PKU-CUSTIPEN Nuclear Reaction Workshop
"Reactions and Spectroscopy of Unstable Nuclei"
Supported by CUSTIPEN, NSFC, CCAST, Peking U, Beijing Normal U.

Time dependence of the isospin composition of the emission particles in the fission events of Ar+Au at 35 MeV/u

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- Summary

Symmetry Energy:

Energy cost to convert protons to neutrons in nuclear medium

→ Symmetry energy

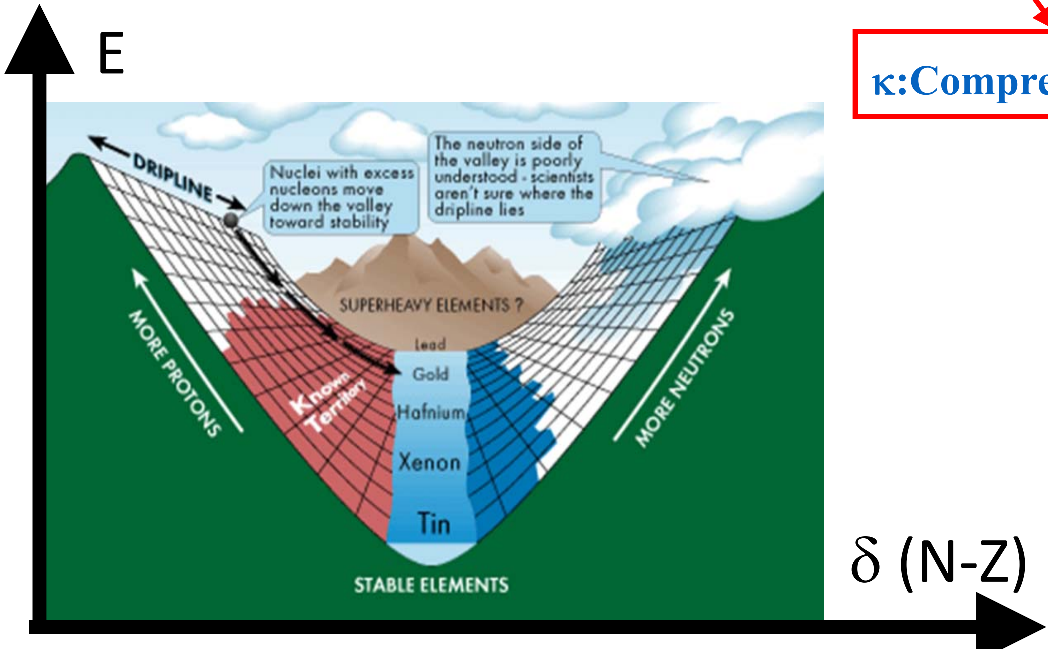
$$E = -a_V A + a_S A^{2/3} + a_C \frac{Z^2}{A^{1/3}} + a_a \frac{(N-Z)^2}{A} + E_{mic}$$

$a_V = 16\,\text{MeV}$ $a_S = 18\,\text{MeV}$ $a_a = 21\,\text{MeV}$ $a_C = 0.7\,\text{MeV}$

$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho) = a_V + \frac{\kappa}{18}\varepsilon^2 - \frac{\kappa^2}{162}\varepsilon^3 + \ldots + \delta^2\left(E_{sym} + \frac{L}{3}\varepsilon + \ldots\right)$$

κ:Compressibility

E_{sym}



$$E_{sym}(\rho) = E_{sym}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

$$\delta = \frac{N-Z}{N+Z}$$

$E_{sym}(\rho)$ plays an essential role in astrophysics/nuclear physics

Astrophysics connection

→Proton fraction

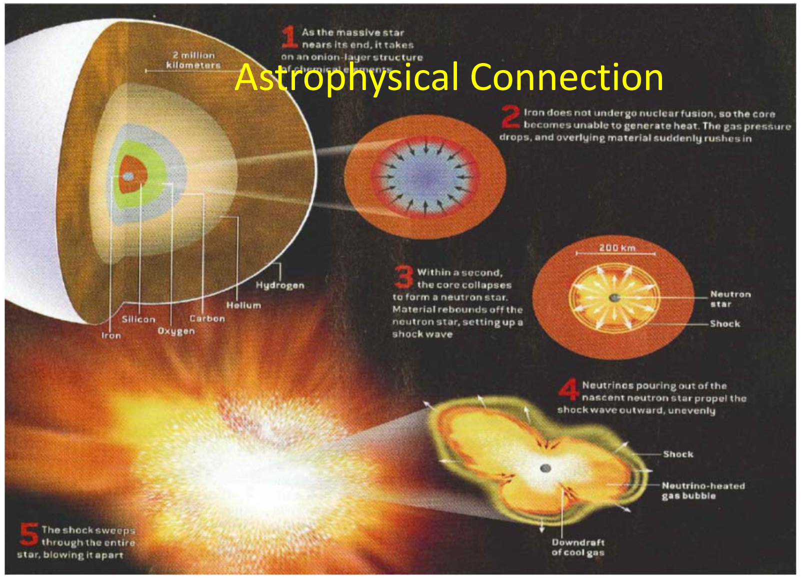
→M-R relation

→ρ_c for D-Urca

→Transition density

……

Phy. Rep. 442(2007) 109; NPA777(2006)479
PRC76(2007),025801; PRC75(2007) 015801
PRC74 (2006),035802; Astro. J. 676 (2008) 1170
Phy. Rep. 411(2005) 325; PLB 642, 436 (2006)



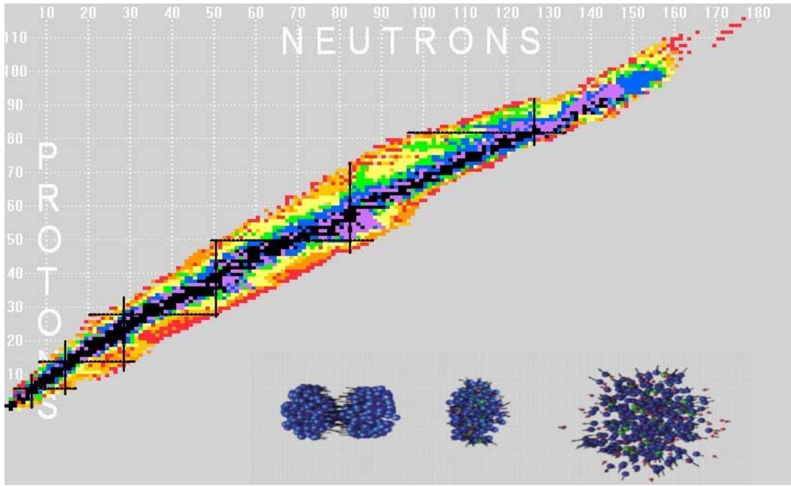
Nuclear Physics connection

→ Nuclear Binding Energy

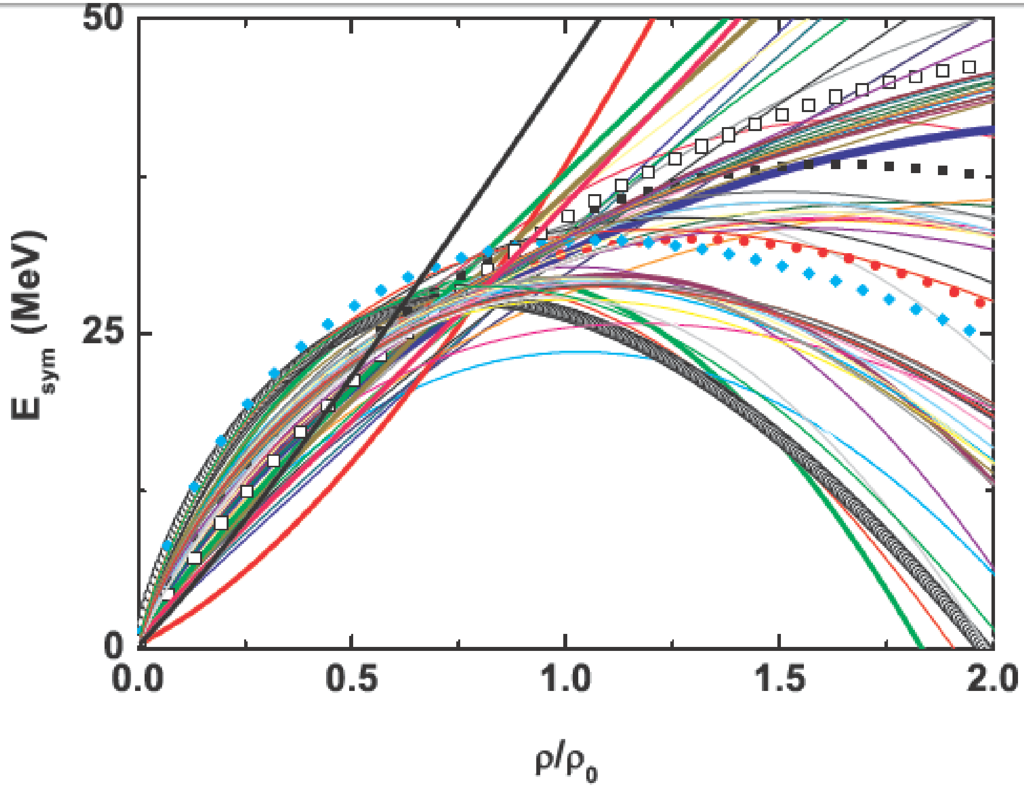
→ 3 body force

→ Tensor force

→ Collision dynamics…



E_{sym} (ρ) very uncertain, particularly at $\rho>\rho_0$

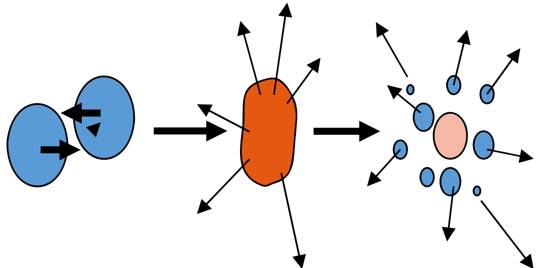


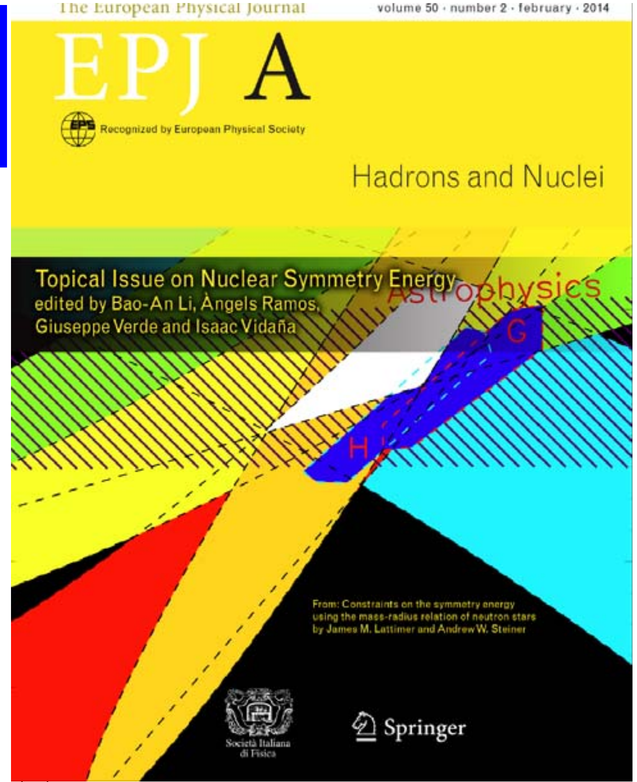
L.W. Chen, C.M. Ko and B.A. Li, Phys. Rev. C72, 064309 (2005); C76, 054316 (2007).

While at sub-saturation densities……

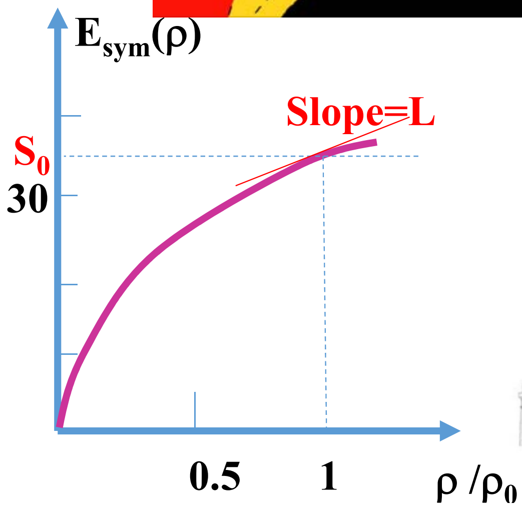
A list for sub-saturation density

At sub-saturation densities





- → **Global nucleon optical potential in n/p-A collisions or (p,n) reactions**
- → **Neutron Skin thickness of Pb-208 (PREX experiment at JLAB)**
- → **Isospin scalaring and isospin fractionaiton in multifragmentation**
- → **Isospin diffusion**
- → **n/p ratio of fast and pre-equilibrium nucleons**
- → **N/Z composition of the emitted fragments**
- → **GDR strength**
- → **Correlation function**
- → **…. ….**



$$S_0 = 32.5 \pm 2.5 \text{ MeV} \quad L = 55 \pm 25 \text{ MeV}$$

How long the E_{sym} effects can persist in HIC?

Isospin Diffusion

Neutron Skin | Isospin scaling | Fast nucleon emission

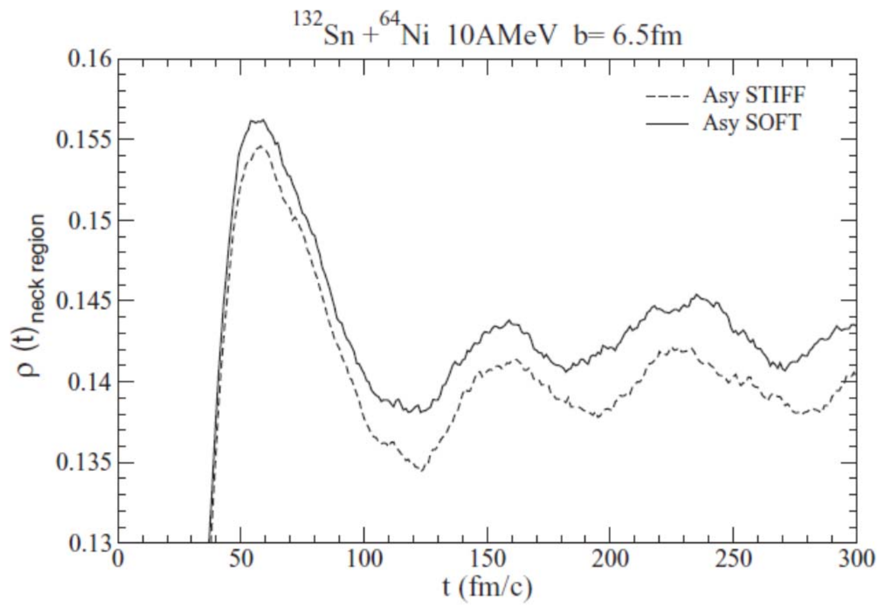
SLOW

Intermediate Process ?

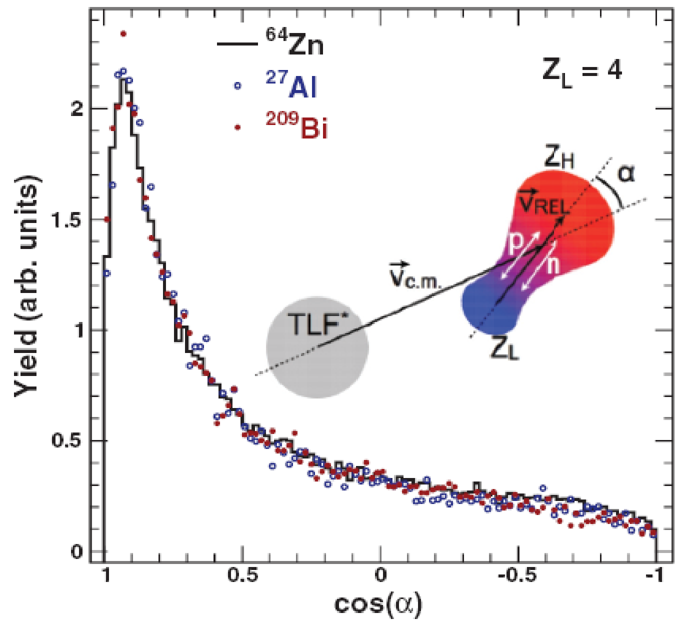
FAST

10^{-19} s

$10^{-21\sim22}$ s

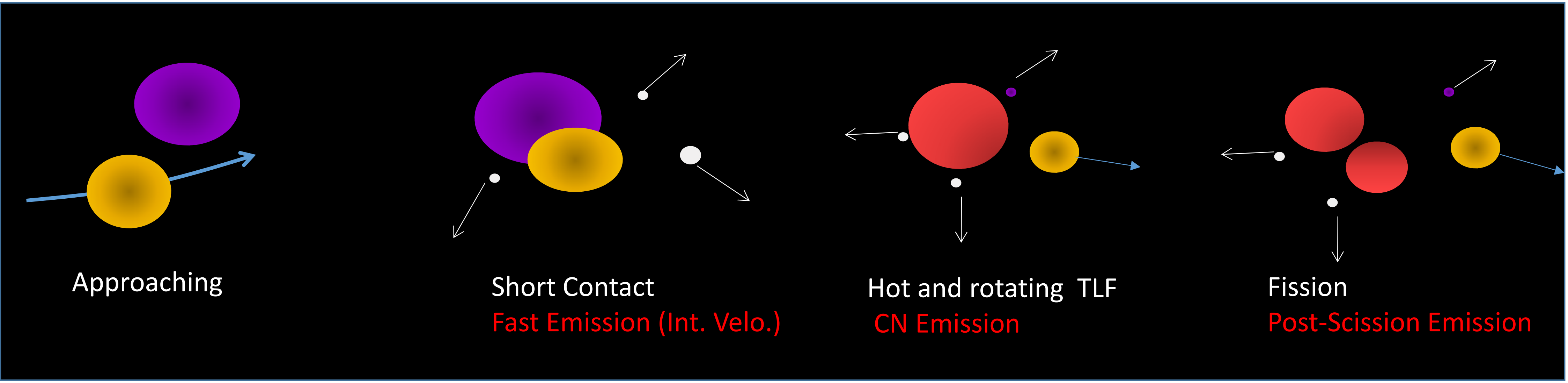


Phys Rev C **83**, 014604 (2011)



Phys Rev C87 (2013) 061601(R)

Using fission to study the long time effect of $E_{sym}(\rho)$



Animation by Tian Junong

- Possible Advantages:
- ☑ Neck part: Very neutron rich, Low Densities
- ☑ Time Scale: Between statistical emission (Q effect) and two body process (very short)

One Step backward: Isospin effect of the particle emission

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Introduction

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Experiment and Results

- Fission Distributions
- Spectra Fitting of Light Charged particles
- Future experiment

Experimental Set Up

- 35 MeV/u Ar+ Au.
- Trigger: 2 fold fragments .AND. 1 LCP
- 2 fold fragments .AND. 1 Proj.-like

1) Six PPAC covering ~1/3 whole space
2) All about 30 cm to the target
3) 3 Si-CsI and 3 Si-Si-CsI (158,127,80) telescopes
4) One 12-unit Si-BGO hodoscope

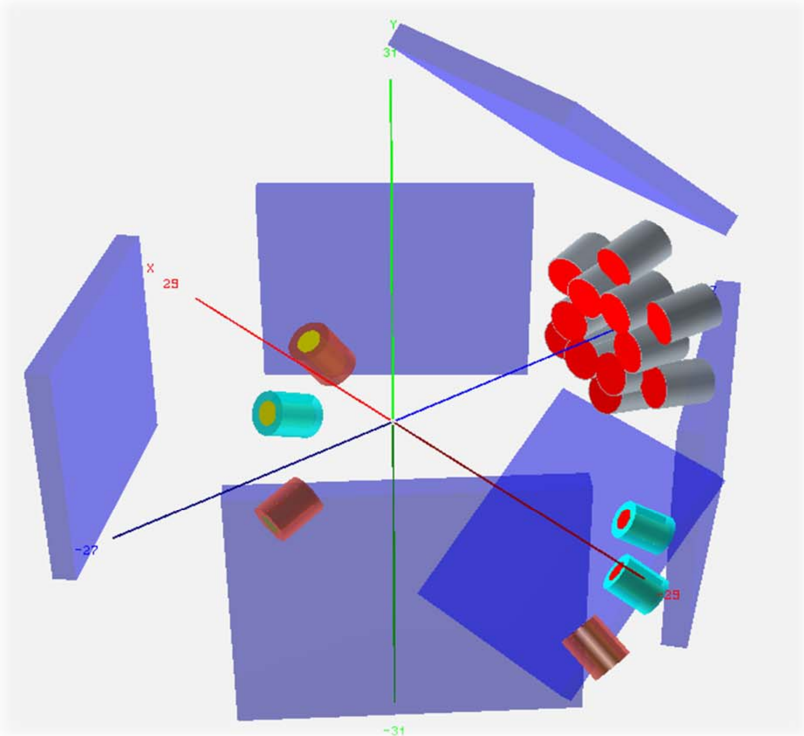
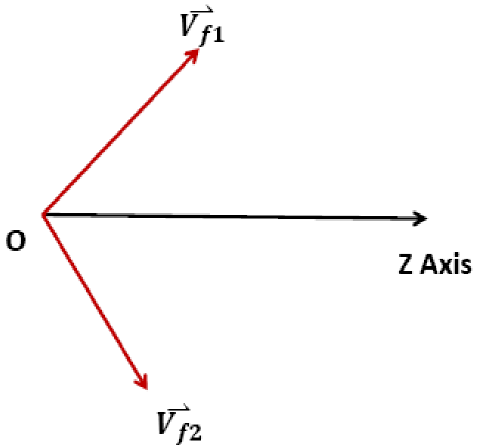


TABLE I: The parameters of the 6 LCP telescopes

Tele. No.	1	2	3	4	5	6
d (mm)	12.0	10.2	10.4	14.0	14.0	14.0
L (cm)	11.5	11.5	11.5	26.0	21.6	28.5
θ (°)	158	155	127	80	59	44
ϕ (°)	-90	90	90	-145	-139	-133
ΔE_1 (μm)	50	50	50	50	50	50
ΔE_2 (μm)	400	/	400	400	/	/
E_{CsI} (mm)	40	40	40	40	40	40

Fission Event Measurement and Reconstruction



$$\frac{m_{f1}}{m_{f2}} = \frac{|V_{f2}|_{\perp}}{|V_{f1}|_{\perp}}$$

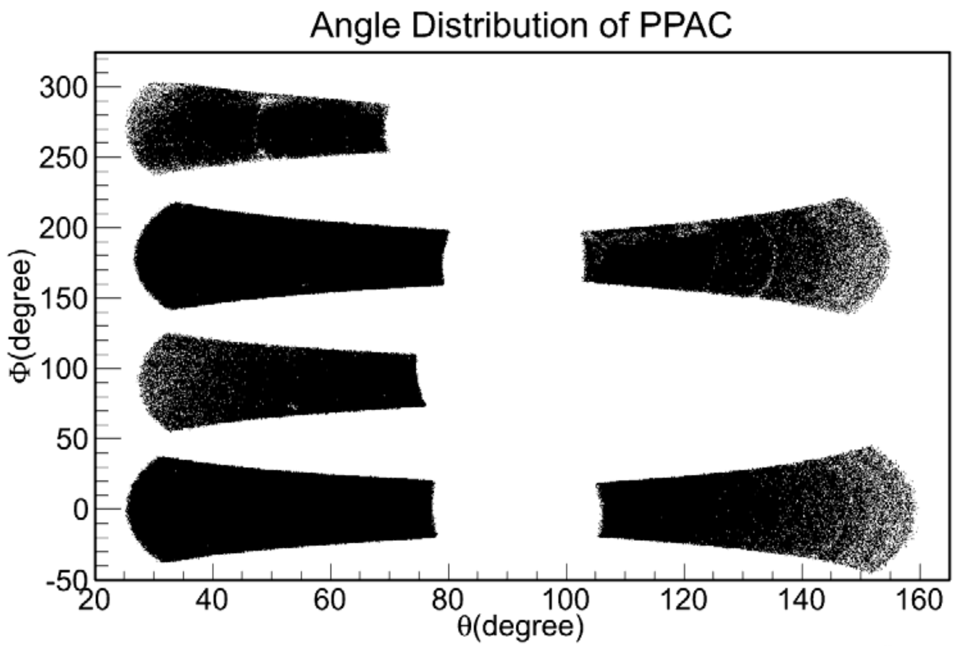
$$m_{CN} = m_{f1} + m_{f2}$$

$$m_{CN}\vec{V}_{CN} = m_{f1}\vec{V}_{f1} + m_{f2}\vec{V}_{f2}$$

$$\vec{V}_{CN} = \frac{m_{f1}\vec{V}_{f1} + m_{f2}\vec{V}_{f2}}{m_{f1} + m_{f2}}$$

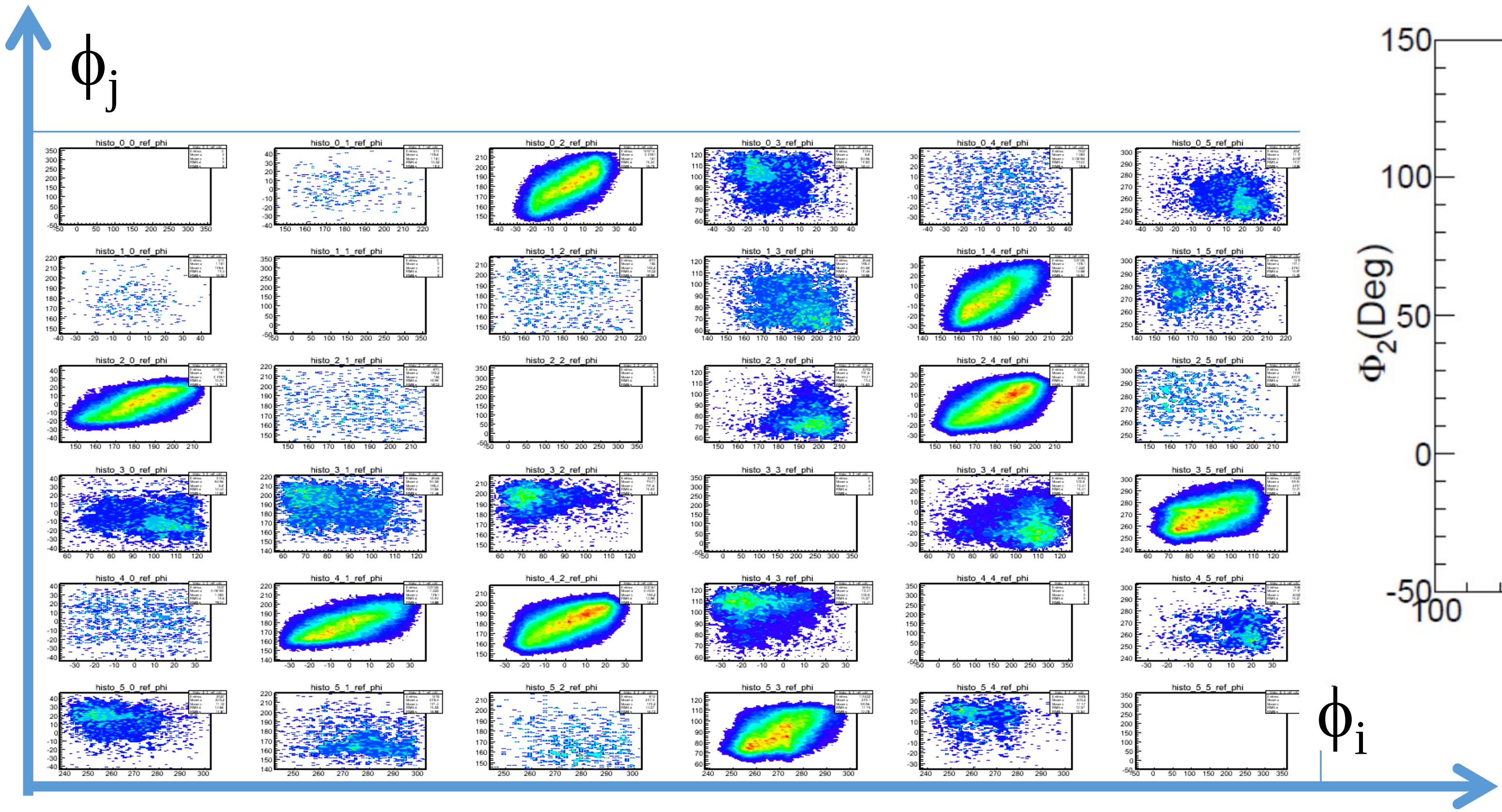
$$\eta = \frac{1 - \frac{m_{f_2}}{m_{f_1}}}{1 + \frac{m_{f_2}}{m_{f_1}}}$$

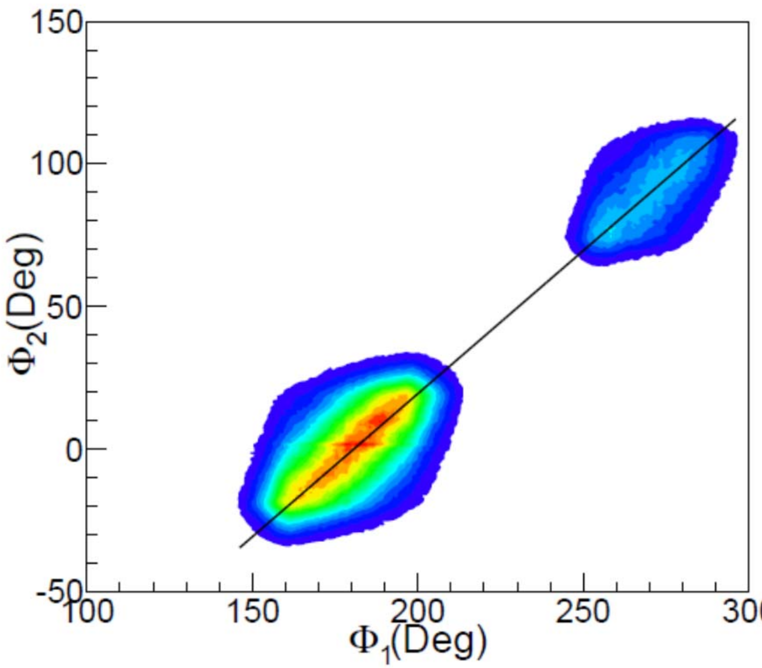
$$\vec{V}_{CN} = \frac{\vec{V}_{f1} + \frac{m_{f2}}{m_{f1}}\vec{V}_{f2}}{1 + \frac{m_{f2}}{m_{f1}}}$$



- Folding angle method → velocity of fragments, mass ratio …

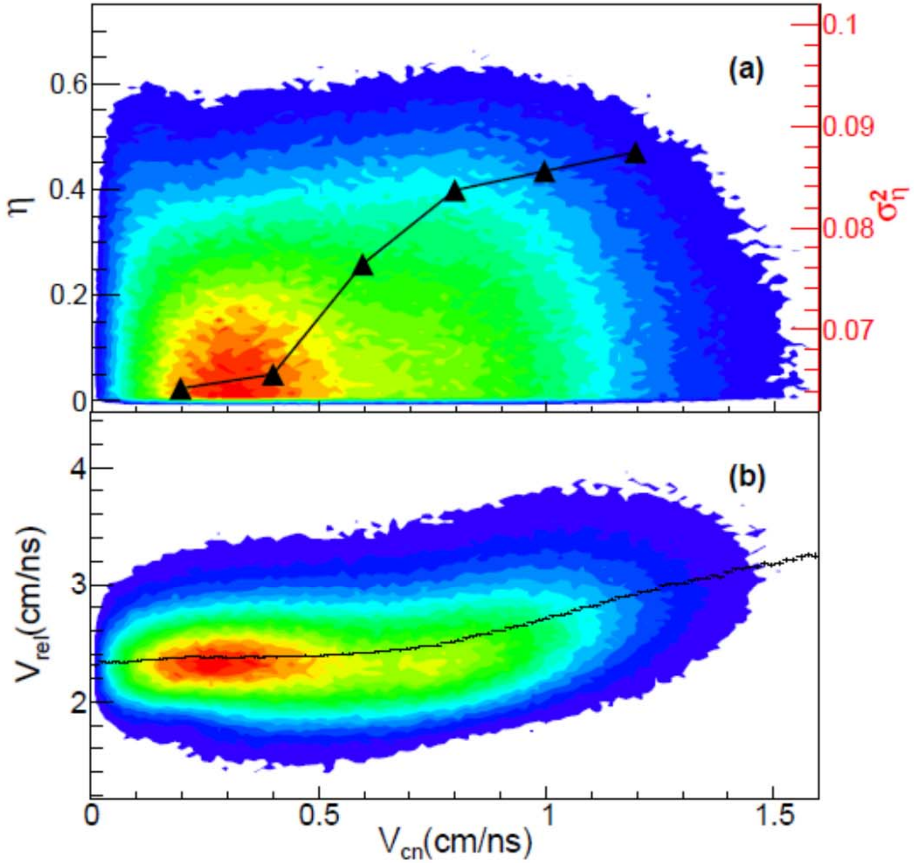
1) Fission fragments correlation

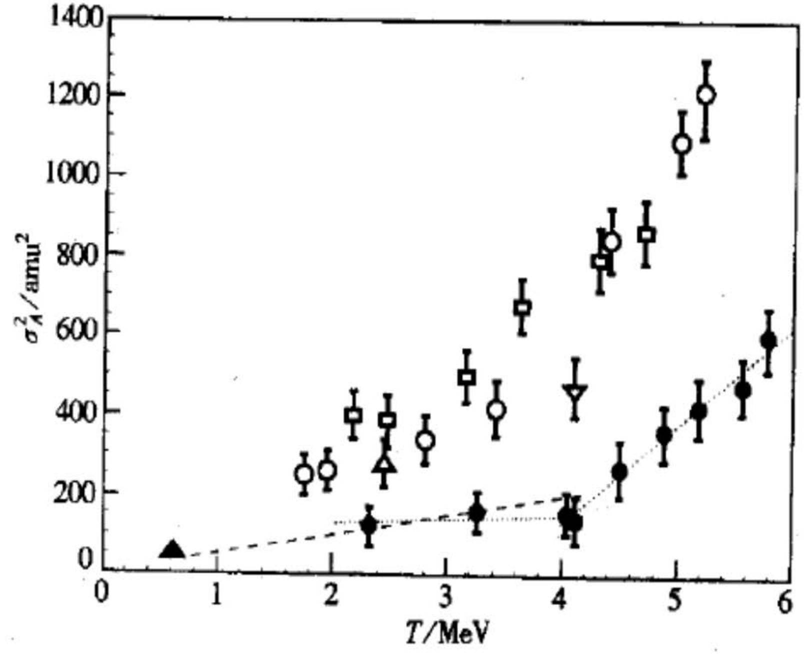




- 2-fold events with face-to-face PPACs fired show good back-to-back correlation!

Fission Distribution

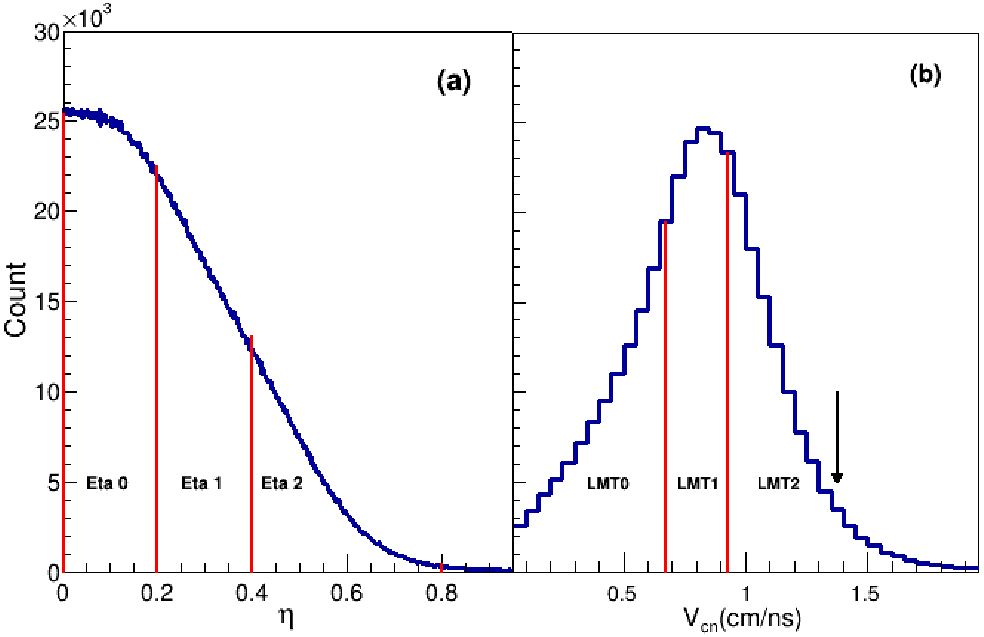


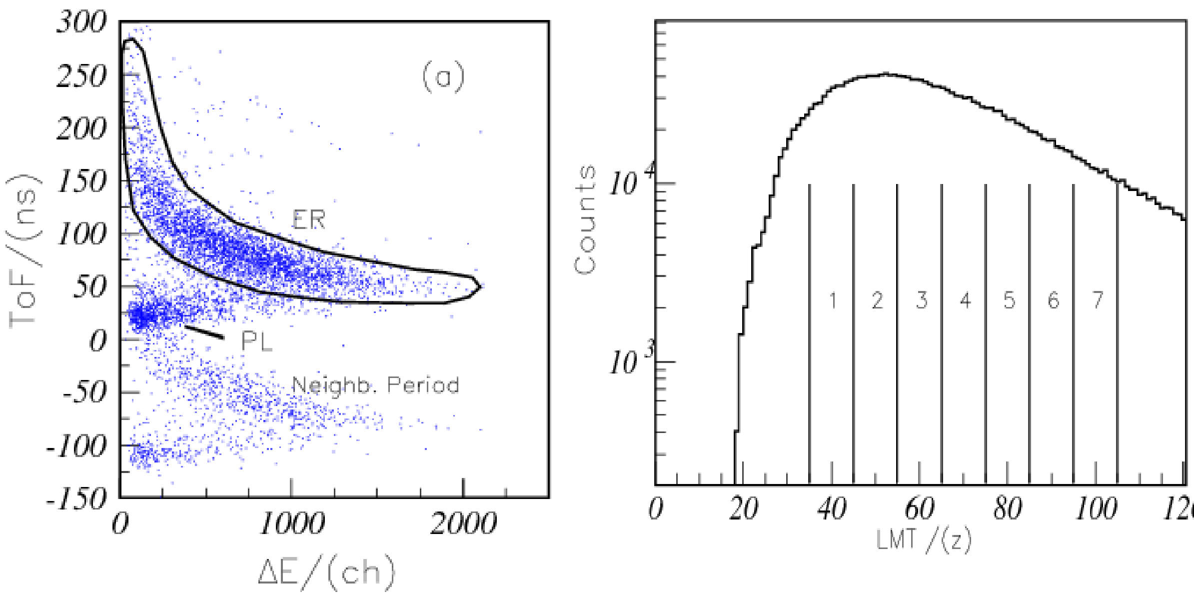


S. Harar, Nucl. Phys. A 471, 205c (1987)
J. W. Zheng et al, HEPNP. 23, 409 (1999)

1) Relative velocity peaks at 2.4 (Viola systematics), and showing slight asymmetry
2) At low and high V_{add}, the relative velocity exhibits different manner

LMT 同文献的比较



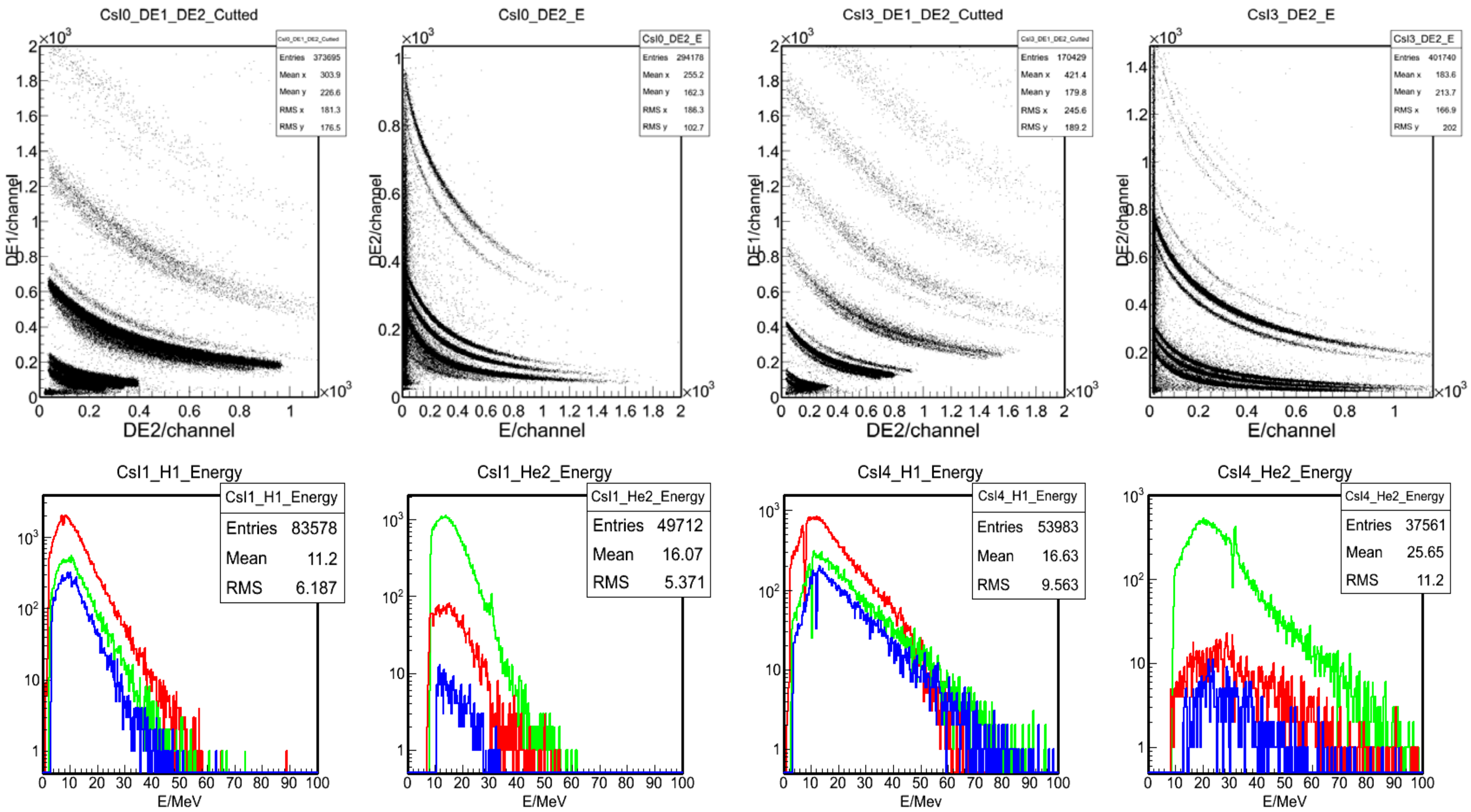


Z. G. Xiao, et al., HEPNP. 25, 643 (2001)

$$\langle LMT \rangle = \begin{cases} 1.273 - 0.092\sqrt{E_{in}/A} & \sqrt{E_{in}/A} > 3.2(\mathrm{MeV/u})^{1/2} \\ 1 & \sqrt{E_{in}/A} \le 3.2(\mathrm{MeV/u})^{1/2} \end{cases}$$

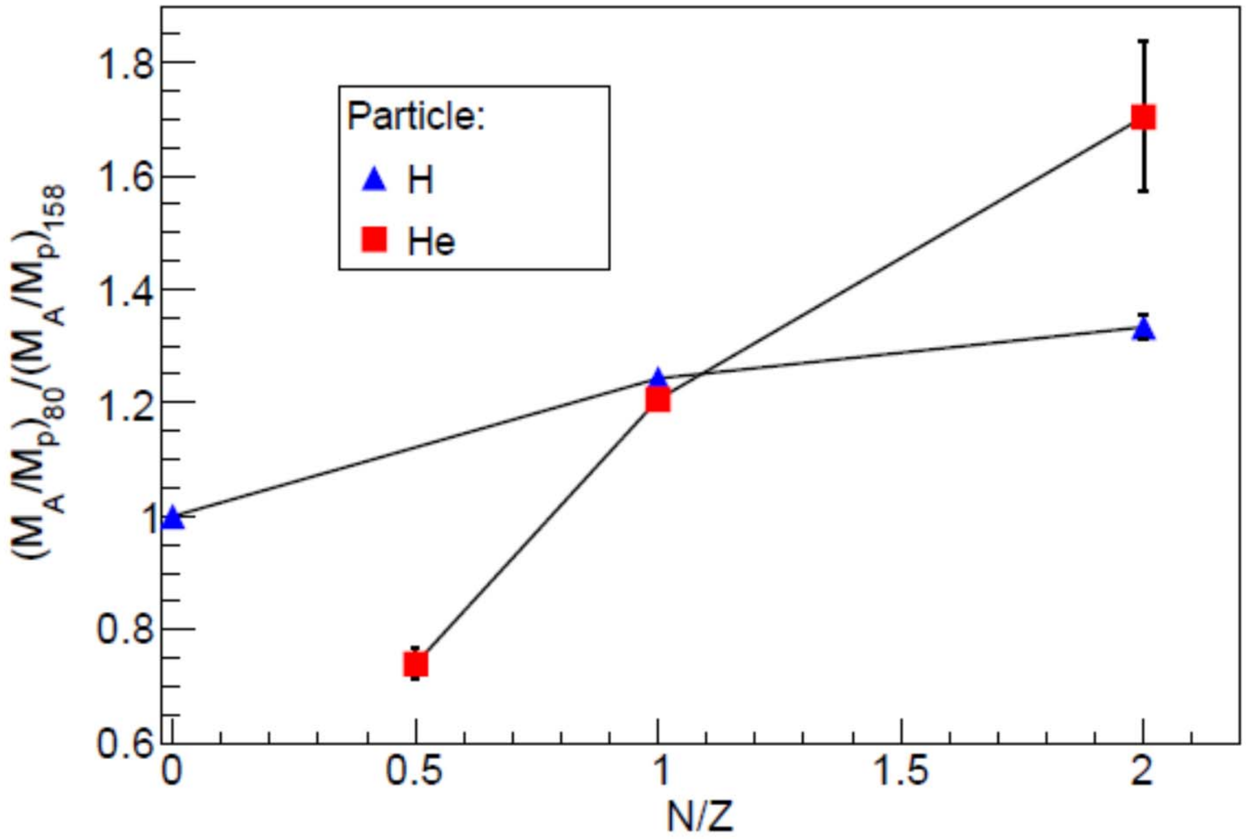
- LMT most probable at 0.56， consistent with Ar+Sn at 35 MeV/u。
- Slightly deviate from the empirical prediction at 0.72， presumably the beam energy exceeds the range.

LCPs in coincidence with fission



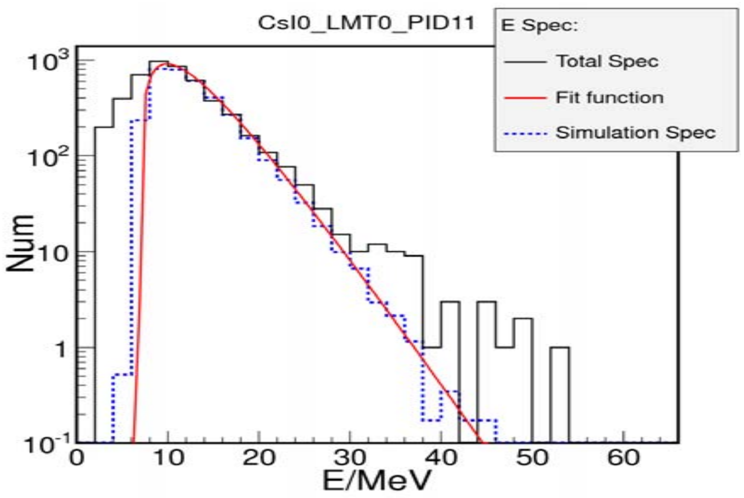
- Mass Resolved spectra obtained at 2 degrees: 158, 80

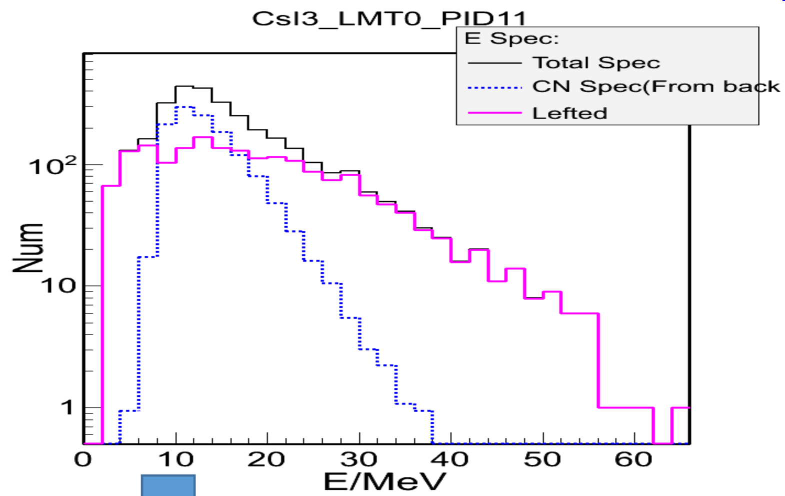
Double angular ratio of particle yield

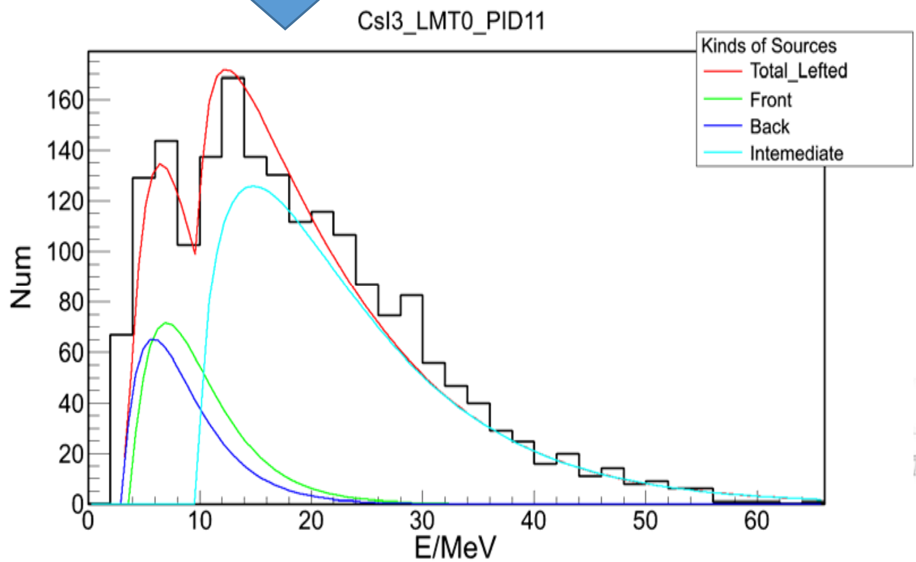


- Model independently, particles emitted at smaller angle are more neutron rich
- Smaller angle emitted particles experience more dynamical contribution

Three moving source analysis







- Three moving source: CN, FF and Int. Velocity

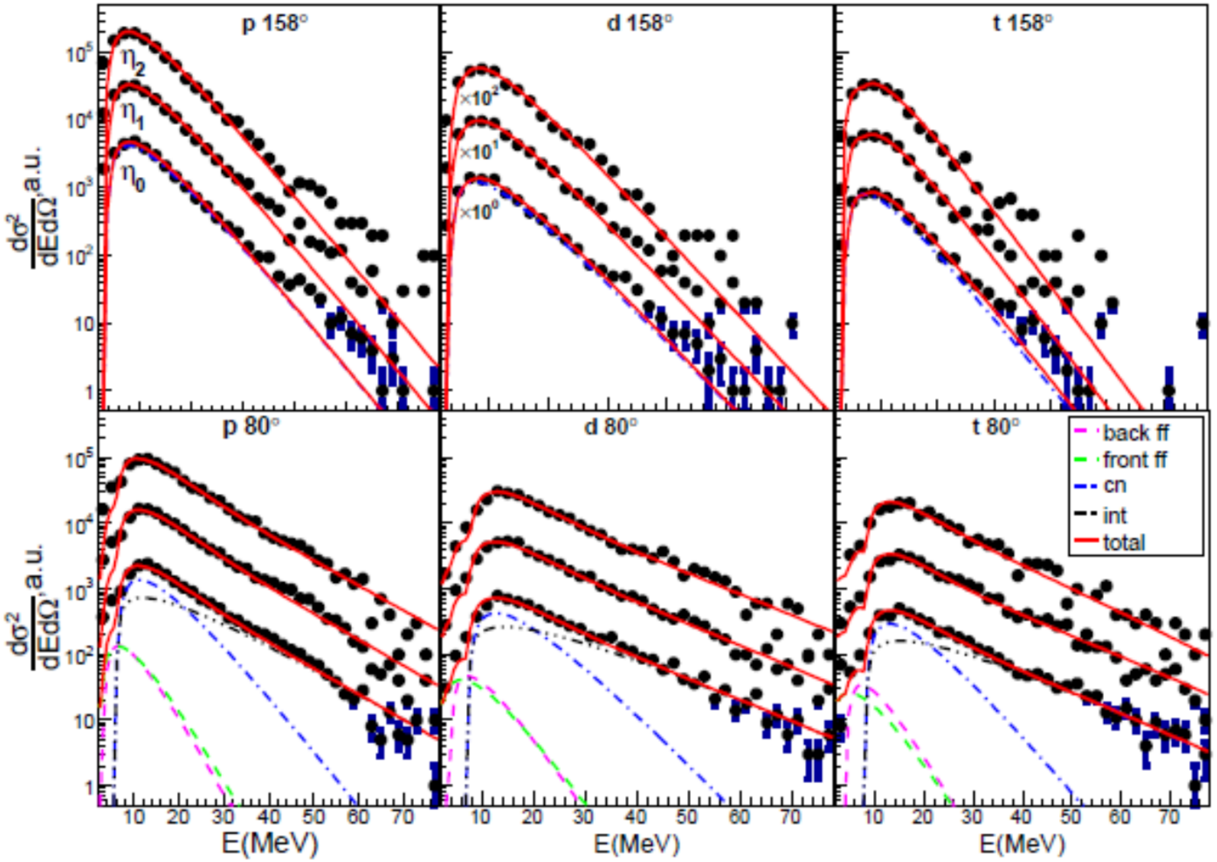
$$\frac{d^2\sigma}{d\Omega dE} = \frac{N}{2(\pi T)^{3/2}} (E - E_c)^{1/2} \exp[-(E - E_c)/T]$$

STEP 1: Fit large angle telescope with CN source

STEP 2: Apply the CN parameters to the middle angle detector

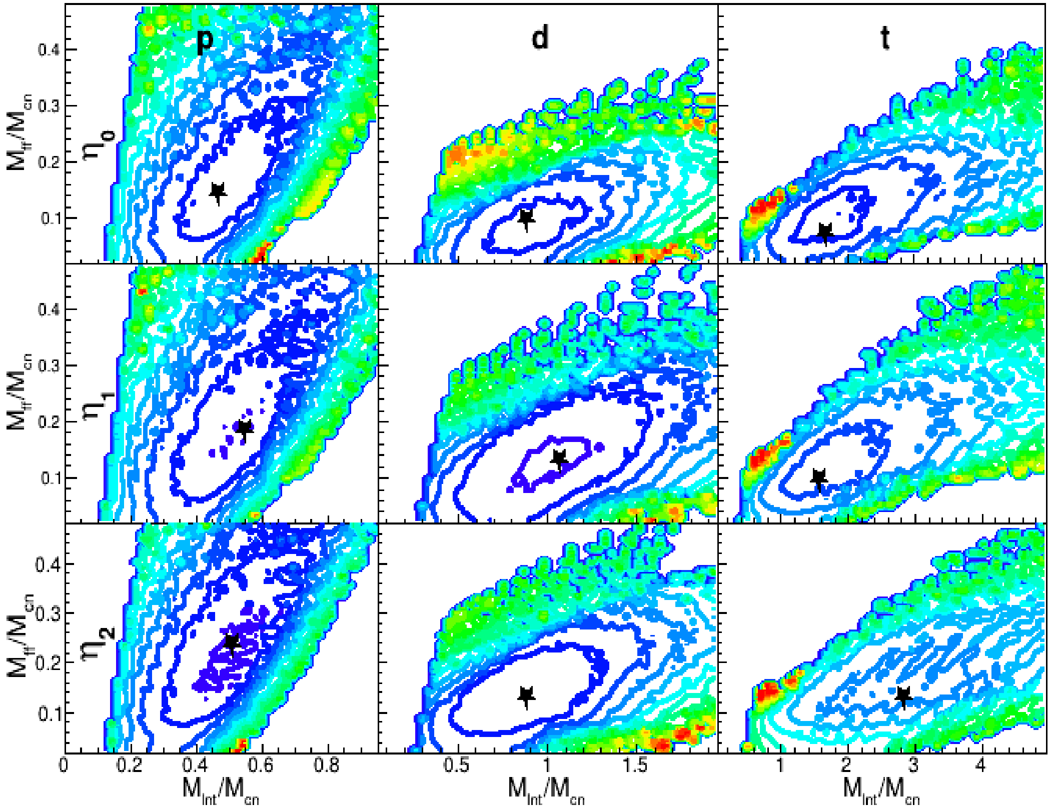
STEP 3: Fit the middle angle spectrum

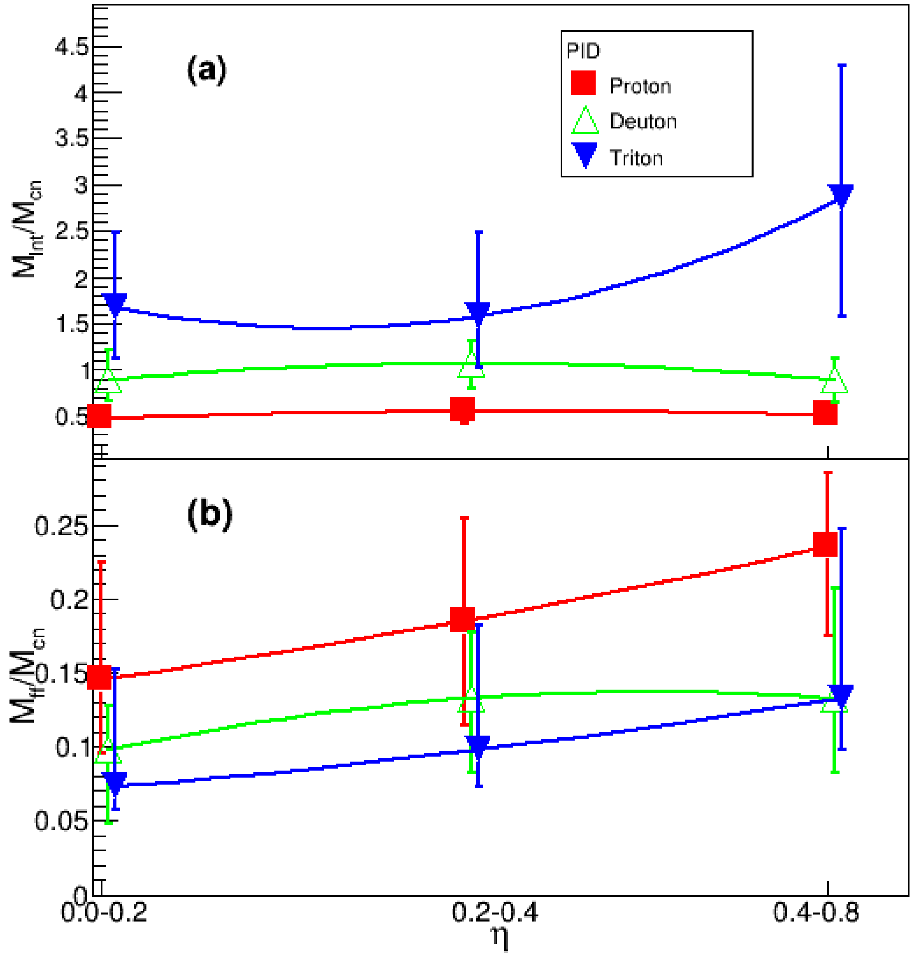
Energy spectra analysis vs mass asymmetry



$$\frac{d^2\sigma}{d\Omega dE} = \frac{N}{2(\pi T)^{3/2}}\left(E - E_c\right)^{1/2} \exp\left[-\left(E - E_c\right)/T\right]$$

Minimum $\chi 2$ analysis



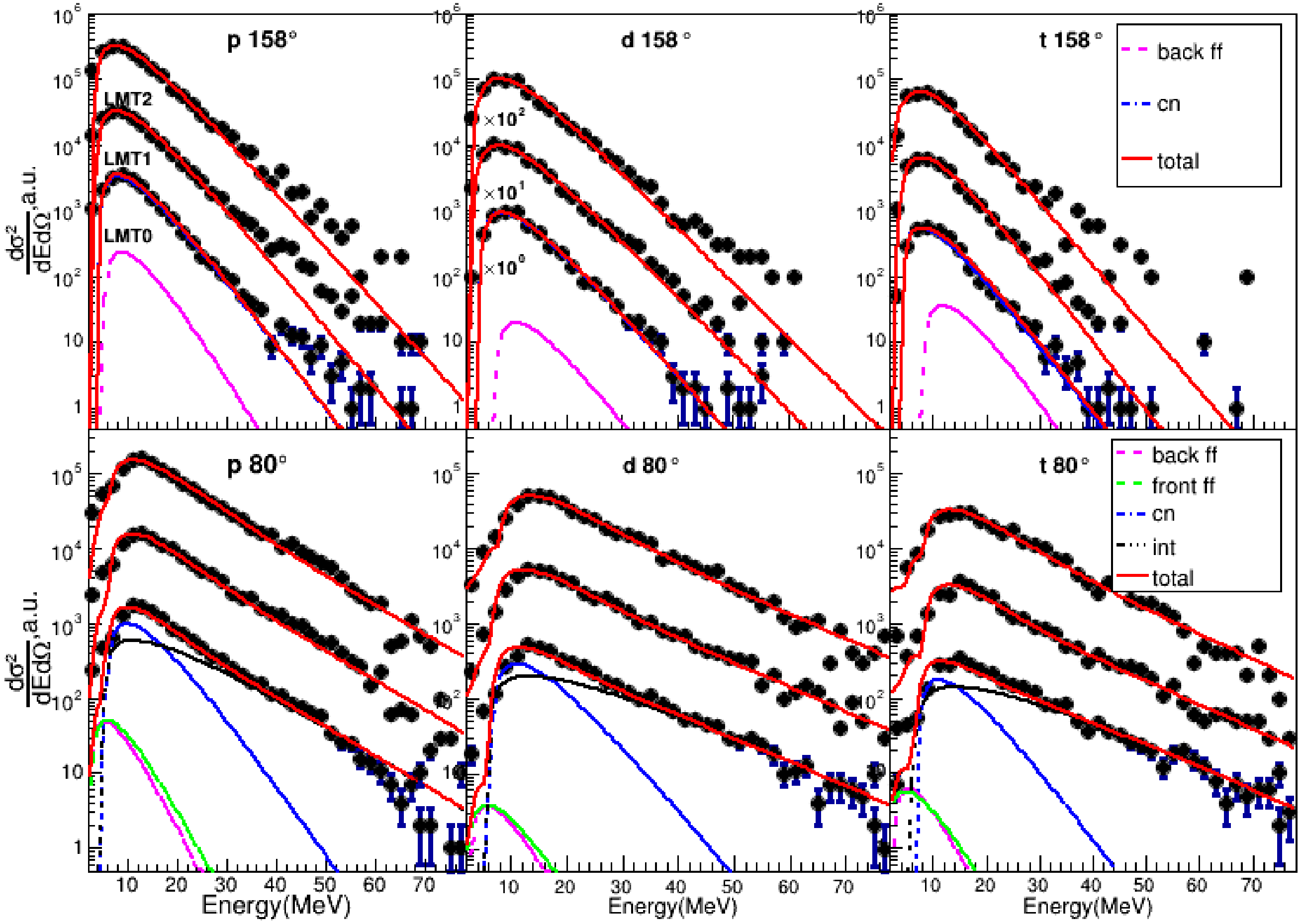


→ M_{ff}/M_{cn} vs. M_{inv}/M_{cn}

→The two ratios show different hierarchy

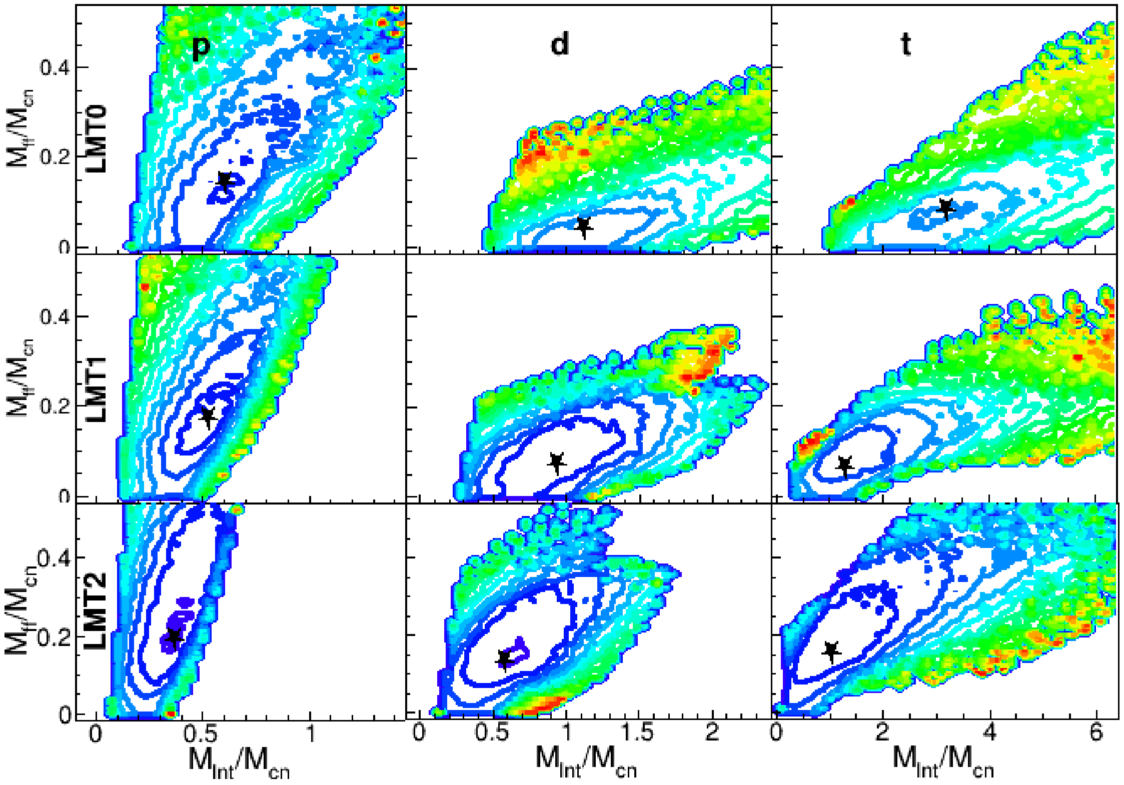
→ The particles emitted in early stage are neutron rich!

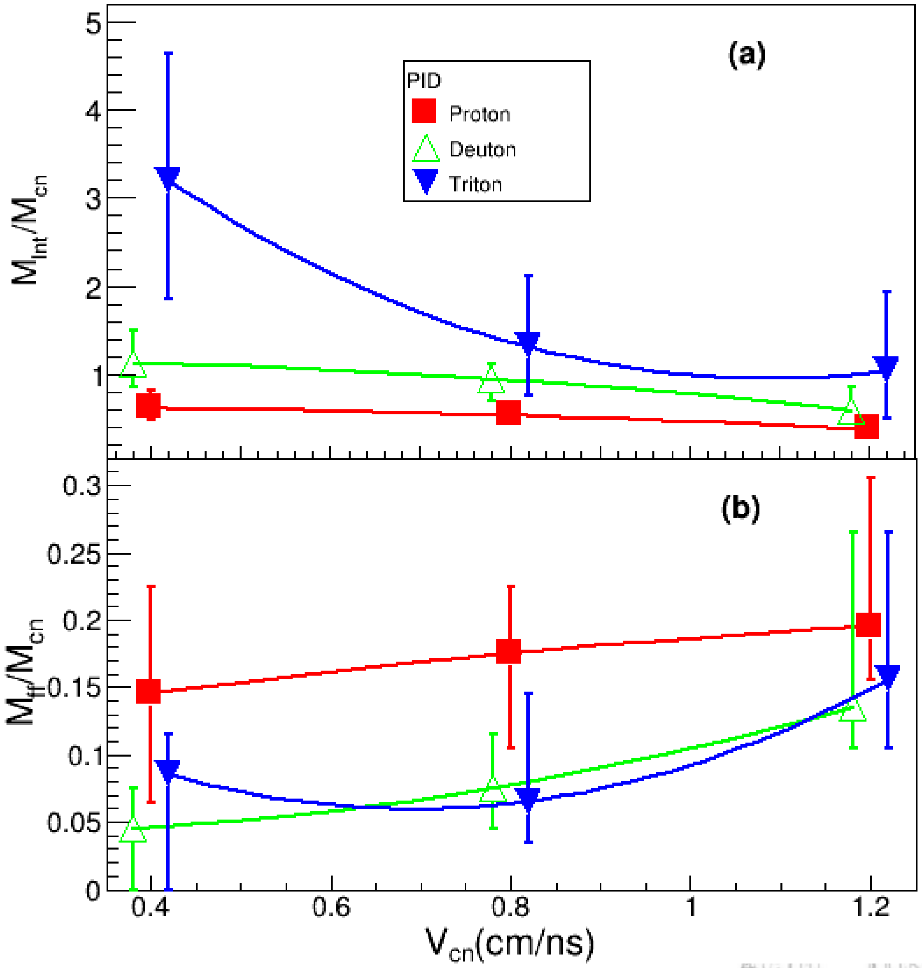
Energy spectra vs. LMT



- As a function of LMT

Minimum χ2 analysis



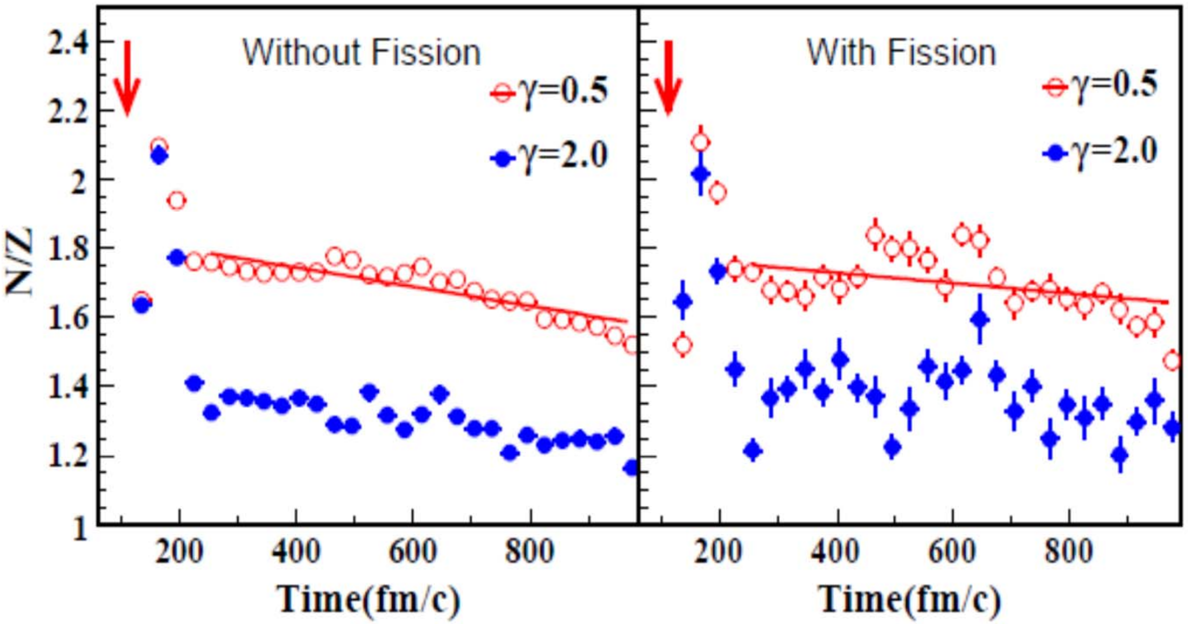


- The hierarchy of Multiplicity ratio remains.
- Error bars are large for the FF source.

IQMD calculations

$$V_{\rm loc} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\sigma+1}\frac{\rho^{\sigma+1}}{\rho_0^\sigma} + \frac{g_0}{2\rho_0}(\nabla\rho)^2 + \frac{C_s}{2}\left[\frac{\rho^{\gamma+1}}{\rho_0^\gamma} - \frac{\kappa_s}{\rho_0}(\nabla\rho)^2\right]\delta^2 + g_\tau\frac{\rho^{\eta+1}}{\rho_0^\eta}$$

α	207 MeV	β	138 MeV
σ	7/6	g_0	18 MeV $\cdot$ fm^2
C_s	32 MeV	κ_s	0.08 fm^2
g_τ	14 MeV	η	5/3



1)Along the whole decay chain, the average N/Z decreases with time.

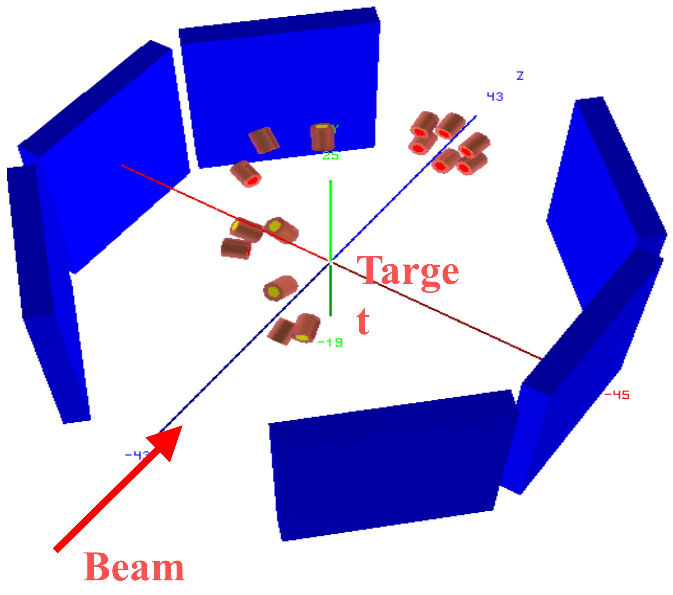
→**The neutron richness of the emitted particles is enhanced at the beginning of the emission.**

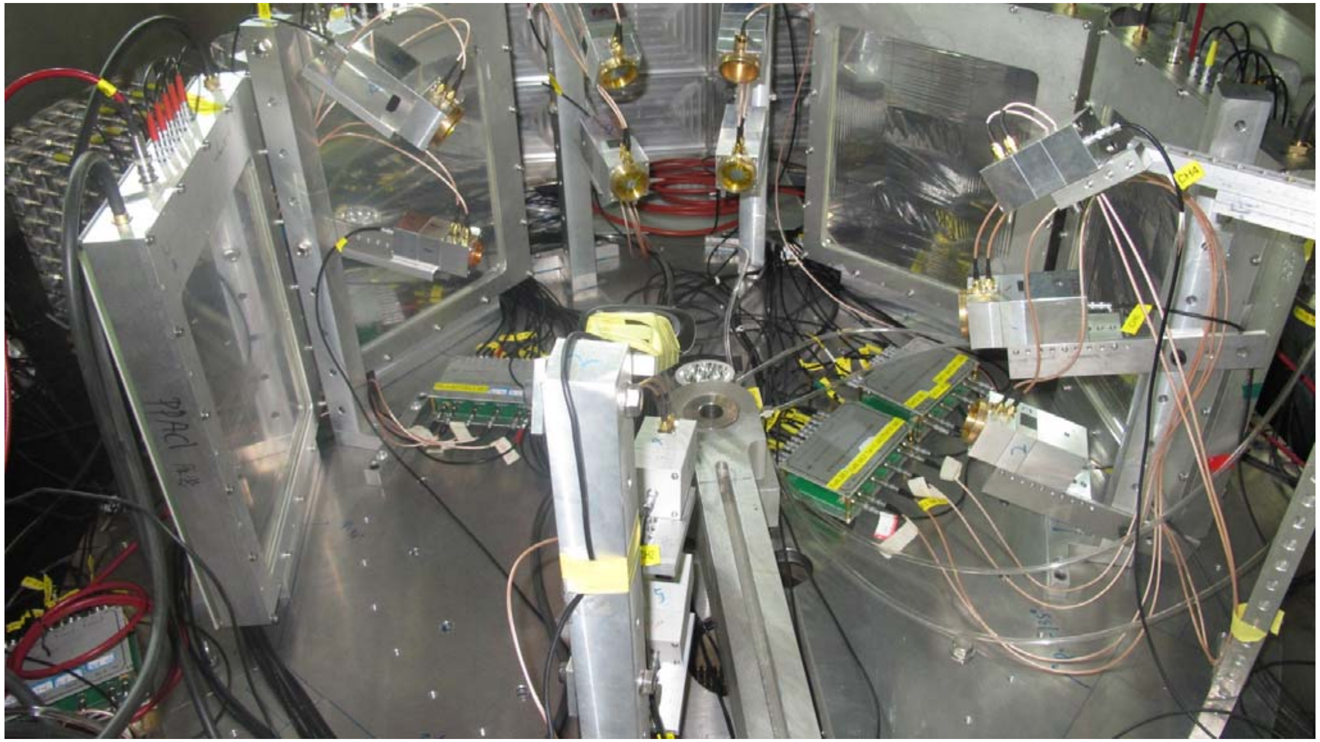
2)The isospin composition N/Z exhibits an obvious dependence on $E_{sym}(\rho)$ till very late stage.

3)The effect of the symmetry energy remains equally significant in the fission.

→ **Scission point can be a clock to investigate the effect of $E_{sym}(\rho)$.**

Further improved experiment

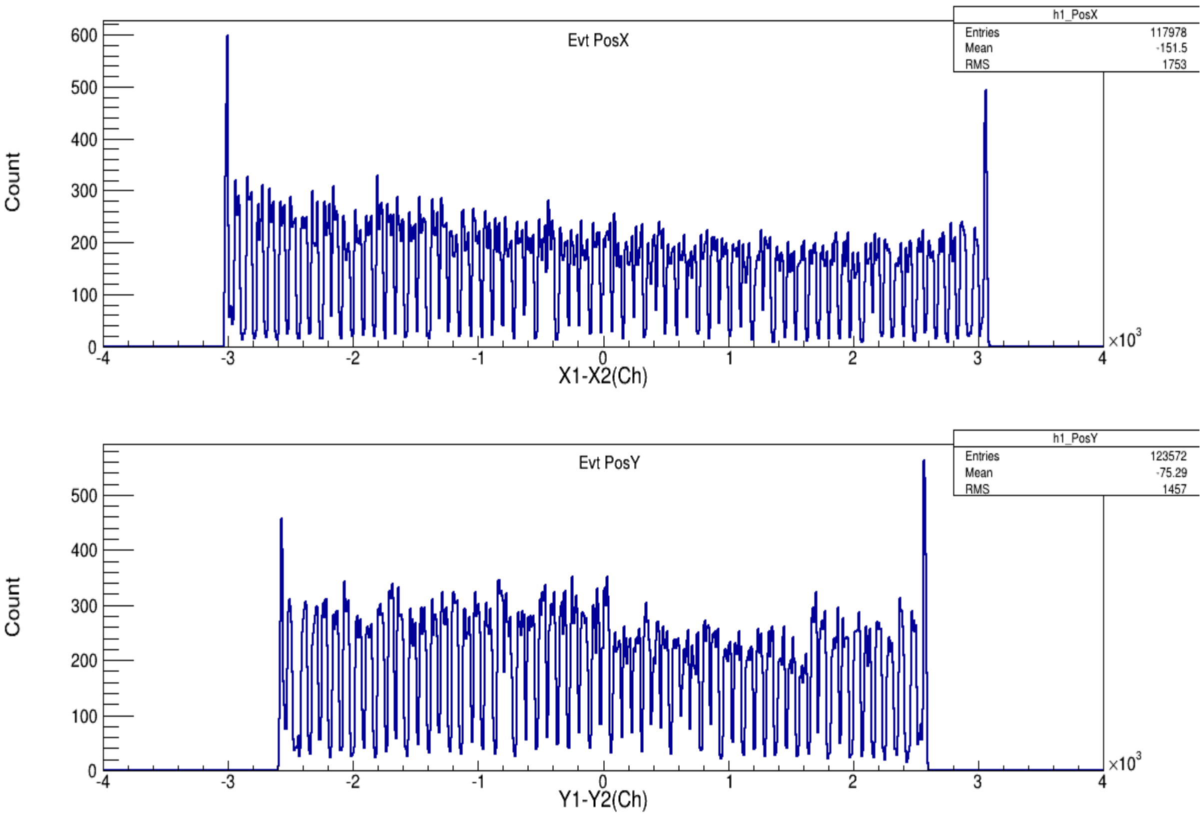


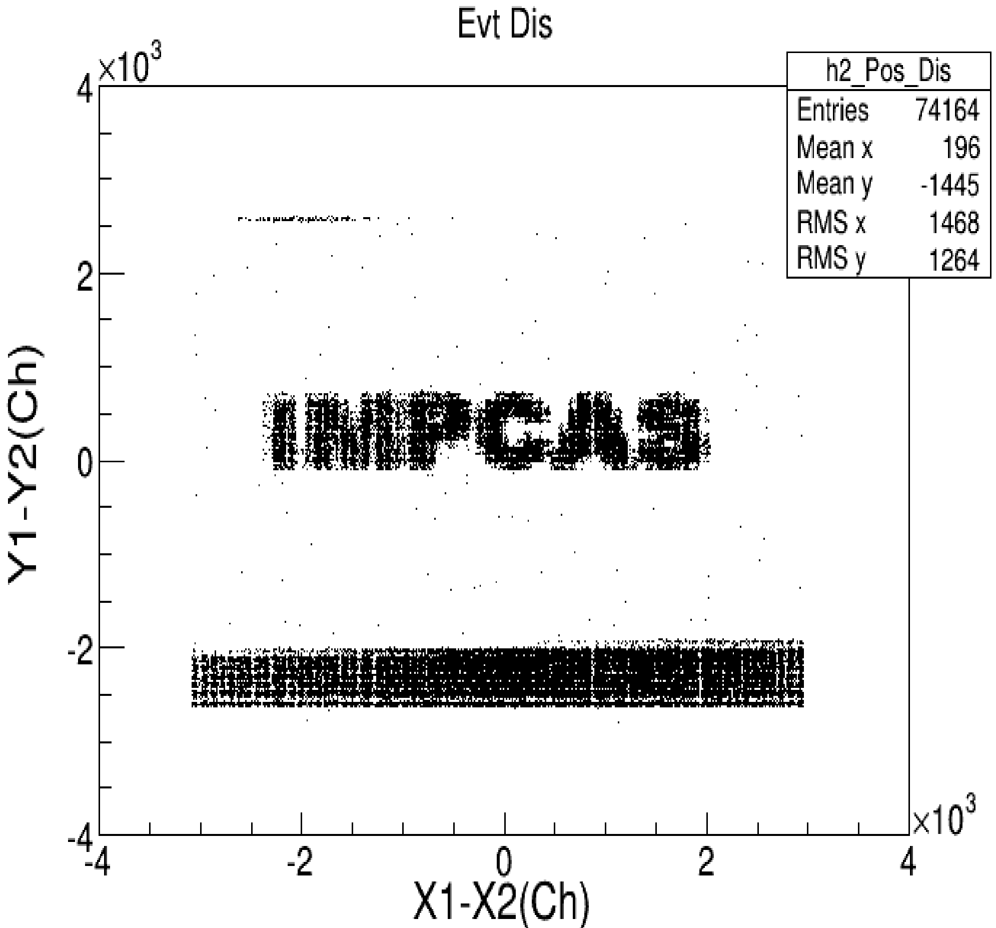


- **Complete in June 2014.**

1. Improved PID by using H.Q. telescopes
2. Lower energy threshold
3. More Detectors(> 5 positions)

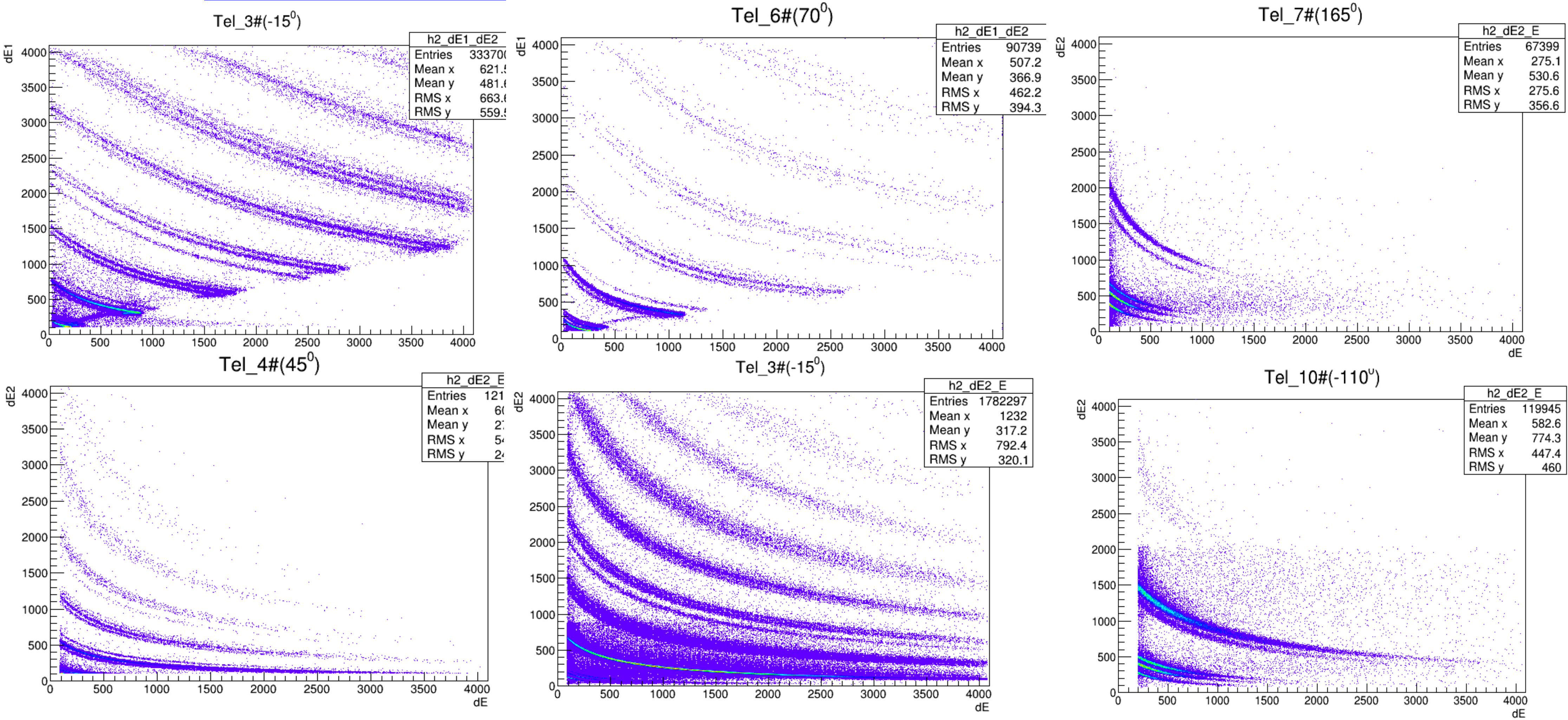
PPAC Performance





- Good Position Resolution and high fission fragment efficiency

Telescope Performance



- Isotope identification achieved in most of the telescopes → More angles

Summary

- In 35 MeV/u 40Ar+197Au collisions:

→LCPs are measured in coincidence with fission events

→Smaller angle products, with more contribution from dynamic emissions, are more neutron rich. A hierarchy from t to d and p are observed for the dynamic emissions, later emissions exhibit the inverse trend.

→Effect of the symmetry energy persists to very late stage. Process with long time scale is sensitive to the underlying effect of the symmetry potential. The time dependent N/Z of the light charged particles can be used as a new probe to $E_{sym}(\rho)$

→Further experimental studies are of interest.

Please refer to R. Wang et al, *Phys. Rev.* **C 89**, 064613 (2014)

Acknowledgements

Collaborators

THU: R. S. Wang, Y. Zhang, H. Yi, L. M. Lv,
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Y. P. Zhang, J. S. Wang, P. Ma, Y. J. Zhou,
Y. Y. Yang, S. L. Jin……

CIAE: Y. X. Zhang, Q. H. Wu

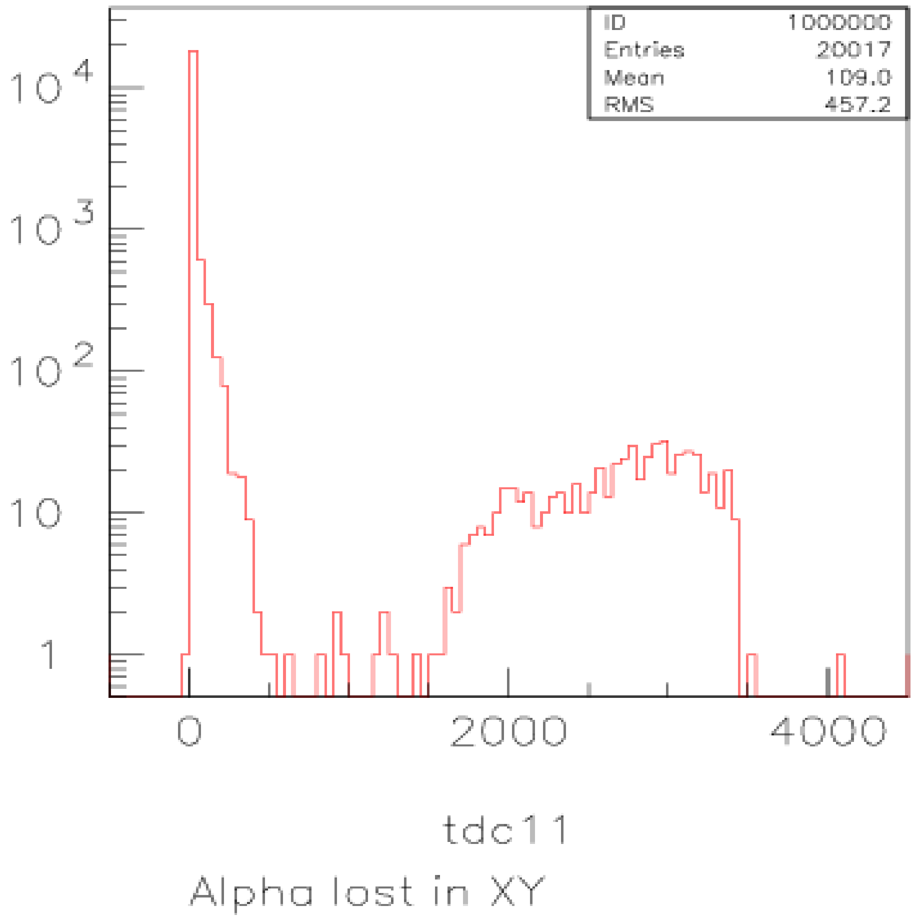
ATC: J. L. Tian

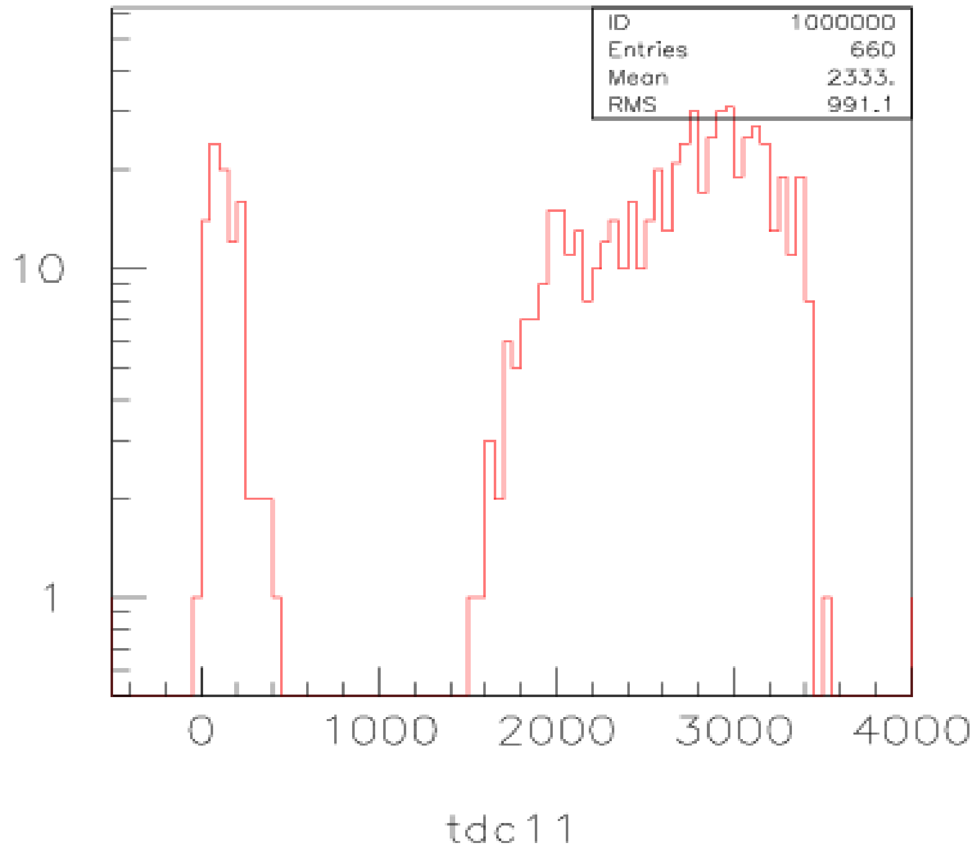
MSU: B. Tsang

Funding: NSFC, Tsinghua University Initiative Scientific Research Program

Thank You for your attention!

PPAC Performance II

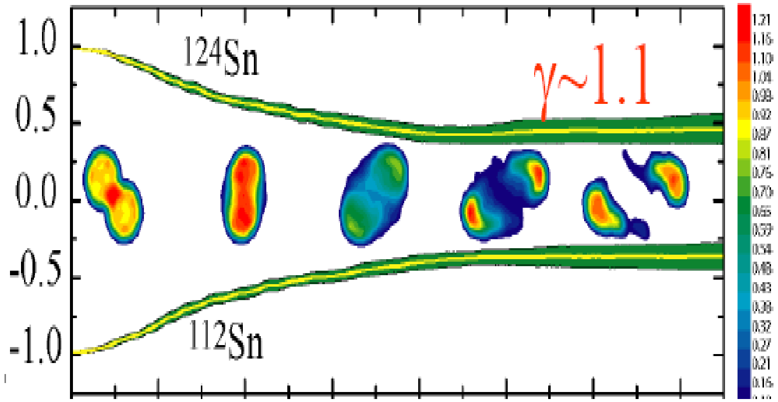




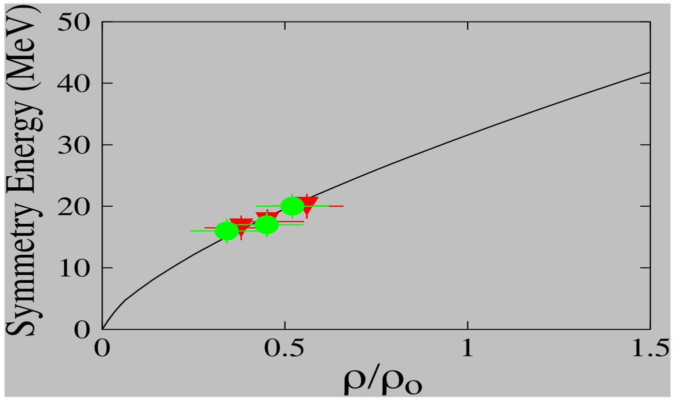
- Identify of fission fragments against light charged particles

Some example probes of $E_{sym}(\rho)$ at $\rho<\rho_0$

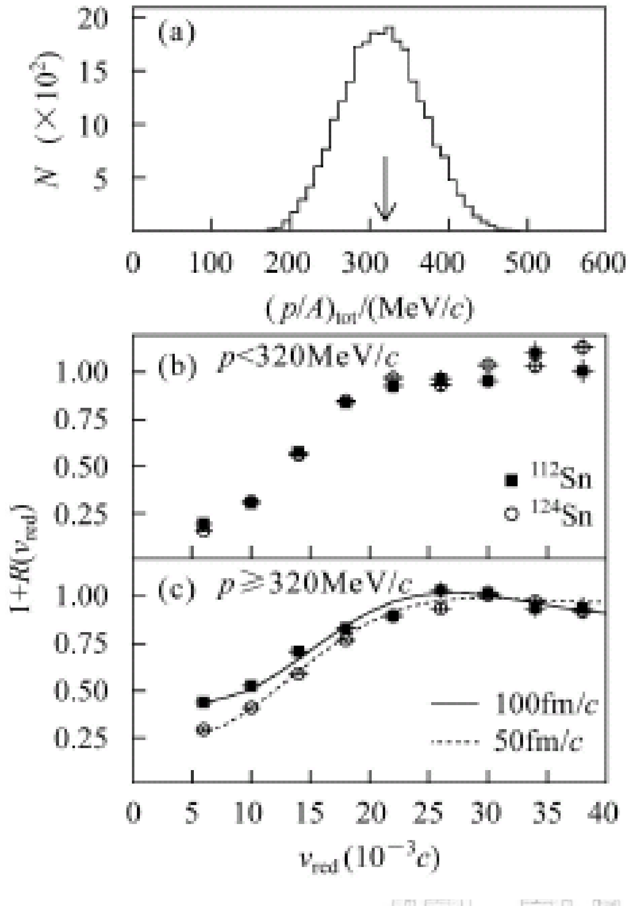
Isospin diffusion



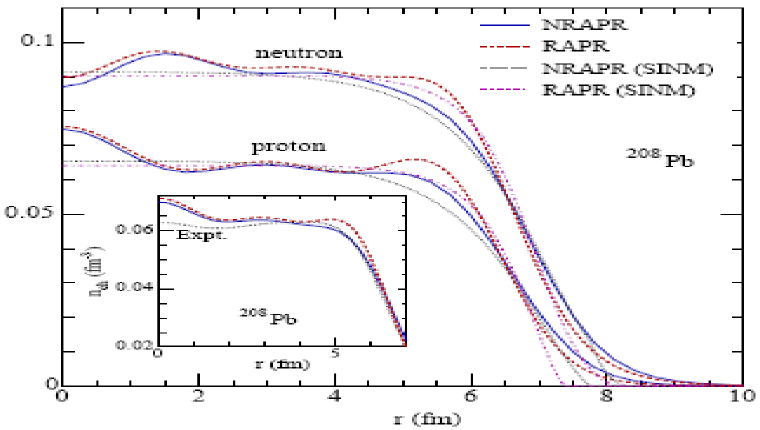
Isoscaling



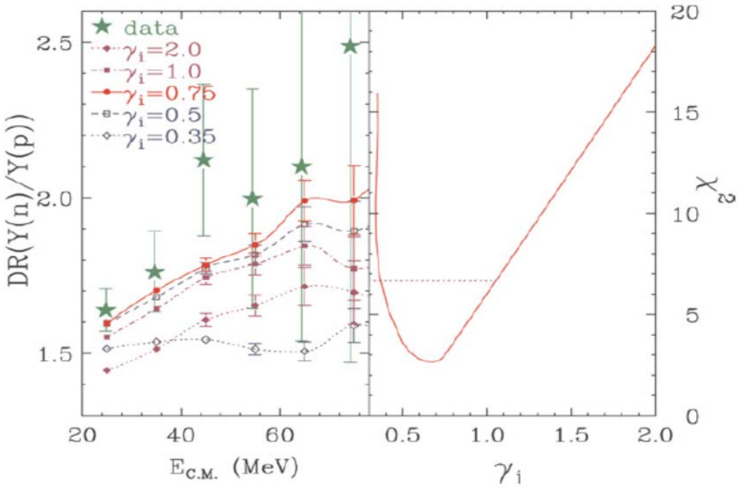
Correlation Function



Neutron Skin in ^{208}Pb or RI

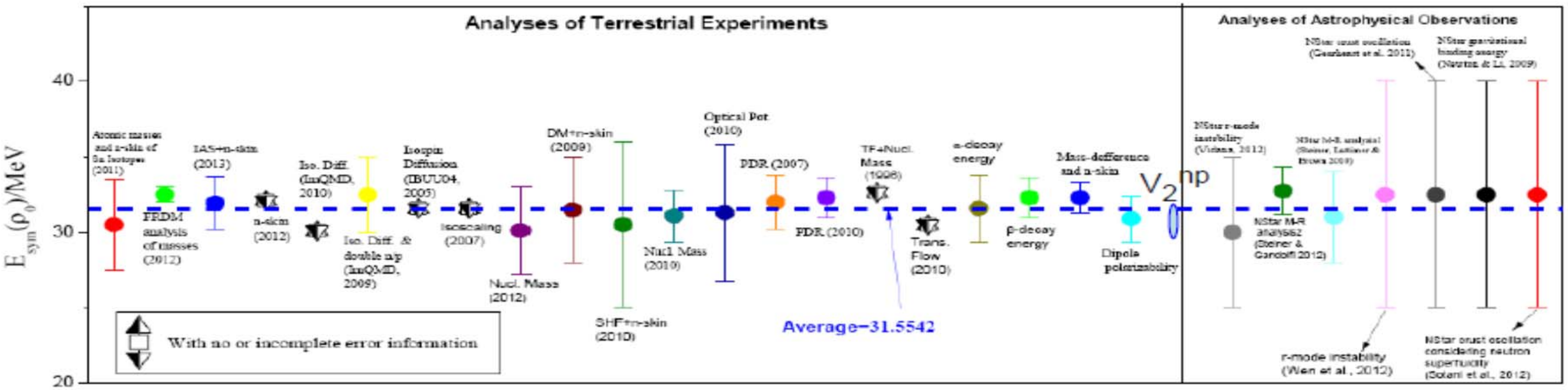


Fast nucleon emission



Current constraints on $E_{sym}(\rho)$ at $\rho<\rho_0$

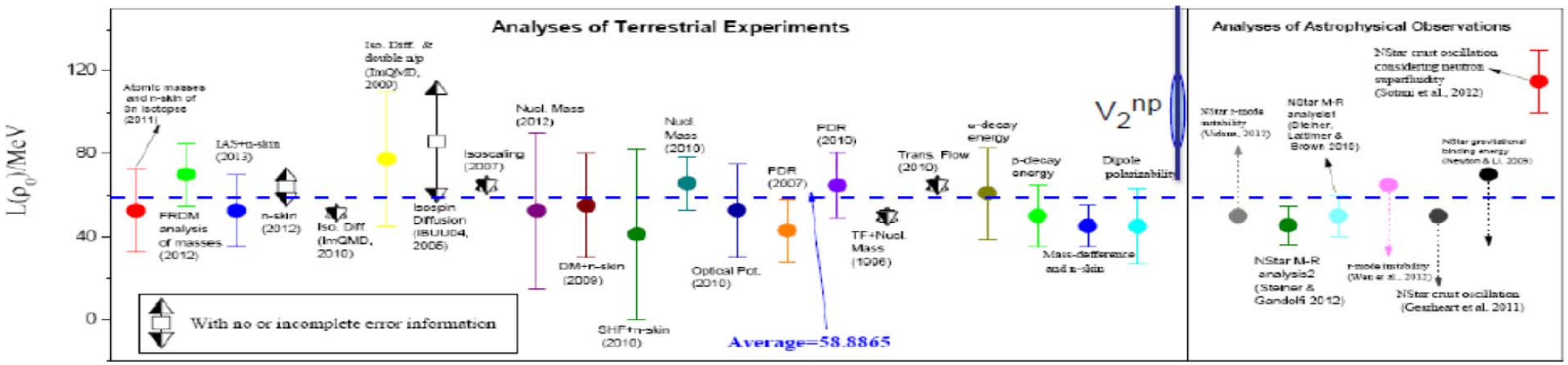
Nusym13 constraints on $E_{sym}(\rho_0)$ and L based on 29 analyses of some data



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

Currently impossible to estimate a physically meaningful error bar

Alex Brown: "K_{sym} is still a random number"



- L.W. Chen, arXiv:1212.0284
  B.A. Li, L.W. Chen, F.J. Fattoyev, W.G. Newton, and C. Xu, arXiv:1212.1178