# Pion data and transport model calculations --Pre-SπRIT project

Tetsuya MURAKAMI
Department of Physics
Kyoto University

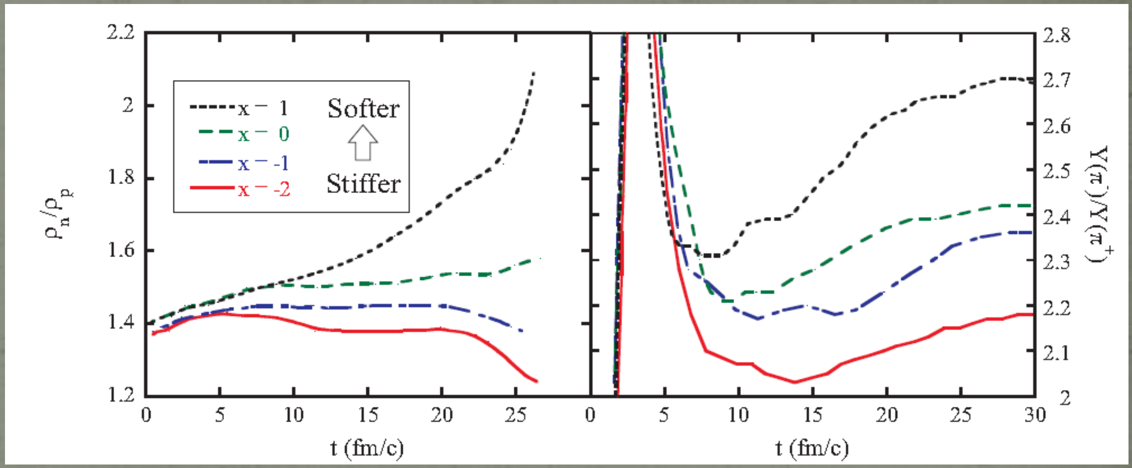
**Based on the Work for long-waiting Mr. Sako-kun's PhD thesis**

# As a probe of symmetry energy at high density we made a bet on pion


**The symmetry pressure at high density would expel neutrons and attract protons.**

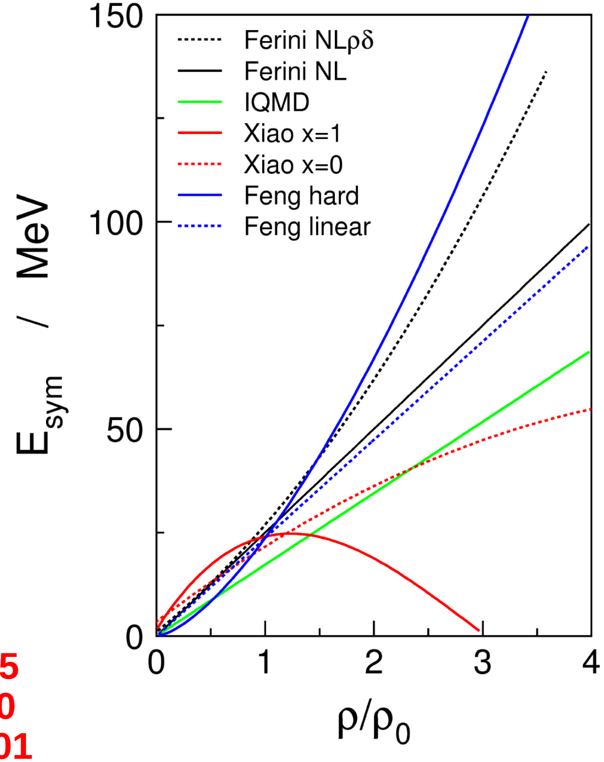
**Prediction of transport theory**

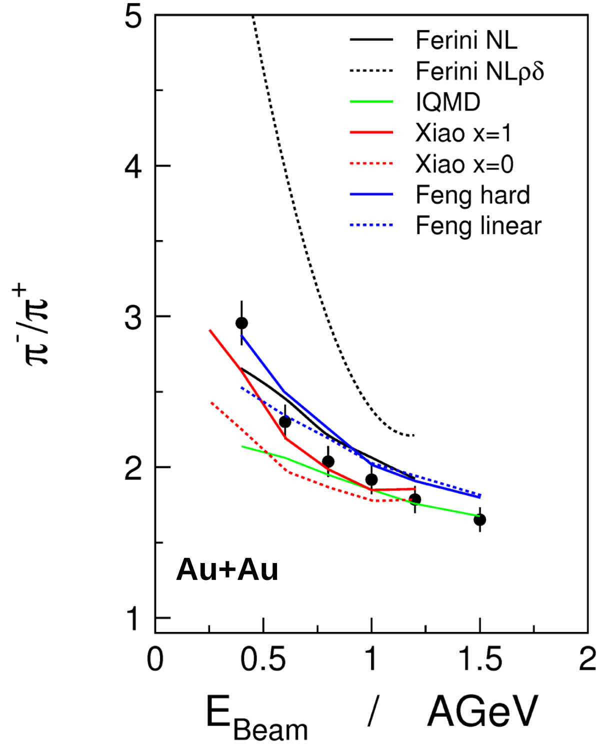
**Suppress Y(n)/Y(p), Y($\pi^-$)/Y($\pi^+$), etc.**




**Bao-An Li et al., Phys. Rev. C 71, 014608 (2005)**

# Now odds become unclear
# because of doubt 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**

# To make a breakthrough

Should know pion production in heavy-ion collision more clearly.

→ How well can we account on pion observables?

# Pioneering work by Nagamiya et al.

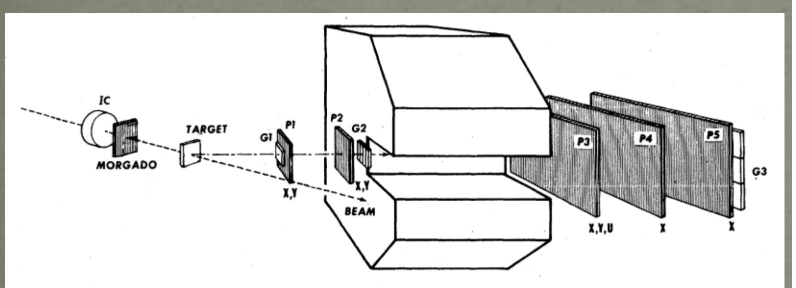
PHYSICAL REVIEW C VOLUME 24, NUMBER 3 SEPTEMBER 1981

## Production of pions and light fragments at large angles in high-energy nuclear collisions

S. Nagamiya, M.-C. Lemaire,* E. Moeller,† S. Schnetzer, G. Shapiro, H. Steiner, and I. Tanihata‡

*Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*

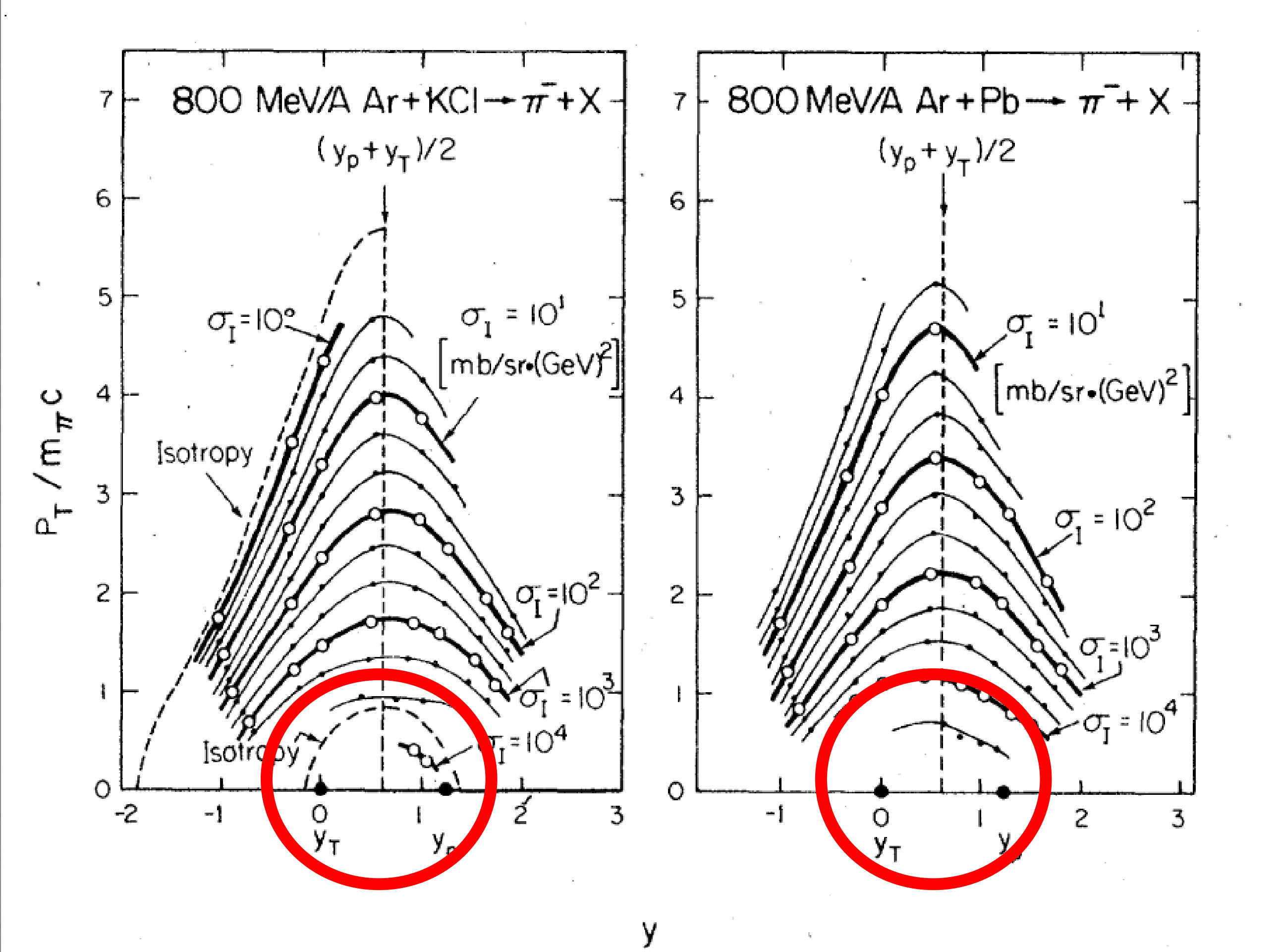
(Received 9 March 1981)




| $E_{beam}^{lab}$/nucl (MeV) | Projectile | Target | Detected particles | Data type available Inclusive | TPC[a] | HME[b] |
|---|---|---|---|---|---|---|
| 400 | Ne | NaF, Cu, Pb | $\pi^{\pm}$, $p$, $d$, $^3$H, $^3$He | Yes | Yes | * |
| 800 | C | C, Pb | $\pi^{-}$, $p$, $d$, $^3$H, $^3$He | Yes | Yes | * |
| | Ne | NaF, Cu, Pb | $\pi^{\pm}$, $p$, $d$, $^3$H, $^3$He | Yes | Yes | Yes |
| | Ar | KCl, Pb | $\pi^{\pm}$, $p$, $d$, $^3$H, $^3$He, $^4$He | Yes | Yes | Yes |
| 2100 | Ne | NaF, Pb | $\pi^{\pm}$, $p$, $d$, $^3$H, $^3$He, $^4$He | Yes | Yes | Yes |
| 800 | $p$ | C, NaF, KCl Cu, Pb | $\pi^{-}$, $p$, $d$, $^3$H, $^3$He | Yes | Yes | No |
| 2100 | $p$ | C, NaF, KCl Cu, Pb | $\pi^{\pm}$, $p$, $d$, $^3$H, $^3$He | Yes | Yes | No |

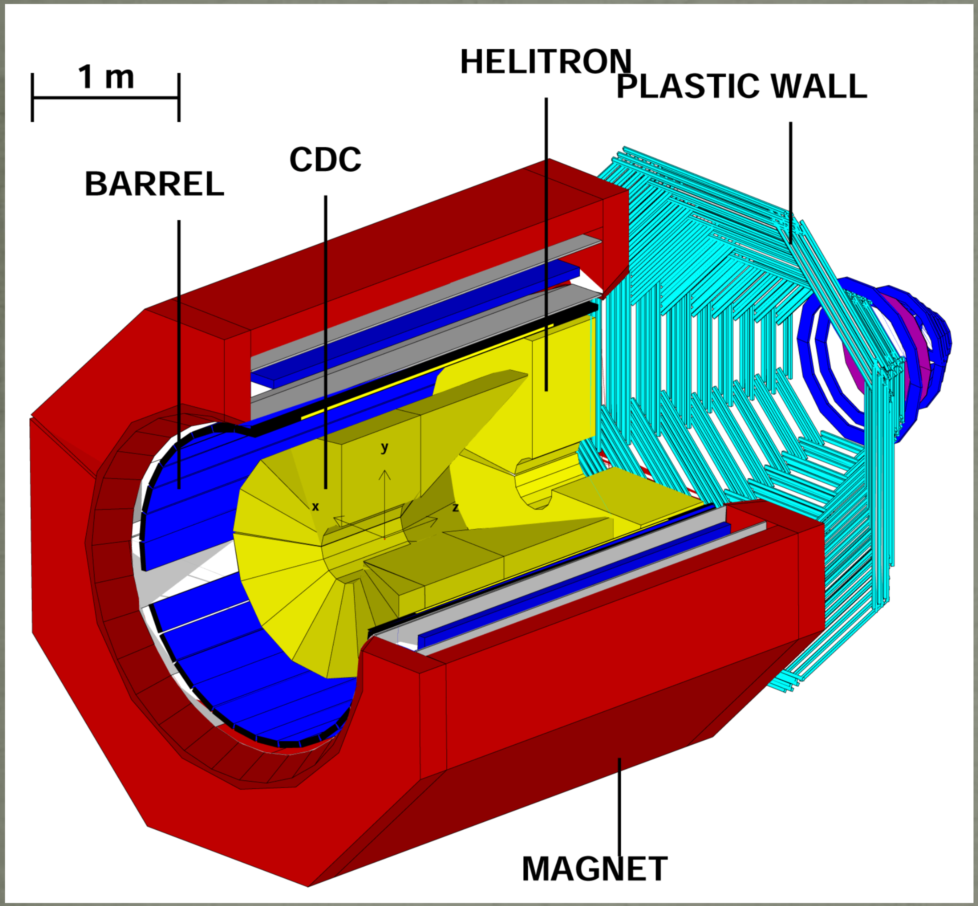
[a]TPC—two-particle correlations.
[b]HME—high-multiplicity events.

# Need to integrate differential cross section

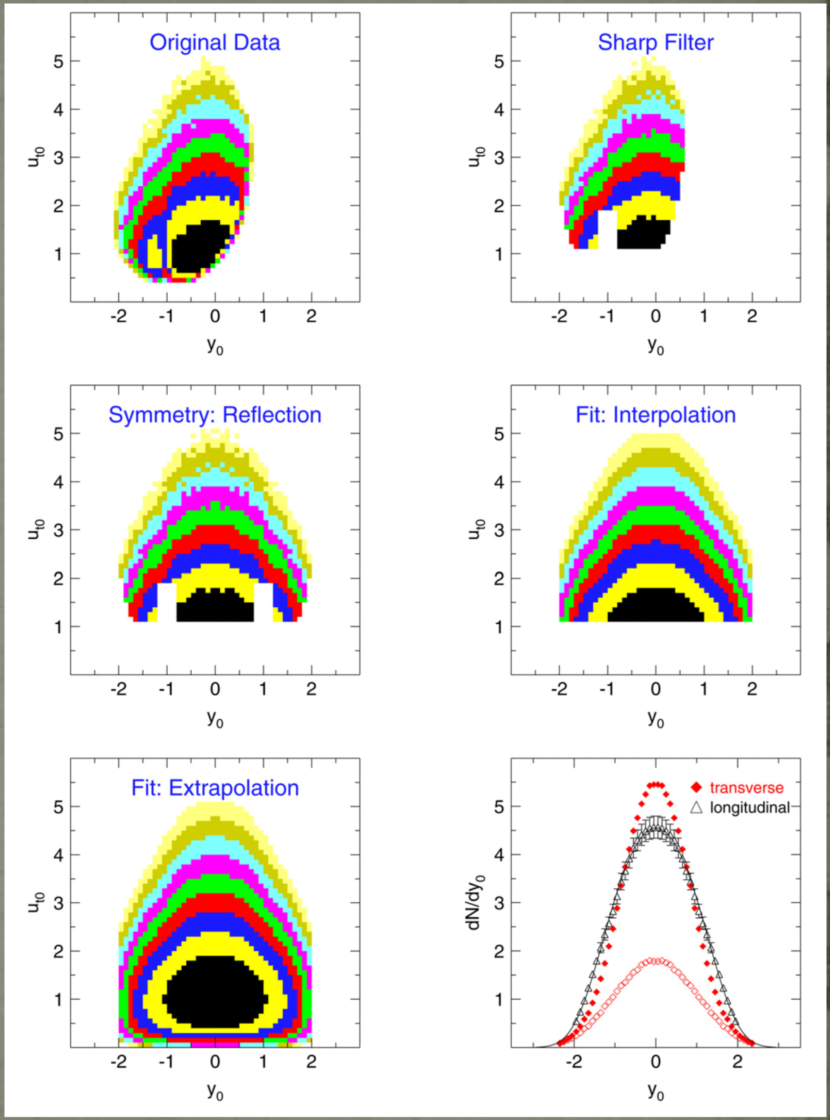



**Established N-N Cascade type picture**

# FOPI @ GSI



1 m
HELITRON
PLASTIC WALL
CDC
BARREL
MAGNET

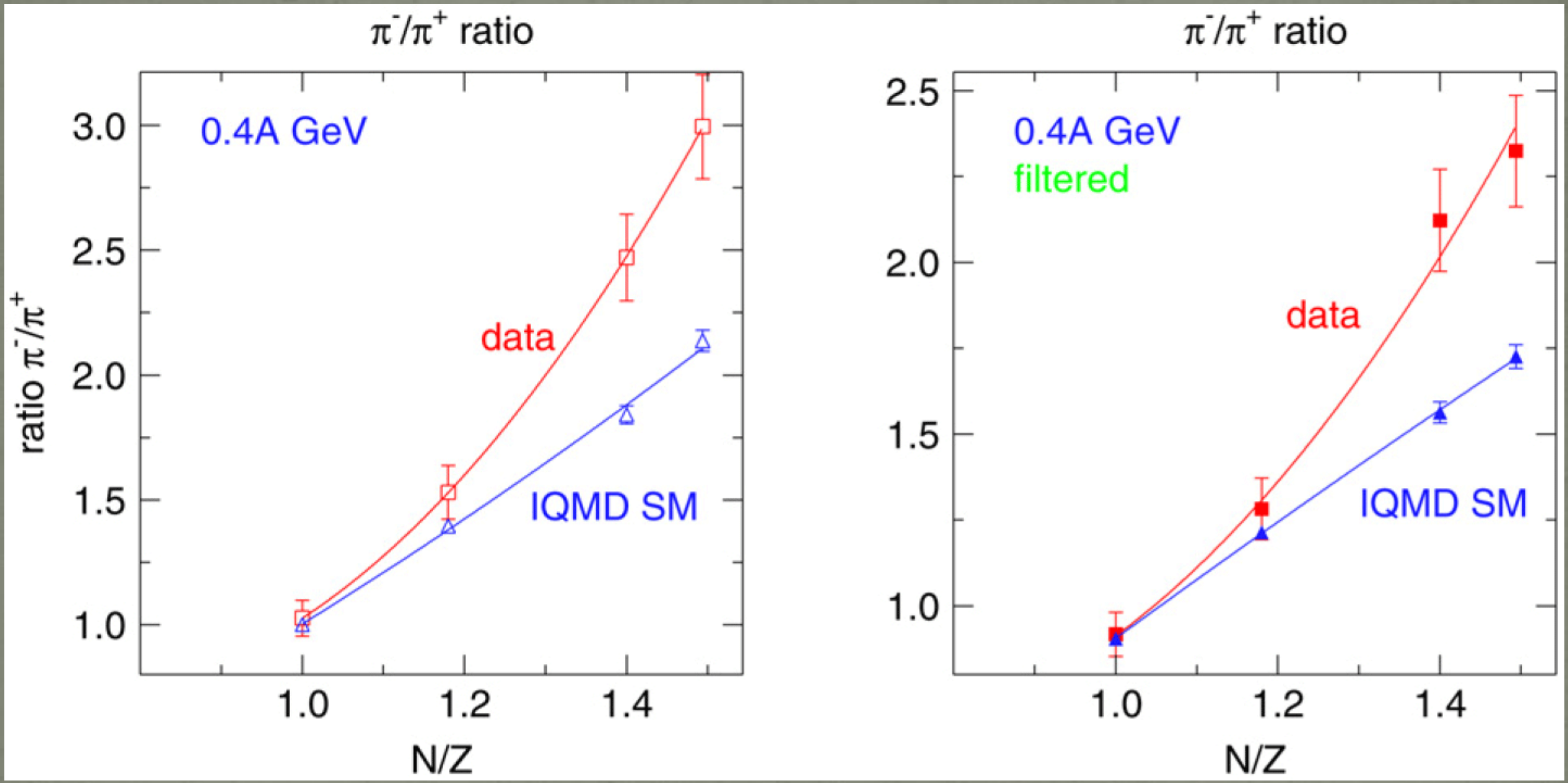



Original Data
Sharp Filter
Symmetry: Reflection
Fit: Interpolation
Fit: Extrapolation
transverse
longitudinal
$u_{t0}$
$y_0$
$dN/dy_0$

| reaction (used) | target thickness | isotopic enrich-ment | energy [AMeV] |
| --- | --- | --- | --- |
| $^{96}Ru+^{96}Ru$ | $431\,\mathrm{mg/cm^2}$ | 96.52 % | 400, 1000, 1528 |
| $^{96}Zr+^{96}Zr$ | $380\,\mathrm{mg/cm^2}$ | 95.6 % | 400, 1000, 1528 |
| $^{197}Au+^{197}Au$ | $202\,\mathrm{mg/cm^2}$ | 100 % | 400, 1000, 1490 |
| $^{40}Ca+^{40}Ca$ | $386\,\mathrm{mg/cm^2}$ | 96 % | 400, 1000, 1500 |

**Need efficiency correction**

# After all FOPI found…….



# Most of previous experimental studies

- Using mass-symmetric collisions so far

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

- Over-simplified the situation

  Impossible to distinguish different moving source frames, like

  NN cm, participant cm, nucleus-nucleus cm etc.

→ Better study mass-asymmetric collisions

# Well before start data taking of S$\pi$RIT

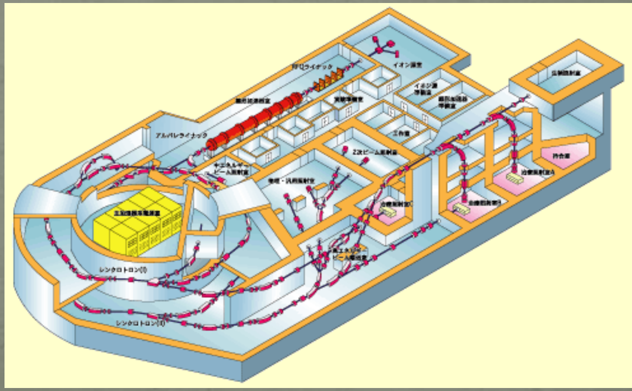
- We started pion experiments using HIMAC since 2007.

RI-beam >> require large acceptance

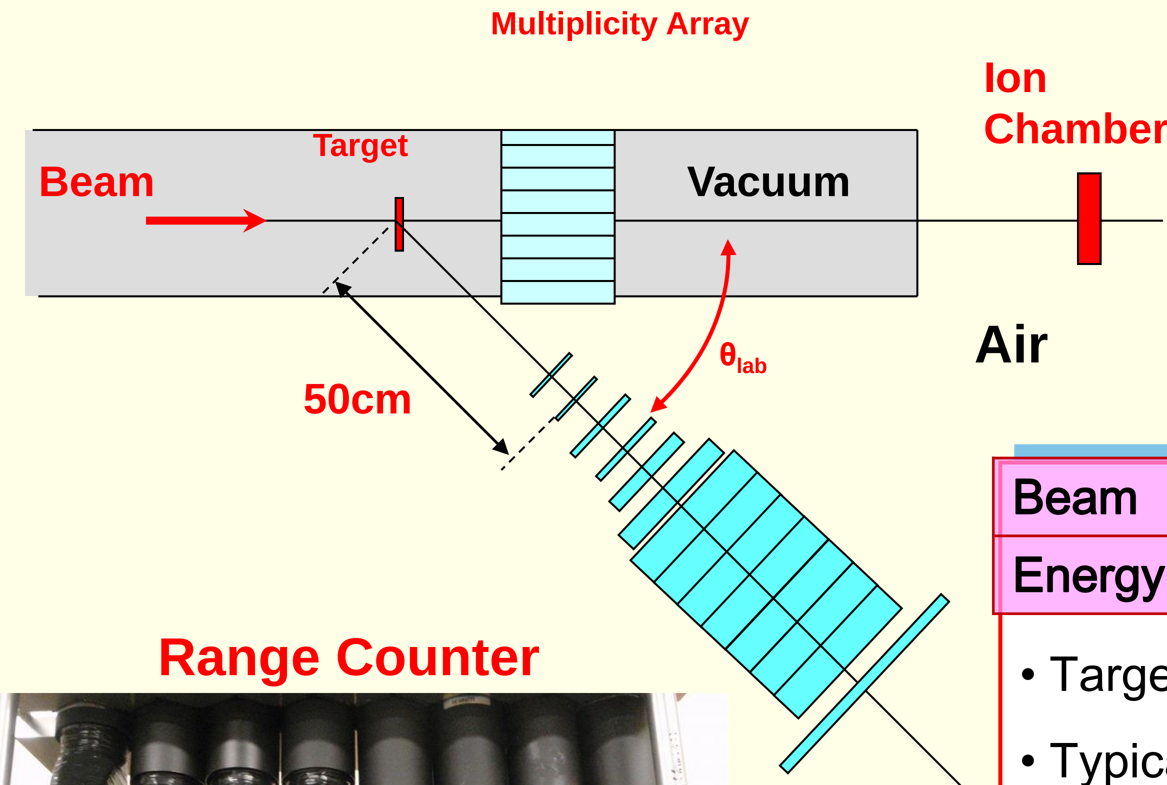
↔

Usual beam >> small acceptance may be usable

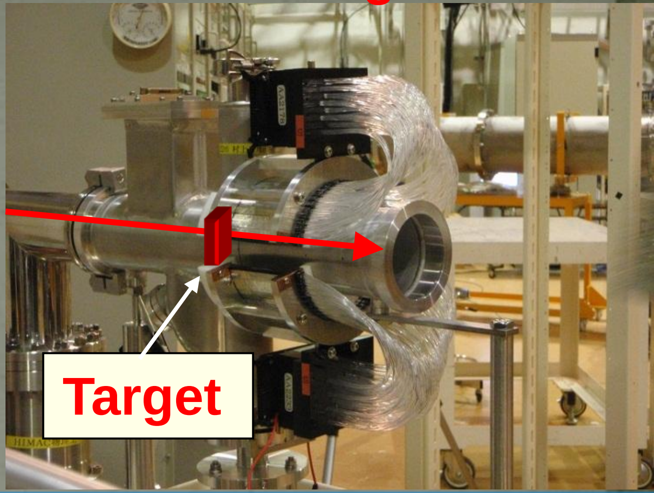
HIMAC; Heavy Ion Medical Accelerator in Chiba



# Pilot Experiments at HIMAC




**Multiplicity Array**
**27-58 deg.**

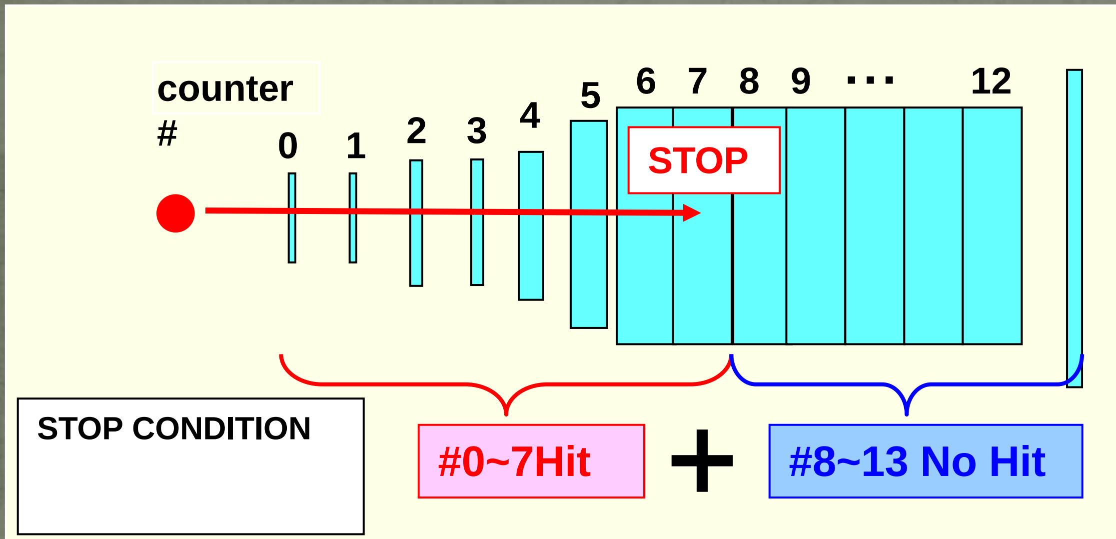



**Range Counter**

| 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

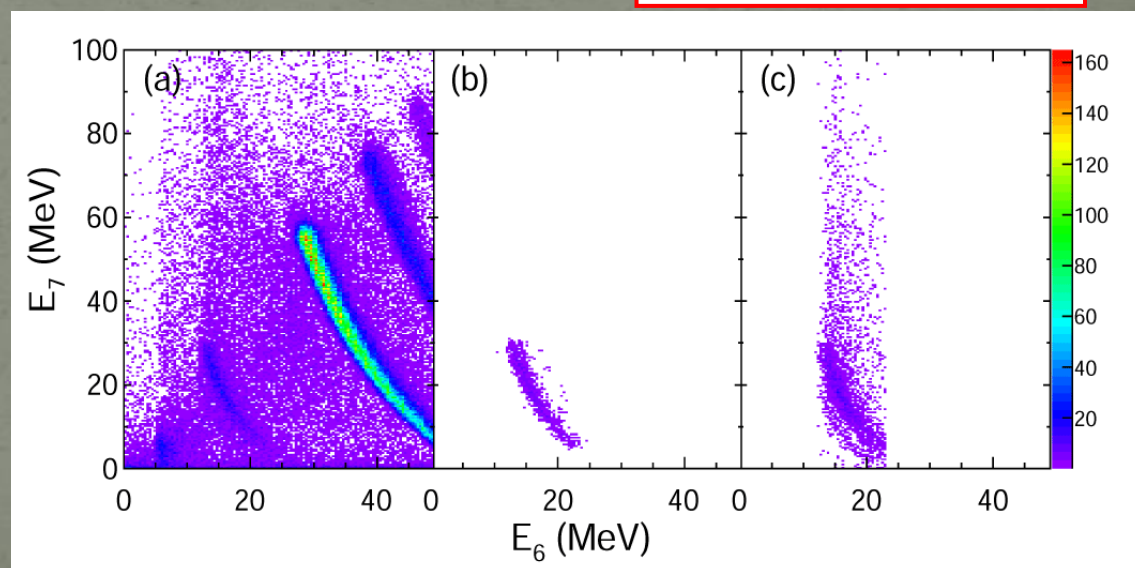



- $\pi^+$ decay to $\mu^+$

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

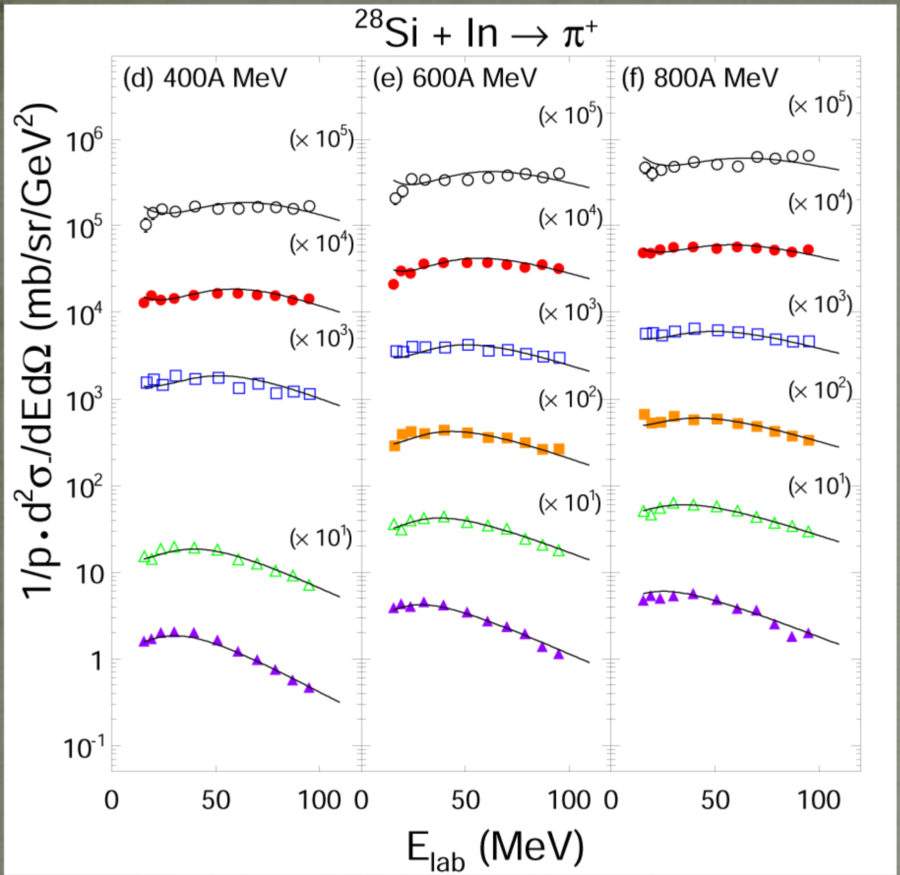
- $\mu^+$ : Energy ~ 4 MeV
  : Range ~ 1 mm

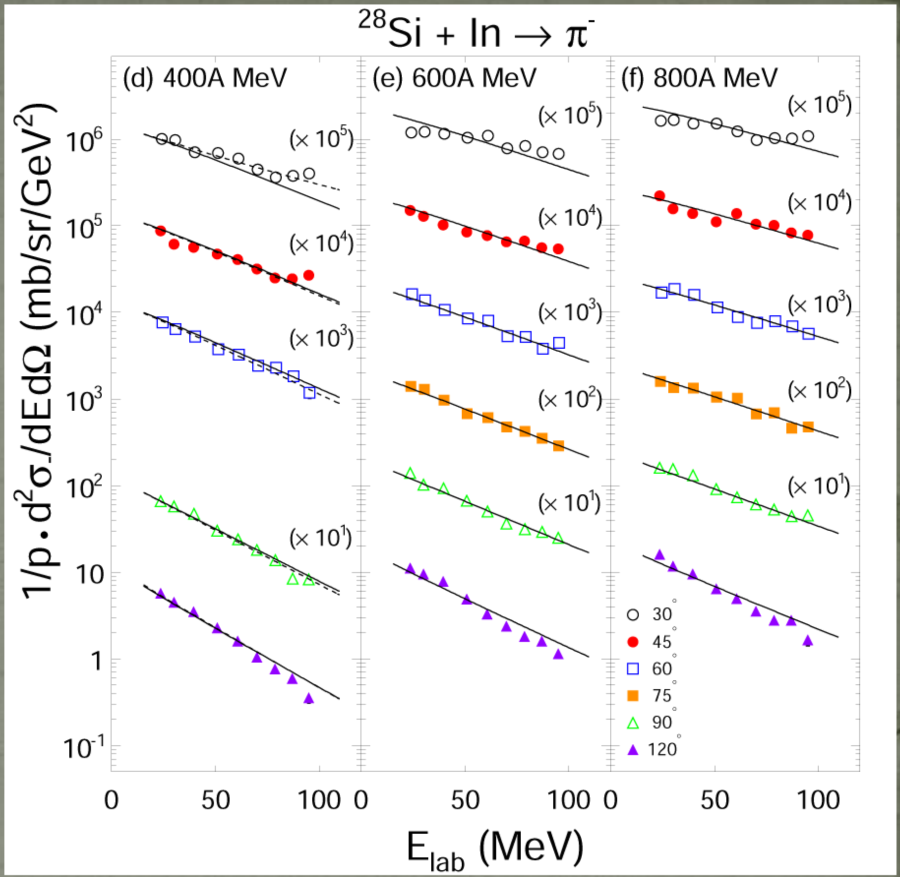
**Double pulse in one layer**




- ～400MeV/u
  Pion's are rare

  less than 1/100 of protons




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

$$E_{mov} = \gamma_{mov}(E_{lab} - \beta_{mov} p_{lab} cos\theta_{lab}),$$
$$P(E_{mov}) = \Delta B_c / E_{mov} ln\{1 + exp[(E_{mov} - B_c)/\Delta B_c]\}.$$

$$1 + a_2 cos^2\theta_{mov} \qquad p_{mov} cos\theta_{mov} = \gamma_{mov}(p_{lab} cos\theta_{lab} - \beta_{mov} E_{lab})$$

**Using other functional form one couldn't fit data so well so far……..**

# Fitting parameters

| $E_{beam}$ (MeV) | $\beta_{mov}$ | $E_0$ (MeV) | $N_-$ | $N_+$ | $B_c$ | $\Delta B$ | $a_2^*$ |
|---|---|---|---|---|---|---|---|
| 400A | 0.19(1) | 36.5(15) | 13.8(8) | 15.8(19) | 28.4(19) | 9.3(5) | – |
| | 0.20(1) | 37.0(12) | 12.6(6) | 14.6(13) | 28.8(14) | 9.5(4) | 0.26(7) |
| 600A | 0.19(1) | 44.3(16) | 22.2(9) | 23.0(20) | 23.0(15) | 8.5(5) | – |
| | 0.19(1) | 44.0(18) | 22.6(11) | 23.5(23) | 23.0(16) | 8.5(5) | -0.05(5) |
| 800A | 0.23(1) | 51.8(23) | 26.4(11) | 25.7(23) | 20.7(17) | 9.1(6) | – |
| | 0.22(1) | 51.5(24) | 27.2(13) | 26.5(26) | 20.8(17) | 9.1(6) | -0.11(5) |

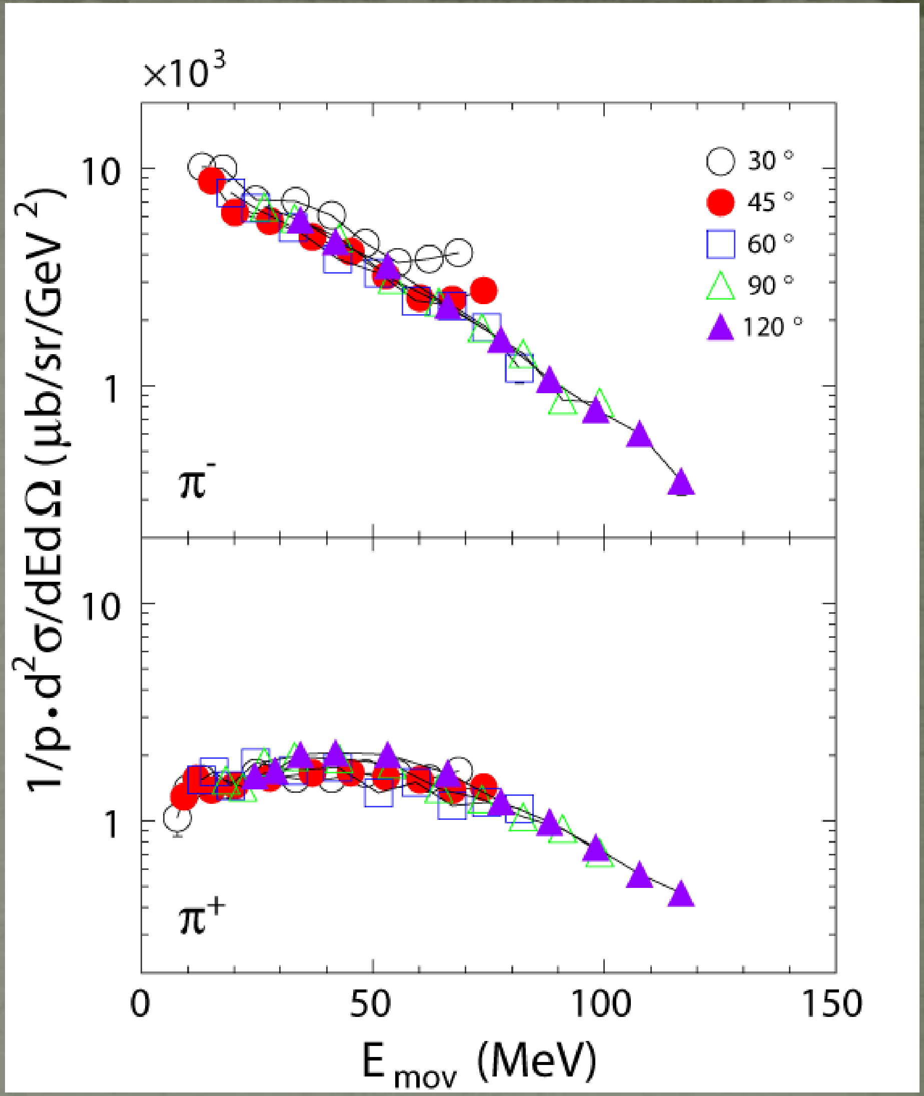
| $E_{beam}$(MeV/nucleon) | $\sigma_{exp}(\pi^+)$ | $\sigma_{exp}(\pi^-)$ |
|---|---|---|
| 400 | 0.33 | 0.63 |
| 600 | 0.87 | 1.37 |
| 800 | 1.41 | 2.10 |

Using moving source frame, it well overlaps.

Isotropic emission from single moving source

Very slow!!!

not mid-rapidity




At 400MeV/nucleon

**Similar phenomena have been observed by INDRA-ALADIN Collaboration; Eur. Phys. J. A 21, 293 (2004)**

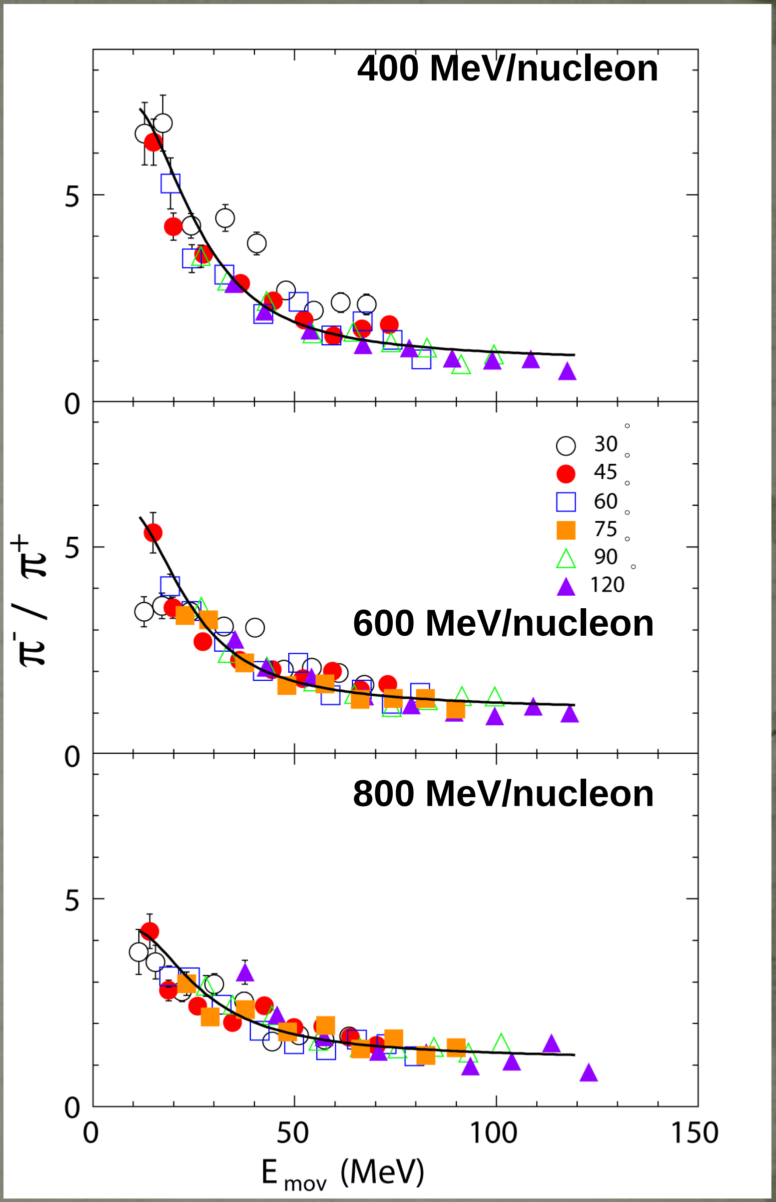
# Differential $\pi^-/\pi^+$ ratio

Weak angular dependence

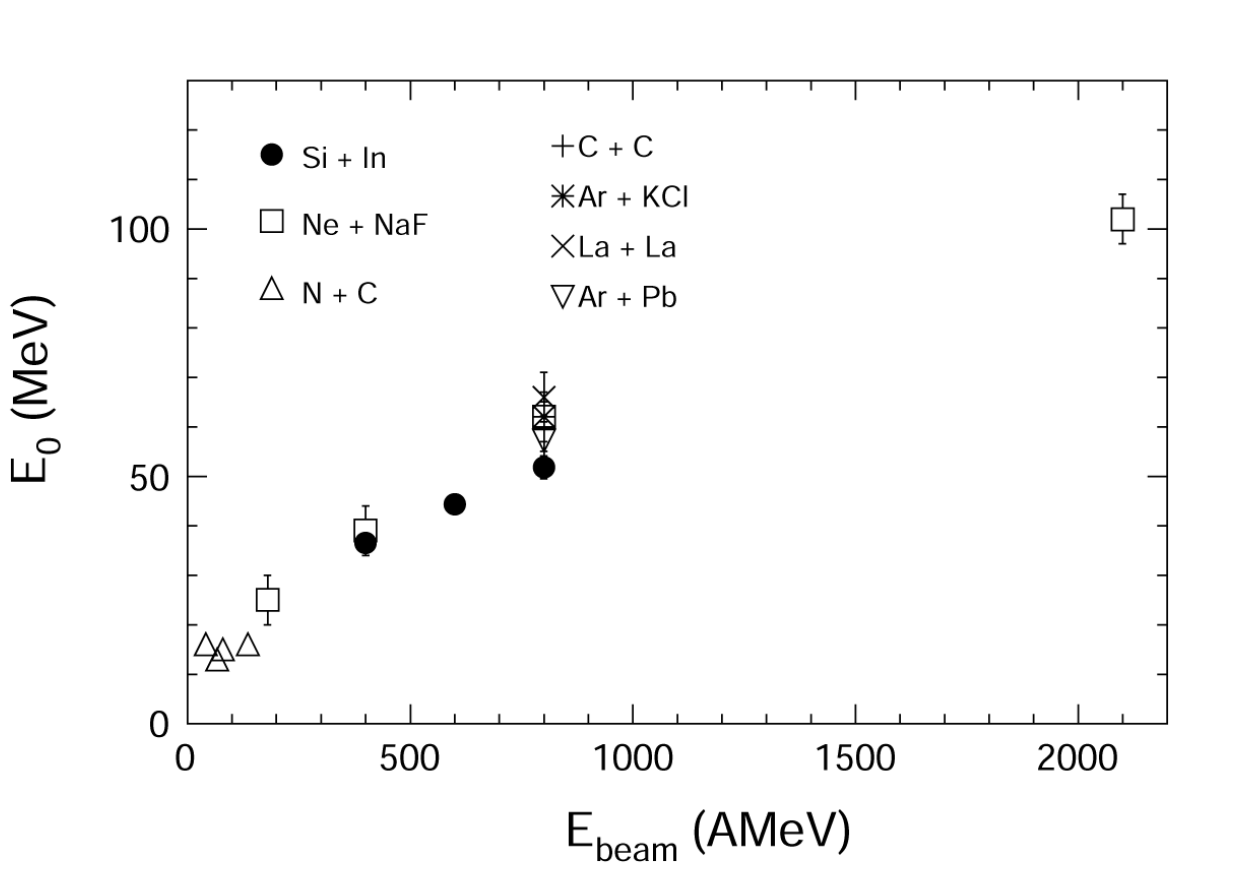
Clear energy dependence

**Simple Coulomb effect?**

**Ratio alone can be fitted by functional form of Maheswari et al. (NP A628 (1998) 669), but**
**It seems to be impossible to reproduce differential cross sections**

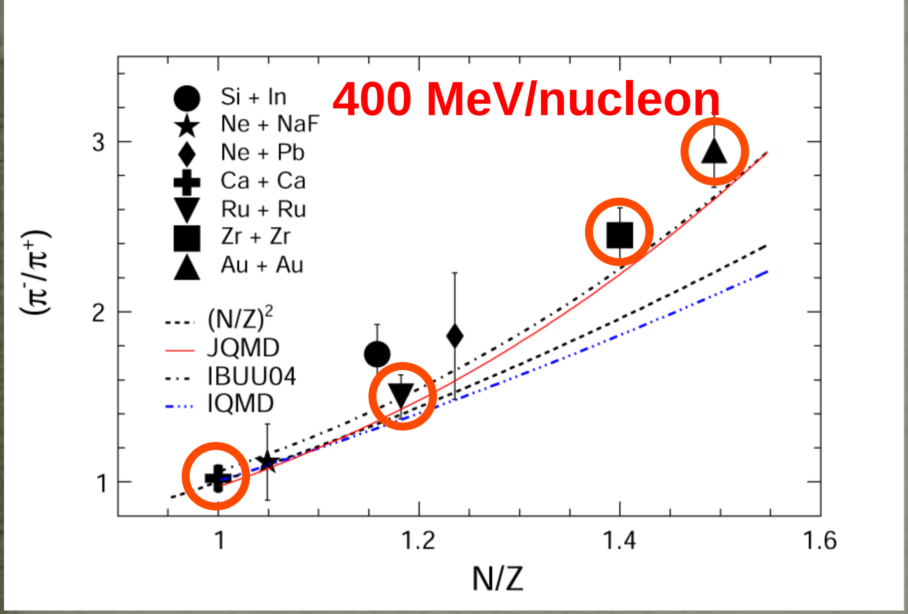


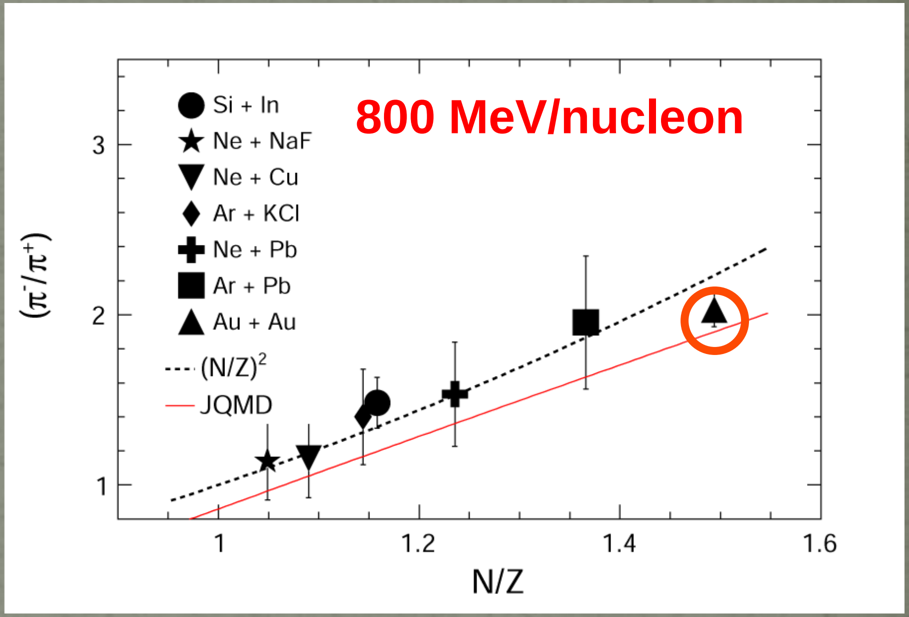
# Using fitted results




# Slope parameters are consistent with old measurements

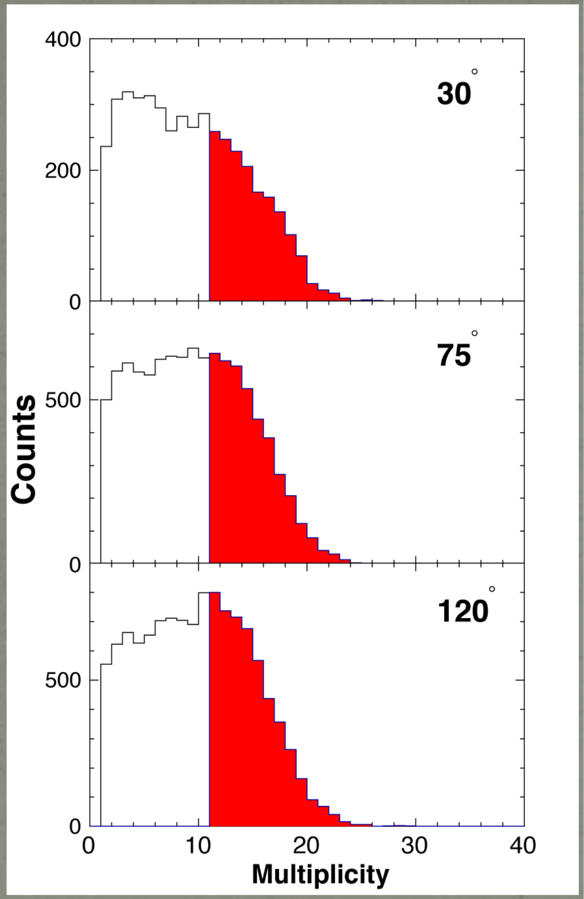
# $\pi^-/\pi^+$ total ratio vs (N/Z) close to $(N/Z)^2$



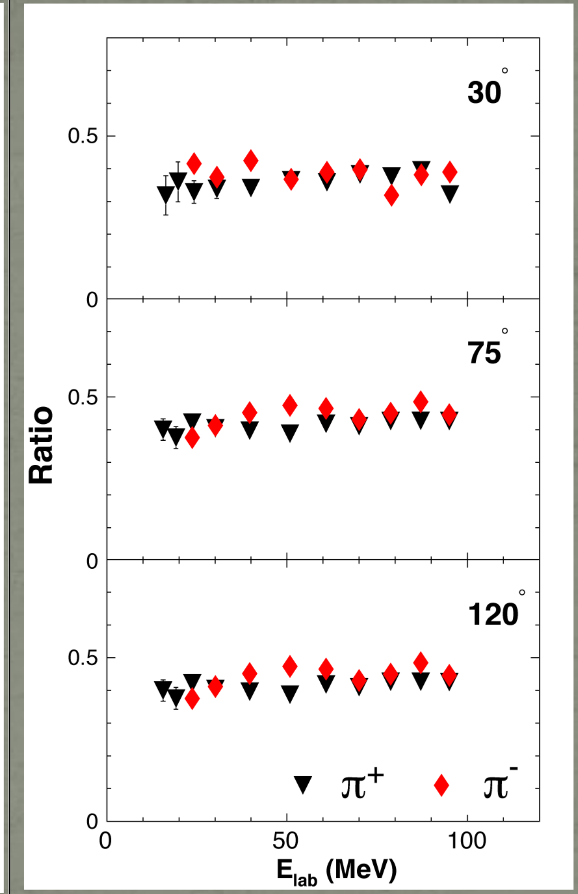




NB: N, Z are estimated for participant IBUU04,IQMD. FOPI data are for the central

# Example of Multiplicity dependence at 600 MeV/nucleon



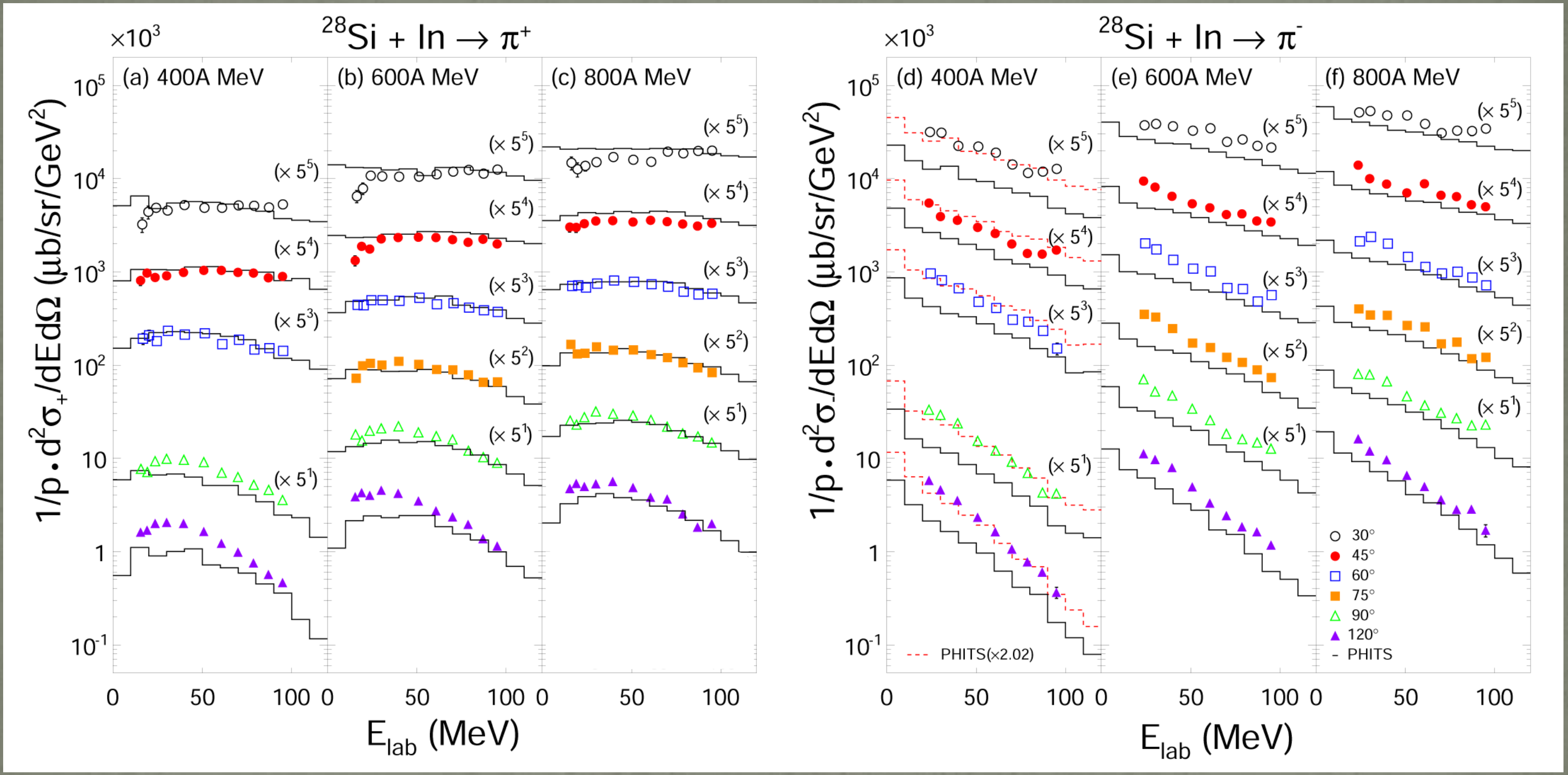

$\pi^+$ associated multiplicity




High multiplicity event/total event

# Can we understand these features with a transport model?

# 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 |
| | $\pm 7\%$ | $\pm 10\%$ | | |

| $E_{beam}$(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 |

# Summary

- Measured doubly differential cross sections of $\pi^+$ and $\pi^-$ for the $^{28}Si$ + In reactions at 400, 600 and 800 MeV/nucleons.
- They are emitted almost 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.

# Collaborators

M, Sako1;2,
T, Murakami1;2,
Y, Nakai2,
Y. Ichikawa1,
K. Ieki3,
S. Imajo1,
T. Isobe2,
M. Matsushita3,
J. Murata3,
S. Nishimura2,
H. Sakurai2,
R.D. Sameshima1,
E. Takada4,

1. Kyoto University
2. Riken
3. Rikkyo University
4. NIRS