Pion production in mass-asymmetric heavy-ion collisions

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Based on Mr. Sako’s upcoming PhD thesis Work

Today's MENU

- What we want to do under B01 project.
  - SAMURAI with SπRIT
  - Current Status
  - Big(?) Problems
- Pilot Experiment at HIMAC
  - Our Objectives
  - What we learn from mass-asymmetric HI collisions
- Summary (Timeline of Experiment)

What we want to do under Boı project

B01: Equation of States of the Neutron-Rich Nuclear Matter at Supra-Density

SπRIT Collaboration

SAMURAI Pion Reconstruction and Ion-Tracker

MSU: W. Lynch, M.B. Tsang, S. Tangwancharoen, Z. Chajecki, J. Estee, R. Shane, Jon Barney, P. Palni

TAMU: A. Mchintosh, S. Yennello, M. Capman

RIKEN : T. Isobe, H. Baba, H. Otsu, K-I Yoneda, H. Sato, Y. Nakai, S. Nishimura, A-K. Perrevoort, J. Lee, H. Sakurai, A. Taketani, He Wang, N. Fukuda, H. Takeda, D. Kameda, H. Suzuki, N. Inabe, T. Kubo

Kyoto Univ.: T. Murakami, N. Nakatsuka, M. Kaneko

Rikkyo Univ.: K. Ieki , Y. Kurita

Liverpool/ Darsbury: M. Chartier, W. Powell, J. Sampson, R.Lemmon

Korea Univ.: B. Hong, G. Jhang

WMU: M. Famiano

INFN: G. Verde, P.Russotto

SIAP CAS: Fei Lu, W.G. Ma

Tsinghau Univ.: Z. Sun

CEA: E. Pollacco

INP: J. Lukasik, P. Pawlowski

ORNL: A. Galindo-Uribarri

Tohoku Univ.: T. Kobayashi

TITech: T. Nakamura, Y. Kondo, Y. Togano

GSI: T. Aumann

Nuclear Equation of State

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$$

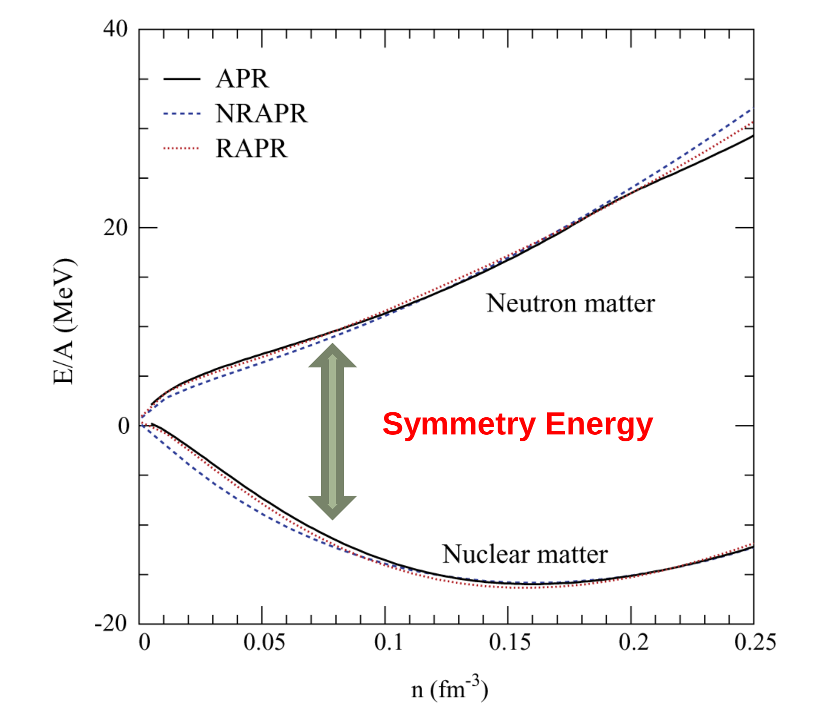
$$\delta = (\rho_n - \rho_p)/\rho$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + o(\varepsilon^3)$$

$$\varepsilon = (\rho - \rho_0)/3\rho_0$$

$$S_0 = E_{sym}(\rho_0) \Rightarrow J\,;sometimes$$

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho=\rho_0} = (3/\rho_0)P_0$$



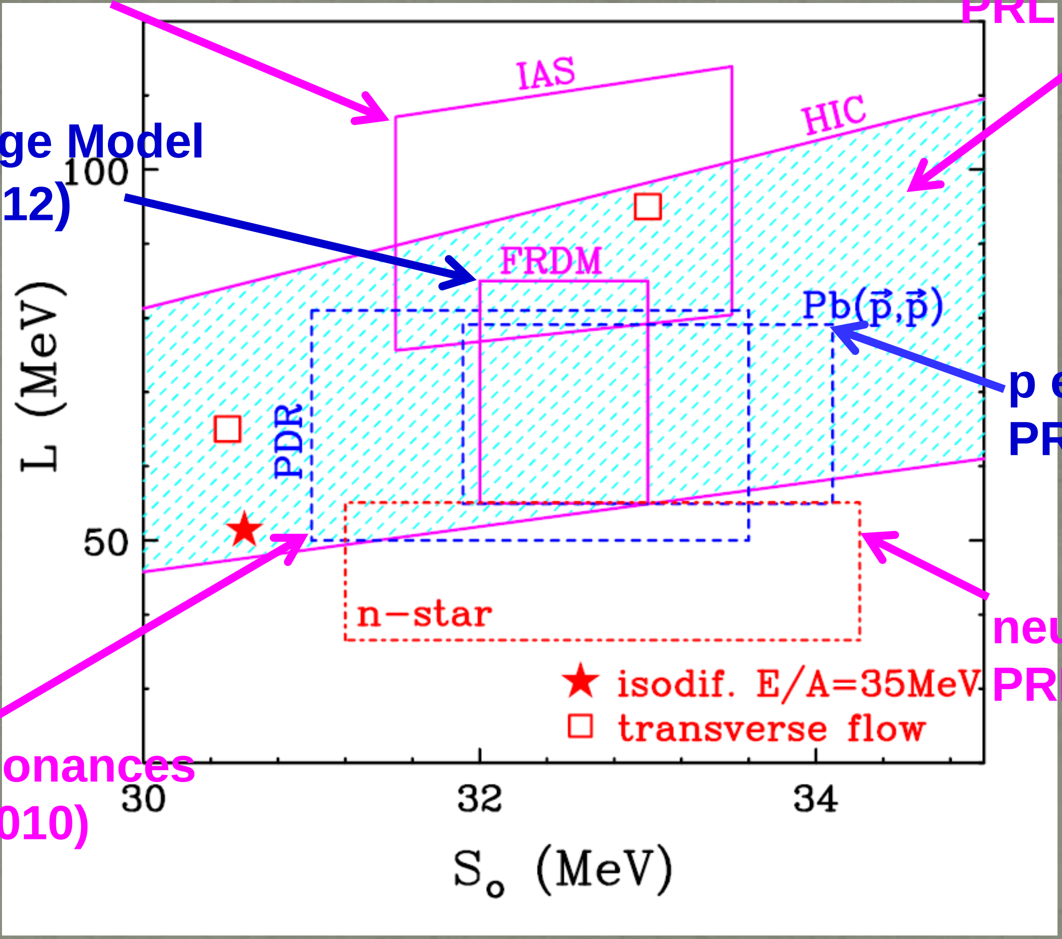
A.W. Steiner et al., Phys. Reports 411 (2005) 325

Present Constraints on Symmetry Energy from different experiments

Isobaric Analogue States
NPA 818, 36 (2009)

heavy ion collisions
PRL 102,122701(2009)

Finite Droplet Range Model
PRL108,052501(2012)



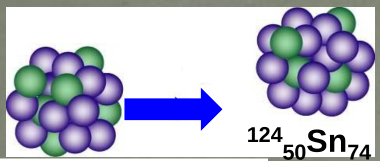
p elastic scattering
PRC82,044611(2010)

neutron-star radius
PRL108,01102(2012)

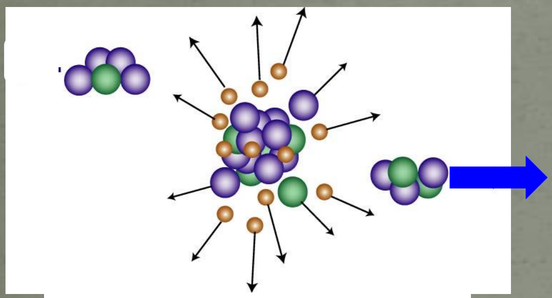
Pygmy Dipole Resonances
PRC 81, 041304 (2010)

Tsang et al. Phys. Rev. C 86, 015803 (2012)

Heavy ion collisions

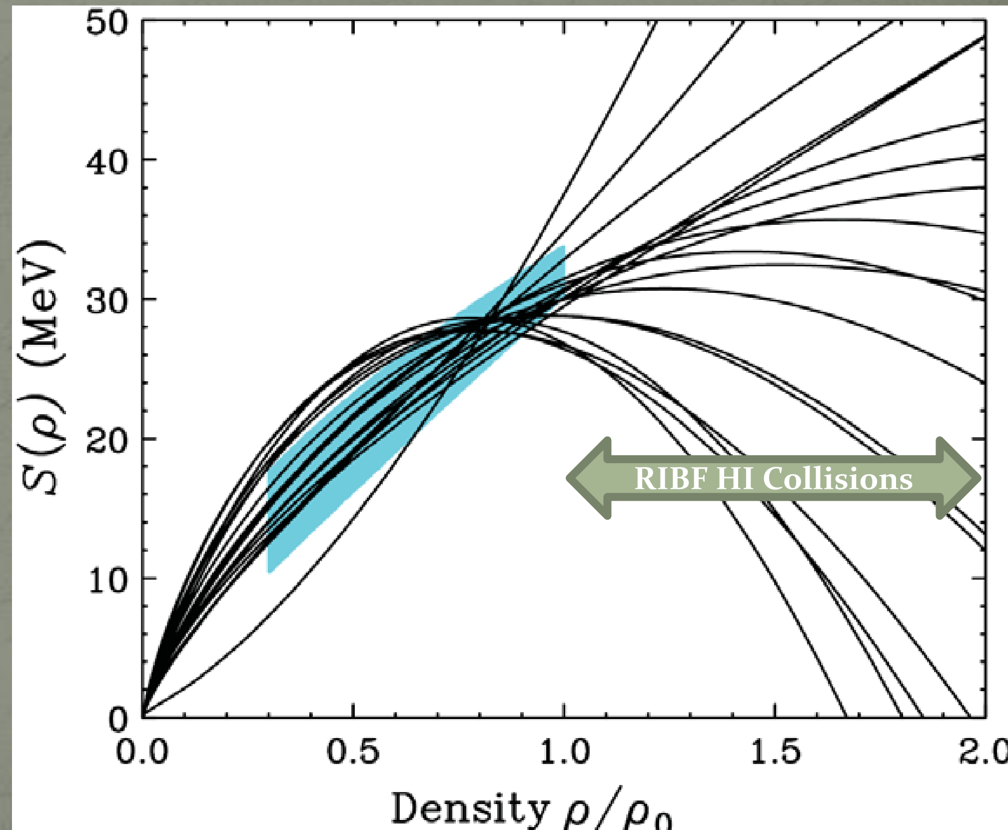


$^{132}_{50}Sn_{82}$ (n-rich)
@200~300 MeV



High-density
(participant region)

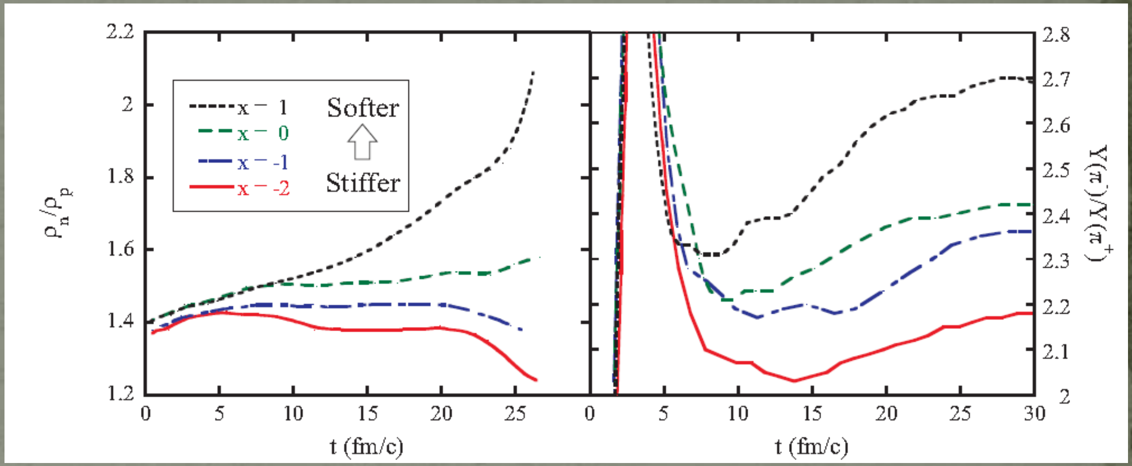
π^-/π^+ ratio



Tsang et al. Phys. Rev. C 86, 015803 (2012)

Influence of symmetry pressure; Possible Probe

The symmetry pressure expels neutrons from and attracts protons to high density region of neutron-rich system. This suppresses Y(n)/Y(p), Y(π^-)/Y(π^+), etc.

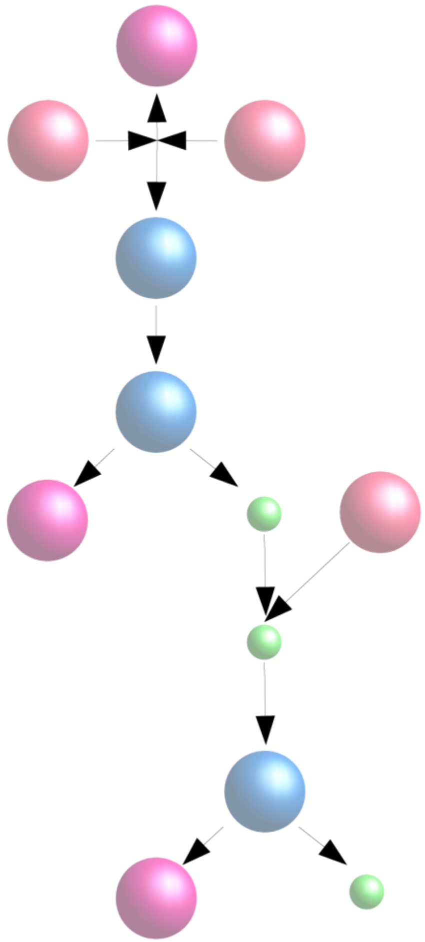


- $\pi^+ - \pi^-$ ratio
- Proton-neutron ratio
- Light ion ratio (t-^{3}He)
- Particle flow of pions, protons, neutrons and light ions

Main mechanism of pion production

Following Three Slides are from
Y.Leifels' presentation at ICNT2013

Inelastic cross sections



- pion production most dominant channel
- threshold energy in fixed target pp collisions 0.29 GeV
- pp and np cross sections differ
- production via resonances (Δ, N*)
- pion production sensitive to N/Z
- in case predominantly via Δ

$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

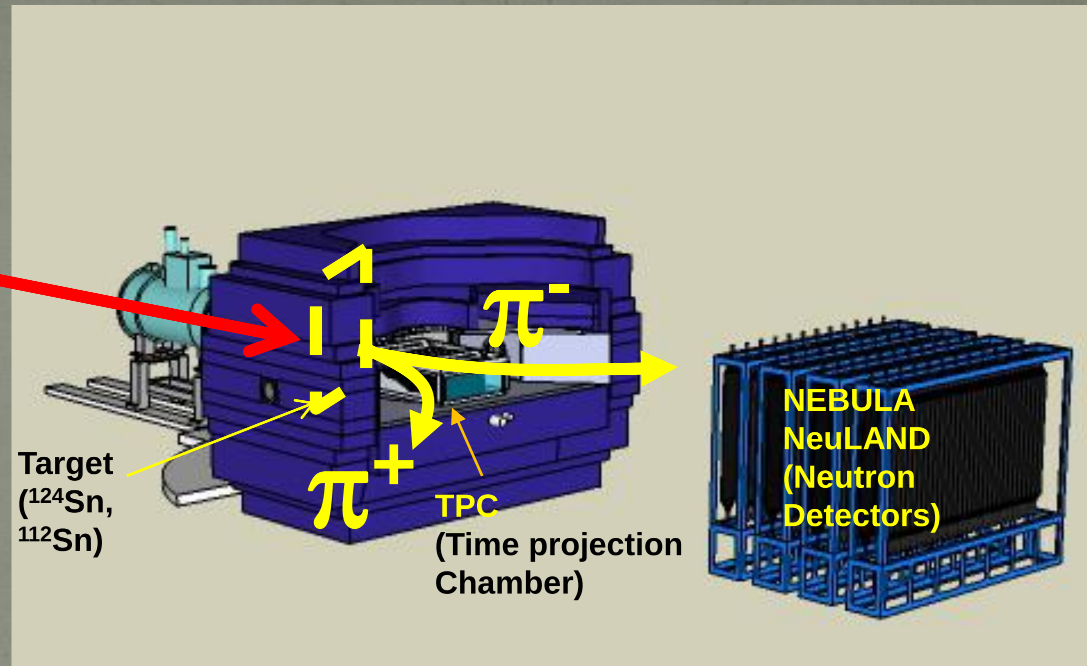
- pion recreation cycle

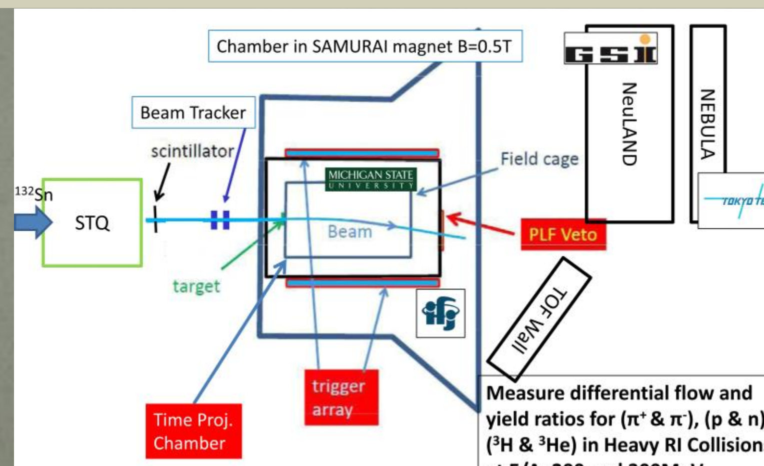
$$NN \rightarrow NN \quad NN \rightarrow N\Delta$$
$$N\Delta \rightarrow NN \quad \Delta \rightarrow N\pi$$
$$N\pi \rightarrow \Delta$$

Experimental Setup at RIBF

Equipment

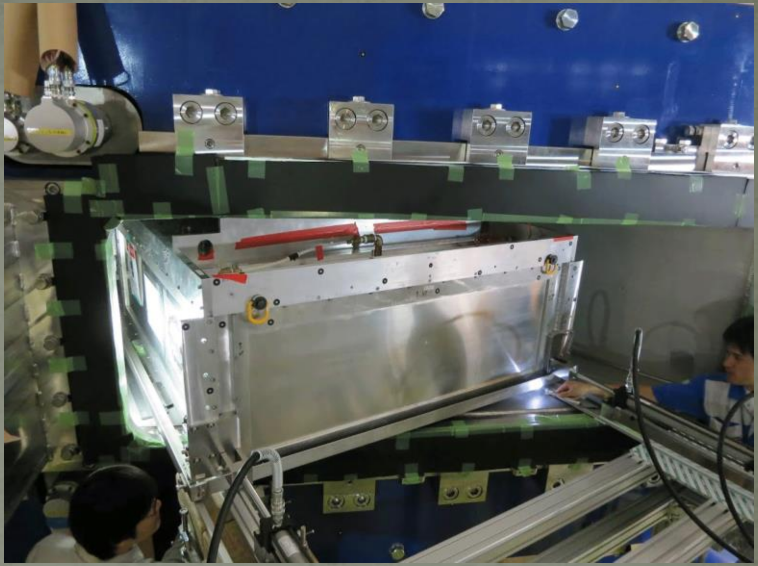
- TPC - measures:
  - π^+ , π^- , p, d, t, ^{3}He, ^{4}He, IMF’s
  - The SAMURAI chamber is at air
- Trigger scint. array:
  - selects central collisions and suppresses peripheral collisions.
- NEBULA:
  - provides neutron information

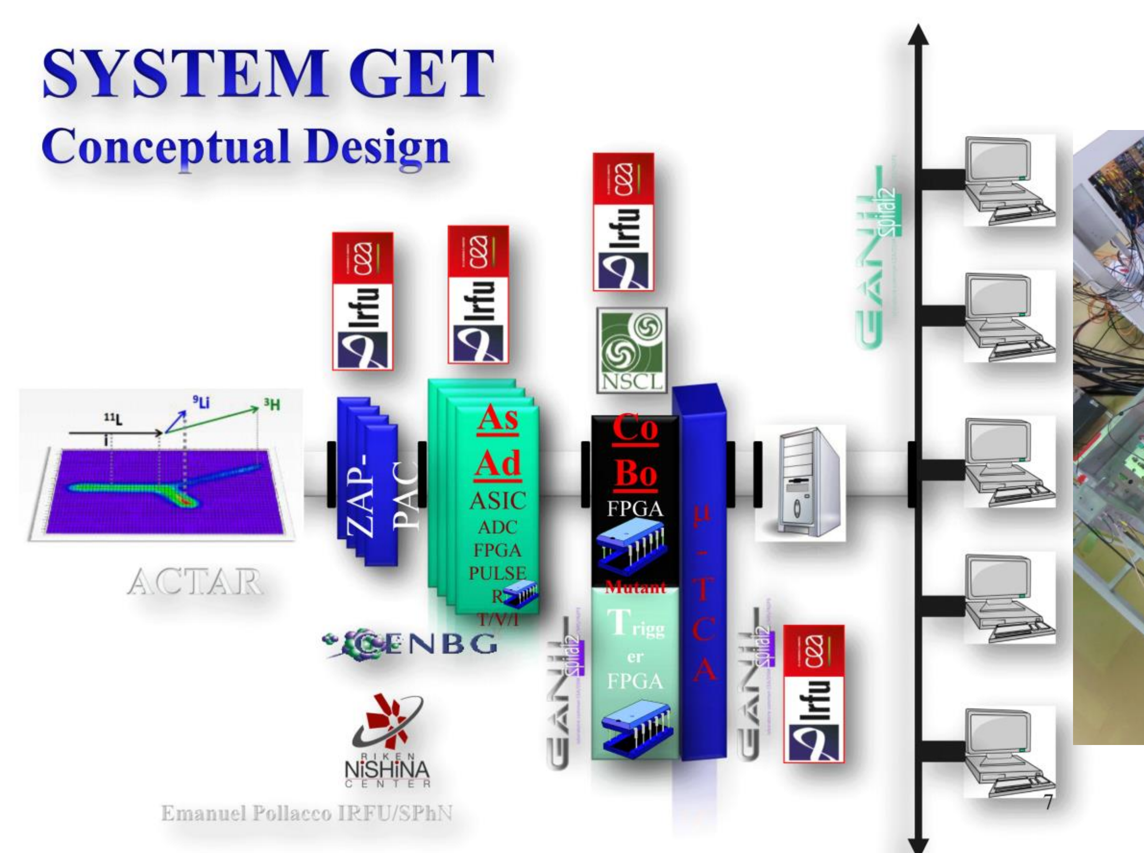


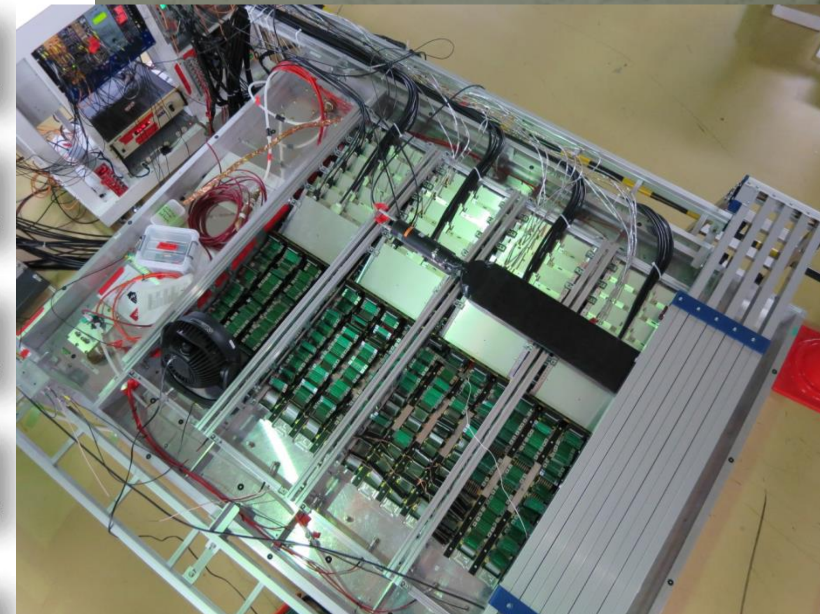


One day in February 2014

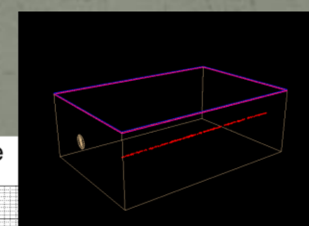
Installation Test of TPC into SAMURAI in July 2014

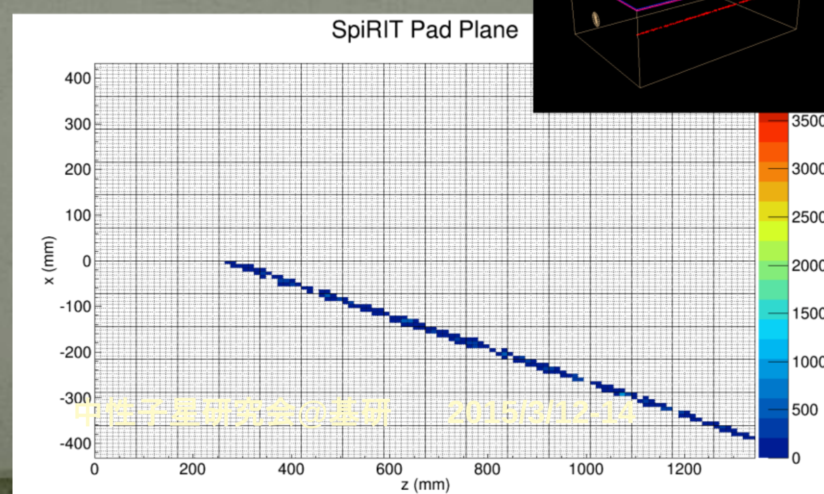






Run157 Event15





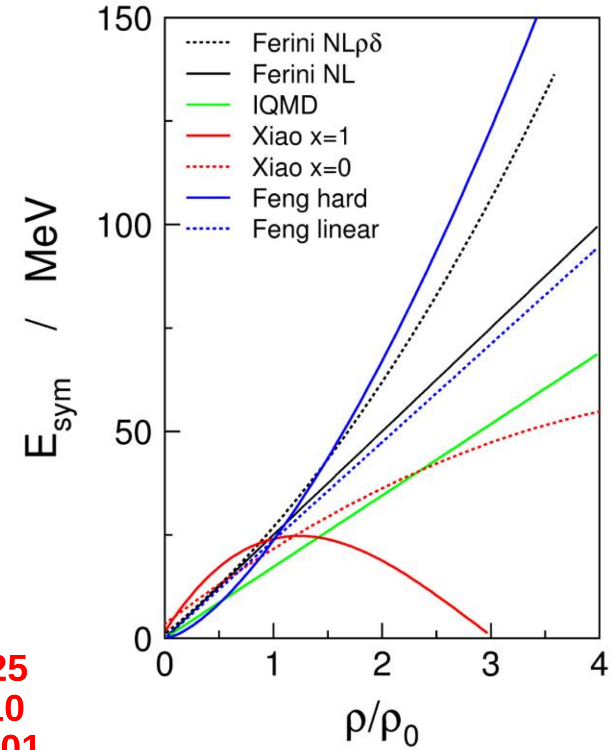
Test using Cosmic Rays

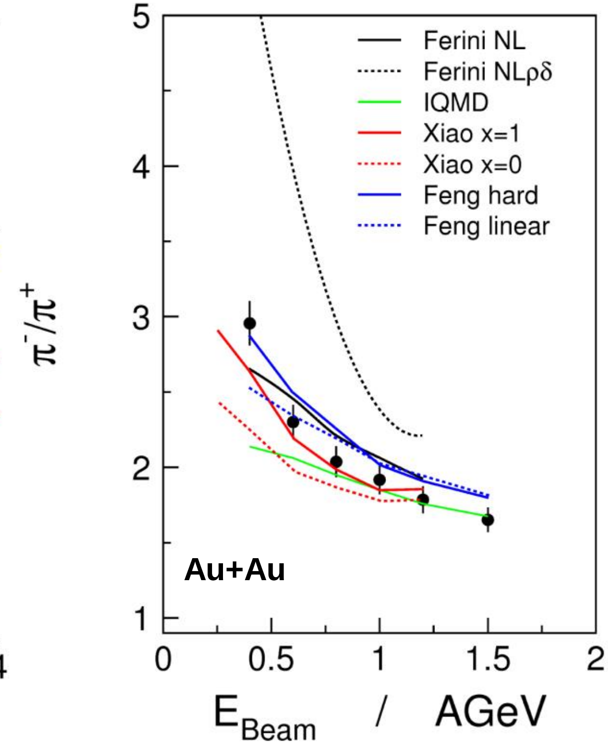
Status Summary

- We started signal test using cosmic ray.
- We will be ready to measure pion and light fragment flow from $^{132}Sn+^{124}Sn$, $^{124}Sn+^{112}Sn$, $^{112}Sn+^{124}Sn$, and $^{108}Sn+^{112}Sn$ collisions at 300 MeV/u using the TPCs at RIKEN RIBF to constraint the symmetry energy above saturation densities by autumn of 2015.

Primary	Beam	Target	E_{beam}/A	δ_{sys}	Goal	Days
^{238}U	^{132}Sn	^{124}Sn	300	0.22	Probe maximum δ	3
	^{124}Sn	^{112}Sn	300	0.15	Probe intermed. δ	3
^{124}Xe	^{108}Sn	^{112}Sn	300	0.09	Probe minimum δ	3
	^{112}Sn	^{124}Sn	300	0.15	Probe intermed. δ	3

Big Problem on Theoretical Prediction





Z. Xiao et al., PRL 102 (2009) 625
J. Xie et al., PLB 718 (2013) 1510
J. Xu et al., PRC 87 (2013) 067601
G. Ferini et al., PRL 97 (2006) 202301
Z.Q.Feng and G.-M. Jin, PLB 683 (2010) 140
J.Hong, P. Danielewicz, PRC 90 (2014) 024605

Possible answer to this mess

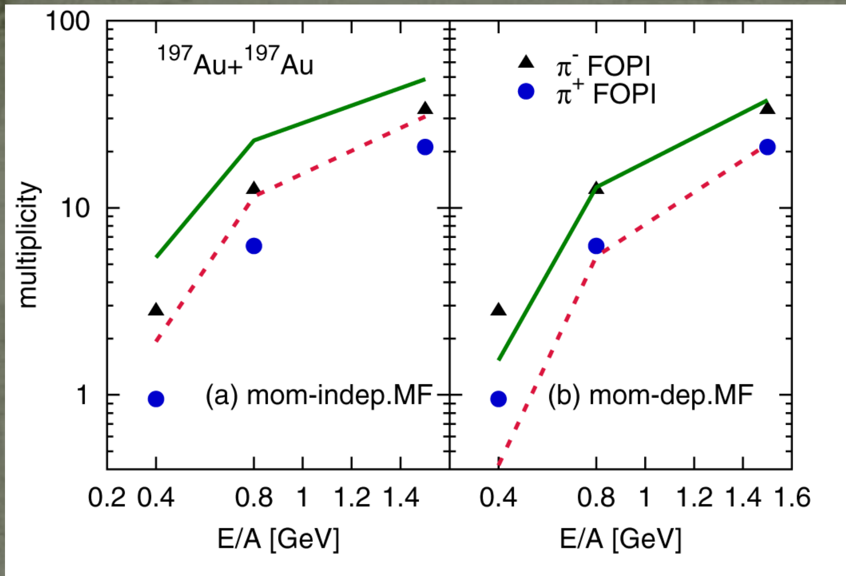
M.Di Toro et al., J. Phys. G: Nucl. Part. Phys. **37 083101**

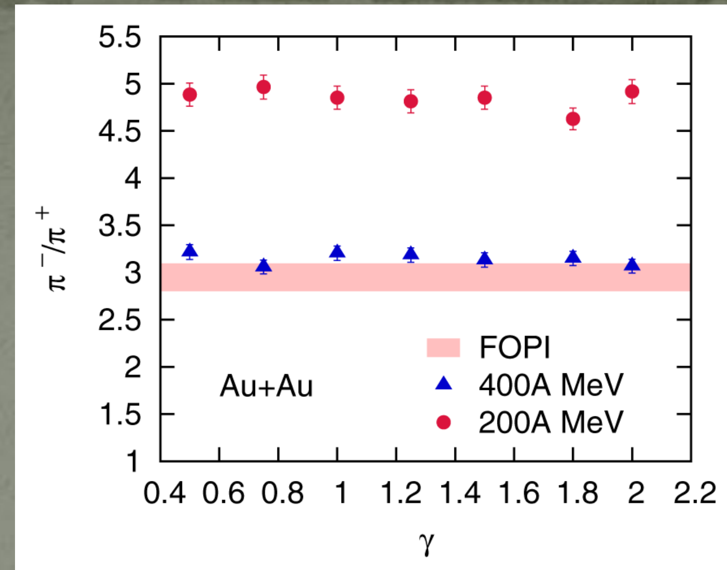
- symmetry energy → n/p ratio, number of nn, np, pp collisions

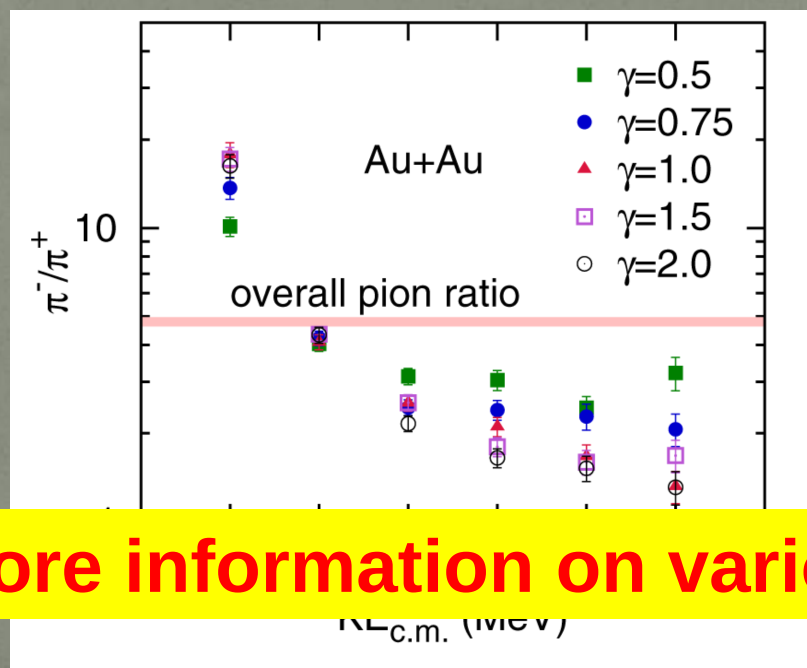
  asy stiff $\frac{n}{p}\downarrow \Rightarrow \frac{Y\left(\Delta^{0,-}\right)}{Y\left(\Delta^{+,++}\right)}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$

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

  asy stiff $\Rightarrow \frac{\pi^-}{\pi^+}\uparrow$







Hong and Danielewicz
Phys. Rev.C 90 (2014) 024605.

Need more information on various ejectiles

Pilot Experiment at HIMAC

Most of previous studies

- Using mass-symmetric collisions

  $(N/Z)_{participant} \approx (N/Z)_{proj} \approx (N/Z)_{targ}$

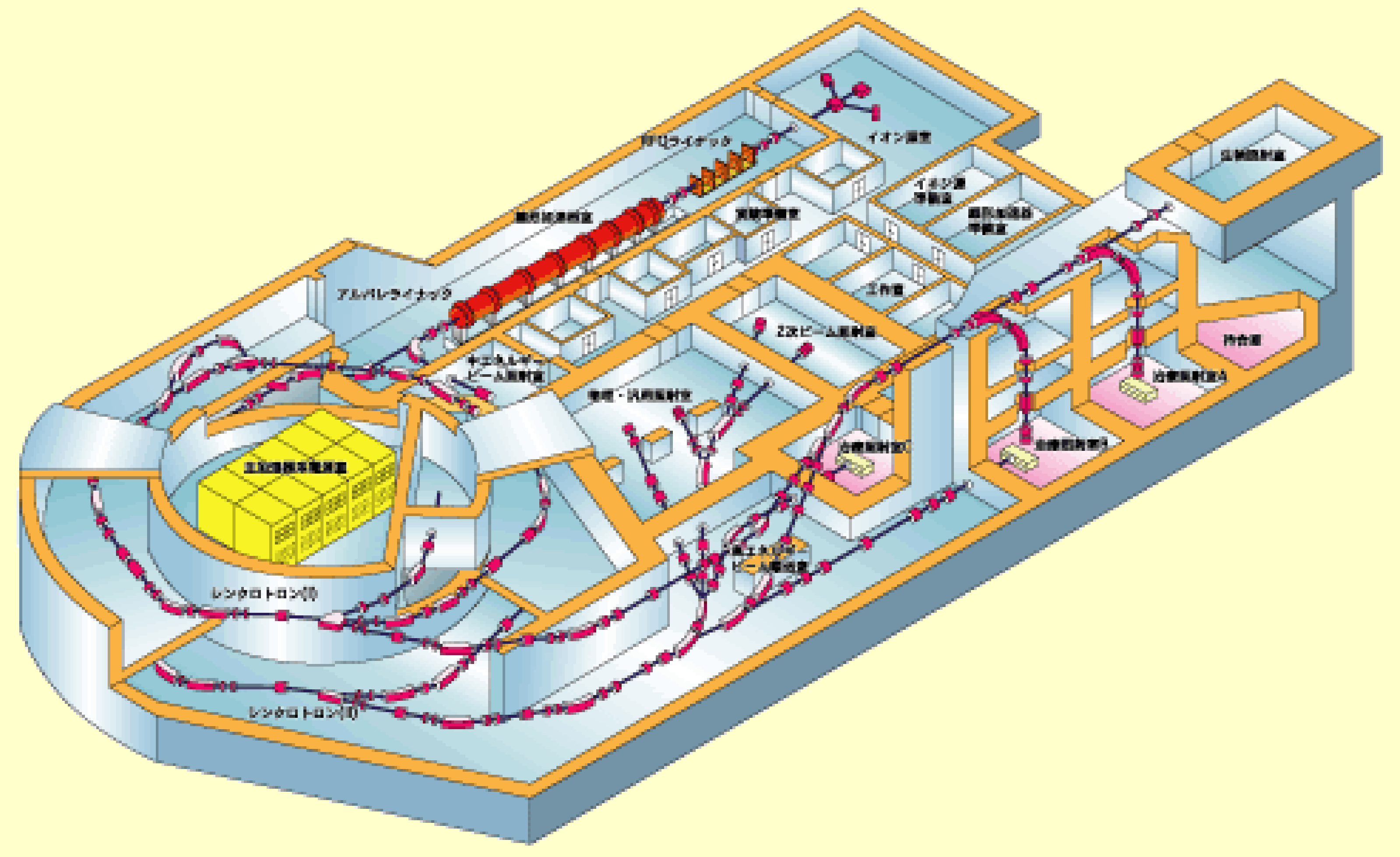
  ↓

- Over-simplify the situation

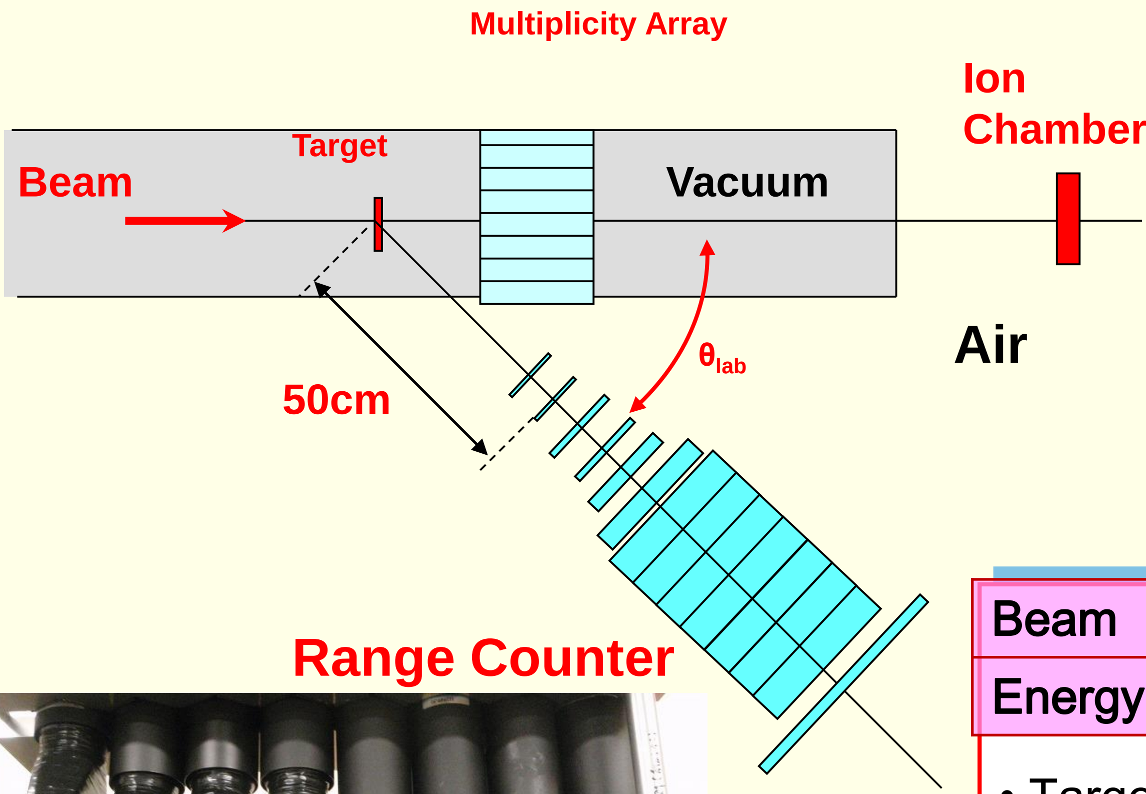
  Impossible to distinguish different moving sourse frames, like NN cm, participant cm, nucleus-nucleus cm etc.

→ Study mass-asymmetric collisions

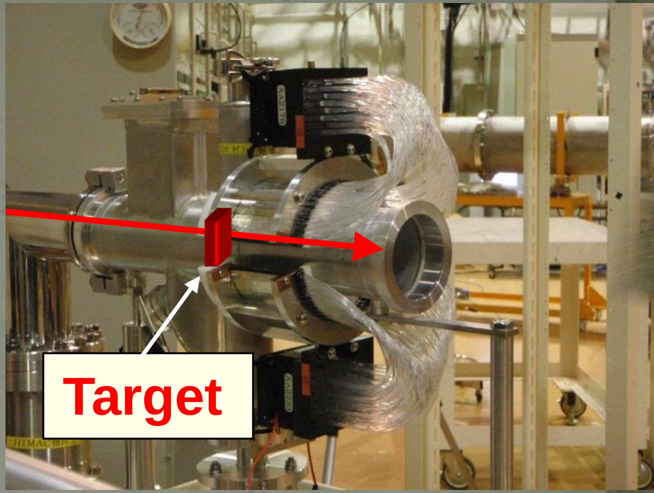
HIMAC



Pilot Experiments at HIMAC



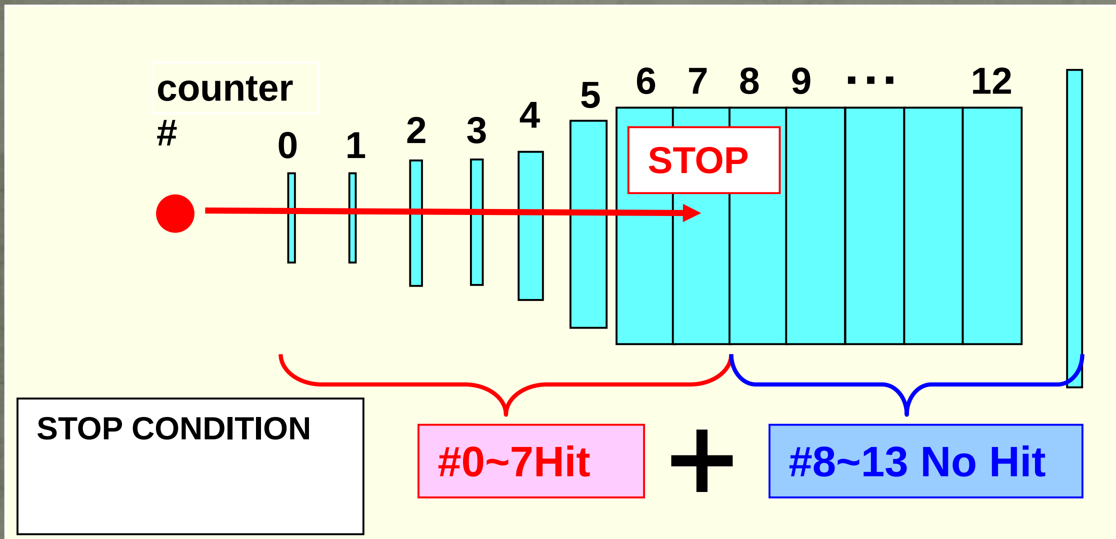
Multiplicity Array



Beam	^{28}Si	^{132}Xe
Energy(AMeV)	400, 600, 800	400

- Target : In ~ 390 mg/cm^2
- Typical Intensity : ~ 10^7 ppp
- Range Counter : 14 layers (+2) of Sci.
- measured angle (θlab)
  : 30, 45, 60, 75, 90, 120 degree
- solid angle : 10 msr

Detection Principle

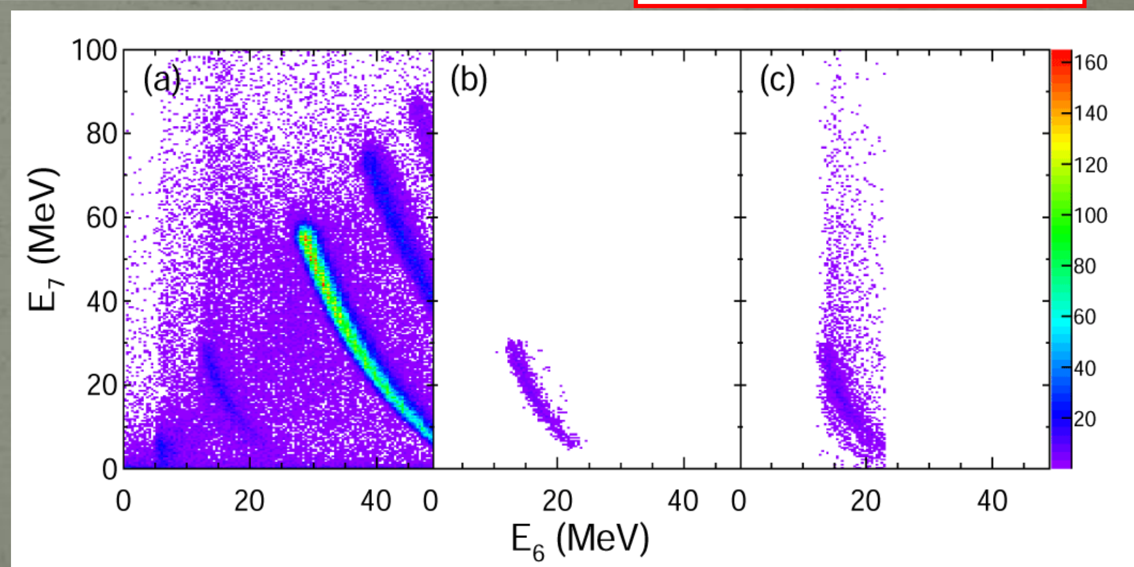


- π^+ decay to μ^+

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- μ^+ : Energy ~ 4 MeV
  : Range ~ 1 ㎜

Double pulse in one layer



- ～400MeV/u
  Pion's are rare

  less than 1/100 of protons

π^+ and half life

<π+ events>

Counter #8 STOP Condition
+
#8 Double Hit

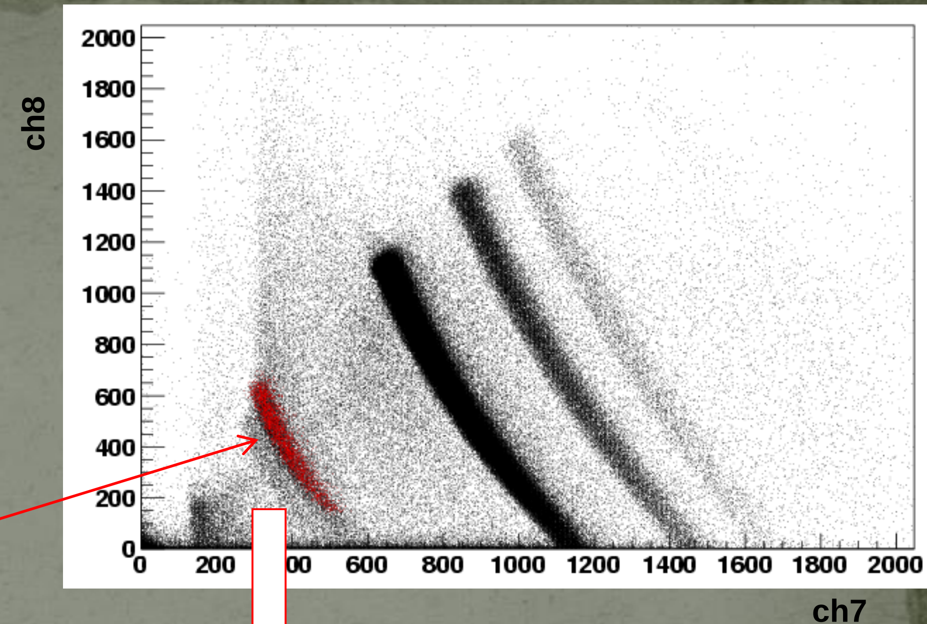
⇓

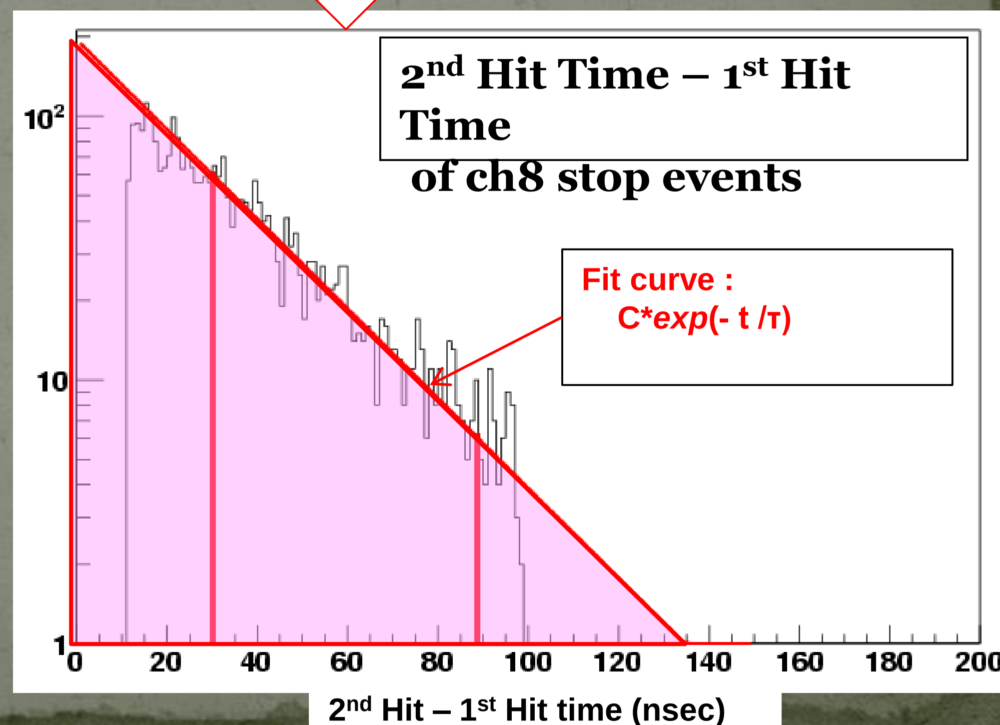
Fit the Histogram "2nd Hit Time -1st Hit Time" by C*exp*(- t /τ)

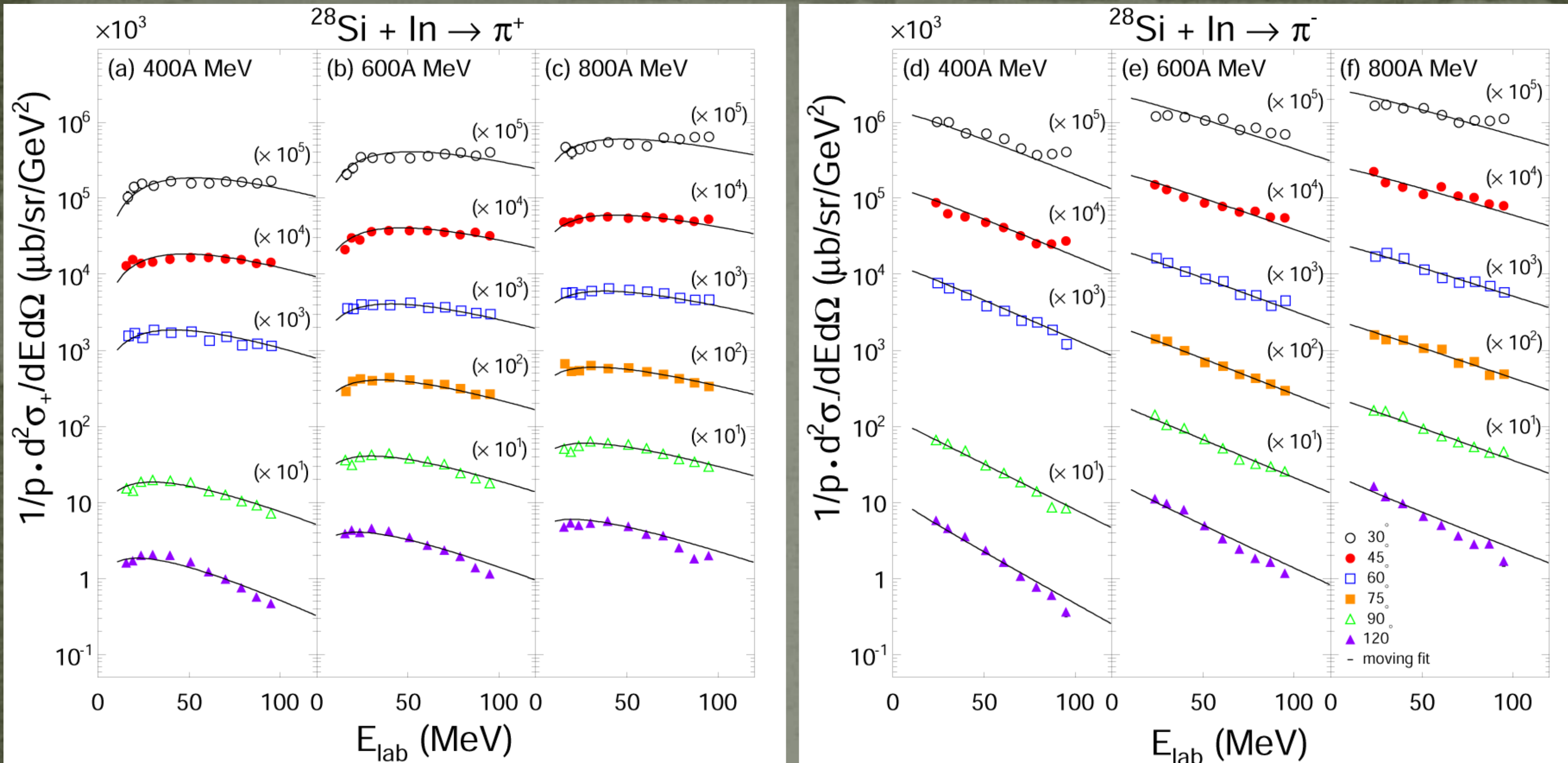
⇒ **τ = 26.0±0.6 nsec**

⇓

Successfully select π^+







$$f_-(E_{mov}) = N_- exp(-E_{mov}/E_0),$$

$$f_+(E_{mov}) = N_+ E_{mov}^P exp(-E_{mov}/E_0),$$

Fitting parameters

E_{beam}(MeV/nucleon)	$\beta_{mov}(c)$	E_0(MeV)	N_-	N_+	P
400	0.20(0.05)	37.0(4.3)	13.7(2.1)	0.19(0.05)	0.91(0.07)
600	0.19(0.04)	44.1(5.0)	22.6(2.9)	0.63(0.13)	0.75(0.05)
800	0.22(0.04)	51.8(5.1)	26.8(2.6)	1.44(0.12)	0.59(0.04)

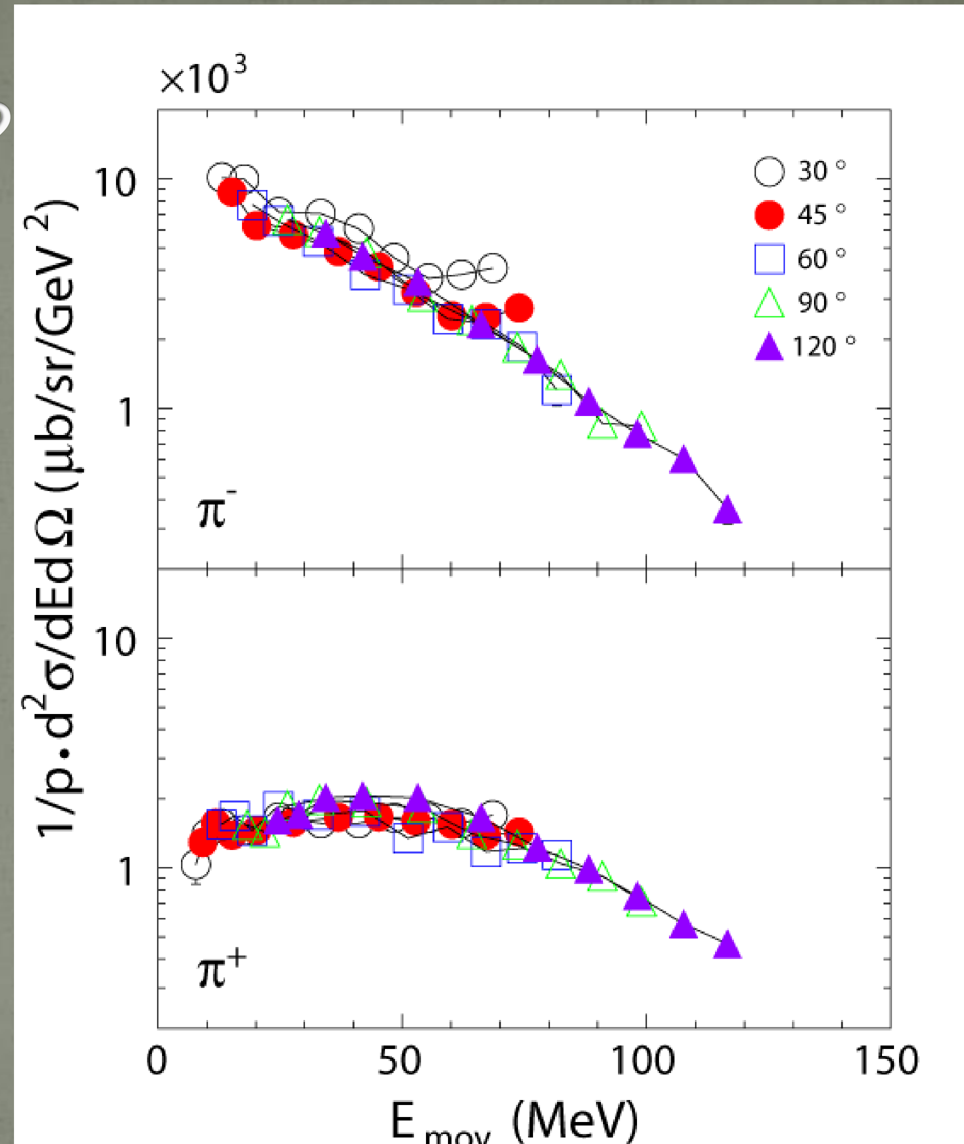
⇓

E_{beam}(MeV/nucleon)	$\sigma_{exp}(\pi^+)$	$\sigma_{exp}(\pi^-)$	$\sigma_{JQMD}(\pi^+)$	$\sigma_{JQMD}(\pi^-)$
400	0.33	0.63	0.28	0.38
600	0.87	1.37	0.90	1.12
800	1.41	2.10	1.68	2.01

How well overlap?

Isotropic emission
from single moving source

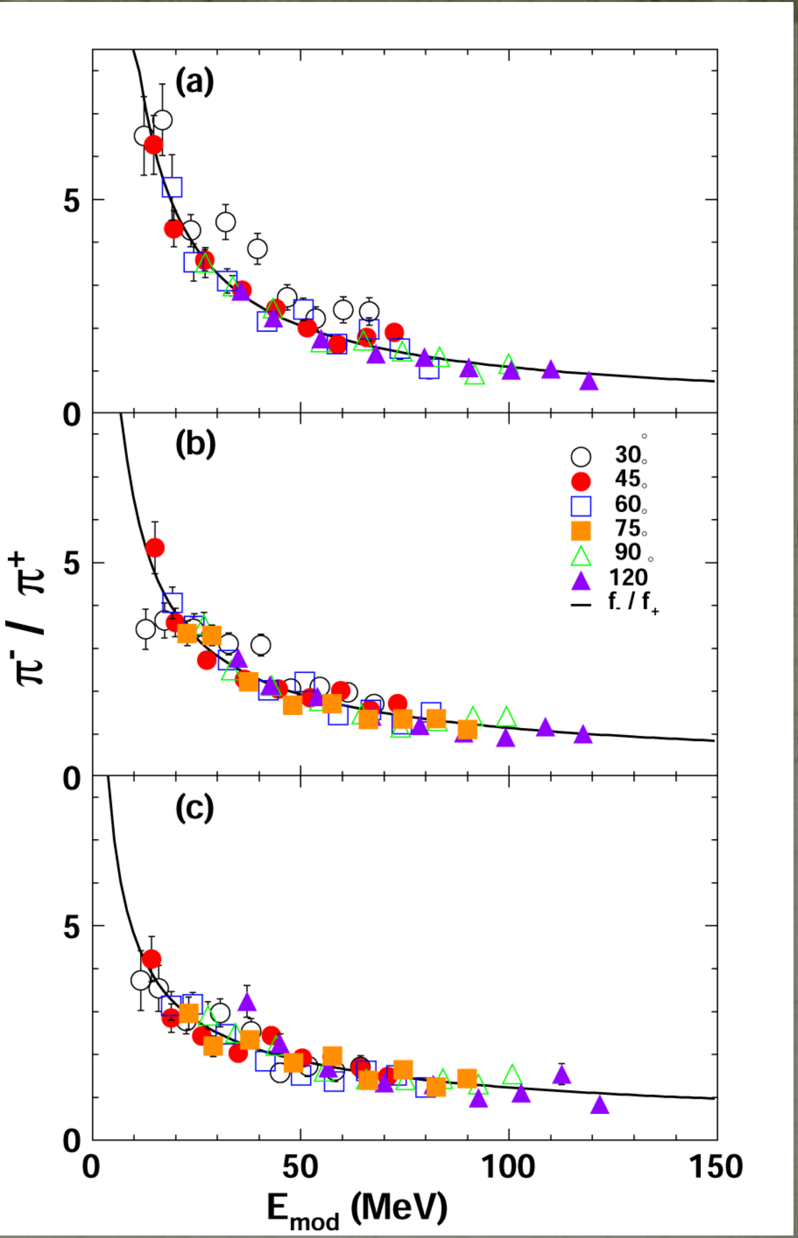
But , very slow!!!

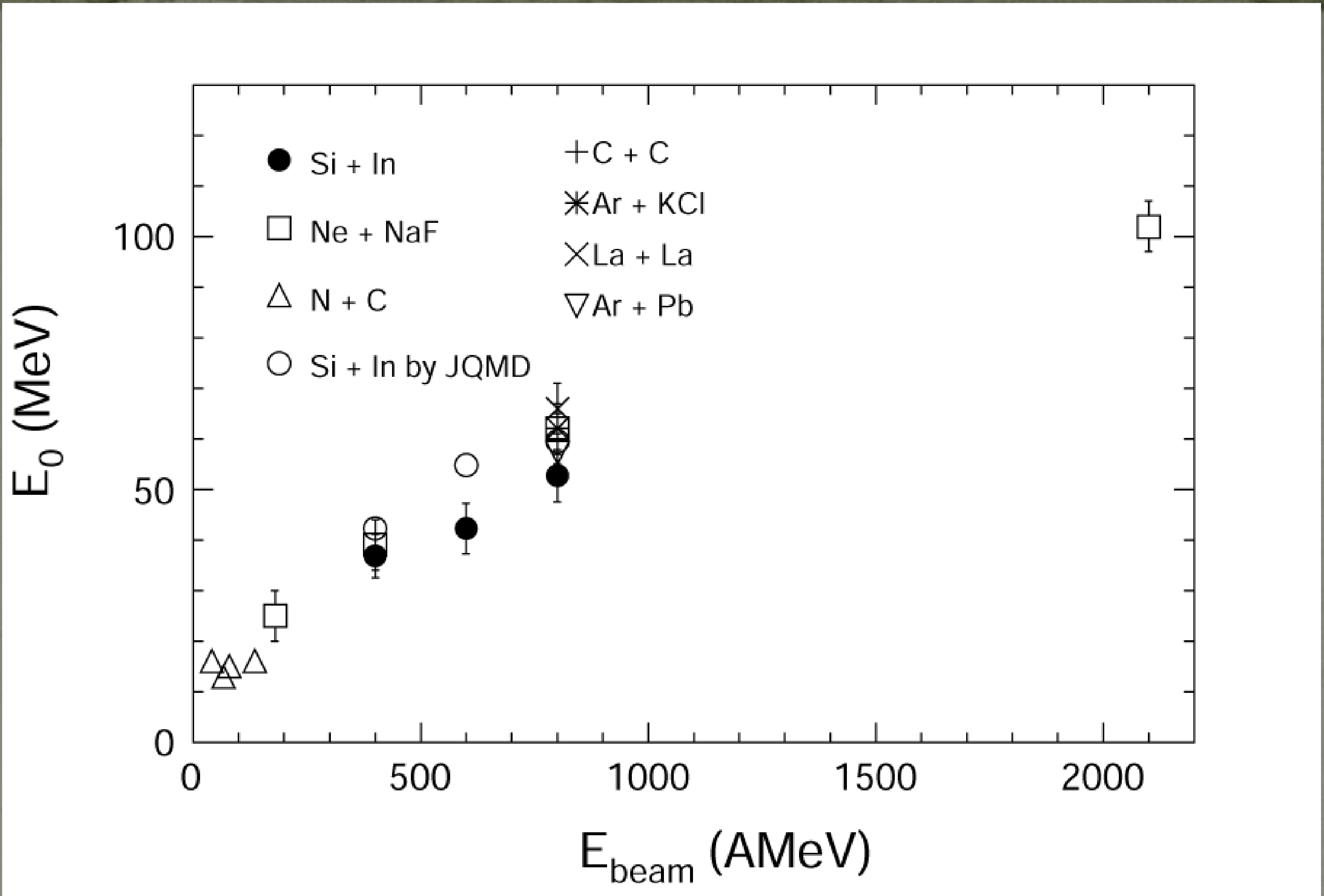


At 400MeV/nucleon

Differential π^-/π^+ ratio

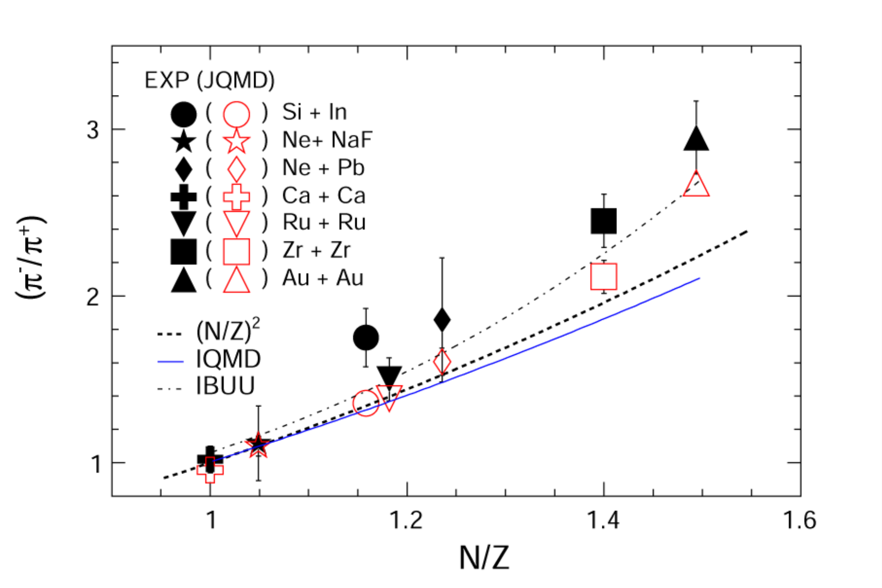
Weak angular dependence

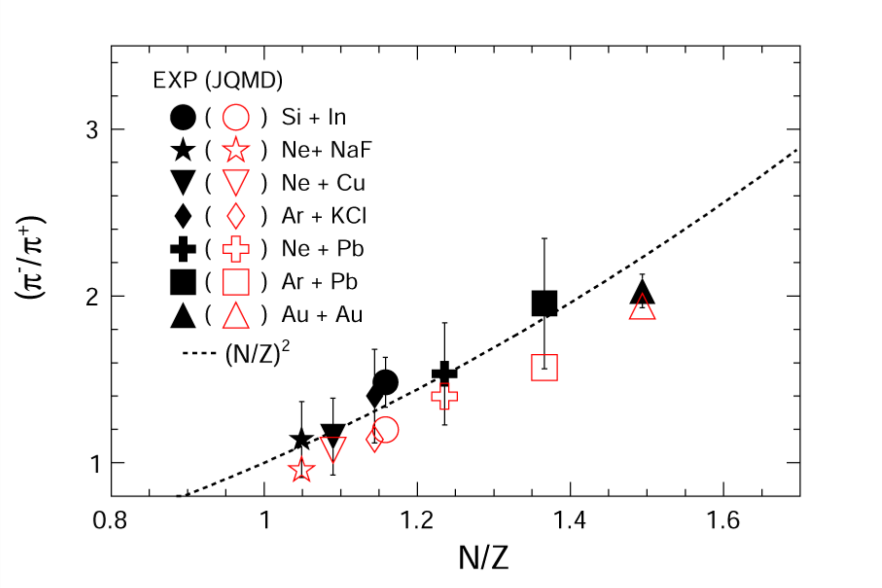




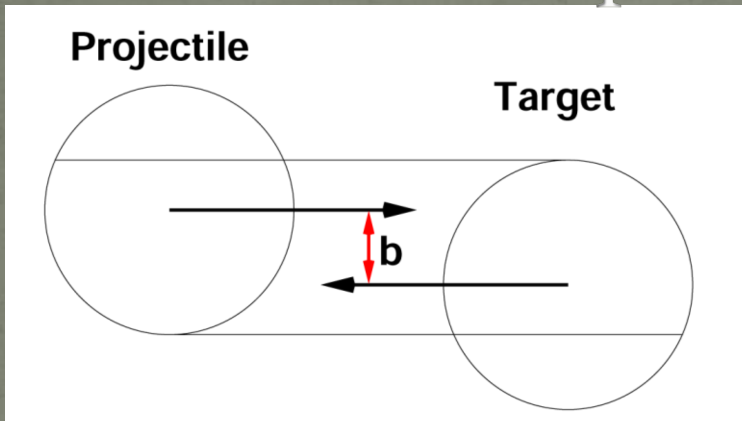
Slope parameters are consistent with old measurements

π^-/π^+ total ratio vs (N/Z) close to $(N/Z)^2$





Estimation of participant size



Semi-analytic formula

$$N_T = A_T F(\nu, b^{(0)}), \qquad \nu = \frac{R_T}{R_p + R_T}, \qquad b^{(0)} = \frac{b}{R_p + R_T}$$

$$F(\nu, b^{(0)}) = \frac{3}{4}(1-\nu)^{1/2}\left(\frac{1-b^{(0)}}{\nu}\right)^2 - \frac{1}{8}[3(1-\nu)^{1/2} - 1]\left(\frac{1-b^{(0)}}{\nu}\right)^3$$

$$A_{part} = A_{tot} F(1/2, b^{(0)})$$

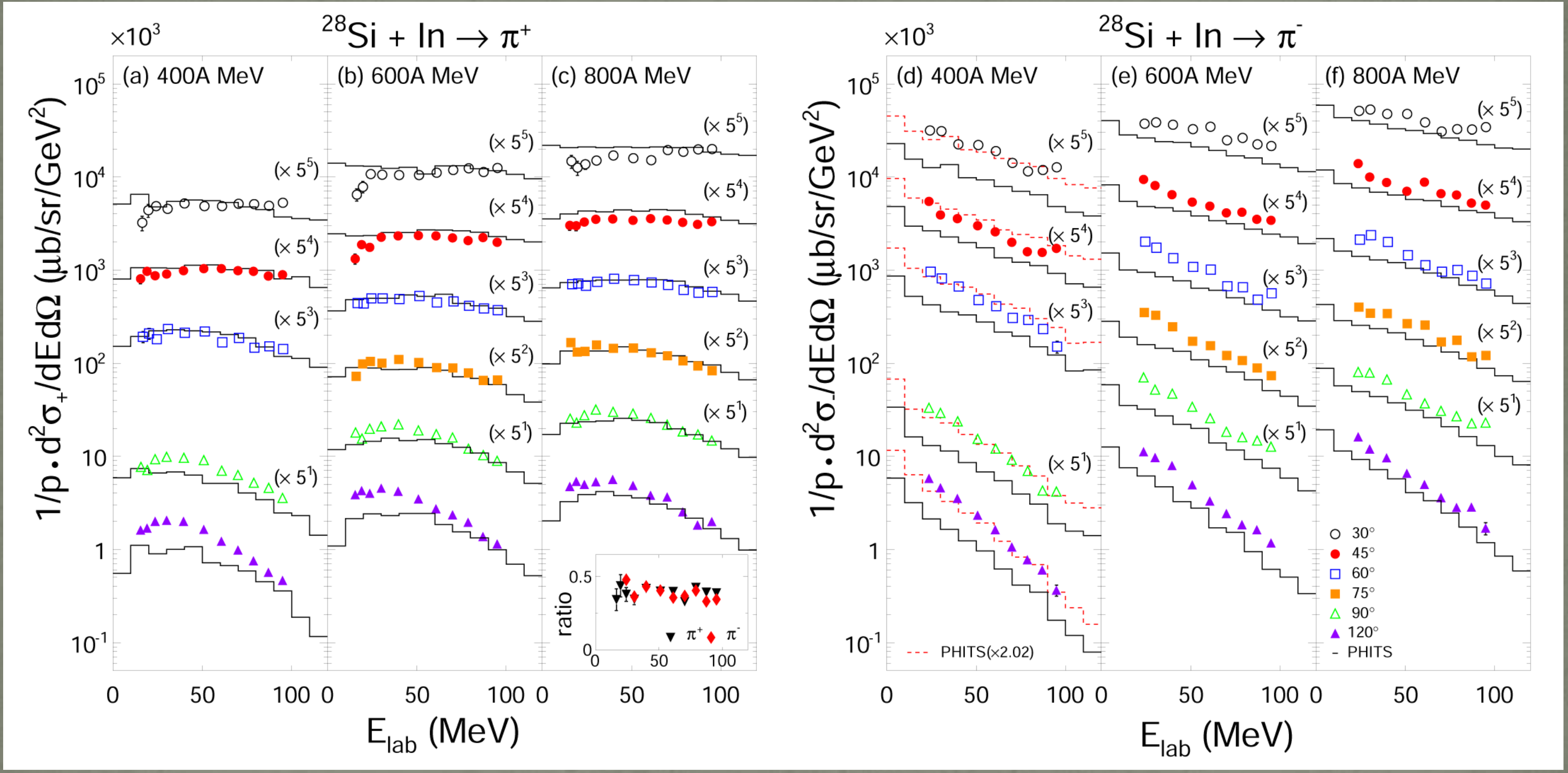
$$F_{\mathrm{I}} = [1-(1-\mu^2)^{3/2}][1-(\beta/\nu)^2]^{1/2},$$

$$F_{\mathrm{II}} = \tfrac{3}{4}(1-\nu)^{1/2}\left(\frac{1-\beta}{\nu}\right)^2 - \frac{1}{8}\left(\frac{3(1-\nu)^{1/2}}{\mu} - \frac{[1-(1-\mu^2)^{3/2}][1-(1-\mu)^2]^{1/2}}{\mu^3}\right)\left(\frac{1-\beta}{\nu}\right)^3,$$

$$F_{\mathrm{III}} = \tfrac{3}{4}(1-\nu)^{1/2}\left(\frac{1-\beta}{\nu}\right)^2 - \tfrac{1}{8}[3(1-\nu)^{1/2} - 1]\left(\frac{1-\beta}{\nu}\right)^3,$$

$$F_{\mathrm{IV}} = 1.$$

Comparison with JQMD

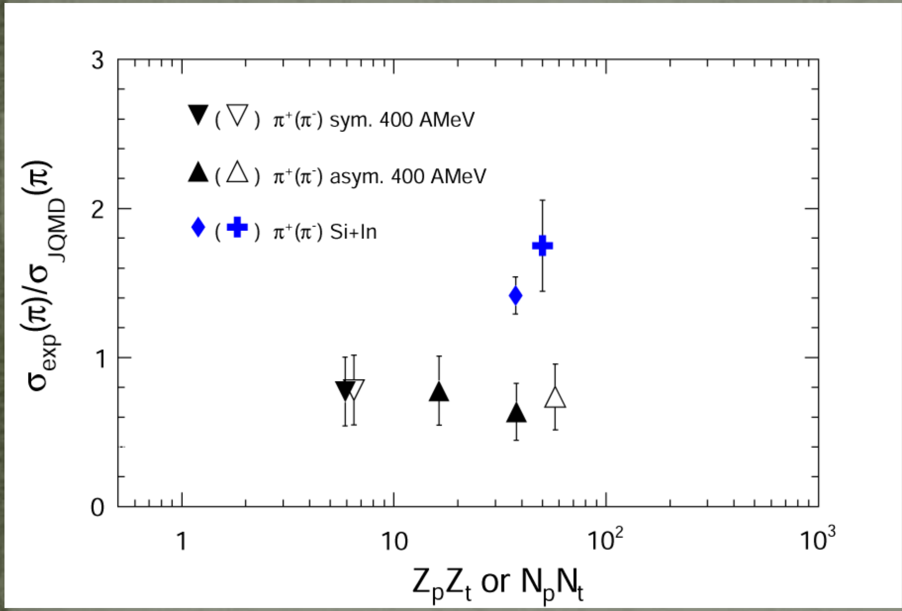


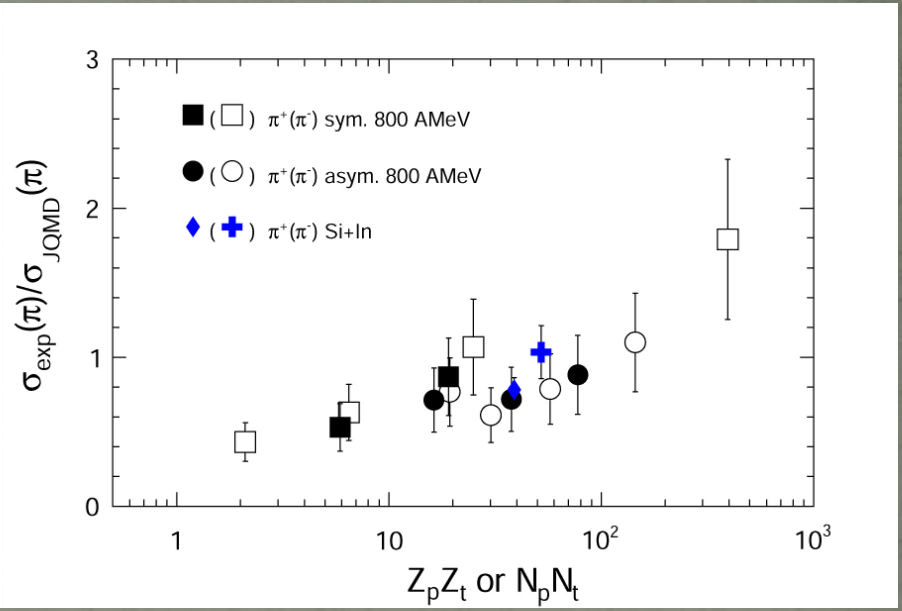
Normalization constant: 2.02, 1.68, and 1.43

E_{beam}(MeV/nucleon)	$\sigma_{exp}(\pi^+)$	$\sigma_{exp}(\pi^-)$	$\sigma_{JQMD}(\pi^+)$	$\sigma_{JQMD}(\pi^-)$
400	0.33	0.63	0.28	0.38
600	0.87	1.37	0.90	1.12
800	1.41	2.10	1.68	2.01

E_{beam}(MeV/nucleon)	$\beta_{mov}(c)$	$\beta_{JQMD}(c)$	$\beta_{CM}(c)$	$\beta_{part}(c)$	$\beta_{mid}(c)$
400	0.20(0.05)	0.31(0.02)	0.18	0.34	0.42
600	0.19(0.04)	0.34(0.04)	0.22	0.41	0.49
800	0.22(0.04)	0.35(0.06)	0.26	0.46	0.55

Systematics in total pion cross sections





Summary

- Measured doubly differential cross sections of π^+ and π^- for the ^{28}Si + In reactions at 400, 600 and 800 MeV/nucleons.
- They are emitted isotropically from the single moving source, whose velocity is quite slower than the mid rapidity.
- The differential pion ratios represented in such moving frames overlap each other at each incident energy.
- PHITS fails to reproduce the observed absolute cross section, the angular dependence of the cross sections and the charged pion ratio.