Light Fragment Production in Central Heavy Ion Collisions and the FOPI ToF Upgrade Project

Min Sang Ryu
Korea University

- Introduction
- Ru+Ru at 0.4 and 1.528 AGeV
    - Invariant spectra and Rapidity distribution
    - Radial flow and Temperature
    - Scaled elliptic flow
- FOPI Time-of-Flight (ToF) Upgrade
- Summary and Outlook

2009.02.22 HIM

Muju resort

FOPI/SIS18 at Darmstadt

PLA

$7^\circ \le \theta < 30^\circ$

HEL

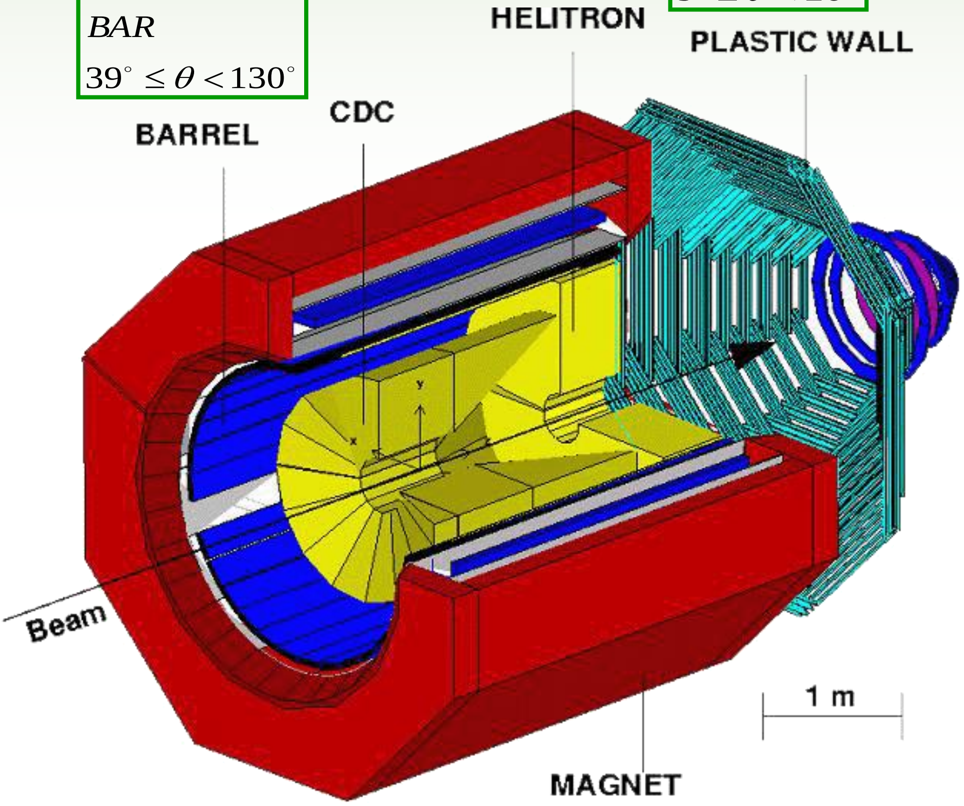
$9^\circ \le \theta < 26^\circ$

CDC

$33^\circ \le \theta < 140^\circ$

BAR

$39^\circ \le \theta < 130^\circ$



Nucl. Phys. (Proc. Suppl.) B 44 708(1995)
J. Ritman *et al.*

CDC & Helitron

- **drift chamber**

BARREL & Plastic Wall

- **plastic scintillation detector**

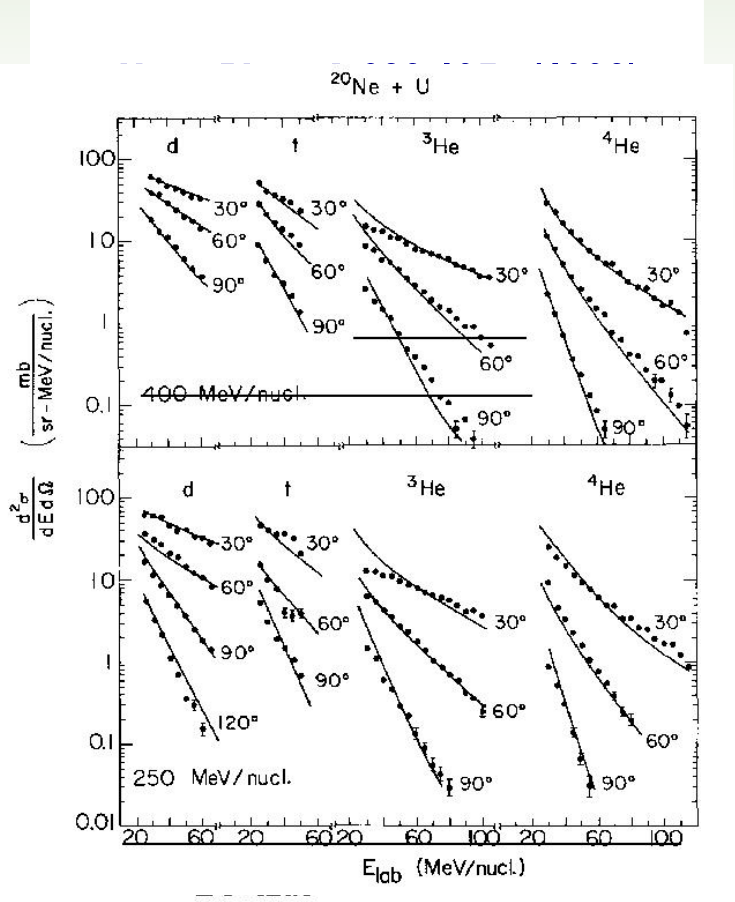
Magnet intensity : 0.6 T

S183 experiment in 1996

$^{96}_{44}$Ru+$^{96}_{44}$Ru collision at 0.4 and 1.528 AGeV

Introduction

- Study the production and collective flow of the light fragments (p, d, t, ^{3}He, and ^{4}He)
  - For the most central events
    - Rapidity distribution and production
    - Radial flow and Temperature
  - Maximum elliptic flow at 0.4 AGeV
  - For semi-central events
    - Scaled elliptic flow (v_2/n) by the nun
      the composite nucleons, n, as func
      scaled transverse momentum (p_t/n)



Nucleon coalescence scenario in heavy-ion collisions

Phys. Rep. 131 223 (1986) L. Csernai and J. Kapusta

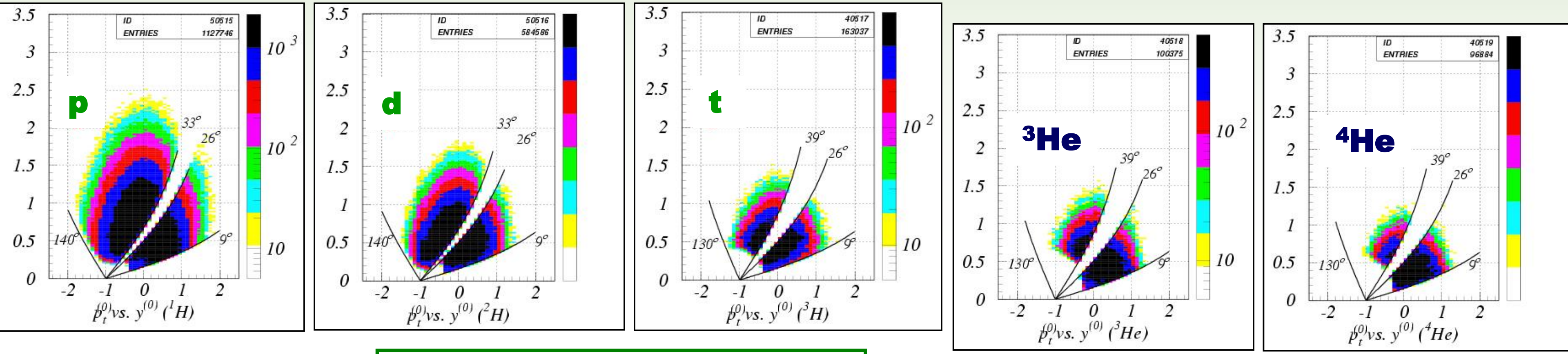
Phase space distribution

$$p_t^{(0)} = \frac{p_t}{m\beta_{cm}\gamma_{cm}}$$

$$y^{(0)} = \frac{y_{lab}}{y_{cm}} - 1.$$

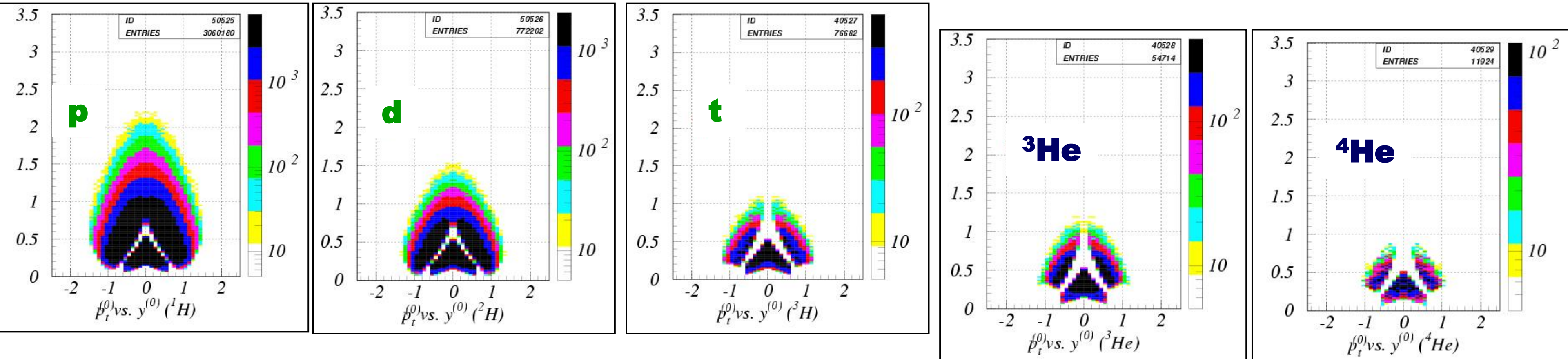
0.4 AGeV

$\sigma_{TMUL} = 101.6mb\,,\ b = 1.798\,fm$



1.528 AGeV

$\sigma_{TMUL} = 95.2mb\,,\ b = 1.741\,fm$

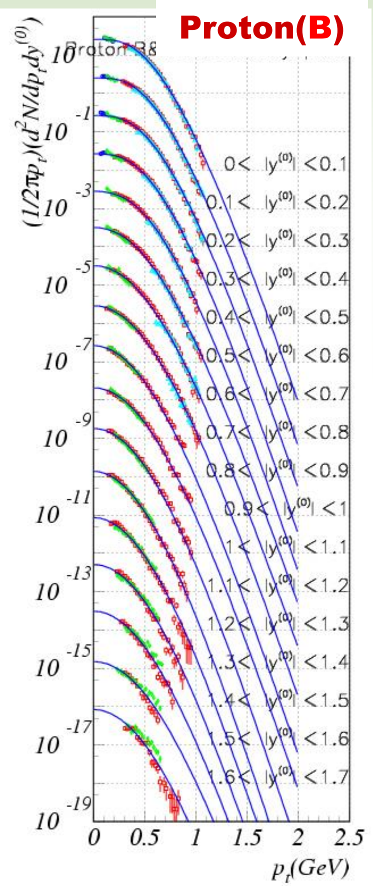


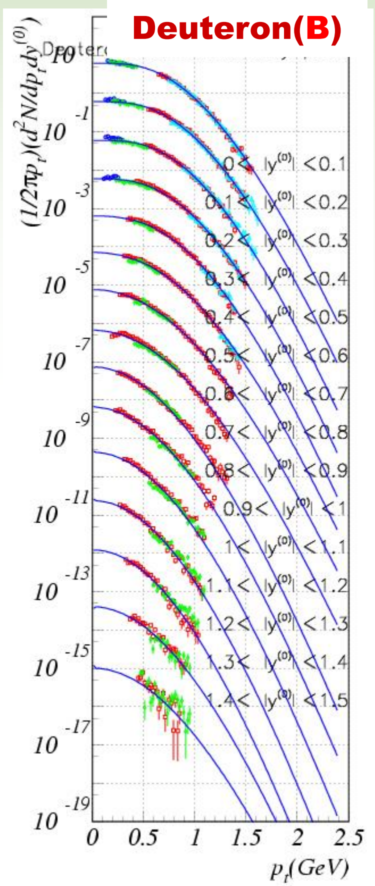
Invariant spectra

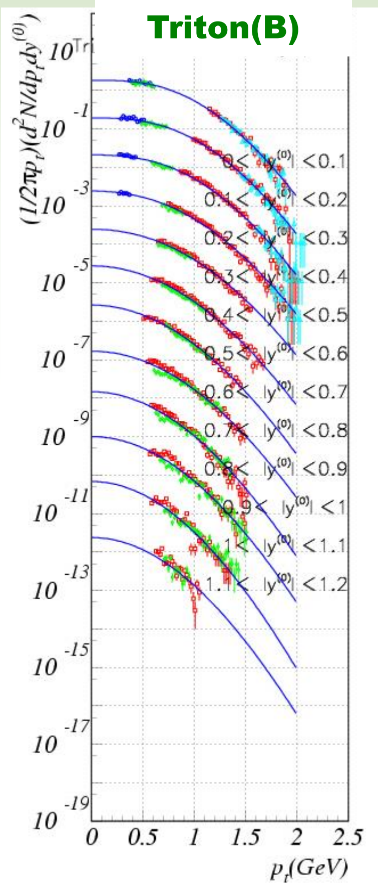
0.4 AGeV

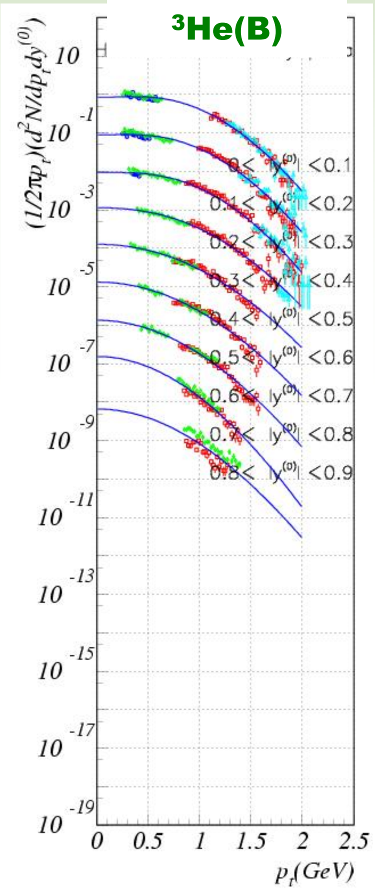
$\sigma_{TMUL} = 101.6mb\,,\ b = 1.798\,fm$

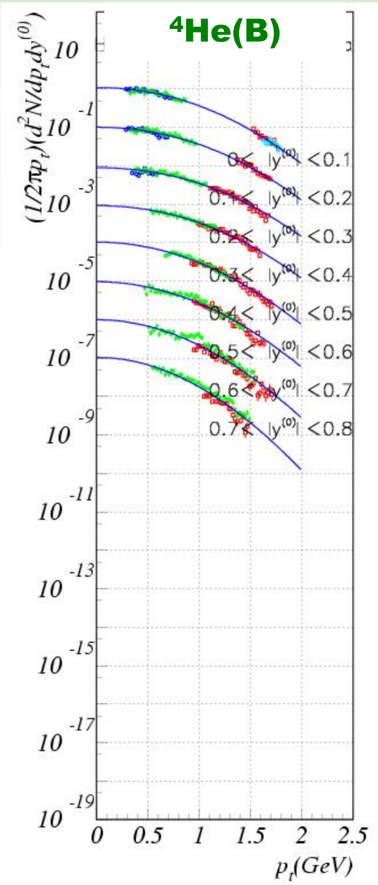
● CDC (backward)
● PLA (backward)
● CDC (forward)
● PLA (forward)


Proton(B)


Deuteron(B)


Triton(B)

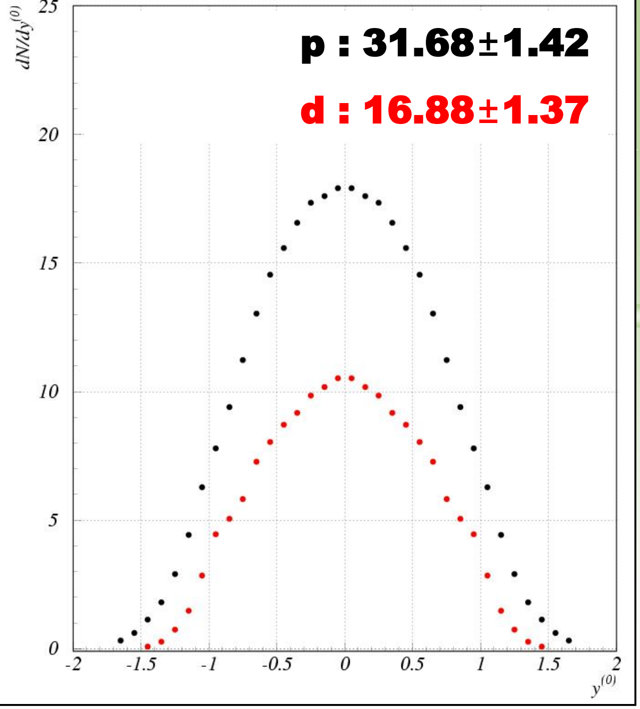

³He(B)

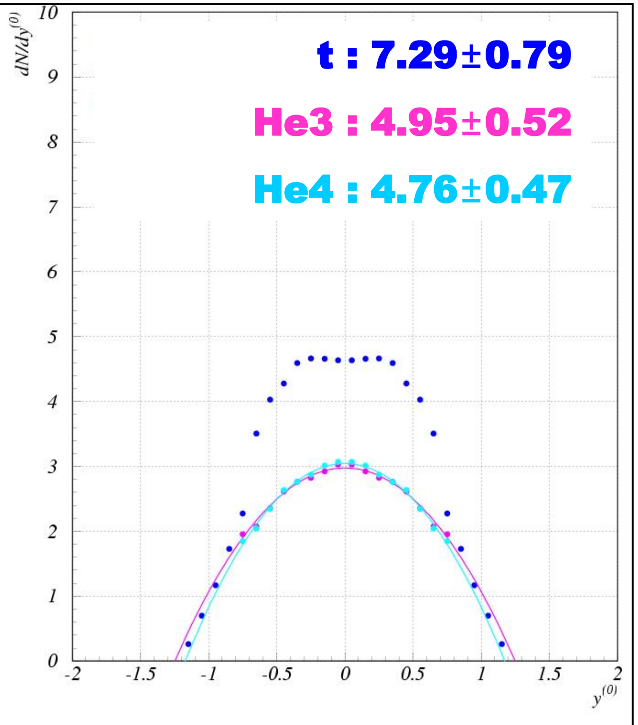

⁴He(B)

PRL 42 14 (1979) P.J. Siemens and J.O. Rasmussen

$$\frac{1}{2\pi p_t}\frac{d^2N}{dp_t\,dy^{(0)}} = C\cdot E\cdot\exp\left(-\frac{\gamma_r E}{T}\right)\cdot\left[\left(\gamma_r+\frac{T}{E}\right)\frac{\sinh\alpha}{\alpha}-\frac{T}{E}\cosh\alpha\right]$$

$$\alpha = \frac{\gamma_r\cdot\beta_r\cdot p}{T}$$





dN/dy

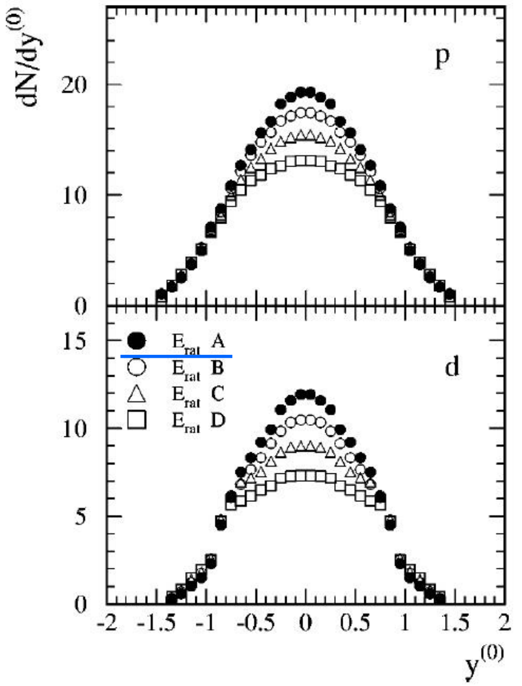
(Phys. Rev. C 66 034901 (2002) B. Hong *et al.*)

0.4 AGeV

$$\sigma_{TMUL} = 101.6mb$$

$$b = 1.798\,fm$$

The yield of Helium isotopes is taken by the 2nd order of polynomial function.



comparison

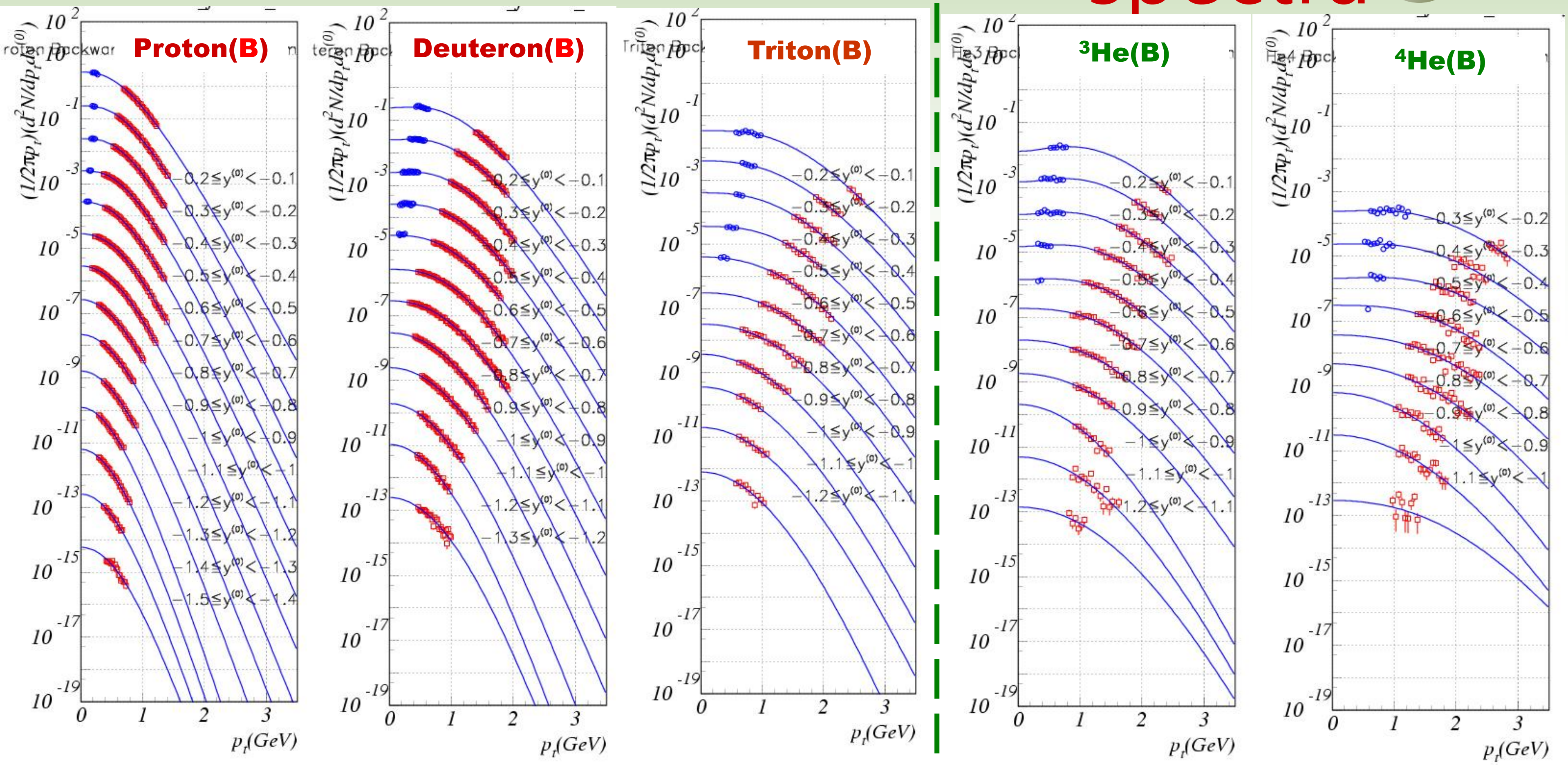
	M.S.Ryu (tmul)	W.Reisdorf (E_{rat})	Y.J.Kim (E_{rat})
b_0 (b_{max}=10.531fm)	0.17	0.15	0.18 (E_{rat} A)
σ (mb)	102		116 (E_{rat} A)
pi−	-0.37	0.70 ± 0.06	
pi+		1.07 ± 0.06	
p	31.68 ± 1.42	33.2 ± 1.7	31.2 ± 2.8
d	16.88 ± 1.37	18.3 ± 1.1	17.2 ± 1.9
t	7.29 ± 0.79	8.3 ± 0.8	
^{3}He	4.95 ± 0.52	5.6 ± 0.5	
^{4}He	4.76 ± 0.47	5.4 ± 0.5	
Q_{IMF} (Q ≥ Z3)	5.5	5.5	
Q_{tot}	80.4	86.87	
$Q_{tot}/Q_{sys}(88)$ (%)	91.4	98.7	

Invariant spectra

● CDC (backward)
● PLA (backward)

1.528 AGeV

$\sigma_{TMUL} = 95.2 mb,\ b = 1.741\,fm$



PRL 42 14 (1979) P.J. Siemens and J.O. Rasmussen

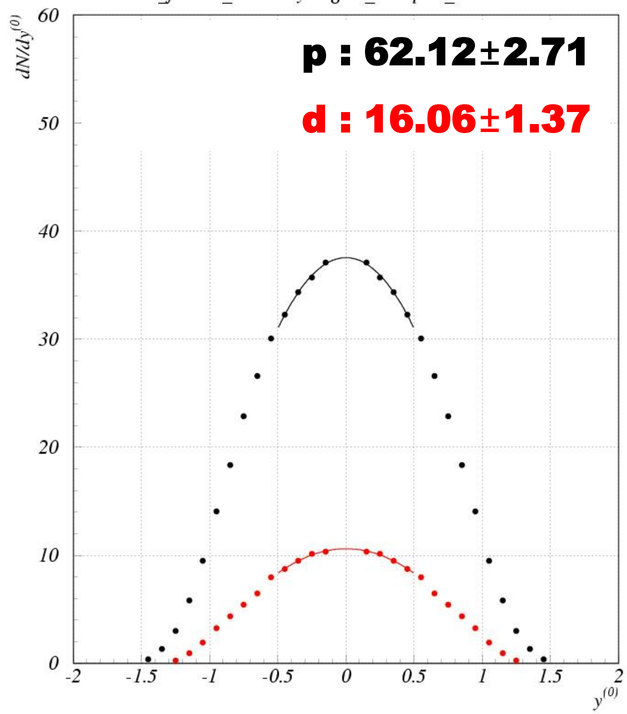
$$\frac{1}{2\pi p_t}\frac{d^2N}{dp_t\,dy^{(0)}} = C\cdot E\cdot\exp\left(-\frac{\gamma_r E}{T}\right)\cdot\left[\left(\gamma_r+\frac{T}{E}\right)\frac{\sinh\alpha}{\alpha}-\frac{T}{E}\cosh\alpha\right]$$

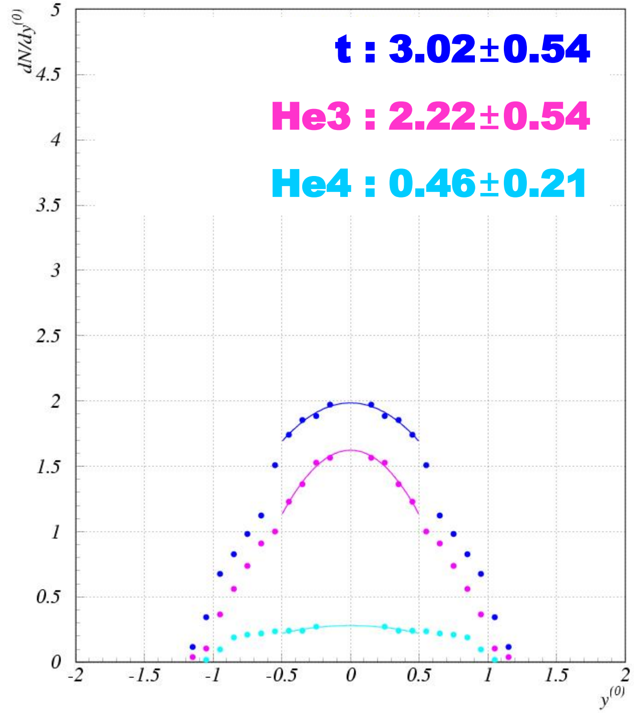
$$\alpha = \frac{\gamma_r\cdot\beta_r\cdot p}{T}$$

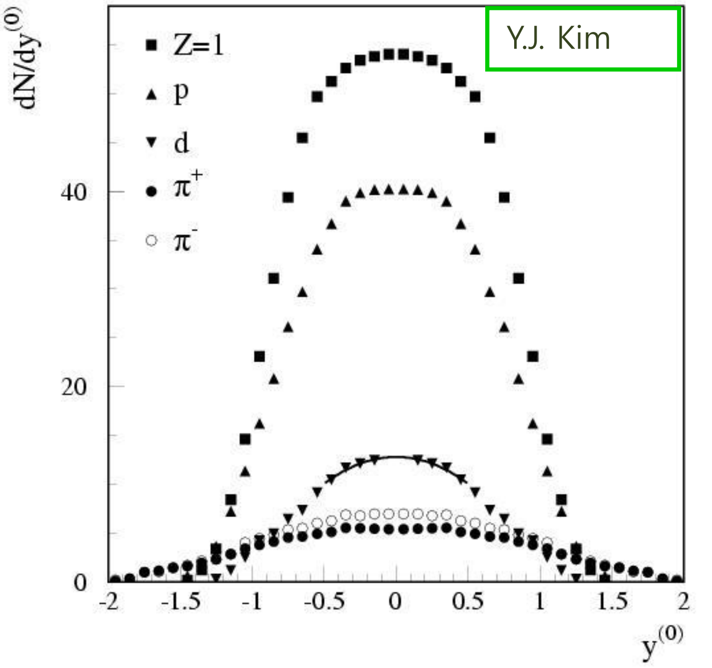
dN/dy

$$\sigma_{TMUL} = 95.2mb$$
$$b = 1.741\,fm$$
$$b_0 = 0.165$$

The yield at mid-rapidity is taken by the 2nd order of polynomial function.



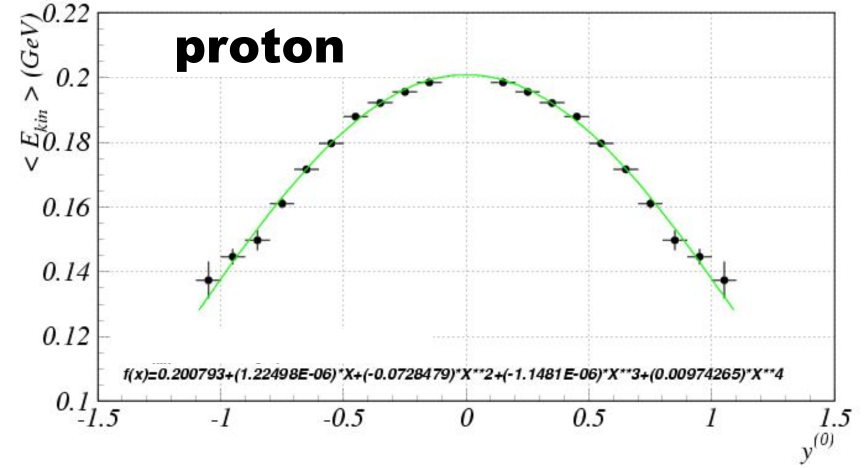




comparison

	M.S.Ryu (tmul)	W.Reisdorf (E_{rat})	Y.J.Kim (E_{rat})
b_0 (b_{max}=10.531fm)	0.165	0.15	
σ (mb)	95		67
pi−	**-3.14**	15.63 ± 0.78	15.4 ± 1.7
pi+		12.49±1.00	13.0 ± 1.4
p	62.12±2.71	64.5±3.2	69.6 ± 5.5
d	16.06±1.37	18.4±1.1	19.2 ± 2.3
t	3.02±0.54	4.1±0.4	
^{3}He	2.22±0.54	2.65±0.24	
^{4}He	0.46±0.21	0.67±0.06	
Q_{tot}	83.42	90.52	
Q_{tot}/Q_{sys}(88) (%)	94.8	102.9	

$\langle\beta_r\rangle$ and T at mid-rapidity

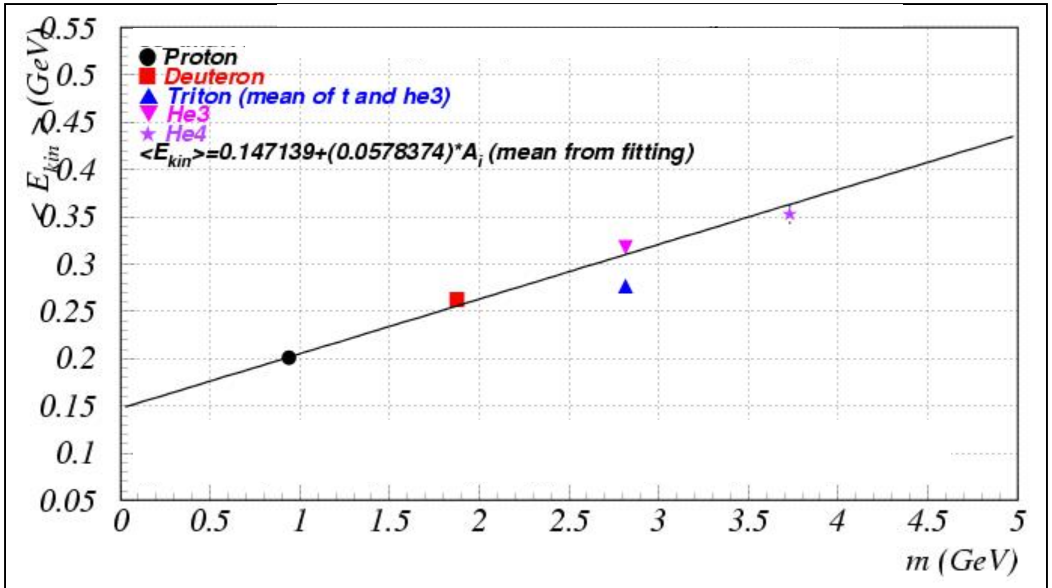


1.528 AGeV

NP A586 755(1995) G. Poggi *et al.*, FOPI.

$$\boxed{\langle E_{kin}\rangle \approx \frac{1}{2} m_0 \langle \beta_r^2 \rangle A + \frac{3}{2} T}$$

In order to get $\langle E_{kin}\rangle$ at mid-rapidity, fitted $\langle E_{kin}\rangle$ vs. $y(0)$ by 4th order of polynomial function.

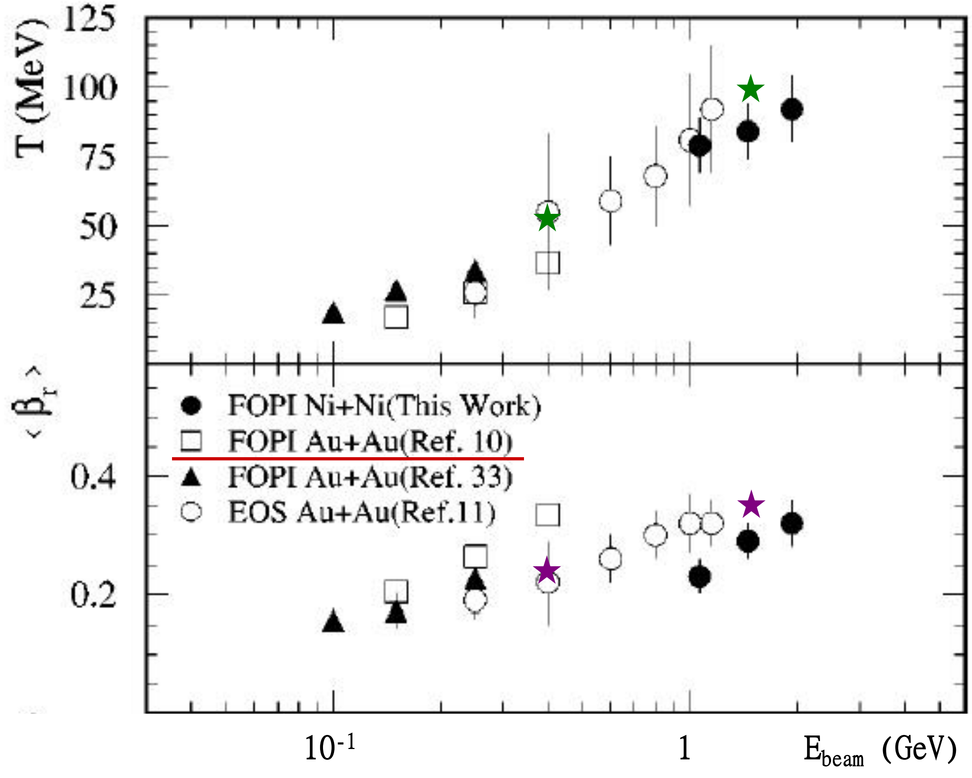


E_0 : thermal energy **E_F : flow energy**

RuRu15	**M.S. Ryu (tmul)**	**W. Reisdorf (Erat)**
b_0 (b_{max}=10.531fm)	**0.165**	**0.15**
σ (mb)	**95**	
E_0 (MeV)	**147.1 (-15.7, +7.9)**	**188±20**
E_F (MeV)	**57.8 (-7.7, +17.4)**	**52.8±10.5**
β_F	**0.351 (-0.056, +0.024)**	**0.337±0.032**
T (MeV)	**98.1 (-5.3, 10.5)**	**111±14**

Comparison

$$\langle E_{kin}\rangle \approx \frac{1}{2} m_0 \langle \beta_r^2 \rangle A + \frac{3}{2} T$$



PR C 57 244 (1998) B. Hong *et al.*, FOPI

RuRu04	**M.S. Ryu (tmul)**	**W. Reisdorf (Erat)**
b_0 (b_{max}=10.53 1fm)	**0.171**	**0.25**
σ (mb)	**102**	
E_0 (MeV)	**78.42 (-6.16, +6.32)**	**96.3 ± 9.6**
E_F (MeV)	**27.57 (-6.01, +7.29)**	**22.0 ± 4.9**
β_F	**0.242 (-0.034, +0.026)**	**0.217 ± 0.023**
T (MeV)	**52.28 (-4.21,+4.11)**	**59.8 ± 6.4**

E_0 : thermal energy **E_F : flow energy**

RuRu15	**M.S. Ryu (tmul)**	**W. Reisdorf (Erat)**
b_0 (b_{max}=10.53 1fm)	**0.165**	**0.25**
σ (mb)	**95**	
E_0 (MeV)	**147.1 (-15.7, +7.9)**	**188±20**
E_F (MeV)	**57.8 (-7.7, +17.4)**	**52.8±10.5**
β_F	**0.351 (-0.056, +0.024)**	**0.337±0.032**
T (MeV)	**98.1 (-5.3, 10.5)**	**111±14**

Azimuthal particle distribution & Reaction plane

$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi + \cdots$$

Direct flow

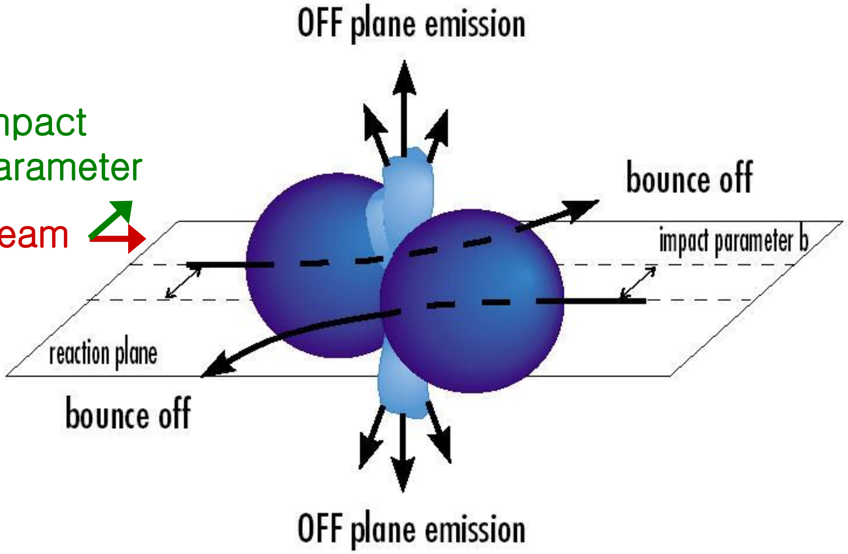
$$v_1 = \langle \cos\phi \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

Elliptic flow

$$v_2 = \langle \cos 2\phi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Impact parameter

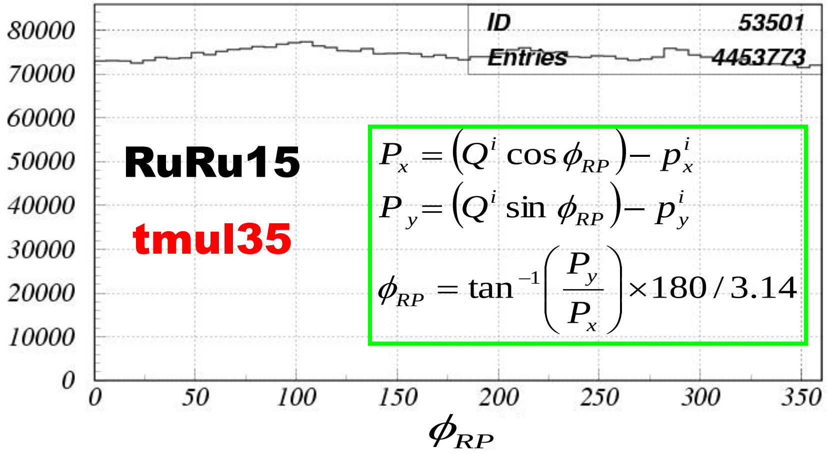
Beam



Transverse momentum method

$$\overrightarrow{Q^i} = \begin{pmatrix} Q^i \cos\phi_{RP} \\ Q^i \sin\phi_{RP} \end{pmatrix} = \sum_{k=1}^{N} w_k \cdot \left| \overrightarrow{p}_t^{\,i} \right| \cdot \begin{pmatrix} \cos\phi_k \\ \sin\phi_k \end{pmatrix}$$

$$\text{where} \begin{cases} w_k = -1 & \text{for } y^{(0)} \le -0.2 \\ w_k = +1 & \text{for } y^{(0)} \ge +0.2 \end{cases}$$



$$P_x = \left(Q^i \cos\phi_{RP}\right) - p_x^i$$

$$P_y = \left(Q^i \sin\phi_{RP}\right) - p_y^i$$

$$\phi_{RP} = \tan^{-1}\left(\frac{P_y}{P_x}\right) \times 180/3.14$$

- hep-ph/9407282 (1994) S. Voloshin & Y. Zhang
- nucl-ex/9711003 (1997) J.Y. Ollitrault

- Nucl. Phys. A638 195(1998) J.Y. Ollitrault
- Phys. Lett. B157 (1985) 146 P. Danielewicz and G. Odyniec

Resolution of reaction plane

nucl-ex/9711003 (1997) J.Y. Ollitrault

Divide randomly each event into two sub-events containing half of the particles, and construct vectors(Q_1, Q_2) of total transverse momenta of the two sub-events.

$$\Delta\phi_{RP} \equiv \left|\Delta\phi_1 - \Delta\phi_2\right|$$

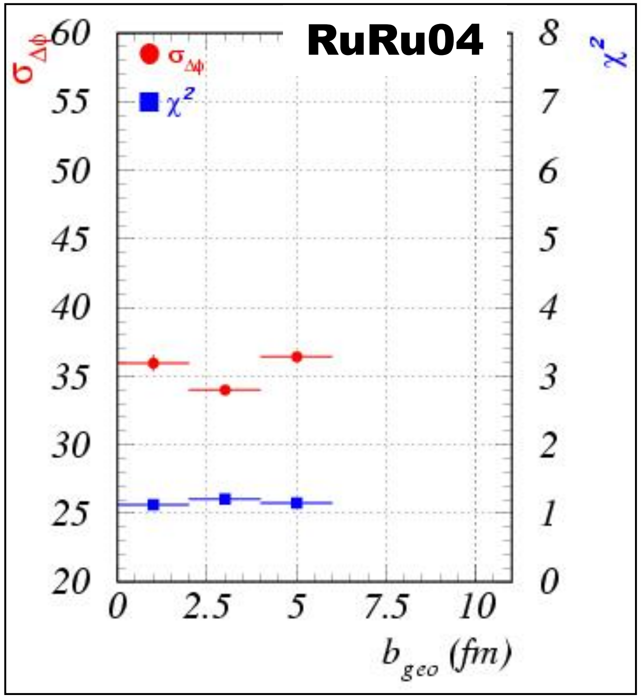
ψ : measured azimuthal angle

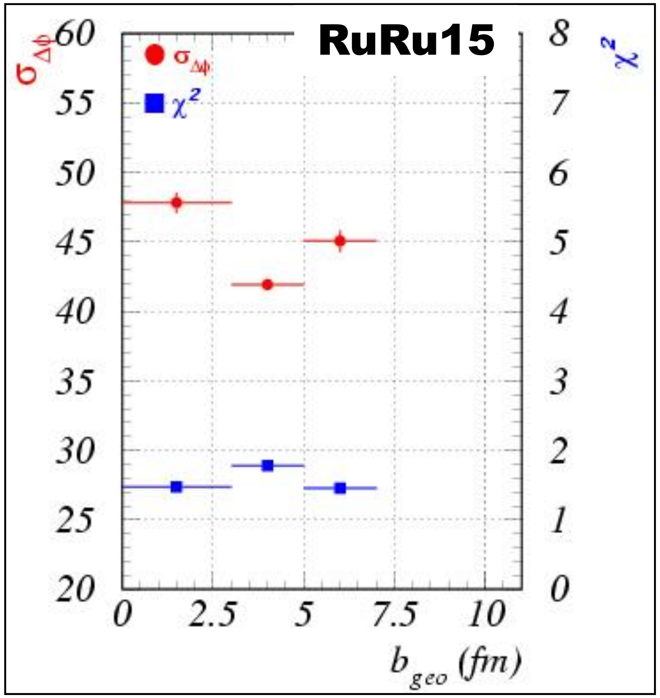
Φ : true azimuthal angle

$$\langle \cos n\psi \rangle = \langle \cos n\phi \rangle \langle \cos n\Delta\phi \rangle$$

$$v_1 = \langle \cos\phi \rangle = \frac{\langle \cos\psi \rangle}{\langle \cos\Delta\phi \rangle}$$

$$v_2 = \langle \cos 2\phi \rangle = \frac{\langle \cos 2\psi \rangle}{\langle \cos 2\Delta\phi \rangle}$$





RuRu04

$$\langle \cos 2\Delta\phi \rangle = 0.384$$

RuRu15

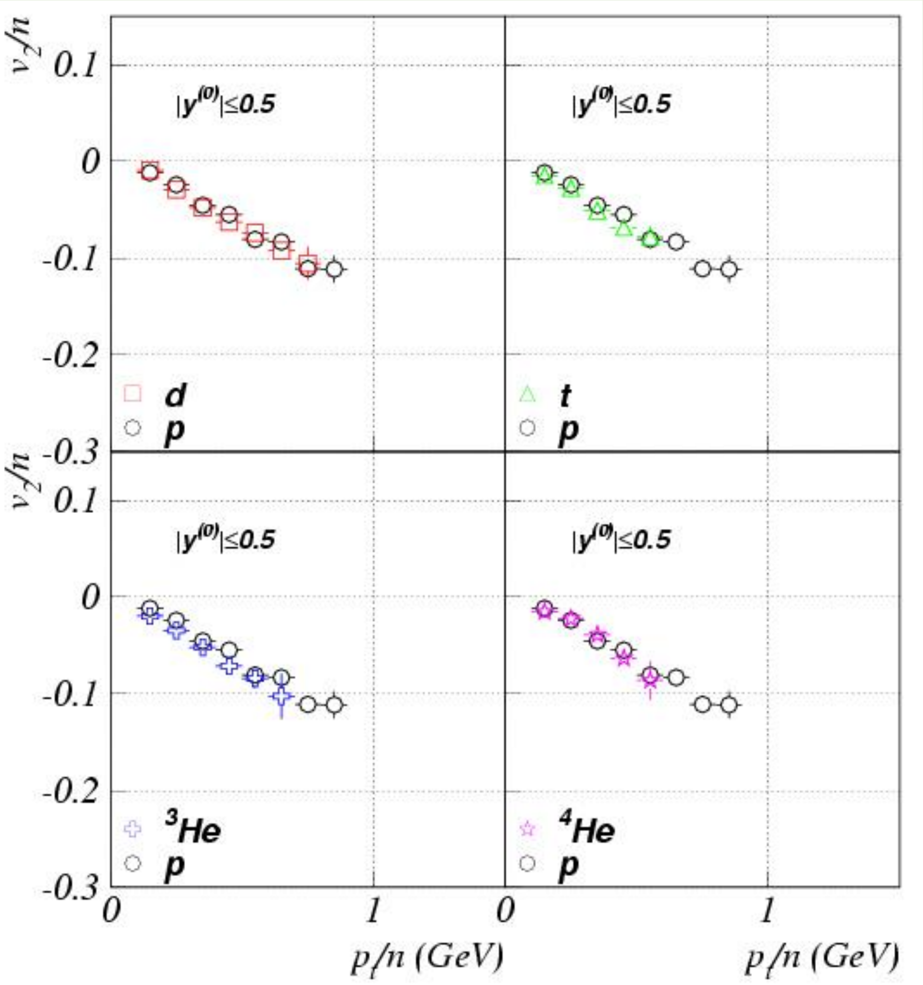
$$\langle \cos 2\Delta\phi \rangle = 0.292$$

Scaled elliptic flow

GSI Scientific Report 2008, M. S. Ryu and B. Hong

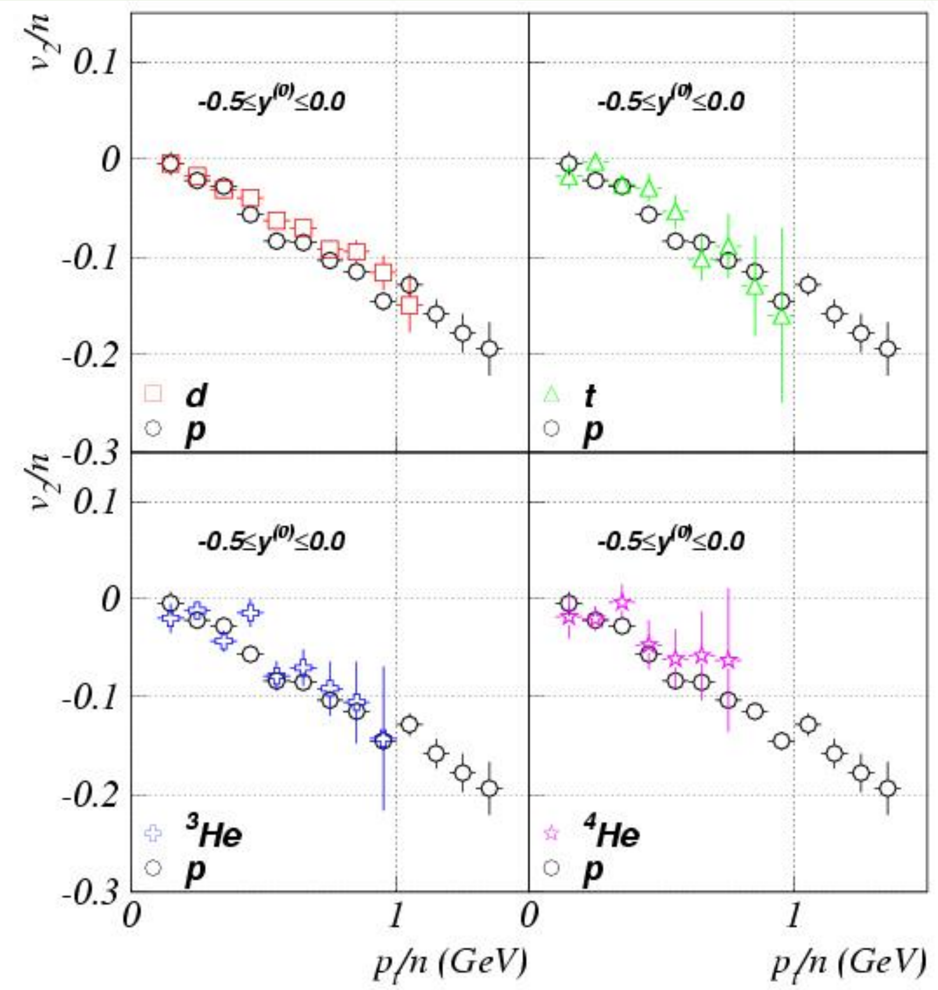
RuRu04

tmul24 $\langle \cos 2\Delta\phi \rangle = 0.384$



RuRu15

tmul35 $\langle \cos 2\Delta\phi \rangle = 0.292$



FOPI ToF Upgrade

Motivation

Nucl. Phys. A 625 325(1997) J. Schaffner-Bielich *et al.*

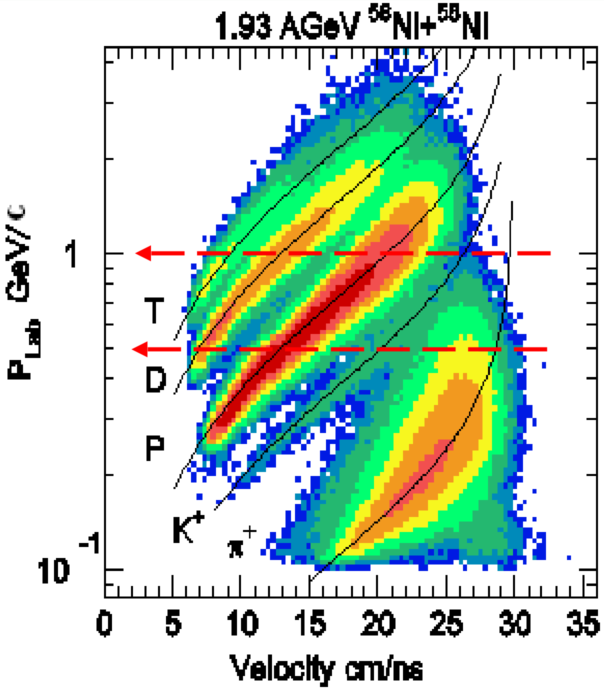
For free NN collisions,

K^+ : NN -> $K^+\Lambda N$: E_{thr}~1.58 GeV

K^- : NN -> K^+K^-NN : E_{thr}~2.5 GeV

Sideward flow of K^+ in Ni+Ni at 1.93A GeV

Phys. Lett. B 486 6 (2000) P. Crochet *et al*.



Nucl. Phys. A 625 307(1997)
D. Best *et al.*

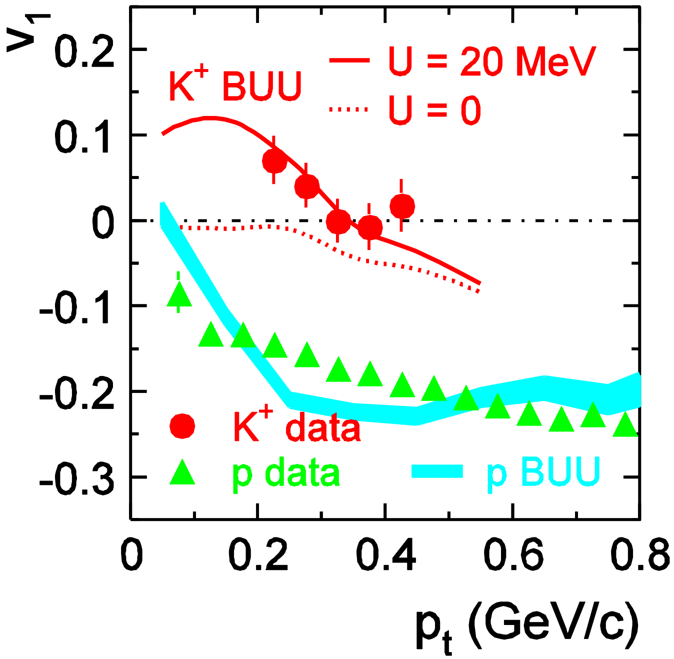
$P_{lab} < 1\,GeV$ with $\sigma_t \sim 100\,ps$

↑

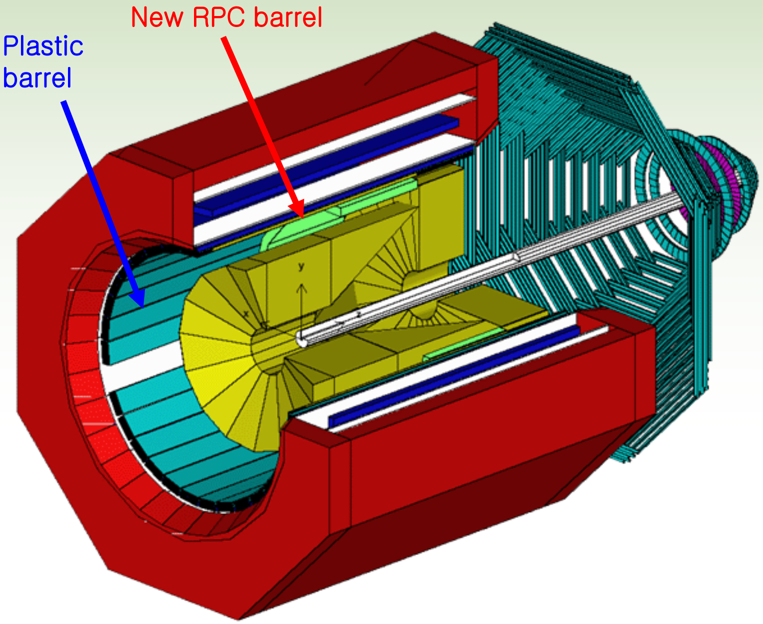
$P_{lab} < 0.5\,GeV$ with $\sigma_t \sim 200\,ps$

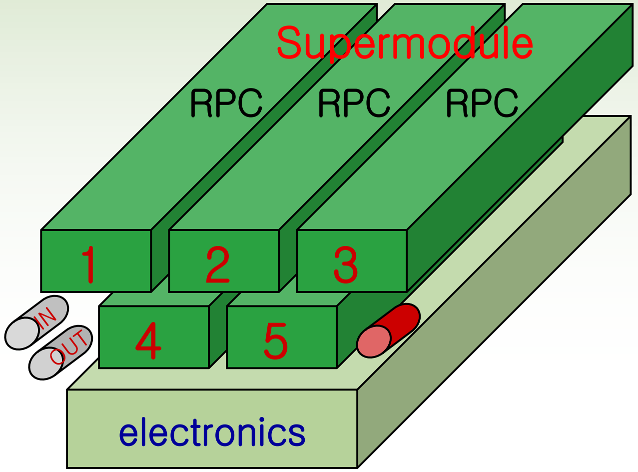
$-1.2 < y^{(0)} < -0.65$

$$y^{(0)} = \frac{y_{lab}}{y_{cm}} - 1.$$

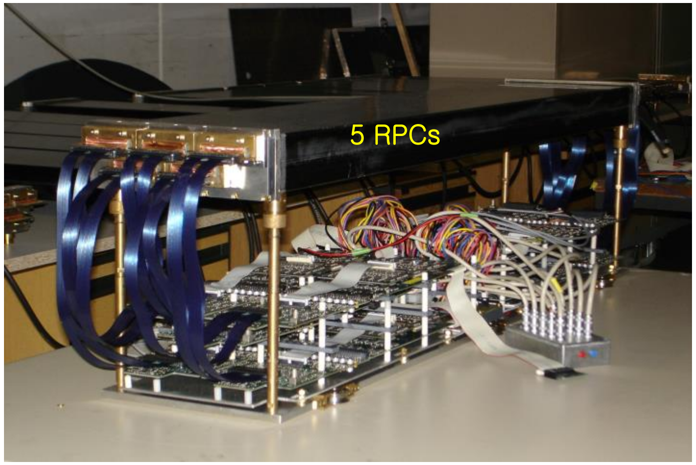


Upgrade of Time-of-Flight

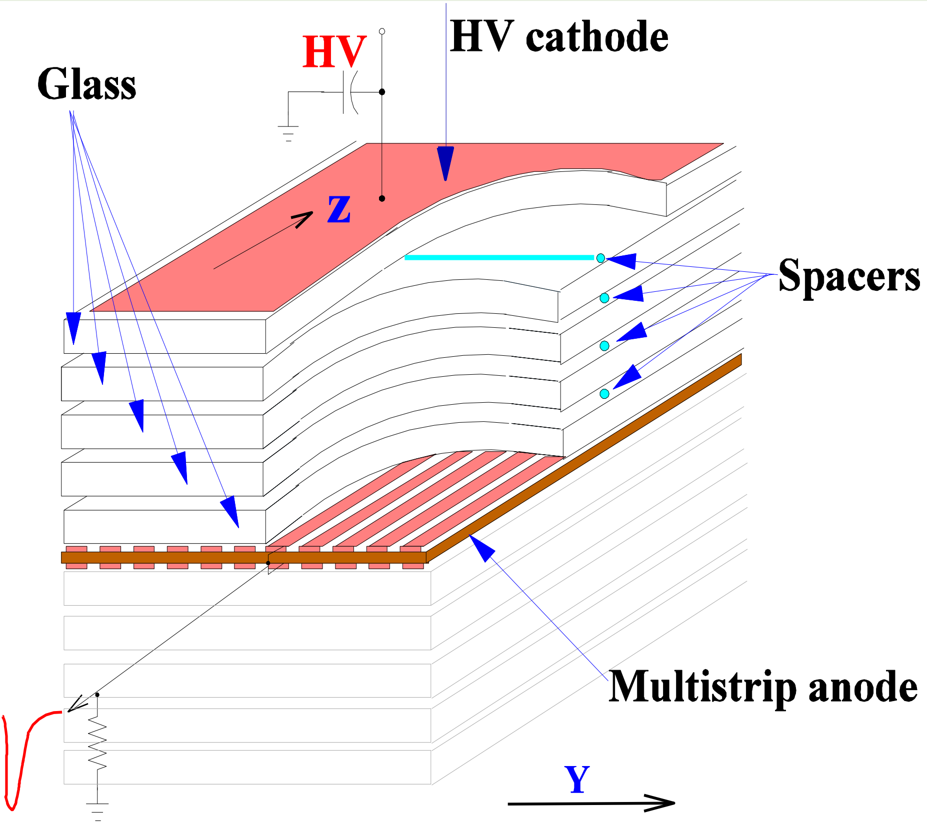




Plastic barrel	New MMRPC barrel
180 scintillators for 30 sectors $39^\circ \le \theta_{lab} \le 130^\circ$ ➔ $67^\circ \le \theta_{lab} \le 140^\circ$	140 MMRPCs for 28 supermodules $37^\circ \le \theta_{lab} \le 68^\circ$
$\sigma_t \le 200\,\mathrm{ps}$	$\sigma_t \le 100\,\mathrm{ps}$
$p_{lab} \le 0.5\,\mathrm{GeV}$	$p_{lab} \le 1\,\mathrm{GeV}$



Multi-strip Multi-gap RPC (MMRPC)



Multi-strip-MRPC (MMRPC)

MMRPC:

Active area	90 x 4.6 cm^2
Glass	1.1 & 0.5 mm (10 plates)
Gap	8 x 220 µm (fishing line)
Strip	16 (1.94/0.6 mm)
Applied voltage	9.6 kV (110kV/cm)
Gas	$C_2F_4H_2$/iso-C_4H_{10}/SF_6=80/5/15
Operation	Avalanche mode

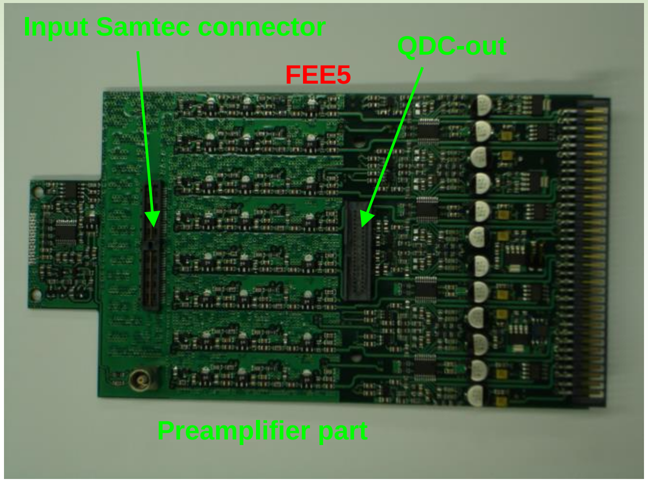
TOF-barrel :

Installation ➔ 28 SMs (140 MMRPCs)

Channels ➔ 4480

FEE5, QDC, and Tacquila3

GSI+HD+I3HP
M.Ciobanu



Ch.Nr. : 16 channels
Bias : +5.4V, -5V
Power : 0.51 W/ch.
Dim : 149 mm * 95 mm

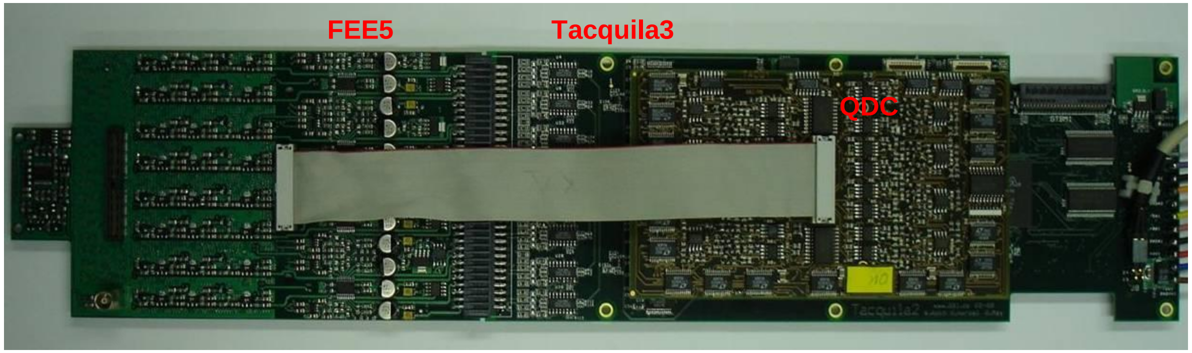
OUT. : 16 diff. PECL for time
16 diff. for amplitude
1 diff. PECL OR

GAIN. :~170
BW :~1.5GHz
Noise :~25μV
t_r :~250ps
$\sigma_{t(FEE)}$:<20 [ps] @(5mV)

K.Koch *et. al.* IEEE Trans. Nucl. Sci. 52 745–747 (2005)

Common stop clock at 40 MHz

GSI-ELEX
R.Schulze,
R.Hardel
K.Koch,
E.Badura



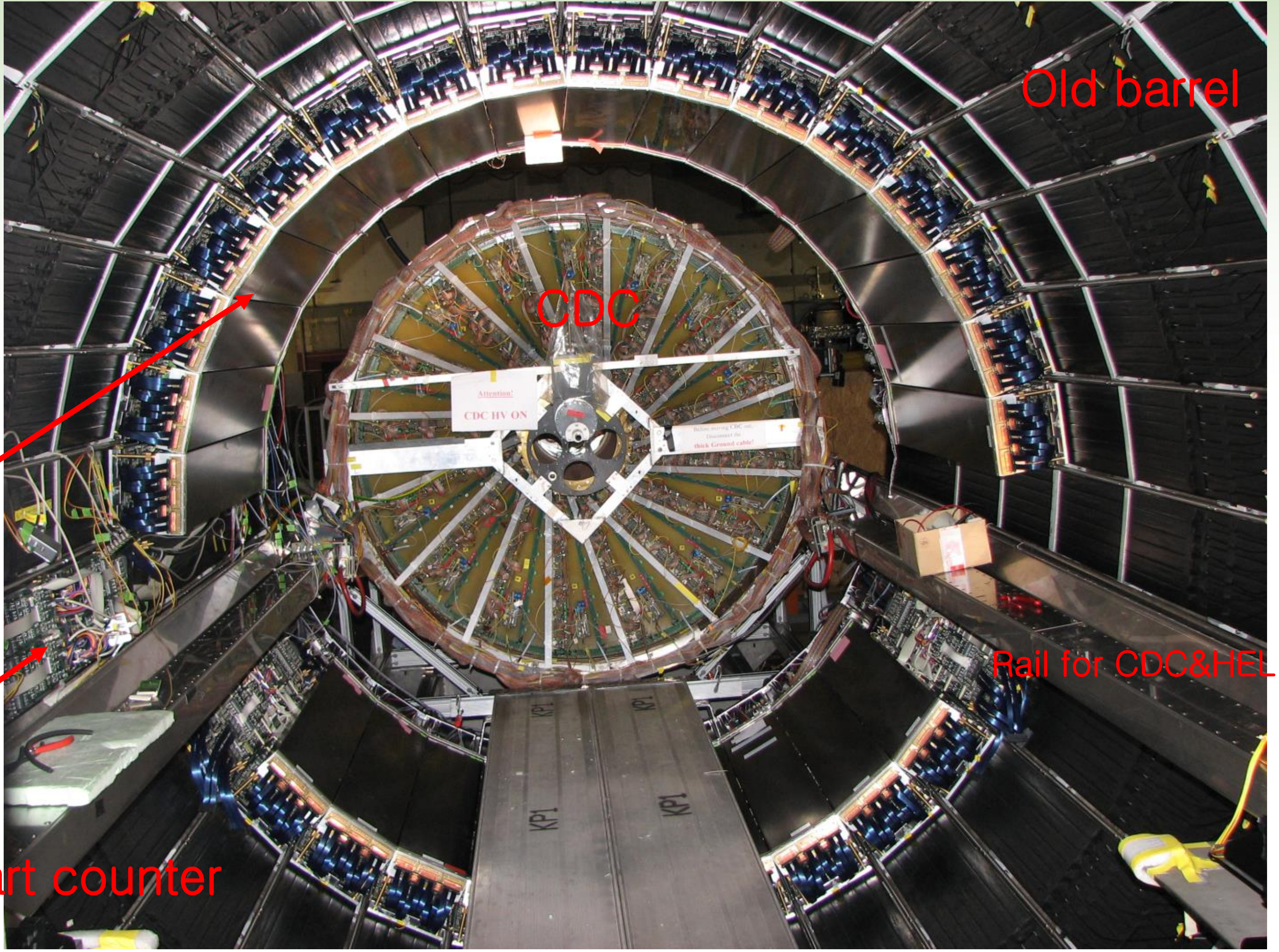
One SM needs 10 systems.

Full system electronic resolution < 25 ps

Picture of new RPC barrel

Mounting and Test

Feb. ~ Aug. in 2007



Supermodule

Electronics for start counter

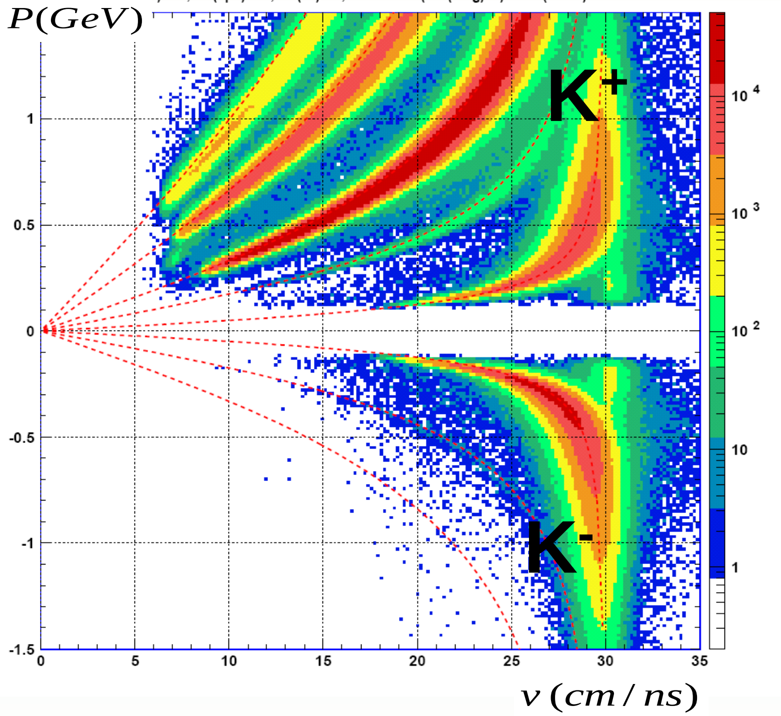
Ni+Ni at 1.9 AGeV

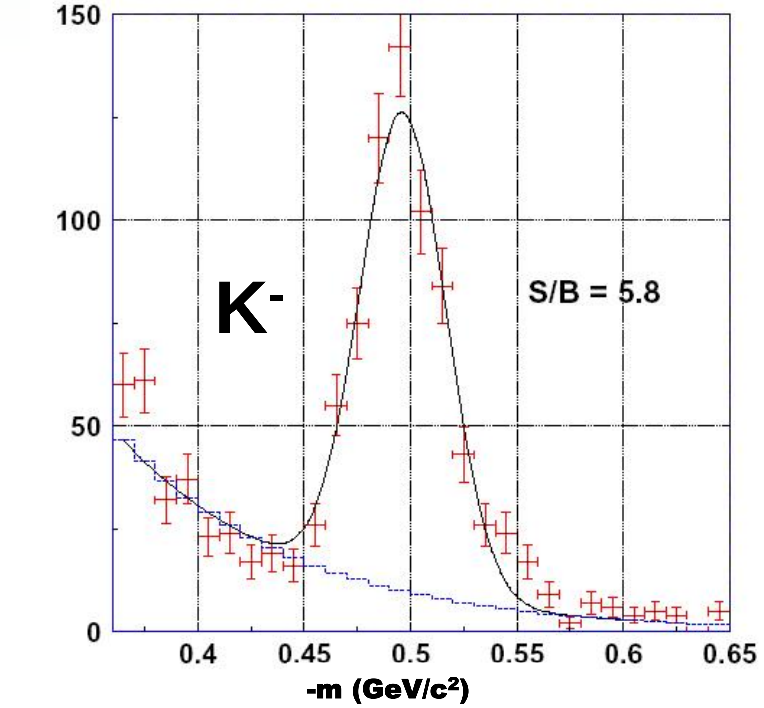
GSI Scientific Report 2008, T. I. Kang and N. Herrmann

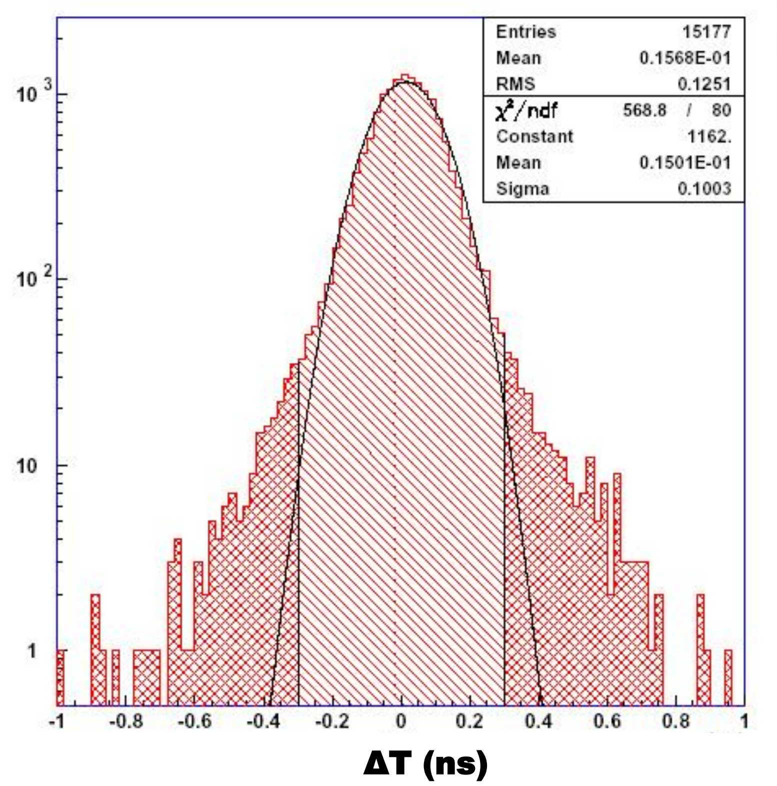
Fast pions

σ_t ~ 100 ps

f_{tail}^{rel} <3% in 3 σ







Experiments with new ToF

- K^+ and K^- production and interaction in dense baryonic matter
  - Ni+Ni collisions at 1.9 AGeV in Sep. 2007.
  - Ni+Ni collisions at 1.9 AGeV in Mar. 2008.
  - Ni+Pb collisions at 1.9 AGeV in Jan./Feb. 2009.
  - Ru+Ru collisions at 1.69 AGeV in Feb./Mar. 2009.

Nucl. Phys. A 625 325(1997)

J. Schaffner-Bielich *et al.*

- Kaonic nuclear cluster ($p+p \rightarrow K^+ + K^-pp \rightarrow K^+ + p + \Lambda$)
  - Proton beam at 3 GeV in this summer.

Phys. Rev. C 65 044005 (2002)

Y. Akaishi and T. Yamazaki

- In-medium effect (π-$p \rightarrow K^0 \Lambda$)
  - Pion beam at 1.15 GeV in 2010.

Phys. Rev. C 62 069904 (2000)

K. Tsushima, A. Sibirtsev, A. W. Thomas

Summary and Outlook

- **Ru+Ru at 0.4 and 1.528 AGeV**
  - dN/dy, yield, β_r, and T for the most central events.
  - Nucleon coalescence signature in scaled differential elliptic flow (v_2/n vs. p_t/n) for the semi-central events

- **FOPI ToF Upgrade**
  - 28 SMs consists of 140 MMRPCs and 4480 channels.
  - 98% efficiency and less 100 ps time resolution at 110 kV/cm.
  - New ToF have operated successfully during last three Ni beam times.

- **Outlook**
  - **Comparison to results from the Iso-spin Quantum Molecular Dynamics (IQMD)**