Conference on Strangeness in Quark Matter
Oct. 05-10, 2008, Tsinghua Uni., Beijing

Nuclear matter at HIRFL-CSR energy regime

Zhigang Xiao
Department of Physics, Tsinghua University

Collaborators

THU:	M. Zhang, P. F. Zhuang
IMP :	H. S. Xu, G. M. Jin, F. Fu, G. C. Yong
Texas A&M:	B. A. Li
SJTU:	L. W. Chen
GSI :	FOPI collaboration

Content

Introduction

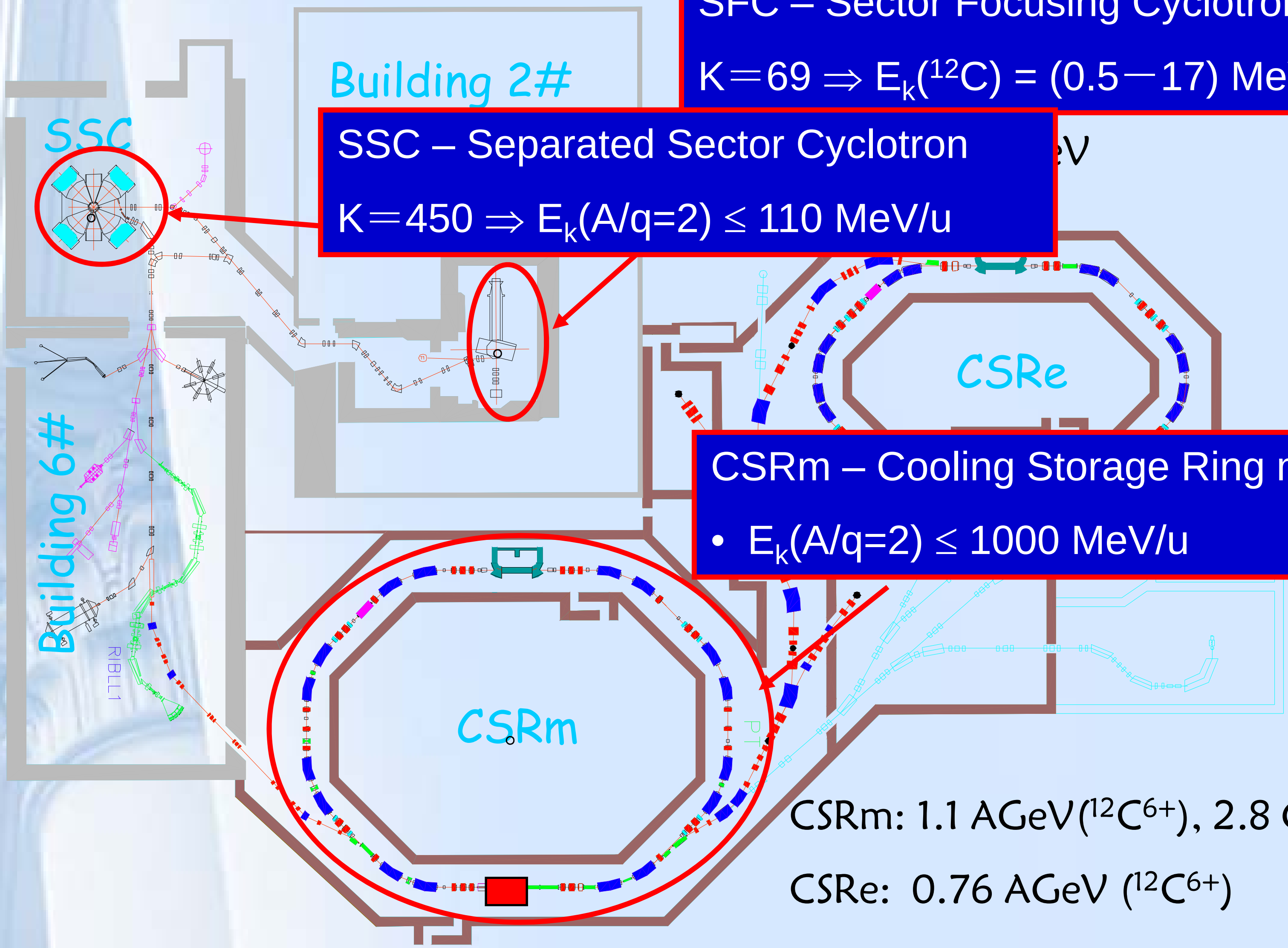
- HIRFL－CSR snapshot
- Equation of state of asymmetric nuclear matter.

Selected aspects of HIC at GeV/u regime

- Aspects of compression in HIC
- Softening of $E_{sym}(\rho)$ at supra-density from π probe
- More simulations for CSR energy regime

Summary

HIRFL-CSR Complex



SFC – Sector Focusing Cyclotron

K＝69 ⇒ $E_k(^{12}C)$ = (0.5－17) MeV/u

SSC – Separated Sector Cyclotron

K＝450 ⇒ E_k(A/q=2) ≤ 110 MeV/u

CSRm – Cooling Storage Ring main

- E_k(A/q=2) ≤ 1000 MeV/u

CSRm: 1.1 AGeV($^{12}C^{6+}$), 2.8 GeV(p)

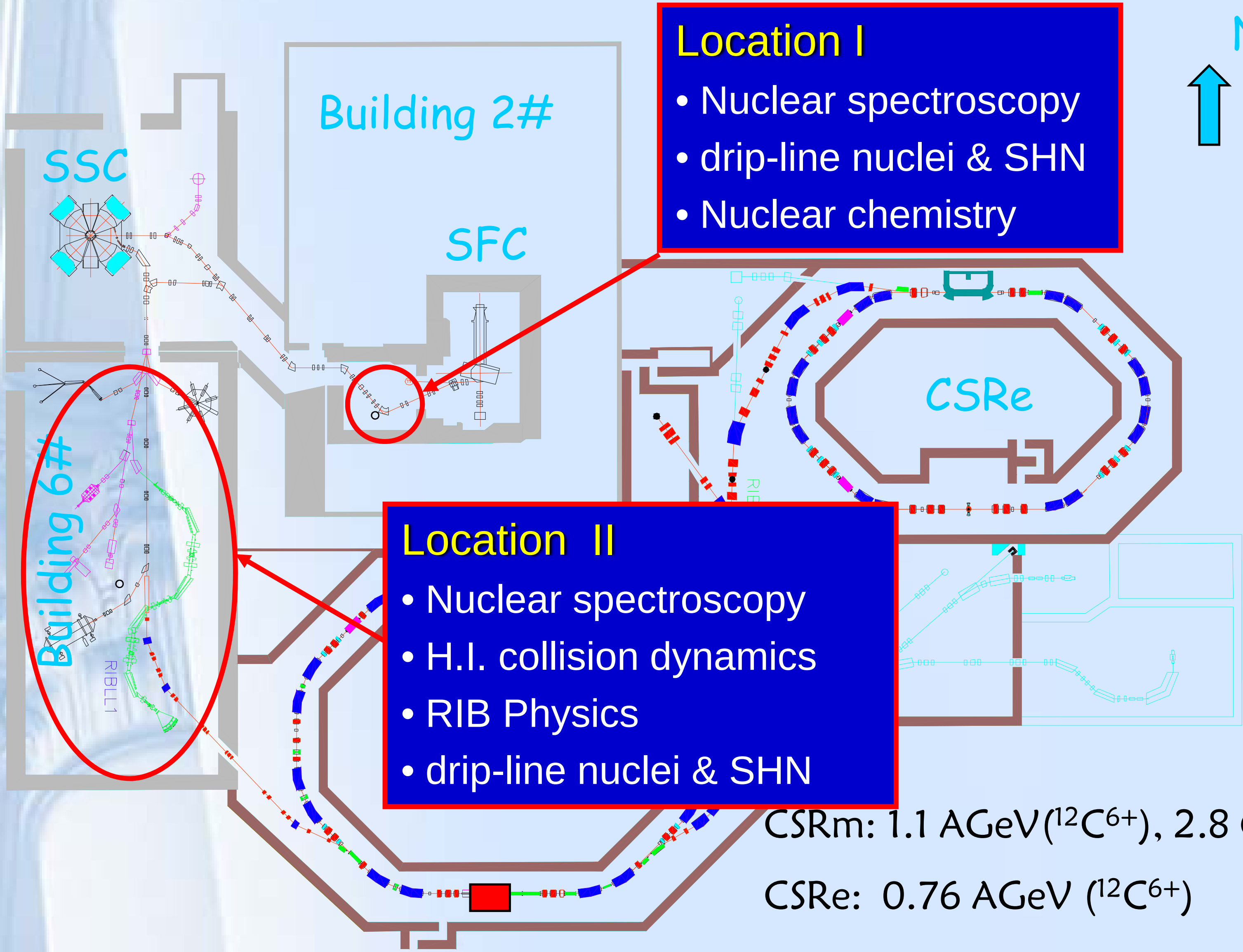
CSRe: 0.76 AGeV ($^{12}C^{6+}$)

HIRFL-CSR Photos

HIRFL-CSR Research Programs

- **Nuclear Physics**
  - Nuclear spectroscopy, Super-Heavy Element (SHE),
  - RIB physics
  - Reaction dynamics and nuclear matter
- **Atomic Physics**
  - Highly Charged Ions, High Energy Density Matter, Molecular & cluster beams
- **Material Science**
- **Radio-biology & cancer therapy with heavy ions**
- **Accelerator physics**
- **Development of Electronics & detectors**

HIRFL-CSR Experiments on Nuclear Physics



Location I

- Nuclear spectroscopy
- drip-line nuclei & SHN
- Nuclear chemistry

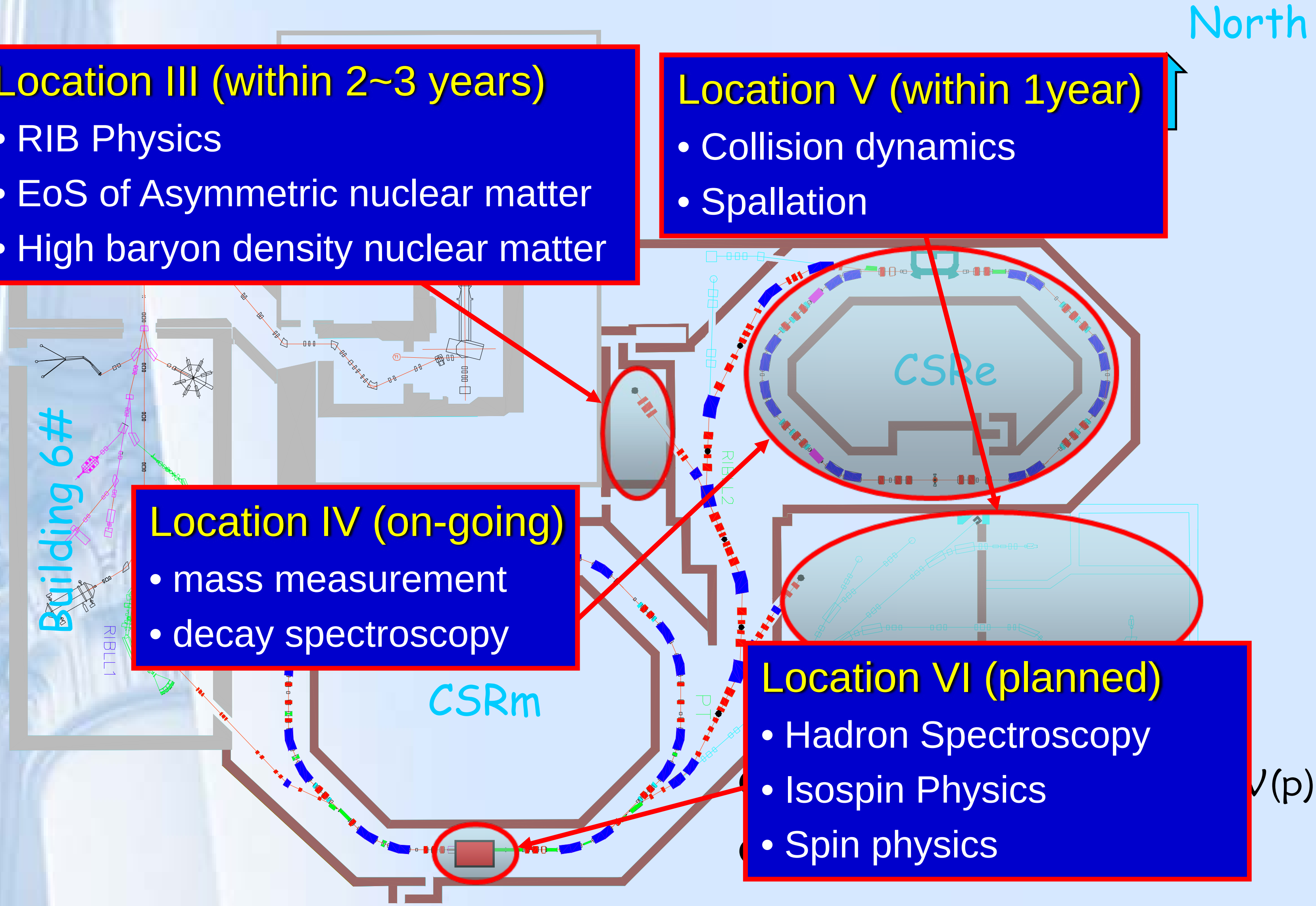
Location II

- Nuclear spectroscopy
- H.I. collision dynamics
- RIB Physics
- drip-line nuclei & SHN

CSRm: 1.1 AGeV($^{12}C^{6+}$), 2.8 GeV(p)

CSRe: 0.76 AGeV ($^{12}C^{6+}$)

HIRFL-CSR Experiments on Nuclear Physics



Location III (within 2~3 years)
- RIB Physics
- EoS of Asymmetric nuclear matter
- High baryon density nuclear matter

Location V (within 1year)
- Collision dynamics
- Spallation

Location IV (on-going)
- mass measurement
- decay spectroscopy

Location VI (planned)
- Hadron Spectroscopy
- Isospin Physics
- Spin physics

Current Main Exp. Setups at HIRFL-CSR

- **SHANS**

  Spectrometer of Heavy Atoms & Nuclear Structure

- **RIBLL 1**

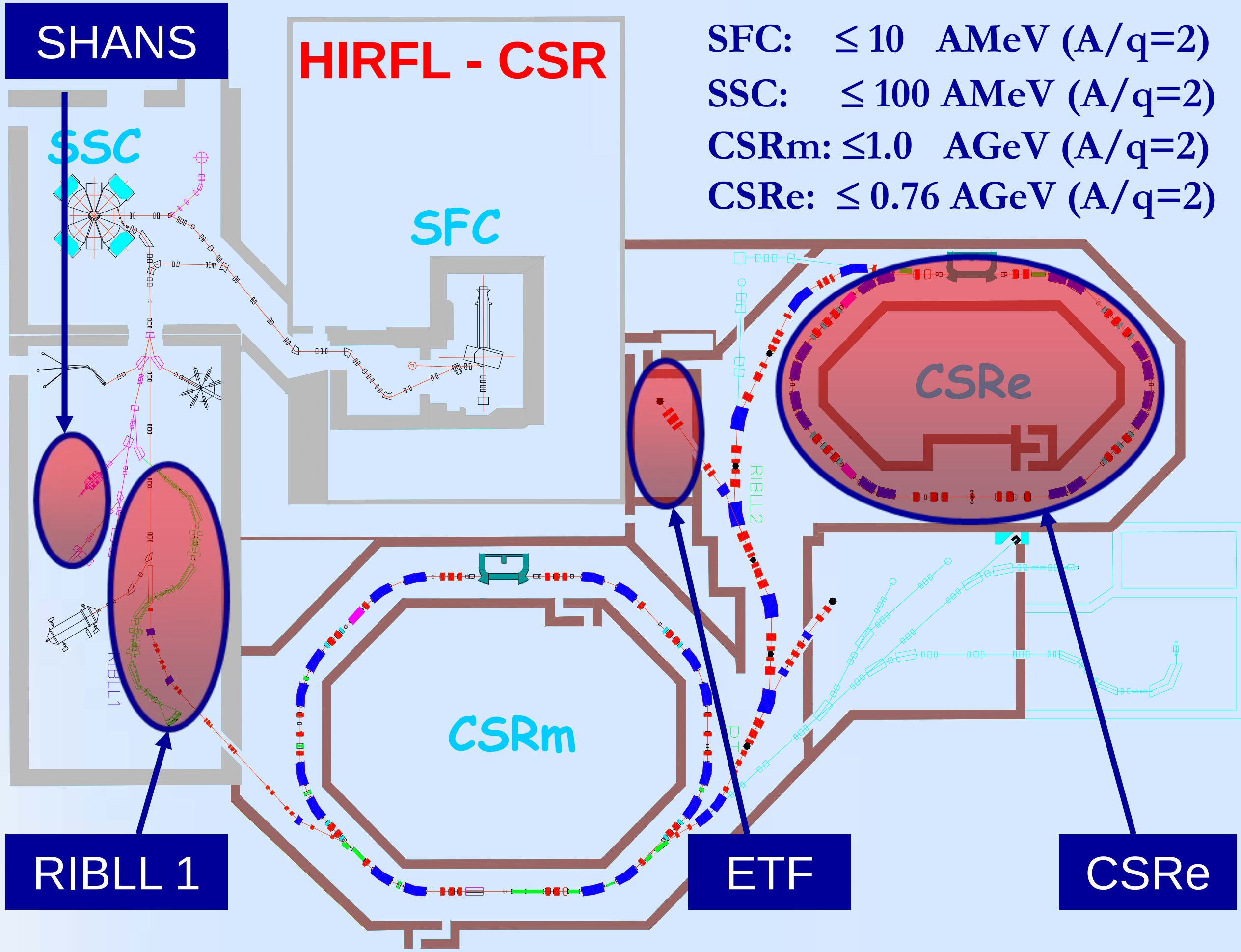
  RIBs produced via PF & transfer with primary beams up to Kr

- **ETF**

  External Target Facility for RIB experiment & asymmetry nuclear matter research

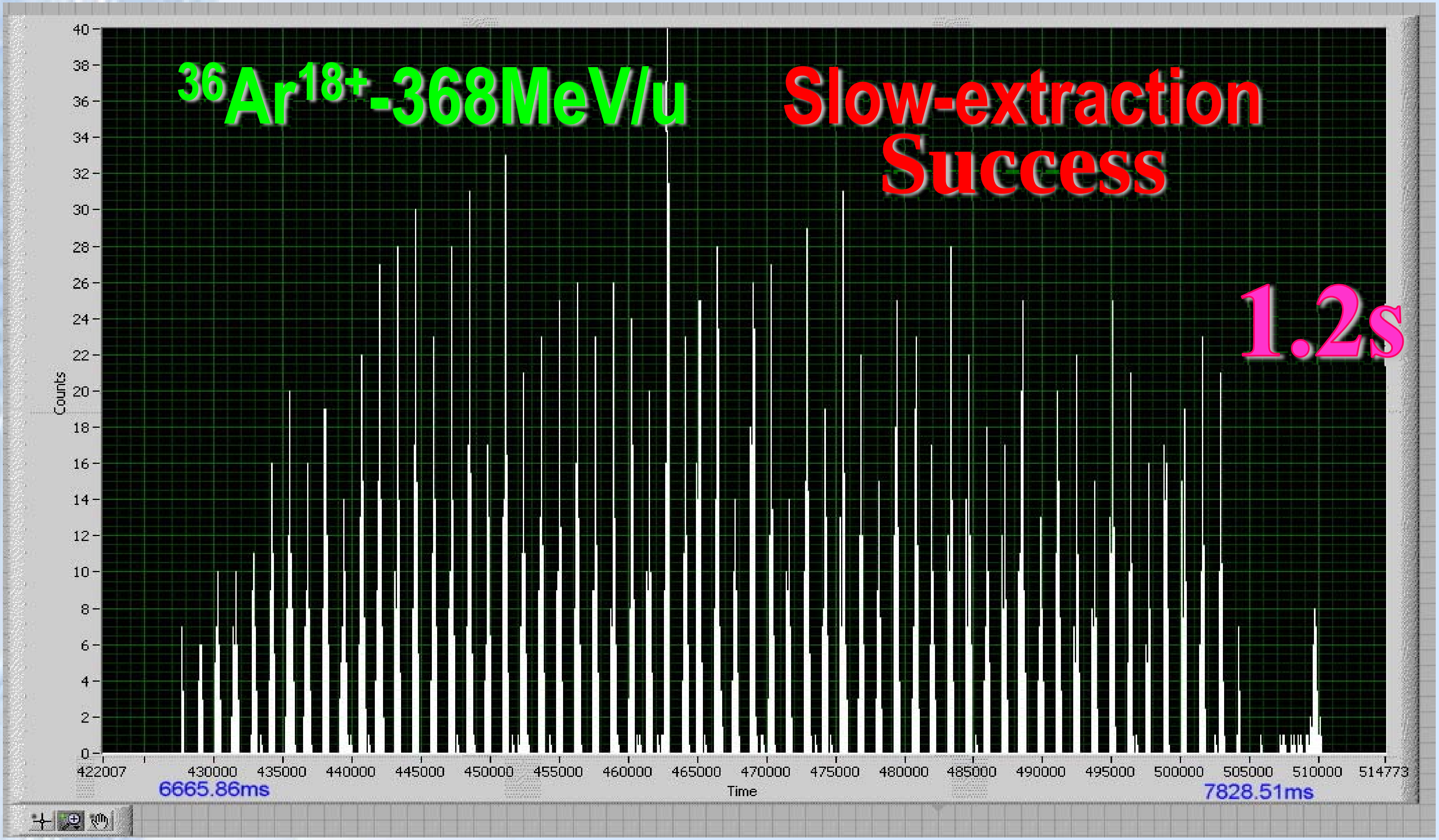
- **CSRe**

  Mass measurement & atomic physics with cooling storage ring



Beam signal for slow extraction in CSRm

2008.01.10 15:00

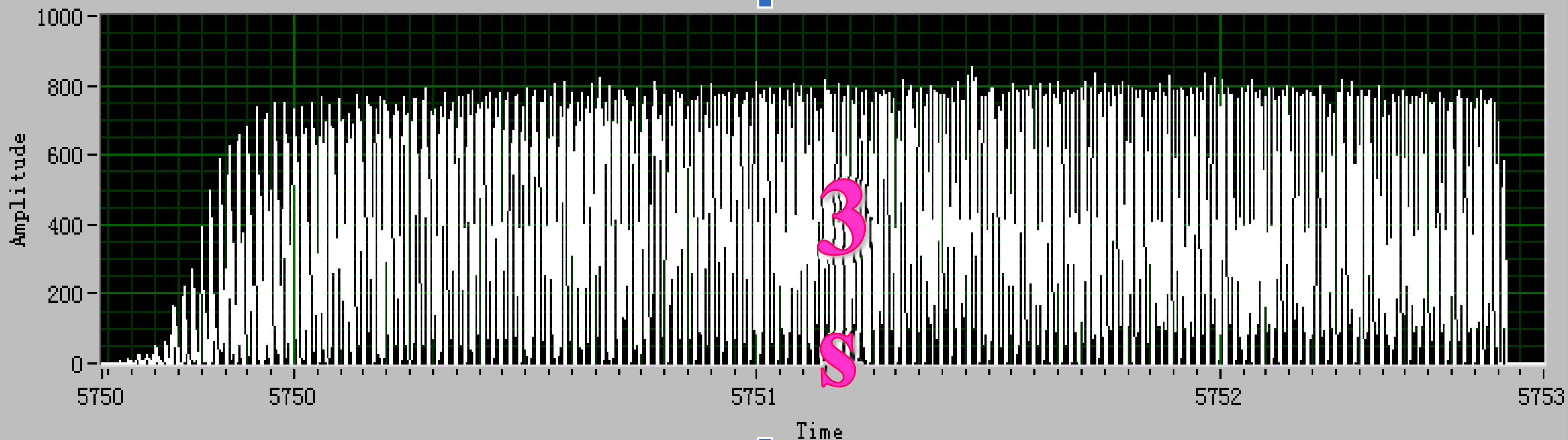


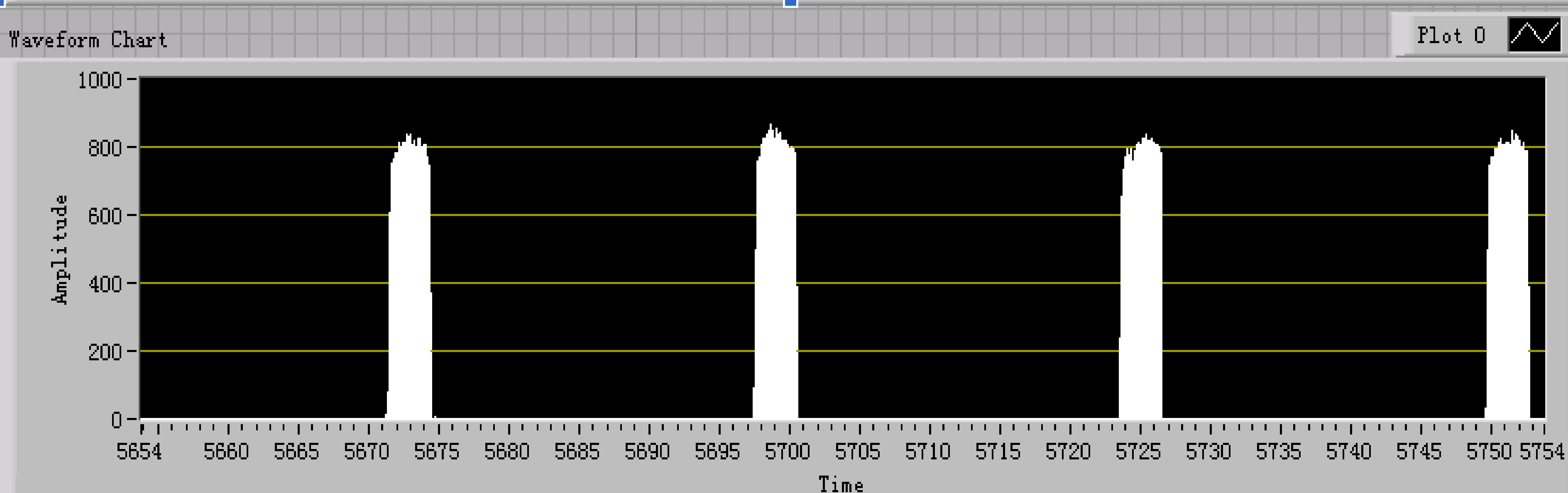
- Spill length: 1.2s
- Main frequency: 50Hz

Slow extraction for $^{12}C^{4+}$-300MeV/u in CSRm

From Scintillation Crystal

2008.05.21 03:31





Current beams at CSR

Ions: $^{12}C^{6+}$, $^{36}Ar^{18+}$, $^{129}Xe^{27+}$

Energy: 1 GeV/u for C & Ar in CSRm

Intensity: 3.2 mA (1.6×10^{10}) for C-7 MeV/u in CSRm

10 mA (7×10^{9}) for C-600 MeV/u in CSRm

1.2 mA (4×10^{8}) for Ar-368 MeV/u in CSRm

0.5 mA (1×10^{8}) for Xe-235 MeV/u in CSRm

15 mA (8×10^{9}) for C-660 MeV/u in CSRe

Experiment: RIB from RIBLL2, test with isochronous mode in CSRe , $\Delta M/M \sim 10^{-5}$

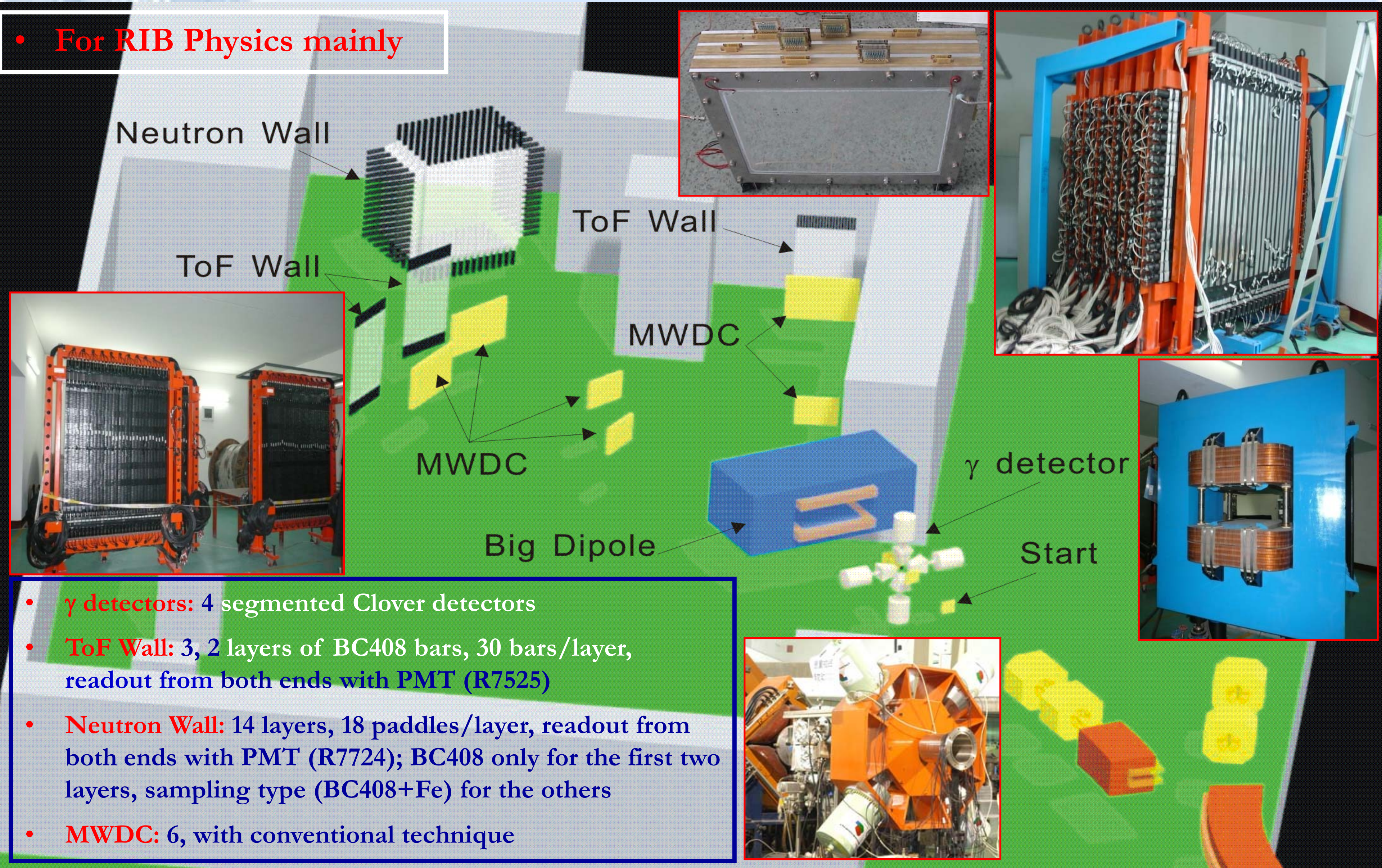
Slow-extraction: 1.2 s for Ar-368MeV/u from CSRm

3.0 s for $^{12}C^{4+}$-300 MeV/u from CSRm

ETF Phase I

(External Target Facility – Phase I)

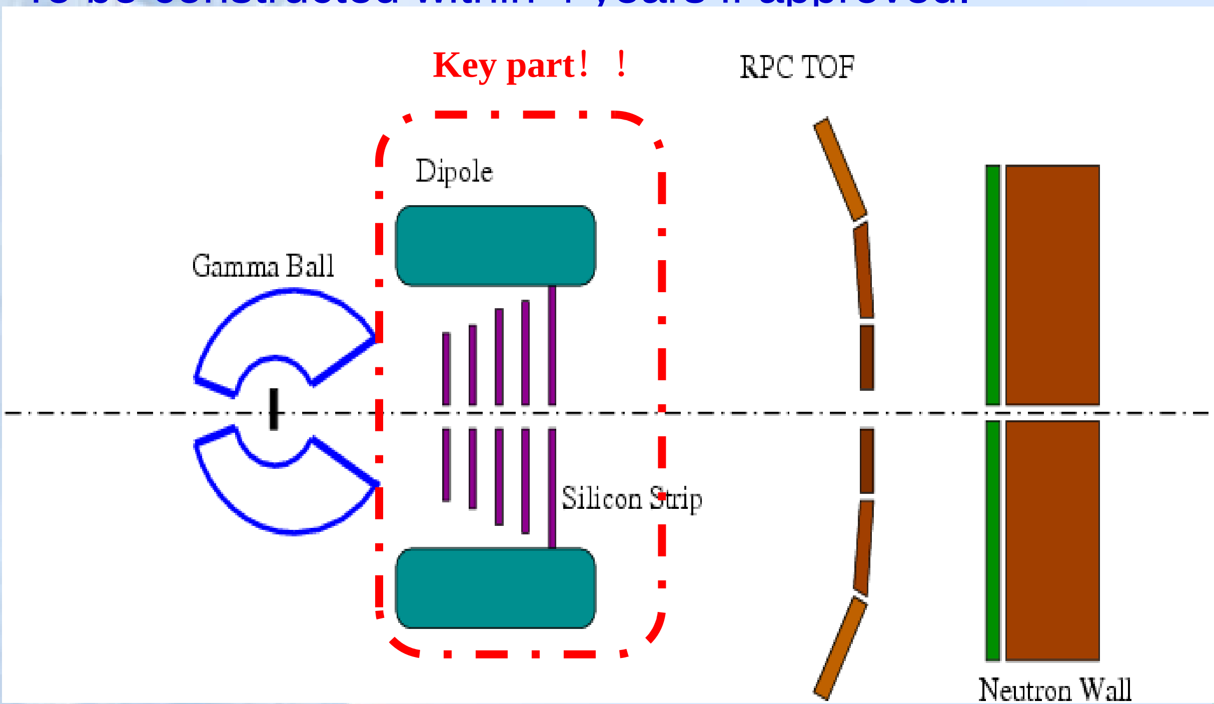
- For RIB Physics mainly



- γ detectors: 4 segmented Clover detectors
- ToF Wall: 3, 2 layers of BC408 bars, 30 bars/layer, readout from both ends with PMT (R7525)
- Neutron Wall: 14 layers, 18 paddles/layer, readout from both ends with PMT (R7724); BC408 only for the first two layers, sampling type (BC408+Fe) for the others
- MWDC: 6, with conventional technique

ETF Phase II

To be constructed within 4 years if approved.



New Detectors

- γ-ball

(CsI(Tl) array

- MWPC

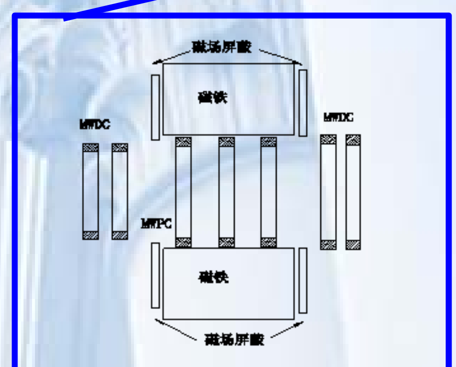
(inside dipole)

- Si-strip array

(inside dipole)

- TPC?

(at target region)



Possible Physics

- For RIB Physics
- For EoS of asymmetry nuclear matter
- For high baryon density matter

Equation of State of nuclear matter

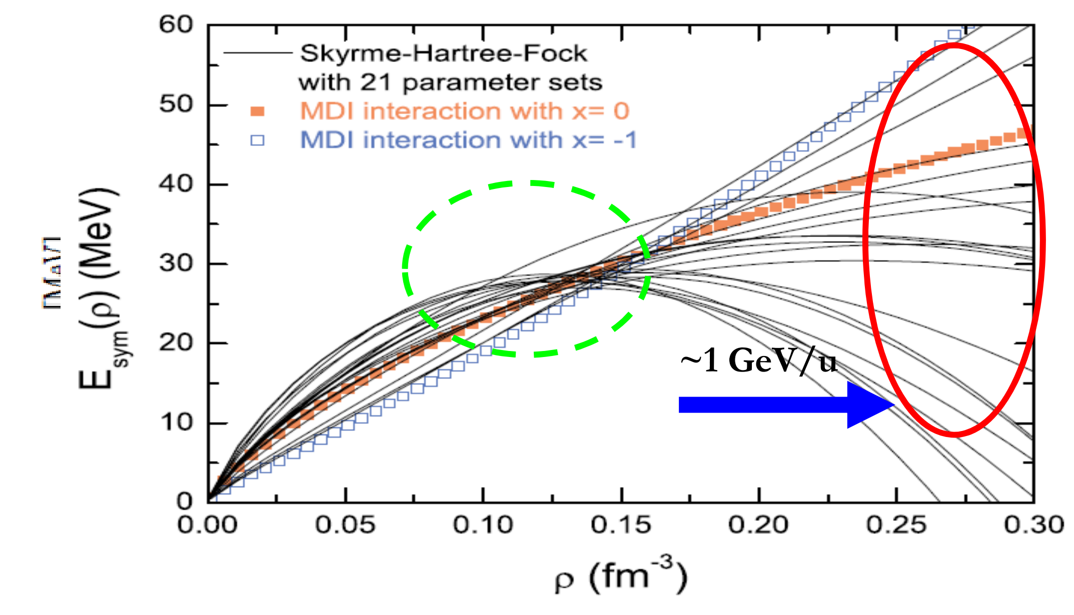
$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho) = a_V + \frac{\kappa}{18}\varepsilon^2 - \frac{\kappa^2}{162}\varepsilon^3 + \ldots + \delta^2\left(E_{sym} + \frac{L}{3}\varepsilon + \ldots\right)$$

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

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

κ:Compressibility

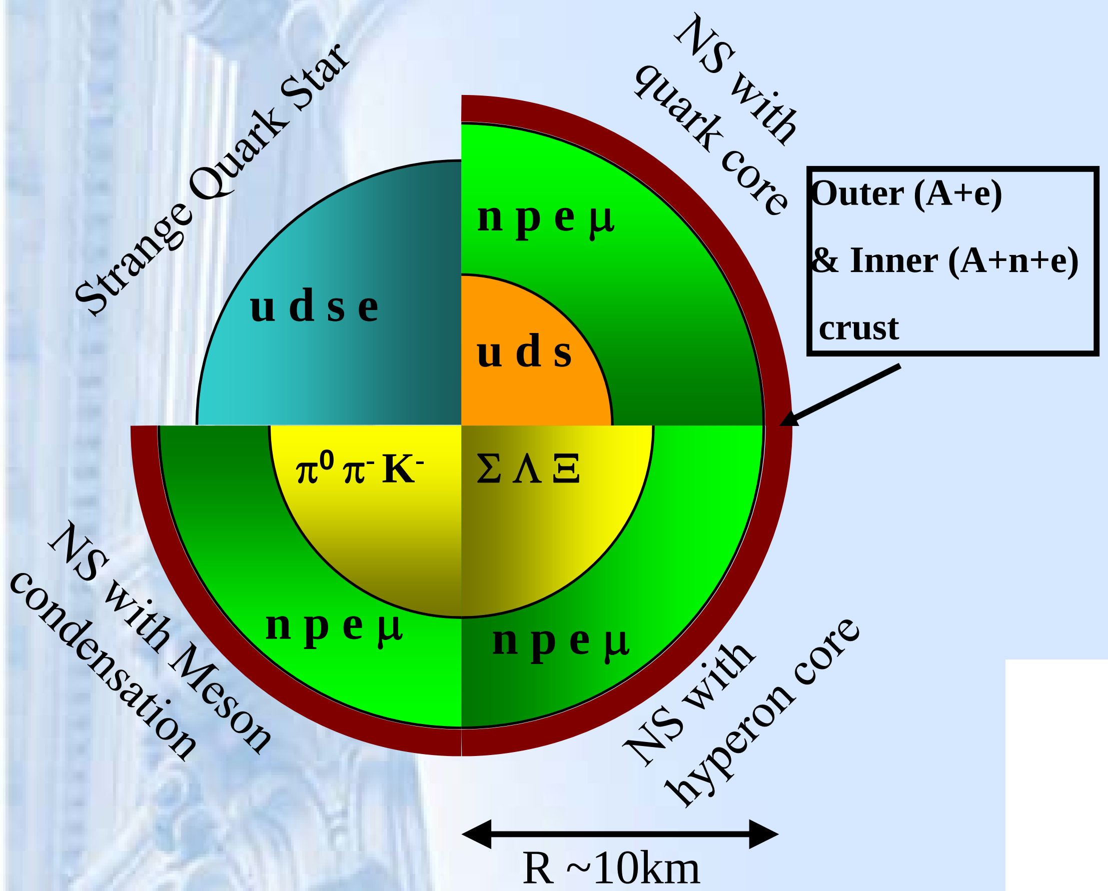
E_{sym}

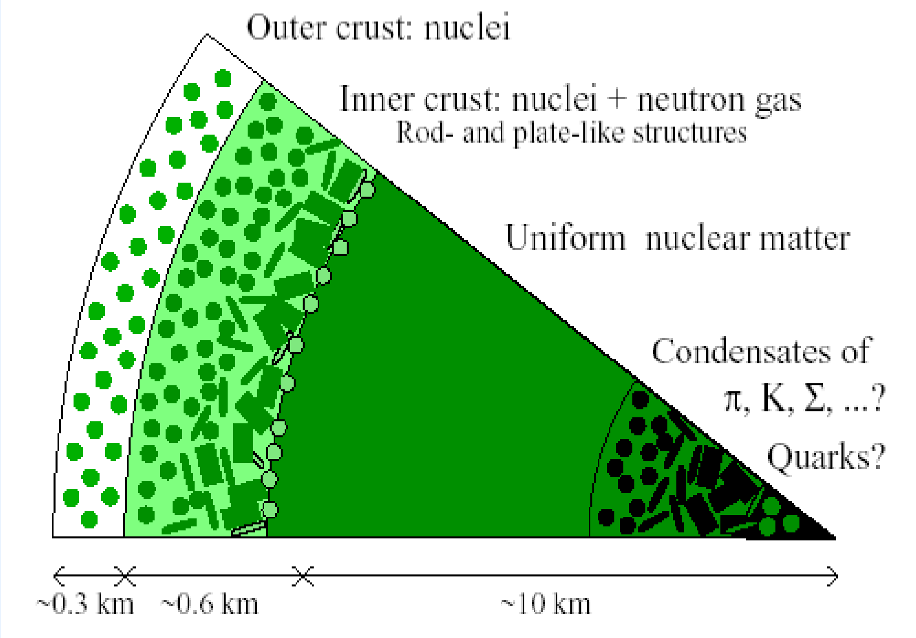


T. Klaehn et al., Phys. Rev. C 74, 035802 (2006)

- Consistence Maintained at ρ_0
- Sensitive on κ & γ.

Neutron Star

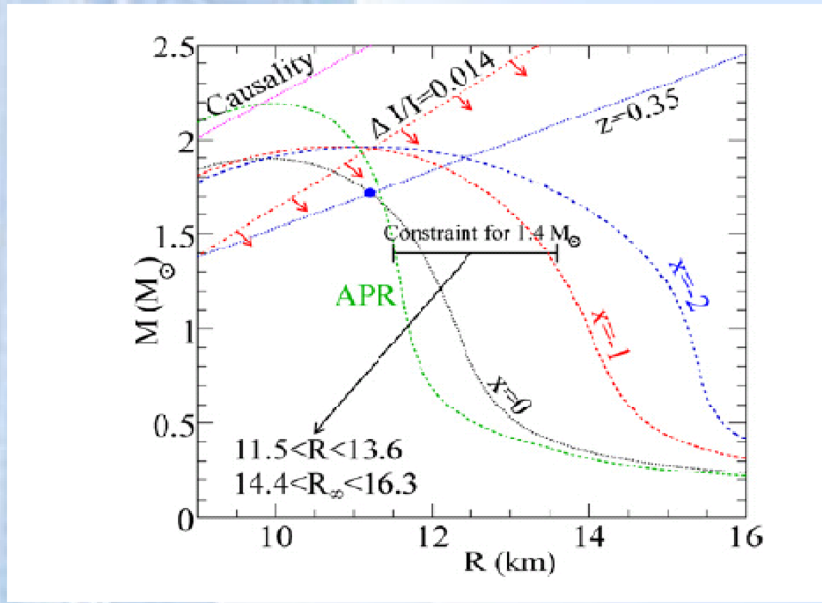


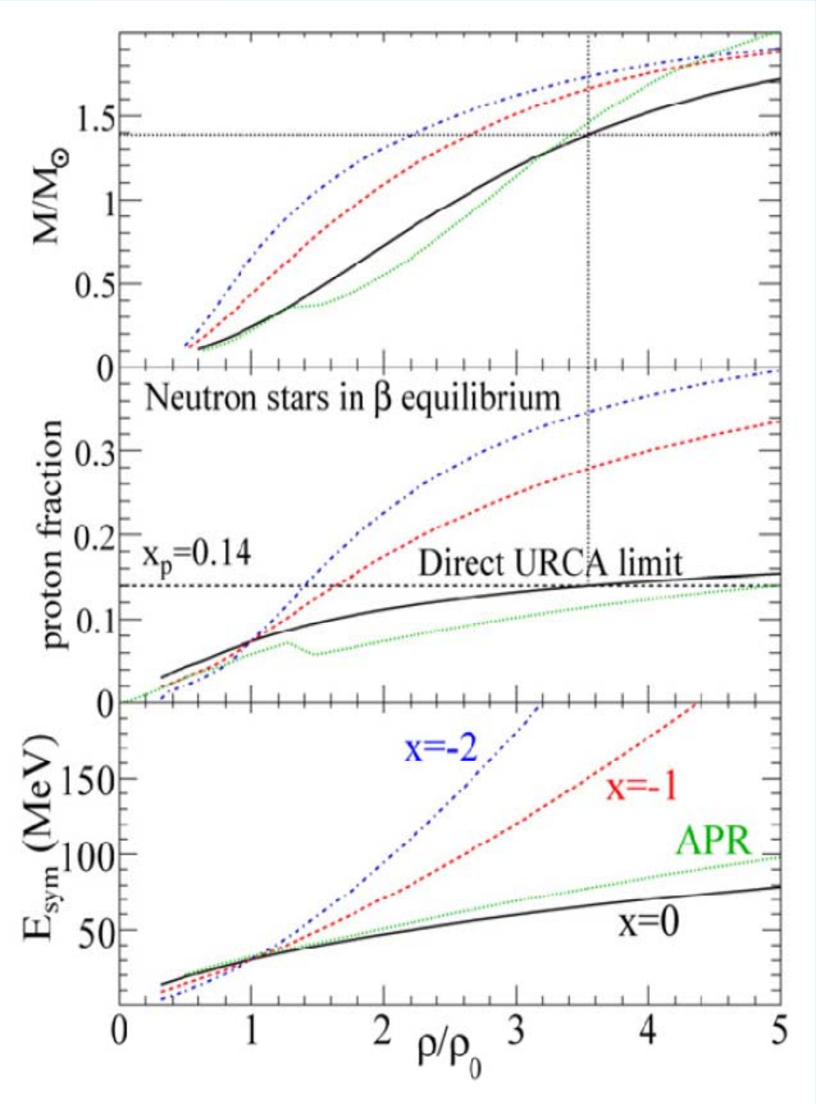


$E_{sym}(\rho)$ controls NS structural properties

- 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

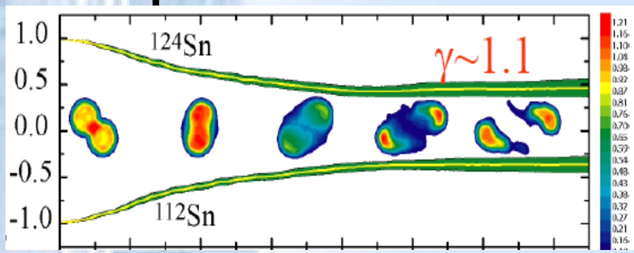




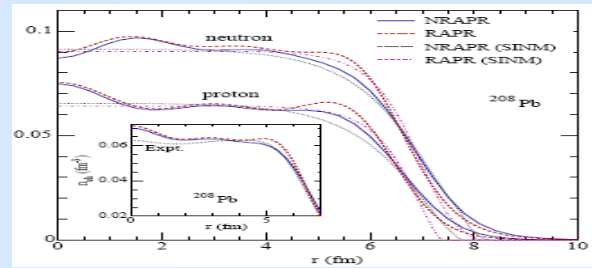
B. A. Li et al., PLB 642, 436 (2006)

Probes to $E_{sym}(\rho)$ I: low density

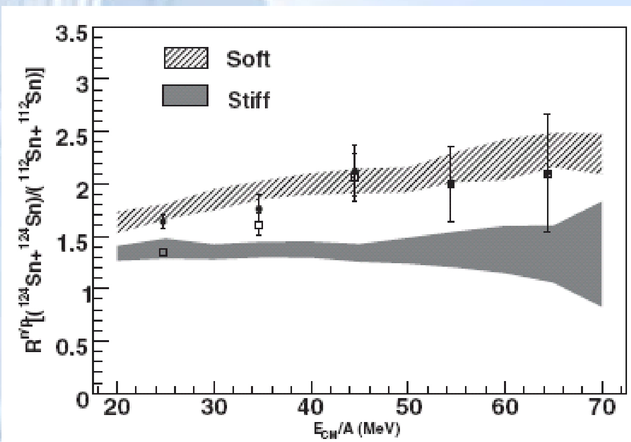
Isospin diffusion



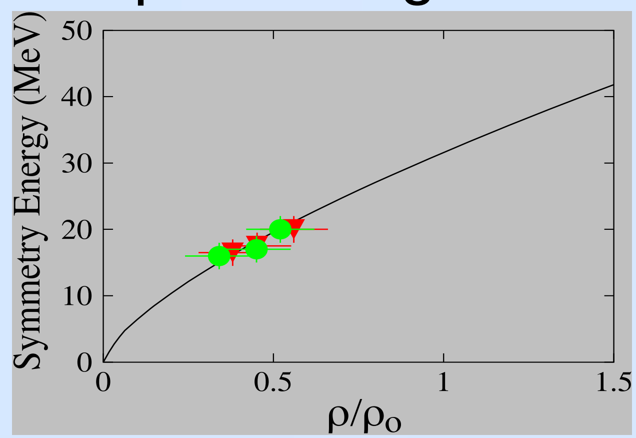
Neutron Skin in ^{208}Pb



Fast nucleon emission



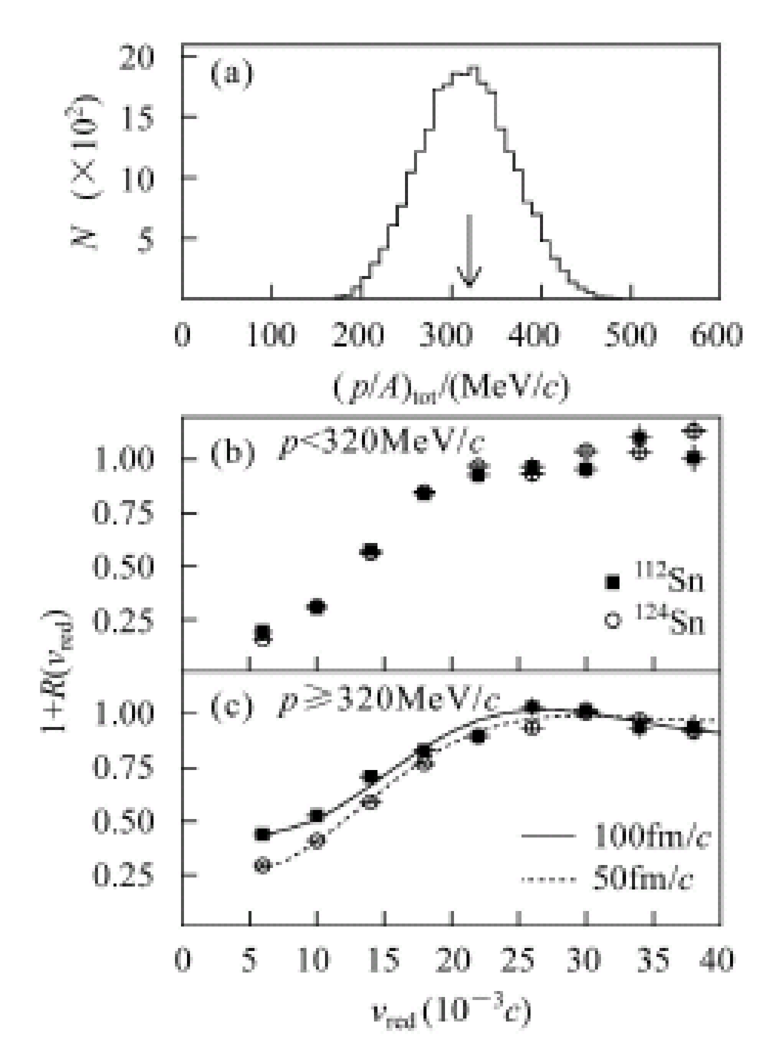
Isospin scaling

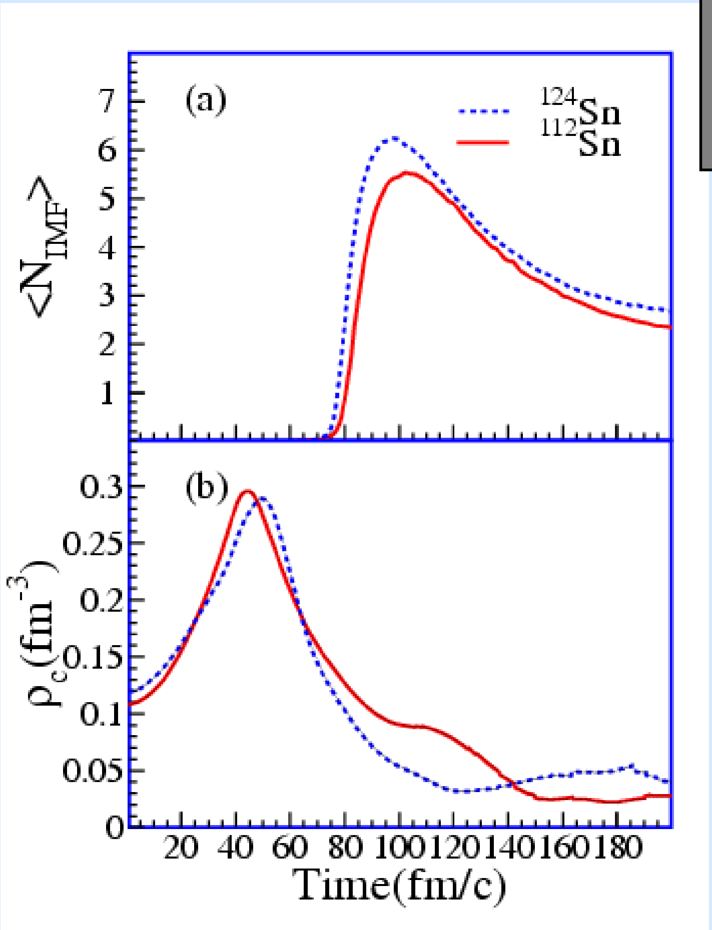


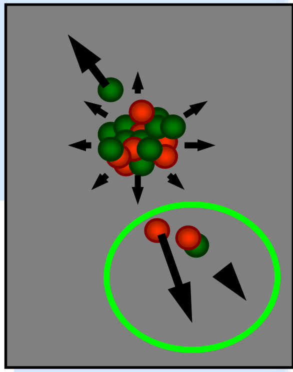
Asy-soft at normal or sub-normal density.

$$E_{sym}(\rho) = 31.6\left(\frac{\rho}{\rho_0}\right)^{0.69\sim1.05}$$

Probe 5： IMF correlation function





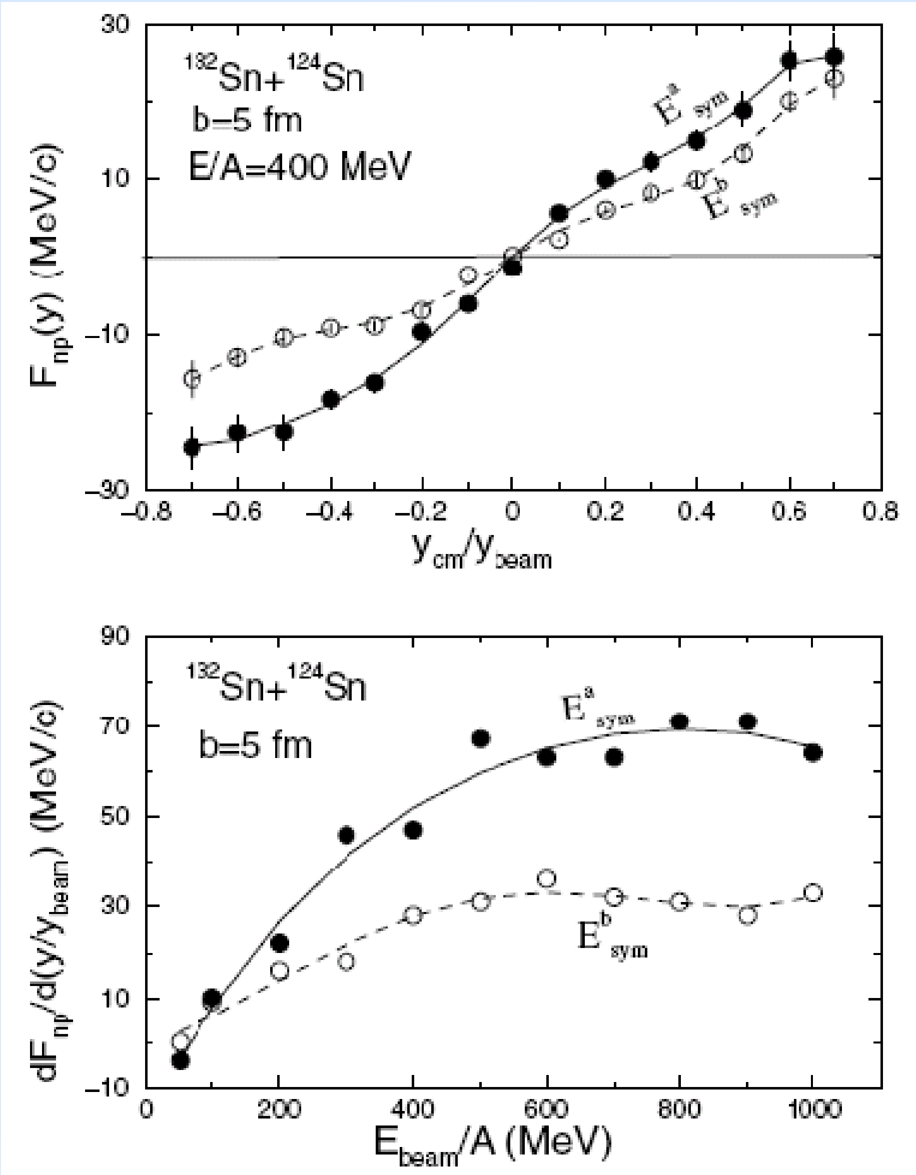


- Waiting for transport studies Z. G. Xiao, R. J. Hu et al., PLB 639 (2006) 436

Probes to $E_{sym}(\rho)$ II: high density

Probe 1:

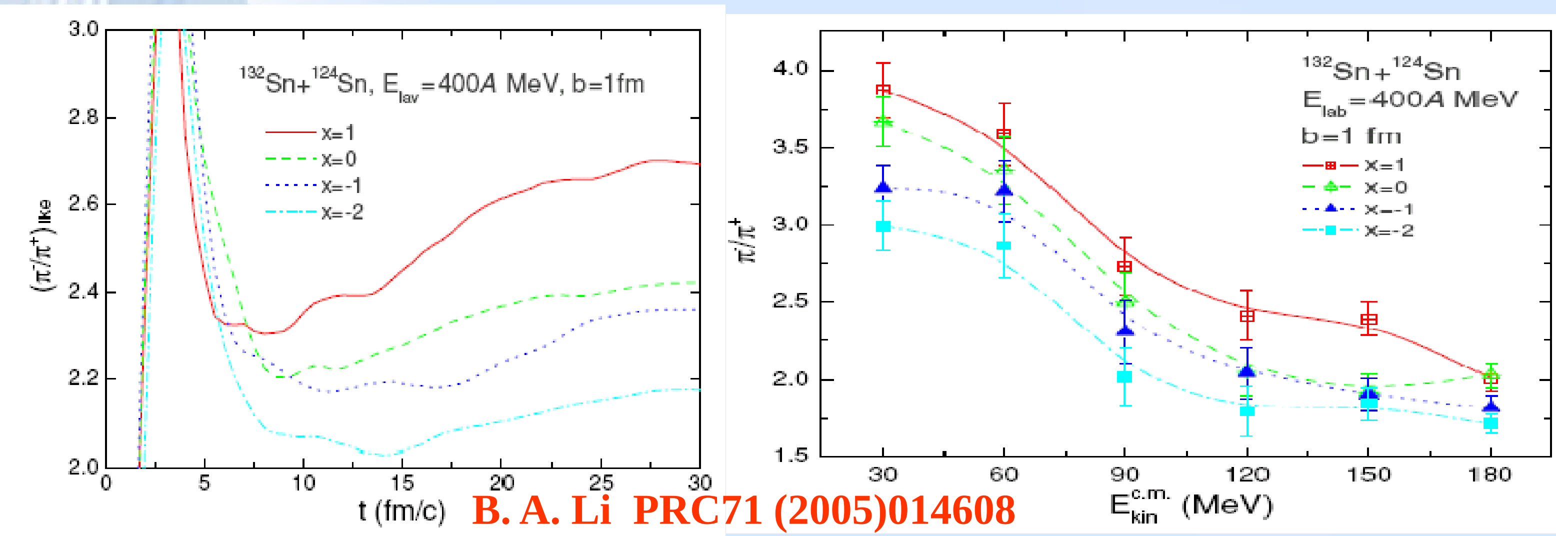
n/p differential flow



B. A. Li et al., PRL88 (2002) 192701

Probes to $E_{sym}(\rho)$ II: high density

Probe 2: π^-/π^+ ratio



B. A. Li PRC71 (2005)014608

- Introduction
- **What do we learn from FOPI at SIS?**
  - **New progress on the charged particles**
  - **New progress on π emission and $E_{sym}(\rho)$ related**
- What do we expect at CSR-ETE?
- Summary

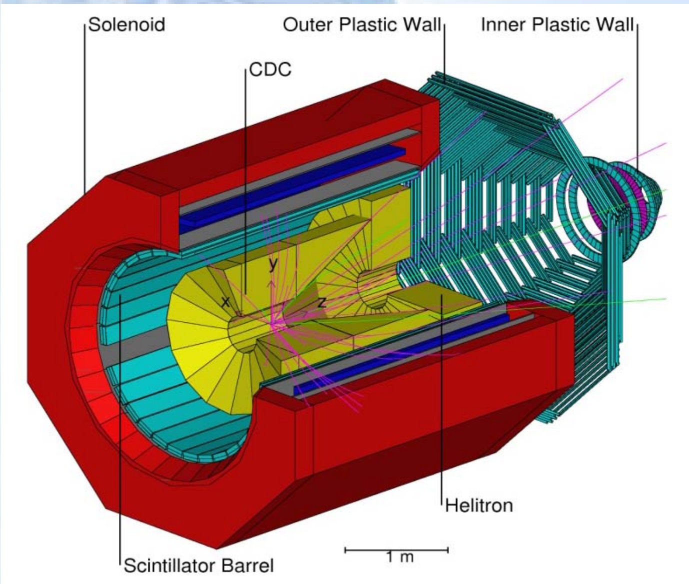
Stopping ↔ Transverse/Longitudinal symmetry

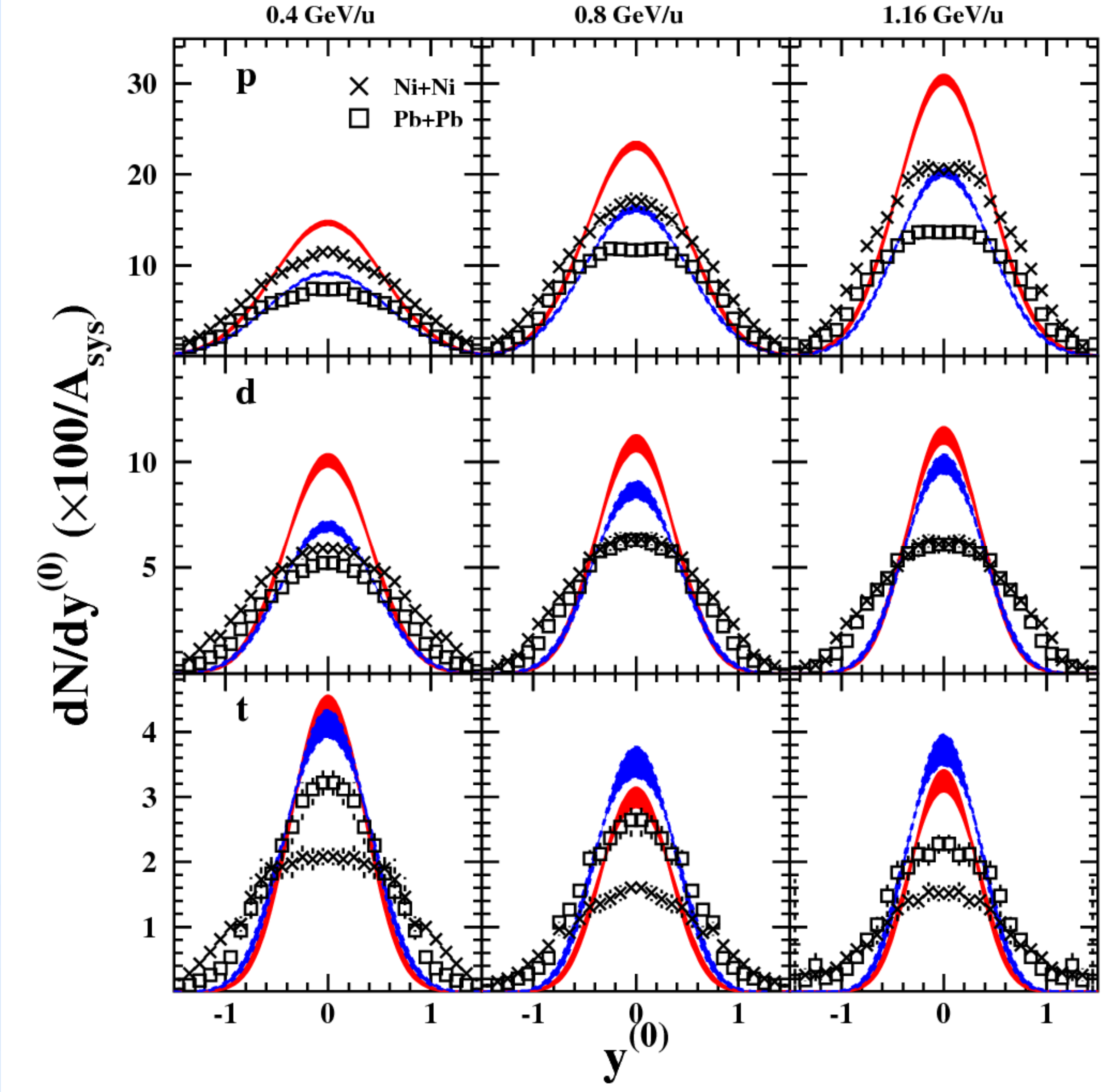
× Ni+Ni

◘ Pb+Pb

E_b=0.4,0.8 and 1.2 GeV/u

- Normalized to same system size





FOPI collaboration et al., In progress

- Stopping hierarchy:

Higher E_{beam}

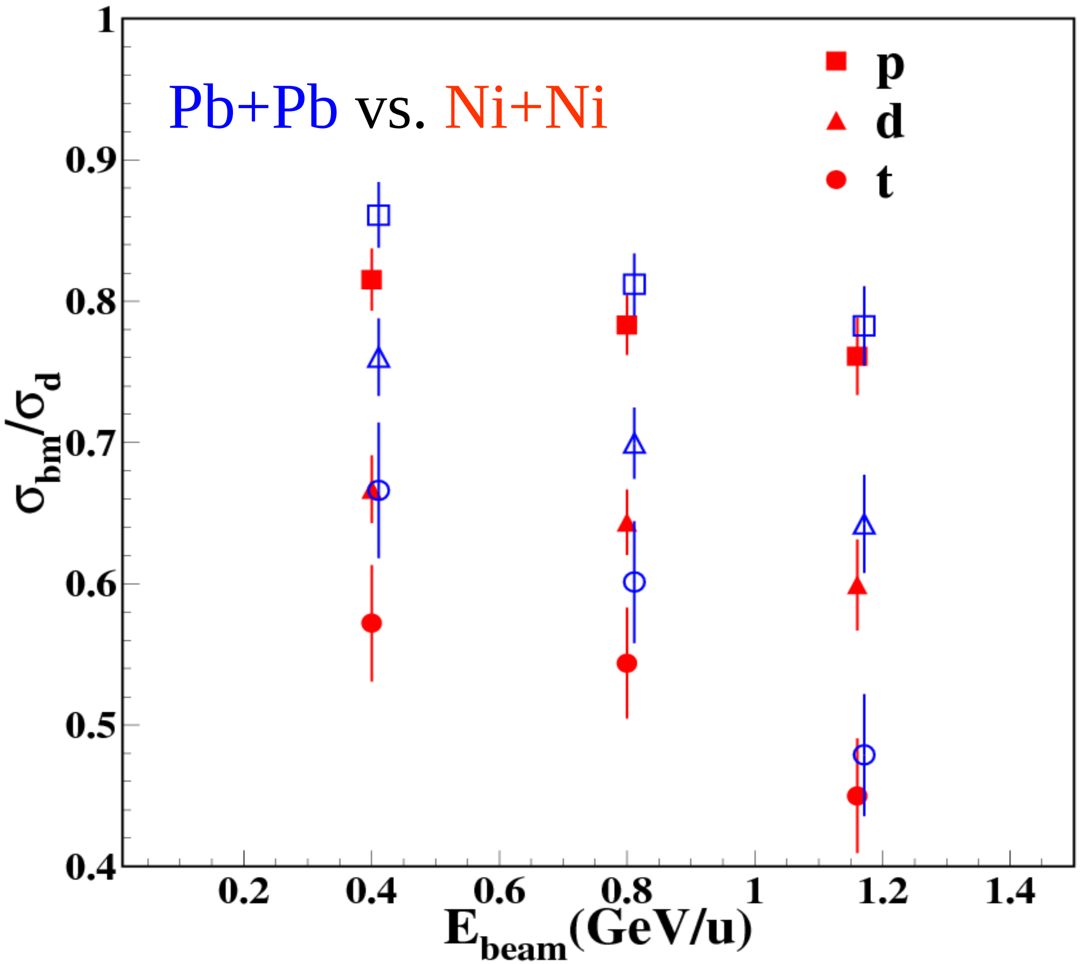
→less stopping;

Lighter system

→less stopping;

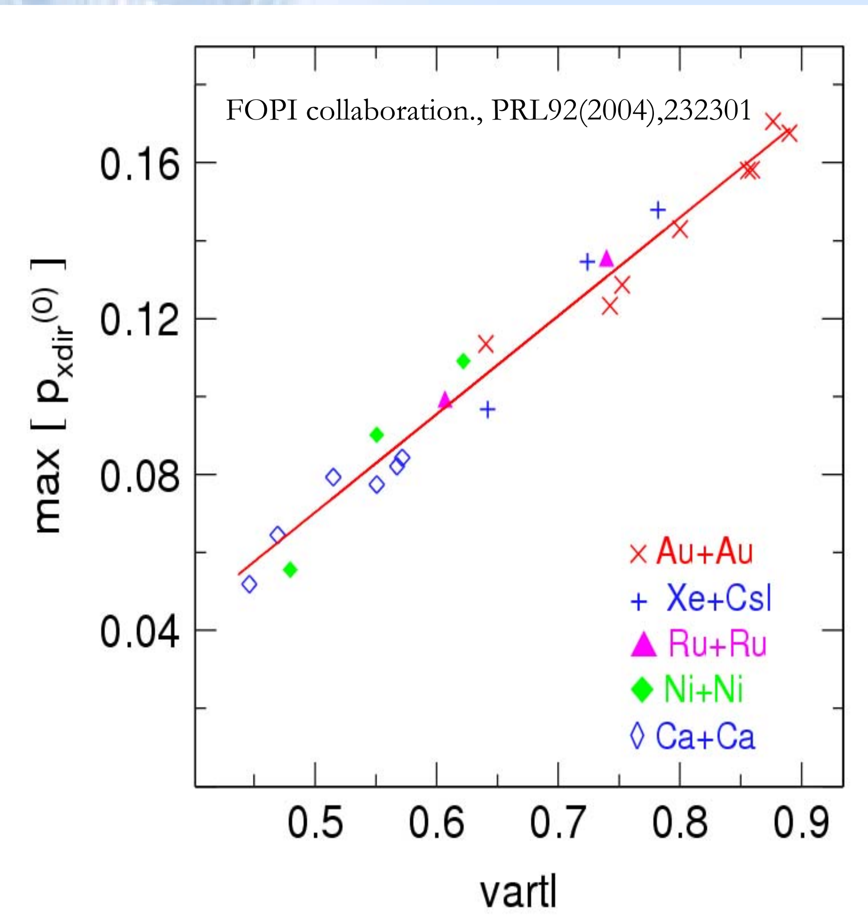
Heavier mass

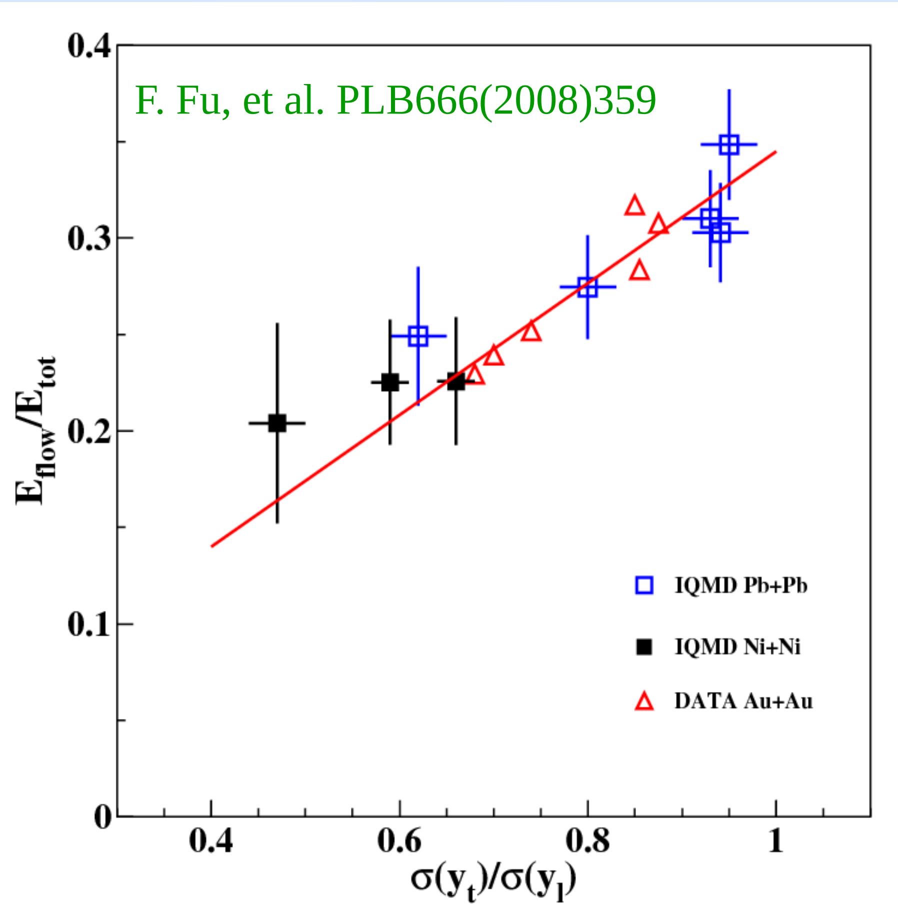
→less stopping;



FOPI collaboration et al., In progress

Stopping *vs.* compression/pressure





More Stopping

More Compressed

Larger signal

More sensitive on EOS

Stopping vs Density gain

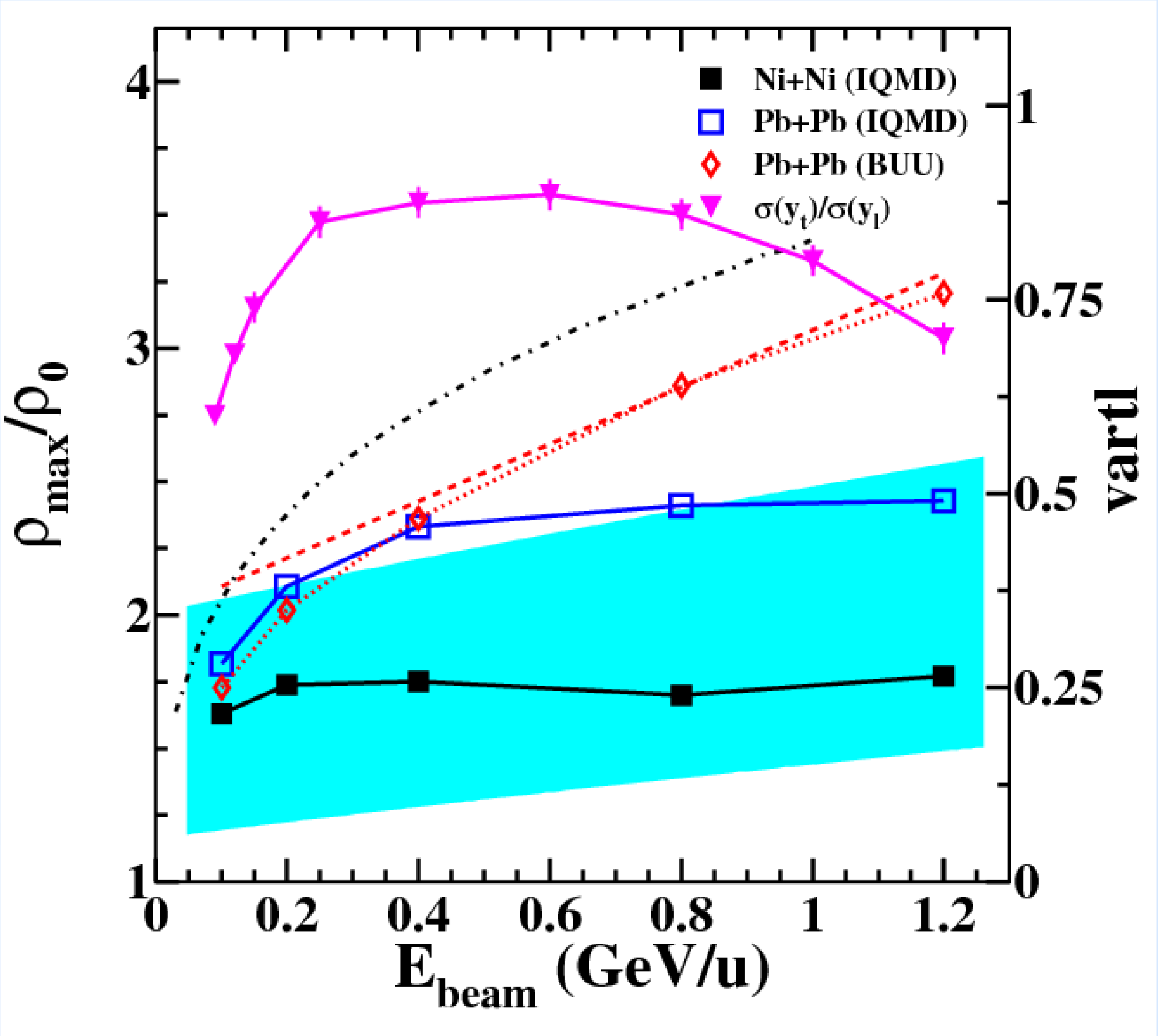
- Less Stopping

↕

- Less compression

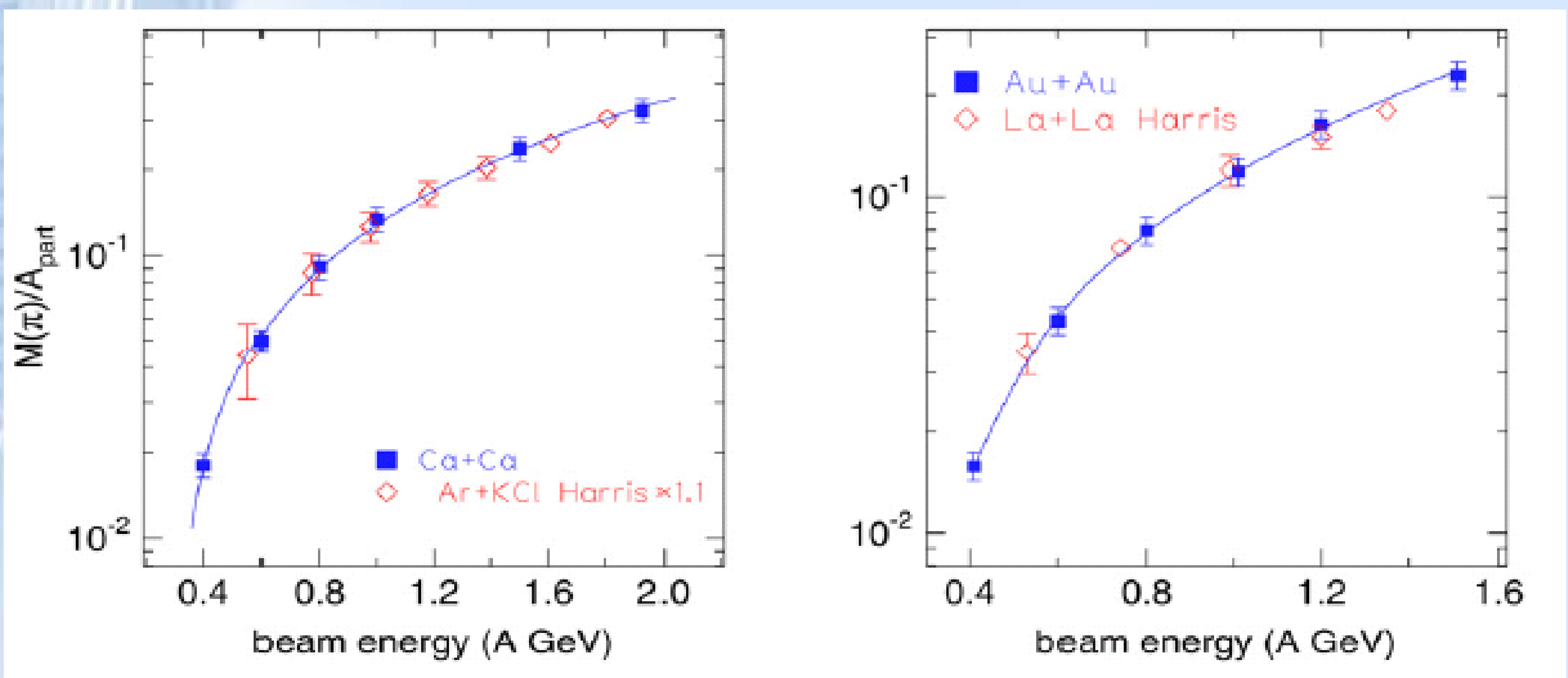
↕

- Lower gain
  for baryon density



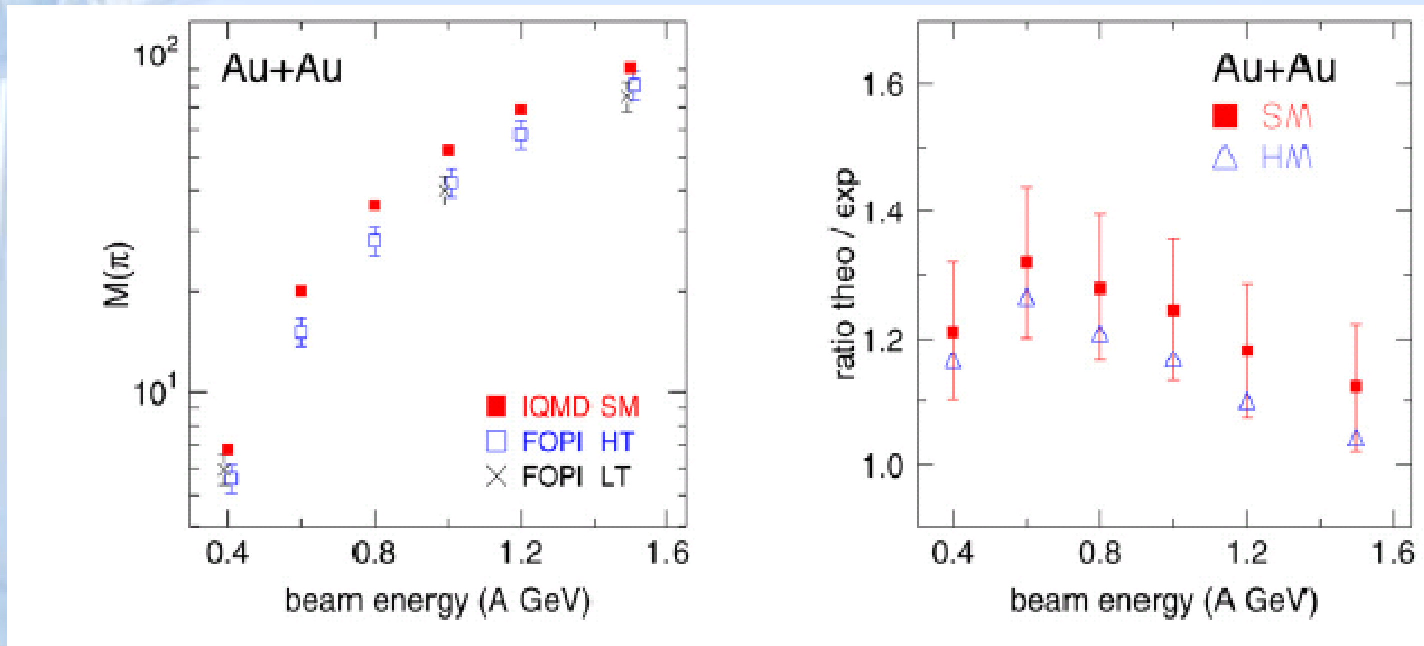
F. Fu, Z. G. Xiao et al., PLB666(2008)359

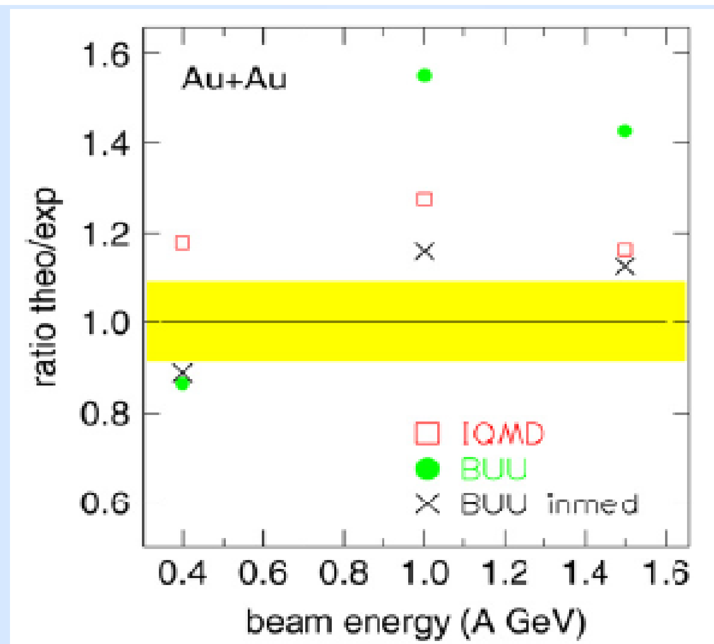
Complete set of π multiplicity



W. Reisdorf et al. for FOPI collaboration NPA 781(2007) 459

Discrepancy between transport and data





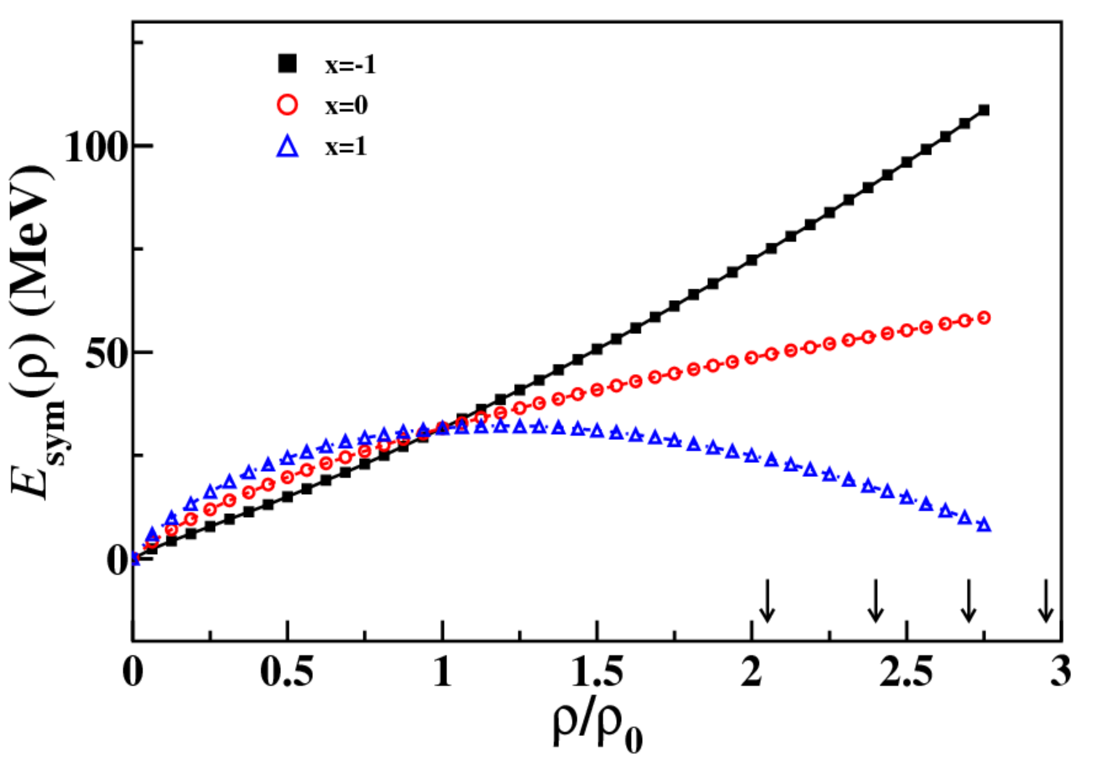
W. Reisdorf et al. for FOPI collaboration

NPA 781(2007) 459

Asymmetric energy at high density: *little known*

$$U(\rho,\delta,\mathbf{p},\tau) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma (1 - x\delta^2) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} + \frac{2C_{\tau,\tau}}{\rho_0}\int d^3\mathbf{p}'\frac{f_\tau(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3\mathbf{p}'\frac{f_{\tau'}(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2}. \quad (1)$$

C. B. Das, S. Das Gupta, C. Gale, B. A. Li PRC67(2003) 034611



IBUU04:

B. A. Li Phys. Rev. Lett. **88**, 192701 (2002)

L. W. Chen et al., PRC 76, 054316

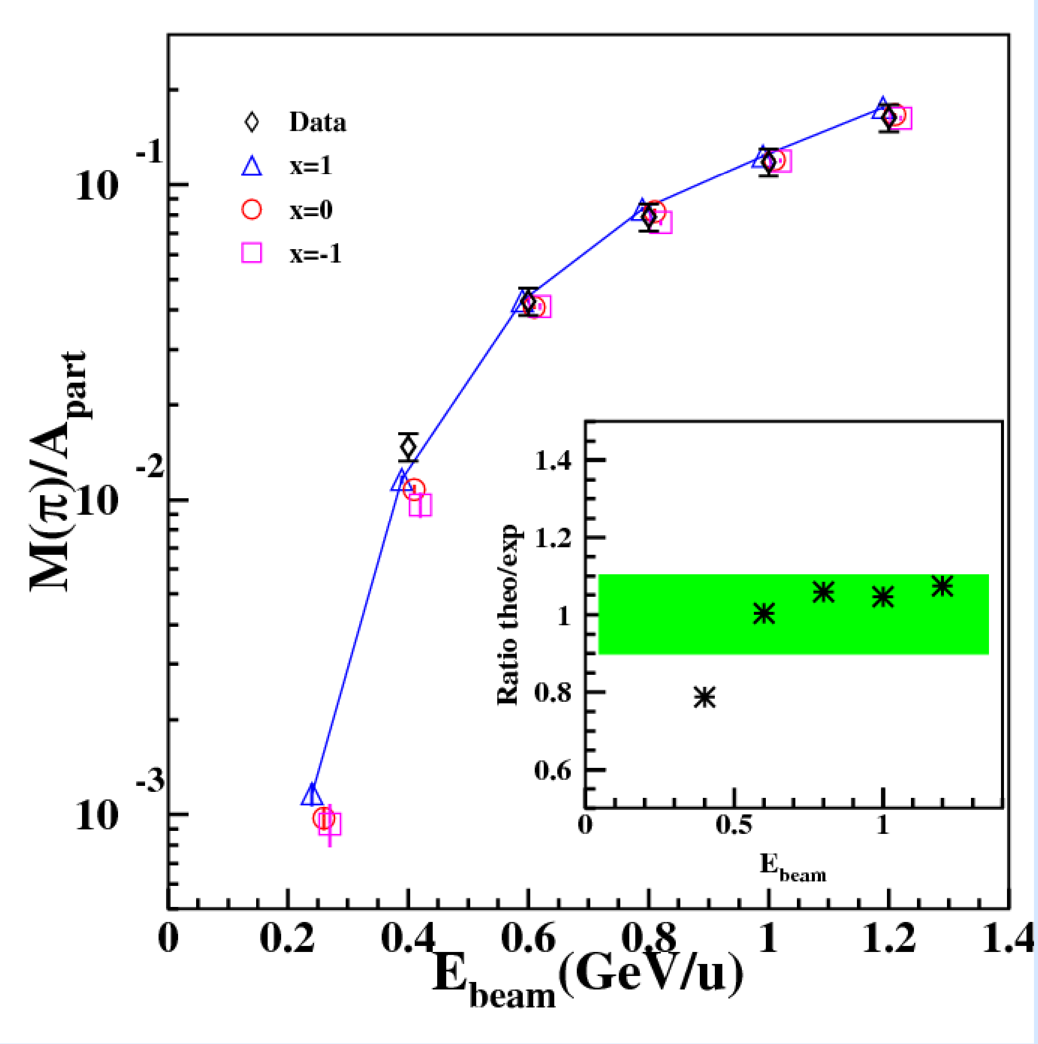
G.C.Yong et al., PRC**73**(2006)034603

B.-A. Li, PRC **69** (2004) 064602

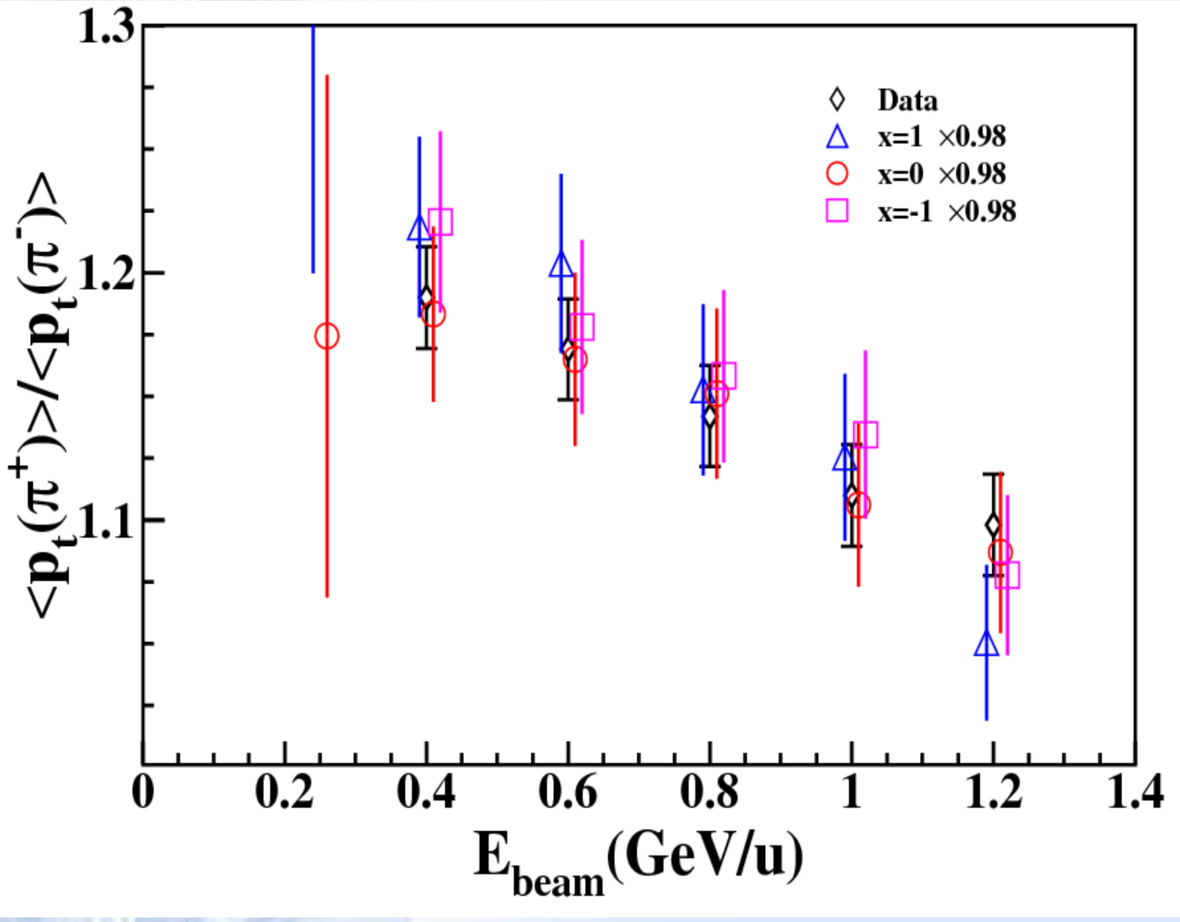
Revisit π and its relevance of $E_{sym}(\rho)$

Multiplicity

Multiplicity reproduced by the model, But shows insignificant sensitivity on the $E_{sym}(\rho)$.

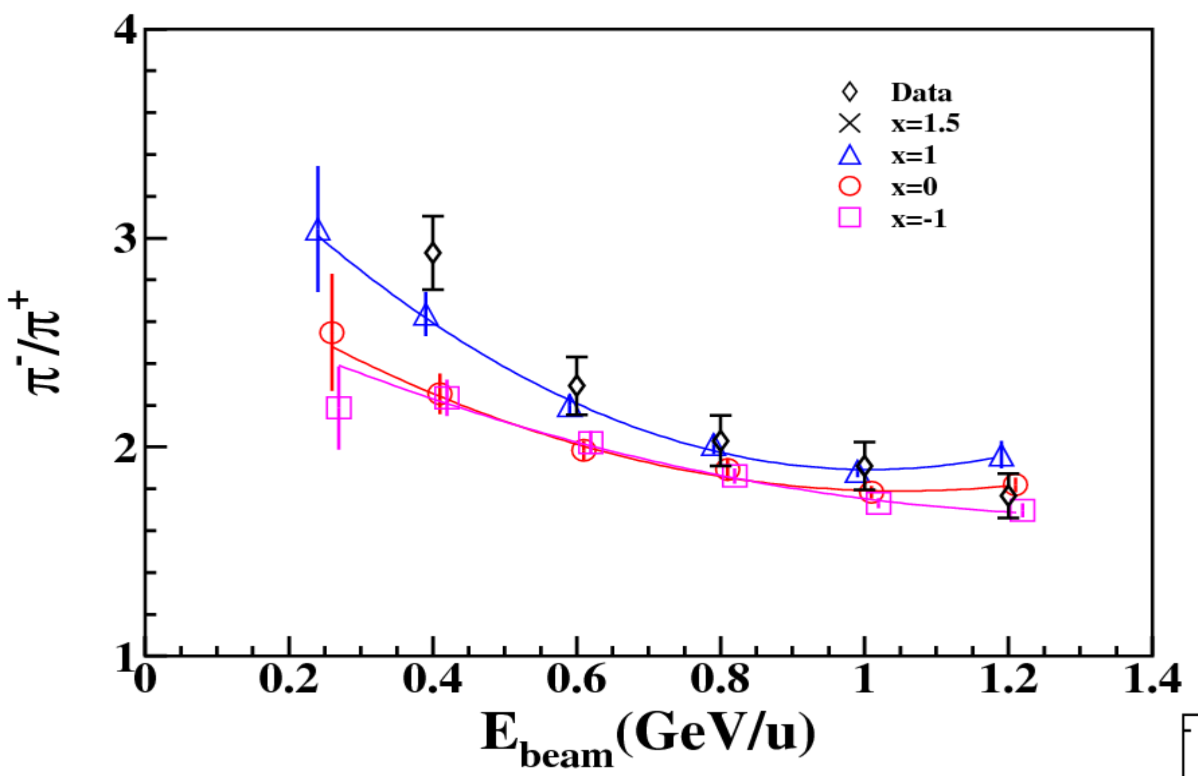


$<p_t(\pi^+)>/<p_t(\pi^-)>$ vs E_{beam}



Not likely distinguishable!

$R(\pi^-/\pi^+)$ vs E_{beam}

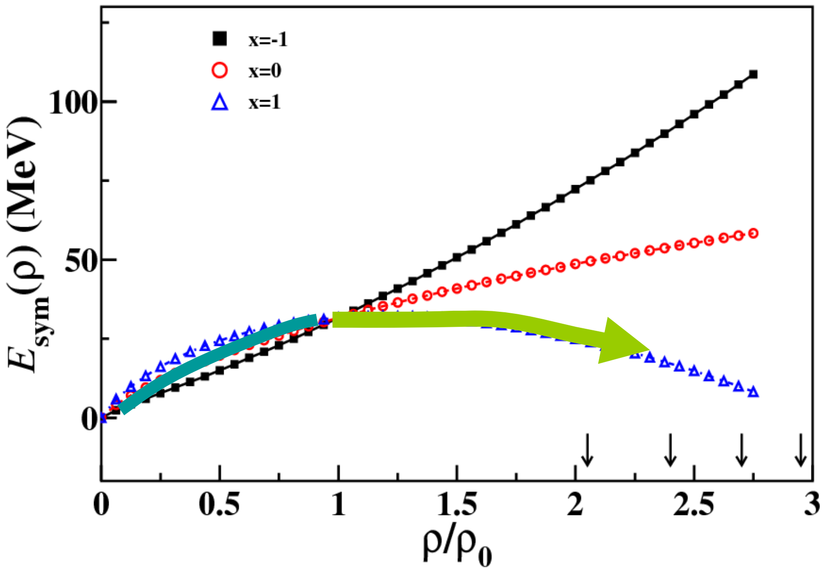


E_b>0.6GeV/u:

Undistinguishable

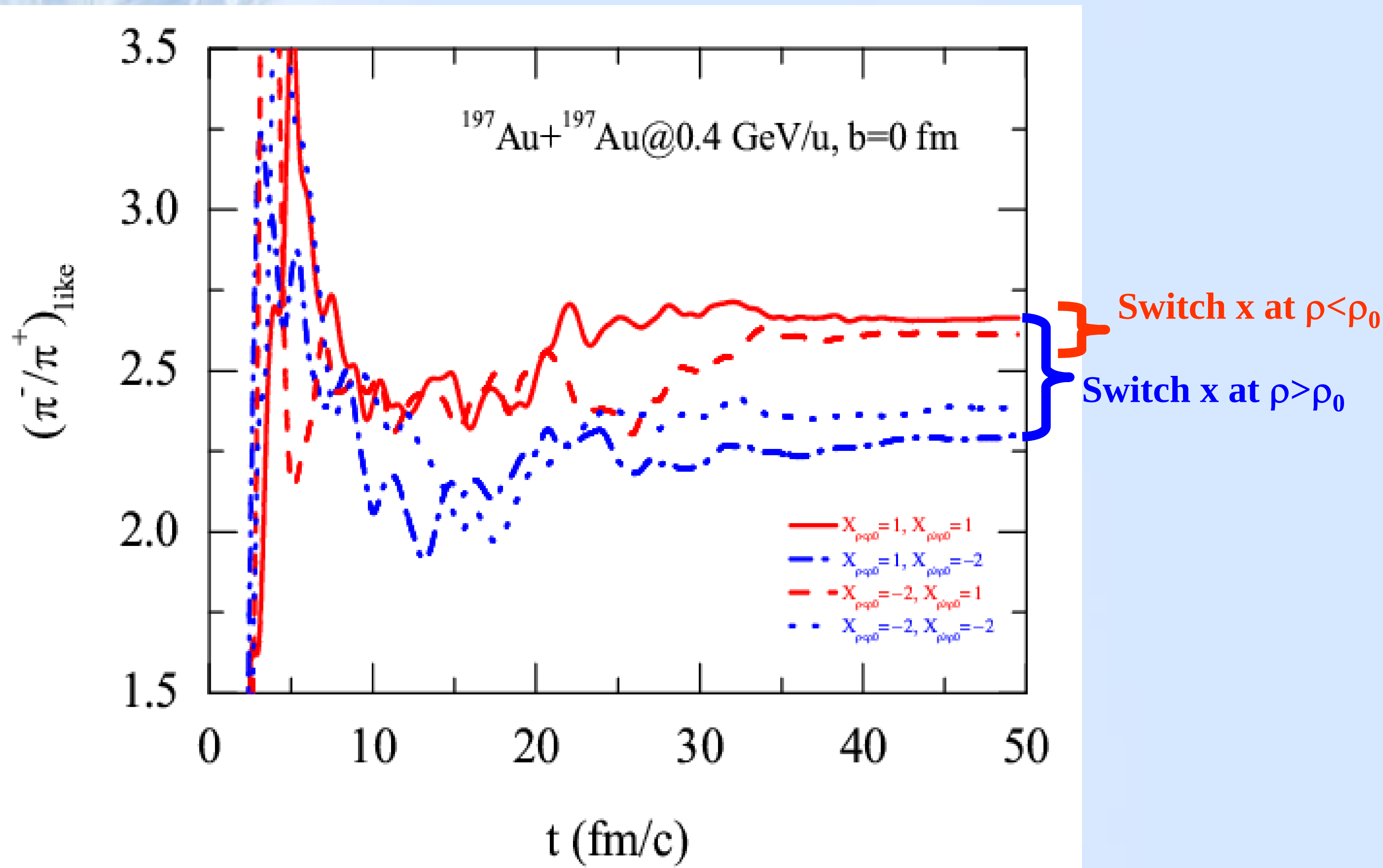
E_b<=0.6GeV/u:

Soft E_{sym} seems to be favored.



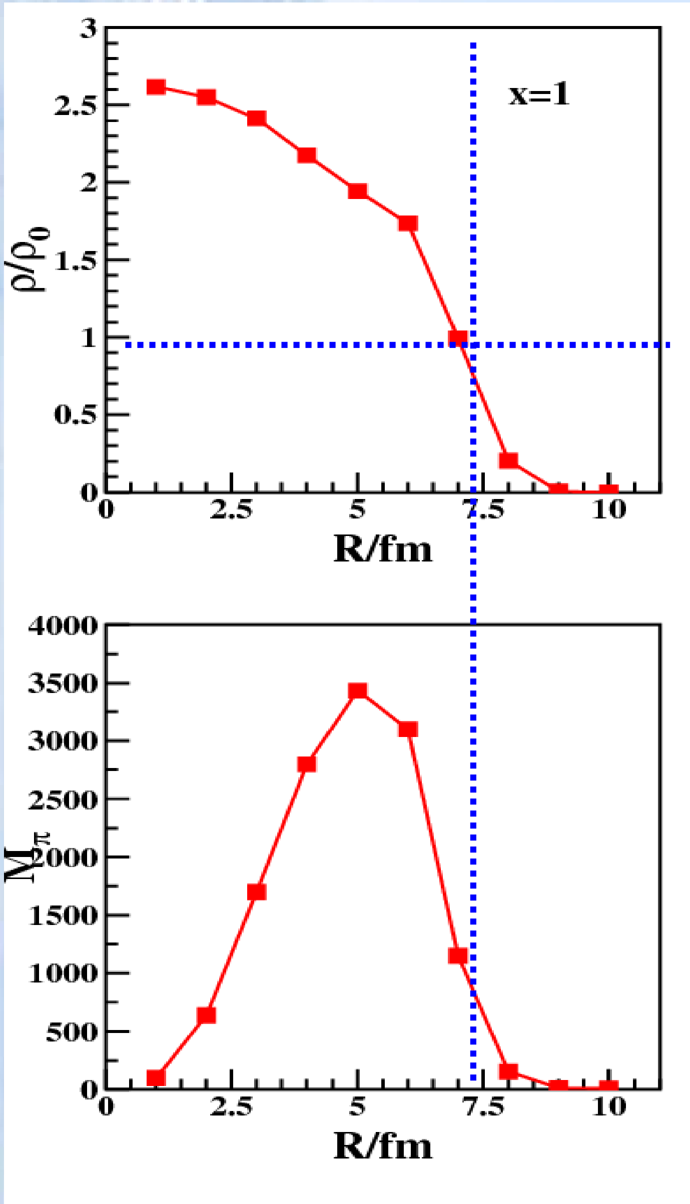
Softening of $E_{sym}(\rho)$ at supra-normal density

High density effect

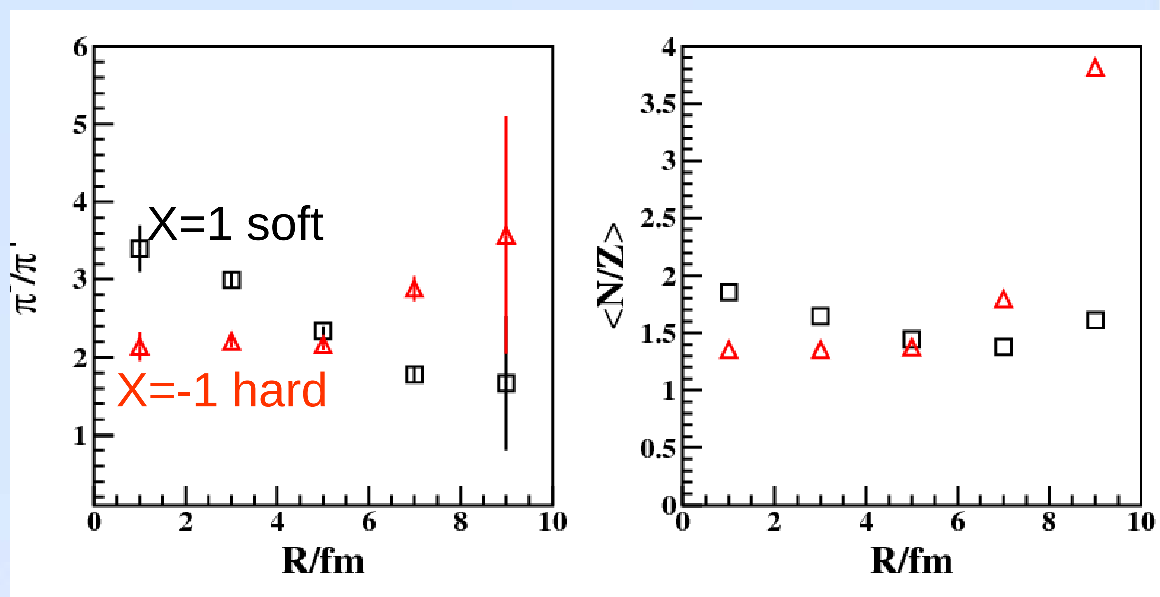


- High density effect is the main contribution

Density profile



High density achieved in the central region, where a larger N/Z asymmetry is experienced with a softer $E_{sym}(\rho)$ is assumed, therefore a higher $R(\pi^-/\pi^+)$ is obtained.

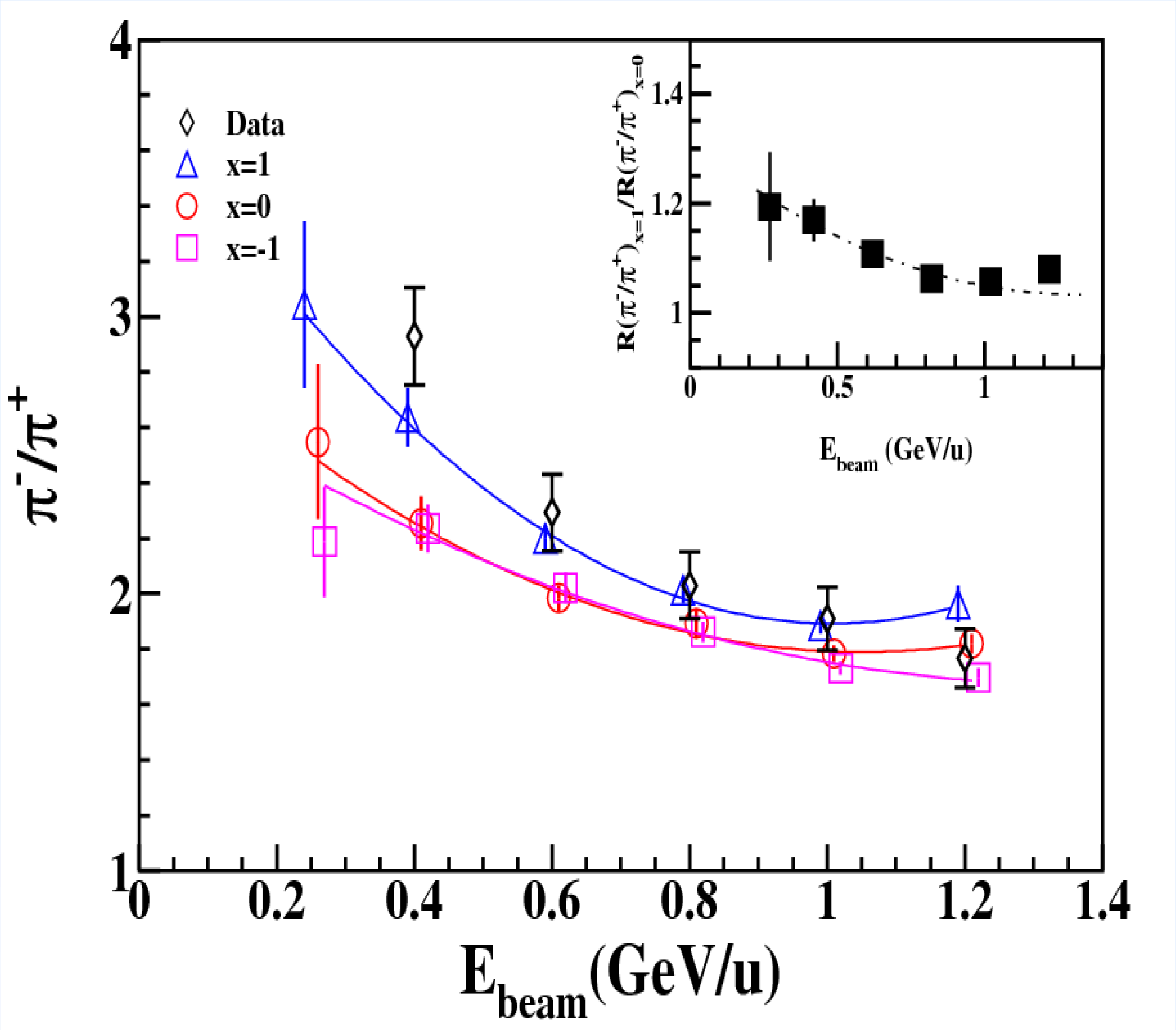


Sensitivity vs E_{beam}

beam energy ↗

stopping ↘

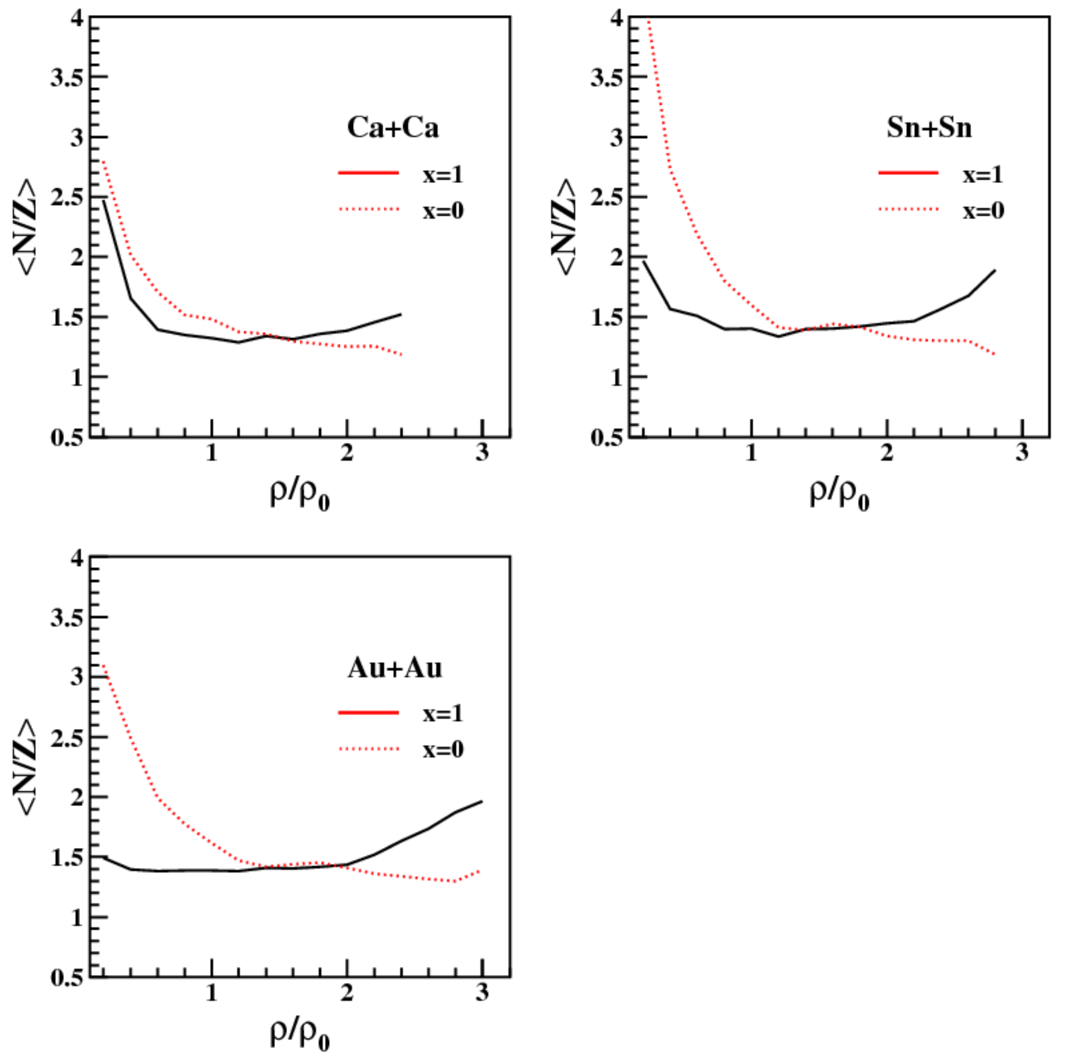
sensitivity ↘



Measurement of pion emissions at CSR energy range (<1GeV for HI) may helps to resolve the $E_{sym}(\rho)$!

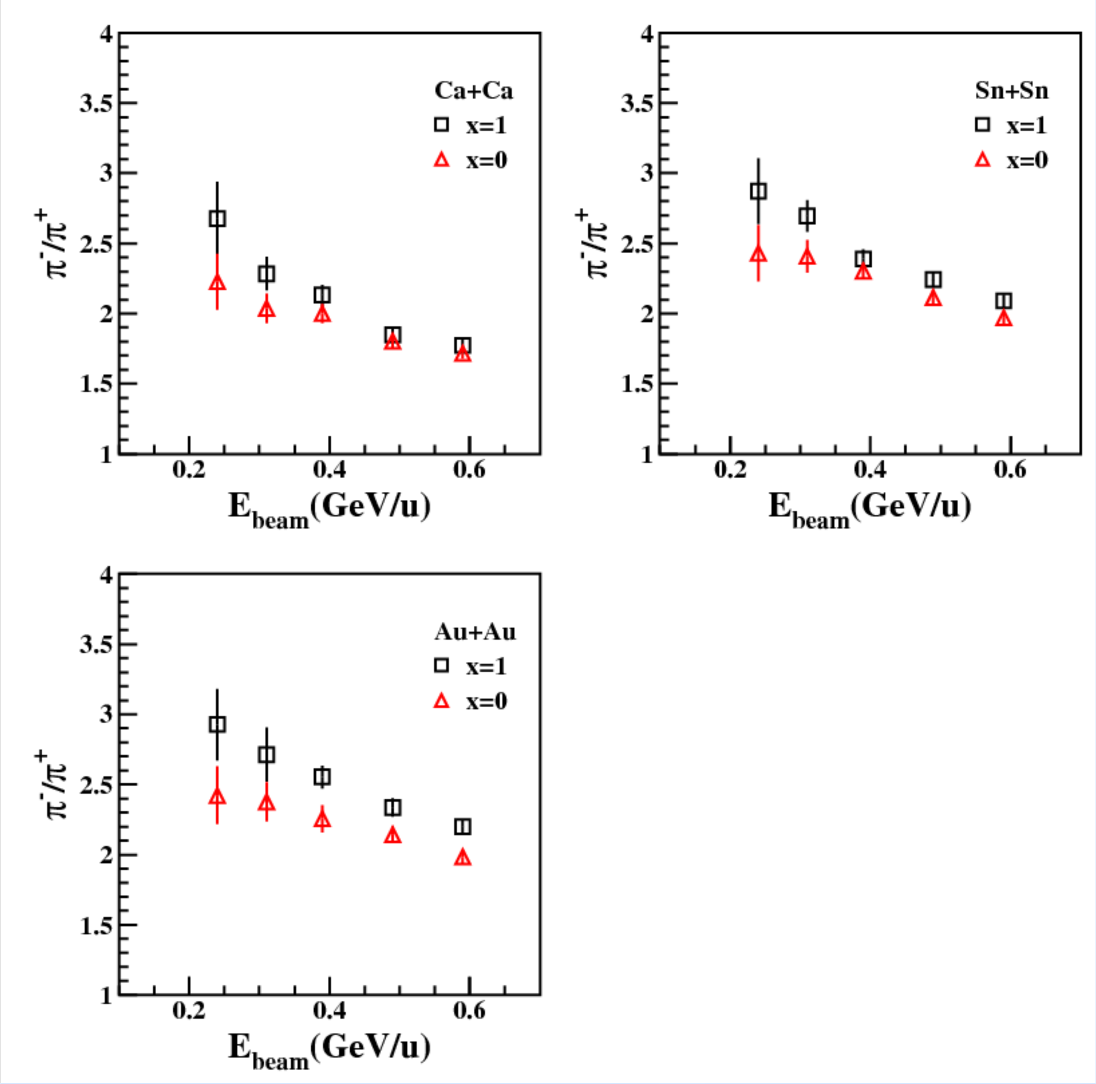
Sensitivity vs System size

Larger colliding system more compressed and the sensitivity on $E_{sym}(\rho)$ increases with system size.



Sensitivity vs System size

And finally an increasing sensitivity of pion probe on $E_{sym}(\rho)$ is evident when passing from Ca+Ca to Au+Au



- Introduction
- What do we learn from FOPI?
- What do we expect at CSR-ETE
  - Advantages & some further projects
  - Experimental considerations
- Summary

☐ Some advantages of pion physics at CSR energy regime

→ Most copious produced, copious information of isospin effect;

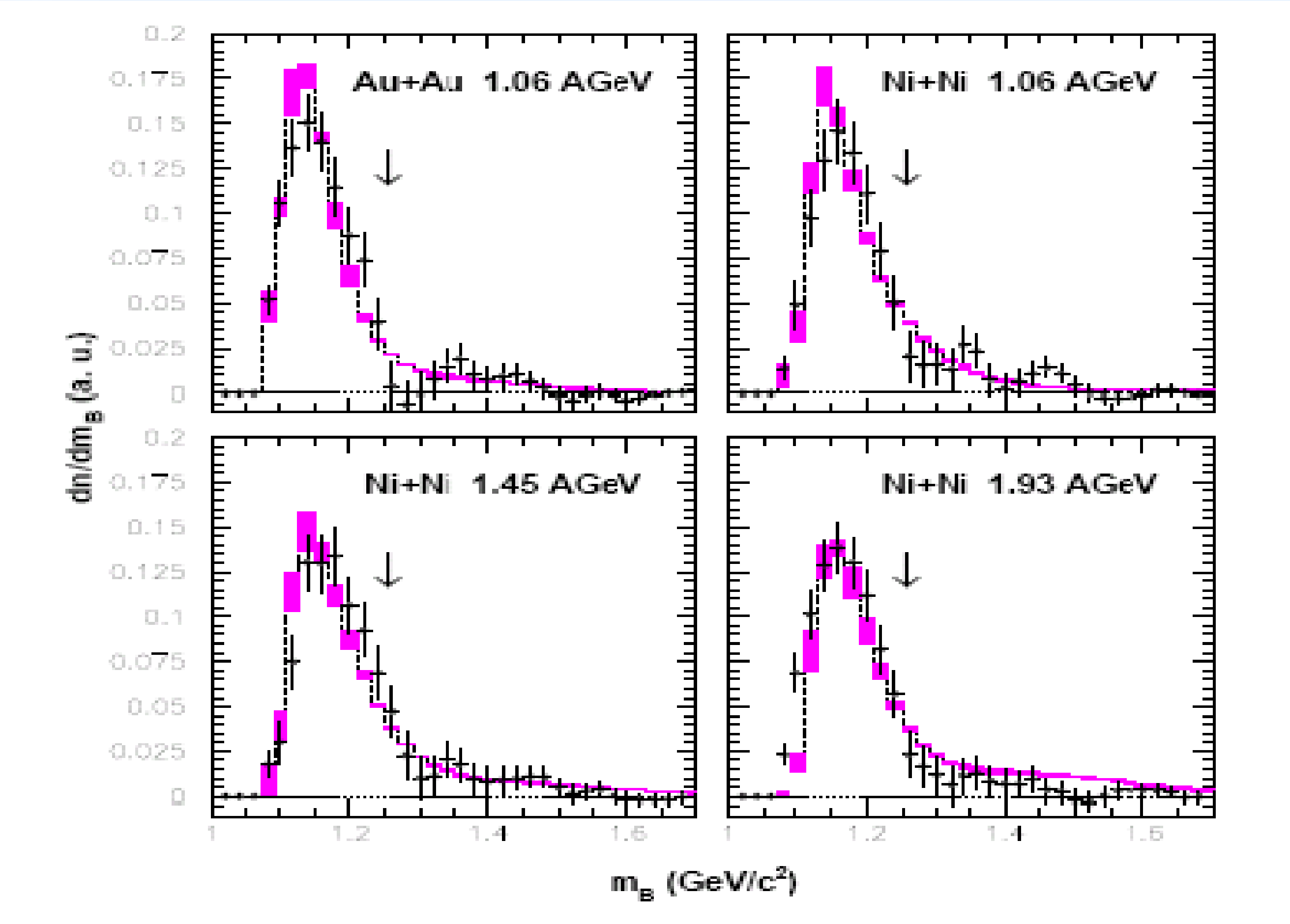
→ Density as high as 2~3ρ_0 , varying rapidly with beam energy;

→ Maximum stopping, maximum sensitivity on the $E_{sym}(\rho)$;

→NOT influenced by the problem of clustering in transport.

→……

What deserves further effort T/E ?

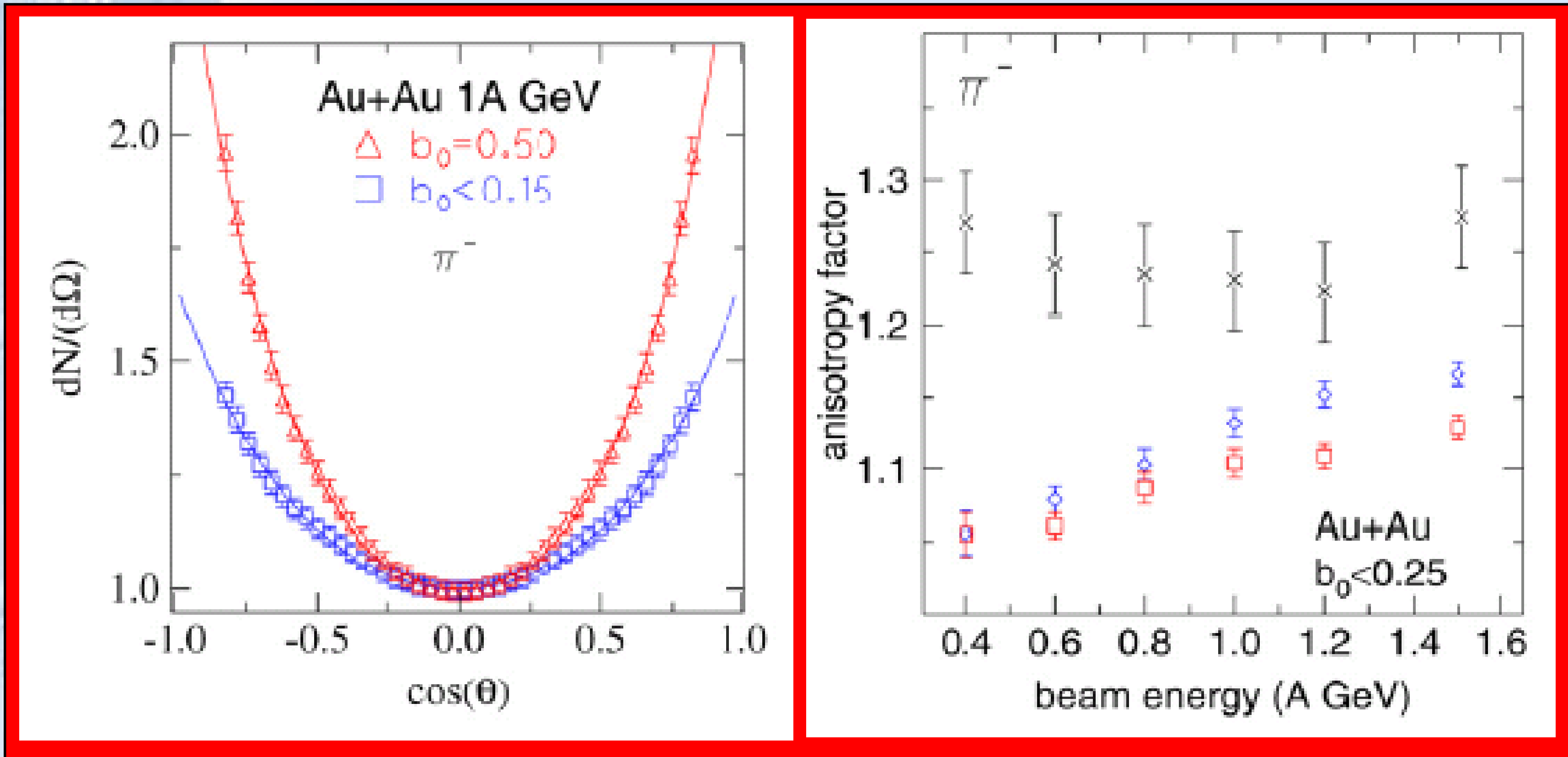


M Eskef et al., ArXiv:Nucl-ex/9809005

Medium effect of Δ properties (formation and decay), which is related to pion emission.

Other dynamics of pion propagation

Anisotropy of pions→ Related to pion absorption in medium

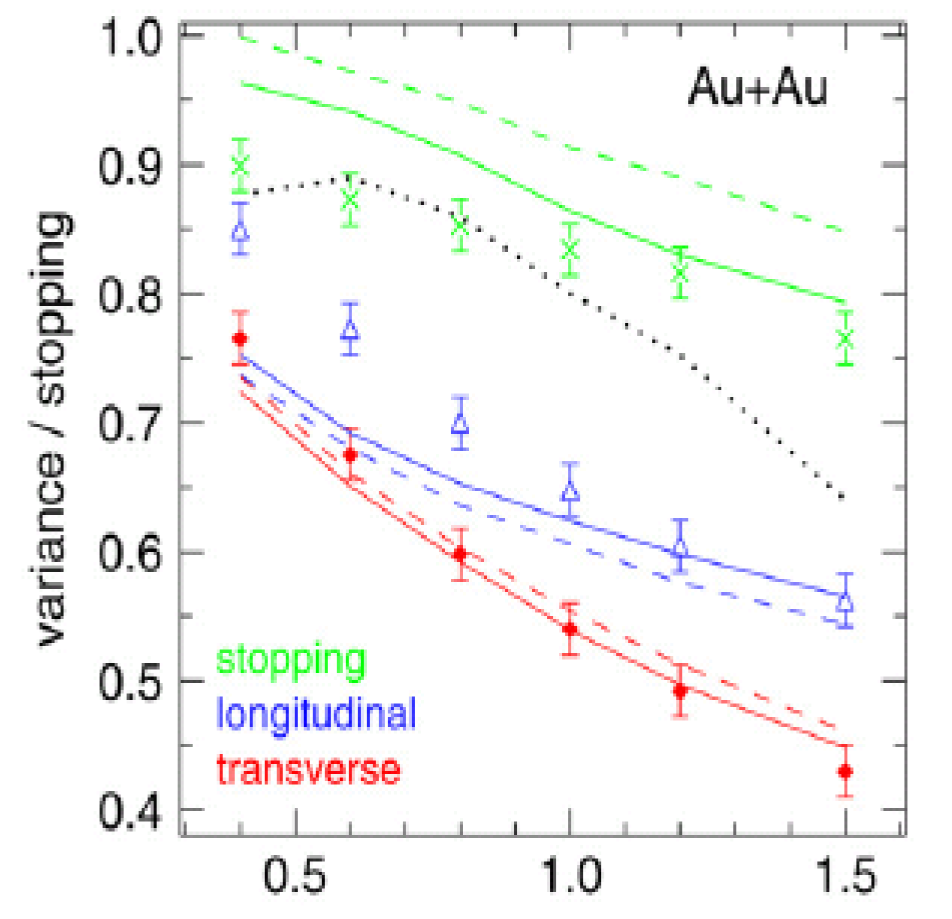


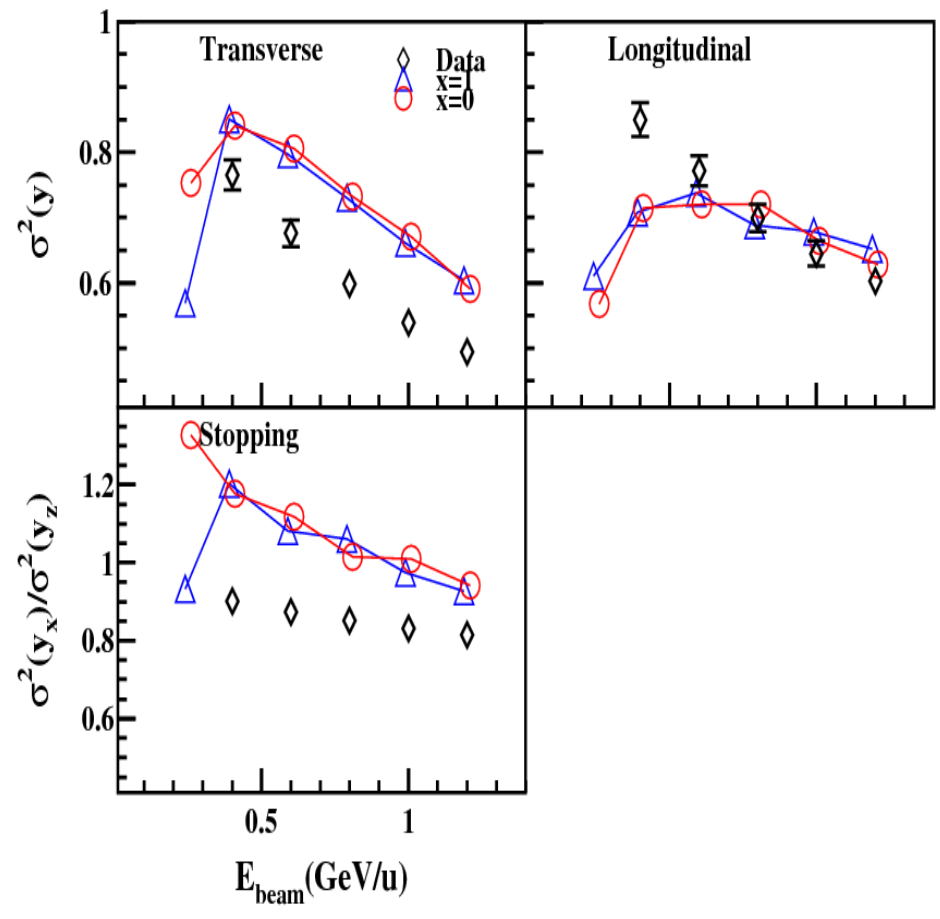
$$f(\cos\theta) = a_0 + a_2 \cos^2\theta + a_4 \cos^4\theta$$

$$A_f = \int_{-1}^{1} f(x)dx / 2a_0$$

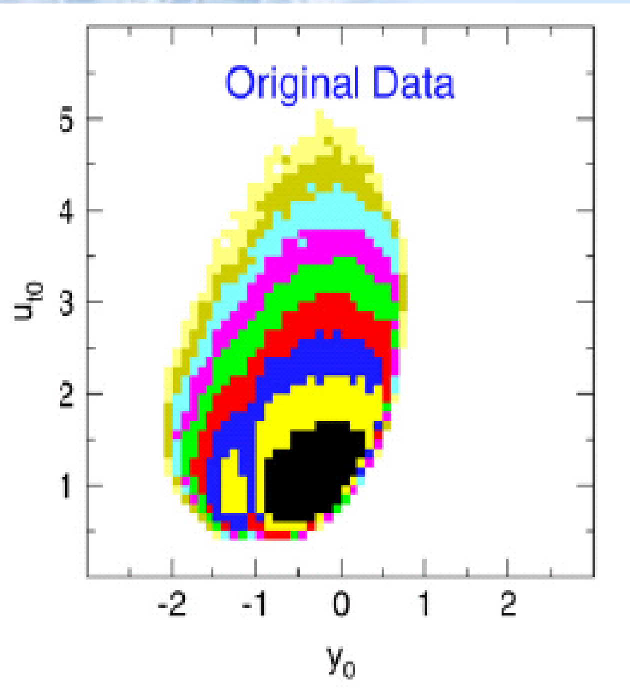
Polar Anisotropy of pions

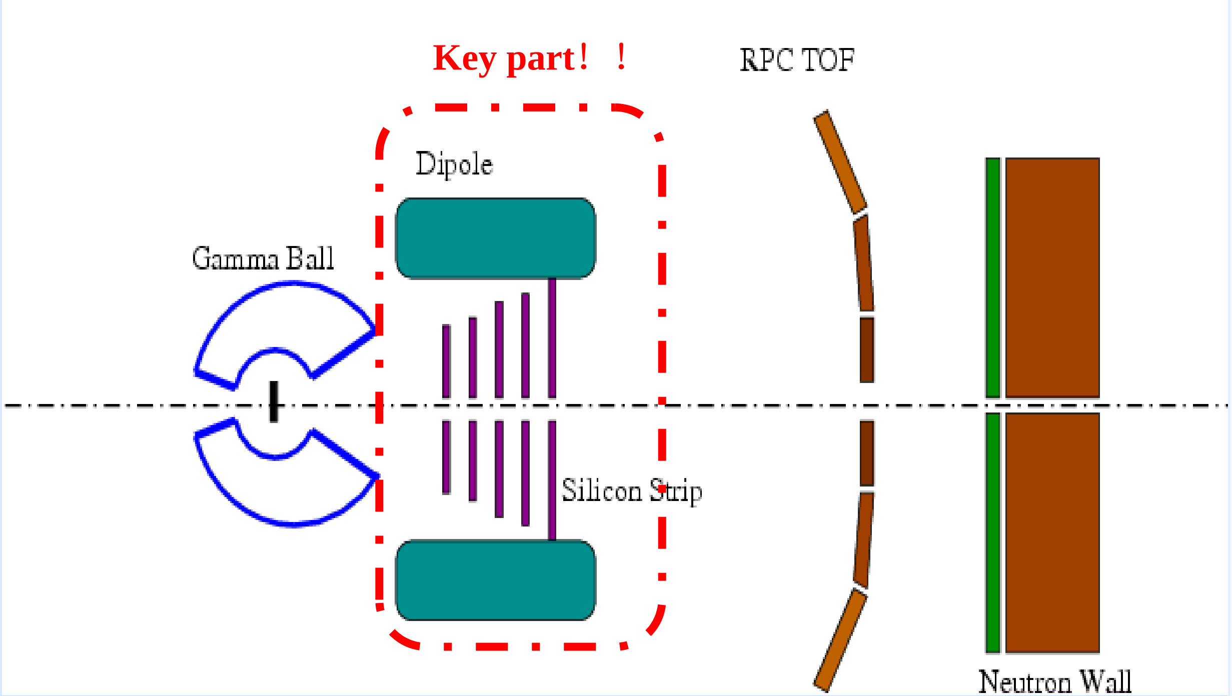
Stopping of pions





External Target Experiment (II)





Feasibility study:

- **How does Sensitivity depend on phase space, system size… ?**
- **Coverage? (low momentum, middle rapidity…)**
- **Detector config. and response are optimized for the physics? How?→ Simulation!**
- **Impact on other physical goals?**

Summary

- **Charged particles at (sub-)GeV/u region enrich physics in clustering and stopping, which carry much information on the collision dynamics, although their constraint on EOS , particularly on $E_{sym}(\rho)$ at high density, is not verified.**

- **The most recent π data set an partial constraint on $E_{sym}(\rho)$, indicating a softening at supra-density region. Further simulation shows that CSR energies (<1GeV/u) are highly favored for this subject as well as many π-related physics with lots of advantages.**

- **However, Many challenges are lying ahead, both theoretically and experimentally. And, many groups have been interested.**

Thank you!