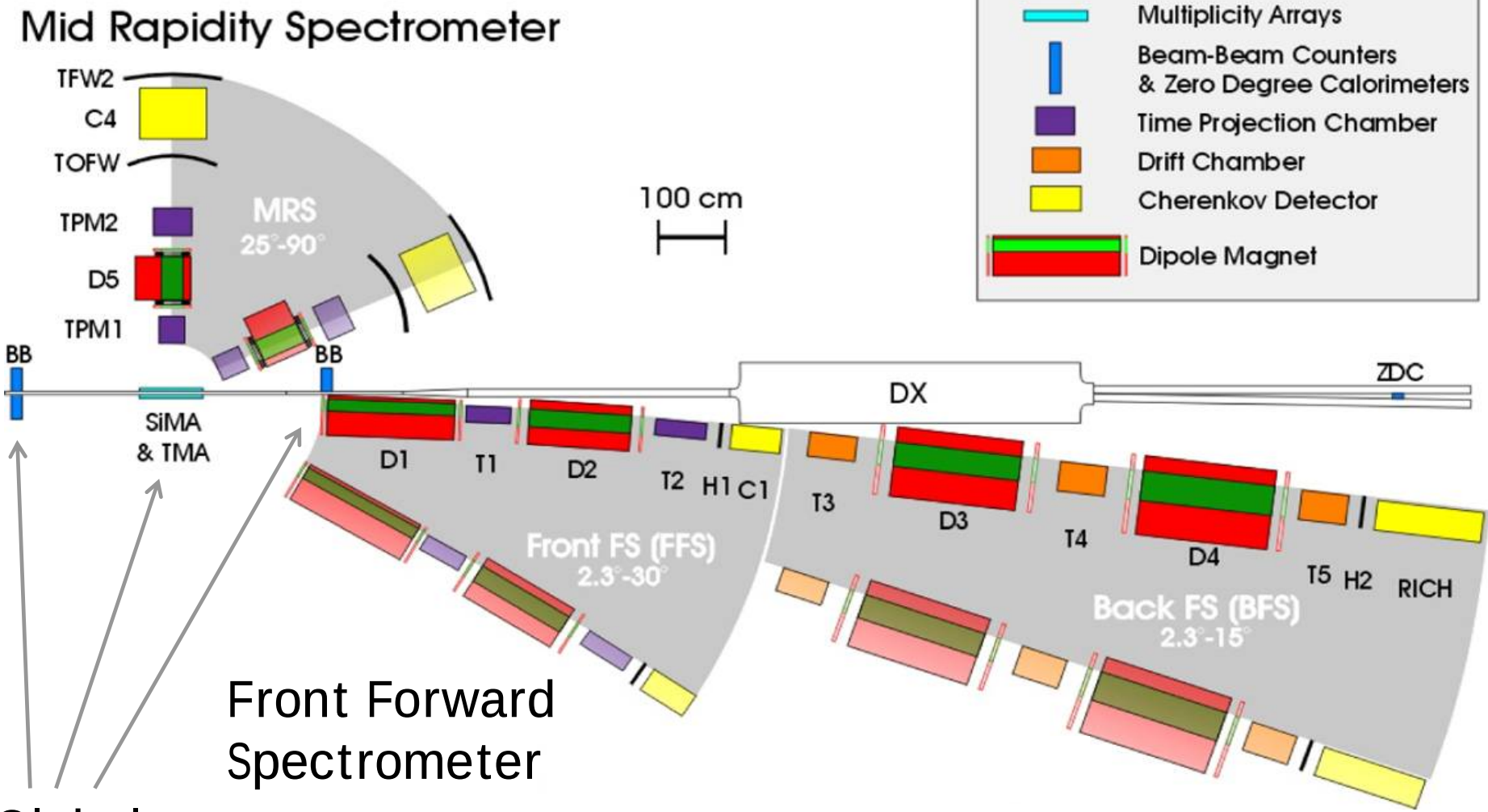
Highlights from the BRAHMS experiment at RHIC

Dipali Pal

University of Kansas

BRAHMS Collaboration

BRAHMS Experimental Setup



Front Forward Spectrometer

Global Detectors

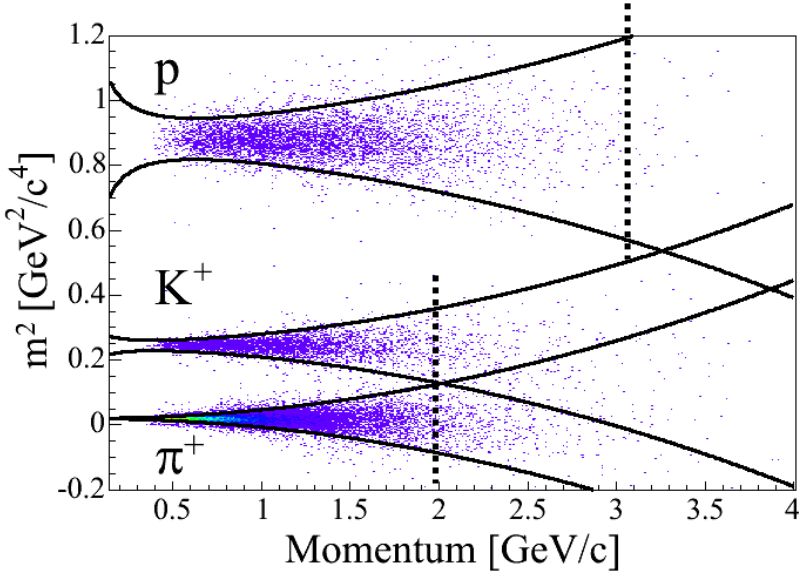
Back Forward Spectrometer

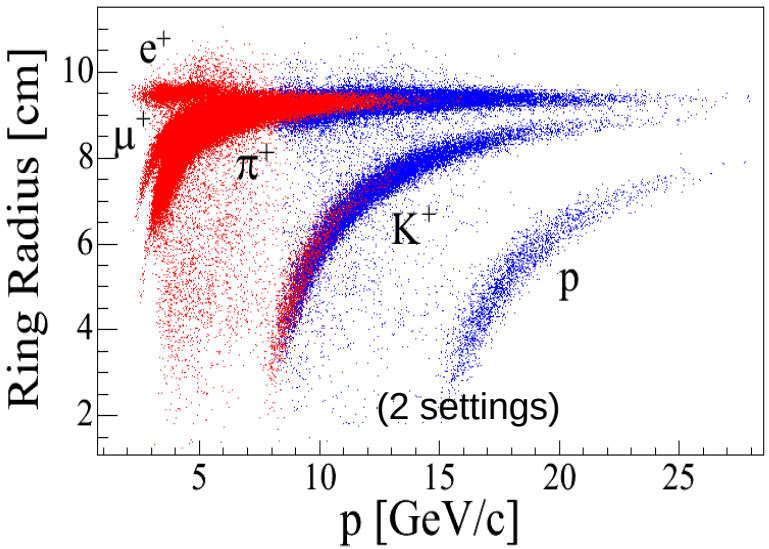
Particle Identification

TIME-OF-FLIGHT

$$m^2 = p^2\left(\frac{c^2 TOF^2}{L^2} - 1\right)$$

	0<η<1 (MRS)		1.5<η<4 (FS)	
p_{max} (2σ cut)	TOFW (GeV/c)	TOFW2 (GeV/c)	TOF1 (GeV/c)	TOF2 (GeV/c)
K/π	2.0	2.5	3.0	4.5
K/p	3.5	4.0	5.5	7.5

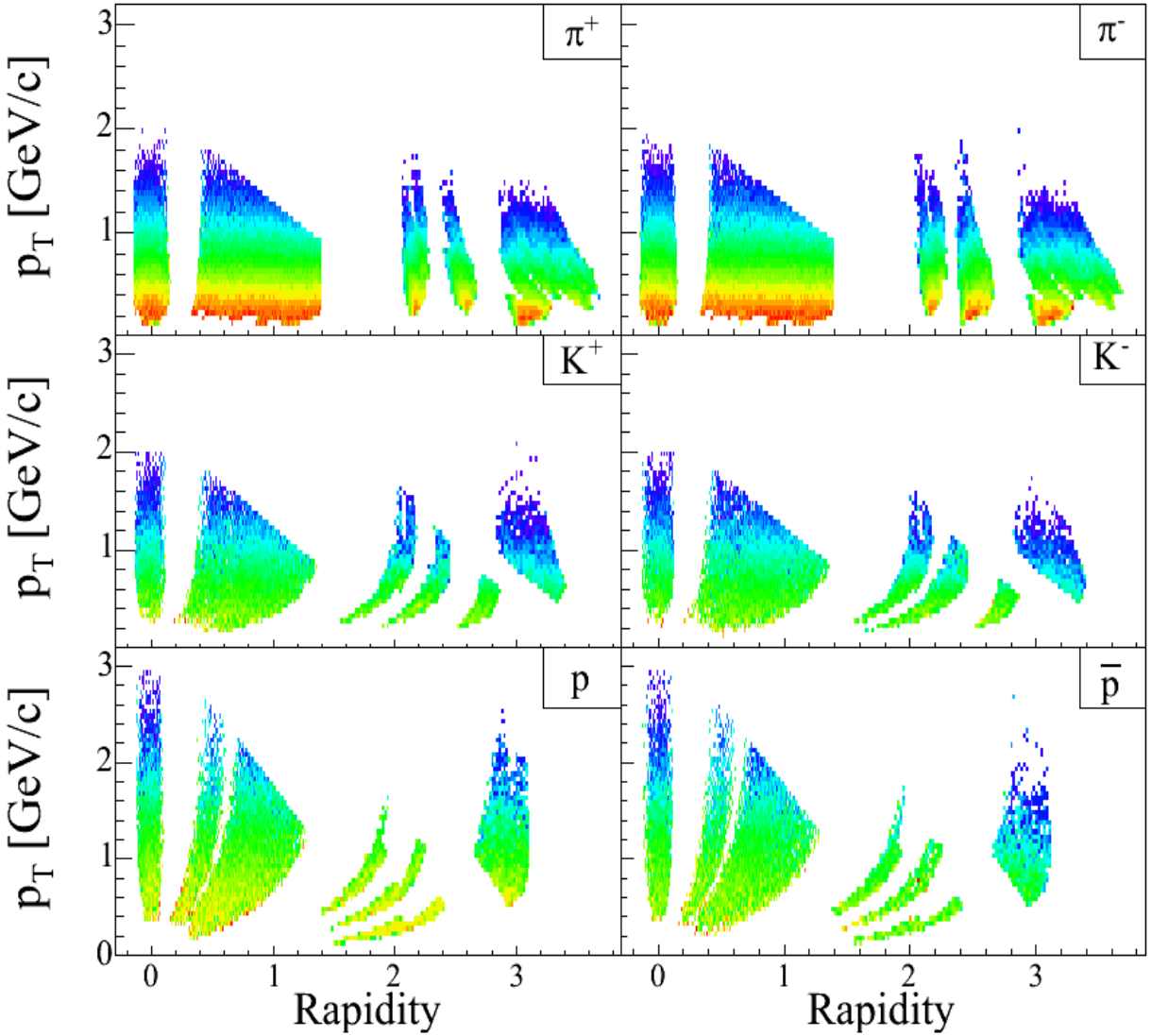




RICH

Ring radius vs momentum gives PID
π / K separation 25 GeV/c
Proton ID up to 35 GeV/c

BRAHMS Acceptance



Pion invariant differential yields

Kaon invariant differential yields

Proton invariant differential yields

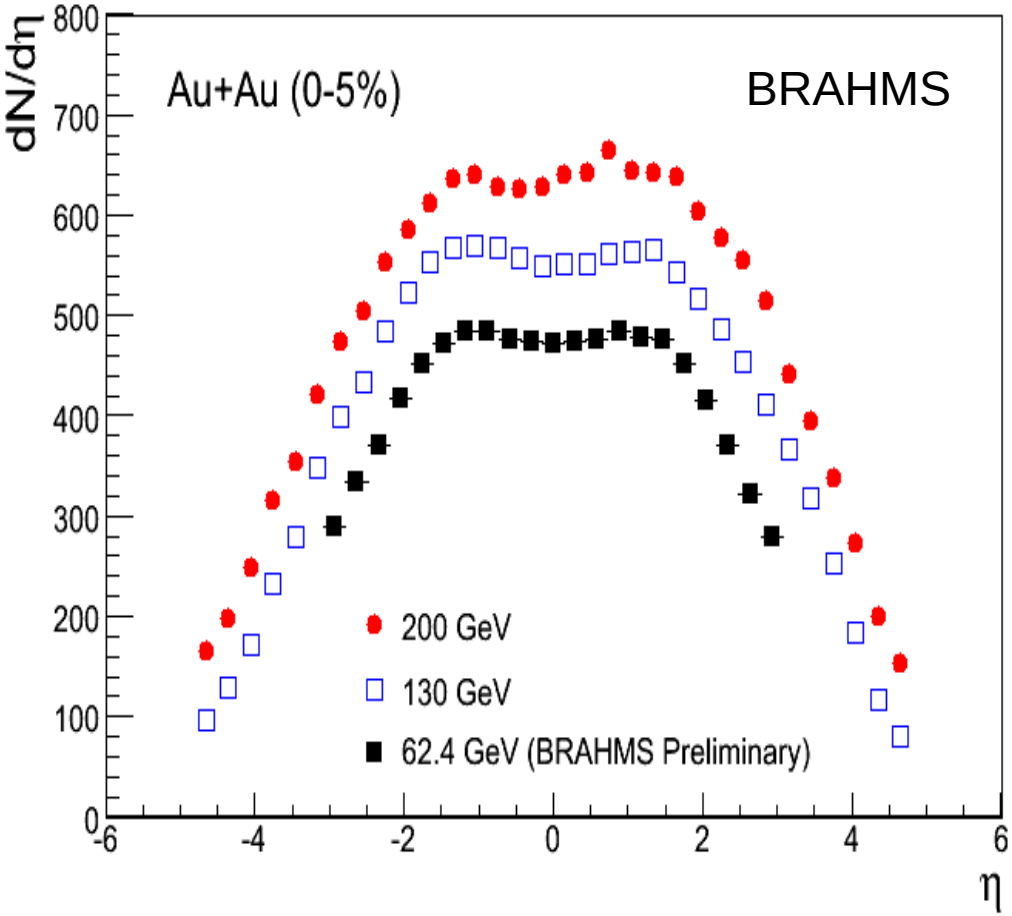
Reaction Systems Studied

Reaction System	Energy (GeV)	
$^{197}Au+^{197}Au$	200	Create hot dense system at highest energy at RHIC with formation Quark Gluon Plasma
$^{197}Au+^{197}Au$	63, 130	Energy scan
$^{63}Cu + ^{63}Cu$	200, 63	Mass, energy scan
d $+^{197}Au$	200	Control experiment to investigate initial/final state and cold nuclear medium effects.
p + p	63, 200	Baseline measurement.

Results

- Multiplicity distributions
  - Energy density and stopping
  - Anti-particle to particle ratios: Chemical freeze out
- Nuclear modification factors, R_{AA} and R_{dA}
  - Particle production mechanisms
- Flow
  - Collision geometry and particle production
- Vector meson production: $\phi \rightarrow KK$
  - Medium effects and strangeness production
- Summary

Particle production



Energy density: Bjorken 1983

$e_{BJ} = 3/2 \times (\langle E_t \rangle / \pi R^2 \tau_0)\, dN_{ch}/d\eta$

assuming formation time t_0=1fm/c:

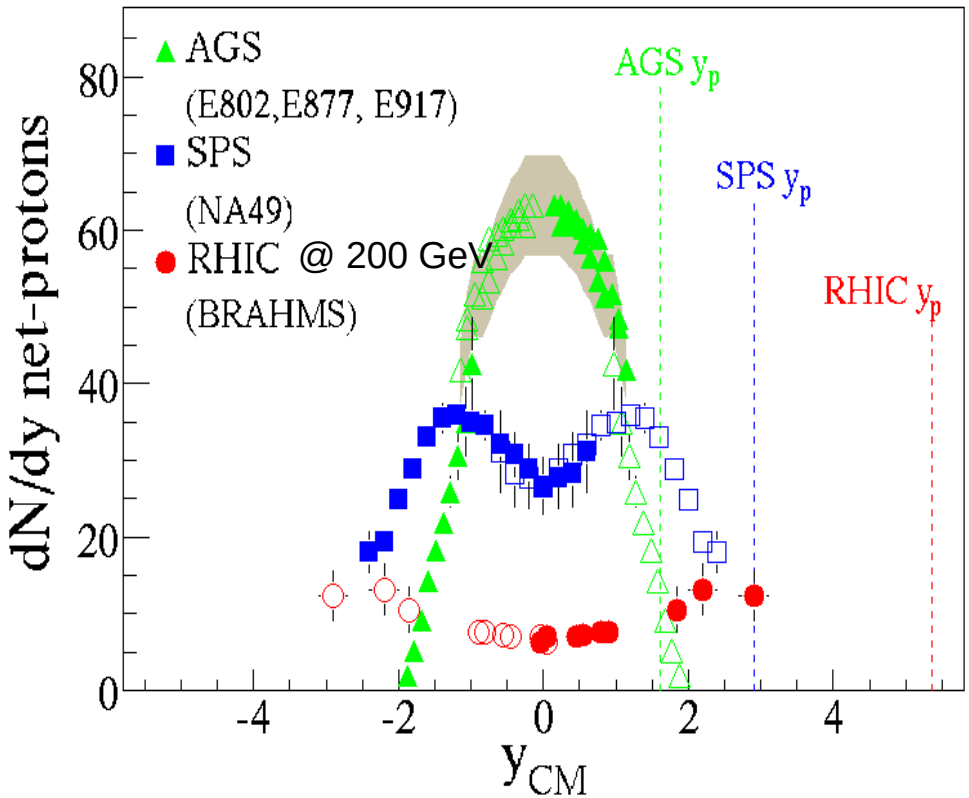
>5.0 GeV/fm^3 for AuAu @ 200 GeV

>4.4 GeV/fm^3 for AuAu @ 130 GeV

>3.7 GeV/fm^3 for AuAu @ 62.4 GeV

At all RHIC energies, initial energy density exceeds critical energy density for phase transition from hadronic matter to QGP.

Particle production and energy loss



$$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy} \cosh y \, dy$$

Total ΔE=25.7±2.1TeV

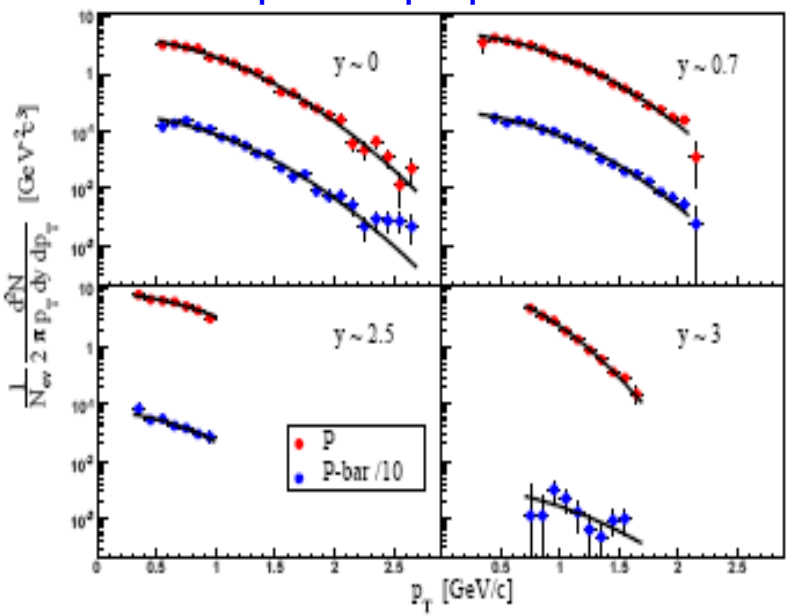
73GeV per nucleon

~73% of beam energy is deposited and available for particle production.

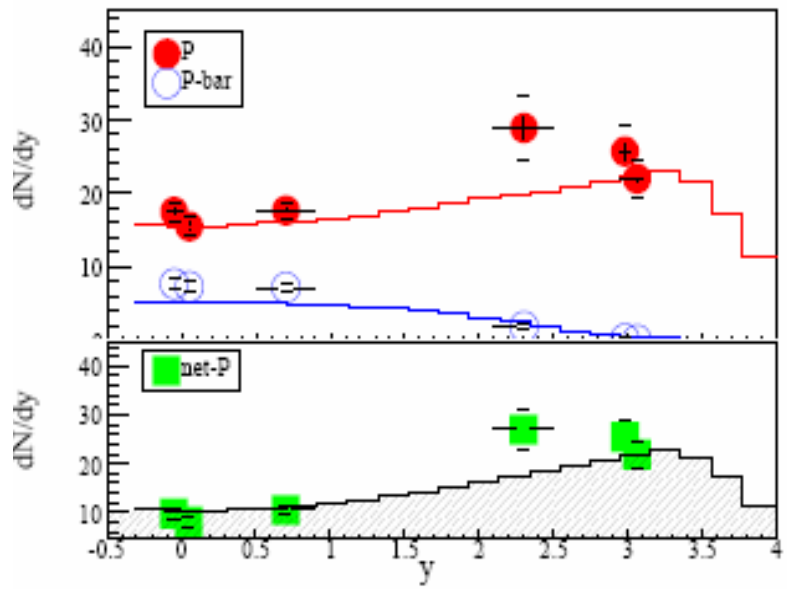
Nuclear stopping @ 62 GeV Au+Au

BRAHMS Preliiminary

p and $\bar{p}$ spectra



dN/dy vs y



Gaussian fitting function:

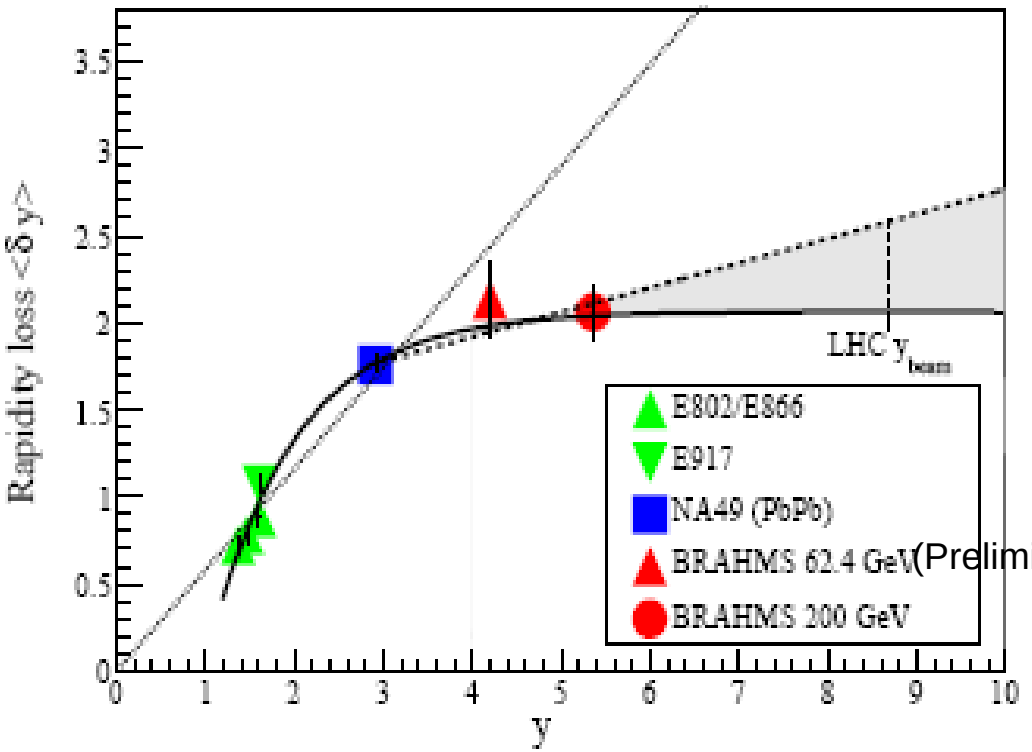
$$f(p_T) \propto \exp(-p_T^2 / 2T^2)$$

Rapidity loss

$$\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\bar{B})}}{dy} dy$$

$< \delta y > = 2.14 +/- 0.22$

Stopping systematics

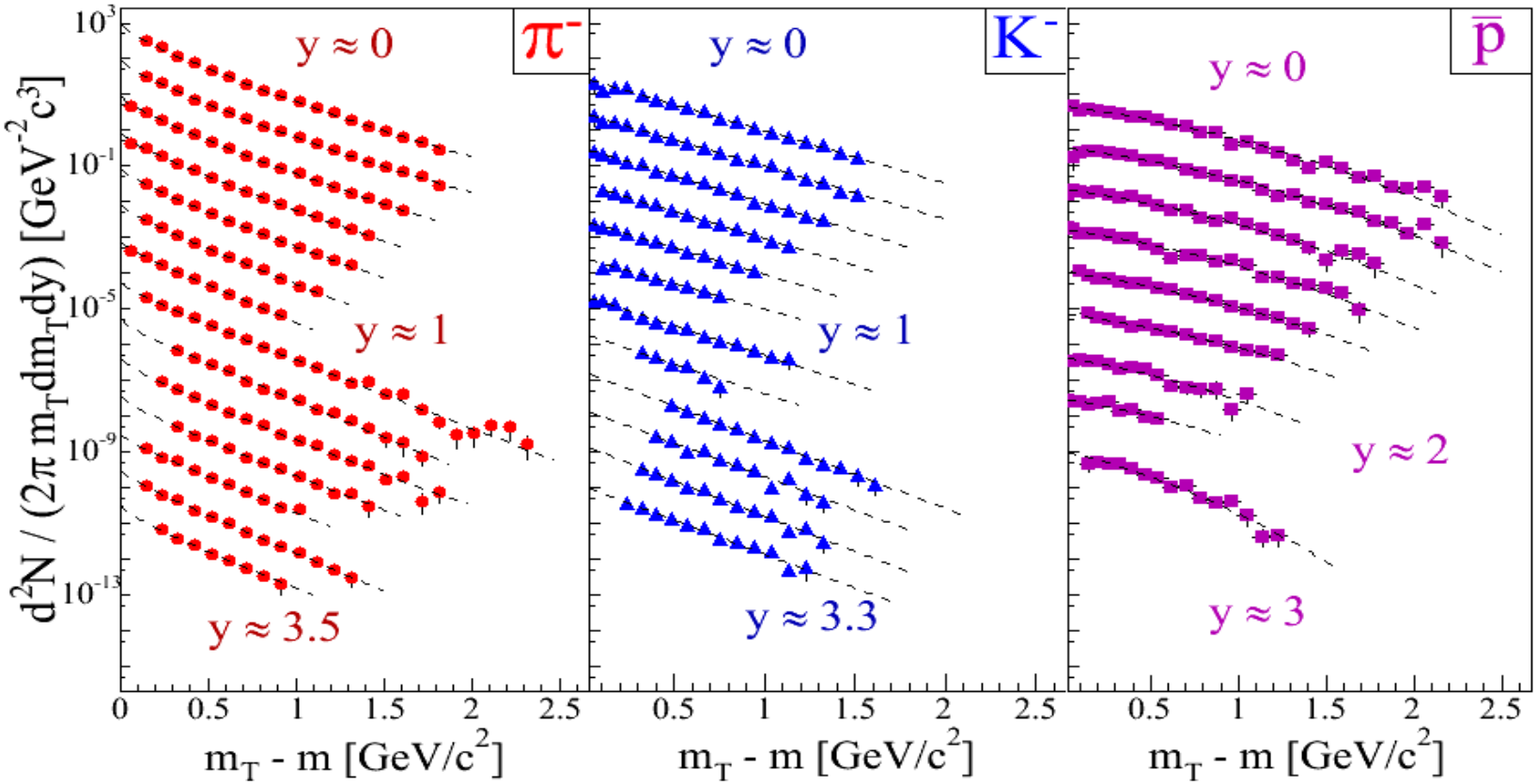


(Preliminary)

- All points are fitted with
  $f(y_{CM}) = A + B\,(1 - \exp(y_{CM}))$
- Linear fit to SPS and RHIC data
- Linear fit to AGS and SPS data

- Rapid increase in rapidity shifts from AGS to SPS
- Slow increase from SPS to RHIC
- Expected rapidity loss at LHC: $2.1 < \delta y < 3.4$

Particle Spectra in Au+Au @ 200 GeV : Top 5% centrality



Pions: power law

$$A\left(1+\frac{p_T}{p_0}\right)^{-n}$$

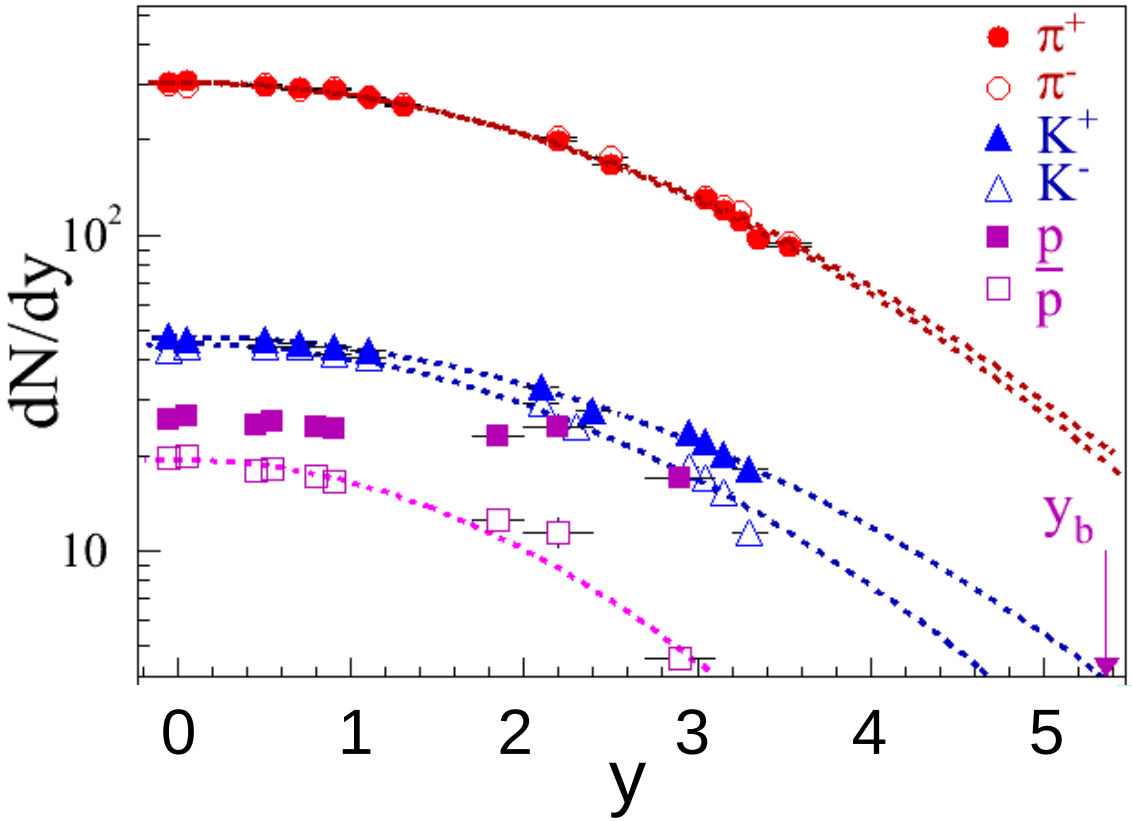
Kaons: exponential

$$A\exp\left(-\frac{m_T-m}{T}\right)$$

Protons: Gaussian

$$A\exp\left[-\frac{p_T^2}{2\sigma^2}\right]$$

Rapidity Densities



At y ~ 0, dN/dy is
~ 300 (300) for π^+ (π^-)
~ 47 (44) for K^+ (K^-)
~ 27 (20) for p (pbar)

N(π) >> N(K) > N(p)
N(π^+) = N(π^-)

N(K^+) > N(K^-) and
N(p) > N(pbar) systematically

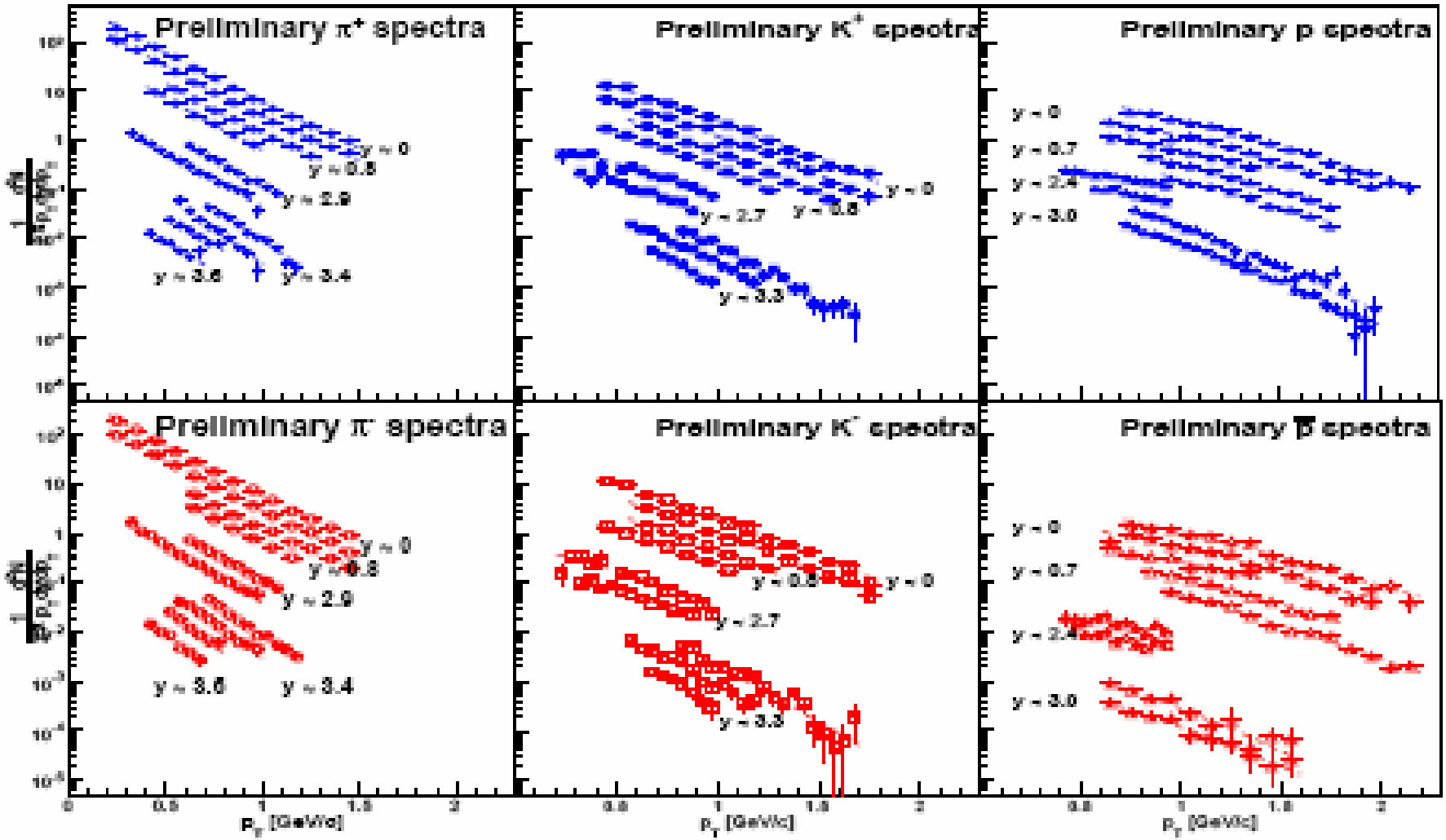
All distributions can be fitted with a Gaussian except protons
➔ Fragmentation component

Integrated multiplicities

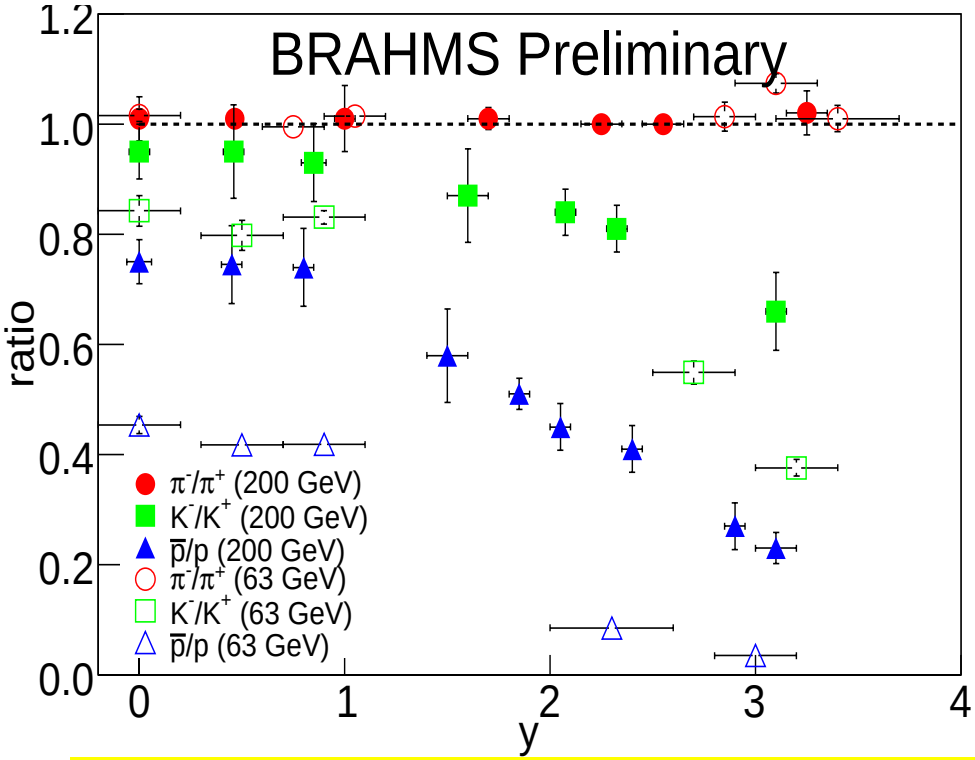
(Gaussian fit)

N(π^-) ~ 1780 N(π^+) ~1760
N(K^+) ~ 290 N(K^-) ~ 240
N(pbar) ~ 85

Particle spectra in Au+Au @ 62.4 GeV
0 – 10% centrality



Anti-particle/particle ratio vs y



Mid-rapidity ratios		
	200 GeV	63 GeV
π^-/π^+	1.0	1.0
K^-/K^+	0.95	0.84
pbar/p	0.75	0.45

Approximate balance between particles and anti-particles at y~0 for 200 GeV
➔Pair creation mechanism

Kaon and proton ratios are lower at all y for 63 GeV

K and p ratios are falling at y>1
➔ Influence of net-baryon rich medium at forward rapidities

Anti particle/particle ratios (II)

Statistical model with chemical and thermal equilibrium

$$\frac{N(\overline{p})}{N(p)} = e^{-6\mu_B/T}$$

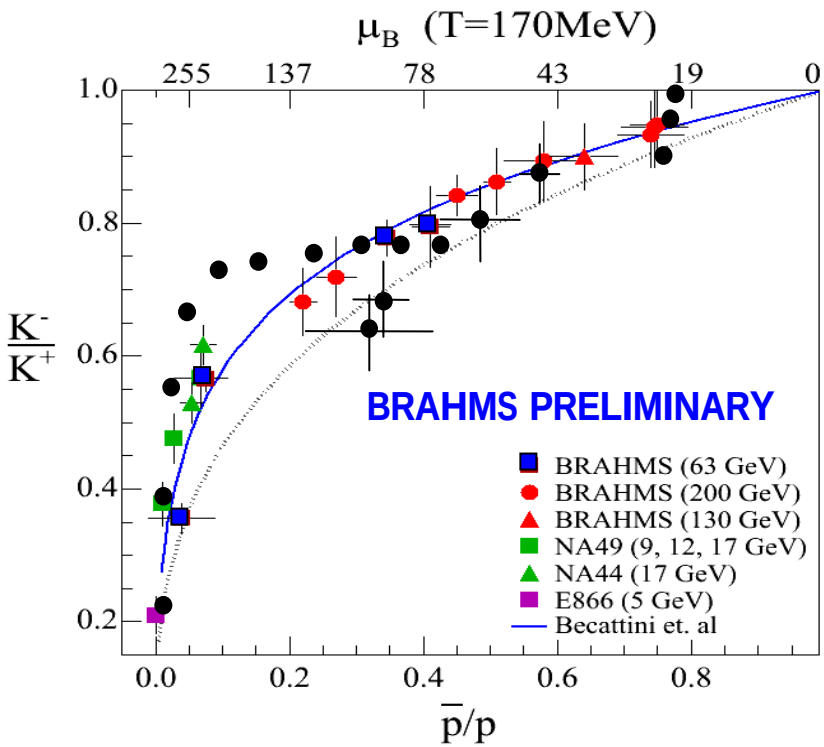
and

$$\frac{N(K^-)}{N(K^+)} = e^{-2(\mu_B-\mu_s)/T}$$

$$\Rightarrow \quad \frac{K^-}{K^+} = \left(\frac{\overline{p}}{p}\right)^{1/3} e^{-2\mu_s/T}$$

Anti particle/particle ratios (III)

Chemical freeze-out



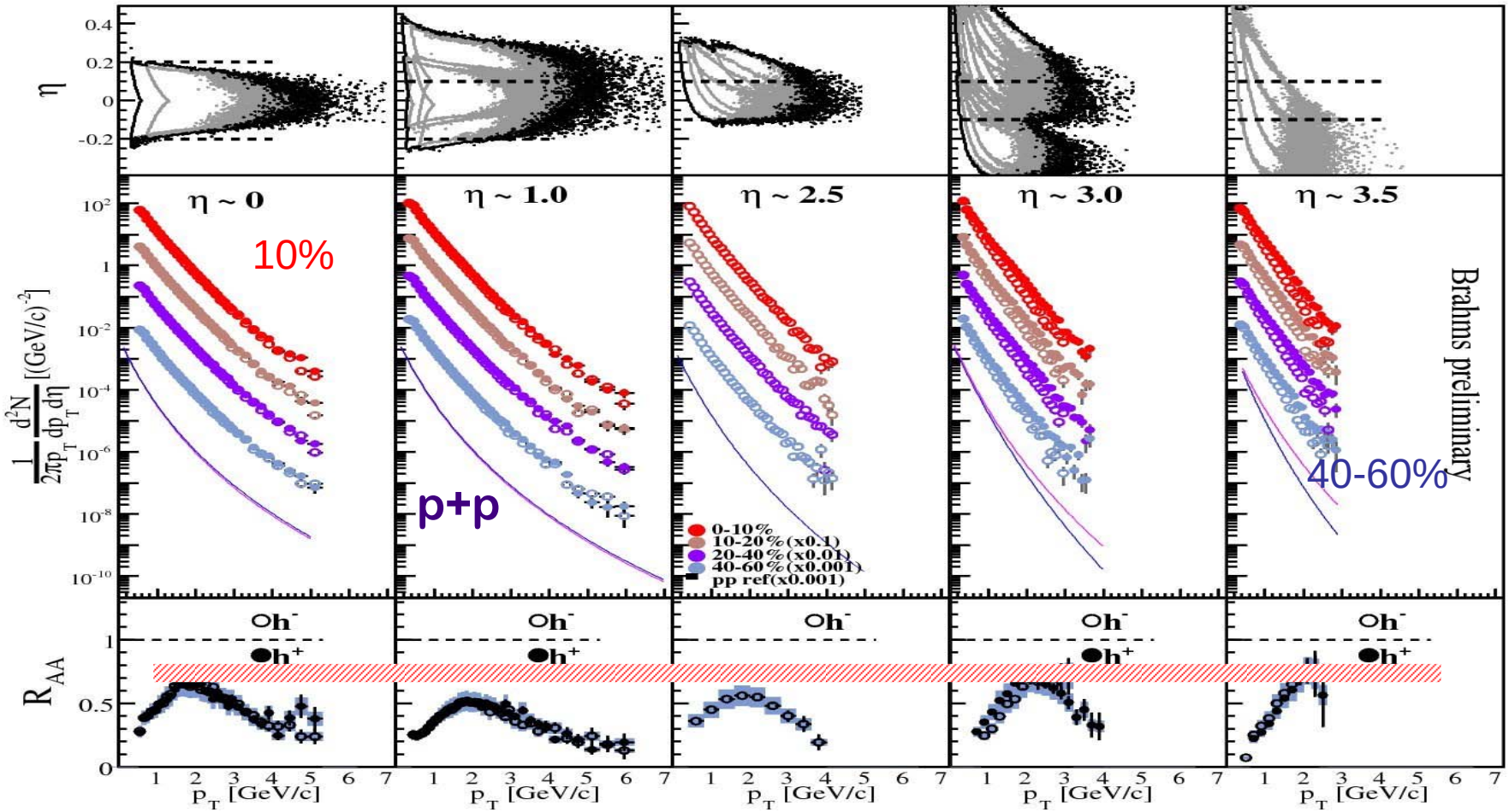
- Good statistical model description with $\mu B = \mu B(y)$ with T~170MeV
- Also describes energy dependency at y=0
  - only μ_B controls the state of matter

Not true for p+p collision

Summary on Multiplicity distribution and particle ratios

- Energy density at RHIC exceeds critical energy density for QGP formation.
- ~73% of beam energy is deposited and available for particle production.
- Rapid increase in rapidity loss from AGS to SPS, then slow increase from SPS to RHIC.
- Anti-particle to particle ratios are consistent with chemical freeze out

Nuclear modification factor
Run4 Au + Au @ 200 GeV: Charged particle spectra

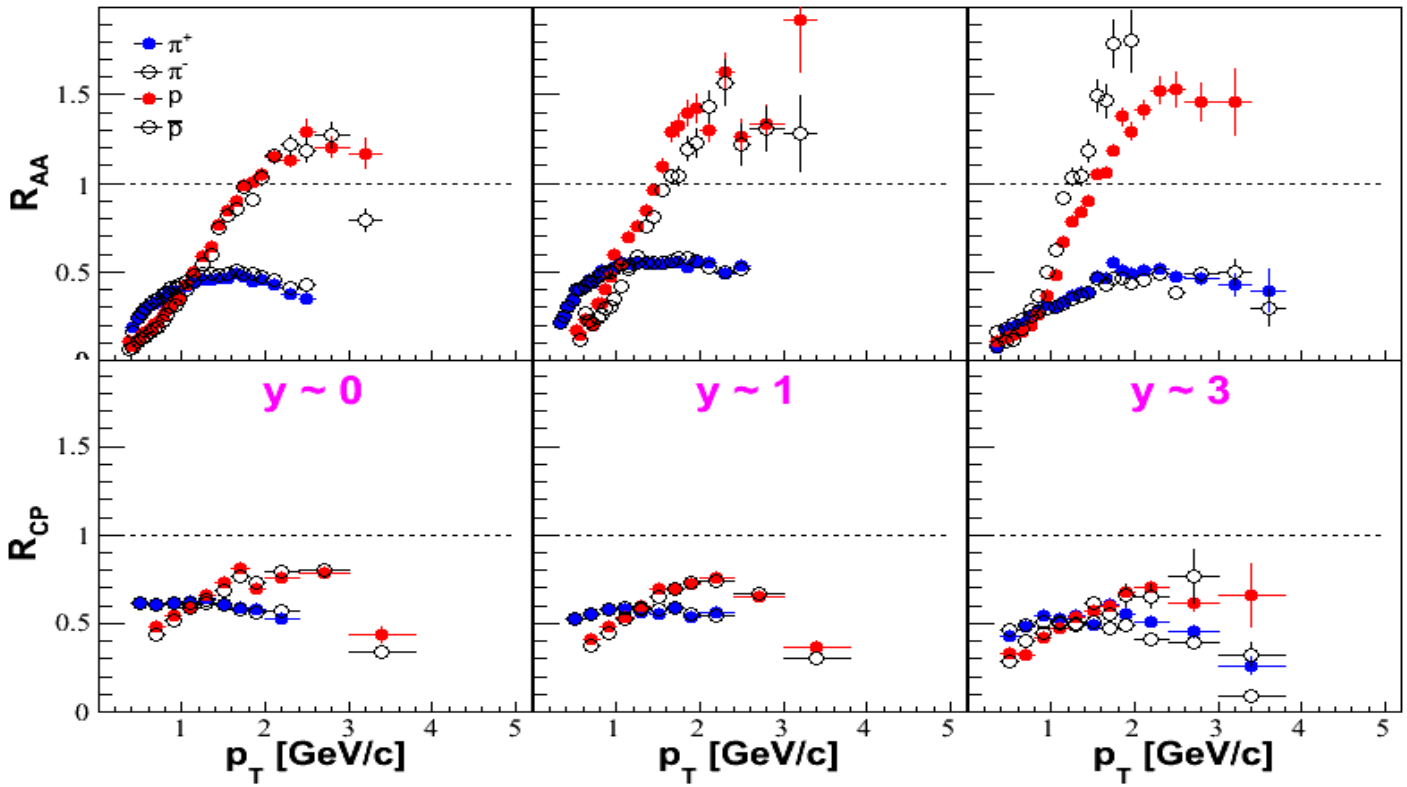


No significant change in R_{AA} with rapidity

Nuclear modification factor

Identified particles: Au+Au @ 200 GeV

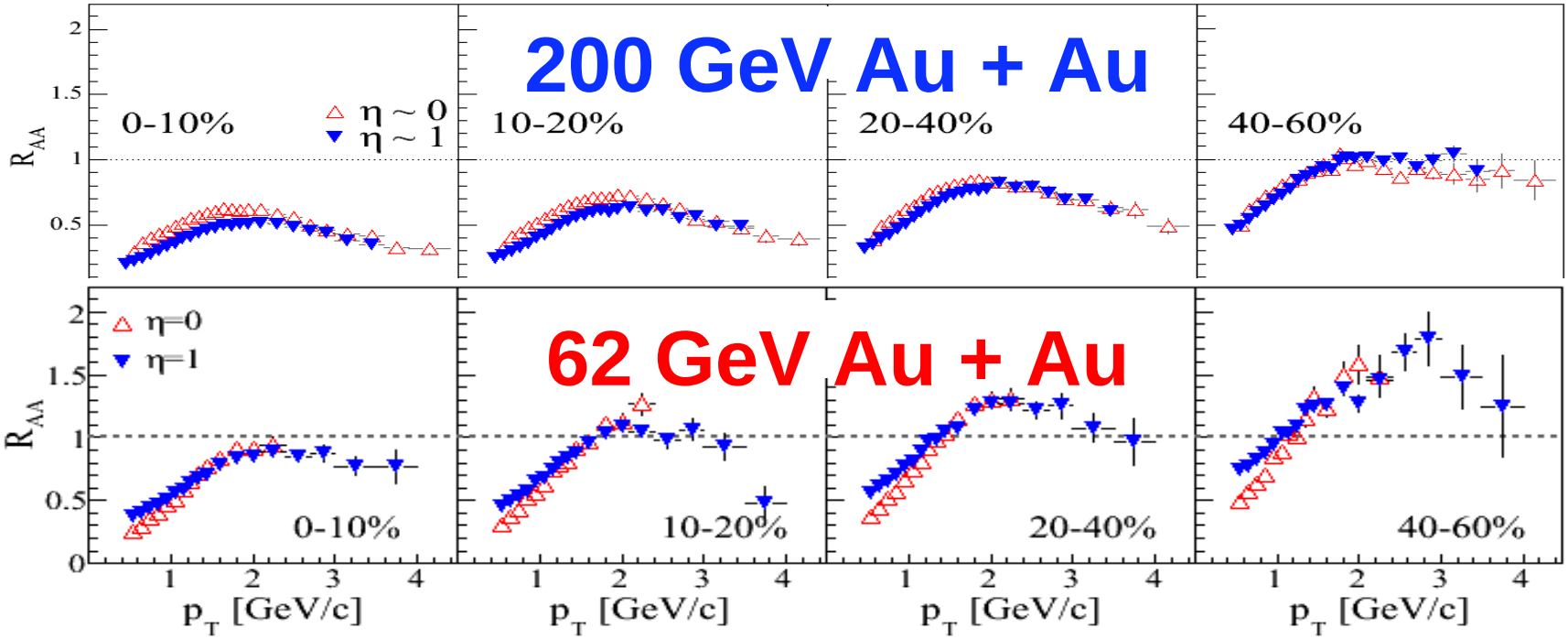
BRAHMS Preliminary



- R_{AA} for mesons show suppression at all y
- Protons/anti-protons show enhancement at intermediate p_T for all y.
- R_{CP} shows different behaviors of baryons and mesons

Au+Au Centrality Comparison at 62 and 200 GeV

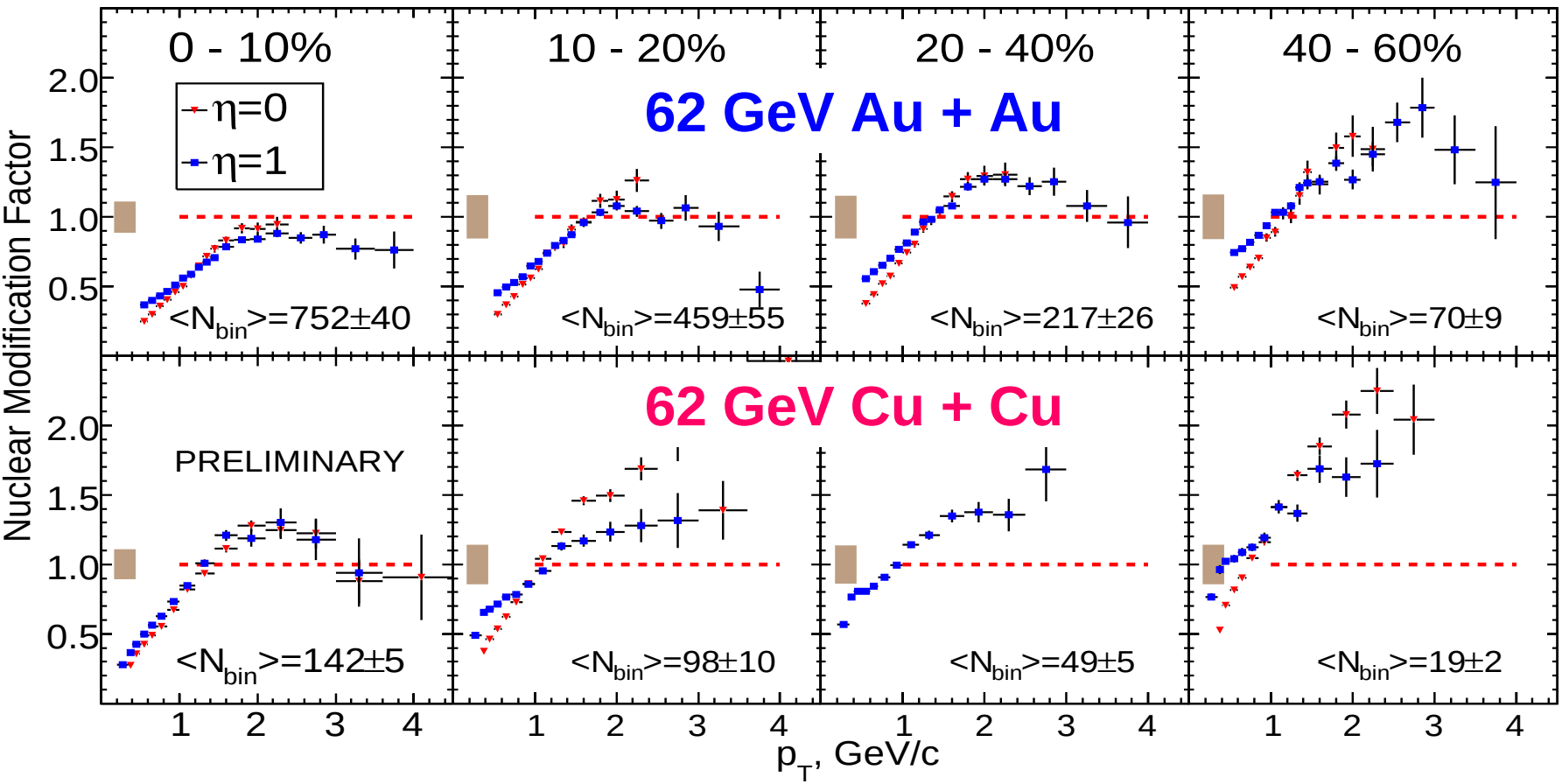
Brahms preliminary



- Less suppression (more enhancement) at 62 GeV than at 200 GeV.

(62 GeV pp reference based on ISR collider data; B. Alper *et al*., Nucl. Phys. B100 (1975) 237.)

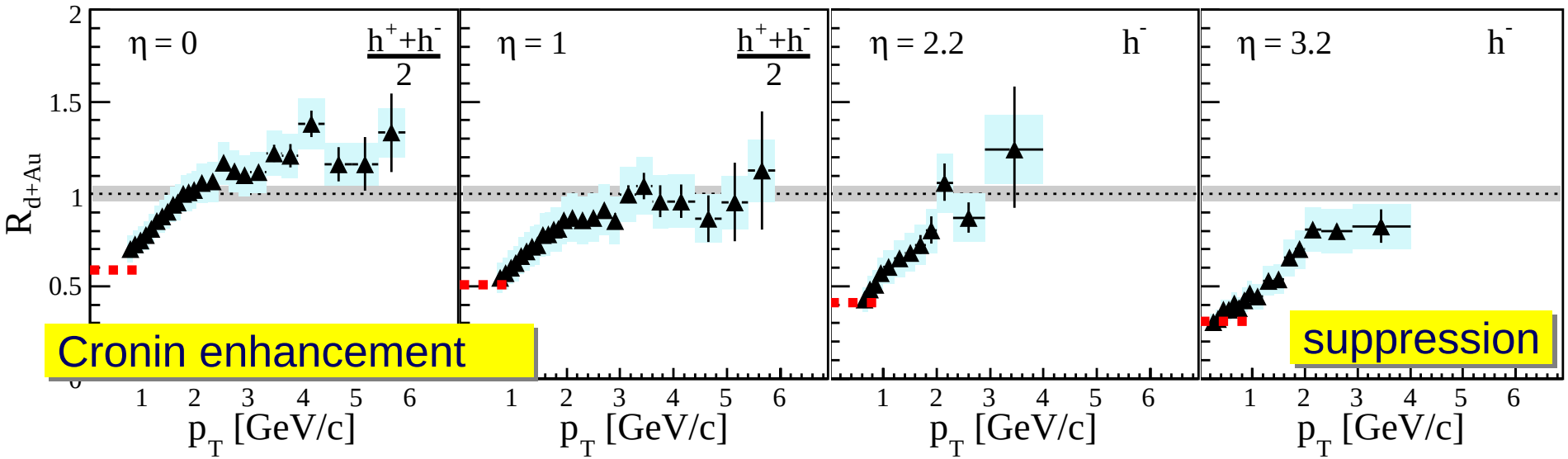
Comparison of Au+Au and Cu+Cu @ 62 GeV



Suppression increases with increasing colliding ion mass

Nuclear modification factor

d+Au at all rapidities



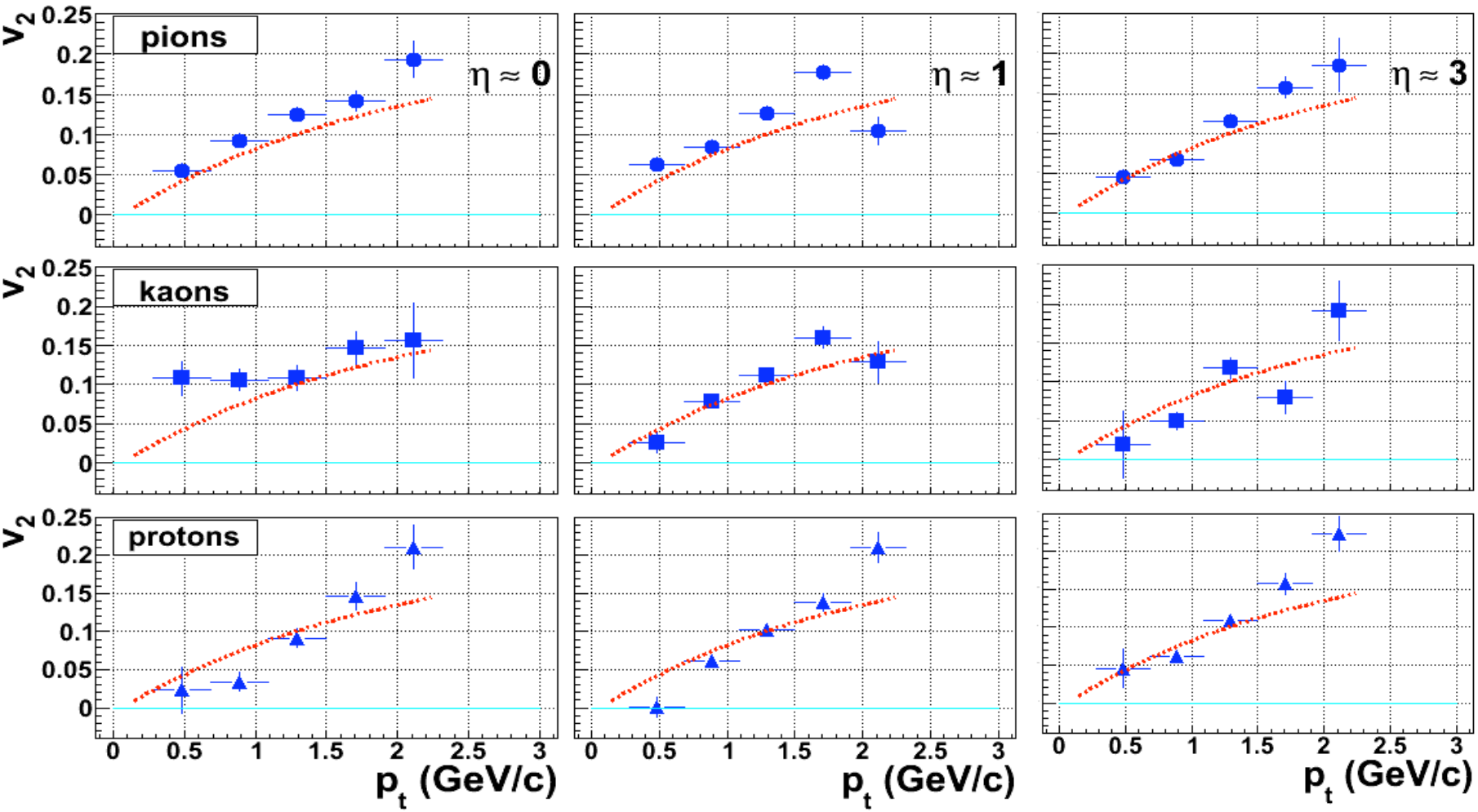
I. Arsene *et al.*, BRAHMS PRL 93 (2004) 242303.

- Unidentified hadrons
- Systematic decrease of R_{dA} with increasing η

Summary on Nuclear Modification Factors

- Charged hadron R_{AA}'s do not change with η.
- Mesons are suppressed and baryons are enhanced
- Suppression increases with collision energy
- Suppression increases with higher colliding ion mass
- No suppression in R_{dA}
  - Cold nuclear matter
  - Cronin enhancement

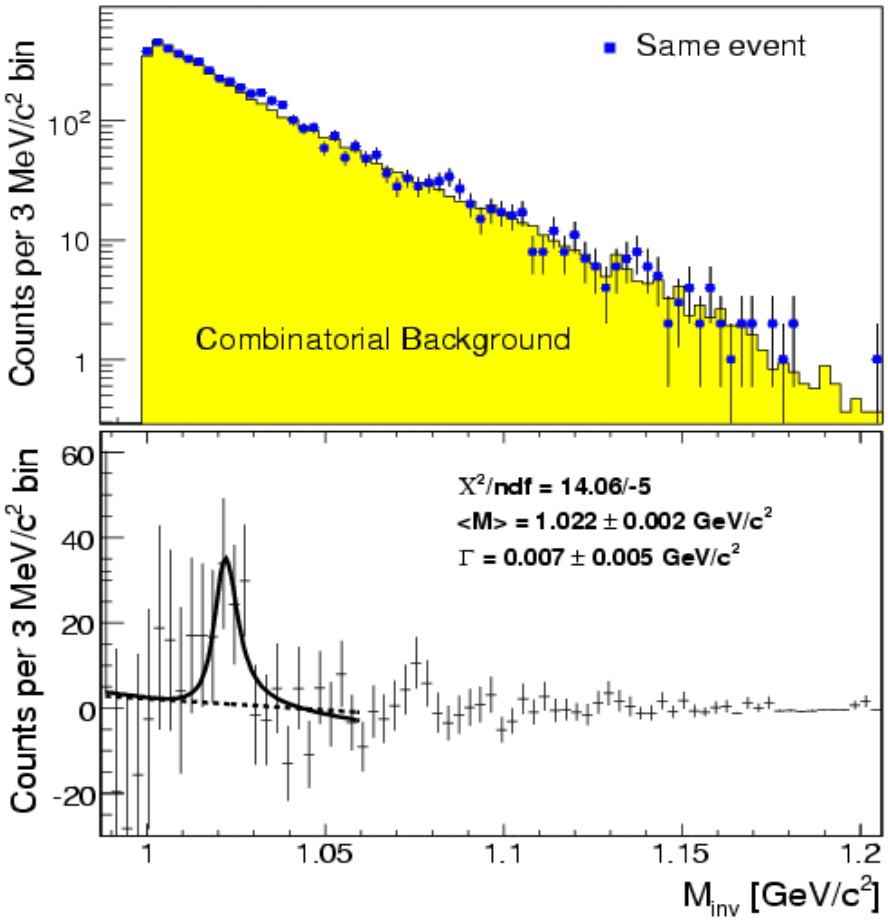
v_2 vs p_T (10 – 50%): BRAHMS Preliminary



---- STAR 0 – 50% hadrons: PRC 72, 014904 (2005)

Very little change in v_2 with η for all three particles

$\phi \rightarrow$ KK reconstruction: Invariant mass spectrum



N_ϕ = 120 +/- 35

Extracted by integrating the signal within 1.013 < M < 1.031 GeV/c²

$$M^2 = (p_1 + p_2)^2$$
$$= p_1^2 + p_2^2 + 2p_1p_2$$
$$= m_1^2 + m_2^2 + 2(E_1E_2 + \vec{p}_1.\vec{p}_2)$$

Measured (same event)

Combinatorial Bkg

- Mixed event
- Normalization

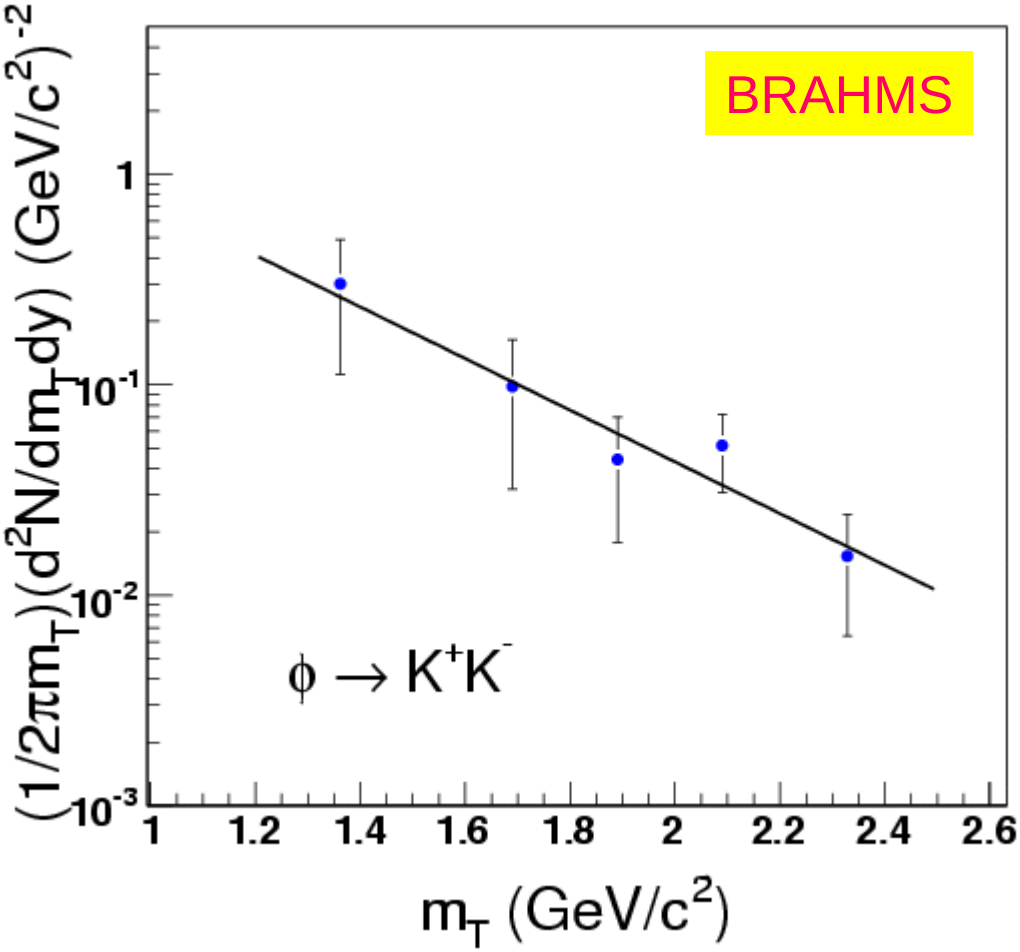
Subtracted = Measured – CB

Fitted with Relativistic Breit Wigner + Linear function from acceptance effects

Centroid and width are consistent with PDG values:

M_ϕ = 1.019456 GeV/c² , Γ = 4.26 MeV/c²

$\phi \rightarrow KK$ m_T spectrum: dN/dy and T at y~1



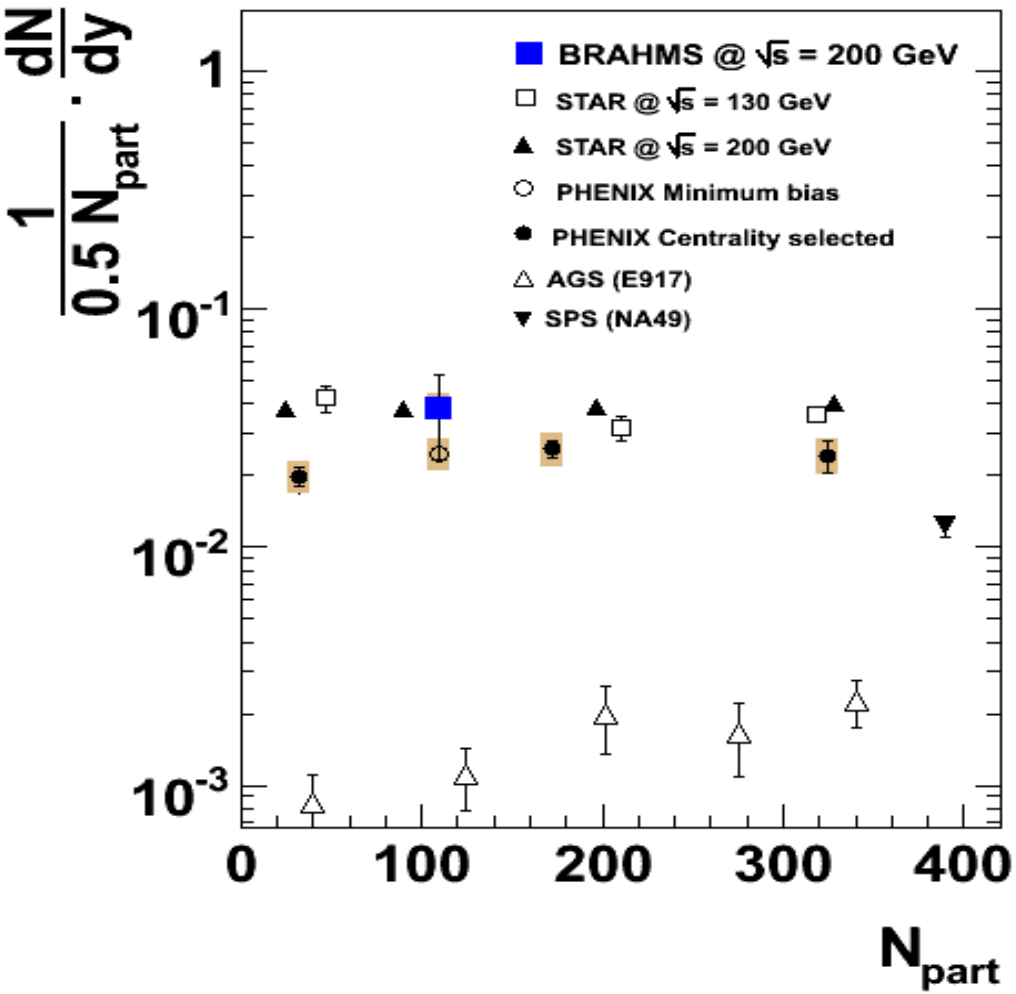
Exponential fitting function:

$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = \frac{dN/dy}{2\pi T(T+M_\phi)} e^{-(m_T - M_\phi)/T}$$

dN/dy = 2.09 +/- 1.00 +/- 0.25

T = 354 +/- 109 +/- 35 MeV

ϕ meson yields at different energies



- Yield increases from AGS to RHIC
- Different trends between AGS and RHIC
- No significant difference between y~0 STAR and y~1 BRAHMS results.

Summary on v_2 and ϕ meson measurements @ 200 GeV Au + Au collisions

- Flow
  - No significant change in v_2 vs p_T with increasing rapidities

- First results on $\phi \rightarrow KK$ at y~1
  - No change in line shape (centroid and width) from PDG
  - Yield per participant pair shows different trends in AGS and RHIC
  - Increase in yield per participant from AGS to RHIC
  - Yield is consistent with STAR

BRAHMS Collaboration @ RHIC

I. Arsene, S. Lindahl, G. Løvhøiden, B. H. Samset, and T. S. Tveter
University of Oslo, Department of Physics, Oslo,Norway

I. G. Bearden, H. Bøggild, C. H. Christensen, P. Christiansen, H. H. Dalsgaard, J. J. Gaardhøje, C. E. Jørgensen, T. M. Larsen, C. Nygaard, B. S. Nielsen, and C. Ristea
Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Copenhagen 2100, Denmark

D. Beavis, C. Chasman, R. Debbe, H. Ito, J. H. Lee, and F. Videbæk
Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.

S. Bekele, E. B. Johnson, E. J. Kim, M. Murray, D. Pal, and S. J. Sanders
University of Kansas, Lawerence, Kansas 66049

C. Besliu, A. Jipa, and O. Ristea
University of Bucharest, Romania

B. Budick
New York University, New York 10003

K. Hagel, J. Natowitz, and R. Wada
Texas A&M University, College Station, Texas, 17843

R. Karabowicz, N. Katrynska, Z. Majka, R. Planeta, and P. Staszel
Smoluchkowski Inst. of Physics, Jagiellonian University, Krakow, Poland

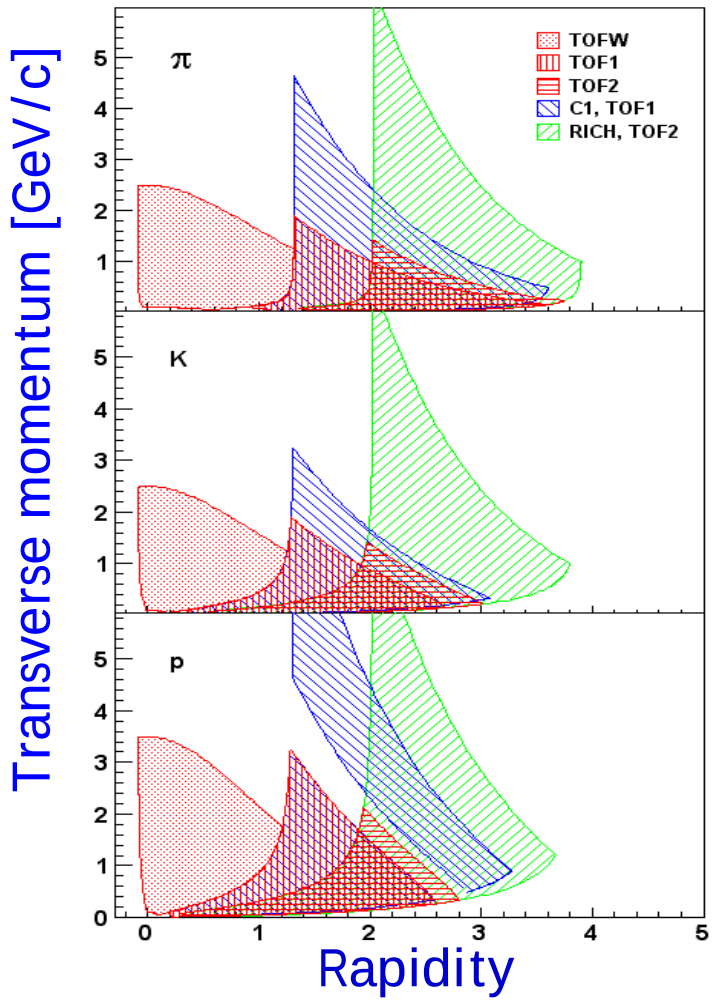
F. Rami
Institut Pluridisciplinaire Hubert Curien and Université Louis Pasteur, Strasbourg, France

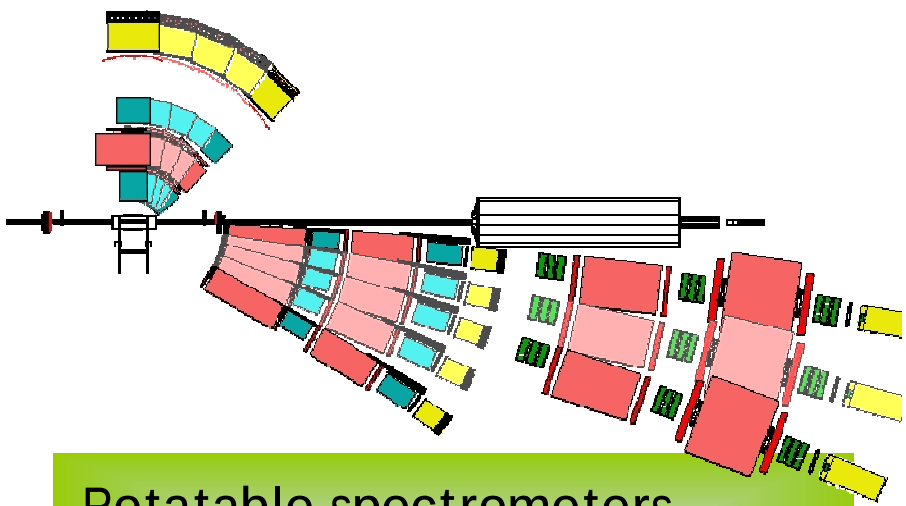
D. Röhrich, H. Yang, and Z. Yin
University of Bergen, Department of Physics and Technology, Bergen, Norway

I. S. Zgura
Institute for Space Science, Bucharest, Romania

Backups

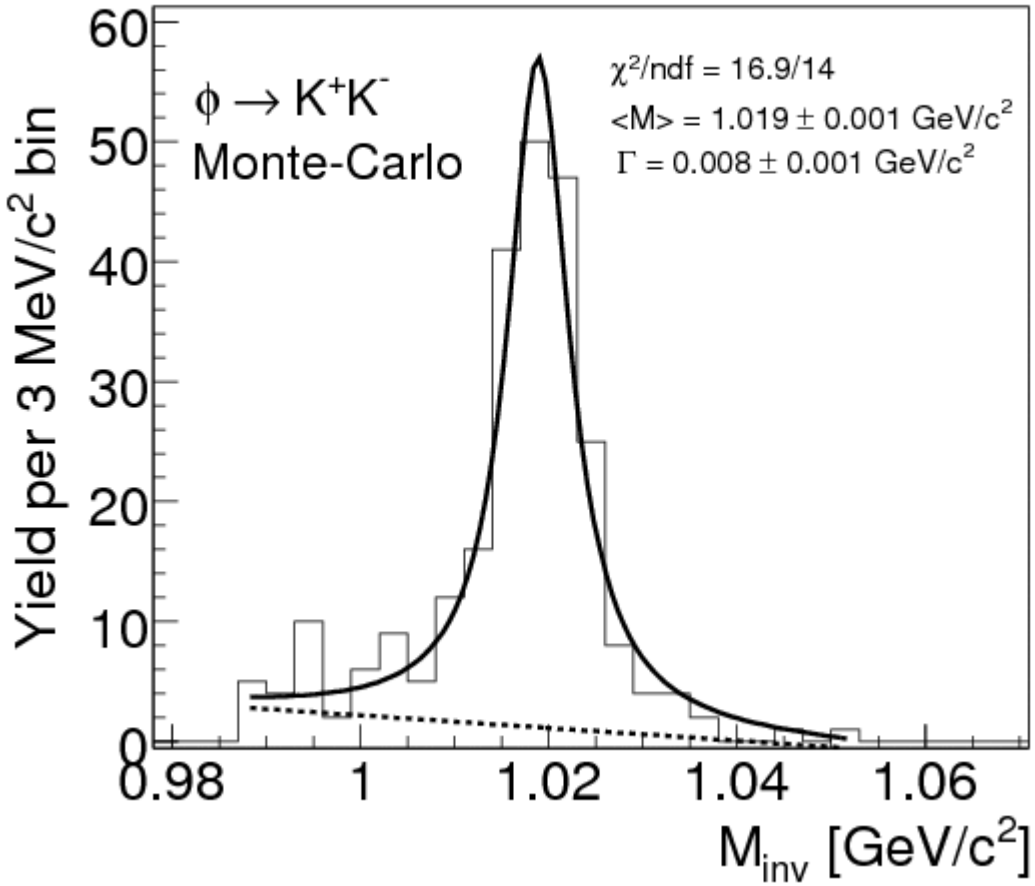
The BRAHMS Acceptance





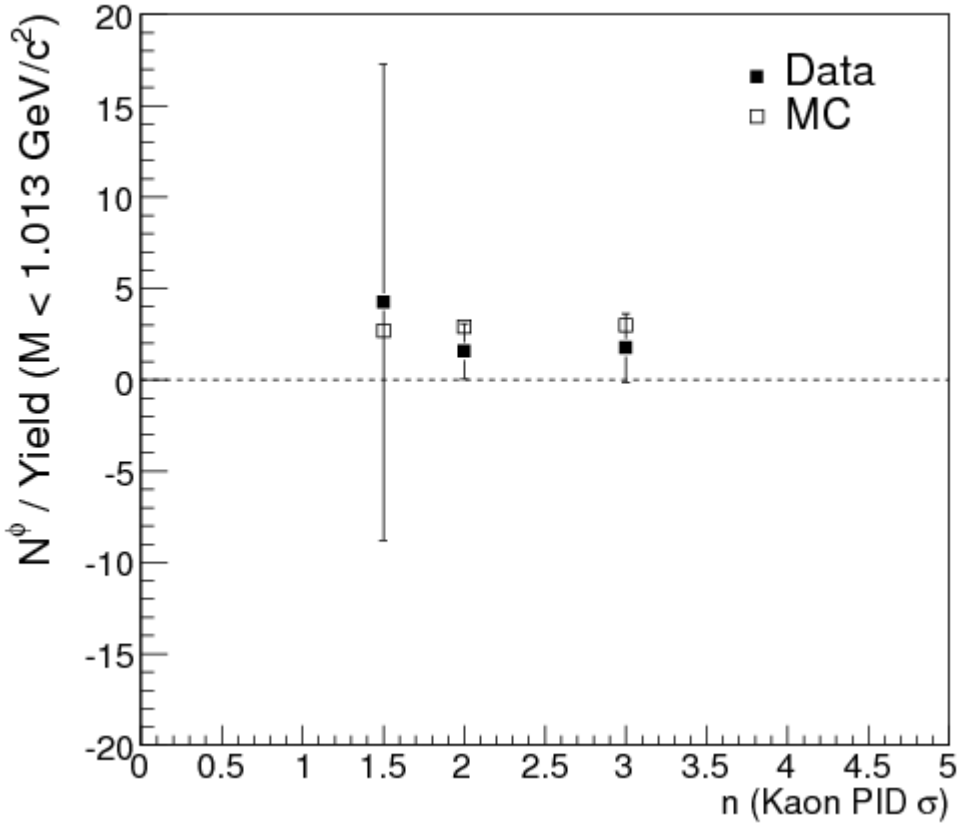
Rotatable spectrometers give unique rapidity coverage : **B**road RAnge Hadron Magnetic Spectrometers

$\phi \rightarrow$ KK invariant mass spectrum from MC



Effect of acceptance on the spectral shape

Ratios of N_ϕ to yields within M < 1.013 GeV



Data and MC behave similarly.

PID

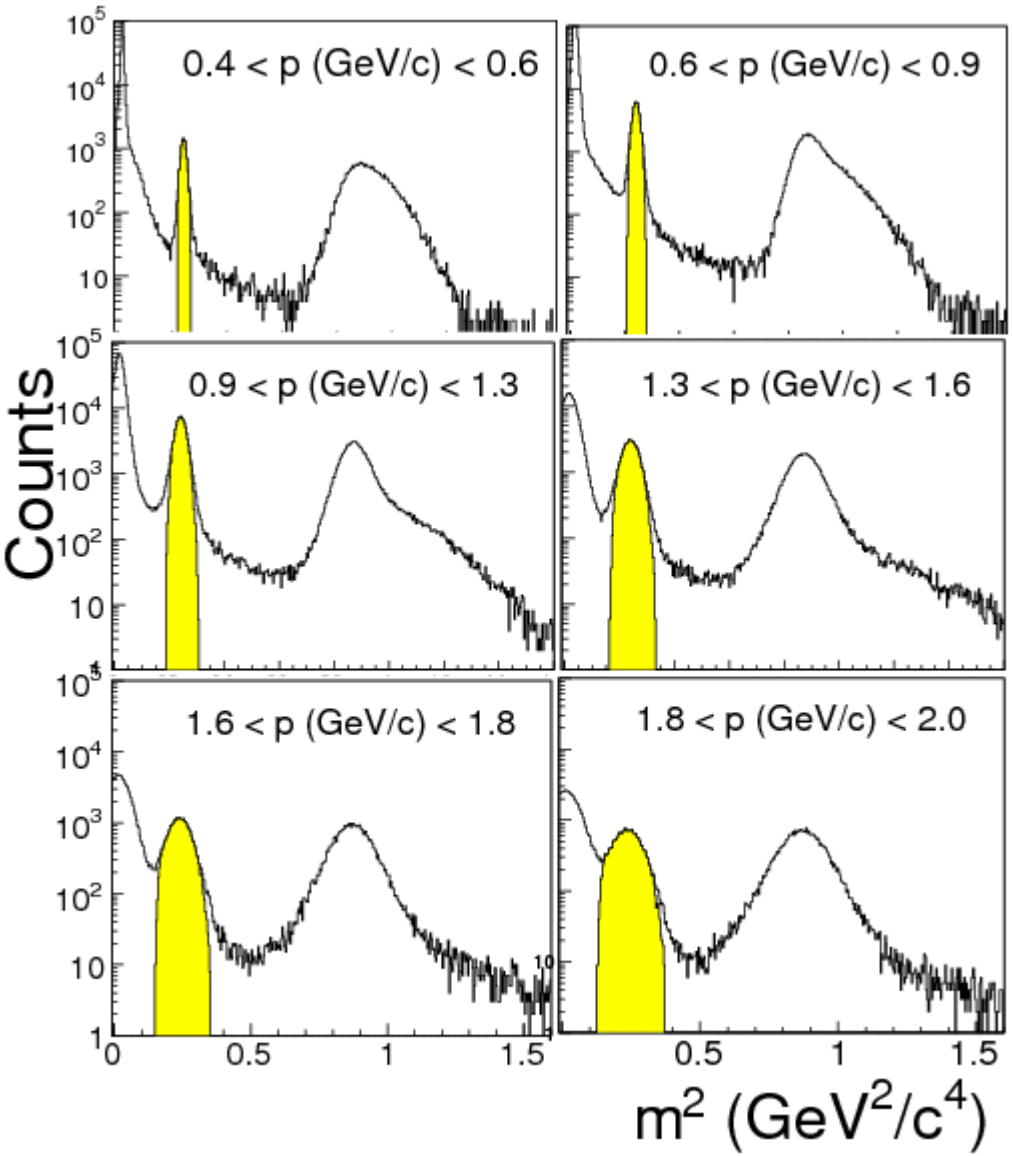


Fig shows positively charged Particles
Similar result for negatively charged particles

π/K separation within
0.4 < p (GeV/c) < 2