Recent Results from BRAHMS at RHIC

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For the BRAHMS Collaboration

Current and Future Directions at RHIC
Aug. 7 2002

Overview

- Introduction
  - Physics
  - Spectrometers and Global Detectors
  - Summary for BRAHMS/RHIC Run2
- Data
  - Charged particle Multiplicity (dN/dη)
  - Acceptance and PID
  - Particle Ratios
  - Particle Spectra and Yields
  - Net-proton

  As functions of rapidity
- Plan for Run3 and beyond
- Summary

The BRAHMS Physics Goal

Probing Hot and Dense Nuclear Matter
By studying:

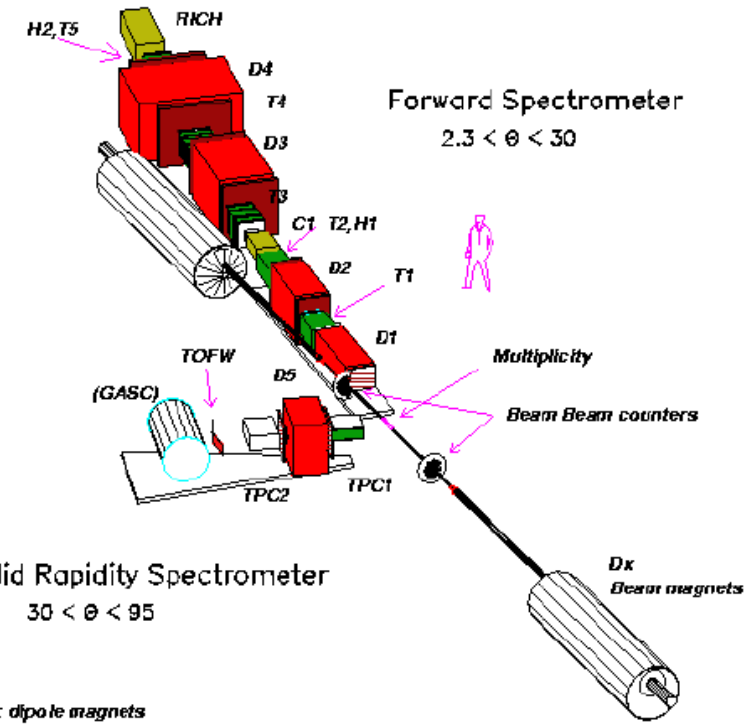
- Particle Production : dN/dη, yield
- Reaction Mechanisms and Dynamics : spectra (yield,shape), ratio
- Baryon Stopping : net-proton
- Hard Process : "high" p_t, small-x
- Source Geometry/Dynamics : HBT, coalescence

Through High Precision Measurements
of Identified Hadrons over wide range of

- Rapidity: $0 < y < 4$
  (Central and Fragmentation regions)
- Transverse momentum: $0.2 < p_t < 4$ GeV/c
  (with the current setup)

BRAHMS

Broad **RA**nge **H**adron **M**agnetic **S**pectrometers



D1, D2, D3, D4, D5 : dipole magnets
T1, T2, T3, T4, T5, TPC1 TPC2: tracking detectors
H1, H2, TOFW : Time-of-flight detectors
RICH, GASC : Cherenkov detectors

- 2 Movable Spectrometers:
(Mid-rapidity Spectrometer and Forward Spectrometer) for track reconstruction and Particle identification

- Global Detectors:
Tiles, Silicon Strips, Beam-Beam counters, Zero-degree Calorimeters for event characterization

- Collaboration of ~55 Physicists from 12 institutions

The BRAHMS Collaboration

I.G. Bearden[7], D. Beavis[1], C. Besliu[10], Y. Blyakhman[6],J. Bondorf[7], J.Brzychczyk[4], B. Budick[6], H. Bøggild[7], C. Chasman[1], C. H.Christensen[7], P. Christiansen[7], J.Cibor[4], R.Debbe[1], J. J. Gaardhøje[7], K. Grotowski[4], K. Hagel[8], O. Hansen[7], H. Heiselberg[7], A. Holm[7], A.K. Holme[12], H. Ito[11], E.Jacobsen[7], Jipa[10], J. I. Jordre[10], F. Jundt[2], C. E. Jørgensen[7], T.Keutgen[9], E. J. Kim[5], T. Kozik[3], T.M.Larsen[12], J. H. Lee[1], Y. K.Lee[5], G. Løvhøjden[2], Z. Majka[3], A. Makeev[8], B. McBreen[1], M. Murray[8], J.Natowitz[8], B.S.Nielsen[7], K. Olchanski[1], D. Ouerdane[7], R.Planeta[4], F.Rami[2], C.Ristea[10], D.Roehrich[9], B. H. Samset[12], S. J. Sanders[11], R.A.Sheetz[1], Z.Sosin[3], P. Staszel[7],T.S. Tveter[12], F.Videbæk[1], R.Wada[8] and A.Wieloch[3], S.Zgura[10].

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[10]University of Bucharest, Romania
[11]University of Kansas, Lawrence,USA
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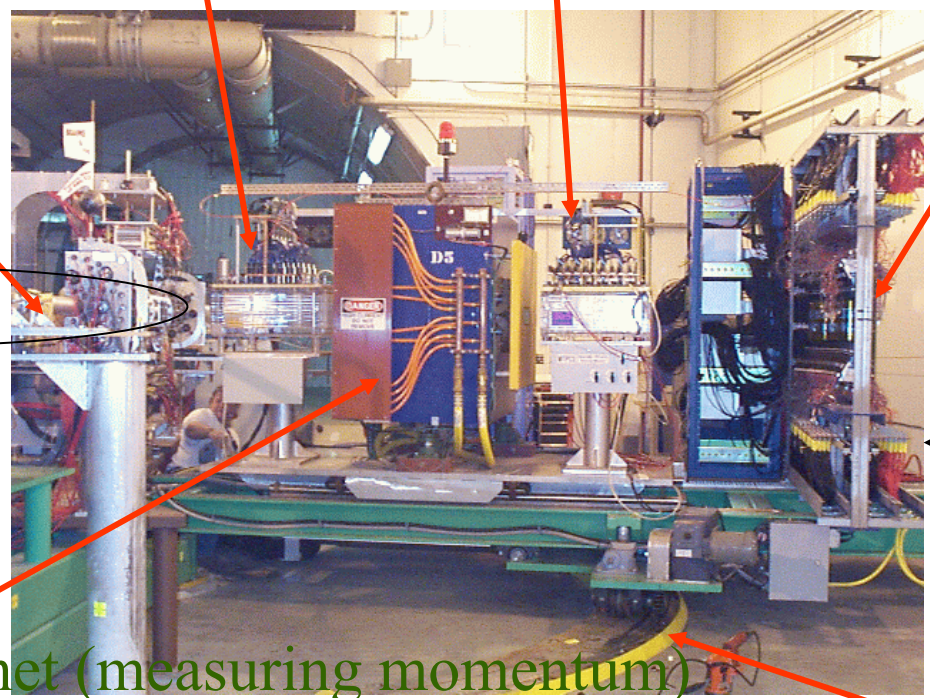
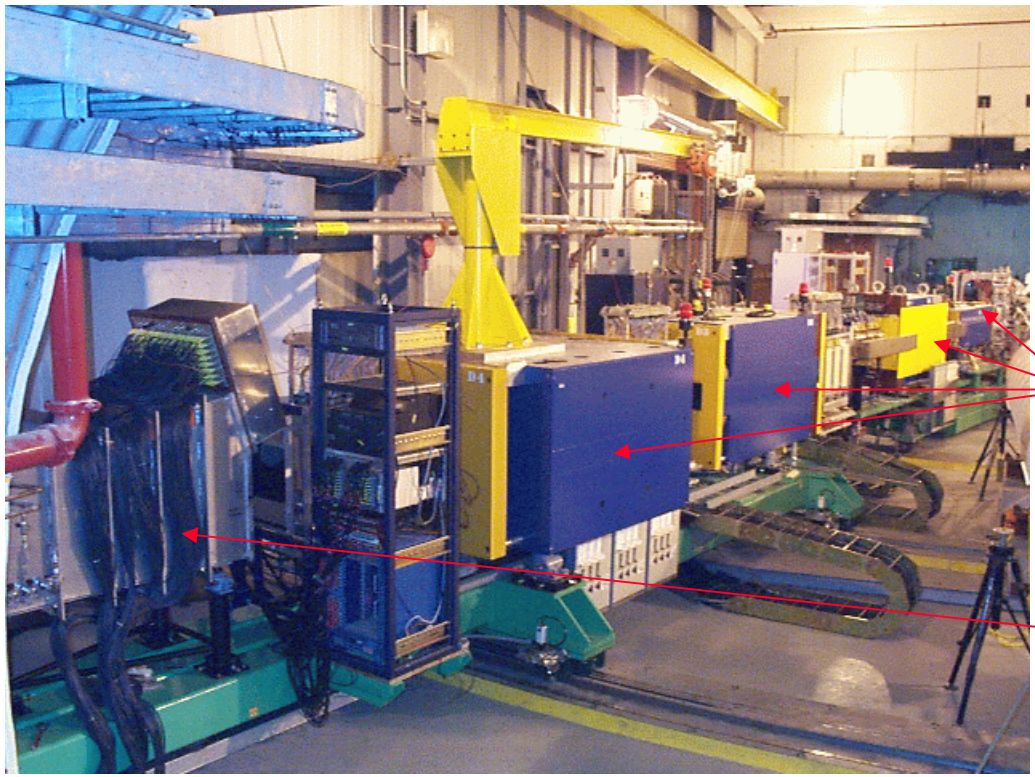
Mid-rapidity Spectrometer
(rotates 30°-95°)

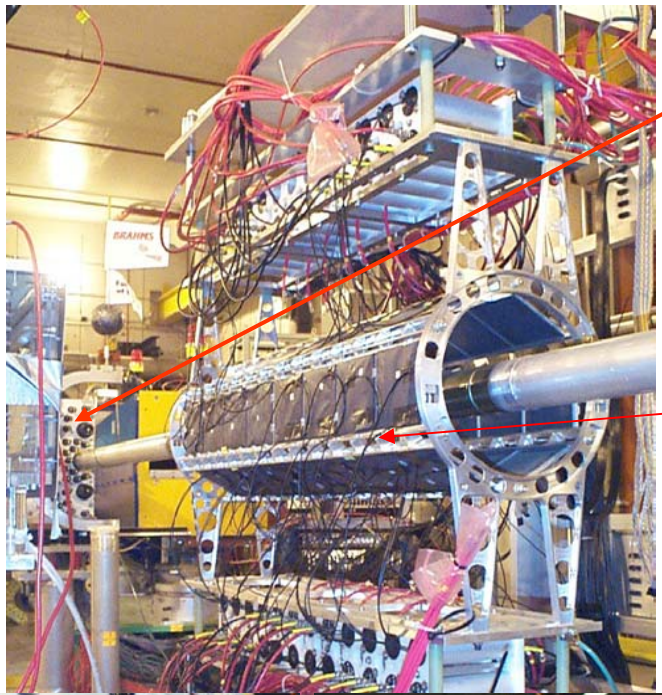


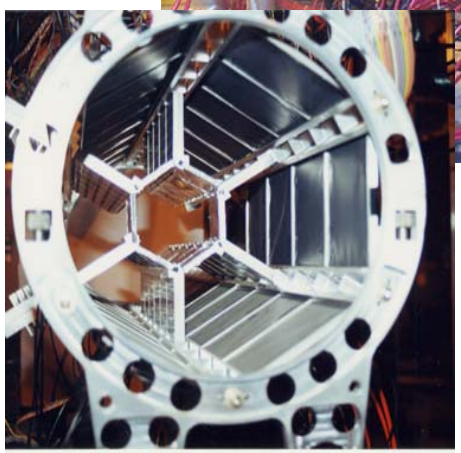
Forward Spectrometer
(rotates 2.5°-30°)

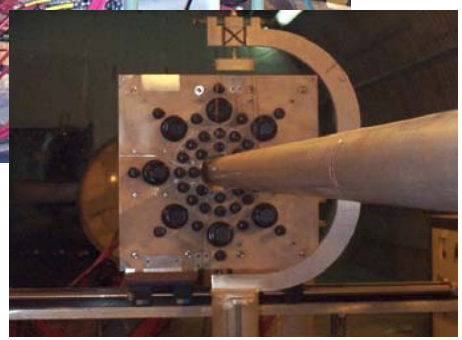


- ~20 m long
- 2 TPC's: T1 and T2
- 3 DC's: T3,T4,T5
- 4 Magnets: D1,D2,D3,D4
- 2 ToF Hodoscopes: H1, H2
- Cerenkov Counter: C1
- RICH

Global Detectors







- Beam-Beam Counters
  - Provide a start time and trigger
  - Measure multiplicity at high η ($2.1 < |\eta| < 4.7$)
- Multiplicity Detectors
  - Tile (TMA) and Si Arrays (SiMA)
  - Provide charged particle multiplicity ($-3 < \eta < 3$)
  - Used to characterize centralities of events
- Zero Degree Calorimeters
  - Identifying collisions

Summary of BRAHMS data from RHIC2001 (Run2) running

Data

- Au+Au and p+p at full energy: $\sqrt{s_{NN}}$ =200 GeV
- All detectors were installed and working at all centralities
- Higher level triggers (Vertex/Centrality/Spectrometer) implemented
- ~25M physics events taken
- Initial scan of "soft" physics
- Selected high-pt and HBT runs

Measurements

- Charged particle multiplicity (dN/dη): published in PRL
- Particle ratios: submitted to PRL
- Identified hadron spectra and yields at selected rapidities
  - Net-proton
  - dN/dy, slope vs y for π,K,p
- High-p_T hadrons/π (up to p_T ~ 6 GeV/c at y ~ 0, p_T~4 at y~2)
- Limited HBT

BRAHMS Publications

- "Rapidity dependence of anti-proton to proton ratios in Au+Au collisions at $\sqrt{s_{nn}}$ =130 GeV"

  Phys. Rev. Lett. 87 (2001) 112305
- "Charged particle densities from Au+Au Collisions at $\sqrt{s_{nn}}$ =130 GeV"

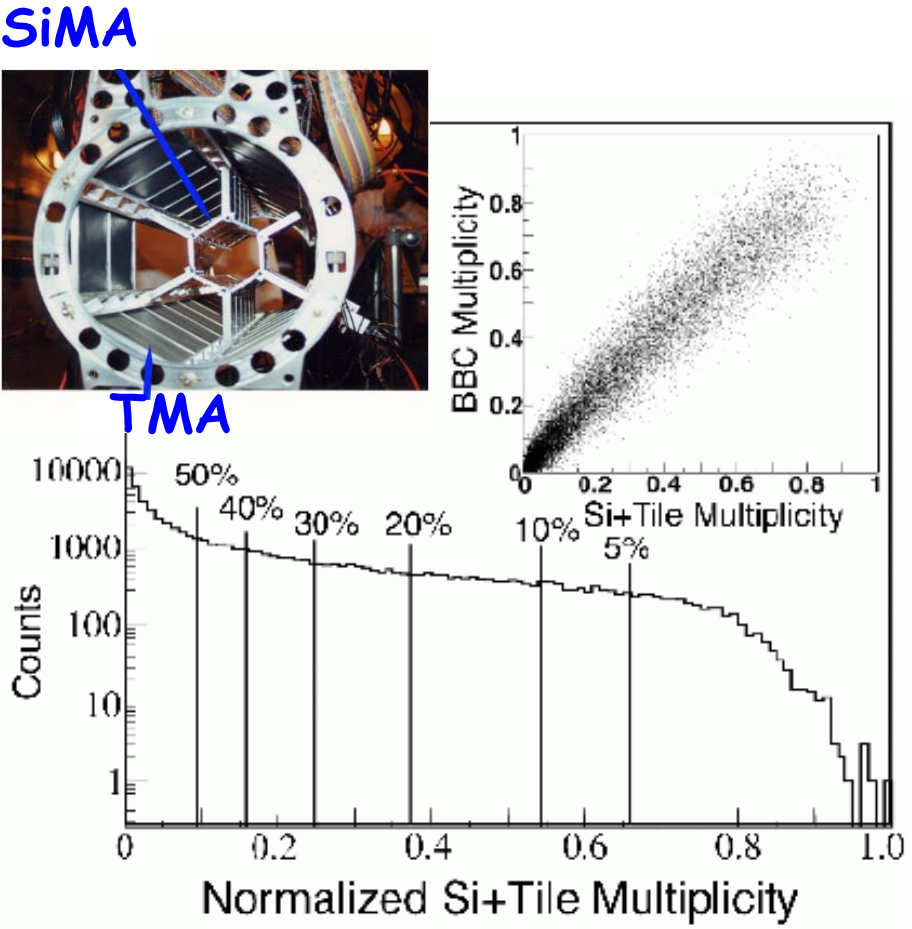
  Phys. Lett. B 523 (2001) 227
- "Pseudorapidity distributions of charged particles from Au+Au collisions at the maximum RHIC energy"

  Phys. Rev. Lett. 88 (2002) 202301
- "Rapidity dependence of anti-particle-to-particle ratios in Au+Au collisions at $\sqrt{s_{nn}}$ =200 GeV"

  Submitted to Phys. Rev. Lett. : **nucl-ex/0207006**

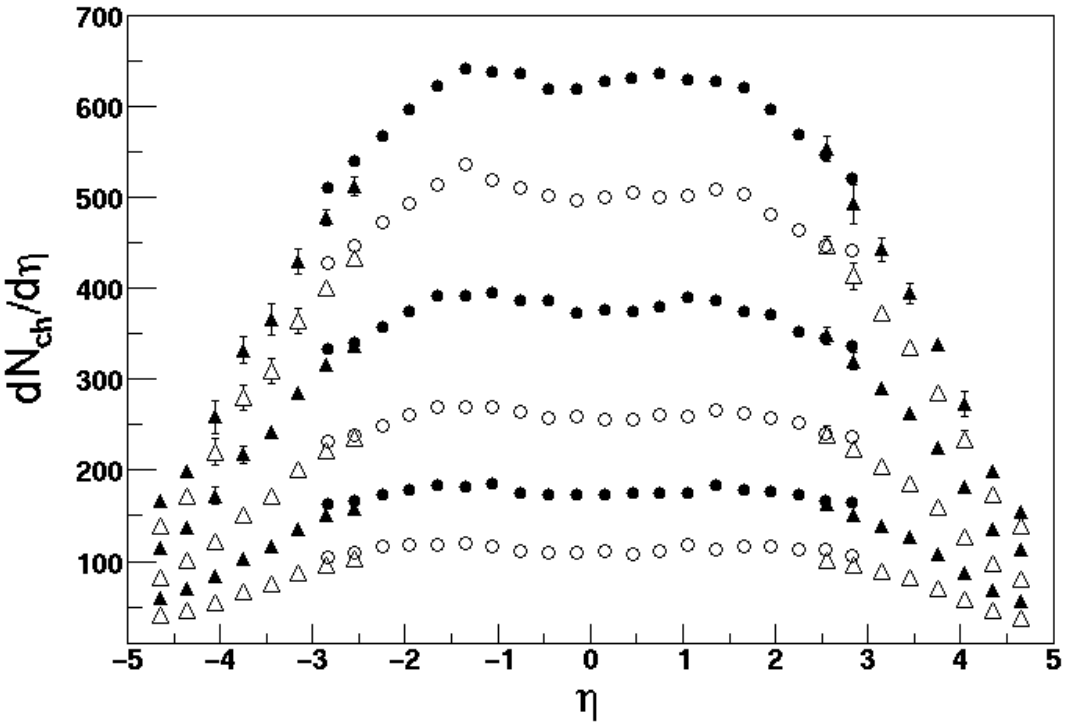
- More information in http://www.rhic.bnl.gov/brahms

Event Characterization:
Collision Centrality Determination



- Measured by the Centrality Detector (SiMA+TMA)
- Corrected for Vertex position dependence
- Minimum-biased multiplicity: Data + MC (HIJING+GEANT)
- BB Multiplicity is used for the centrality determination for BB analysis (consistent with SiMA+TMA selections)
- Npart is calculated using HIJING

Multiplicity: $dN_{ch}/d\eta$ at $\sqrt{S_{NN}}$=200 GeV



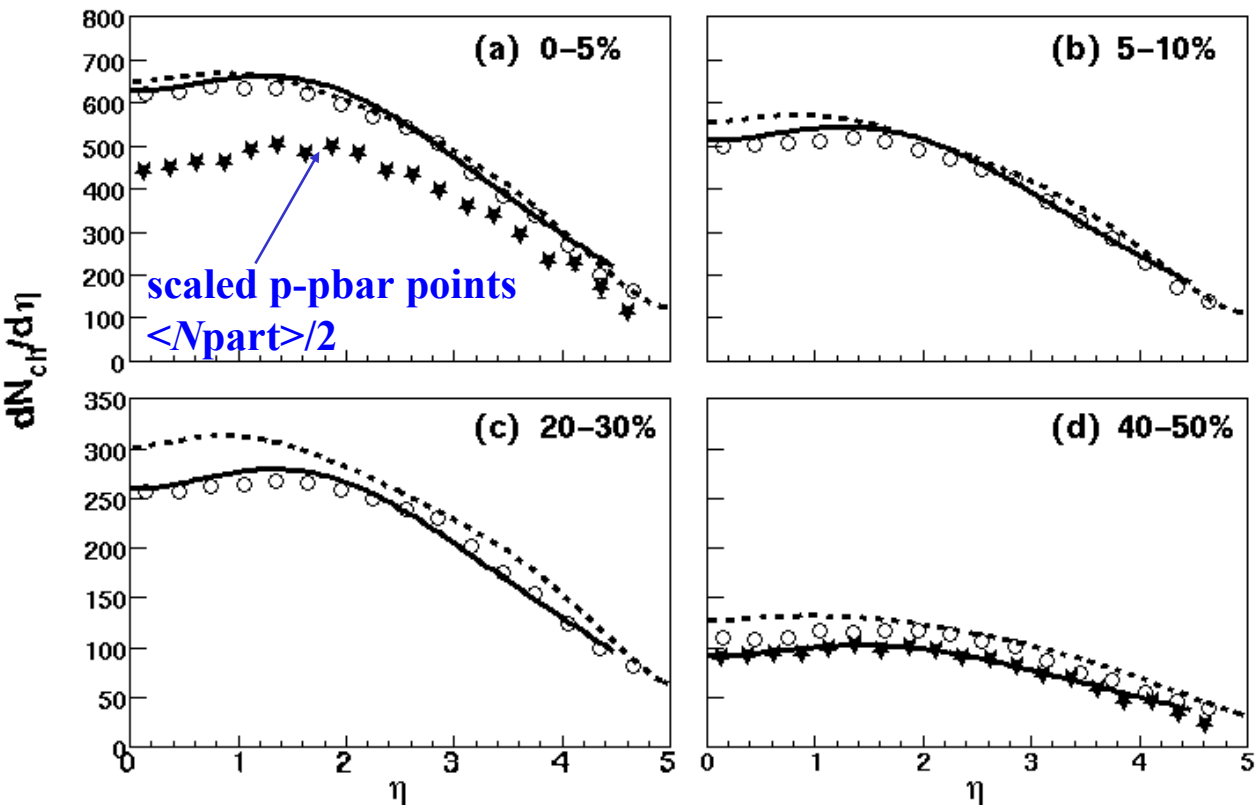
Published in PRL 88 (2002)

- Centrality bins shown are for 0-5%,5-10%, 10-20%,and 40-50%. (Statistical errors only)
- Systematic errors ~ 8-10%
- SiMA: $-3 < \eta < 3$
- Beam-Beam Counter: $2 < |\eta| < 4.7$
- Consistent with measurements using reconstructed tracks in TPC at $y = 0$

BRAHMS

$dN_{ch}/d\eta$ - Comparison to Model Predictions

$\sqrt{s_{NN}}$=200GeV

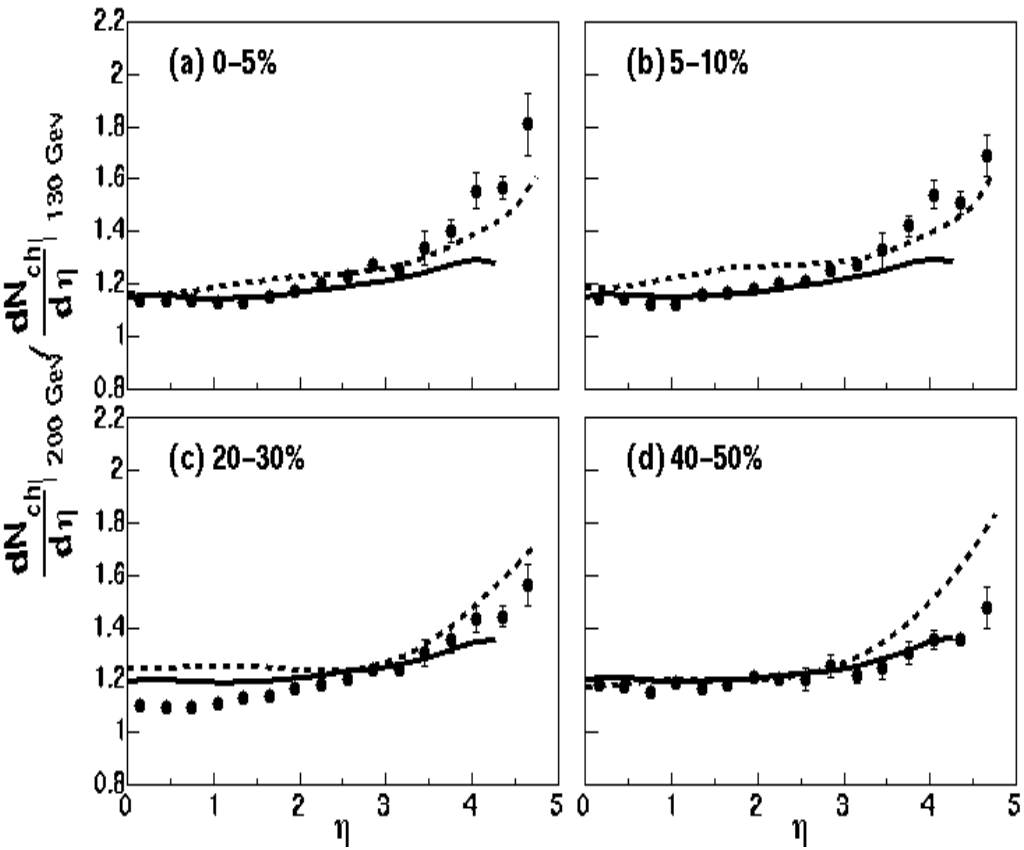


---- AMPT (HIJING + final-state re-scattering)

—— High density QCD Gluon Saturation: Kharzeev and Levin, PLB523 (2001) 79

Strong enhancement relative to ppbar for central collisions

$dN_{ch}/d\eta$: 200GeV/130GeV



- For most central (5%)
  - $dN/d\eta$ at y~0: 625 ± 55 (~14% up from 130 GeV)
  - Total N_{ch}: ~ 4630 ± 370 (~21% up)
  - $dN/d\eta$ width ($\Delta\eta$) : 7.5 ± 0.5 (~4% up)
  - $dN_{ch}/d\eta/(0.5\langle N_{part}\rangle)$ at η~0: 3.50 ± 0.30 (~13% up)
- The increase at large η: Change in width of $dN_{ch}/d\eta$ with an increase in beam rapidity.

Limiting Fragmentation: from SPS to RHIC

- Fragmentation region

  Translate to the beam's reference frame →

  $\eta' = \eta - y_{beam}$

  (assuming $\eta \approx y$)

- When shifed by y_{beam}

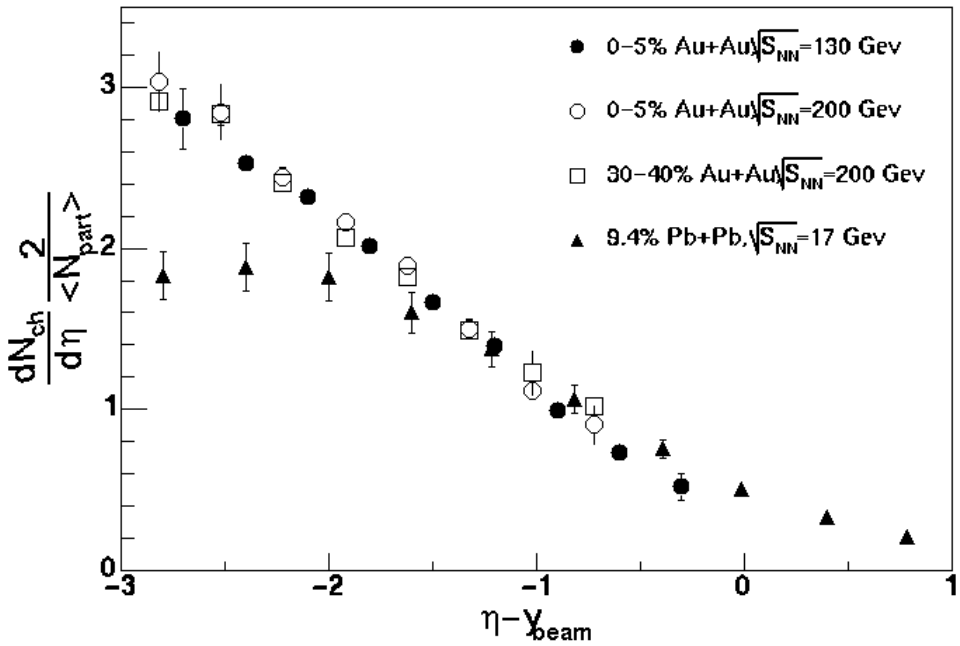
  No Energy Dependence (130GeV → 200GeV)

- Consistent with the limiting fragmentation picture

  No Dependence on System size and Energy

Excitation of the fragment baryons saturate at a moderate collision energy

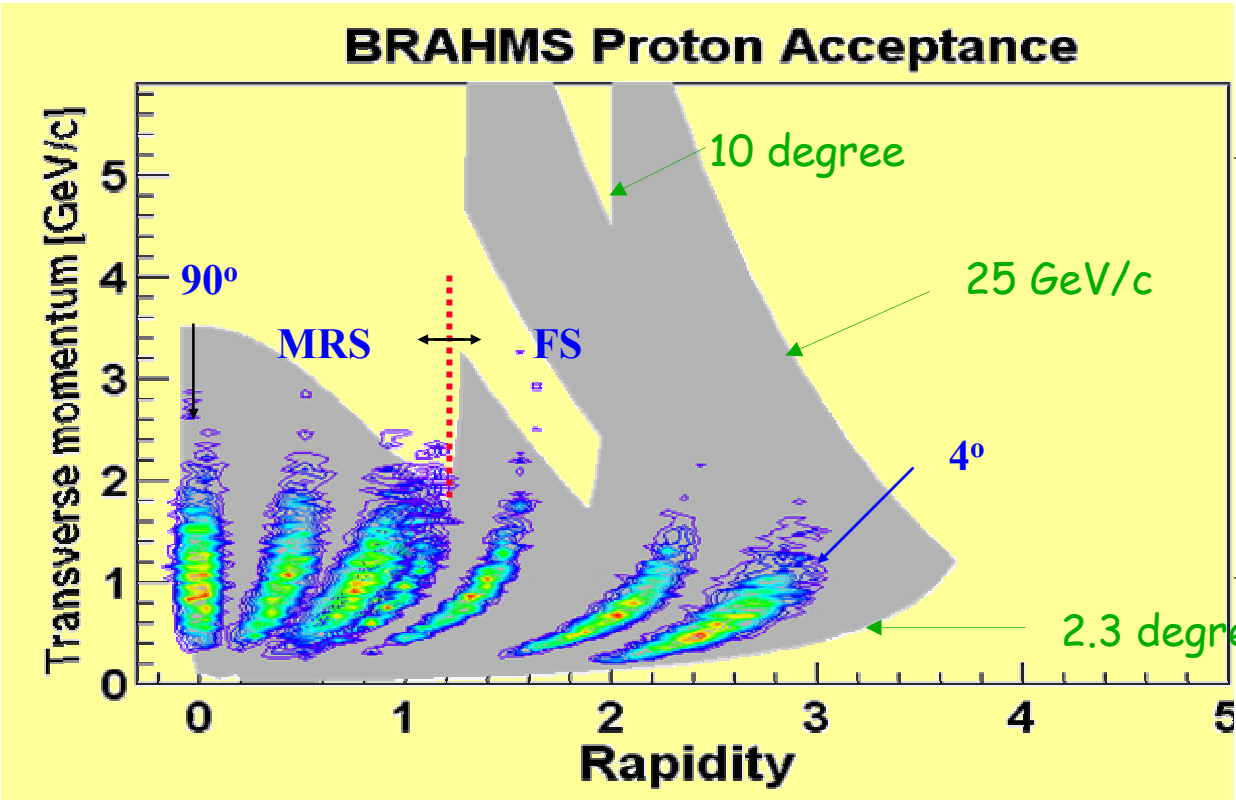
Central Collisions (5%)

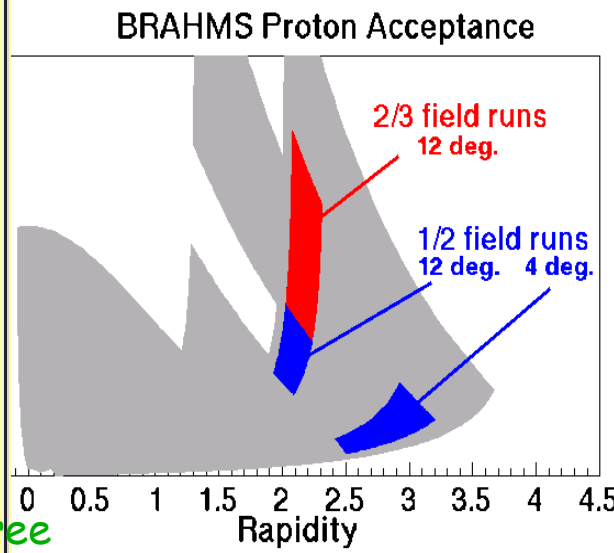


Limiting fragmentation holds from SPS → RHIC

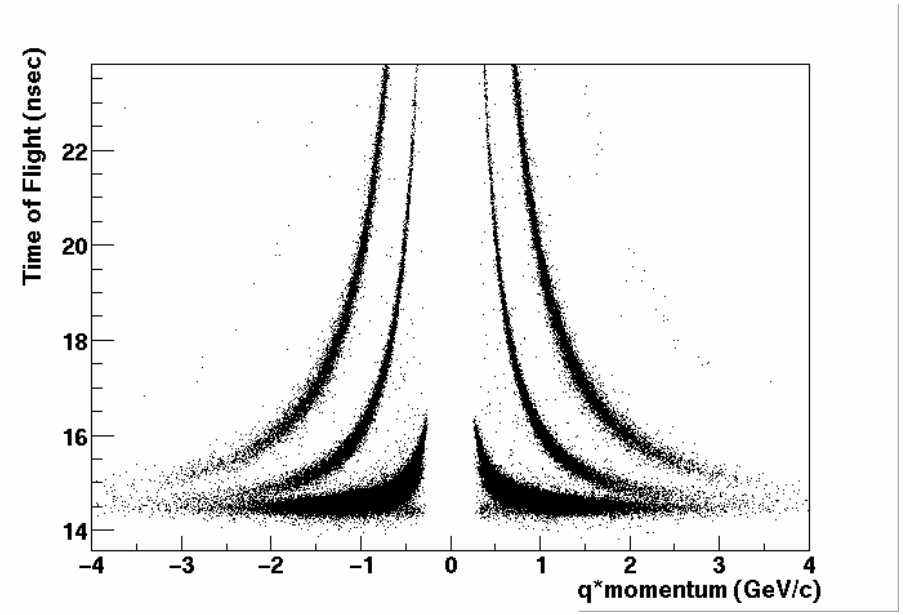
BRAHMS Acceptance

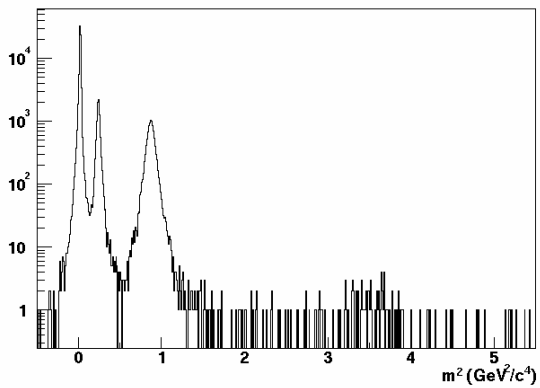
A wide range of y and pt is covered
by rotating two spectrometers with various magnetic fields.

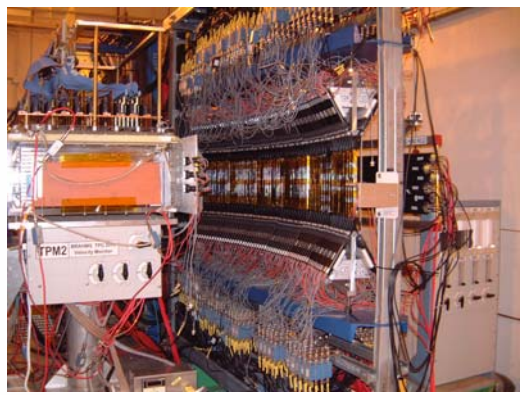




MRS particle identification : TOFW



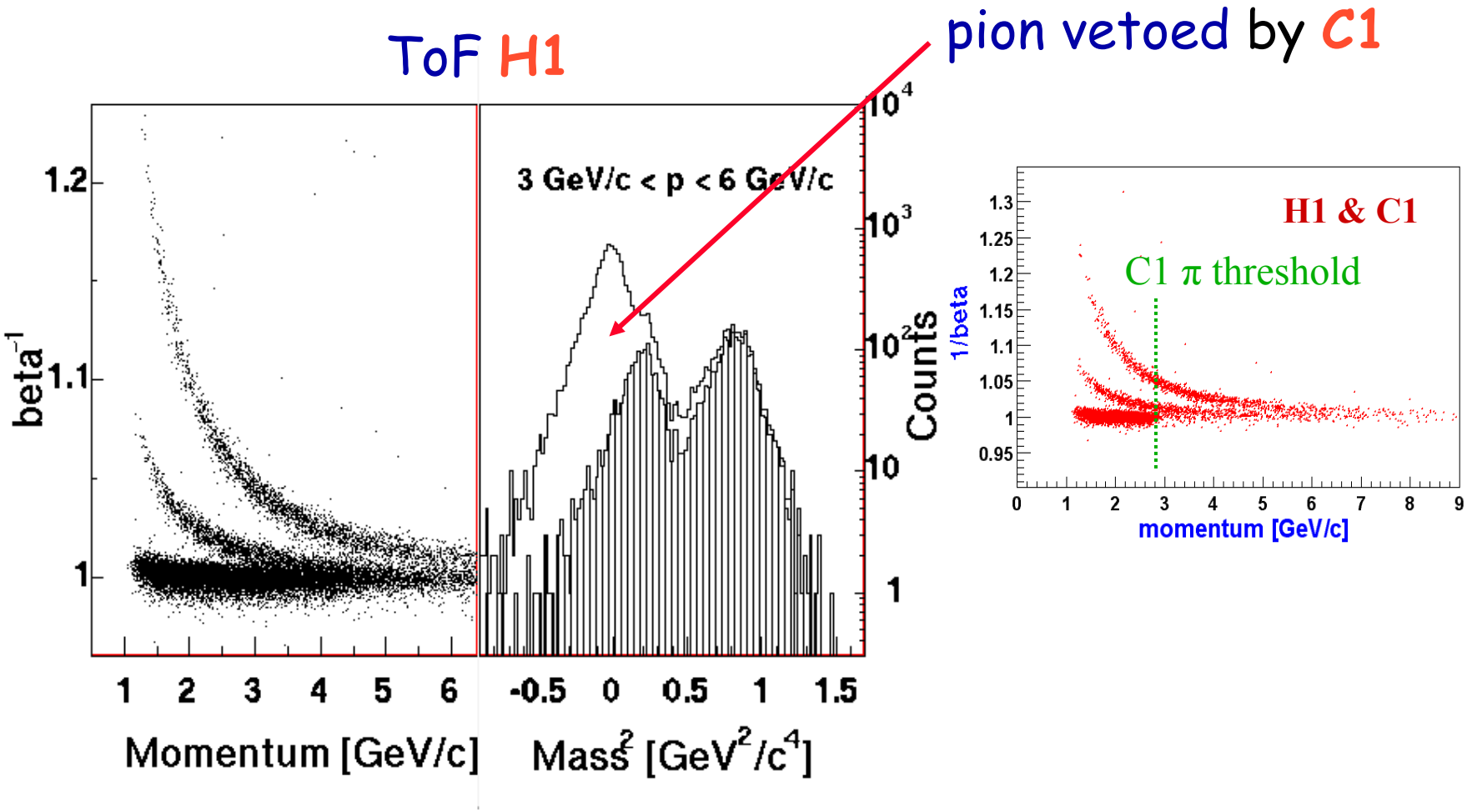




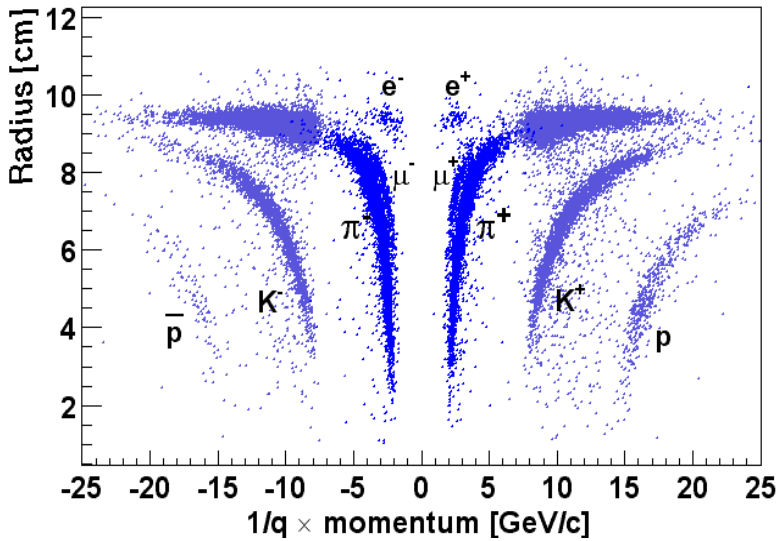
- 125 slats: time of flight resolution ~ 75*p*sec
- π/K separation ~ up to 2.5 GeV/c
- K/p separation ~ up to 4 GeV/c
- Cherenkov counter will be installed for identifying higher p_T particles

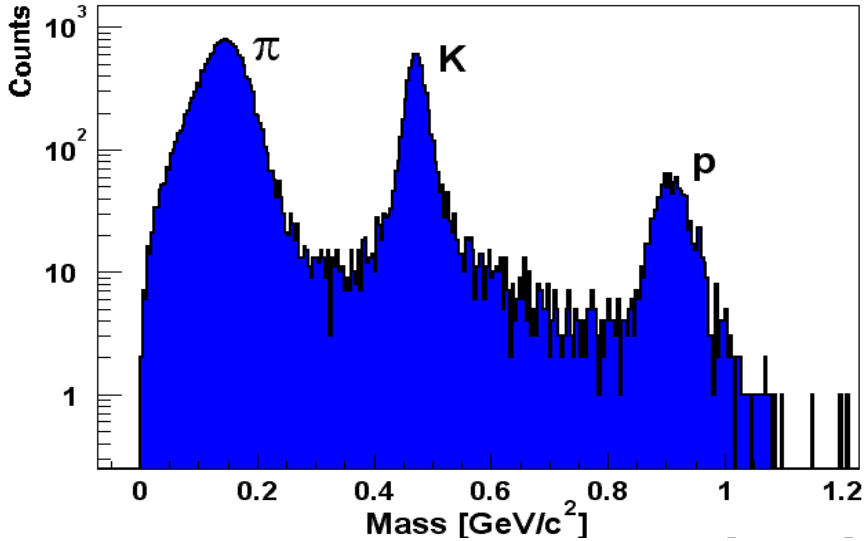
(π/K separation: up to 8 GeV)

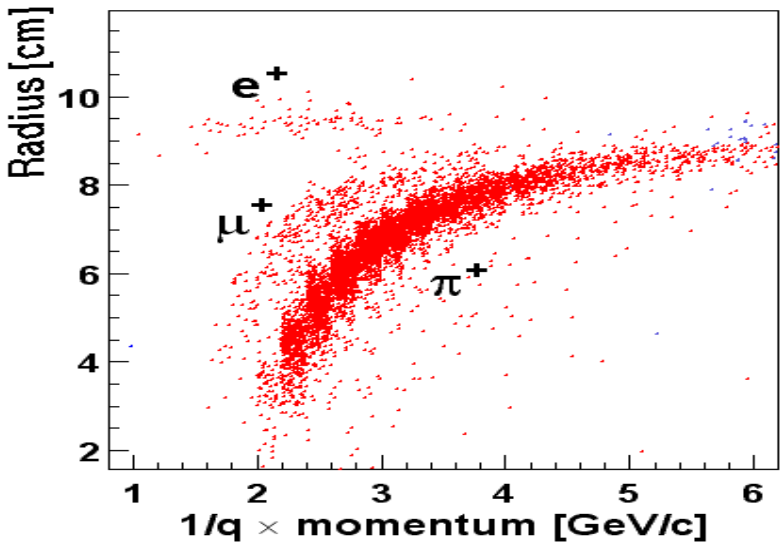
PID in Front Forward Spectrometer : ToF + C1

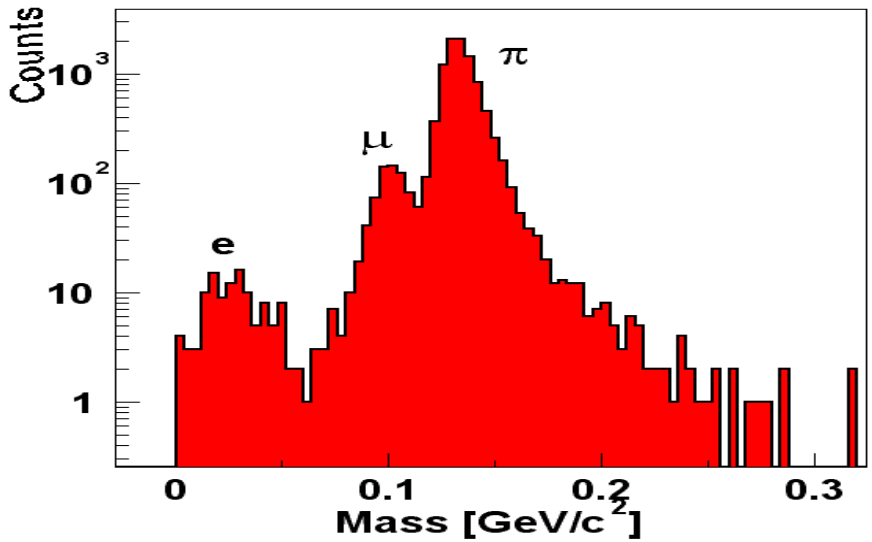


PID in Back Forward Spectrometer : RICH



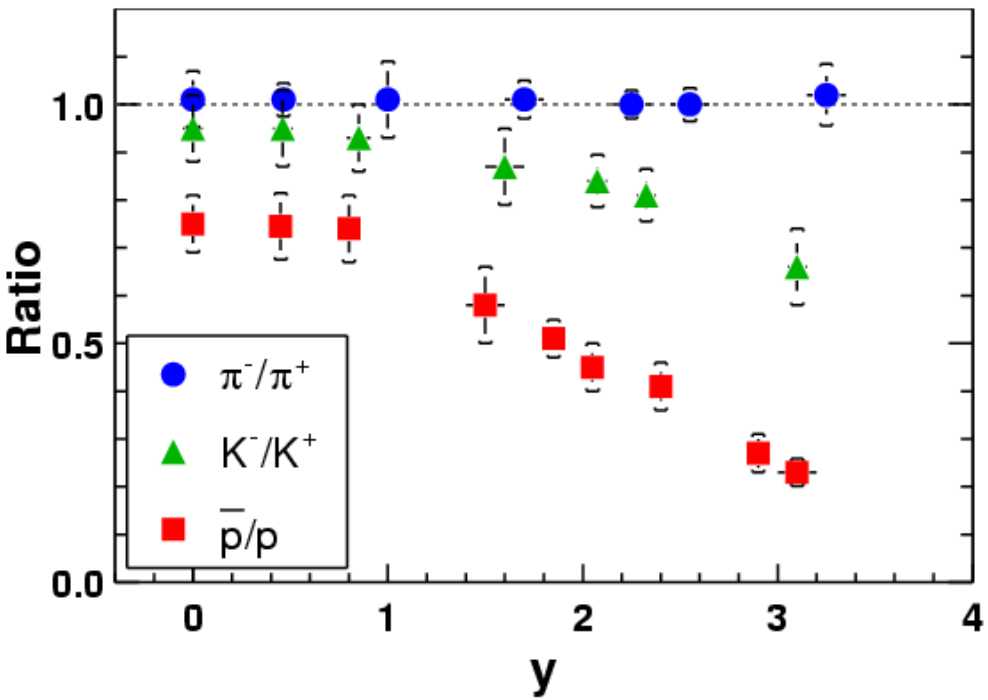






BRAHMS

Anti-particle/particle ratios vs rapidity at $\sqrt{S_{NN}}$=200 GeV

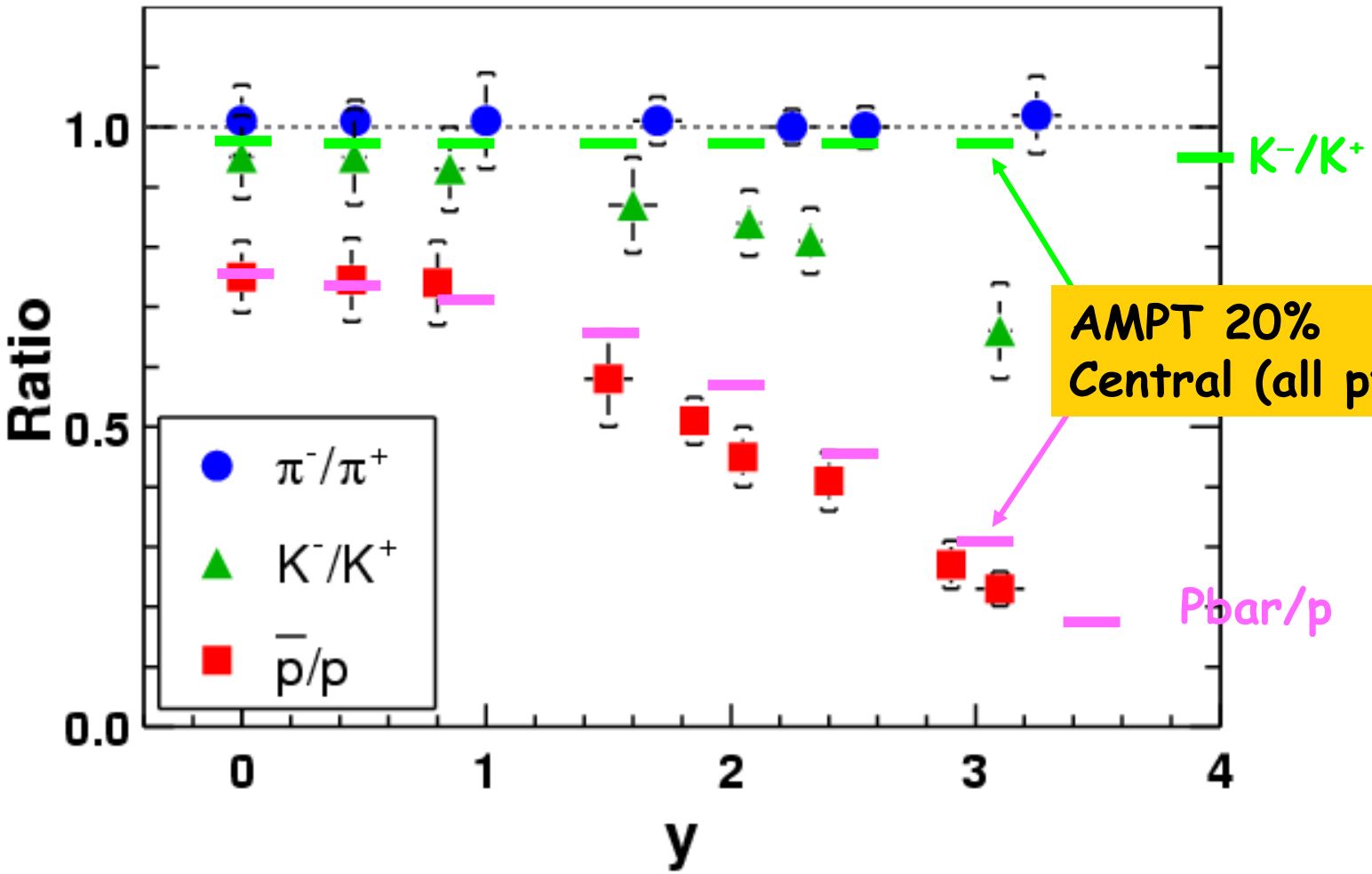


Submitted to PRL : nucl-ex/0207006

- At y=0 (20% central)
  pbar/p = 0.75 ±0.04
  K^-/K^+ = 0.95 ±0.05
  π^-/π^+ = 1.01 ±0.04
- Highest pbar/p ratio but still incomplete transparency (~17% increase from 130 GeV)
- Ratios ~identical over +-1 unit around mid-rapidity.
- Weak centrality and p_T dependence
- No Hyperon feed down applied: less then 5% correction assuming Lambda/p ~ 0.5 and pbar/p ~ Lambda-Bar/Lambda

BRAHMS

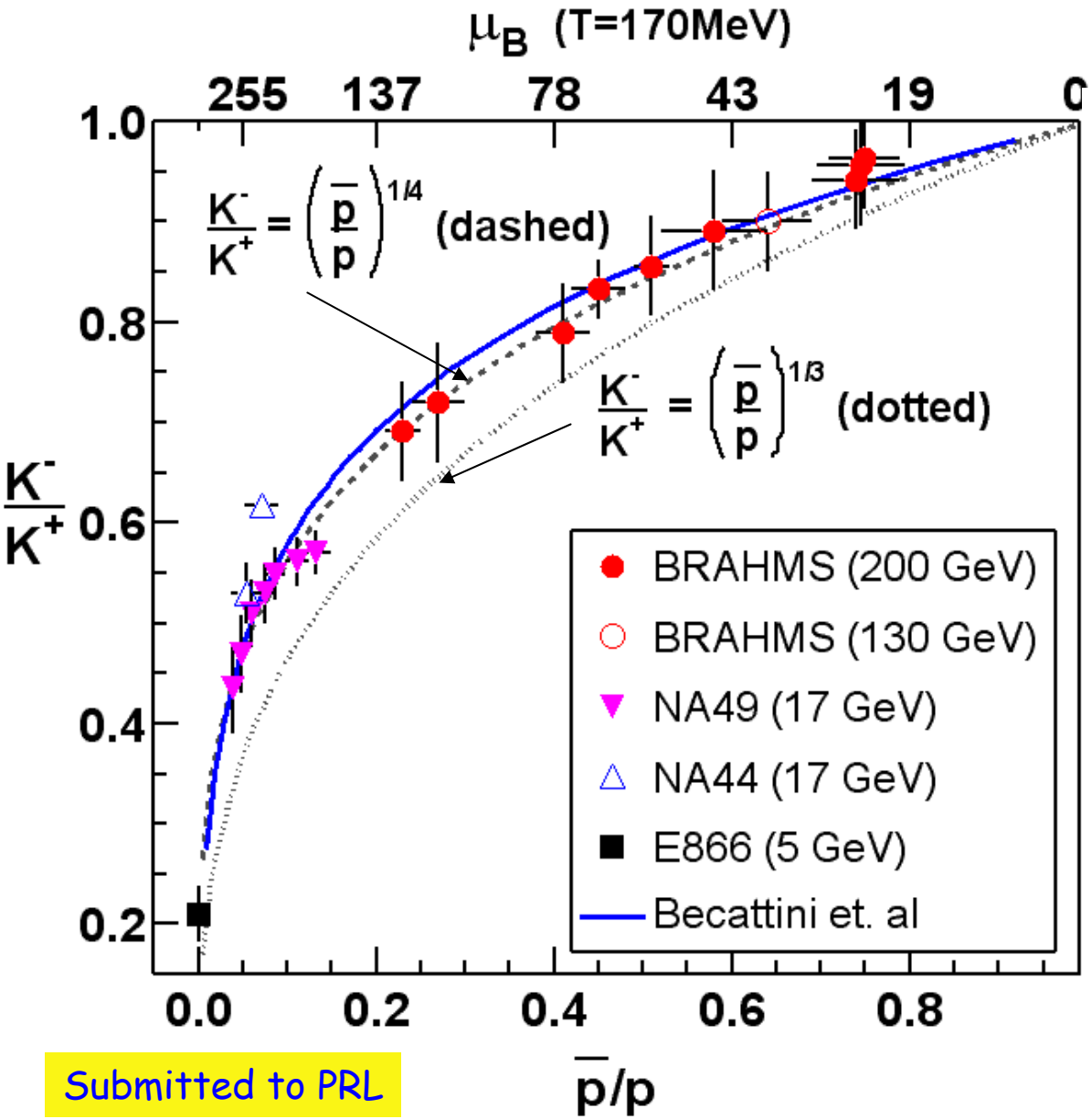
Ratios: Data and AMPT at $\sqrt{S_{NN}}$=200 GeV



BRAHMS 20% Central: Submitted to PRL

BRAHMS

Universal Correlation in K-/K+ vs pbar/p?



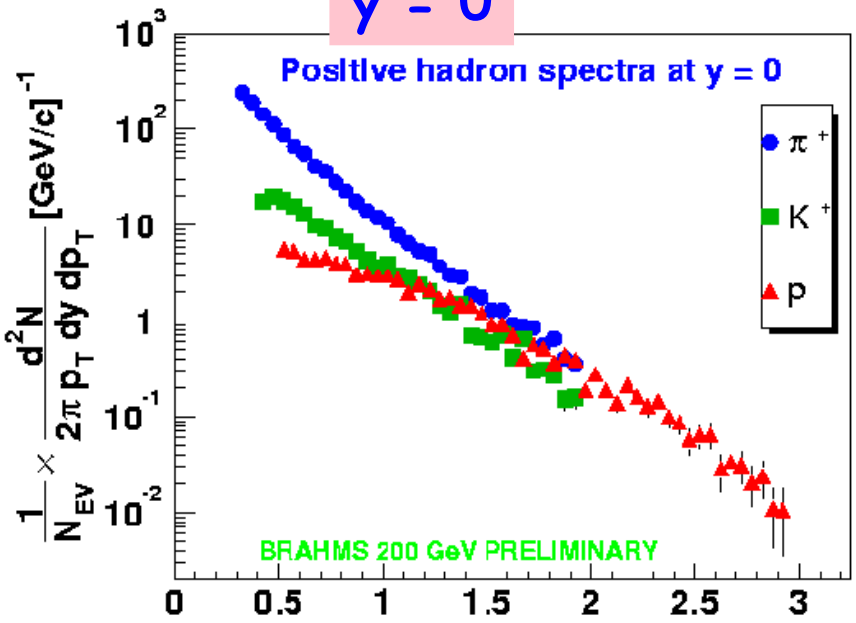
Submitted to PRL

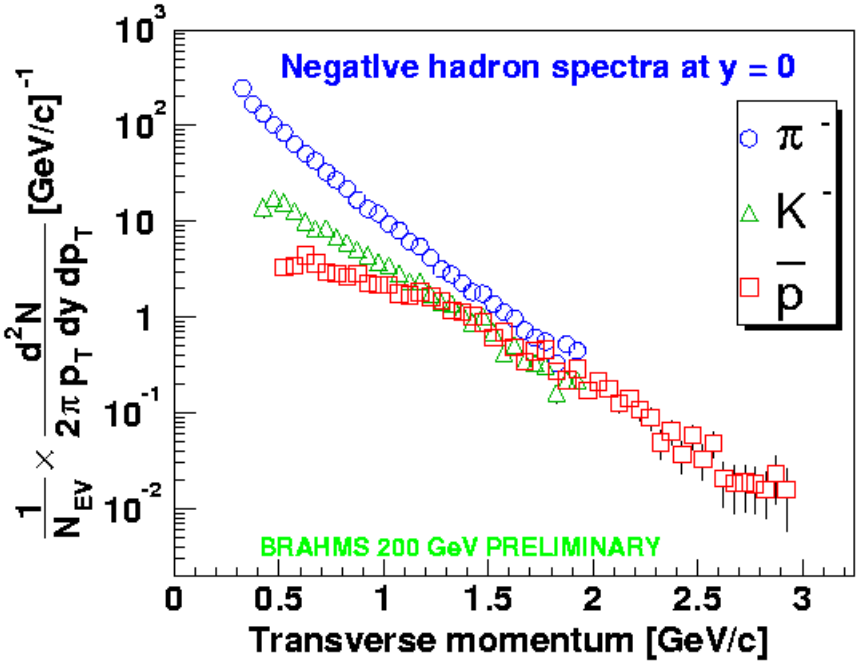
- K^-/K^+
  = $\exp(2\mu_s/T)\exp(-2\mu_q/T)$
  = $\exp(2\mu_s/T)(pbar/p)^{1/3}$
- $K^-/K^+=(pbar/p)^{1/4}$ is a fit to the data points
- Good agreement with the statistical-thermal model prediction by Beccatini et al. (PRC64 2001): Based on SPS results and assuming T=170 MeV

Spectra

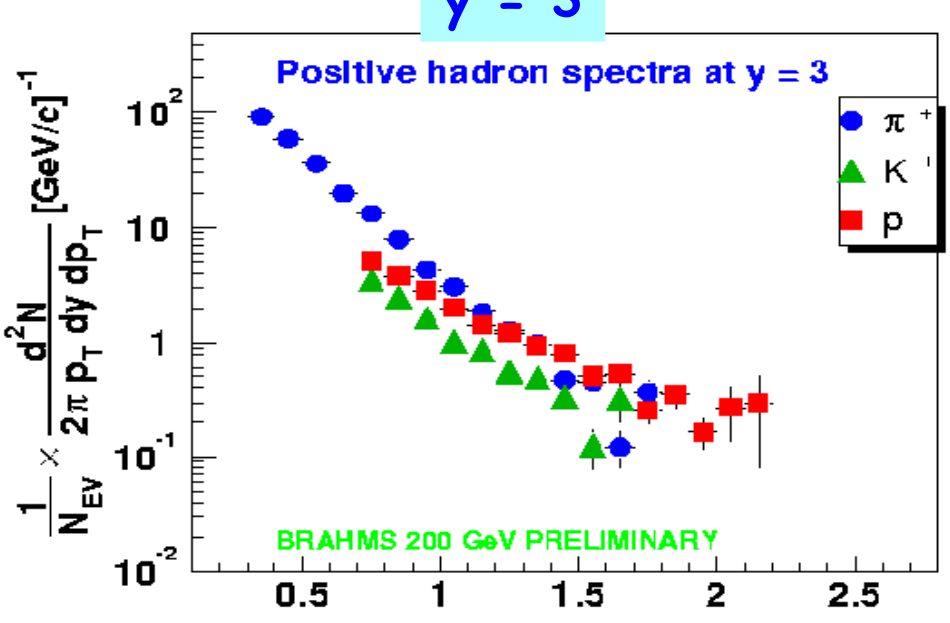
BRAHMS Preliminary: 200 GeV 10% Central

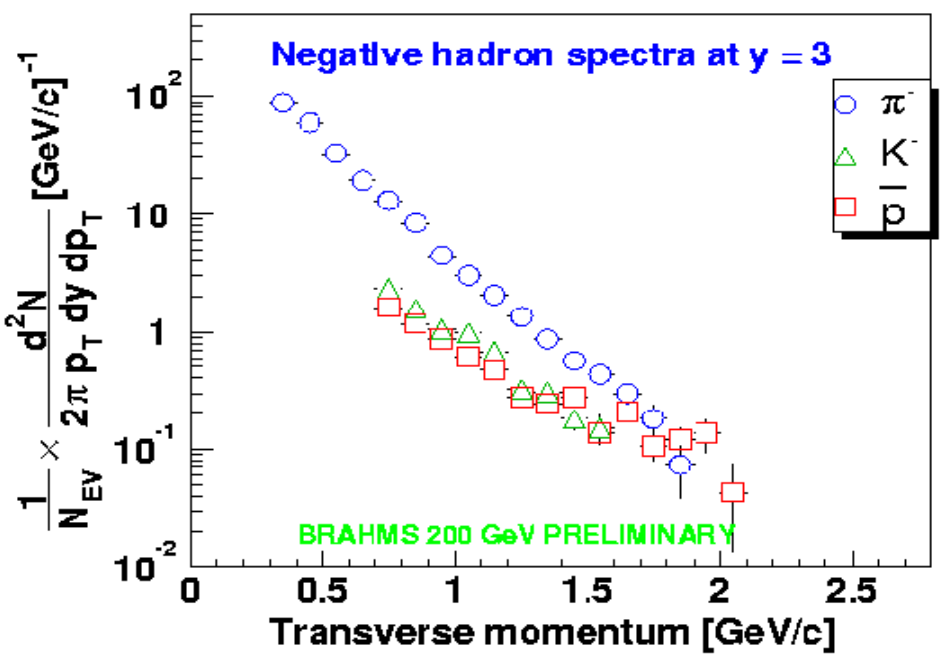
y = 0



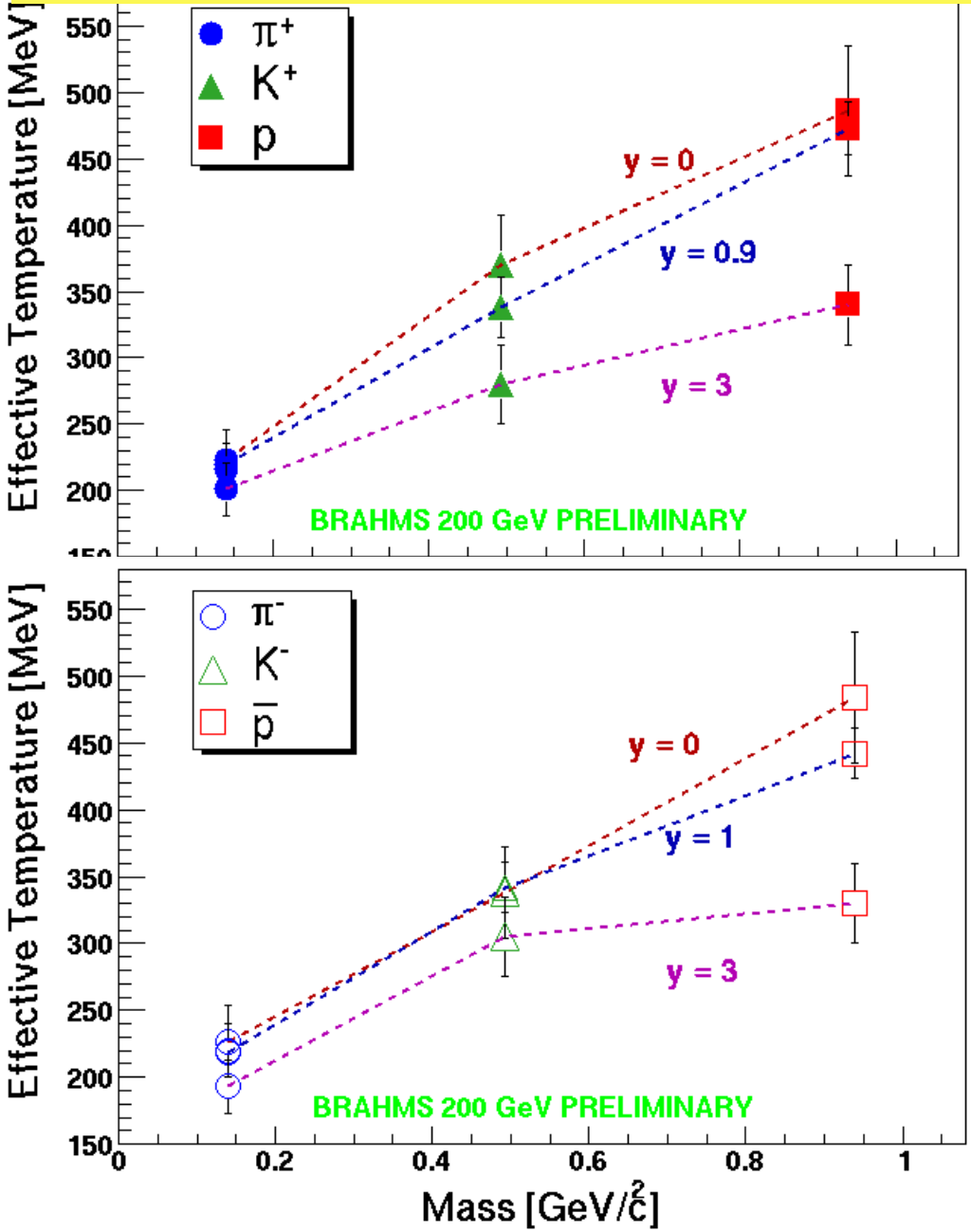


y = 3





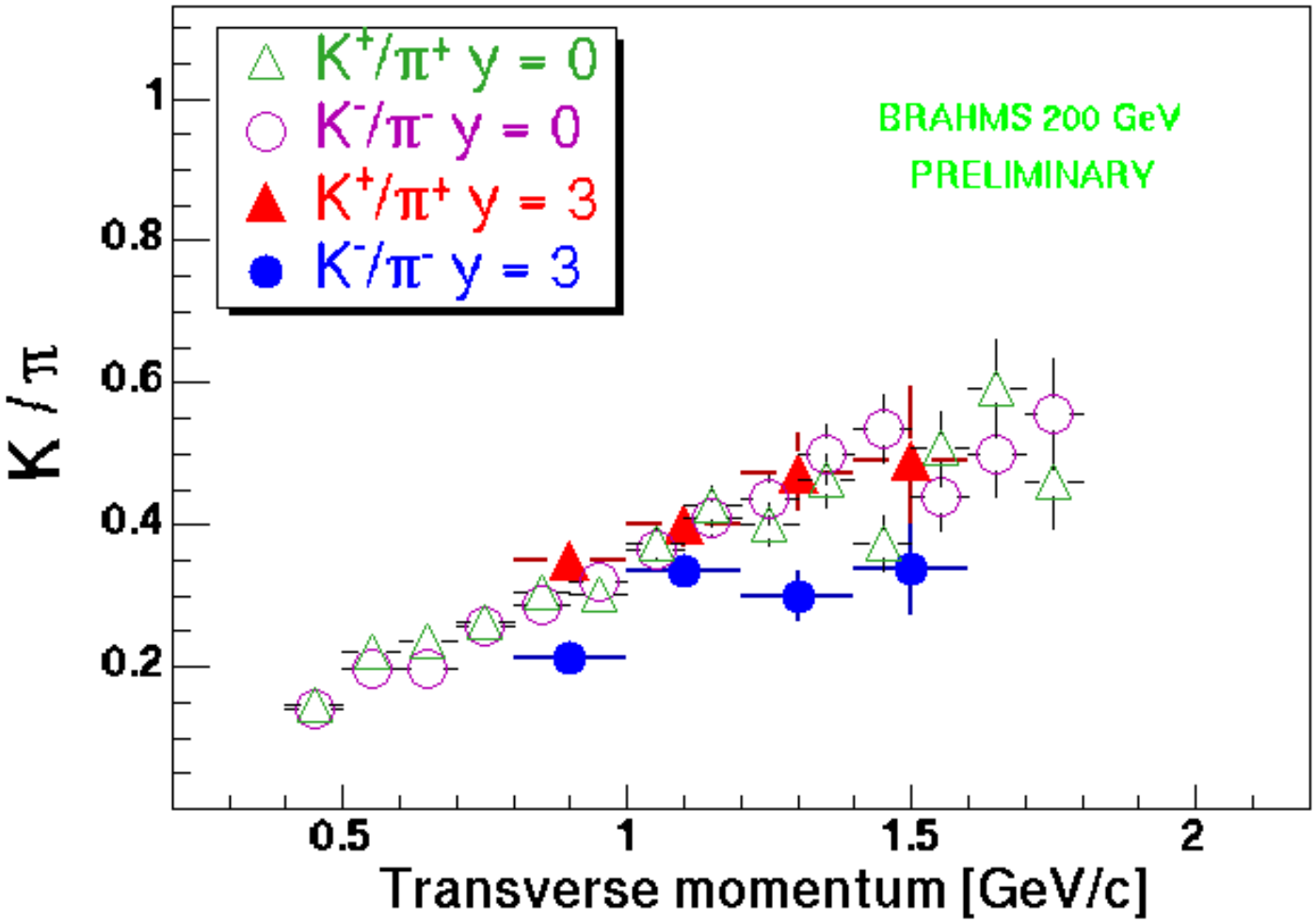
BRAHMS Preliminary: 200 GeV 10% Central



Inverse p_T Slope vs. mass

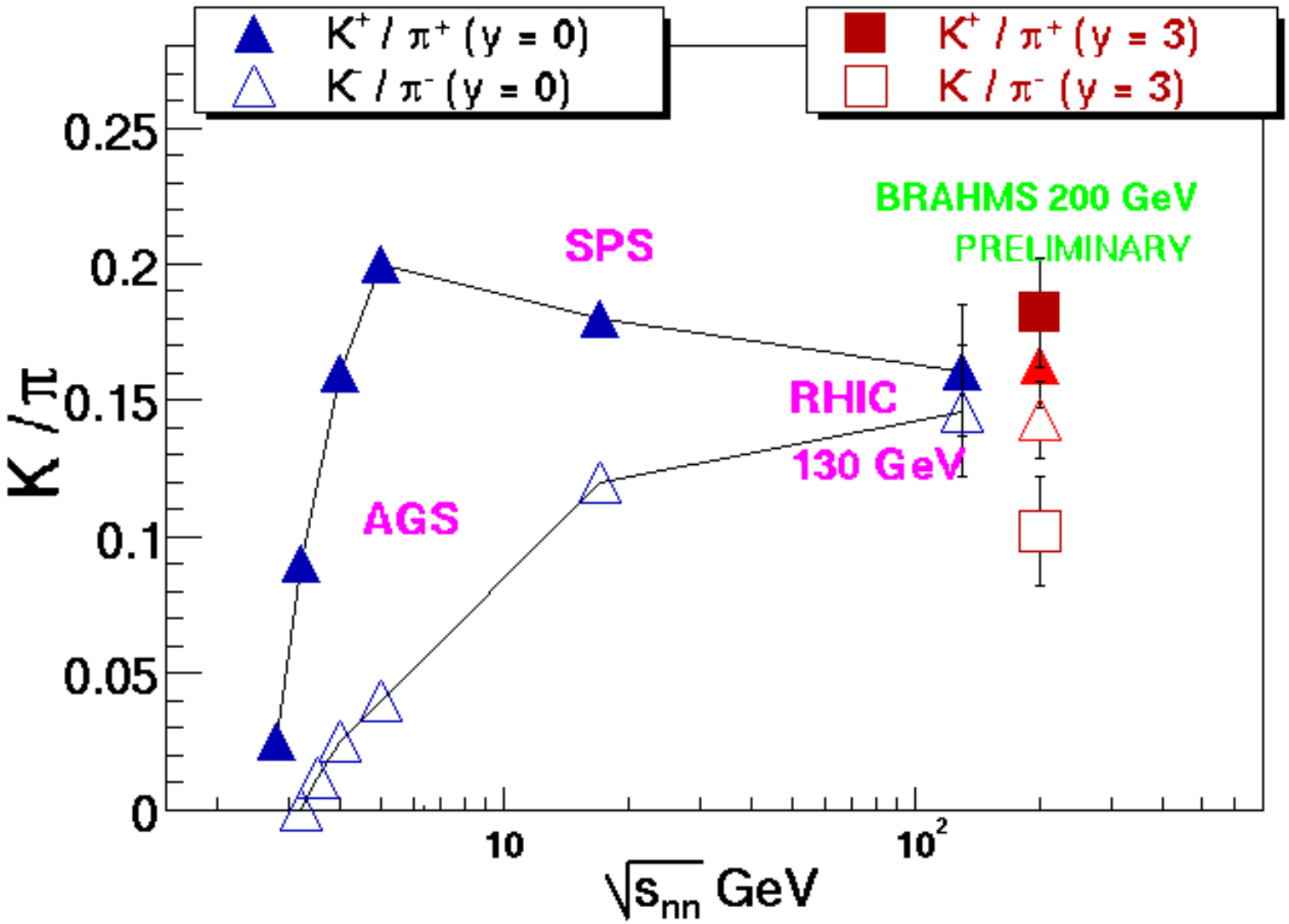
- All fits are in p_T:
  over same range for all particles, at all rapidities
- Negative ≈ Positive
- Inverse slope decreases as y increases
- Flow at all covered rapidities

Strangeness : ratio K/π

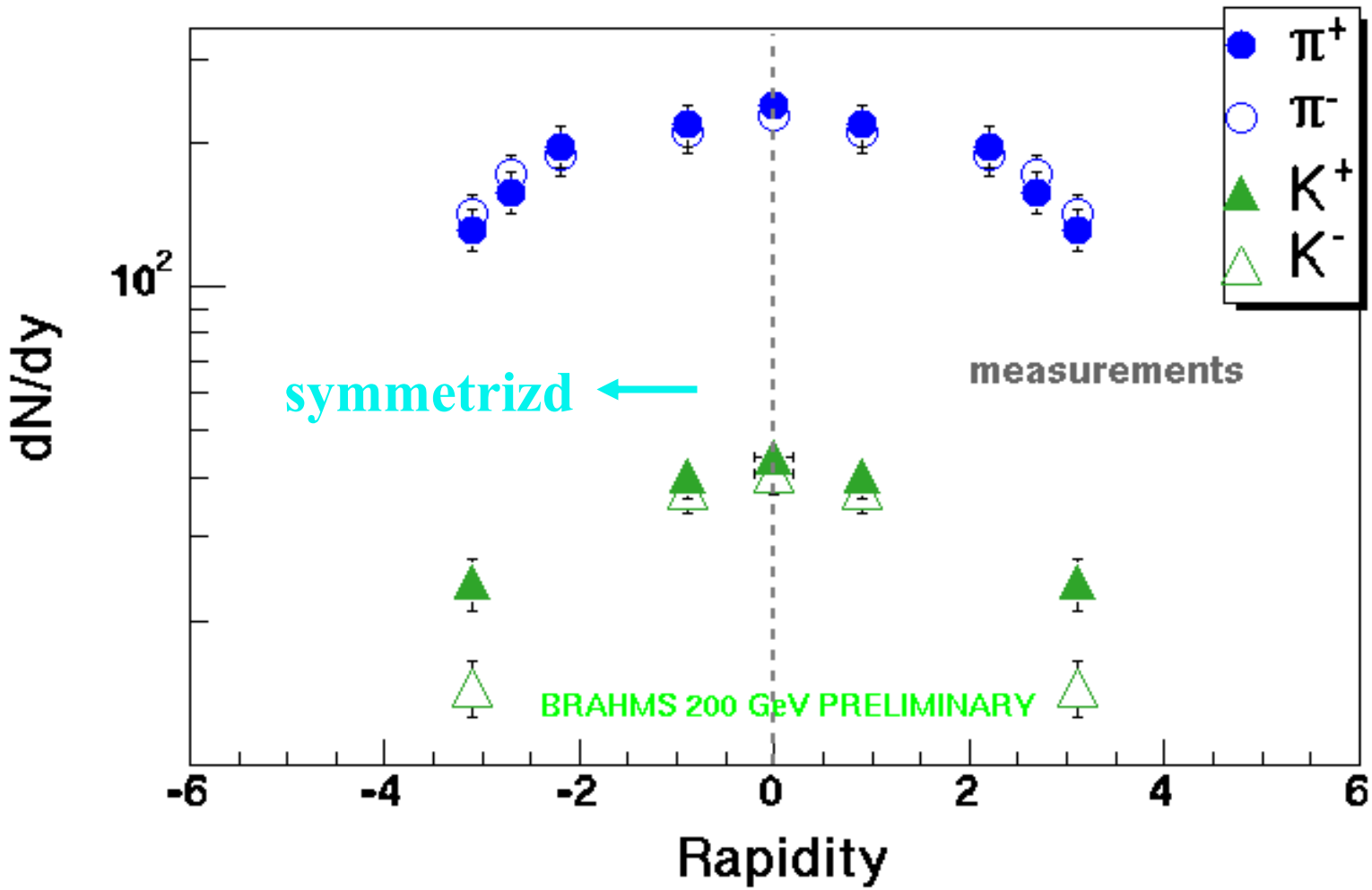


K/π ratio increases as p_T increases at y=0 and y=3

Strangeness : K/π systematics



dN/dy for π and K

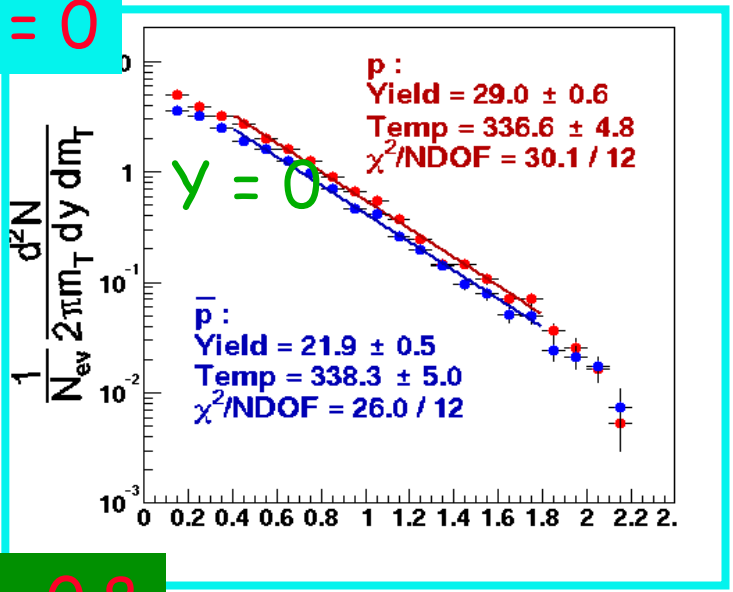


- dN/dy highest at y = 0 with little decrease up to y = 1
- Faster decrease for higher y, K- faster than K+

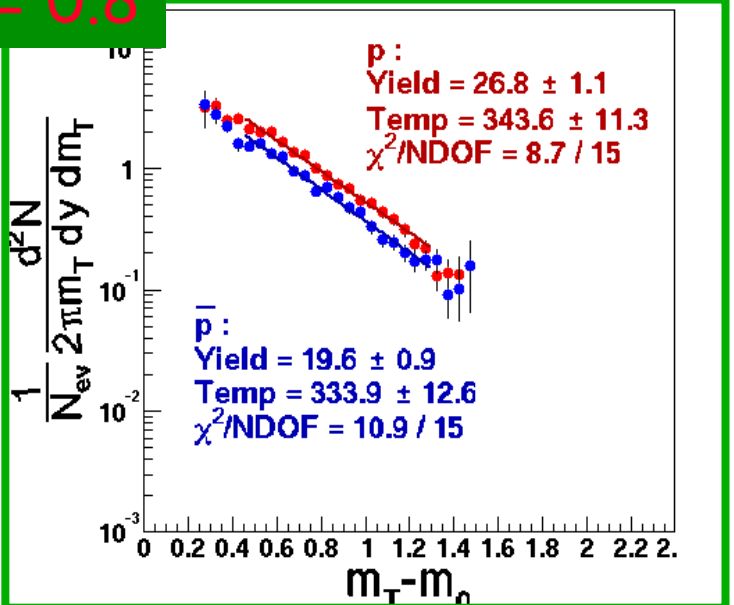
p and pbar yields

BRAHMS Preliminary $\sqrt{s_{NN}}$=200 GeV: 10% Central

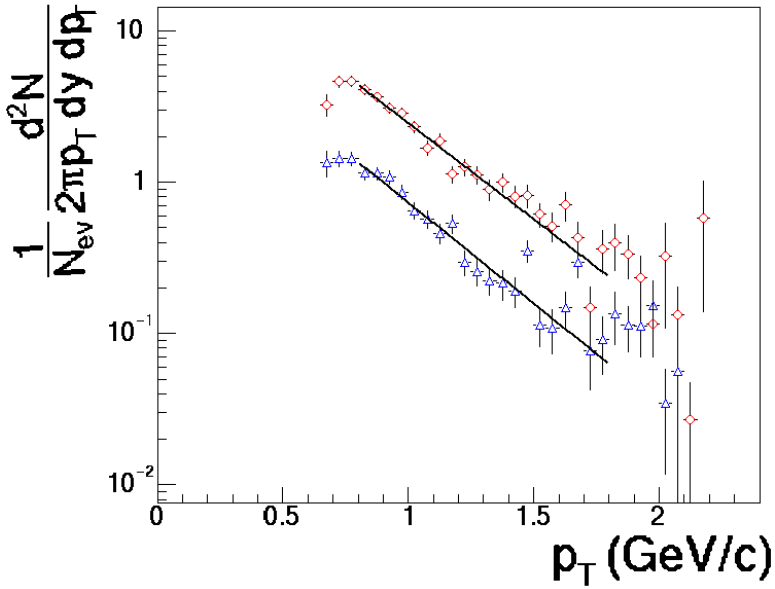
Y = 0



Y = 0.8

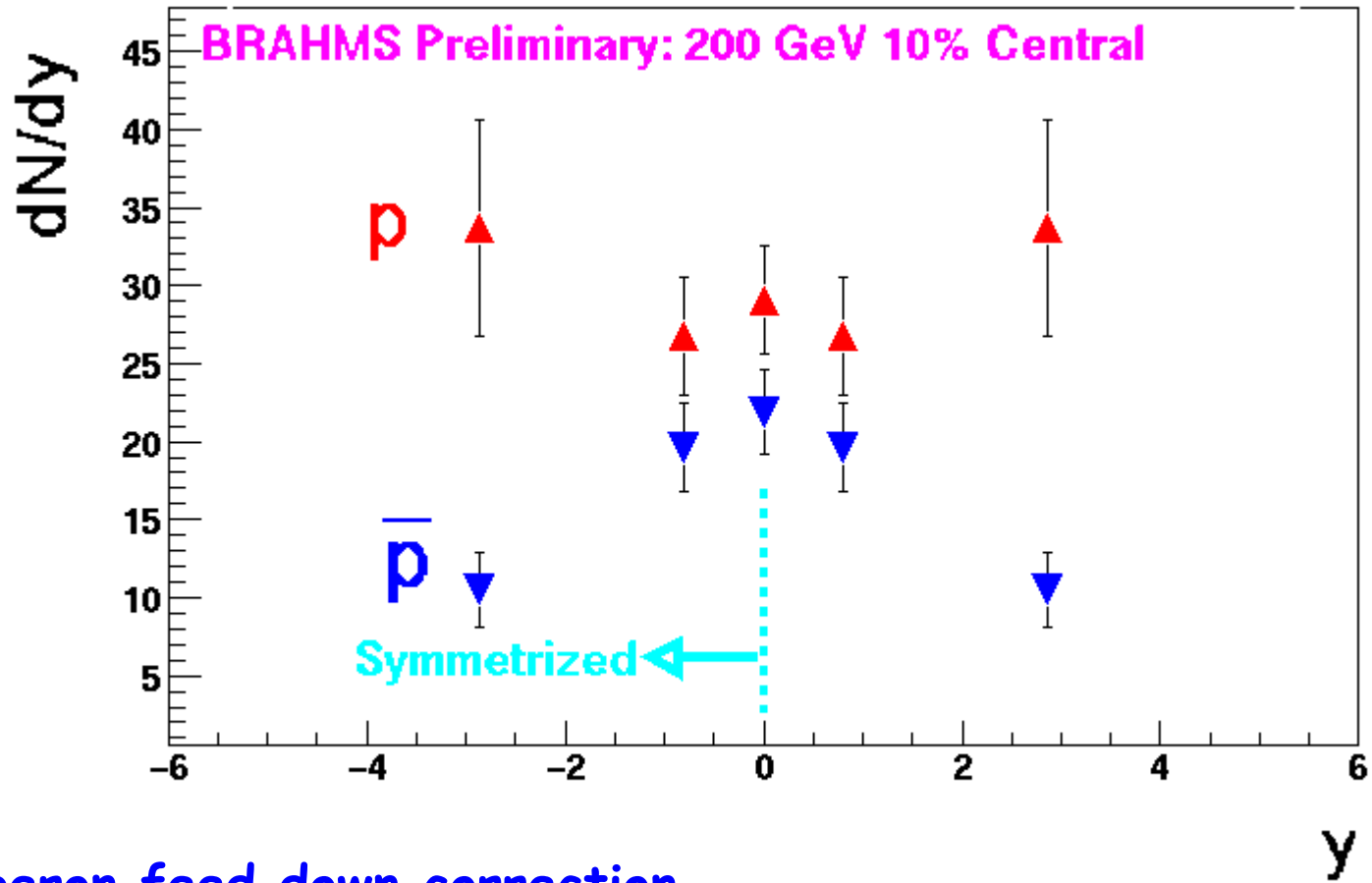


Y = 2.9



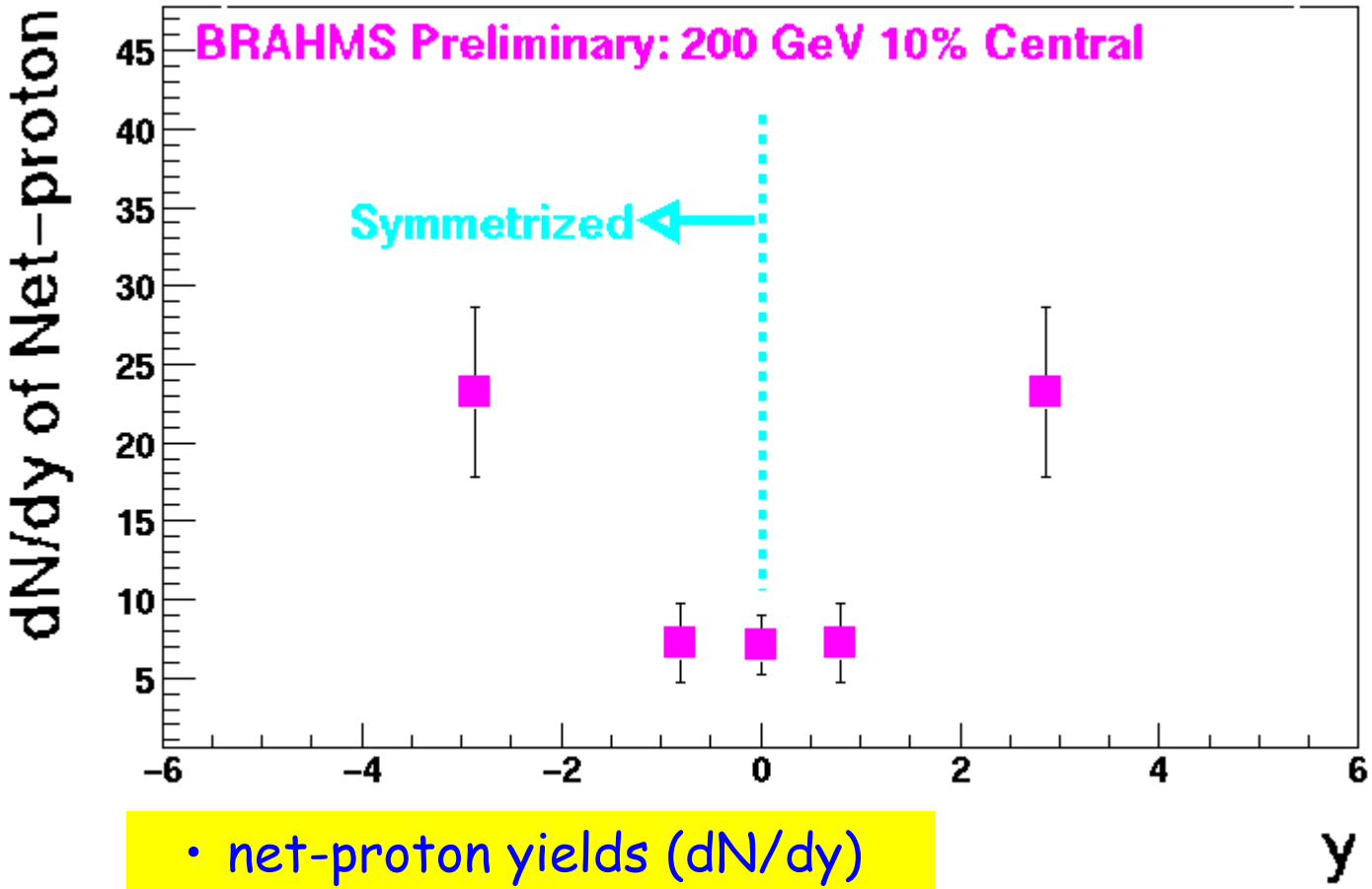
- **pbar**
  Yield =10.5 ± 0.8
  (Inverse pt slope =325.5±17.29)
- **proton**
  Yield = 33.7 ±1.8
  (Inverse pt slope = 341.8 ± 13.8

dN/dy for p and pbar



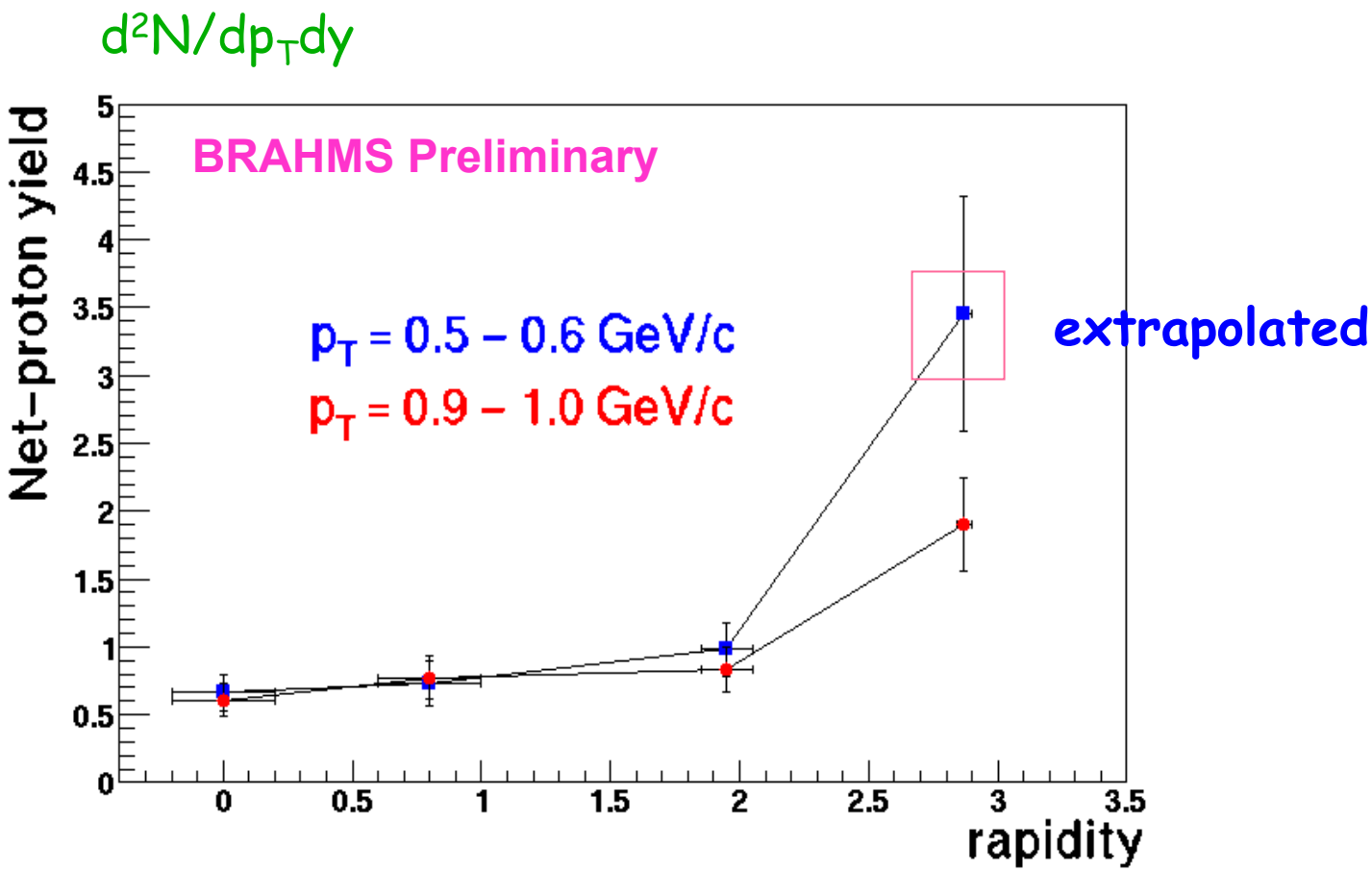
- No Hyperon feed down correction
- Systematic errors included (10-20%)

net-proton distributions



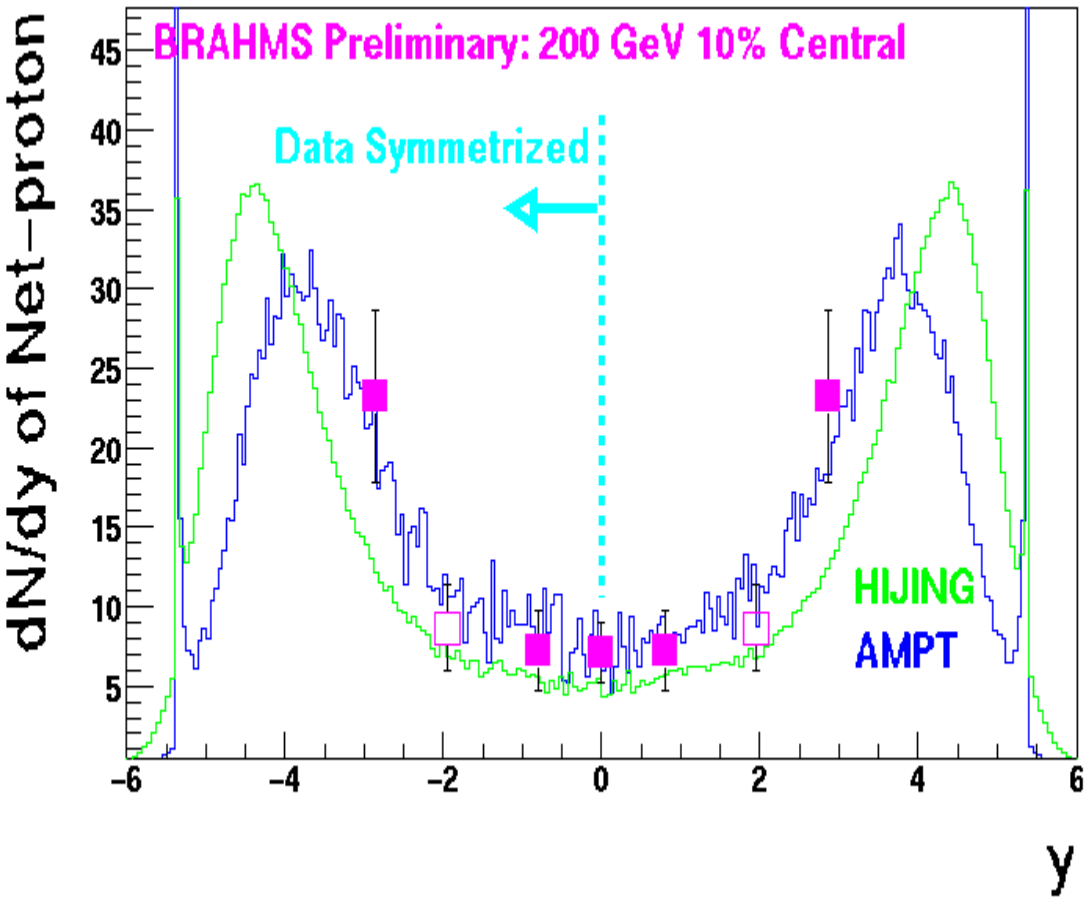
- net-proton yields (dN/dy)
  - At Y=0: 7.1 ±1.7 (Stat+Sys)
  - At y=2.9: 23.2 ± 4.5

Net-proton vs rapidity at selected p_T



- Measured + Extrapolated points

dN/dy of Net-proton and Models



- "Plateau" at $|y| < \pm 2$
- Hyperon feed down will reduce the yields by 10-20%
- Net-baryon at y =0: ~14.2 (if N(proton)/N(neutron) ≈ 1)
- More data to be analyzed (at y~2, and y~3)
- AMPT in reasonable agreement (HIJING + re-scattering!)

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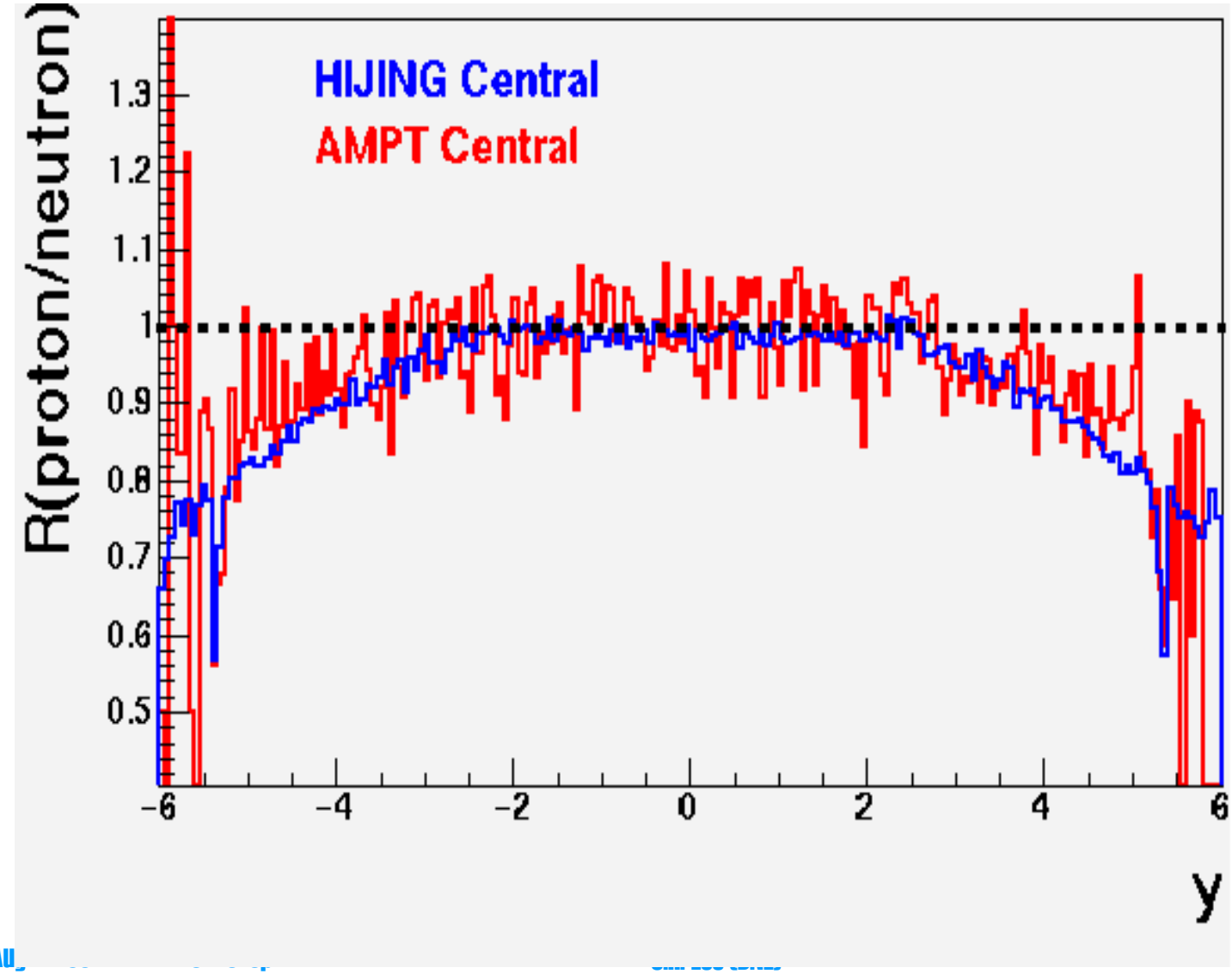
R (proton/neutron) in Models



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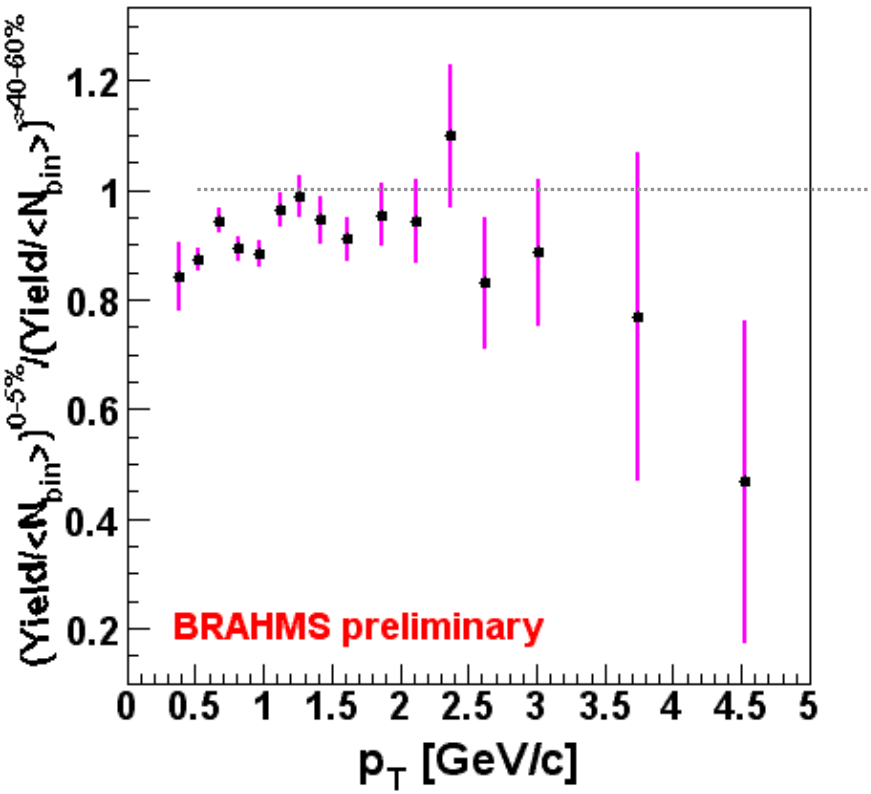
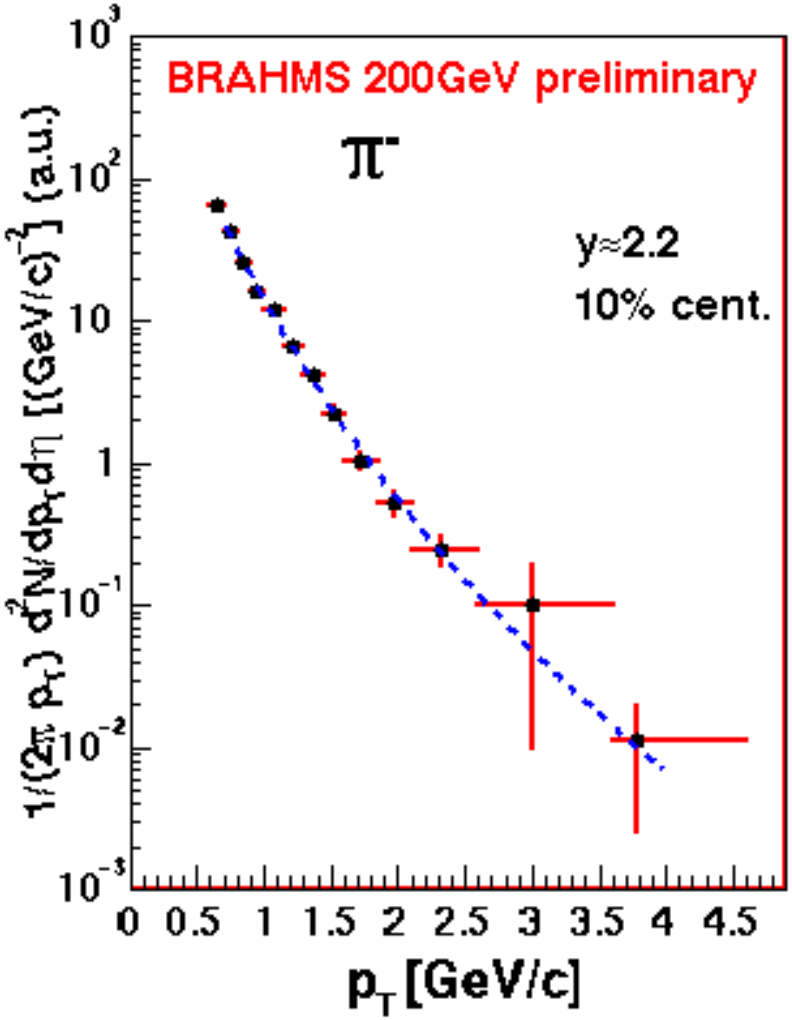
High-p_T Physics:
Central/Semi-peripheral collisions at y = 0



- Charged hadron spectra scaled by the number of binary collisions.
- high p_T suppression in central collisions compared to semi-peripheral.

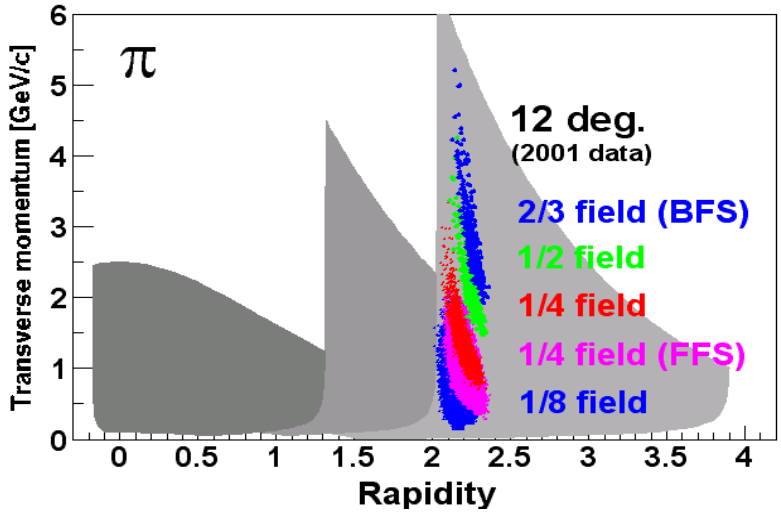
N_{bin}: Monte-Carlo Gluber model with σ_{NN}=42 mb: STAR nucl-ex0206011

π^- spectra (at y≈2.2)

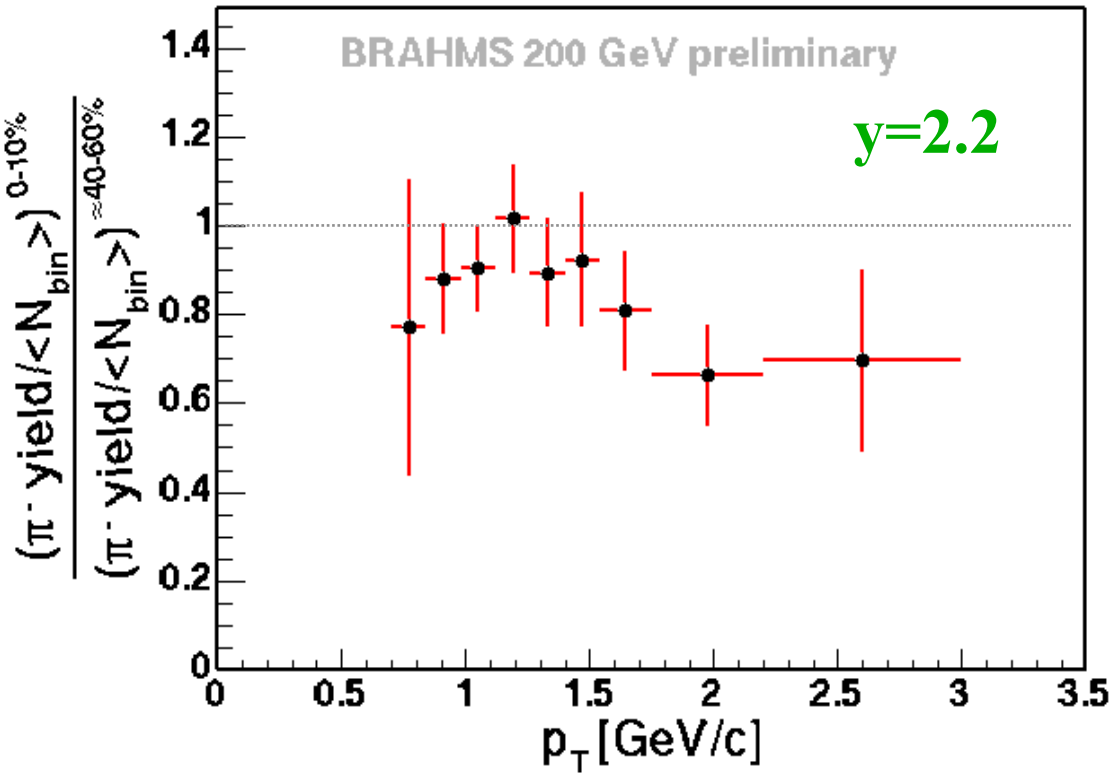


Power-law fit to the data:

$$1/p_T\, d^2N/dp_T d\eta \approx A(1+p_T/1.77[\mathrm{GeV/c}])^{-10.8}$$



Central/Semi-peripheral collision at y≈2.2



- Indicates suppression of high p_T pions at y≈2
- Sets in at lower p_T (compared to y=0)?

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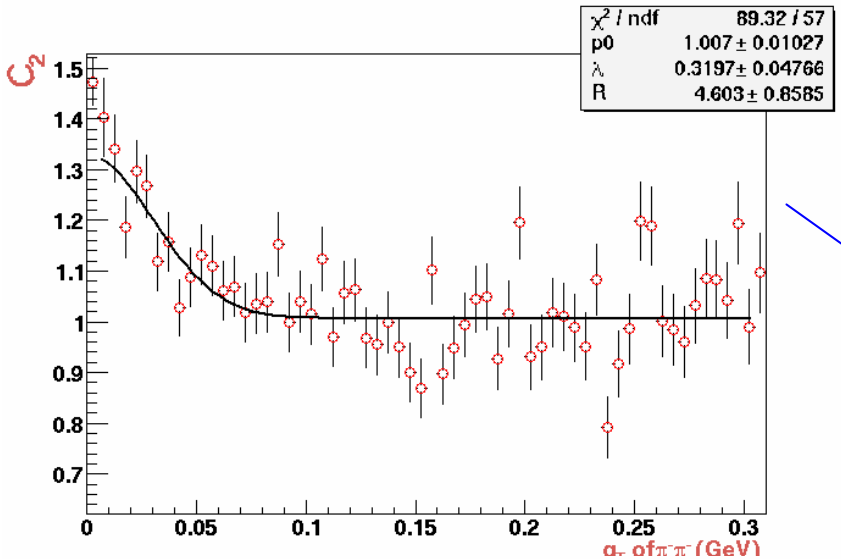
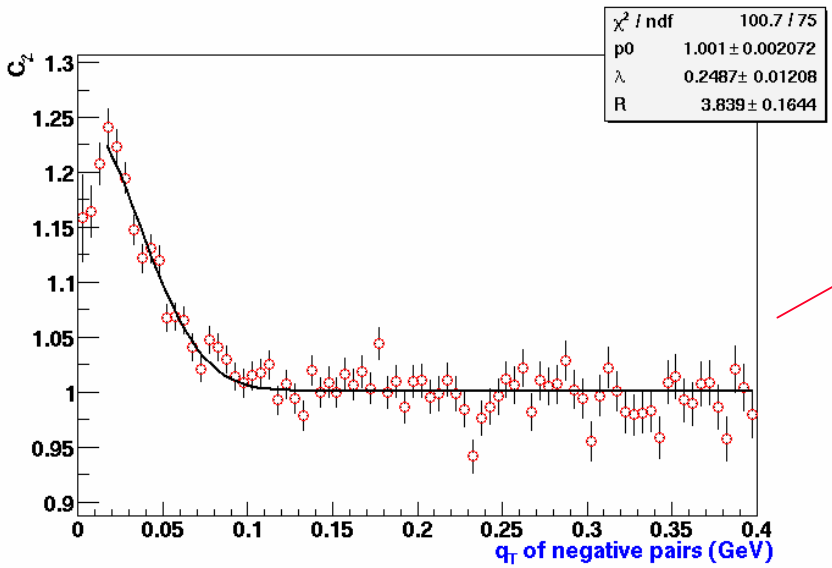
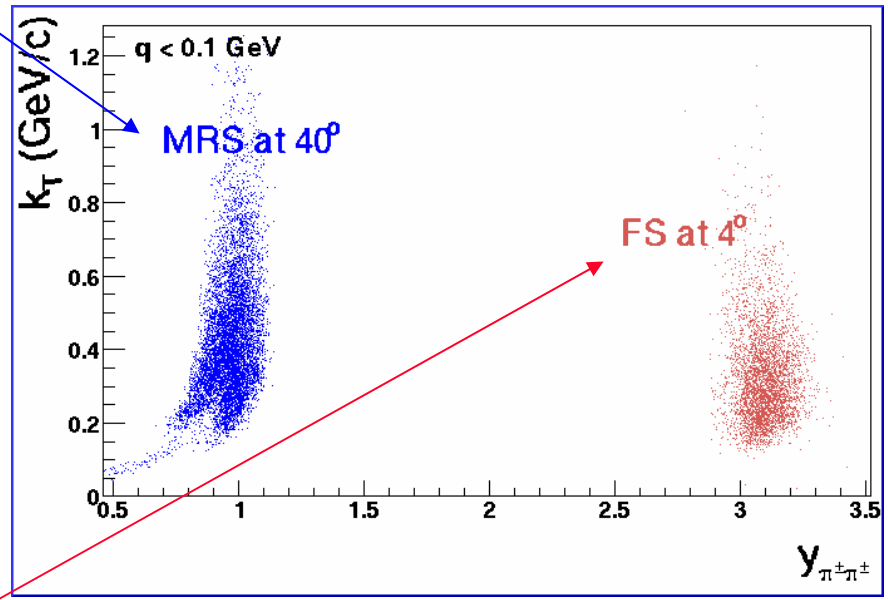
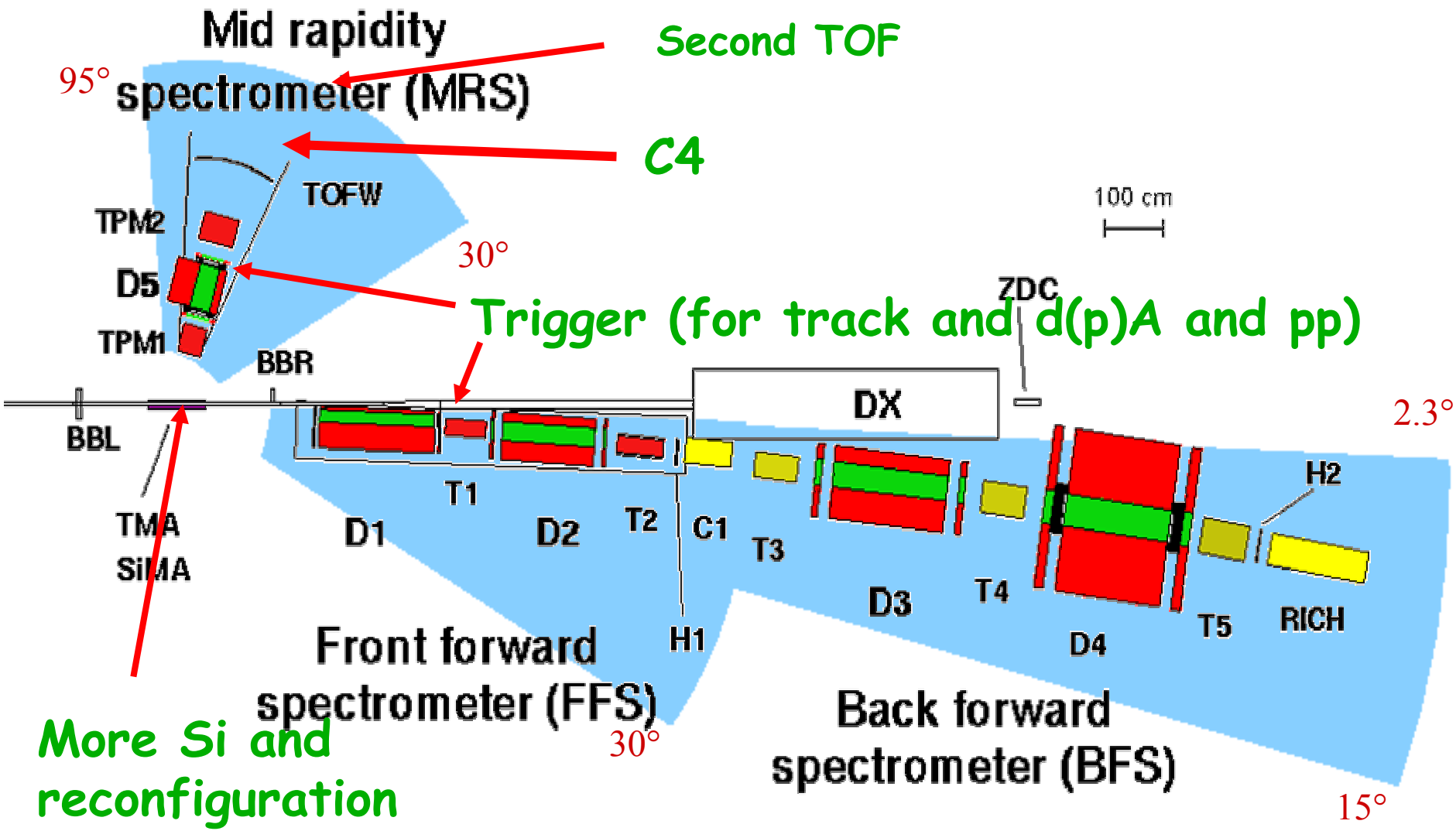
HBT:
Rapidity-Dependent Transverse Source Size Measurements





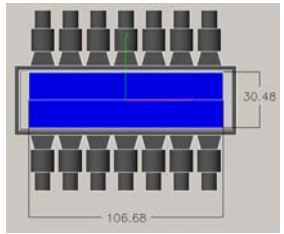


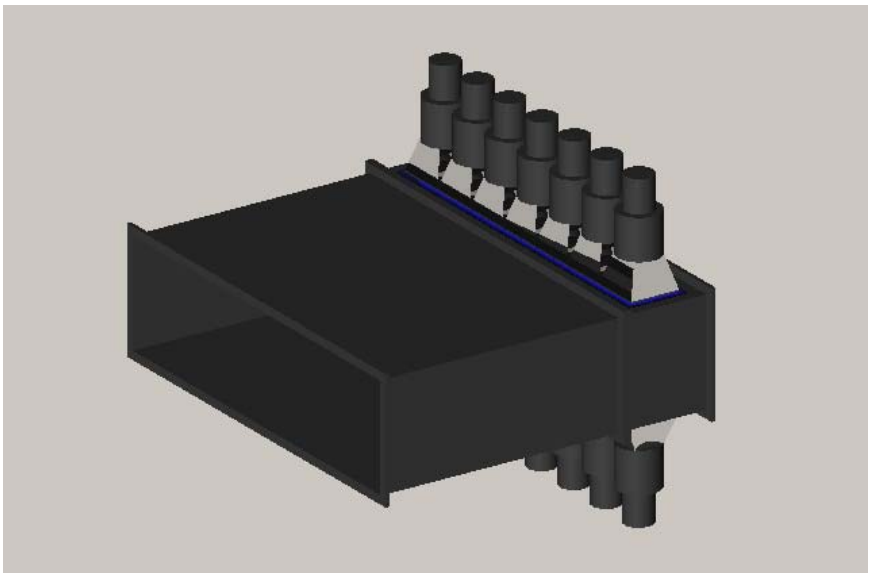
Hardware additions for Run3



More Si and reconfiguration

Extended PID for High pt measurements





- New Cherenkov detector C4: Addition to TOFW at Mid-Rapidity Spectrometer
- π/K identification up to p = 8 GeV/c (Forward Spectrometer PID up to p = 25 GeV/c)
- "high-pt" pion measurement up to 5 GeV at y ~ 0 (luminosity limited)
- Will be installed for Run3 (2002-3)

Summary:
BRAHMS Measurements of Au+Au at 200 GeV

- Highest particle multiplicity in nuclear collisions (21% increase from 130 GeV)
- At forward η: consistent with "limiting fragmentation" picture
- Partonic models: good general agreement with data

- K^-/K^+, pbar/p: approximately constant over +-1 unit of rapidity and fall off with y
- Universal correlation: $K^-/K^+=(pbar/p)^{1/4}$

- Inverse slope decreases with rapidity
- Measured dN/dy over 3 units of rapidity
- near flat net-proton yield in y<+-2
- Significant increase in net protons at y=3
- Good aggreement with AMPT: re-scattering still significant at RHIC

- ❑ **Low to high chemical potential from y=0 to y=3**
- ❑ **Net baryon central plateau (y < +-2)**
- ❑ **Incomplete yet significant transparency**
- ❑ **More Complete measurements including pp,dA expected in Run3 and beyond**

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Models, models…

- **HIJING**: emphasis on purturbative QCD processes leading to multiple mini-jet production from parton scattering (X.Wang and M.Gyulassy Phys. Rev. D (1991) 3501)
- **AMPT**: (A Multiphase Transport Model) HIJING to generate the initial phase space of parton, then extends to quark-gluon to hadronic-matter transition and the final hadron interaction (B. Zhang, C.M. Ko, B. Li, Z.Lin Phys. Rev. C 61 (2001) 067901)
- **UrQMD**: hadronic + string including all known resonances (S.A.Bass et al. Prog. Part. Nucl. Phys. 41 (1998)
- **FRITIOF**: string dynamics + LUND. Hadron behaves like relativistic strings with confined color field (H.Pi, Comp. Phys. Comm. 71 (1992))
- …

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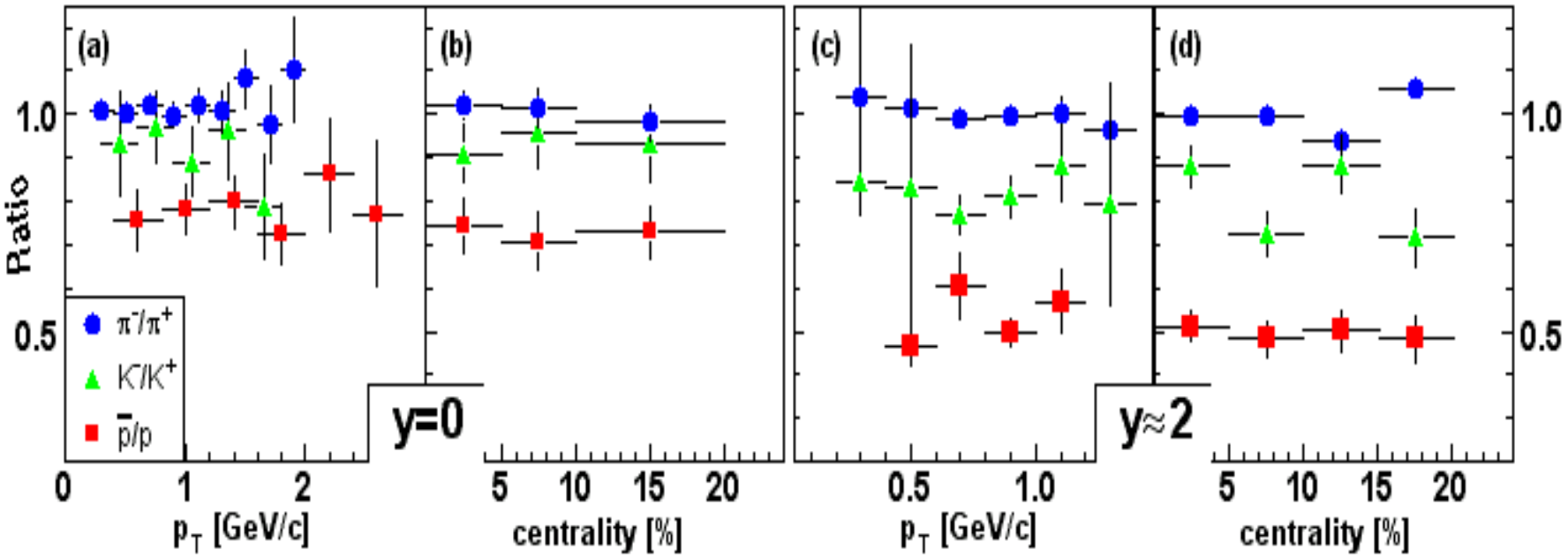
Particle Ratios: centrality and pt dependence



- No centrality dependence in range 0-20%
- No transverse momentum dependence

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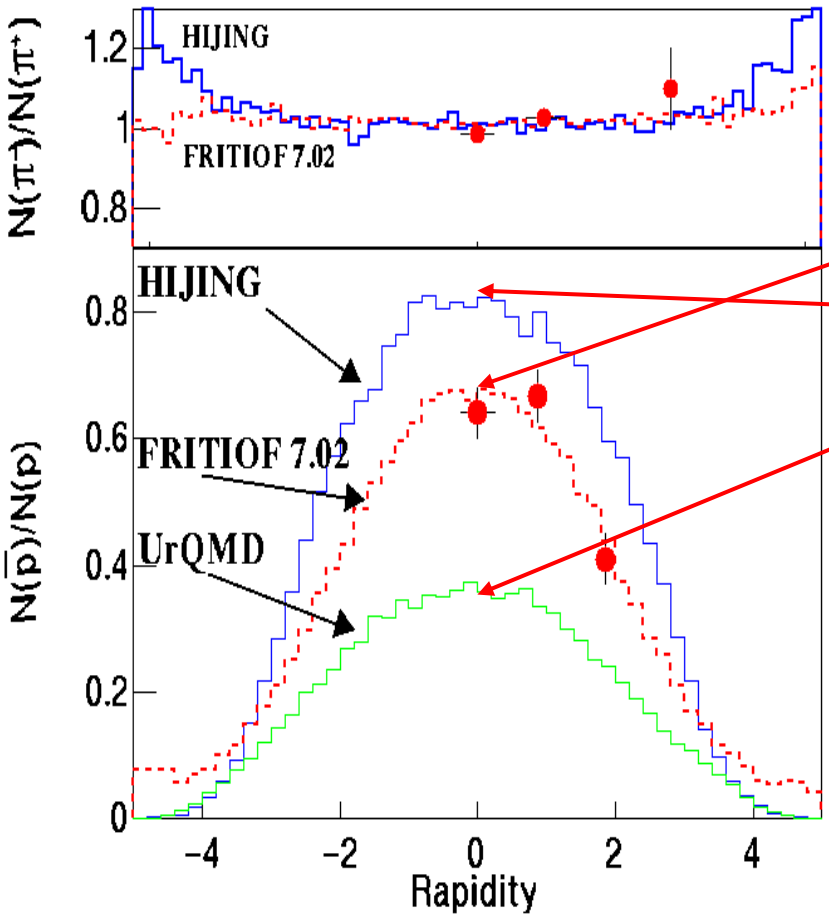
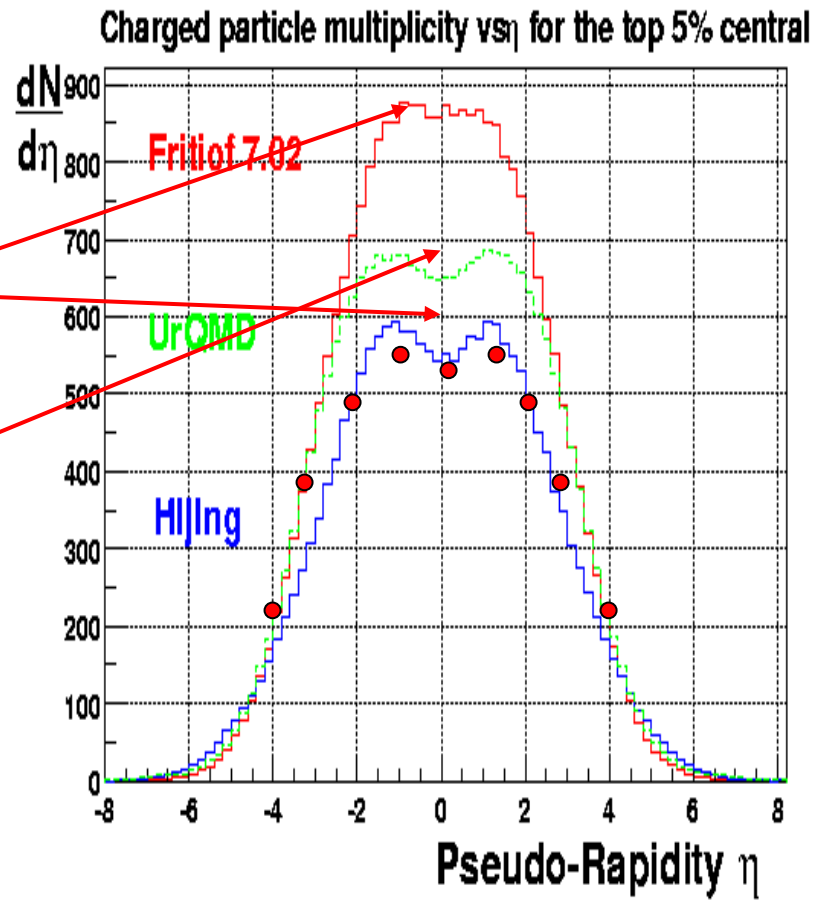
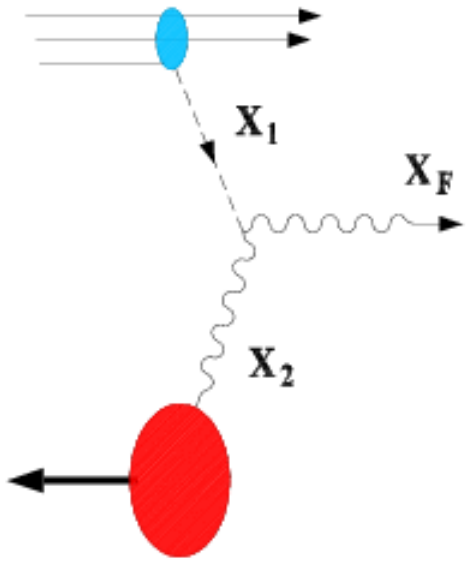
How consistent are the models?

130 GeV







Production of high rapidity (large x_F) charged hadrons can be described with this diagram; the momentum fraction of each parton is written as:

$$x_{1,2} = (p_t/\sqrt{s})e^{\pm y}$$

p_t and y are the transverse mom and rapidity of the measured hadron.

A proton of 30 GeV/c measured at 3° would probe $x_2 \sim 5 \times 10^{-4}$

BRAHMS ability to work at high rapidity (~4) opens a window to study the presence of a Color Glass Condensate in the initial conditions of d-A collisions

$$x_1 - x_2 = x_F$$

$$x_1 x_2 = p_T^2/s$$

$$0 < x_{1,2} < 1 \quad -1 < x_F < 1$$