Enrico De Filippo (INFN Catania) for the NEWCHIM collaboration

*Sensitivity of N/Z ratio in projectile break-up of isobaric systems: a new probe for **symmetry energy** ?*

Physics case: competition between dynamical and statistical IMFs production.

Influence of the N/Z ratio of the entrance channel in the dynamical fission of the quasi-projectile: enhanced cross-section for dynamical emission for the system with higher N/Z

The new data of InKiIsSy experiment (Inverse Kinematics Isobaric Systems), $^{124}Xe+^{64}Zn,^{64}Ni$ at 35 A.MeV complements the previous ones: TimeScale $^{64,58}Ni + ^{124,112}Sn$ (direct) and $^{124,112}Sn+^{64,58}Ni$ (inverse) kinematics .

First "InKiIsSy" experiment results

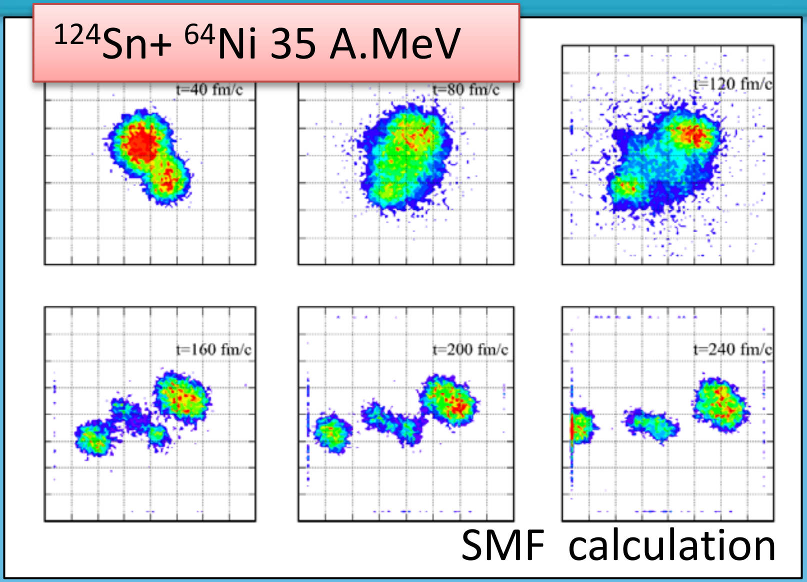
Constrained Molecular Dynamics (CoMD-3) simulations (preliminary)

Perspectives with radioactive beams below Fermi energies (E/A<15 A.MeV) .

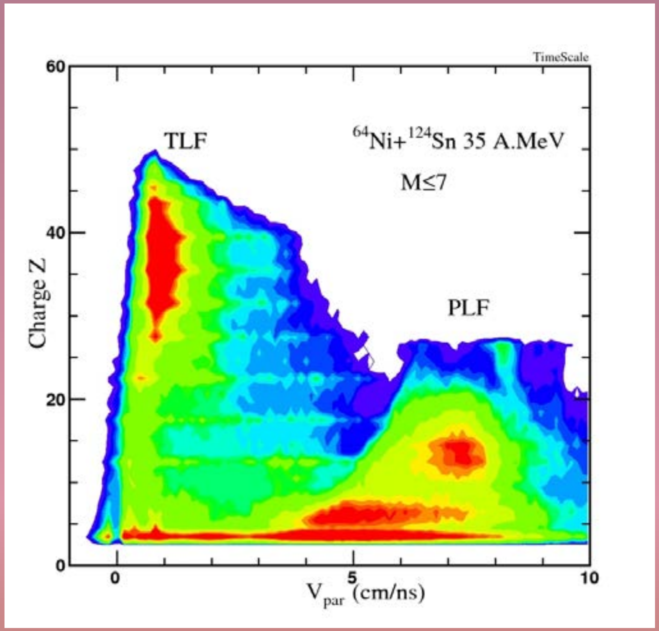
NUSYM15
5th INTERNATIONAL SYMPOSIUM ON NUCLEAR SYMMETRY ENERGY

In "Timescale" and "Inkiissy" experiments we mainly look at:

1) The "**neck**" emission where light IMFs (Z<≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density ("neck"). This is generally a **FAST** process (<100 fm/c)



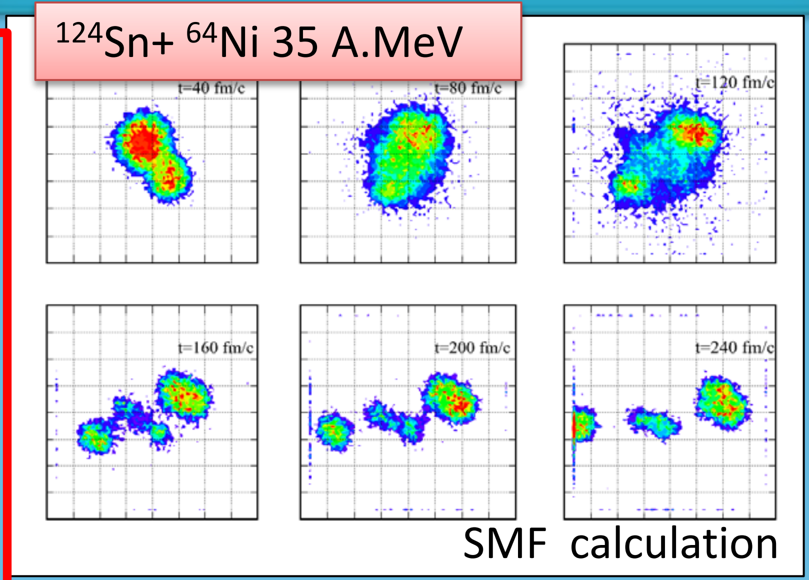
2) Excitation of a primary Projectile-like PLF* (TLF*) followed by its dynamical (non-equilibrated) asymmetrical splitting (**dynamical fission**). In this case emission of the **lighter IMF** is preferentially backwards in the PLF reference system.



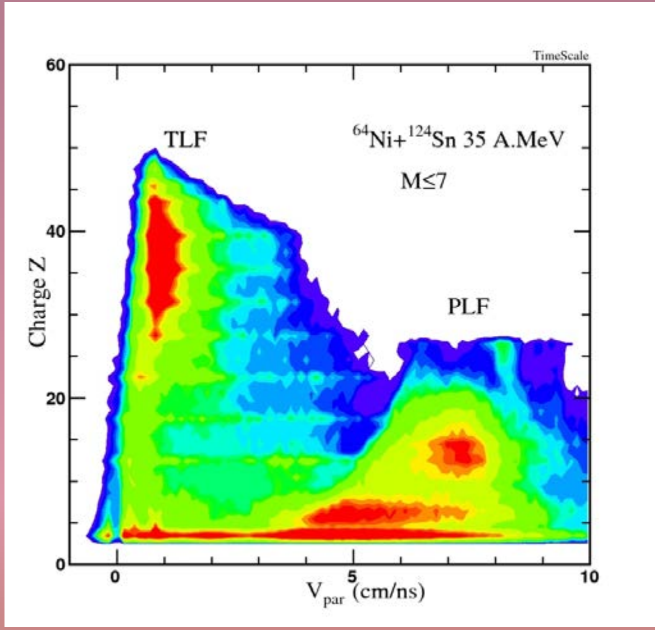
Role of **N/Z of entrance channel** in the reaction mechanisms

In “Timescale” and “Inkiissy” experiments we mainly look at:

1) The “**neck**” emission where light IMFs (Z<≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density (“neck”). This is generally a **FAST** process (<100 fm/c)

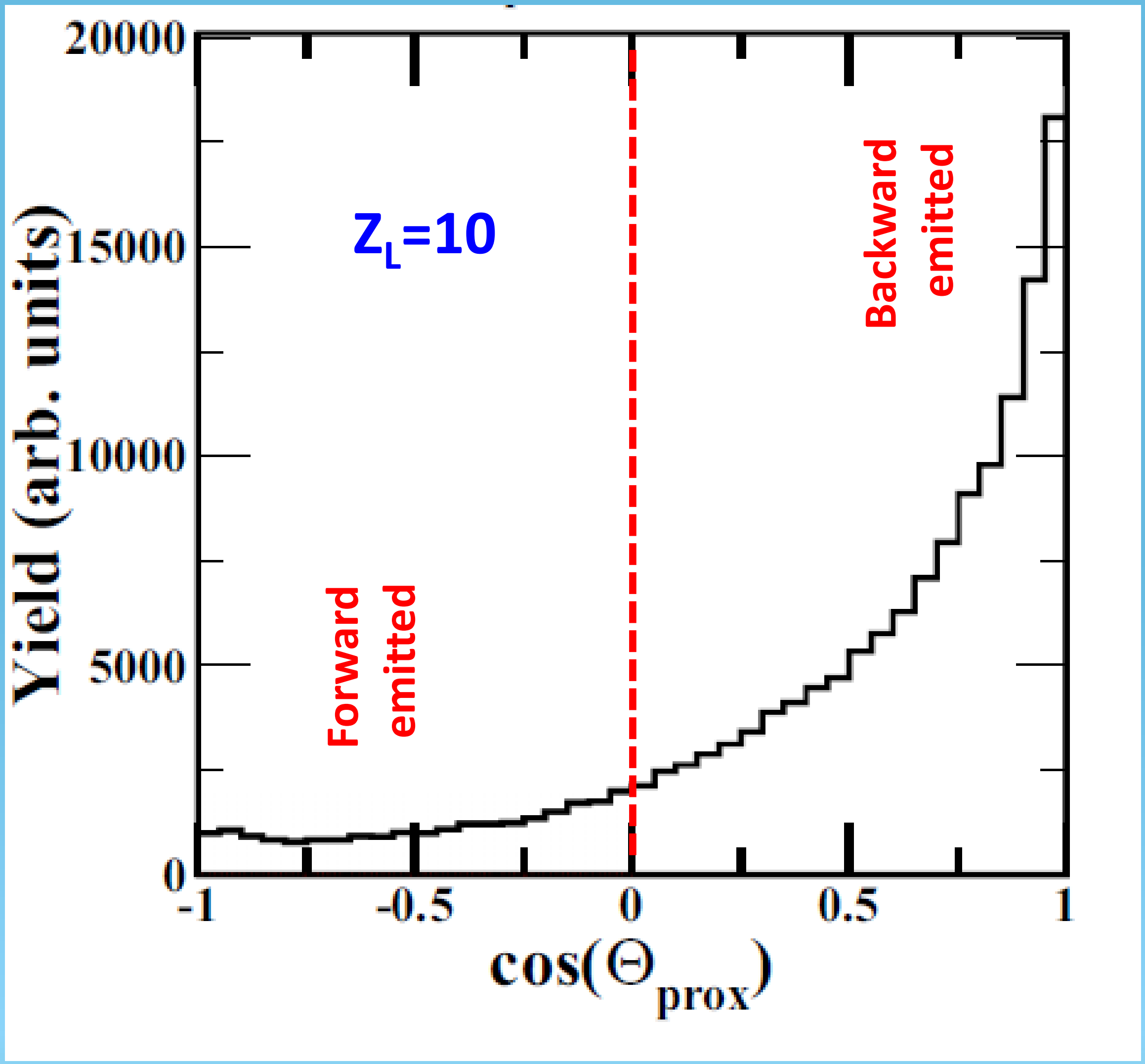


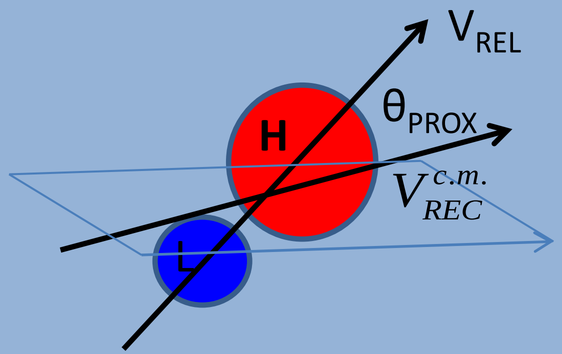
2) Excitation of a primary Projectile-like PLF* (TLF*) followed by its dynamical (non-equilibrated) asymmetrical splitting (**dynamical fission**). In this case emission of the **lighter IMF** is preferentially backwards in the PLF reference system.

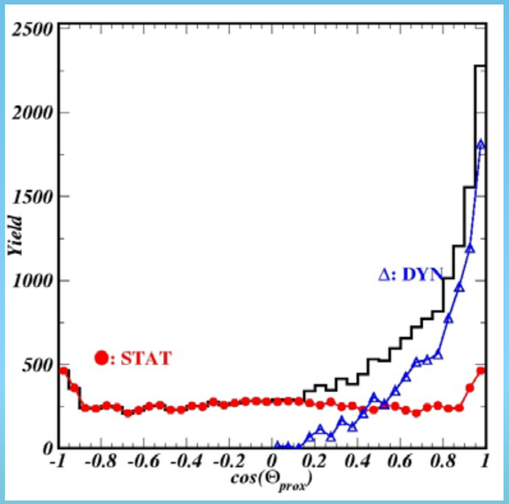


Role of N/Z of entrance channel in the reaction mechanisms

METHOD: disentangling dynamical vs. statistical emission: Angular Distributions





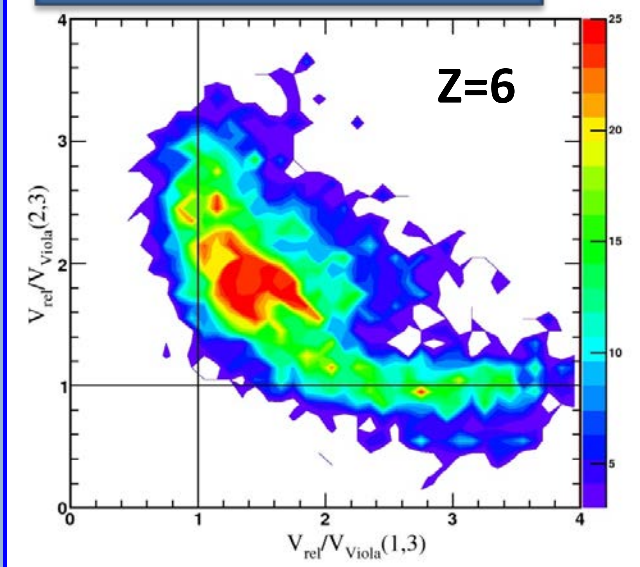


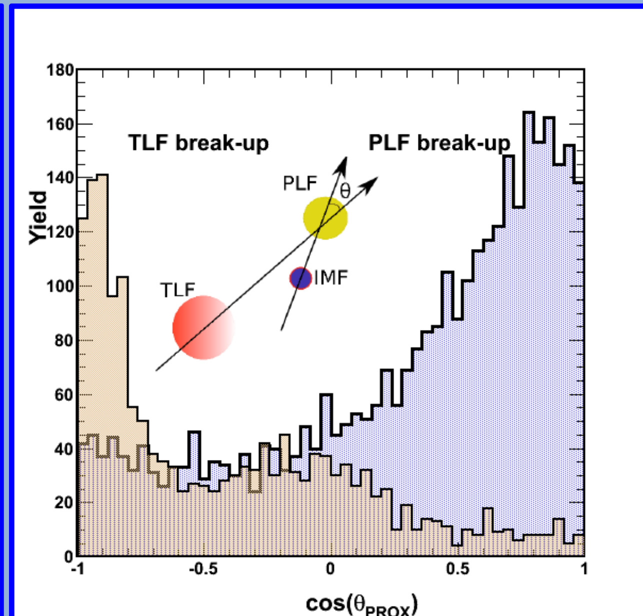
See also P. Russotto et al. PRC **91**, 014619 (2015)

S. Hudan et al., PRC **86** 021603(R) (2012)

Disentangling dynamical vs. statistical emission in **ternary** events

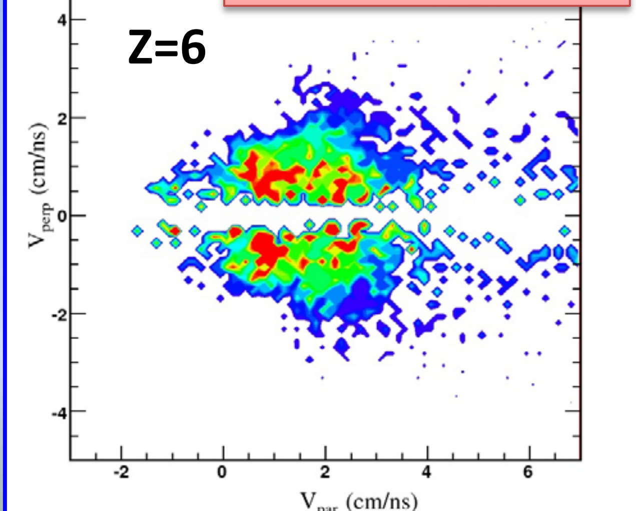
$^{64}Ni+^{124}Sn$ 35 A.MeV

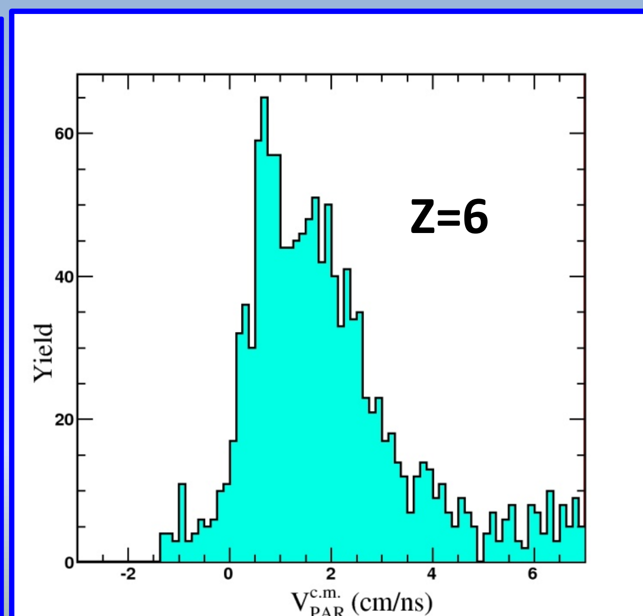


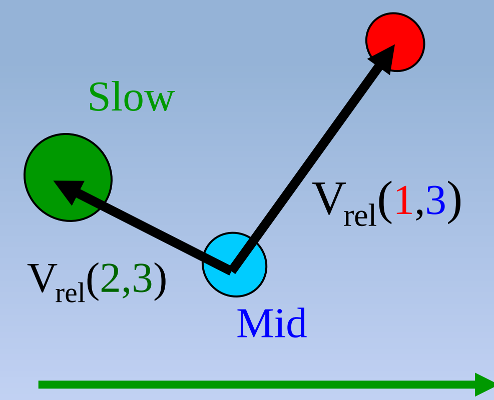


- $\cos(\theta)\approx\pm1$
- aligned emission of the lighter fragment in the backward emisphere of **PLF** (+1) and **TLF** (-1) towards midrapidity

abs(cos(θ_{PROX})>0.8



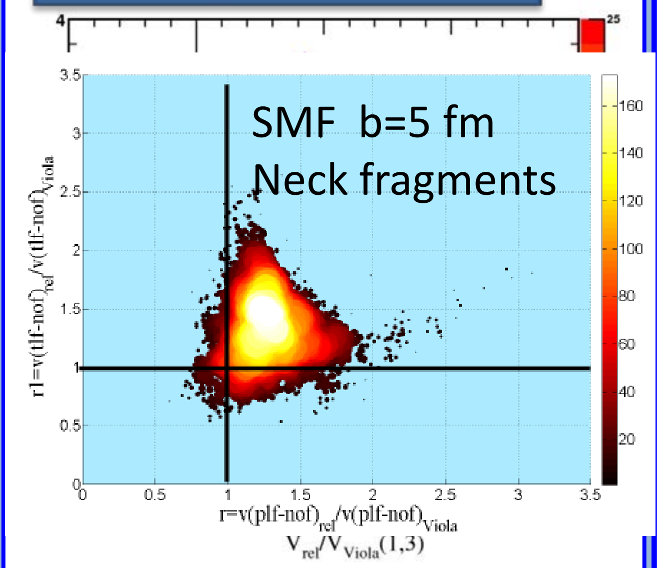


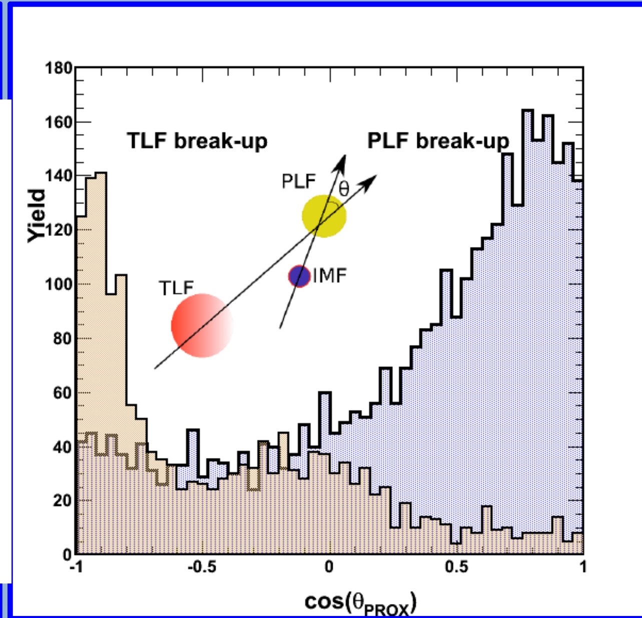


The three heaviest fragments are ordered according to decreasing value of parallel velocity.

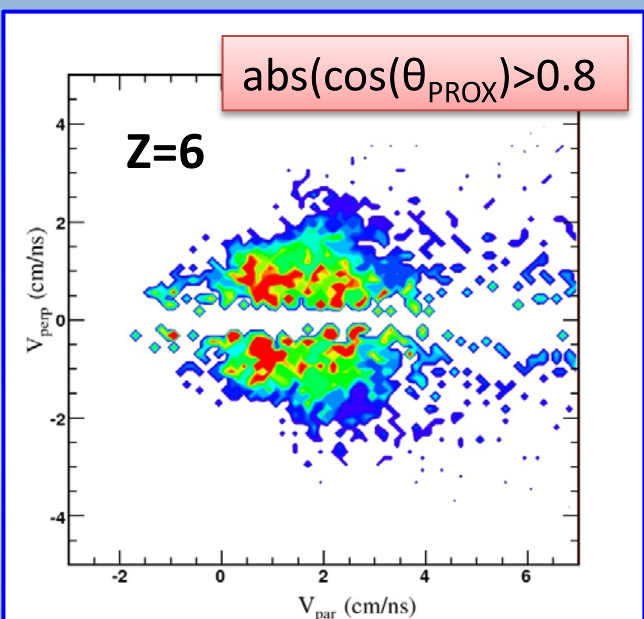
Disentangling dynamical vs. statistical emission in **ternary** events

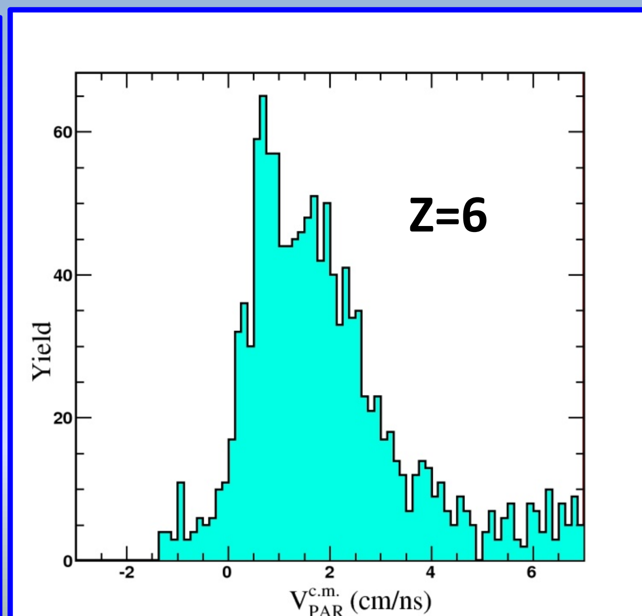
^{64}Ni+^{124}Sn 35 A.MeV

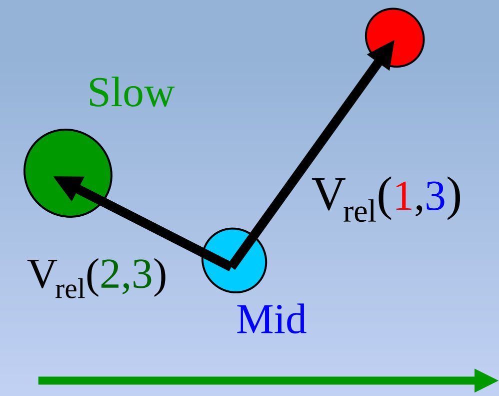




cos(θ)≈±1
aligned emission of the lighter fragment in the backward emisphere of **PLF** (+1) and **TLF** (-1) towards midrapidity



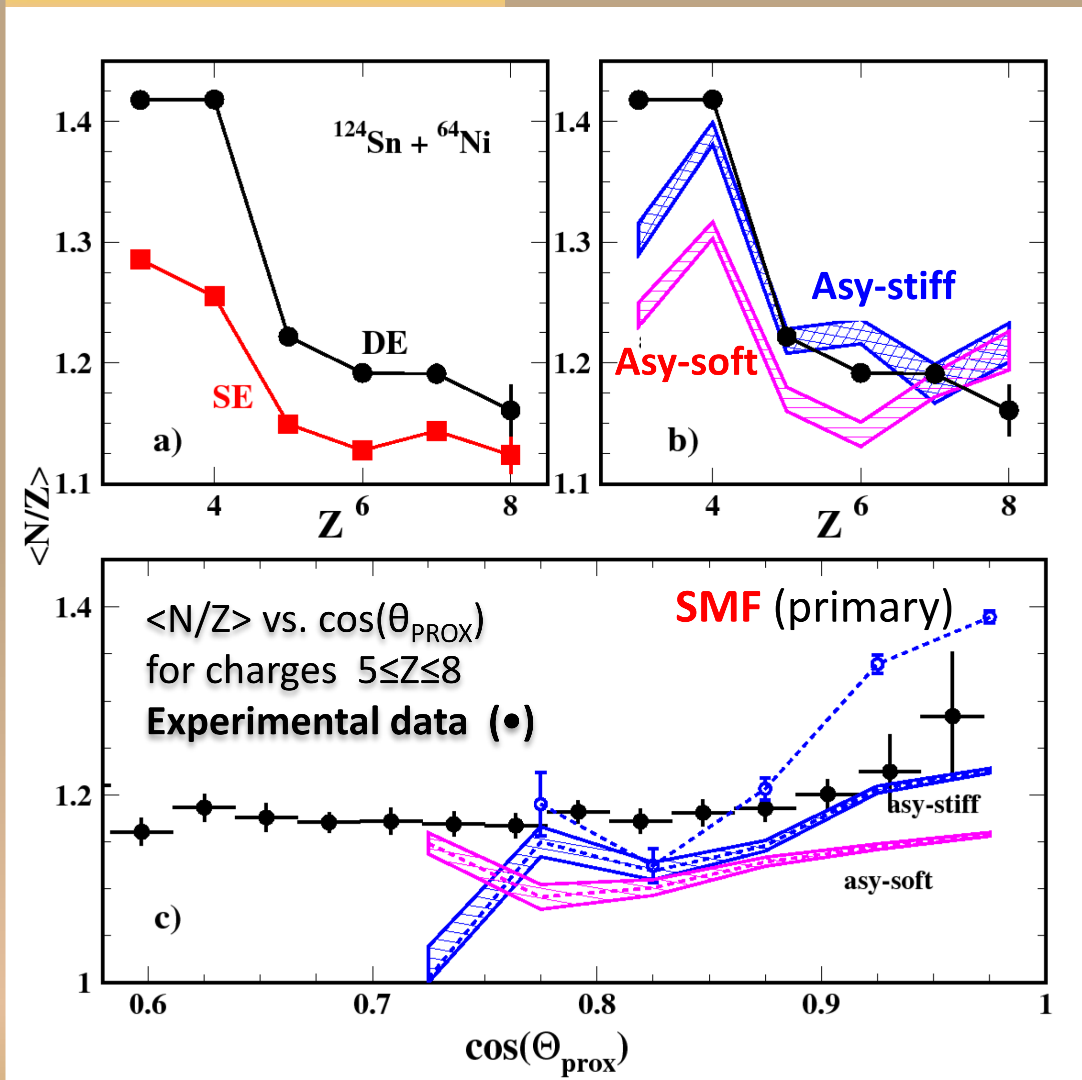




The three heaviest fragments are ordered according to decreasing value of parallel velocity.

Neck emission and Symmetry term of EoS

$^{124}Sn+^{64}Ni$ 35 A.MeV



E.d.F. et al, Phys. Rev. C ***86*** *014610 (2012)*

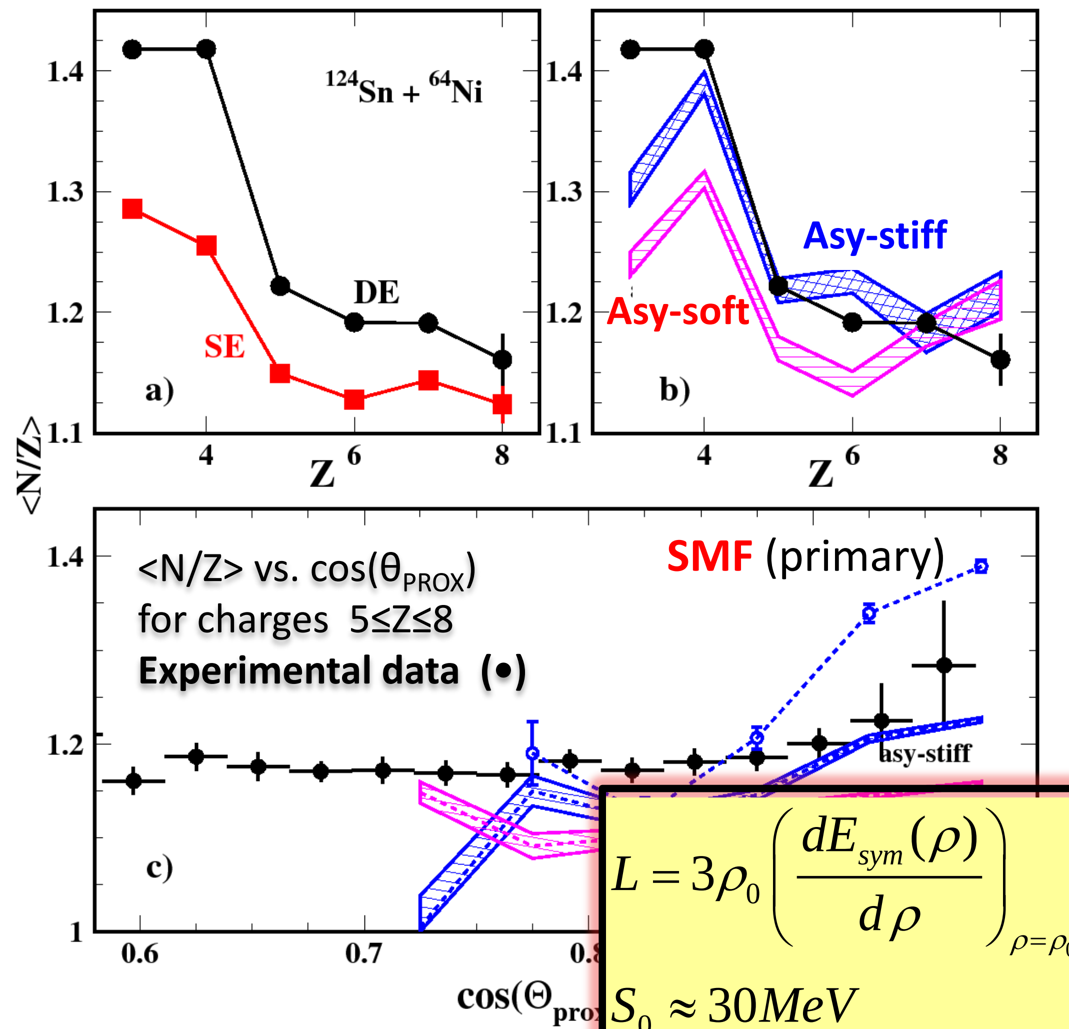
Experimental <N/Z> distribution of IMFs as a function of their atomic number compared with results SMF+GEMINI calculations (hatchad area) for two different parametrizations of the symmetry potential (asy-soft and asy-stiff)

- ● Dynamically emitted particles
- ■ Statistically emitted particles

See also: S. Hudan et al., PRC **86** 021603(R), 2012.
K. Brown et al., PRC **87** 061601(R) 2013.
K. Stiefel et al. PRC90 061605 (2014)

Neck emission and Symmetry term of EoS

$^{124}Sn+^{64}Ni$ 35 A.MeV



E.d.F. et al, Phys. Rev. C ***86*** *014610 (2012)*

Experimental <N/Z> distribution of IMFs as a function of their atomic number compared with results SMF+GEMINI calculations (hatchad area) for two different parametrizations of the symmetry potential (asy-soft and asy-stiff)

- Dynamically emitted particles
- Statistically

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

≈ 80±10 MeV for the asy-stiff

≈ 25 MeV for the asy-soft

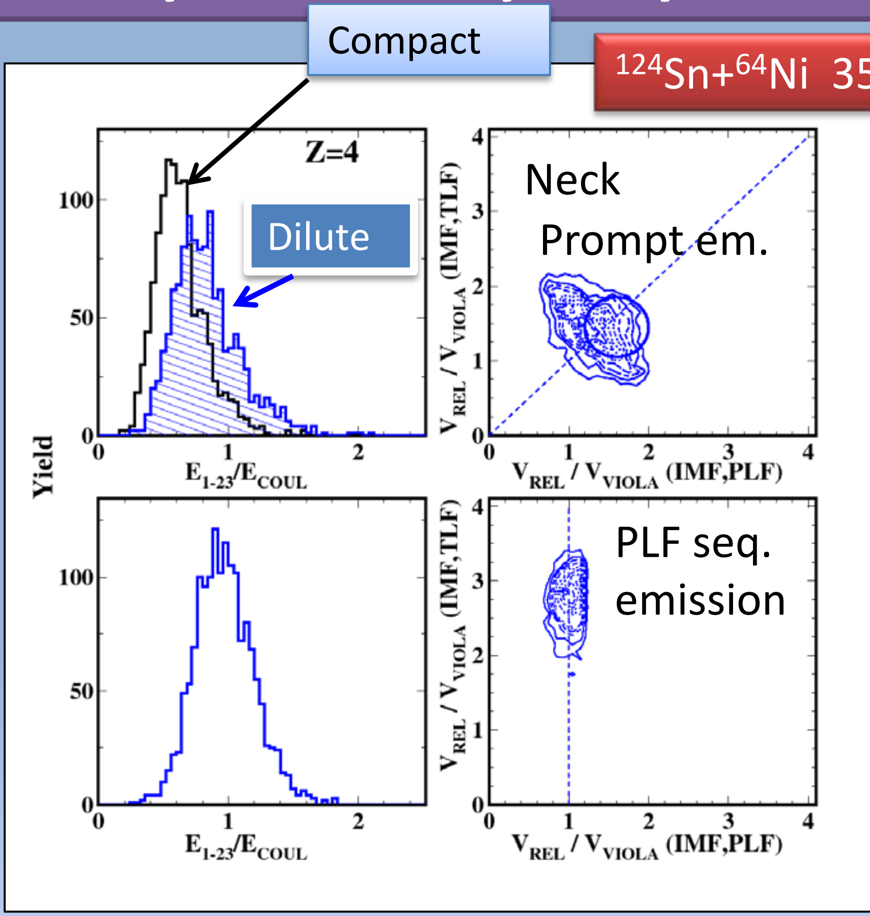
$$S_0 \approx 30 MeV$$

K. Brown et al., PRC **87** 061601(R) 2013.

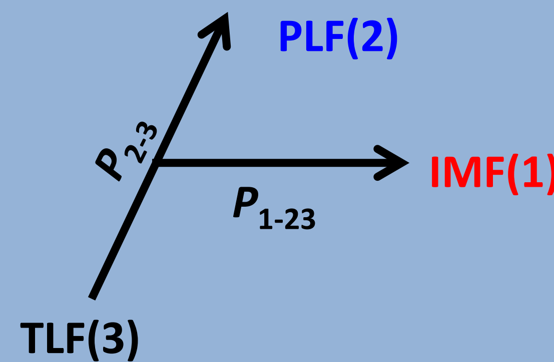
K. Stiefel et al. PRC90 061605 (2014)

Density: three body analysis in the experimental data

$^{124}Sn+^{64}Ni$ 35 A.MeV



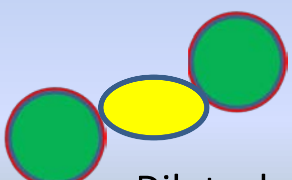
In the 3-bodies center-of-mass system:



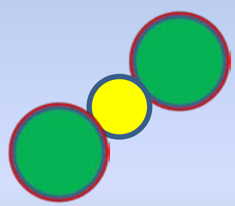
$$E_{TOT}^{c.m.} = E_1 + E_2 + E_3 = \frac{p_{1-23}^2}{\mu_{1-23}} + \frac{p_{23}^2}{\mu_{23}} = E_{1-23} + E_{23}$$

The experimental data are analysed with two different assumption for Coulomb: a compact (normal density) and dilute configuration

The ratio $E_{1-23}/E_{COULOMB}$ is calculated considering for the IMFs a dilute configuration with $r_0=1.8A^{1/3}$ fm (filled histogram corresponding to about 0.05 ρ_0)



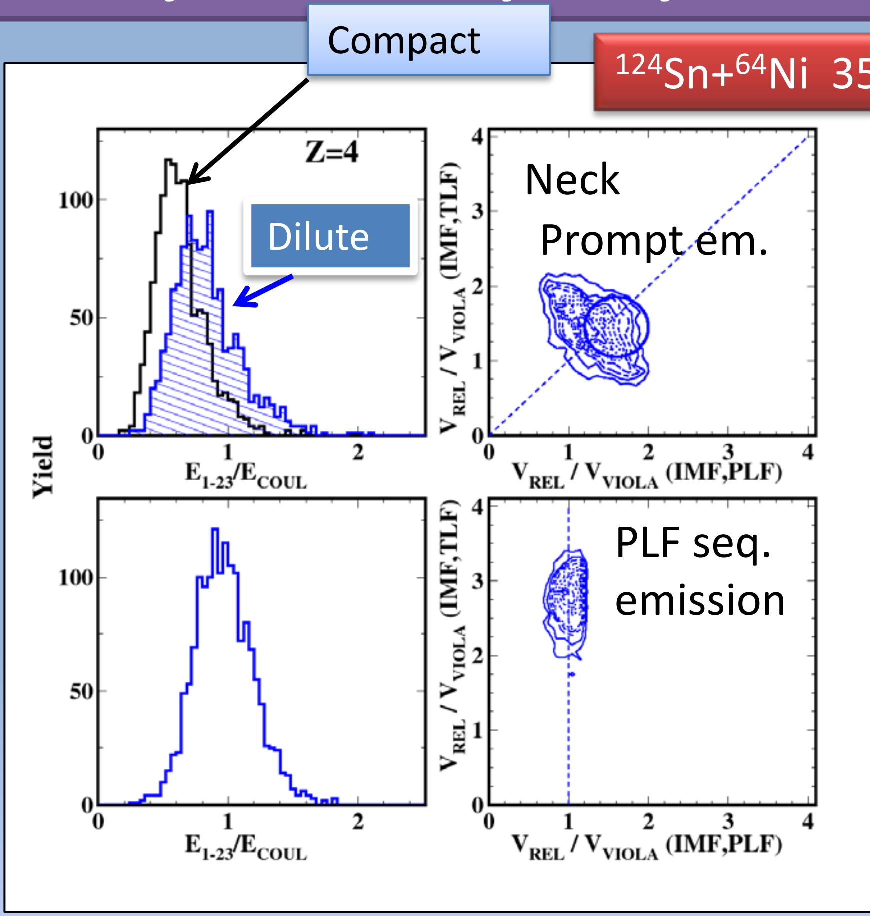
Dilute, large radius



Compact, normal radius

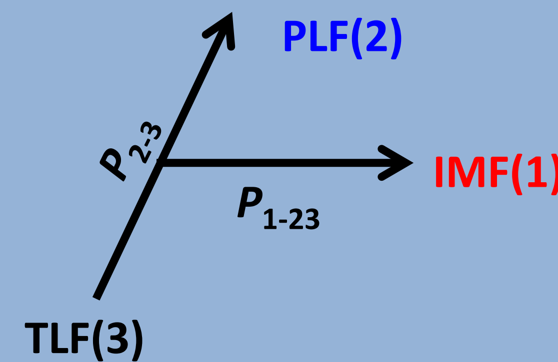
E.d.F. et al., EPJ WoC 66, 03032 (2014)

Density: three body analysis in the experimental data



$^{124}Sn+^{64}Ni$ 35 A.MeV

In the 3-bodies center-of-mass system:

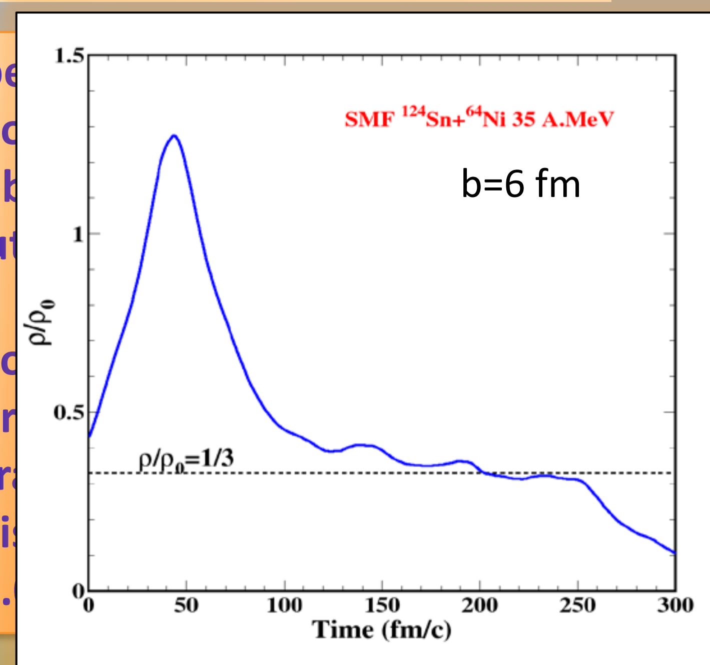


$$E_{TOT}^{c.m.} = E_1 + E_2 \ldots$$

SMF $^{124}Sn+^{64}Ni$ 35 A.MeV

The expe
with two
Coulomb
and dilut

The ratio
consider
configura
(filled his
about 0.



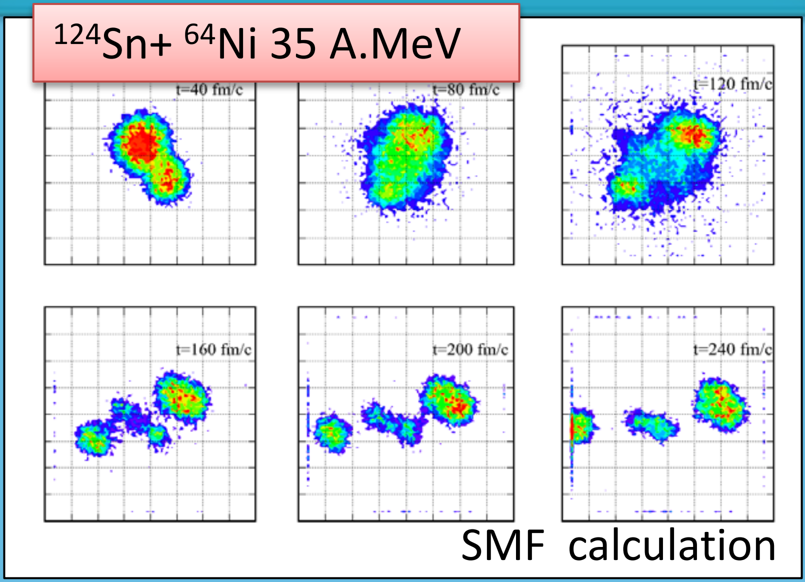
Dilute, large radius

Compact, normal radius

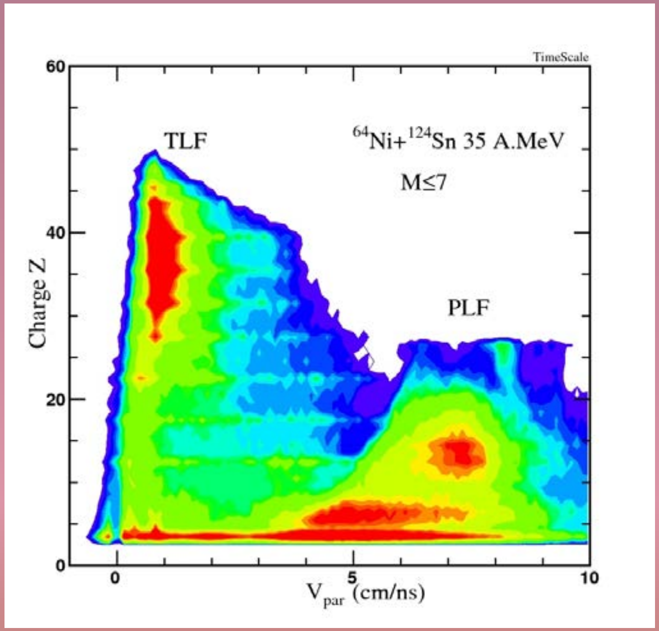
E.d.F. et al., EPJ WoC 66, 03032 (2014)

In "Timescale" and "Inkiissy" experiments we mainly look at:

1) The "**neck**" emission where light IMFs (Z<≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density ("neck"). This is generally a **FAST** process (<100 fm/c)



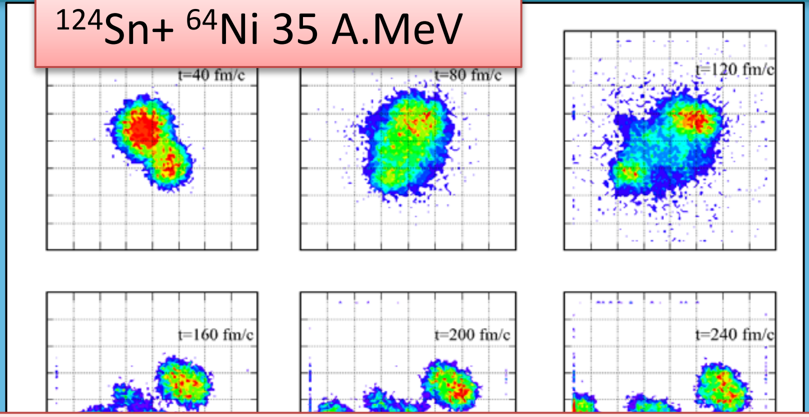
2) Excitation of a primary Projectile-like PLF* (TLF*) followed by its dynamical (non-equilibrated) asymmetrical splitting (**dynamical fission**). In this case emission of the **lighter IMF** is preferentially backwards in the PLF reference system.



Role of **N/Z of entrance channel** in the reaction mechanisms

In "Timescale" and "Inkiissy" experiments we mainly look at:

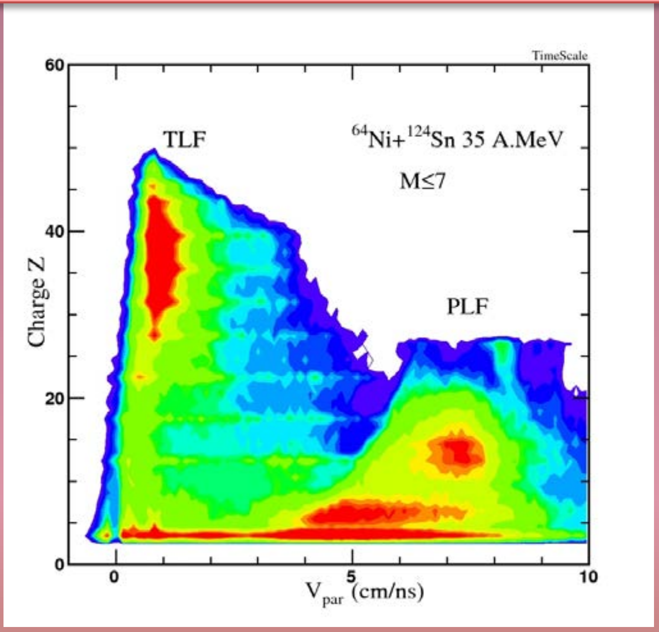
$^{124}Sn + ^{64}Ni$ 35 A.MeV



1) The "**neck**" emission where light IMFs (Z<≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density ("neck"). This is generally a **FAST** process (<100 fm/c)

With respect to the prompt neck emission, the emission of heavy IMFs from projectile-like fragment break-up appears at a later stage

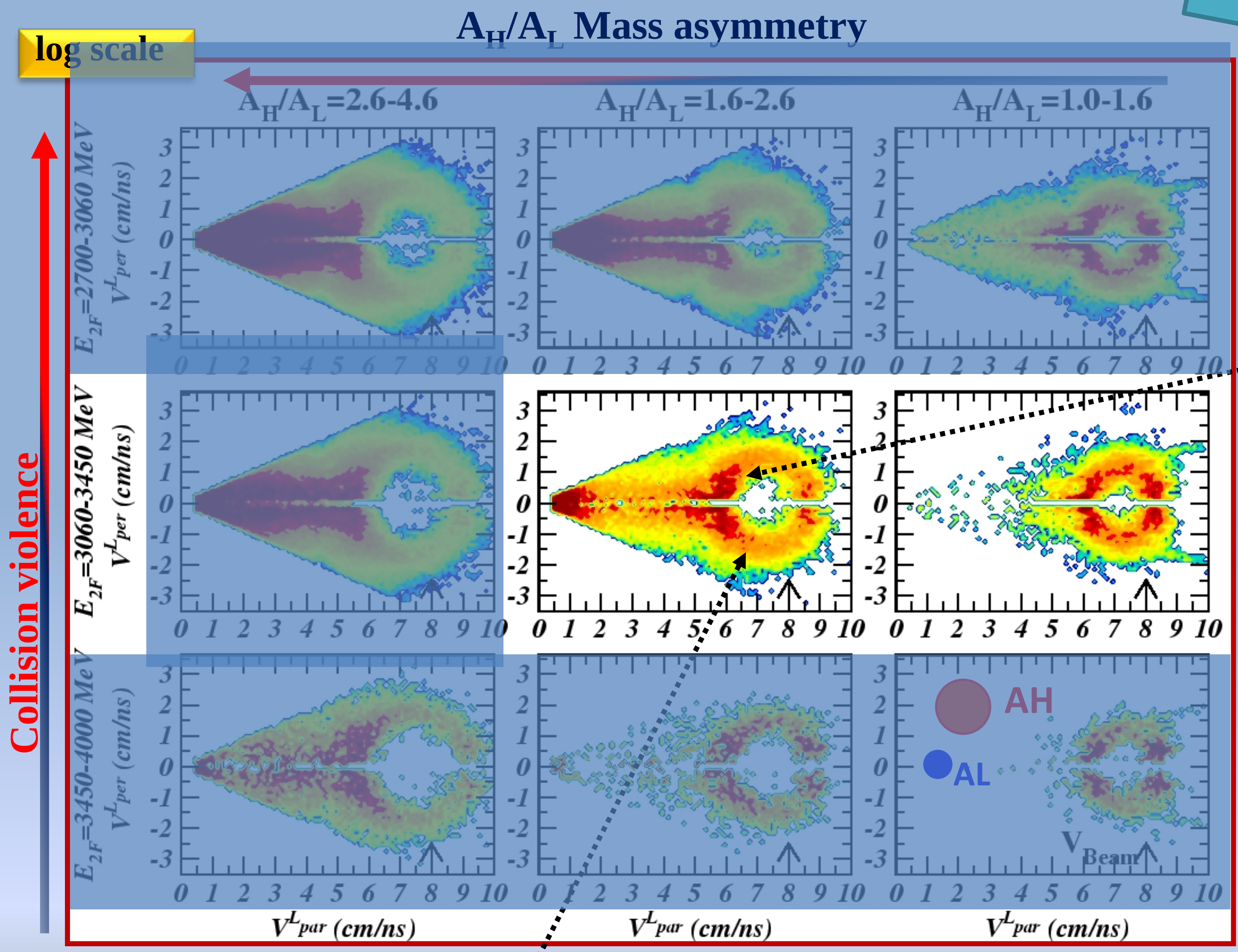
2) Excitation of a primary Projectile-like PLF* (TLF*) followed by its dynamical (non-equilibrated) asymmetrical splitting (**dynamical fission**). In this case emission of the **lighter IMF** is preferentially backwards in the PLF reference system.



Role of **N/Z of entrance channel** in the reaction mechanisms

The quasi-projectile break-up

$^{124}Sn+^{64}Ni$ 35 AMeV
Neutron rich



AH
AL

The lighter fragments are emitted preferentially backwards in the PLF reference system, i.e., towards the target nucleus: *Dynamical Fission* → fast and non-equilibrated fission

E.De Filippo et al.,PRC 71 064604 (2005)
P. Russotto et al., PRC 81, 064605 (2010)

Coulomb ring 5<≈ V_{beam} = 8. cm/ns→ Well defined PLF source: scattering of PLF followed by its splitting in H&L fragments → sequential mechanism

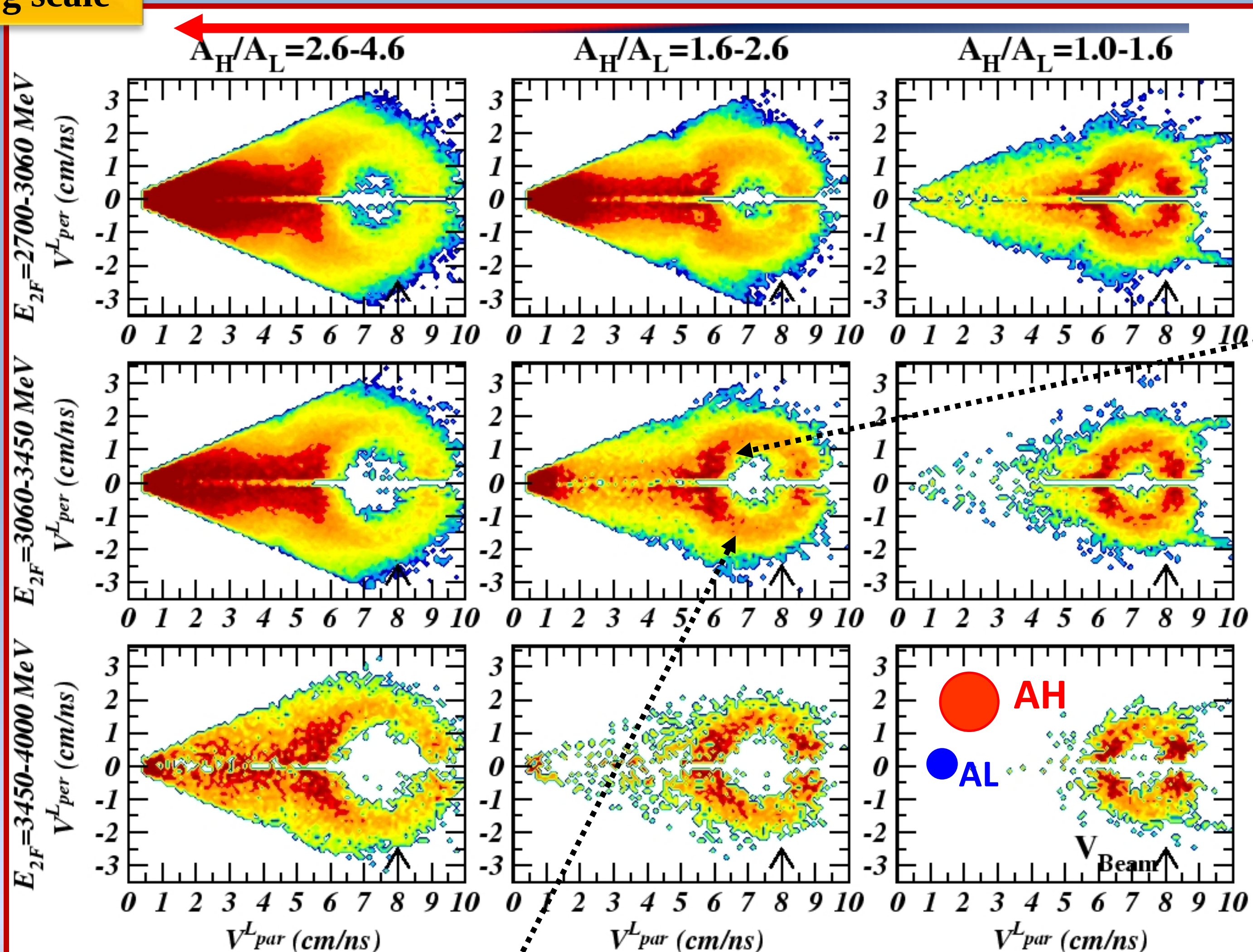
The quasi-projectile break-up

$^{124}Sn+^{64}Ni$ 35 AMeV
Neutron rich

A_H/A_L Mass asymmetry

log scale

Collision violence



AH

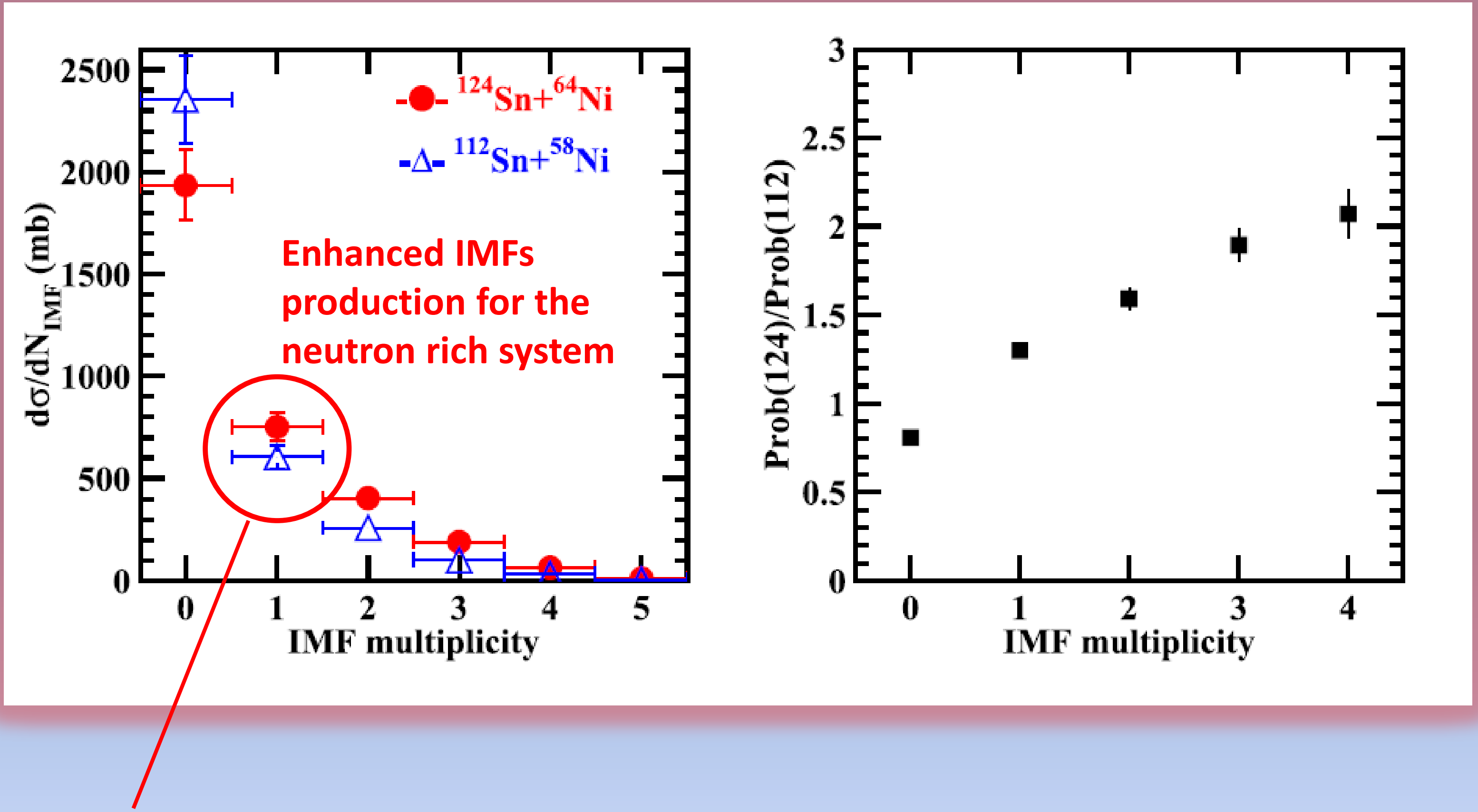
AL

The lighter fragments are emitted preferentially backwards in the PLF reference system, i.e., towards the target nucleus: *Dynamical Fission* → fast and non-equilibrated fission

E.De Filippo et al.,PRC 71 064604 (2005)
P. Russotto et al., PRC 81, 064605 (2010)

Coulomb ring 5<≈ V_{beam} = 8. cm/ns→ Well defined PLF source: scattering of PLF followed by its splitting in H&L fragments → sequential mechanism

Cross section as a function of the IMF multiplicity associated with PLF residue



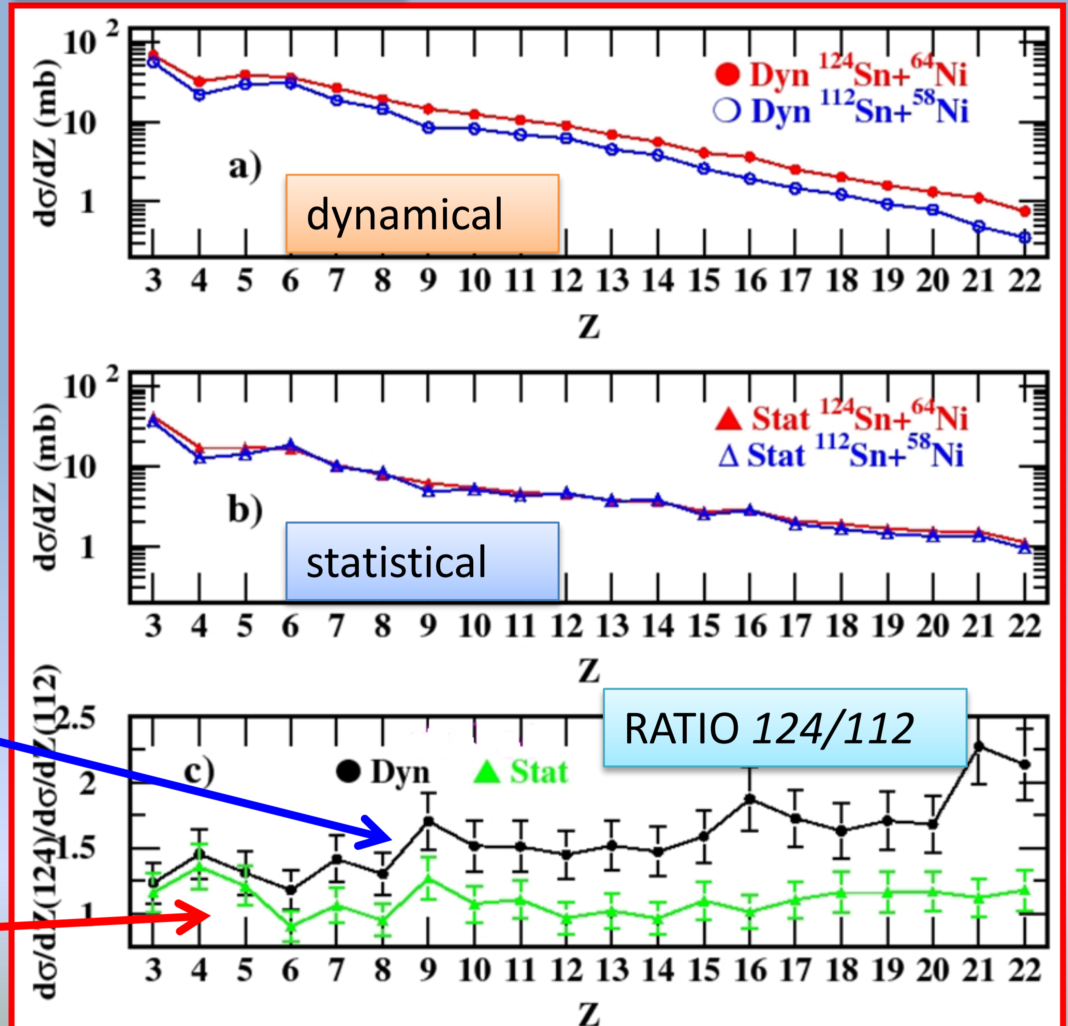
The analysis is done for M_{IMF}=1 events (ternary splitting). b/b_{max}>0.4

P. Russotto et al. , Phys. Rev. C91, 014610 (2015)

Comparison of IMFs cross sections for $^{124}Sn+^{64}Ni$ and $^{112}Sn+^{58}Ni$

P. Russotto et al. , Phys. Rev. C91, 014610 (2015)

Cross-sections

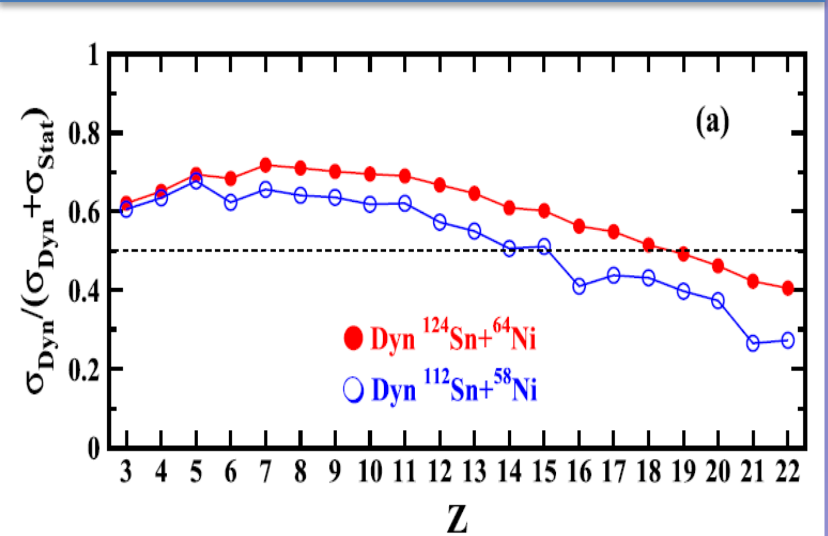


- **Dynamical component: enhanced for the neutron rich**
- **Statistical component: almost equal (A ratio: ~1.1 close to the mass ratio between the systems)**

see also A.B. McIntosh et al. PRC 81 034603 (2010)

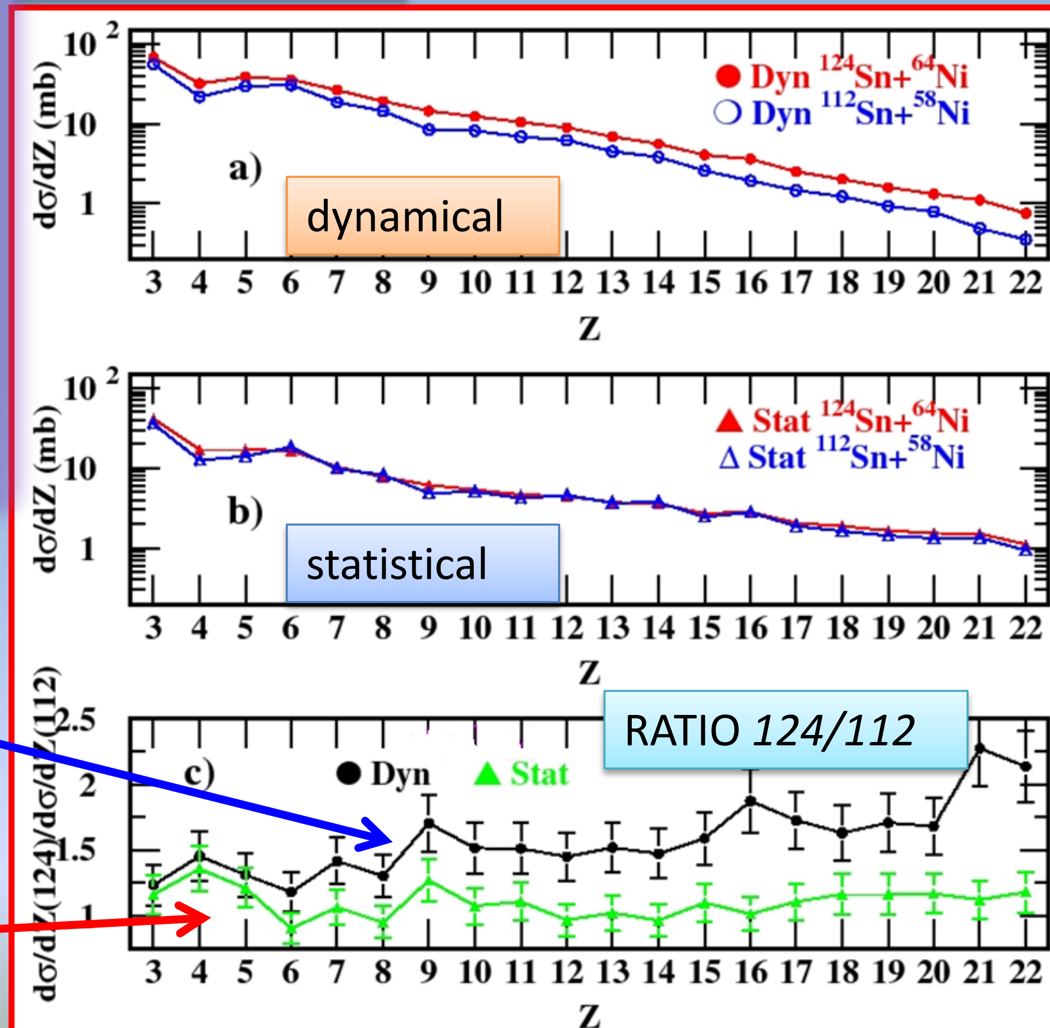
Comparison of IMFs cross sections for $^{124}Sn+^{64}Ni$ and $^{112}Sn+^{58}Ni$

Ratio of $\sigma_{dyn}/(\sigma_{dyn}+\sigma_{stat})$ as a function of IMFs charge Z for the two systems.



P. Russotto et al. , Phys. Rev. C91, 014610 (2015)

Cross-sections



- **Dynamical component: enhanced for the neutron rich**
- **Statistical component: almost equal (A ratio: ~1.1 close to the mass ratio between the systems)**

see also A.B. McIntosh et al. PRC 81 034603 (2010)

The INKIISSY EXPERIMENT $^{124}Xe + ^{64}Zn,^{64}Ni$

Main experimental result: the dynamical component is enhanced for the neutron rich system.

Is it a **size (mass)** effect or **isospin** effect ?

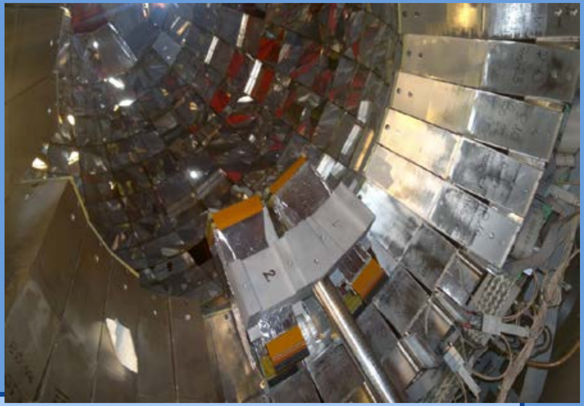
The idea is to use uses a projectile/target combination having the same mass of the neutron rich $^{124}Sn+^{64}Ni$ system and a N/Z $^{124}Xe+^{64}Zn$ as the neutron poor one $^{112}Sn+^{58}Ni$ at the same bombarding energy of 35 A.MeV using the 4π detector CHIMERA and the Farcos module prototype.

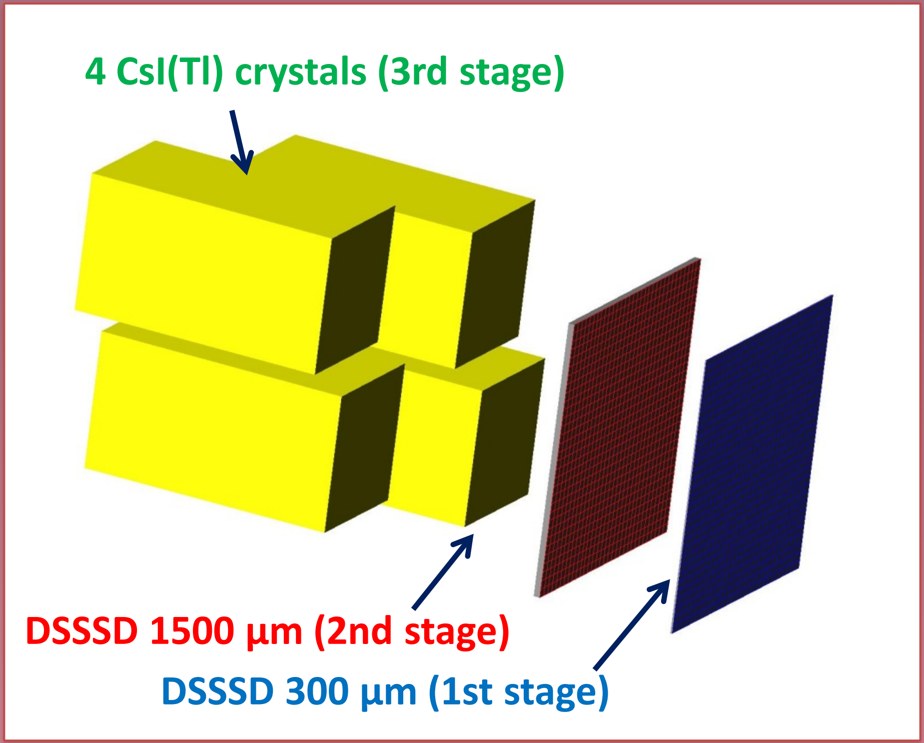
System	N/Z Projectile	N/Z target	N/Z compound
$^{124}Sn+^{64}Ni$	1.48	1.29	1.41
$^{124}Xe+^{64}Ni$	1.30	1.29	1.29
$^{124}Xe+^{64}Zn$	1.30	1.13	1.24
$^{112}Sn+^{58}Ni$	1.24	1.07	1.18

A new setup: the 4π CHIMERA + a module of FARCOS prototype

FARCOS: Femtoscope Array for COrrelations and Spectroscopy (INFN, Ganil, Huelva . . .)

- **Based on (62x64x64 mm^3) clusters**
- **1 square (0.3x62x62 mm^3) DSSSD 32+32 strips**
- **1 square (1.5x62x62 mm^3) DSSSD 32+32 strips**
- **4 60x32x32 mm^3 CsI(Tl) crystals**

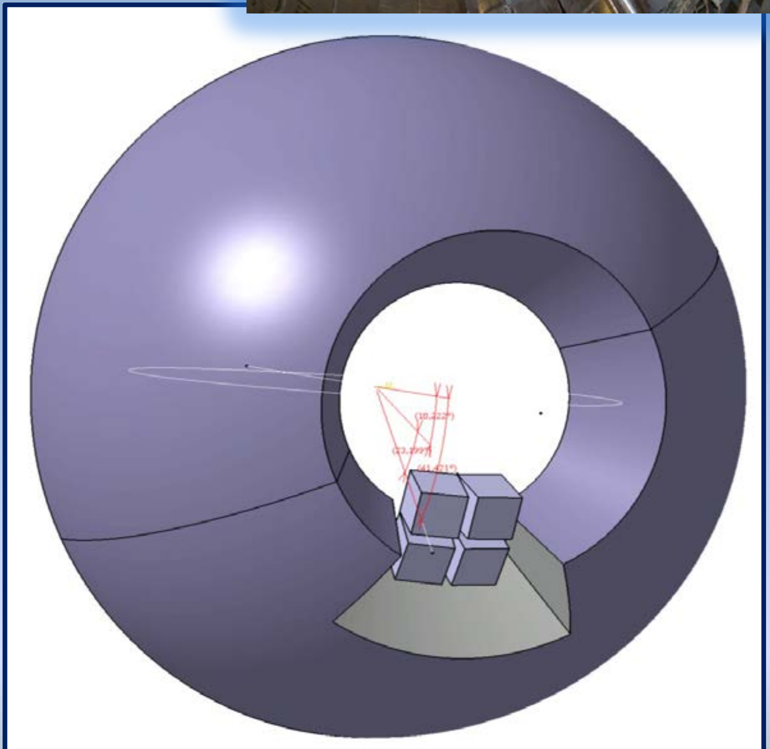




132 channels by each cluster

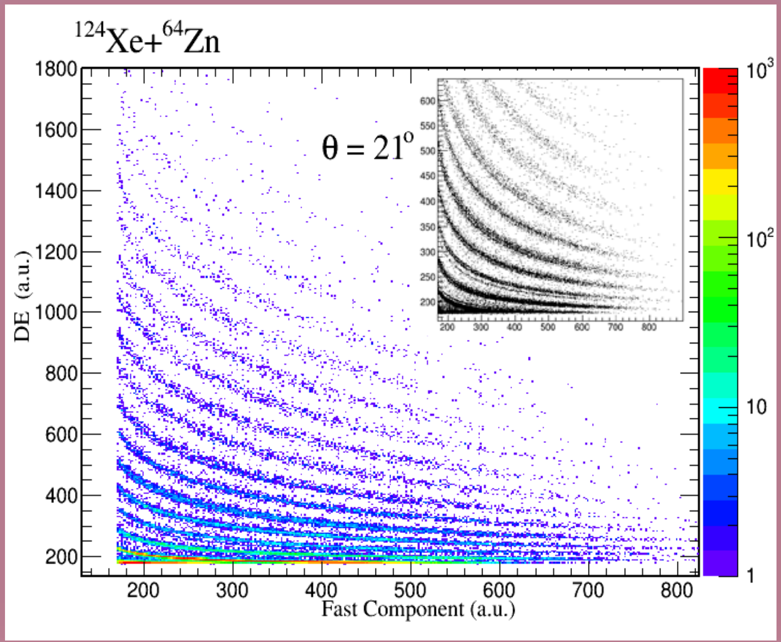
High angular and energy resolution

→ E.V. Pagano talk on Thursday

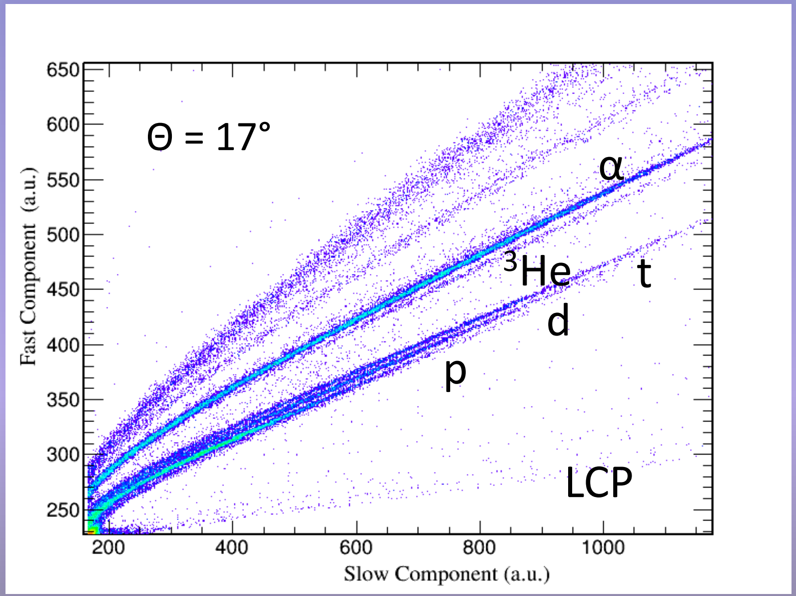


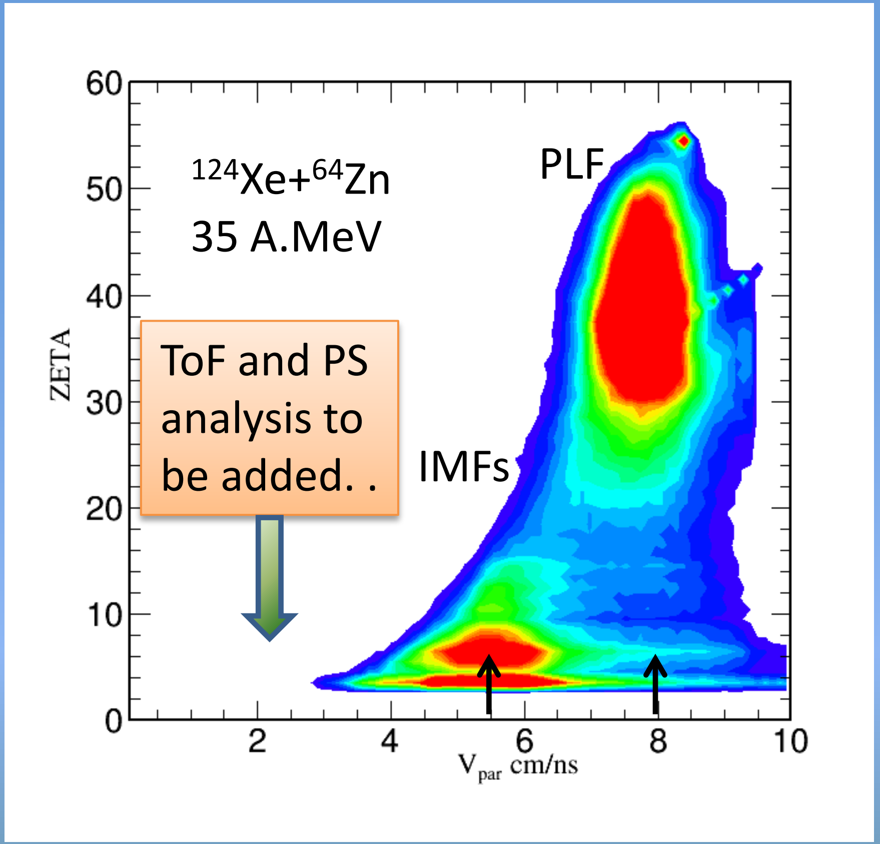
4 telescopes 25 cm from the target
$\theta_{lab} \sim$ 15-45 deg, $\Delta\phi \sim$ 75 deg

InKiIsSy: data analysis: first results

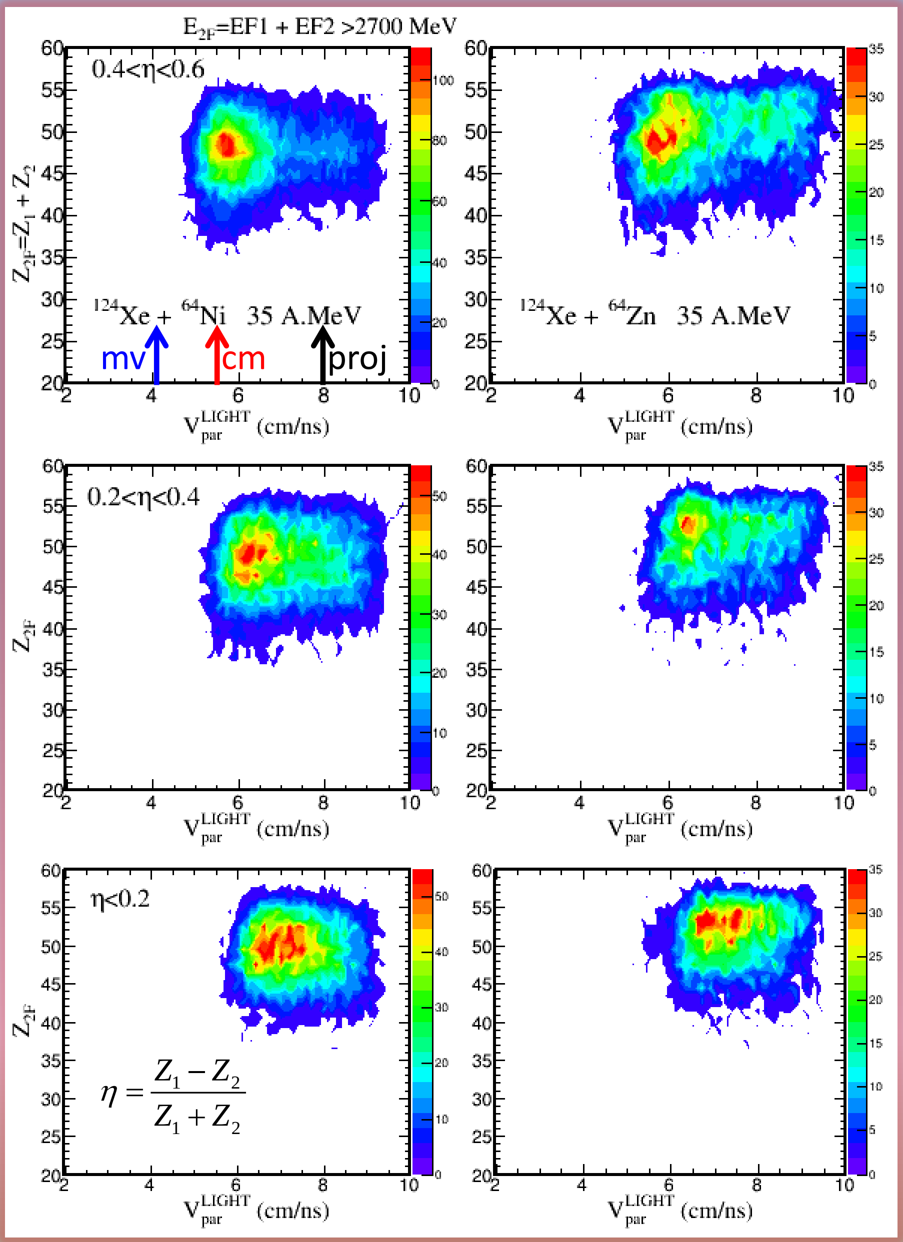


Data analysis (particle's calibration, identification) almost completed for particles punching-trough the 300 μm silicon detectors in the forward rings.





Analysis of the two largest fragments Z_1,Z_2 with V_{par}>4 cm/ns and M_{IMF}<=3, Z1+Z2>35

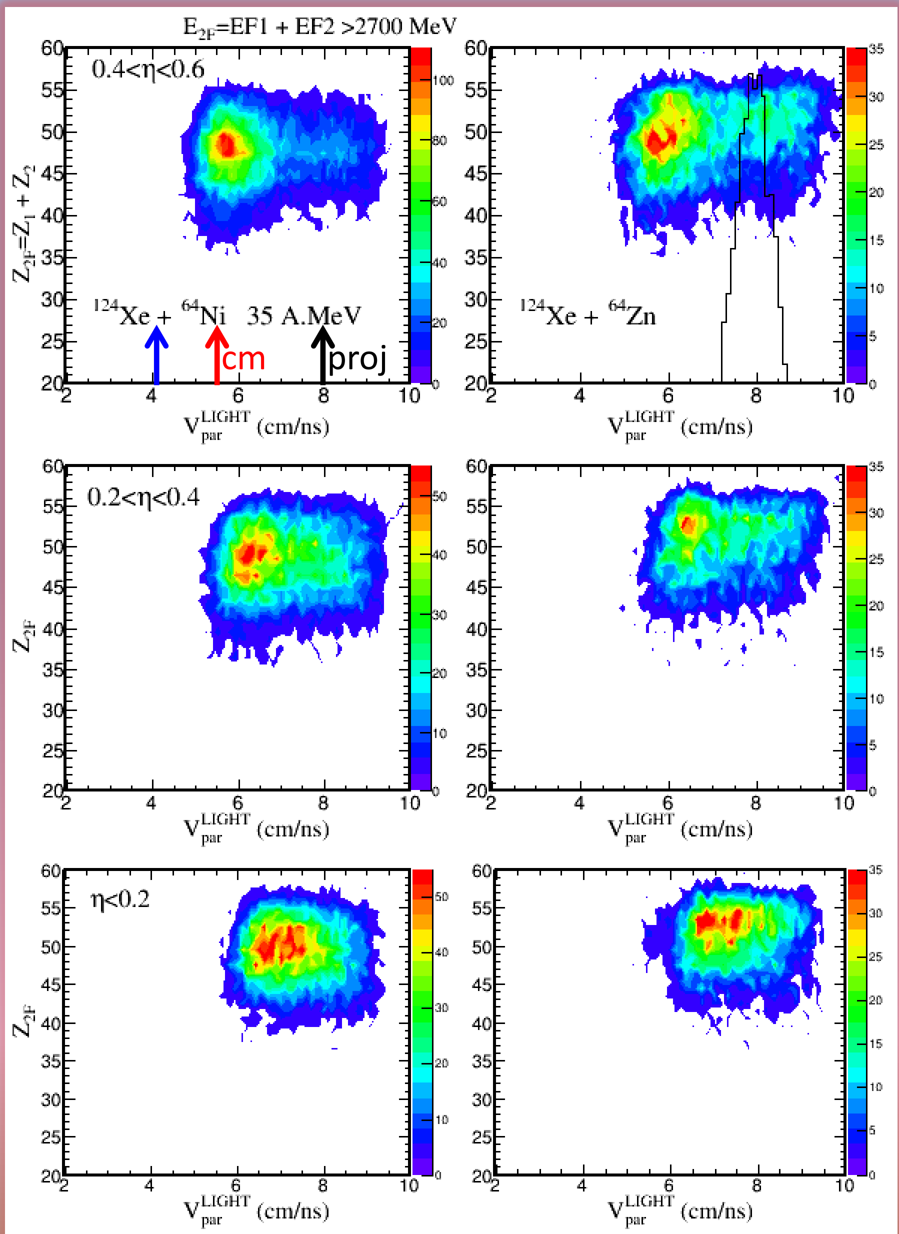


V_{PAR} ofLight fragment Z_2: two velocity components

PRELIMINARY Results

$$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

Analysis of the two largest fragments Z_1,Z_2 with V_{par}>4 cm/ns and M_{IMF}<=3, Z1+Z2>35

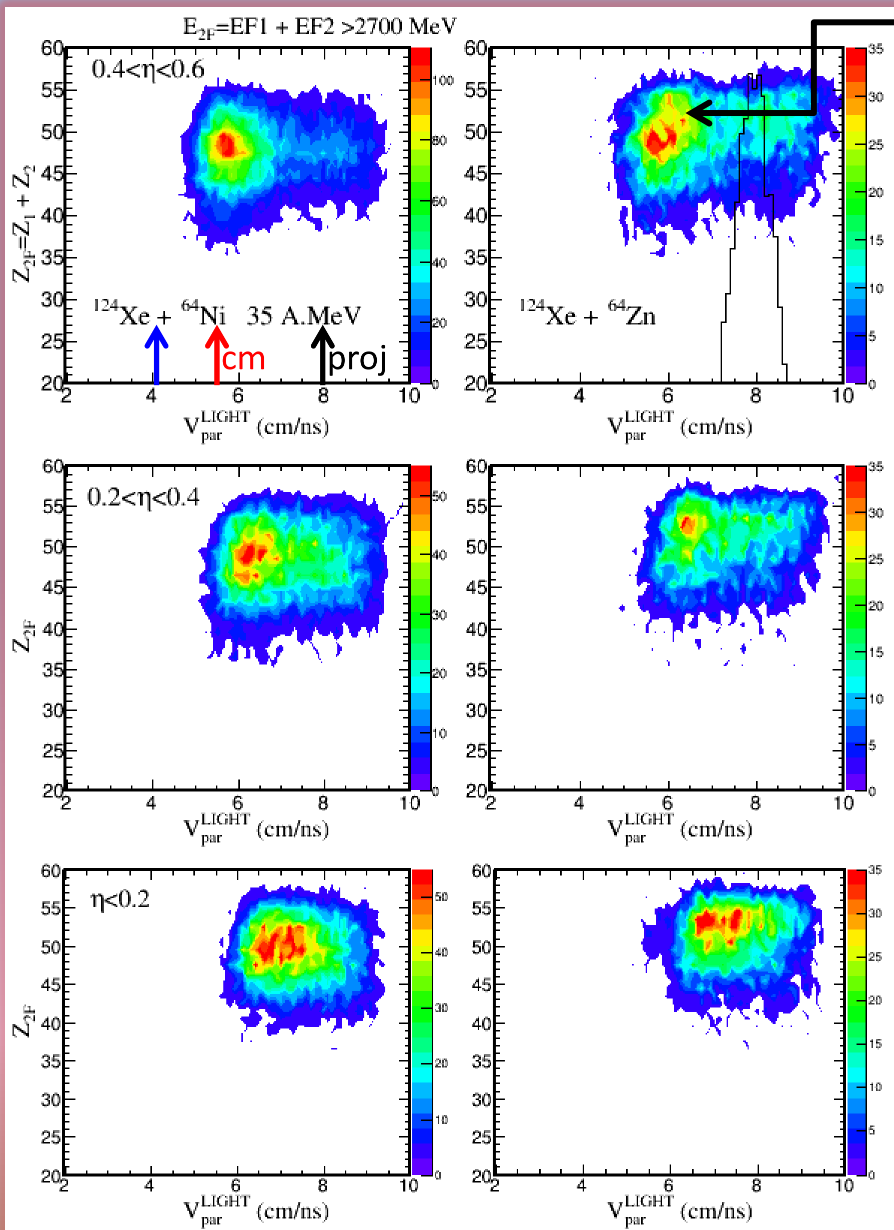


V_{PAR} ofLight fragment Z_2: two velocity components

PRELIMINARY Results

$$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

Analysis of the two largest fragments Z_1,Z_2 with V_{par}>4 cm/ns and M_{IMF}<=3, Z1+Z2>35

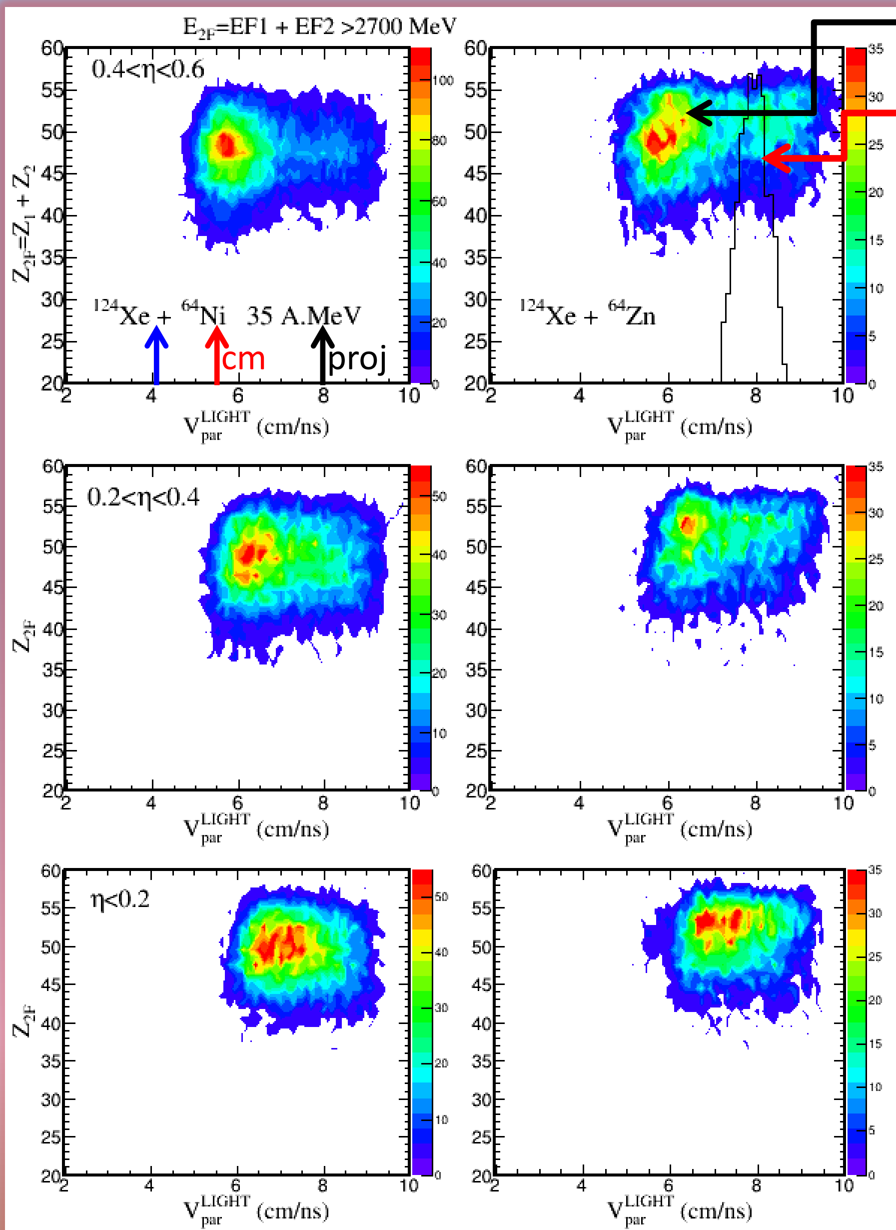


V_{PAR} ofLight fragment Z_2: two velocity components

PRELIMINARY Results

$$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

Analysis of the two largest fragments Z_1, Z_2 with V_{par}>4 cm/ns and M_{IMF}<=3, Z1+Z2>35

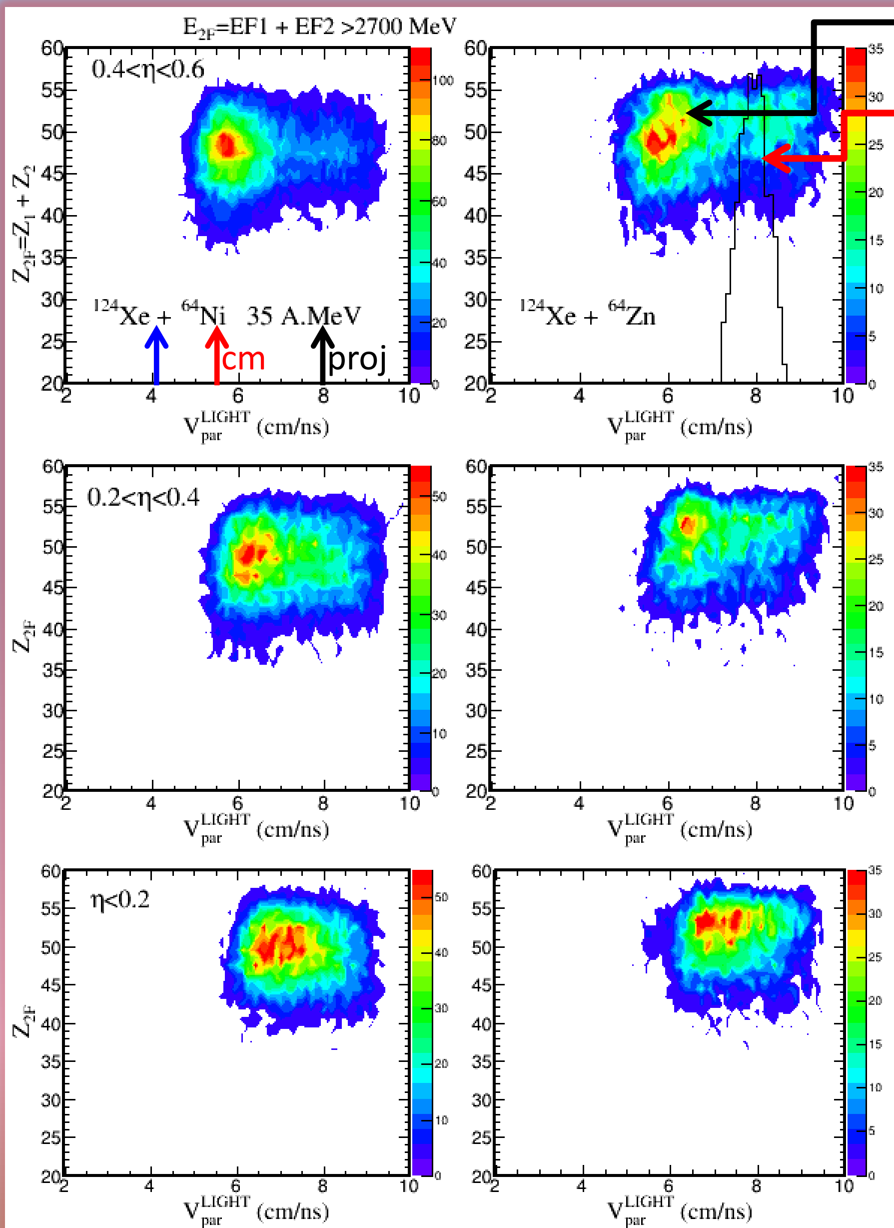


V_{PAR} ofLight fragment Z_2: two velocity components

PRELIMINARY Results

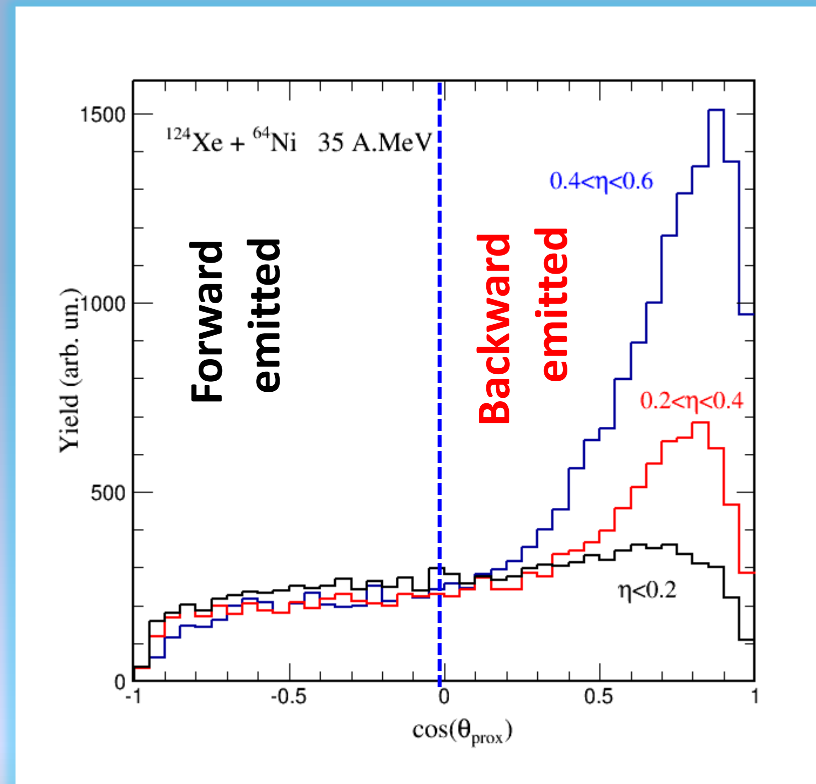
$$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

Analysis of the two largest fragments Z_1,Z_2 with V_{par}>4 cm/ns and M_{IMF}<=3, Z1+Z2>35



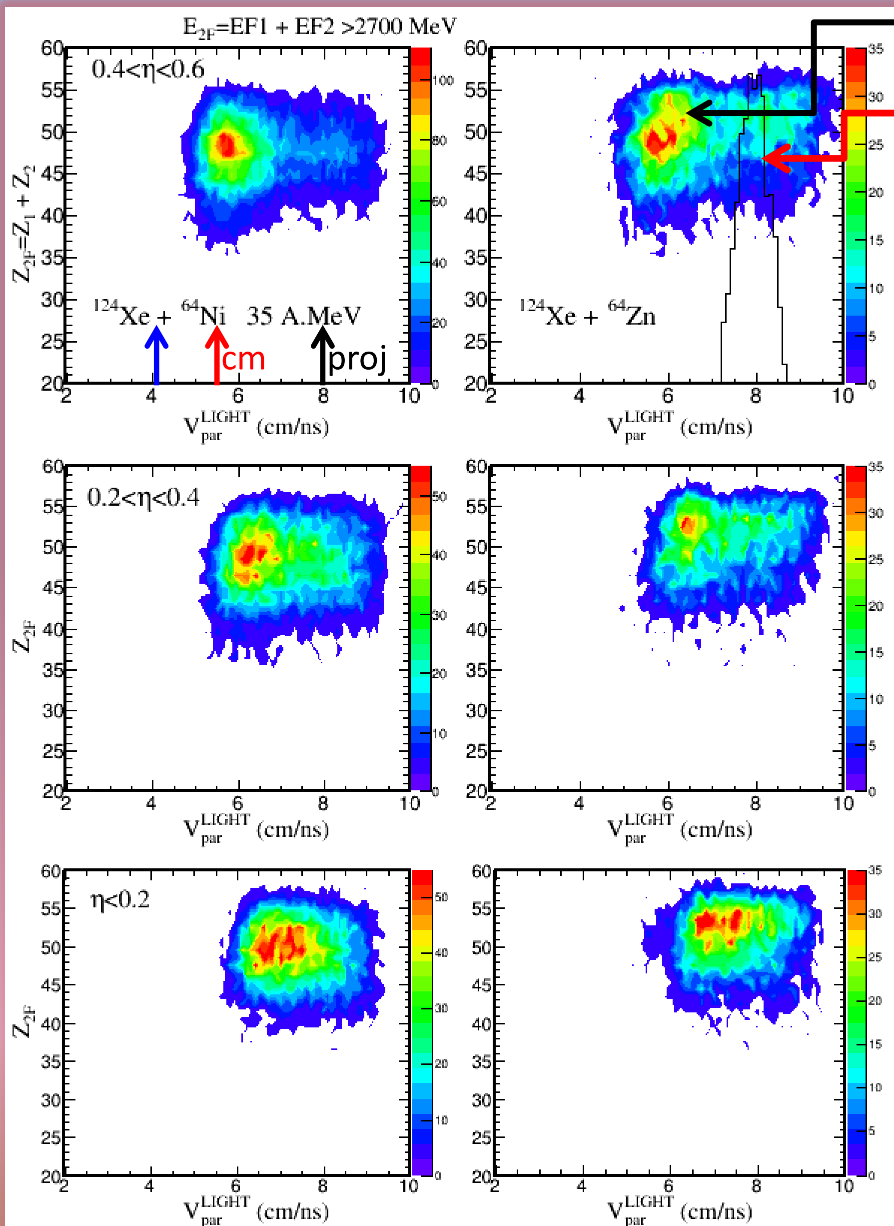
VPAR ofLight fragment Z_2: two velocity components

PRELIMINARY Results



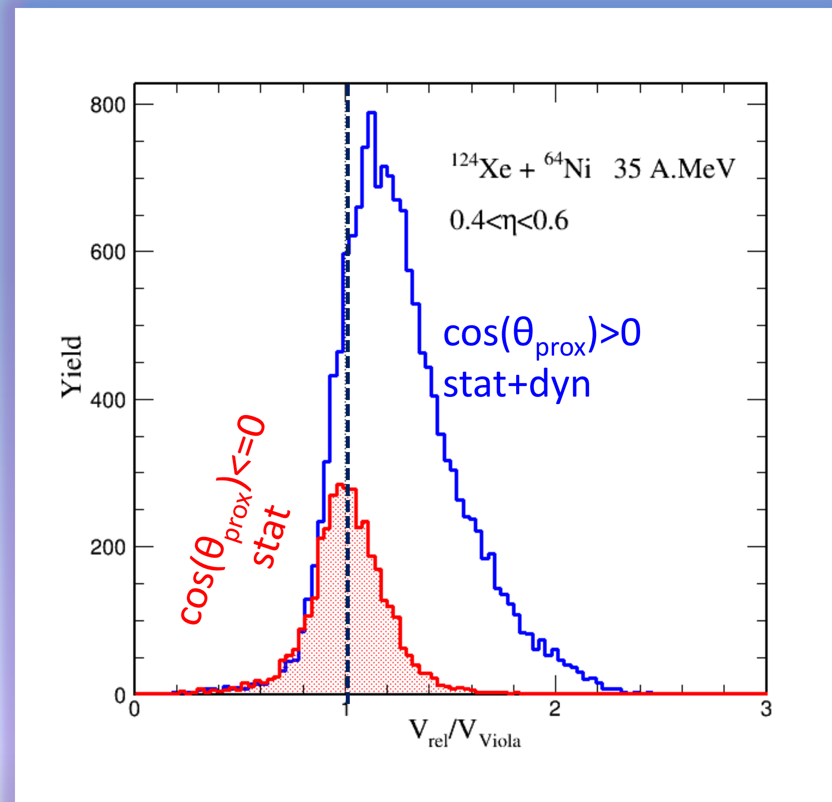
$$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

Analysis of the two largest fragments Z_1, Z_2 with V_{par}>4 cm/ns and M_{IMF}<=3, Z1+Z2>35



V_{PAR} ofLight fragment Z_2: two velocity components

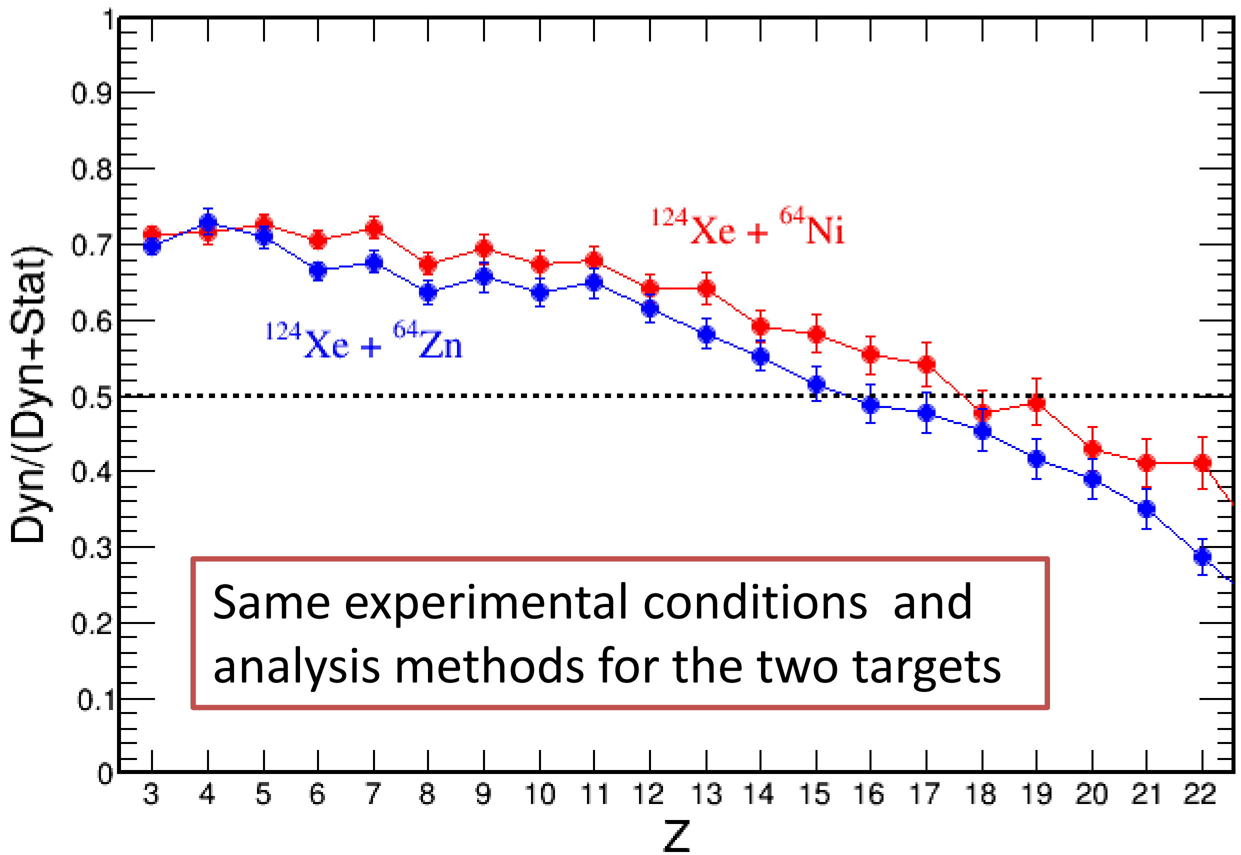
PRELIMINARY Results



$$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

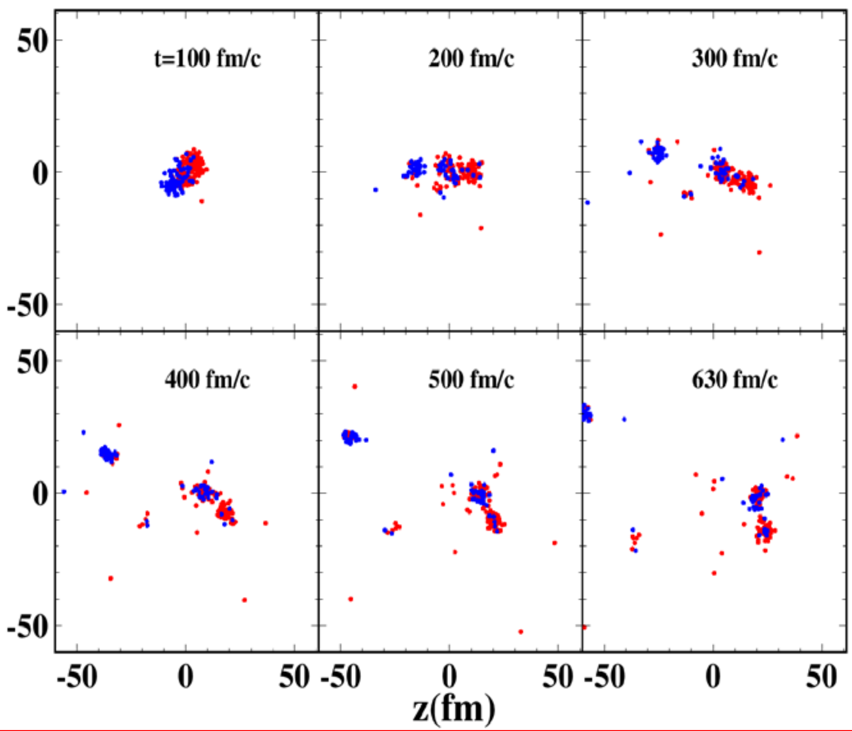
Analysis of new data with conditions as similar as possible to the previous Sn + Ni experiment as described in detail in Phys. Rev. C91, 014610 (2015).

PRELIMINARY Results



Same experimental conditions and analysis methods for the two targets

Dynamics of PLF break-up with the Constrained Molecular Dynamics model



CoMD-II time steps of one event leading to PLF fission in **^{124}Sn+^{64}Ni@35 A.MeV**

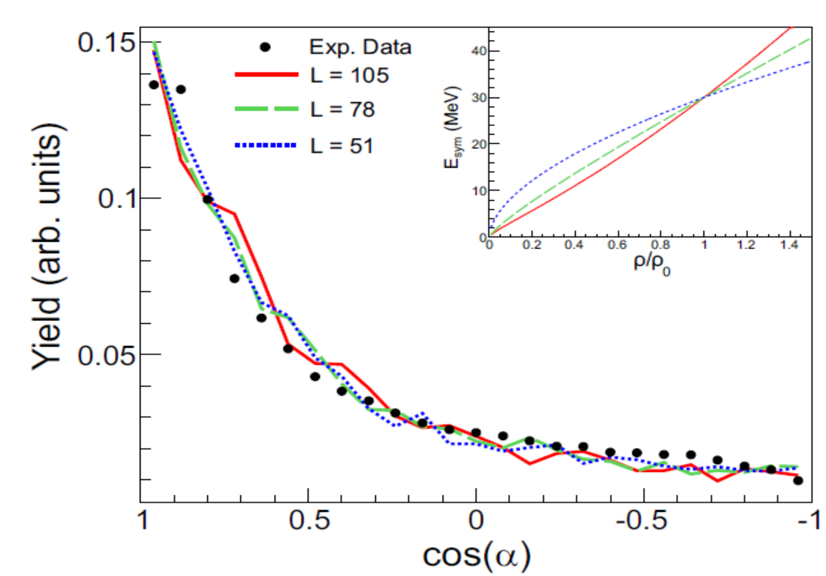
*M. Papa et al. (CHIMERA coll.), PRC **75**, 054616 (2007).*

E. De Filippo and A. Pagano EPJA 50, 32 (2015).

CoMD-II simulation on ^{64}Zn+^{64}Zn at 45 A.MeV

For a binary break-up with Z_H>11 and Z_L=4

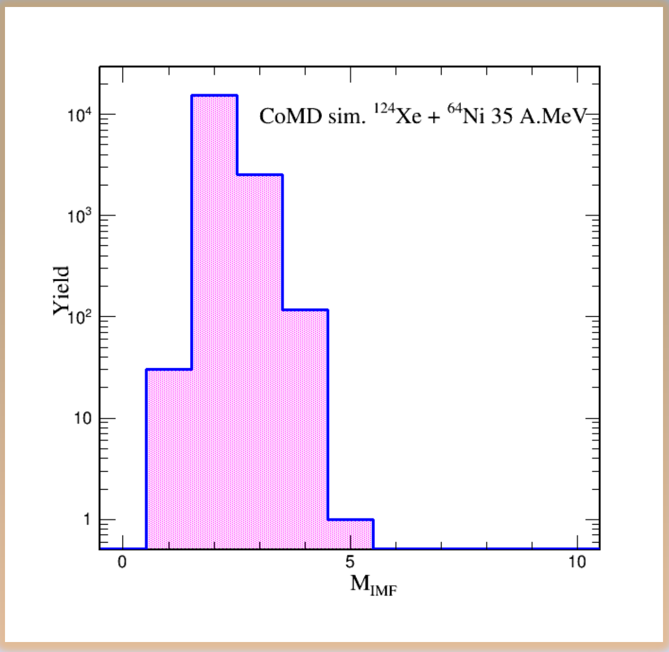
K. Stiefel, Z. Kohley et al., PRC90, 061605 (2014)



Constrained Molecular Dynamics simulation (CoMD-3)

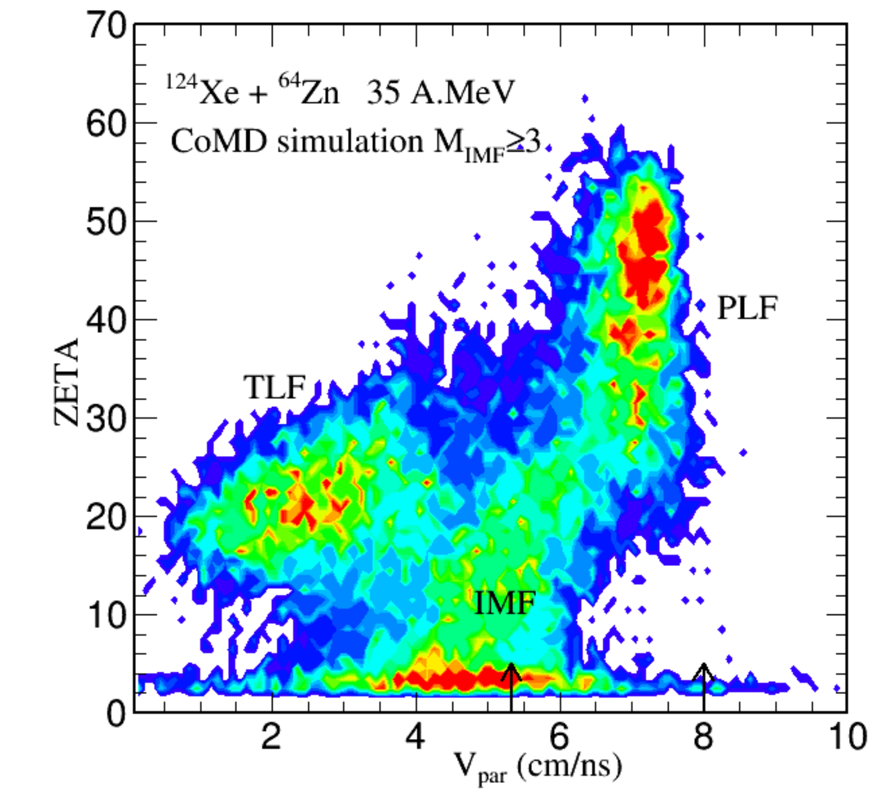
- ✓ 124Xe + 64 Zn @ 35 A.MeV
- ✓ **Preliminary** test at 650 fm/c and stiffness parameter on $E_{sym}(\rho)$, $\gamma=1$
- ✓ Checking for projectile break-up events

Model → see M. Papa, Phys. Rev. ***C87,*** *014001 (2013) and refs therein*

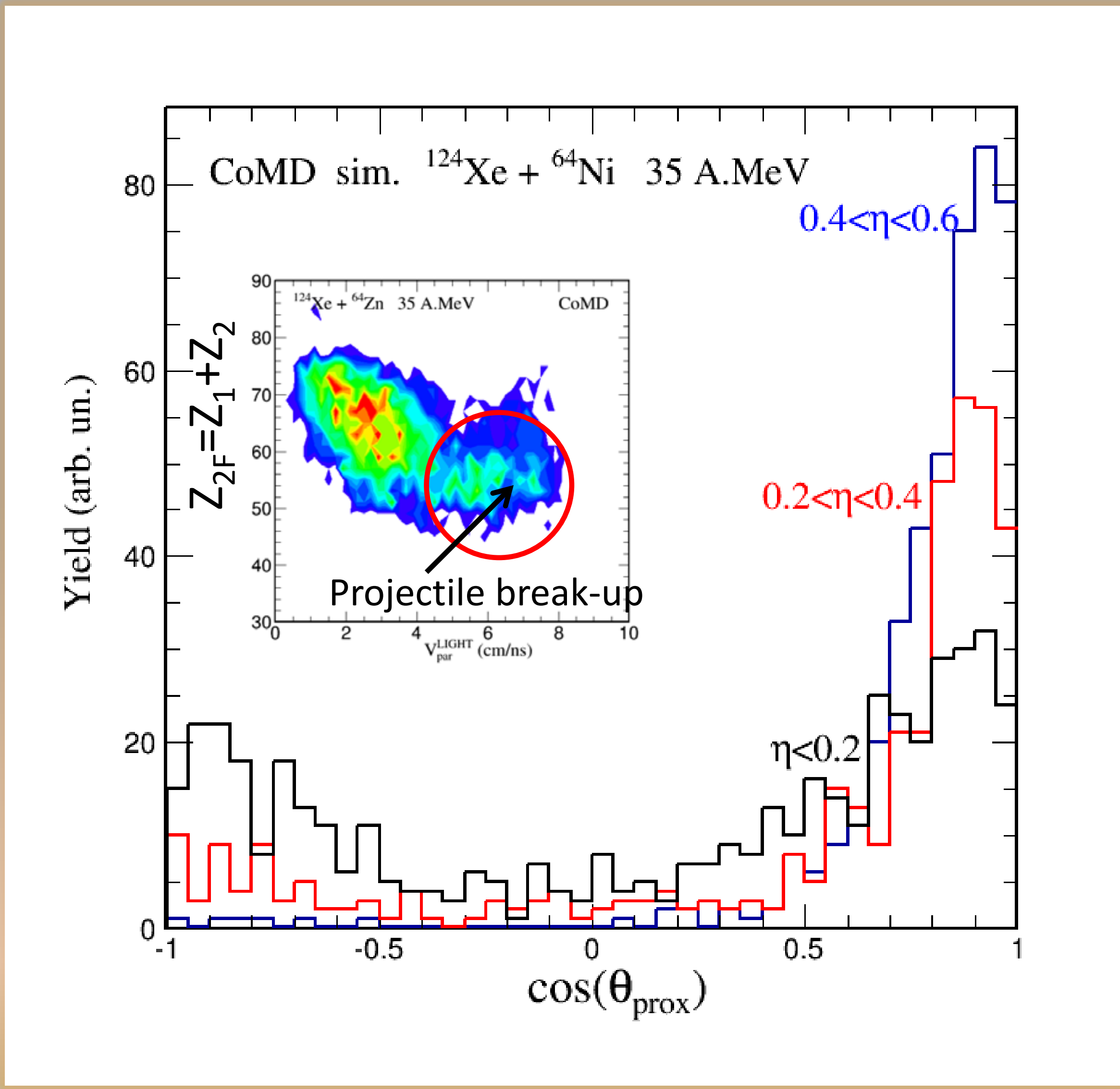


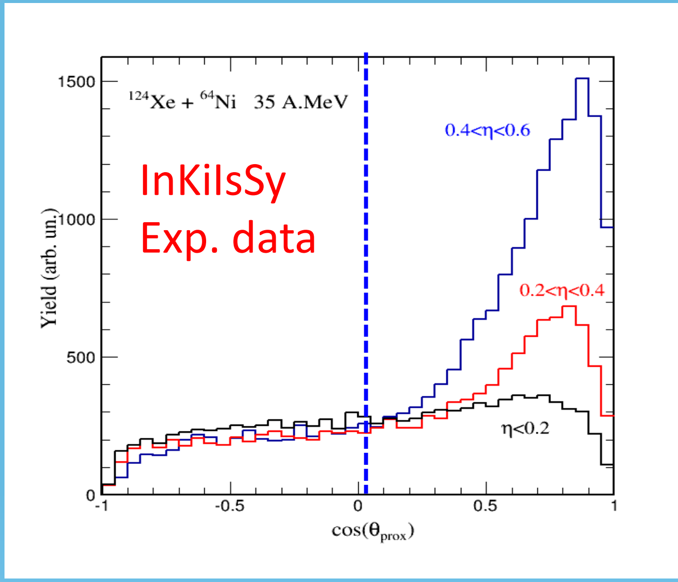
IMFs Multiplicity (b>4 fm)

Selection: Three biggest fragments in events with $M_{IMF}\geq3$



Constrained Molecular Dynamics simulation (CoMD-3)

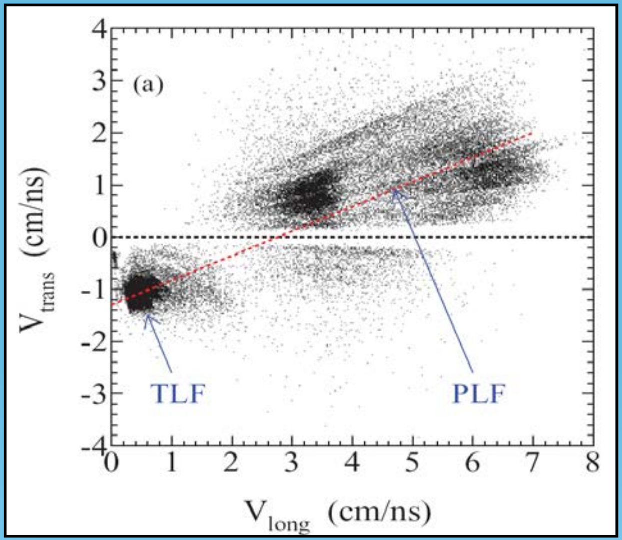




Dynamical fission: interest to extend these studies at lower energies

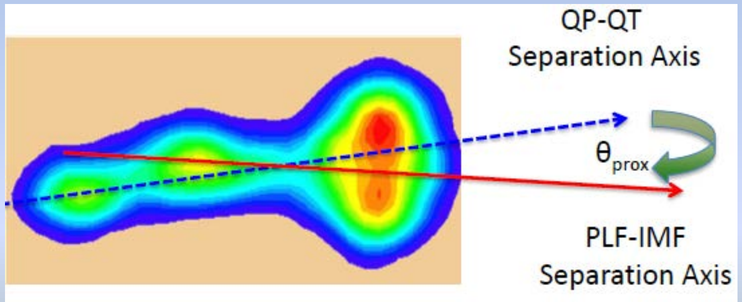
P. Glassel et al., *Zeit. Phys. A 310, 189 (1983)*
Study of **$^{84}Kr+^{166}Er$ and $^{129}Xe+^{122}Sn$ at 12.5 AMeV.** Strong Coulomb proximity effects observed for not fully equilibrated PLF fission.
A. Stefanini et al., $^{100}Mo+^{100}Mo$, $^{120}Sn+^{120}Sn$ at 20 A.MeV, *Z. Phys. A351,167 (1995)*

OLD



Skwira et al. (CHIMERA collaboration)
Phys. Rev. Lett. 101, 262701 (2008)
J. Wilczynski et al., PRC 81, 024605 (2010)
C. Rizzo et al., PRC 90, 054618 (2014).
$^{197}Au + ^{197}Au$ collisions have been studied at **15 AMeV** and more recently at **23 A.MeV**.
A new process of fast reseparation of this heavy system into three or four fragments of comparable size is observed

NEW

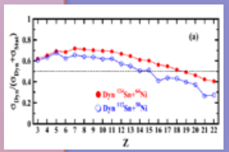


P. Cammarata et al., Texas A&M
IWM-2014, *EPJ-WebOfConf vol. 88*
Study of three-body break-up mechanism in **$^{136}Xe+^{64}Ni$, $^{124}Xe+^{58}Ni$, $^{124}Sn+^{64}Ni$** at 15 A.MeV with FAUST array

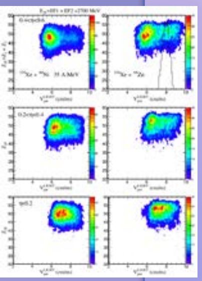
RECENT

Summary

The evaluation of cross-sections for dynamical and statistical IMFs emission has shown that the dynamical emission is enhanced for a neutron rich system while the statistical emission is equally probable for the two systems .

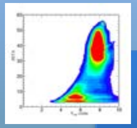


The dynamical IMF emission can be a good probe in order to contraint the density dependence of the symmetry energy but this need calculations following the full range of time-scales and IMF mass emission involved in PLF binary splitting. **Still a challenge for dynamical models (SMF, CoMD. . .).**



We have shown **first results of the Inkiissy** experiment, **$^{124}Xe+^{64}Zn,^{64}Ni$** at 35 A.MeV using a system that is isobaric with the **$^{124}Sn+^{64}Ni$** one. In this experiment a first prototype of a Farcos block (4 telescopes) was used coupled to the Chimera 4π detector. **IMF-IMF** correlations in Farcos will improve our capability to analyse events with $M_{IMF}>1$. As well Farcos will permit to study **p-p** correlations in more central collisions.

Sensitivity of N/Z ratio to dynamical fission: this effect could be a new signature or probe of Isospin effect in reaction mechanisms.



InkiIssy data analysis …… continue

*The **INKIISSY** experiment at LNS:*

Spokes: P. Russotto, E. De Filippo, A. Pagano

**L. Acosta, L. Auditore, V. Baran,
T. Cap, G. Cardella, M. Colonna,
E. De Filippo, L. Francalanza, B. Gnoffo,
G. Lanzalone, I. Lombardo, C. Maiolino,
T. Minniti, G. Marquinez-Durán, S. Norella,
A. Pagano, E.V. Pagano, M. Papa, E. Piasecki,
S. Pirrone, G. Politi, F. Porto, L. Quattrocchi,
F. Rizzo, E. Rosato, P. Russotto, K. Siwek-Wilczynska, A. Trifirò, M. Trimarchi,
G. Verde, M. Vigilante,
J. Wilczyński**

NUSYM15
5th INTERNATIONAL SYMPOSIUM ON NUCLEAR SYMMETRY ENERGY