中間エネルギー重イオン衝突における荷電パイオン生成

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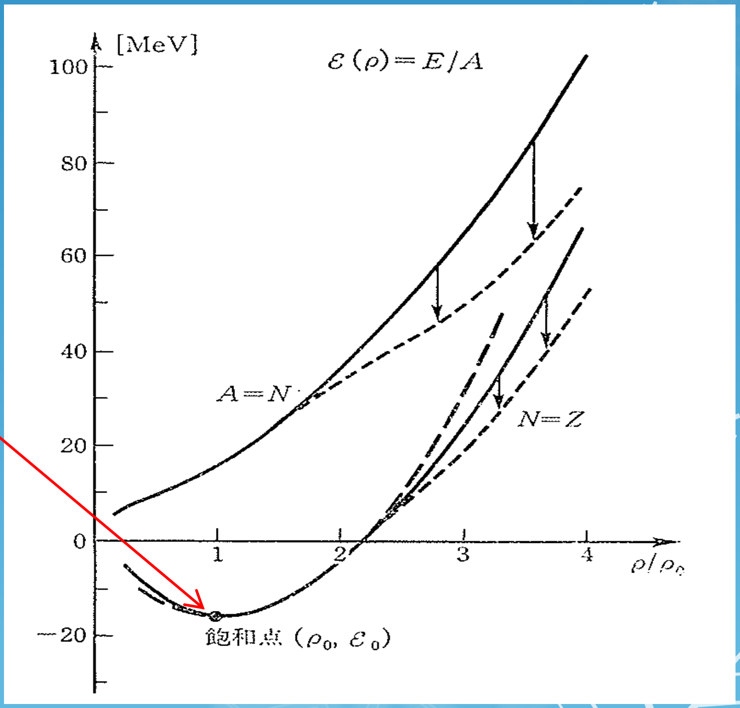
Contents

- イントロダクション
  - 荷電Pionの測定
- 実験紹介
  - パイオンレンジカウンター
- 議論
  - π-/π+比のビームエネルギー依存性とN/Z依存性

原子核物質(Nuclear Matter)

- クーロン力を無視して、核力のみが働く無限の核子系として核物質という概念を導入した。
- 飽和性
  - ρ_0=0.16 nucleon・fm^{-3}
  - E/A ~ -16 MeV
- 高密度を実現するには重イオン衝突



状態方程式Equation of State (EoS)

- EoS : the pressure (P) in nuclear matter is expressed as the function of density(ρ), temperature(T), and asymmetric parameter(δ)

energy/nucleon　　entropy/nucleon

$$P = P(\rho,T,\delta) = -\left.\frac{\partial F}{\partial V}\right|_{T,\delta} ; F(\rho,T,\delta)/A = \varepsilon(\rho,T,\delta) - T\sigma(\rho,T,\delta)$$

- EoS at zero temperature (for neutron stars)

$$P = P(\rho,0,\delta) = -\left.\frac{\partial E}{\partial V}\right|_{T,\delta} = \rho^2 \left.\frac{\partial E(\rho,0,\delta)}{\partial \rho}\right|_{T,\delta}$$

$\rho_{n,p}$: neutron, proton density

→ $\rho = \rho_n + \rho_p$

saturation density : ρ_0 ~0.16 fm^{-3}

δ: isospin asymmetric parameter

$\delta \equiv (\rho_n - \rho_p)/(\rho_n + \rho_p)$

EoS for asymmetric nuclear matter

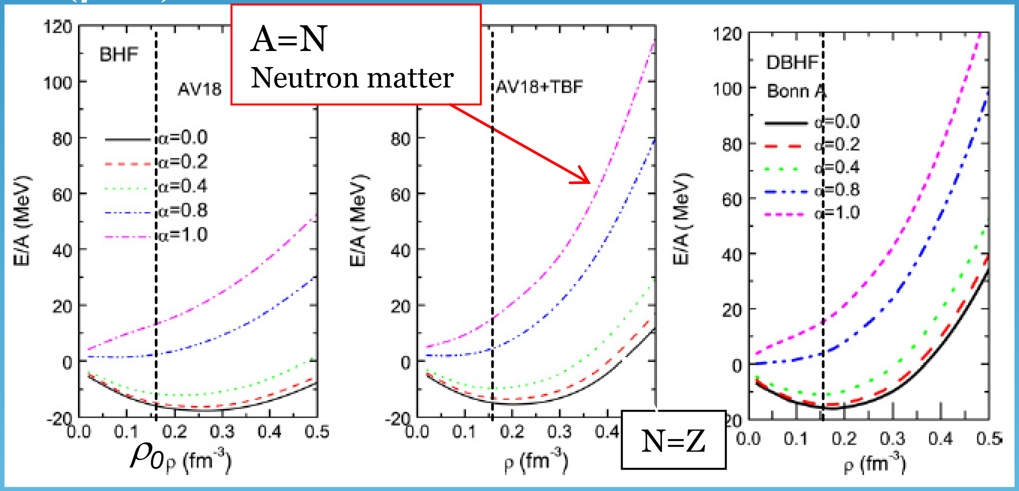
- The energy per nucleon in the isospin asymmetric nuclear matter

negligible

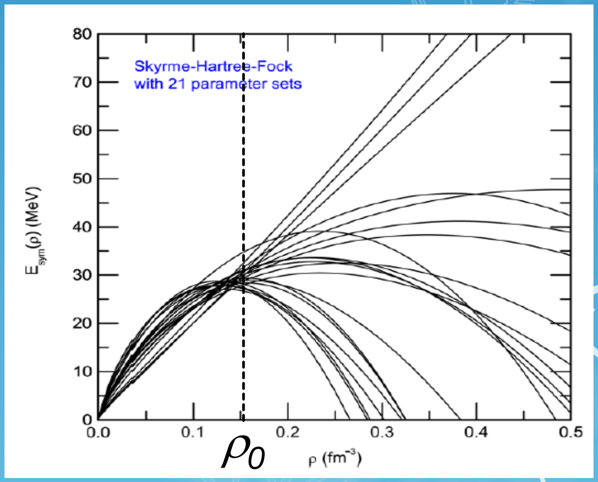
$$\varepsilon(\rho,\delta)=\varepsilon(\rho,0)+E_{sym}(\rho)\delta^2+O(\delta^4)$$

Symmetric part | Asymmetric part

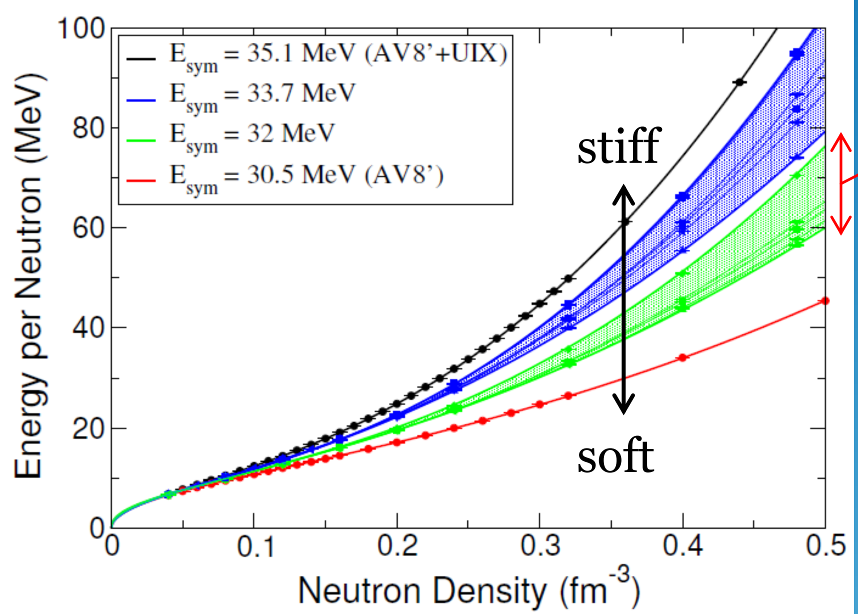
$\varepsilon(\rho,\delta)$



$E_{sym}(\rho)$: Symmetry Energy



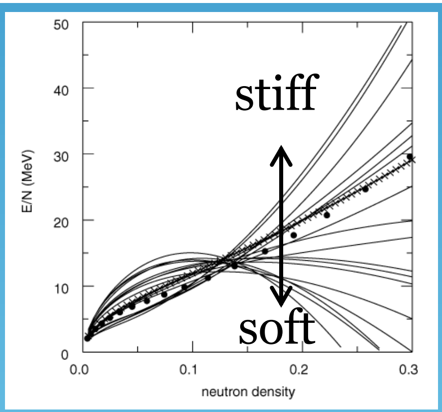
Eos and Neutron Star

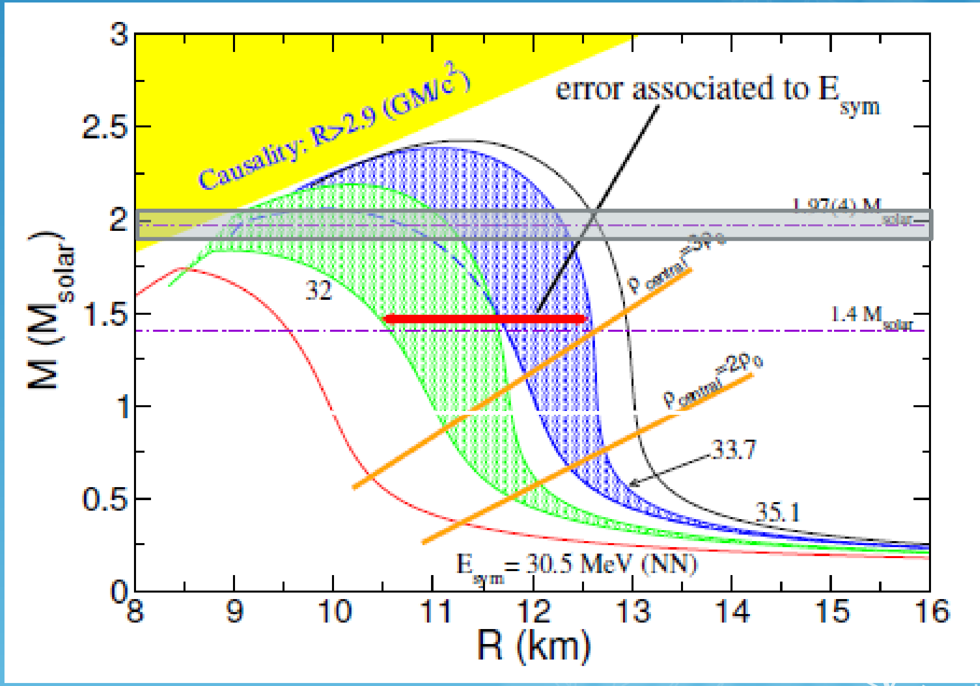


dierent forms of
three-neutron interaction

TOV(Tolman–Oppenheimer–Volkov) equation

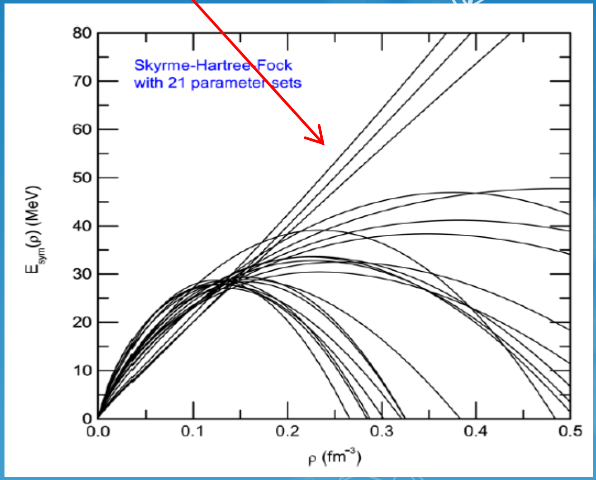
$$\frac{dP}{dr} = -\frac{[\rho(r) + P(r)][M(r) + 4\pi, r^3 P(r)]}{r^2 - 2rM(r)},$$





Symmetry Energy at supra-saturation density

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



- High density behavior of symmetry energy is not fixed.
- Probes
  - n/p differential flow,n-p correlation flow, π^-/π^+, Σ^-/Σ^+, K^0/K^+ , etc
- We select π^-/π^+ ratio from heavy-ion collision at intermediate energy (several hundred MeV/u)
  - density of overlap region ~ 2 ρ_0
  - Nearby pion threshold → pion is created by decay of Δ particles

Pion production from heavy-ion collision

- E_{beam}<1 GeV/u
  - ほぼ、decay of Δparticles
  - Δ resonance model

	π^+	π^0	π^-
nn	0	1	5
pp	5	1	0
np = pn	1	4	1

$$\pi^- / \pi^+ \equiv (5N^2 + NZ)/(5Z^2 + NZ) \approx (N/Z)^2$$

- 生成された荷電パイオン比は反応過程でのN/P比を反映した観測量となっている

Theoretical Calculation

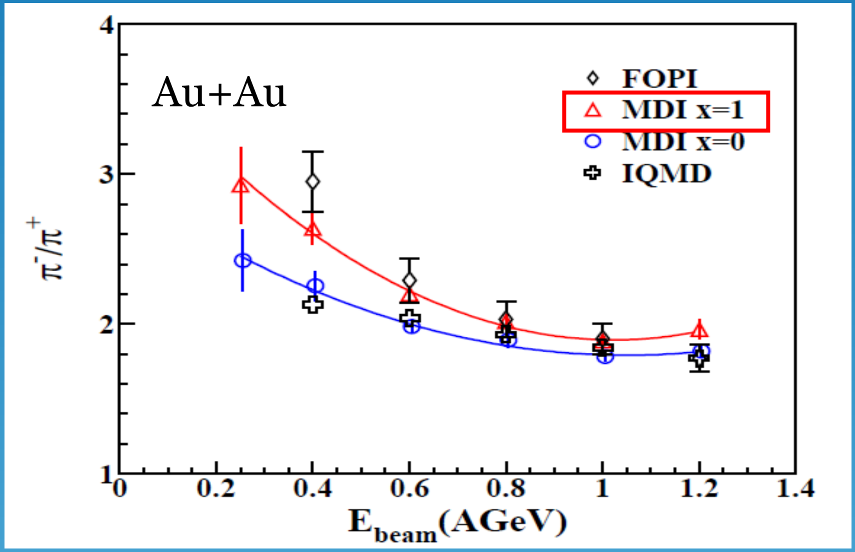
- IBUU：isospin-dependent Boltzmann-Uehling-Uhlenbeck

$$\frac{\partial f}{\partial t} + v\nabla_r f - \nabla_r U \nabla_p f = -\int \frac{d^3 p_2 d^3 p_{1'} d^3 p_{2'}}{(2\pi)^9} \sigma v_{12} [f f_2 (1-f_{1'})(1-f_{2'}) - f_{1'} f_{2'} (1-f)(1-f_2)]$$
$$\times (2\pi)^3 \delta^3 (p + p_2 + p_{1'} + p_{2'})$$

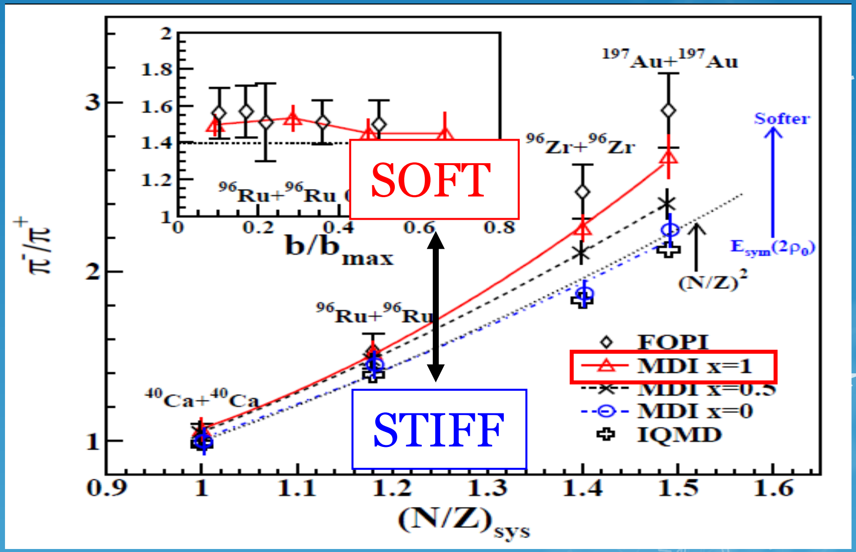
- f：nucleon phase space distribution function
- 一粒子hamiltonian h(r,p)=p^2/2M+u(r,p)
- f(r,p)に従って分布するテスト粒子を平均場の元で二核子衝突を記述する。平均場の中に取り入れるEoSの違いが反応に関与するp,nを決定し、生成されるパイオンにEoS反映される
- x parameter：EoSの性質を変えずに、対称エネルギーの密度依存性を変化させる為の変数。
- 衝突項（右辺）=0にするとVlasov equationとなる。

π-/π+の依存性

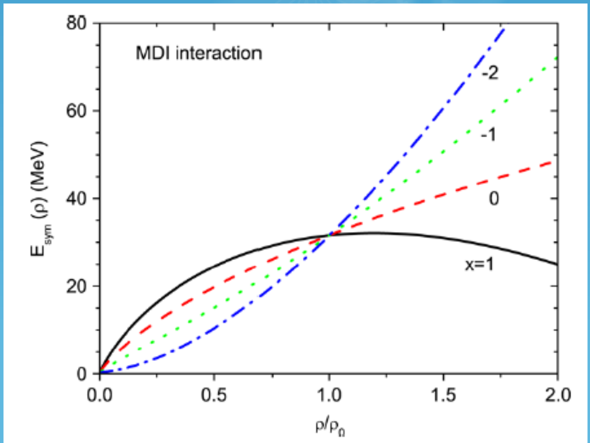
ビームエネルギー依存性



N/Z依存性



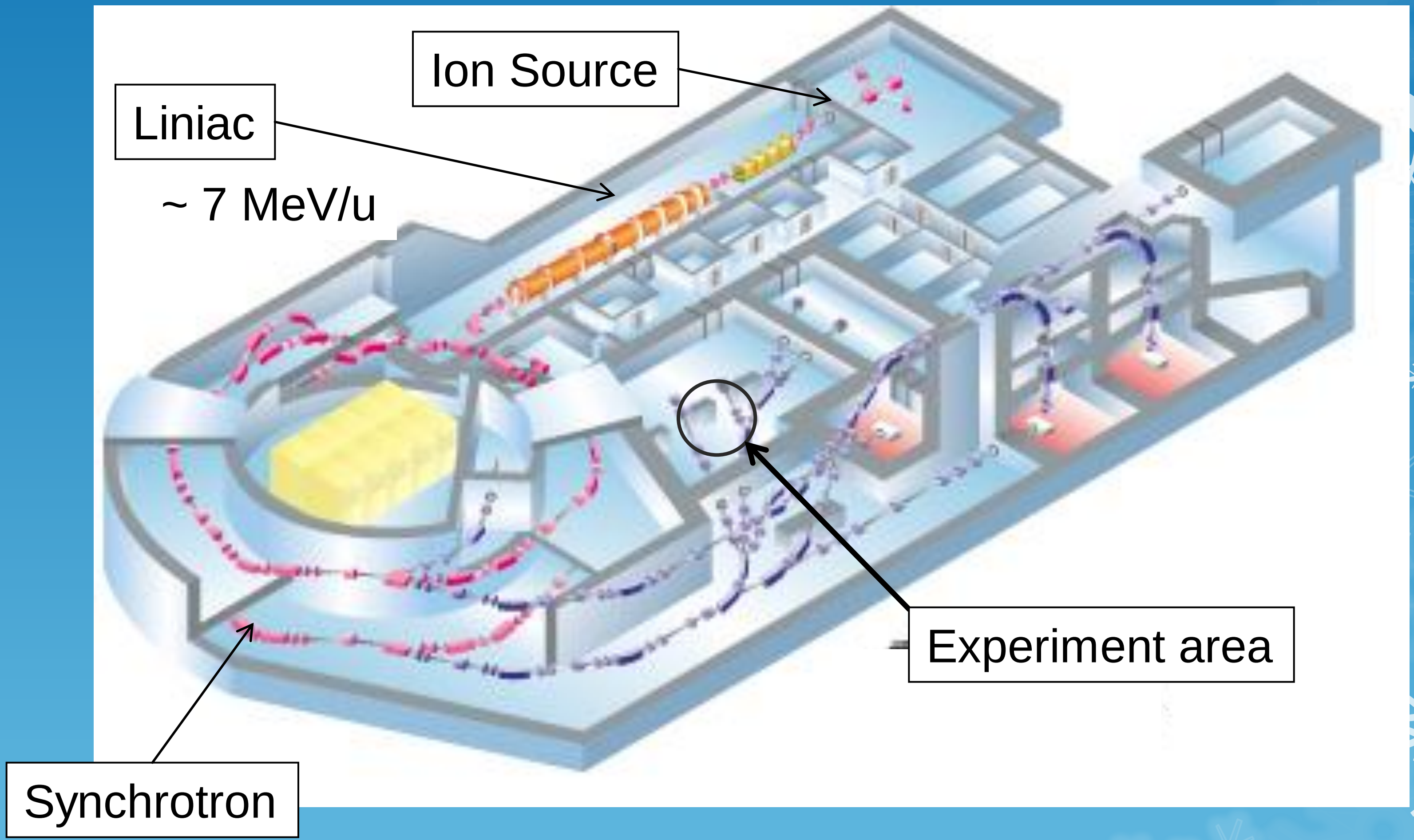
Zhigang Xiao et al. arXiv:0808.0186v2[ncl-th]19Jan2009



我々の実験の特徴

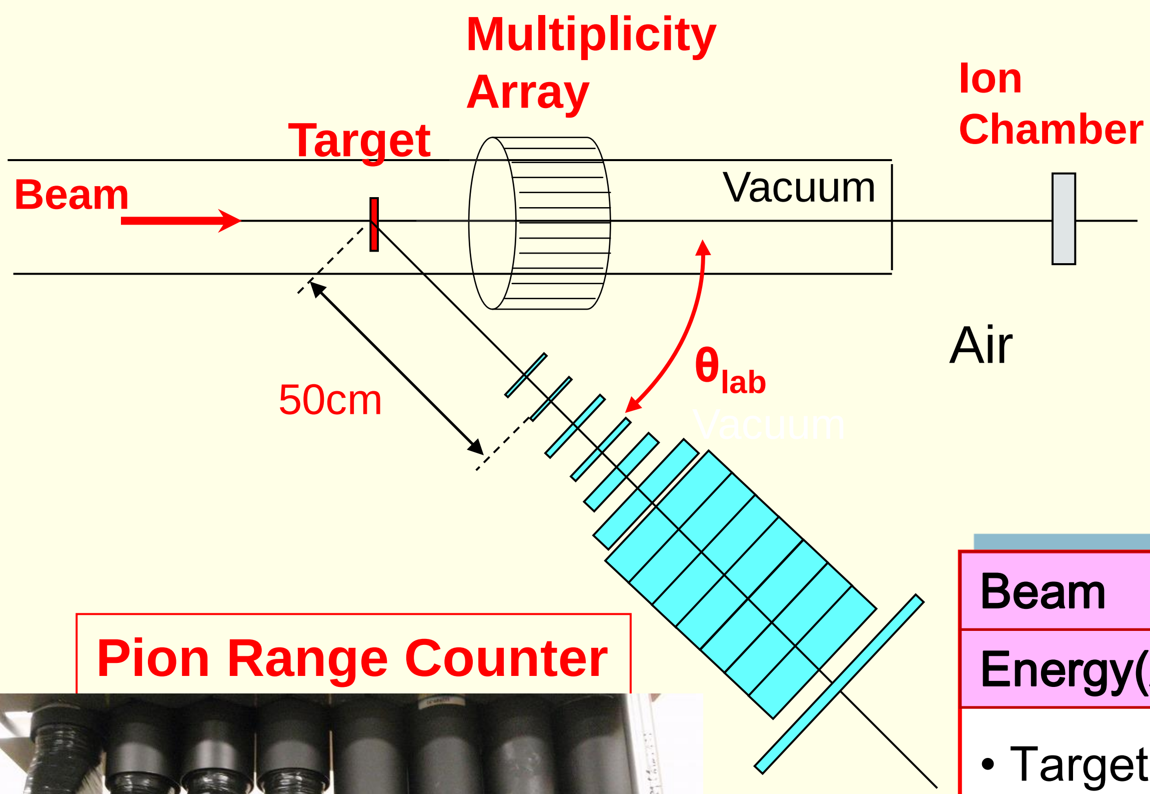
- シンプルな装置、荷電パイオンを同時に、かつ広いエネルギーレンジでの測定
- Beam energy dependence using Si beam
  - 400, 600, 800 MeV/nucleon
  - Mass asymmetric reaction : Si + In (A=28,115)
    - We can get the information of the rapidity of pion source.
- Xe+In at 400MeV/nucleon
  - N/Z dependence
- Xeアイソトープ+CsI at 400 MeV/nucleon

HIMAC :
Heavy Ion Medical Accelerator in Chiba

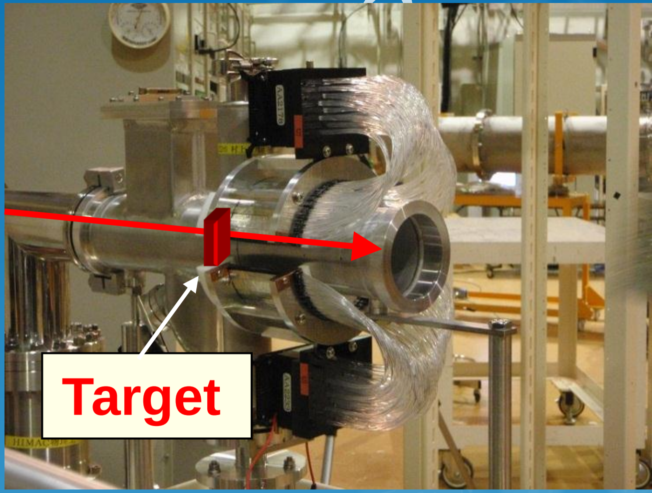


Max energy : 800 MeV/u

Experimental Setup



Multiplicity Array

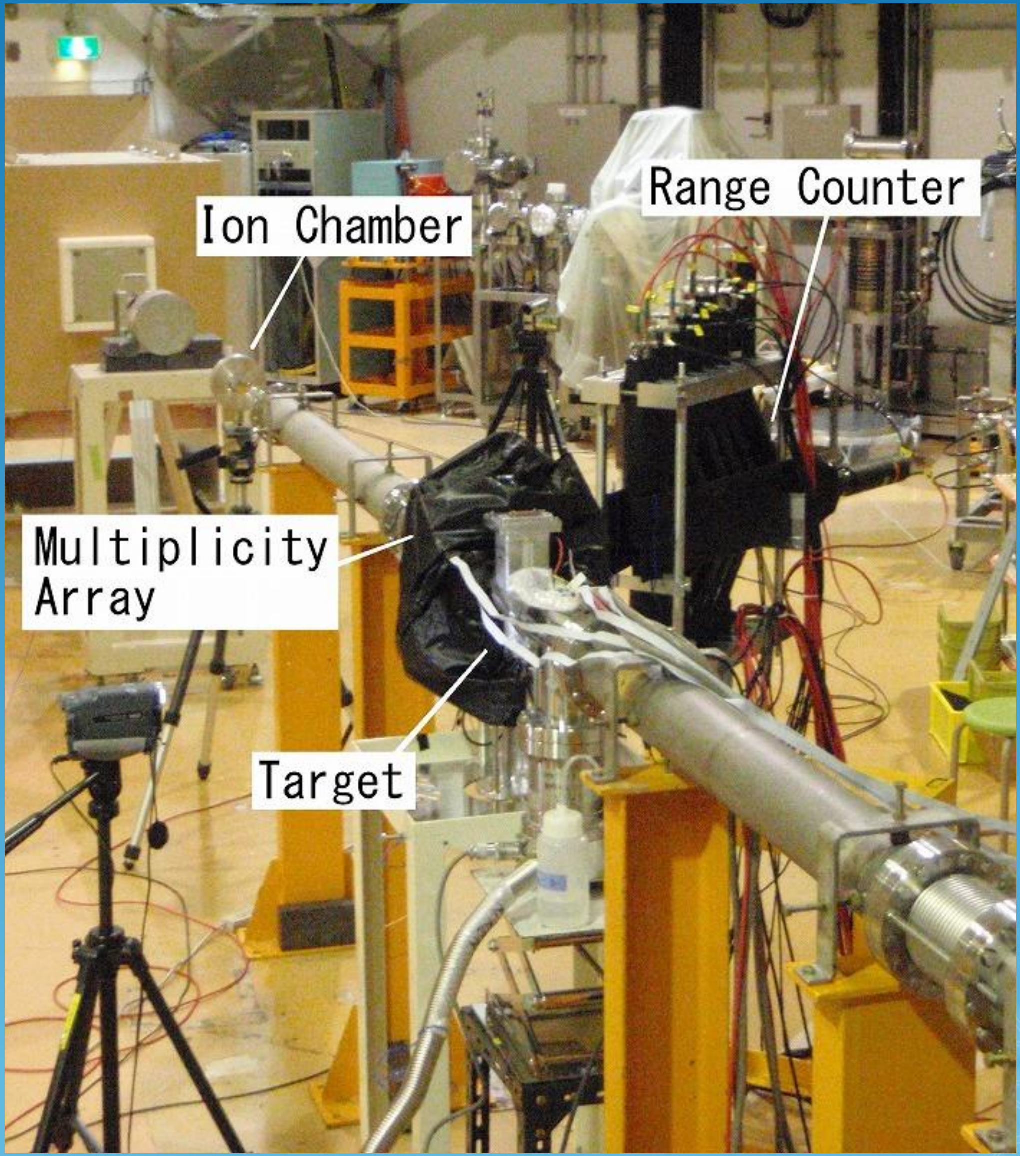


Pion Range Counter

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 (θ_{lab})
  : 30, 45, 60, 75, 90, 120 degree
- solid angle : 10 msr

Experimental Setup



π^+ と π^-の同定原理

＜In flight＞ dE/dx is identical for both π^+ and π^-

＜After STOP＞

π^+

- π^+ decay to μ^+

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

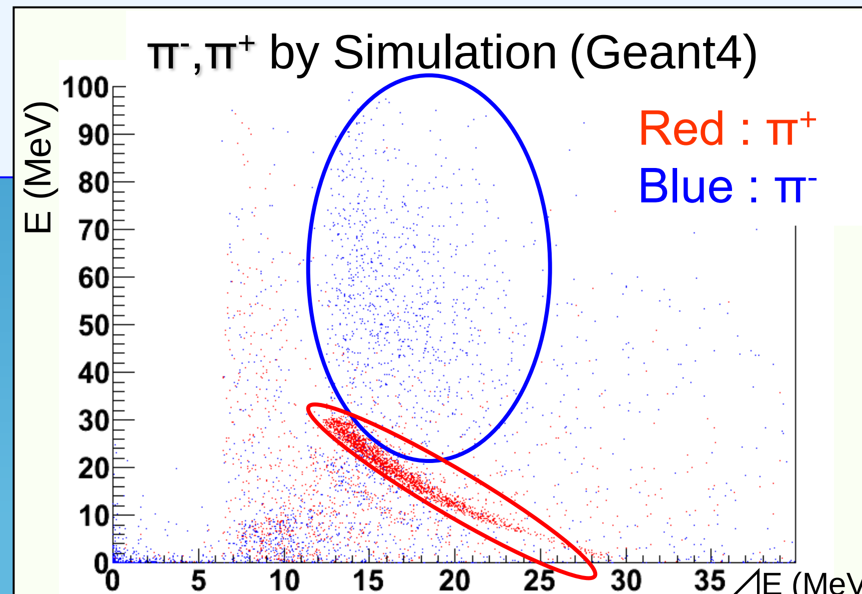
- μ^+
  - Energy ~ 4 MeV
  - Range ~ 1 mm

→ π^+ : Double Hits in one counter

π^-

- create a pionic atom and captured by a nucleus
- decay to various particles

→ Unable to use the same identification method as π^+



＜π identification step＞

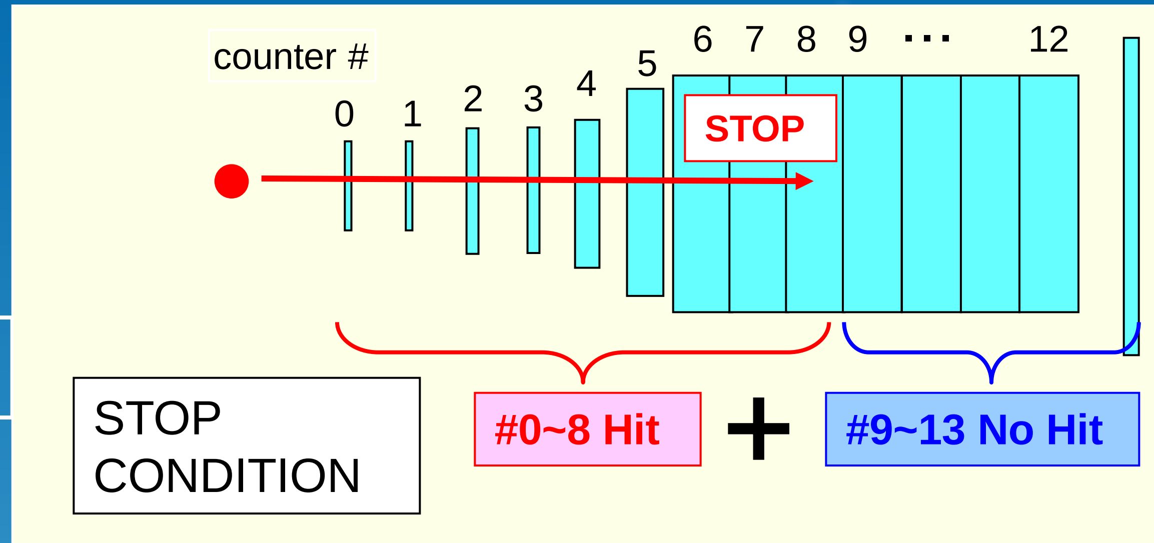
① π^+ ID using Double Hit Condition

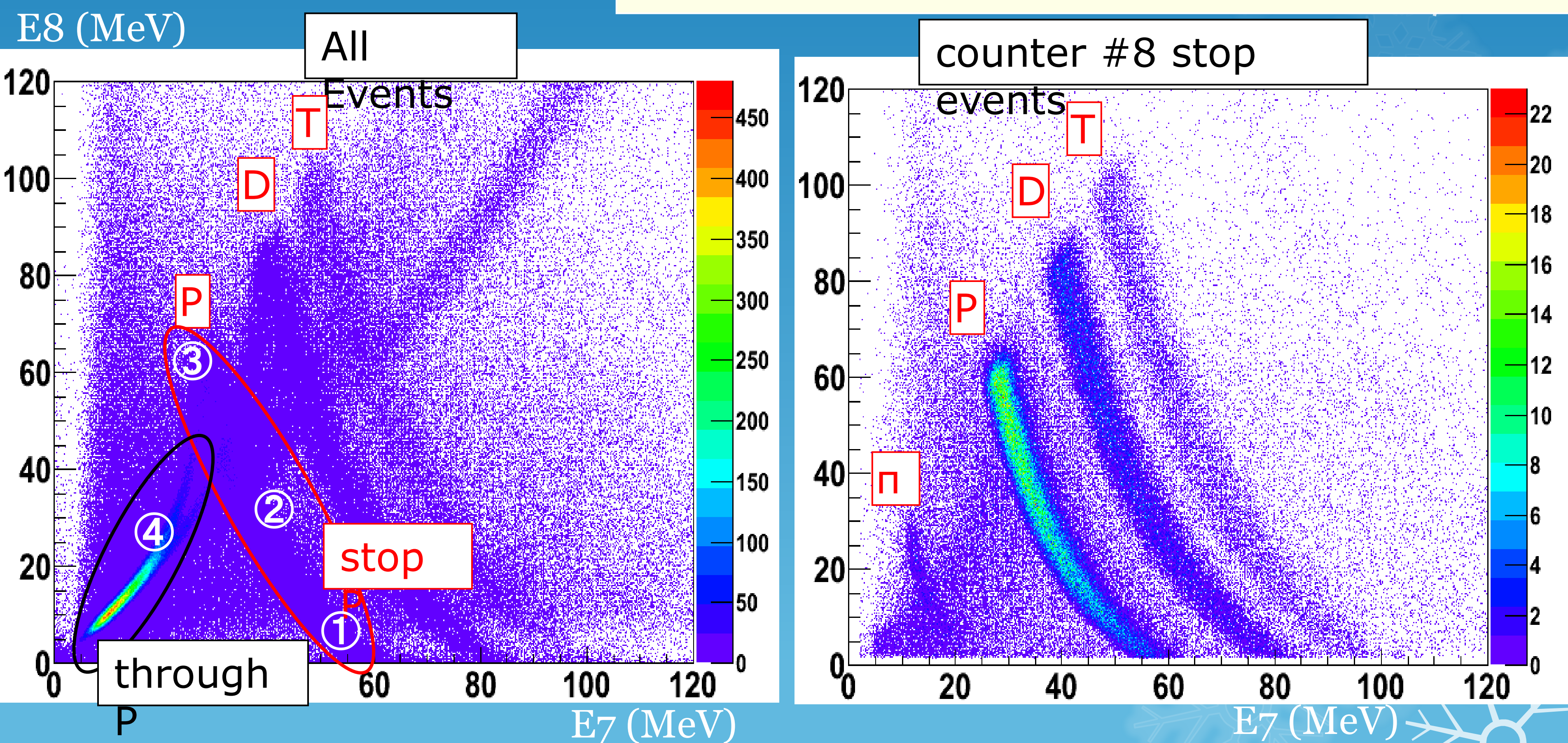
② $\pi^\pm$ID using ⊿E conditions of well defined π^+

③ $\pi^- = \pi^\pm - \pi^+$

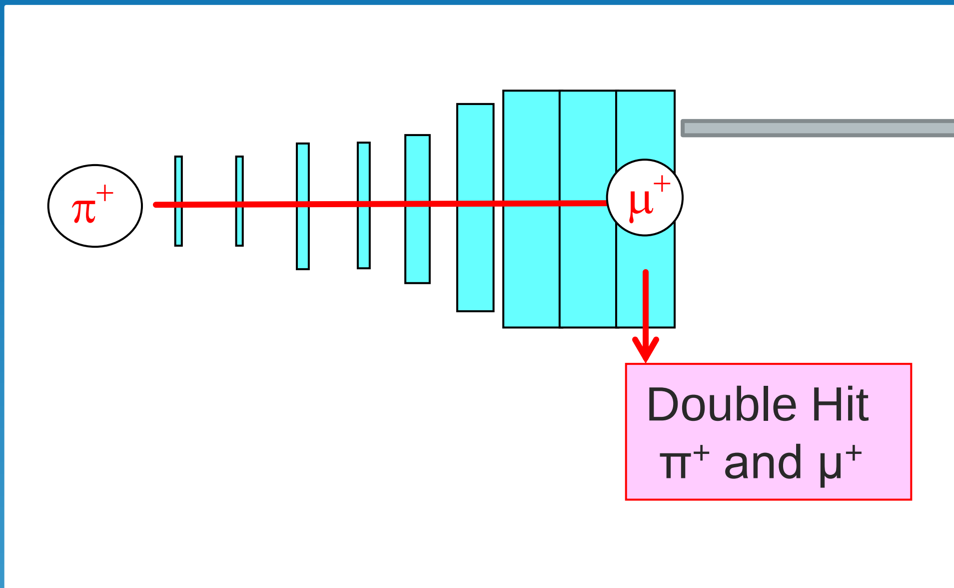
Histogram of Range Counter

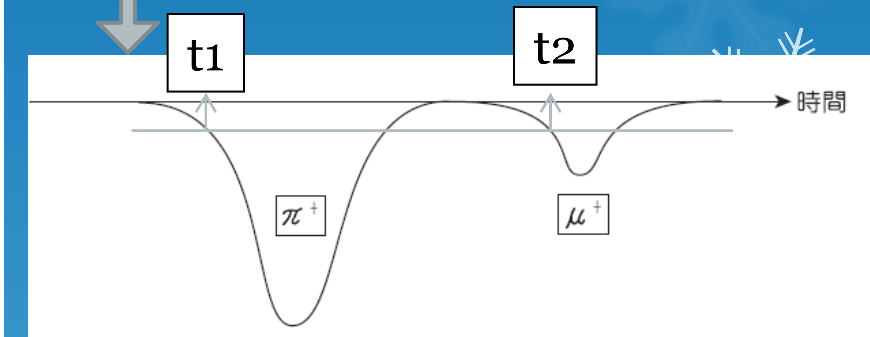
Example counter : #8



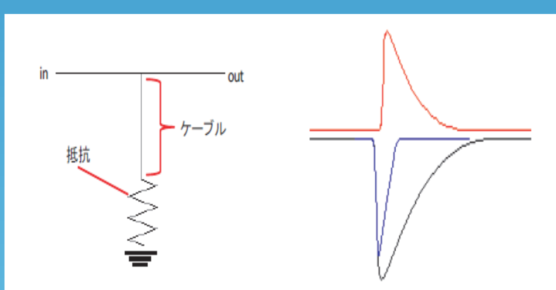


Double Hit Condition



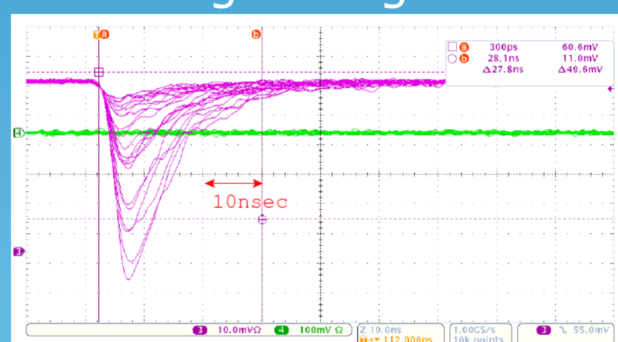


クリッピングを行い、信号幅を10nsecに

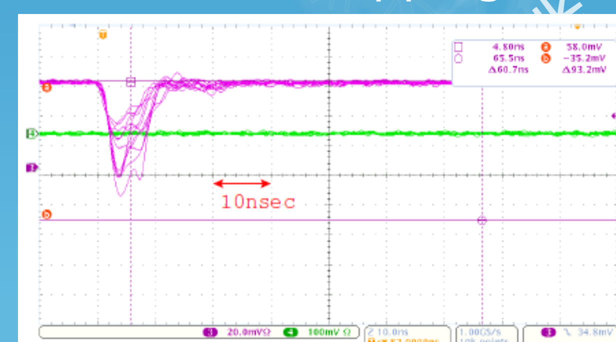


Srソース

Original signal



After clipping



π+ Identification

Double Hits Detection
- multihit TDC

<π+ events>

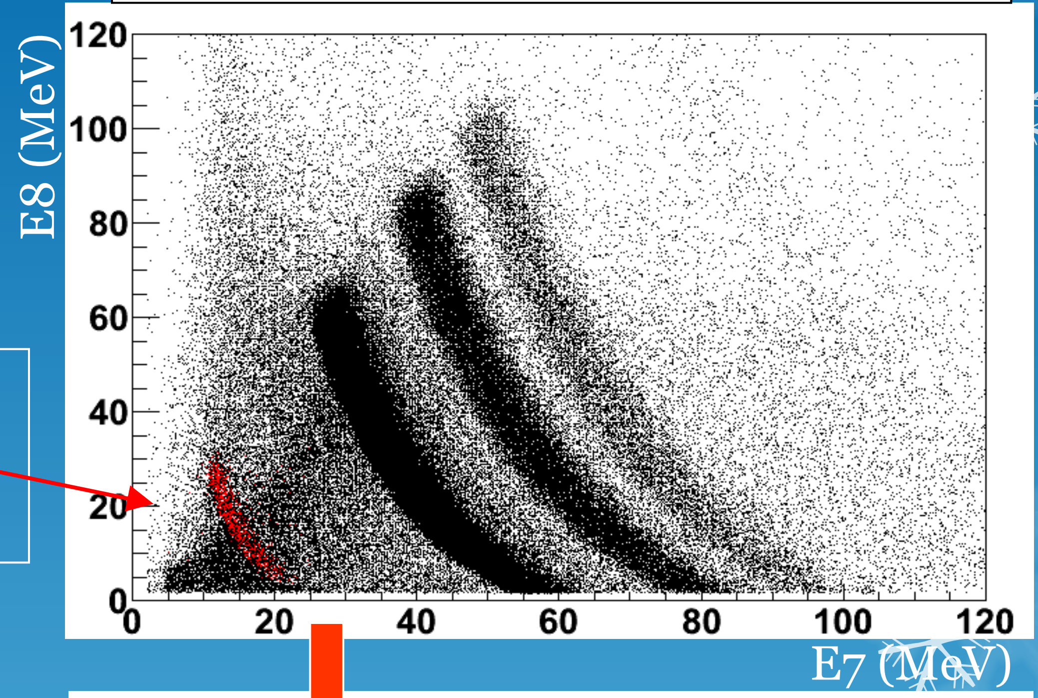
Counter #8 STOP Condition
+
#8 Double Hit Condition

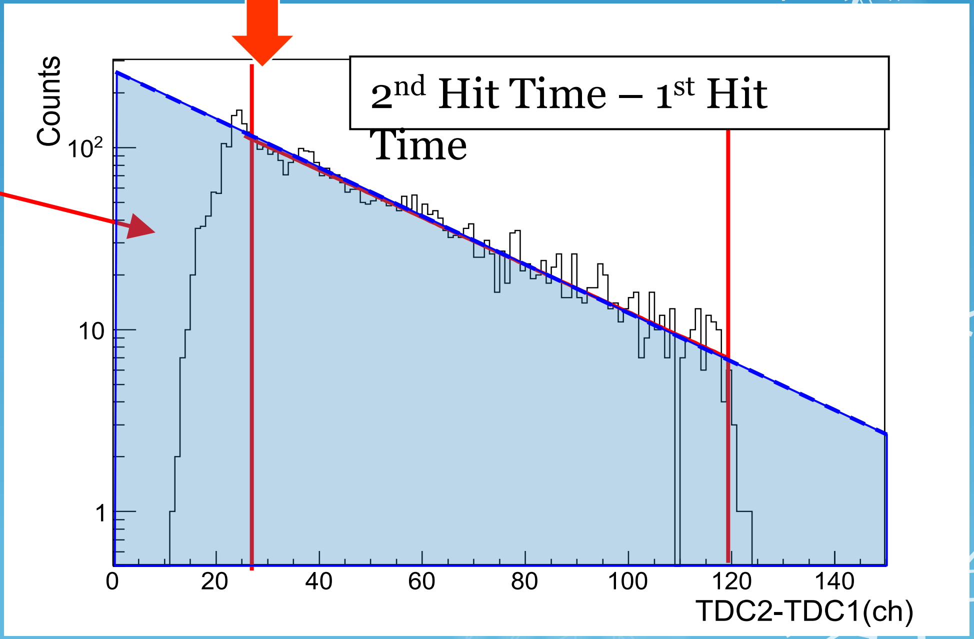
Fit the Histogram
"2nd Hit Time -1st Hit Time"
by $C exp(- t/\tau)$

⇒ **τ = 26.0±0.6 nsec**

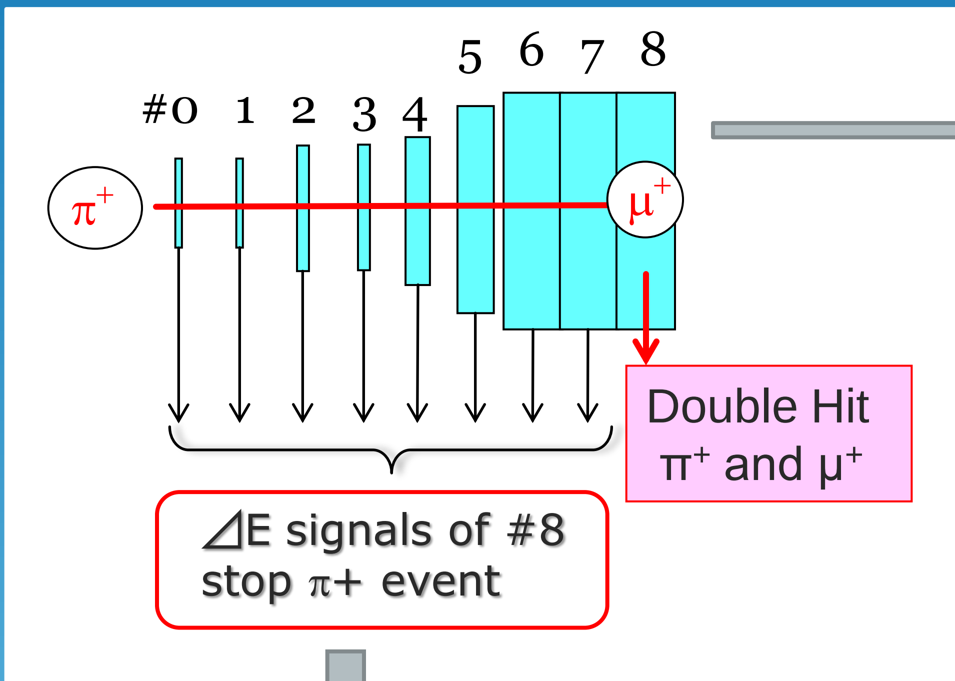
We could clearly select π+

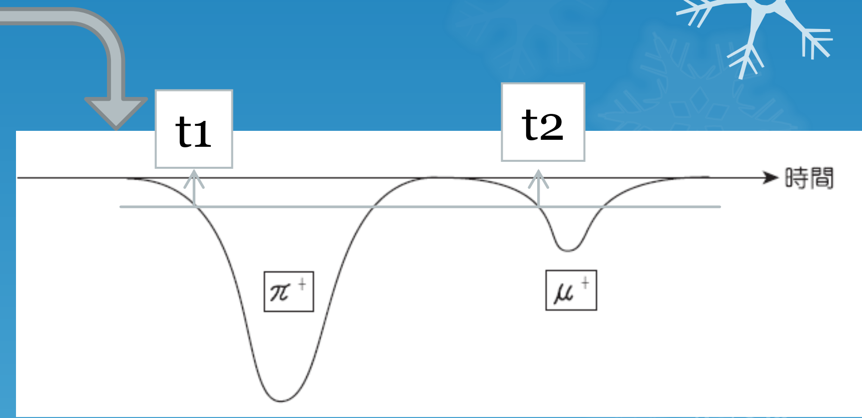
#8 stop events (black) & stop π+ (red)





π^+イベントを使ったパイオンの同定



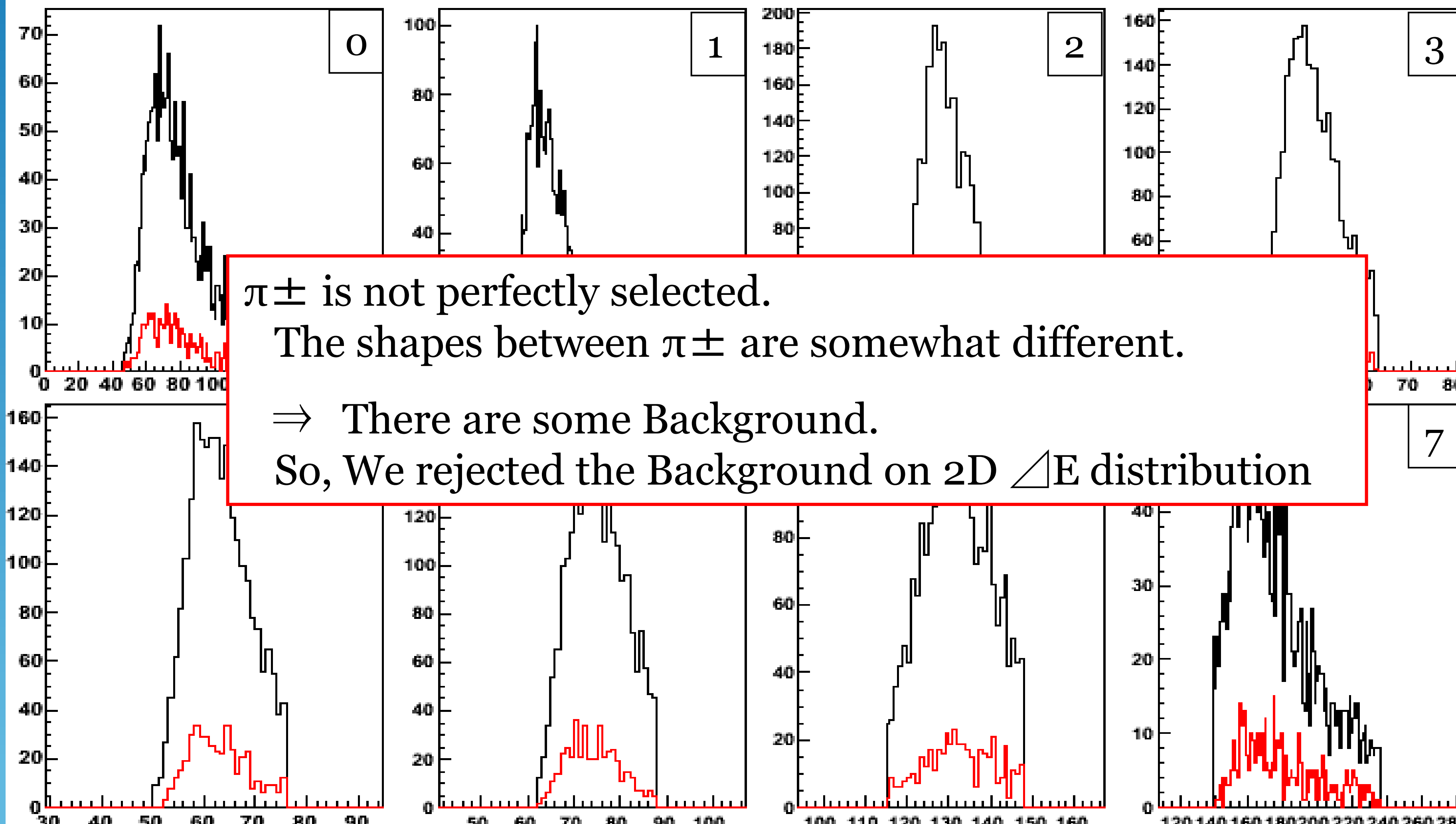


Select total pions using this delta E signals of selected pi+

⊿E cut from #0 to 7 in 1 D

π+(red) : STOP + ⊿E CUT + Double Hit Conditions

π±(black) : STOP + ⊿E CUT Conditions



π± is not perfectly selected.

The shapes between π± are somewhat different.

⇒ There are some Background.

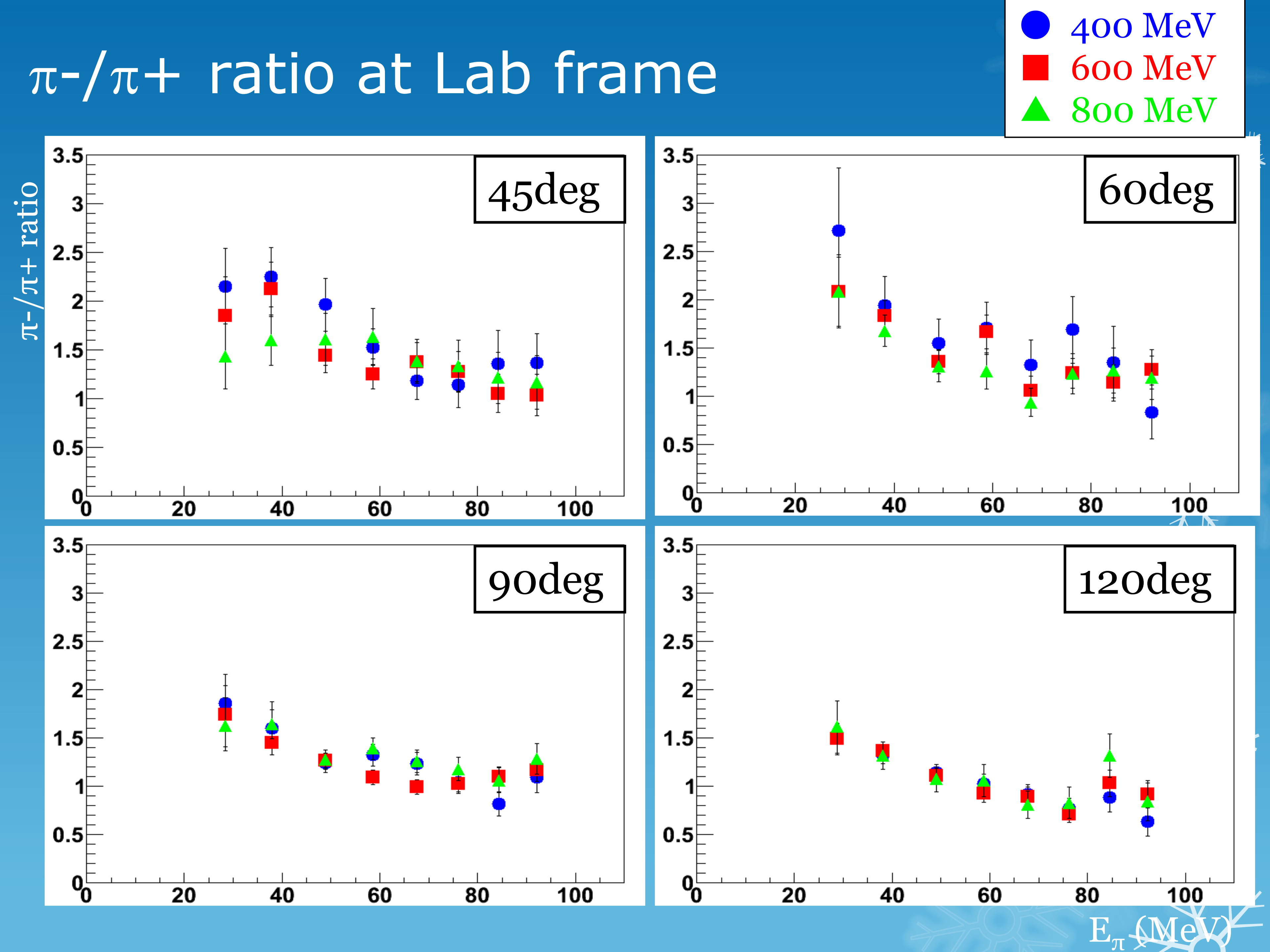
So, We rejected the Background on 2D ⊿E distribution

Analysis Frame

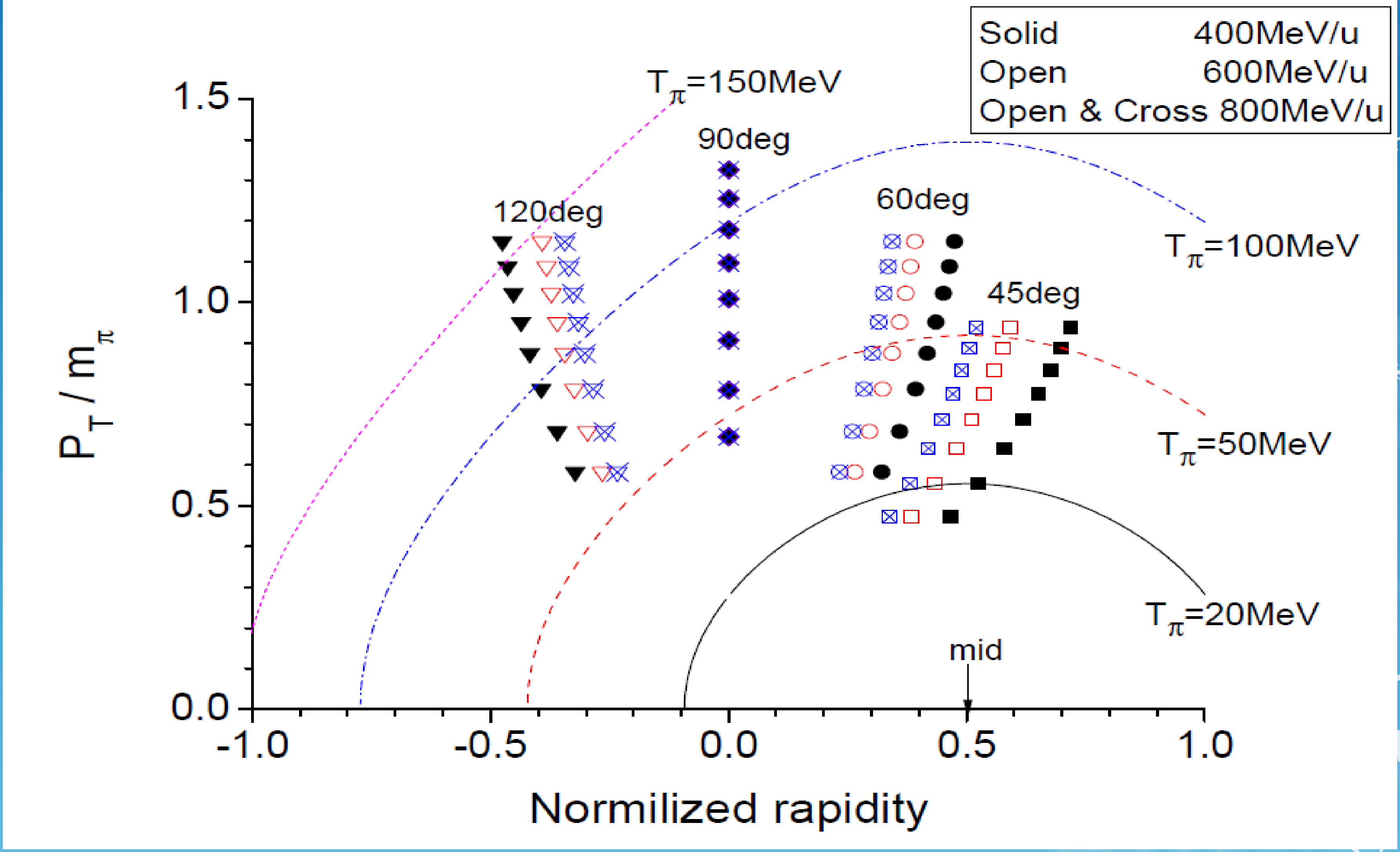
- Target frame (lab frame)
- Projectile frame
- CM frame (c.m.s. of projectile and target)
- mid Rapidity frame (N-N frame)

We discuss the data
in Target and Mid Rapidity frames.

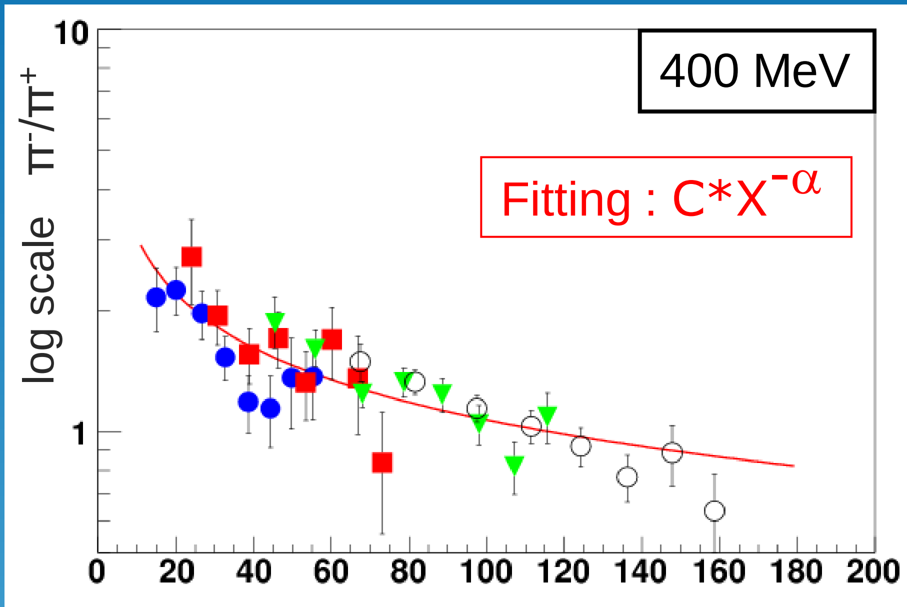
π-/π+ ratio at Lab frame

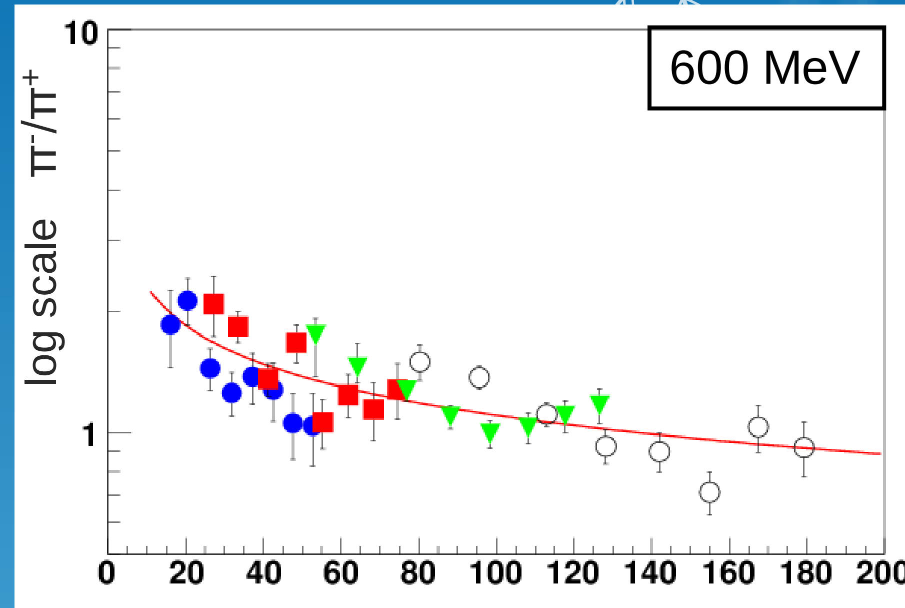


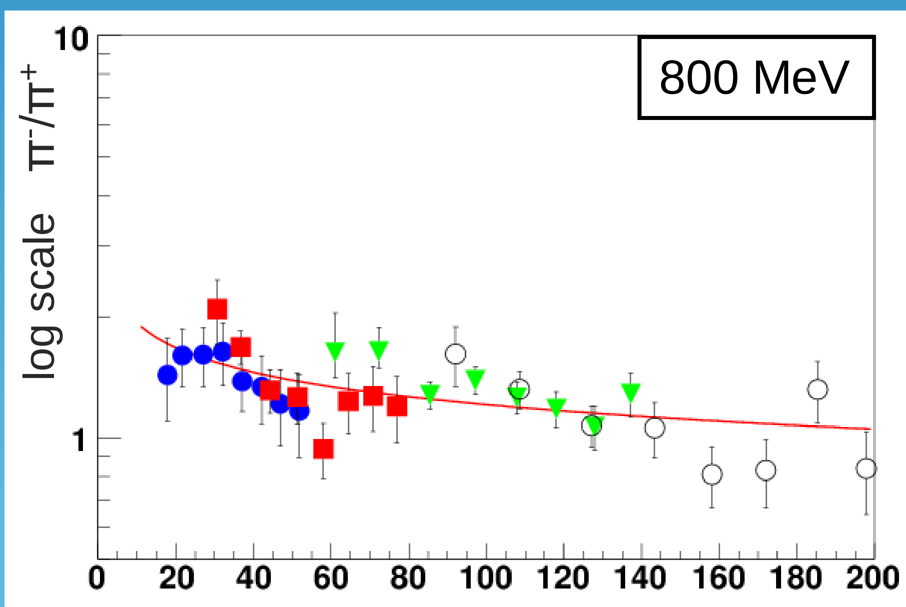
$$y = \frac{1}{2}\ln\left(\frac{E + P_{//}}{E - P_{//}}\right)$$



π^+/π^- ratio : Si + In







slope α:

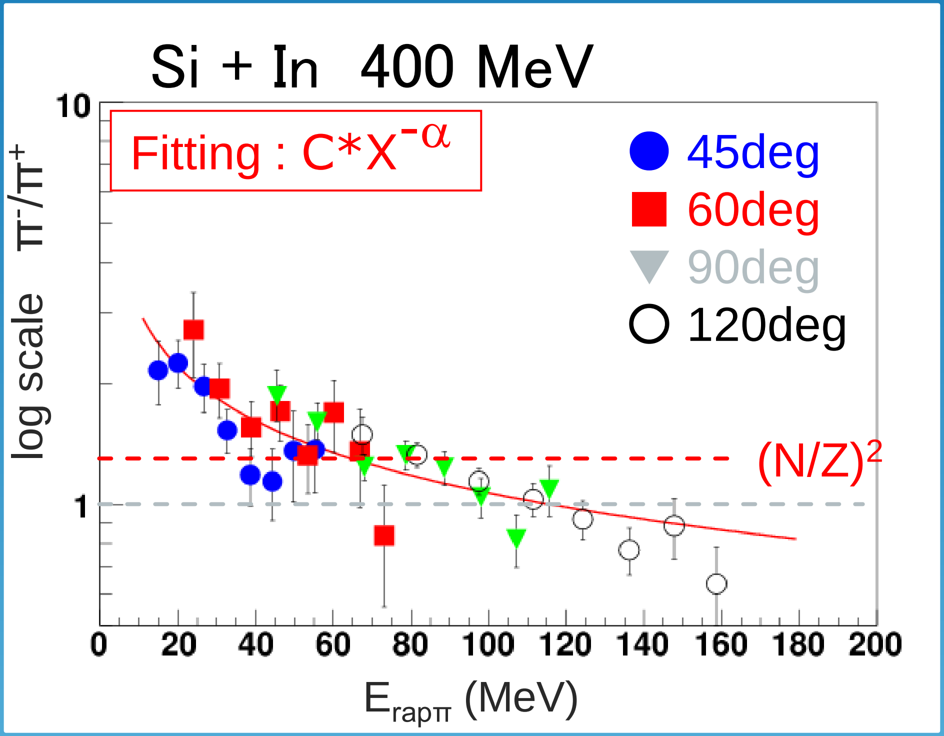
- 400 : (4.5±0.5) × 10^{-1}
- 600 : (3.2±0.5) × 10^{-1}
- 800 : (2.0±0.5) × 10^{-1}

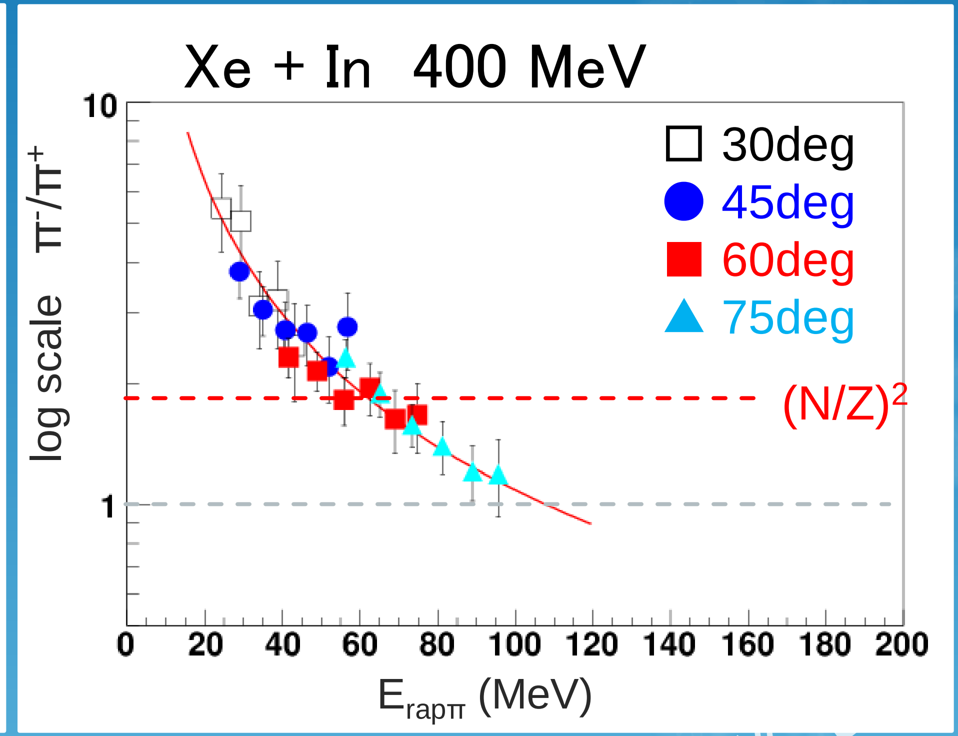
● 45deg
■ 60deg
▼ 90deg
○ 120deg

Slopes depend on Beam Energy

$E_{rap\pi}$ (MeV)

N/Z dependence : Si and Xe beam





- slope α
  - Si + In : $(4.5\pm0.5)\times10^{-1}$
  - Xe+In :$(11.0\pm0.8)\times10^{-1}$

- Average <N/Z>
  - Si + In : 1.14
  - Xe+In : 1.39

$$\pi^- / \pi^+ \equiv (5N^2 + NZ)/(5Z^2 + NZ) \approx (N/Z)^2$$

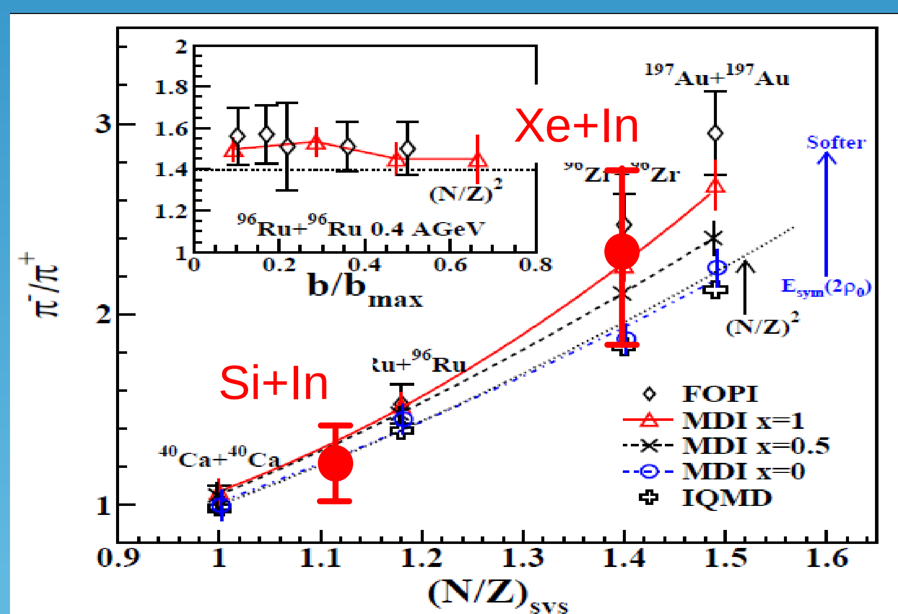
Rough Estimation : integrated-pion ratio

$$
\begin{aligned}
\sigma_{\pm} &= \int d\Omega \int dE \frac{d\sigma}{dEd\Omega} \\
&= \int \sin\theta d\theta \int d\varphi \int dE \frac{d\sigma}{dEd\Omega} \\
&\approx 2\pi \sum_i \sin\theta_i \Delta\theta_i \sum_i \Delta E_i \frac{d\sigma_{\pm}}{dEd\Omega}
\end{aligned}
$$

Sum the data point like this formula

$$\sigma_{\pm i} = 2\pi \sum_i \sin\theta_i \Delta E_i \frac{d\sigma_{\pm i}}{dEd\Omega}$$

$$\frac{\pi_-}{\pi_+} = \frac{\sigma_-}{\sigma_+}$$



Zhigang Xiao et al.
Phys. Rev. Lett. 102(2009)062502

- estimate <N/Z>
  Si + In : 1.14
  Xe+In : 1.39

Summary

- Supra-saturation density のSymmetry Energyに実験的制限を加える為に、重イオン衝突から発生する荷電パイオン比を測定した。
  - Pion ratio from Si+In of 400, 600, and 800 MeV/nucleon
    Xe+In of 400 MeV/nucleon
  - We show pion ratio as universal function.
    - Pion production process is simple
  - Pion ratio has beam energy and N/Z dependence and is qualitatively consistent with Theoretical asumption.