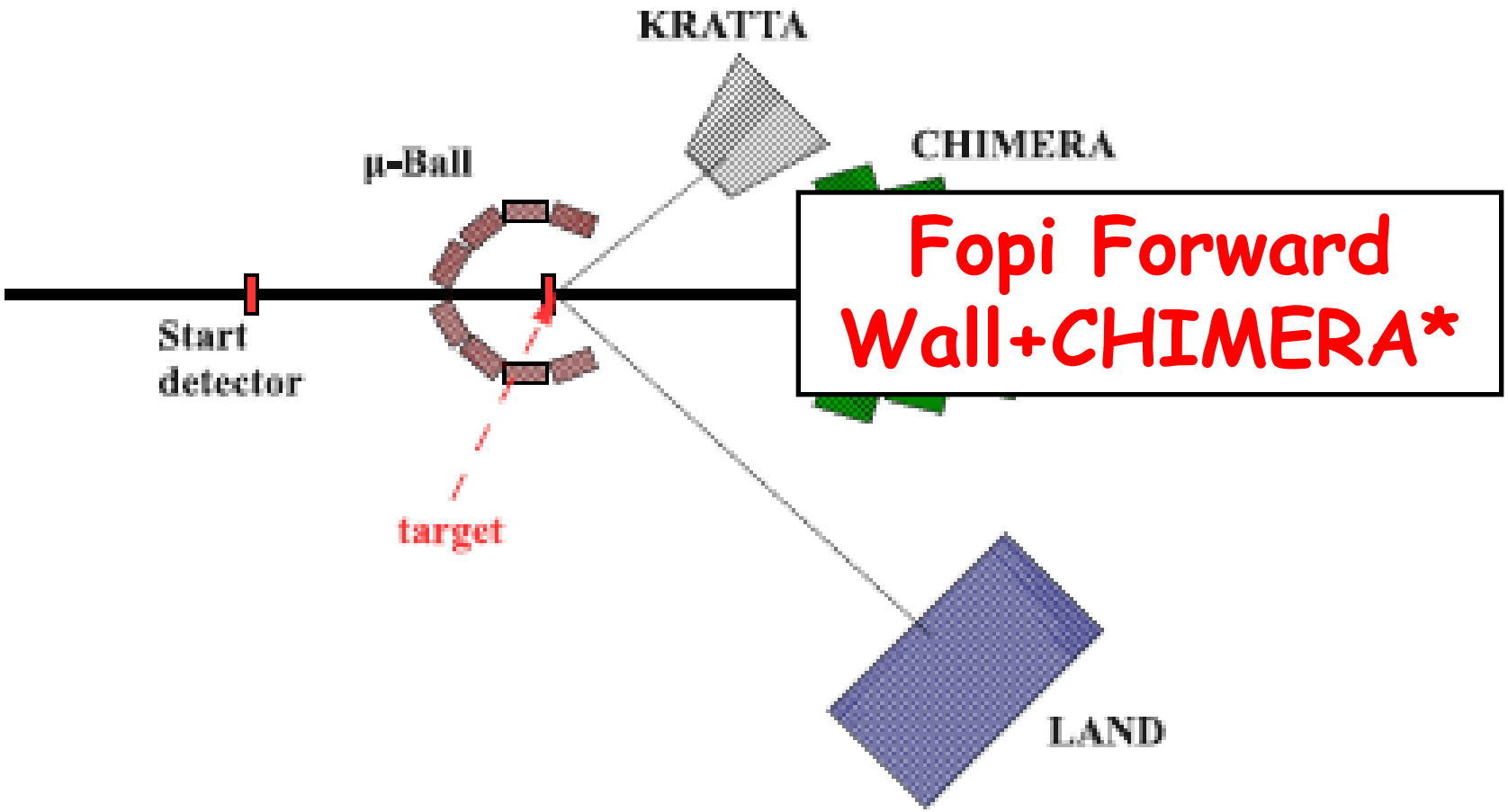
$\gamma = 0.75 \pm 0.20$; L=73±13

preliminary

ASY-EOS future set-up?



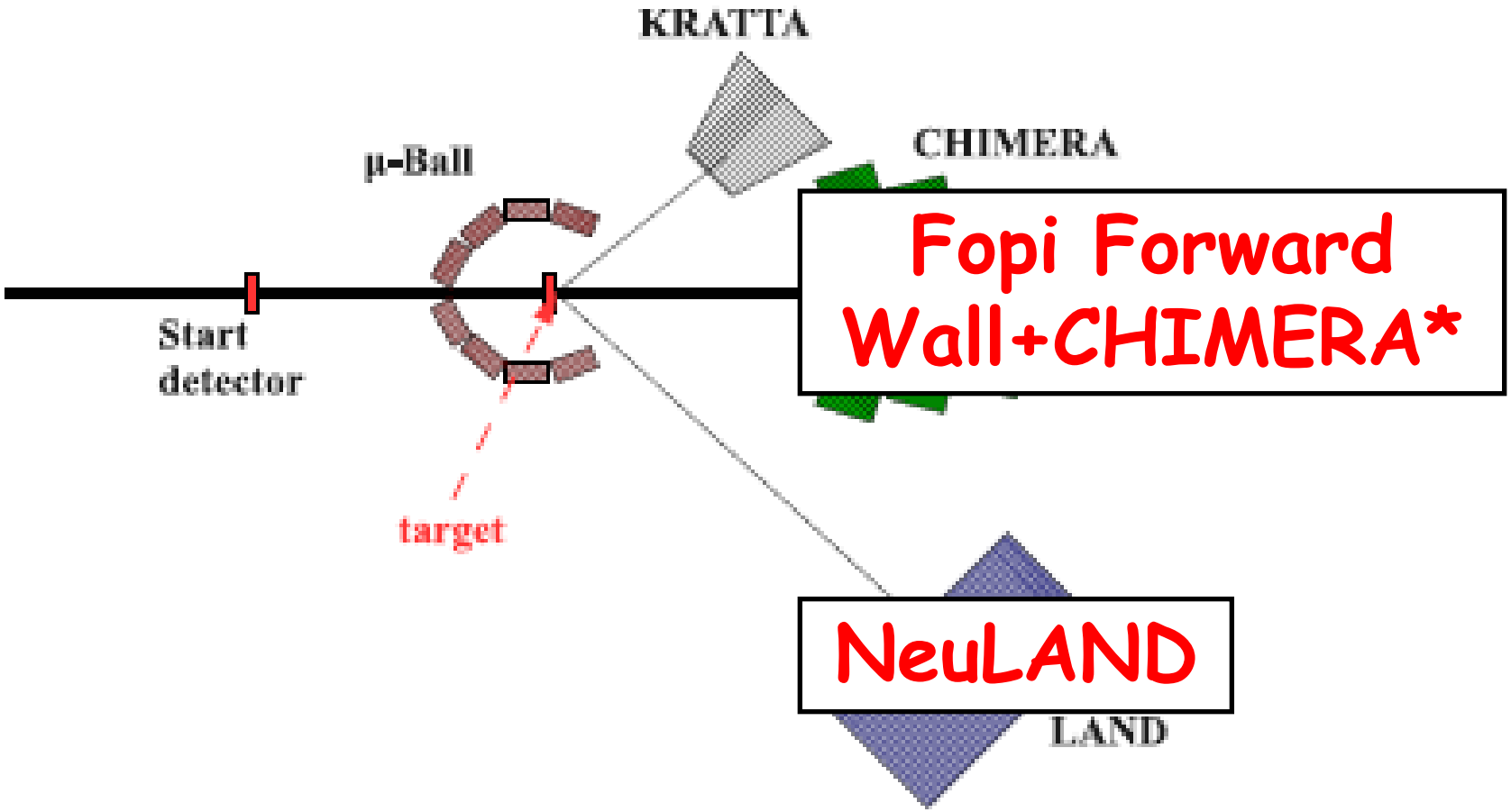
ASY-EOS future set-up?



Fopi Forward Wall+CHIMERA*

* Ring 1-2-3 (θ<7°)

ASY-EOS future set-up?



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(θ<7°)

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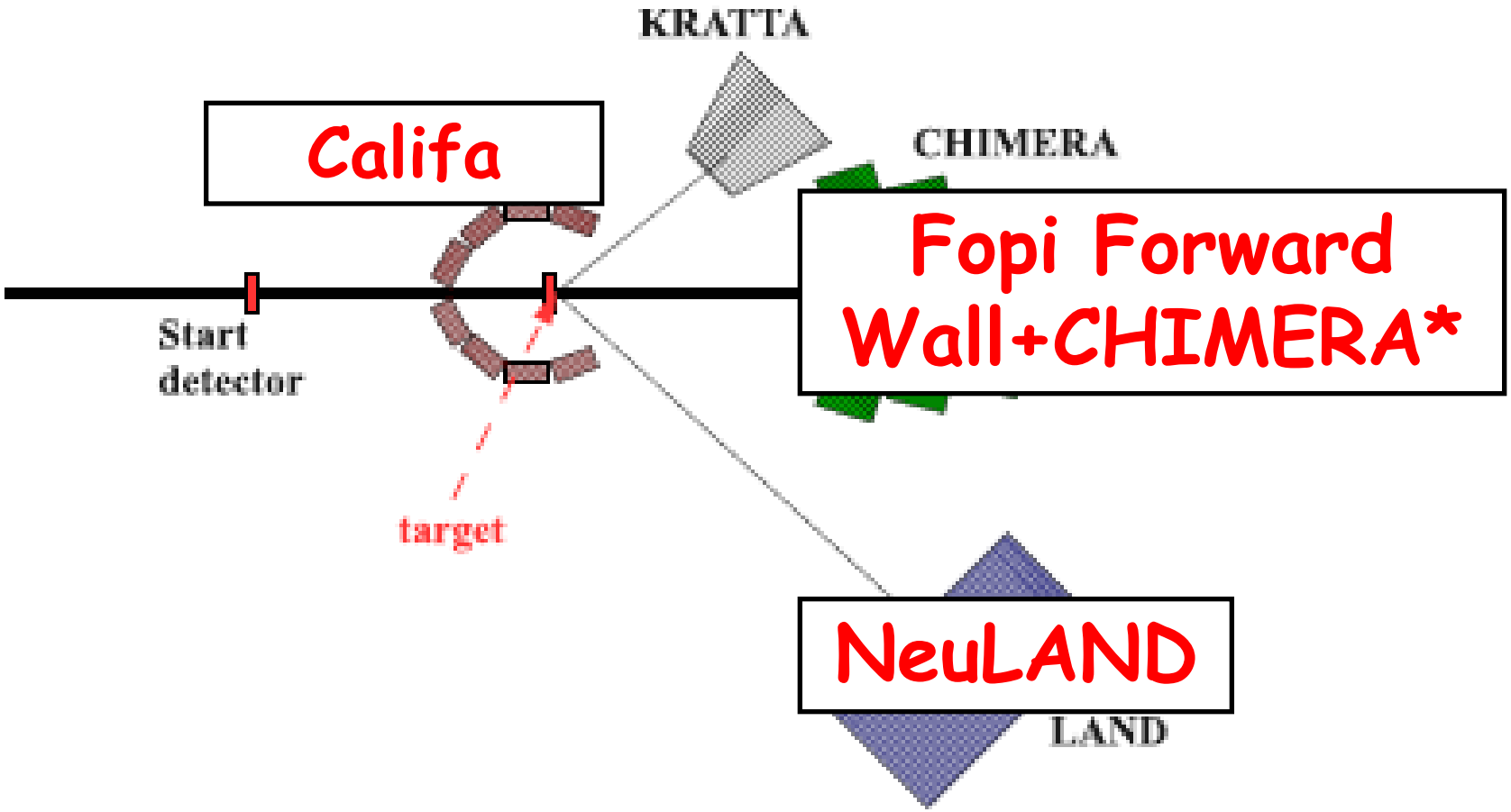

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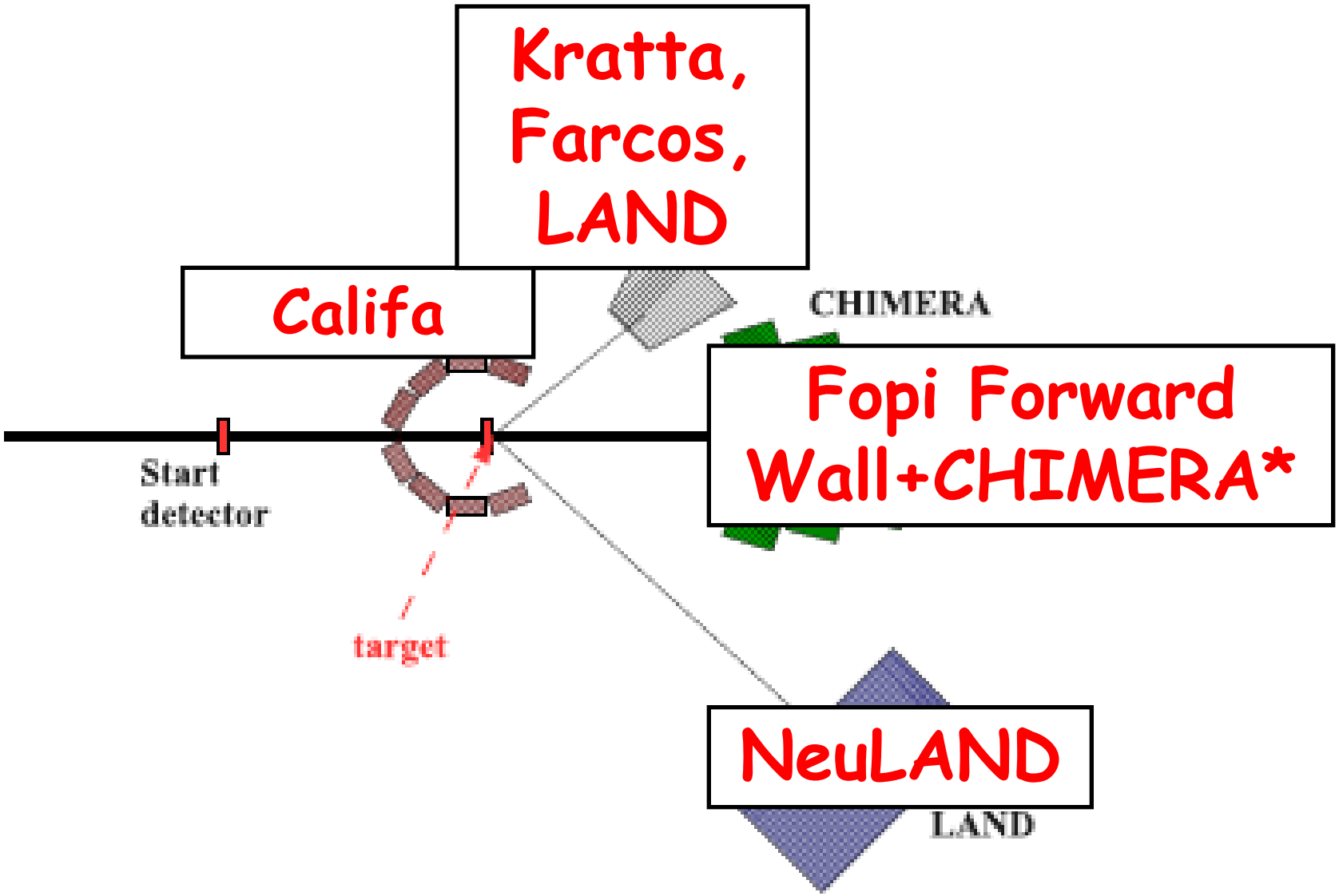
ASY-EOS future set-up?



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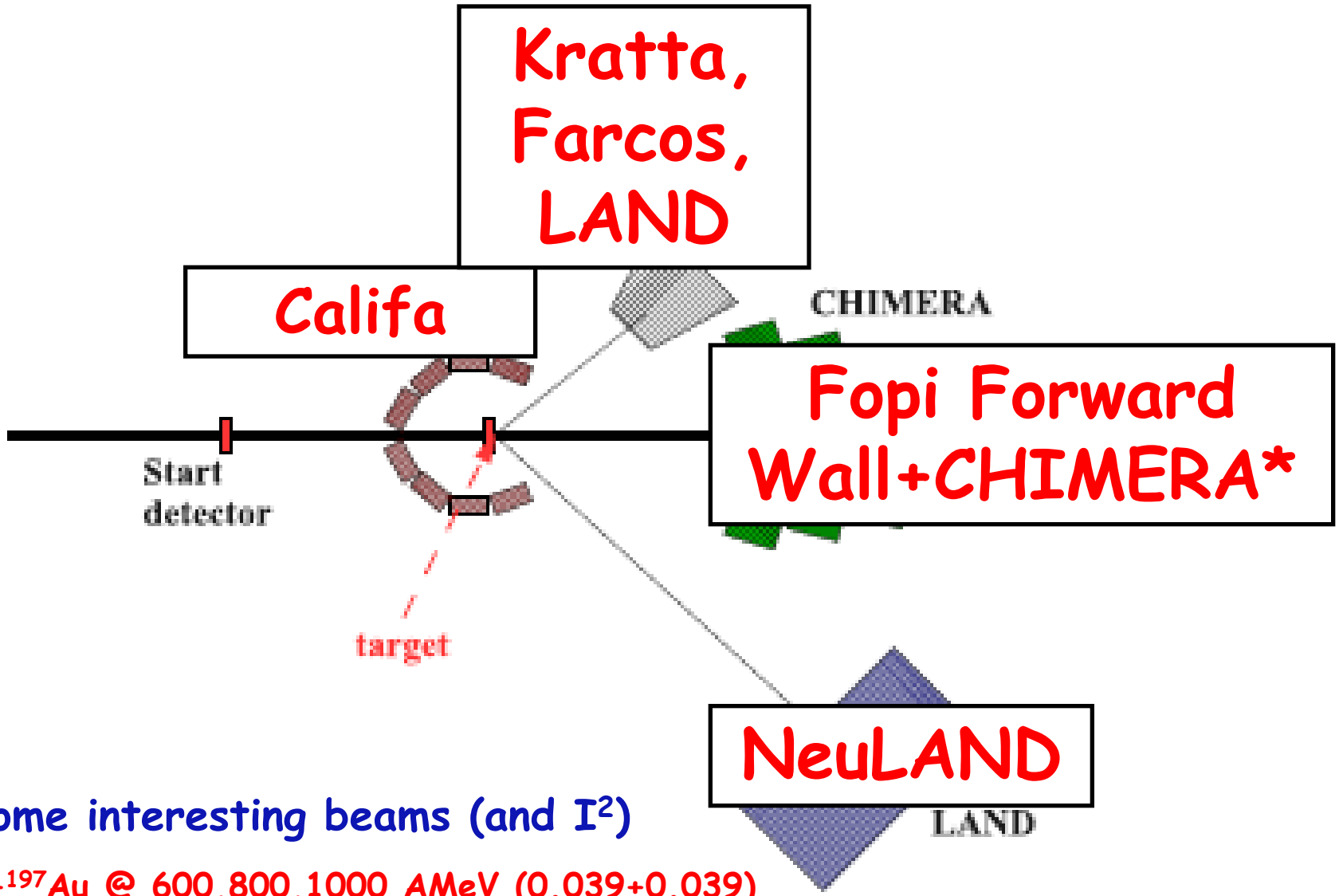
ASY-EOS future set-up?



Some interesting beams (and I^2)

$^{197}Au+^{197}Au$ @ 600,800,1000 AMeV (0.039+0.039)

$^{132}Sn+^{124}Sn$ @ 400, 800, 1000 AMeV (0.059+0.037)

$^{106}Sn+^{112}Sn$ @ 400, 800, 1000 AMeV (0.003+0.011)

* Ring 1-2-3 ($\theta<7°$)

Conclusions

Symmetry Energy:

- Low densities: several constraints quite consistent
- High density:
  - pion constraints not consistent
  - n/p flows suggests…a route "Towards a model-independent constraint of the high-density dependence of the symmetry energy"
  - Finalizing ASY-EOS data analysis is in progress
- Work on code consistency needed…everywhere
- New and better experiments on n,p flows and ratio, pions and kaons, also with high asymmetric beams (e.g. ^{132}Sn) and new detectors (Riken TPC, NeuLand@R3B)
- International collaborations and efforts

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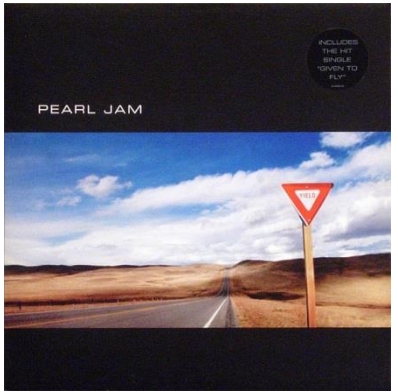
On the road…..



The Asy-Eos Collaboration

P. Russotto[1,a], M. Chartier[2], M.D. Cozma[3], E. De Filippo[1], A. Le Fèvre[4], S. Gannon[2], I. Gašparić[5,6], M. Kiš[4,5], S. Kupny[7], Y. Leifels[4], R.C. Lemmon[8], Q. Li[9], J. Łukasik[10], P. Marini[11,12], P. Pawłowski[10], S. Santoro[13,14], W. Trautmann[4], M. Veselsky[15], L. Acosta[16], M. Adamczyk[7], A. Al-Ajlan[17], M. Al-Garawi[18], S. Al-Homaidhi[17], F. Amorini[16], L. Auditore[13,14], T. Aumann[6], Y. Ayyad[19], V. Baran[16,20], Z. Basrak[5], R. Bassini[21], J. Benlliure[19], C. Boiano[21], M. Boisjoli[12], K. Boretzky[4], J. Brzychczyk[7], A. Budzanowski[10], G. Cardella[1], P. Cammarata[11], Z. Chajecki[22], A. Chbihi[12], M. Colonna[16], B. Czech[10], M. Di Toro[16,23], M. Famiano[24], V. Greco[16,23], L. Grassi[5], C. Guazzoni[21,25], P. Guazzoni[21,26], M. Heil[4], L. Heilborn[11], R. Introzzi[27], T. Isobe[28], K. Kezzar[18], A. Krasznahorkay[29], N. Kurz[4], E. La Guidara[1], G. Lanzalone[16,30], P. Lasko[7], I. Lombardo[31,32], W.G. Lynch[22], Z. Matthews[3], L. May[11], T. Minniti[13,14], M. Mostazo[19], A. Pagano[1], M. Papa[1], S. Pirrone[1], R. Pleskac[4], G. Politi[1,23], F. Porto[16,23], R. Reifarth[4], W. Reisdorf[4], F. Riccio[21,25], F. Rizzo[16,23], E. Rosato[31,32], D. Rossi[4,22], H. Simon[4], I. Skwirczynska[10], Z. Sosin[7], L. Stuhl[29], A. Trifirò[13,14], M. Trimarchi[13,14], M.B. Tsang[22], G. Verde[1], M. Vigilante[31,32], A. Wieloch[7], P. Wigg[2], H.H. Wolter[33], P. Wu[2], S. Yennello[11], P. Zambon[21,25], L. Zetta[21,26], and M. Zoric[5]

[1] *INFN-Sezione di Catania, Catania, Italy*
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[3] *IFIN-HH, Magurele-Bucharest, Romania*
[4] *GSI Helmholtzzentrum, Darmstadt, Germany*
[5] *Ruder Bošković Institute, Zagreb, Croatia*
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[14] *Università di Messina, Messina, Italy*
[15] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*
[16] *INFN-Laboratori Nazionali del Sud, Catania, Italy*
[17] *KACST Riyadh, Riyadh, Saudi Arabia*
[18] *King Saud University, Riyadh, Saudi Arabia*
[19] *University of Santiago de Compostela, Santiago de Compostela, Spain*
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[28] *RIKEN, Wako, Japan*
[29] *Institute of Nuclear Research, Debrecen, Hungary*
[30] *Università Kore, Enna, Italy*
[31] *INFN-Sezione di Napoli, Napoli, Italy*
[32] *Università di Napoli, Napoli, Italy*
[33] *LMU, München, Germany*

Constraints of the Symmetry Energy

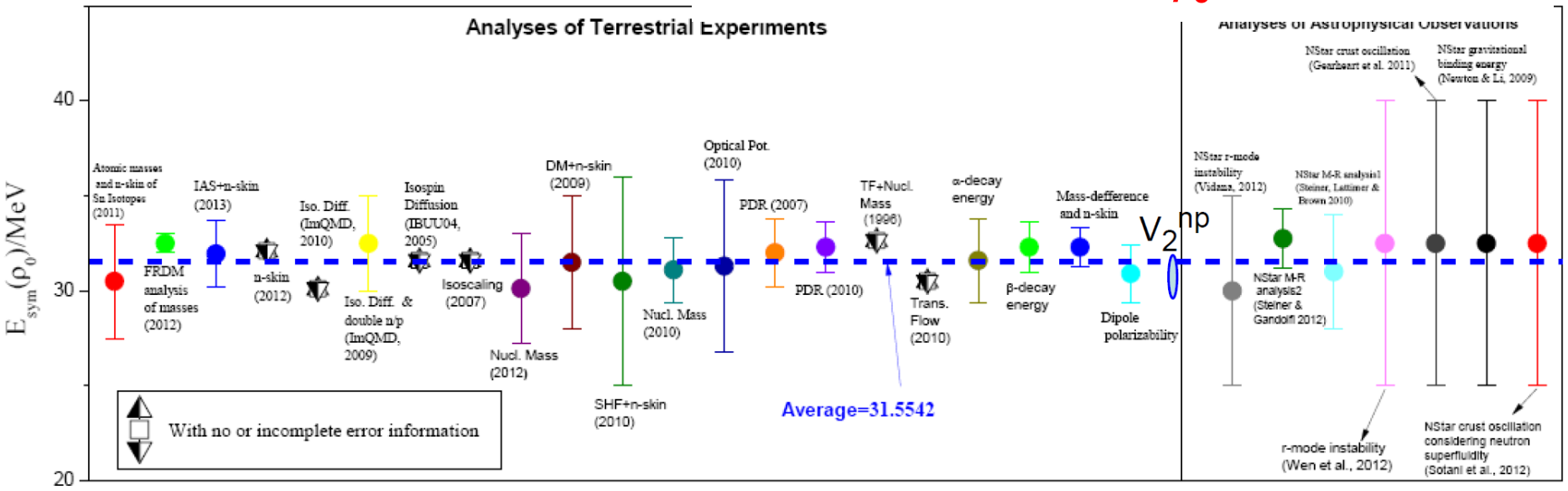
B.A. Li NuSym13 summary talk

$$E_{Sym}(\rho) = S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \ldots,$$

Terrestrial laboratories

- Several constraints (quite consistent among them) around and below ρ_0
- Few constraints above ρ_0

Nusym13 constraints on $E_{sym}(\rho$



Results with Tübingen QMD

Au+Au 400 A MeV b< 7.5 fm

UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS
momentum independent power-law
parameterization of the symmetry energy

Tübingen-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets
momentum dependent (Gogny inspired)
parameterization of the symmetry energy

M.D. Cozma, PLB 700, 139 (2011);
arXiv:1102.2728

stiffnes

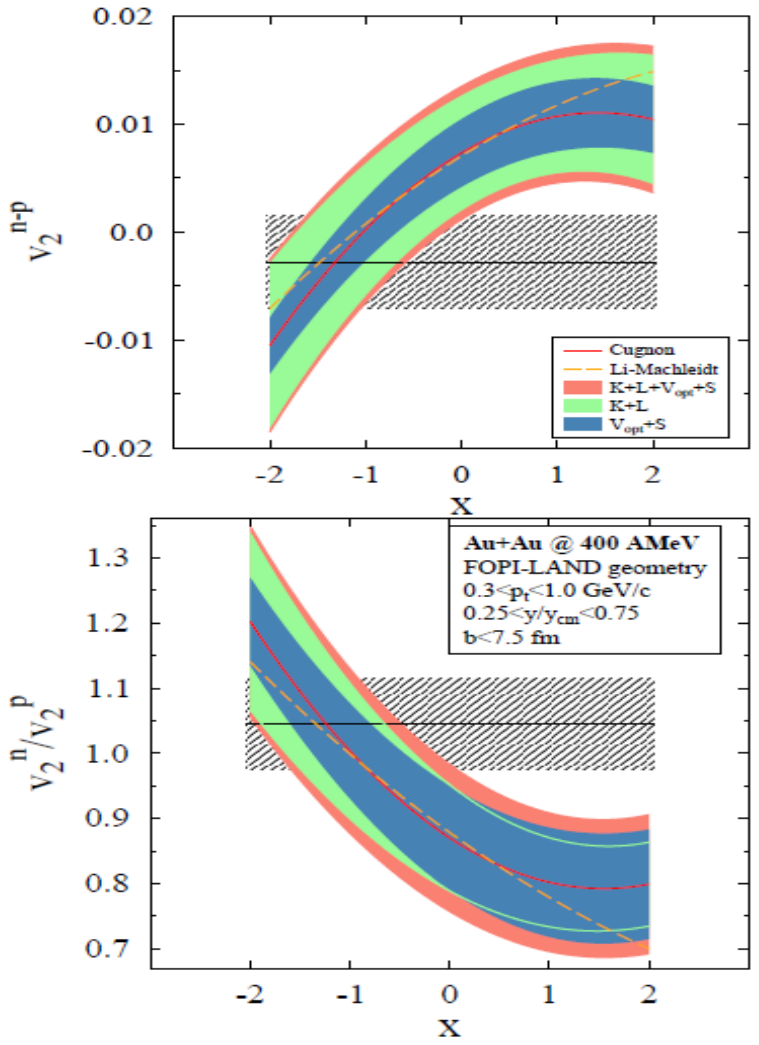


FIG. 2: Model dependence of npEFD and npEFR and comparison with FOPI-LAND experimental data, integrated over impact parameter b≤7.5 fm. Sensitivity to the different model parameters, compressibility modulus (K), width of nucleon wave function (L), optical potential (V_{opt}) and parametrization of the symmetry energy (S) are displayed. The total model dependence is obtained by adding, in quadrature, individual sensitivities.

M.D. Cozma et al., Towards a model-independent constraint of the high-density dependence of the symmetry energy

arXiv:1305.5417 [nucl-th] PRC88 044912 (2013)

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$x = -1.35 \pm 1.25$

M.D. Cozma et al., Towards a model-independent constraint of the high-density dependence of the symmetry energy

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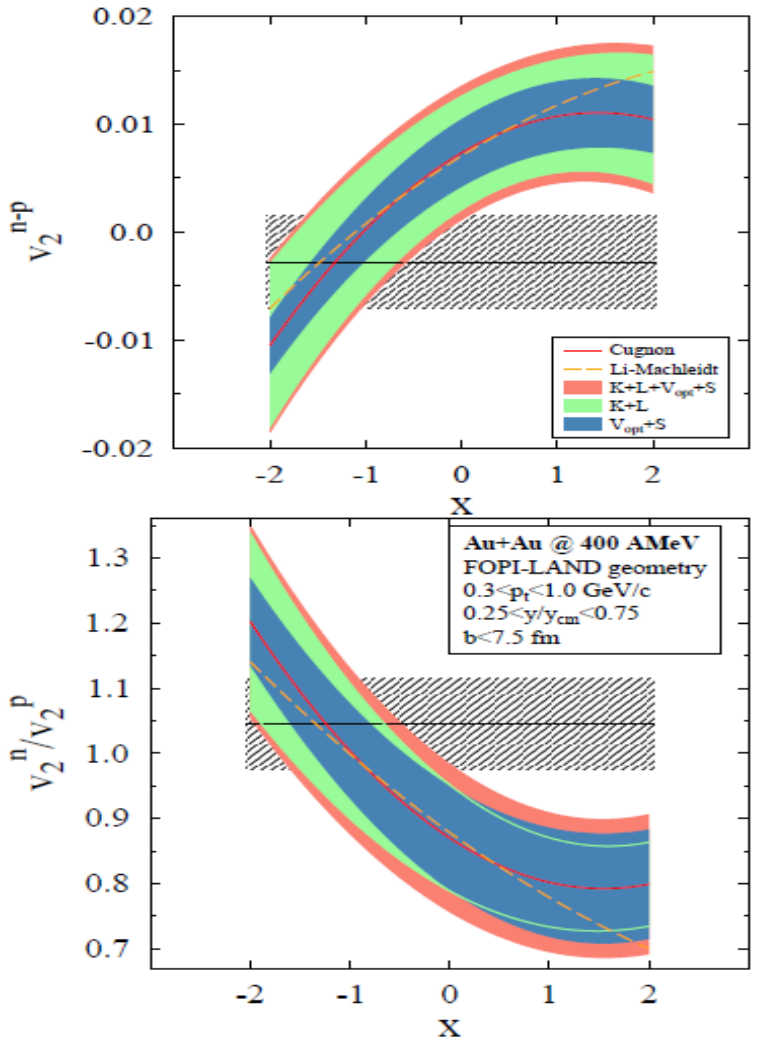
stiffnes



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Results with Tübingen QMD and UrQMD

$x = -1.0 \pm 1.0$

M.D. Cozma et al.,
Towards a model-independent constraint of the high-density dependence of the symmetry energy,

arXiv:1305.5417 [nucl-th]

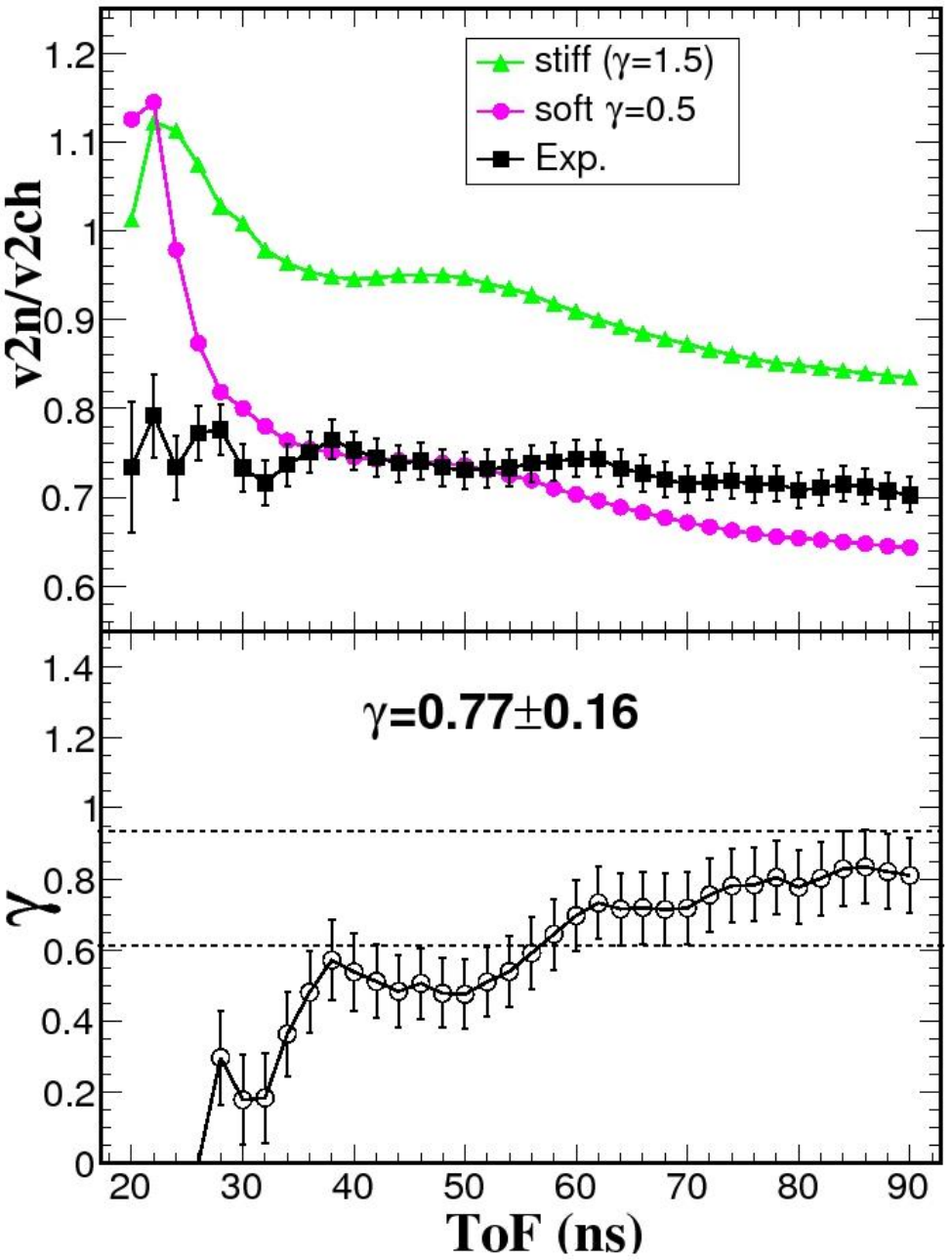
PRC88 044912 (2013)

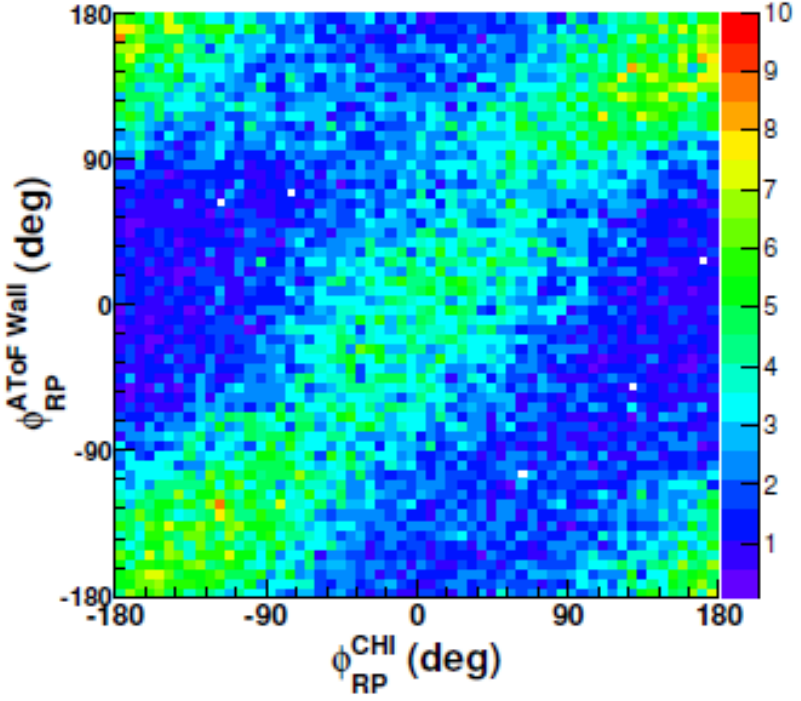
Gamma extrapolation II

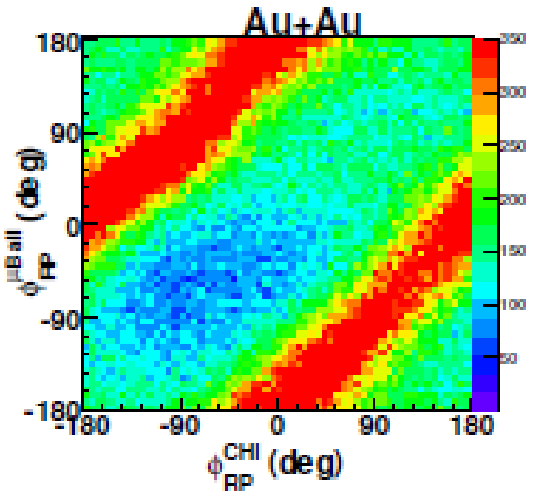
Au+Au @ 400 AMeV
b<7.5 fm

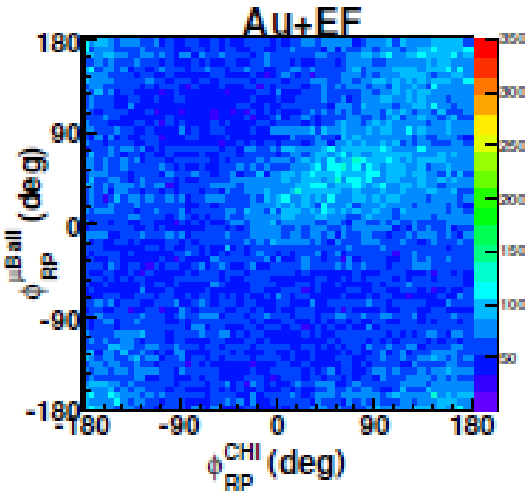
Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

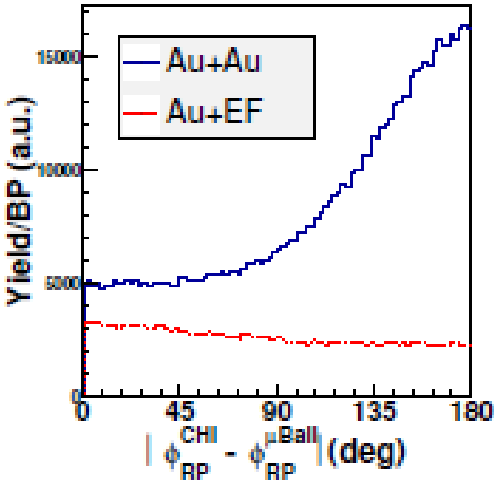
Charged Particles:
(Au+Au)-(Au+EF)

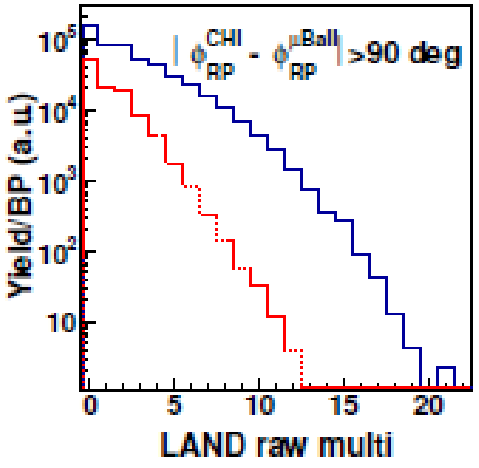


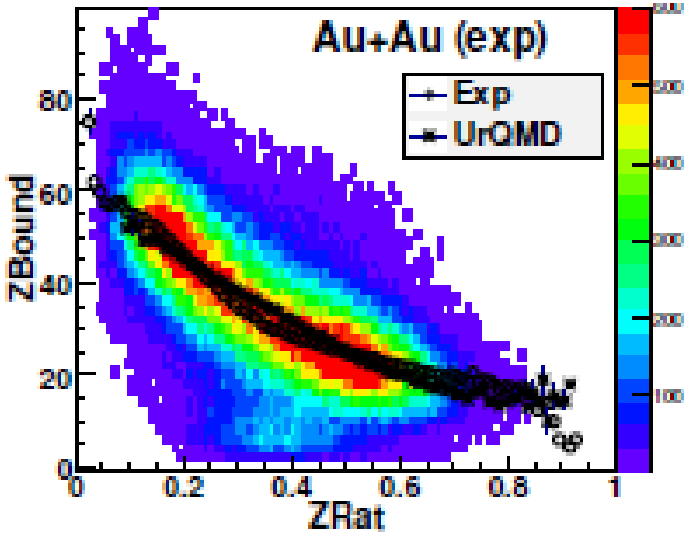

$\phi^{AToF\ Wall}_{RP}$ (deg)
ϕ^{CHI}_{RP} (deg)

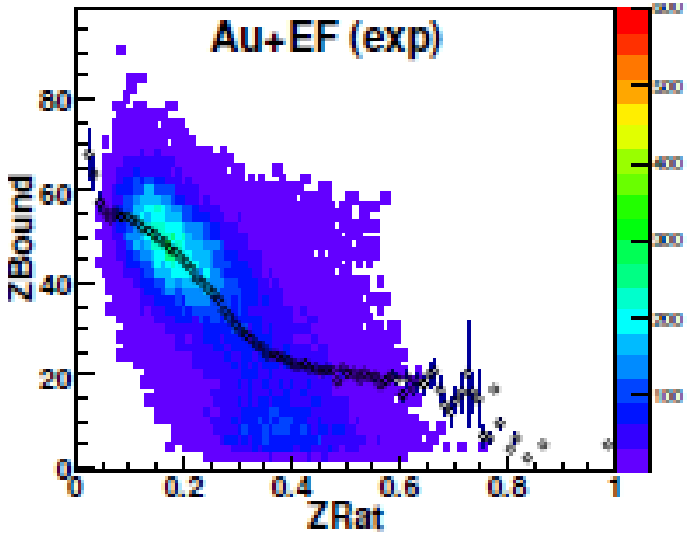

Au+Au
$\phi^{\mu Ball}_{RP}$ (deg)
ϕ^{CHI}_{RP} (deg)

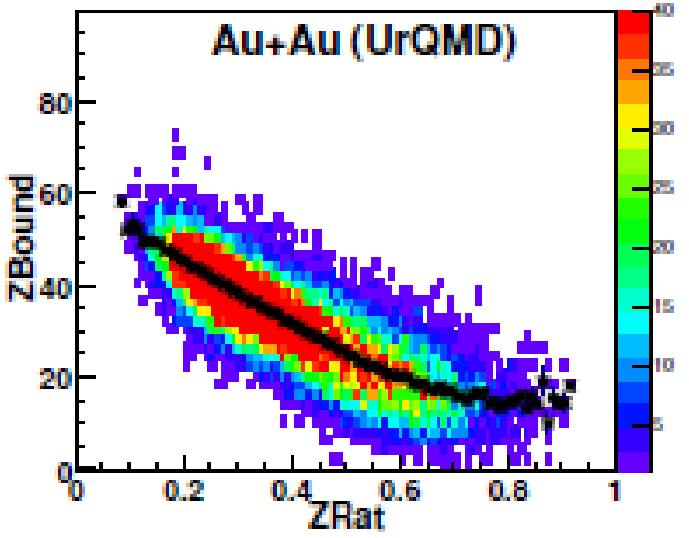

Au+EF
$\phi^{\mu Ball}_{RP}$ (deg)
ϕ^{CHI}_{RP} (deg)

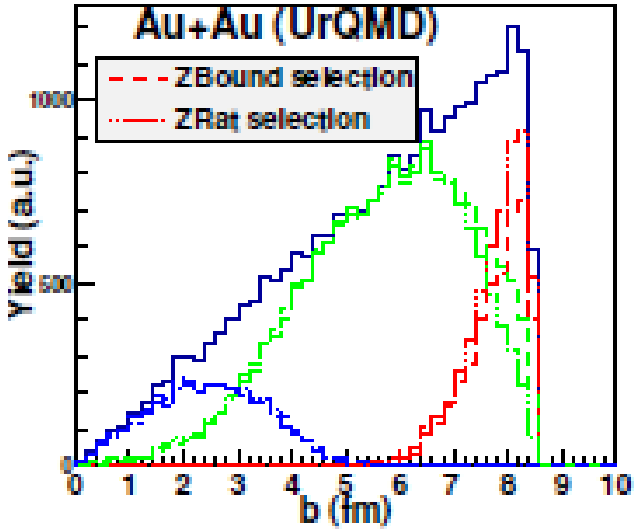

Au+Au
Au+EF
Yield/BP (a.u.)
$|\phi^{CHI}_{RP} - \phi^{\mu Ball}_{RP}|$ (deg)


$|\phi^{CHI}_{RP} - \phi^{\mu Ball}_{RP}|$ >90 deg
Yield/BP (a.u.)
LAND raw multi


Au+Au (exp)
Exp
UrQMD
ZBound
ZRat

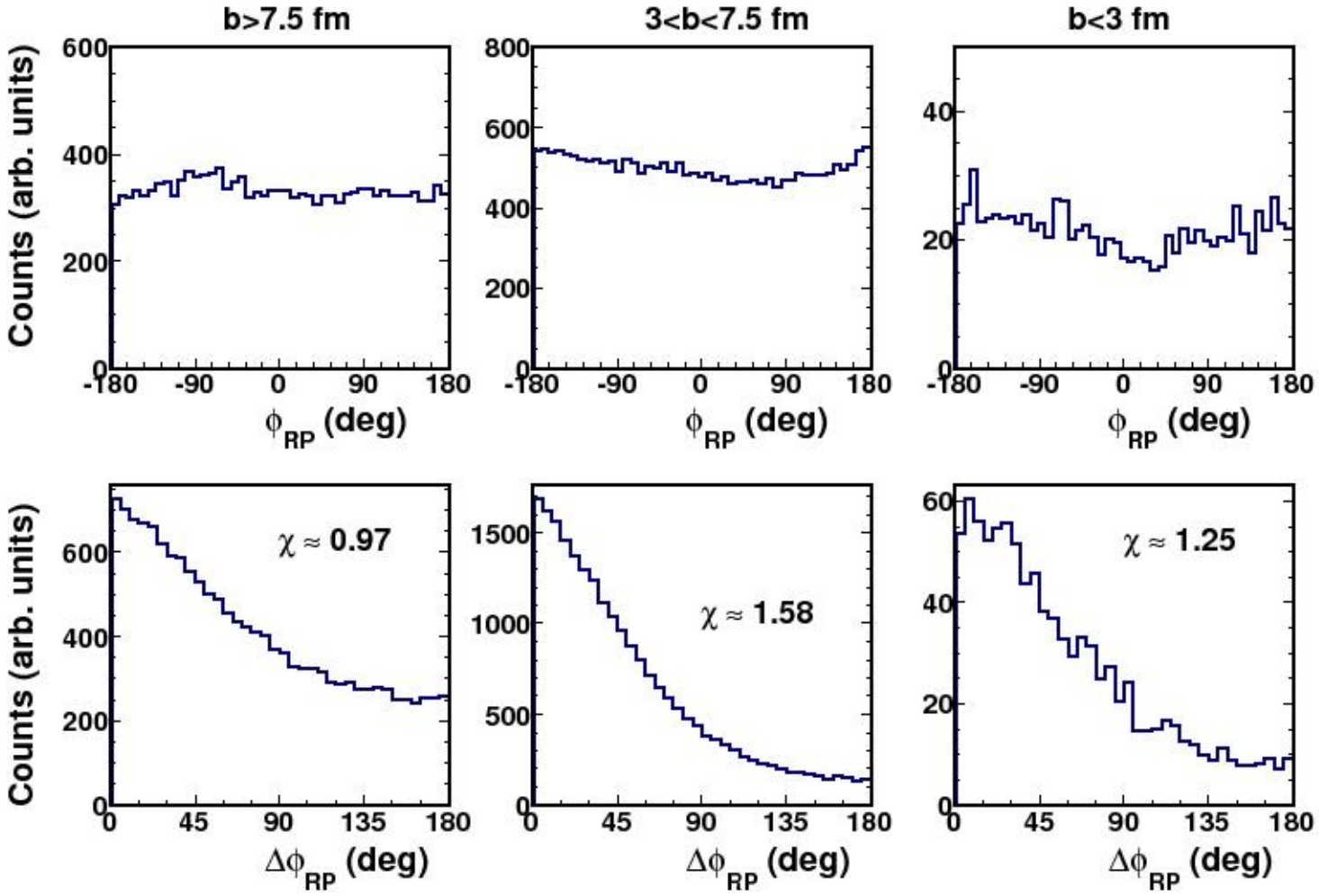

Au+EF (exp)
ZBound
ZRat


Au+Au (UrQMD)
ZBound
ZRat


Au+Au (UrQMD)
ZBound selection
ZRat selection
Yield (a.u.)
b (fm)

Reaction Plane orientation

Au+Au @ 400 AMeV



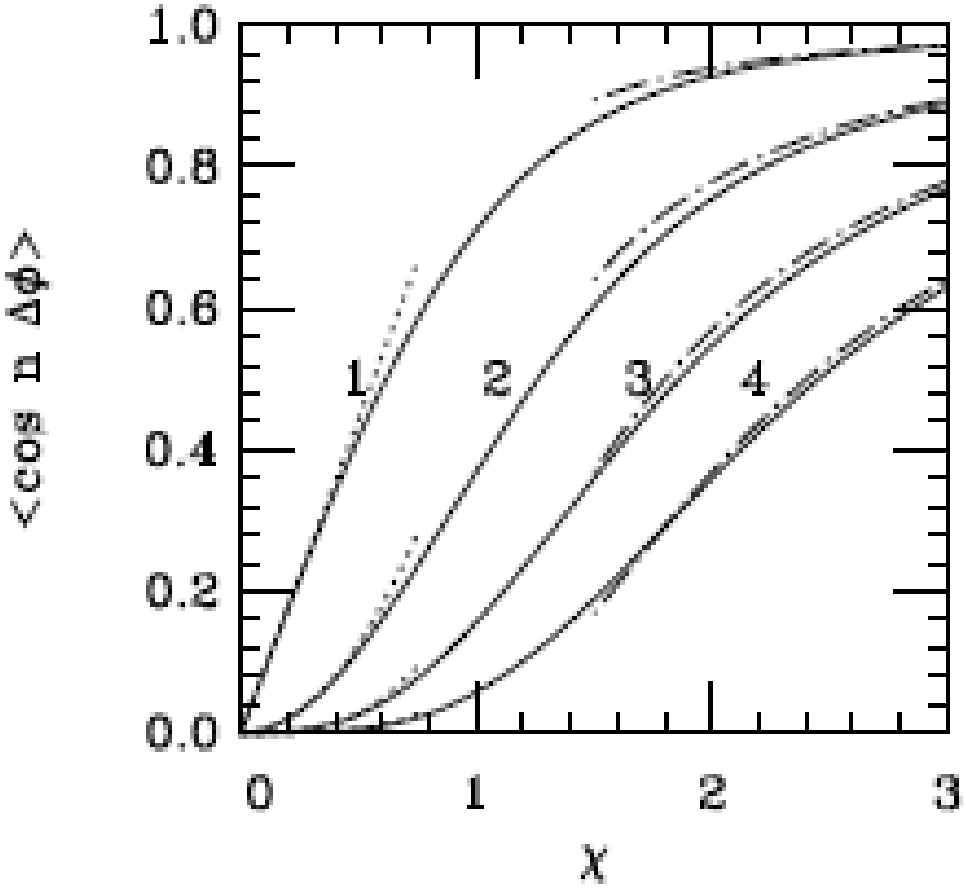
CHIMERA *M(Y_{cm}>0.1) ≥4 + AToF M(Y_{cm}>0.1) ≥4*

$$\vec{Q} = \sum_{i=1}^{M} w_i Z_i \gamma \vec{\beta}_t^{\,i} \qquad w_i = \begin{cases} 1 \text{ for } Y_{cm}>0.1 \\ 0 \text{ for } Y_{cm}<0.1 \end{cases}$$

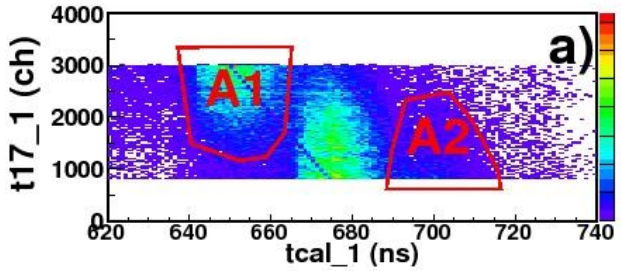
detectors and chosen weight	$y_{c.m.} > 0.1$	$y_{c.m.} > 0.2$
CHIMERA alone, equal weight	1.39	1.30
CHIMERA+AToF, equal weight	1.45	1.37
CHIMERA alone, Z	1.51	1.42
CHIMERA+AToF, Z	1.58	1.50
CHIMERA alone, $Z\beta_t\gamma$	1.52	1.42
CHIMERA+AToF, $Z\beta_t\gamma$	1.59	1.49

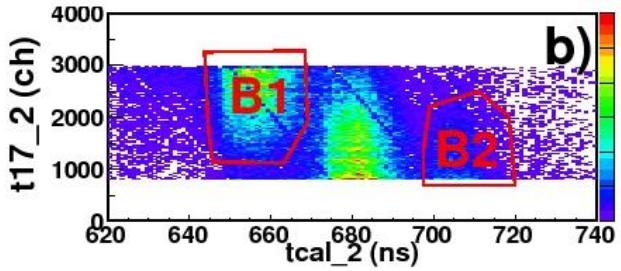
ad. from P. Danielewicz et al., PLB 1985

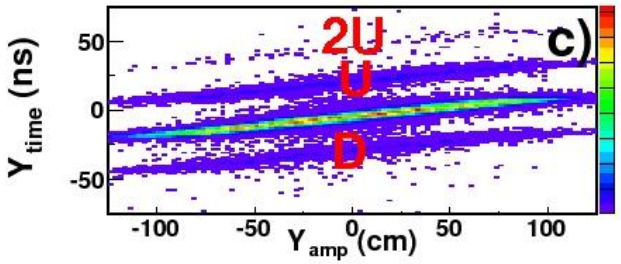
J-Y Ollitrault arXiv:nucl-ex/9711003v2

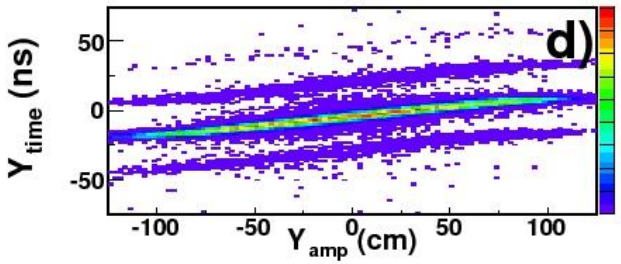

1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
1
2
3
4
<cos n Δφ>
x

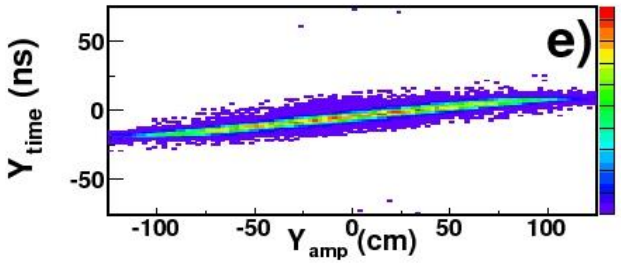
Timing problems in LAND

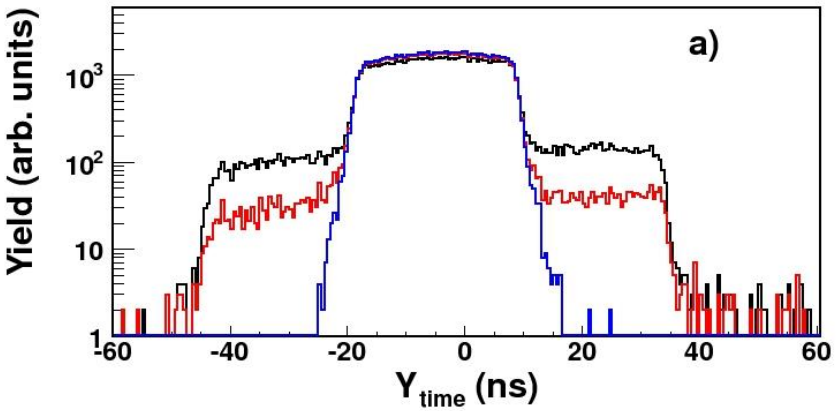


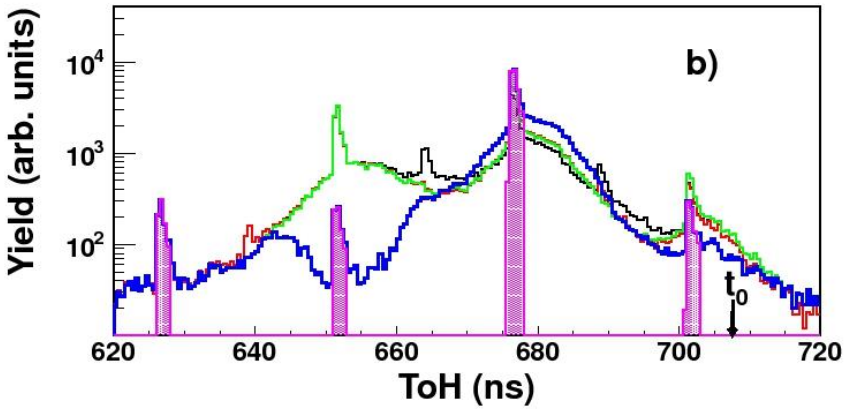




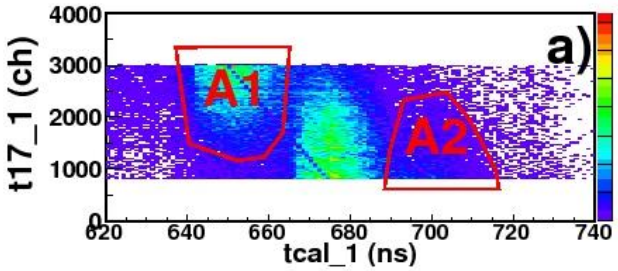


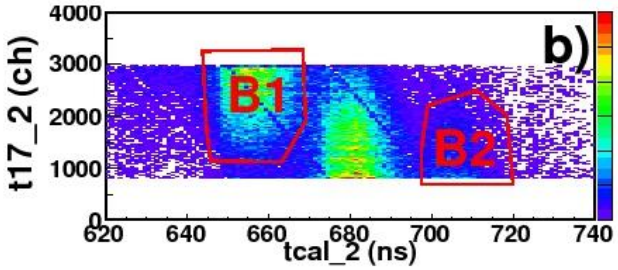


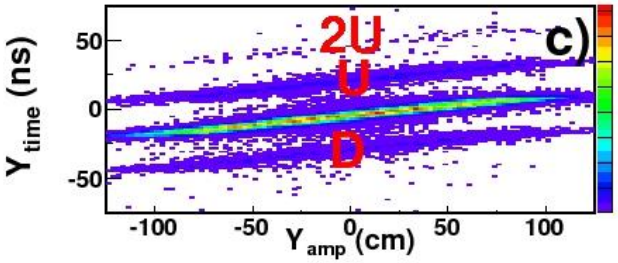


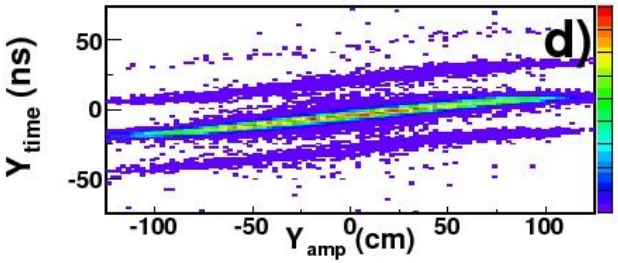


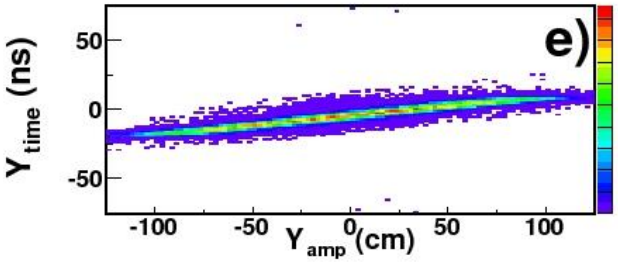
Timing problems in LAND

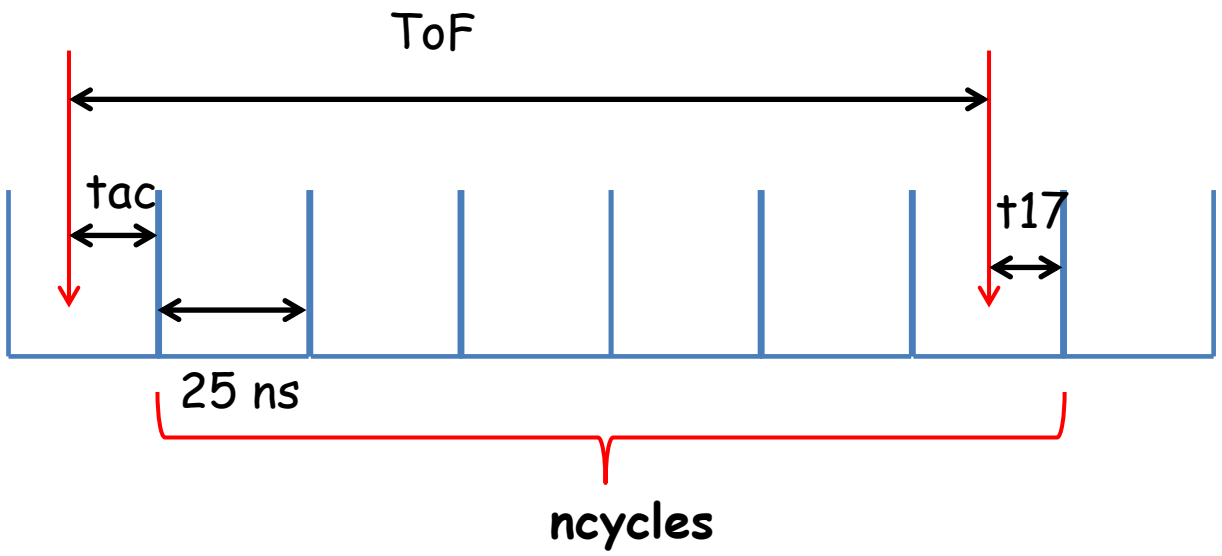




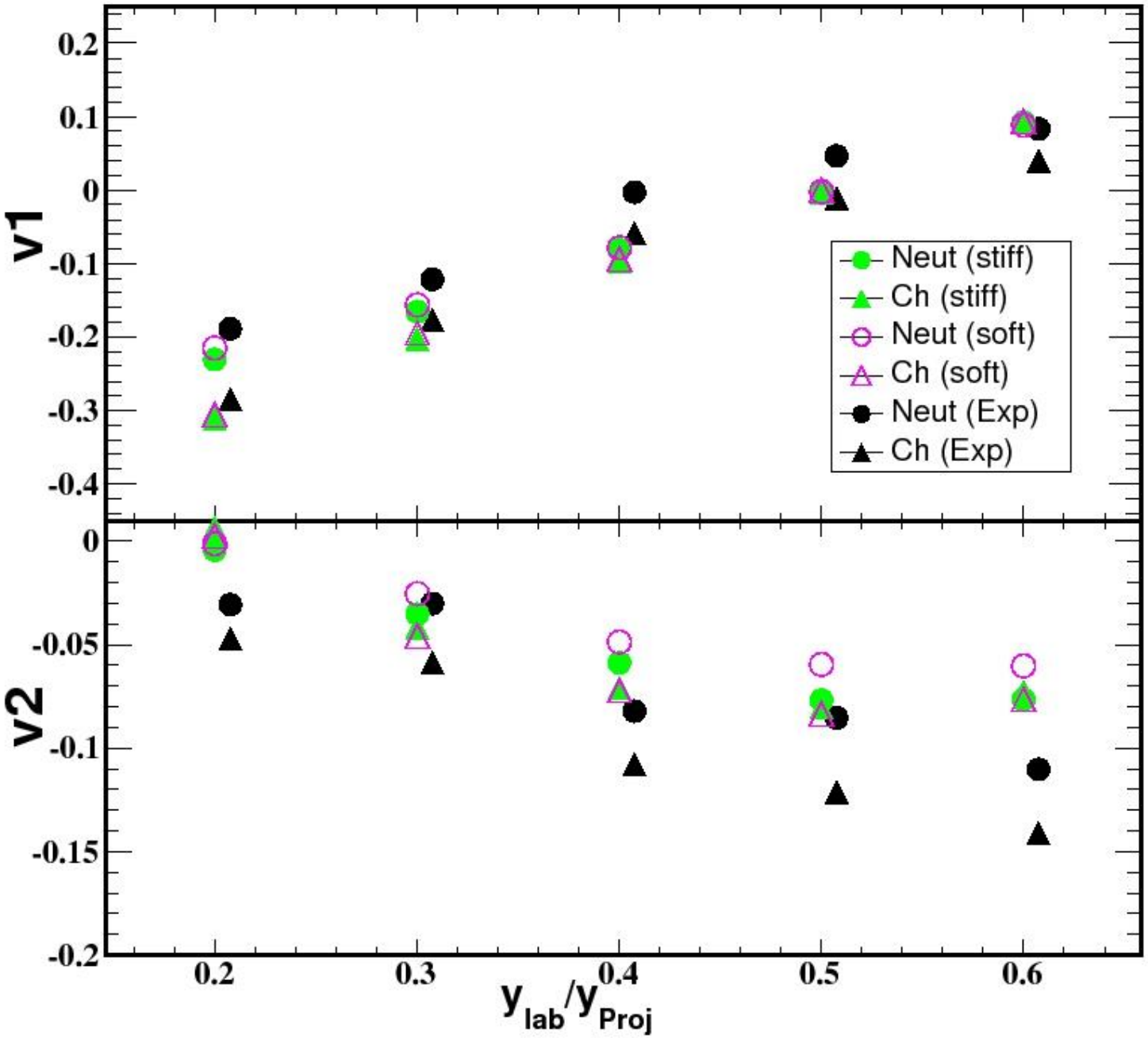




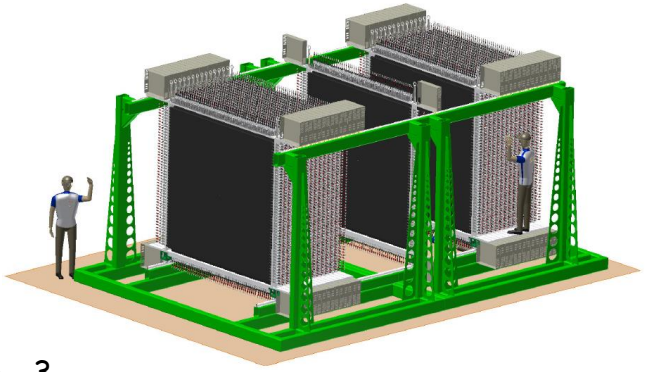




ToF= tac+25*ncycles-t17


v1
v2
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
-0.05
-0.1
-0.15
-0.2
0.2
0.3
0.4
0.5
0.6
y_{lab}/y_{Proj}
Neut (stiff)
Ch (stiff)
Neut (soft)
Ch (soft)
Neut (Exp)
Ch (Exp)

NeuLAND @ FAIR/GSI



- TDR finalized in Oct 2011 and submitted
- total volume 2.5x2.5x3 m^3
- each bar readout by two PMT
- 3000 modules (plastic scintillator bars) 250x5x5 cm^3
- 30 double planes with 100 bars each, bars in neighboring planes
- mutually perpendicular
- $\sigma_t \leq 150$ ps and $\sigma_{x,y,z} \leq 1.5$ cm
- one-neutron efficiency ~95% for energies 200-1000 MeV
- multi-neutron detection capability

I. Gasparic AsyEOS2012 workshop, 6.9.2012, Siracusa, Italy

Califa
CALorimeter for the In Flight detection of γ rays and light charged pArticles

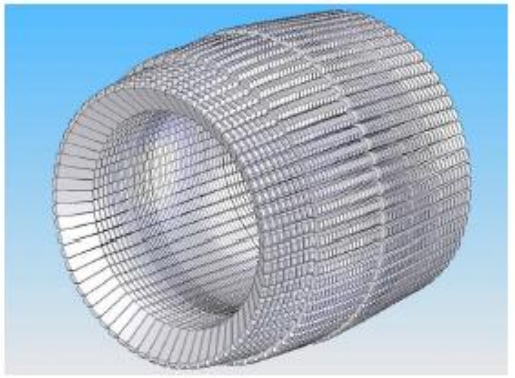


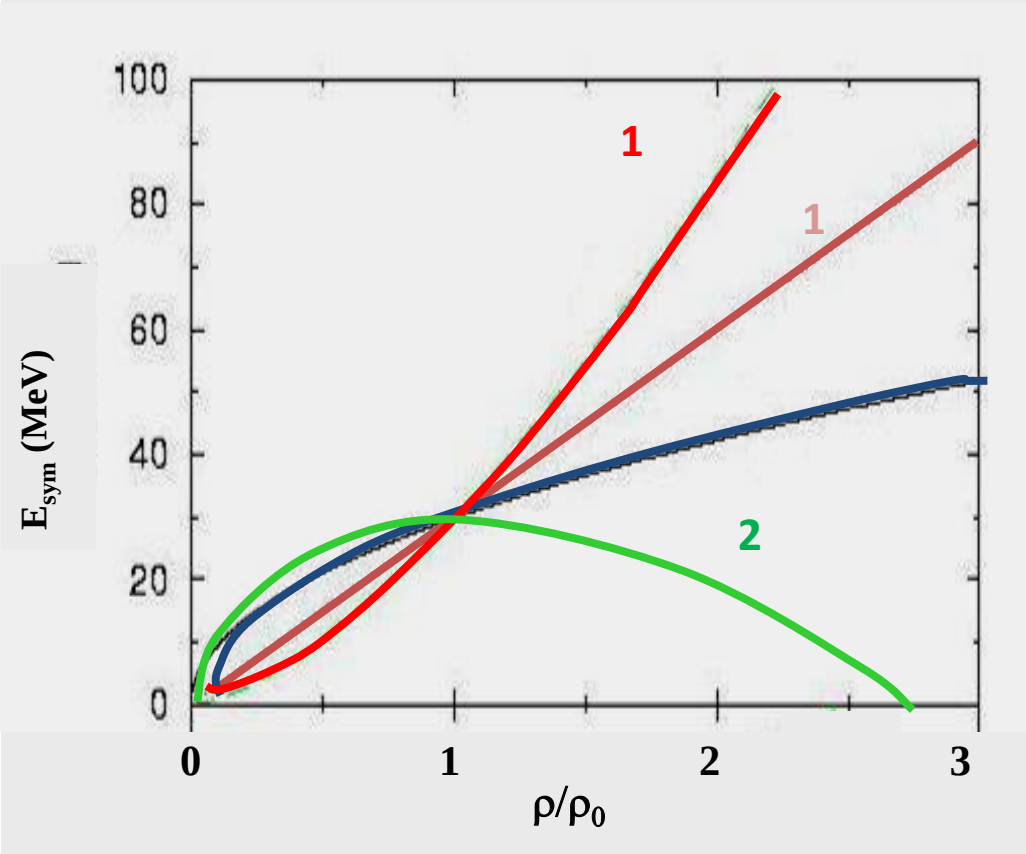
Fig. 2. Artistic view of the CALIFA calorimeter. The inner radius of the barrel is approximately 30 cm long.

TAGLI
07/06/2015

Summary

- Brief intro on High Density investigation of Symmetry Energy with H-I
- Suggestion for a route toward model independency…
- First results of the ASY-EOS experiment and future possibilities
- Conclusions

Esym at high density: pions



- Results model dependent
- Density dependence of symmetry energy unambiguously soft or hard
- BUT
- symmetry energy → n/p ratio, number of nn, np, pp collisions

$$\text{asystiff}\,\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

- medium → effective masses (N, π, Δ), cross sections → thresholds

$$\text{asystiff} \Rightarrow \frac{\pi^-}{\pi^+}\uparrow$$

→ Interpretation of pion data not straight forward

See:

Z. Xiao et al., PRL 102 (2009) **IBUU04**

Z.Q. Feng, PLB 683 (2010) **ImIQMD**

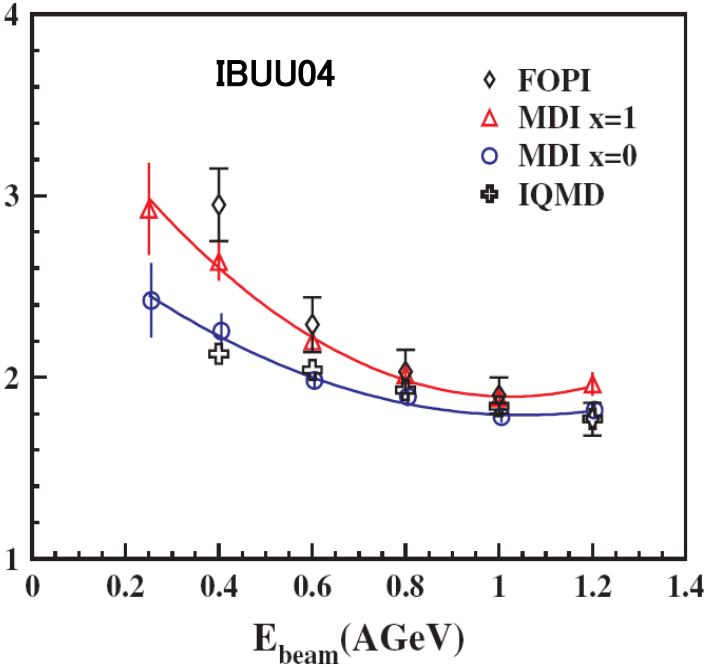
W.J. Xie , et al., PLB 718 (2013) **ImIBL**

G. Ferini, et al., NPA 762 (2005) **RMF**

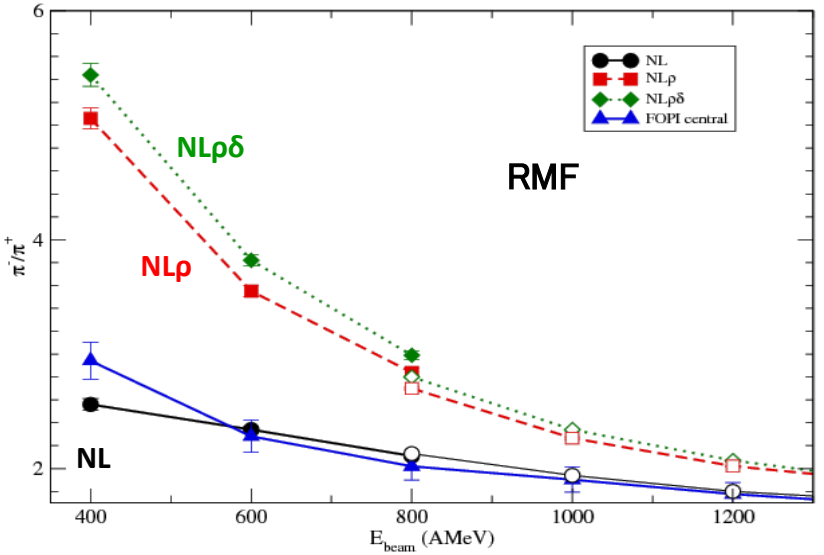
From IWM 2011 – Y. Leifels

E_{sym} at high density: π^-/π^+ ratio

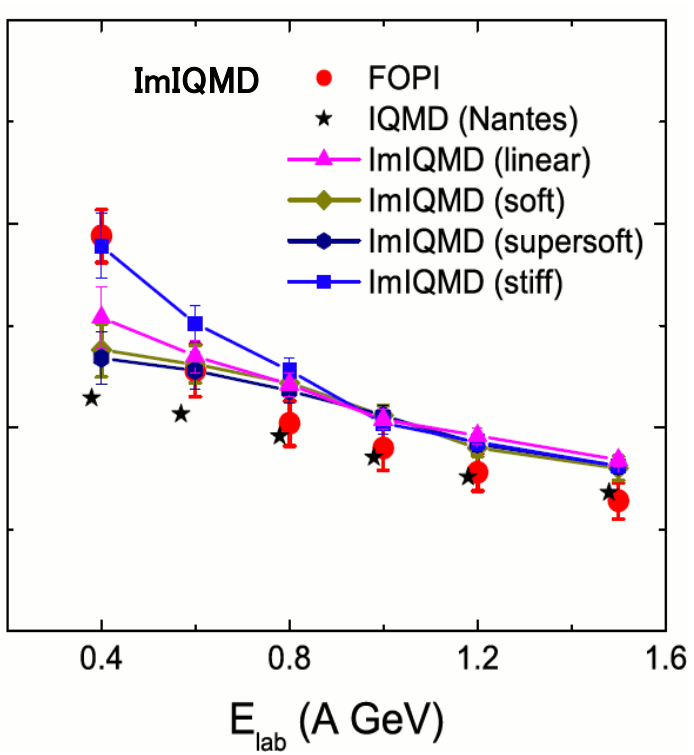
Z. Xiao et al., PRL 102 (09)



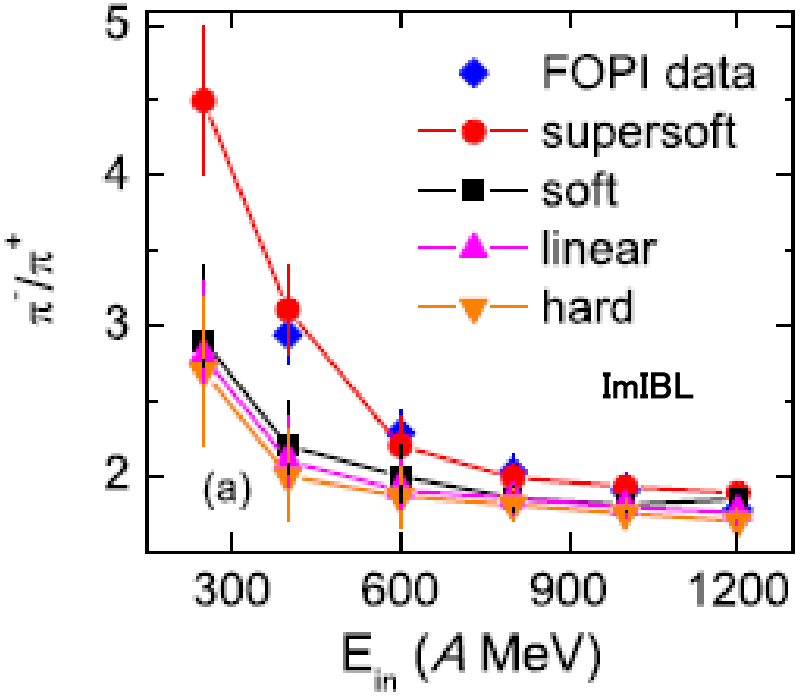
Ferini, at al., NPA 762 (2005)



Z.Q. Feng, PLB 683 (2010)



W.J. Xie , at al., PLB 718 (2013)

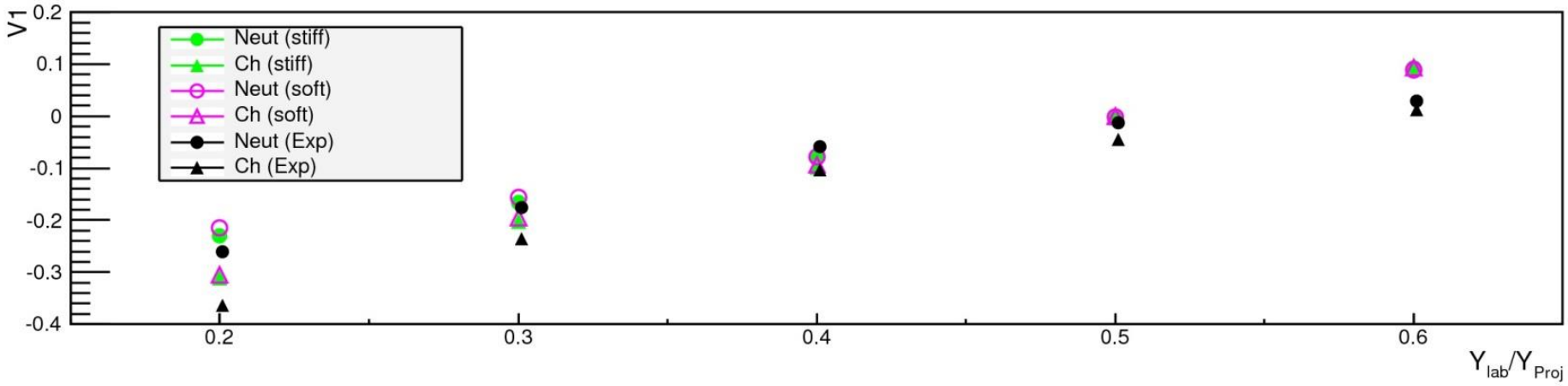


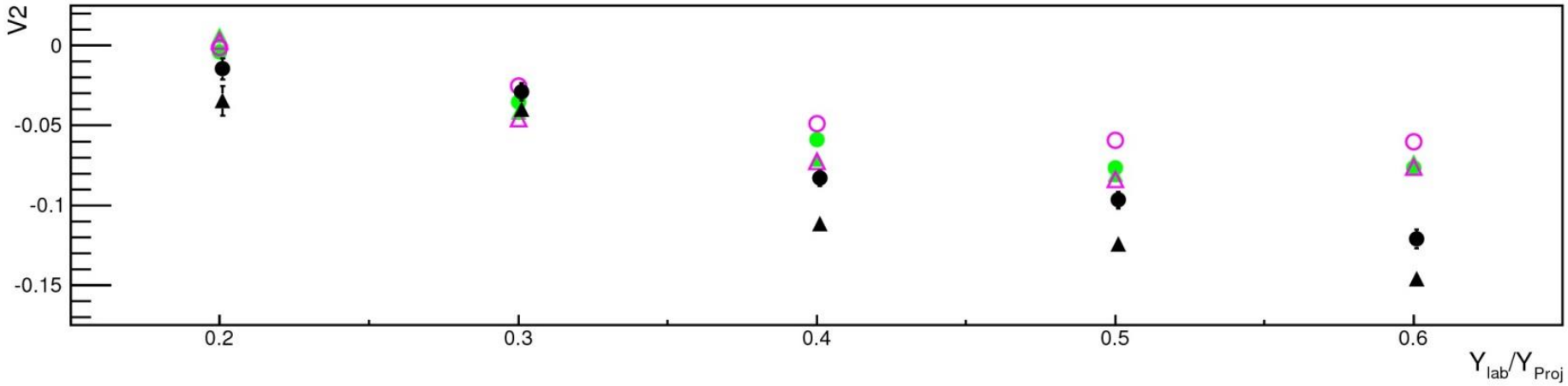
Comparison with UrQMD

Au+Au @ 400 AMeV b<7.5 fm

Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

Charged Particles:
(Au+Au)-(Au+EF)





Only charged particles!!!

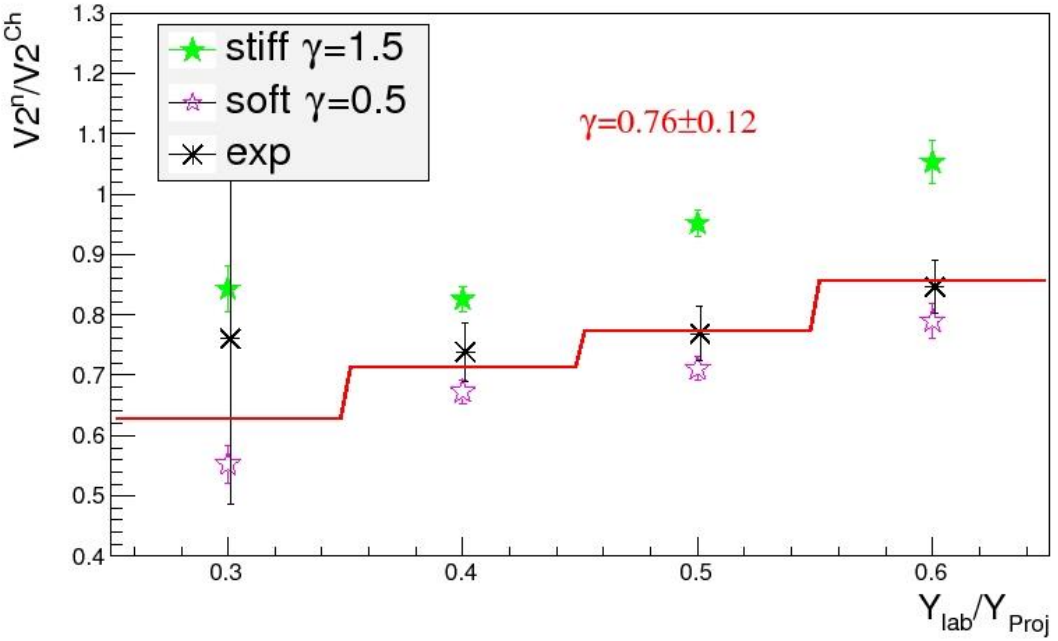
preliminary

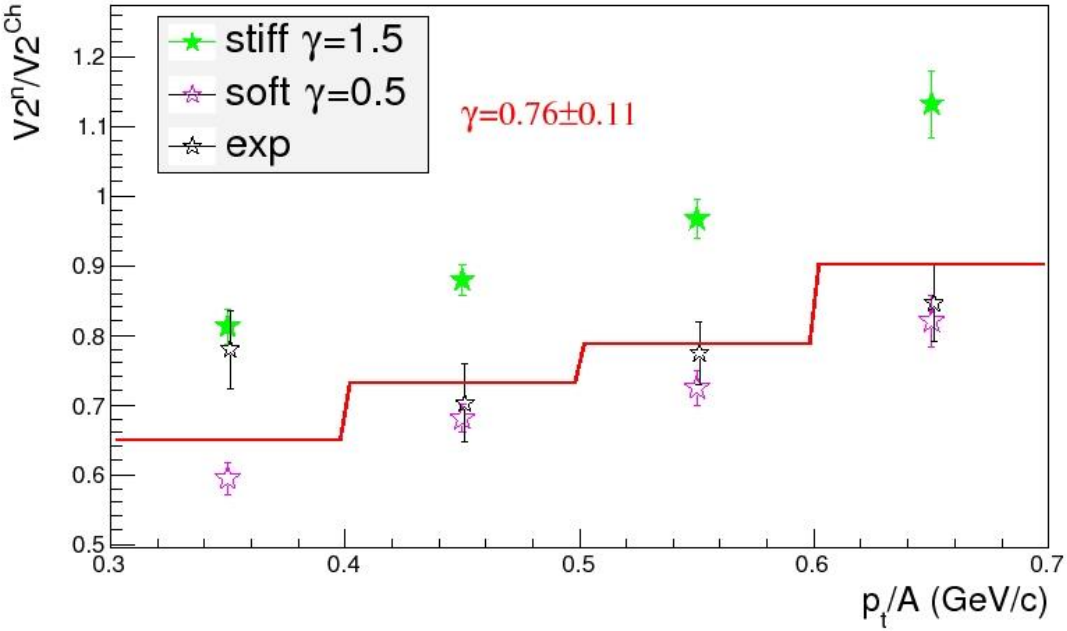
Last result: improved background evaluation

Au+Au @ 400 AMeV
b<7.5 fm

Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

Charged Particles:
(Au+Au)-(Au+EF)

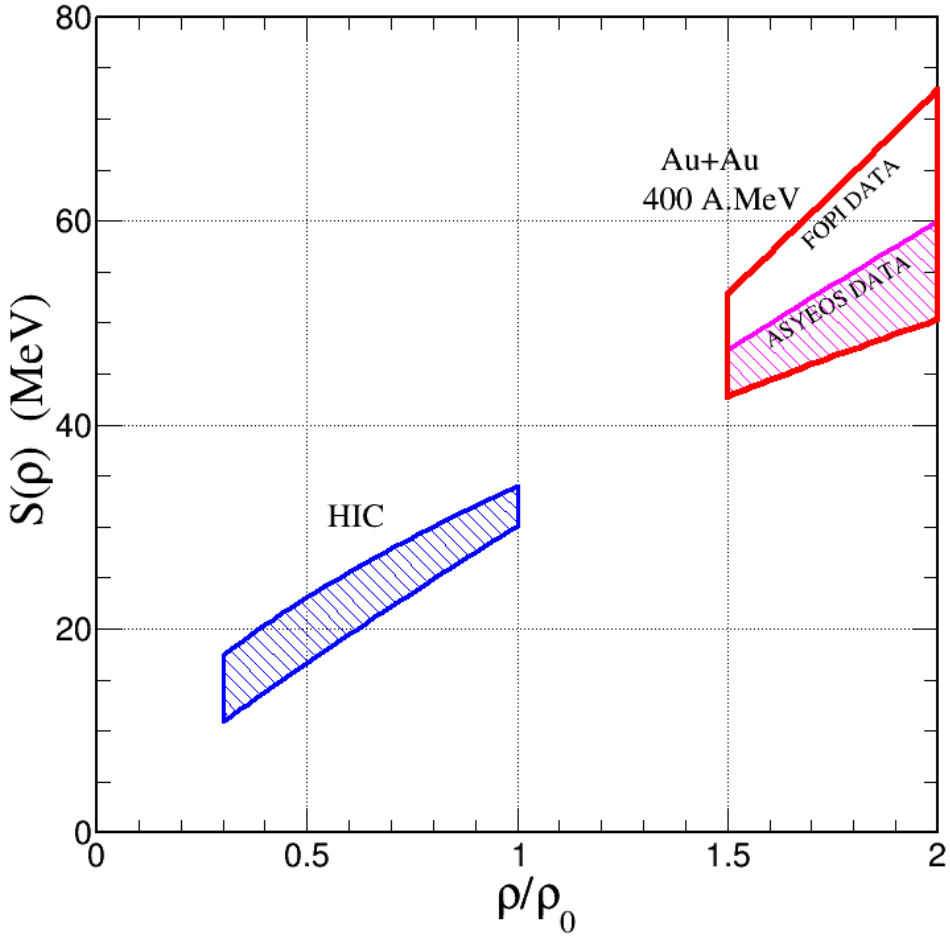




preliminary

The analysis is in progress…

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho - \rho_o}{\rho_o}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho - \rho_o}{\rho_o}\right)^2 + \ldots,$$



HIC: (mainly Isospin diffusion for Sn+Sn) M.B. Tsang et al., PRC 86, 015803 (2012)

FOPI DATA : P.Russotto et al., Phys. Lett. B 697 (2011)

$\gamma = 0.9 \pm 0.4$; L=83±26

ASYEOS DATA: THIS WORK

$\gamma = 0.7 \pm 0.2$; L=70±13

From E. De Filippo, procs of IWM-EC 2014 (to be pubblished)

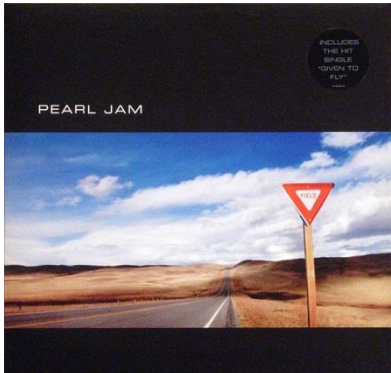
preliminary

Conclusions

- High density Symmetry Energy:
  - pion constraints not consistent
  - n/p flows suggests…a route "Towards a model-independent constraint of the high-density dependence of the symmetry energy"
  - Finalizing ASY-EOS data analysis is in progress
- New and better experiments on n,p flows and ratio, pions and kaons, also with high asymmetric beams (e.g. ^{132}Sn) and new detectors (Riken TPC, NeuLand@R3B)
- Low densities Symmetry Energy:
  - several constraints quite consistent;
  - CHIMERA @ LNS: careful studies of reaction dynamics and correlation between timescale, dynamical pattern and Isospin effects

- International collaborations and efforts

On the road…..



This is a collective work of CHIMERA and EXOCHIM collaborations

TIMESCALE and INKIISSY

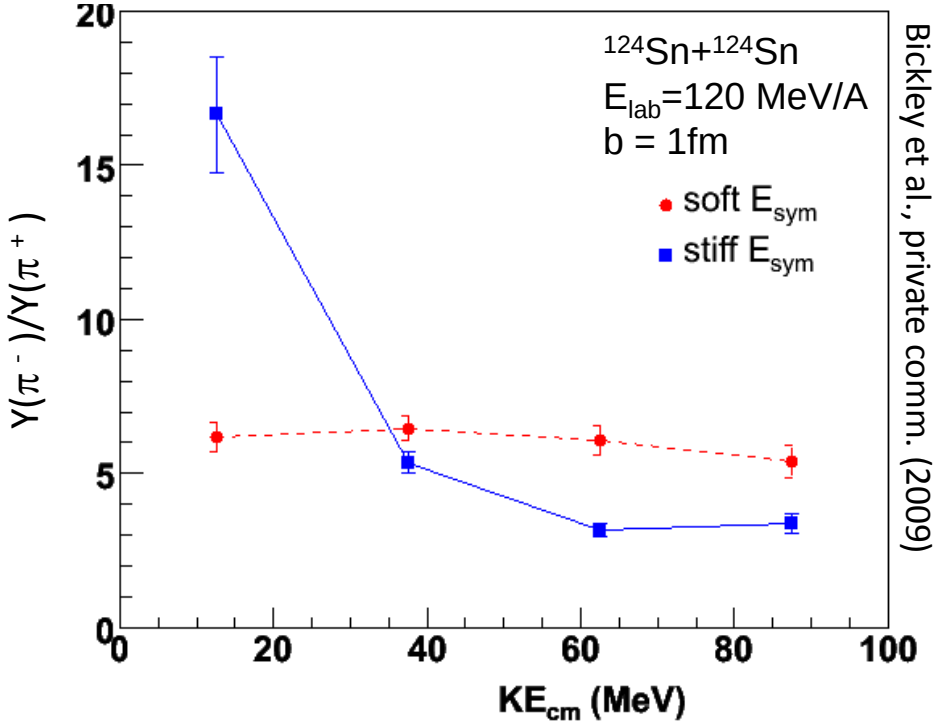
L. Acosta, F. Amorini, L. Auditore, V. Baran, I. Berceanu, T. Cap, G. Cardella, M. Colonna, E. De Filippo, L. Francalanza, E. Geraci, S. Gianì, B. Gnoffo, L. Grassi, A. Grzeszczuk, P. Guazzoni, J. Han, E. La Guidara, G. Lanzalone, Lombardo, C. Maiolino, T. Minniti, A. Pagano, E.V. Pagano, M. Papa, E. Piasecki, S. Pirrone, G. Politi, A. Pop, F. Porto, L. Quattrocchi, F. Rizzo, E. Rosato, P. Russotto, S. Santoro, A. Trifirò, M. Trimarchi, G. Verde, M. Vigilante, J. Wilczyński, L. Zetta.

BACK UP
26/04/2015

Probing ρ>ρ0 via pion production

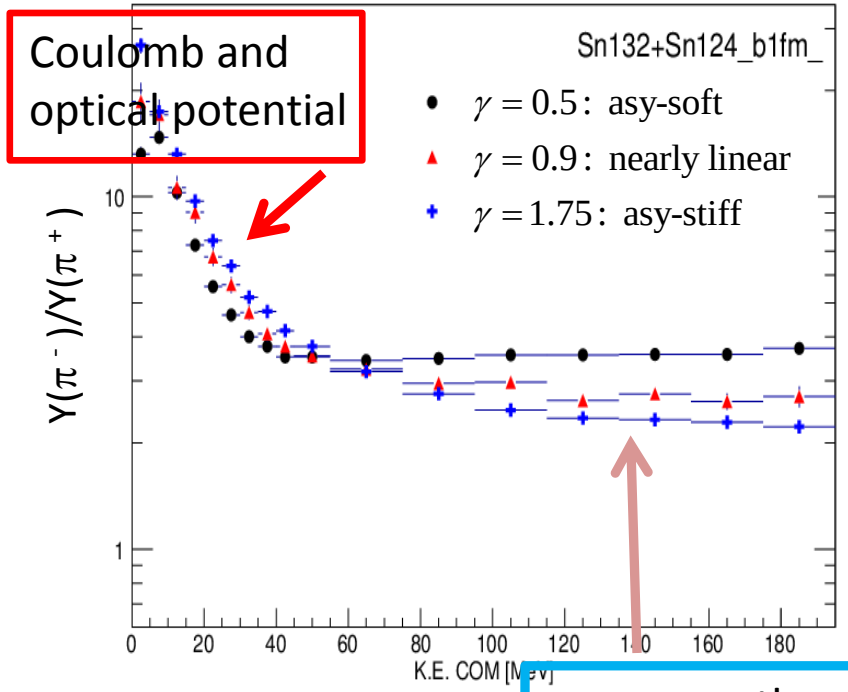
W.G. Lynch talk @ NuSym 2014

E/A =120 MeV



Bickley et al., private comm. (2009)

E/A = 300 MeV



J. Hong, P. Danielewicz, private commicatons (2013)

more n-n than p-p collisions for soft Symmetry energy

- Pion ratio depends strongly on the symmetry energy.
- Ratios of spectra are more sensitive than ratios of integrated yields.
  - Integrated yields at E/A≥400 MeV suggest soft symmetry energy at $\rho \geq 2.5\rho_0$ (Xiao PRL, 102, 062502 (2009)
- Built two TPC's to probe these observables
  - E/A<150 MeV at MSU and E/A=200-350 MeV at RIKEN (probes $\rho \approx 2\rho_0$).

Device: SAMURAI TPC (U.S. Japan Collaboration)

T. Murakami[a], Jiro Murata[b], Kazuo Ieki[b], Hiroyoshi Sakurai[c], Shunji Nishimura[c], Atsushi Taketani[c], Yoichi Nakai[c], Betty Tsang[d], William Lynch[d], Abigail Bickley[d], Gary Westfall[d], Michael A. Famiano[e], Sherry Yennello[g], Roy Lemmon[h], Abdou Chbihi[i], John Frankland[i], Jean-Pierre Wieleczko[i] , Giuseppe Verde[j], Angelo Pagano[i], Paulo Russotto[i], Z.Y. Sun[k], Wolfgang Trautmann[l]

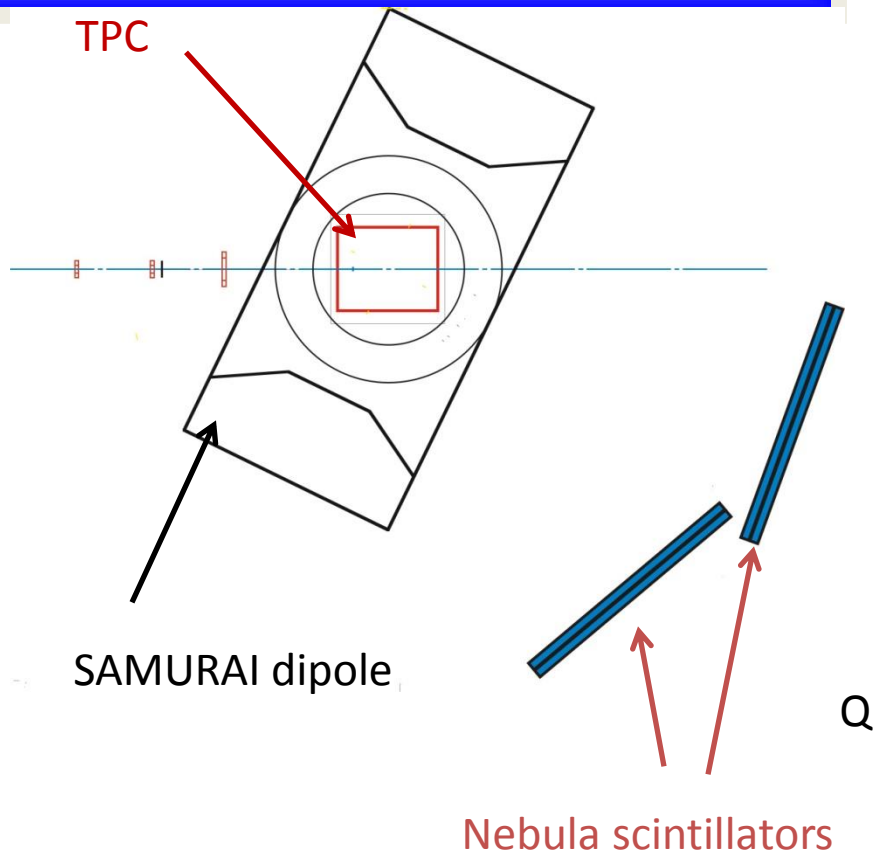
[a]Kyoto University, [b]Rikkyo University, [c]RIKEN, Japan, [d]NSCL Michigan State University, [e]Western Michigan University, [g]Texas A&M University, USA, [h]Daresbury Laboratory, [i]GANIL, France, UK, [j]LNS-INFN, Italy, [k]IMP, Lanzhou, China, [l]GSI, Germany

The SAMURAI TPC would be used to constrain the density dependence of the symmetry energy through measurements of:

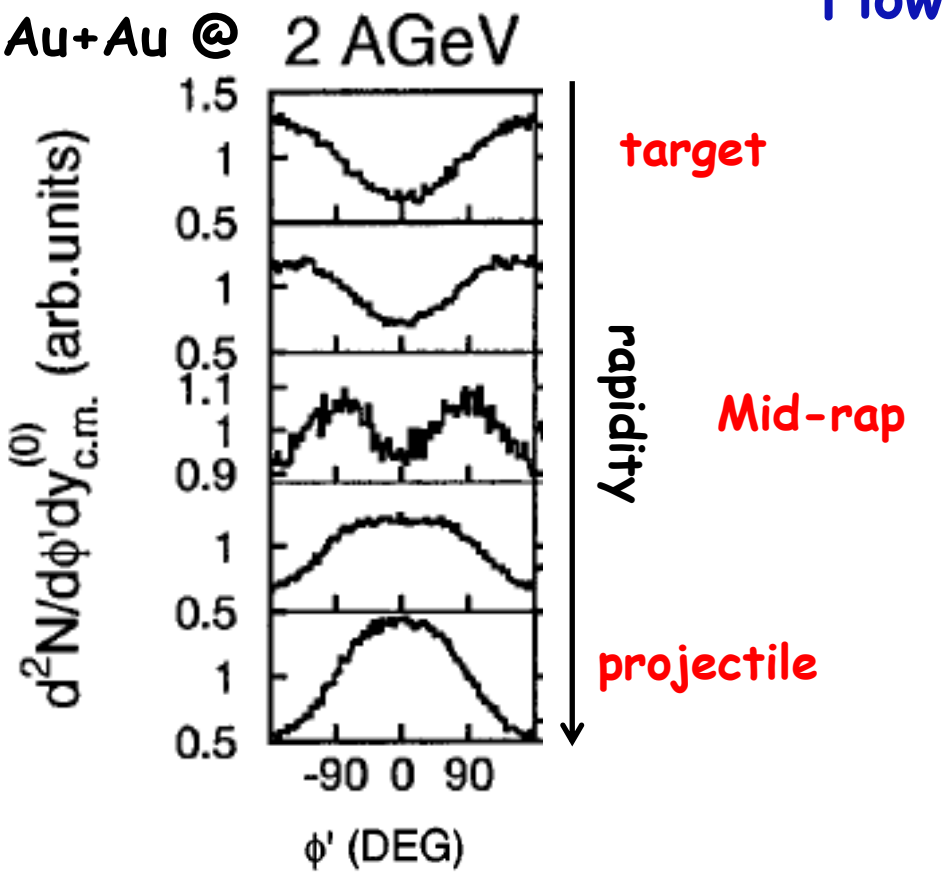
- Pion production
- Flow, including neutron flow measurements with the nebula array.

The TPC also can serve as an active target both in the magnet or as a standalone device.

- Giant resonances.
- Asymmetry dependence of fission barriers, extrapolation to r-process.



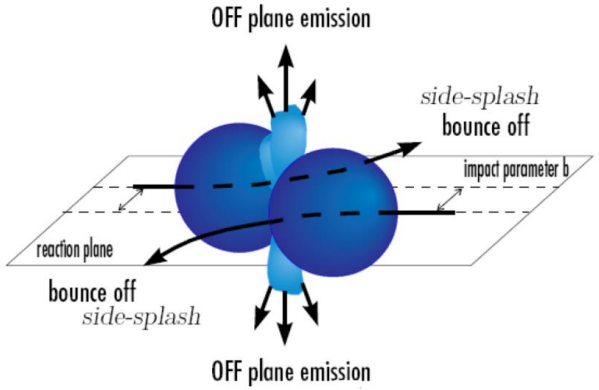
Flows



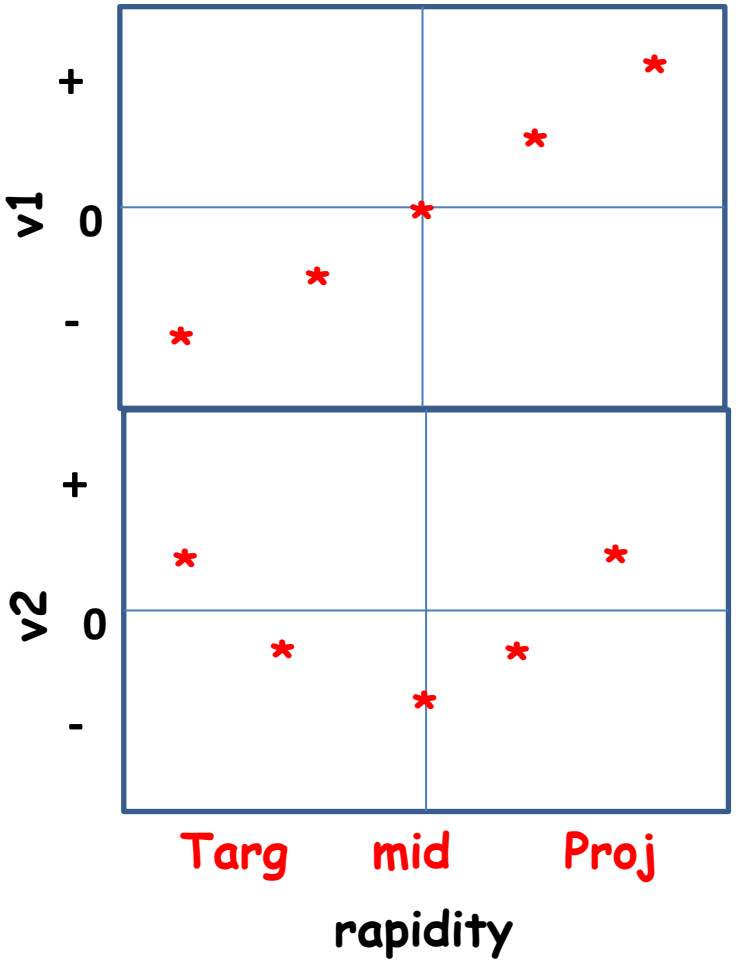
C.Pinkenburg et al., (E895),Phys.Rev.Lett. 83 (1999) 1295, *nucl-ex/9903010*

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

Y = rapidity
pt = transverse momentum

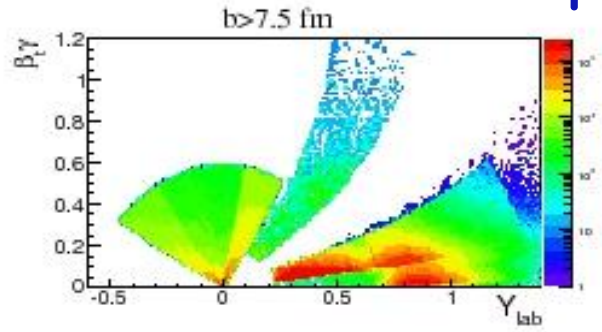


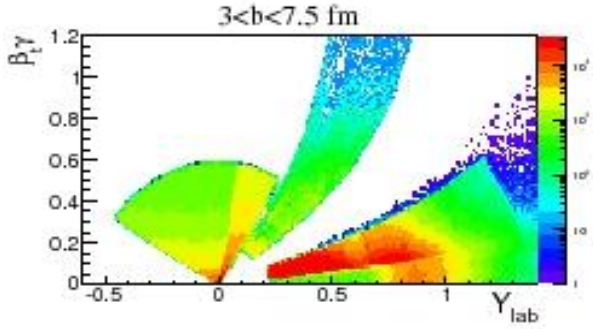
Not to scale: qualitative

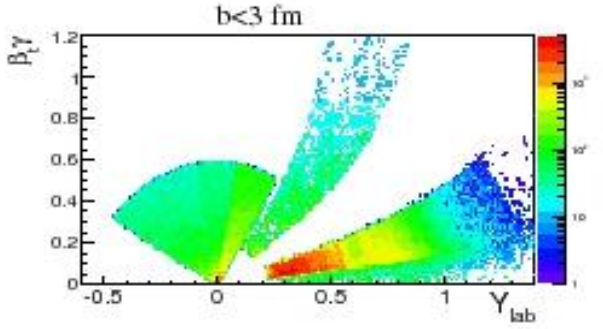


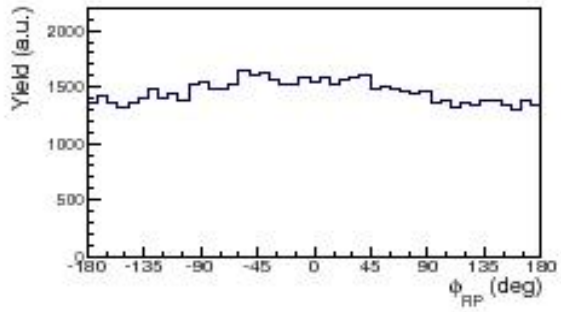
Reaction plane orientation

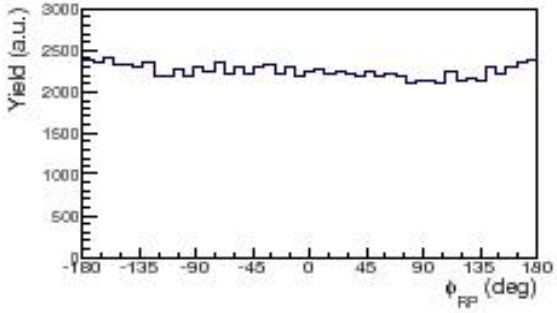
Au+Au @ 400 AMeV

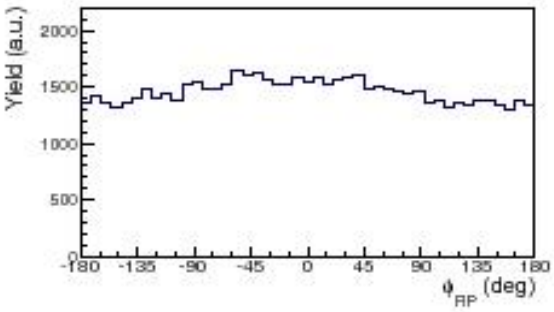


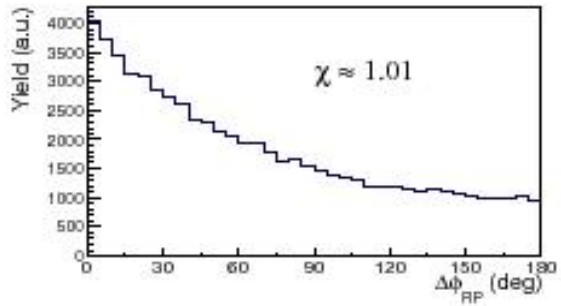


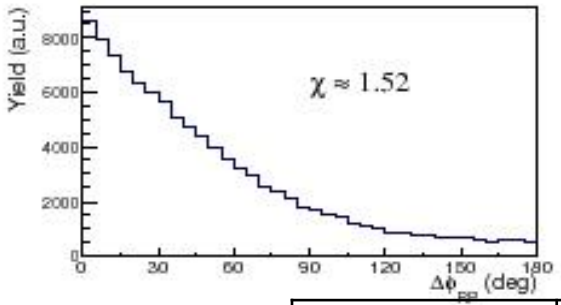


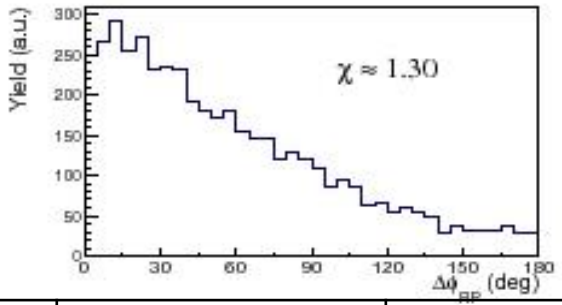












CHIMERA $M(Y_{cm}>0.1)\geq 4$

$$\vec{Q} = \sum_{i=1}^{M} w_i Z_i \gamma \vec{\beta}_t^{\,i} \qquad w_i = \begin{cases} 1 & \text{for } Y_{cm}>0.1 \\ 0 & \text{for } Y_{cm}<0.1 \end{cases}$$

b selection	χ~	<cos (2 ΔΦ) >~	ΔΦ (deg)~
b>7.5 fm	1.01	0.36	34
3<b<7.5 fm	1.52	0.60	26
b< 3 fm	1.30	0.52	29

ad. from P. Danielewicz et al., PLB 1985

J-Y Ollitrault arXiv:nucl-ex/9711003v2

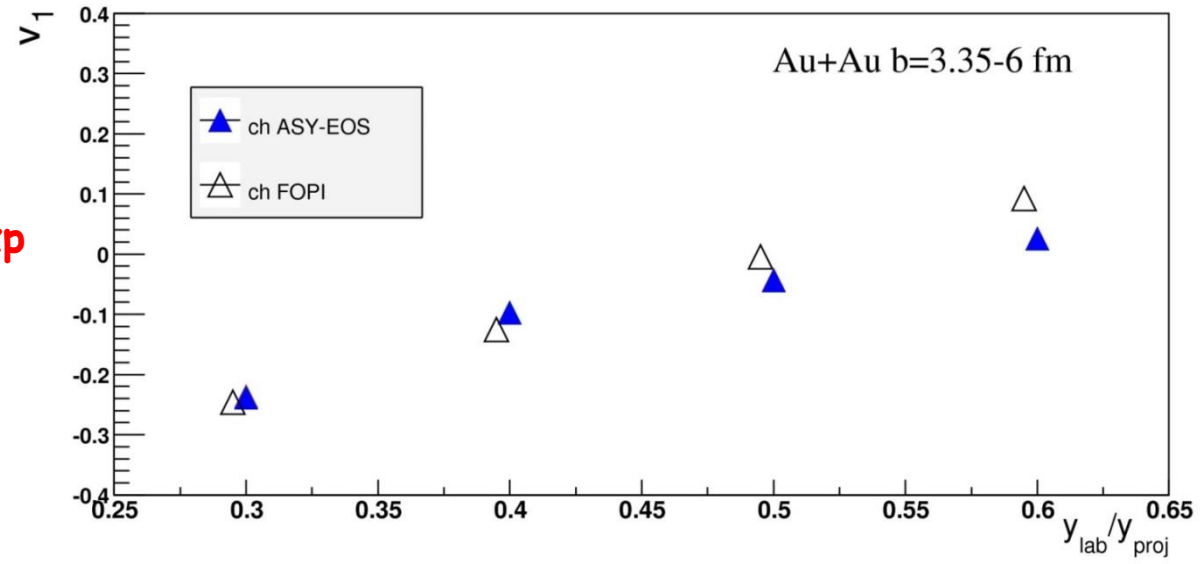
Comparing ASY-EOS with FOPI: rapidity dep. of charged particles

Au+Au @ 400 A.MeV

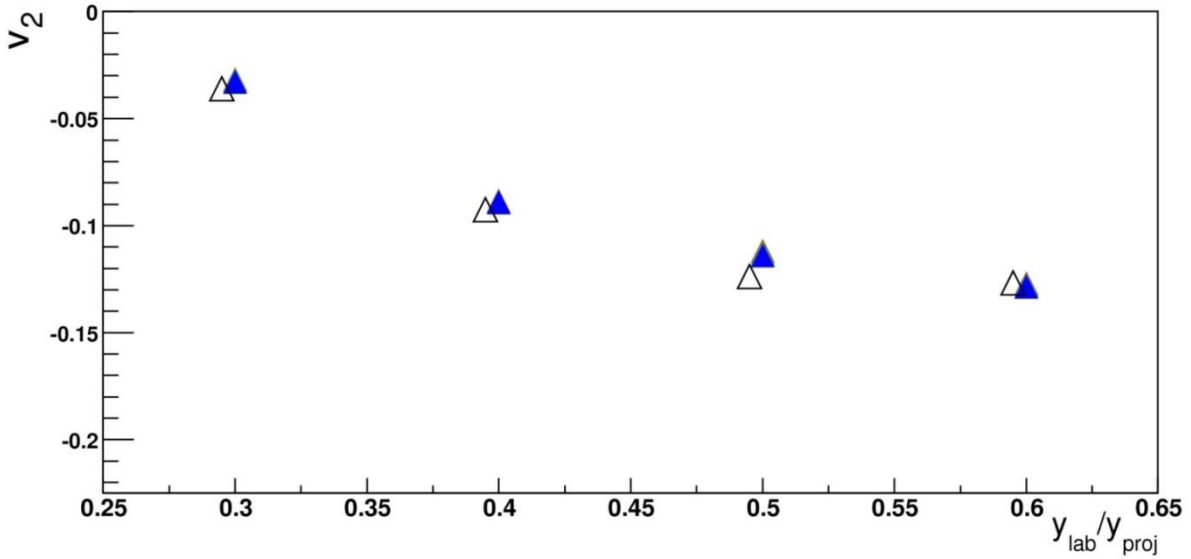
3.35<b<6 fm (c2)

θ_{lab} cut as LAND in ASY-EOS exp

Courtesy of W. Reisdorf



Good agreement between v2 of charged particles of FOPI and ASY-EOS exps …good benchmark for us

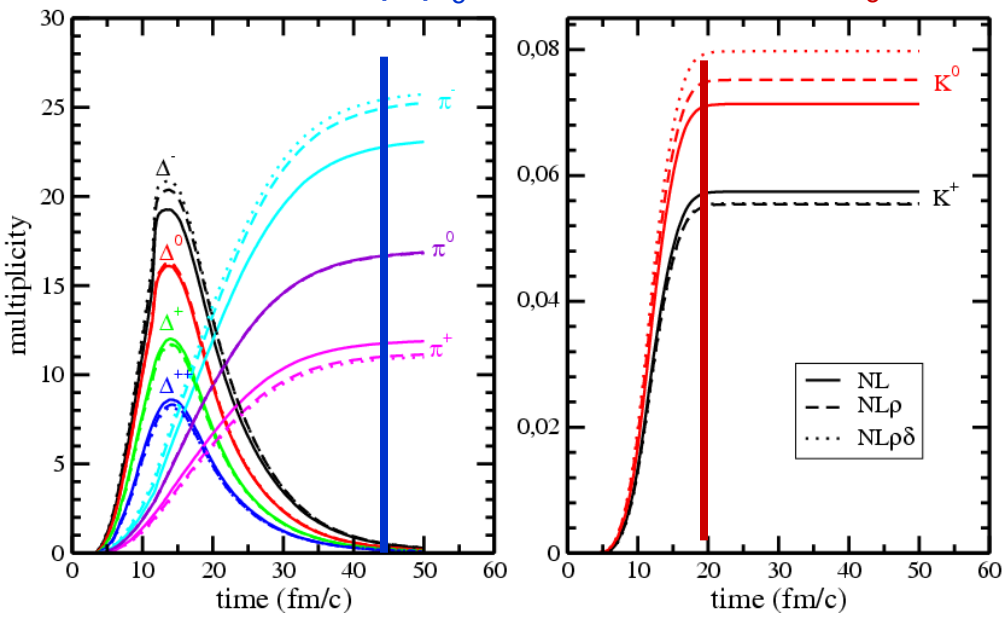


preliminary

Pion and Kaon freeze-out in HIC

Low ρ/ρ_0 High ρ/ρ_0

π^+, π^-



K^+, K^0

Ferini et al., PRL97, 202301

Warning ?

FOR OTHER INTERESTING OBSERVABLE SEE:

Zhi-Gang Xiao et al., Eur. Phys. J. A (2014) 50: 37

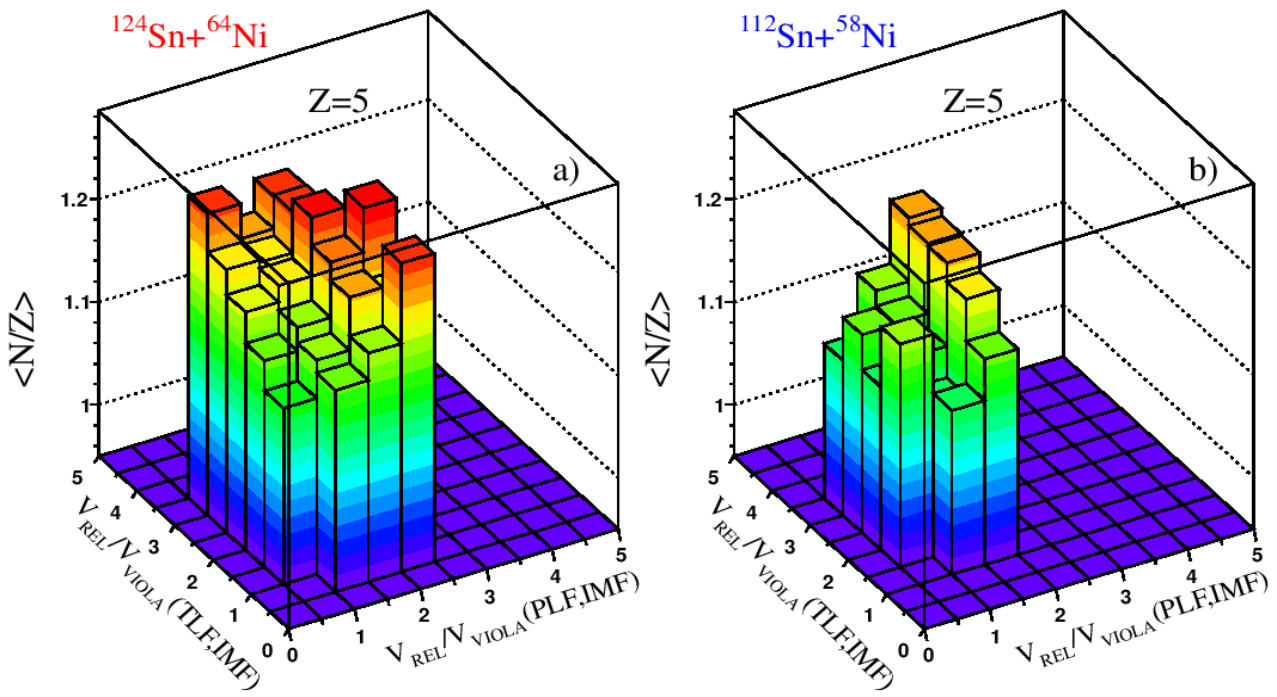
- Strong
- Freeze-out at late times (low ρ/ρ_0)
- Difficult to isolate π^+ and π^- produced in the high density stage

- Weakly interacting in medium
- Freeze-out already at 20 fm/c: more reliable as high ρ probes

For exp. results see
X.Lopez et al. (Fopi coll.) PRC 75, 011901 2007

FIG. 1 (color online). Time evolution of $\Delta^{-,0,++}$ resonances, pions $\pi^{-,0}$ (left), and kaons $K^{0,+}$ (right) for a central ($b = 0$ fm impact parameter) Au + Au collision at 1A GeV incident energy. Transport calculation using the NL, NLρ, NL$\rho\delta$, and DDF models for the isovector part of the nuclear EOS are shown.

Correlations between <N/Z> for Z=5 and relative velocities in the r1-r2 plane for a neutron rich and a neutron poor system



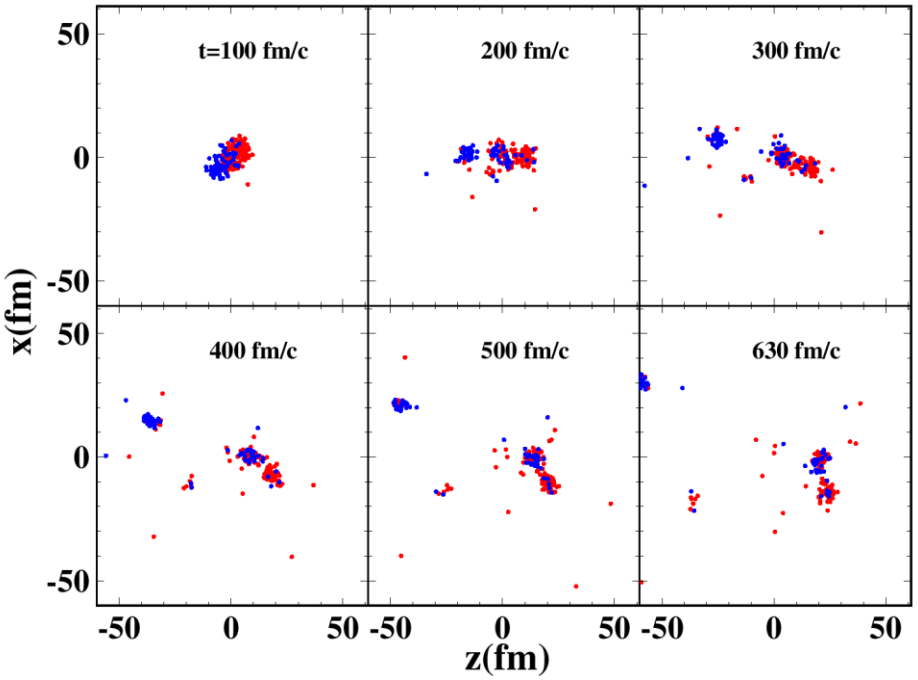
In order to study correlations between fragments formation dynamics and fragments isotopic composition we have plotted <N/Z> for different bins in the V_{rel}/V_{viola}(PLF-IMF) – V_{rel}/V_{viola}(TLF-IMF) plane

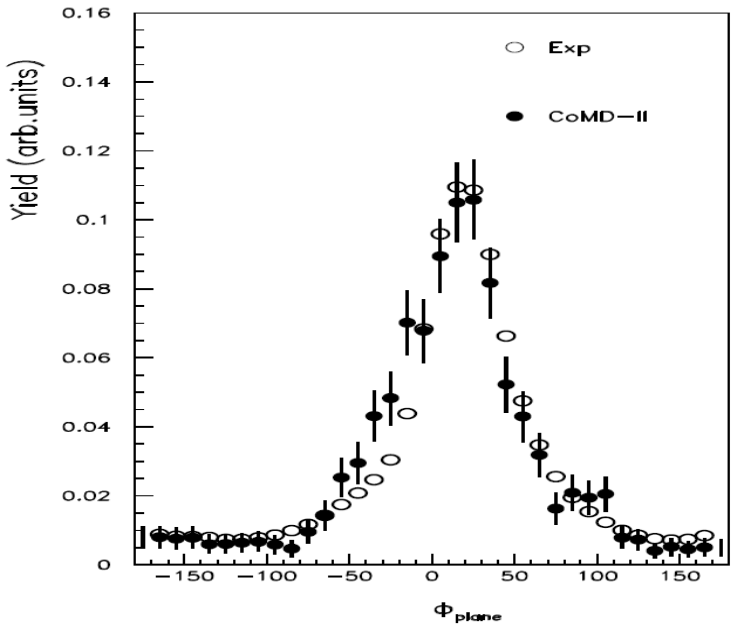
Correlating isospin and kinematical observables: a powerful constraint for transport theories

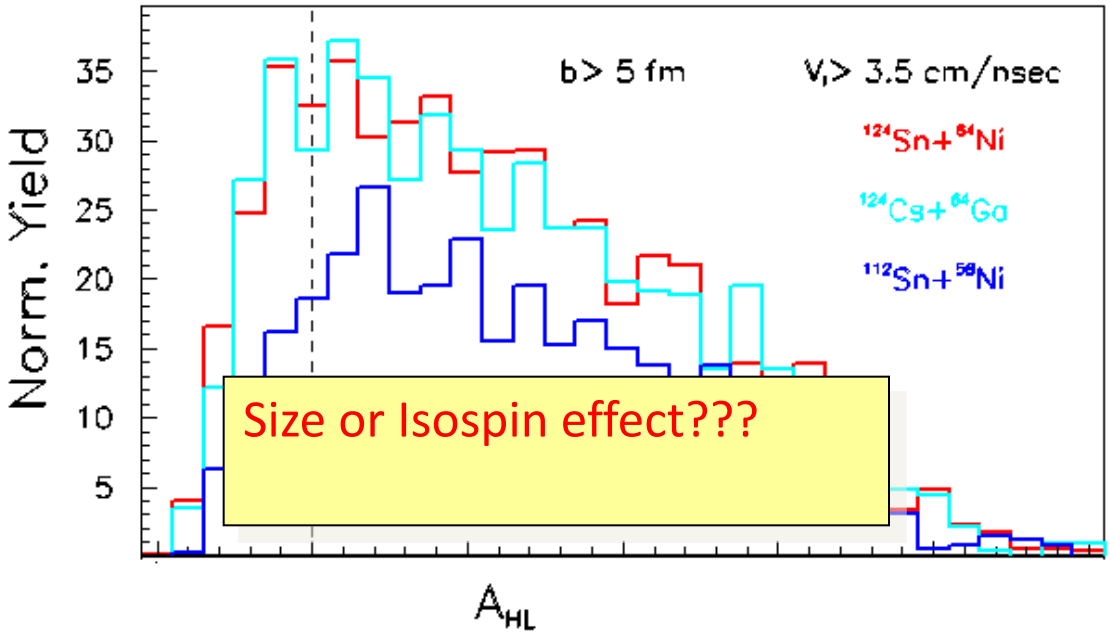
The correlation shows that the greatest neutron enrichment is linked to greater deviations from Viola systematics.

Constrained Molecular Dynamical-II (CoMD-II)

M.Papa et al., PRC 75 054616 (2007)







N/Z

1.48+1.29 (1.41)

1.25+1.06 (1.19)

1.24+1.07 (1.18)

M.Papa et al., Procs of IWM2007

AVERNE 25 al Max
2 in più al 24/11/2014

BACK UP
28/11/2014

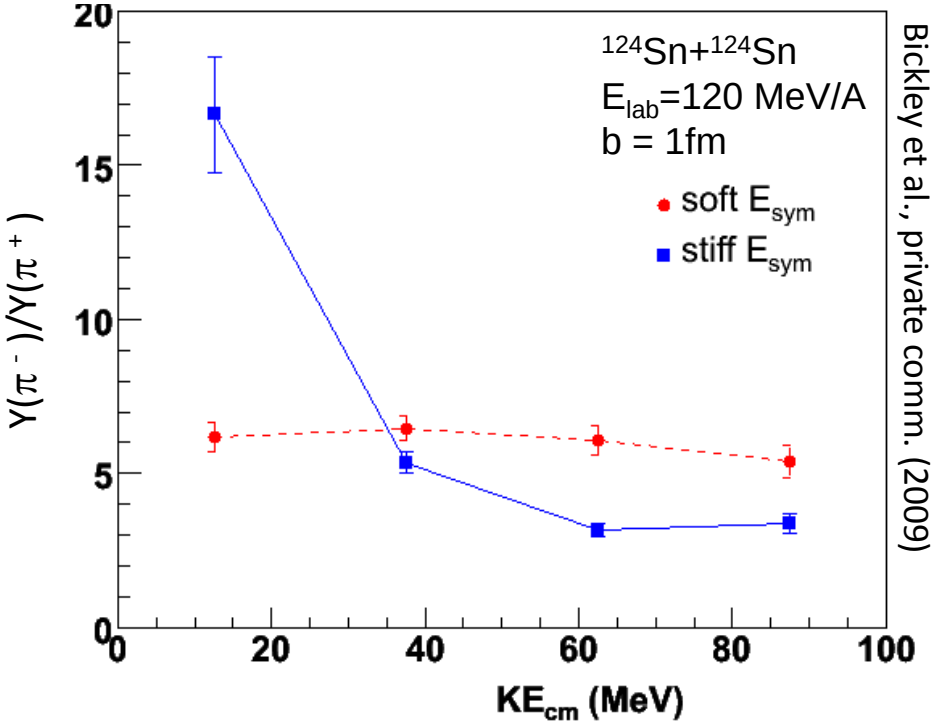
Summary

- Brief intro on High Density investigation of Symmetry Energy with H-I
- Suggestion for a route toward model independency…
- First results of the ASY-EOS experiment
- Future possibilities
- Conclusions

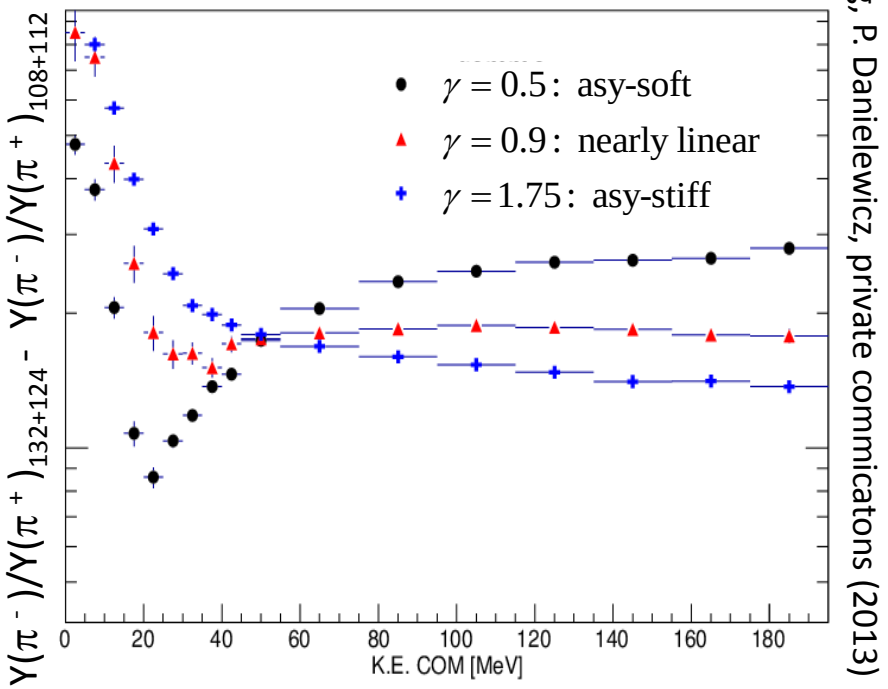
Difference between ^{132}Sn+ ^{124}Sn and ^{108}Sn+ ^{112}Sn collisions

W.G. Lynch talk @ NuSym 2014

E/A =120 MeV

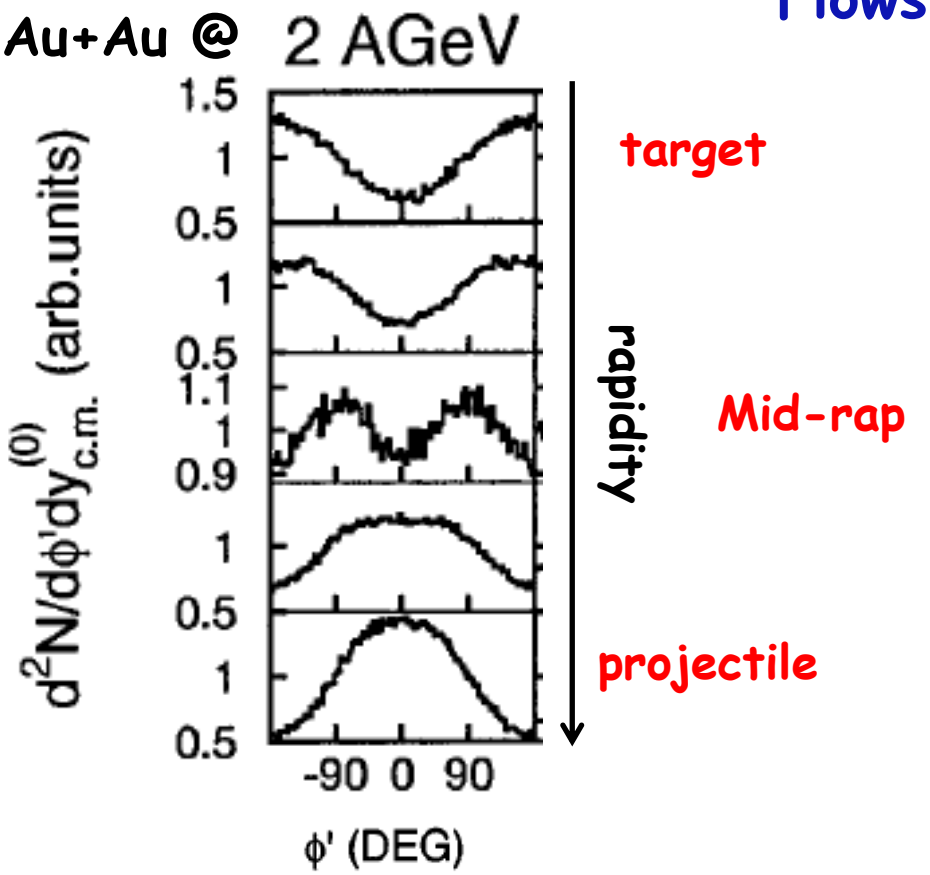


E/A = 300 MeV



- Pion ratio depends strongly on the symmetry energy.
- Ratios of spectra are more sensitive than ratios of integrated yields.
  - Integrated yields at E/A≥400 MeV suggest soft symmetry energy at $\rho \geq 2.5\rho_0$ (Xiao PRL, 102, 062502 (2009)
- Built two TPC's to probe these observables
  - E/A<150 MeV at MSU and E/A=200-350 MeV at RIKEN (probes $\rho \approx 2\rho_0$).

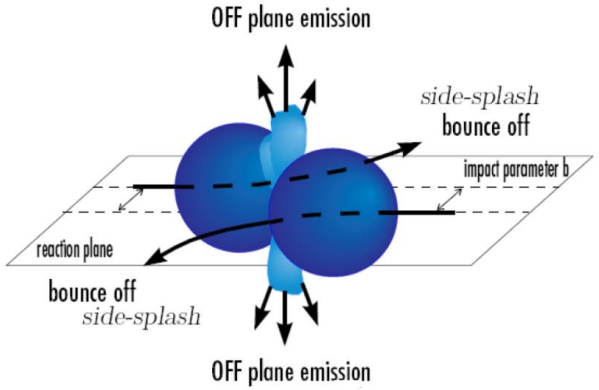
Flows II



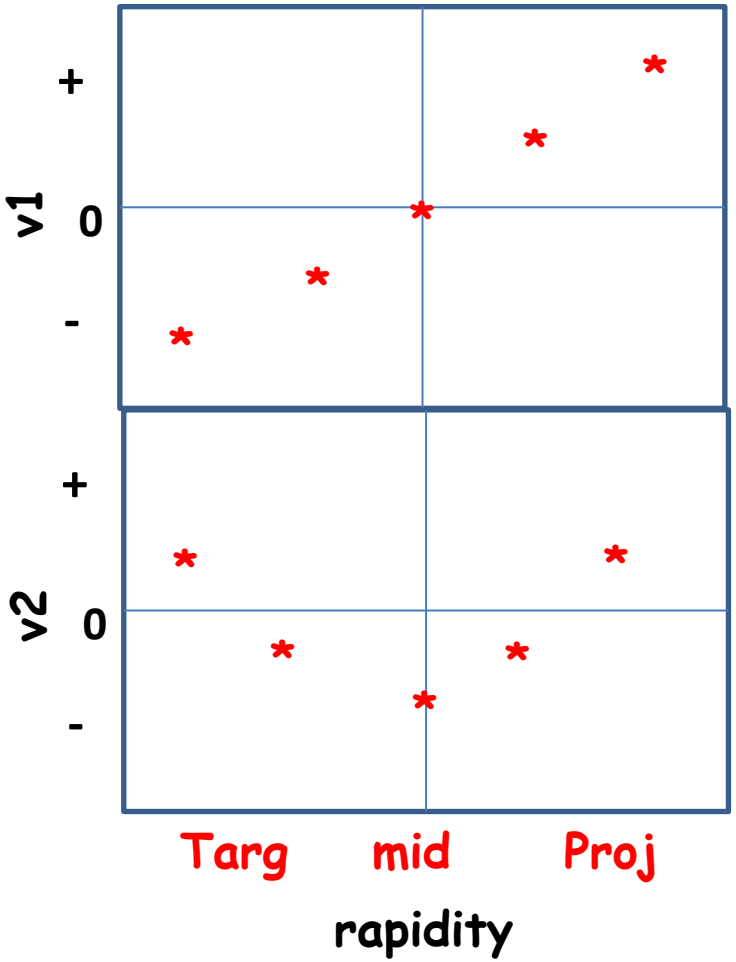
C.Pinkenburg et al., (E895),Phys.Rev.Lett. 83 (1999) 1295, *nucl-ex/9903010*

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

Y = rapidity
pt = transverse momentum

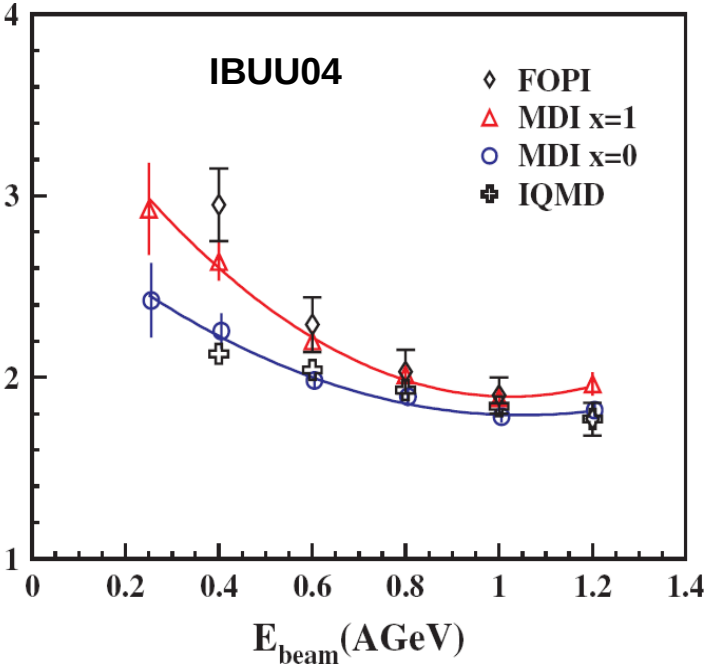


Not to scale: qualitative

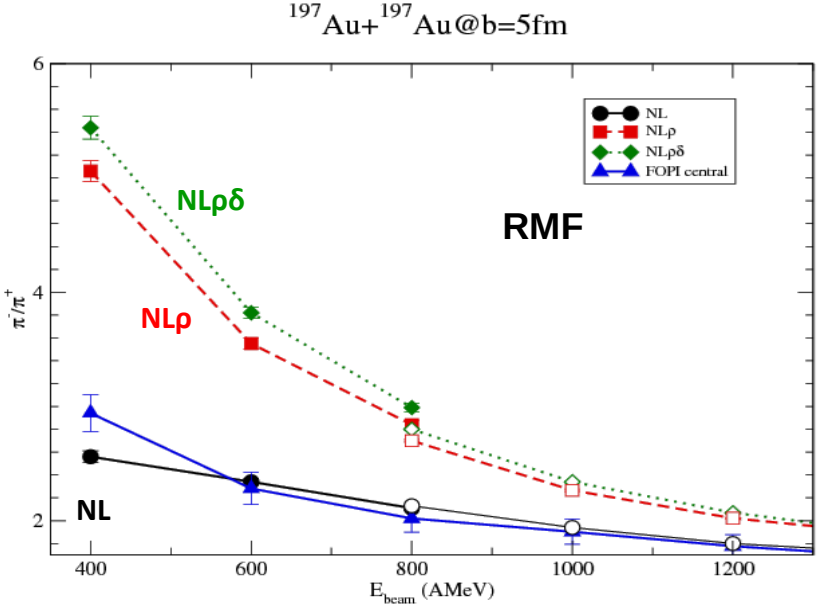


Esym at high density: pions

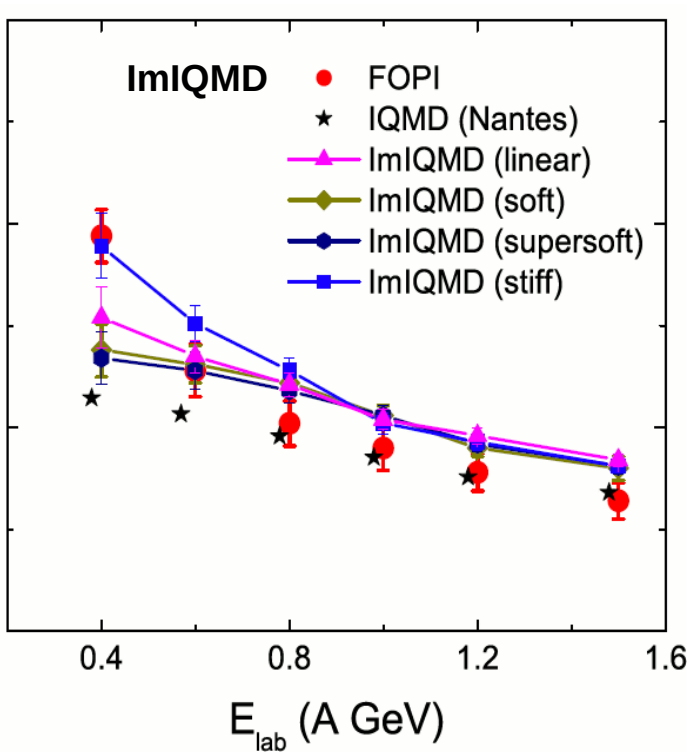
Z. Xiao et al., PRL 102 (09)



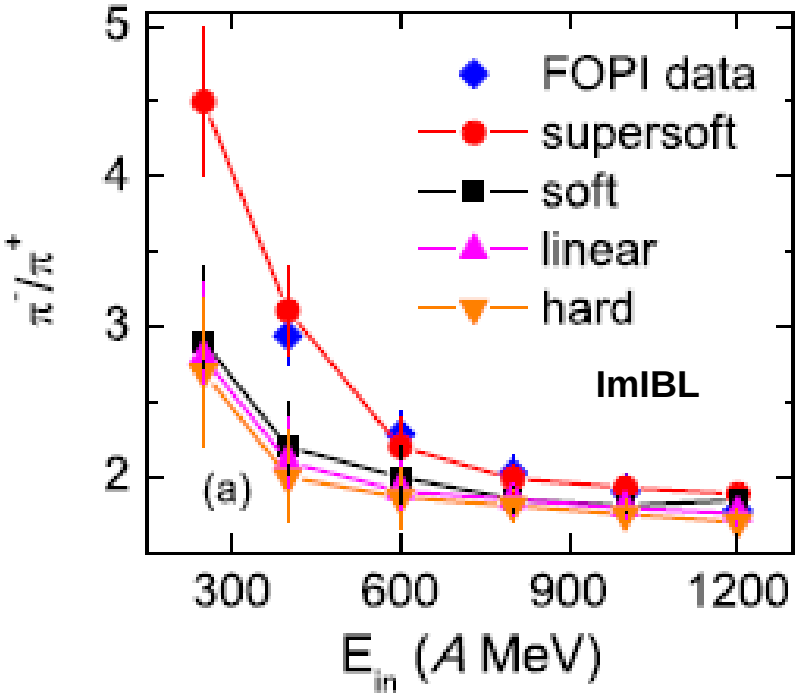
Ferini, at al., NPA 762 (2005)



Z.Q. Feng, PLB 683 (2010)

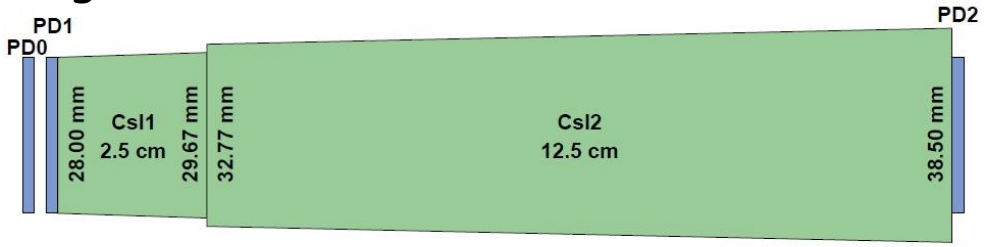


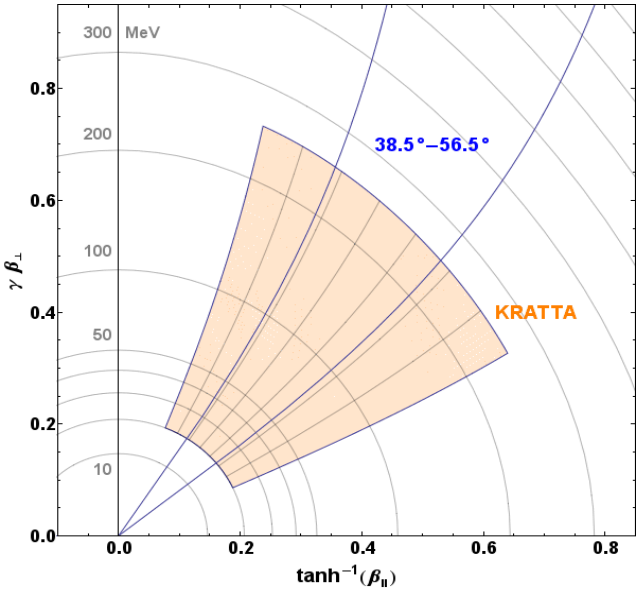
W.J. Xie , at al., PLB 718 (2013)



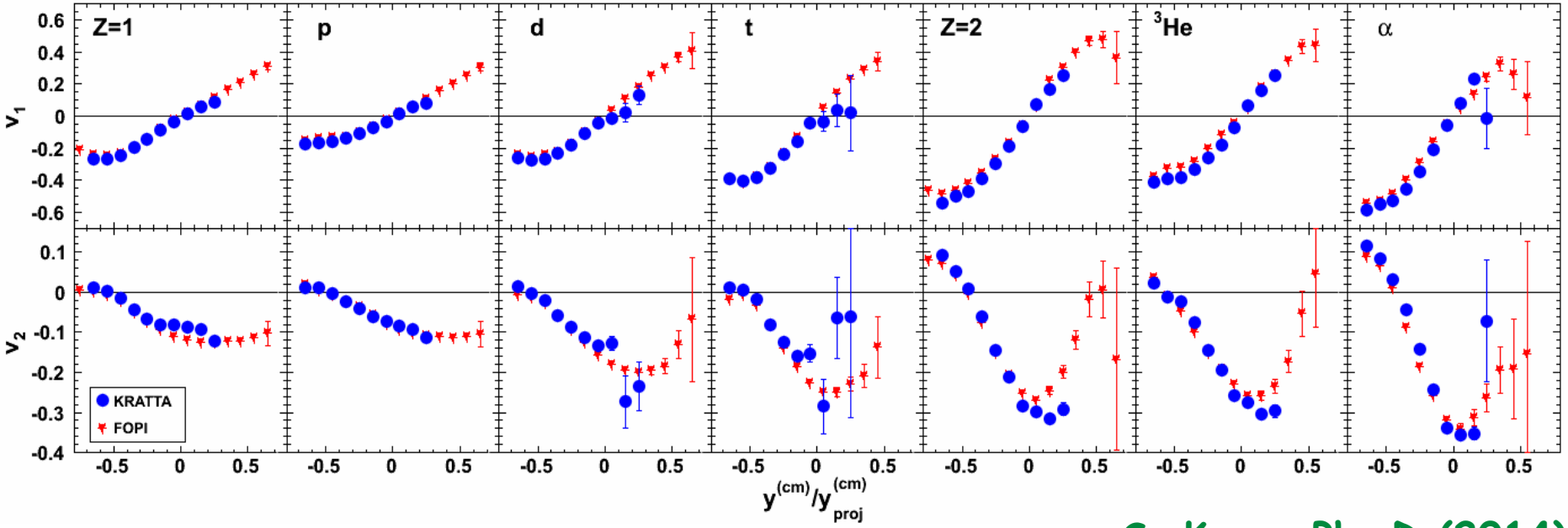
Comparing KraTTA* with FOPI: rapidity dep. of isotopes

35 modules (5 x7), 20.7°<θ<63.5°
40 cm from target.
Digitized with 100 MHz, 14 bits Flash ADCs





Au+Au @ 400 A.MeV
3.35<b<6 fm (c2)
θ_{lab} cut as LAND

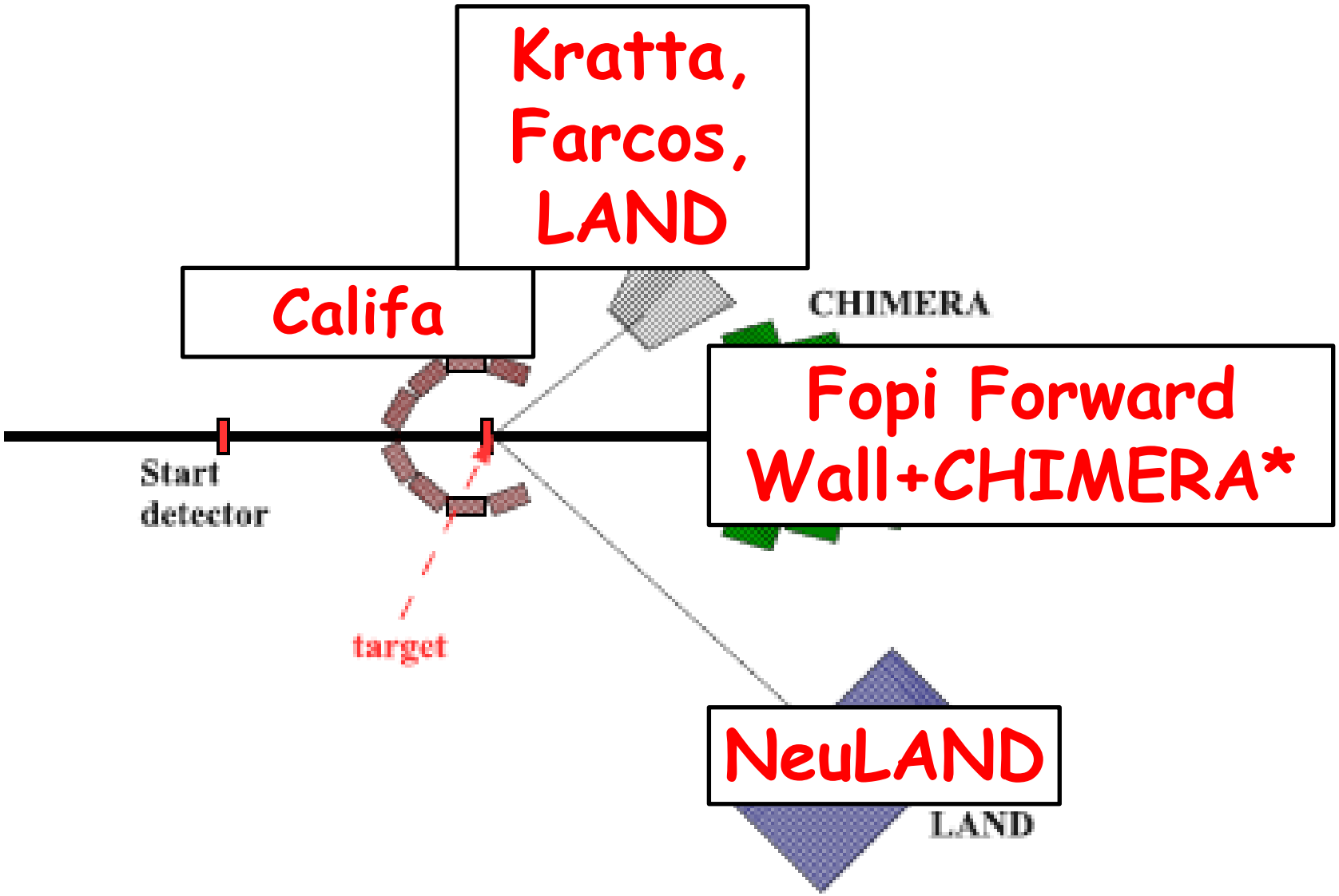


*J. Lukasik et al., NIM A 709, 120 (2013)

S. Kupny Ph. D (2014)

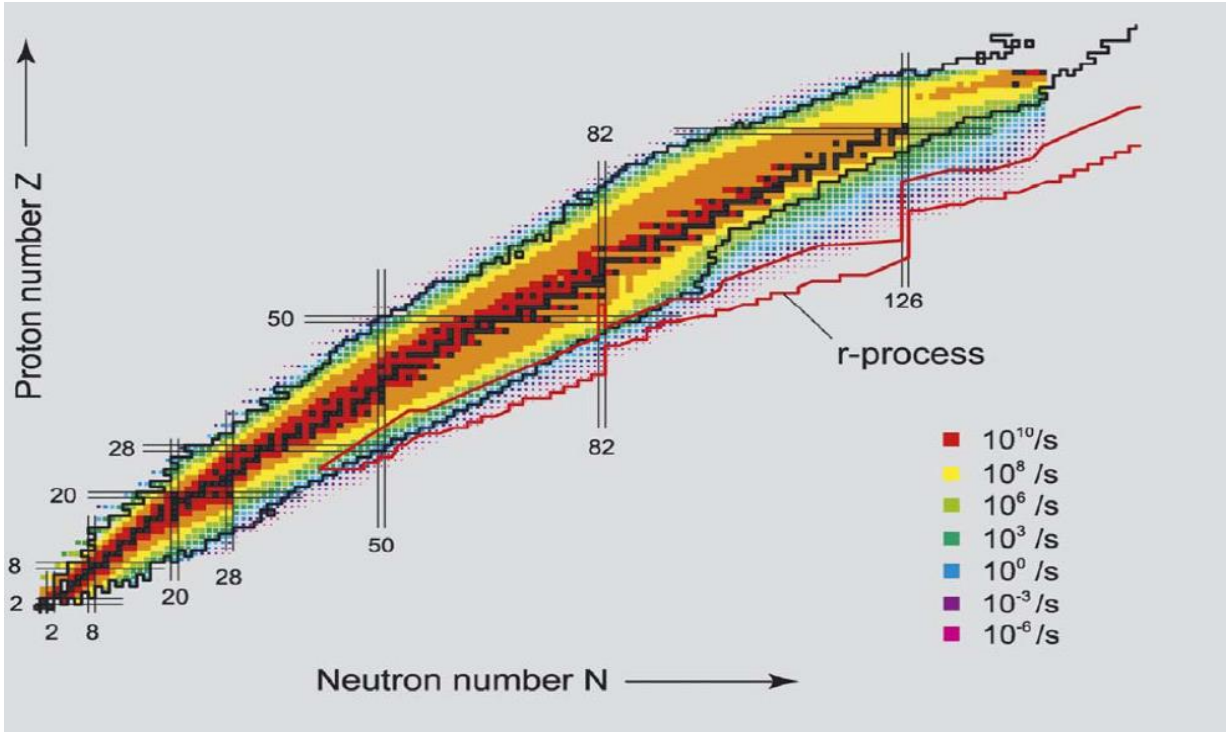
Systematic+ Integ

ASY-EOS future set-up?



* Ring 1-2-3
(θ<7°)

FAIR rates



Some interesting beams (and I^2)

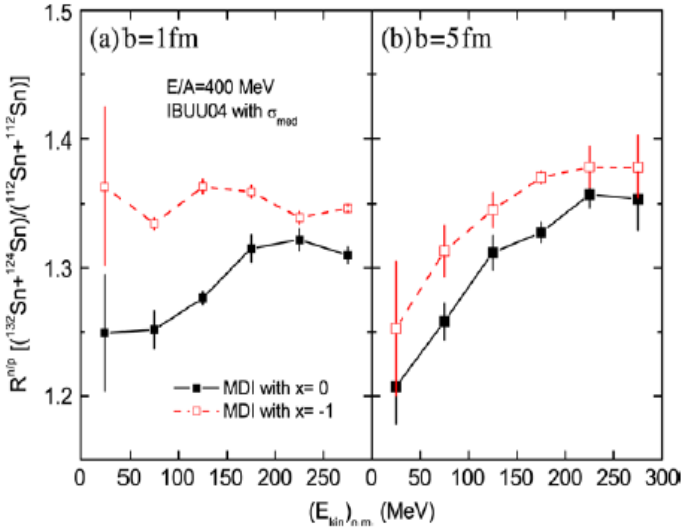
$^{197}Au+^{197}Au$ @ 600,800,1000 AMeV (0.039+0.039)

$^{132}Sn+^{124}Sn$ @ 400, 800, 1000 AMeV (0.059+0.037)

$^{106}Sn+^{112}Sn$ @ 400, 800, 1000 AMeV (0.003+0.011)

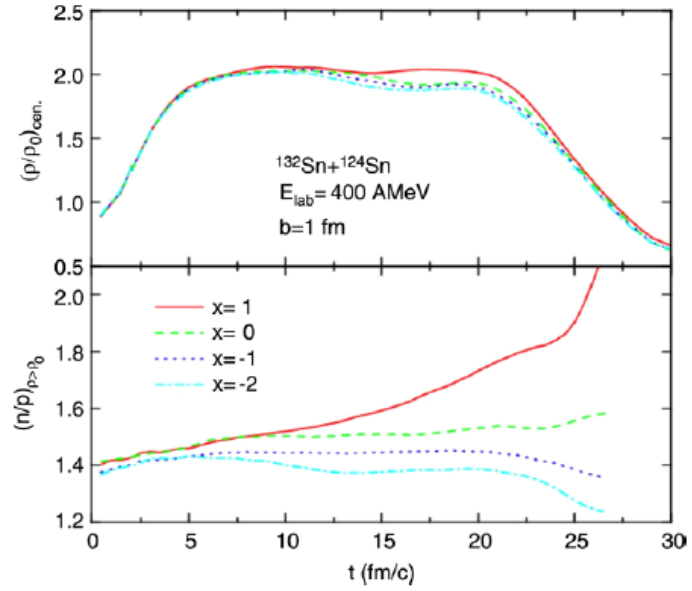
Why ^{132}Sn?

B.-A. Li et al. / Physics Reports 464 (2008) 113–281

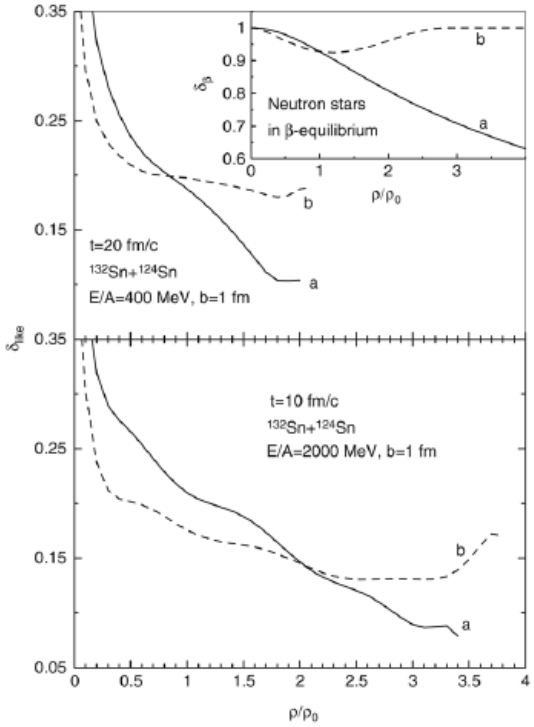


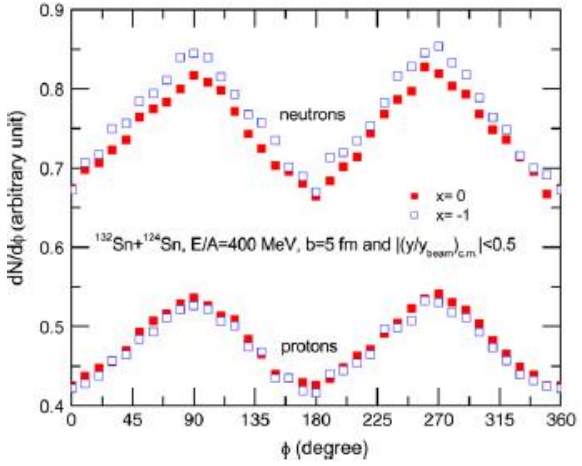
atio of free nucleons taken from the reactions of ^{132}Sn + ^{124}Sn and ^{112}Sn +
m (right panel). Taken from Ref. [67].

B.-A. Li et al. / Physics Reports 464 (2008) 113–281

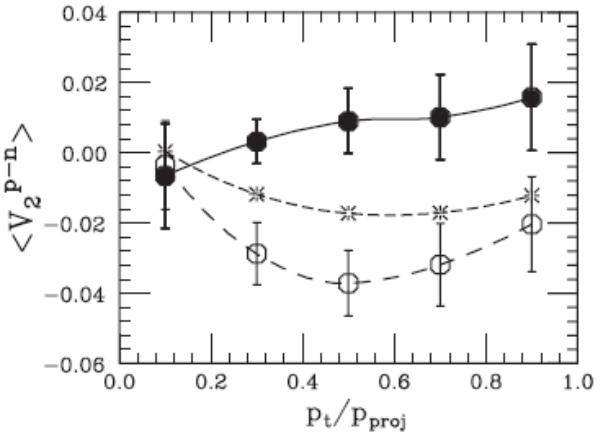


B.-A. Li et al. / Physics Reports 464 (2008) 113–281



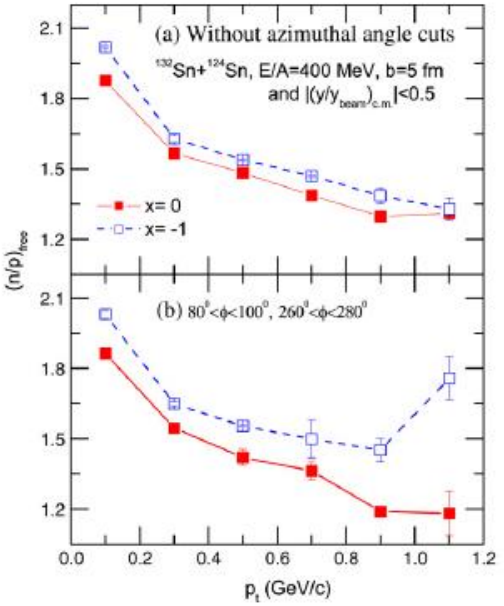


V. Baran et al. / Physics Reports 410 (2005) 335–466



1.5 A GeV ($b = 6$ fm) from the three different models f
ill circles and solid line: $NL\rho\delta$. Open circles and dashe
ext and the previous caption.

ics Reports 464 (2008) 113–281 233



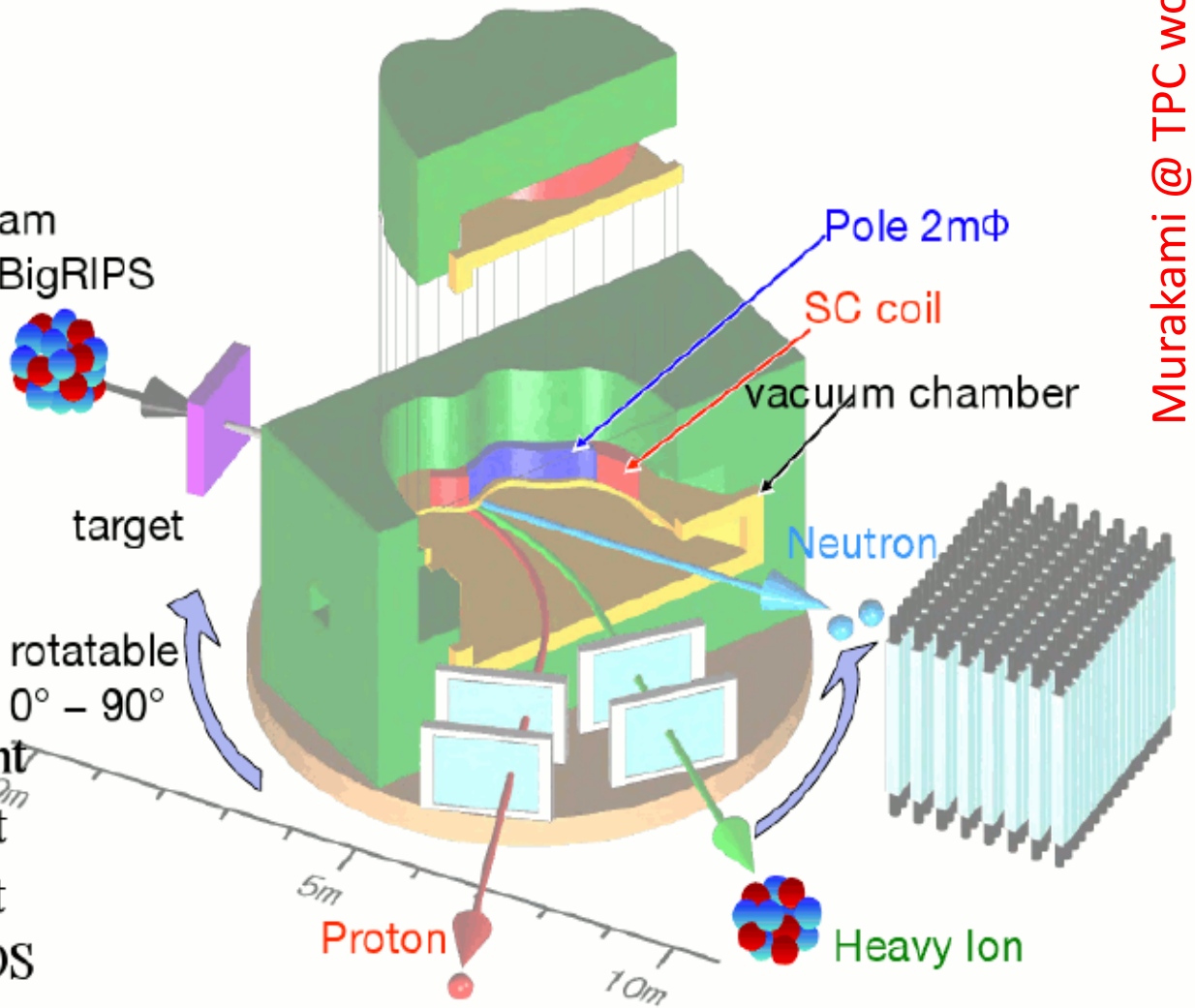
Design Characteristics

Kinematically complete measurements
Detecting multiple (all) particles in coincidence

→ Large p acceptance
Large θ φ acceptance

- ✓ Superconducting magnet
- ✓ Heavy Ion detectors
- ✓ Proton detectors
- ✓ Neutron detectors
- ✓ Large vacuum chamber
- ✓ Rotational stage

- Invariant mass measurement
- Missing mass measurement
- pol d induced measurement
- Multi fragmentation for EOS

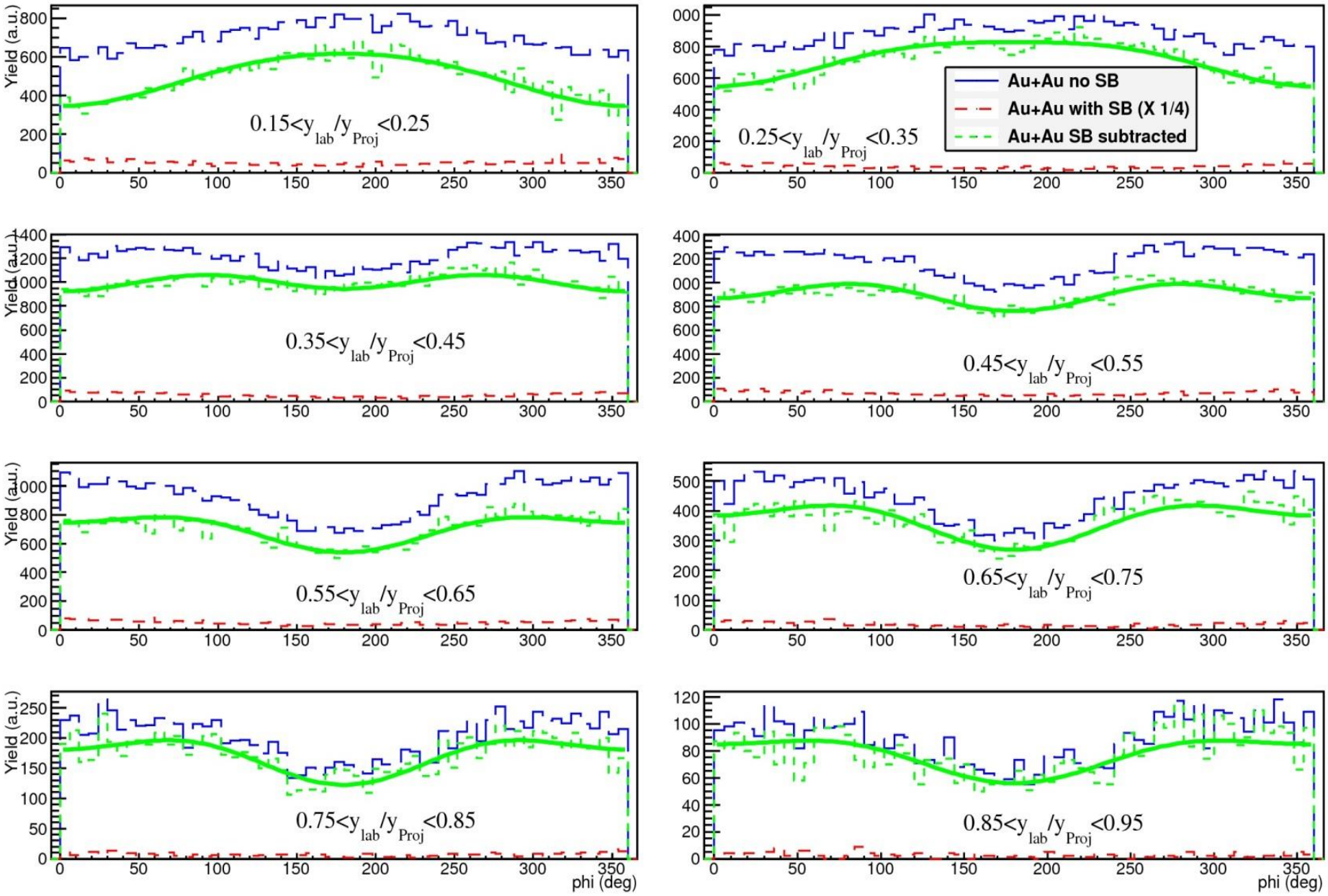


Murakami @ TPC workshop, MSU

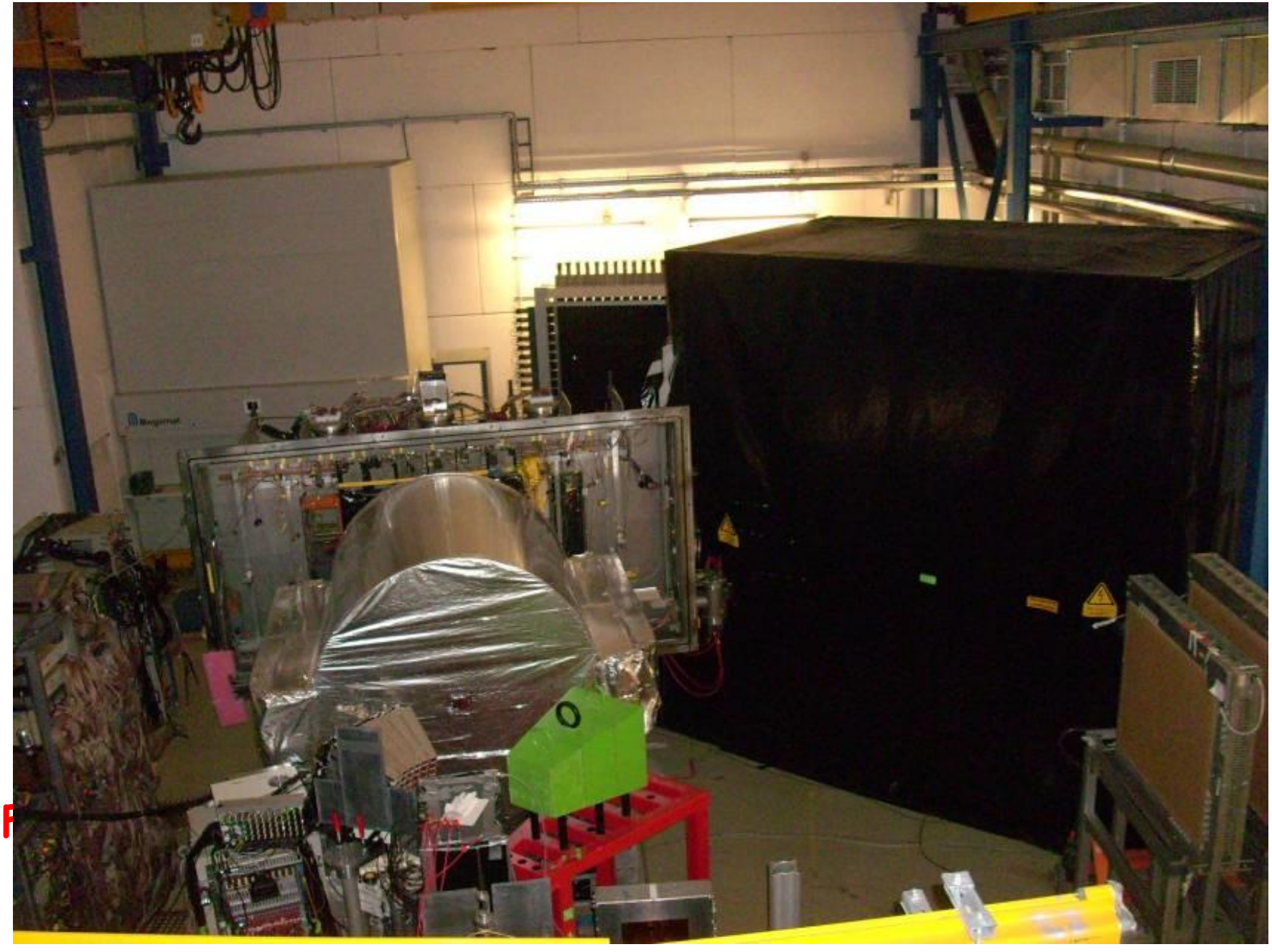
FROM IWM2014

Neutron azimuthal distributions from LAND

Au+Au @ 400 AMeV
b< 7.5 fm



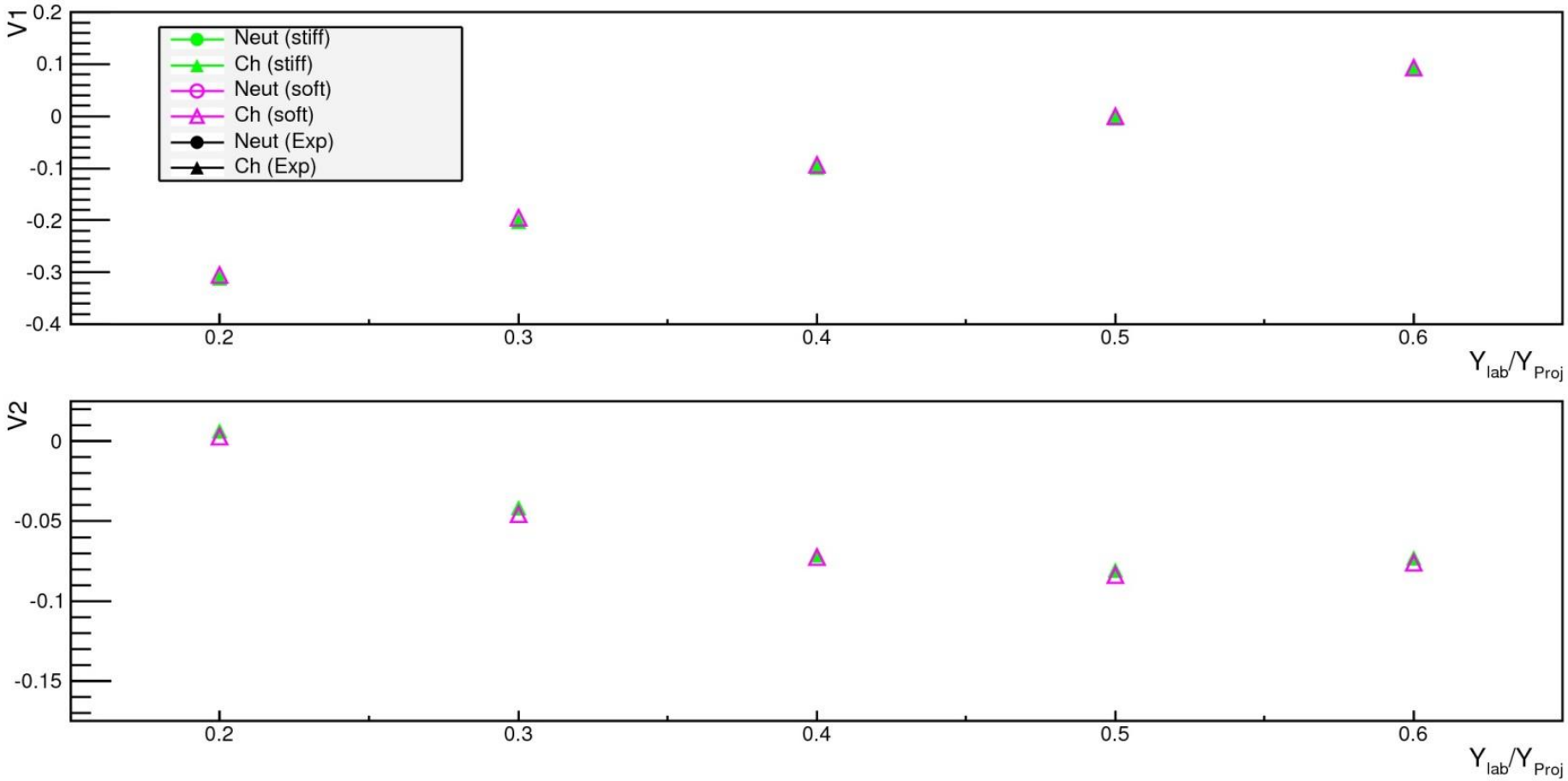
How much background to subtract ?



Comparison with UrQMD

Au+Au @ 400 AMeV b<7.5 fm

Wbg= 110 %



Only charged particles!!!

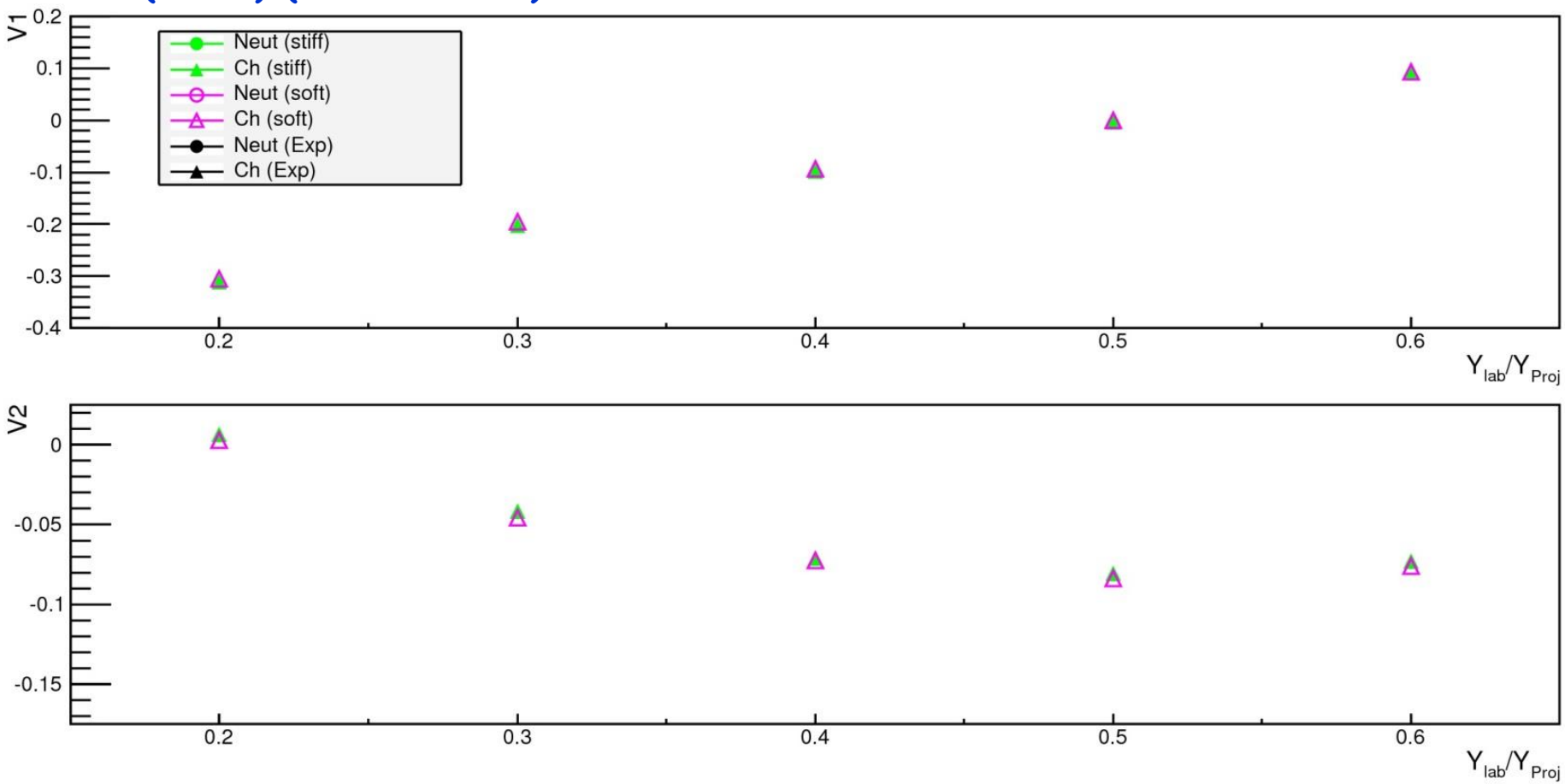
preliminary

Comparison with UrQMD

Au+Au @ 400 AMeV b<7.5 fm

Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

Charged Particles:
(Au+Au)-(Au+EF)



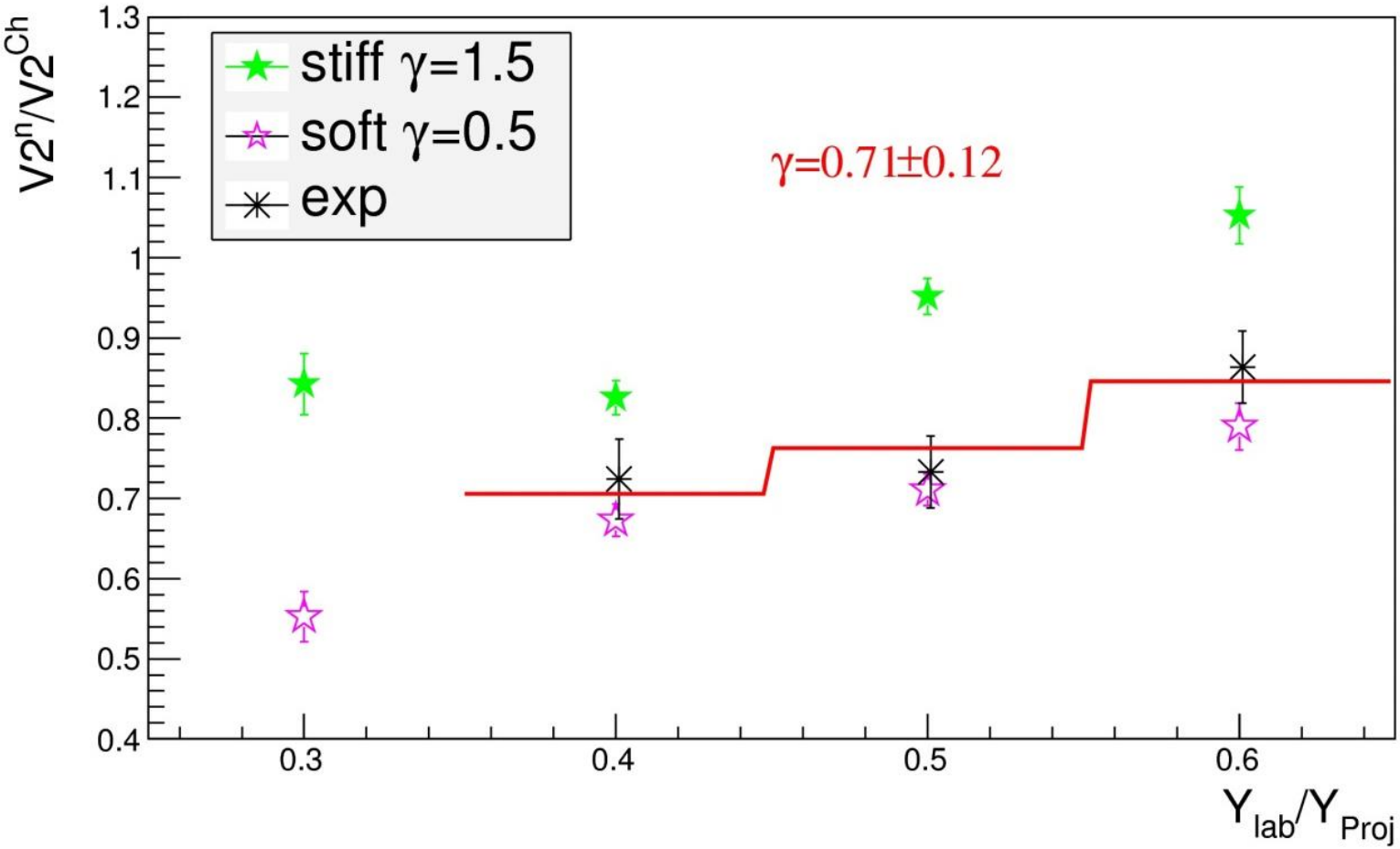
Only charged particles!!!

preliminary

γ extrapolation from rapidity dependence

Au+Au @ 400 AMeV b<7.5 fm

Wbg= 110 %

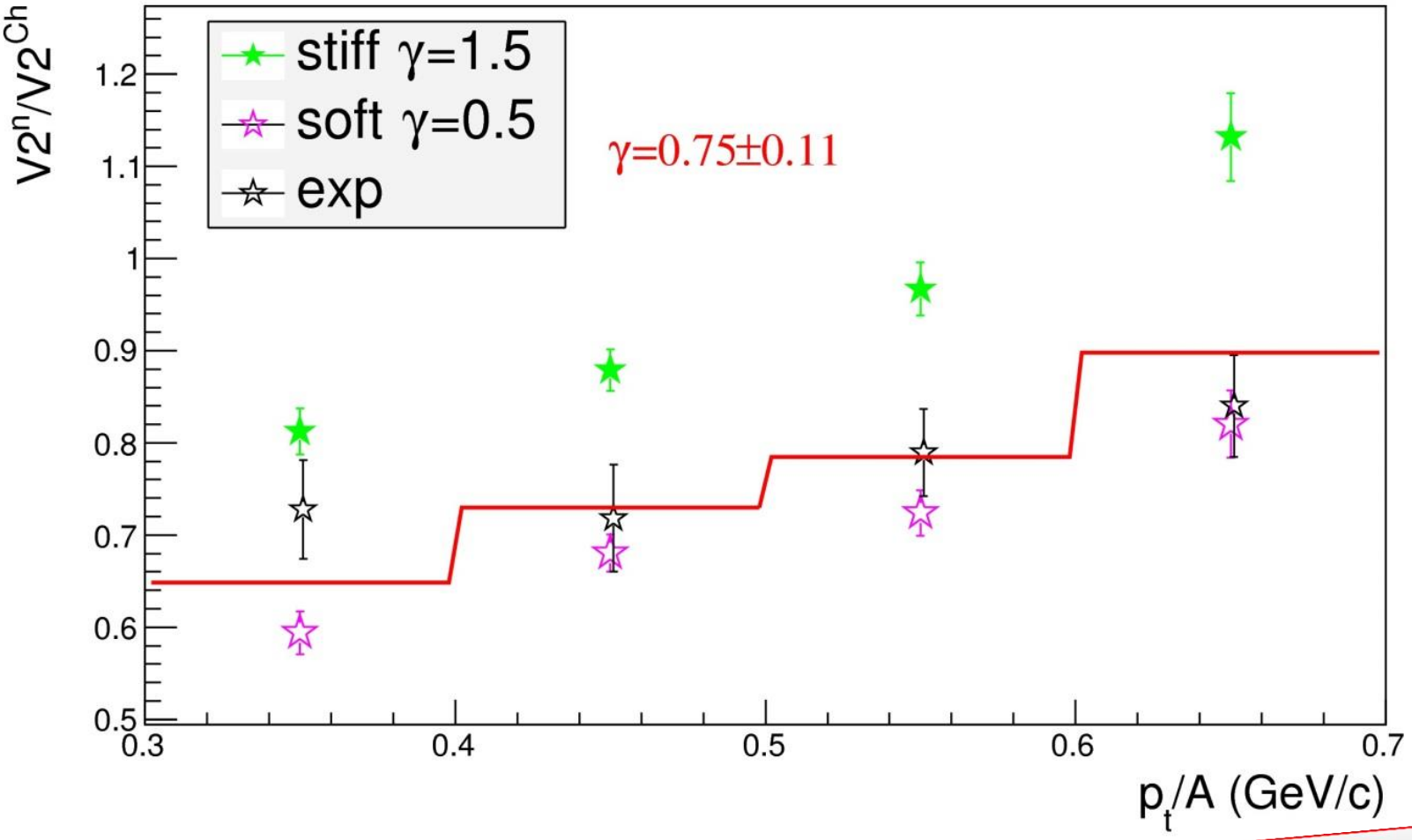


preliminary

γ extrapolation from transverse momentum dependence

Au+Au @ 400 AMeV b<7.5 fm

Wbg= 110 %

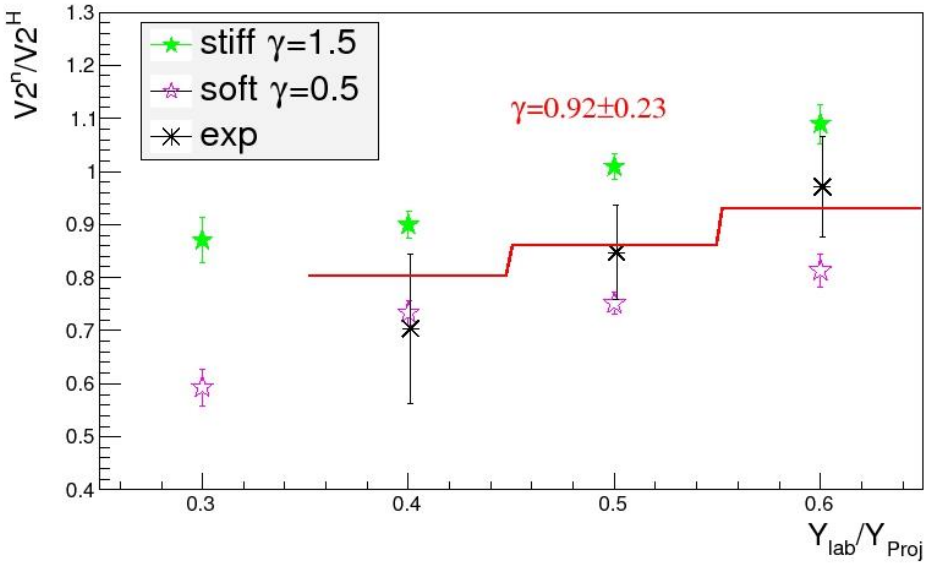


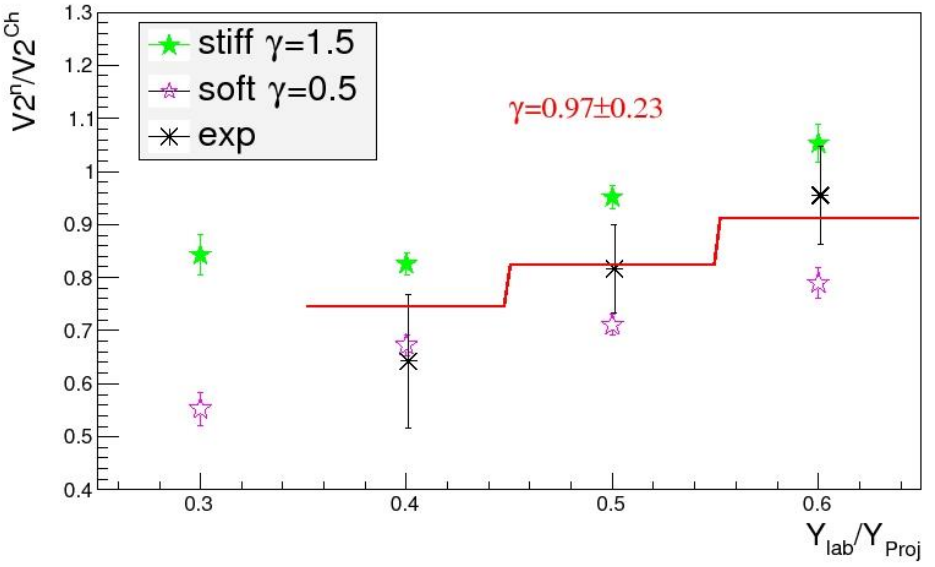
preliminary

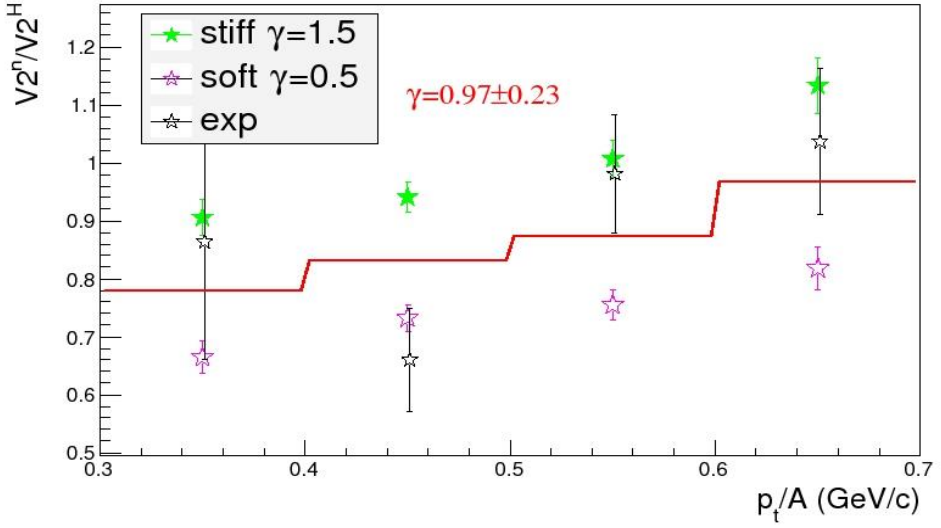
γ extrapolation : v2n/v2ch vs v2n/v2H (FOPI-LAND data)

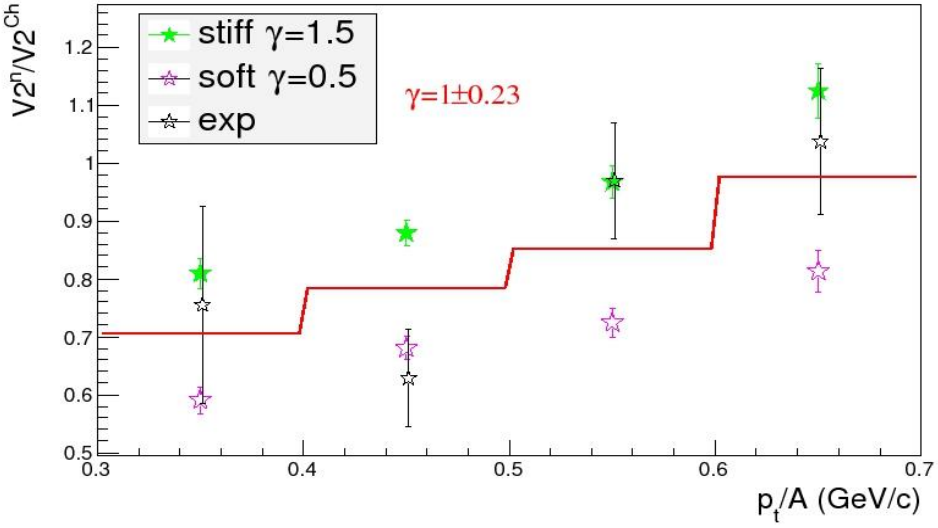
Au+Au @ 400 AMeV
b<7.5 fm

$0.25<y_{lab}/y_{proj}<0.75$
θ_{lab} cut as in ASY-EOS set-up

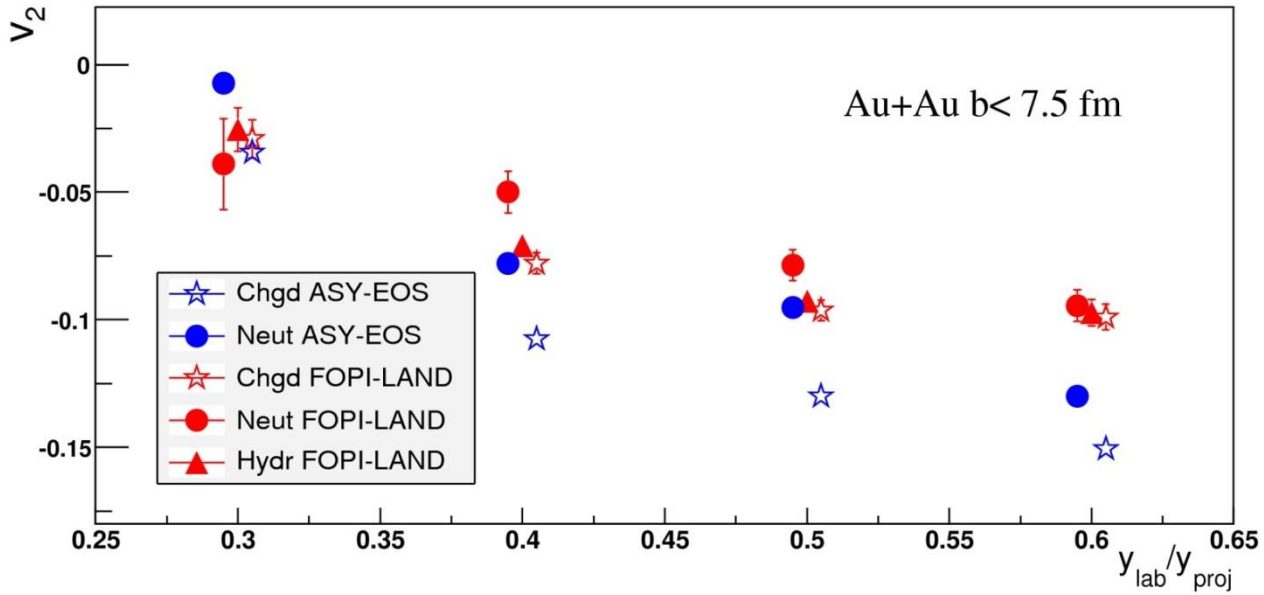


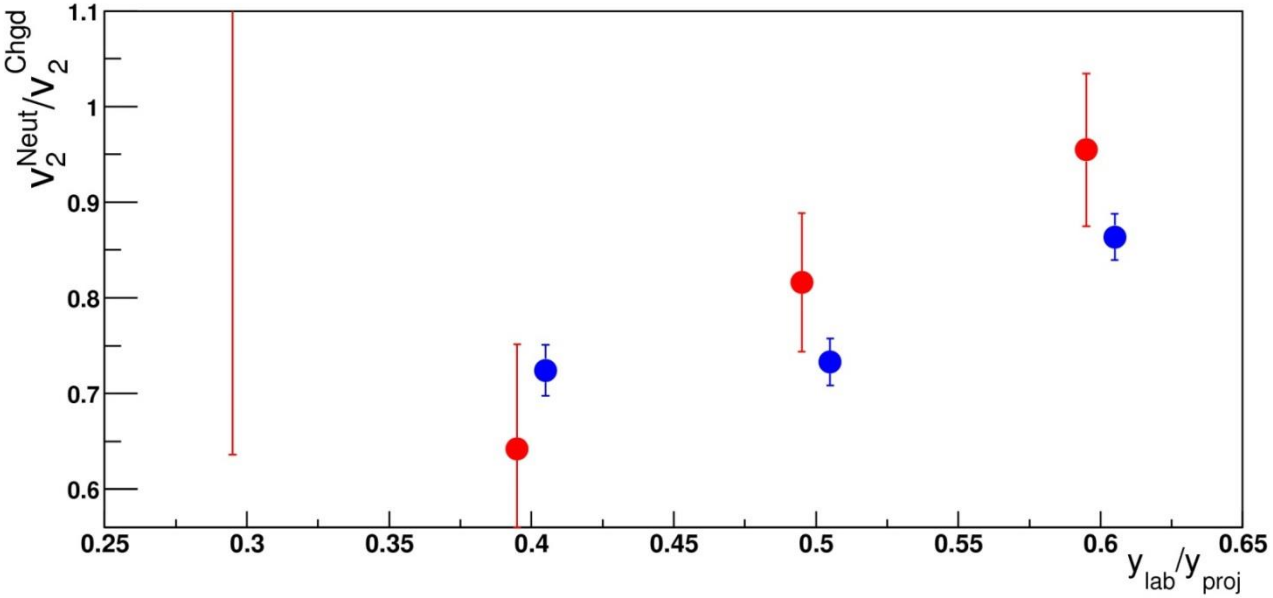






Comparing ASY-EOS with FOPI-LAND exp: rapidity dependence





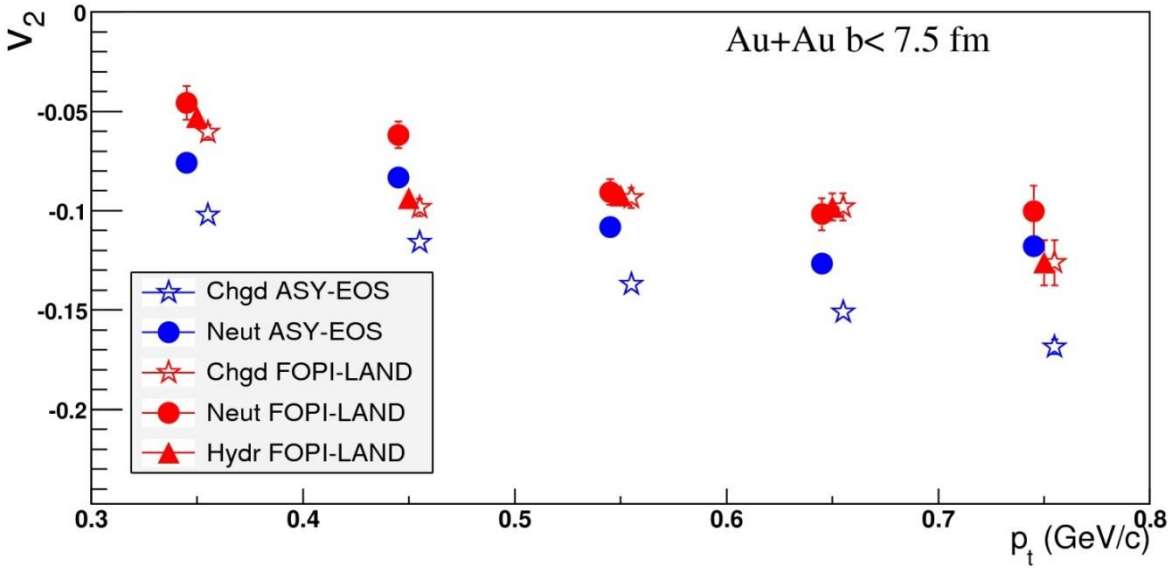
Au+Au @ 400 AMeV
b<7.5 fm
$0.25 < y_{lab}/y_{proj} < 0.75$

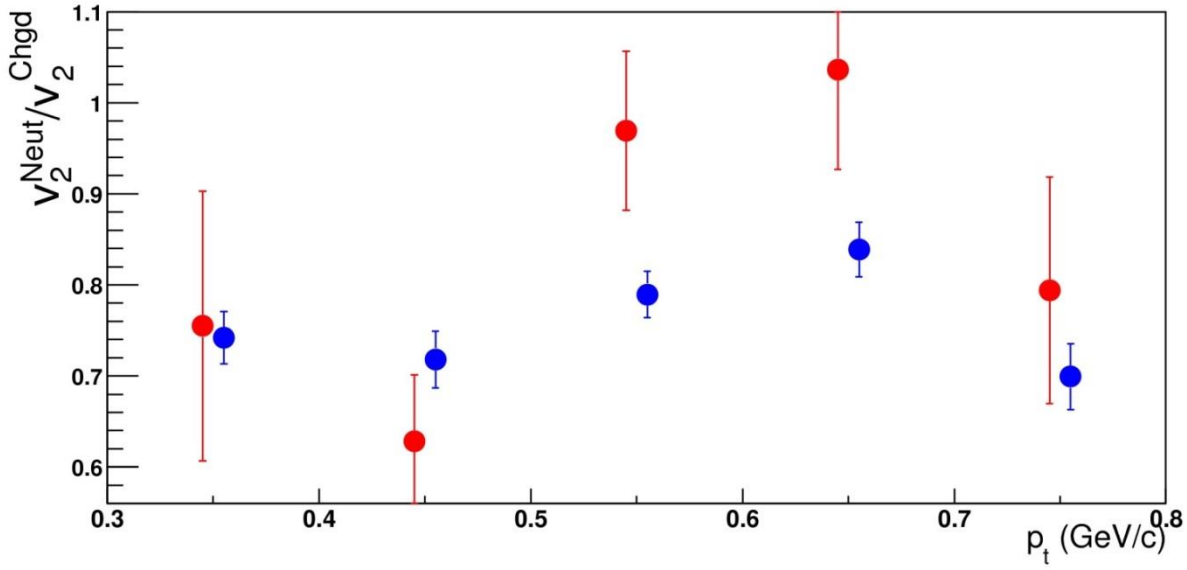
θ_{lab} cut as in ASY-EOS set-up

Wbg= 110 %

preliminary

Comparing ASY-EOS with FOPI-LAND exp: transverse momentum dep.





Au+Au @ 400 AMeV
b<7.5 fm
$0.25 < y_{lab}/y_{proj} < 0.75$

θ_{lab} cut as in ASY-EOS set-up

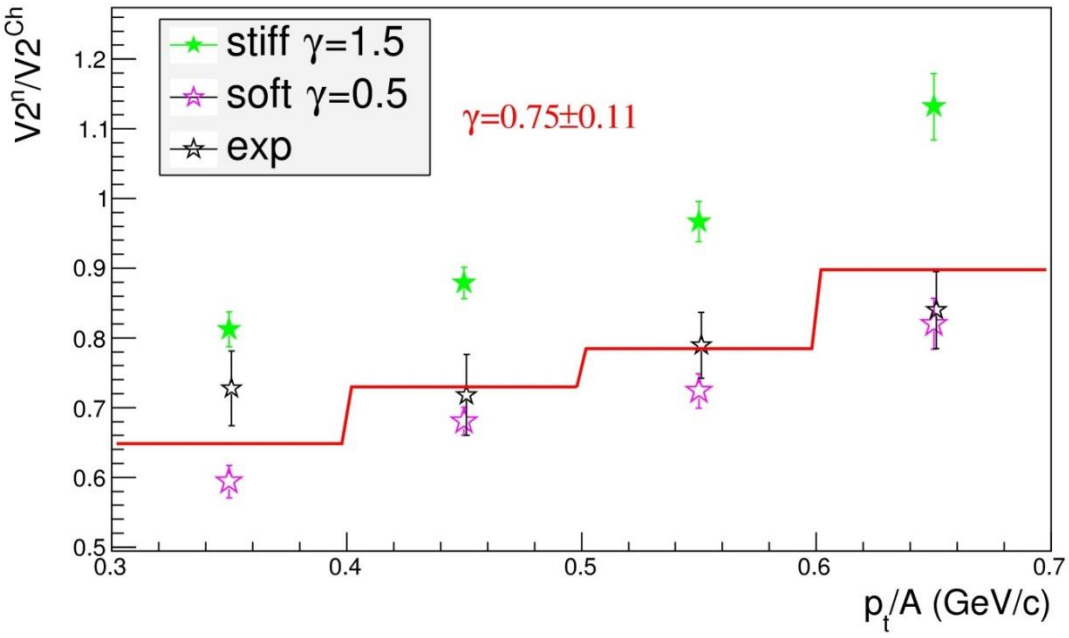
Wbg= 110 %

preliminary

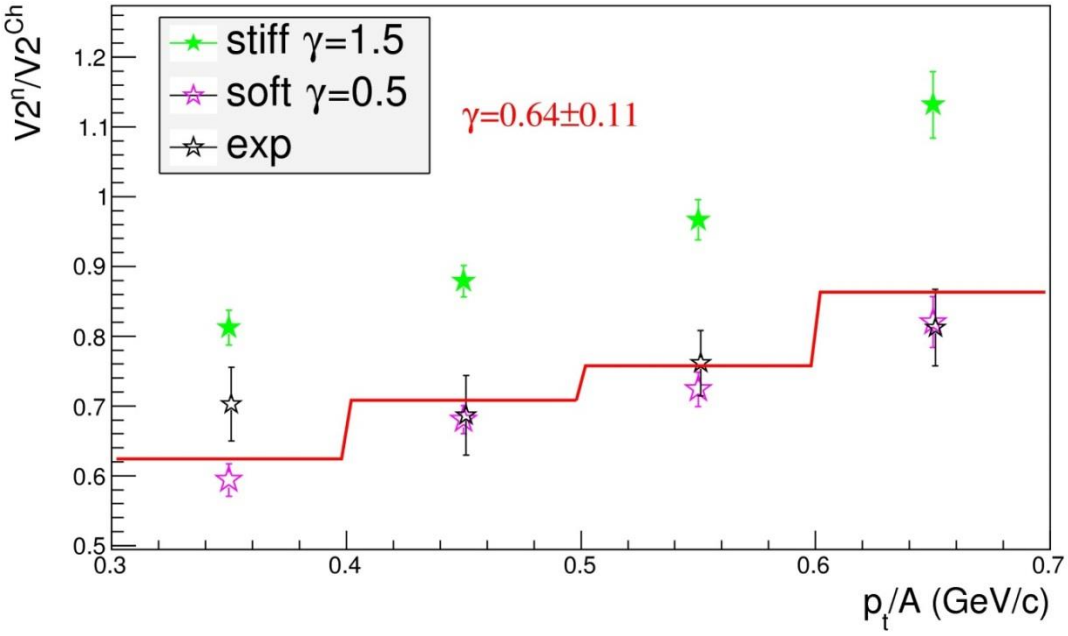
γ extrapolation from transverse momentum dependence : Wbg influence

Au+Au @ 400 AMeV
b<7.5 fm

Wbg= 110 %



Wbg= 100 %

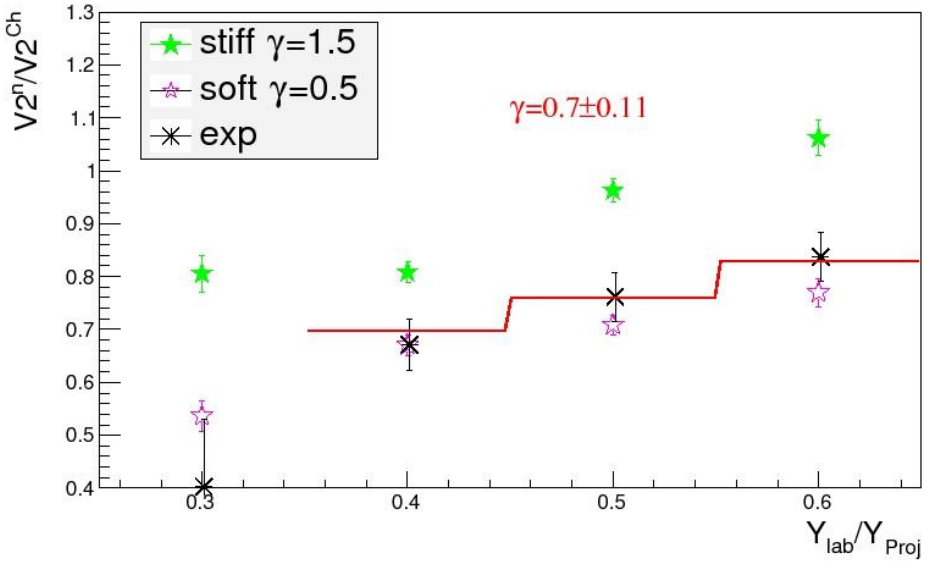


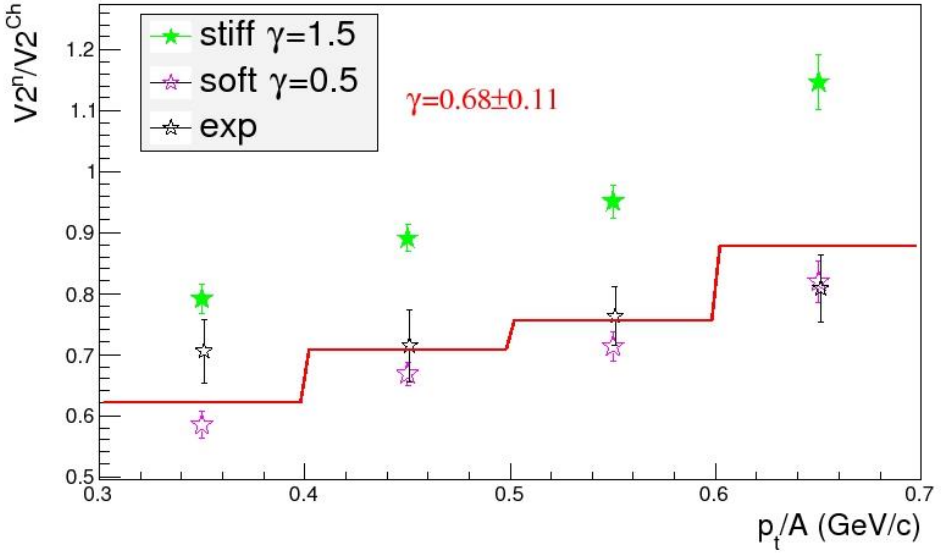
preliminary

γ extrapolation: impact parameter selection influence

Au+Au 3<b<7.5 fm

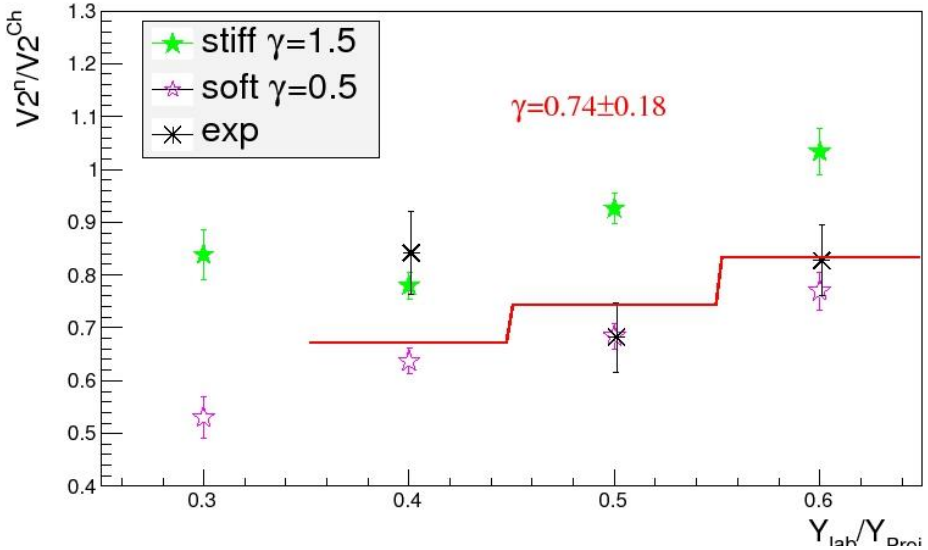
Wbg= 110 %



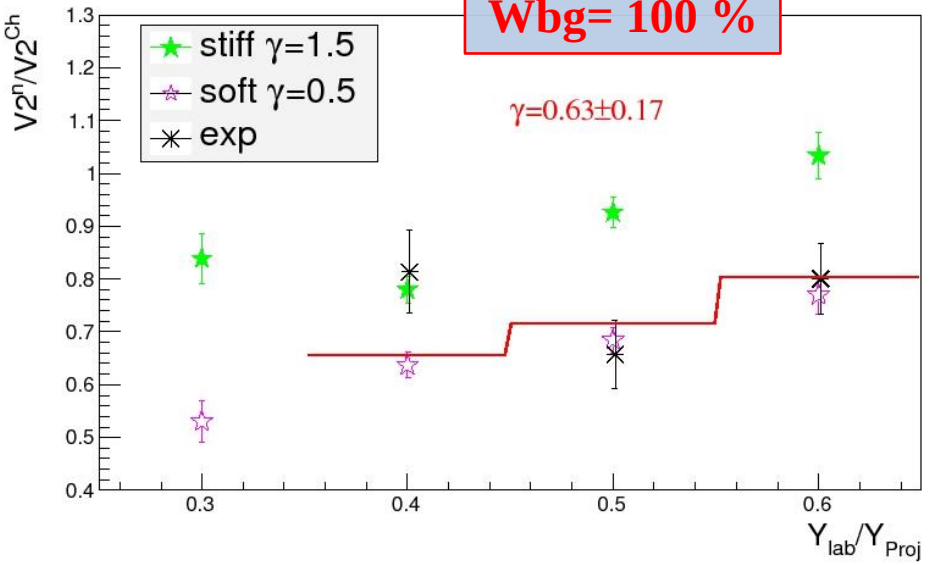


Au+Au 3.35<b<6 fm

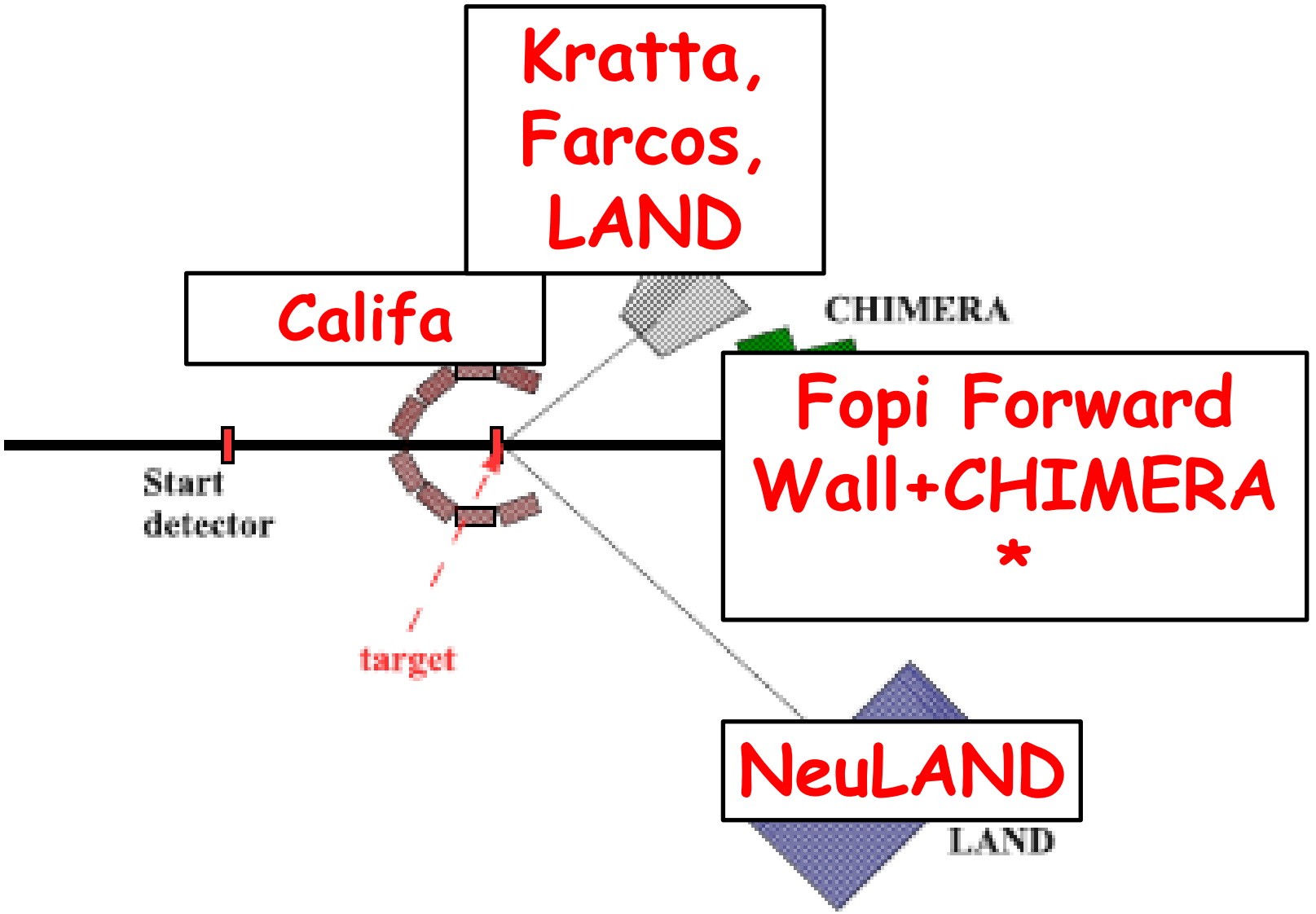
Wbg= 110 %



Wbg= 100 %



ASY-EOS future set-up?



* Ring 1-2-3
(θ<7°)

The analysis is in progress…

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \ldots,$$

IAS isobaric analog states
Danielewicz/Lee 2008

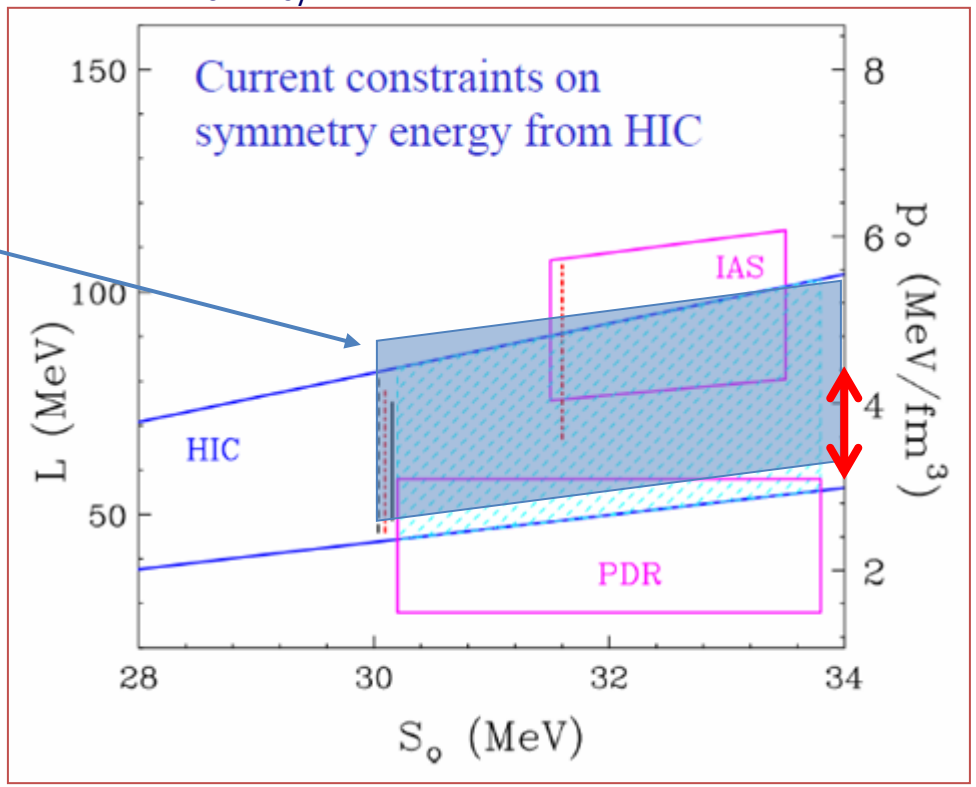
HIC heavy-ion collisions
isospin diffusion, n/p ratios
Tsang et al., 2009

PDR pygmy dipole resonance
Klimkiewicz et al. 2007

see also "Complete Electric Dipole Response in ^{208}Pb"
Tamii et al.,
PRL 107, 062502 (2011)

$L=3\rho_0 \cdot \partial E_{sym}/\partial\rho$

From "old" elliptic n/p flow*



$\gamma=0.7\pm0.2$
$L=70\pm13$ (FP1)

symmetry pressure
$P_0=(L/3)\rho_0$

$S_0=E_{sym}(\rho_0)$

from M.B. Tsang et al., PRL 102, 122701 (2009)
vertical lines: analyses with ImQMD (Zhang et al.) and IBUU04 (Li and Chen)

*P.Russotto et al., Phys. Lett. B 697 (2011)

preliminary

TAGLI

05/05/14

From ver>=0.08

Yield and Flows of Charged Particles from FOPI

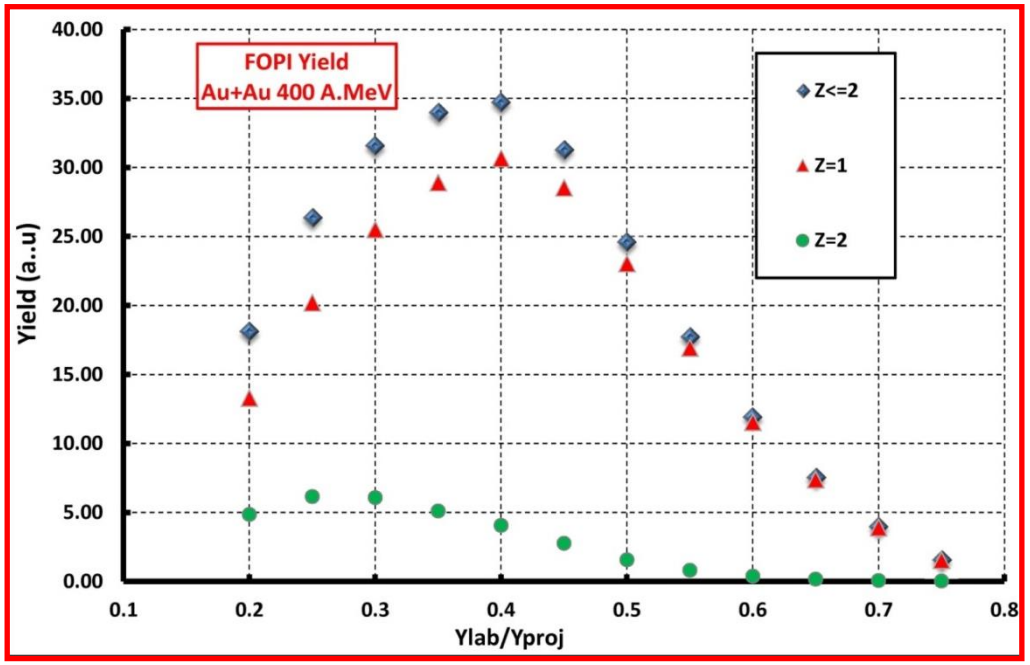
Au+Au @ 400 A.MeV

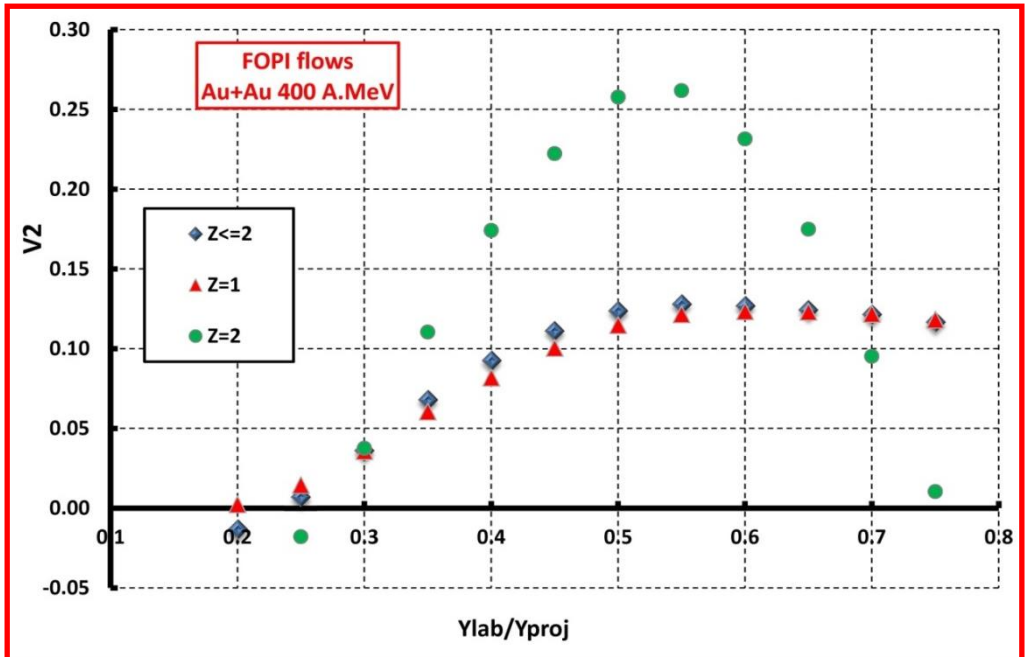
3.35<b<6 fm (c2)

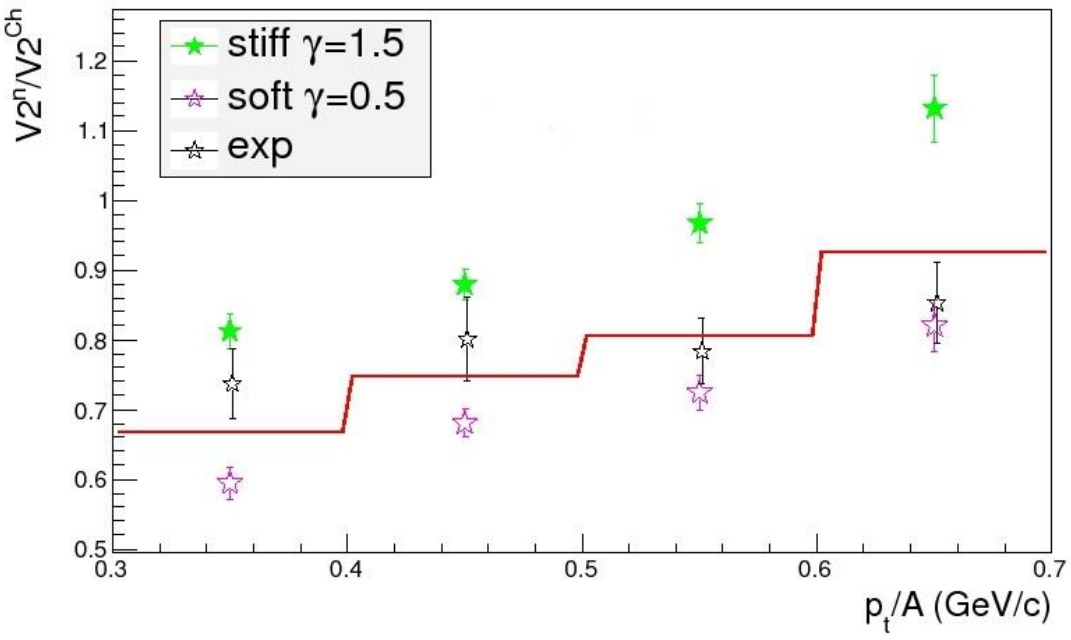
θ_{lab} cut as in ASY-EOS set-up

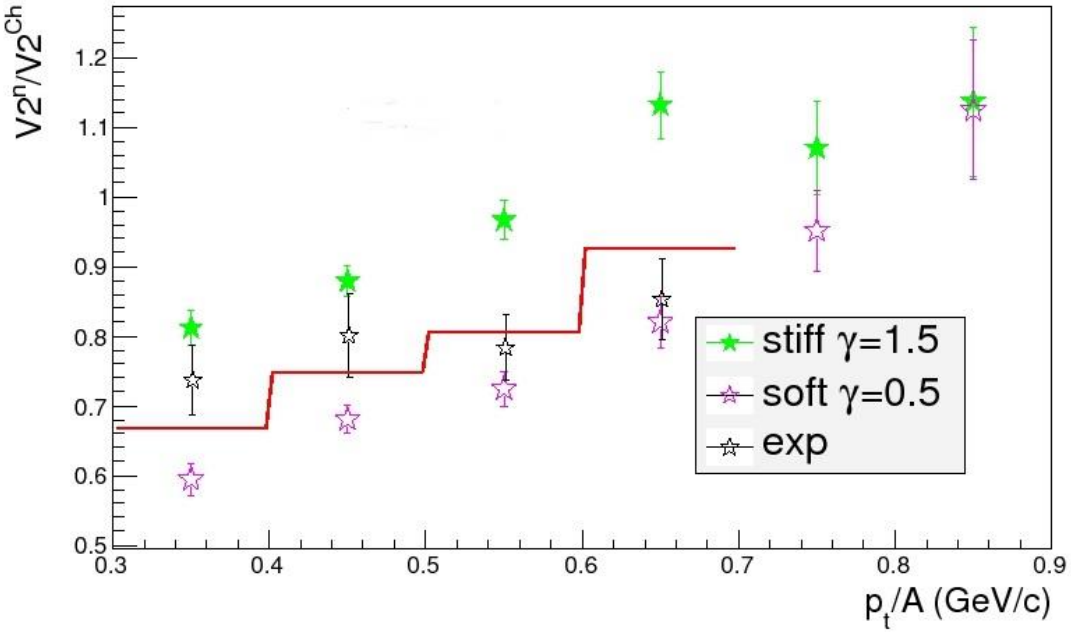
Courtesy of W. Reisdorf

- Yield of Helium is small in such exp. conditions
- Although v2 of Helium is strong, v2 of charged particles is close to the Hydrogen one

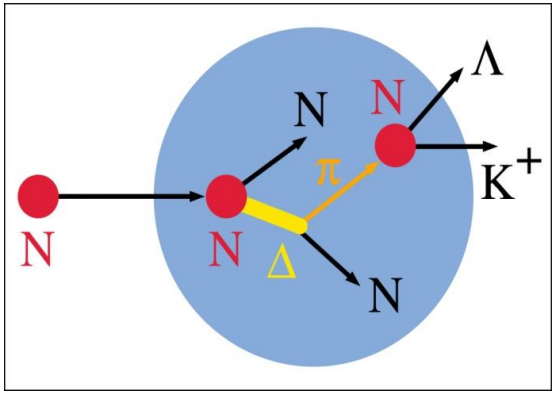




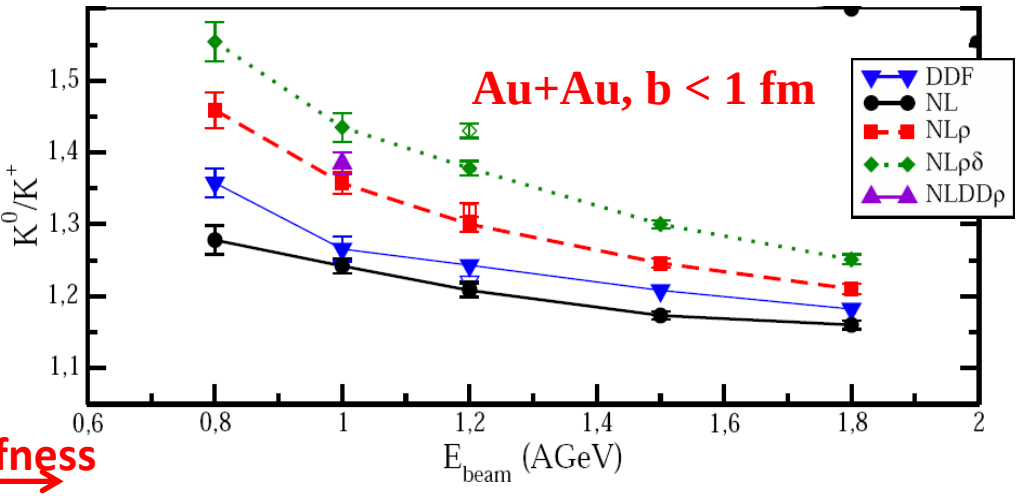

stiff γ=1.5
soft γ=0.5
exp
V2^n/V2^Ch
p_t/A (GeV/c)


stiff γ=1.5
soft γ=0.5
exp
V2^n/V2^Ch
p_t/A (GeV/c)

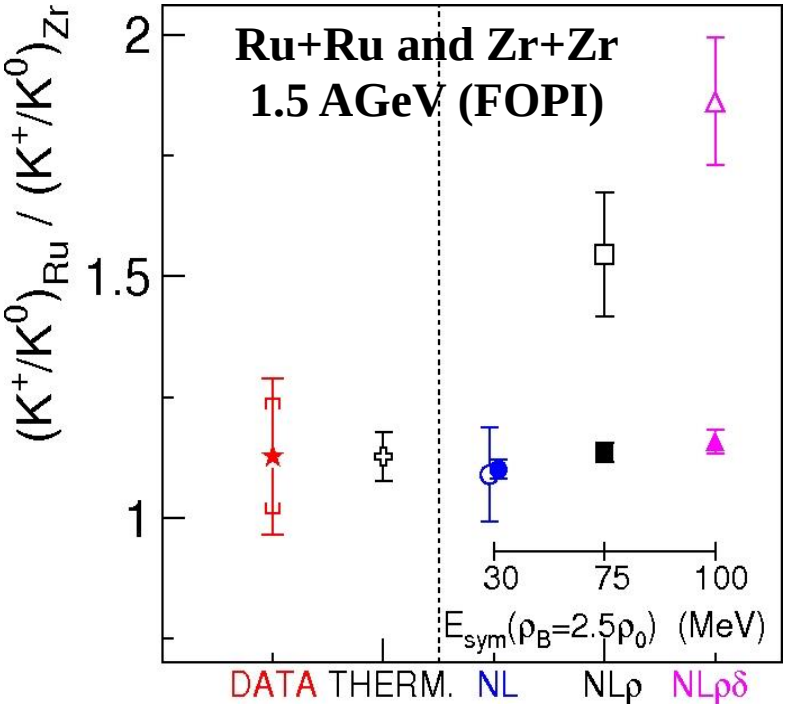
Esym at high density: kaons



Ferini et al., PRL 97, 202301 (2006)



stiffness



X. Lopez et al. 2007

RMF calculations

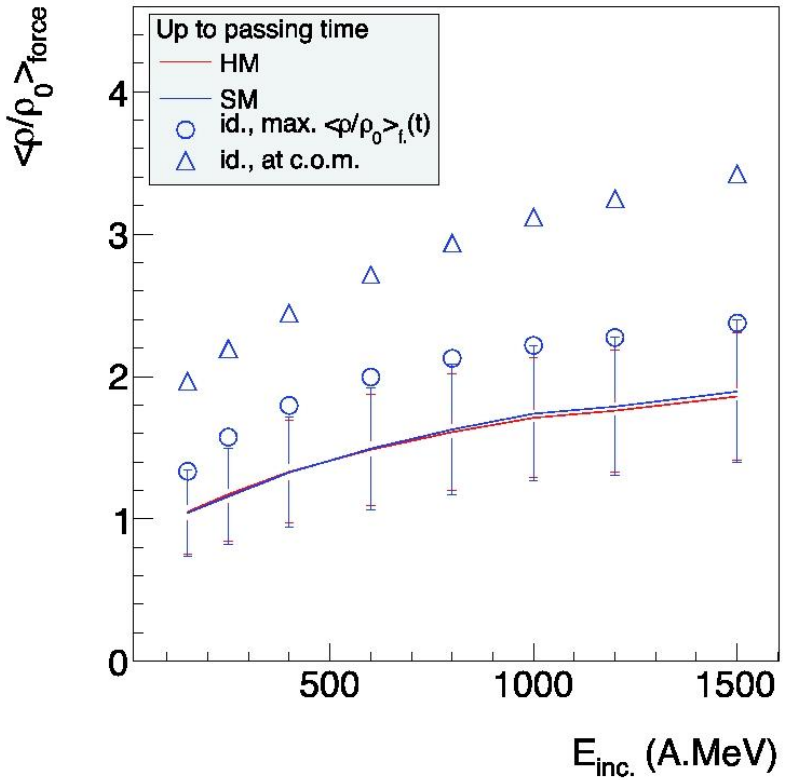
INM: T=60 MeV and $\rho_B=2.5\rho_0$

RBUU: transport simulation

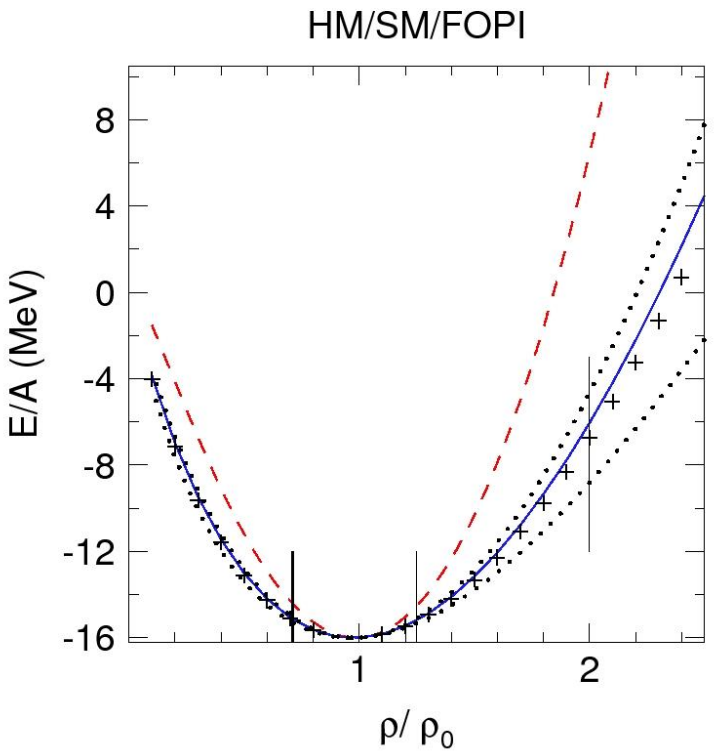
- Higher thresholds
- Weakly interacting in medium
- Freeze-out already at 20 fm/c: more reliable than pions as high ρ probes

From IWM 2011 – Y. Leifels

Which densities are we exploring?



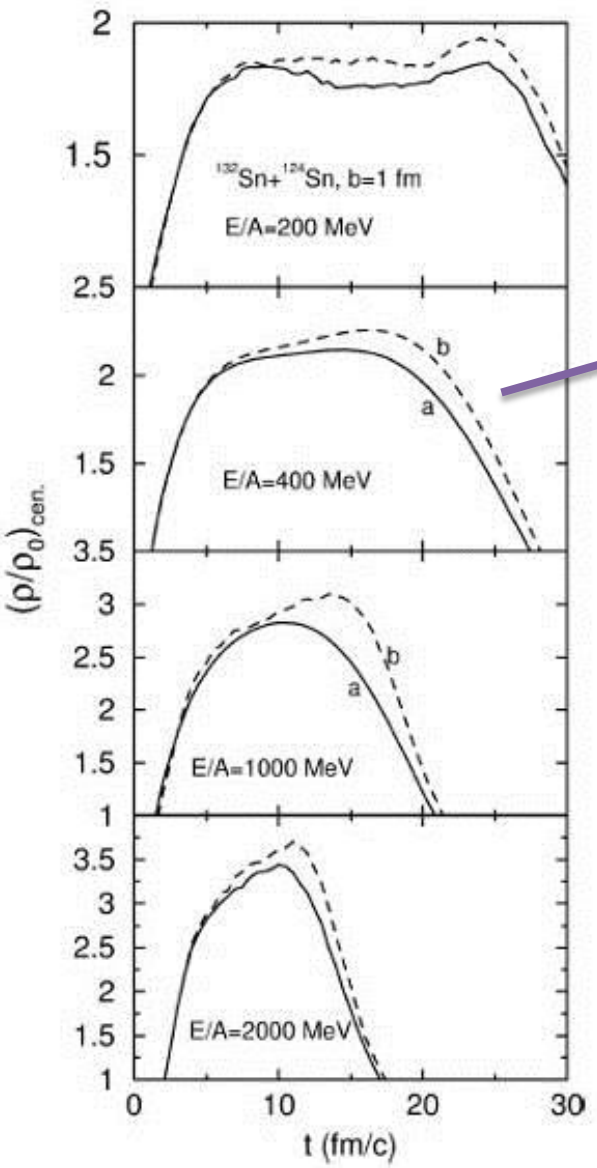
Mean value of the reduced density, computed up to the passing time, weighted by the force of the mean field seen by the participant protons, as a function of the incident energy as predicted by IQMD in Au+Au collisions at b=3 fm, for various EOS's. The error bars are the standard deviations. The blue symbols refer to the SM EOS: the circles depict the instantaneous maximum value of the force-weighted density reached over all times. The triangle is the same, restricted to the central compression zone.



See Constraining the nuclear matter equation of state around twice saturation density
A. Le Fevre, Y. Leifels, W. Reisdorf, J. Aichelin, Ch. Hartnack, and N. Herrmann
GSI Annual Report 2013 submitted

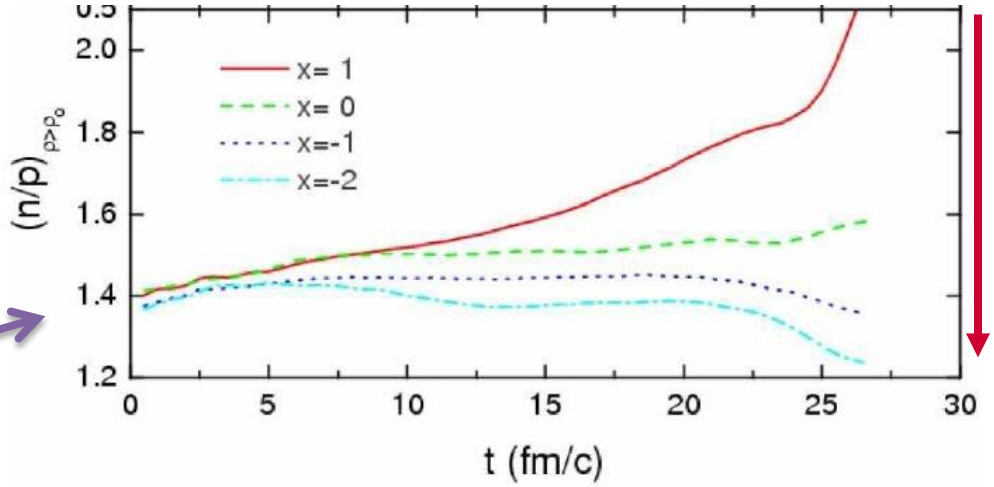
High density symmetry energy in relativistic heavy ion collisions

Which densities can be explored in the early stage of the reaction ?

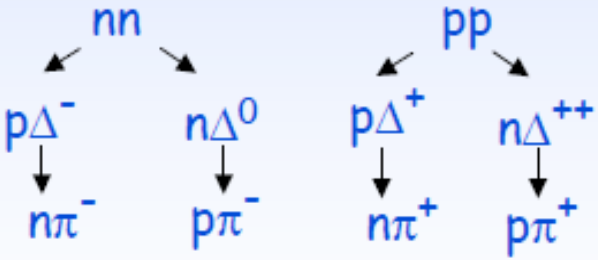


Bao-An Li, NPA 708 (2002)

B.A. Li et al., PRC71 (2005)



- N/Z of high density regions sensitive to $E_{sym}(\rho)$
- High $\rho>\rho_0$: asy-stiff more repulsive on neutrons



NN collisions in high density regions

π^-/π^+ reflecting the $(N/Z)_{dense}$

π^-/π^+ sensitive to $E_{sym}(\rho)$ at high ρ

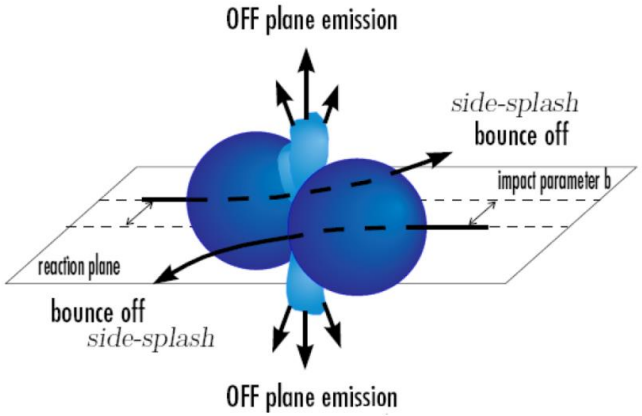
High densities: flows

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

Y = rapidity
pt = transverse momentum

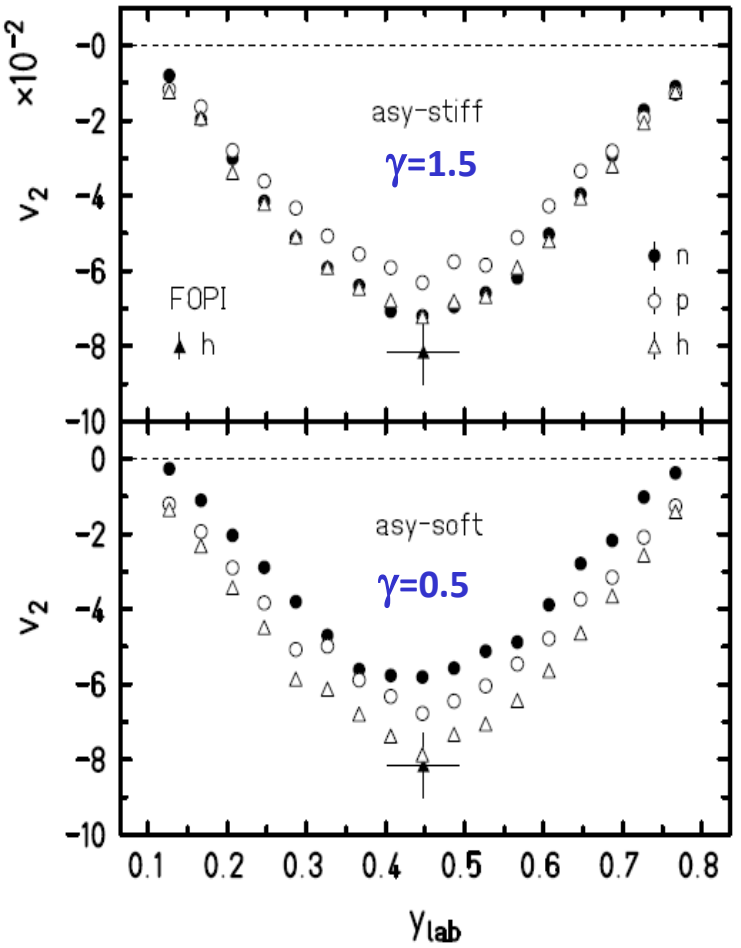
$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

Elliptic flow: competition between in plane (V2>0) and out-of-plane ejection (V2<0)

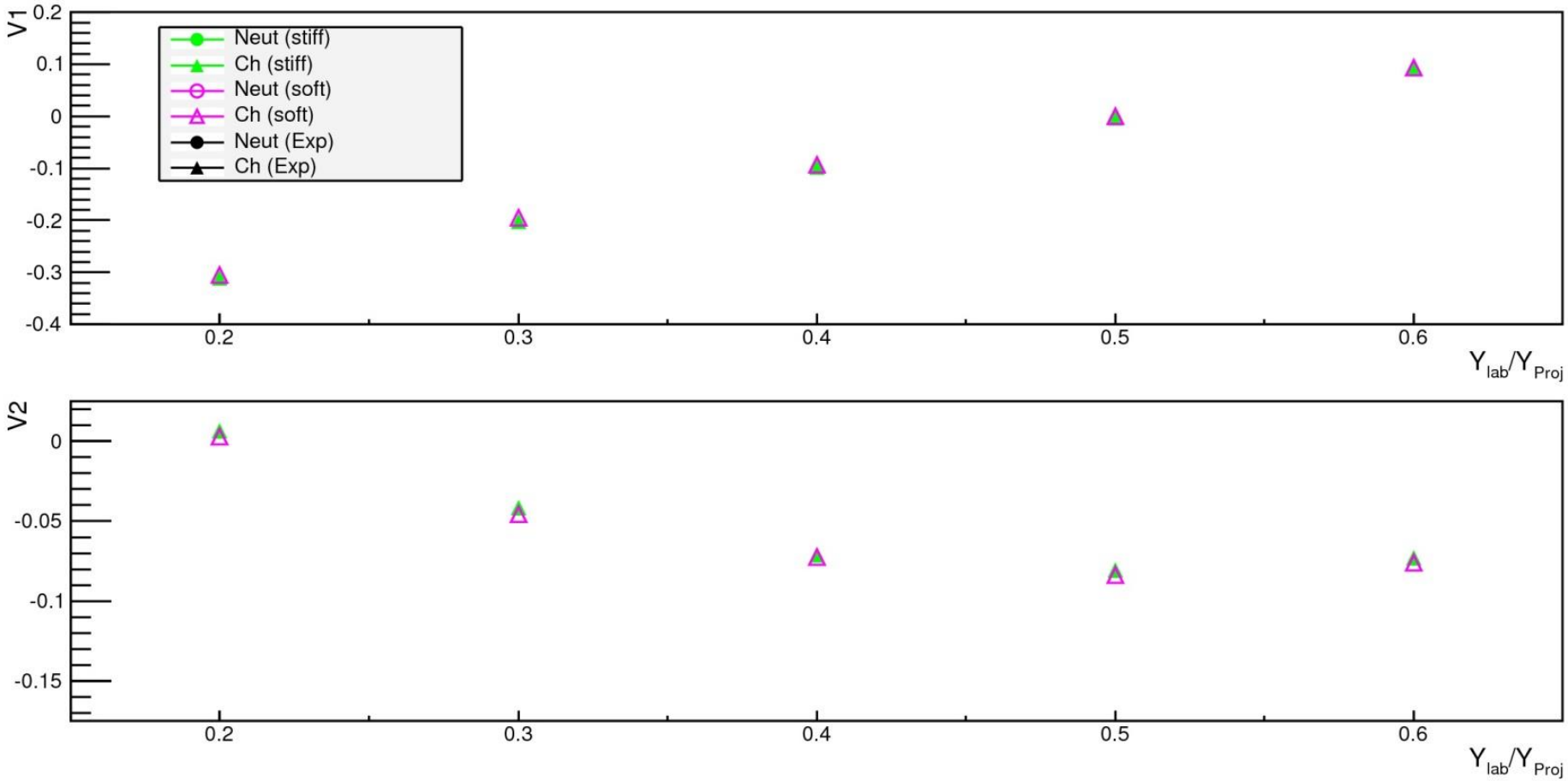


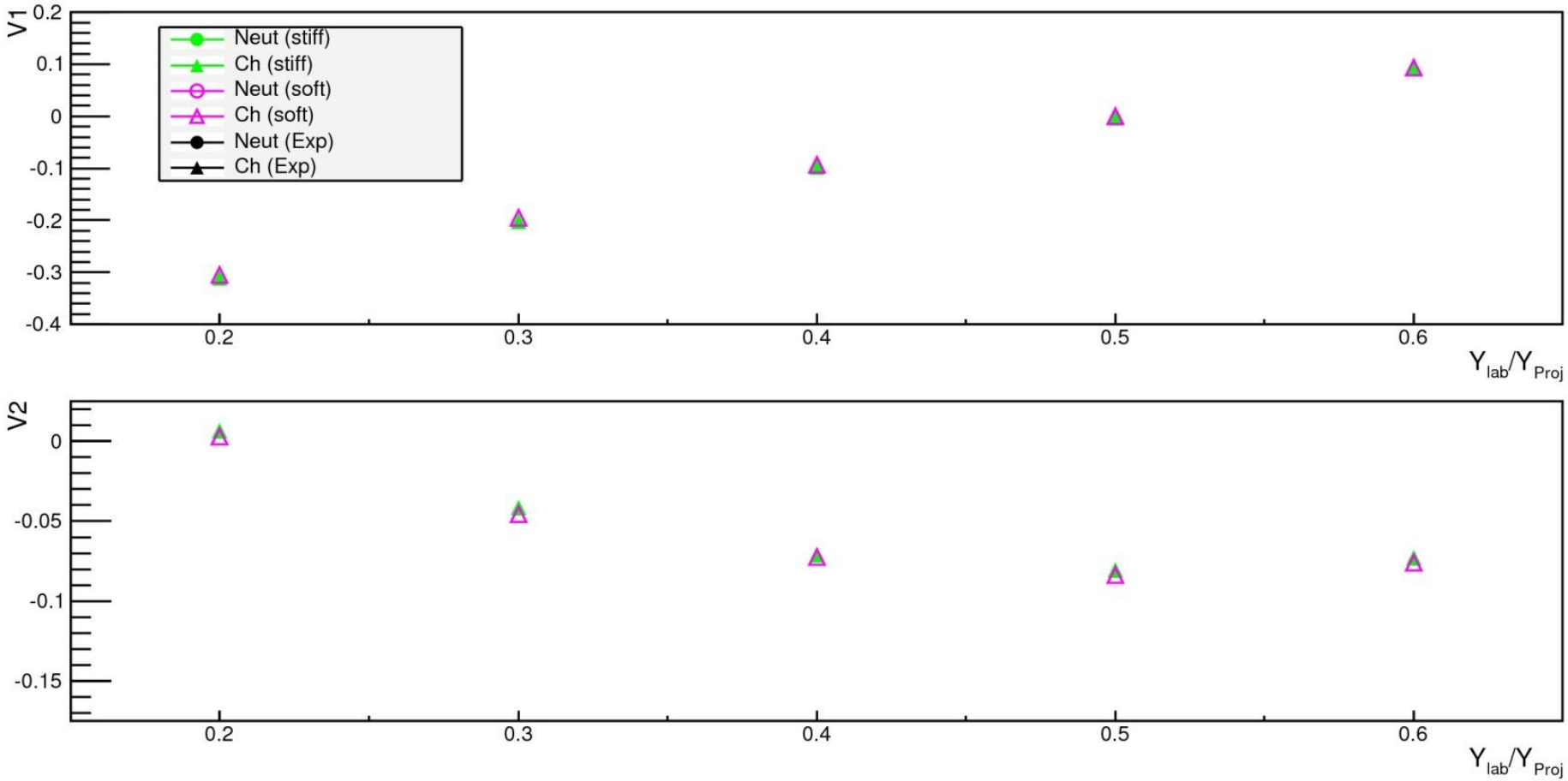
$$E_{sym}=E_{sym}^{pot}+E_{sym}^{kin}$$
$$=22\ \text{MeV}\cdot(\rho/\rho_0)^{\gamma}+12\ \text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

UrQMD :Au+Au @ 400 AMeV
5.5<b<7.5 fm

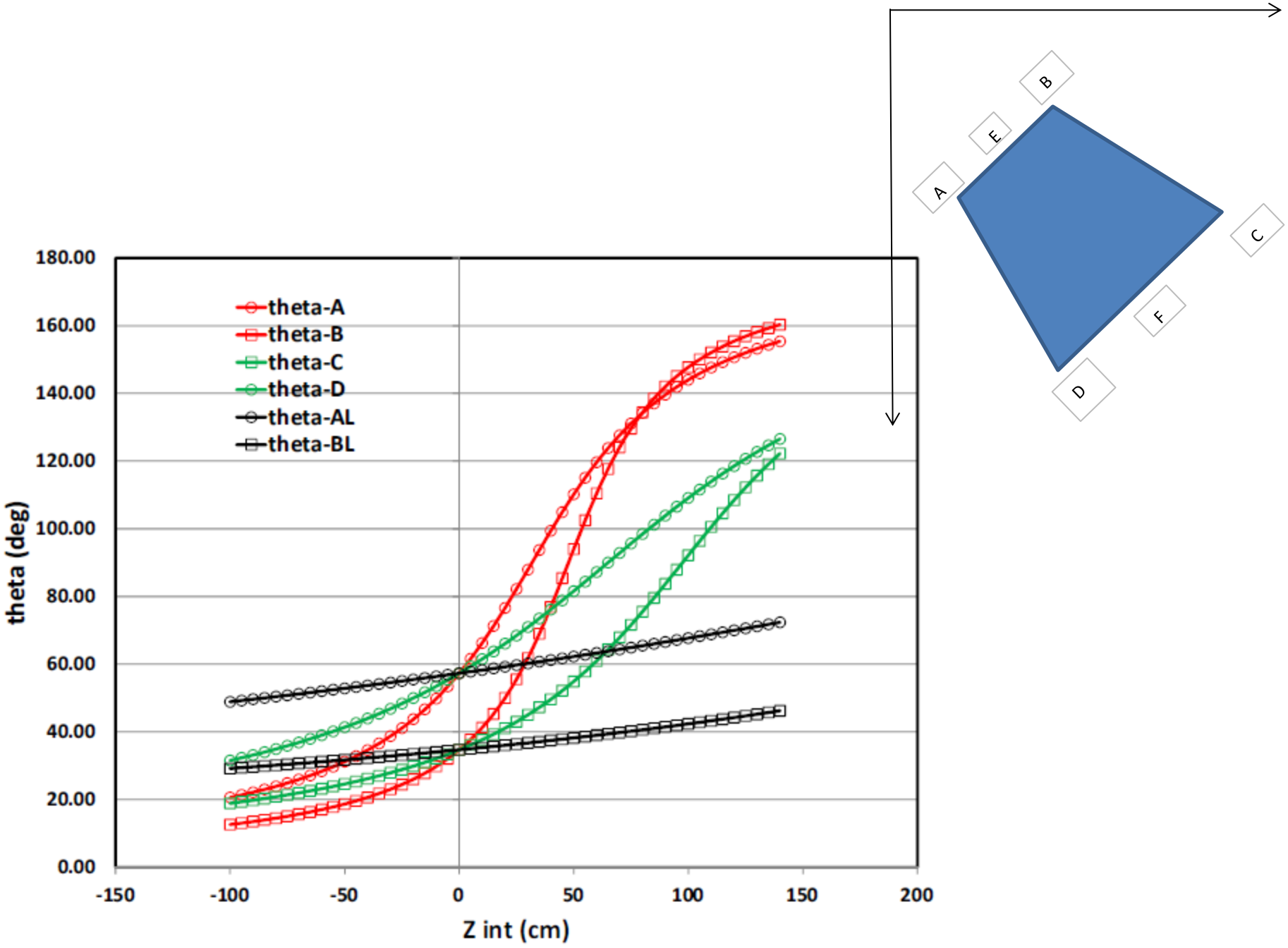


Qingfeng Li, J. Phys. G31 1359-1374 (2005)
P.Russotto et al., Phys. Lett. B 697 (2011)


V1
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Neut (stiff)
Ch (stiff)
Neut (soft)
Ch (soft)
Neut (Exp)
Ch (Exp)
0.2
0.3
0.4
0.5
0.6
Y_lab/Y_Proj
V2
0
-0.05
-0.1
-0.15
0.2
0.3
0.4
0.5
0.6
Y_lab/Y_Proj


V1
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Neut (stiff)
Ch (stiff)
Neut (soft)
Ch (soft)
Neut (Exp)
Ch (Exp)
0.2
0.3
0.4
0.5
0.6
Y_lab/Y_Proj
V2
0
-0.05
-0.1
-0.15
0.2
0.3
0.4
0.5
0.6
Y_lab/Y_Proj

THANKS
AGAIN!


theta-A
theta-B
theta-C
theta-D
theta-AL
theta-BL
theta (deg)
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-150
-100
-50
0
50
100
150
200
Z int (cm)
A
B
C
D
E
F

Device: SAMURAI TPC (U.S. Japan Collaboration)

T. Murakami[a], Jiro Murata[b], Kazuo Ieki[b], Hiroyoshi Sakurai[c], Shunji Nishimura[c], Atsushi Taketani[c], Yoichi Nakai[c], Betty Tsang[d], William Lynch[d], Abigail Bickley[d], Gary Westfall[d], Michael A. Famiano[e], Sherry Yennello[g], Roy Lemmon[h], Abdou Chbihi[i], John Frankland[i], Jean-Pierre Wieleczko[i] , Giuseppe Verde[j], Angelo Pagano[i], Paulo Russotto[i], Z.Y. Sun[k], Wolfgang Trautmann[l]

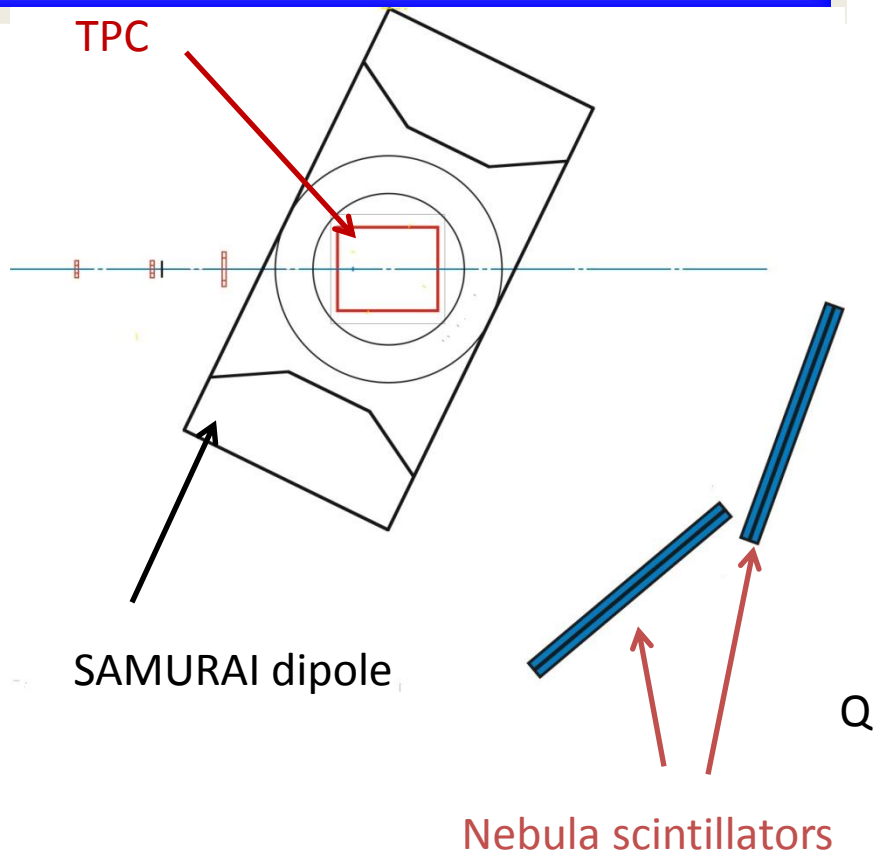
[a]Kyoto University, [b]Rikkyo University, [c]RIKEN, Japan, [d]NSCL Michigan State University, [e]Western Michigan University, [g]Texas A&M University, USA, [h]Daresbury Laboratory, [i]GANIL, France, UK, [j]LNS-INFN, Italy, [k]IMP, Lanzhou, China, [l]GSI, Germany

The SAMURAI TPC would be used to constrain the density dependence of the symmetry energy through measurements of:

- Pion production
- Flow, including neutron flow measurements with the nebula array.

The TPC also can serve as an active target both in the magnet or as a standalone device.

- Giant resonances.
- Asymmetry dependence of fission barriers, extrapolation to r-process.



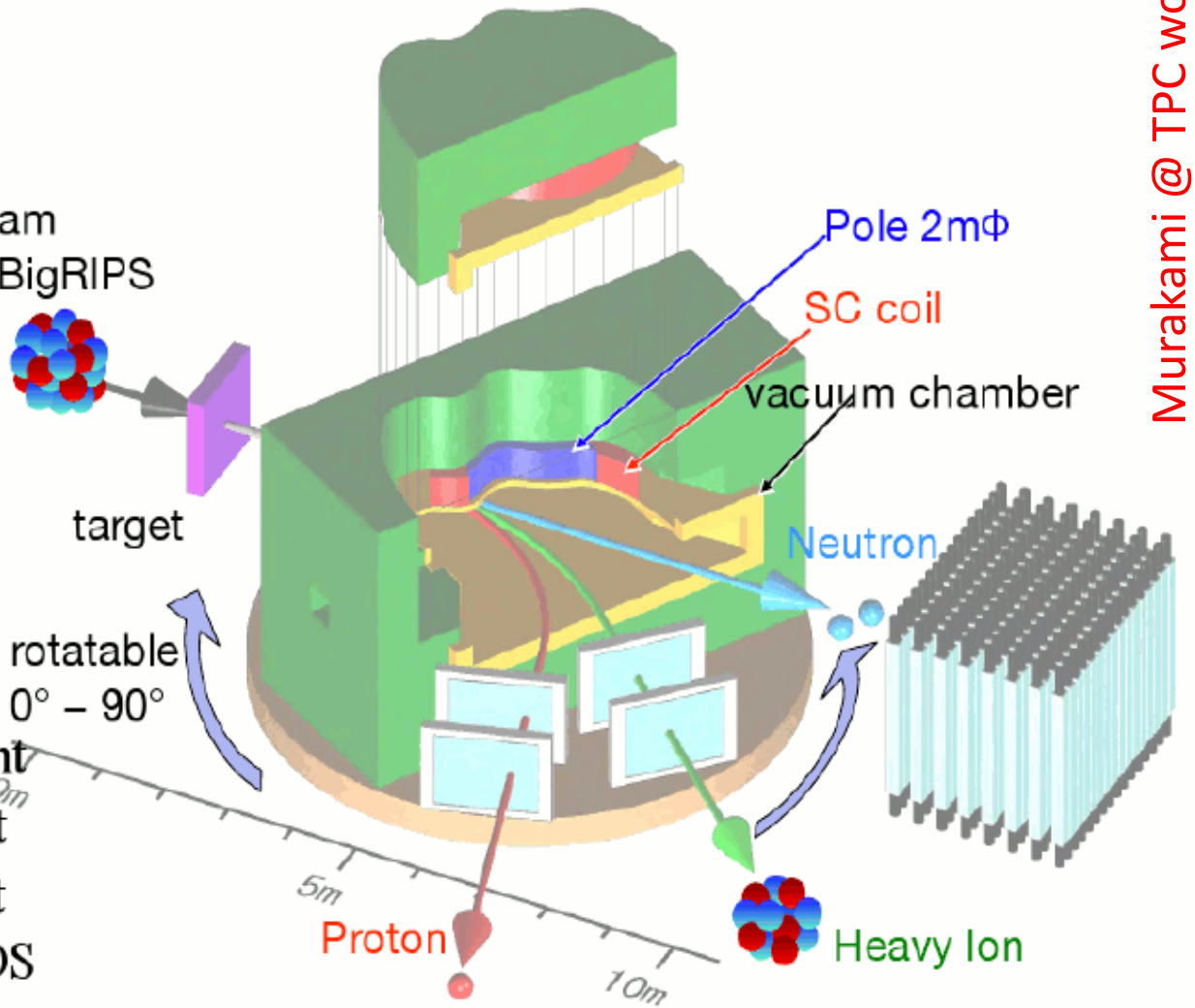
Design Characteristics

Kinematically complete measurements
Detecting multiple (all) particles in coincidence

→ Large p acceptance
Large θ φ acceptance

- ✓ Superconducting magnet
- ✓ Heavy Ion detectors
- ✓ Proton detectors
- ✓ Neutron detectors
- ✓ Large vacuum chamber
- ✓ Rotational stage

- Invariant mass measurement
- Missing mass measurement
- pol d induced measurement
- Multi fragmentation for EOS



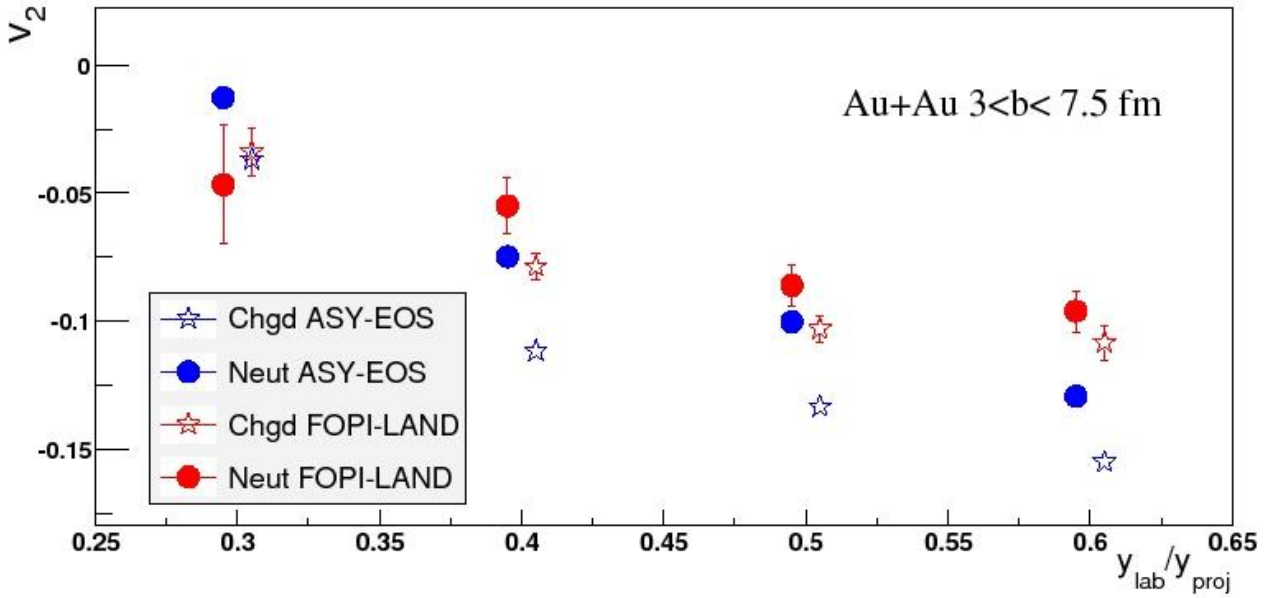
Murakami @ TPC workshop, MSU

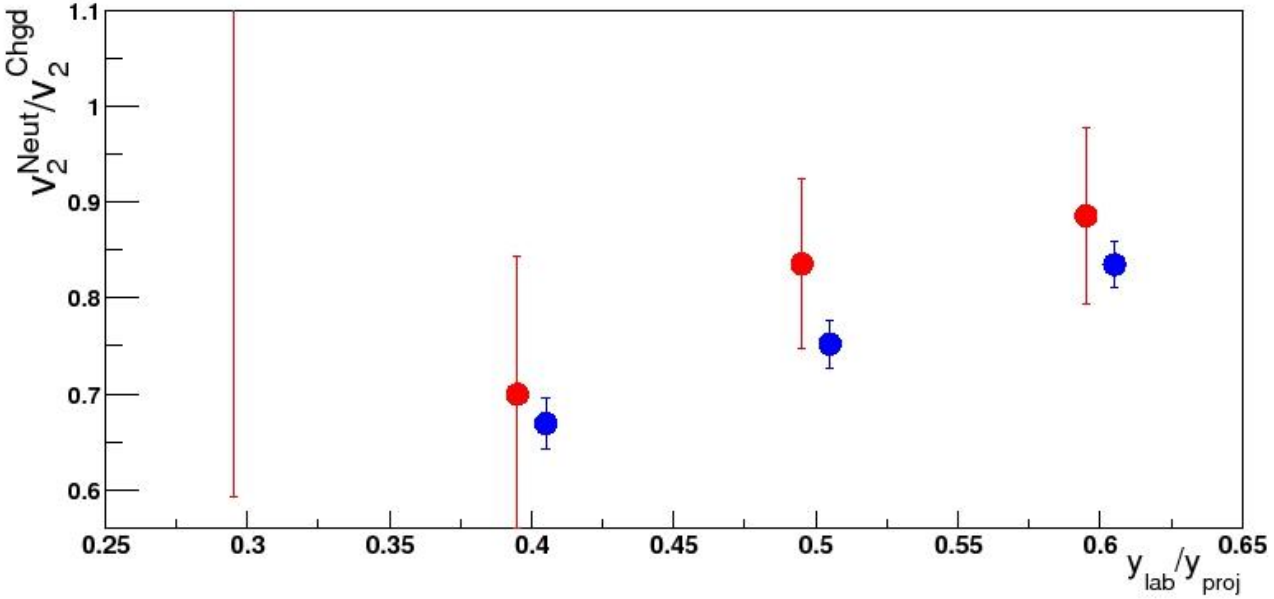
TAGLI

29/04/14

From ver0.07

Comparing ASY-EOS with FOPI-LAND exp: rapidity dependence II





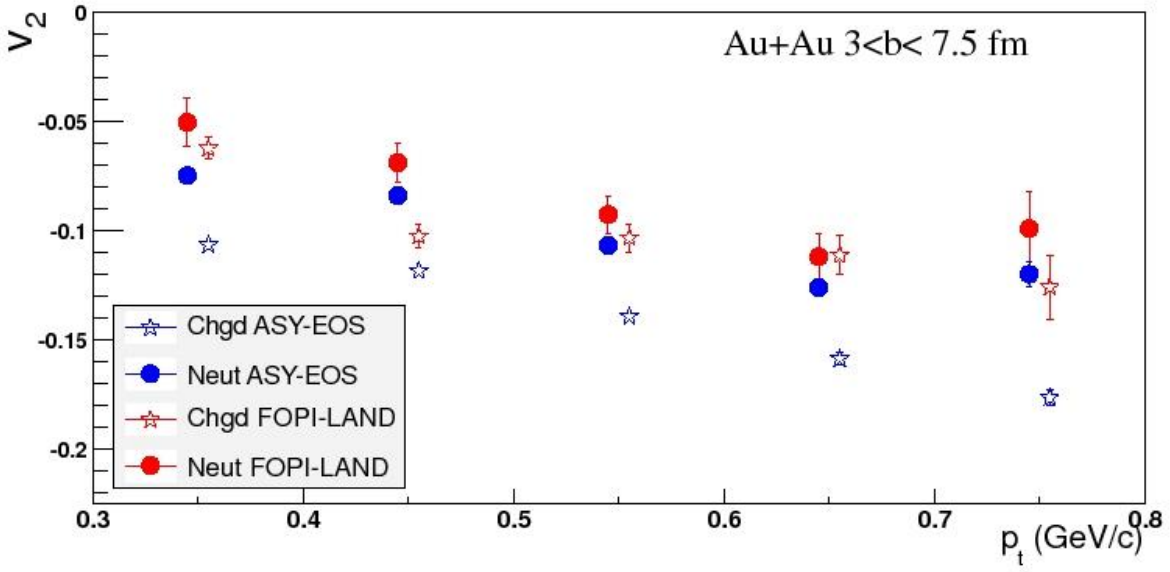
Au+Au 3<b<7.5 fm

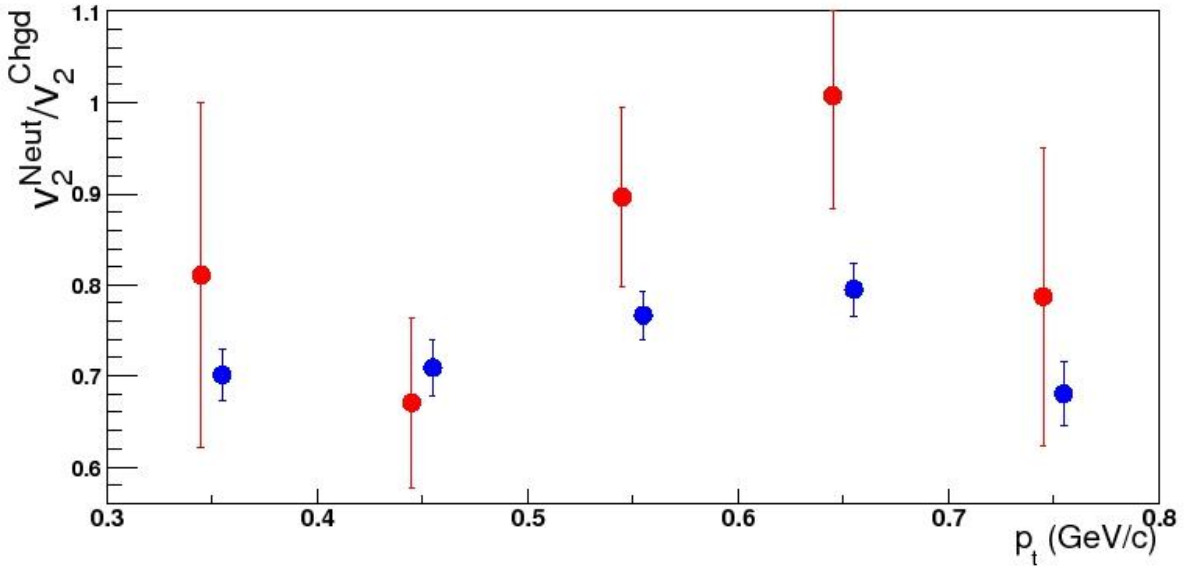
$0.25<y_{lab}/y_{proj}<0.75$

Wbg= 110 %

preliminary

Comparing ASY-EOS with FOPI-LAND exp: transverse momentum dep. II





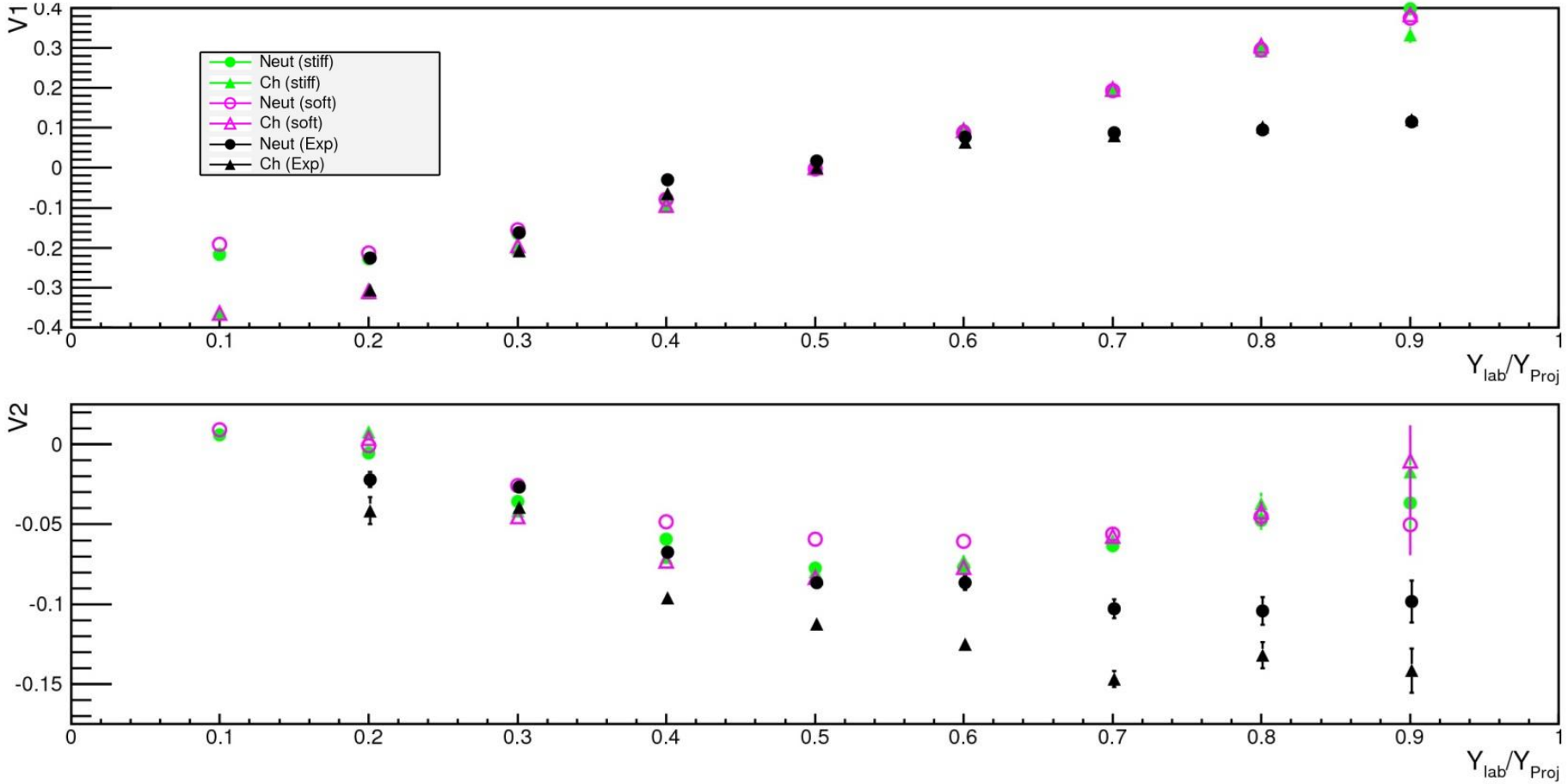
Au+Au 3<b<7.5 fm

$0.25<y_{lab}/y_{proj}<0.75$

Wbg= 110 %

preliminary

FROM NUFRA



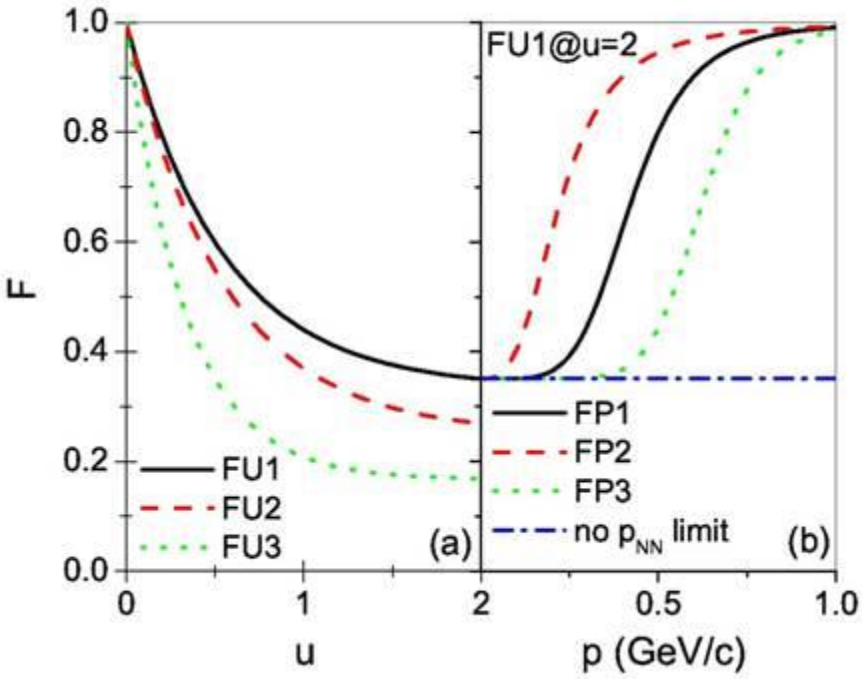
proNeut2000_706_cf3_cc_w4_vv1.dat_proChgd2000_706_cf3_cc_w4_vv1.dat_FP1_chww__compvvv

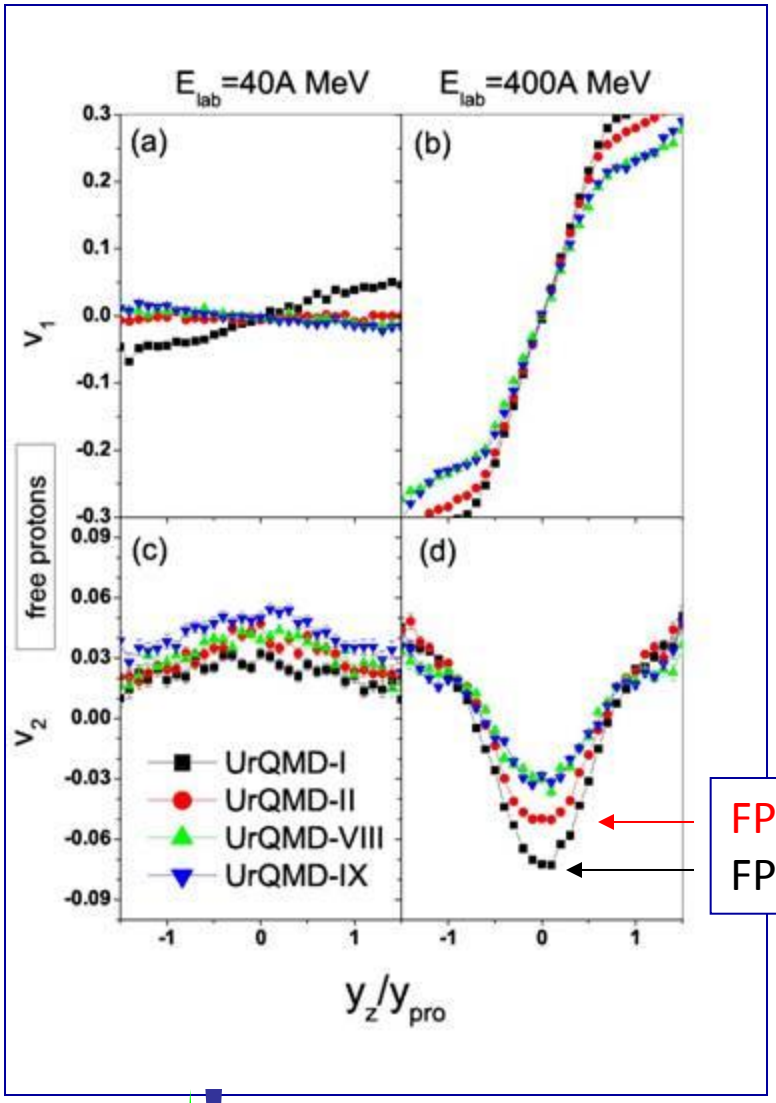
RISERVE

URQMD

parameterizations in UrQMD

Medium modifications (FU1, …) and momentum dependence (FP1, …) of **nucleon-nucleon elastic Xsects**
Qingfeng Li et al., PRC 83, 044617 (2011)





note change in color code black-red for FP1 and FP2 between left and right

w/o momentum dep.

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **32** (2006) 407–415 doi:10.1088/0954-3899/32/4/001

Medium modifications of the nucleon–nucleon elastic cross section in neutron-rich intermediate energy HICs

Qingfeng Li[1,4], Zhuxia Li[2], Sven Soff[3], Marcus Bleicher[3] and Horst Stöcker[1,3]

[1] Frankfurt Institute for Advanced Studies (FIAS), Johann Wolfgang Goethe-Universität, Max-von-Laue-Str 1, D-60438 Frankfurt am Main, Germany
[2] China Institute of Atomic Energy, PO Box 275 (18), Beijing 102413, People's Republic of China
[3] Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Str 1, D-60438 Frankfurt am Main, Germany

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Abstract

Several observables of unbound nucleons which are to some extent sensitive to the medium modifications of nucleon–nucleon elastic cross sections in neutron-rich intermediate energy heavy ion collisions are investigated. The splitting effect of neutron and proton effective masses on cross sections is discussed. It is found that the transverse flow as a function of rapidity, the Q_{zz} as a function of momentum, and the ratio of halfwidths of the transverse to that of longitudinal rapidity distribution $R_{t/l}$ are very sensitive to the medium modifications of the cross sections. The transverse momentum distribution of correlation functions of two nucleons does not yield information on the in-medium cross section.

(Some figures in this article are in colour only in the electronic version)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **32** (2006) 151–164 doi:10.1088/0954-3899/32/2/007

Probing the equation of state with pions

Qingfeng Li[1], Zhuxia Li[2], Sven Soff[3], Marcus Bleicher[3] and Horst Stöcker[1,3]

DDH3$\rho\delta$ > DDHρ > Pas.

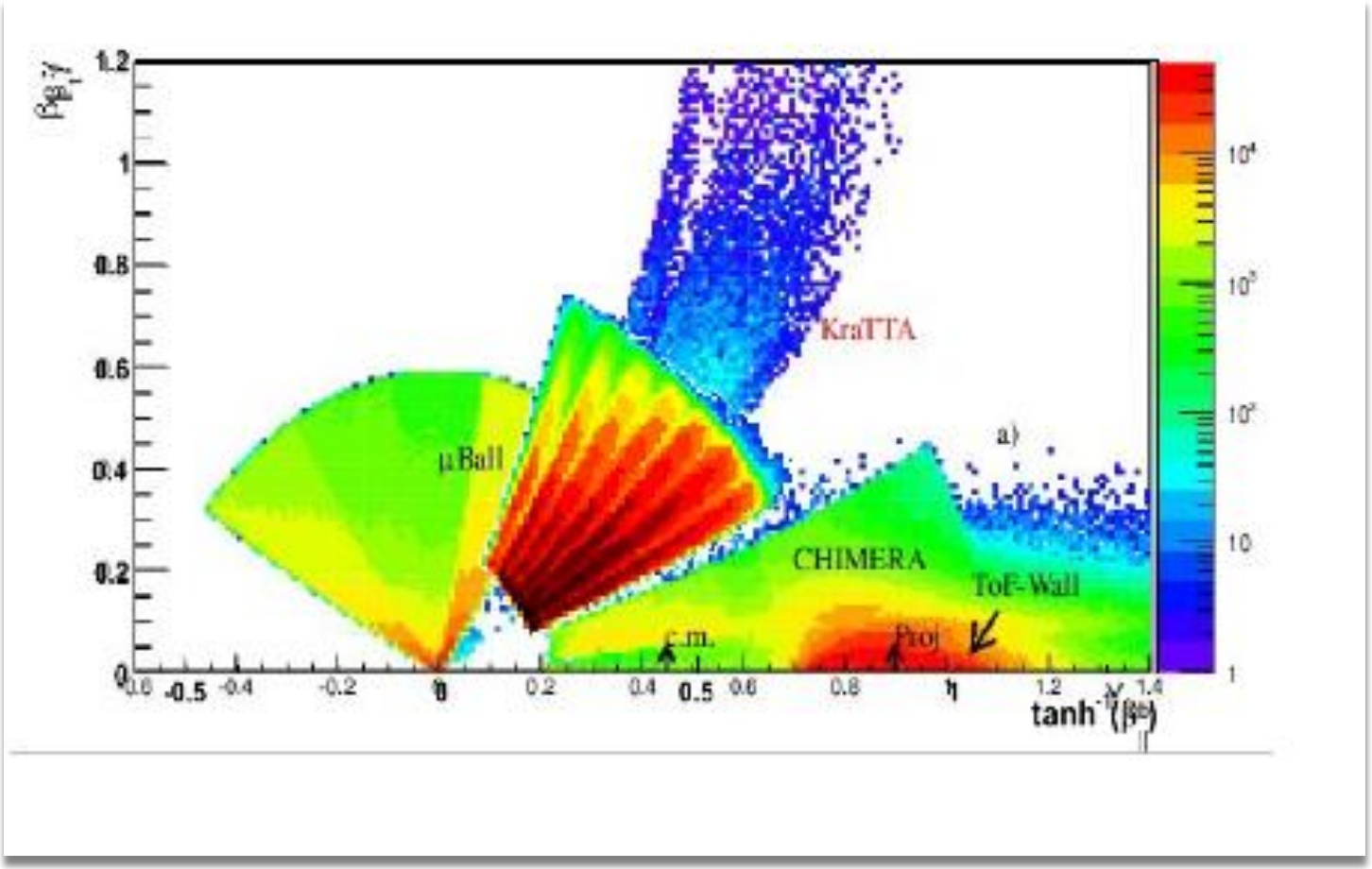
3. Momentum-dependent interactions for all baryons are introduced. The form of the momentum dependence is taken from the IQMD model [13, 38], which reads

$$U_{\mathrm{md}} = t_{\mathrm{md}} \ln^2[1 + a_{\mathrm{md}}(\Delta \mathbf{p})^2]u, \tag{1}$$

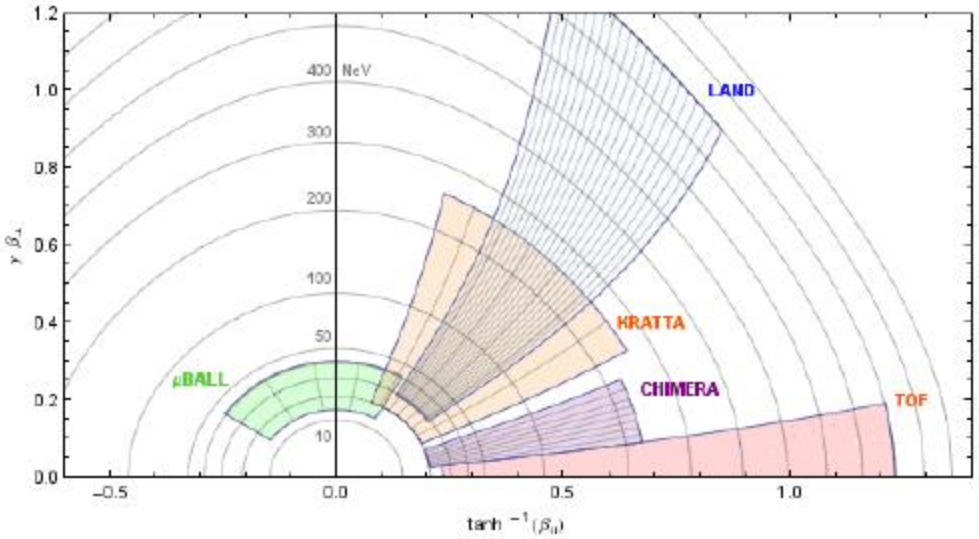
in which $\Delta \mathbf{p} = \mathbf{p}_i - \mathbf{p}_j$ represents the relative momentum of two nucleons i and j. The parametrizations of t_{md} and a_{md} are listed in table 1. We note that Li *et al* have used an isospin-dependent momentum-dependent parametrization in the BUU model, which is guided by a Hartree–Fock calculation using the Gogny-effective interaction [39, 40]. However, here we do not consider the isospin dependence in the momentum-dependent part of the mean field.

KraTTA

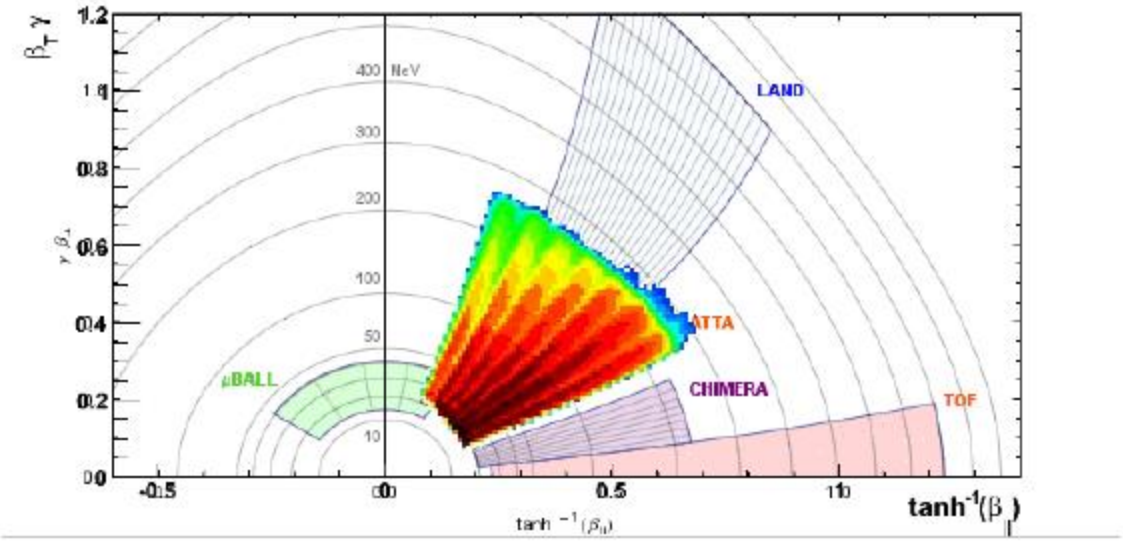
OK


KraTTA
μBall
CHIMERA
ToF-Wall
a)
c.m.
Proj
1.2
1
0.8
0.6
0.4
0.2
0
-0.6
-0.5
-0.4
-0.2
0
0.2
0.4
0.5
0.6
0.8
1
1.2
1.4
10^4
10^3
10^2
10
1
$\tanh^{-1}(\beta_{cm})$

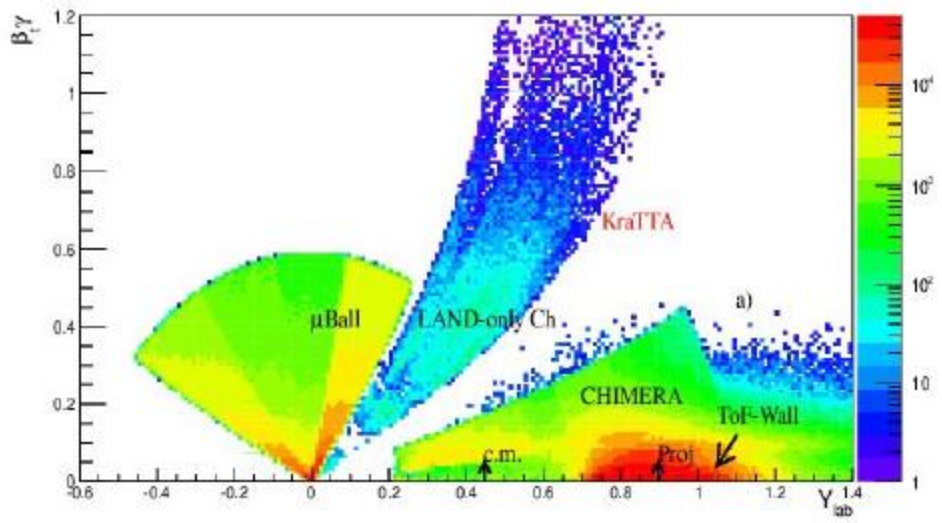
Acceptance of the setup (protons)



Acceptance of the setup (protons)



Acceptance of the setup (protons)



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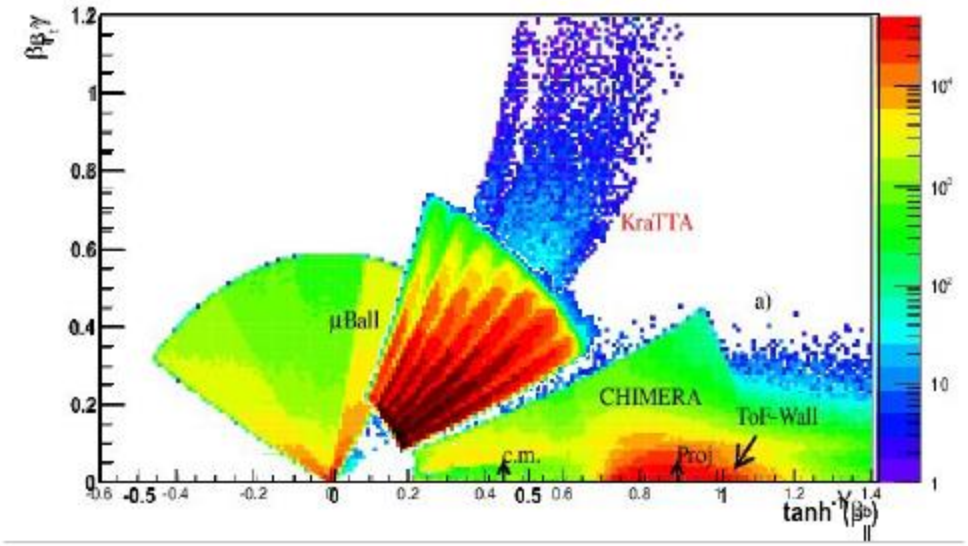
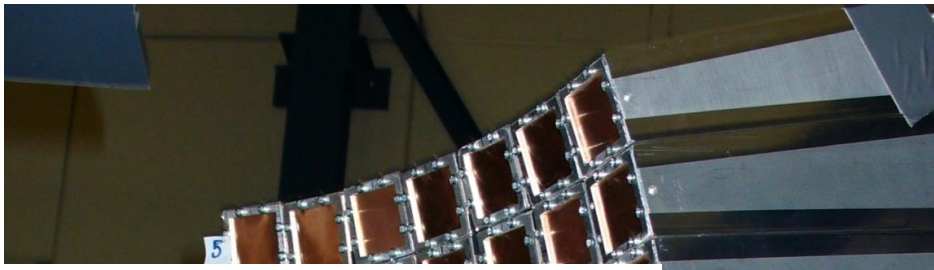
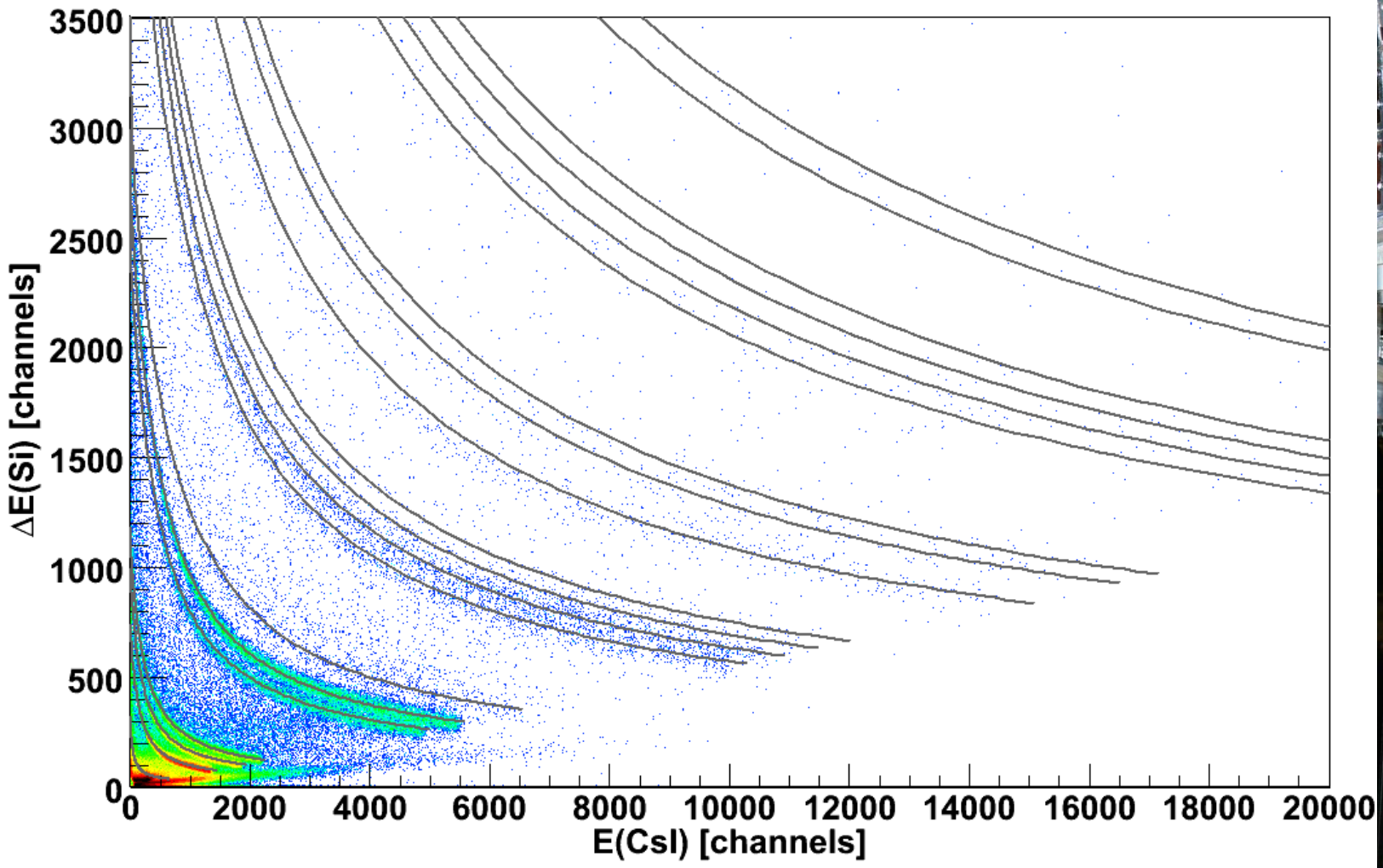


KraKow Triple Telescopes Array: KRATTA (Poland)

35 modules (5 x7), 20.7°<θ<63.5°
Distance from the target: 40 cm.
Light particles and IMFs emitted at midrapidity

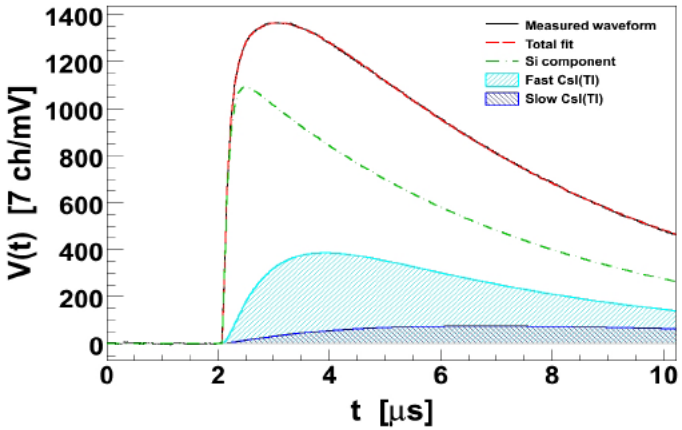




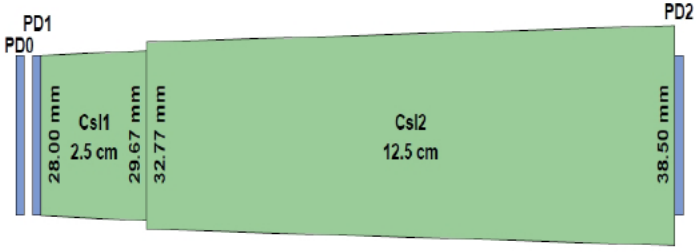
Wed Dec 15 17:15:57 2010

KRATTA - KRAkow Triple Telescope Array - NEW

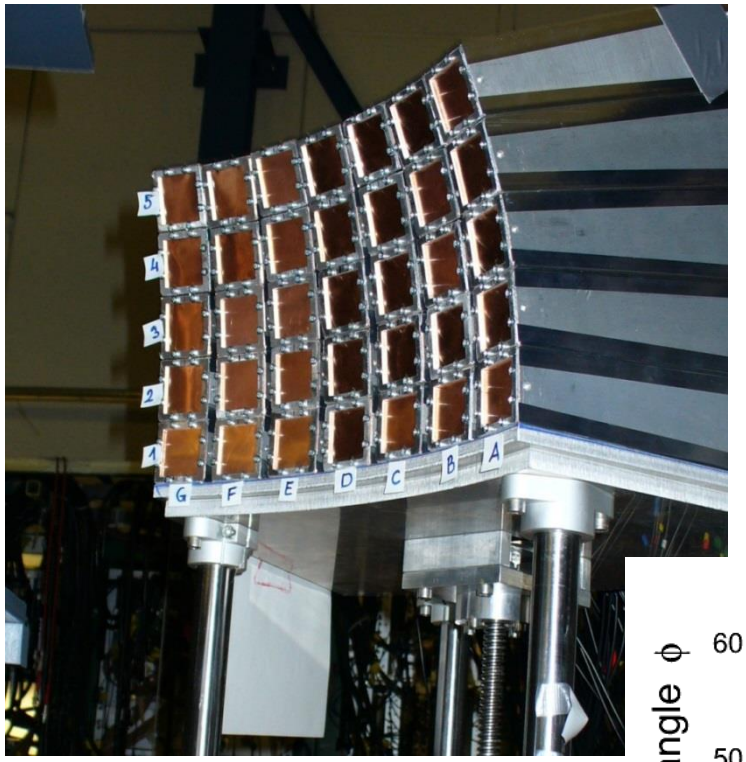
- light charged particles and intermediate mass fragments detector
- 35 modules, each one contains:
  - Thin and thick $CsI(Tl)$ crystals
  - Three silicon photodiodes
- isotopic resolution from $\Delta E - \Delta E - E$ and pulse shape discrimination in a wide range of energies

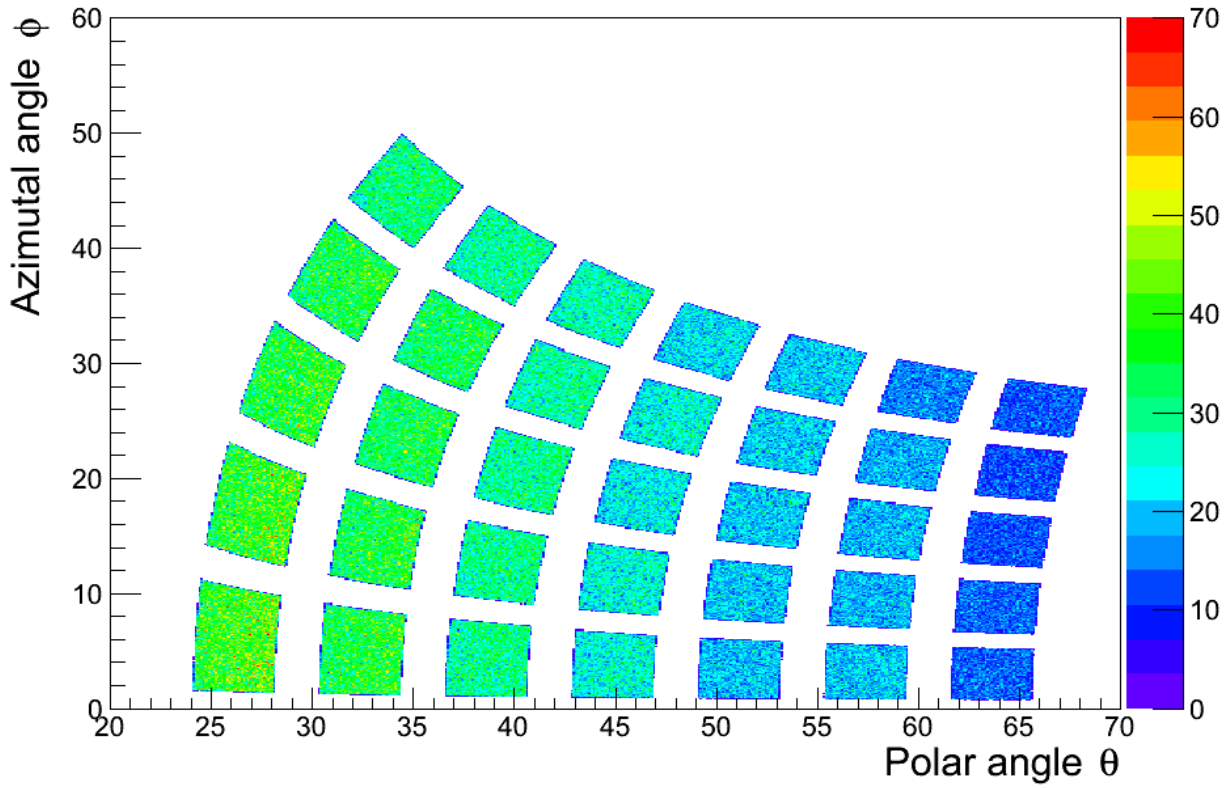


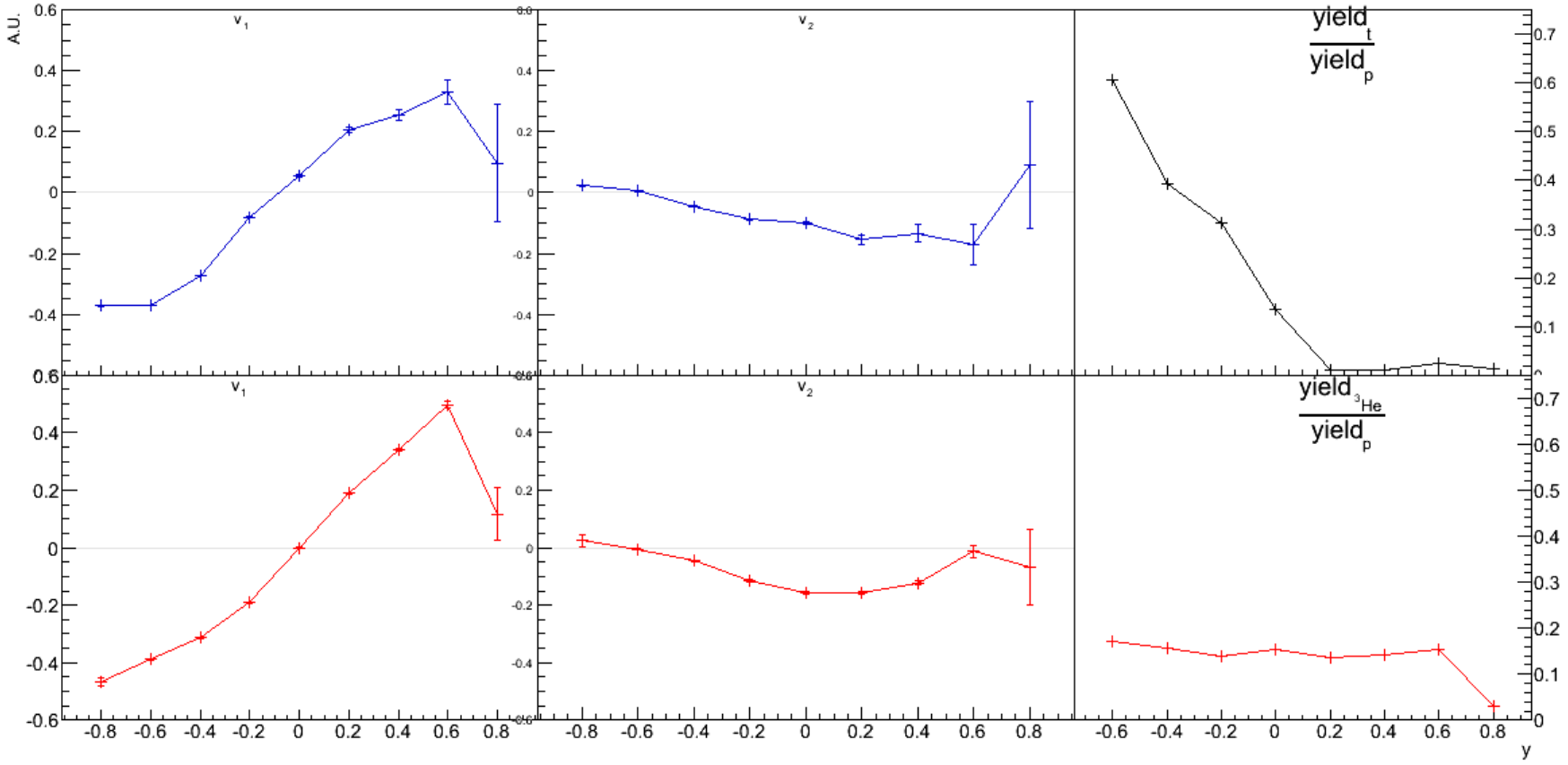
Measured light waveform and its decomposition



Active elements of the module


5
4
3
2
1
G
F
E
D
C
B
A


Azimutal angle ϕ
Polar angle θ
0
10
20
30
40
50
60
20
25
30
35
40
45
50
55
60
65
70
0
10
20
30
40
50
60
70


A.U.
v1
v2
yield_t / yield_p
v1
v2
yield_3He / yield_p
y

FOPI
OK

FOPI forward wall

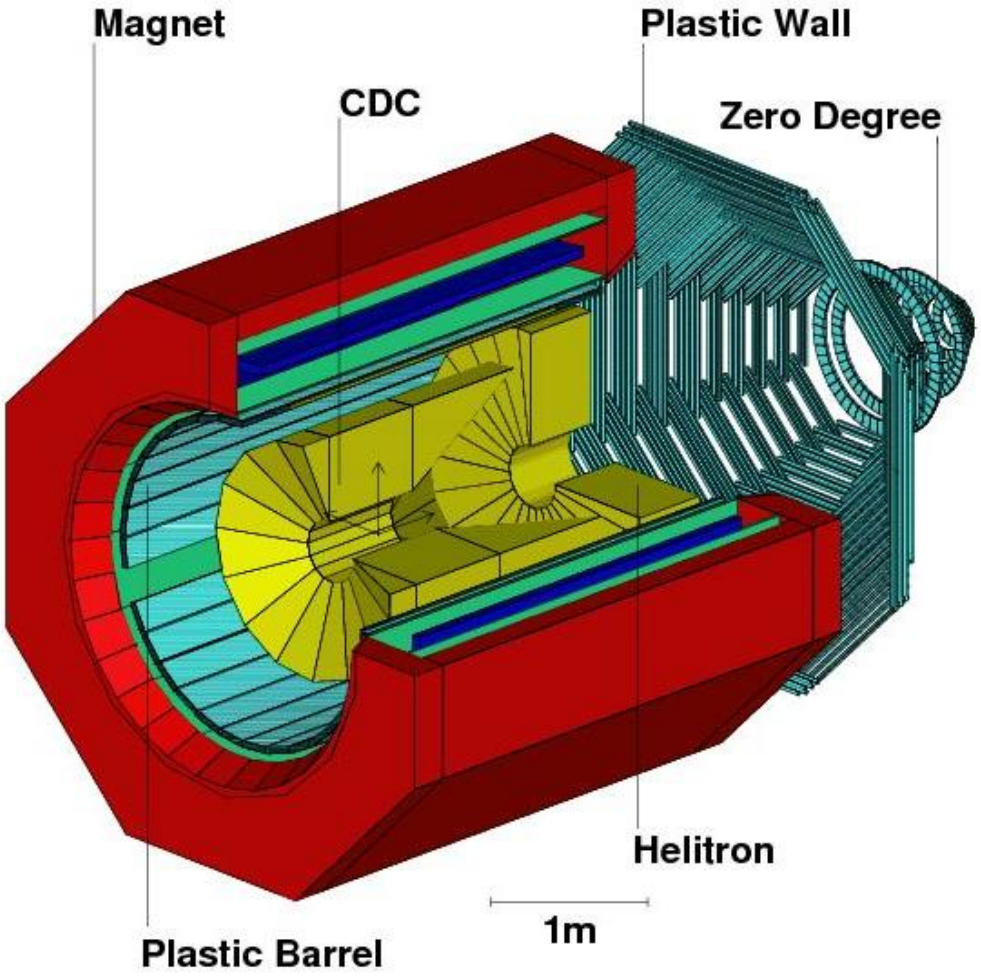


Figure 2.1: Schematic drawing of the FOPI detector.

2.10 The Forward Wall

The forward wall covers polar angles from 1.2 ° to 30 ° and the full azimuthal range. It consists of two parts: the outer wall called "Plastic Wall" (PLAWA) and the inner wall called "Zero Degree" (ZD).

2.10.1 The Plastic Wall (PLAWA)

Like the Plastic Barrel the Plastic Wall is made of 512 plastic scintillator strips divided into eight sectors. Each sector is composed of 64 strips. The light produced by a charged particle on a given strip is read out at both ends of the strip via photo multipliers. Each strip delivers four signals, two energies (E_L,E_R) and two times (t_L,t_R). The energy loss ΔE of a particle is proportional to $\sqrt{E_L \cdot E_R}$ and its time of flight is proportional to $\frac{1}{2} \cdot (t_L + t_R)$. The position of a particle hitting the PLAWA is given by the angular position of the strip which fired. The time resolution is linked to the active length of the scintillator strip, thus it varies from 80 ps for strips in the inner sector to 120 ps for strips in the outer sector. The resolution of the hit position varies from 1.2 cm to 2.0 cm [74, 75].

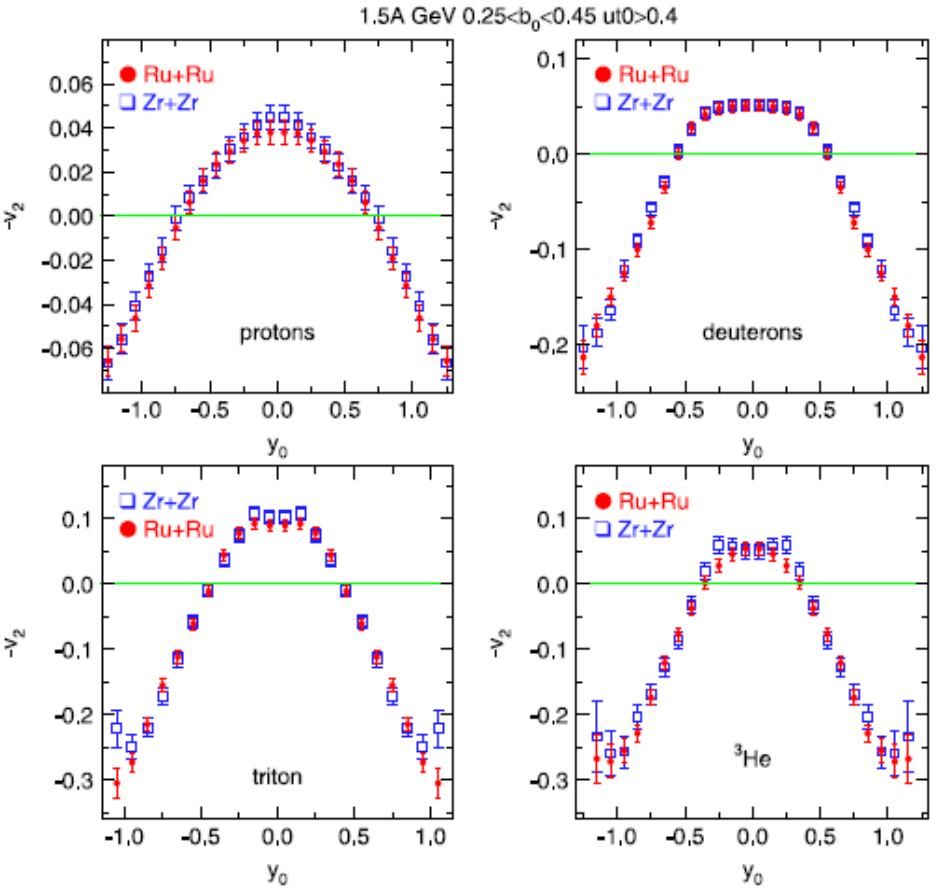
2.10.2 The Zero Degree Detector

This detector covers polar angles from 1.2 ° to 7.0 ° and consists of 252 plastic scintillator strips grouped into 7 concentric rings. Each module is read out by only one photo multiplier and delivers the energy loss (ΔE) and the time of flight of charged particles. The time resolution of this detector is about 200 ps.

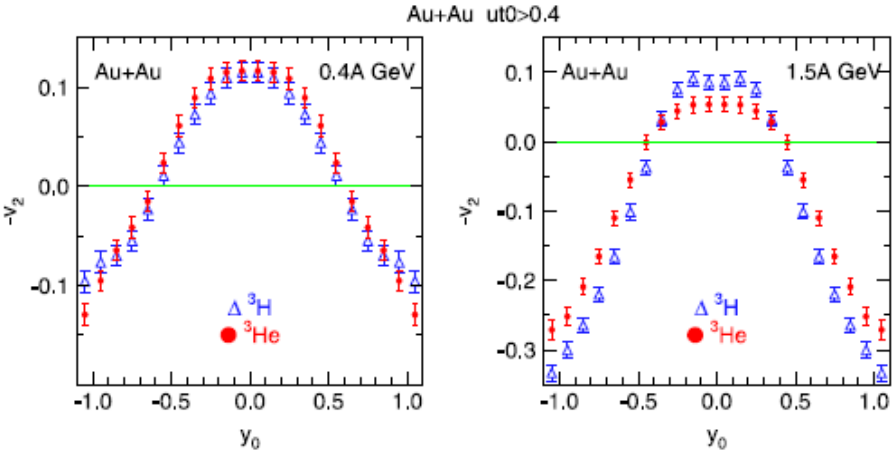
FOPI systematic

Complete systematic (25 systems-energies) for flow of Light Charged Particles
W. Reisdorf et al., NPA876 2012

p,d,t,^{3}He elliptic flow Ru+Ru,Zr+Zr 1.5AGeV

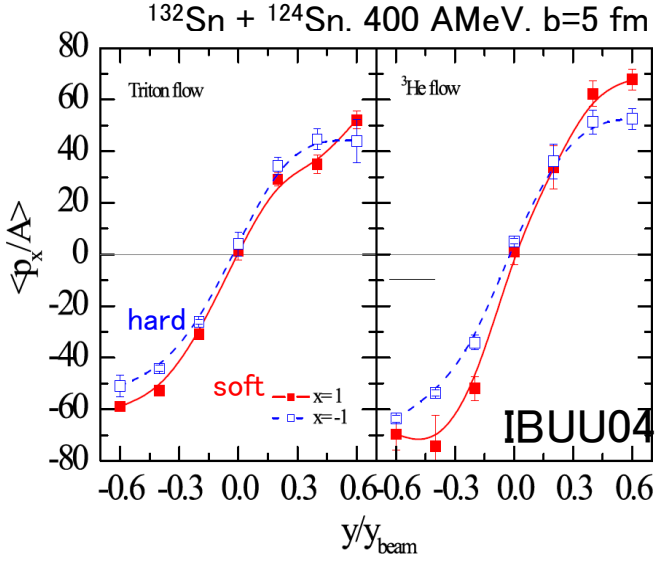


t,^{3}He elliptic flow Au+Au,0.4-1.5AGeV



t/^{3}He flow

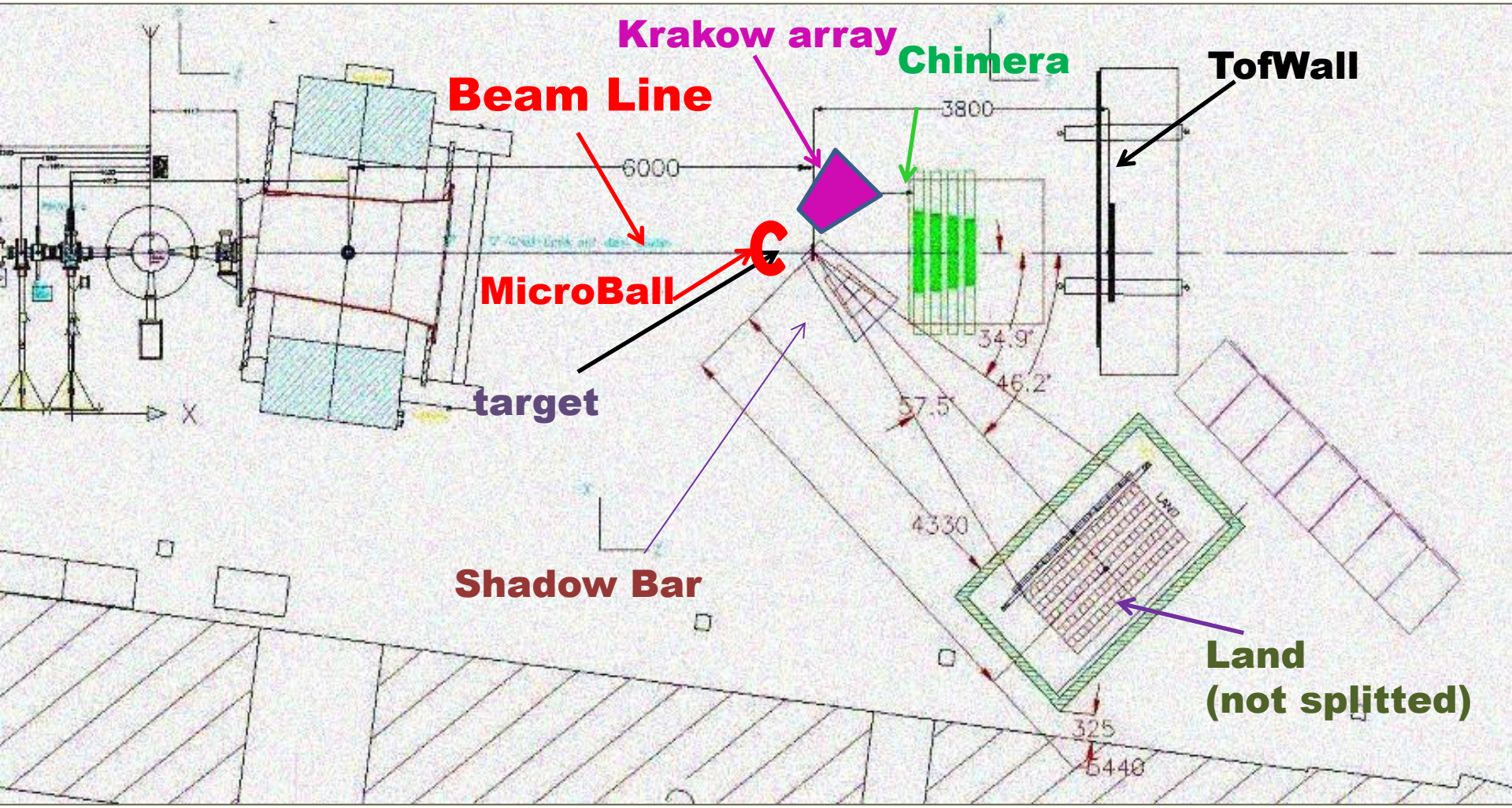
Gao-Chan Yong et al., nucl-the:0906.0939



Difference in t/^{3}He elliptic flow increasing with energy

NEW EXP

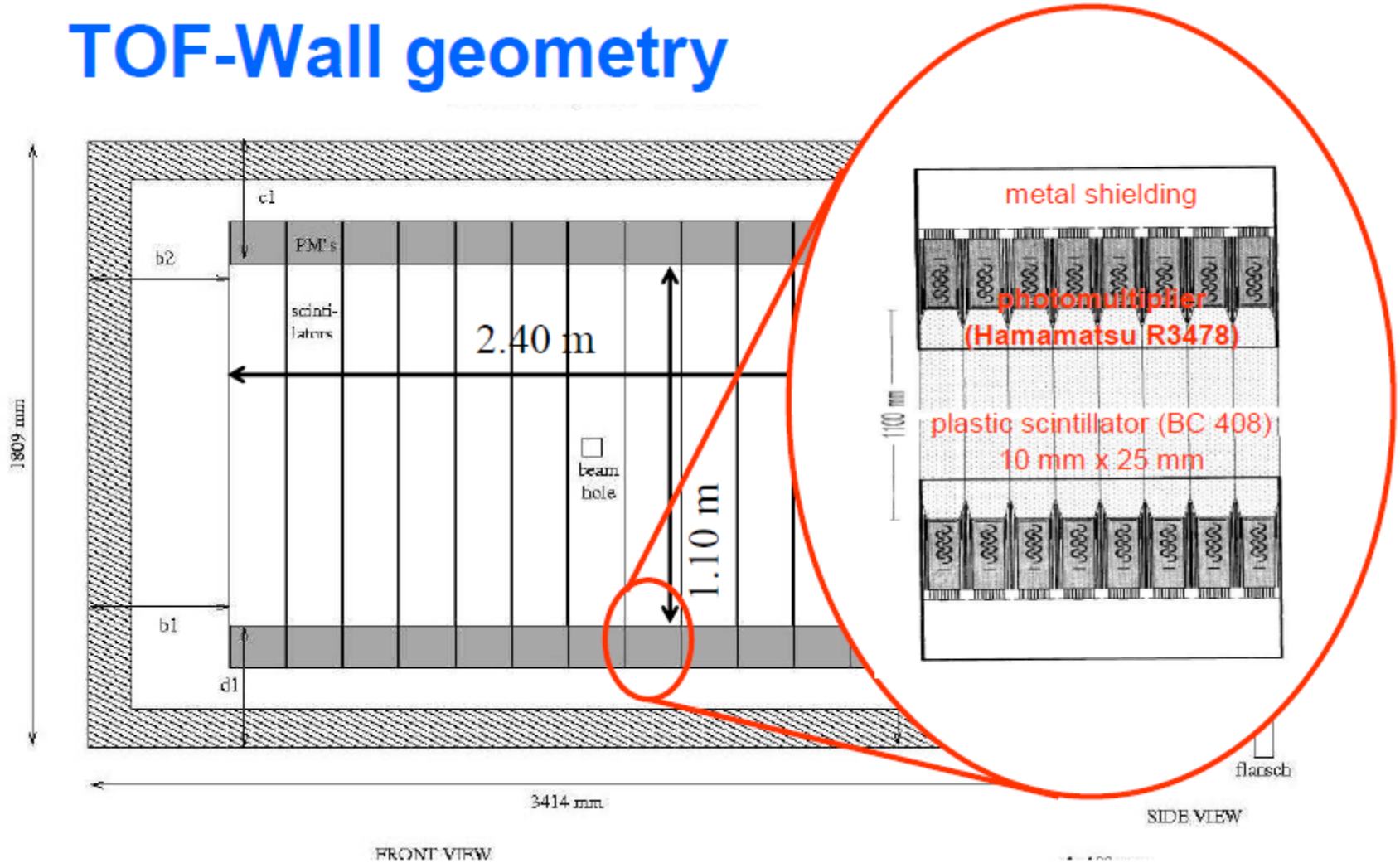
ASY-EOS S394 experiment @ GSI Darmstadt (Germany)



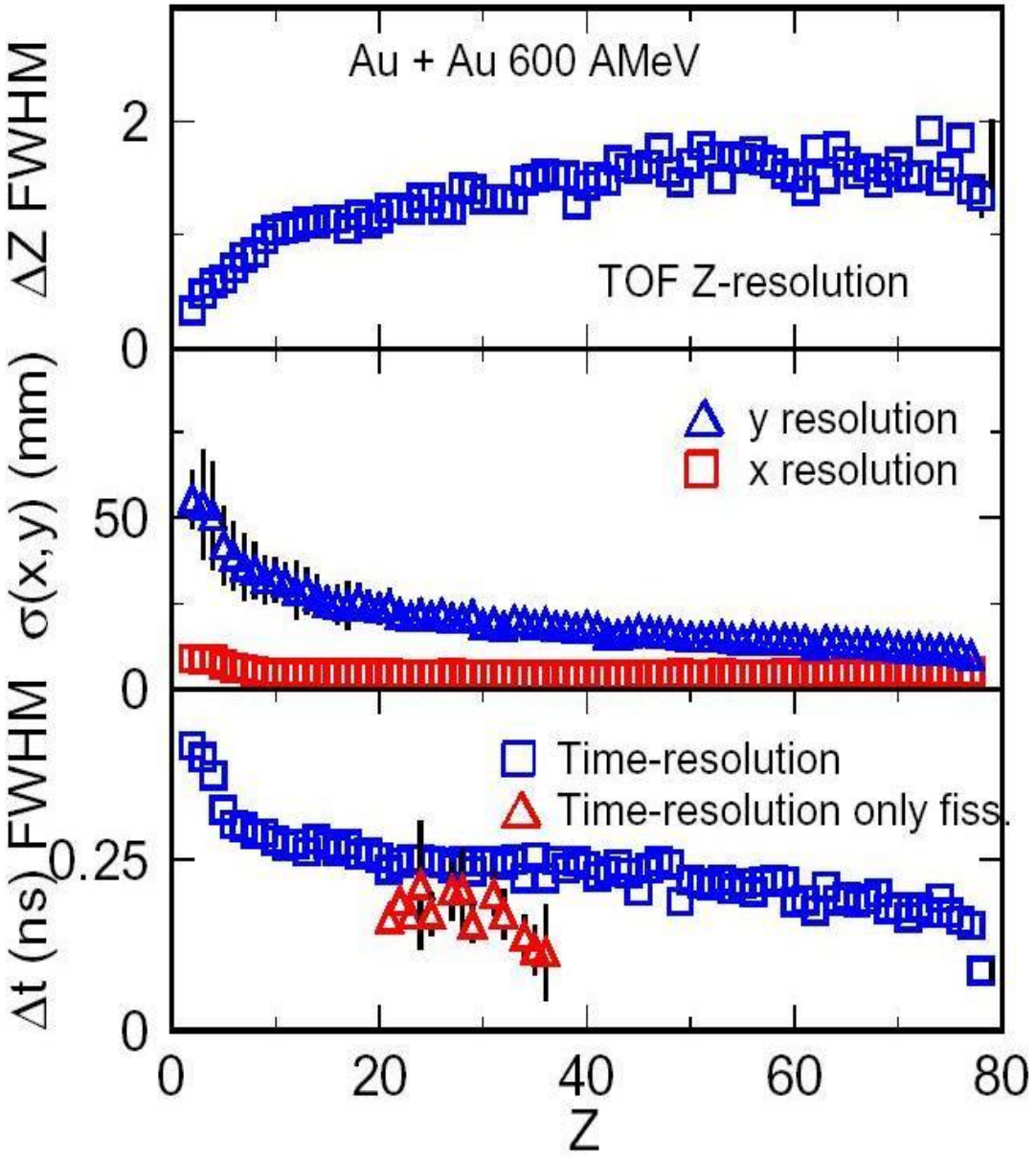
Aladin ToF-Wall

96 plastic bars 2.5X 100 cm
2 walls (front and rear) $\theta < 7°$
Z, velocity & X-Y position.
Impact parameter and
reaction plane determination

TOF-Wall geometry



Time, charge and space resolution

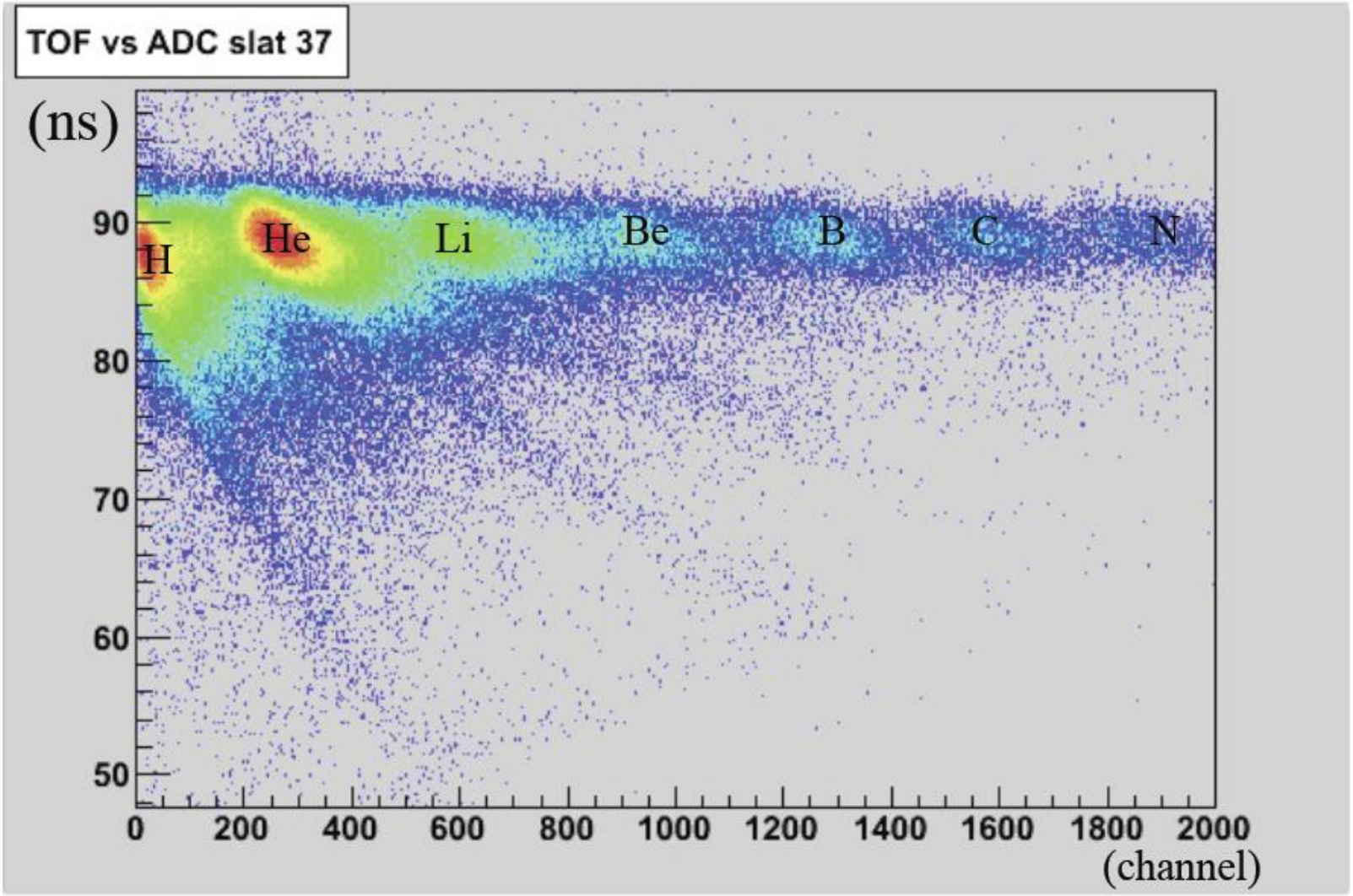


FWHM = 2.35 σ

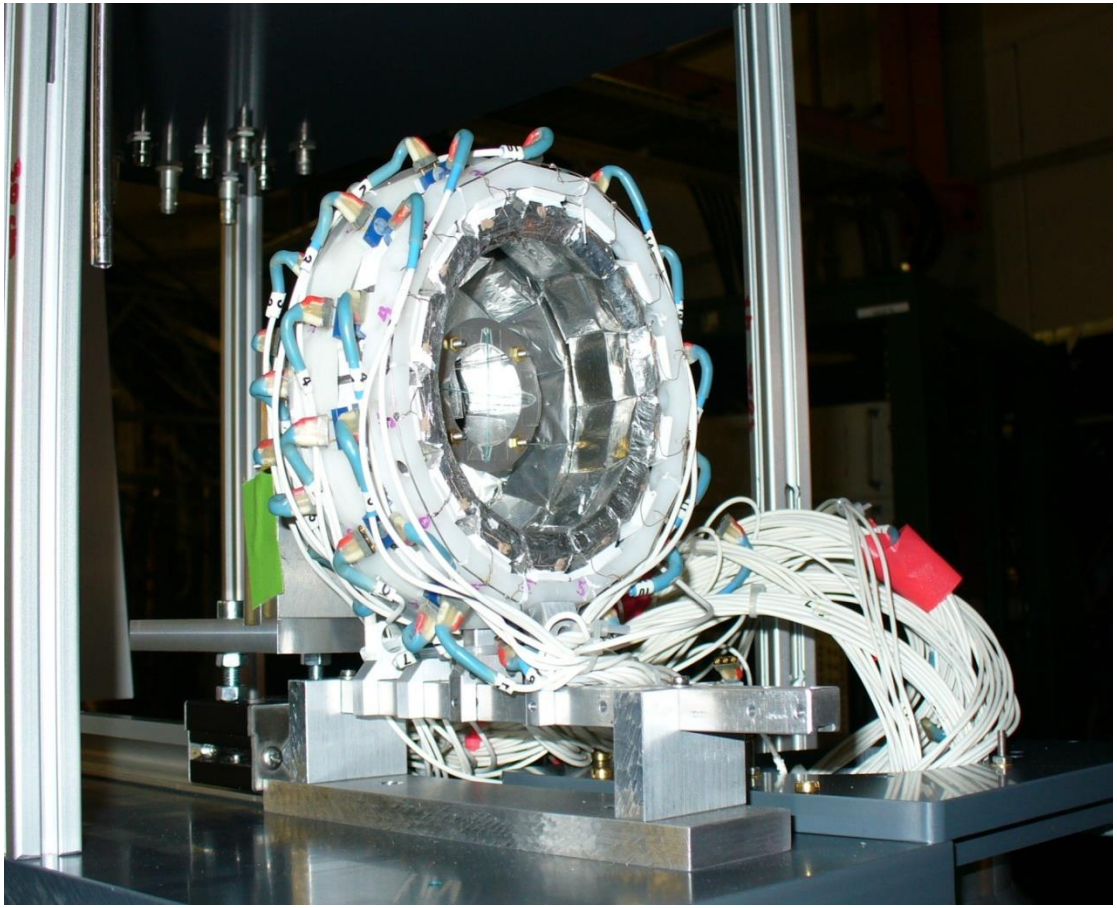
A. Schüttauf

Aladin ToF-Wall (GSI)

96 plastic bars 2.5X 100 cm
2 walls (front and rear) $\theta < 7°$
Z, velocity & X-Y position.
Impact parameter and
reaction plane determination



MicroBall (USA)



μBall:

4 rings, 50 CsI(Tl)

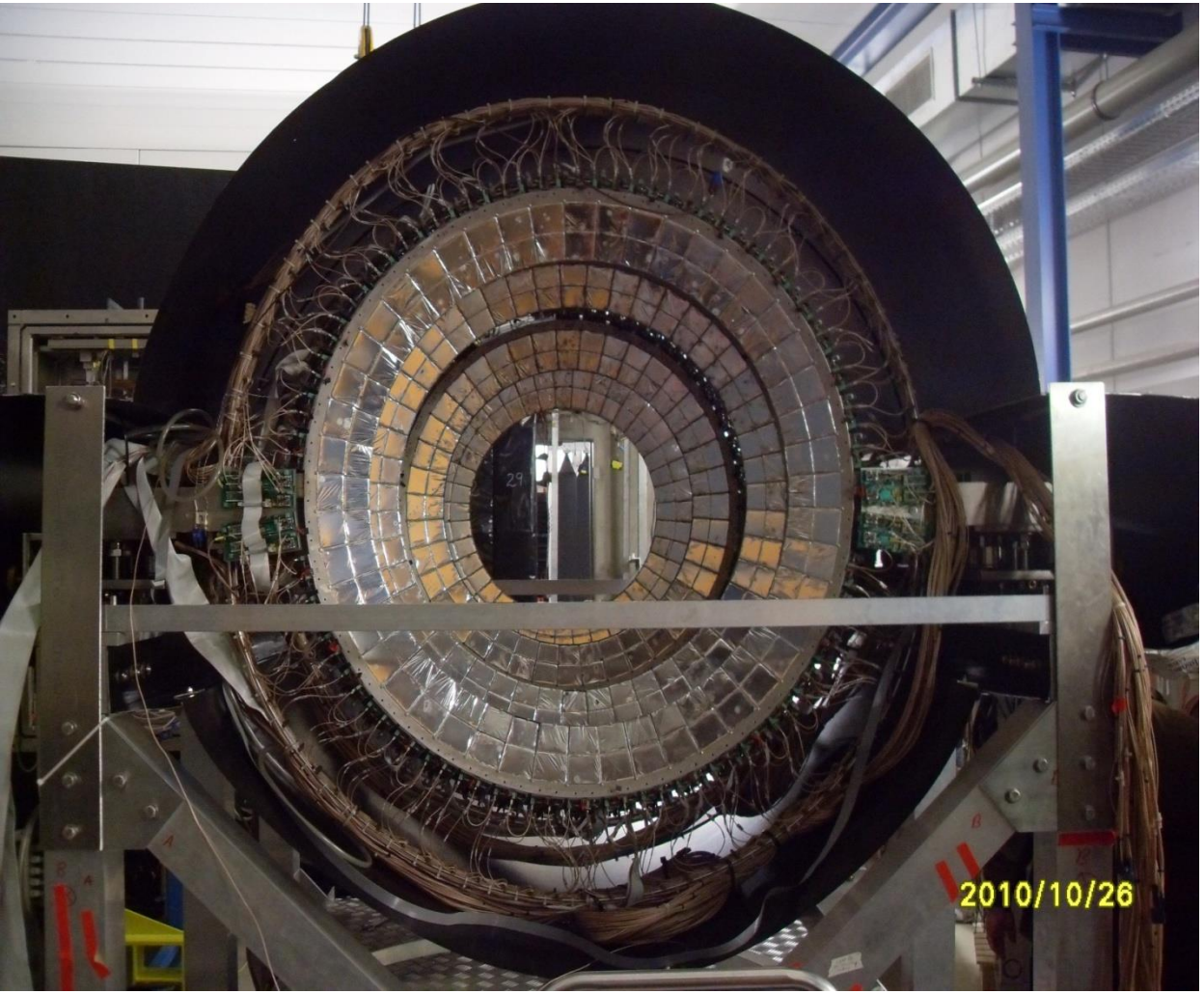
~ 1 cm thick

60°<θ<147°.

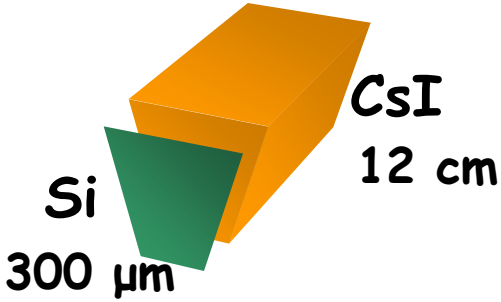
Discriminate target vs. air interactions (backward angles).

Multiplicity measurements.

CHIMERA



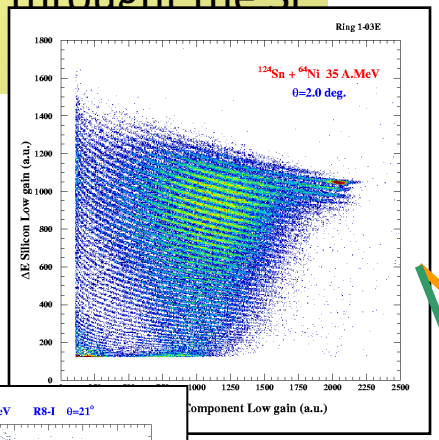
352 CsI 12 cm thick
+ 32 Si (telescopes)
8 Rings covering 7°<θ<20°
Light ions
Z, Ekin & θ-ϕ.
Impact parameter and reaction plane determination



Particles identification techniques with CHIMERA

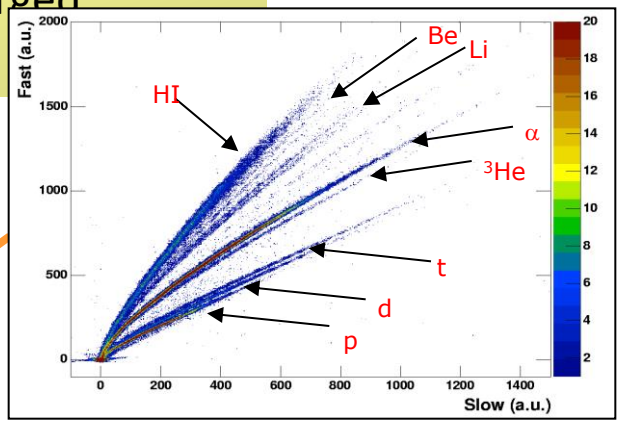
ΔE(Si)-E(CsI)

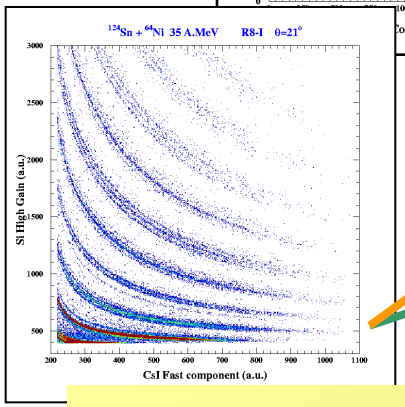
Charge Z for particles punching throught the Si detector



PSD in CsI(Tl)

Z and A for light charged particles





Si

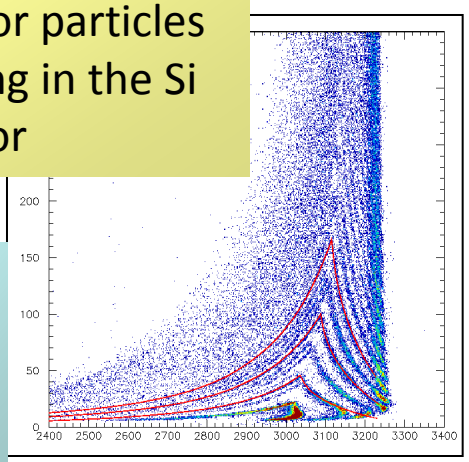
~300 µm

CsI(Tl)

3-12 cm

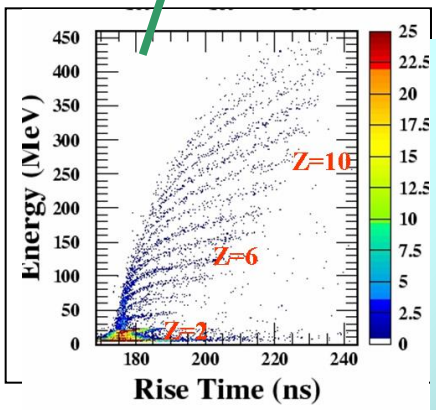
ΔE(Si)-ToF

Mass for particles stopping in the Si detector



ΔE(Si)-E(CsI)

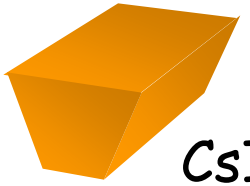
Charge Z and A for light ions (Z<9) punching throught the Si detector



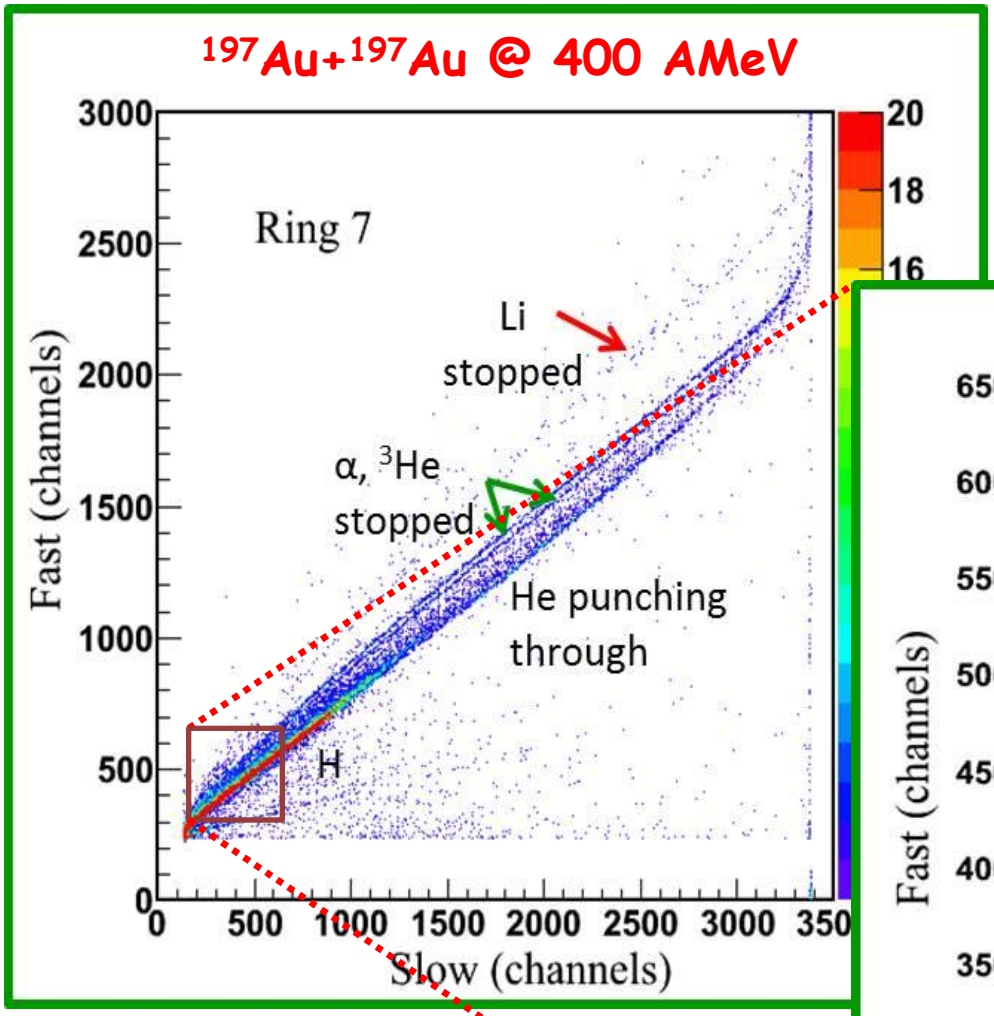
E(Si)-Rise time

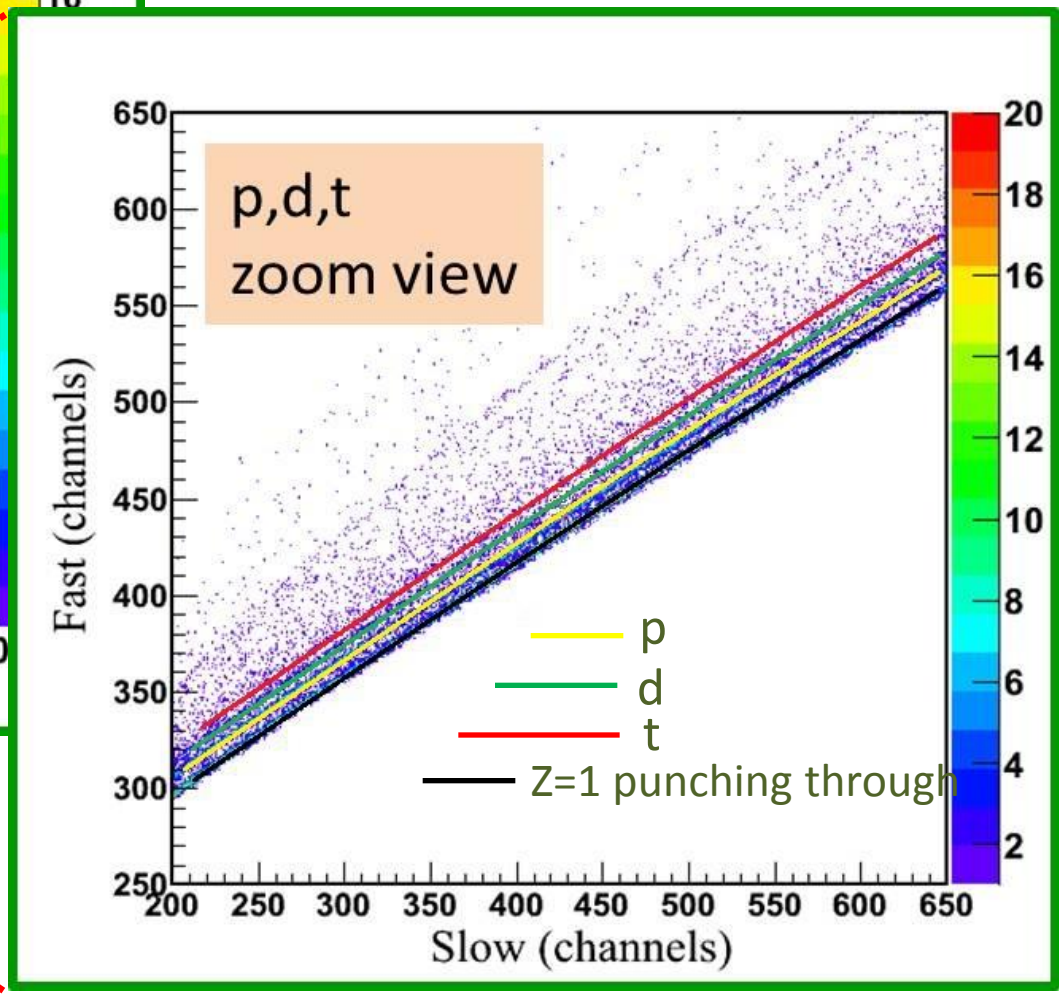
Charge Z for particle stopping in Si detectors (NEW)

Identification in CHIMERA...



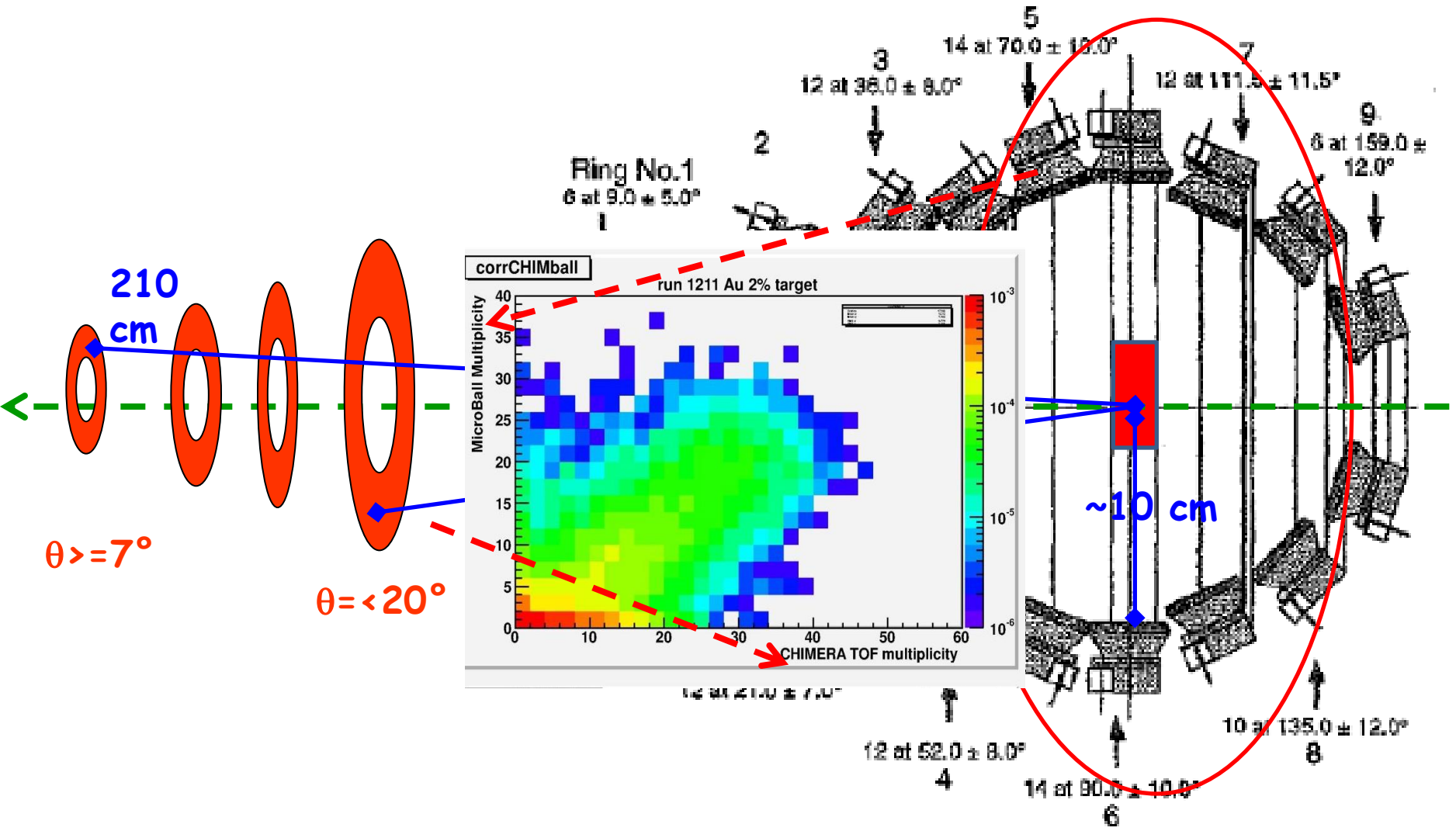
CsI(Tl)





MicroBall

Au+Au @ 400 AMeV



Not in scale

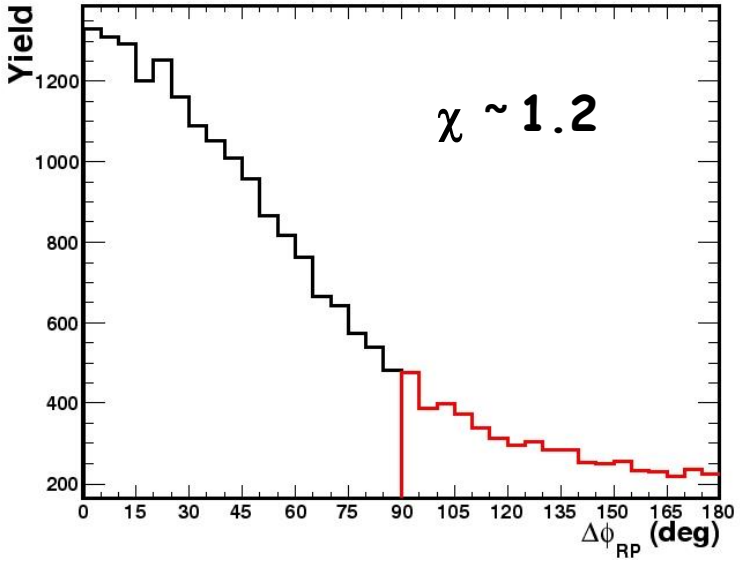
CHIMERA: MicroBall ~ 10:1

..and test of resolution using sub-events mixing technique:

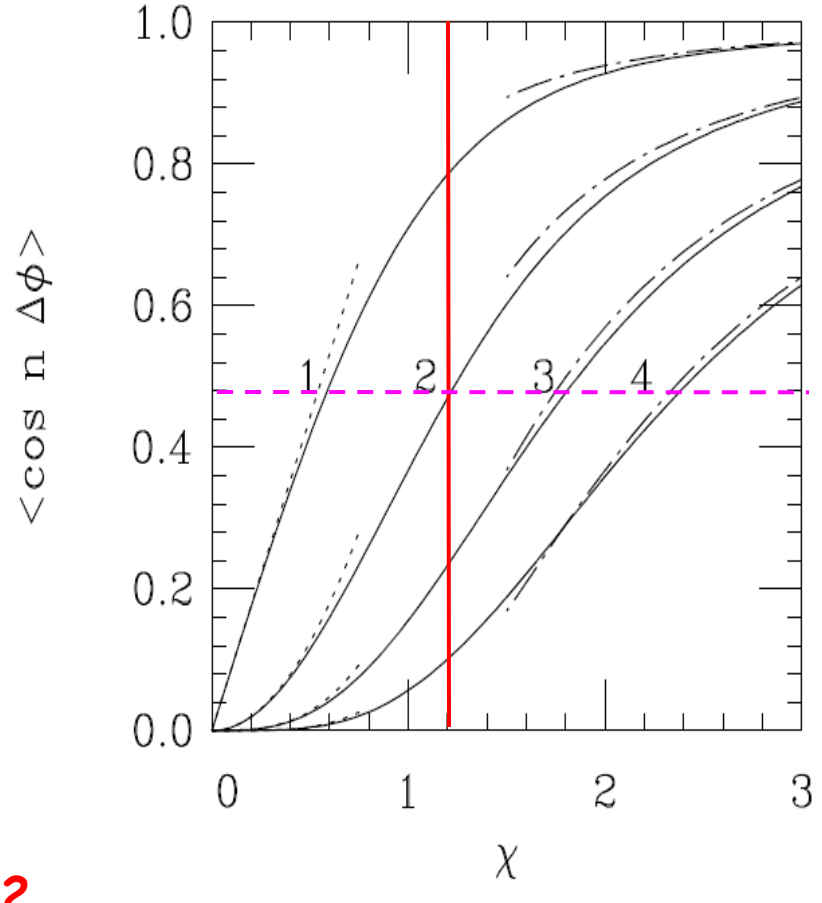
Preliminary!!!

J-Y Ollitrault arXiv:nucl-ex/9711003v2

Au+Au (2%) 400 A.MeV (run 1670)



$$\frac{N(90^\circ < \Delta\phi_R < 180^\circ)}{N(0^\circ < \Delta\phi_R < 180^\circ)} = \frac{\exp(-\chi_I^2)}{2} = \frac{\exp(-\chi^2/2)}{2}.$$



$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} c_n \cos n\phi\right)$$

measured azimuthal angle ψ is related to the true azimuthal angle ϕ by $\psi = \phi - \Delta\phi$

$$\langle \cos n\psi \rangle = \langle \cos n\phi \rangle \langle \cos n\Delta\phi \rangle.$$

measured true

~0.5 for n=2

Δφ ~30°

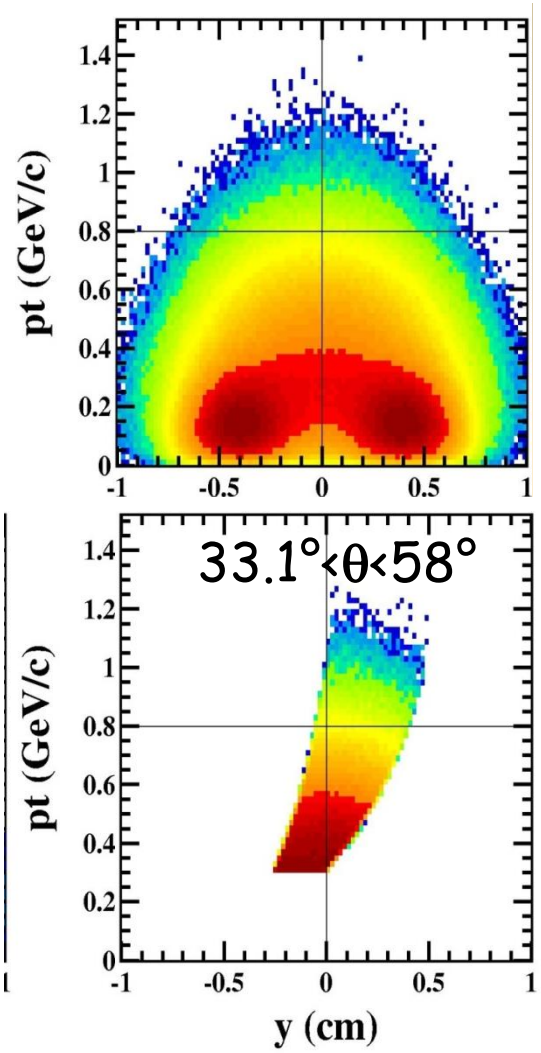
ToFWall, μBall & Ring 6E data not used!

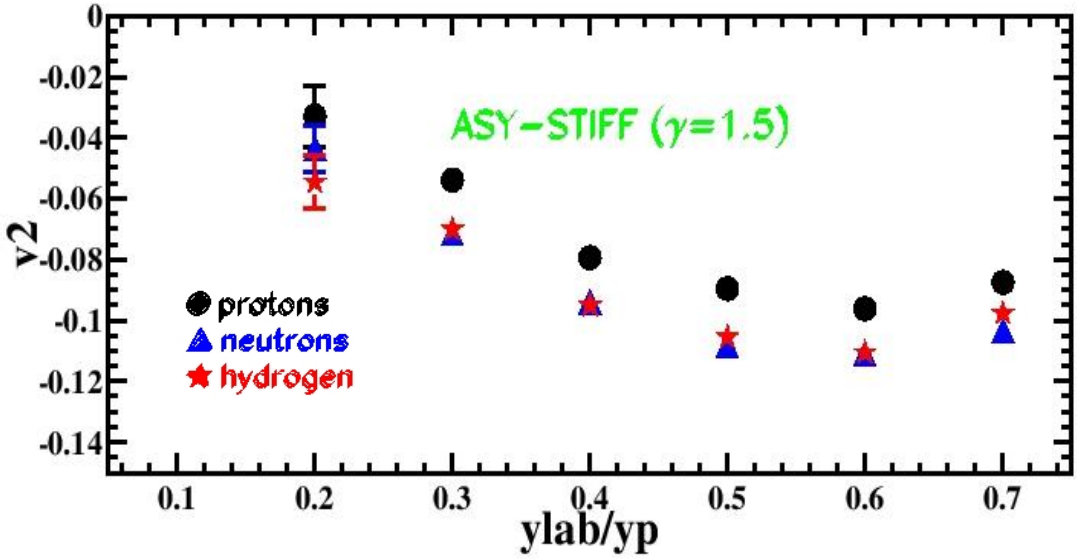
Large Area Neutron Detector (LAND)

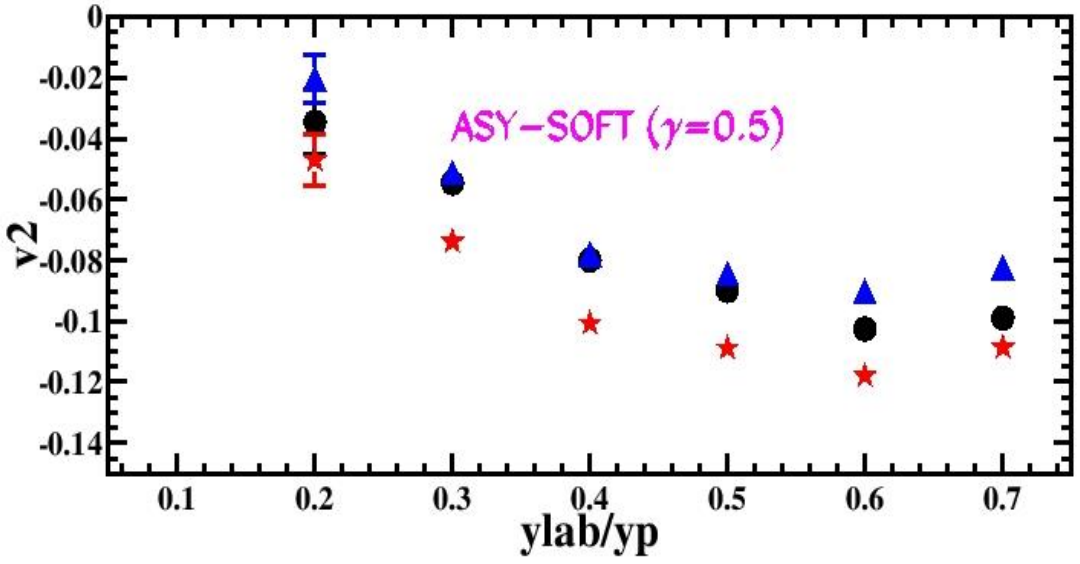
Au+Au @ 400 AMeV

b=5.5-7.5 fm
UrQMD simulations

ASYEOS exp: "better" coverage of mid-rapidity







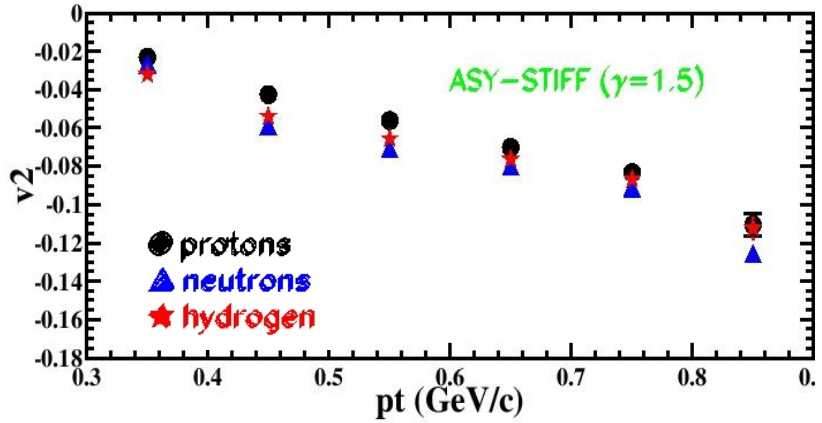
Au+Au @ 400 AMeV UrQMD simulations

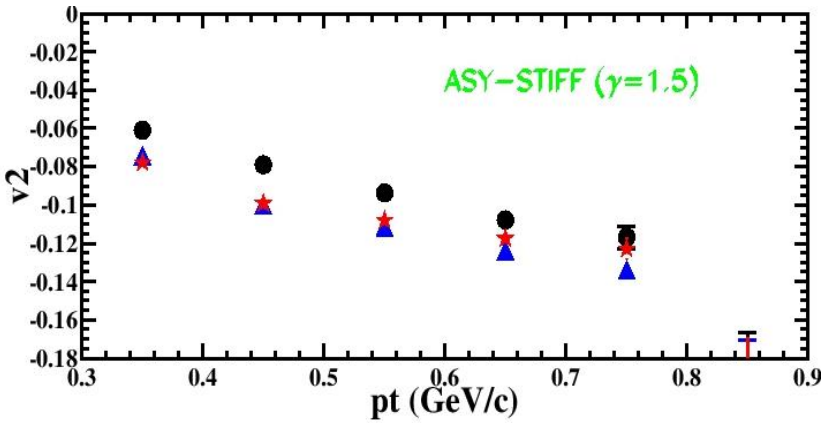
b=5.5-7.5 fm

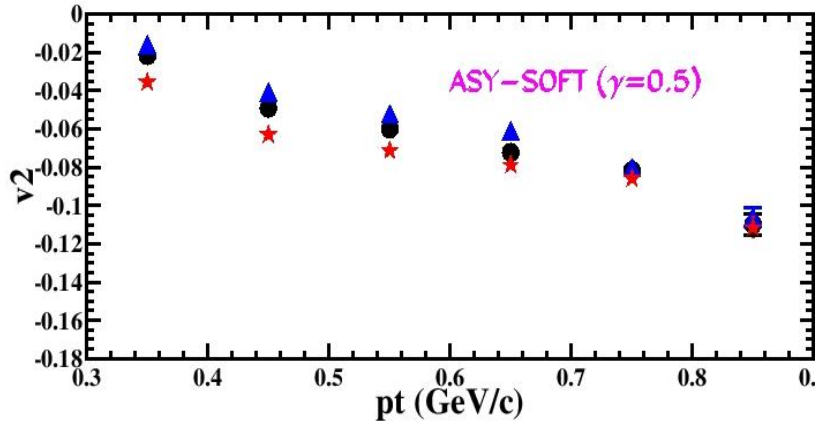
$33.1 < \vartheta_{lab} < 58$ deg

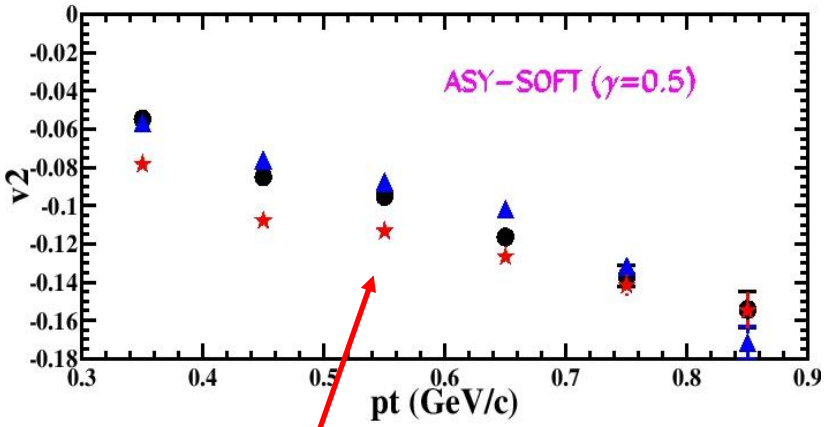
unfiltered

filtered







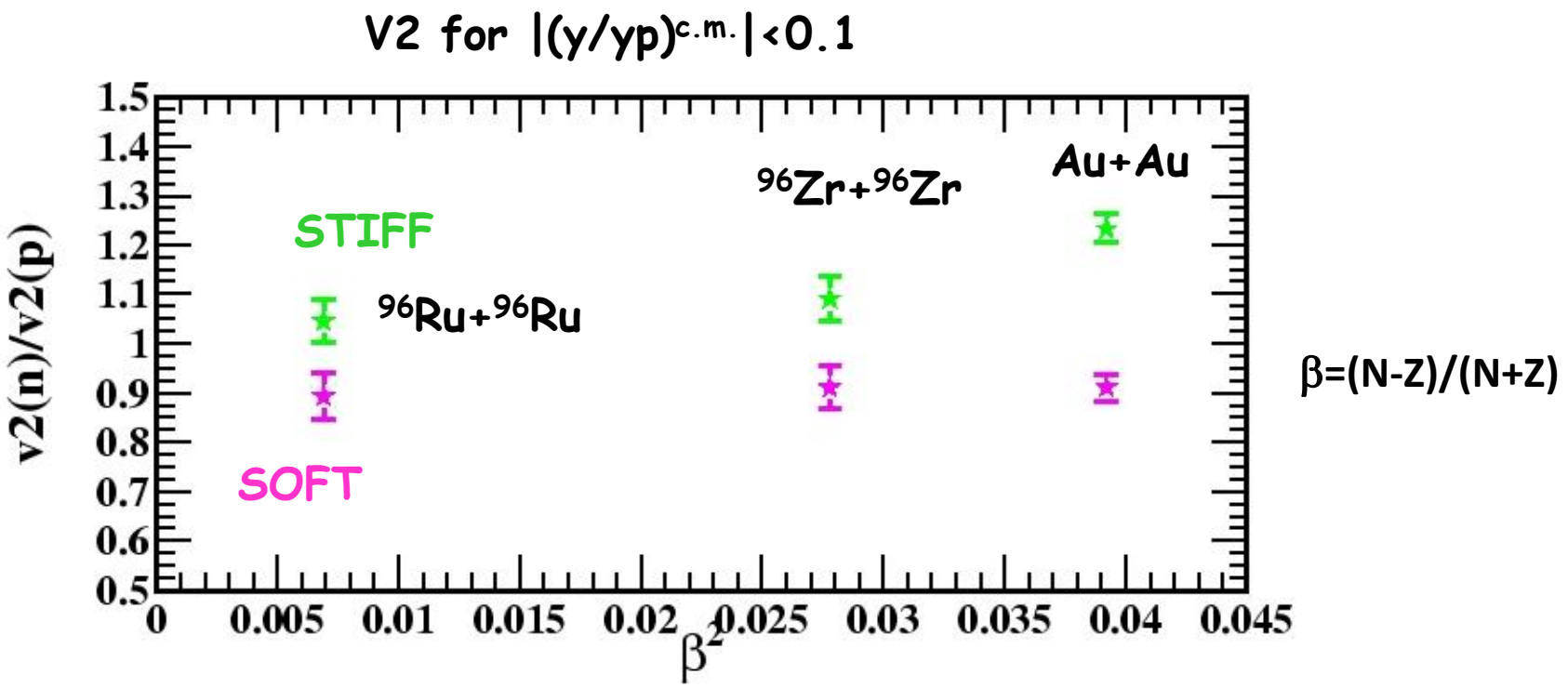


inversion survives acceptance cuts of the experiment

v2-pt-zoom-vxxx-exp.jpg

v2-pt-zoom-vxxx-exp.jpg

URQMD simulations: @ 400 AMeV



Au+Au b=5.5-7.5 fm

^{96}Zr+^{96}Zr b=4-6 fm

^{96}Ru+^{96}Ru b=4-6 fm

preliminar

Mass splitting impact on Elliptic Flow

$^{197}Au+^{197}Au$, 400 AMeV, b=5 fm, $y^{(0)} \leq 0.3$

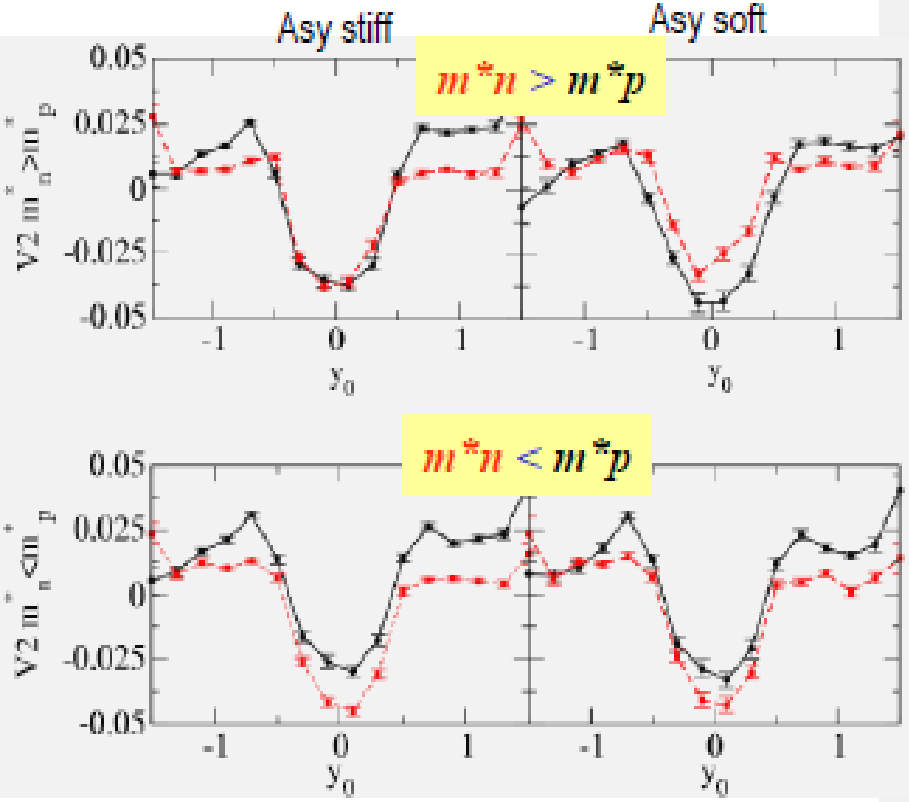
From M.Di Toro talk at Asy-Eos2010

$m^*_n < m^*_p$: larger neutron squeeze out at mid-rapidity

- Larger neutron repulsion for asy-stiff

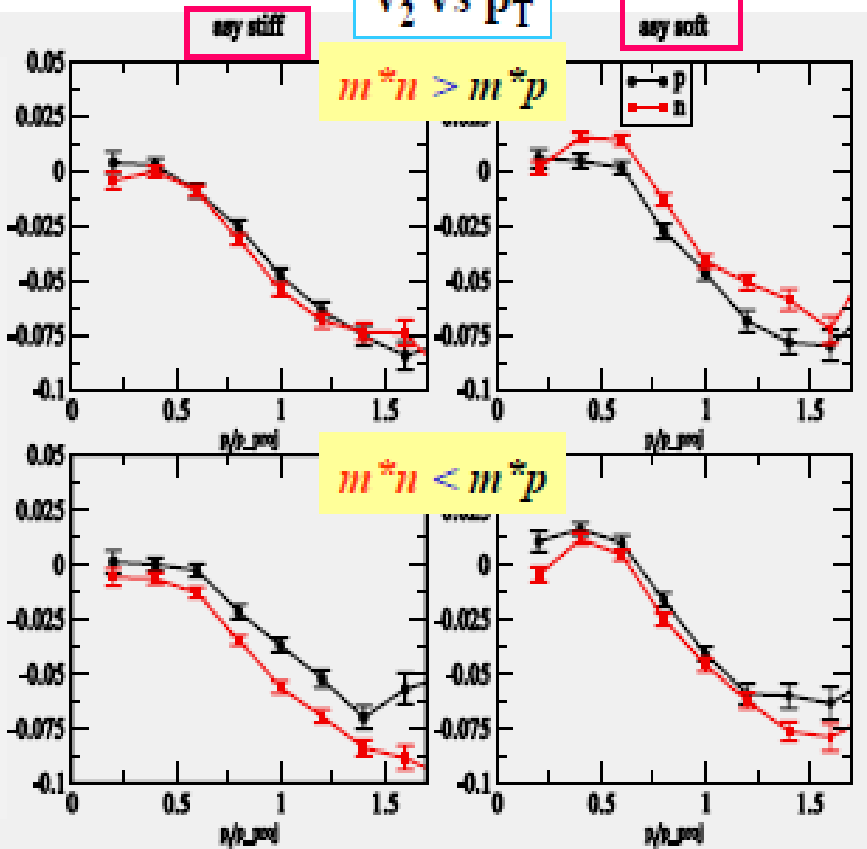
Increasing relevance of isospin effects for $m^*_n < m^*_p$

v_2 vs scaled rapidity



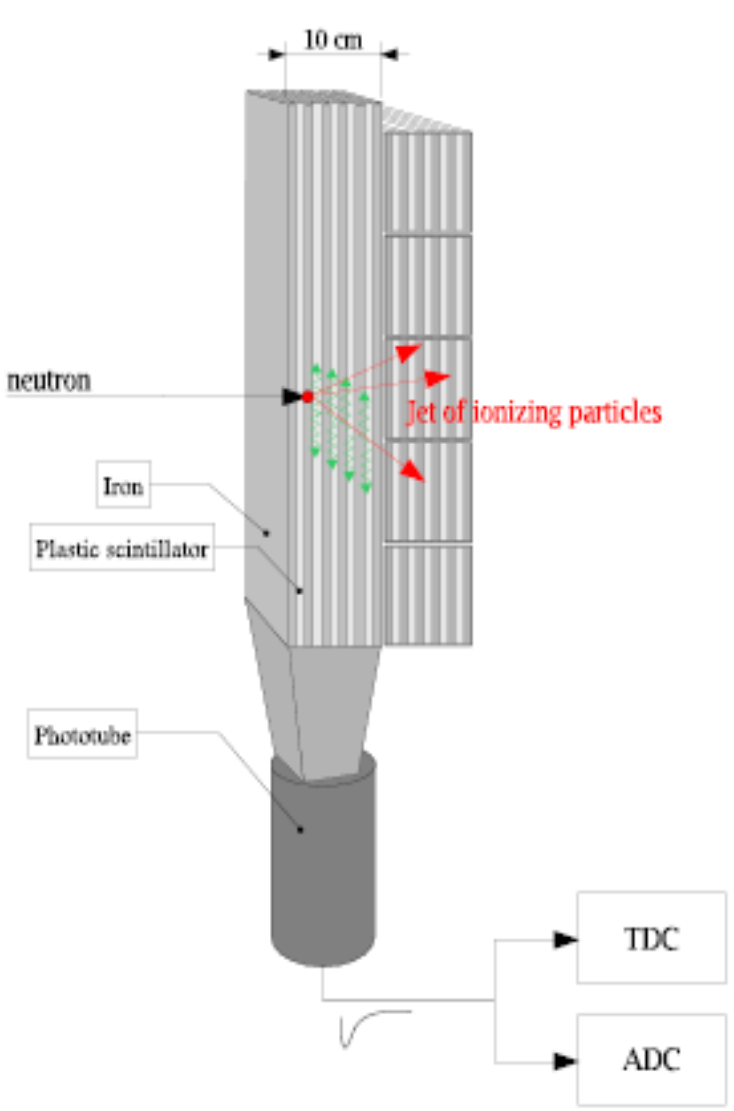
v_2 vs p_T

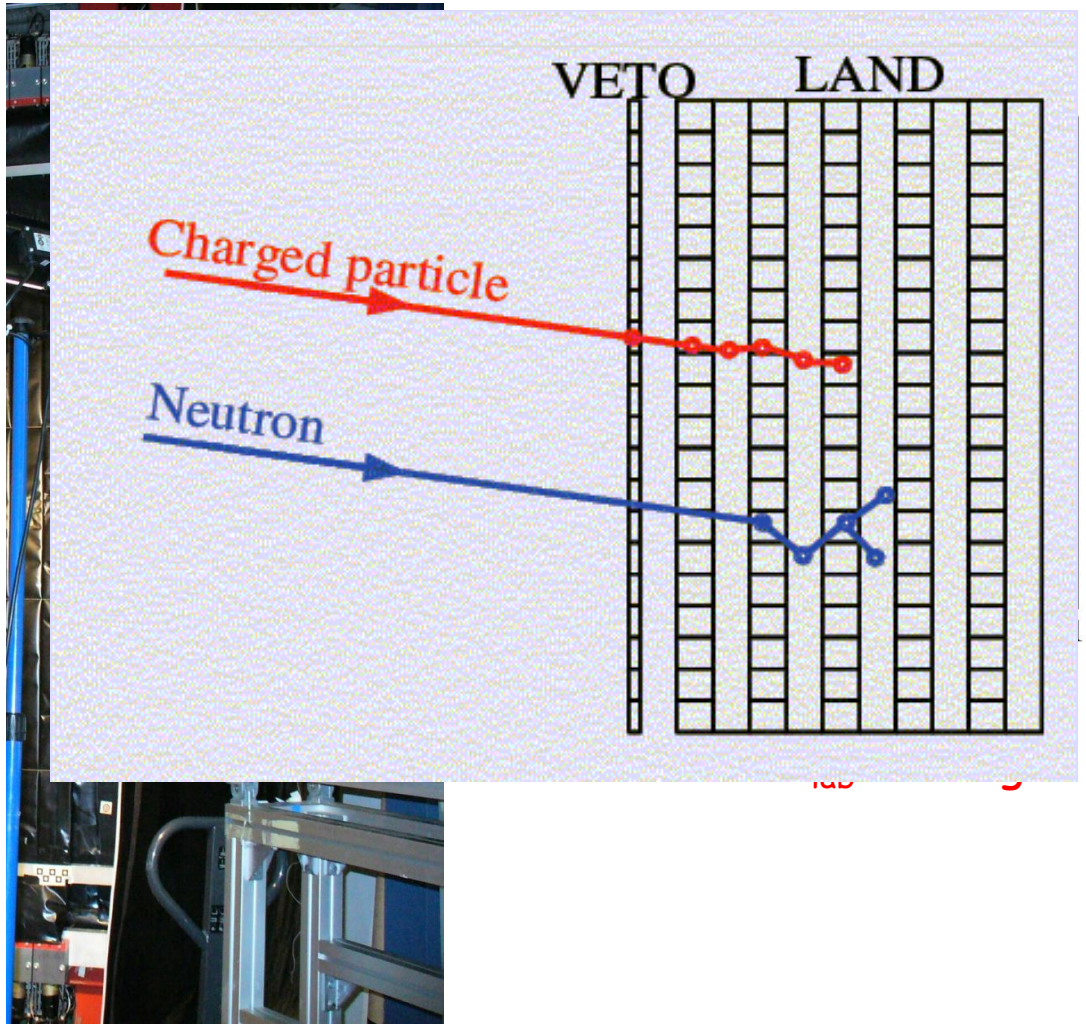
$y^{(0)} \leq 0.3$



LAND

Large Area Neutron Detector :LAND (GSI)



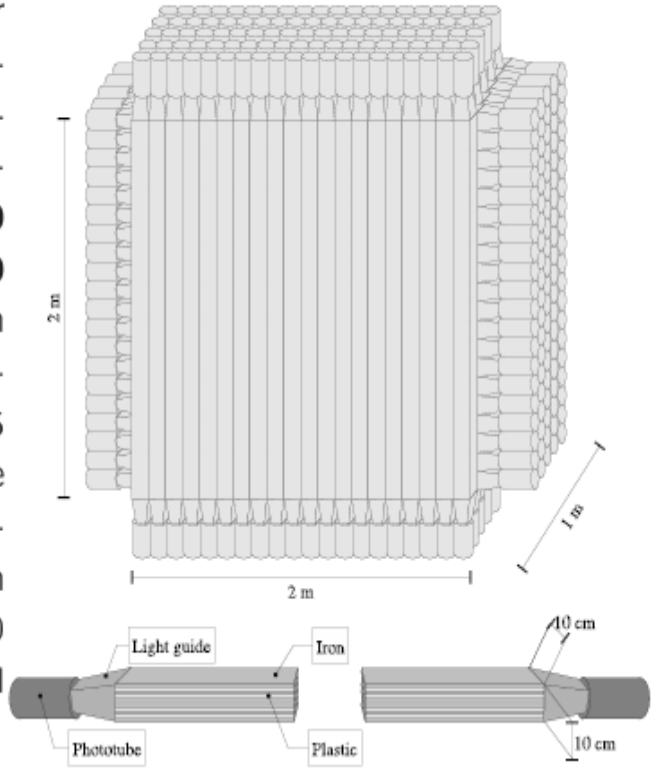


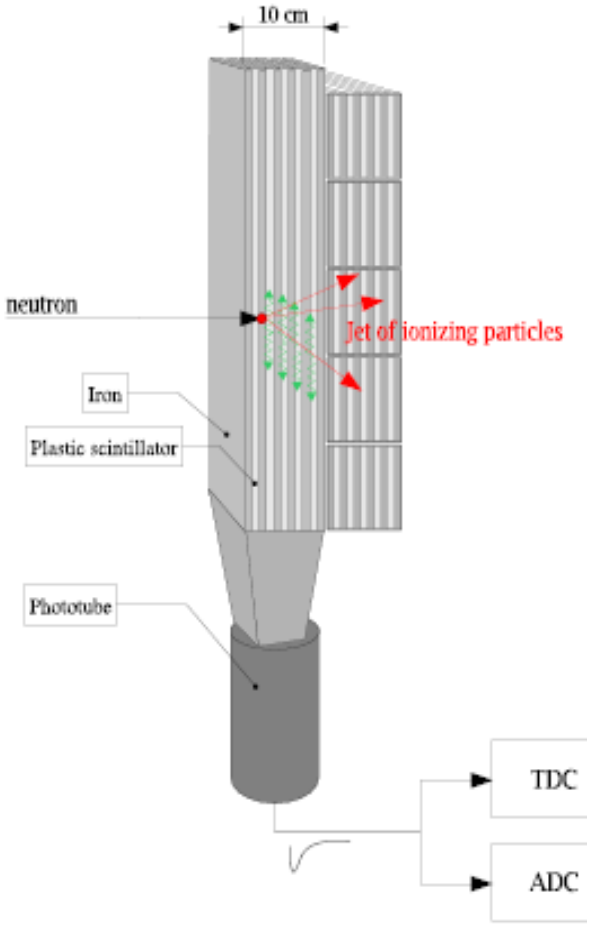
Neutrons and Hydrogen detection.
Flow measurements

Th.Blaich et al.,NIM A314 (1992)

Large Area Neutron Detector (LAND)

The Large Array Neutron Detector (LAND) is a device providing a valuable information on neutron multiplicities produced in relativistic nuclear reactions. It consists of **10 planes**, each plane containing **20 detectors**, called "paddles". Each paddle is made of 0.5 cm thick plastic scintillator layers separated by 0.5 cm thick iron layers. From each side of a paddle the ends of the plastic layers are joined to one common photo-multiplier. Each paddle is 10 cm large. The paddles are oriented either vertically or horizontally.



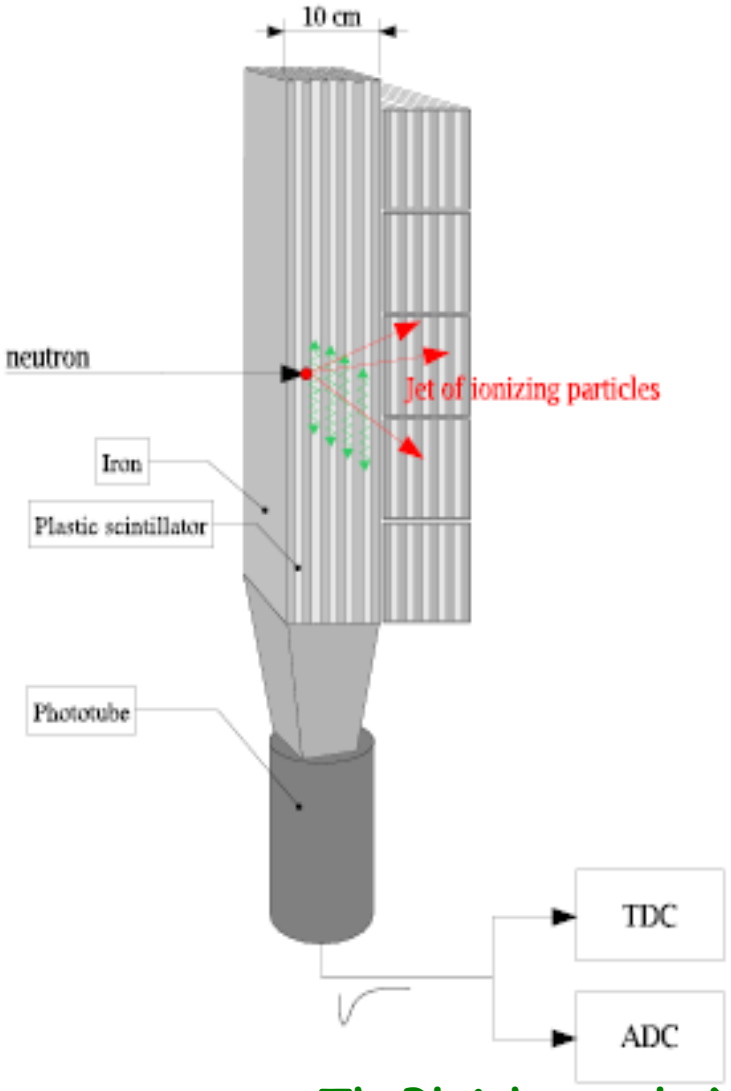


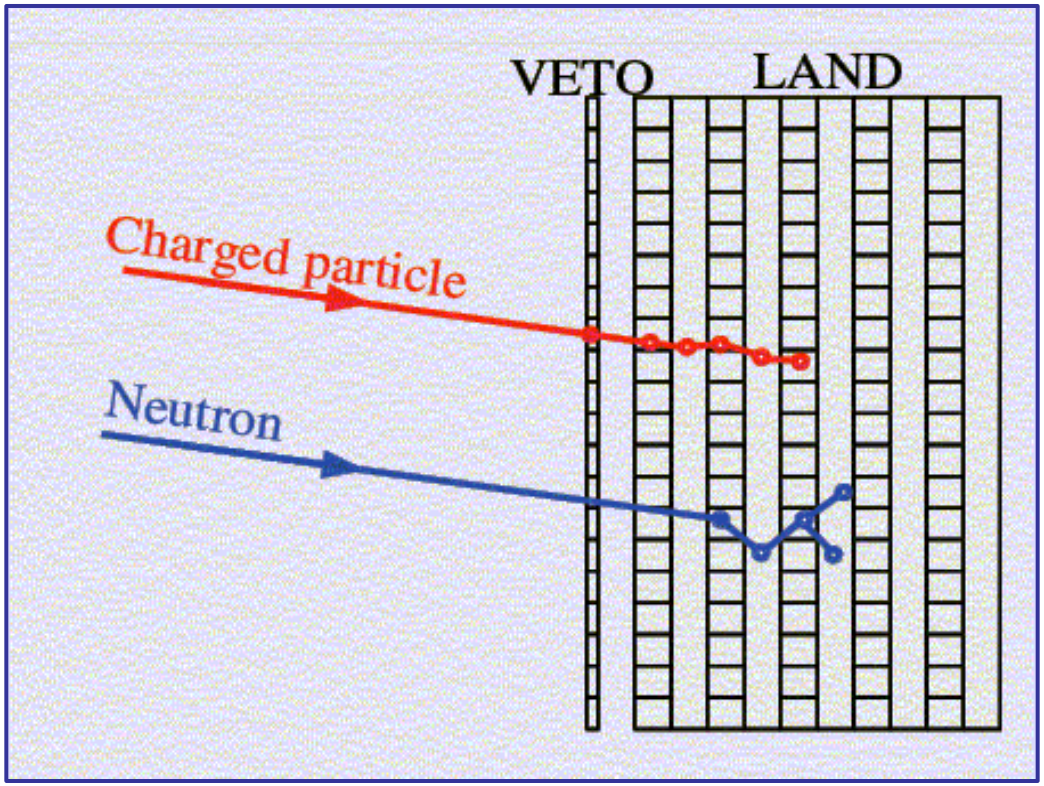
Th.Blaich et al.,NIM A314 (1992)

Adapted from P.Pawloski,IWM2007

Neutrons efficiency>80% (for E>400MeV)
No ^{1,2,3}H isotopic discriminations

Large Area Neutron Detector (LAND)





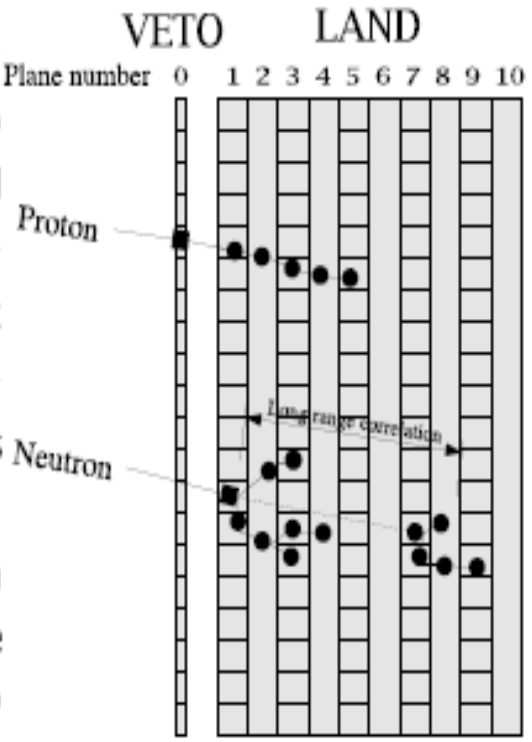
neutron and proton detection

Th.Blaich et al.,NIM A314 136-154 (1992)
P. Pawloski et al., "Study of neutron emission using Land detector", Procs of IWM2007

Large Area Neutron Detector (LAND)

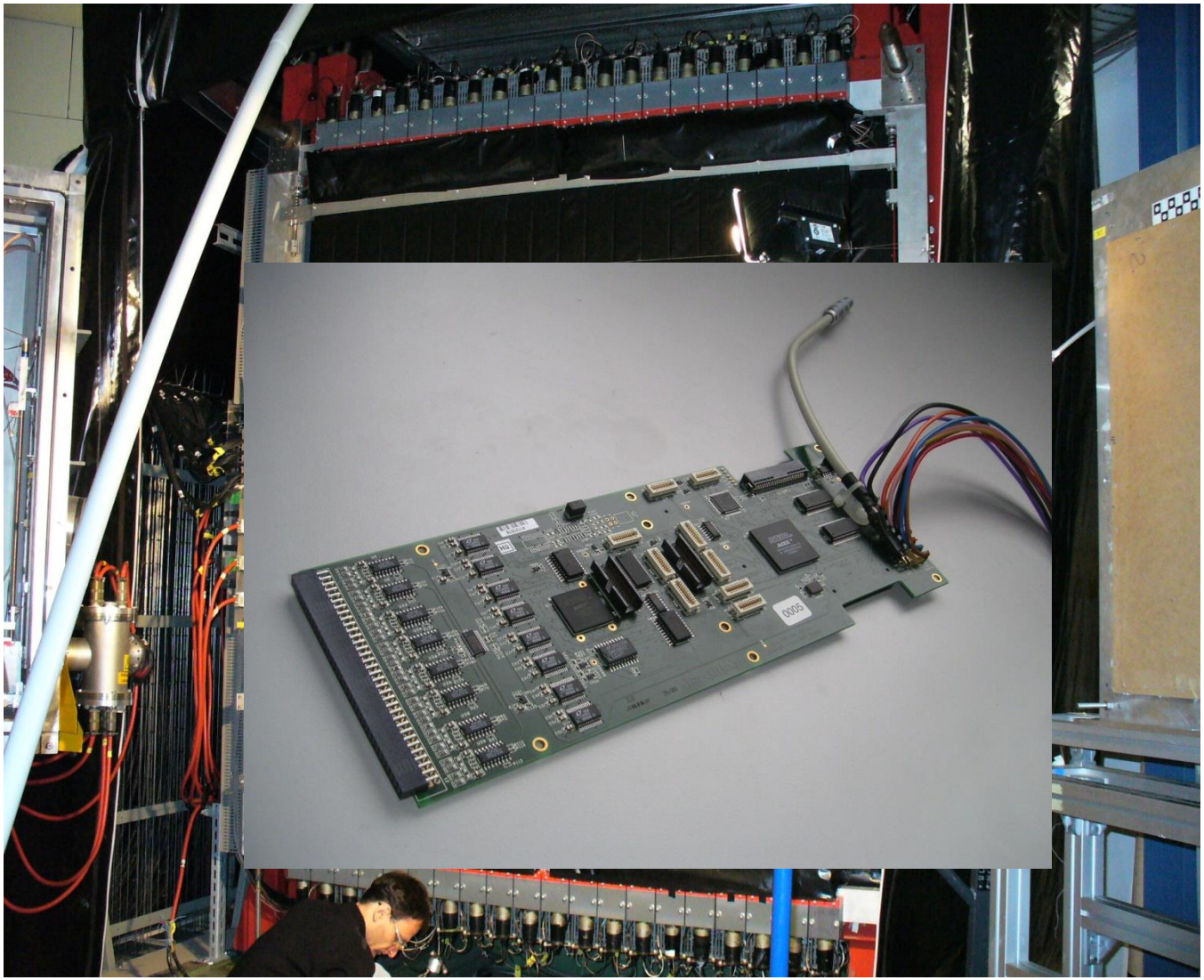
A recursive procedure starts from a hit registered in the VETO wall and searches for a correlated hit in the first LAND plane. Then, for this hit, another correlated hit is searched in the 2 plane. The procedure is repeated until no more correlation can be found. The correlated hits are marked as "secondary" hits and are removed from total pool of the hits. The first hit ("primary" or "seed") determines the properties of a particle: its time and position give its velocity vector.

Next, one searches for the chains starting from one of hits registered in the first LAND plane (among that not correlated with the VETO hits), then from the second one, and so on. All these hits are considered to be generated by neutron.



Adapted from P.Pawloski,IWM2007

Large Area Neutron Detector (LAND)



new TACQUILA electronic

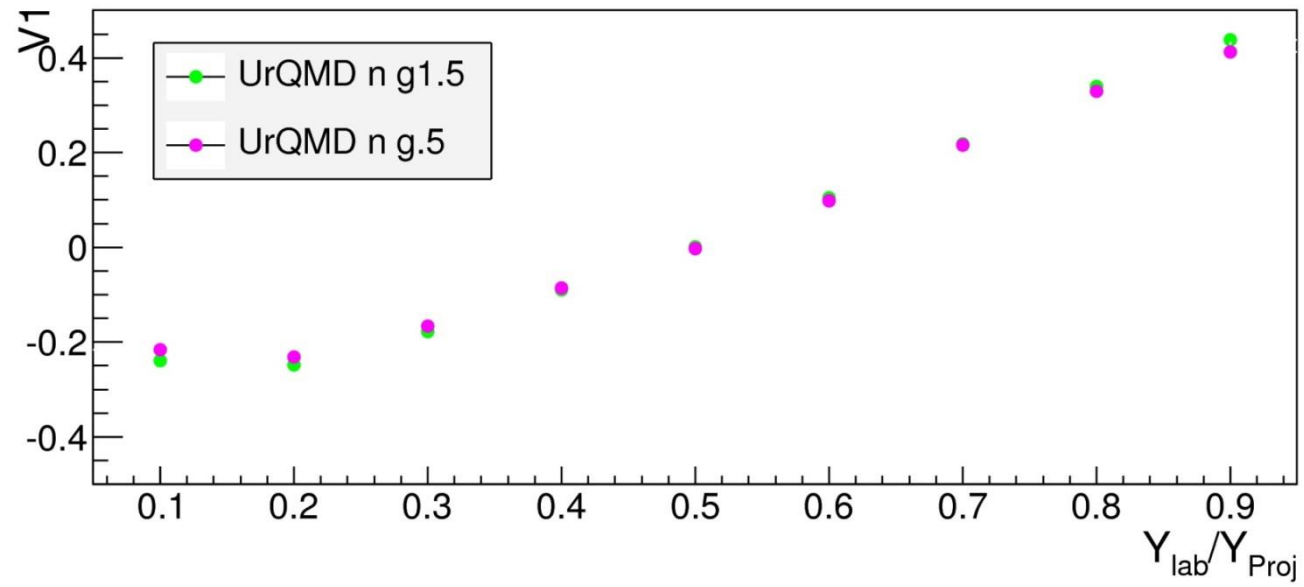
A compact electronics for time measurements with very high resolution ~ 10ps RMS.
Developed for the FoPi TOF-upgrade.
The PCB consists of 16 channels based on the TAC GSI-ASIC.
Optional with amplitude measurement card (QDC).

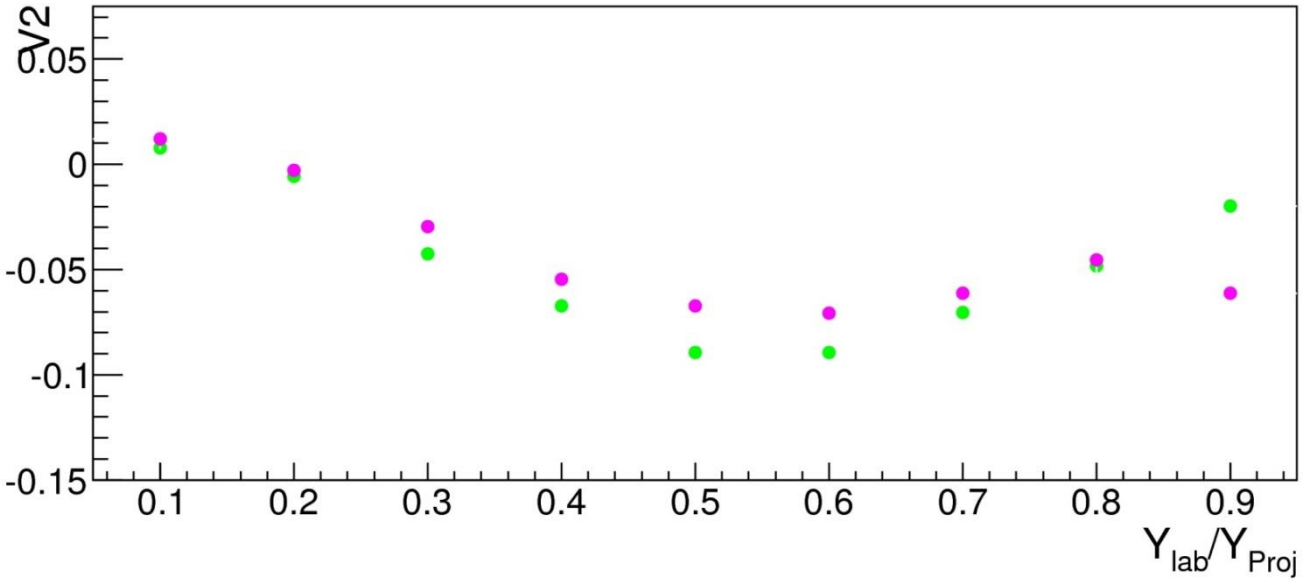
Neutrons and Hydrogen detection.
Flow measurements

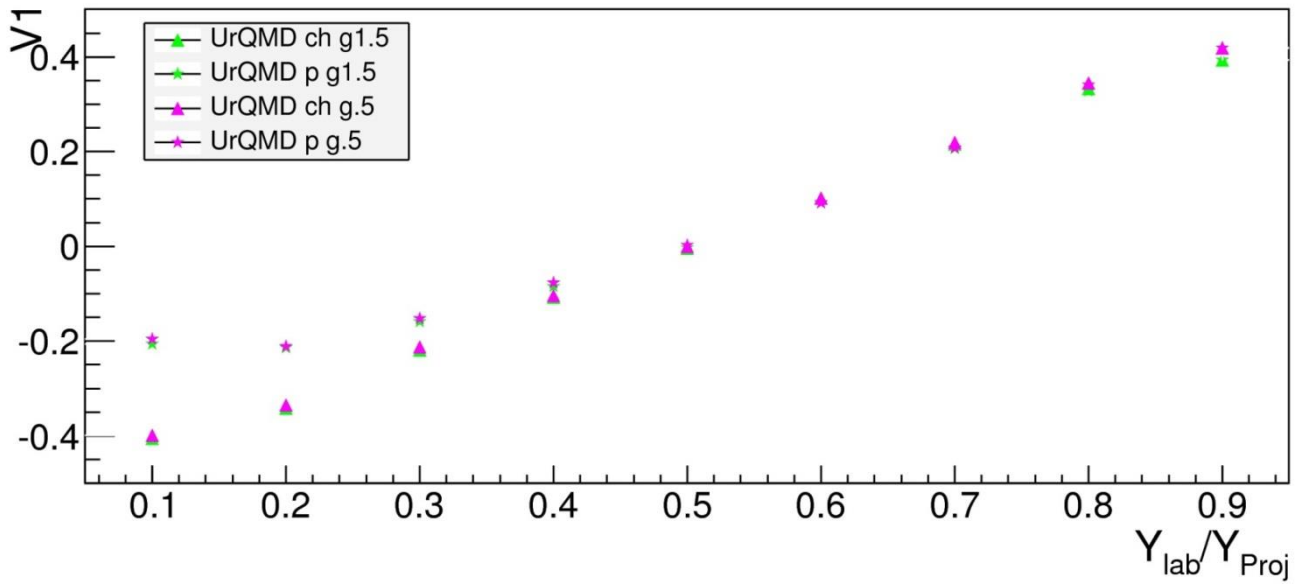
Th.Blaich et al.,NIM A314 (1992)

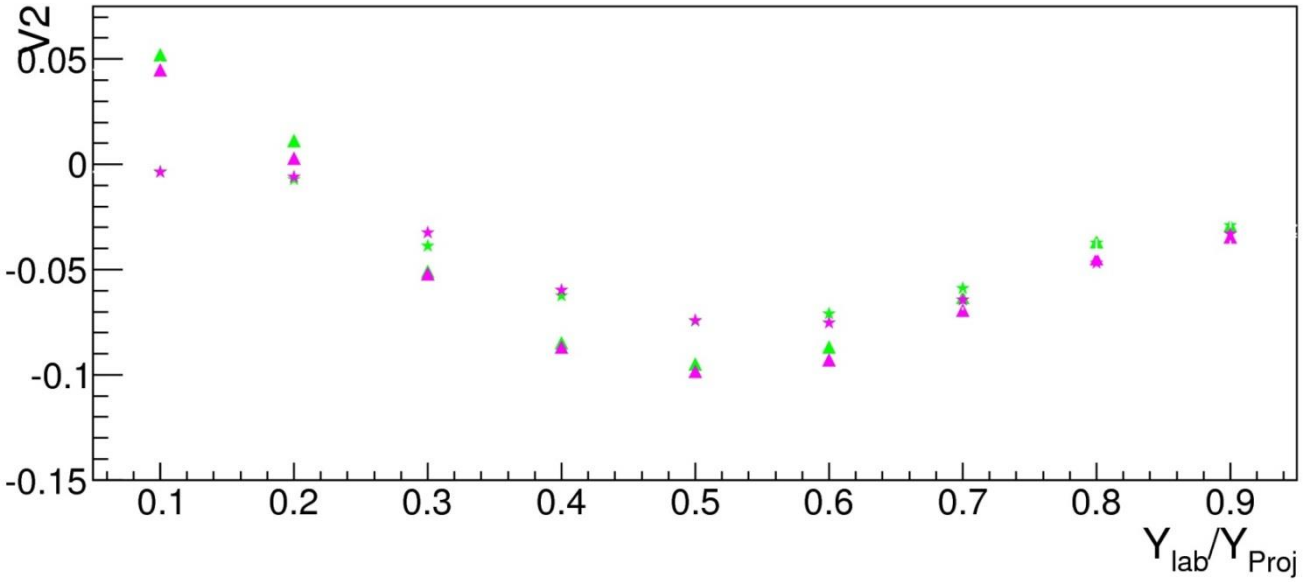
FROM EVO

URQMD 08/04/14


v1
UrQMD n g1.5
UrQMD n g.5
0.4
0.2
0
-0.2
-0.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Y_lab/Y_Proj


v2
0.05
0
-0.05
-0.1
-0.15
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Y_lab/Y_Proj

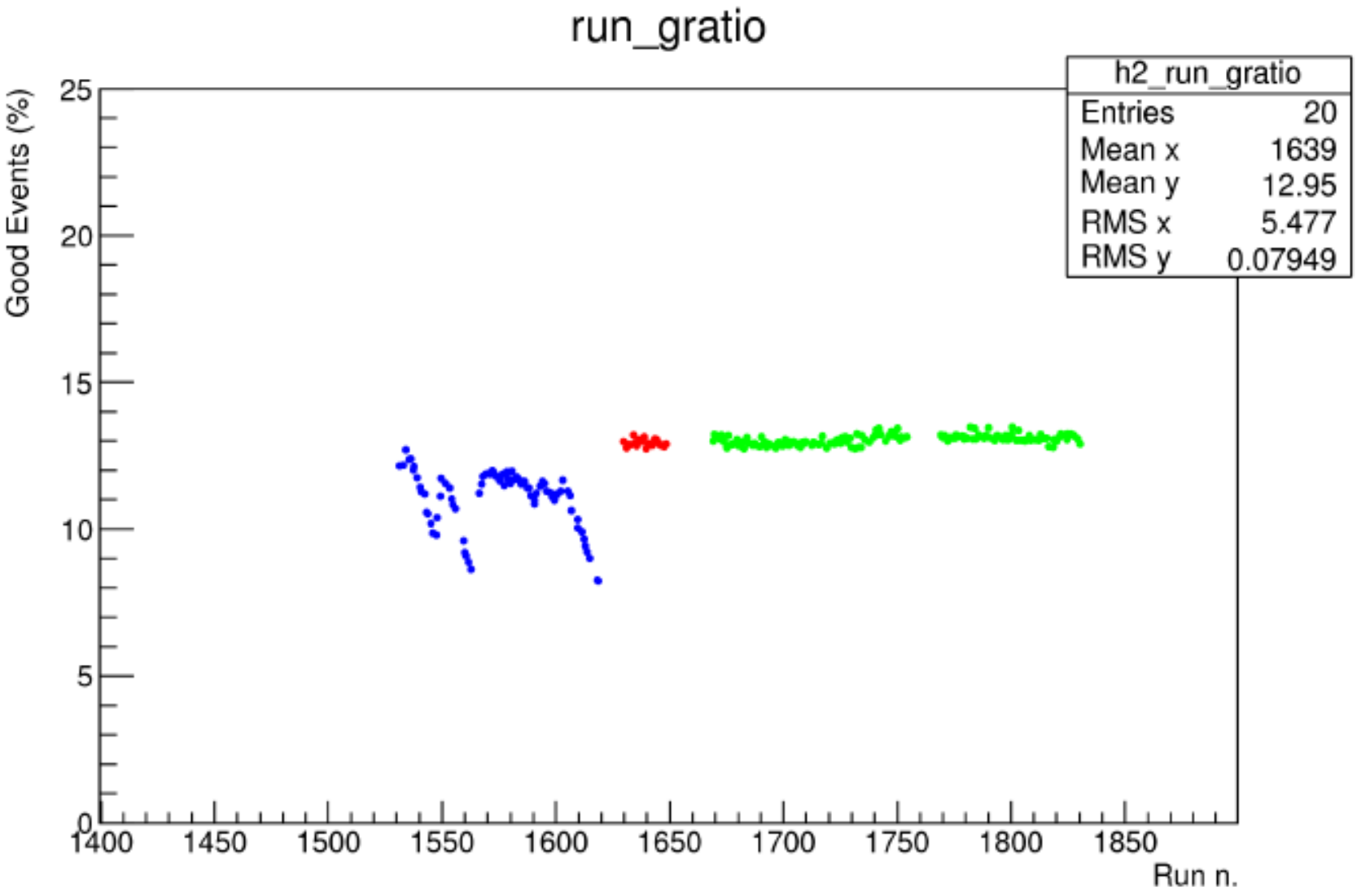

v1
UrQMD ch g1.5
UrQMD p g1.5
UrQMD ch g.5
UrQMD p g.5
0.4
0.2
0
-0.2
-0.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Y_lab/Y_Proj


v2
0.05
0
-0.05
-0.1
-0.15
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Y_lab/Y_Proj

FROM EVO

GOOD EVENTS

26/03/14

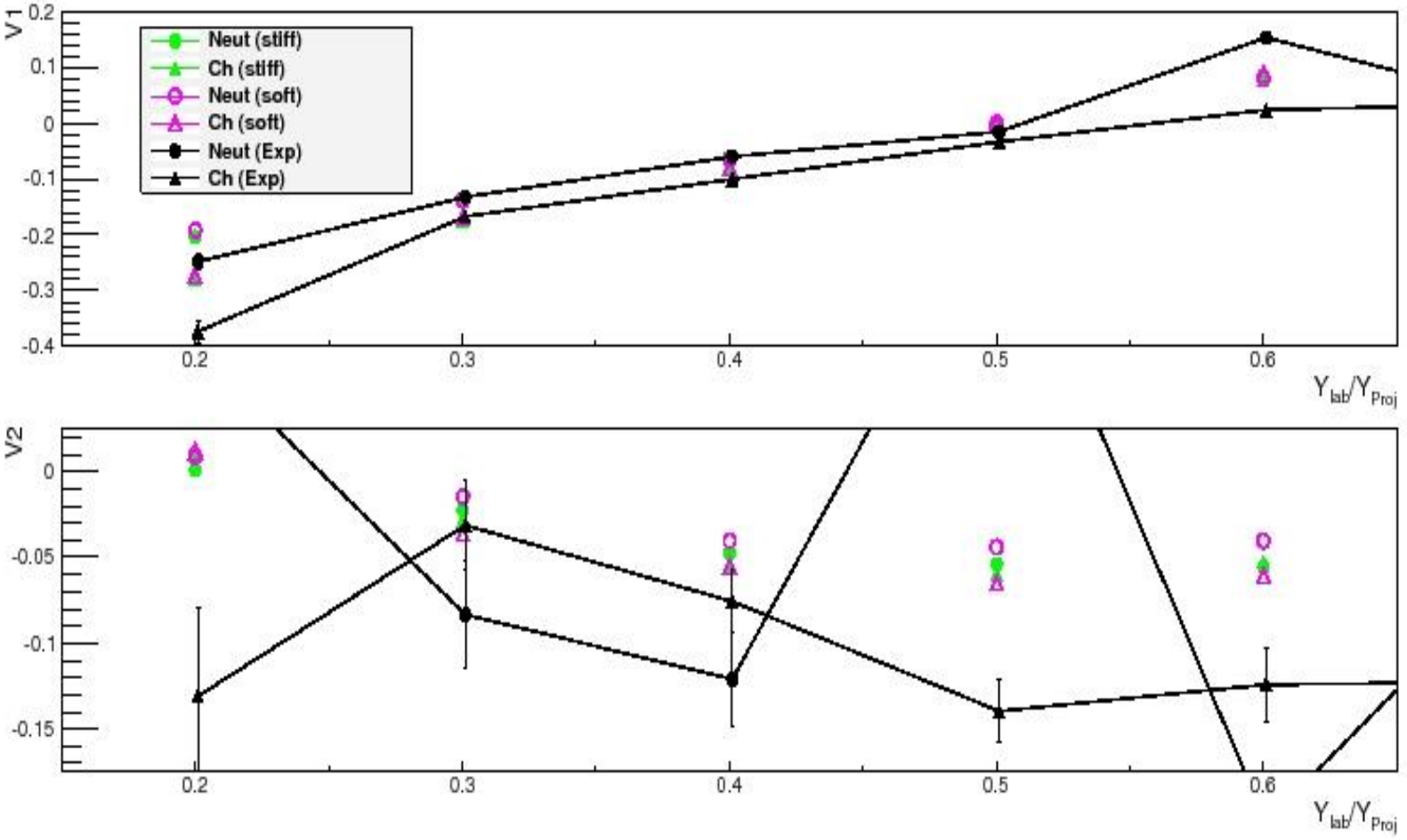

run_gratio
h2_run_gratio
Entries 20
Mean x 1639
Mean y 12.95
RMS x 5.477
RMS y 0.07949
Good Events (%)
25
20
15
10
5
0
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
Run n.

FROM EVO

Zr Ru

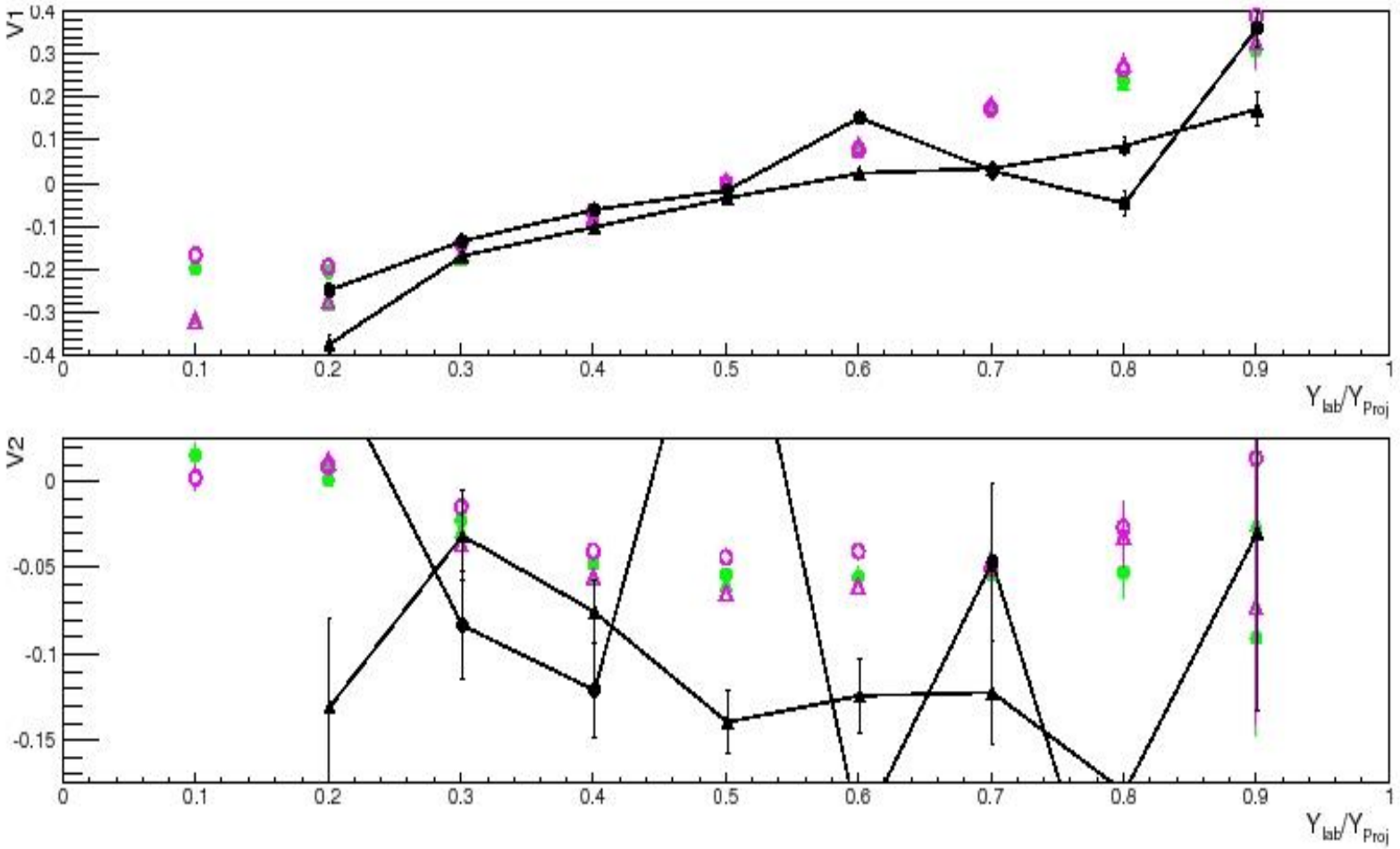
26/02/14

Zr+Zr-(SB+Zr+H3B03)

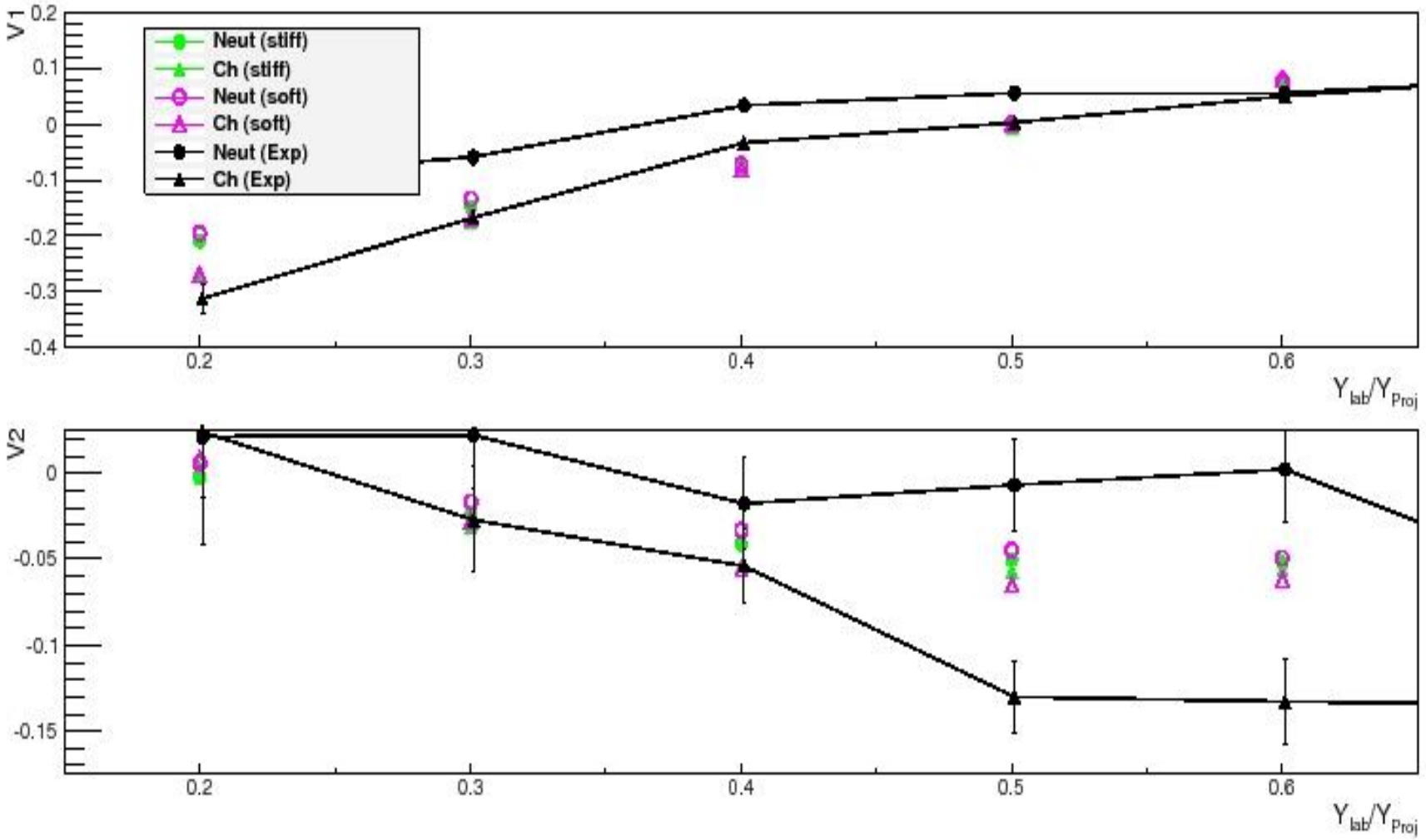


proNeut200_706_cf10_cc_w5.9_0.85_vv1.dat_proChgd2000_706_cf10_cc_w5.9_0.85_vv1.dat_FP1_chww__flows.jpg

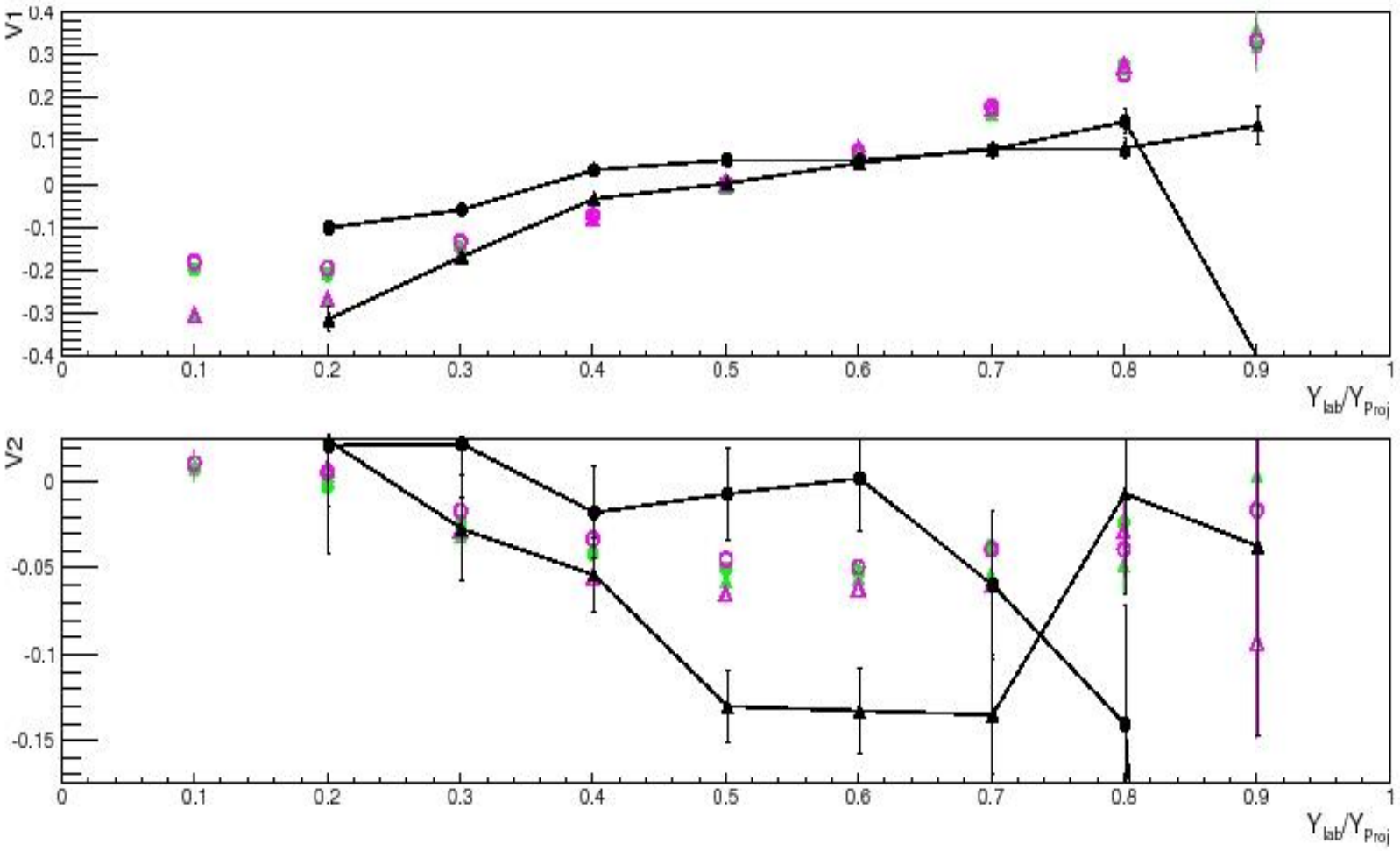
Zr+Zr-(SB+Zr+H3B03)

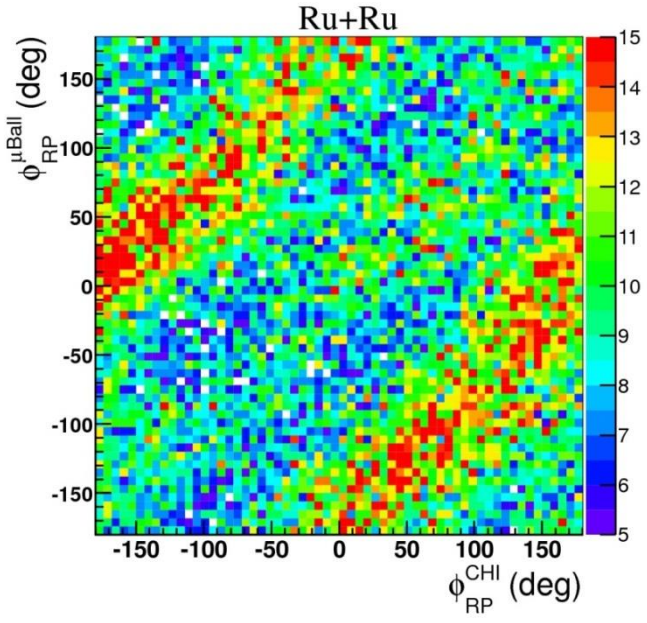


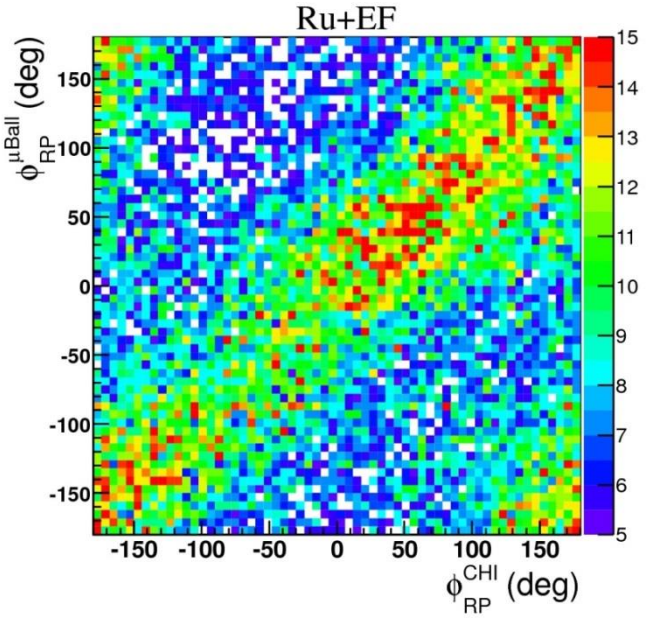
Ru+Ru-(SB)

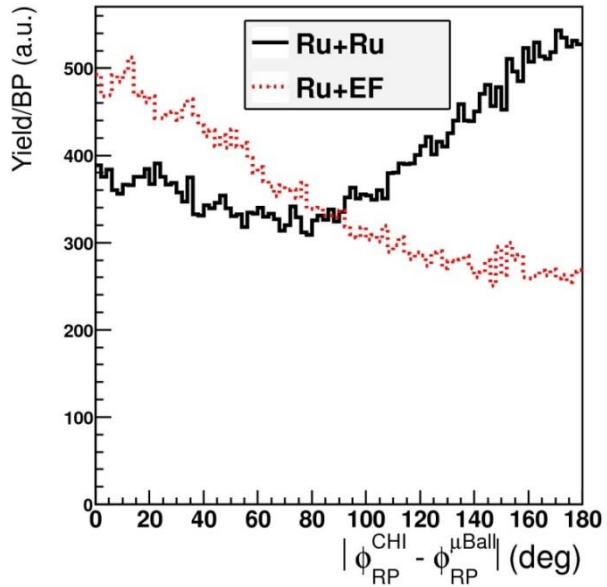

V1
Neut (stiff)
Ch (stiff)
Neut (soft)
Ch (soft)
Neut (Exp)
Ch (Exp)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0.2
0.3
0.4
0.5
0.6
Y_lab/Y_Proj
V2
0
-0.05
-0.1
-0.15
0.2
0.3
0.4
0.5
0.6
Y_lab/Y_Proj

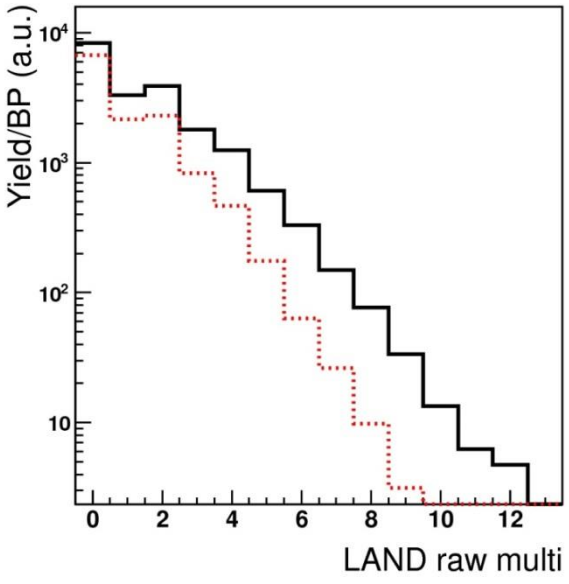
Ru+Ru-(SB)

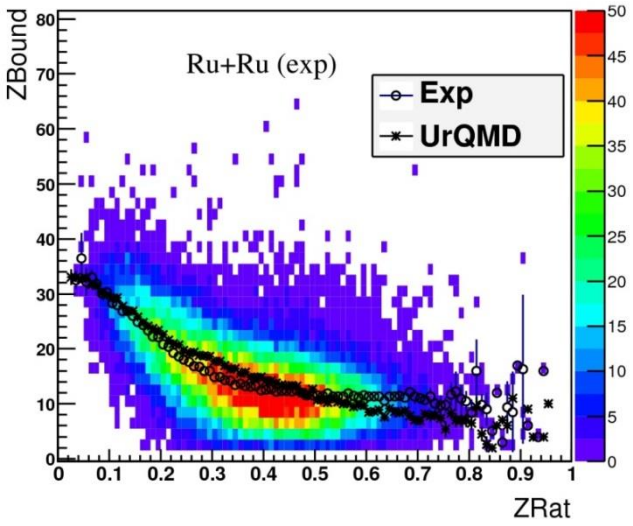

V1
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Y_{lab}/Y_{Proj}
V2
0
-0.05
-0.1
-0.15
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Y_{lab}/Y_{Proj}

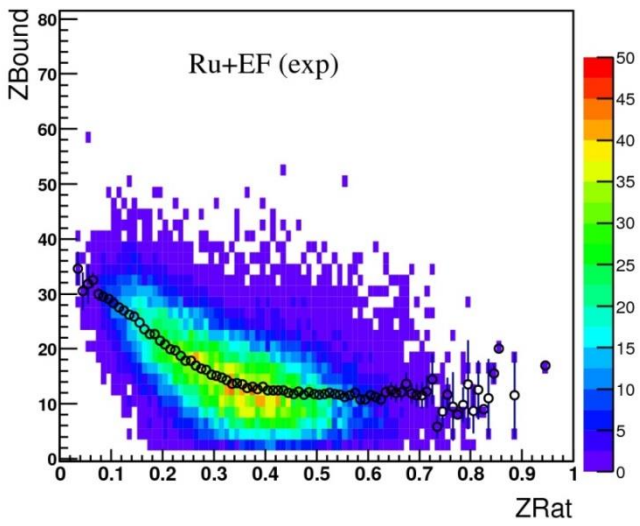

Ru+Ru
$\phi_{RP}^{\mu Ball}$ (deg)
ϕ_{RP}^{CHI} (deg)

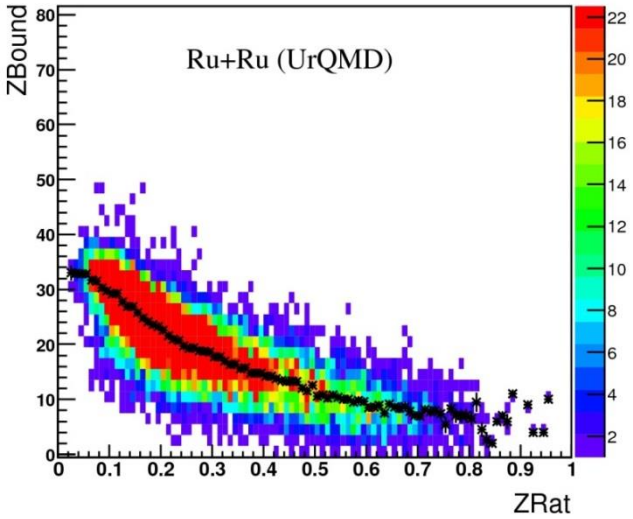

Ru+EF
$\phi_{RP}^{\mu Ball}$ (deg)
ϕ_{RP}^{CHI} (deg)

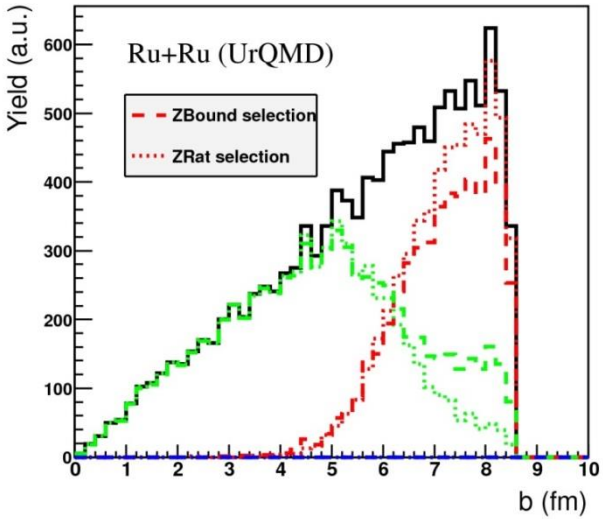

Ru+Ru
Ru+EF
Yield/BP (a.u.)
$|\phi_{RP}^{CHI} - \phi_{RP}^{\mu Ball}|$ (deg)


Yield/BP (a.u.)
LAND raw multi


Ru+Ru (exp)
Exp
UrQMD
ZBound
ZRat


Ru+EF (exp)
ZBound
ZRat

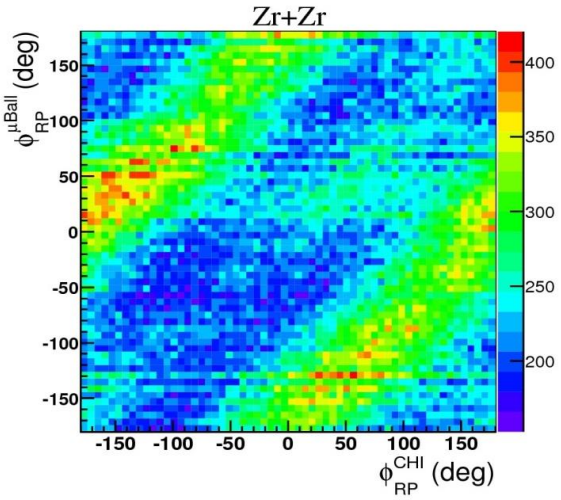

Ru+Ru (UrQMD)
ZBound
ZRat

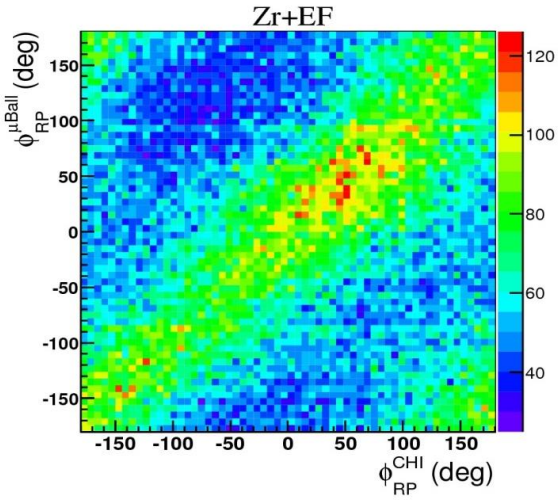

Ru+Ru (UrQMD)
ZBound selection
ZRat selection
Yield (a.u.)
b (fm)

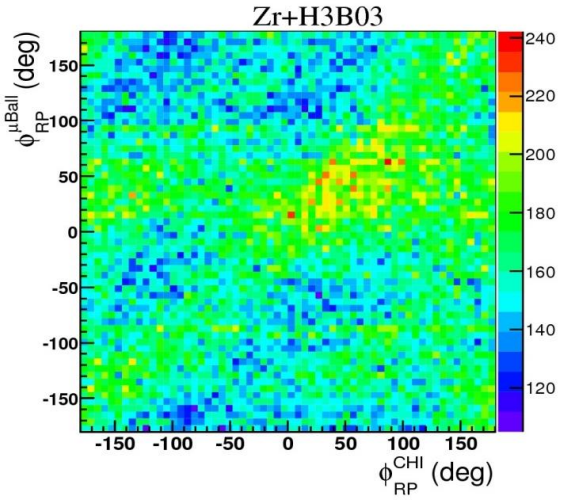
FROM FM

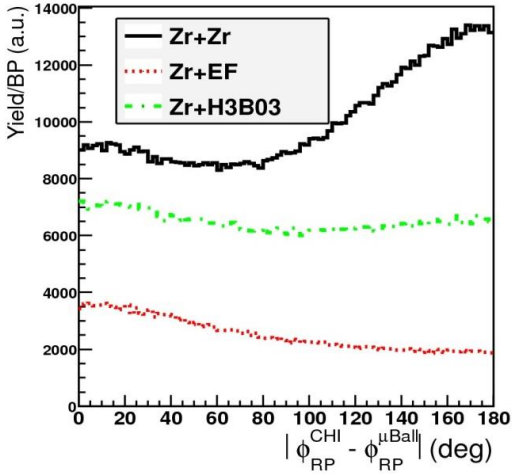
Zr

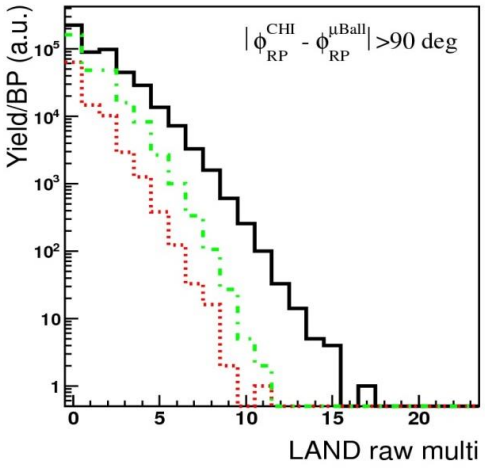
18/12/13

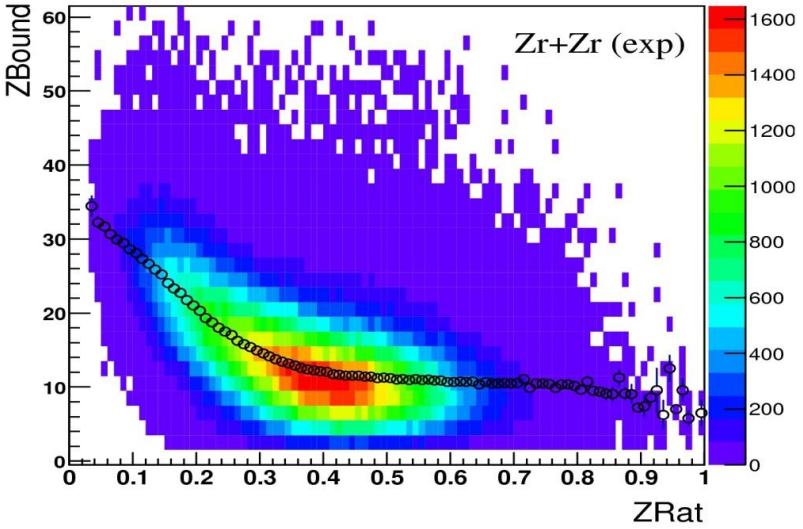

Zr+Zr
$\phi^{\mu Ball}_{RP}$ (deg)
ϕ^{CHI}_{RP} (deg)

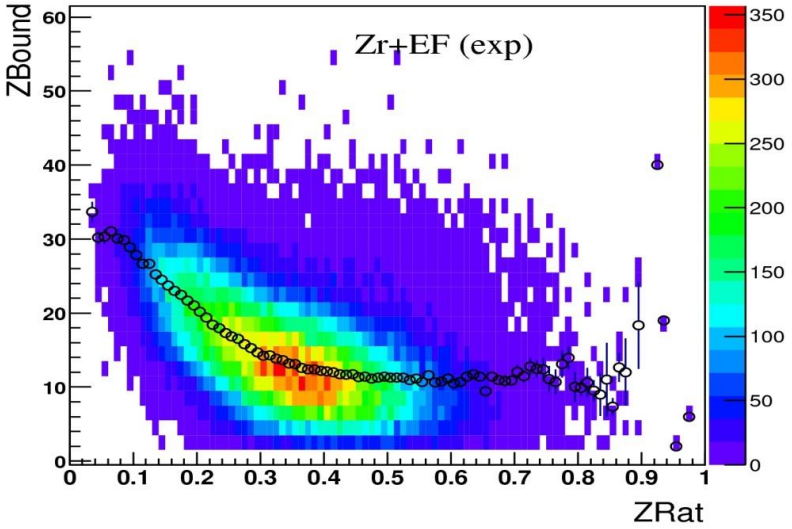

Zr+EF
$\phi^{\mu Ball}_{RP}$ (deg)
ϕ^{CHI}_{RP} (deg)

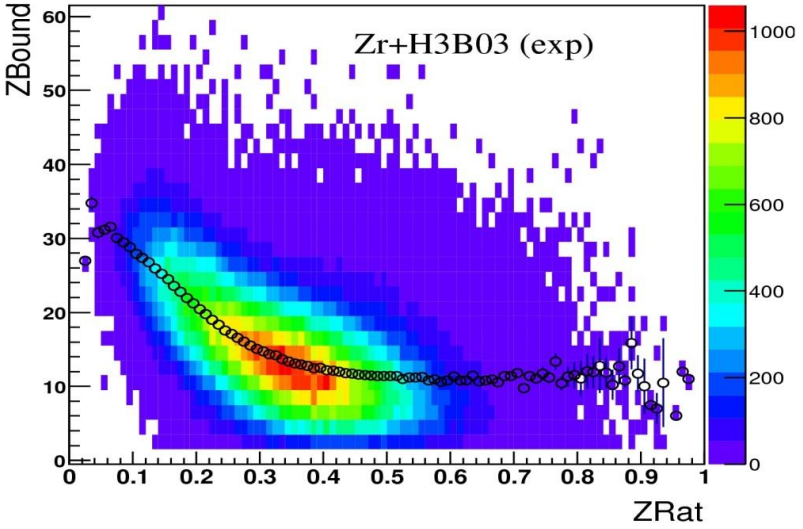

Zr+H3B03
$\phi^{\mu Ball}_{RP}$ (deg)
ϕ^{CHI}_{RP} (deg)


Zr+Zr
Zr+EF
Zr+H3B03
Yield/BP (a.u.)
$|\phi^{CHI}_{RP} - \phi^{\mu Ball}_{RP}|$ (deg)


$|\phi^{CHI}_{RP} - \phi^{\mu Ball}_{RP}|$ >90 deg
Yield/BP (a.u.)
LAND raw multi


Zr+Zr (exp)
ZBound
ZRat
0
10
20
30
40
50
60
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
400
600
800
1000
1200
1400
1600

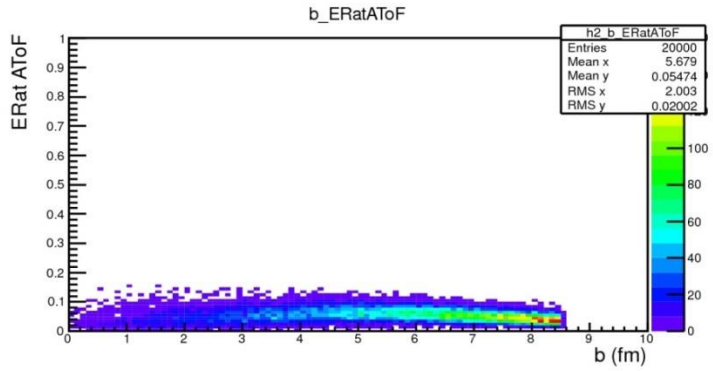

Zr+EF (exp)
ZBound
ZRat
0
10
20
30
40
50
60
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
50
100
150
200
250
300
350

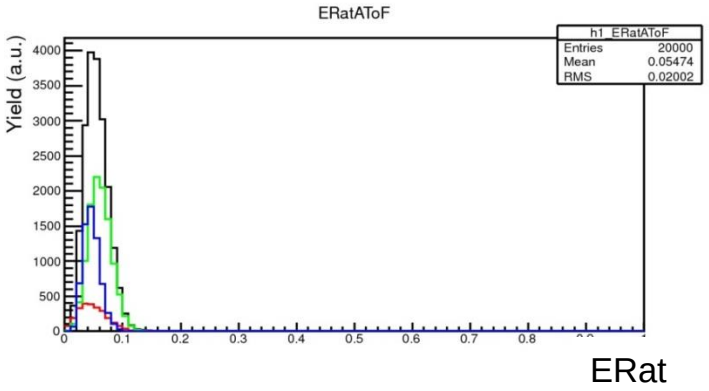

Zr+H3B03 (exp)
ZBound
ZRat
0
10
20
30
40
50
60
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
400
600
800
1000

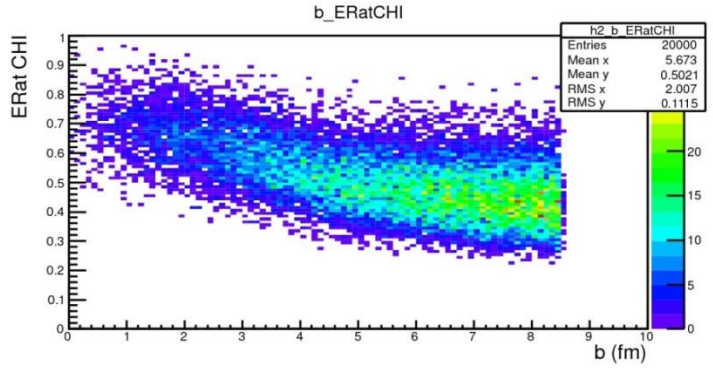
FROM EVO

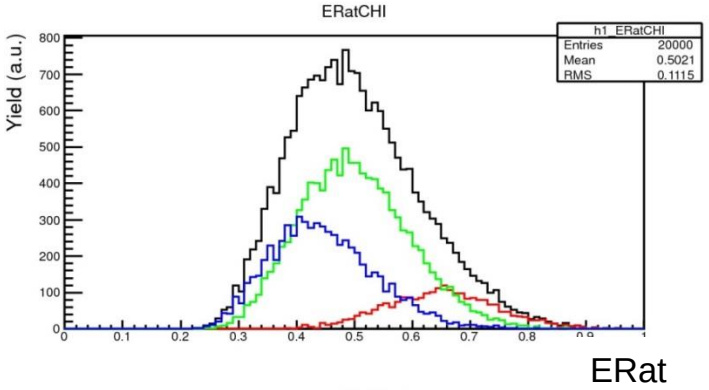
b sel

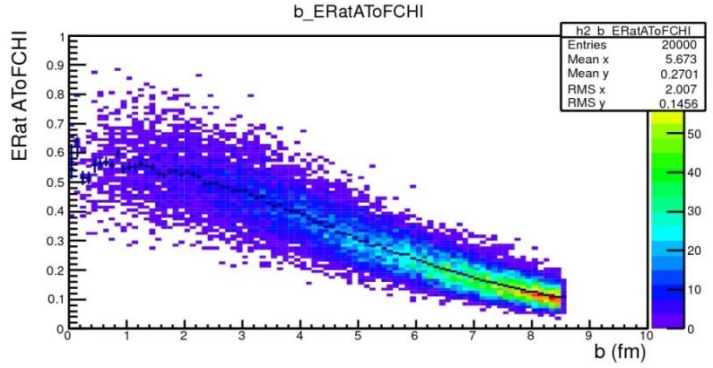
23/10/13

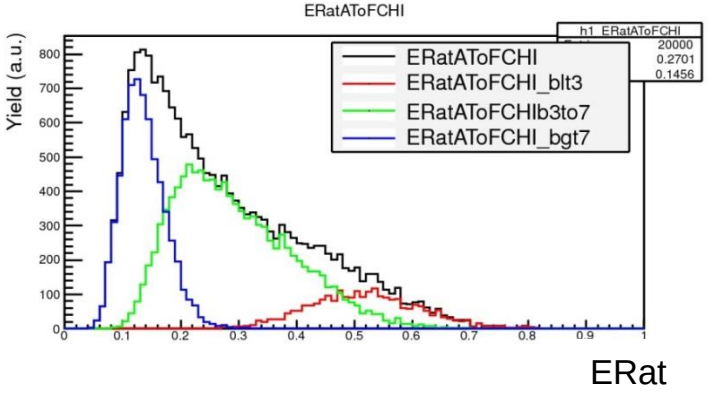












Au+Au 400 AMeV b<8.5 fm

UrQMD simulated

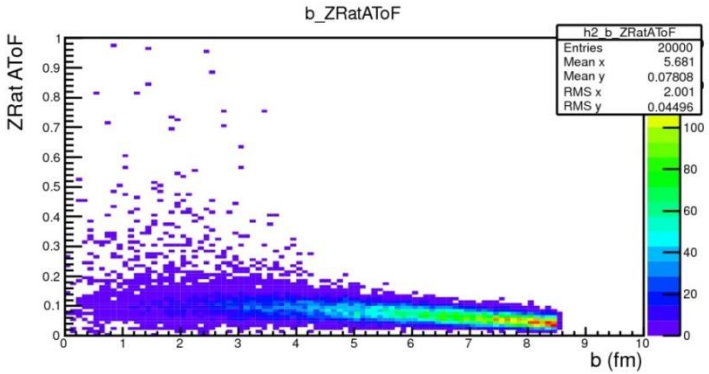
b <3 fm

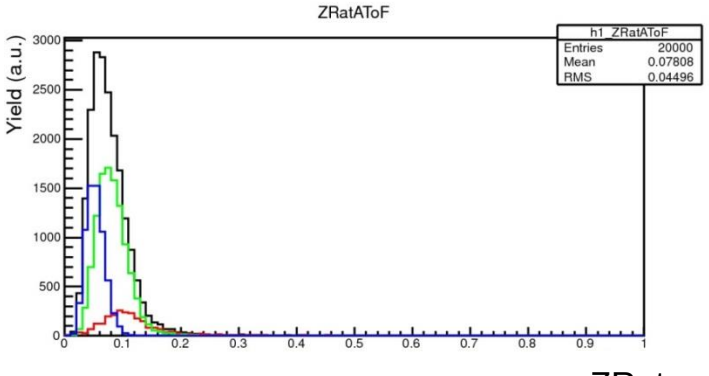
3<b<7 fm

7<b<8.5 fm

$$ERat = \frac{\sum_i E_i^{Kin} \sin^2 \theta_i}{\sum_i E_i^{Kin} \cos^2 \theta_i}$$

c_ERat.jp



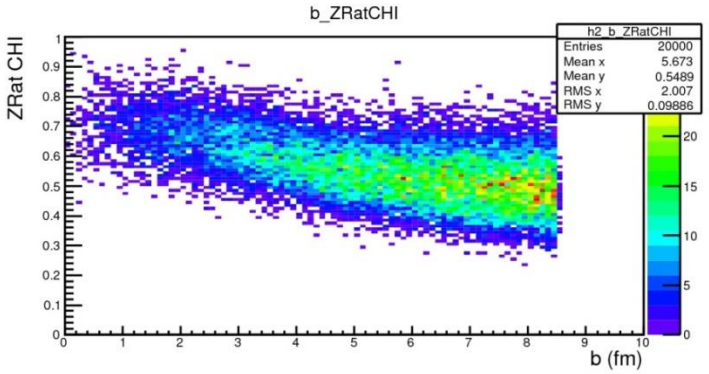


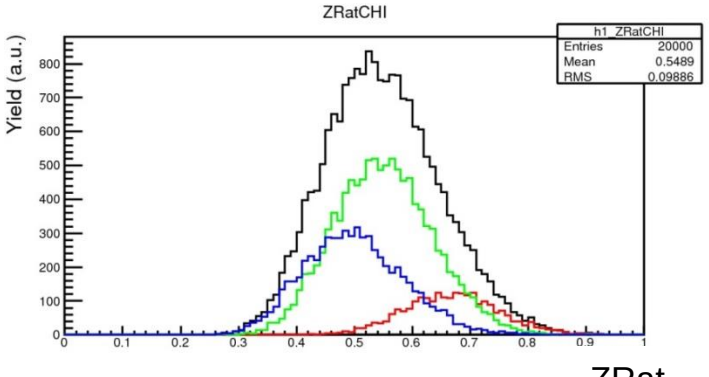
b <3 fm

3<b<7 fm

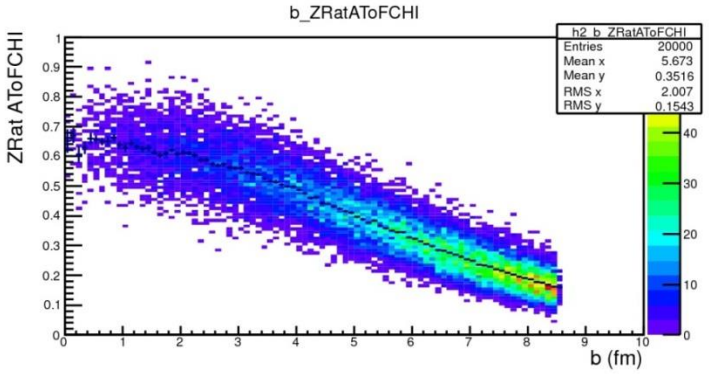
7<b<8.5 fm

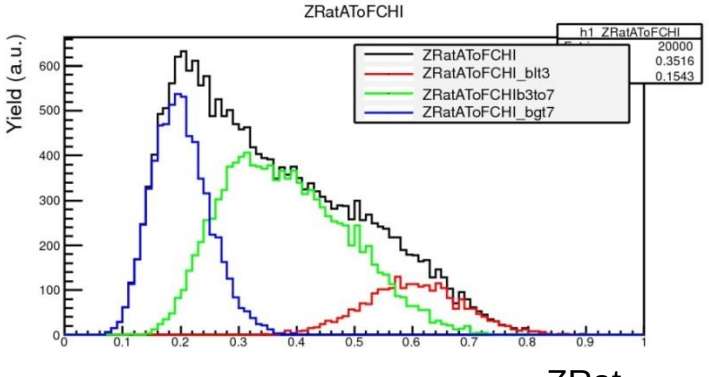
ZRat





ZRat

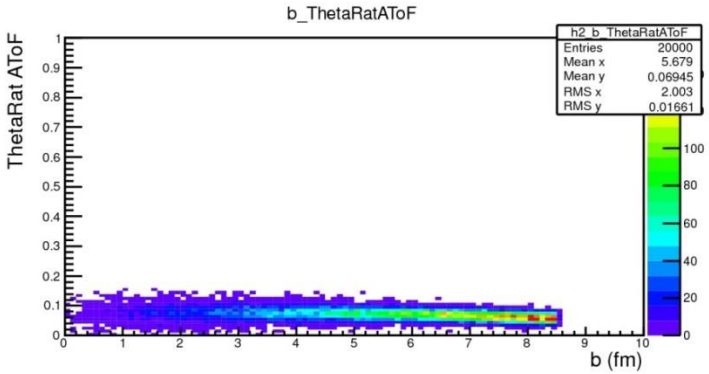


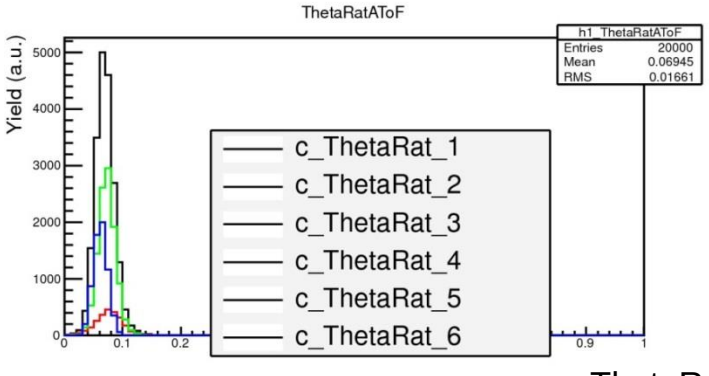


ZRat

$$ZRat = \frac{\sum_i Z_i \sin^2 \theta_i}{\sum_i Z_i \cos^2 \theta_i}$$

c_ZRat.jp



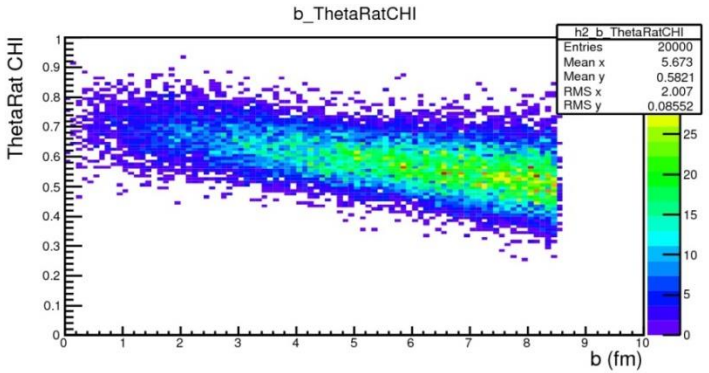


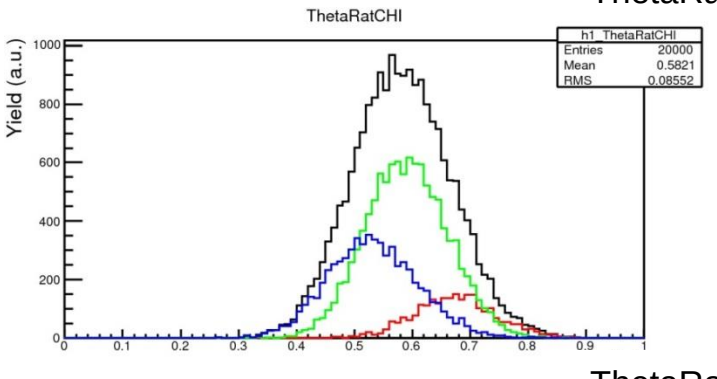
ThetaRat

b <3 fm

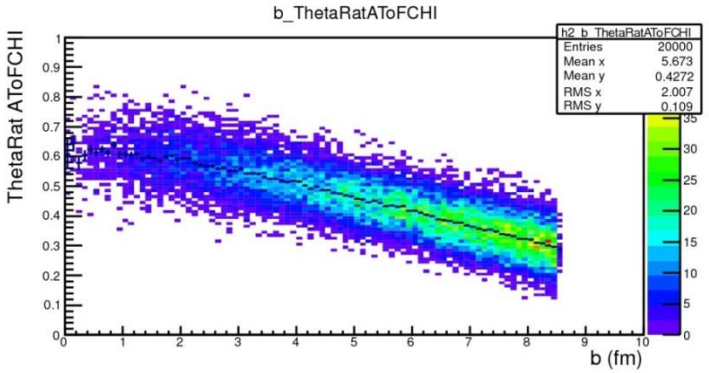
3<b<7 fm

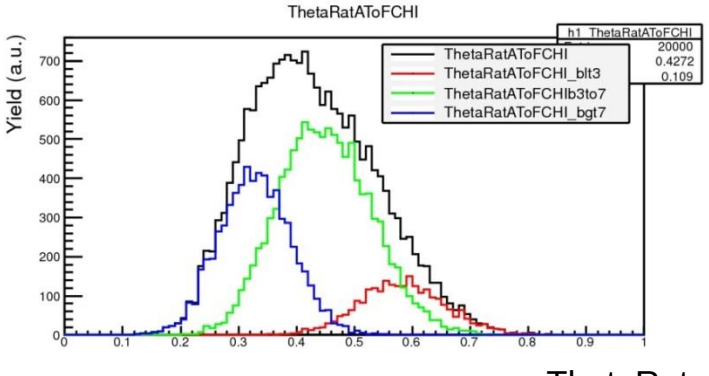
7<b<8.5 fm





ThetaRat

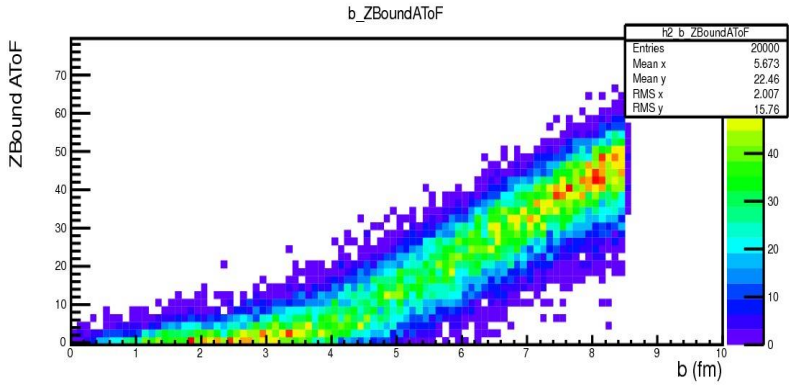


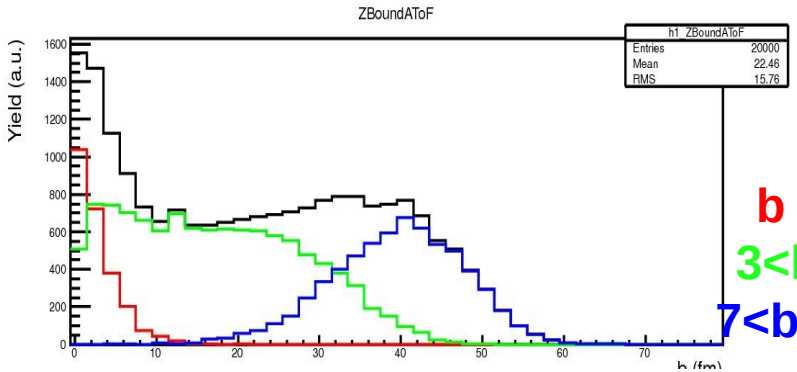


ThetaRat

$$ThetaRat = \frac{\sum_i \sin^2 \square_i \square}{\sum_i \cos^2 \square_i \square}$$

c_ThetaRat.j



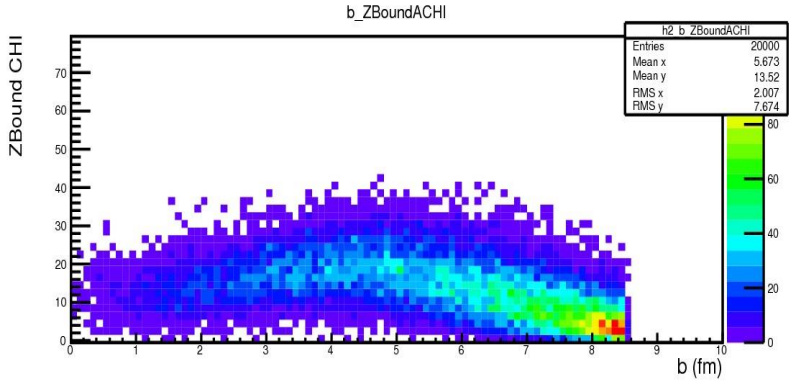


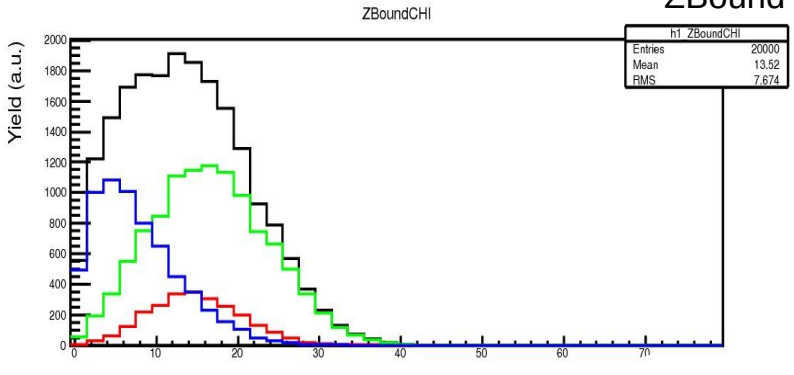
b <3 fm

3<b<7 fm

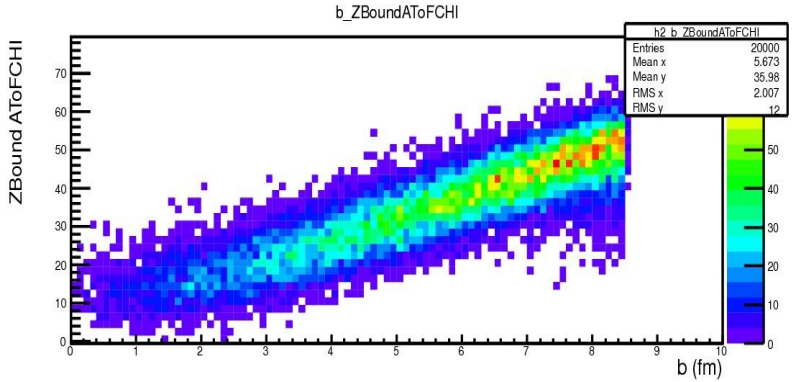
7<b<8.5 fm

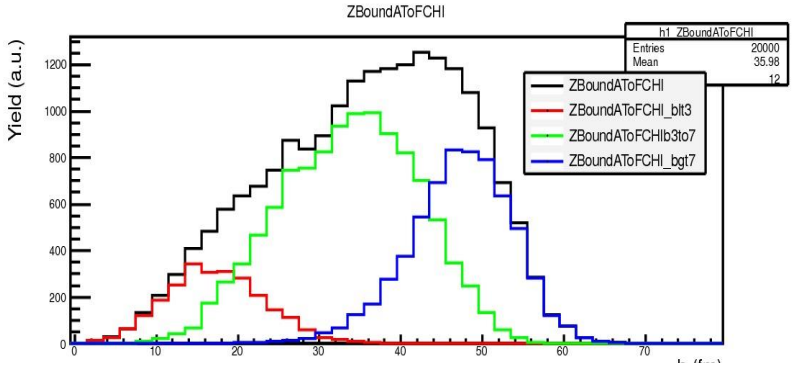
ZBound





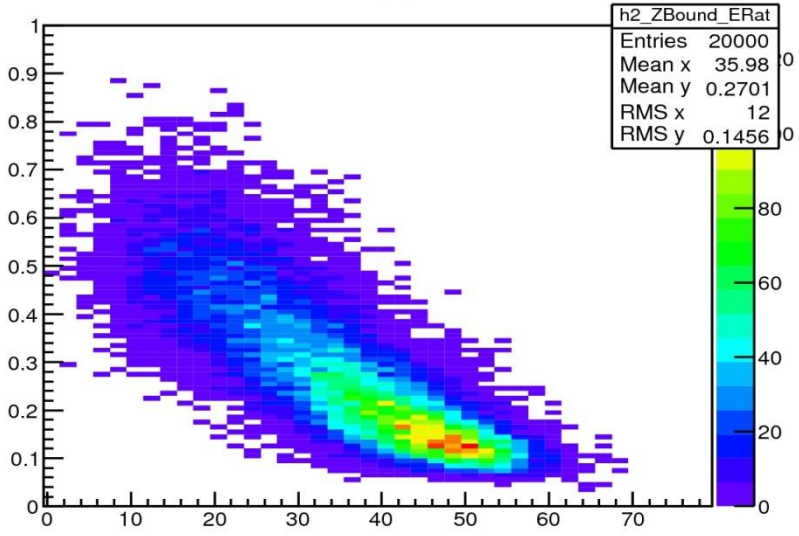
ZBound



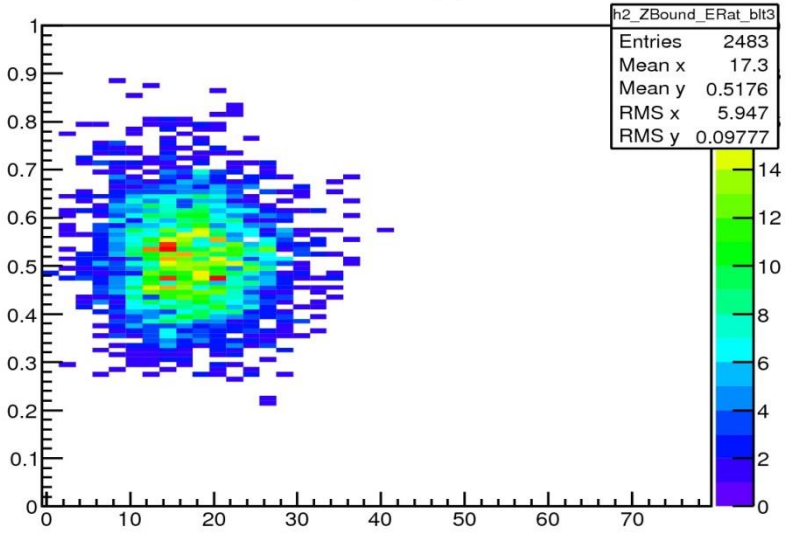


ZBound

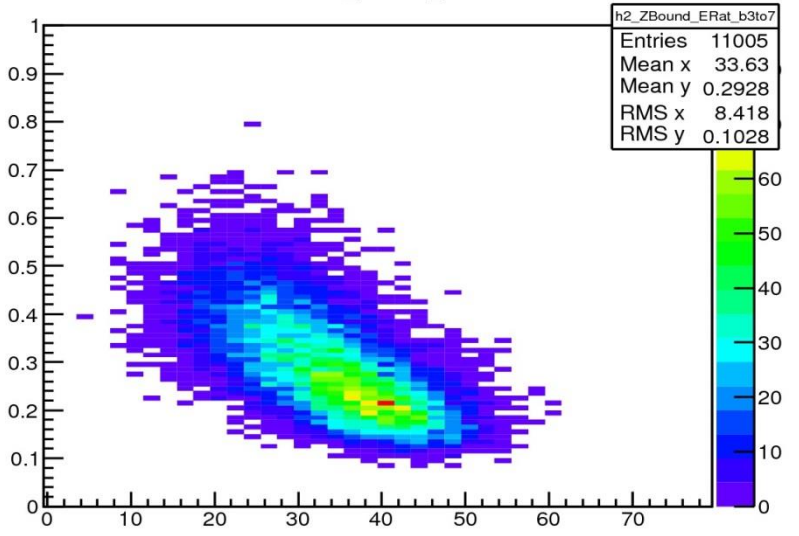
ZBound_ERat



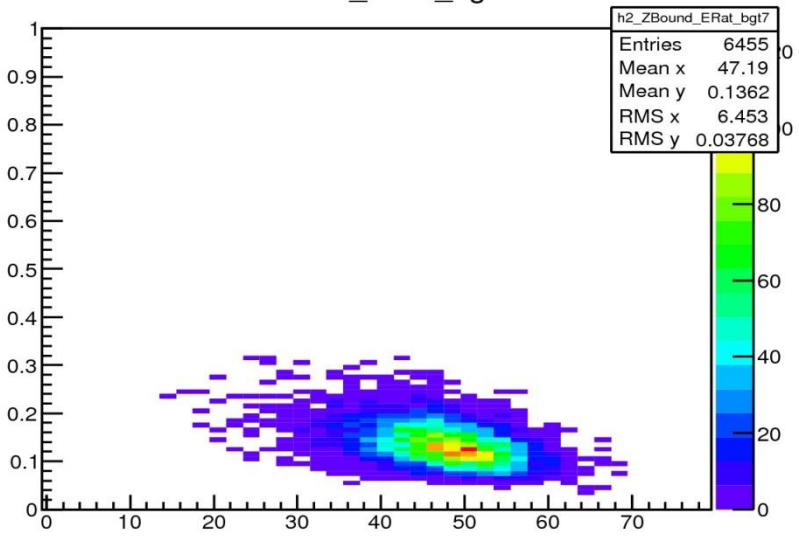
ZBound_ERat_blt3



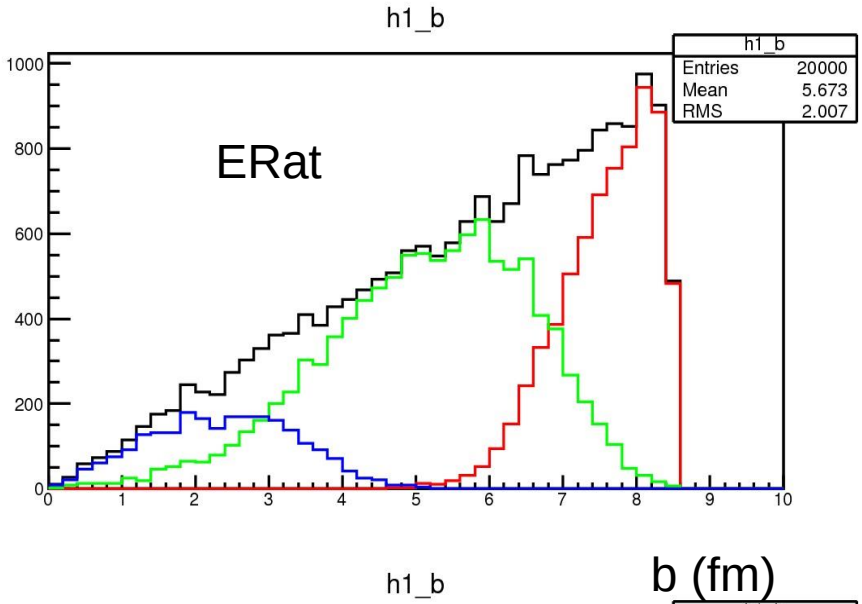
ZBound_ERat_b3to7

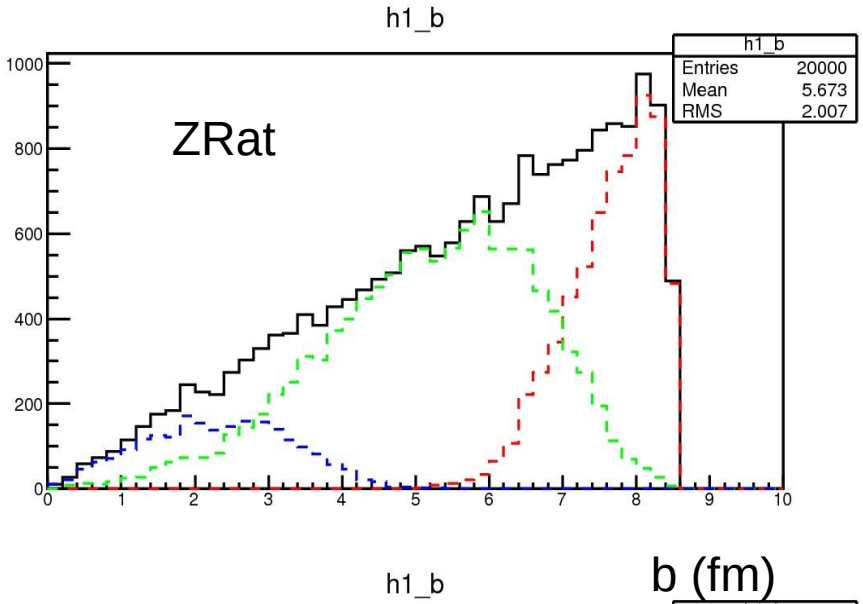


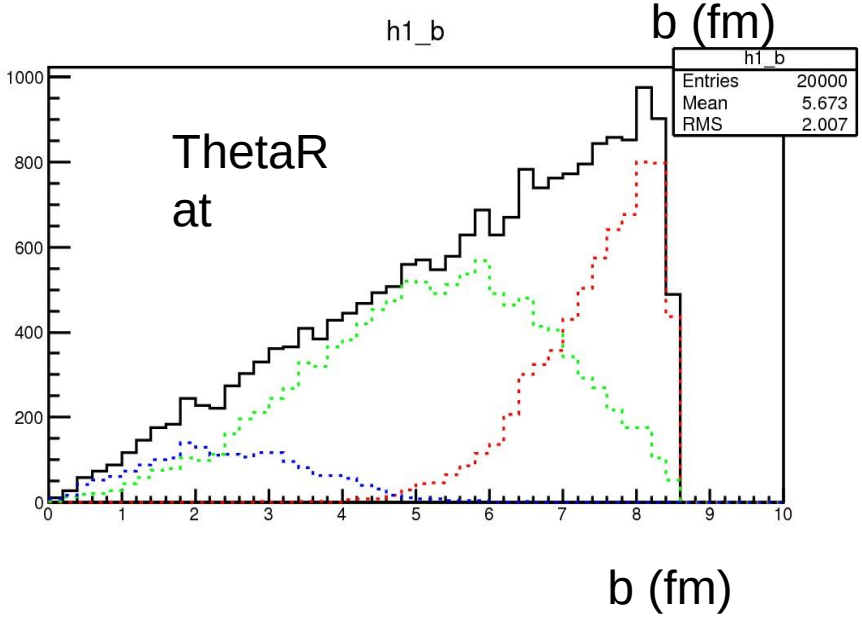
ZBound_ERat_bgt7

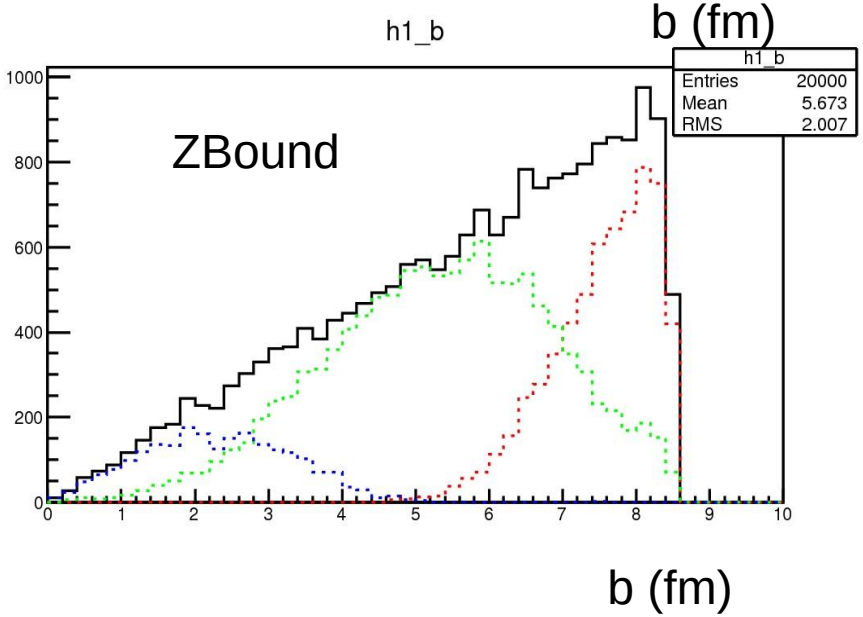


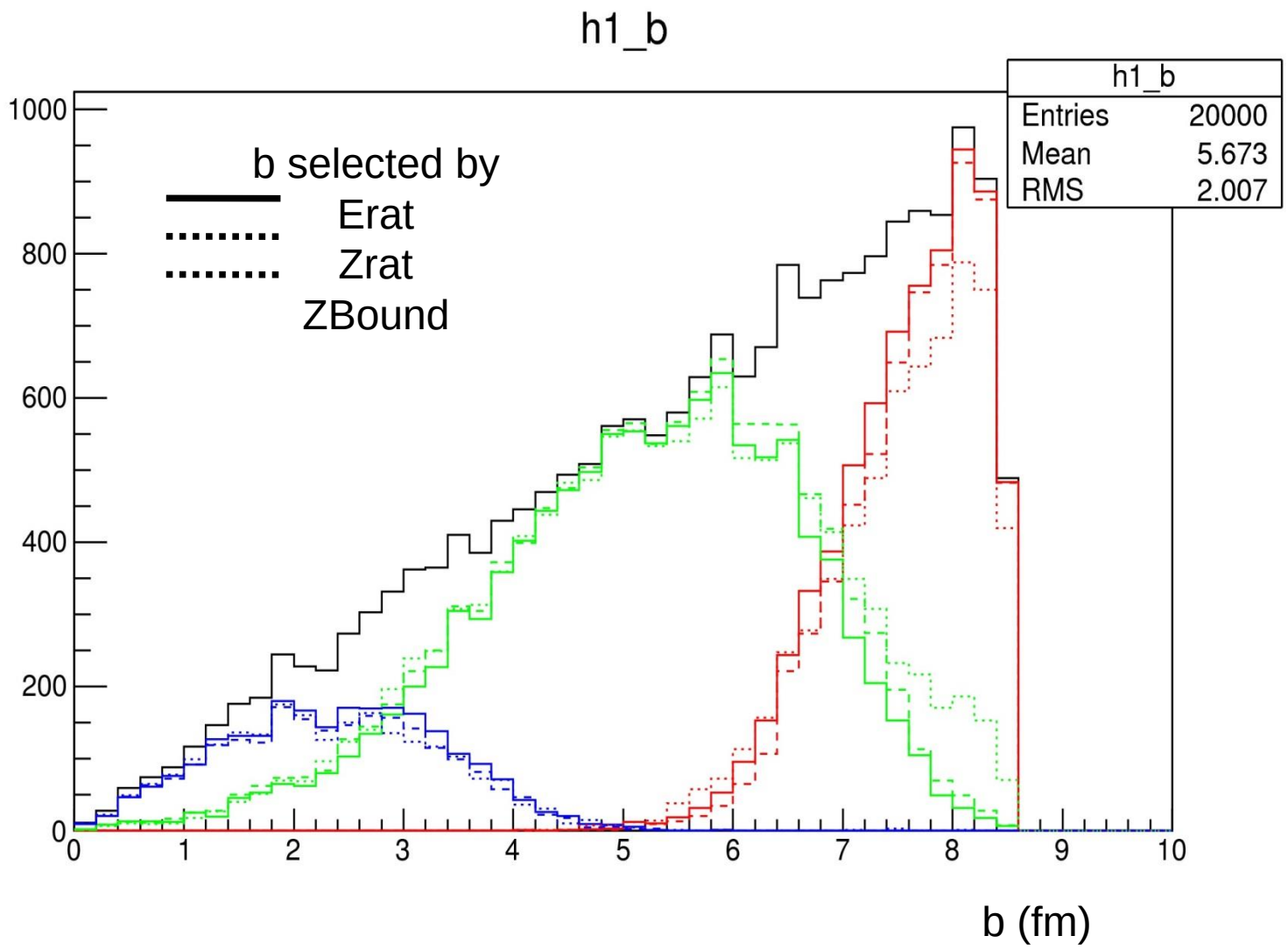
b selected by



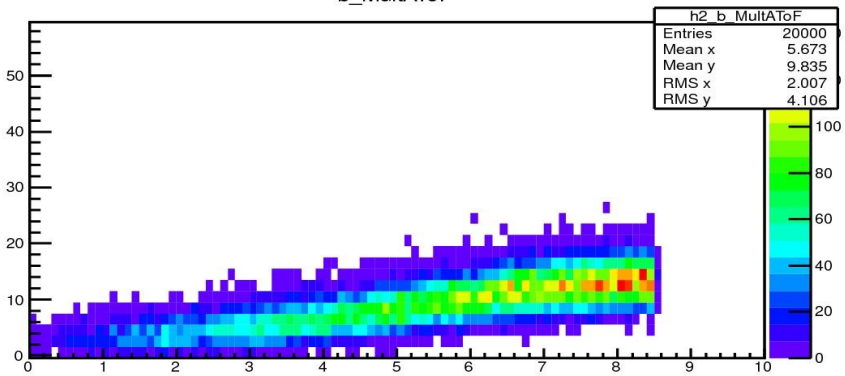




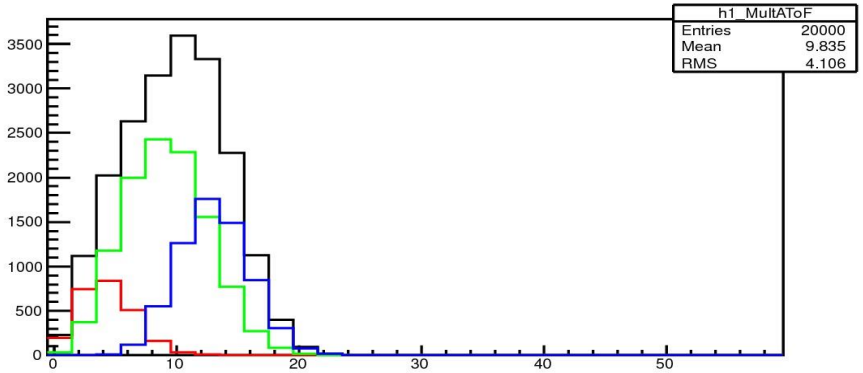



h1_b
h1_b
Entries 20000
Mean 5.673
RMS 2.007
b selected by
Erat
Zrat
ZBound
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
b (fm)

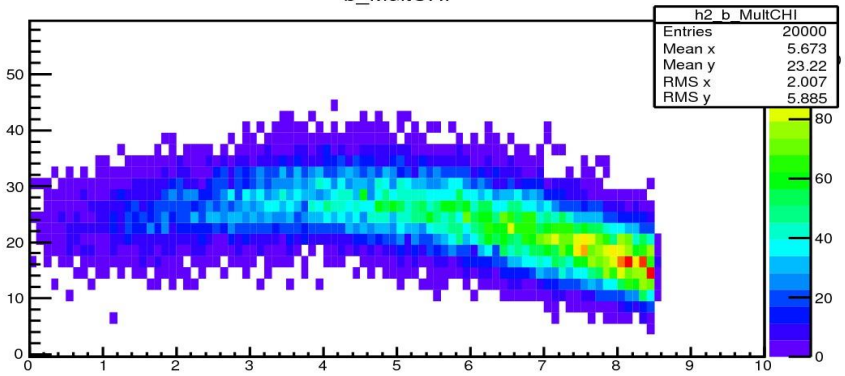
b_MultAToF



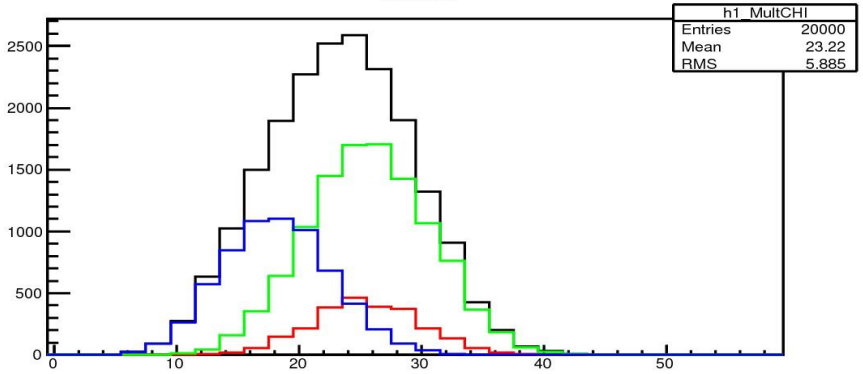
MultAToF



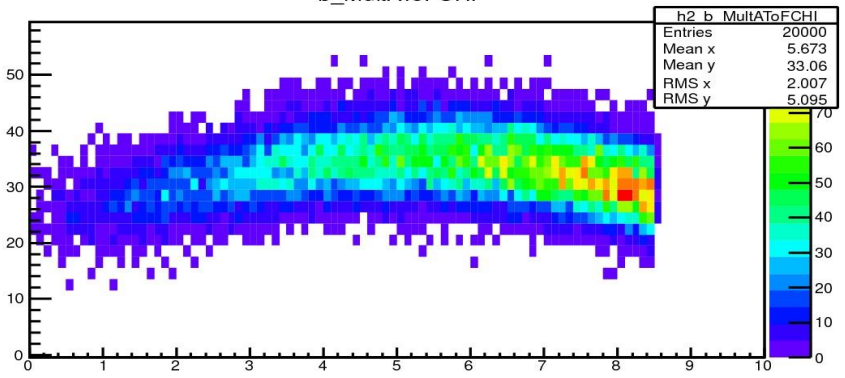
b_MultCHI



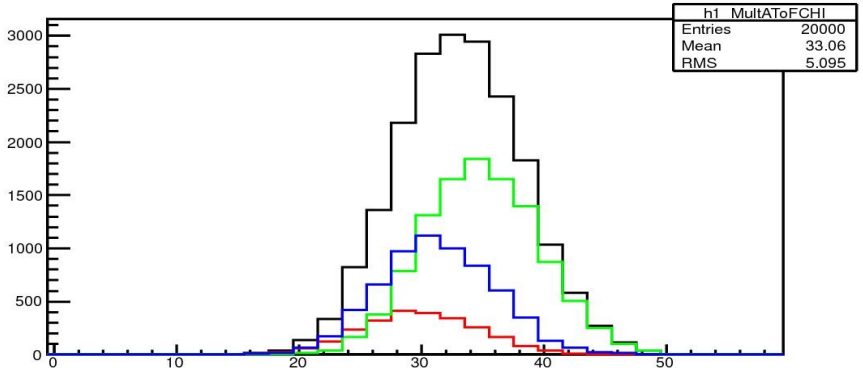
MultCHI

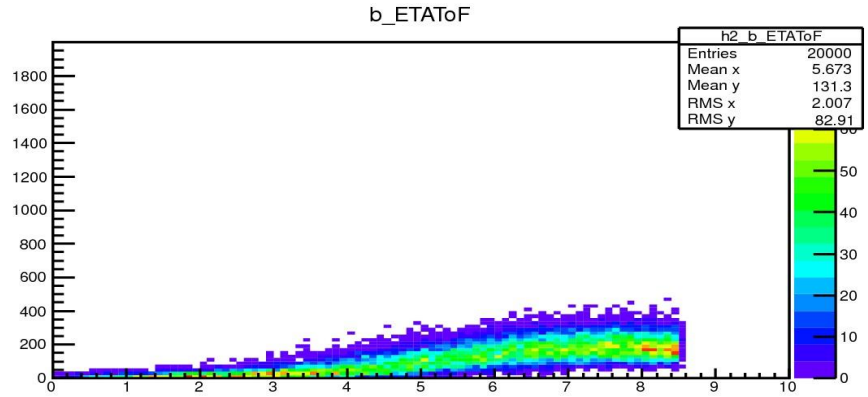


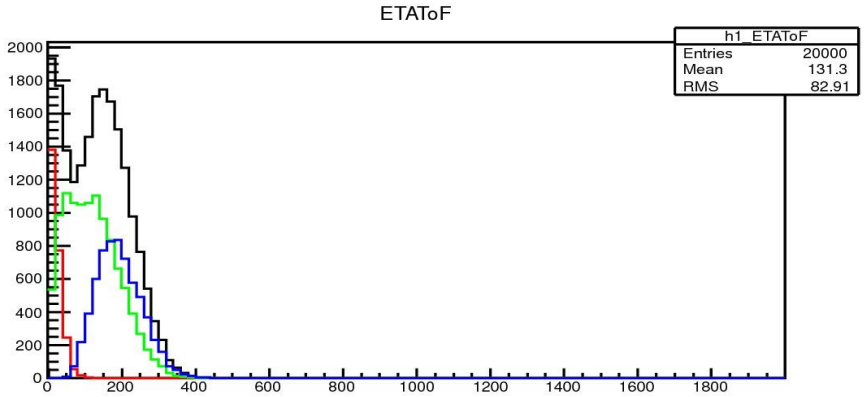
b_MultAToFCHI

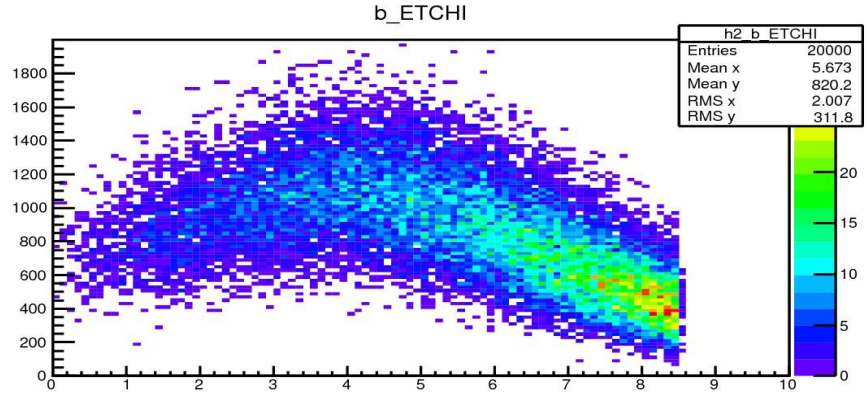


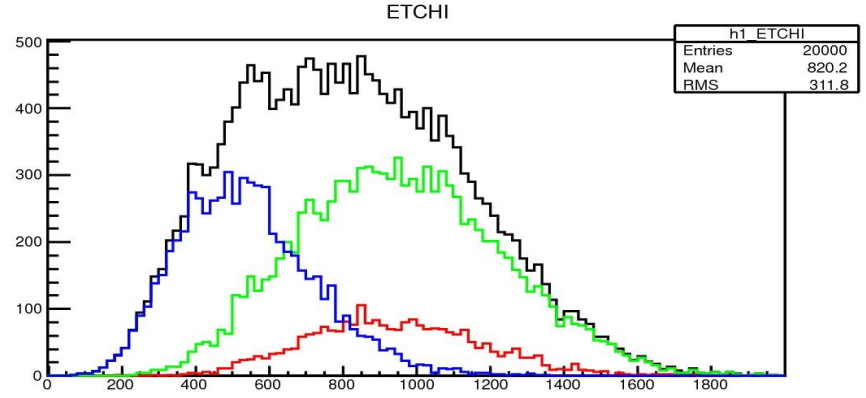
MultAToFCHI

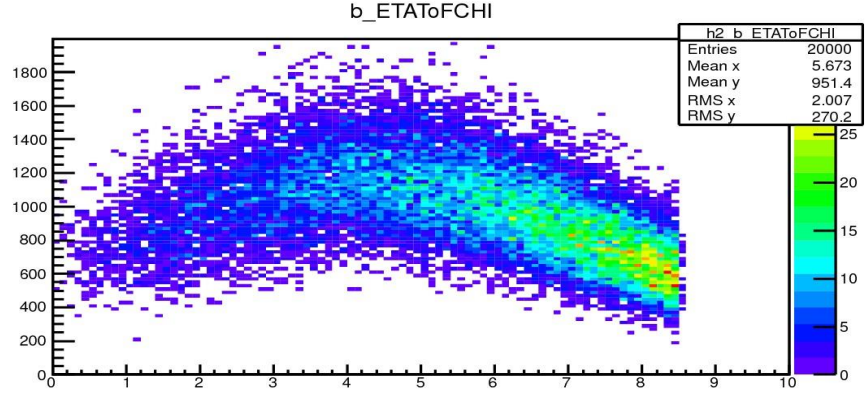


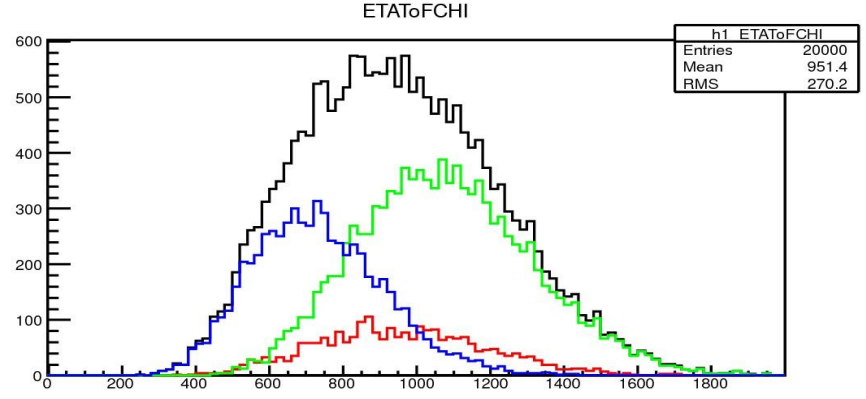

b_ETAToF
h2_b_ETAToF
Entries 20000
Mean x 5.673
Mean y 131.3
RMS x 2.007
RMS y 82.91


ETAToF
h1_ETAToF
Entries 20000
Mean 131.3
RMS 82.91

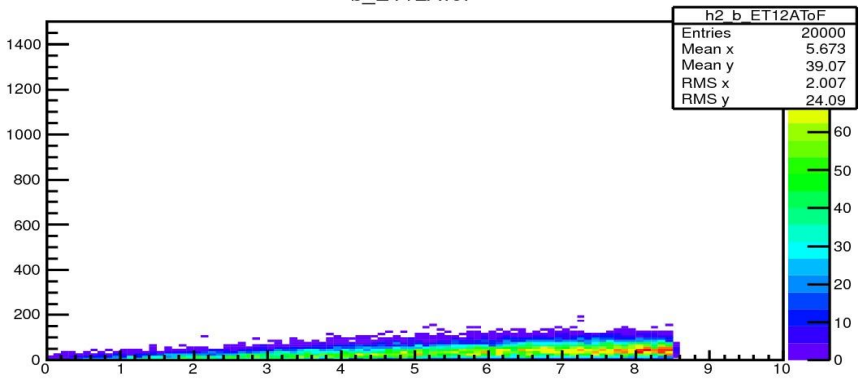

b_ETCHI
h2_b_ETCHI
Entries 20000
Mean x 5.673
Mean y 820.2
RMS x 2.007
RMS y 311.8


ETCHI
h1_ETCHI
Entries 20000
Mean 820.2
RMS 311.8

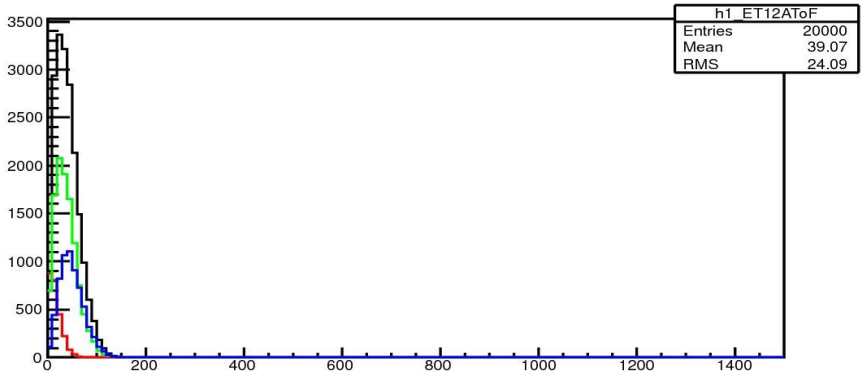

b_ETAToFCHI
h2_b_ETAToFCHI
Entries 20000
Mean x 5.673
Mean y 951.4
RMS x 2.007
RMS y 270.2


ETAToFCHI
h1_ETAToFCHI
Entries 20000
Mean 951.4
RMS 270.2

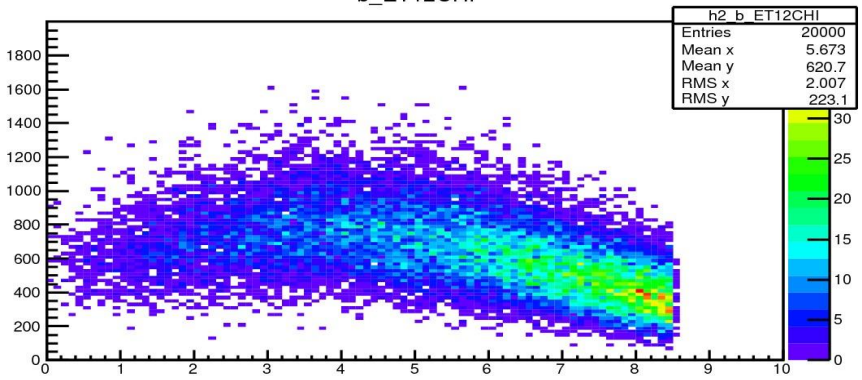
b_ET12AToF



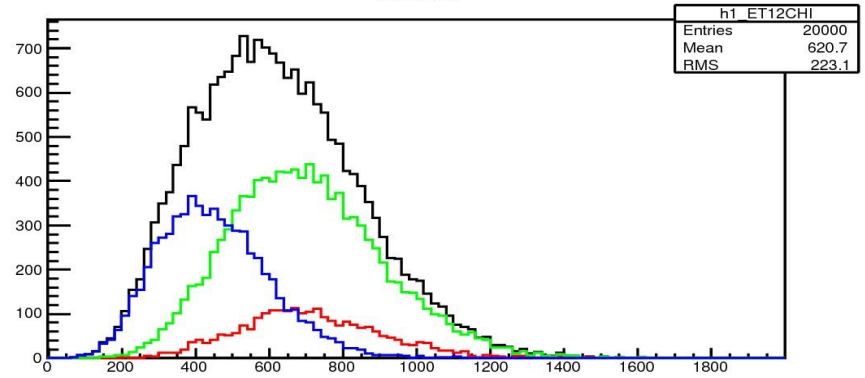
ET12AToF



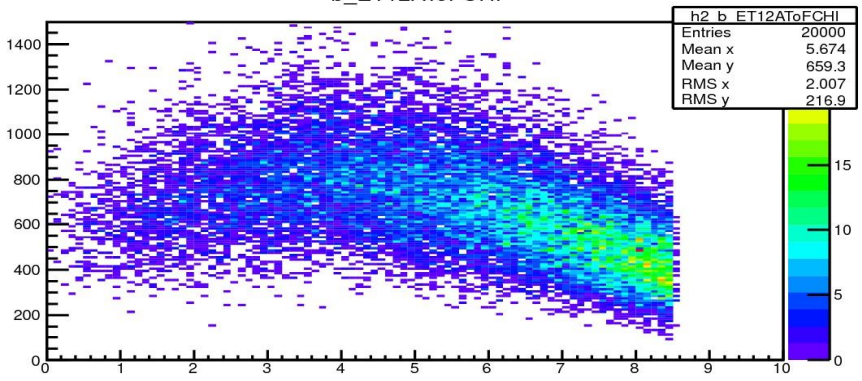
b_ET12CHI



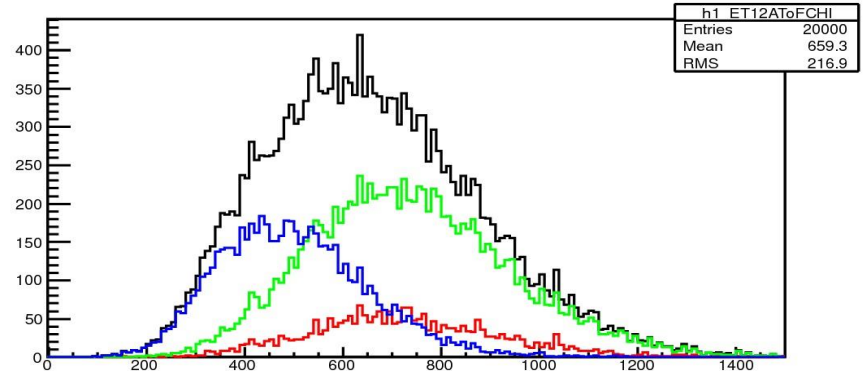
ET12CHI

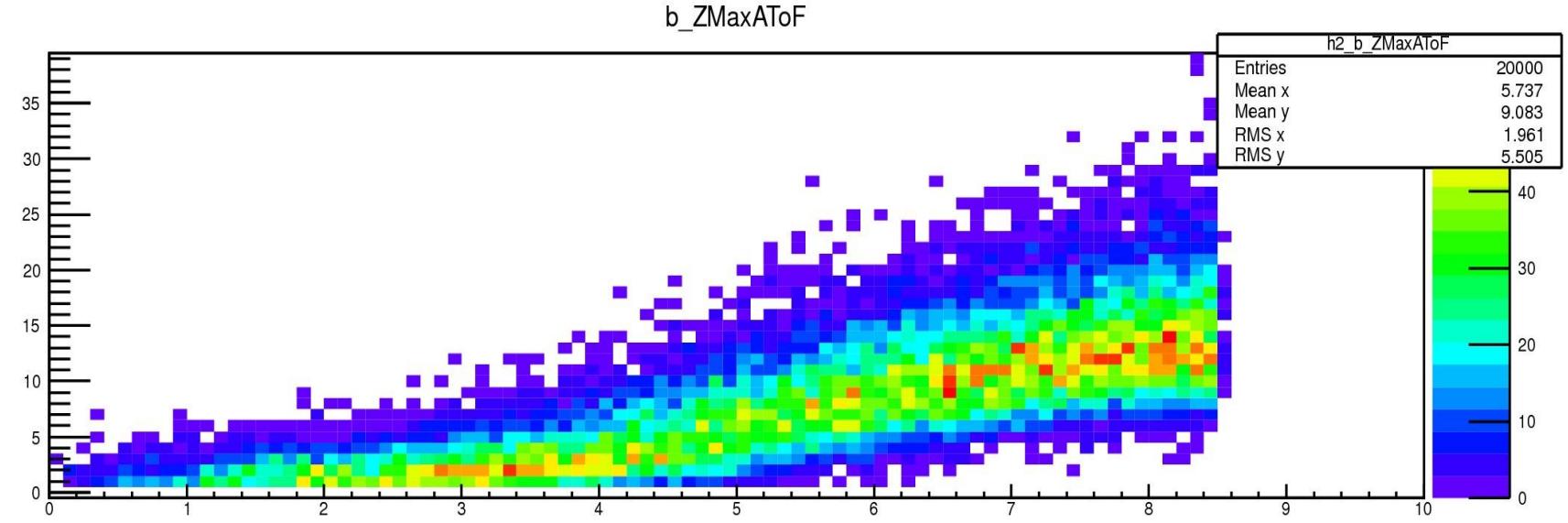


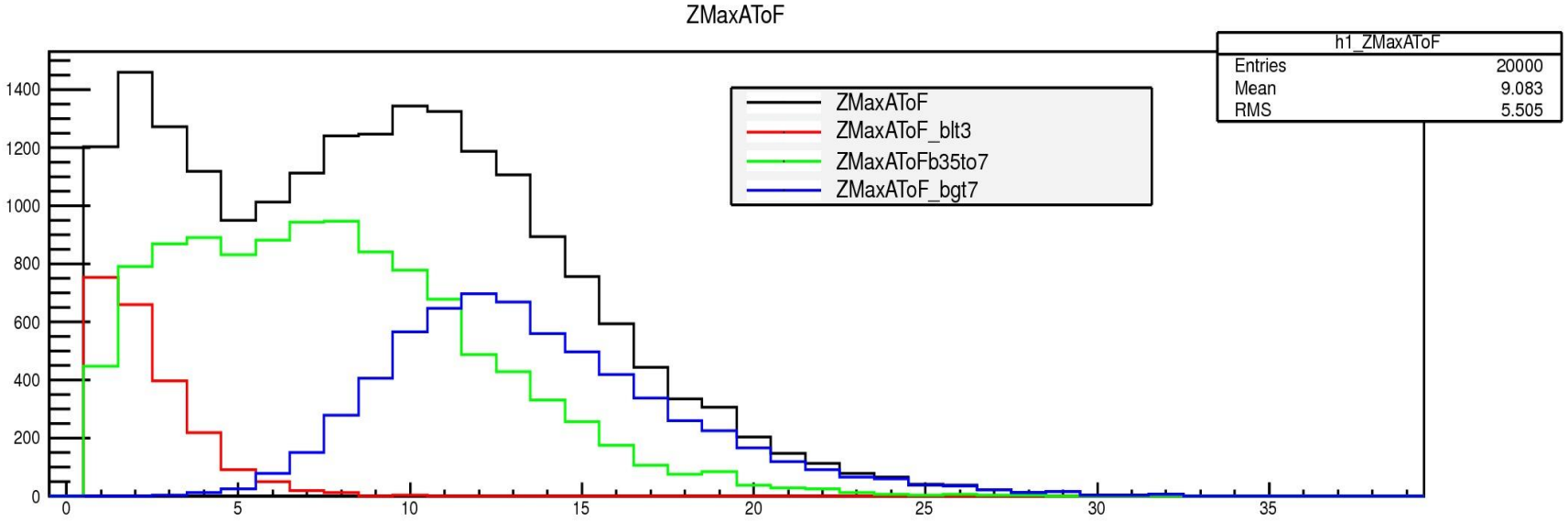
b_ET12AToFCHI



ET12AToFCHI




b_ZMaxAToF
h2_b_ZMaxAToF
Entries 20000
Mean x 5.737
Mean y 9.083
RMS x 1.961
RMS y 5.505


ZMaxAToF
h1_ZMaxAToF
Entries 20000
Mean 9.083
RMS 5.505
ZMaxAToF
ZMaxAToF_blt3
ZMaxAToFb35to7
ZMaxAToF_bgt7

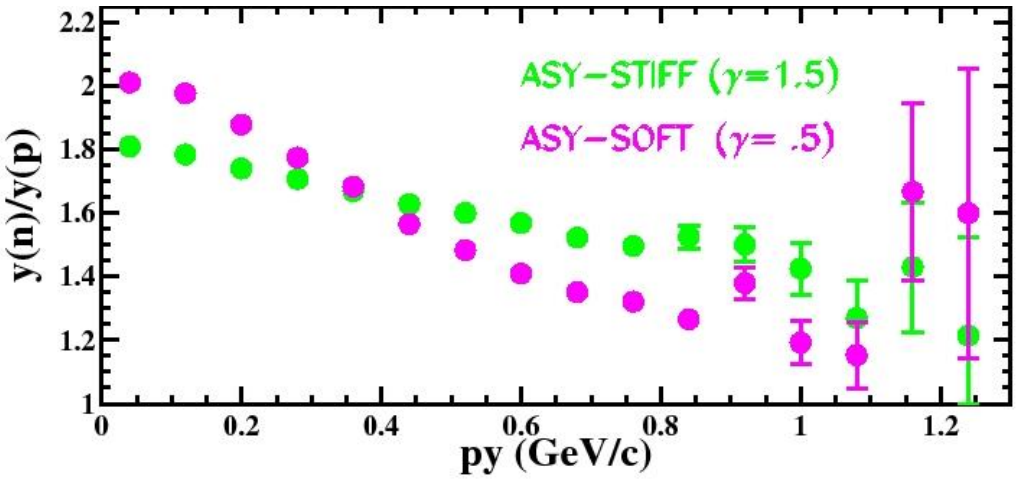
RISERVE

Y(p)/Y(n)

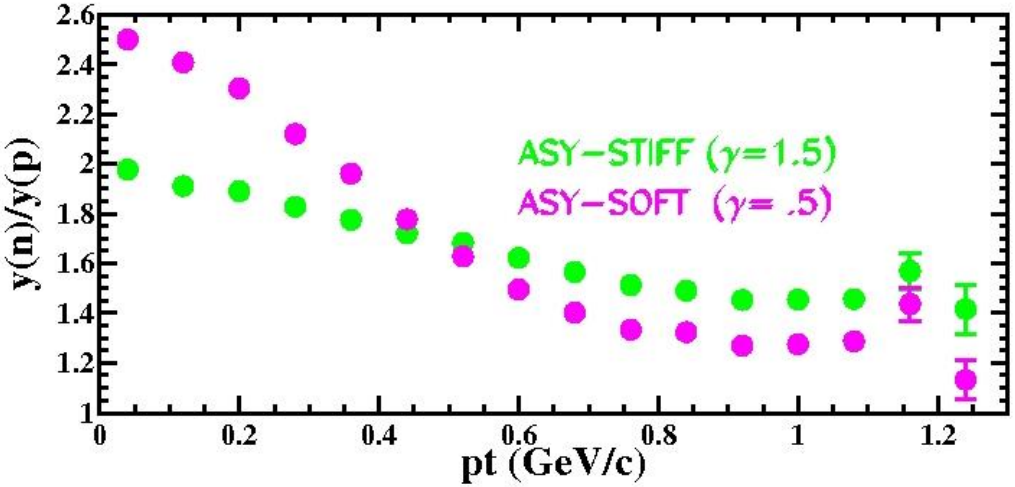
OK

URQMD simulations Au+Au @ 400 AMeV

0.35<y/yp<0.65



5.5<b<7.5 fm



b<3 fm

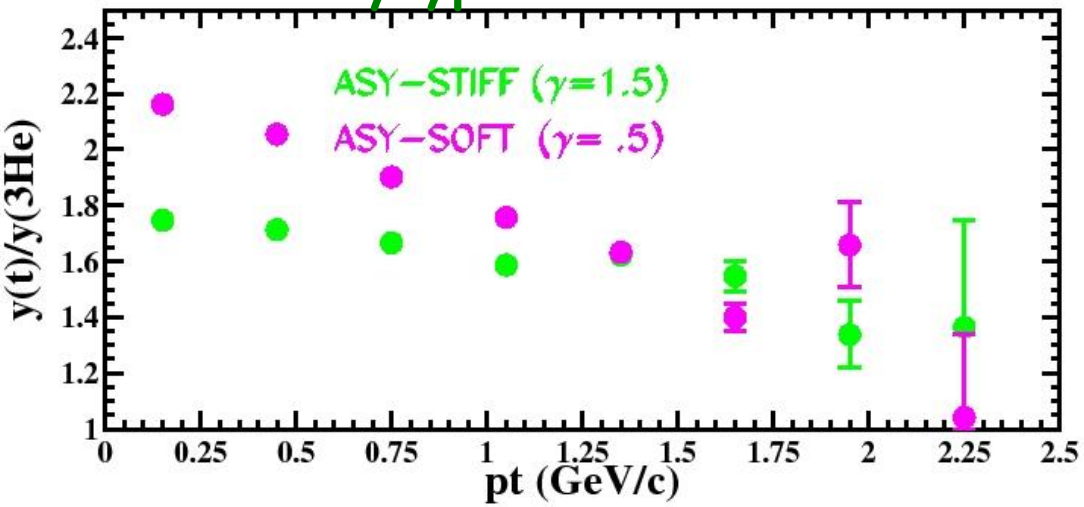
RISERVE

Y(t)/Y(3He)

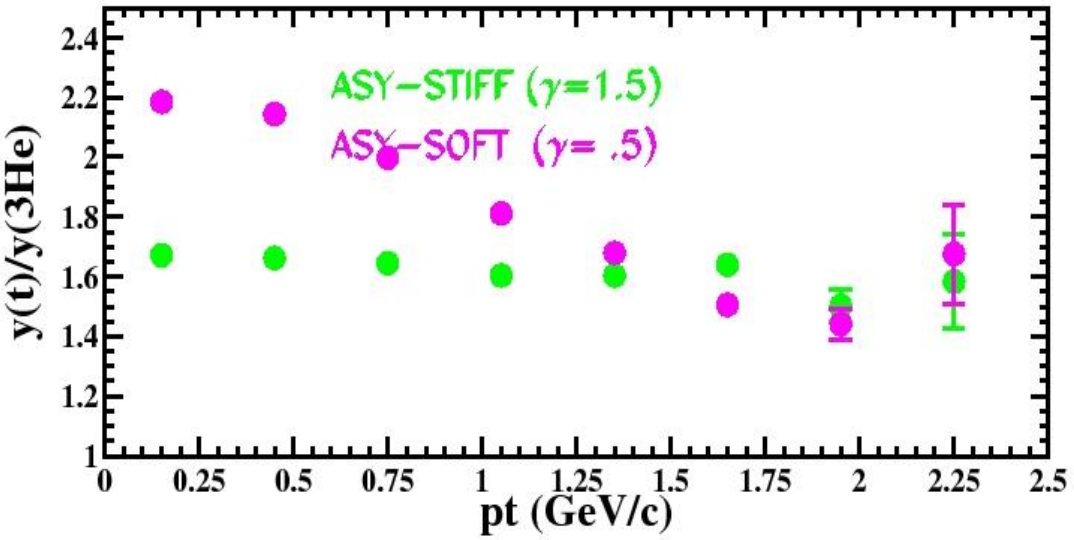
OK

Au+Au @ 400 AMeV

0.25<y/yp<0.75



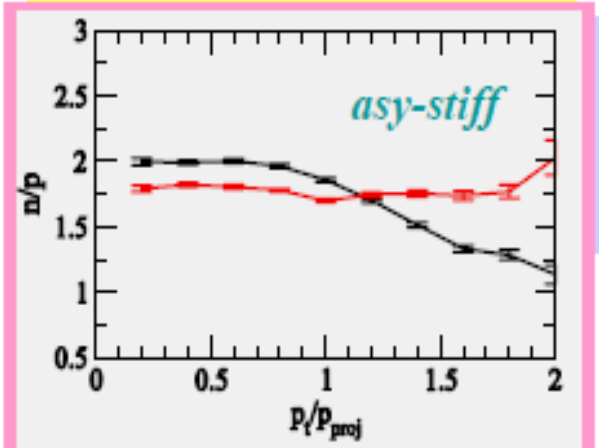
5.5<b<7.5 fm

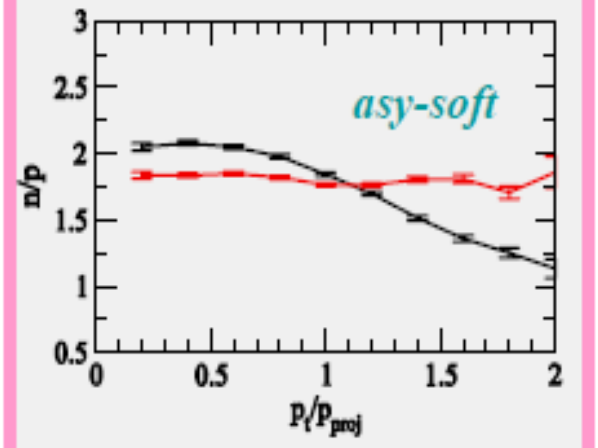


b<3 fm

Mass splitting: N/Z of Fast Nucleon Emission

n/p ratio yields

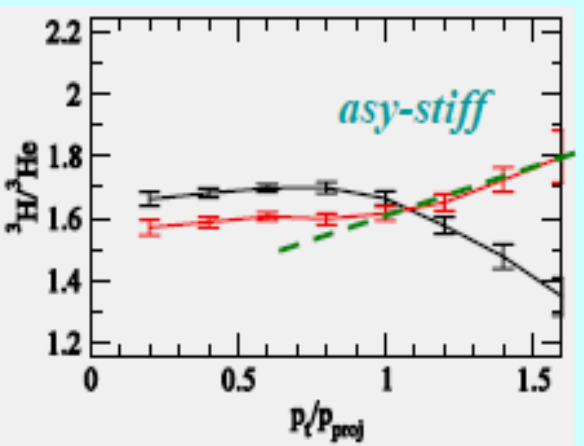


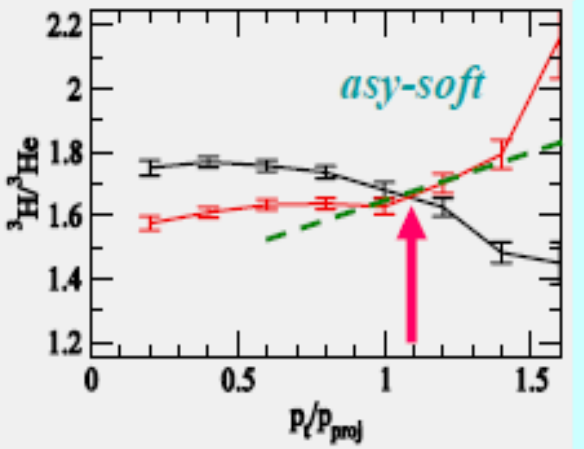


$^{197}Au+^{197}Au$
400 AMeV
central,
$y(0) \leq 0.3$

- $m^*_n > m^*_p$
- $m^*_n < m^*_p$

Light isobar $^3H/^3He$ yields





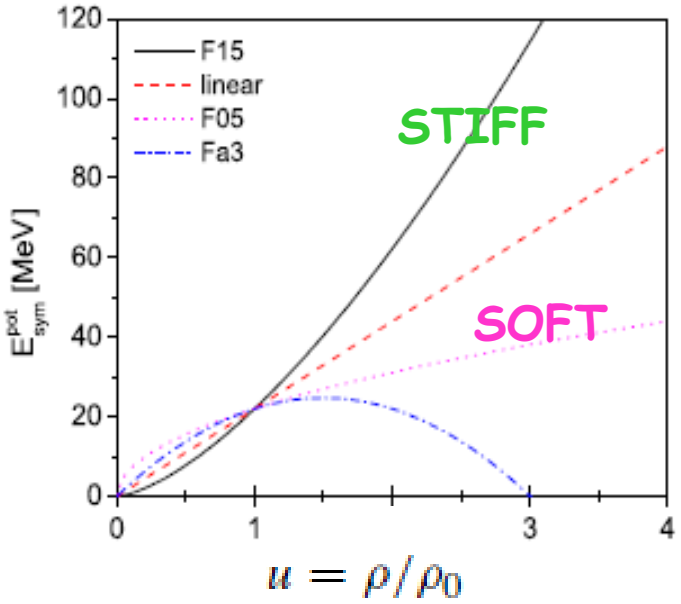
Observable very sensitive at high p_T
to the mass splitting and not to the asy-stiffness

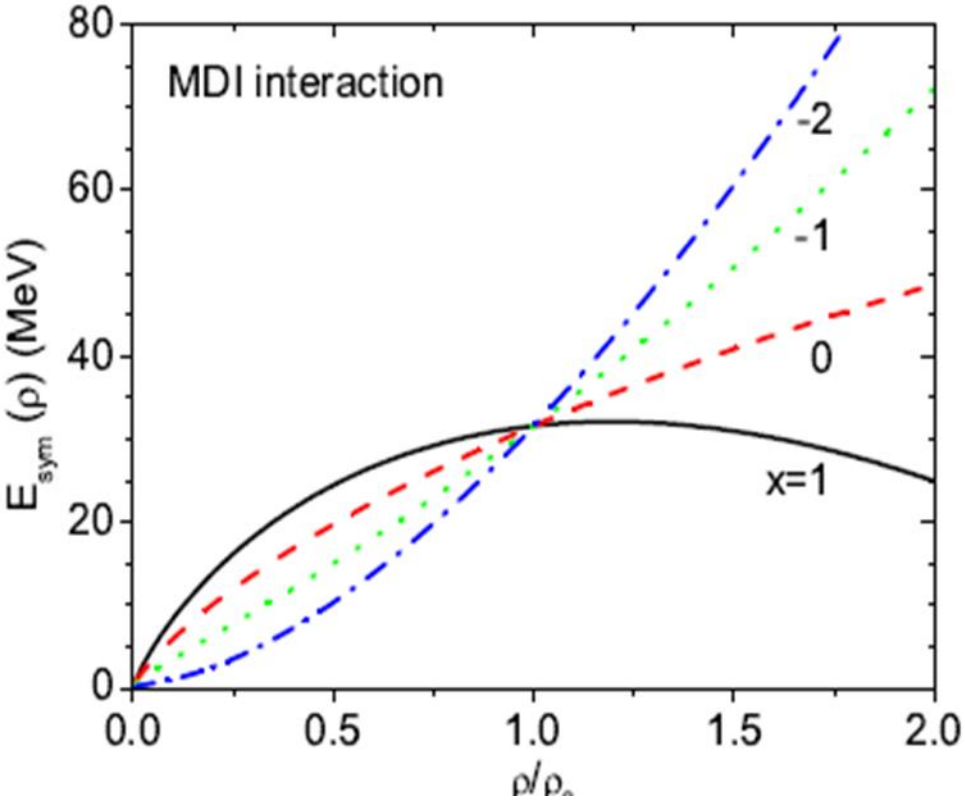
V.Giordano et al., PRC 81(2010)

From M.Di Toro talk
at Asy-Eos2010

COZMA

OK



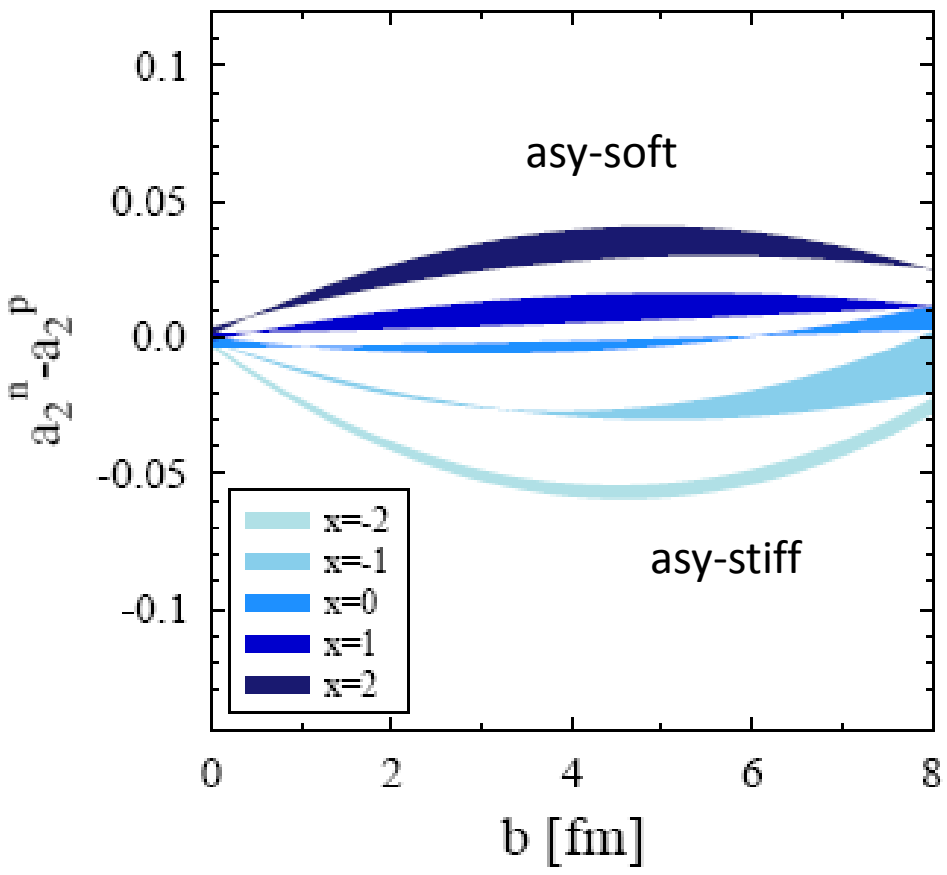


$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22\ \text{MeV} \cdot (\rho/\rho_0)^{\gamma} + 12\ \text{MeV} \cdot (\rho/\rho_0)^{2/3}$$

new: result obtained with Tübingen QMD*)

M.D. Cozma, PLB 700, 139 (2011); arXiv:1102.2728

difference of neutron and proton squeeze-outs
Au + Au @ 400 A MeV



- $a_2 = 2v_2$
- with FOPI filter
- bands show uncertainty due to isoscalar field "soft to hard"

conclusion in paper: super-soft not compatible with FOPI-LAND data

UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS

T-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets

* V.S. Uma Maheswari, C. Fuchs, Amand Faessler, L. Sehn, D.S. Kosov, Z. Wang, NPA 628 (1998)

results with Tübingen QMD and momentum dependent forces*

*M.D. Cozma, PLB 700, 139 (2011); arXiv:1102.2728

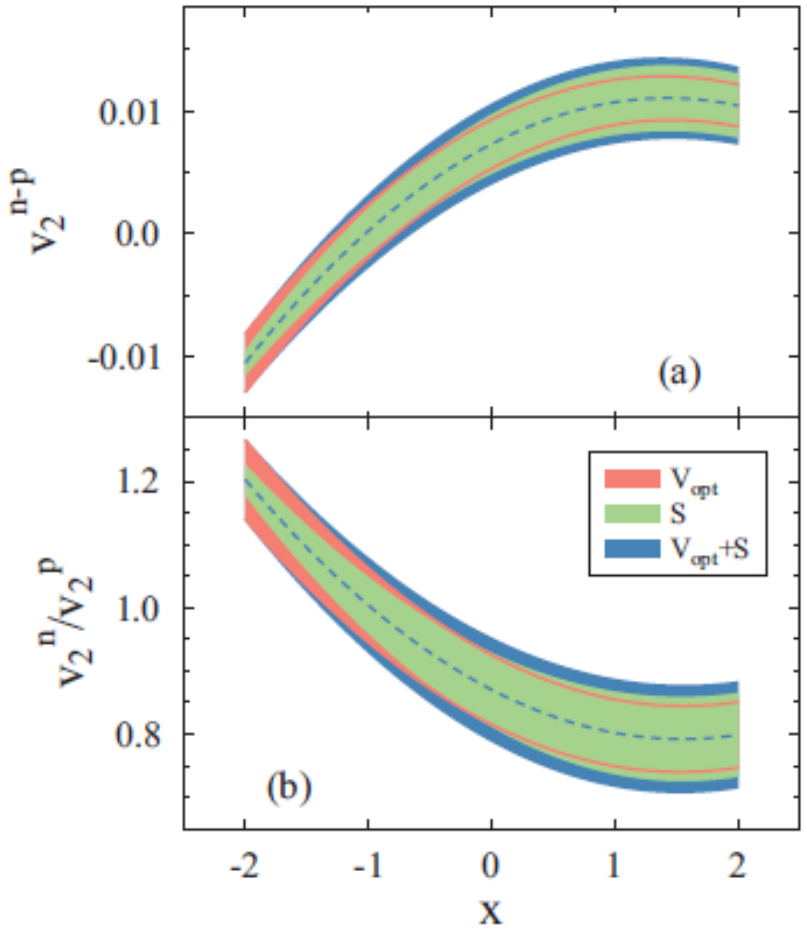
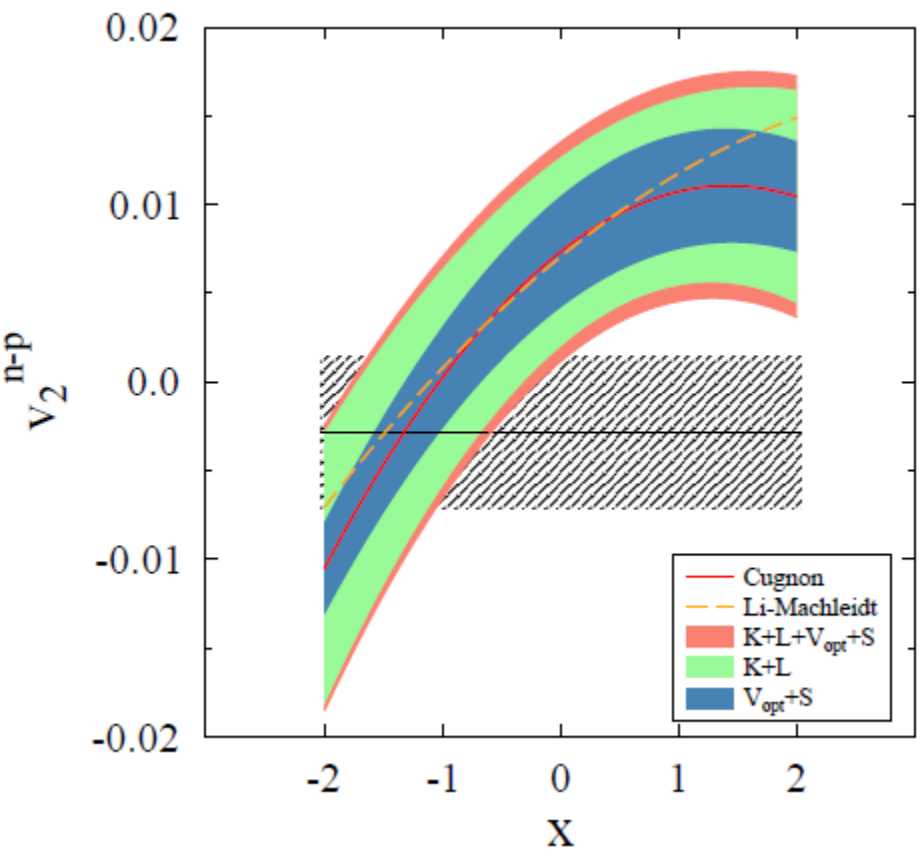


FIG. 1. (Color online) Variations in the values of the impact parameter integrated ($b \leqslant 7.5$ fm) npEFD (a) and npEFR (b) due to different choices for the optical potential (V_{opt}), parametrization of symmetry-energy (S) as well as the combined, quadratically added, uncertainty.

M.D. Cozma et al., Towards a model-independent constraint of the high-density dependence of the symmetry energy,

arXiv:1305.5417 [nucl-th] PRC88 044912 (2013)



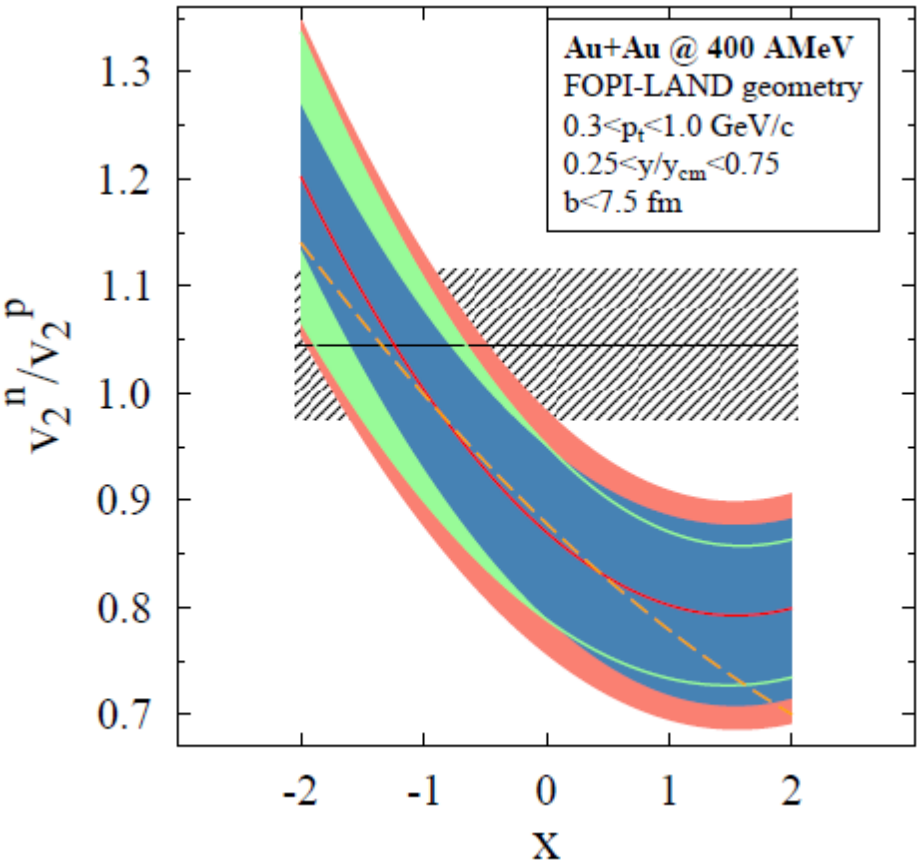


FIG. 2: Model dependence of npEFD and npEFR and comparison with FOPI-LAND experimental data, integrated over impact parameter b$\leq$7.5 fm. Sensitivity to the different model parameters, compressibility modulus (K), width of nucleon wave function (L), optical potential (V_{opt}) and parametrization of the symmetry energy (S) are displayed. The total model dependence is obtained by adding, in quadrature, individual sensitivities.

FUTURE SETUP

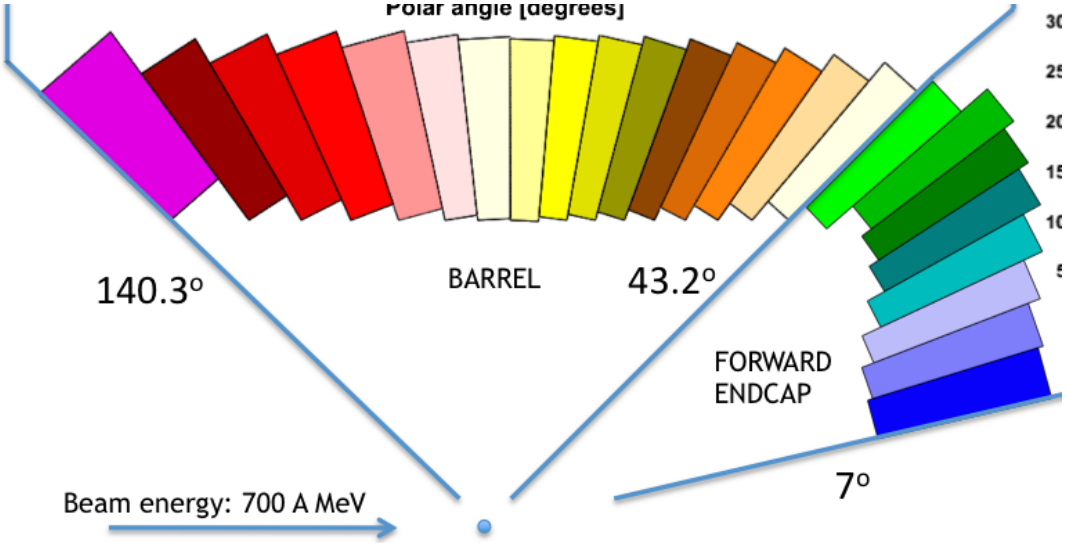
NeuLAND technical design

200 MeV	Generated					
Detected	%	1n	2n	3n	4n	5n
	1n	**88**	31	6	1	0
	2n	2	**62**	37	10	2
	3n	0	5	**49**	38	14
	4n	0	0	8	**48**	54
	5n	0	0	0	3	**26**

1000 MeV	Generated					
Detected	%	1n	2n	3n	4n	5n
	1n	**89**	12	1	0	0
	2n	7	**78**	23	3	0
	3n	0	8	**63**	26	5
	4n	0	0	12	**63**	40
	5n	0	0	0	7	**46**

The construction of the full detector will take about 3.5 years, and will be done in 3 steps. In the first step (November 2012), we will use a small assembly of 150 bars to determine time and position resolution with neutrons and validate simulation results. The neutrons of energies between 250 and 1500 MeV will be produced by proton knock-out reactions using a deuteron beam. In the second step, a 20% of detector will be available for physics experiments in the end of 2014 in Cave C at GSI, which will already profit from an improved resolution for neutron detection. The fully-equiped NeuLAND detector will be commissioned and available for the first experiments at Cave C in 2016. In 2017, the detector will move to its final

Califa
CALorimeter for the In Flight detection of γ rays and light charged pArticles



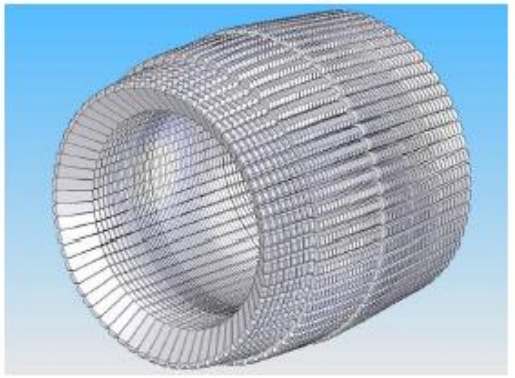


Fig. 2. Artistic view of the CALIFA calorimeter. The inner radius of the barrel is approximately 30 cm long.

CsI(Tl) read by APD with digital read-out

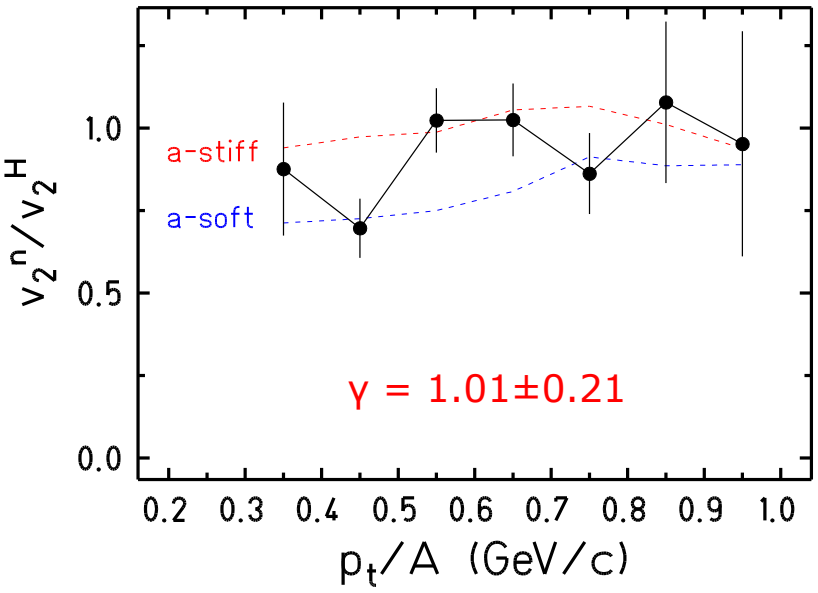
type	polar angle coverage °	azim. base mm	polar base mm	polar o. angle °	azim. o. angle °	height mm	weight kg	number of rings	number of pieces
I	43.2 - 55.5	29.36	15.32	92.20	94.02	220.0	0.73	3	384
II	55.5 - 70.4	29.39	15.34	92.27	94.90	180.0	0.58	3	384
III	70.4 - 87.6	29.25	15.35	92.39	95.48	170.0	0.55	3	384
IV	87.6 - 101.2	29.37	17.85	92.92	95.50	160.0	0.60	2	256
V	101.2 - 132.6	29.37	24.80	92.74	94.54	140.0	0.63	4	512
VI	132.6 - 140.35	67.77	69.69	95.00	94.54 - 93.90	120.0	3.14	1	32

RISERVE

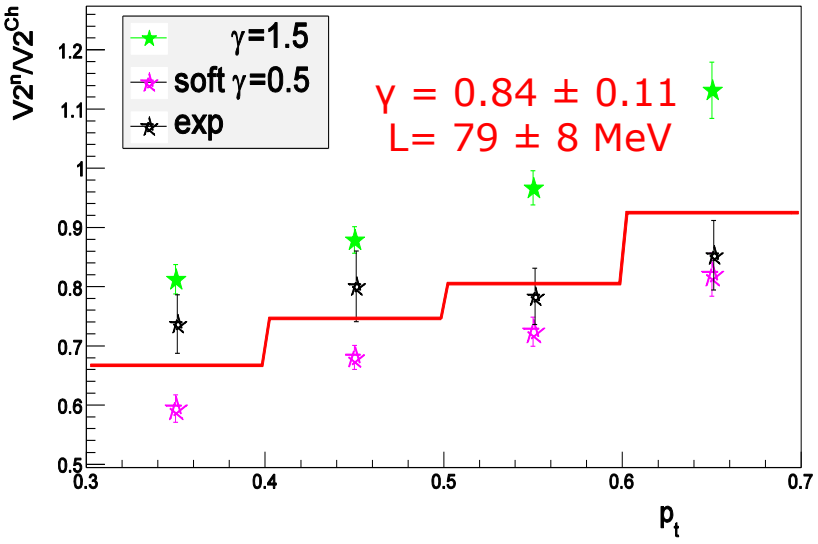
PREV EXP

latest news from Catania:

1991 data, Russotto et al., PLB 697, 471



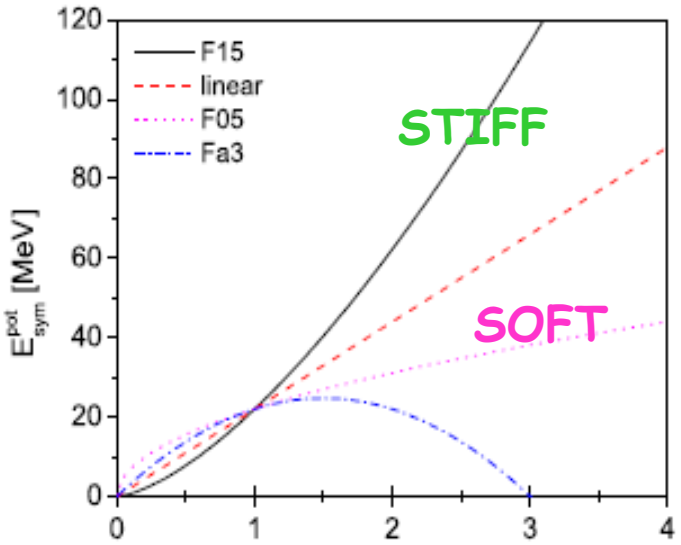
2011 data, Russotto et al., 2014, preliminary



preliminary result from S394:
obviously less fluctuations and smaller errors,
previous result confirmed within uncertainties

Main motivation: symmetry energy at supra-saturation densities

UrQMD simulations

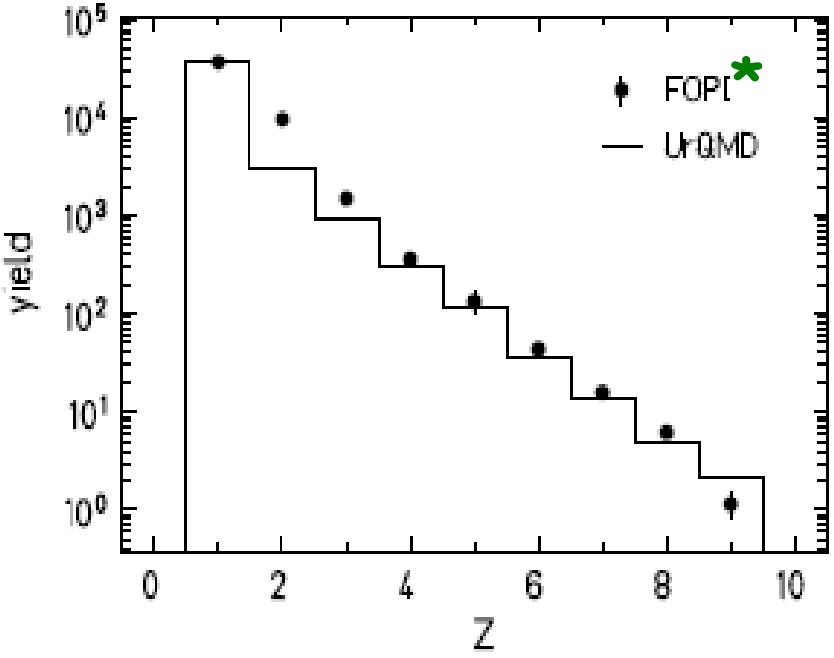


$$u = \rho/\rho_0$$

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22\,\text{MeV} \cdot (\rho/\rho_0)^{\gamma} + 12\,\text{MeV} \cdot (\rho/\rho_0)^{2/3}$$

See Qingfeng Li, J. Phys. G31 1359-1374 (2005) and references

UrQMD vs. FOPI data: Au+Au @ 400 AMeV b< 2.5 fm

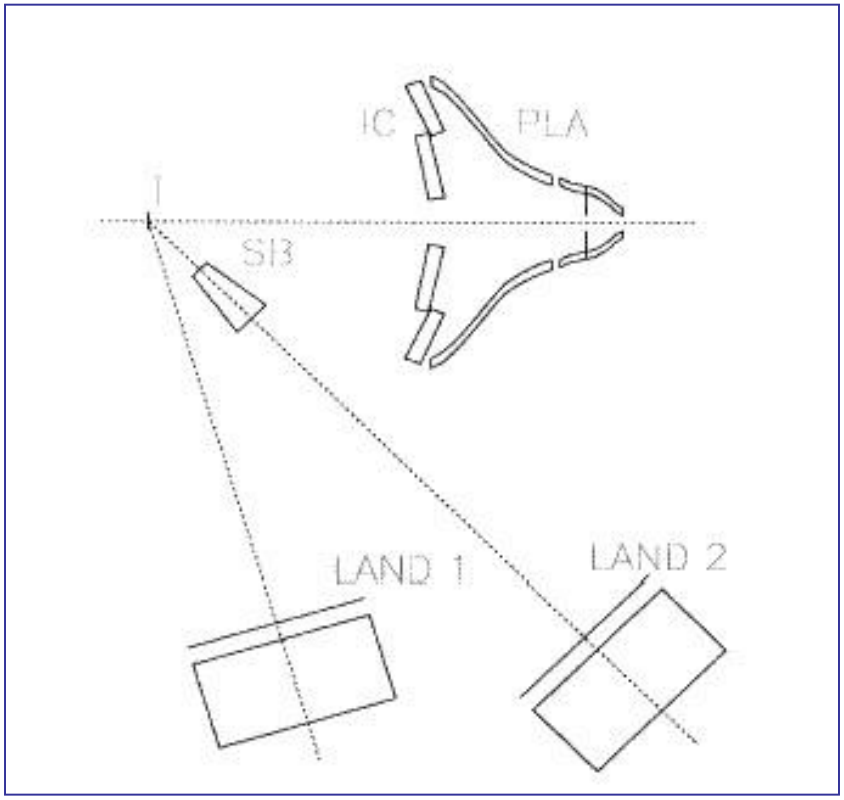


* W. Reisdorf, et al., Nucl. Phys. A 612 (1997) 493.

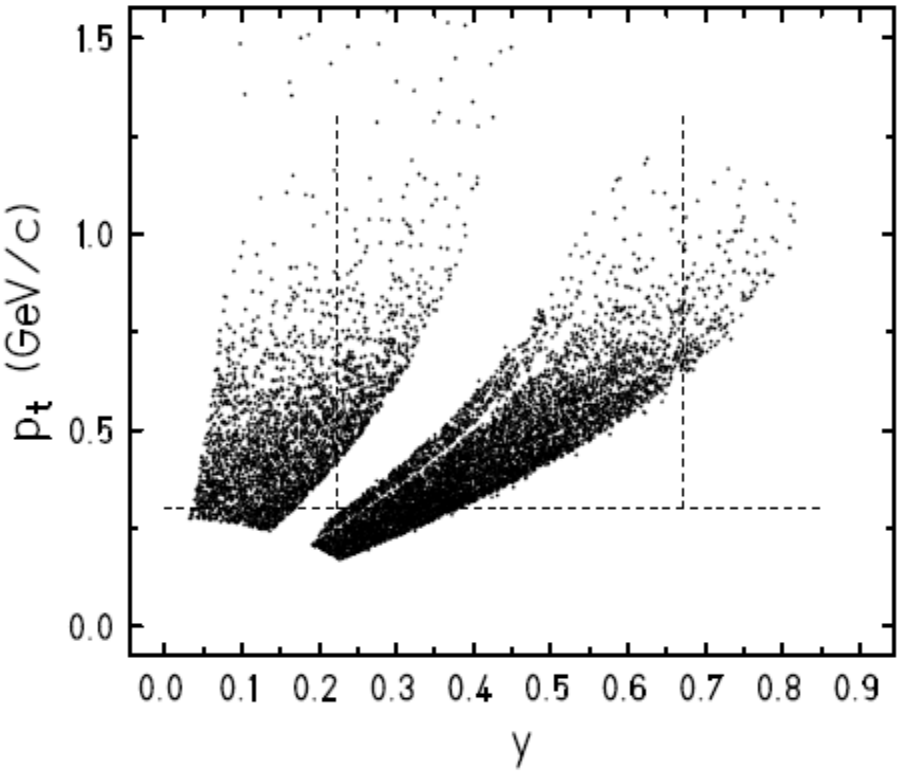
Coalescence condition: Dr <3 fm and Dp< 275 MeV/c

FOPI/LAND experiment on neutron squeeze out (1991)

Au+Au 400 A MeV



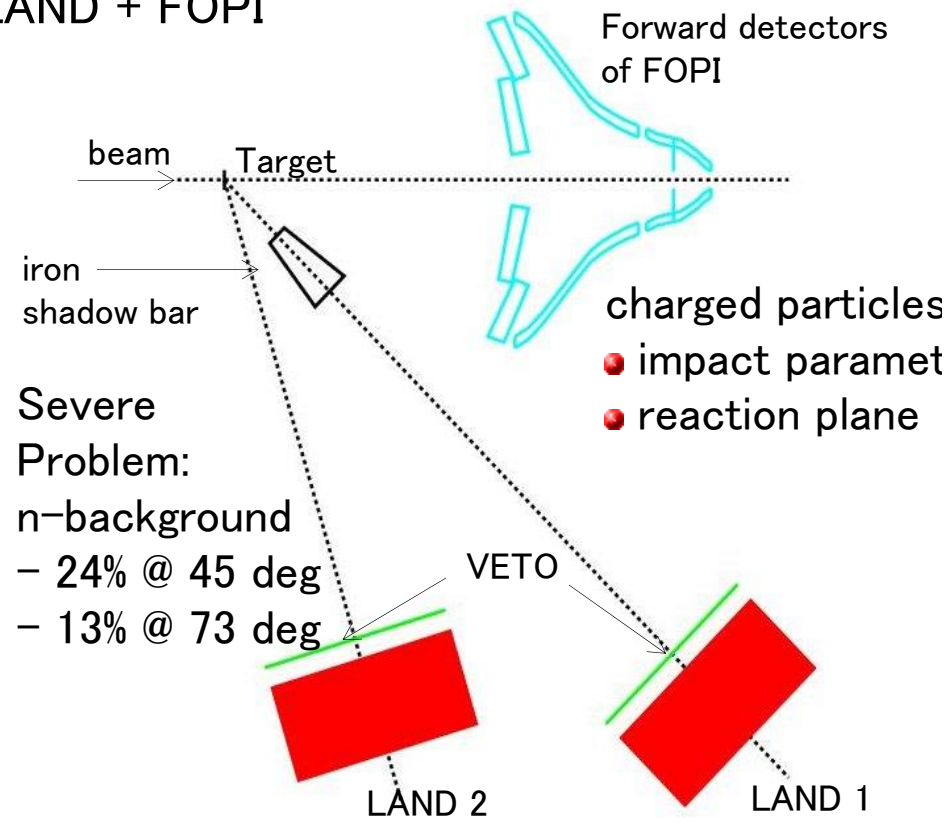
LAND coverage
$37° < \theta_{lab} < 53°$
$61° < \theta_{lab} < 85°$



Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

High densities

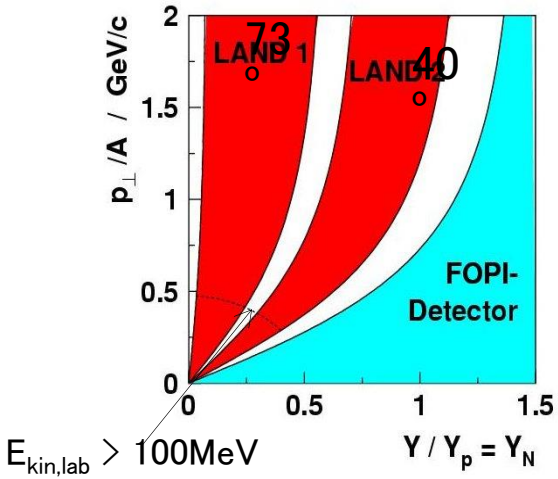
n/p flow
LAND + FOPI

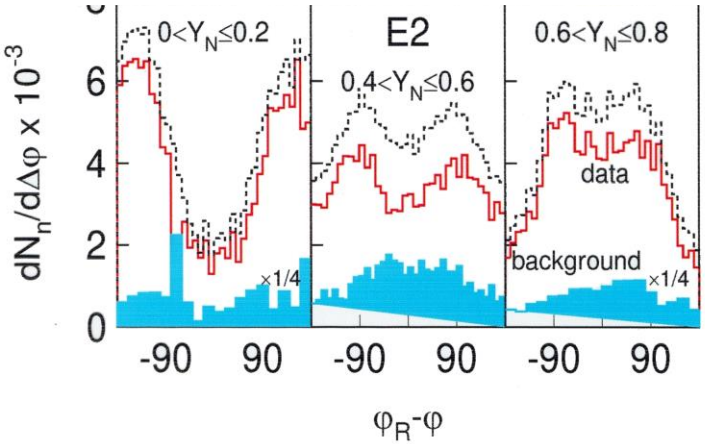


charged particles
- impact paramet
- reaction plane

Severe
Problem:
n-background
– 24% @ 45 deg
– 13% @ 73 deg

- time-of-flight of neutrons

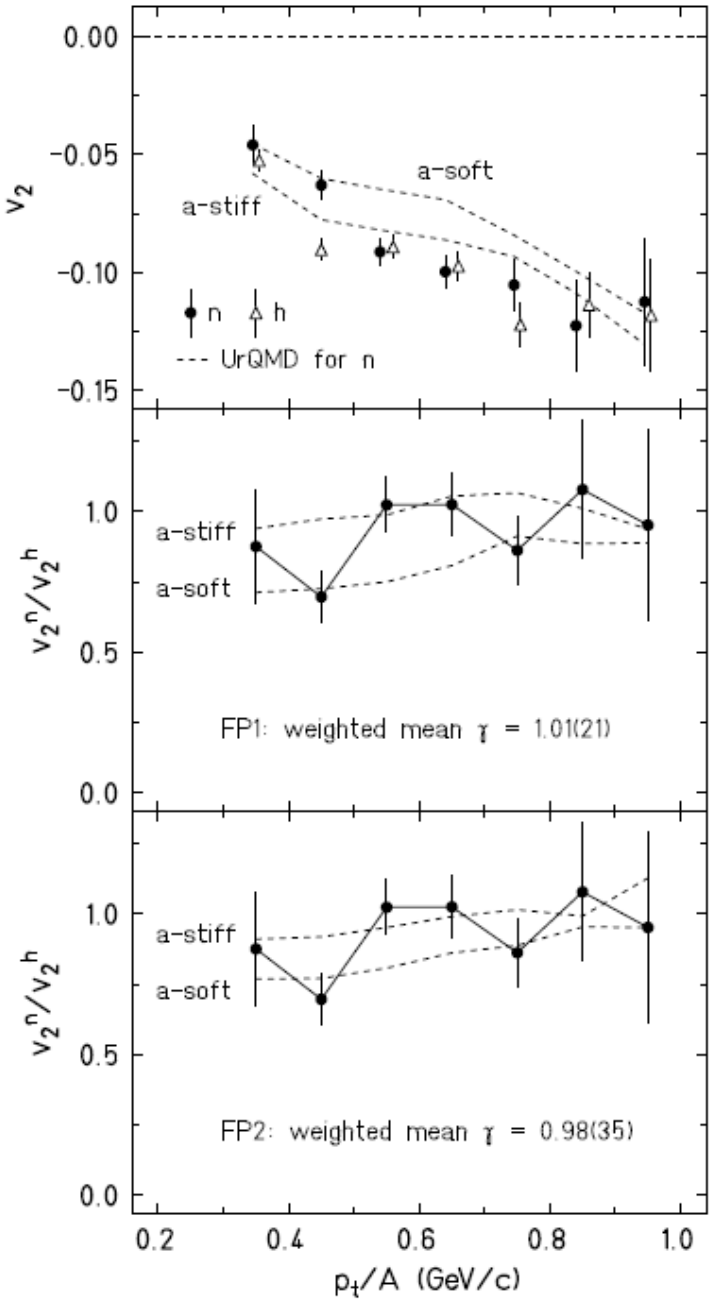




Analysys of FOPI/LAND data (1991)

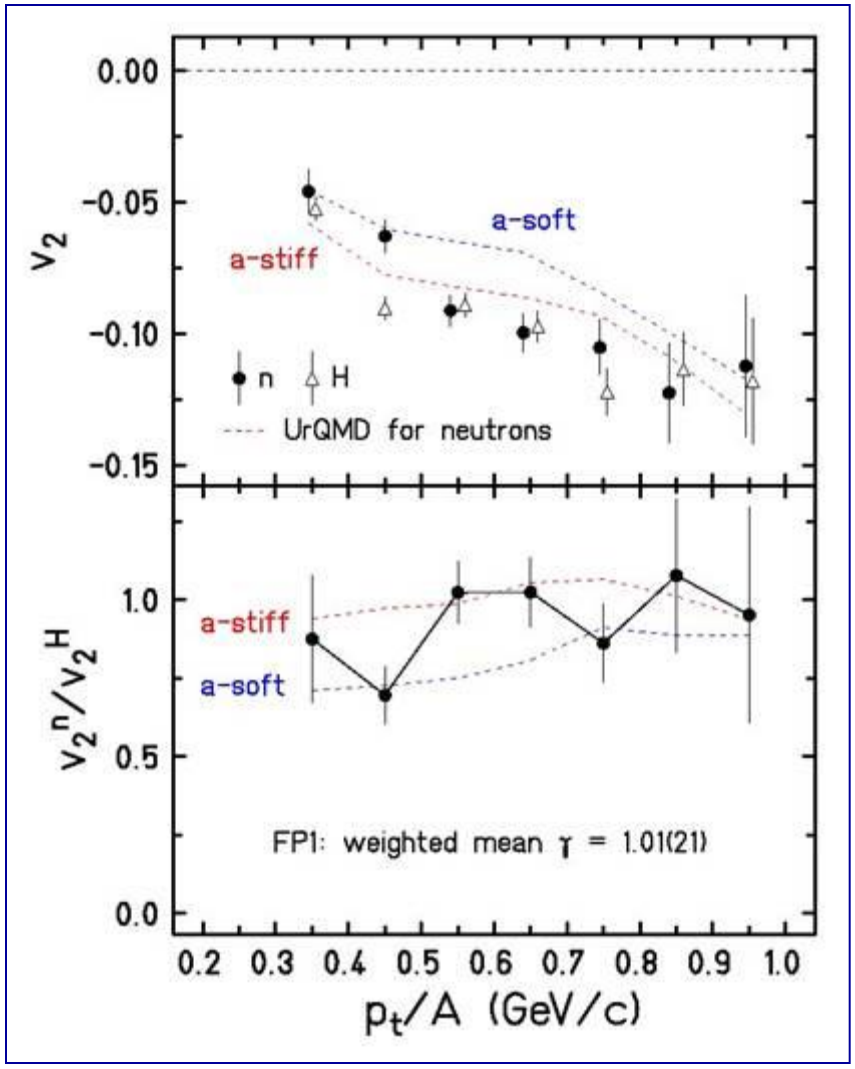
Au+Au 400 A MeV
b< 7.5 fm

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22MeV \cdot (\rho/\rho_0)^{\gamma} + 12MeV \cdot (\rho/\rho_0)^{2/3}$$



Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

Analysys of FOPI/LAND data (1991)



Au+Au 400 A MeV
b< 7.5 fm

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22MeV \cdot (\rho/\rho_0)^{\gamma} + 12MeV \cdot (\rho/\rho_0)^{2/3}$$

Neutron/hydrogen
FP1: $\gamma = 1.01 \pm 0.21$
FP2: $\gamma = 0.98 \pm 0.35$
neutron/proton
FP1: $\gamma = 0.99 \pm 0.28$
FP2: $\gamma = 0.85 \pm 0.47$

adopted: $\gamma = 0.9 \pm 0.4$

Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

test of systematic uncertainties

physical parameters:	
impact parameter	$\Delta\gamma = 0.43 \pm 0.32$ (PM3 vs. PM3-5)
transverse momentum	$\Delta\gamma < 0.1$ (p_t<0.8 vs. p_t<1.2 GeV/c)
rapidity	$\Delta\gamma < 0.15$ (for PM3-5)
	statistics not really sufficient to evaluate errors more precisely
data analysis:	
various sorting gates	$\Delta\gamma < 0.1$
include protons separately	$\Delta\gamma$ negligible (protons not sensitive)
background subtraction	$\Delta\gamma = 0.21$ (100% vs. 60% of measured background)
UrQMD:	
Pauli blocking (y/n)	$\Delta\gamma = 0.08$ (for PM3-5)
constant S_0 ($=a_4$)	$\Delta\gamma = 0.07$ (S_0=22 vs. S_0=18 MeV)

GENERAL

Expansion
of the symmetry energy
at $\rho=\rho_0$

$$E_{sym}(\rho) = E_{sym,0} + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + .$$

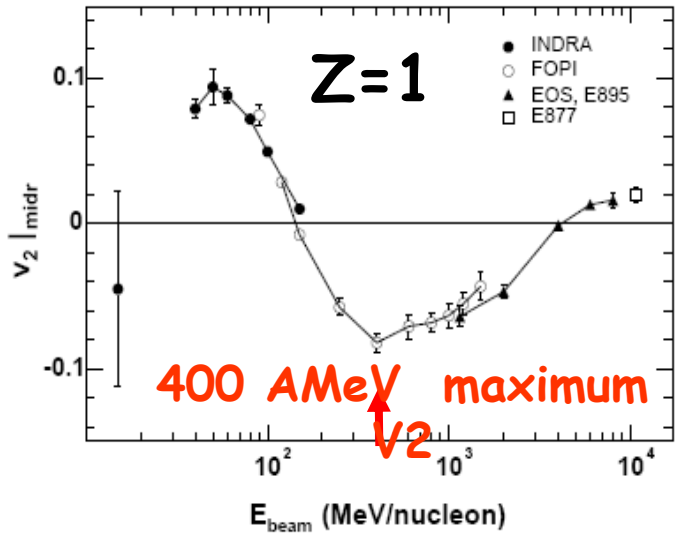
$$\text{slopeparameter} L = 3\rho_0 \left| \frac{dE_{sym}(\rho)}{d\rho} \right|_{\rho_0}$$

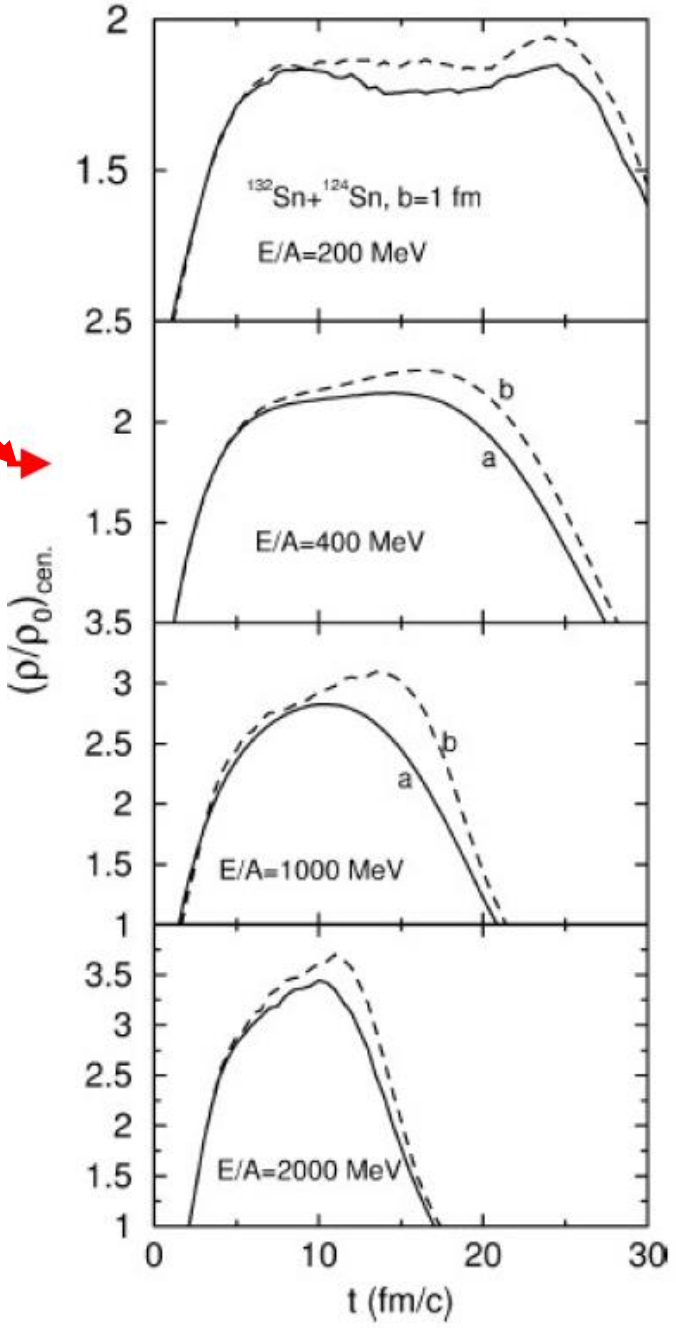
High density over a long time

$\rho \cdot \Delta t$= maximum here

in the central region
of ^{132}Sn + ^{124}Sn central collisions
according to the isospin dependent
transport model of
Bao-An Li, NPA 708(2002)

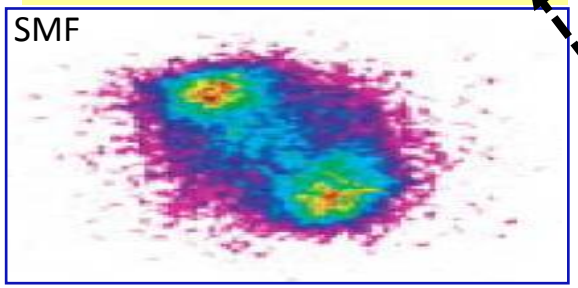
A. Andronic et al., Eur. Phys.
J. A 30 (2006) 31.



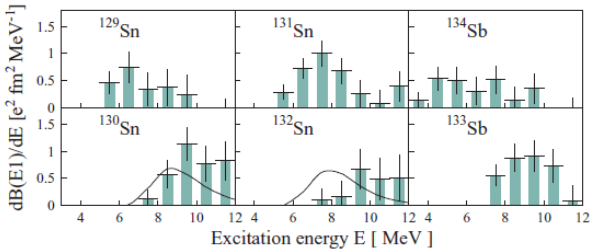


Study of the density dependence of the symmetry energy

Density $\rho < \approx \rho_0$ (sub- and around saturation density, ρ_0=0.17 fm^{-3})

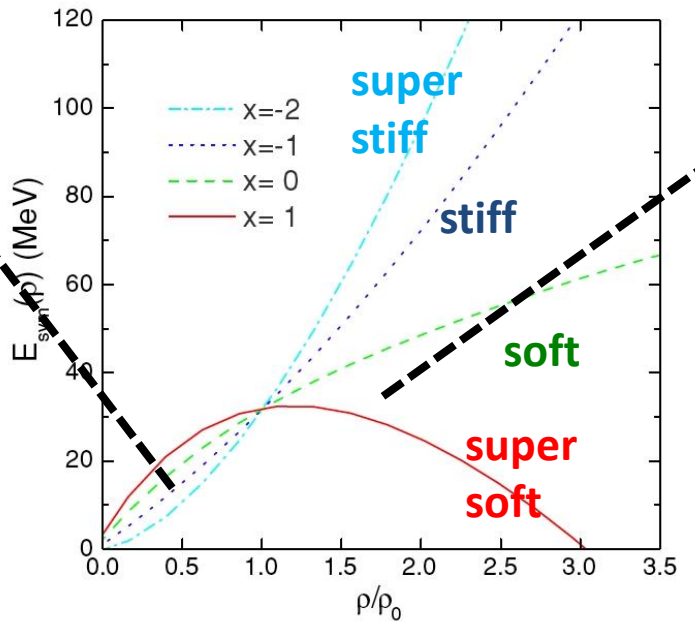


Isospin Transport properties in HI collisions at Fermi Energies, (diffusion, fractionation, migration), flows, n/p emission , clusterization….



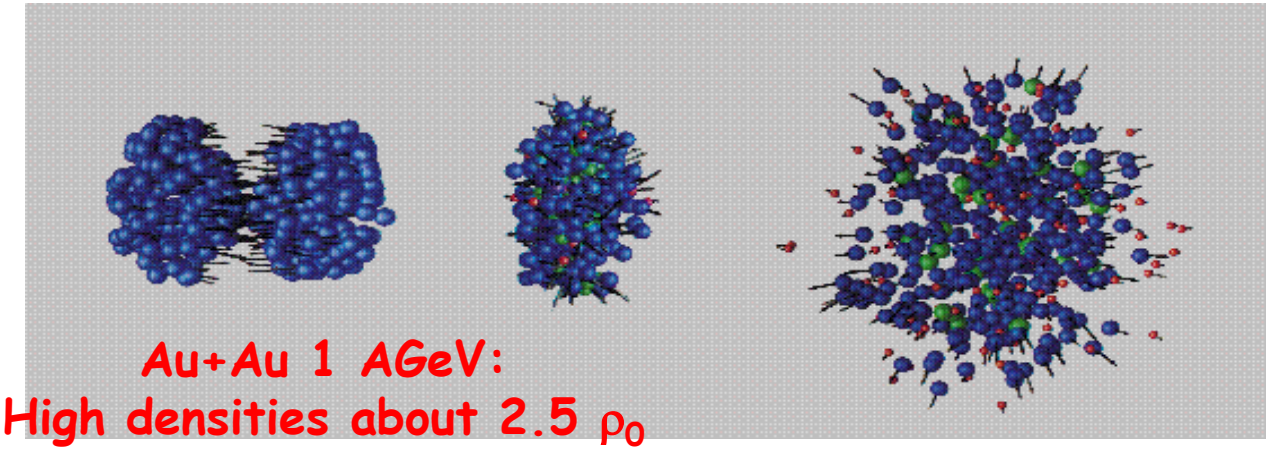
Nuclear structure (IAS), Resonances (PDR,GDR) n thickness …

Z. Xiao, Bao-An Li et al., PRL 102, 062502 (2009)



Density $\rho > \rho_0$ (supra-saturation): connected with *neutron stars, supernovae expl.*

Pre-equilibrium emission, particle production (π,K), collective flows in relativistic HI collisions



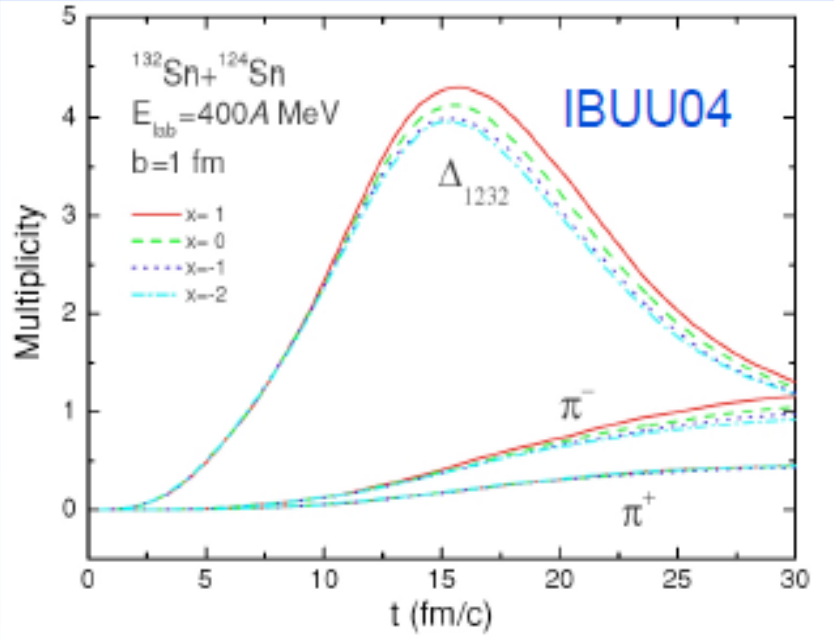
Au+Au 1 AGeV: High densities about 2.5 ρ_0

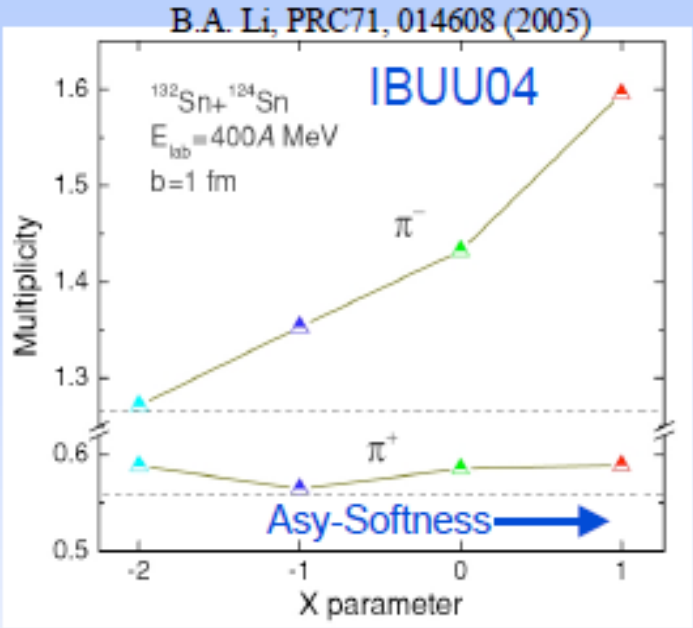
Adapted from H.Wolter –ASYEOS 2010, Noto (Italy)

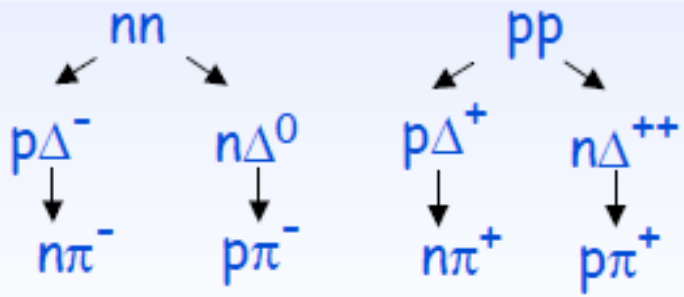
PION && KAONS

sistemare

Meson production: Pions





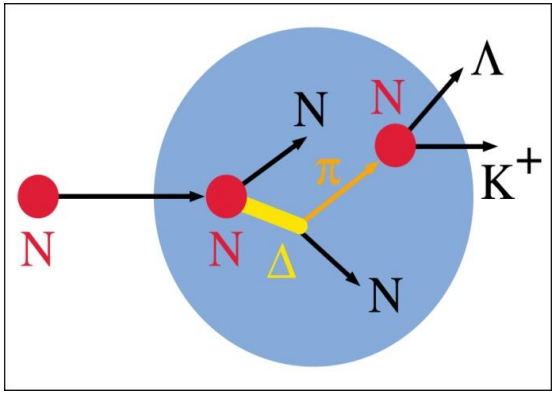


π-/π+ sensitive to $E_{sym}(\rho)$ at high ρ

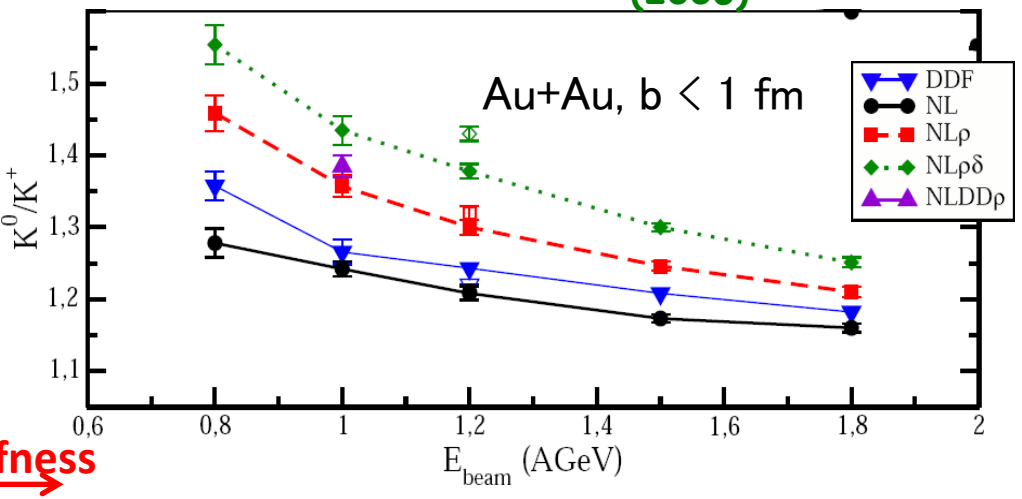
NN collisions in high density regions

π–/π+ reflecting the $(N/Z)_{dense}$

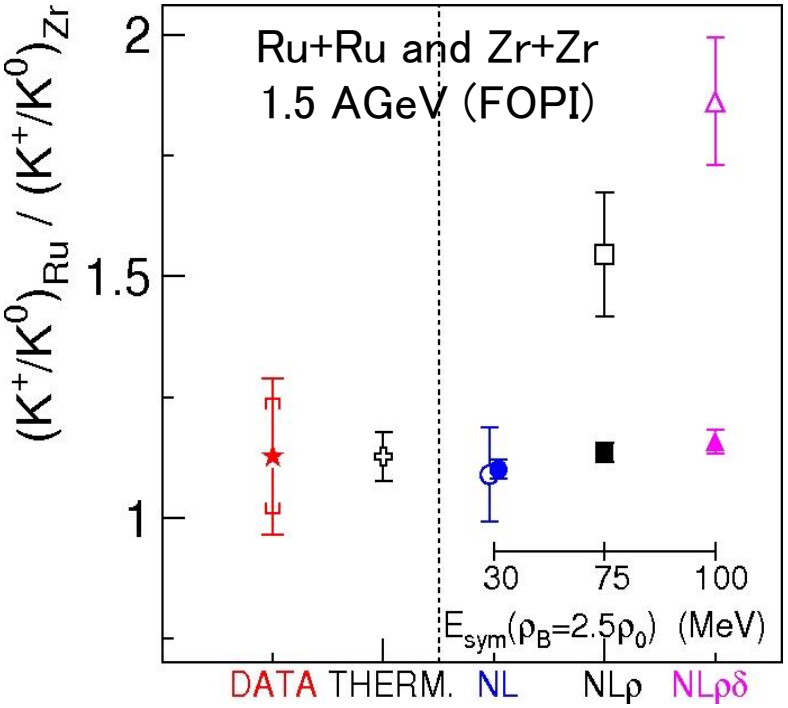
Esym at high density: kaons



Ferini et al., PRL 97, 202301 (2006)



stiffness



X. Lopez et al. 2007

RMF calculations

INM: T=60 MeV and $\rho_B=2.5\rho_0$

RBUU: transport simulation

- higher sensitivity at lower energies
- requires excellent kaon dentification and long beam times

From IWM 2011 – Y. Leifels

particella	*massa* (MeV/c^2)	*decadimento*	*vita media* (s)
$K^{\pm}$	494	$K^{\pm} \to \pi^{\pm}\pi^0$	$1.24\ 10^{-8}$
K^0	498	$K^0 \to \pi^-\pi^+$	$0.89\ 10^{-10}$
Λ^0	1116	$\Lambda^0 \to p\pi^-$	$2.63\ 10^{-10}$

$$\pi^- p \to K^0 \Lambda^0 \qquad \pi^- p \to K^0 K^- p$$
$$\pi^+ n \to K^+ \Lambda^0 \qquad \pi^+ n \to K^+ K^- p$$

ma *non si osserva* $\pi^- n \to K^- \Lambda^0$. Un'altra peculiarità osservata è

probabilità di produzione di K^+ $\gg$ probabilità di produzione di K^-
probabilità di interazione di K^+ $\ll$ probabilità di interazione di K^-

$\pi^0 \to \gamma\gamma$	0.988	*interazione elettromagnetica*
$\pi^0 \to e^+e^-\gamma$	0.012	$\tau = 0.84\ 10^{-16}\ s$
$\pi^0 \to e^+e^-$	$6.2\ 10^{-8}$	
$\pi^+ \to \mu^+\nu_\mu$	1.000	*interazione debole*
$\pi^+ \to e^+\nu_e$	$1.2\ 10^{-4}$	$\tau = 2.60\ 10^{-8}\ s$

I modi di decadimento dei mesoni K carichi e le probabilità di decadimento sono

$K^+ \to$	$\mu^+\nu_\mu$	0.635	*decadimenti*
	$e^+\nu_e$	$1.6\ 10^{-5}$	*leptonici*
	$\pi^0 e^+\nu_e$	0.048	*decadimenti*
	$\pi^0\mu^+\nu_\mu$	0.032	*semileptonici*
	$\pi^+\pi^0$	0.212	*decadimenti*
	$\pi^+\pi^+\pi^-$	0.056	*adronici*
	$\pi^+\pi^0\pi^0$	0.017	

$$K^+ = u\bar{s} \qquad K^- = d\bar{s} \qquad \pi^+ = u\bar{d}$$
$$K^0 = \bar{u}s \qquad \bar{K}^0 = \bar{d}s \qquad \pi^+ = \bar{u}d$$

Probing the Nuclear Equation of State by K^+ Production in Heavy-Ion Collisions

C. Fuchs, Amand Faessler, and E. Zabrodin
Institut für Theoretische Physik der Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany

Yu-Ming Zheng
China Institute of Atomic Energy, P.O. Box 275 (18), Beijing 102413, China
(Received 10 July 2000; revised manuscript received 15 November 2000)

In the energy range considered here, the nucleon-nucleon inelastic channels can be restricted to the excitation of the lowest mass resonance $\Delta(1232)$ and perturbative kaon ($K^{+,0}$) production through baryon-baryon collisions $BB \rightarrow BYK$, where B stands for nucleons or resonances and Y for hyperons (Λ, $\Sigma^{\pm,0}$). Pions are produced via the decay of the $\Delta(1232)$ resonance and—after propagation and rescattering—can contribute to the kaon yield through collisions with baryons: $\pi B \rightarrow YK$. All of

Circumstantial Evidence for a Soft Nuclear Symmetry Energy at Suprasaturation Densities

Zhigang Xiao,[1] Bao-An Li,[2,*] Lie-Wen Chen,[3] Gao-Chan Yong,[4] and Ming Zhang[1]

[1]*Department of Physics, Tsinghua University, Beijing 100084, P.R. China*
[2]*Department of Physics, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA*
[3]*Institute of Theoretical Physics, Shanghai Jiao Tong University, Shanghai 200240, P.R. China*
[4]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, P.R. China*

(Received 1 August 2008; revised manuscript received 1 December 2008; published 13 February 2009)

Among the most sensitive probes of the $E_{\rm sym}(\rho)$ at suprasaturation densities proposed in the literature [6], the π^-/π^+ ratio in heavy-ion collisions is particularly promising. Qualitatively, the advantage of using the π^-/π^+ ratio is evident within both the $\Delta(1232)$ resonance model [38] and the statistical model [39] for pion production. Assuming only first chance inelastic nucleon-nucleon collisions produce pions and neglecting their reabsorptions, the Δ resonance model predicts a primordial π^-/π^+ ratio of $(\pi^-/\pi^+)_{\rm res} \equiv (5N^2 + NZ)/(5Z^2 + NZ) \approx (N/Z)^2_{\rm dense}$, where the N and Z are neutron and proton numbers in the participant region of the reaction. The π^-/π^+ ratio is thus a direct measure of the isospin asymmetry $(N/Z)_{\rm dense}$ of the dense matter formed. The latter is determined by the $E_{\rm sym}(\rho)$ through the dynamical isospin fractionation [40], namely, the high (low) density region is more neutron-rich (poor) with a lower $E_{\rm sym}(\rho)$ at suprasaturation densities. Since effects of the $E_{\rm sym}(\rho)$ are

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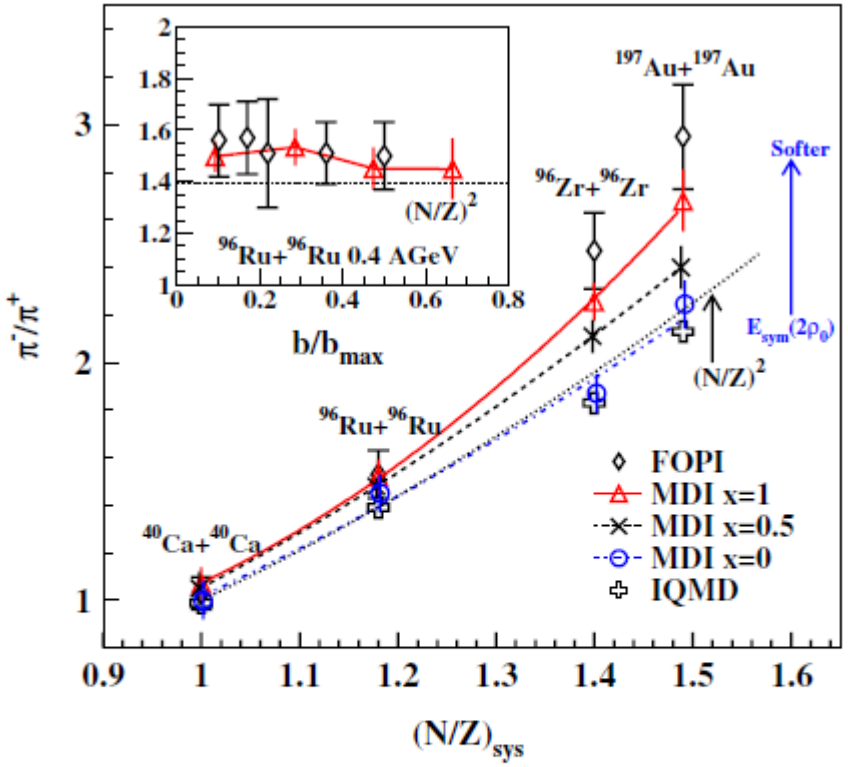

FIG. 2 (color online). The π^-/π^+ ratio as a function of the neutron/proton ratio of the reaction system at 0.4A GeV with the reduced impact parameter of $b/b_{max} \leq 0.15$. The inset is the impact parameter dependence of the π^-/π^+ ratio for the ^{96}Ru + ^{96}Ru reaction at 0.4A GeV.

PHYSICS REPORTS (Review Section of Physics Letters) 135, No. 5 (1986) 259–315. North-Holland, Amsterdam

PARTICLE PRODUCTION IN HIGH ENERGY NUCLEUS–NUCLEUS COLLISIONS

	π^+	π^0	π^-
nn	0	1	5
pp	5	1	0
np = pn	1	4	1

For collisions of identical nuclei, $N/Z^{\text{fireball}} = N/Z^{\text{proj}} = N/Z^{\text{targ}}$. We have N^2 nn collisions, Z^2 pp collisions and $2NZ$ collisions of np or pn type. The latter contribute to Δ production with half the weight of nn and pp because the np amplitude has a 50%, $T = \frac{1}{2}$ component, non-productive for single Δ formation. Summing with proper weights, we find

$$\frac{\sigma(\pi^-)}{\sigma(\pi^+)} = \frac{\langle \pi^- \rangle}{\langle \pi^+ \rangle} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2 . \tag{4.3}$$

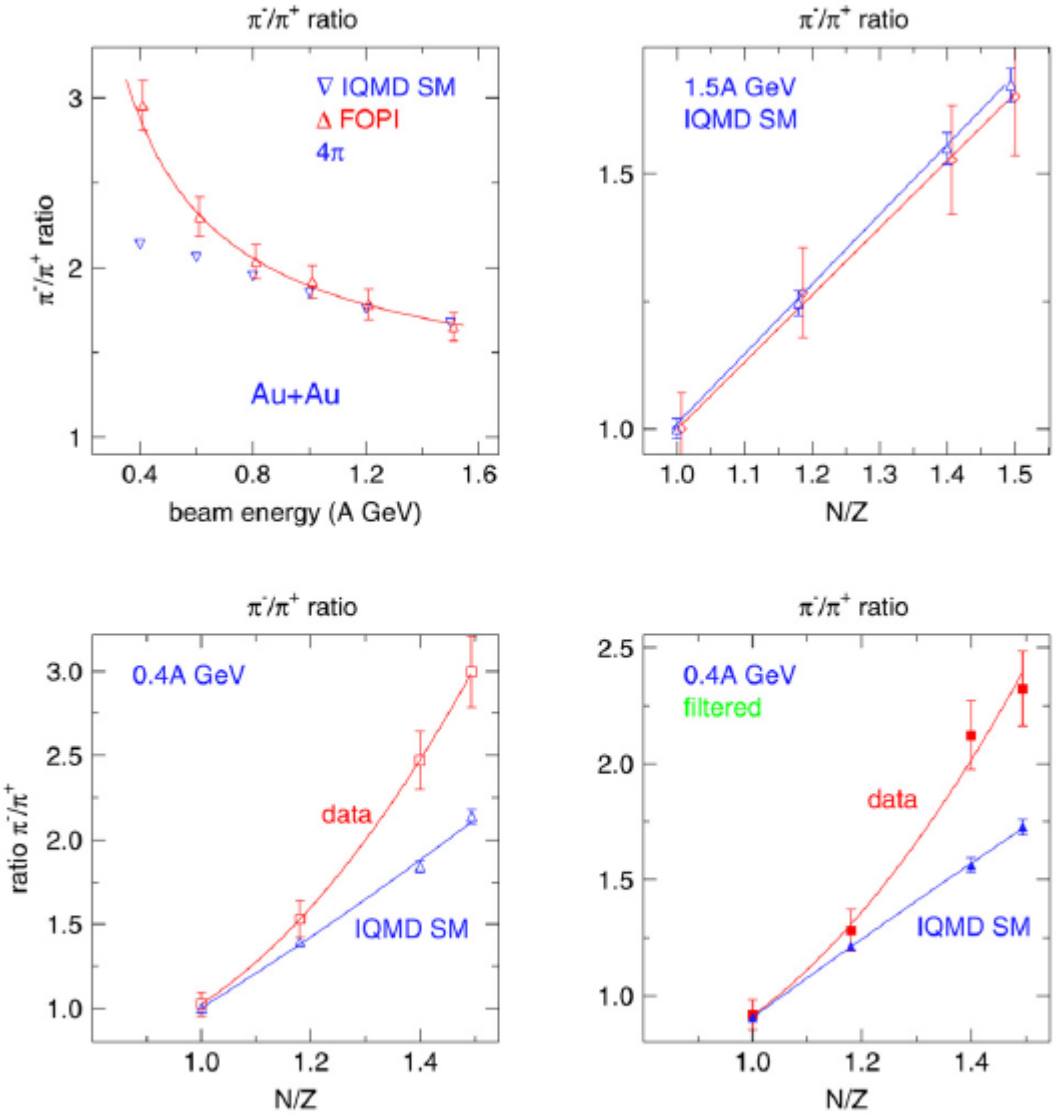

Fig. 25. Upper left panel: excitation function of the 4π-integrated ratio of π^-/π^+ yields in central Au + Au collisions. The experimental data are joined by a least squares fit of the function $c_0 + c_{-1}(E/A)^{-1}$ excluding the lowest energy point. The IQMD SM prediction (triangles) is also given. Upper right and lower left panels: the N/Z dependence at 1.5 A, respectively 0.4 A GeV of the π^-/π^+ ratio. The solid lines are least squares fits of linear or quadratic (N/Z) dependence. Lower right panel: same as lower left panel, but for filtered data.

Physics Letters B 683 (2010) 140–144

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Probing high-density behavior of symmetry energy from pion emission in heavy-ion collisions

Zhao-Qing Feng*, Gen-Ming Jin

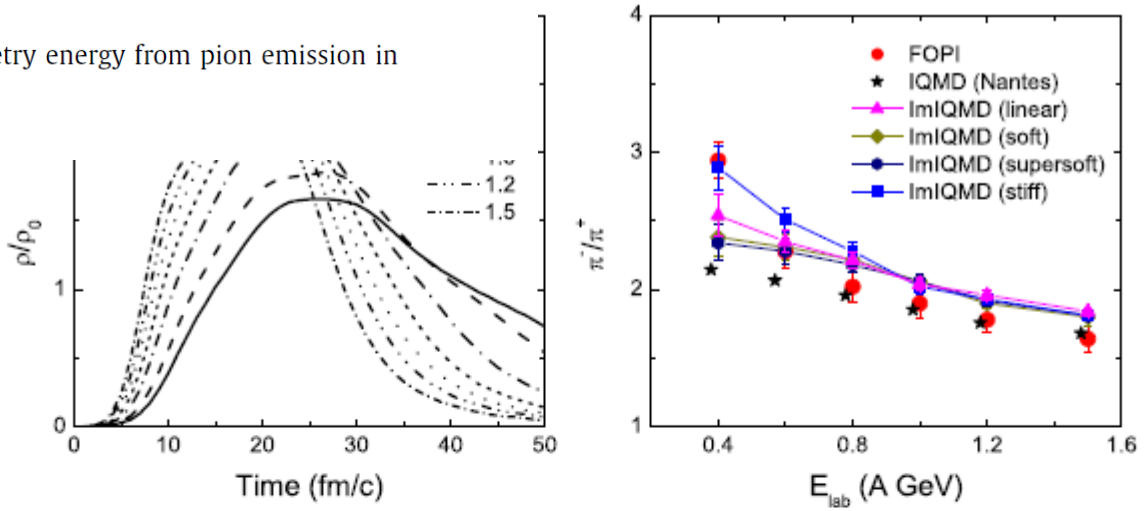

Fig. 3. Evolution of average central density at different incident energies (left panel) and the excitation functions of the π^-/π^+ ratios at different stiffness of the symmetry energy (hard, linear, soft and supersoft), and compared with IQMD results [10] as well as the FOPI data [3] (right panel).

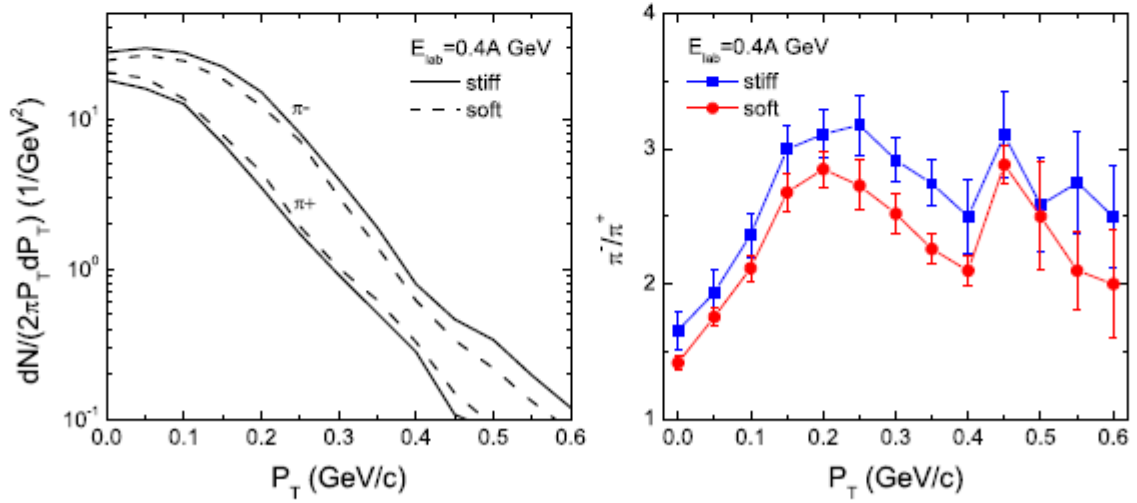

Fig. 4. Distributions of transverse momentum of final π^- and π^+ and the ratio π^-/π^+ for the cases of stiff and soft symmetry energies in the reaction $^{197}Au + {}^{197}Au$ at incident energy $E_{lab} = 0.4$ A GeV.

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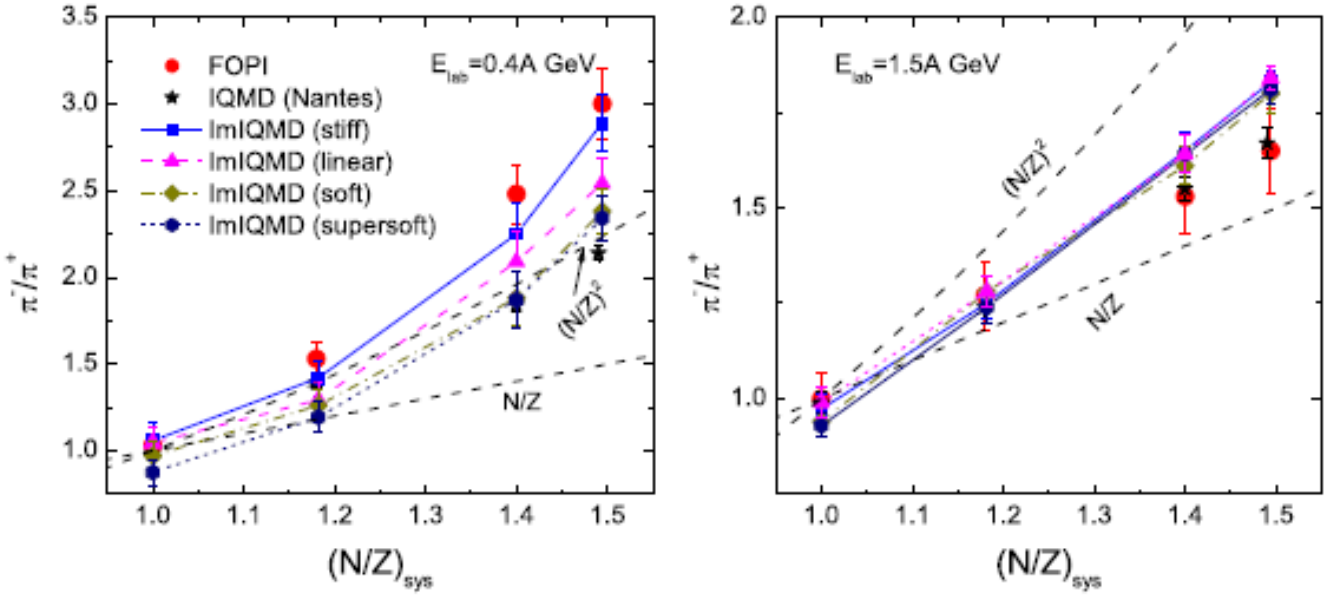


Fig. 5. The π^-/π^+ yields as a function of the neutron over proton N/Z of reaction systems for head on collisions at incident energy $E_{\rm lab} = 0.4$ A GeV and 1.5 A GeV, respectively.

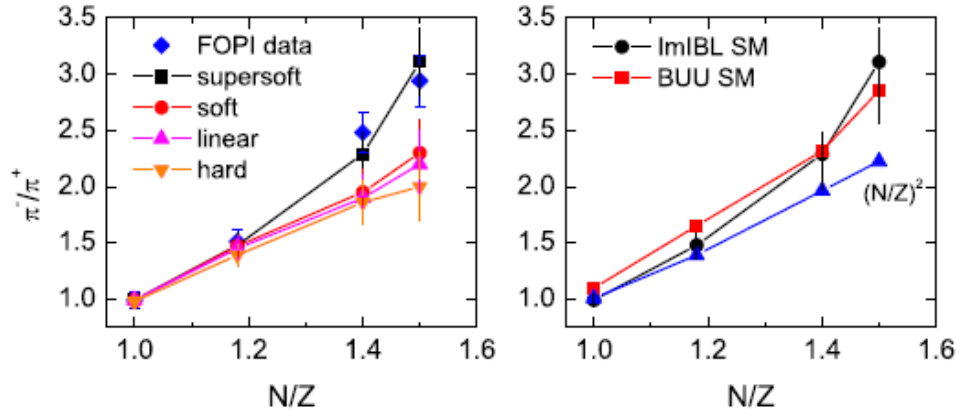


Fig. 3. (Color online.) The π^-/π^+ ratio as a function of the neutron/proton ratio of reaction systems for central ^{40}Ca + ^{40}Ca, ^{96}Ru + ^{96}Ru, ^{96}Zr + ^{96}Zr and ^{197}Au + ^{197}Au collisions at 400A MeV. The results are calculated by different stiffness of the symmetry energy using the ImIBL model with the SM (left panel) and different transport theories (right panel).

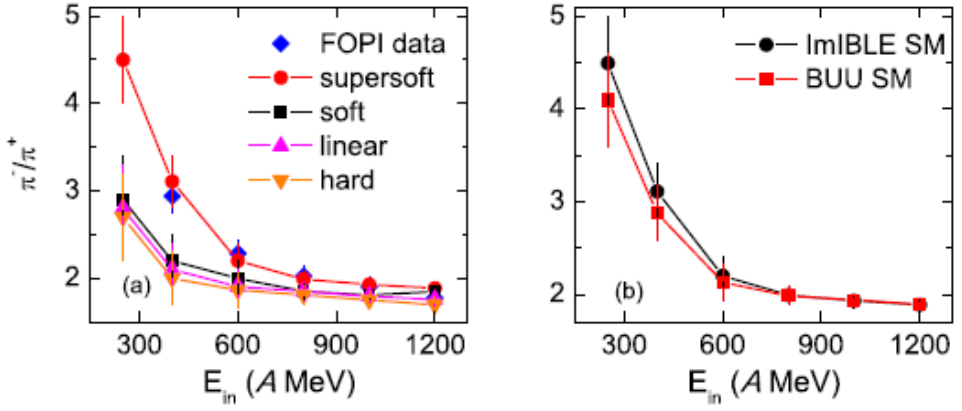
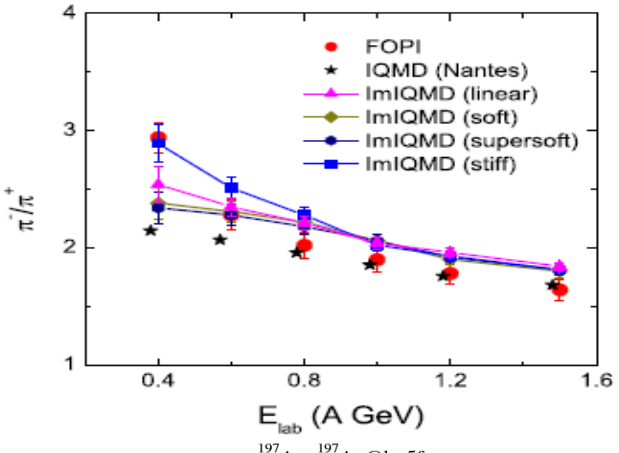


Fig. 4. (Color online.) Excitation functions of the π^-/π^+ ratio in central ^{197}Au + ^{197}Au collisions for different stiffness of the symmetry energy using the ImIBL model with the SM (left panel) and different transport theories (right panel).

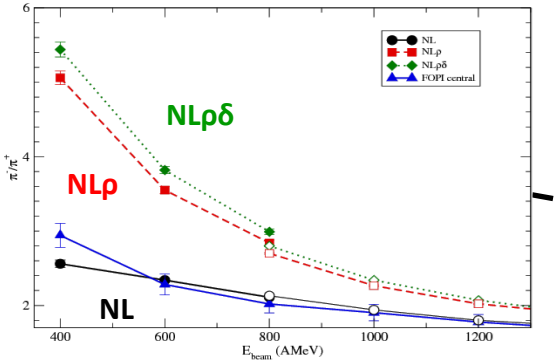
High densities: π^-/π^+ ratio

FOPI Data,

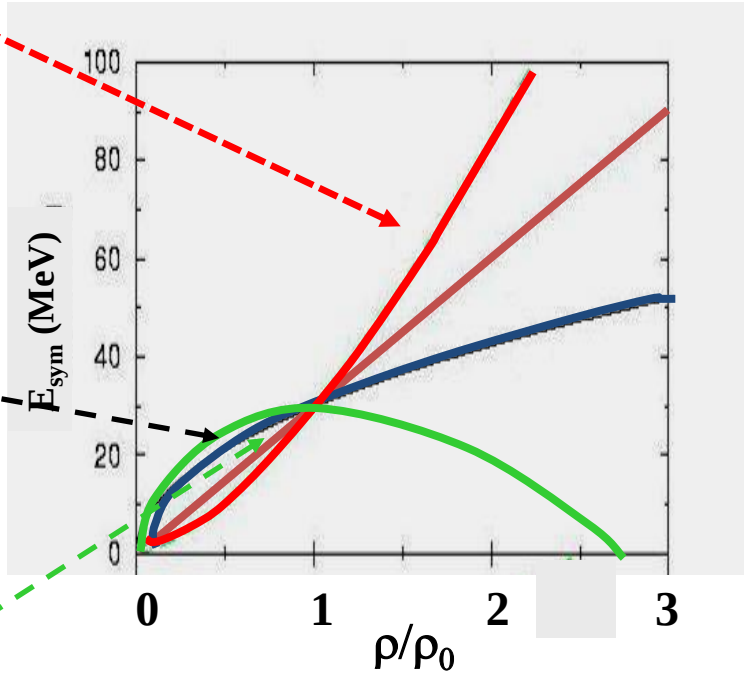
W.Reisdorf et al. NPA781 (2007)

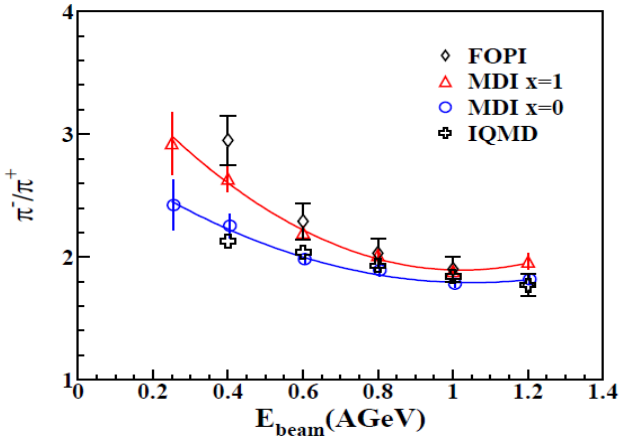


Z.Q. Feng, PLB 683 (2010)



Ferini, at al., NPA 762 (05)





Z. Xiao et al., PRL 102 (09)

Pion ratio->High densities???:

Inconsistent with each

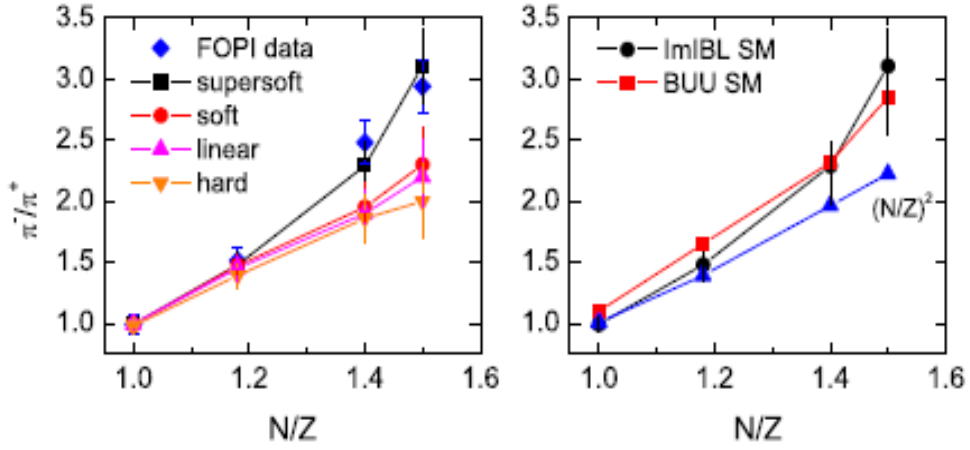


Fig. 3. (Color online.) The π^-/π^+ ratio as a function of the neutron/proton ratio of reaction systems for central $^{40}Ca + {}^{40}Ca$, $^{96}Ru + {}^{96}Ru$, $^{96}Zr + {}^{96}Zr$ and $^{197}Au + {}^{197}Au$ collisions at 400A MeV. The results are calculated by different stiffness of the symmetry energy using the ImIBL model with the SM (left panel) and different transport theories (right panel).

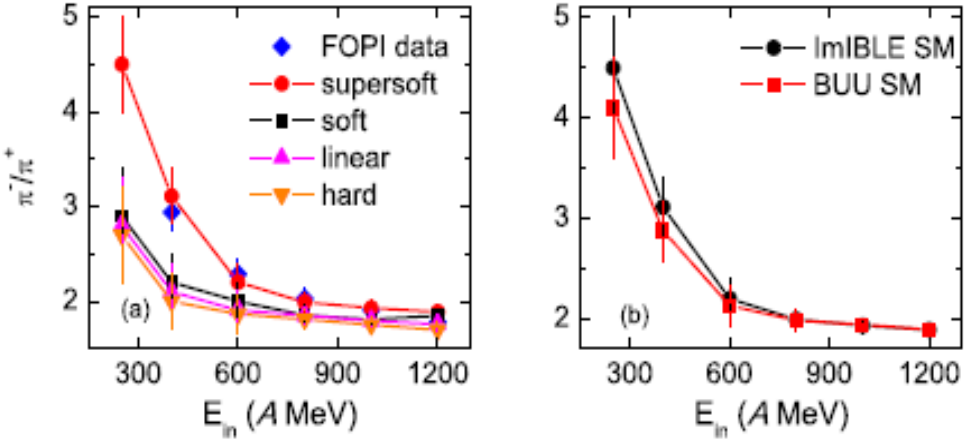
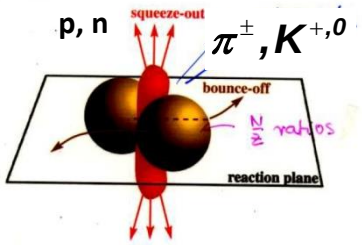


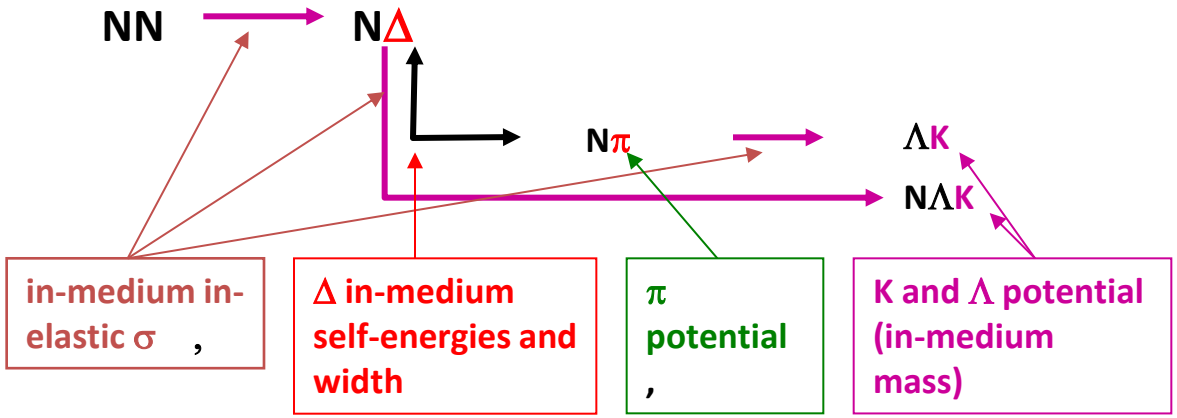
Fig. 4. (Color online.) Excitation functions of the π^-/π^+ ratio in central $^{197}Au + {}^{197}Au$ collisions for different stiffness of the symmetry energy using the ImIBL model with the SM (left panel) and different transport theories (right panel).

High-density Symmetry Energy: Particle Production

Difference in neutron and proton potentials



1. „direct effects“: difference in proton and neutron (or light cluster) emission and momentum distribution
2. „secondary effects“: production of particles, isospin partners $\pi^{-,+}$, $K^{0,+}$



1. Mean field effect: U_{sym} more repulsive for neutrons, and more for asystiff
→ pre-equilibrium emission of neutron, reduction of asymmetry of residue

$$\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

decrease with asy – stiffness

2. Threshold effect, in medium effective masses:
→ m^*_N, m^*_Δ, contribution of symmetry energy; m^*_K, models for K-potentials

$$\sigma = \sigma(s_{in} - s_{th})\ \frac{\pi^-}{\pi^+}\uparrow$$ *increase with asy – stiffness*

s_{thres} independent of isospin, due to simple model of Δ self energies

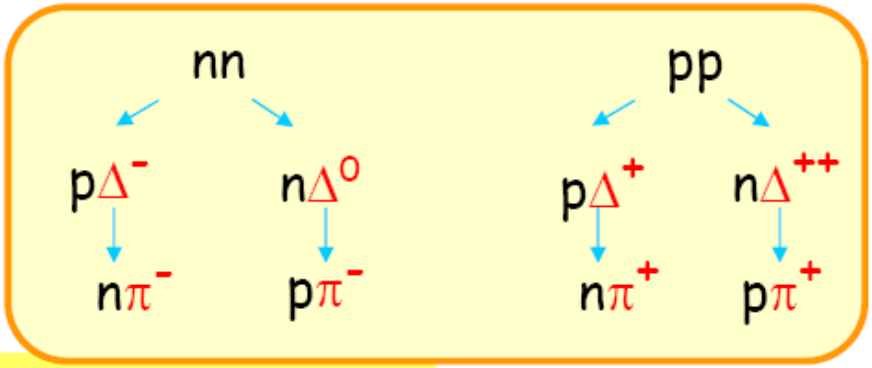
$$\Sigma_i(\Delta^-) = \Sigma_i(n)$$
$$\Sigma_i(\Delta^0) = \frac{2}{3}\Sigma_i(n) + \frac{1}{3}\Sigma_i(p)$$
$$\Sigma_i(\Delta^+) = \frac{1}{3}\Sigma_i(n) + \frac{2}{3}\Sigma_i(p)$$
$$\Sigma_i(\Delta^{++}) = \Sigma_i(p) \quad ,$$

G.Ferini et al.,PRL 97 (2006) 202301

PION PRODUCTION

G.Ferini et al., NPA 762 (2005) 147, NM Box
PRL 97 (2006) 202301, HIC

Main mechanism $NN \Rightarrow N\Delta \rightarrow \pi N$



$$\Rightarrow \frac{\pi^-}{\pi^+}$$

n→p "transformation"

Vector self energy more repulsive for neutrons and more attractive for protons

1. C.M. energy available: "threshold effect"

$$\varepsilon_{n,p} = E^*_{n,p} + f_\omega \rho_B \mp f_\rho \rho_{B3} \longrightarrow \begin{matrix} s_{nn}(NL) < s_{nn}(NL\rho) < s_{nn}(NL\rho\delta) \\ s_{pp}(NL) > s_{pp}(NL\rho) > s_{pp}(NL\rho\delta) \end{matrix}$$

π(-) enhanced
π(+) reduced

2. Fast neutron emission: "mean field effect"

$$\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow \Rightarrow decrease: NL \rightarrow NL\rho \rightarrow NL\rho\delta$$

Some compensation in "open" systems, HIC, but "threshold effect" more effective, in particular at low energies

No evidence of Chemical Equilibrium!!

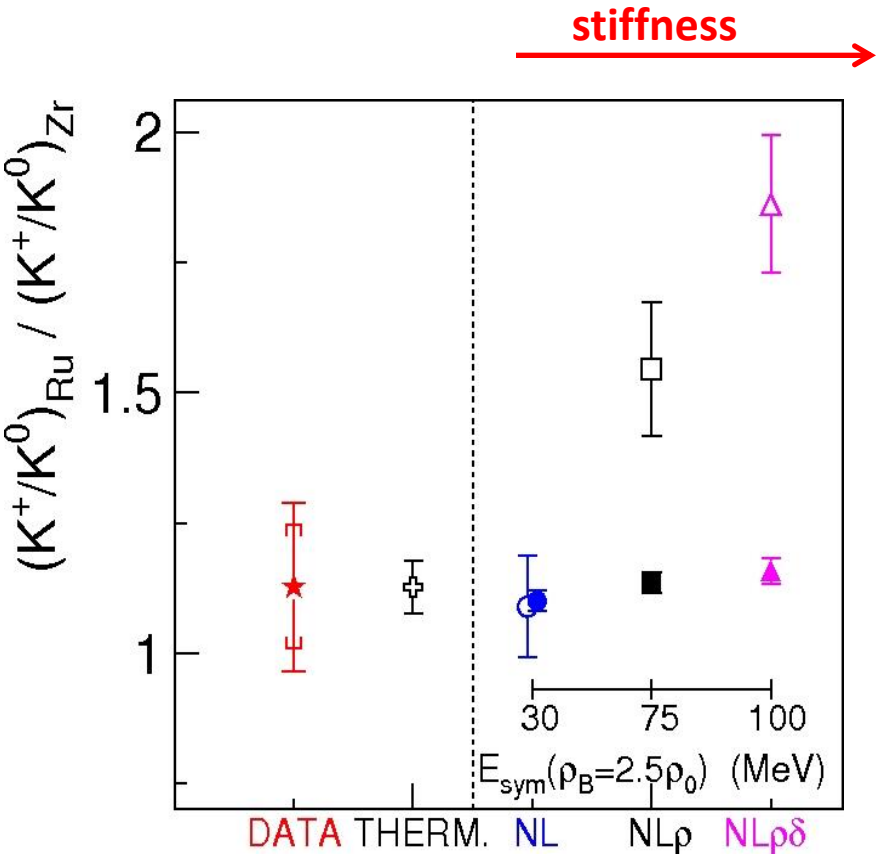
Esym at high density: kaons

RMF calculations

INM: T=60 MeV and $\rho_B=2.5\rho_0$

RBUU: transport simulation

Ru+Ru and Zr+Zr
1.5 AGeV



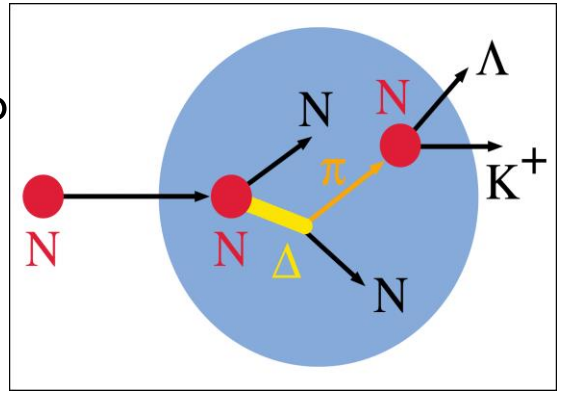
- higher sensitivity at lower energies
- requires excellent kaon identification and long beam times

X. Lopez et al. 2007

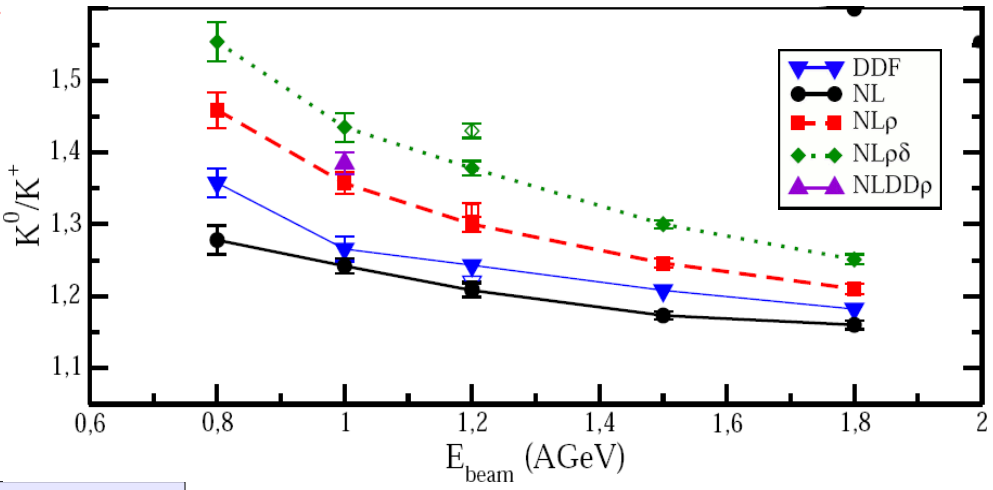
From IWM 2011 – Y. Leifels

Esym at high density: kaons

Kaon productio



stiffness



- Production of kaons at energies below the pp production threshold

$$\sigma(NN \to K^+ + \Lambda + N) = 1.6($$
$$NN \to K^- + K^+ + NN) = 2.!$$

- Multistep production process
- Sensitive to isospin of the primary collision partners
- K^+/K^0 ratio sensitive to EOS

Ferini et al., PRL 97, 202301 (2006)

RMF calculations

INM: T=60 MeV and $\rho_B=2.5\rho_0$

RBUU: transport simulation

From IWM 2011 - Y. Leifels

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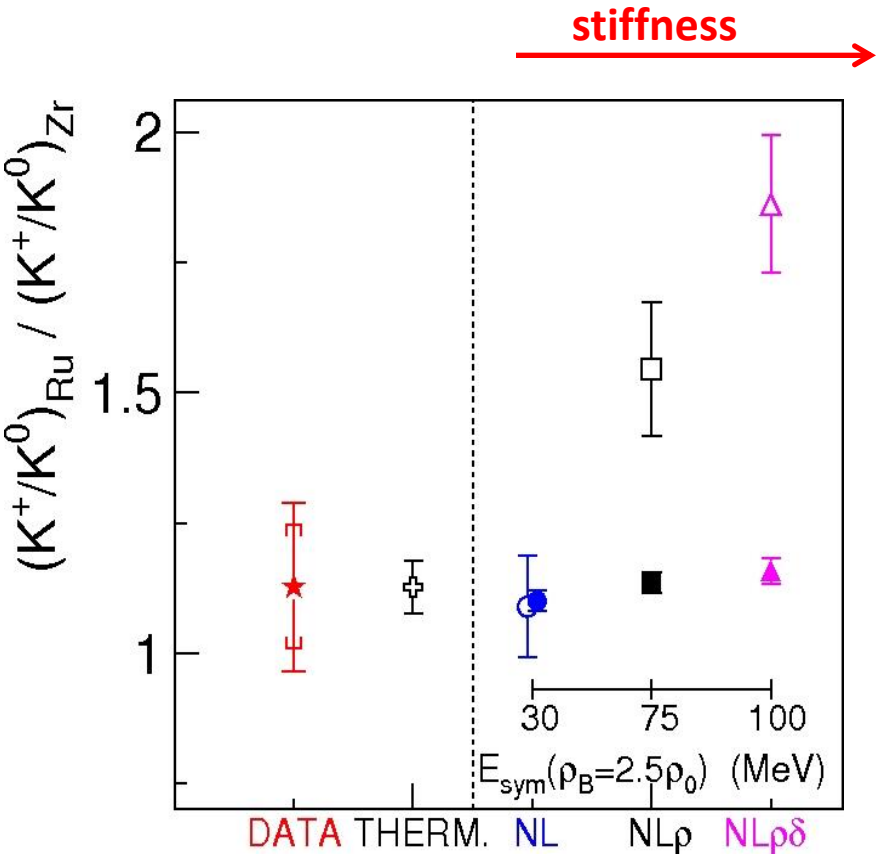
Ru+Ru and Zr+Zr
1.5 AGeV

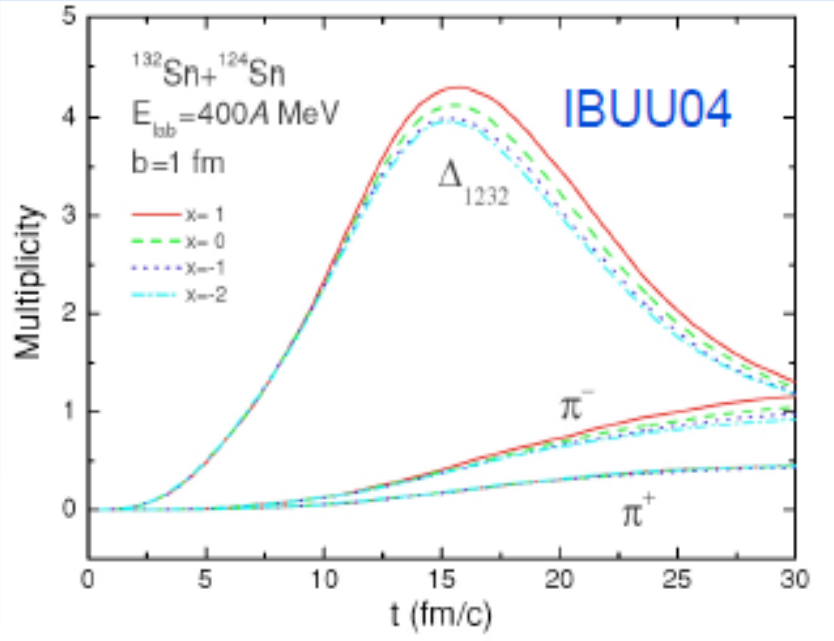


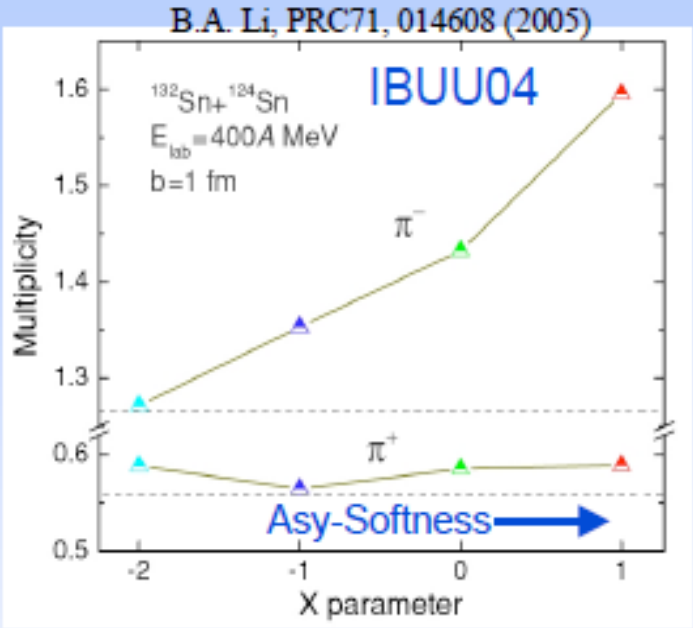
- higher sensitivity at lower energies
- requires excellent kaon identification and long beam times

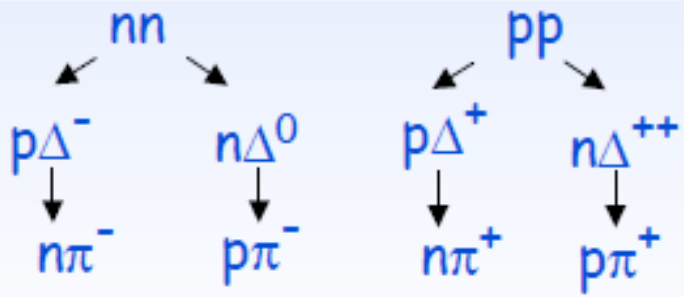
X. Lopez et al. 2007

From IWM 2011 – Y. Leifels

Meson production: Pions





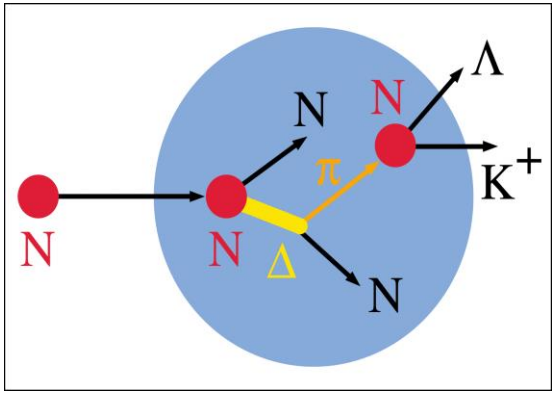


π-/π+ sensitive to $E_{sym}(\rho)$ at high ρ

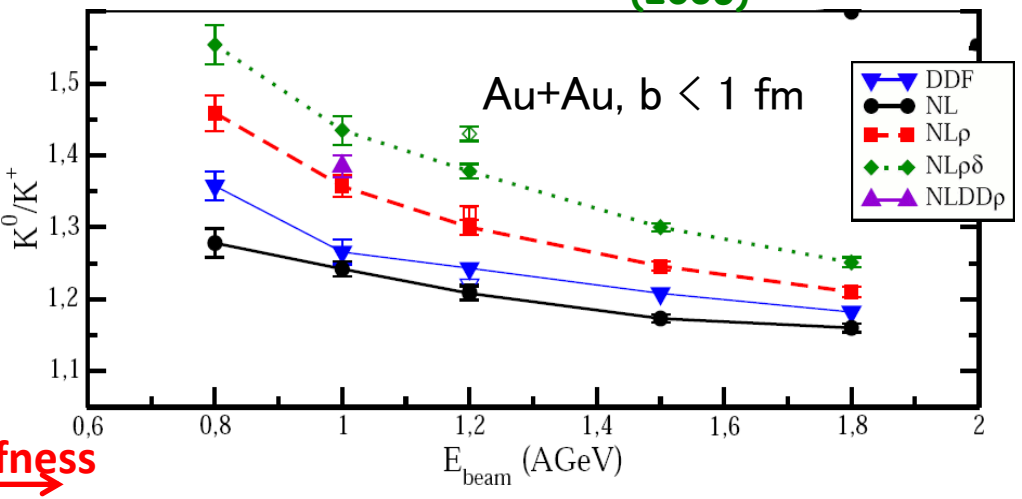
NN collisions in high density regions

π–/π+ reflecting the $(N/Z)_{dense}$

Esym at high density: kaons



Ferini et al., PRL 97, 202301 (2006)



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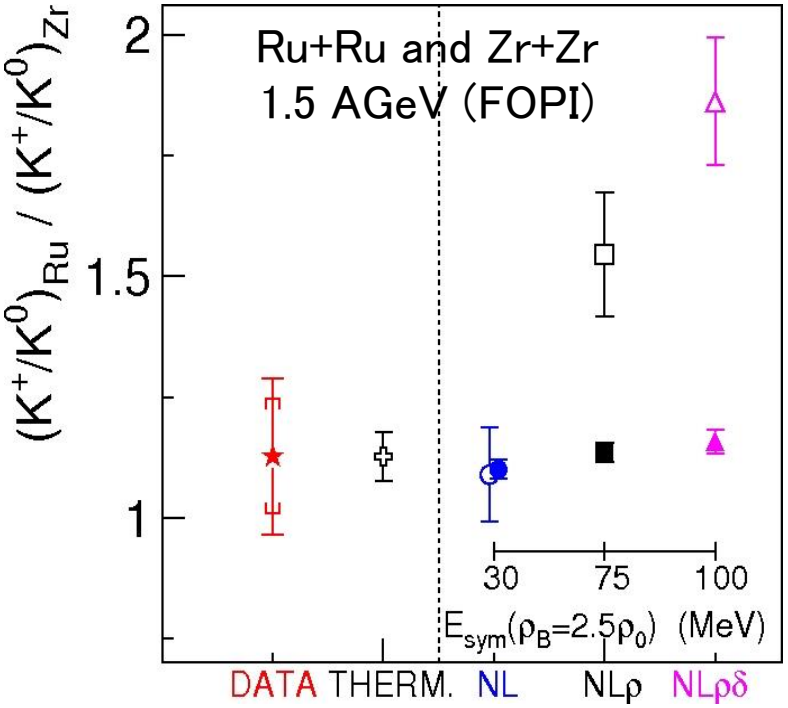

X. Lopez et al. 2007

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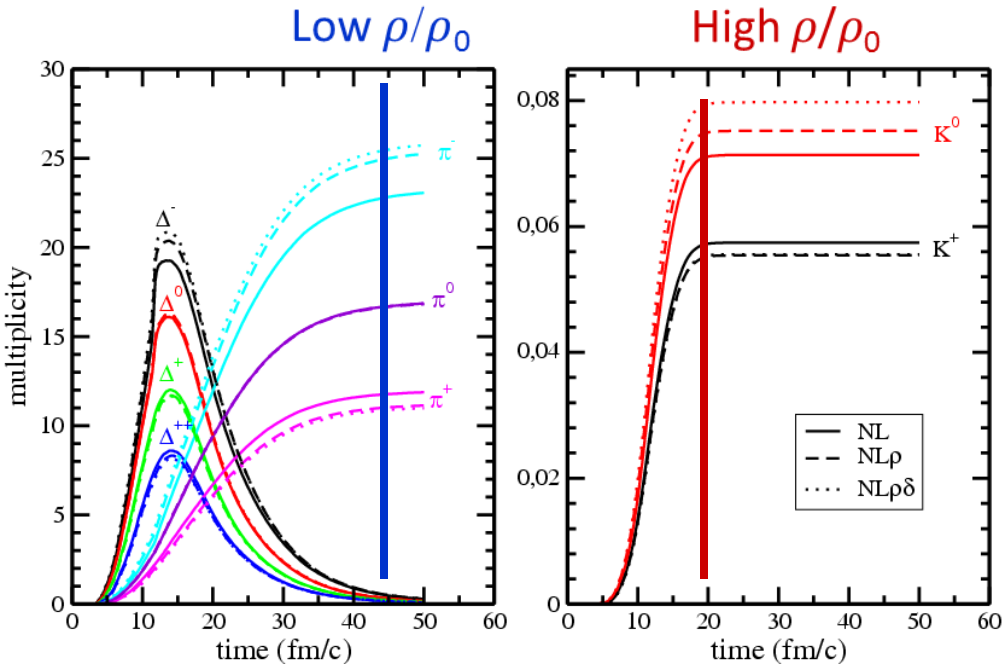
From IWM 2011 – Y. Leifels

Pion and Kaon freeze-out in HIC

π^+, π^-



K^+, K^0

Ferini et al., PRL97, 202301

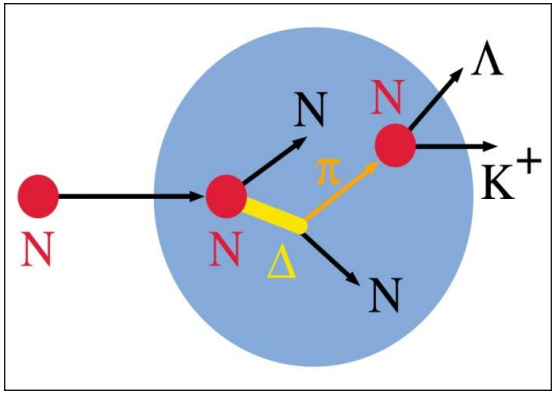
Warning with pions:

- Strongly interacting in medium
- Freeze-out at late times (low ρ/ρ_0)
- Difficult to isolate π+ and π- produced in the high density stage

Kaons: more sensitive probes?

- Higher thresholds
- Weakly interacting in medium
- Freeze-out already at 20 fm/c: more reliable as high ρ probes

Esym at high density: kaons



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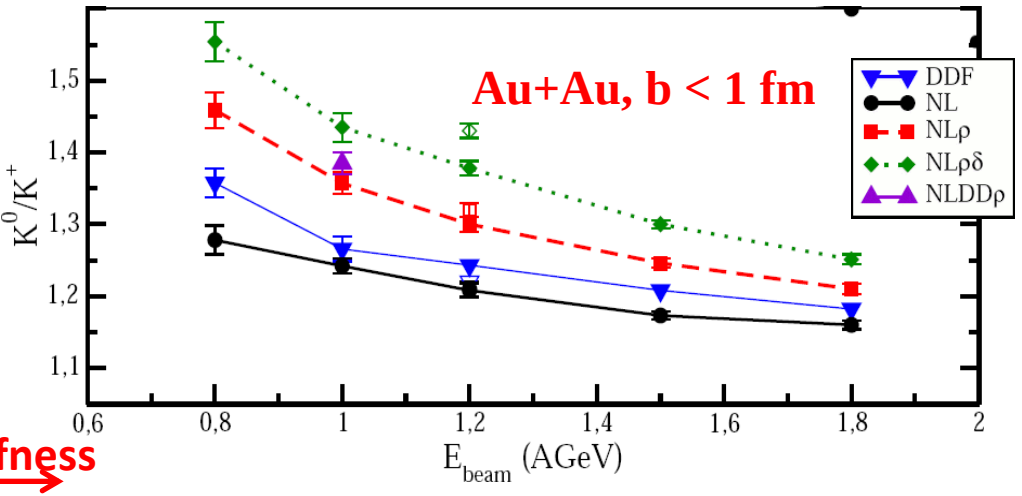

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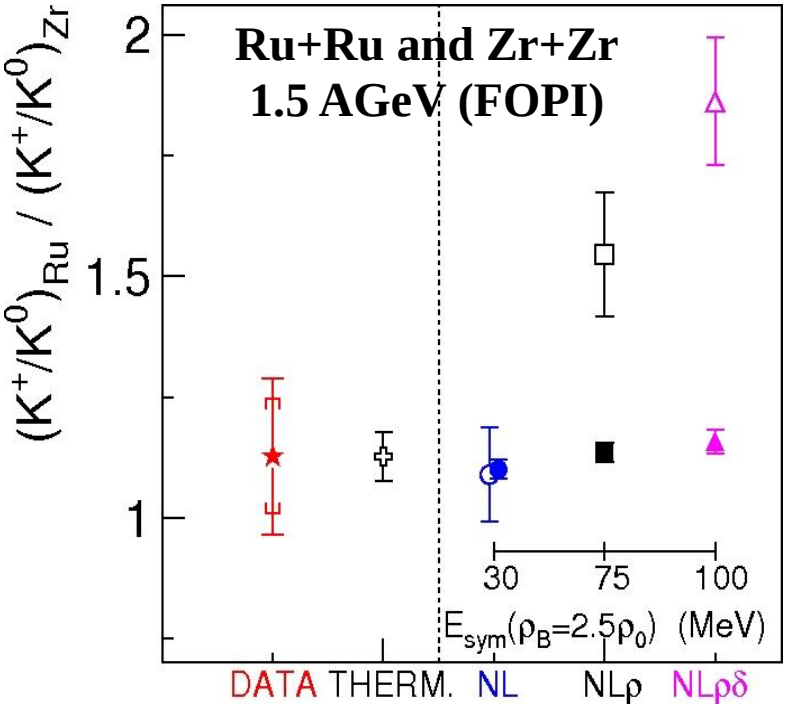

X. Lopez et al. 2007

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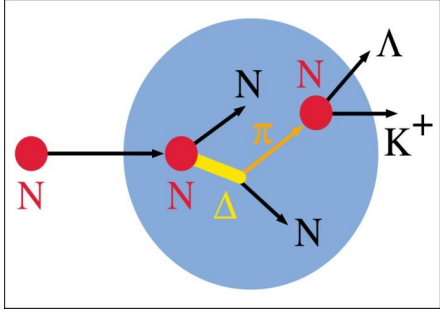

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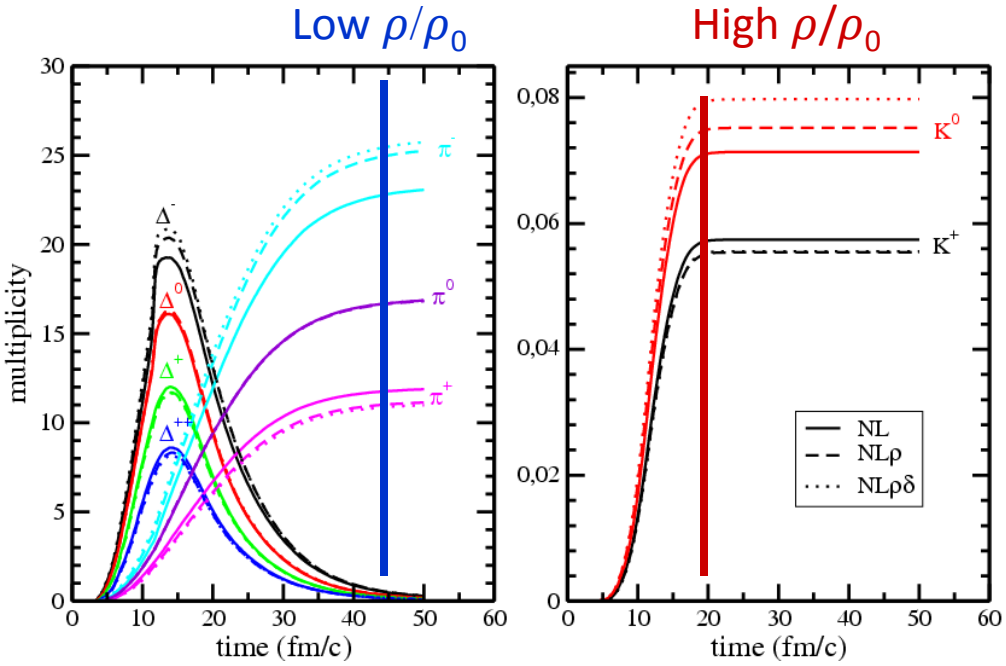

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RBUU, Ferini et al., PRL97, 202301

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