2014年中国物理学会秋季会议

哈尔滨工业大学 9月11-14日，2014

Recent status and plans for symmetry energy studies

肖志刚

清华大学物理系

Experimental Nuclear Physics Group

1. 费米能区至亚GeV能区核反应与核物质状态方程实验研究；

PLB06’, PLB08’, PRL09’, JPG09’,PRC09’,10’, NPA10’, PRC14’ ,EPJA14’,CPC12’……

2. 基于CIAE 在束γ阵列的核谱学研究；

^{138}Nd (PRC13’), ^{99}Tc(PLB), ^{138}Pm(EPJA), ^{129}Xe

3. 围绕大科学工程的探测器研发

NIM13’, 13’, NED14’,CPC13’,14’

4. 国际合作： Sπirit TPC/SOLID/FOPI/KTH/iThemba/STAR

(…… PRL112(2014)202502 ……)

http://qm.phys.Tsinghua.edu.cn/enpg

Contents

- Introduction: EOS of asymmetric nuclear matter
- Experimental Results relevant to $E_{sym}(\rho)$ at $\rho < \rho_0$
- R&D for the HIRFL-CSR External target Experiment (CEE)
- Summary

Symmetry Energy:

Energy cost to convert protons to neutrons in nuclear medium

Symmetry energy

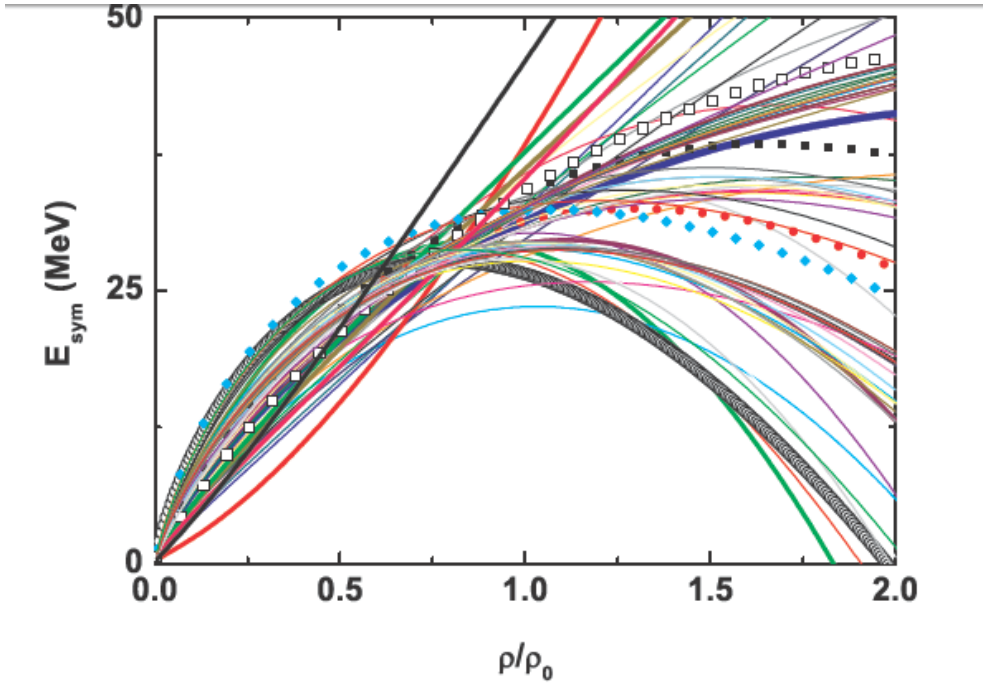
$$E = -a_V A + a_S A^{2/3} + a_C \frac{Z^2}{A^{1/3}} + a_a \frac{(N-Z)^2}{A} + E_{\text{mic}}$$

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

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

κ:Compressibility

E_{sym}

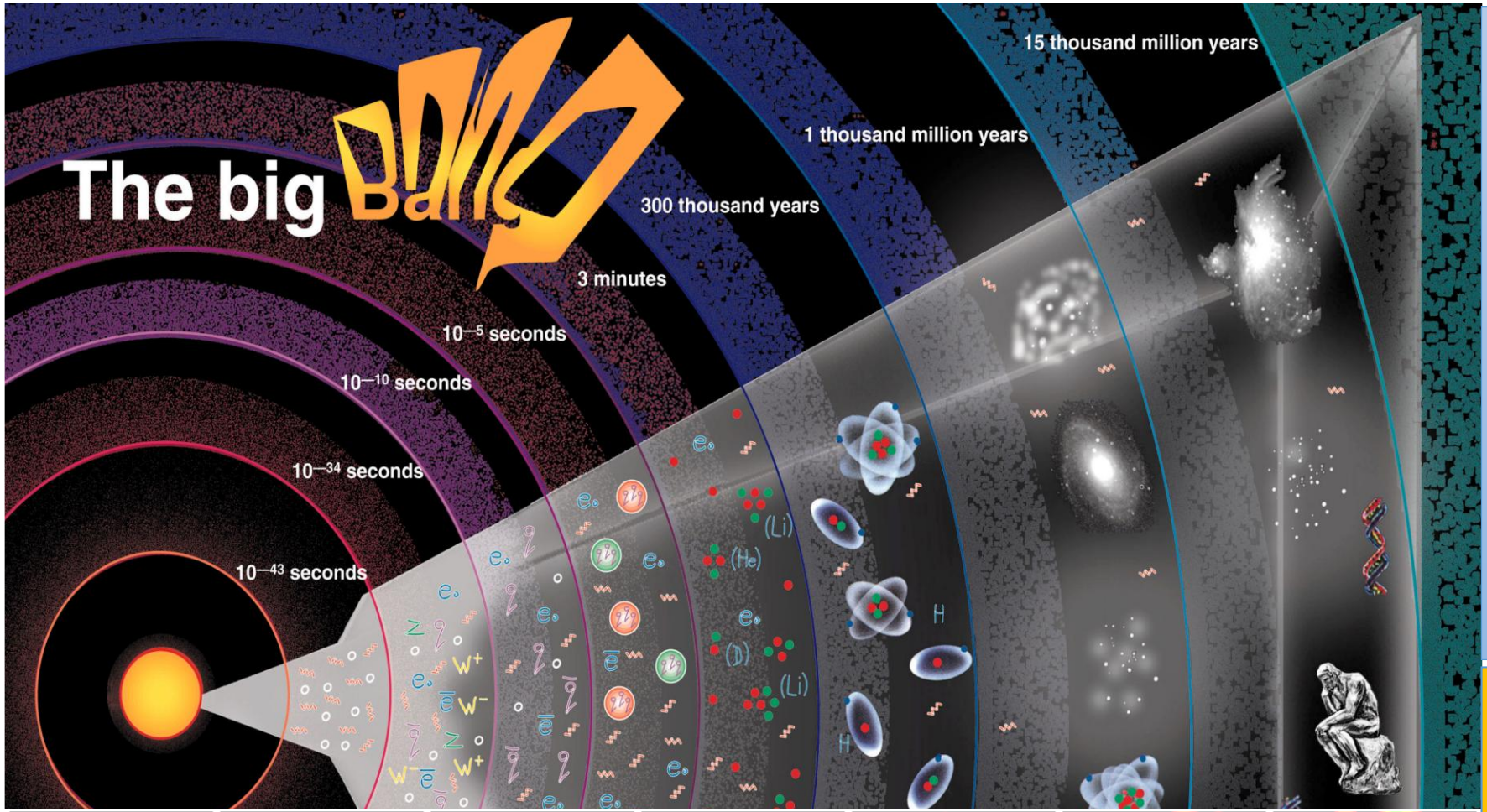


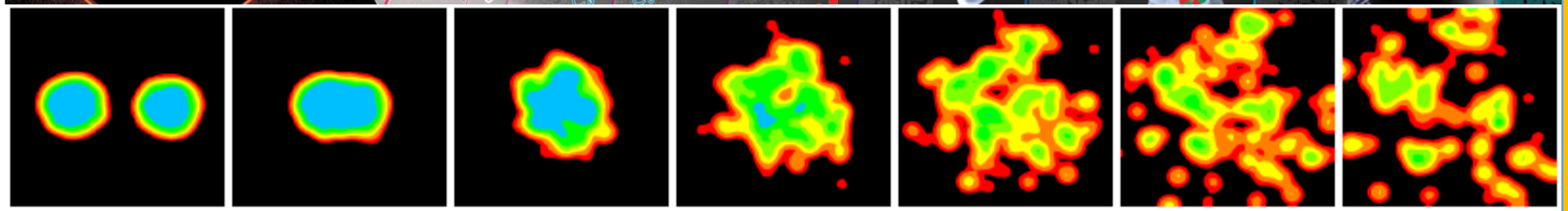
$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

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

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

From Big Bang to Heavy Ion Collisions





Chemical potentials in formation of light nuclei

$$\mu\,(^{A}Z) = Z\,\mu_p + N\,\mu_n$$

Symmetry energy in asymmetric objects

$$E/A\,(\rho,\delta) = E/A\,(\rho,0) + \delta^2 \cdot S(\rho)$$

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

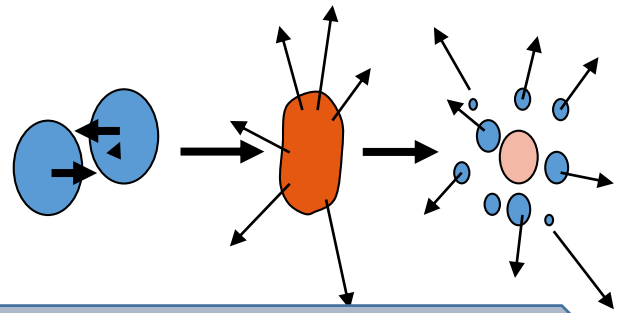
→ 3 body force

→ Tensor force

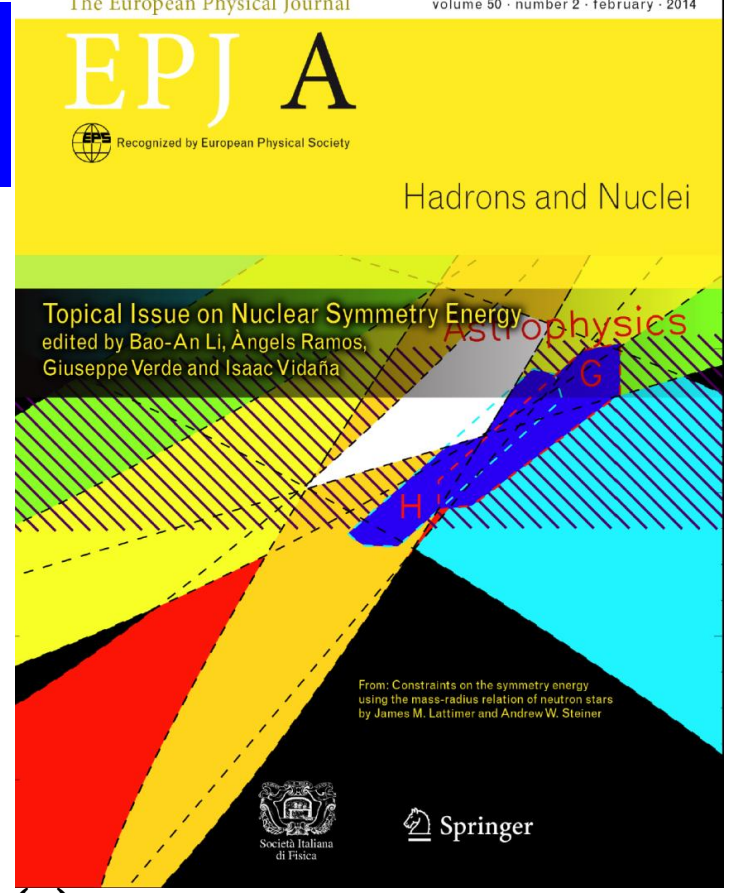
→ Collision dynamics…

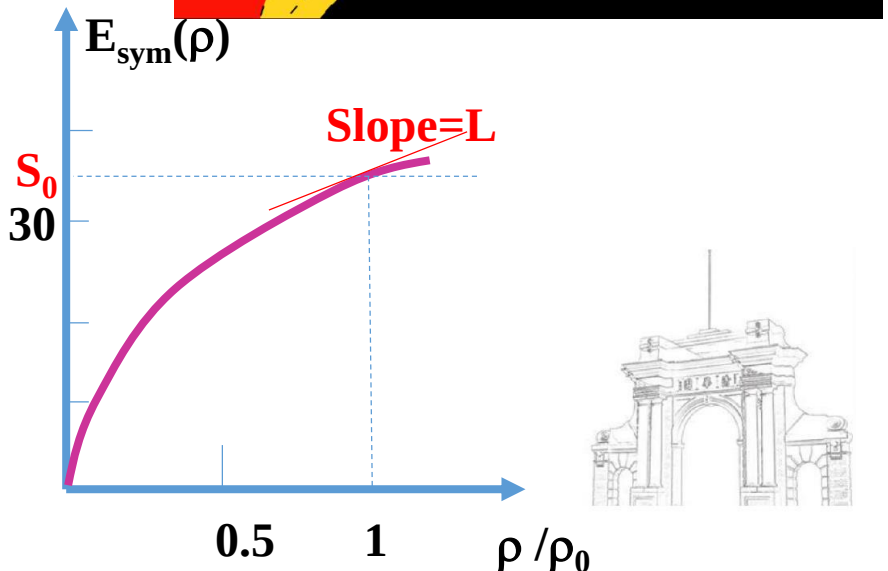
Probe list for sub-saturation density E_{sym}

At sub-saturation densities



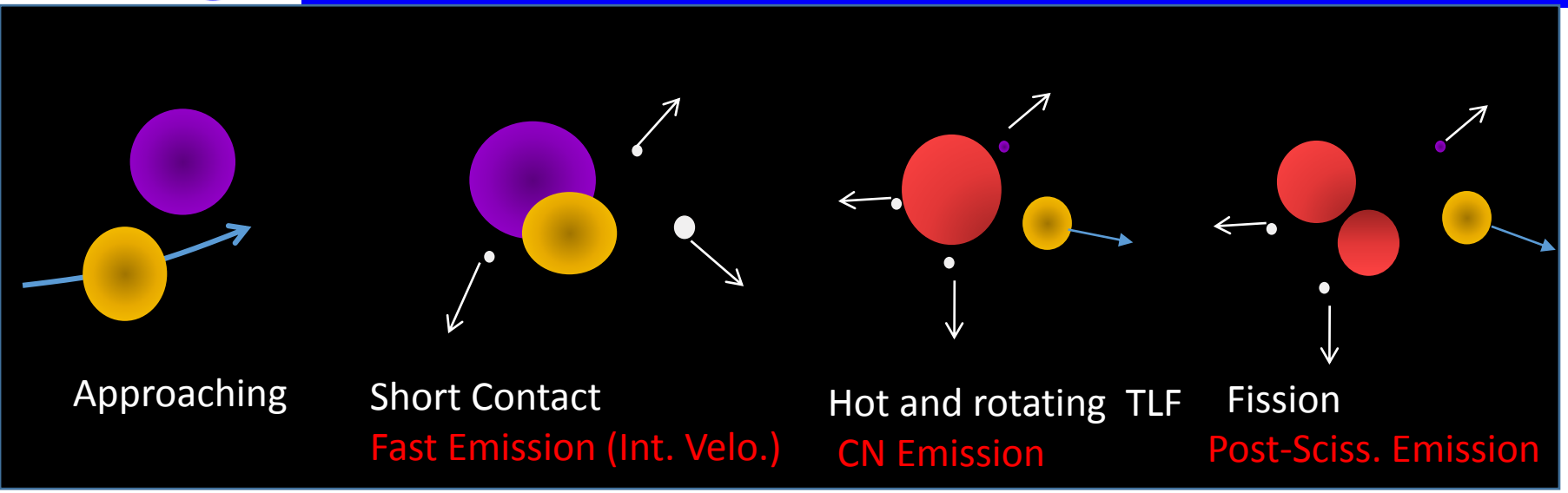
- → Global nucleon optical potential in n/p-A collisions or (p,n) reactions
- → Neutron Skin thickness of Pb-208 (PREX experiment at JLAB)
- → Isospin scalaring and isospin fractionaiton in multifragmentation
- → Isospin diffusion
- → n/p ratio of fast and pre-equilibrium nucleons
- → N/Z composition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

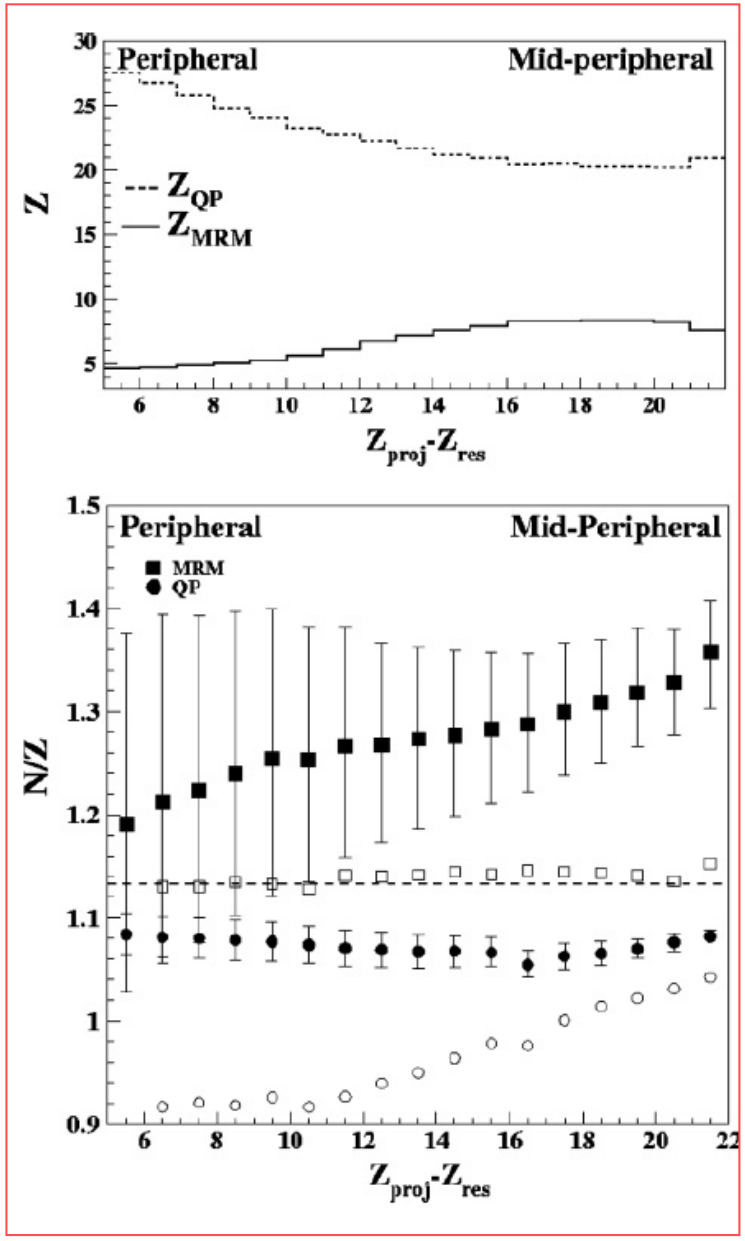




$S_0 = 32.5 \pm 2.5$ MeV $L = 55 \pm 25$ MeV

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





- Possible Advantages:
- ☑ Neck part: Very neutron rich, Low Densities

L.G. Sobotka, PRC50（1994）R1272

D. Theliault *et al.*, PRC74（2006）051602(R)

- ☑ Time Scale: Between statistical emission (Q effect) and two body process (very short)

D. J. Hinde *et al.*, Phys. Rev. C **39**, 2268 (1989).

M. Gui *et al.*, Phys. Rev. C **48**, 1791 (1993).

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

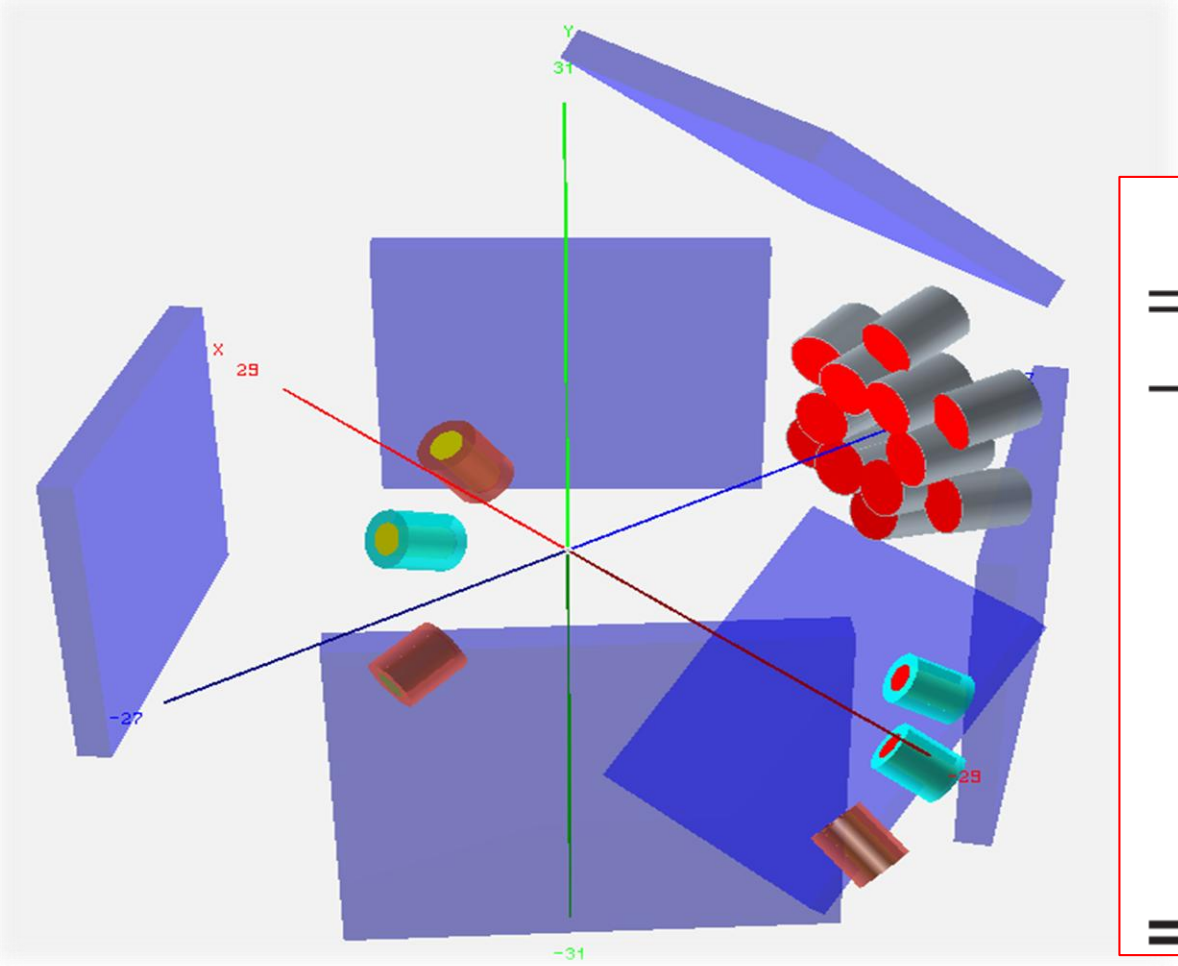
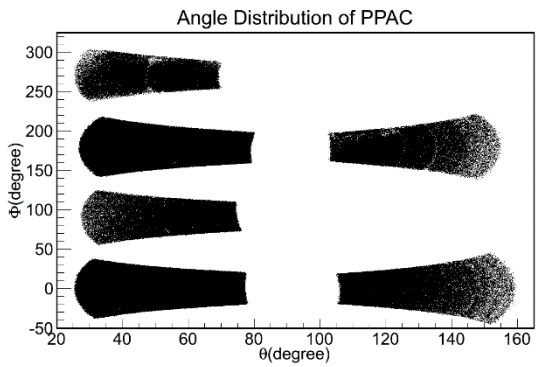
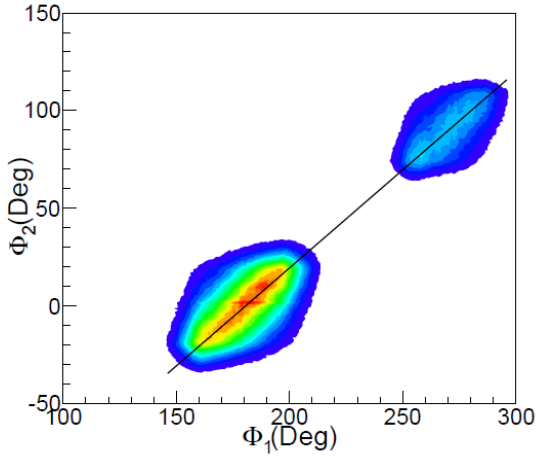


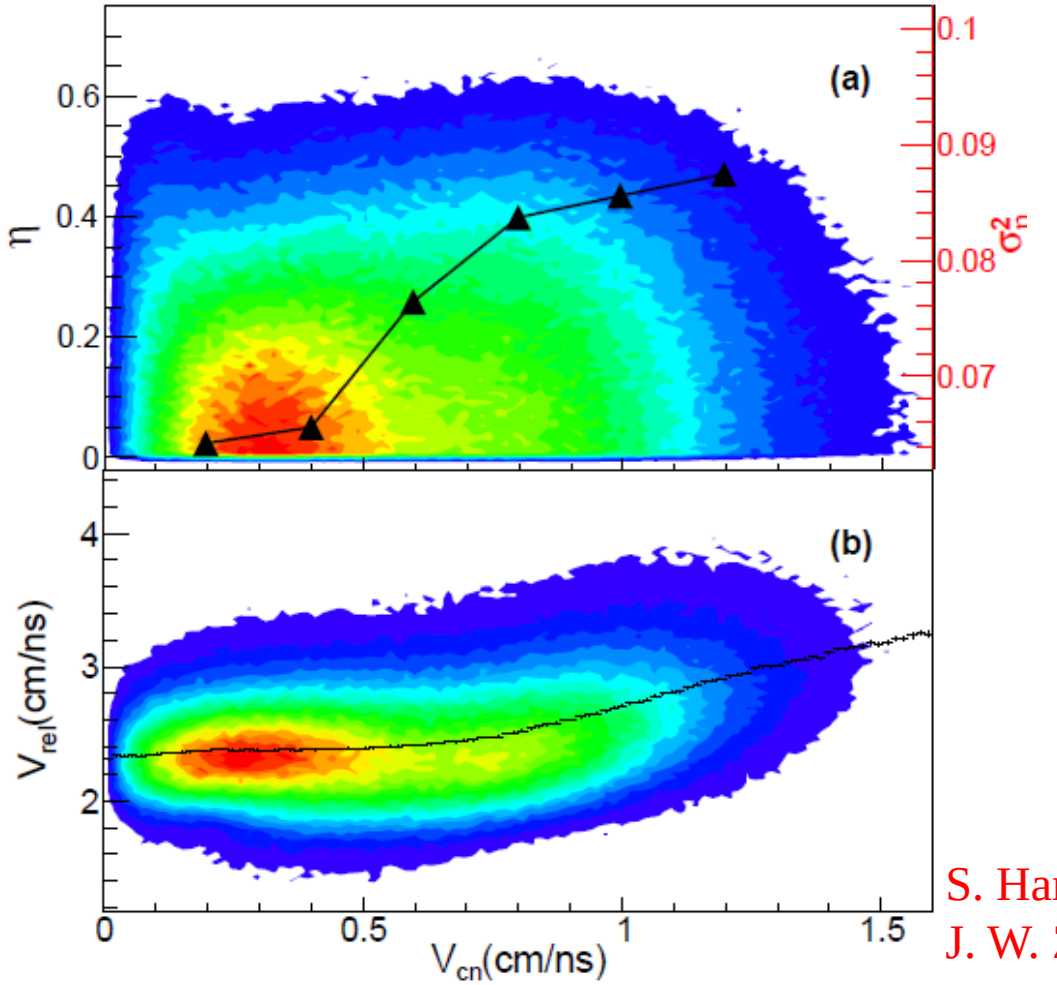
TABLE I: The parameters of the 6 LCP telescopes

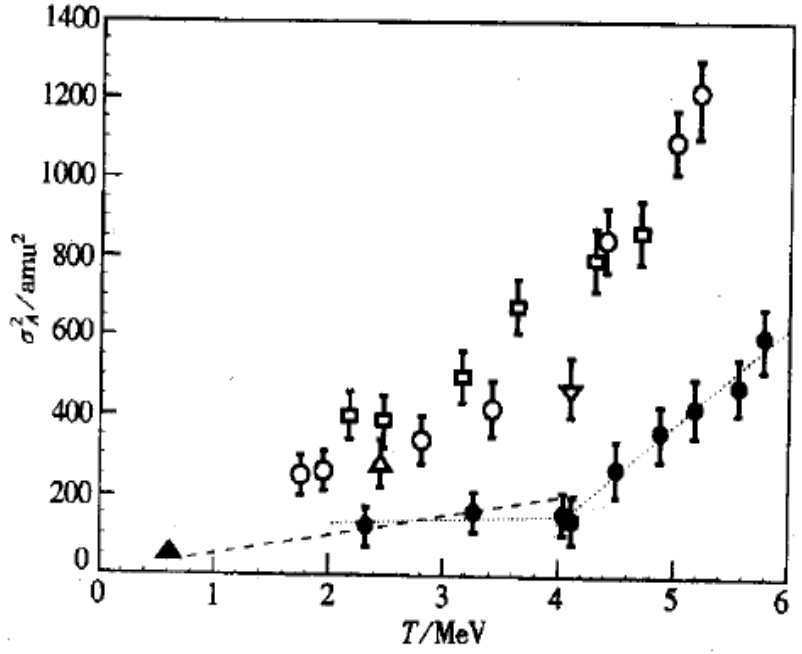
Tele. No.	1	2	3	4	5	6
d (mm)	12.0	10.2	10.4	14.0	14.0	14.0
L (cm)	11.5	11.5	11.5	26.0	21.6	28.5
θ (°)	158	155	127	80	59	44
ϕ (°)	-90	90	90	-145	-139	-133
ΔE_1 (μm)	50	50	50	50	50	50
ΔE_2 (μm)	400	/	400	400	/	/
E_{CsI} (mm)	40	40	40	40	40	40

Fission Distribution







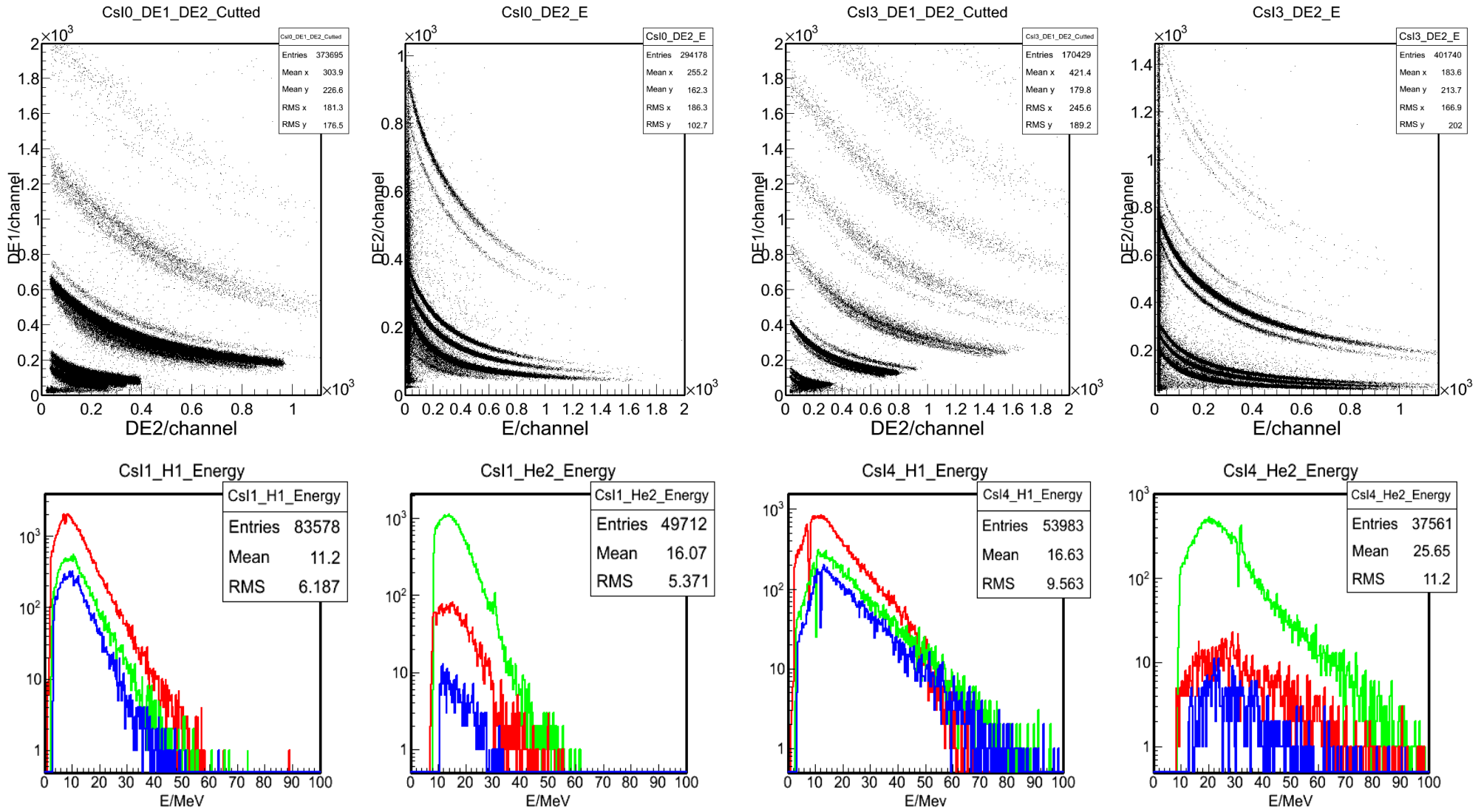


S. Harar, Nucl. Phys. A 471, 205c (1987)
J. W. Zheng et al, HEPNP. 23, 409 (1999)

1) Relative velocity peaks at 2.4 (Viola systematics), and showing slight asymmetry

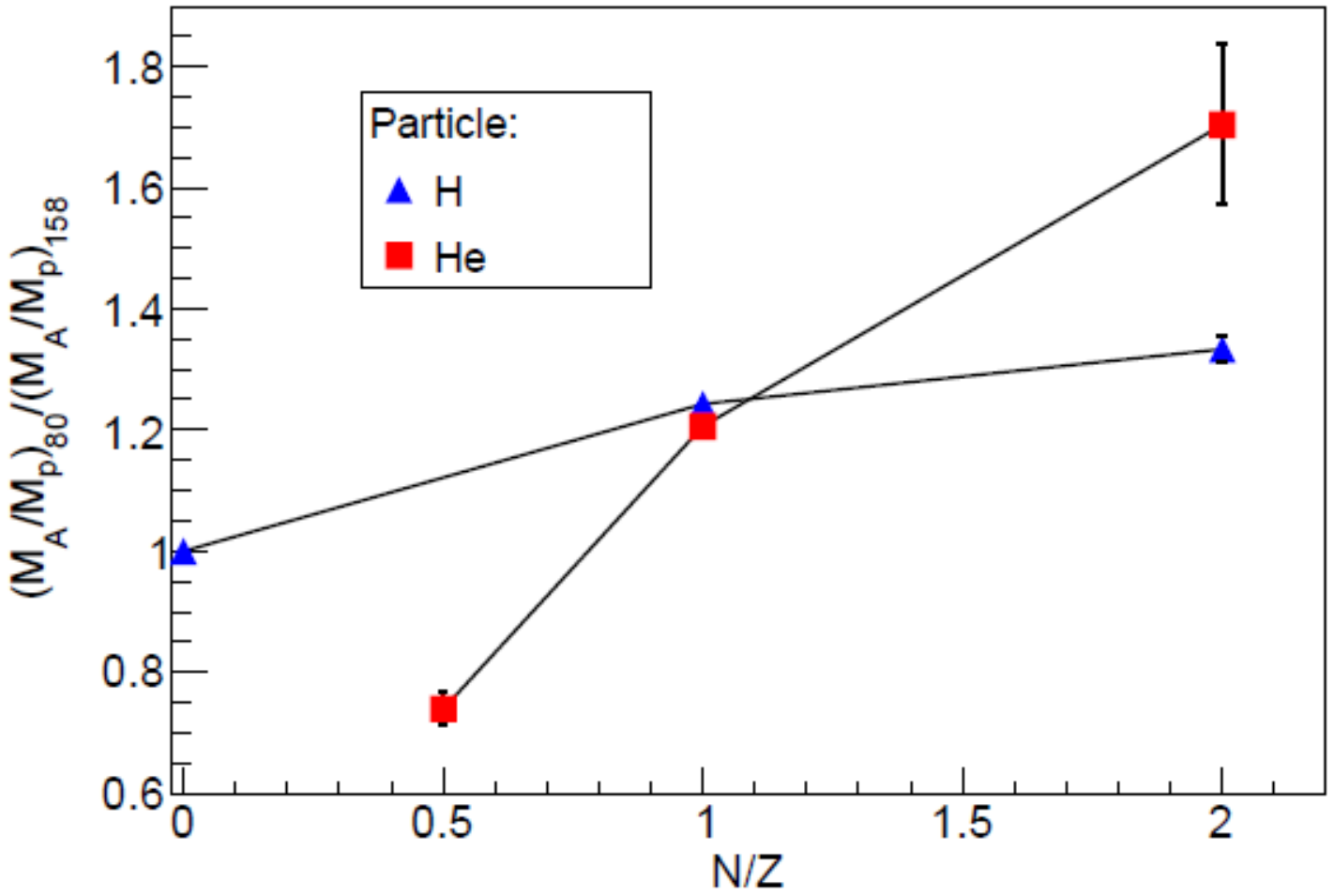
2) At low and high V_{add}, the relative velocity exhibits different manner

LCPs in coincidence with fission



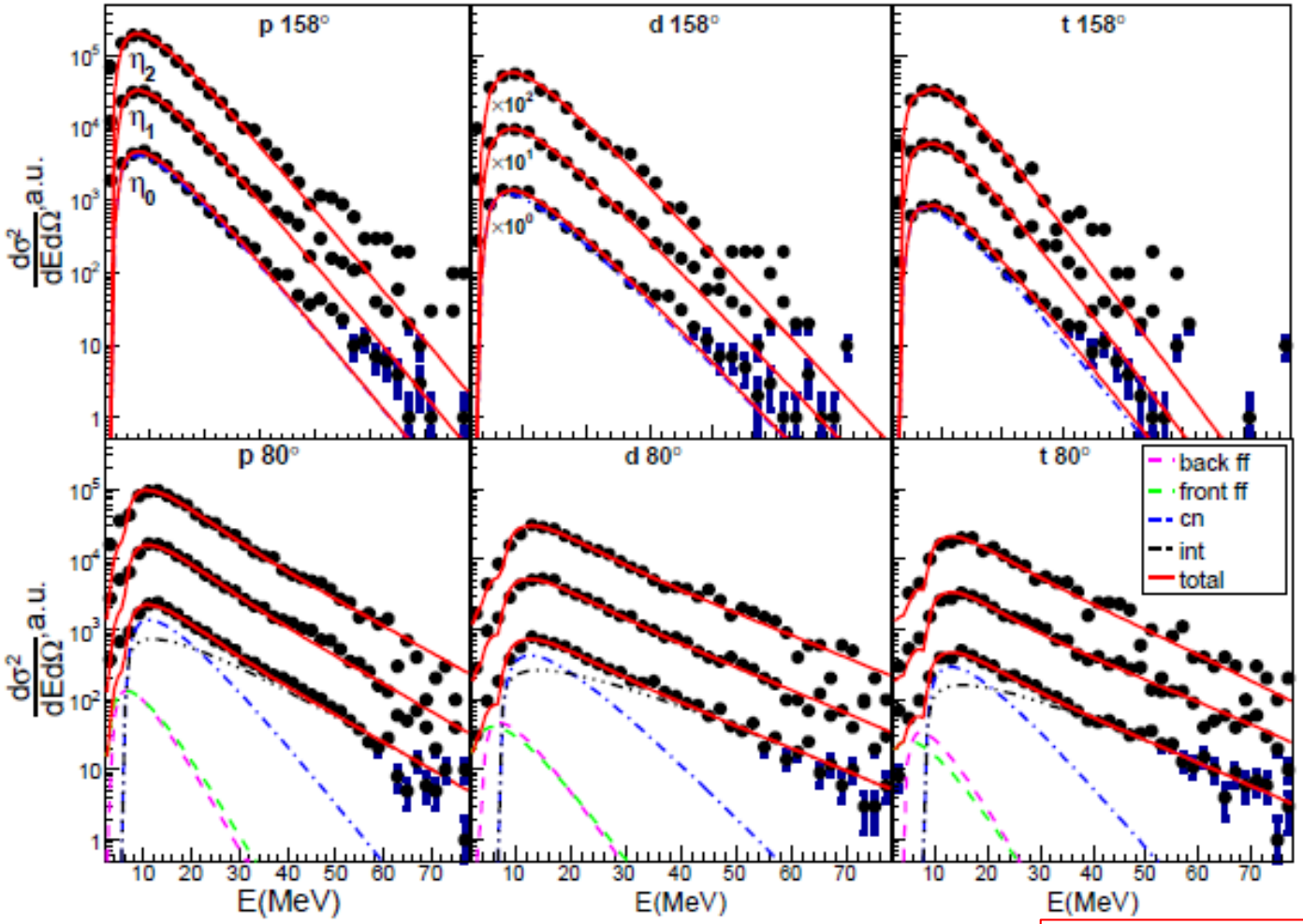
- Mass Resolved spectra obtained at 2 degrees: 158, 80

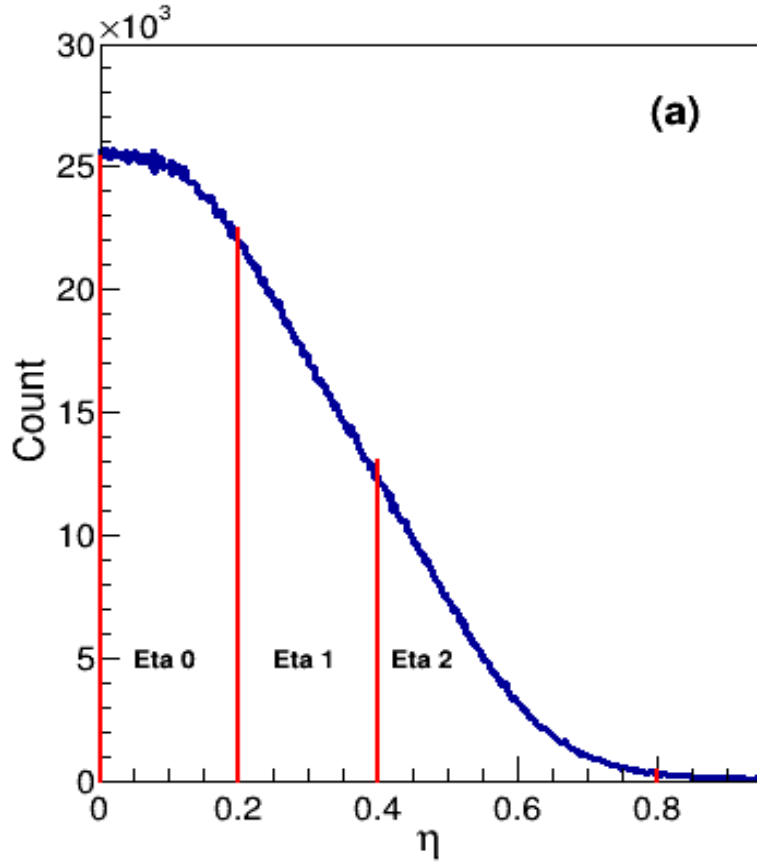
Double angular ratio of particle yield



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

Energy spectra analysis vs mass asymmetry

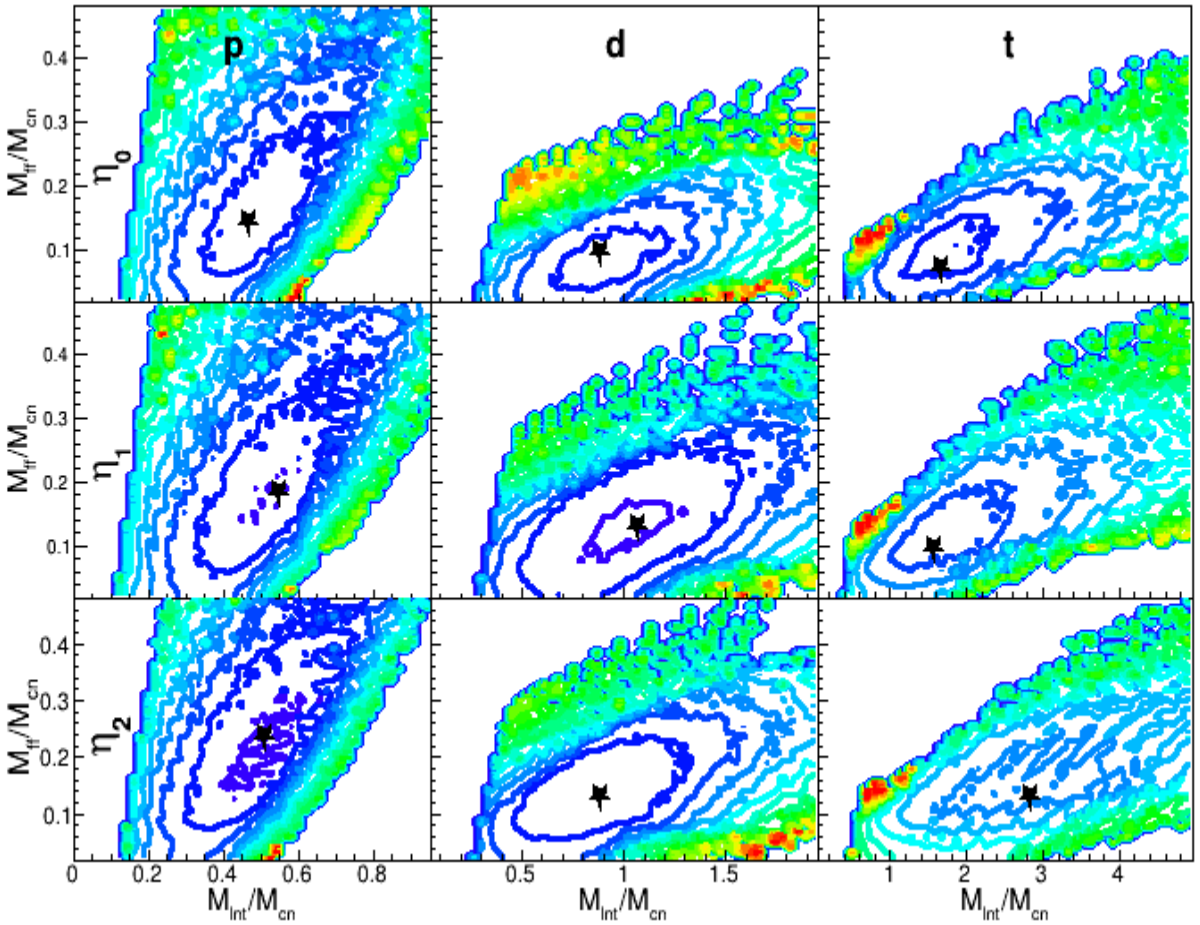


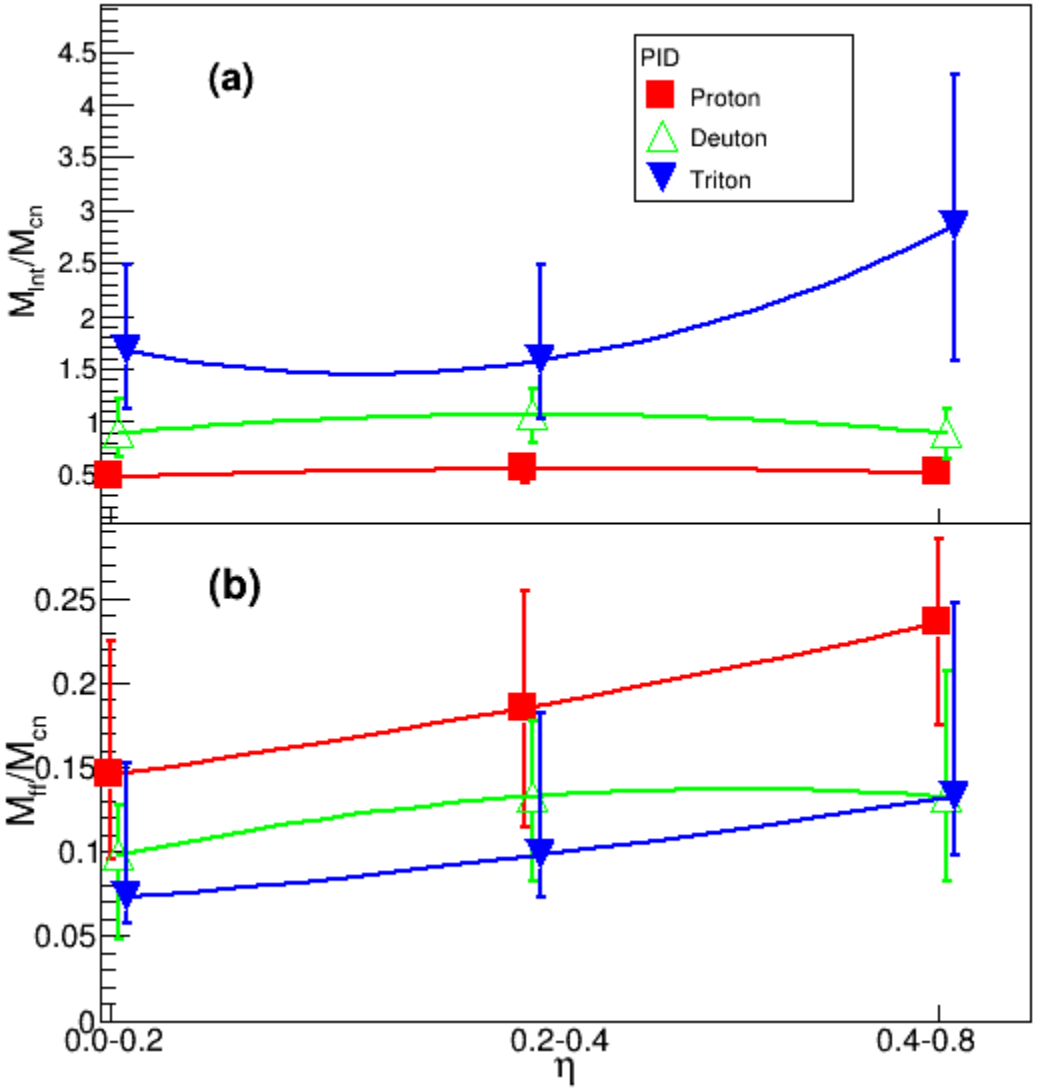


- Three moving source: CN, FF and Int. Velocity

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

Minimum χ2 analysis



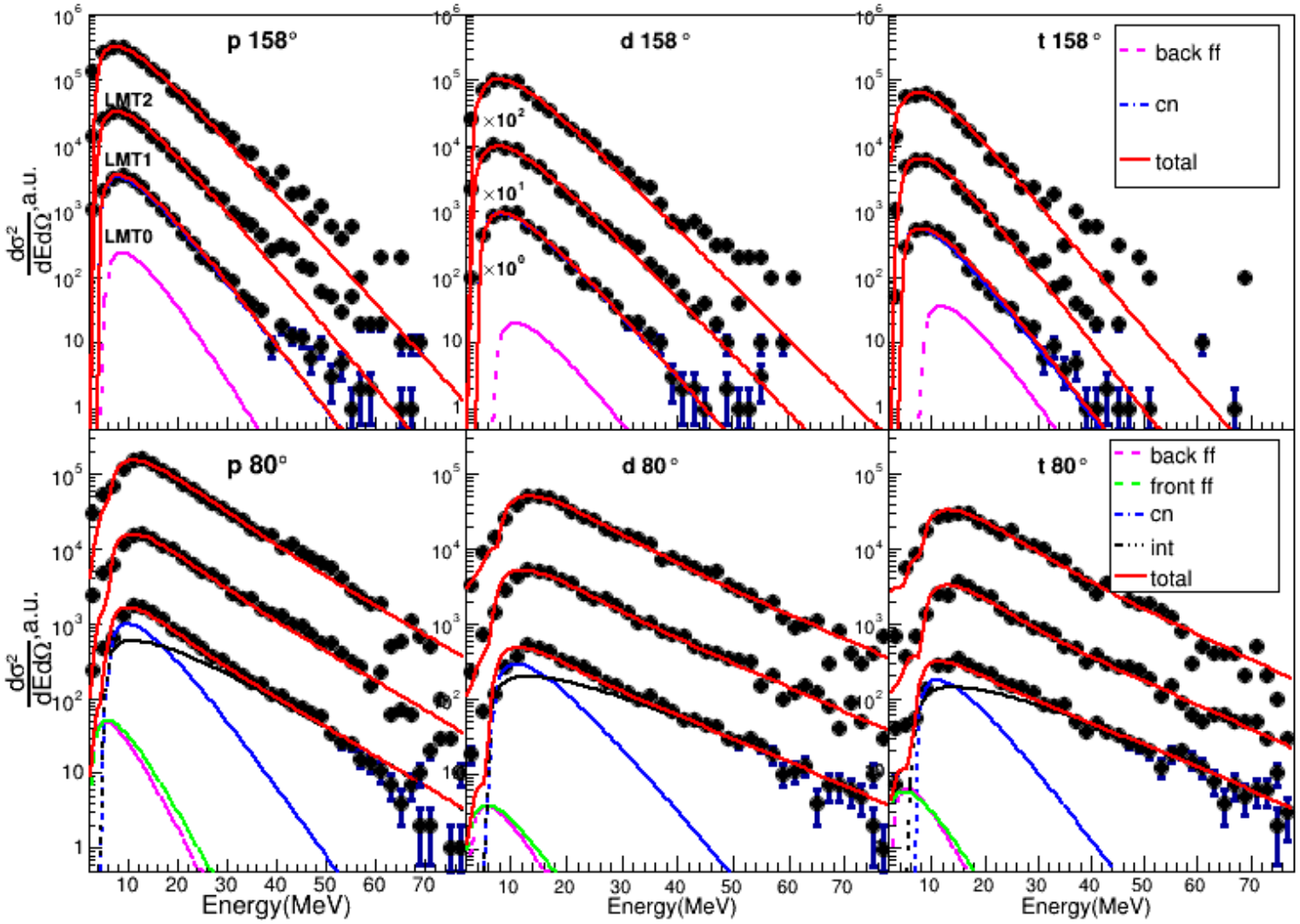


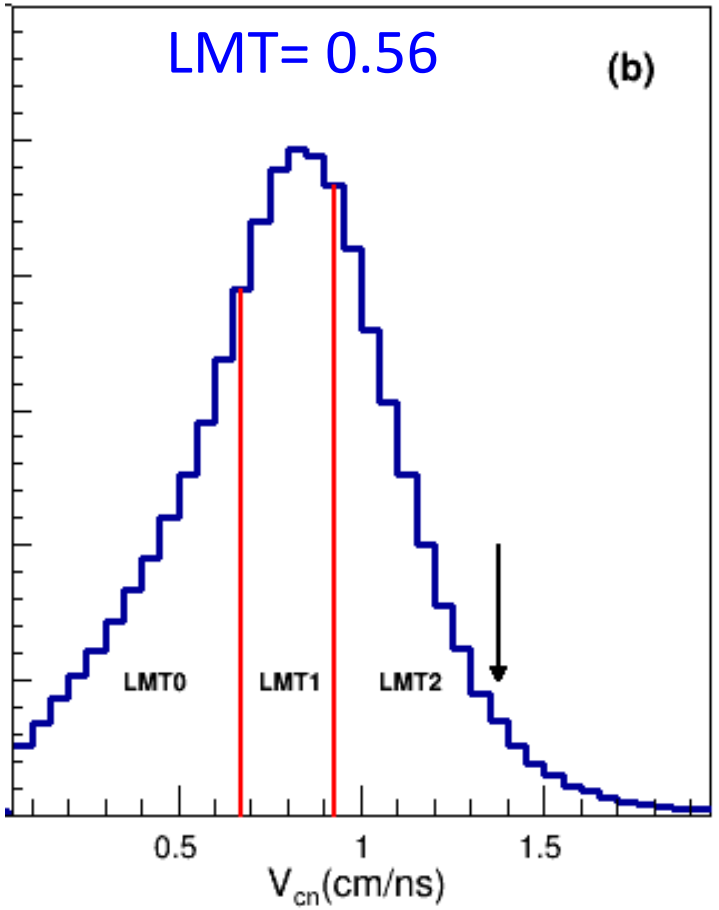
→ M_{ff}/M_{cn} vs. M_{inv}/M_{cn}

→The two ratios show different hierarchy

→ **The particles emitted in early stage are neutron rich!**

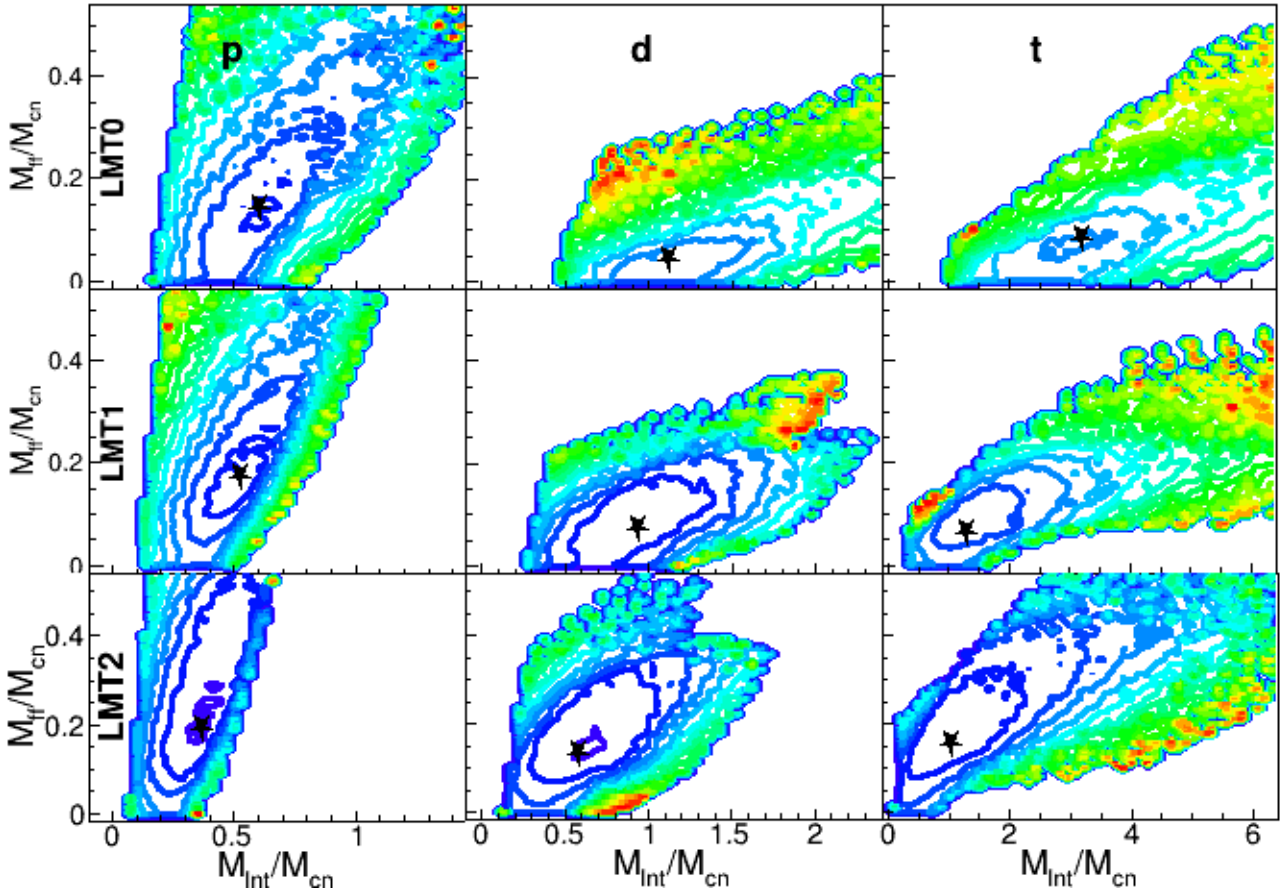
Energy spectra vs. LMT

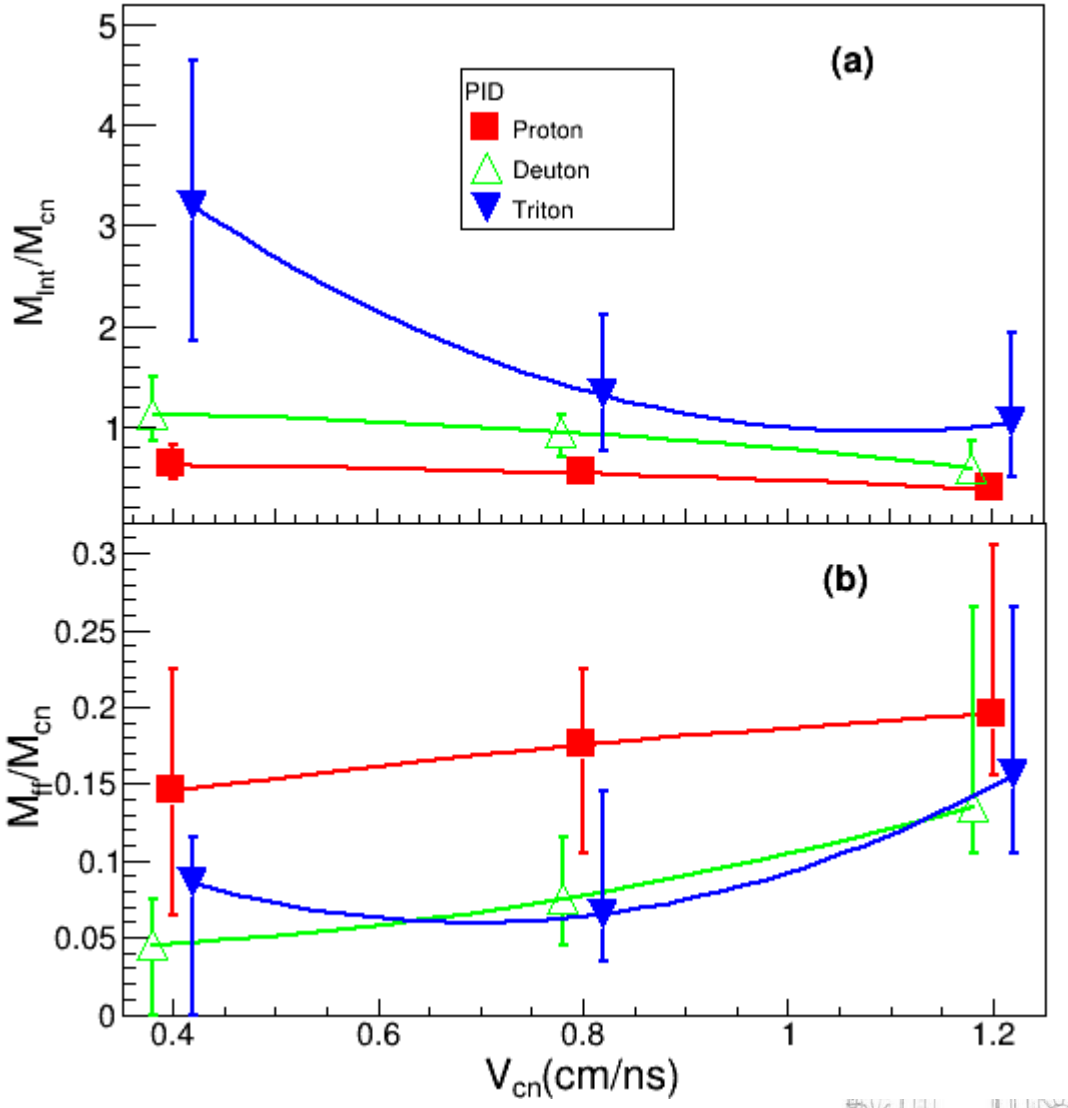




- As a function of LMT

Minimum χ2 analysis



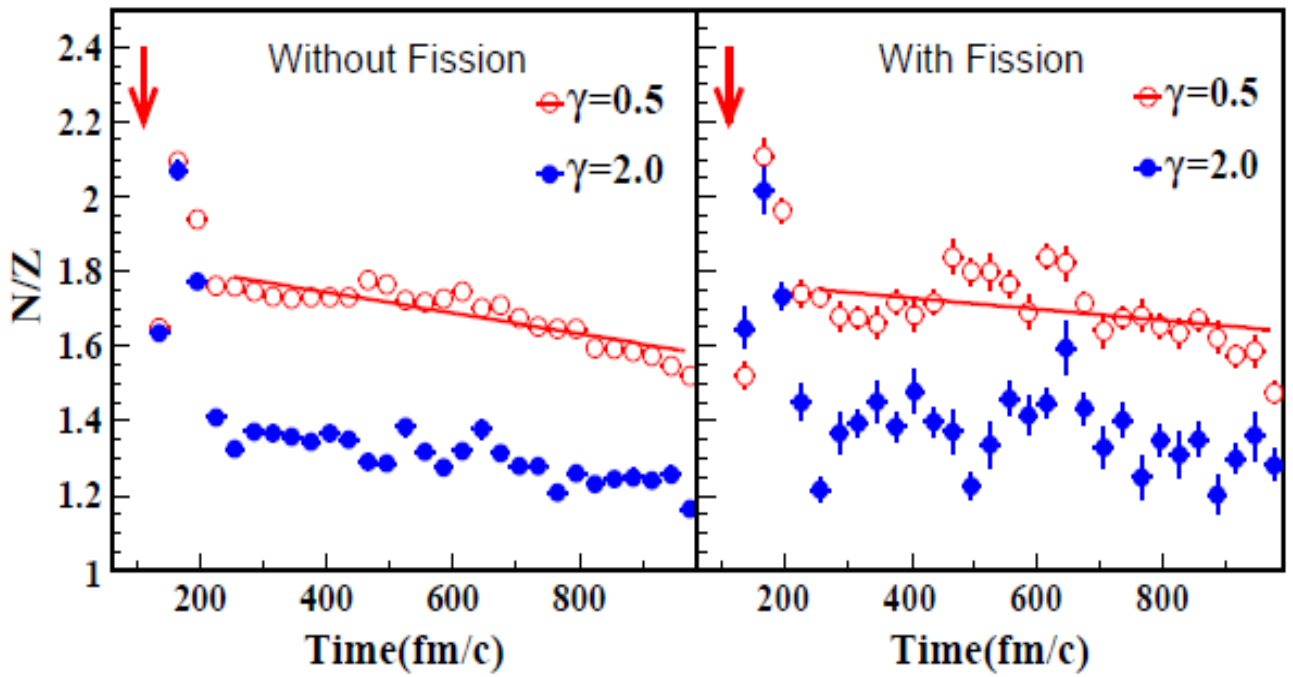


- The hierarchy of Multiplicity ratio remains.
- Error bars are large for the FF source.

IQMD calculations

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

α	207 MeV	β	138 MeV
σ	7/6	g_0	18 MeV · 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.**

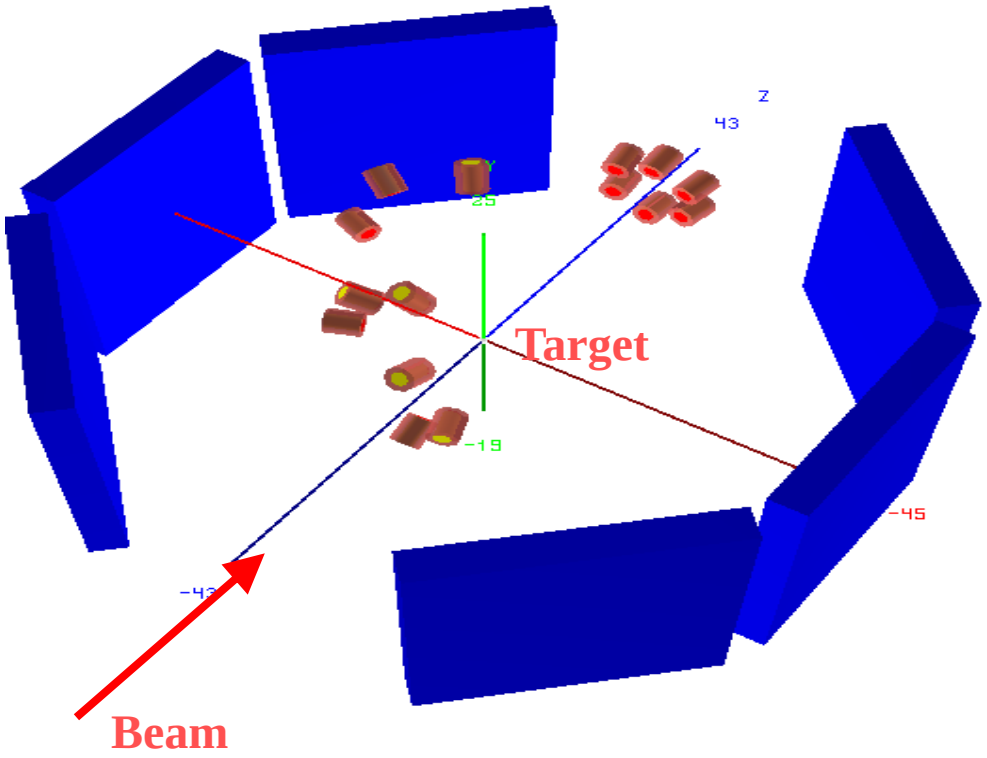
2)The isospin composition N/Z exhibits an obvious dependence on $E_{sym}(\rho)$ till very late stage.

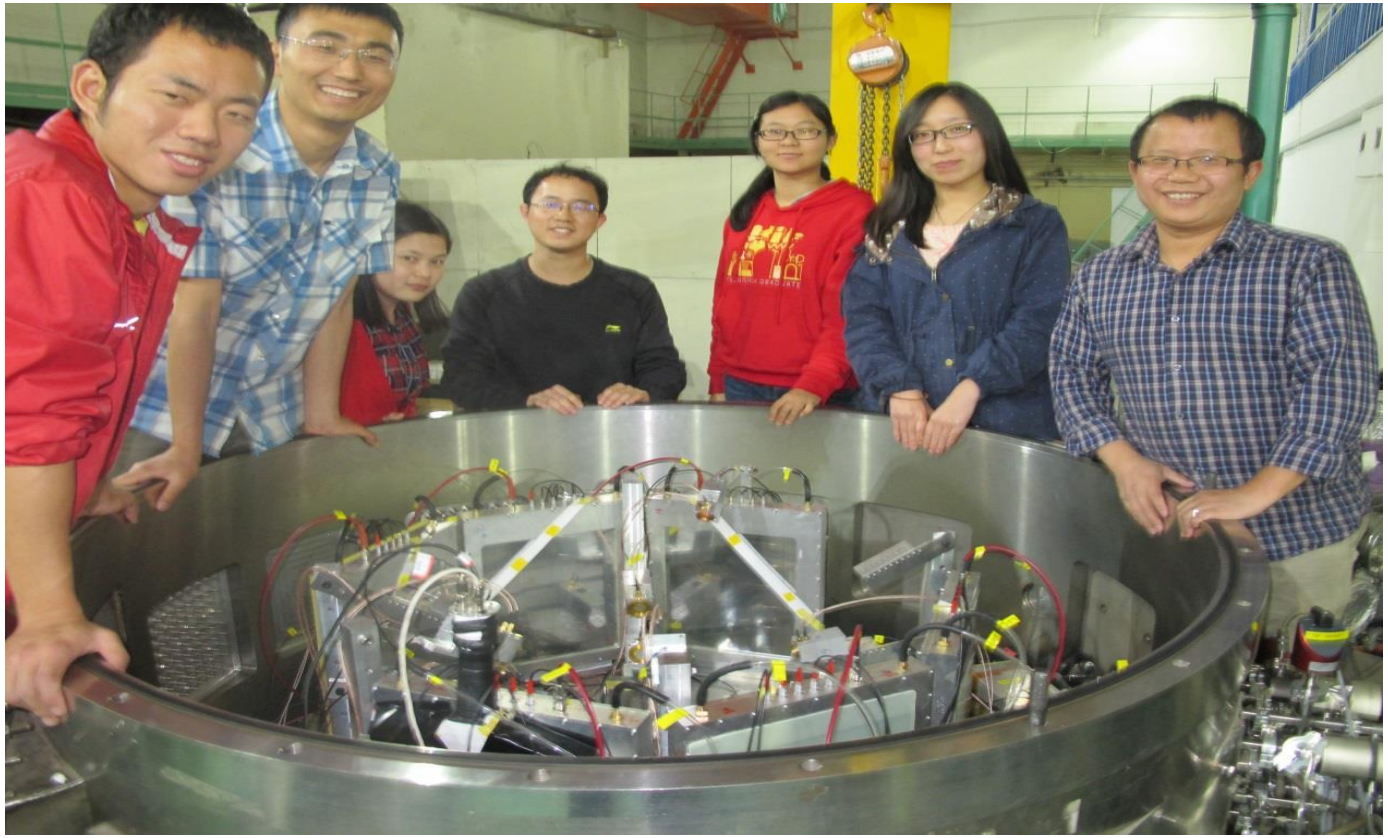
3)The effect of the symmetry energy remains equally significant in the fission.

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

R.S.Wang, Y. Zhang, XZG et a., PRC89 (2014) 064613

Further improved experiment

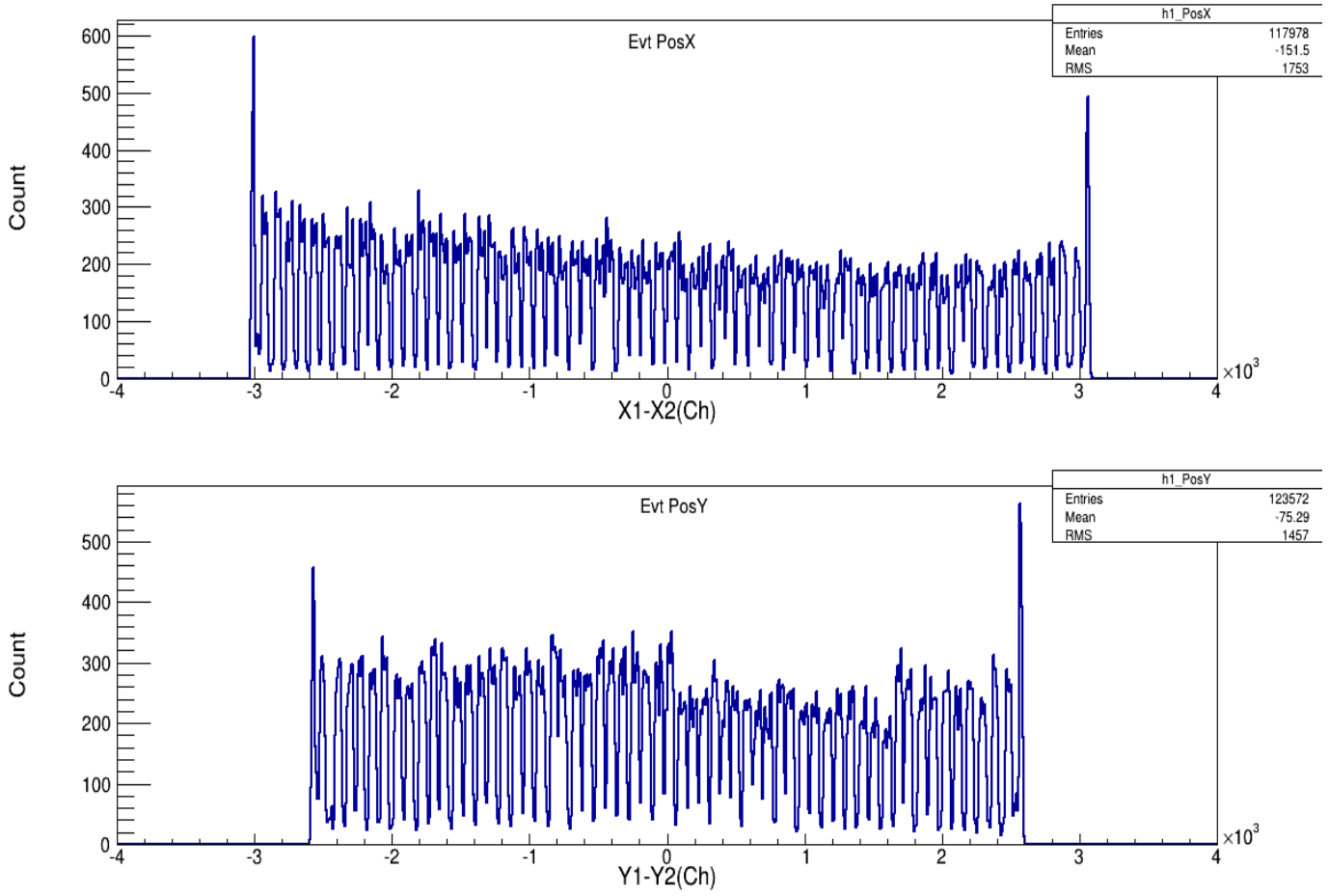


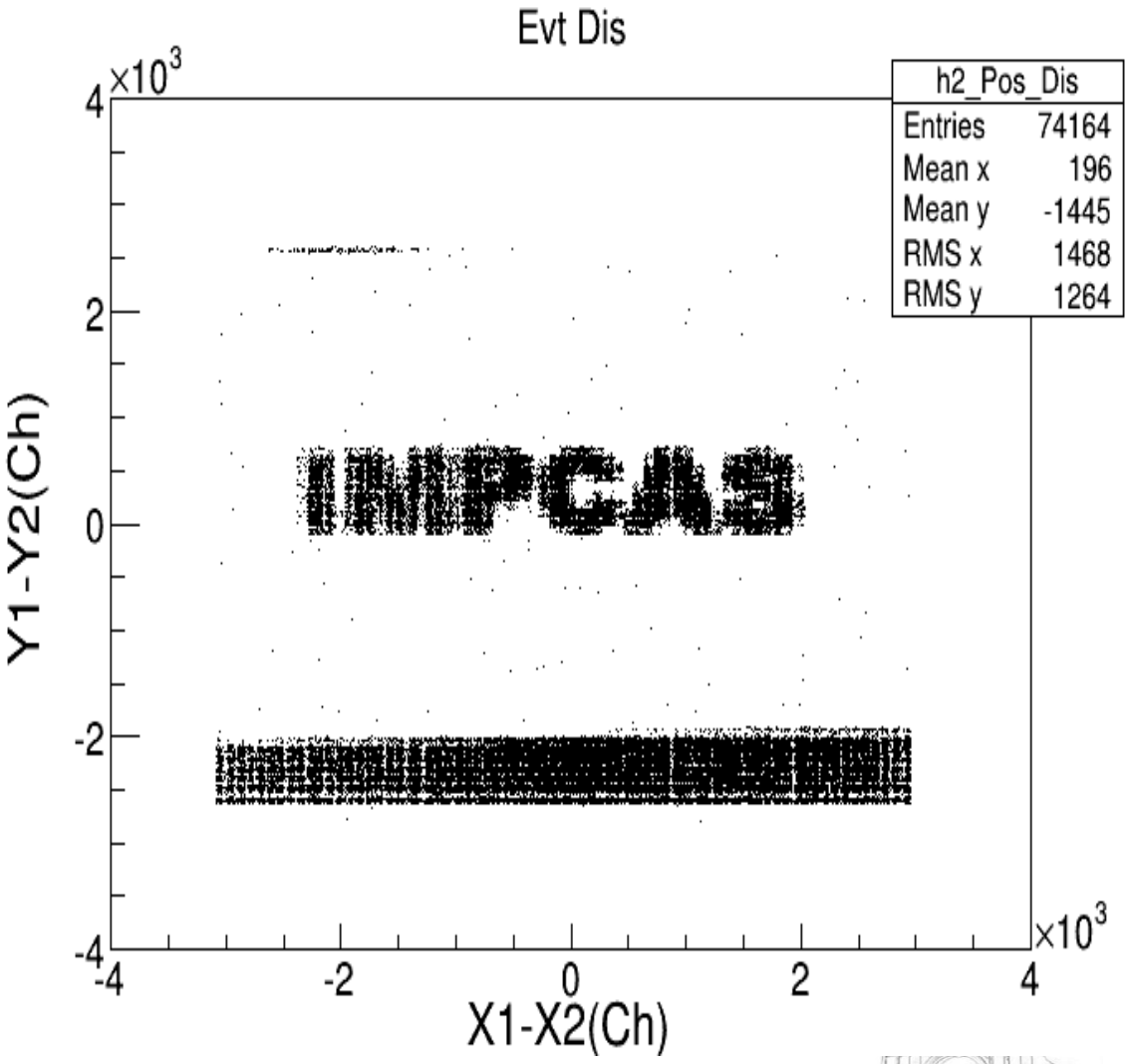


- **Complete in June 2014.**

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

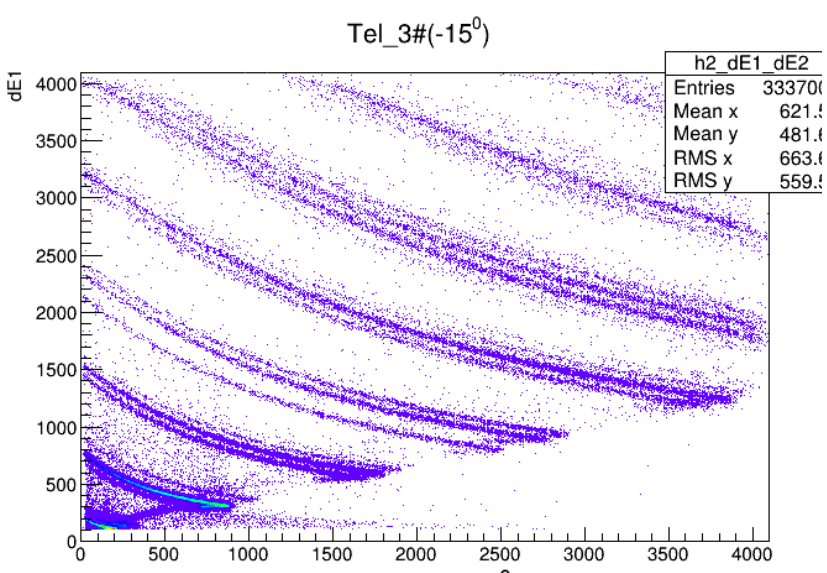
PPAC Performance

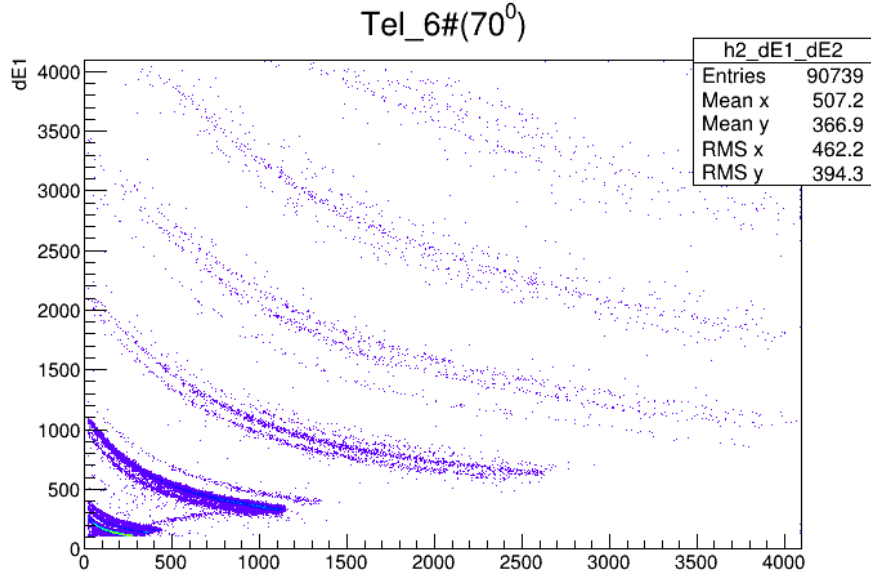


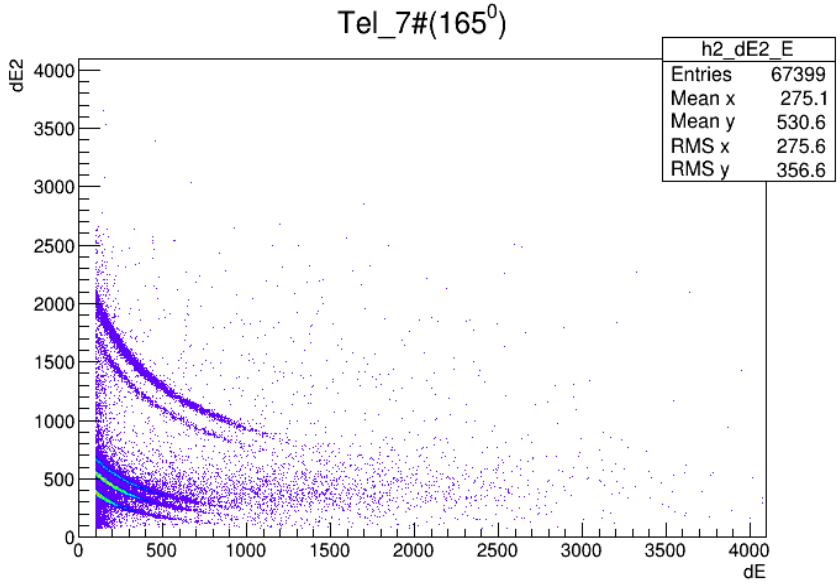


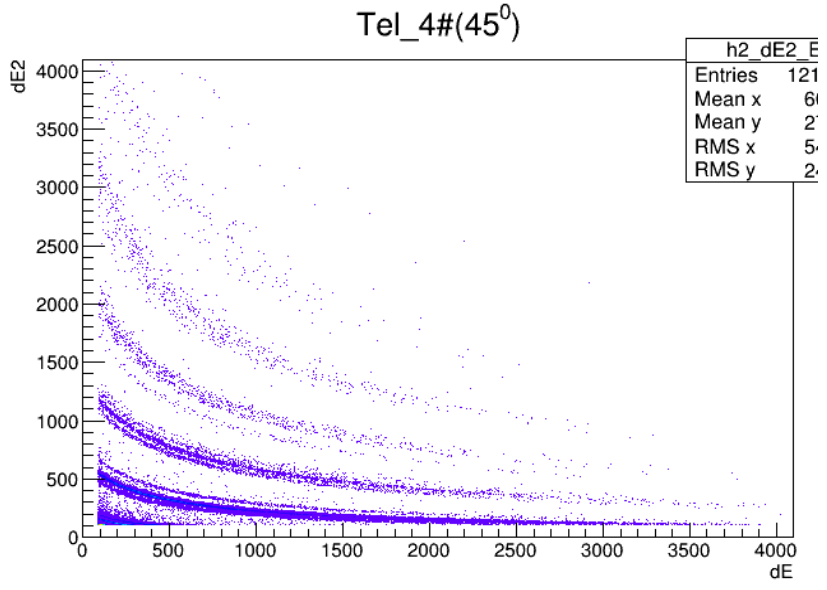
- Good Position Resolution and high fission fragment efficiency

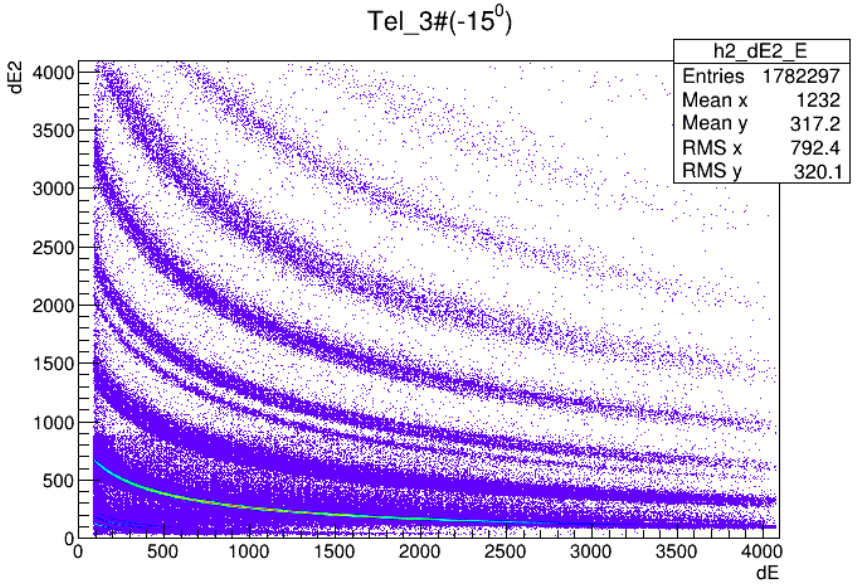
Telescope Performance

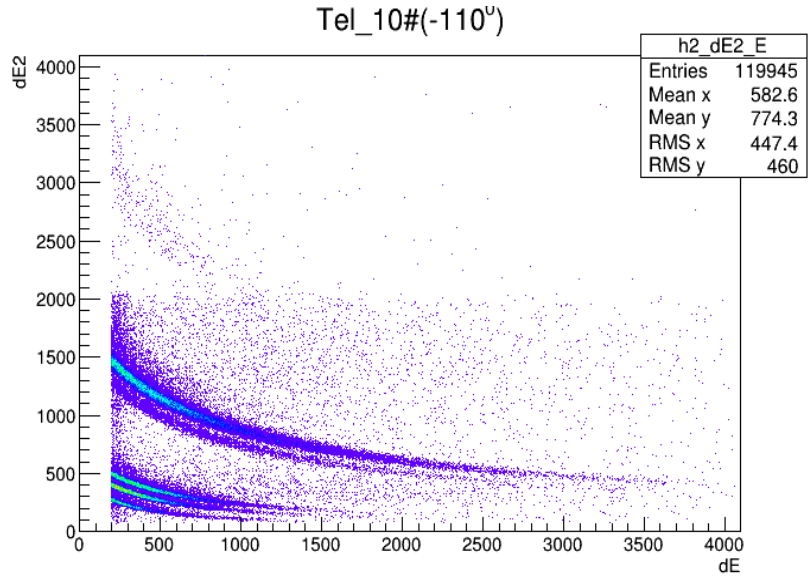






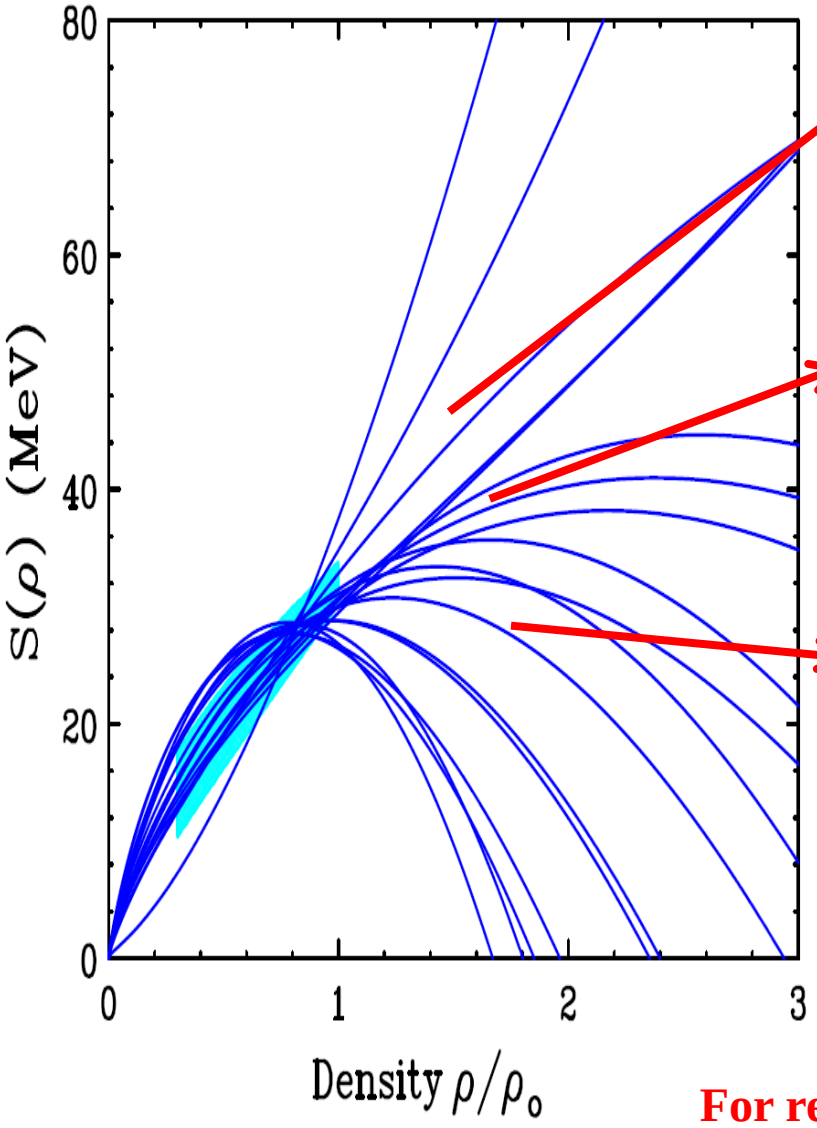






- Isotope identification achieved in most of the telescopes → More angles

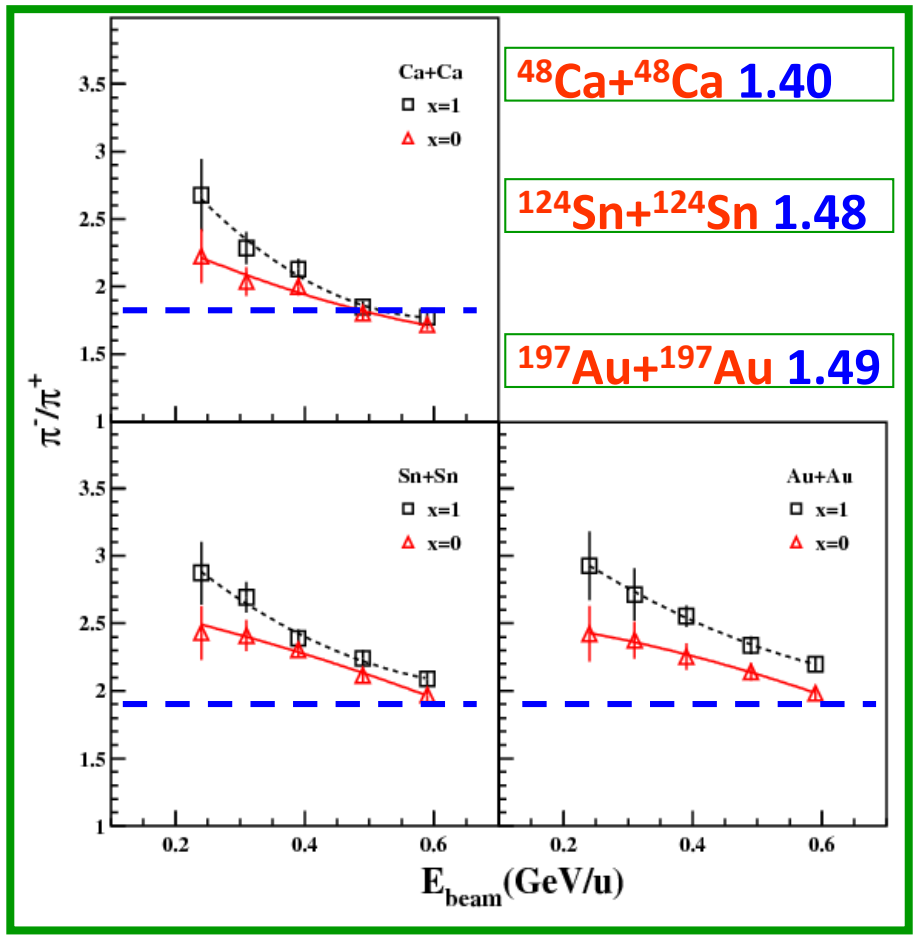
Above saturation: Very uncertain

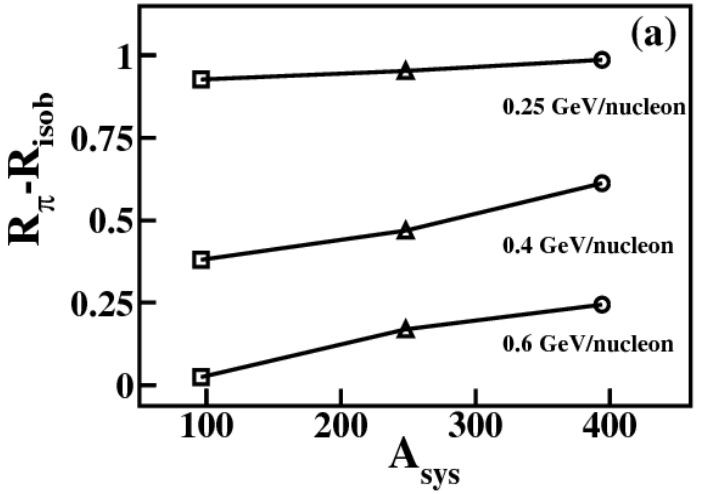


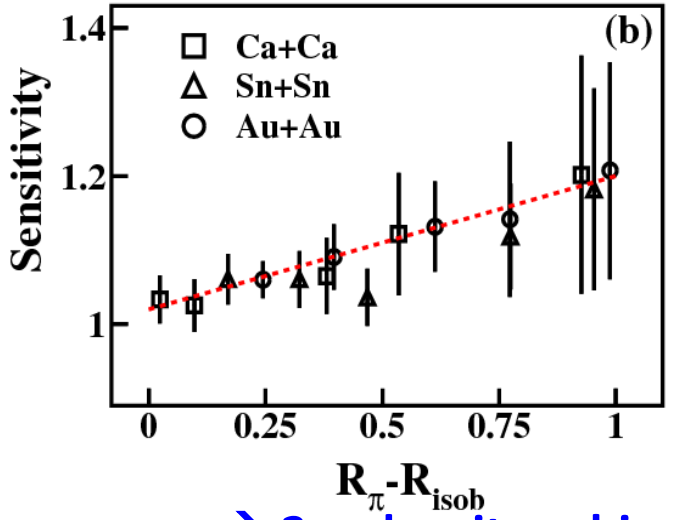
- **Stiff** π^-/π^+ — Physics Letters B 683 (2010) 140–144
- **Moderate** — P. Russotto *et al., Phys. Lett. B* ***697, 471 (2011).***
  M.D. Cozma, Phys. Lett. B **700, 139 (2011).**
  P. Russotto et al., EPJA, to be published
  - n/p differential flow
- **Soft** π^-/π^+ — XZG et al, PRL 102 (2009) 062502
  Z. Q. Feng et al, PLB 718 (2013) 1510
- **No sensitivity** π^-/π^+ — J. Hong et al. ArXiv: 1307.7654 [nucl-th]

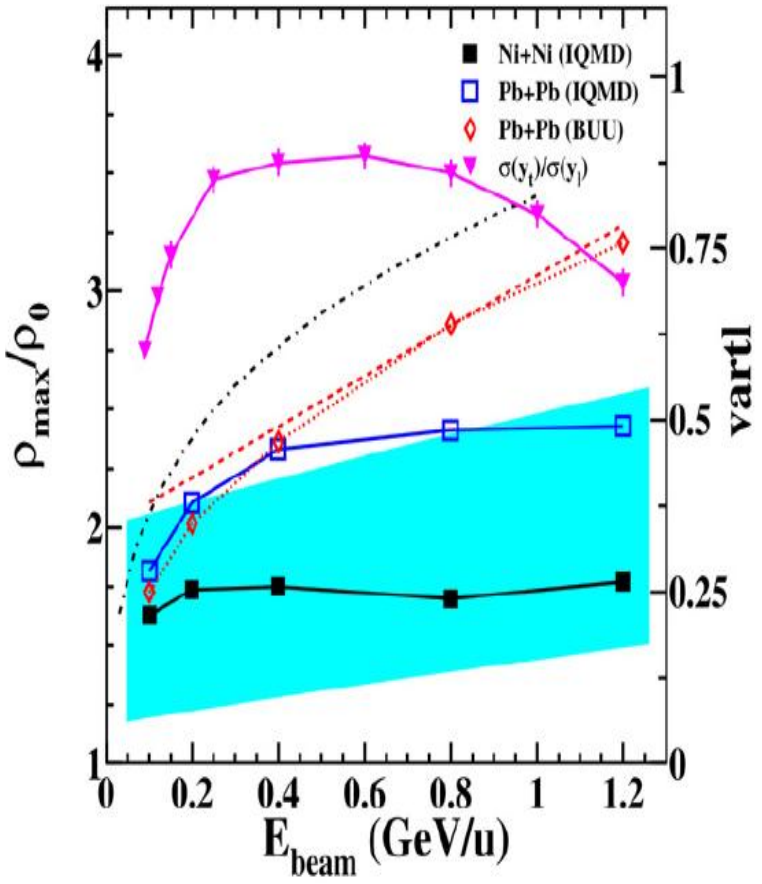
For review: XZG, G.C. Yong, L. W. Chen, B. A. Li et al., Eur. Phys. J. A (2014) 50: 37

Why the energy region below 0.5 GeV/u is favored?







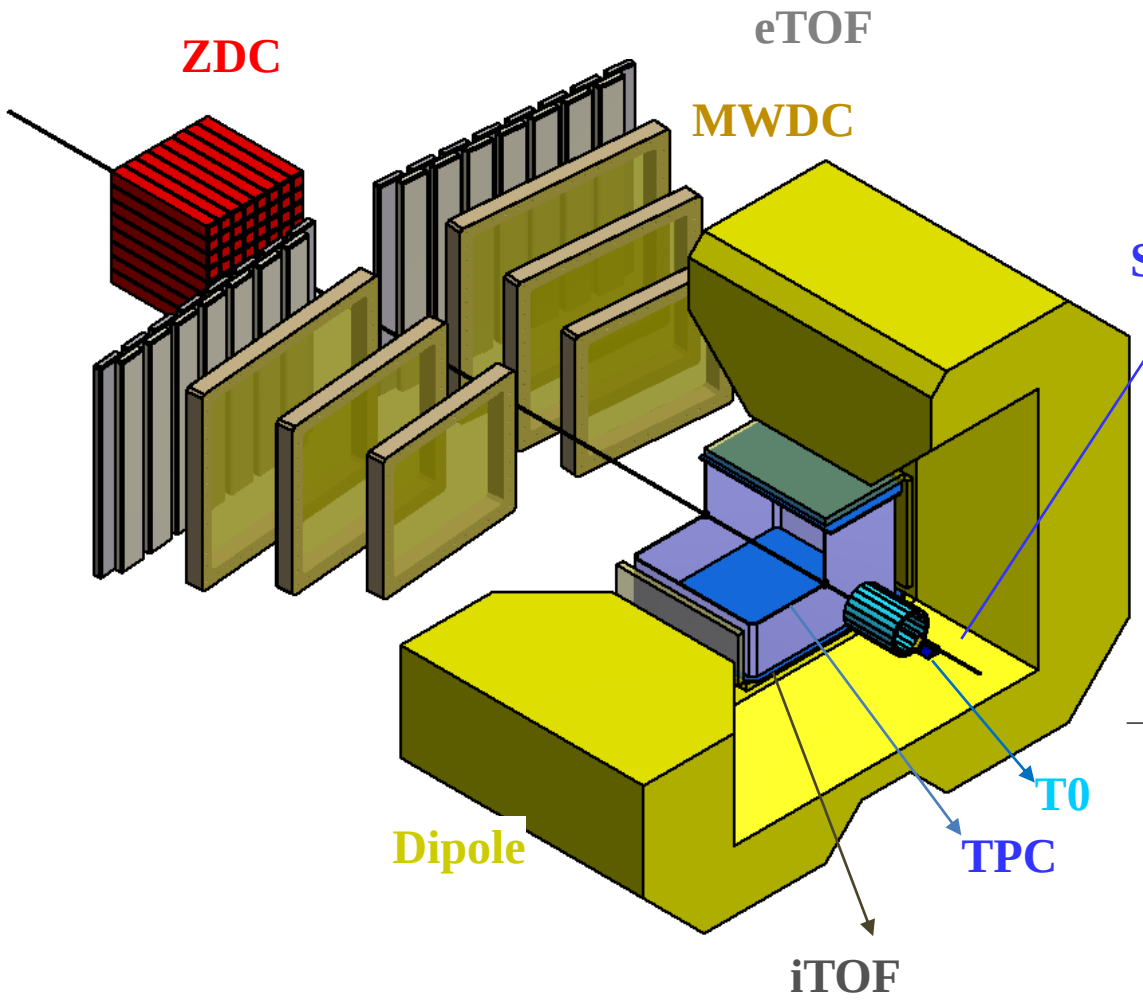


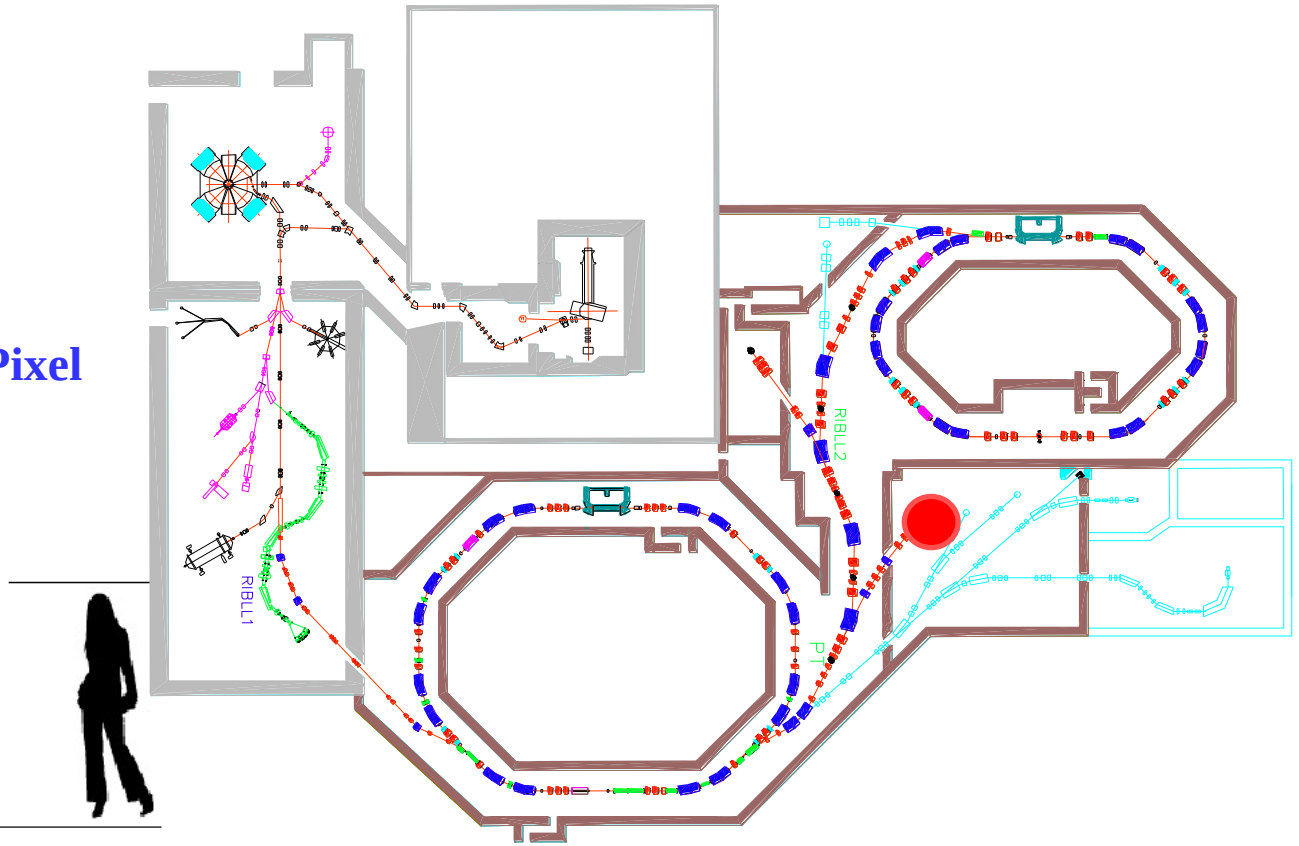
M. Zhang, XZG et al, PRC80(2009)034616
F. Fu, XZG, PLB 666(2008)359

→ $2\rho_0$ density achievable.

→ Degree of Isospin fractionation is maximum in this energy region;

$E_{sym}(\rho)$ at supra-saturation studies at HIRFL-CSR



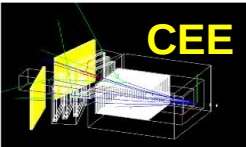


SFC: ≤ 10 AMeV (H.I.), 17~35 MeV (p)

SSC: ≤ 100 AMeV (H.I.), ≤ 110 MeV (p)

CSRm: ≤ 1000 AMeV (H.I.), ≤ 2.8 GeV (p)

Pre-CEE collaboration

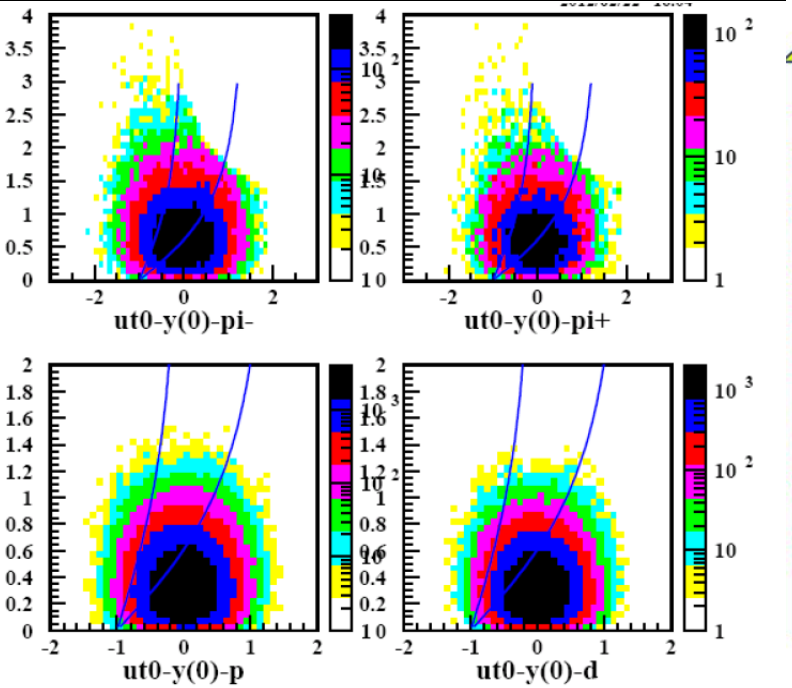


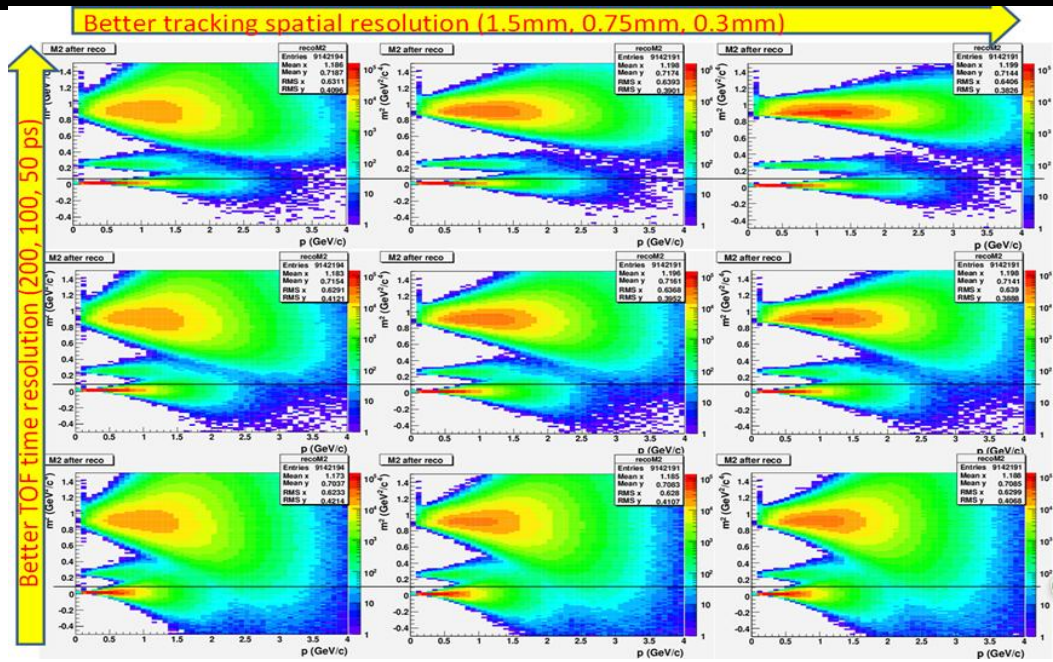
R&D works: Simulations

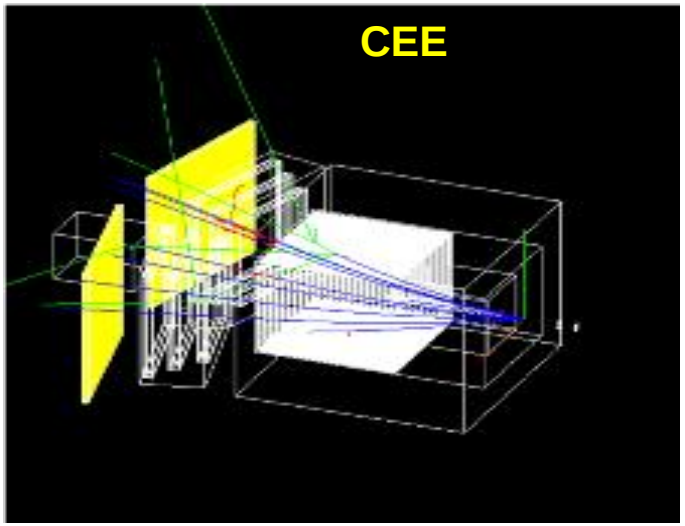
G4 Simulations:

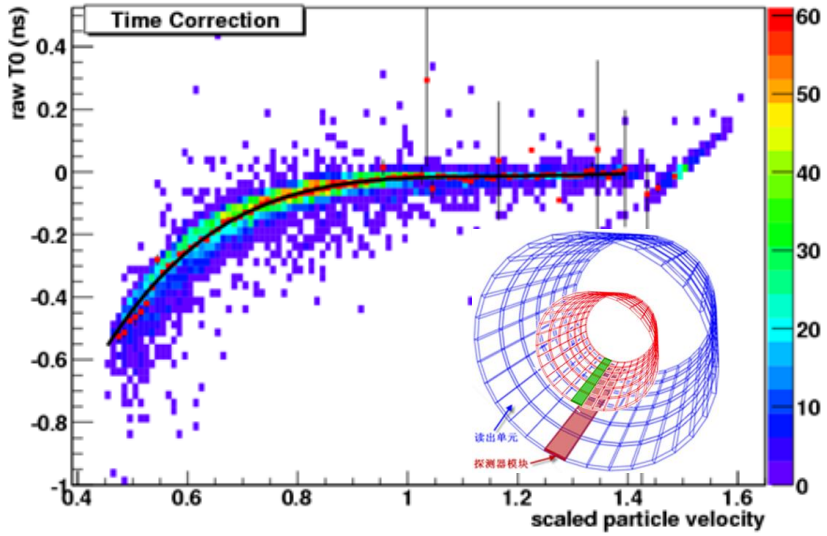
- ☺ Physics Simulations /design
- ☺ G4 simulation platform
- ☺ Performance requirements
- ☺ Tracking with MWDC
- ☺ TOF design and performance

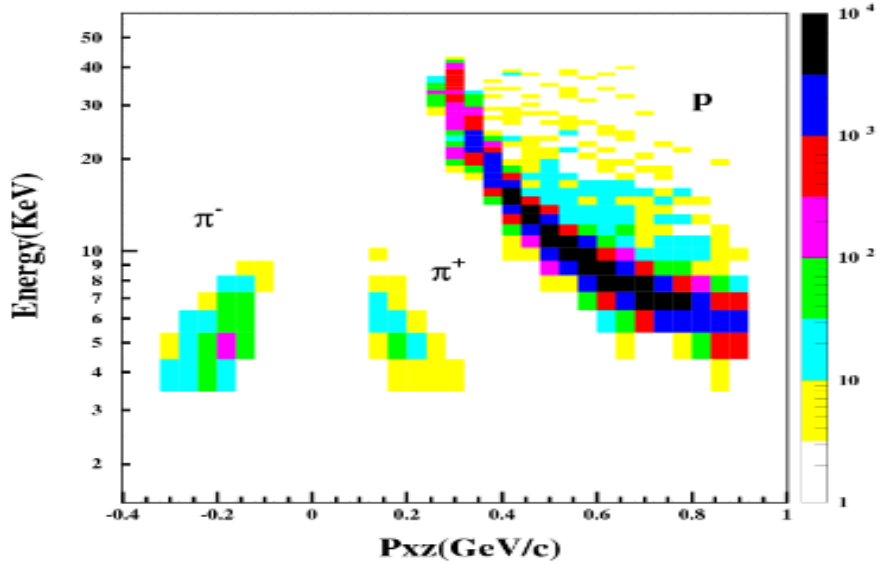
……





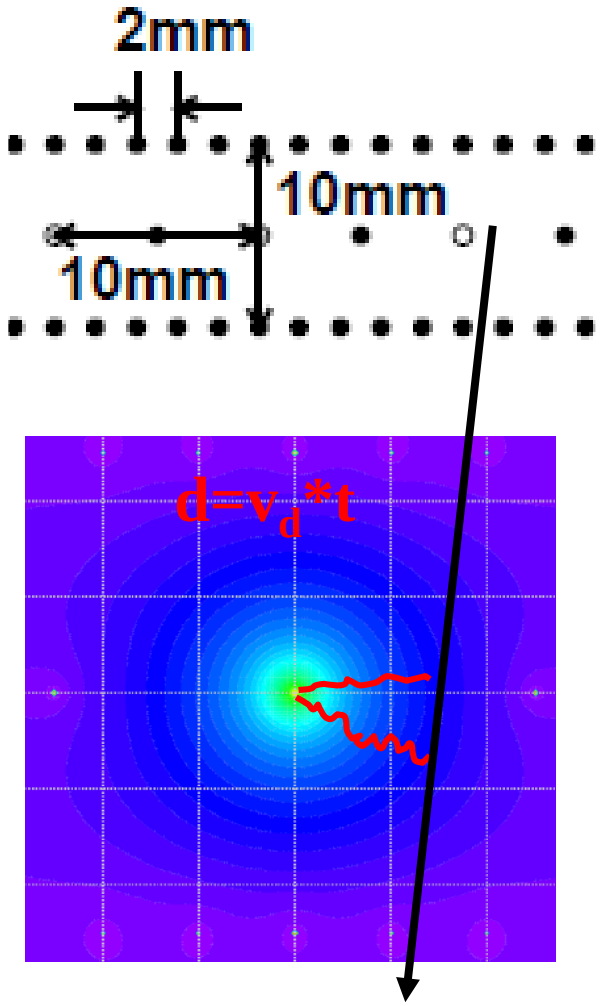


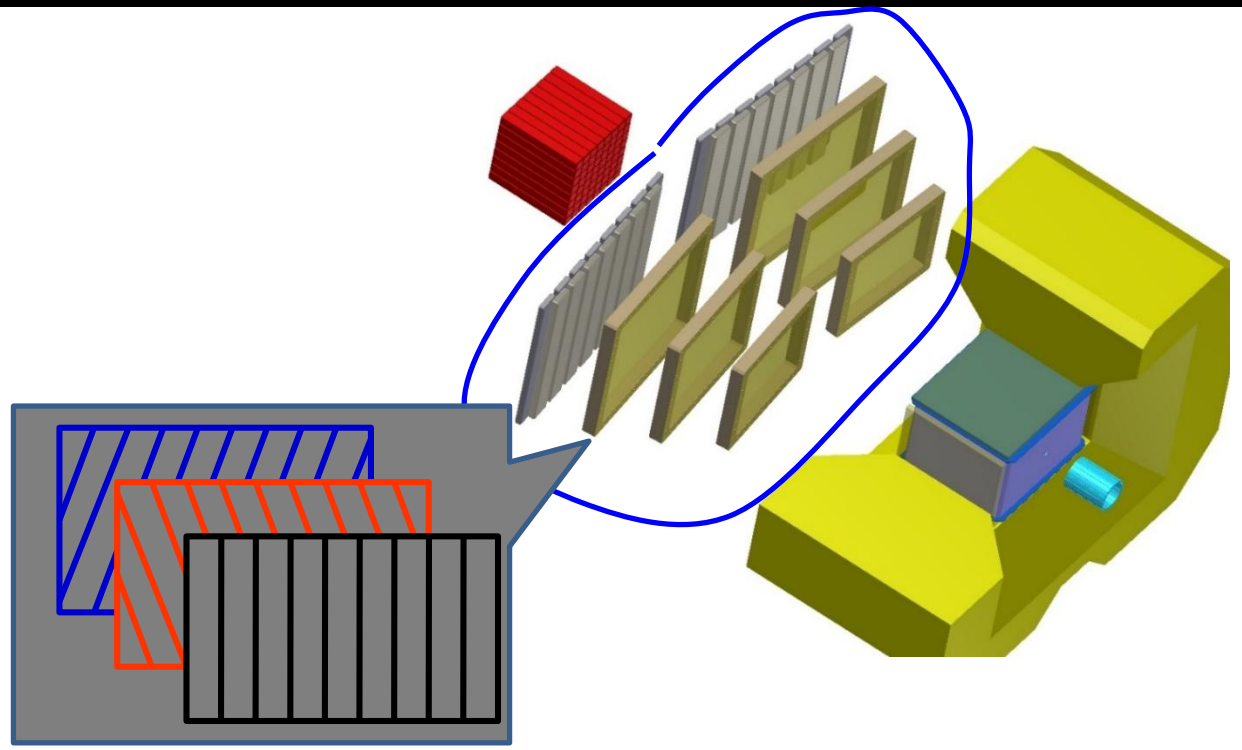




Forward MWDC conceptual design

Forward tracking needed



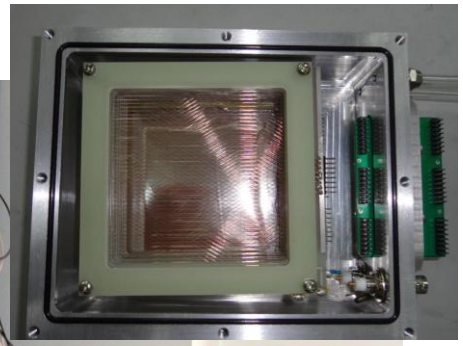


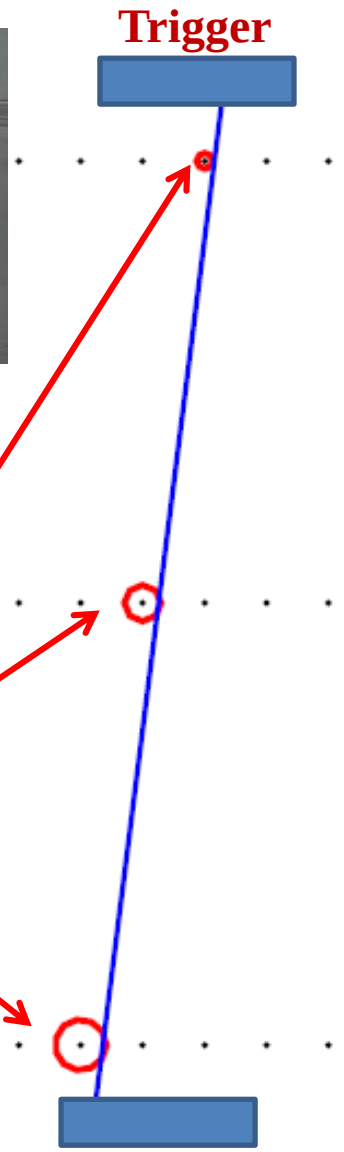
MWDC:

- E field is formed in cell
- Track leaves ionizations
- Deduce drift length from t_d
- Construct track from multi cells

MWDC	
Transv. Hit resolution	0.3 mm
# of layers	3*3
# of channels	3000
Total area	8 m^2
Momentum Resolution	5%

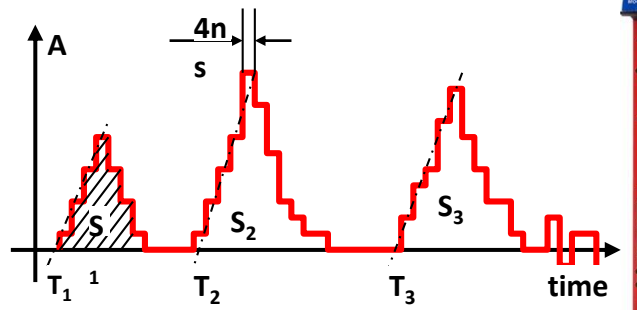
R&D of MWDC array



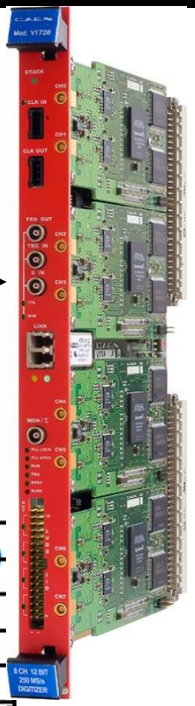


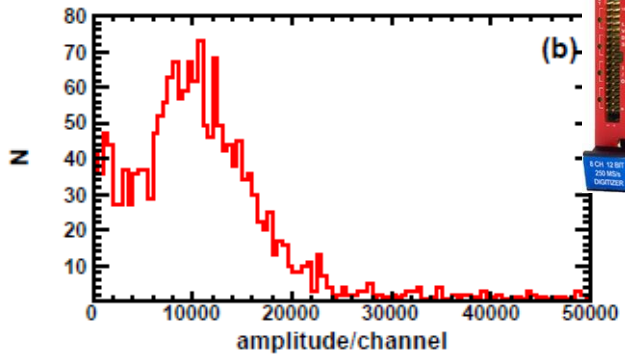
Conventional electronics

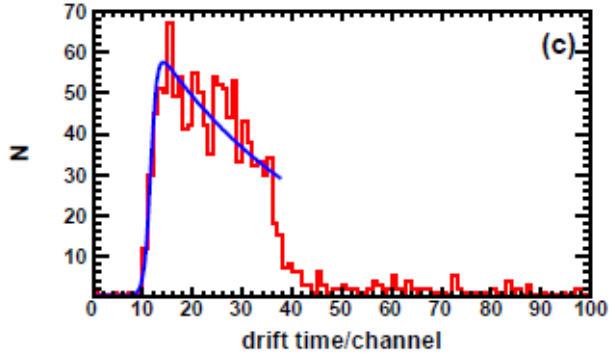
FLADC for timing measurement



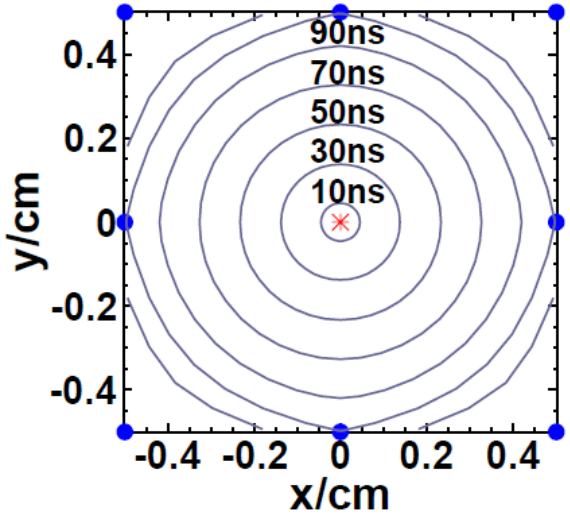
FLADC信号记录示意图

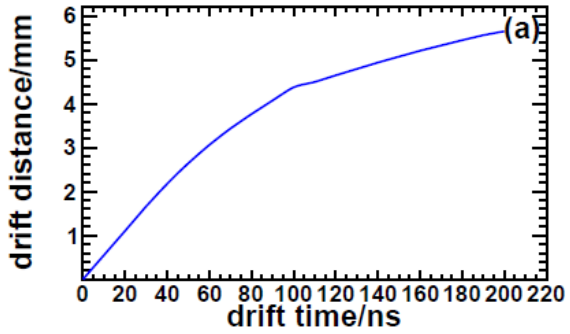


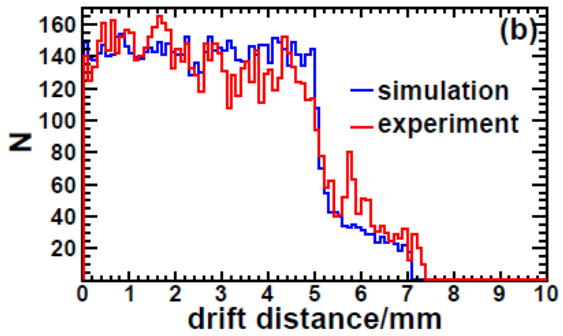


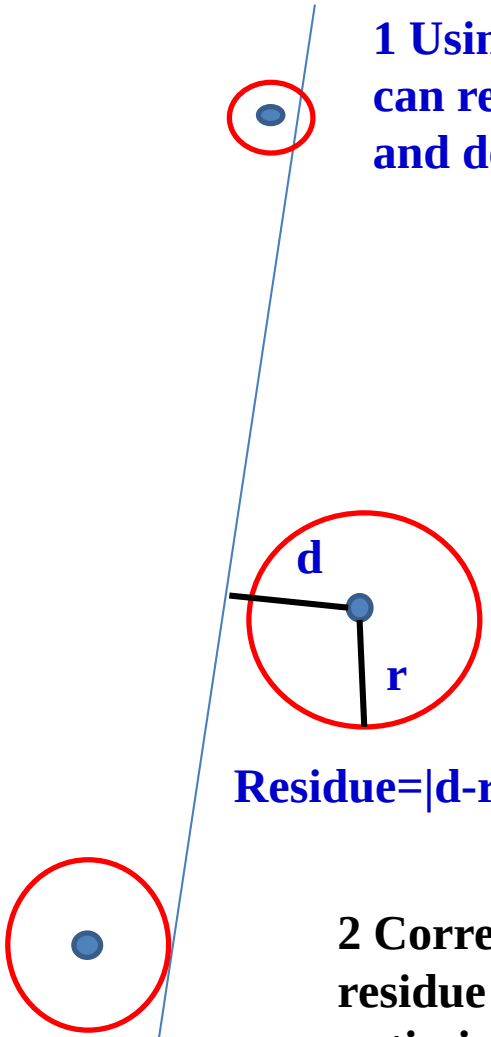


Spatial Timing Relation Calibration





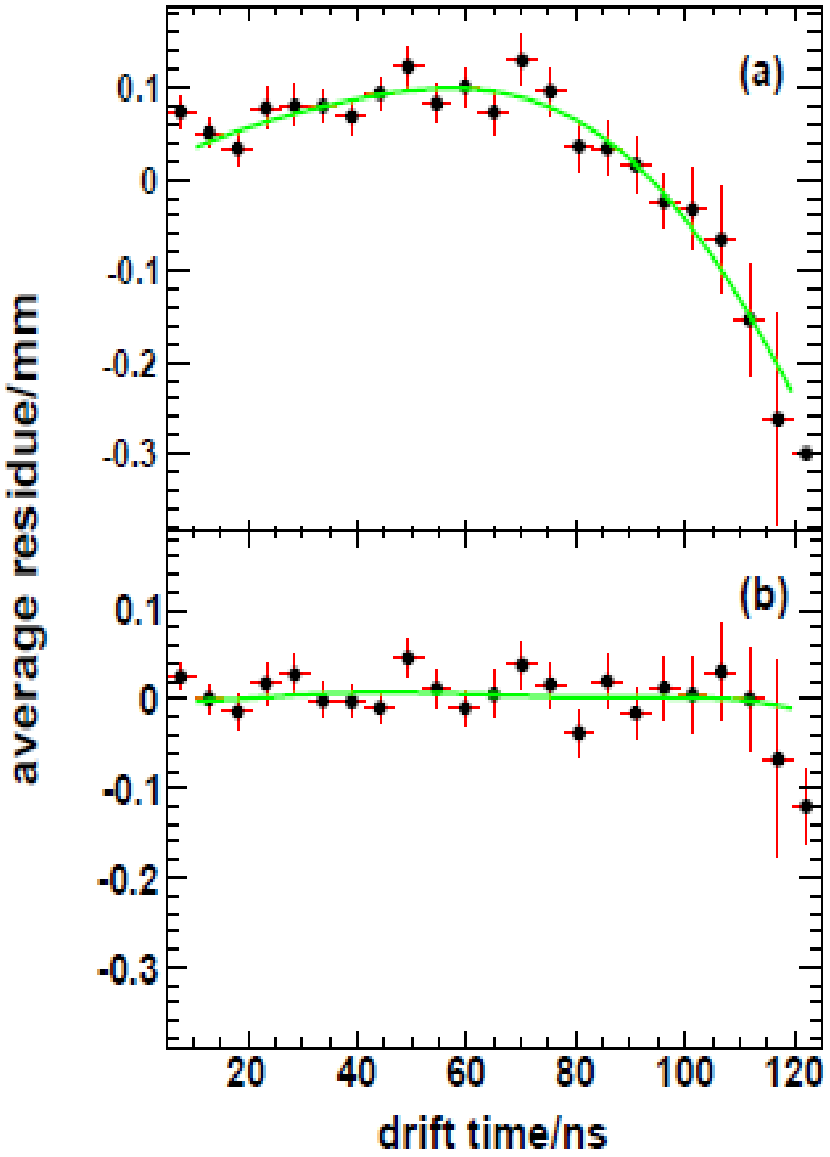




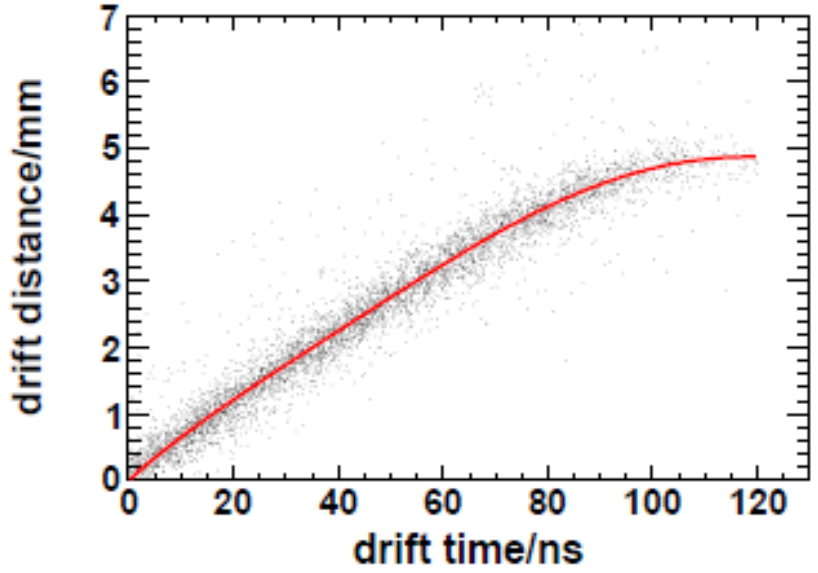
1 Using R-T relation, one can reconstruct the track and deduce the residue.

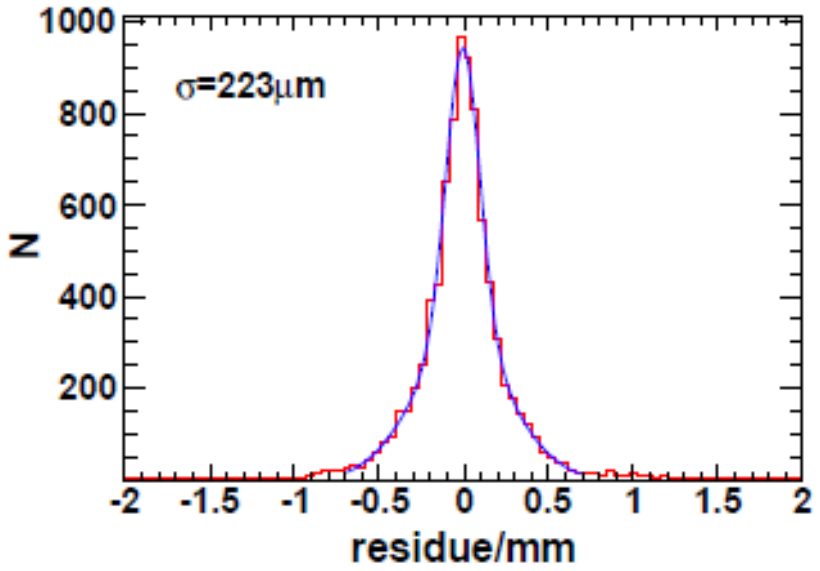
Residue=|d-r|

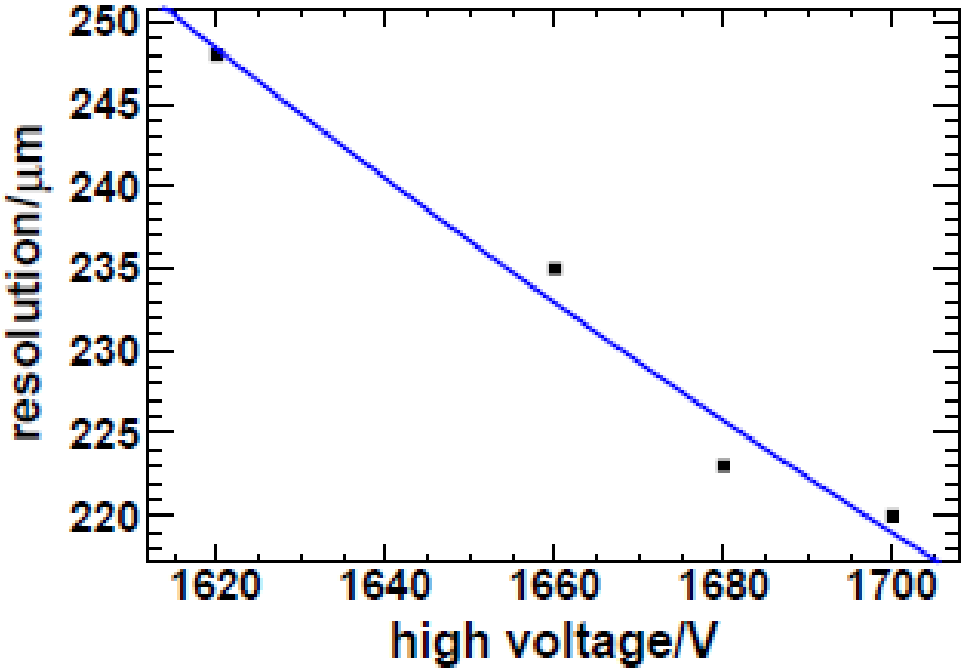
2 Correct the STR till the residue distribution is optimized.



MWDC array performance







σ=220 μm

Yi Han, XZG et al, Chin. Phys. C, 2014 to be published.

3-D track finding and reconstruction in MWDC

1 To fit the drift length measured by X, U and V wires by minimizing the χ2

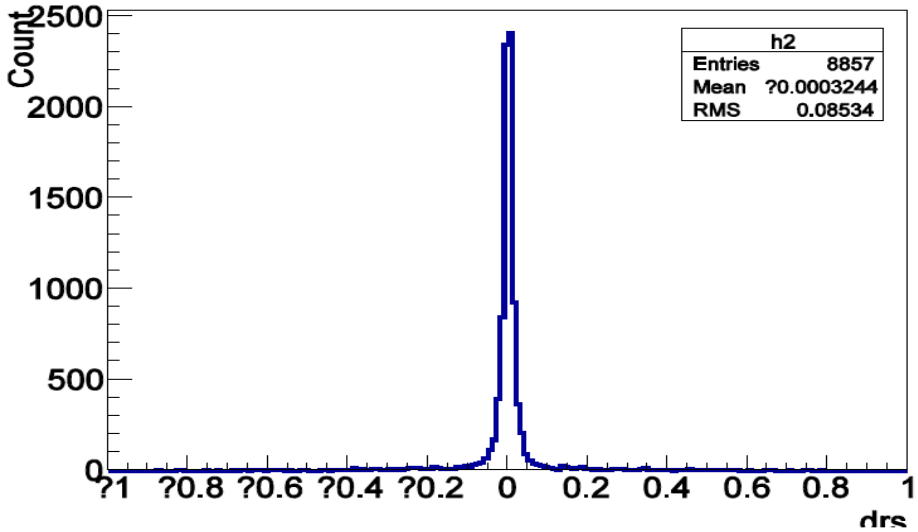
$$\chi^2 = \sum_i \frac{[x_i - (a'\cos\alpha_i + c'\sin\alpha_i)z_i - (b'\cos\alpha_i + d'\sin\alpha_i)]^2}{[1 + (a'cos\alpha_i + c'sin\alpha_i)^2](\delta d_i)^2}$$

2 Analytically a set of equations can be derived and solved:

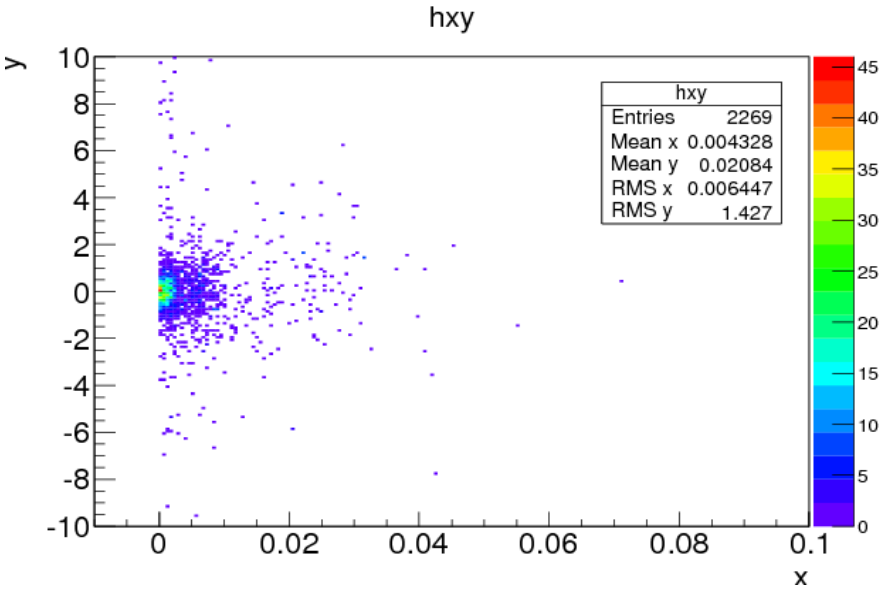
$$\begin{cases} \sum_i (z_i^2(cos\alpha_i)^2 a' + z_i(cos\alpha_i)^2 b' + z_i^2 sin\alpha_i cos\alpha_i c' + z_i sin\alpha_i cos\alpha_i d' - x_i z_i cos\alpha_i) = 0 \\ \sum_i (z_i(cos\alpha_i)^2 a' + (cos\alpha_i)^2 b' + z_i sin\alpha_i cos\alpha_i c' + sin\alpha_i cos\alpha_i d' - x_i cos\alpha_i) = 0 \\ \sum_i (z_i^2 sin\alpha_i cos\alpha_i a' + z_i sin\alpha_i cos\alpha_i b' + z_i^2 (sin\alpha_i)^2 c' + z_i (sin\alpha_i)^2 d' - x_i z_i sin\alpha_i) = 0 \\ \sum_i (z_i sin\alpha_i cos\alpha_i a' + sin\alpha_i cos\alpha_i b' + z_i (sin\alpha_i)^2 c' + (sin\alpha_i)^2 d' - x_i sin\alpha_i) = 0 \end{cases}$$

3 Then the parameters of the straight track can be derived.

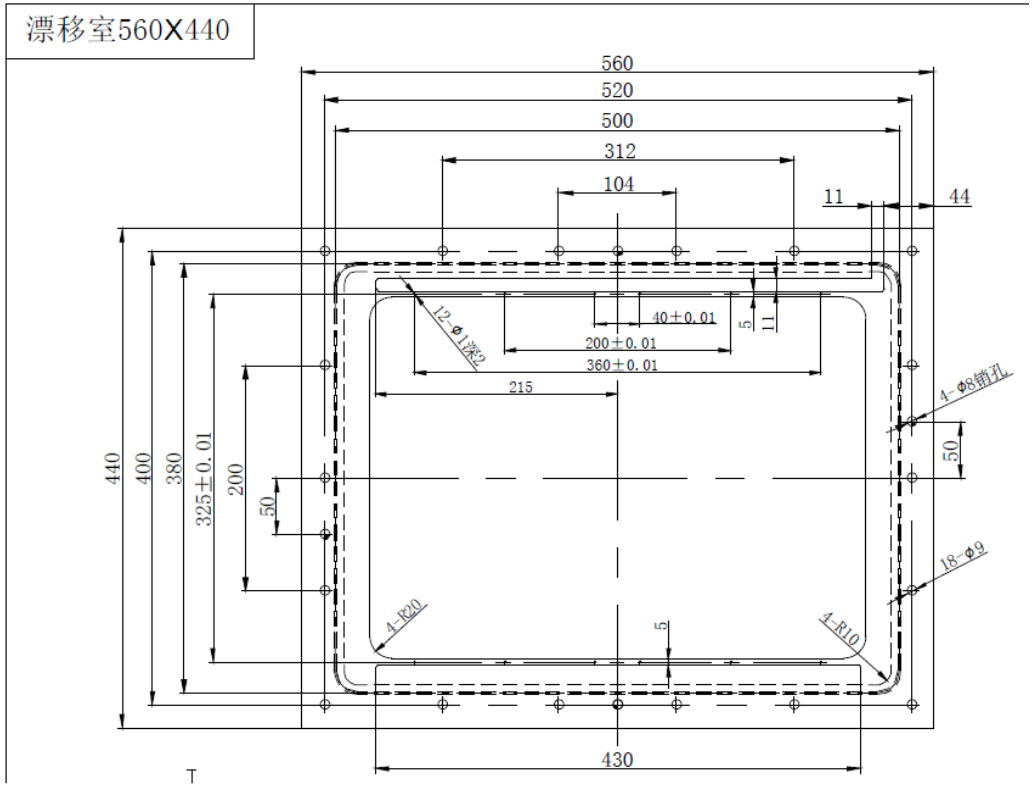
With the multiple scattering effect, the reconstruction vertex is at the order of 2 mm.



3D residue distribution from Geant 4 simulation. (include track finding)



Manufactory of large MWDC



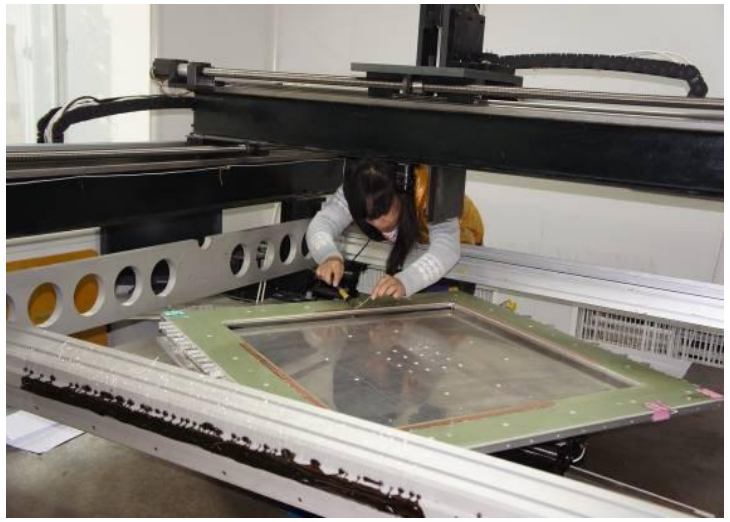
In progress:

Assembly of larger area MWDC

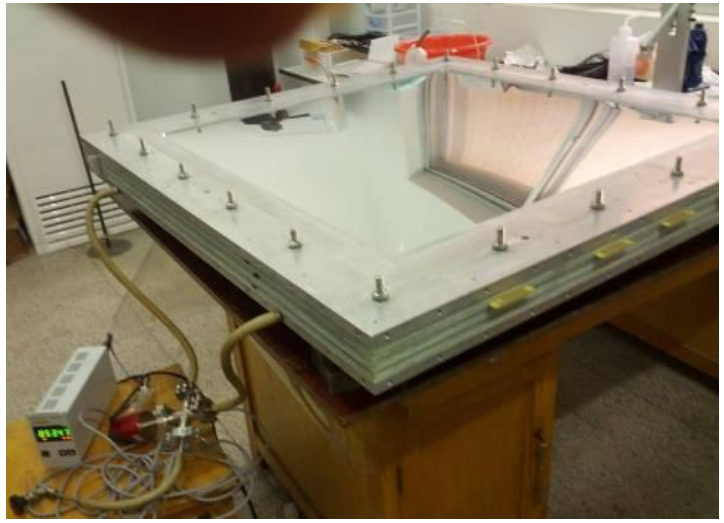
Development of FLADC-based DAQ

Day one Beam time:

2015, March

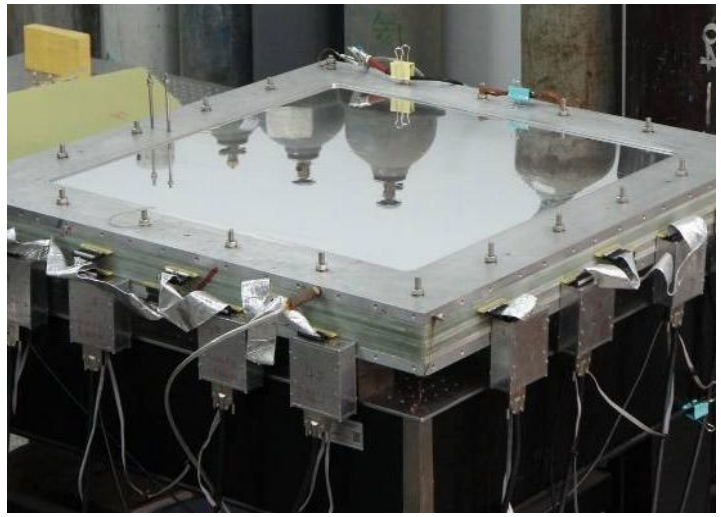


Soldering Wire and Frame



Leak rate Test

Wire Frame/Tension Preset



A Large MWDC to be completed

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 early 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 $E_{sym}(\rho)$.

- **For the HIRFL-CSR External target Experiment:**

→R&D on going well

→Hope to have the chance to contribute to the $E_{sym}(\rho)$ studies.

Acknowledgements

Collaborators

THU: R. S. Wang, Y. Zhang, H. Yi, L. M. Lv, Y. Huang. W. J. Cheng. H. J. Li, M. Lin, Z. Zhang

IMP: G. M. Jin, L. M. Duan, R. J. Hu, H. R. Yang, 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

CCNU: N. Xu, F. Liu SINAP: F. Lu, Y. G. Ma

CCNU: M. Shao, L. Zhao, J. F. Yang

IMP: Z. Y. Sun, G. Q. Xiao ….

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Thank You for your attention!