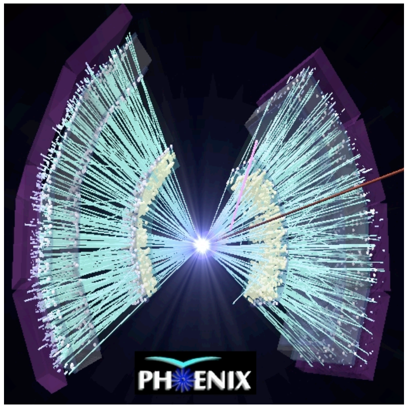
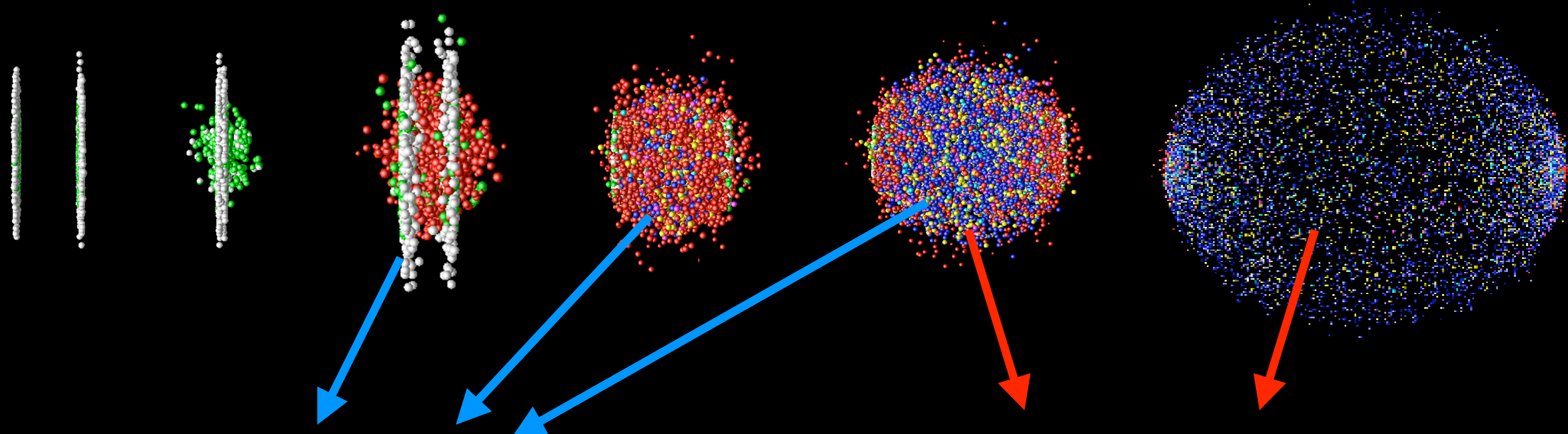
Identified Charged Particle Spectra and Yields in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV



Tatsuya Chujo (BNL)
for the PHENIX Collaboration

BROOKHAVEN NATIONAL LABORATORY

History of Heavy Ion Collisions



□, □□□ e^+e^-, □$^+$□$^-$

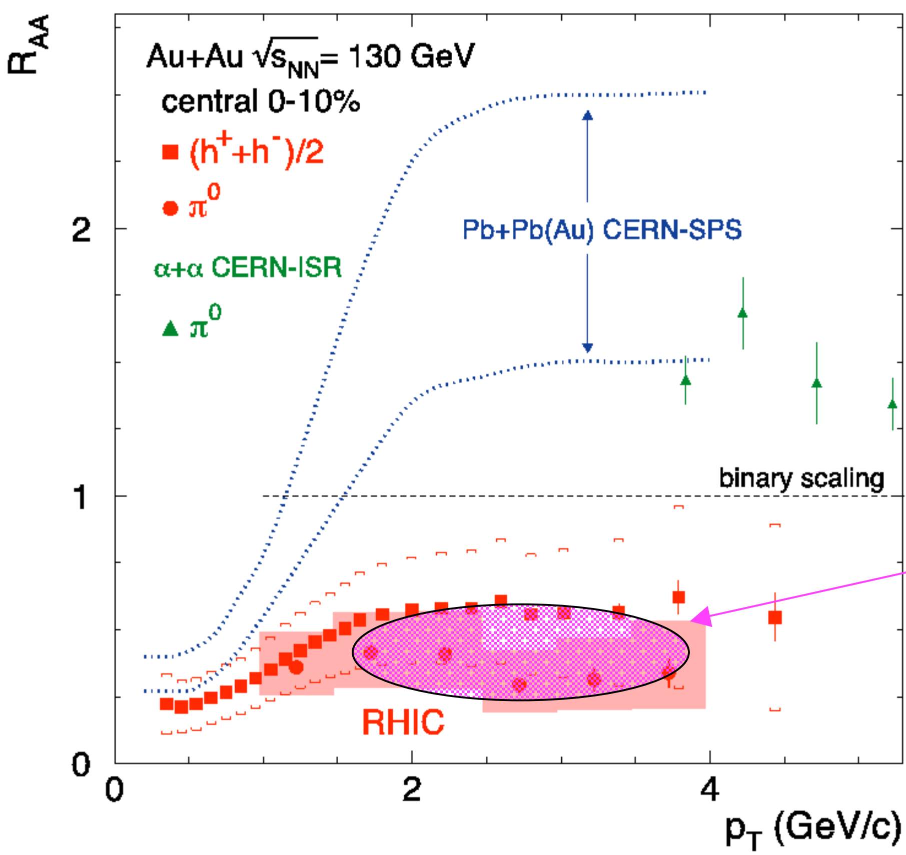
□, K, p, n, □, □, □, □, □, d,…

Real and virtual photons from q scattering sensitive to the early stages (penetrative probes).

Hadrons reflect medium properties when inelastic collisions stop (chemical freeze-out).

130 GeV Highlight (1)
□[0],*h* suppression at high p_T

PHENIX PRL 88, 022301 (2002)



- Both charged hadron and □[0] are suppressed in AuAu central at high p_T at RHIC (R_{AA} < 1).
  □ A possible explanation is the parton energy loss via gluon radiation in dense medium ("jet quenching").
- But **R_{AA} (□[0]) < R_{AA}(h)** : Suggests the importance to study the particle composition at high p_T.

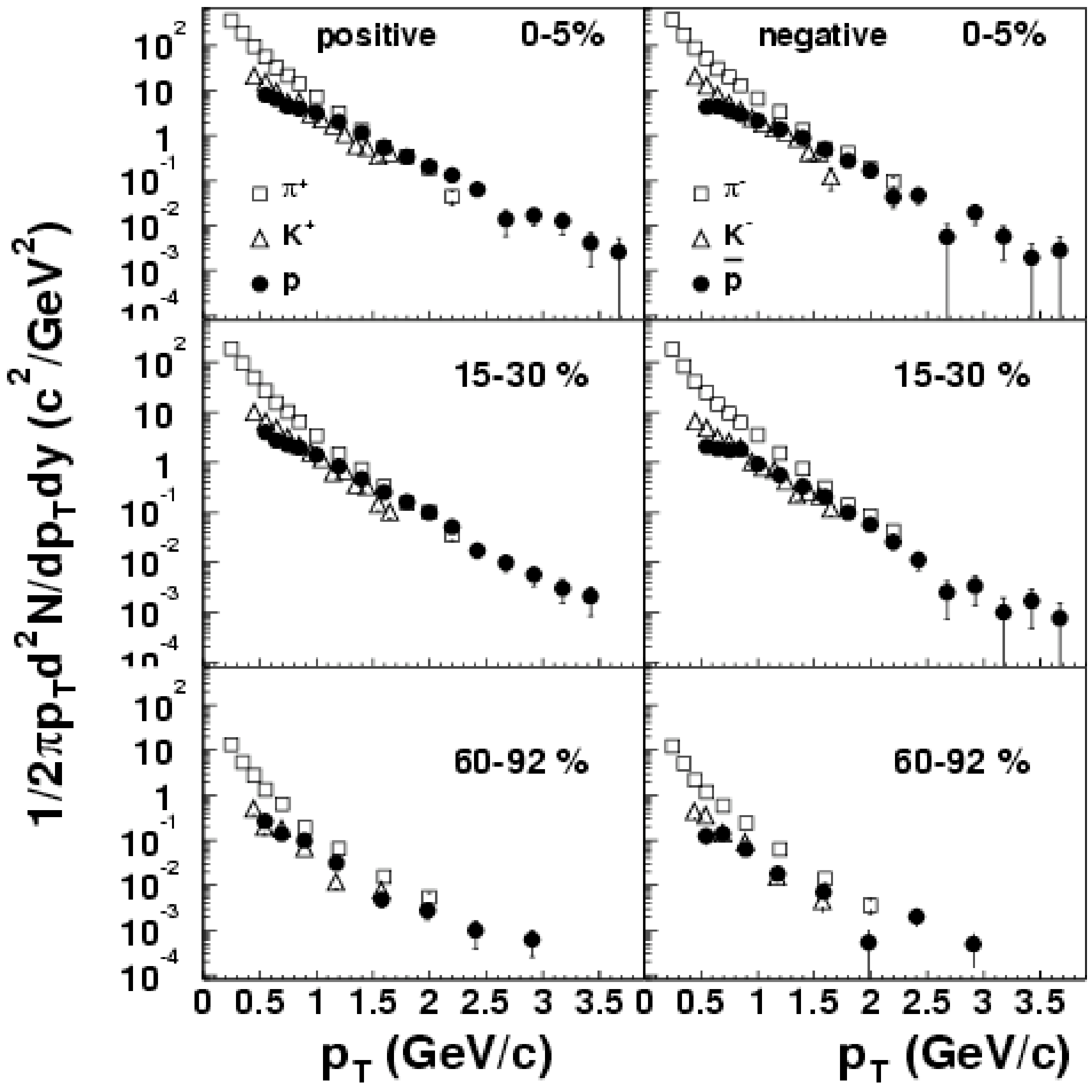
Nuclear Modification

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\square}{T_{AA}\, d^2\square^{NN}/dp_T d\square}$$

$<N_{binary}>/\square_{inel}^{p+p}$

NN cross section

130 GeV Highlight (2)
Proton vs. pion



- Proton yield is comparable to yield in central AuAu at p_T = 1.5 ~ 3.5 GeV/c.

- Needed more statistics for quantitative study.

 200 GeV DATA

- Detailed study of centrality dependence of spectra shape ratios, and yields.

PHENIX
PRL 88, 242301 (2002)

In this presentation…

We present the results on high statistics identified charged hadron p_T spectra, ratios and yields as a function of collision centrality in Au+Au collisions at s_{NN} = 200 GeV at mid-rapidity from PHENIX.

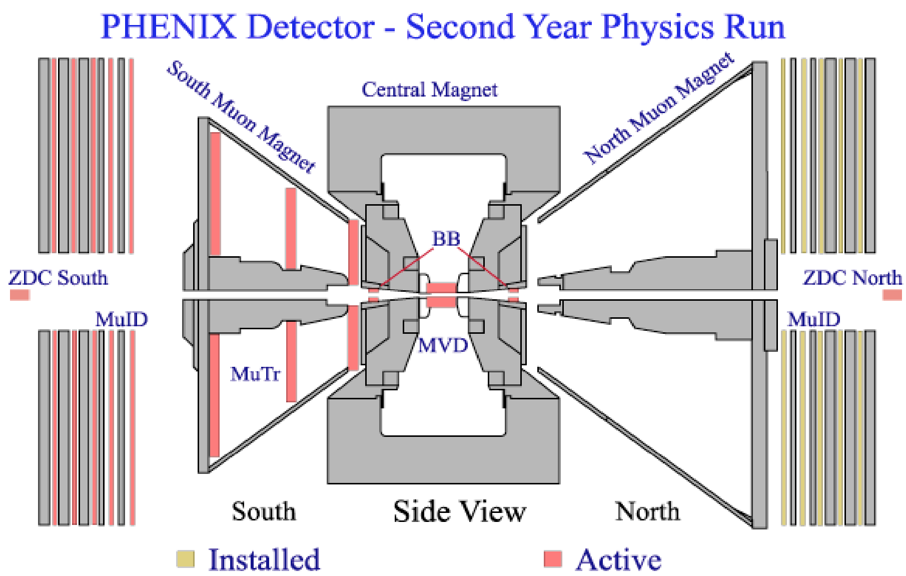
PHENIX Collaboration, S.S.Adler et al., submitted to PRC, nucl-ex/0307022

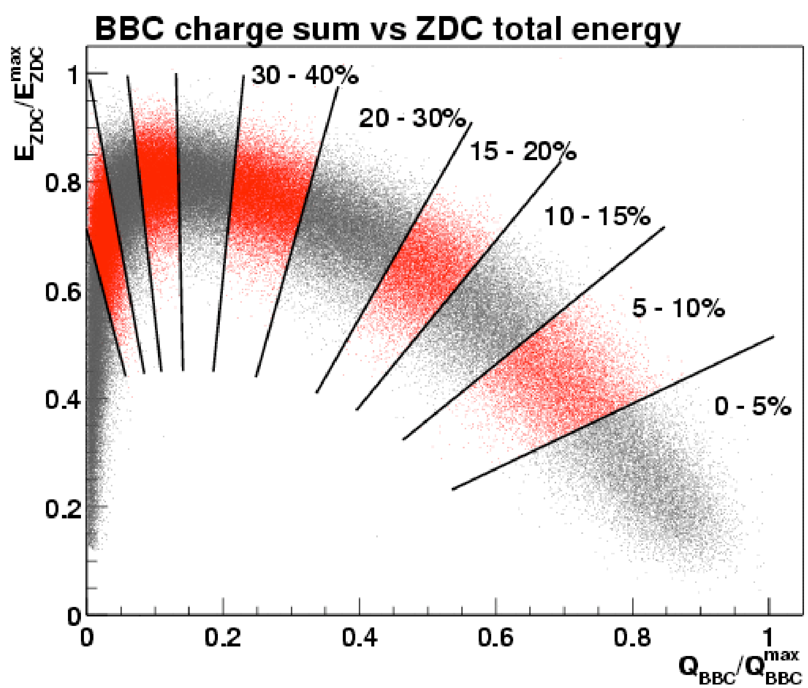
1. **Centrality dependence of p_T spectra for , K, p and pbar.**
2. **Particle ratios vs. p_T and N_{part}.**
3. **$<p_T>$ and dN/dy vs. N_{part}.**
4. **Scaling properties of identified charged hadrons.**

All data tables and figures are available from the PHENIX web site.
http://www.phenix.bnl.gov/papers.html

PHENIX Experiment

Collision Centrality Determination

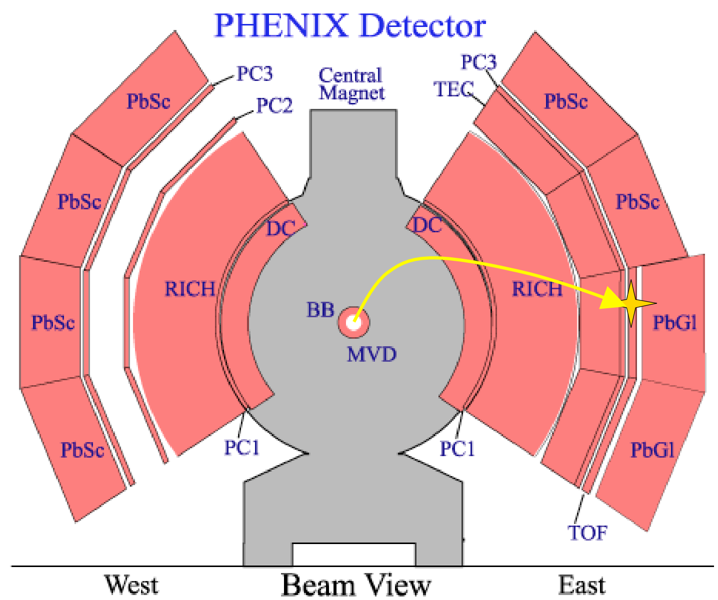




- Centrality selection : Used charge sum of Beam-Beam Counter (**BBC**, |η|=3~4) and energy of Zero-degree calorimeter (**ZDC**) in minimum bias events (92% of total inelastic cross sections).
- Extracted $\mathbf{N}_{\mathbf{coll}}$ and $\mathbf{N}_{\mathbf{part}}$ based on Glauber model.

Event and Track Selections

- Event Selection
  - Minimum bias events
  - Z vertex cut : ±30 cm
  - Total number of events :
    20 M minimum bias
    (x 140 of 130 GeV analysis).



- Track Selection
  - Drift chamber tracks with z information from PC1.
  - Track association at TOF within 2σ window in both ϕ and z.
  - Fiducial cut in z and ϕ directions to remove the edge effect.

Charged Hadron PID

- **Detectors for hadron PID**
  - DCH+PC1+TOF+BBC
  - □□ = □/8, -0.35 < □ < 0.35

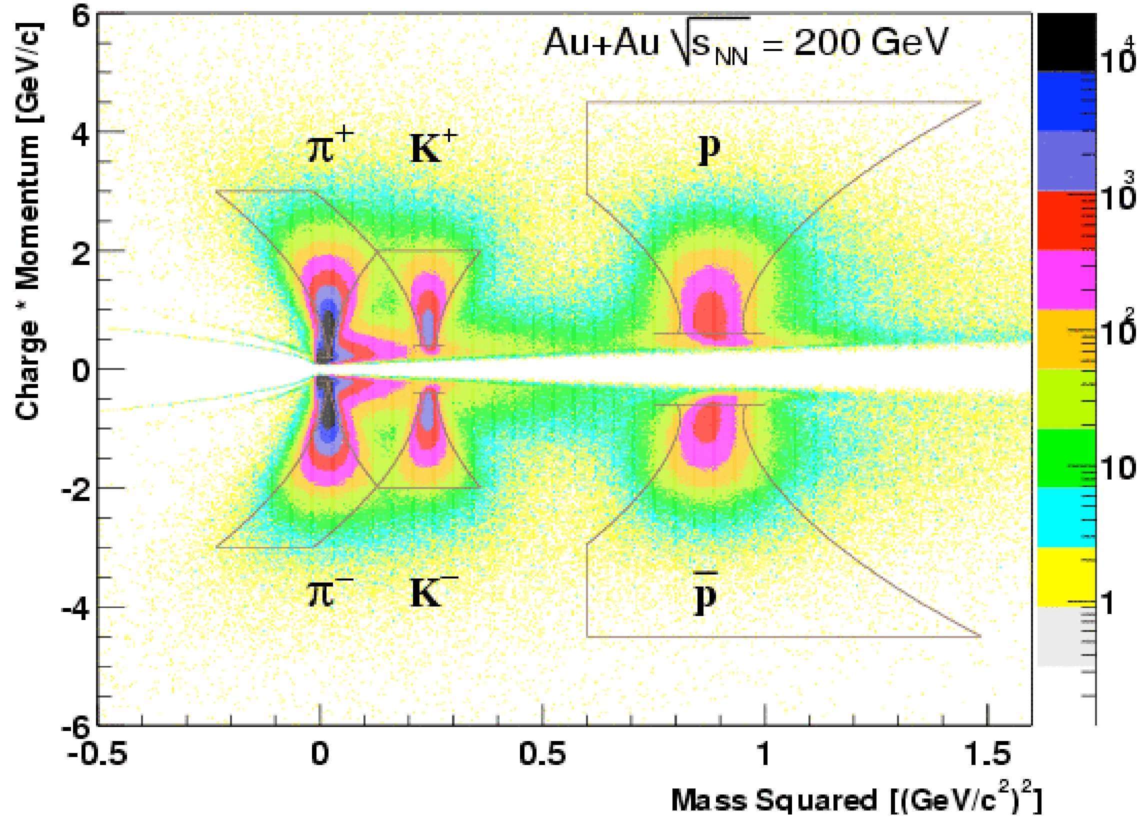
- **Momentum Resolution**

$$\square p / p \,\square\, 0.7\% \oplus 1.0\% \,\square\, p \text{ (GeV}/c)$$

- **TOF resolution** □$_{TOF}$ ~ 115 ps.

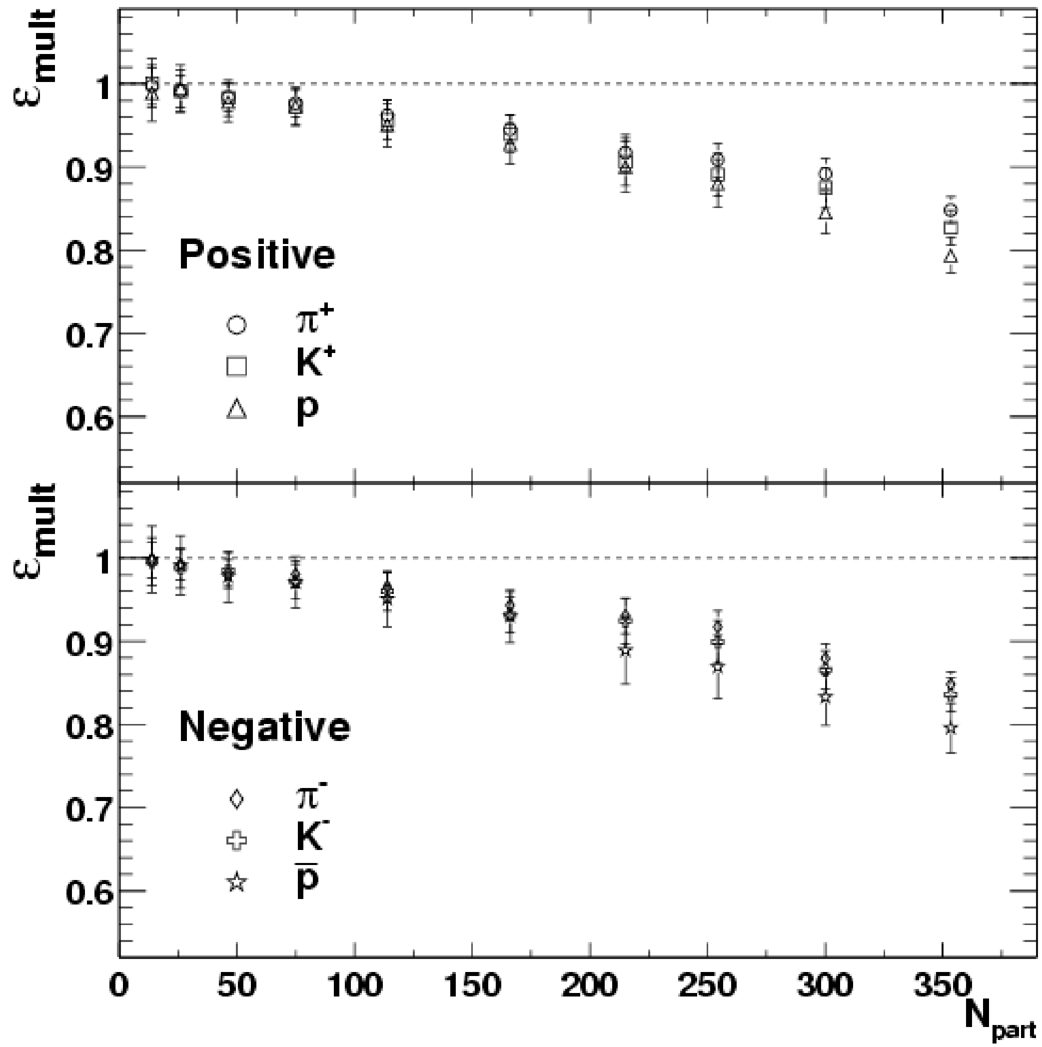
- **Hadron PID** in m^2 vs. p space with asymmetric PID cuts.
  - 0.2< □ < 3.0 GeV/c ,
  - 0.4< K < 2.0 GeV/c,
  - 0.6< p < 4.5 GeV/c.

- BG contamination level :
  - 10% K in □ @ 3 GeV/c,
  - 10% □ in K @ 2 GeV/c,
  - 5% K in p @ 4 GeV/c.



Tatsuya Chujo

Detector Occupancy Correction



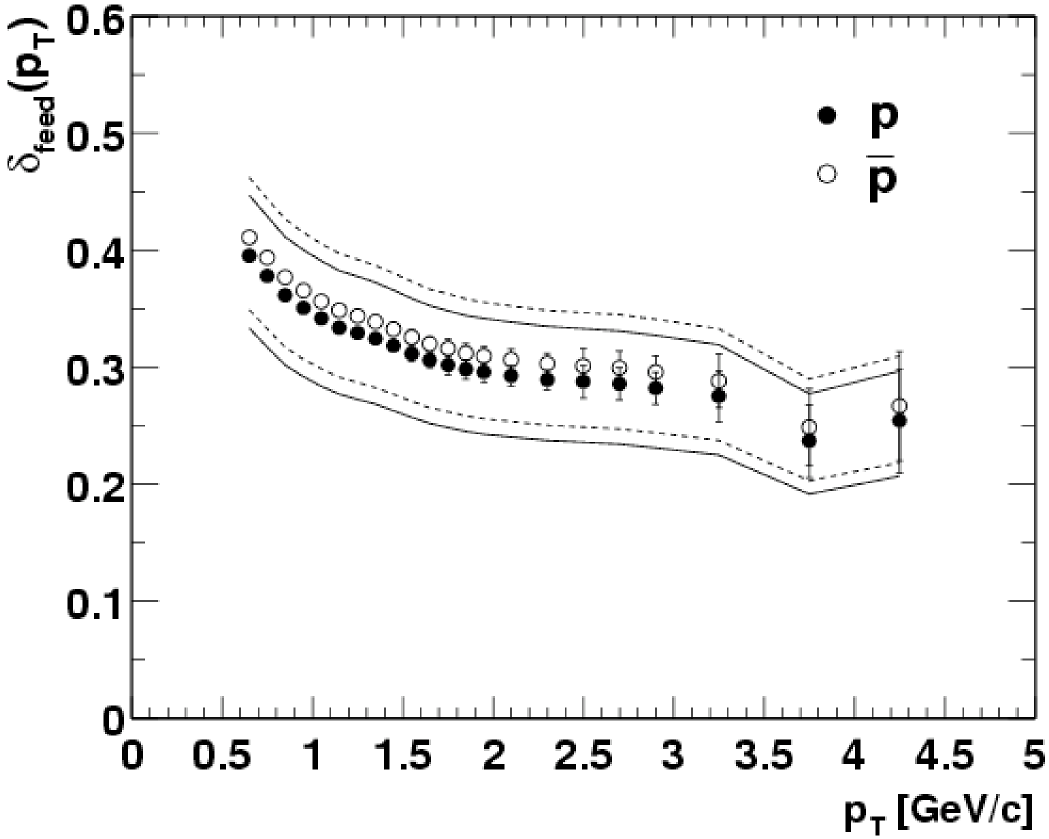
- Due to the high multiplicity environment in Au+Au, corrections for detector occupancy is necessary.

- **Estimate track reconstruction efficiency by embedding single MC event in real data for each particle species and centrality.**

$$\varepsilon_{mult} = \frac{\#\ \text{of reconstructed embedded tracks}}{\#\ \text{of embedded tracks}}$$

- **Results**
  - **For most peripheral : ~ 99%**
  - **For most central :**
    80% (p), 83% (K), 85% (π).

Feed-down correction for p and pbar



$$C_{feed}(j,p_T) = 1 \square \square_{feed}(j,p_T)$$

~40% at 0.6 GeV/c, ~25% at 4 GeV/c

p and pbar spectra are corrected to remove the feed-down contribution from weak decays using HIJING.

Assumptions:

1. pbar/p, □bar/□ ratios are independent of p_T and centrality.
2. m_T scaling for high p_T region.
3. No drastic change from 130 GeV to 200 GeV.

Tuned HIJING (central) output to reproduce □/p (□bar/pbar) measured ratio at 130 GeV AuAu.

Estimate fractional contributions of p (pbar) from □ (□bar) decay in all measured p (pbar).

Final p_T Spectra

Invariant Yield

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = \frac{1}{2\pi p_T}\cdot\frac{1}{N_{evt}(i)}\cdot C_{ij}(p_T)\cdot\frac{N_j(i,p_T)}{\Delta p_T \Delta y}$$

$$C_{ij}(p_T) = \frac{1}{\varepsilon_{acc}(j,p_T)}\cdot\frac{1}{\varepsilon_{mult}(i,j)}\cdot C_{feed}(j,p_T)$$

Acceptance, Decay, Mult. scattering (single particle MC)

Detector Occupancy

Feed-down (for p, pbar)

i : Collision centrality.
j : Particle species (π, K, p, pbar).
N_{evt} : Number of events in centrality i.
$N_j(i, p_T)$: Number of counts.

(1) Particle Spectra

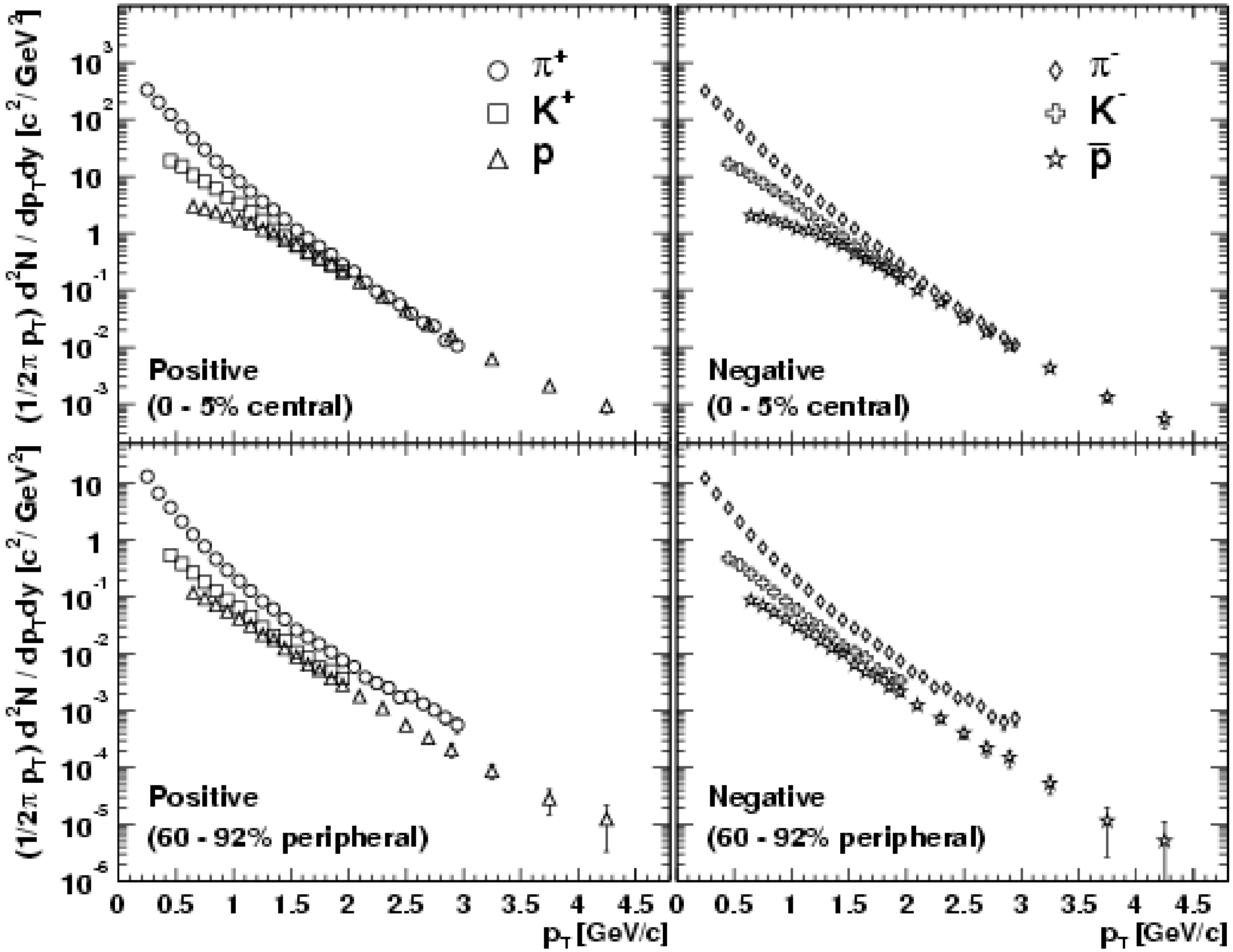
p_T Spectra (central vs. peripheral)

Central

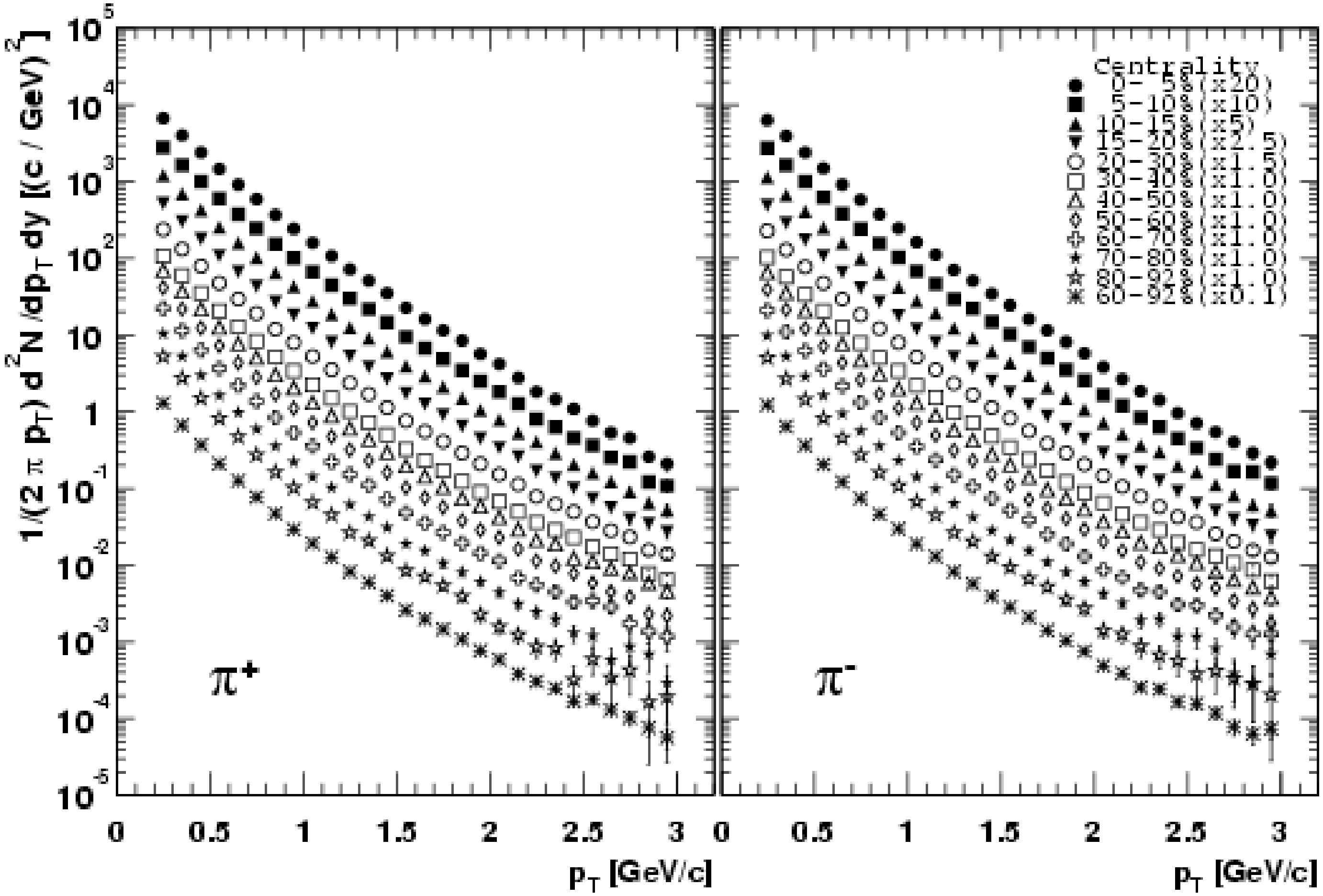
- low-pt slopes increase with particle mass
- proton and anti-proton yields equal the pion yield at high p_T.

Peripheral

- mass dependence is less pronounced
- similar to pp

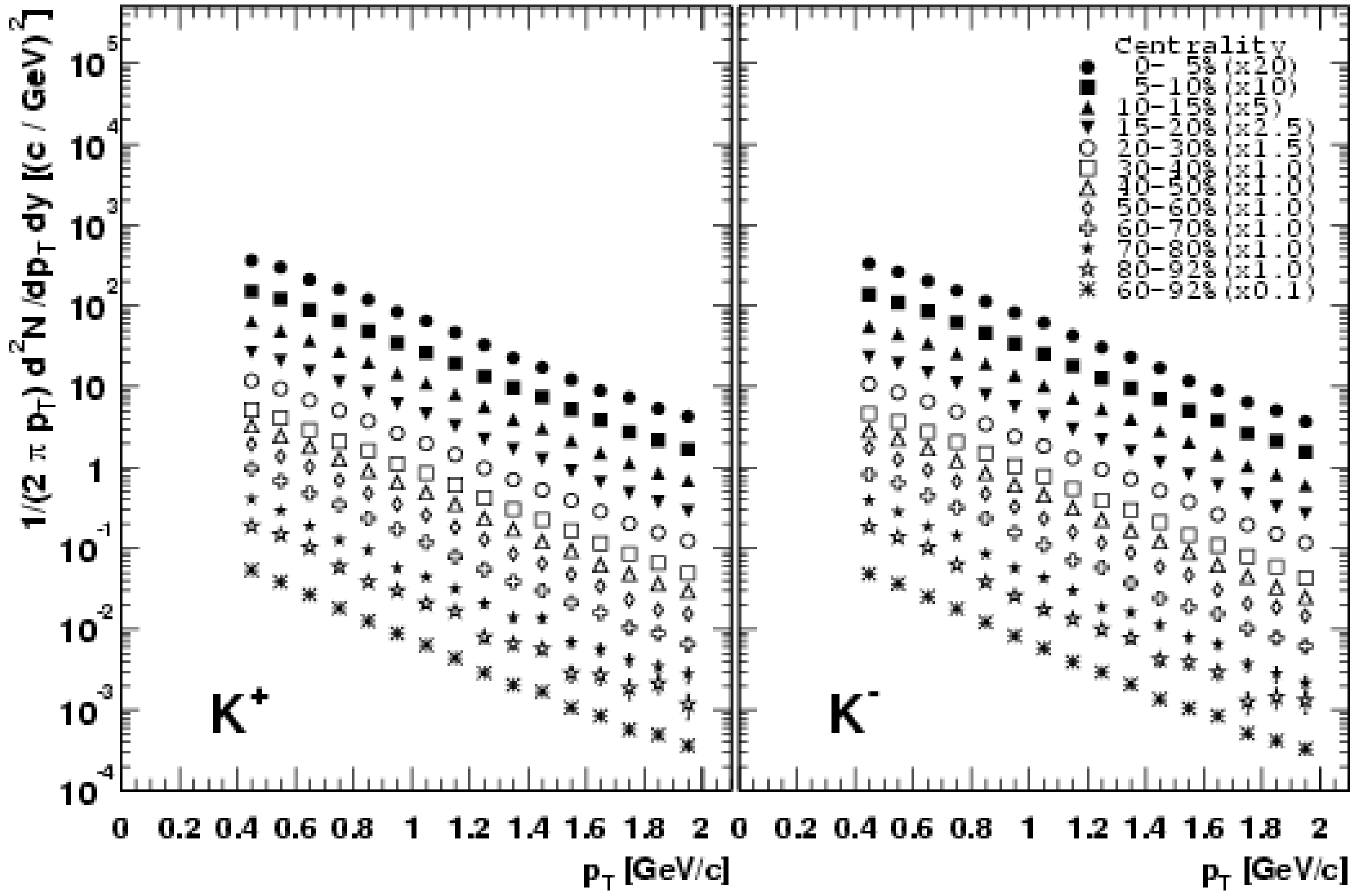


Charged pion spectra in AuAu 200 GeV



- Approximately power-low shape for all centrality.
- The spectra fall faster with increasing p_T for more peripheral collisions.

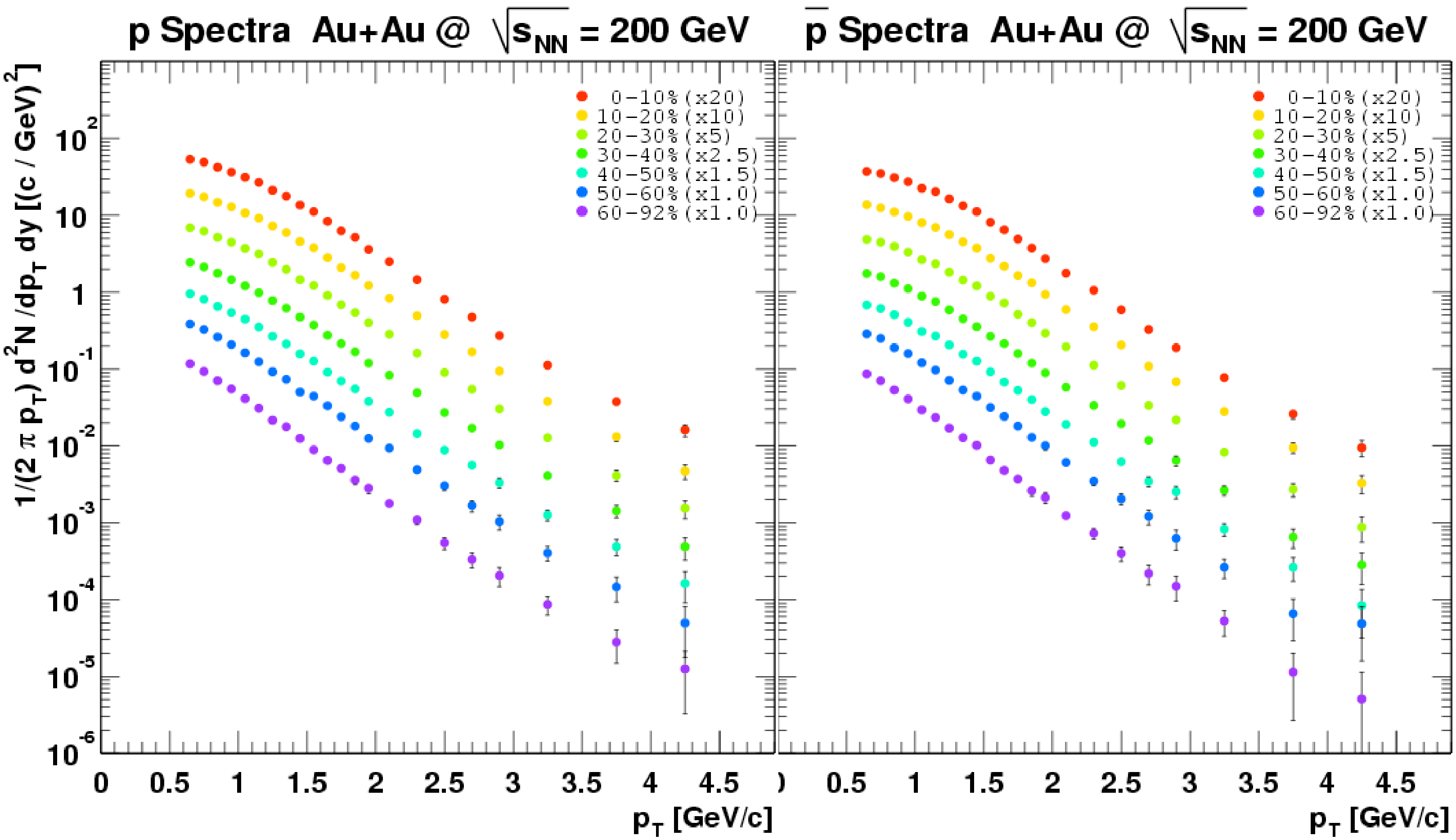
Charged kaon spectra in AuAu 200 GeV



- **Approximately exponential shape in p_T for all centrality.**

Proton and anti-proton spectra in AuAu 200 GeV

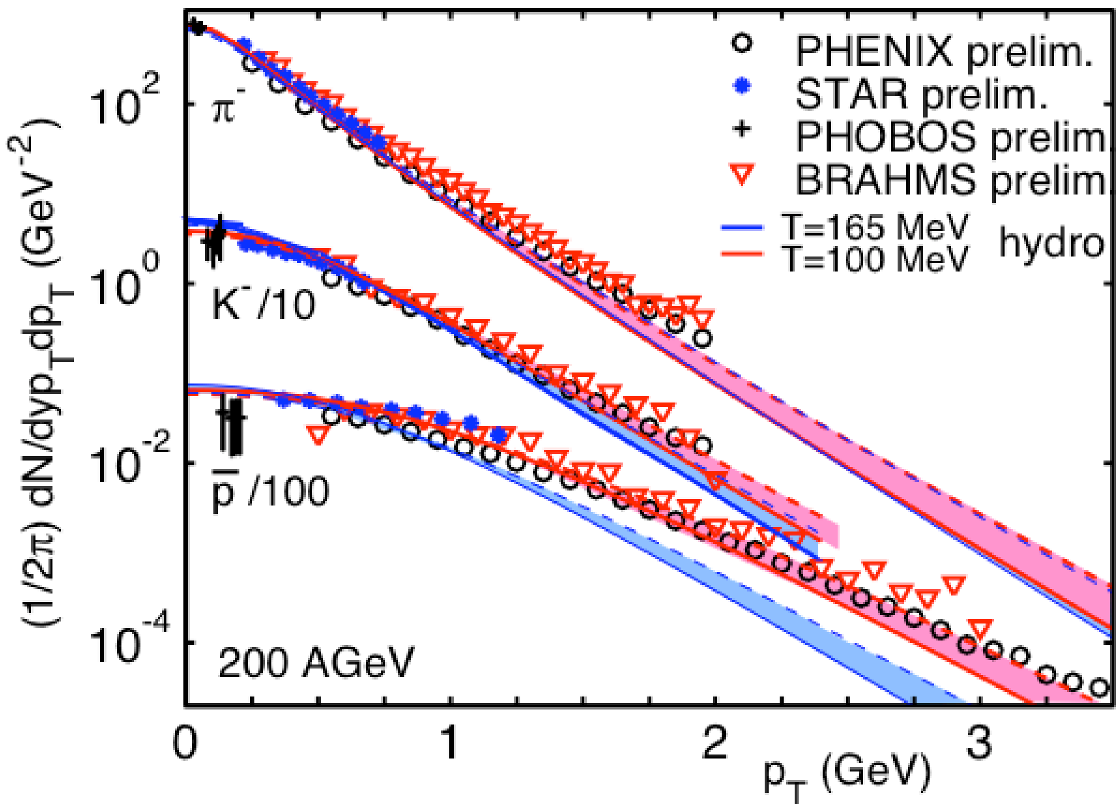
PHENIX



- Corrected for weak decay feed-down effect (~40% at 0.6 GeV/c, ~25% at 4 GeV/c).
- **Strong centrality dependence in spectra shape at low p_T (< 1.5 GeV/c).**

p_T Spectra for All 4 Experiments and Hydrodynamical Model

Data: PHENIX: NPA715(03)151; STAR: NPA715(03)458; PHOBOS: NPA715(03)510; BRAHMS: NPA715(03)478
Hydro-calculations including chemical potentials: P.Kolb and R. Rapp, Phys. Rev. C 67 (03) 044903

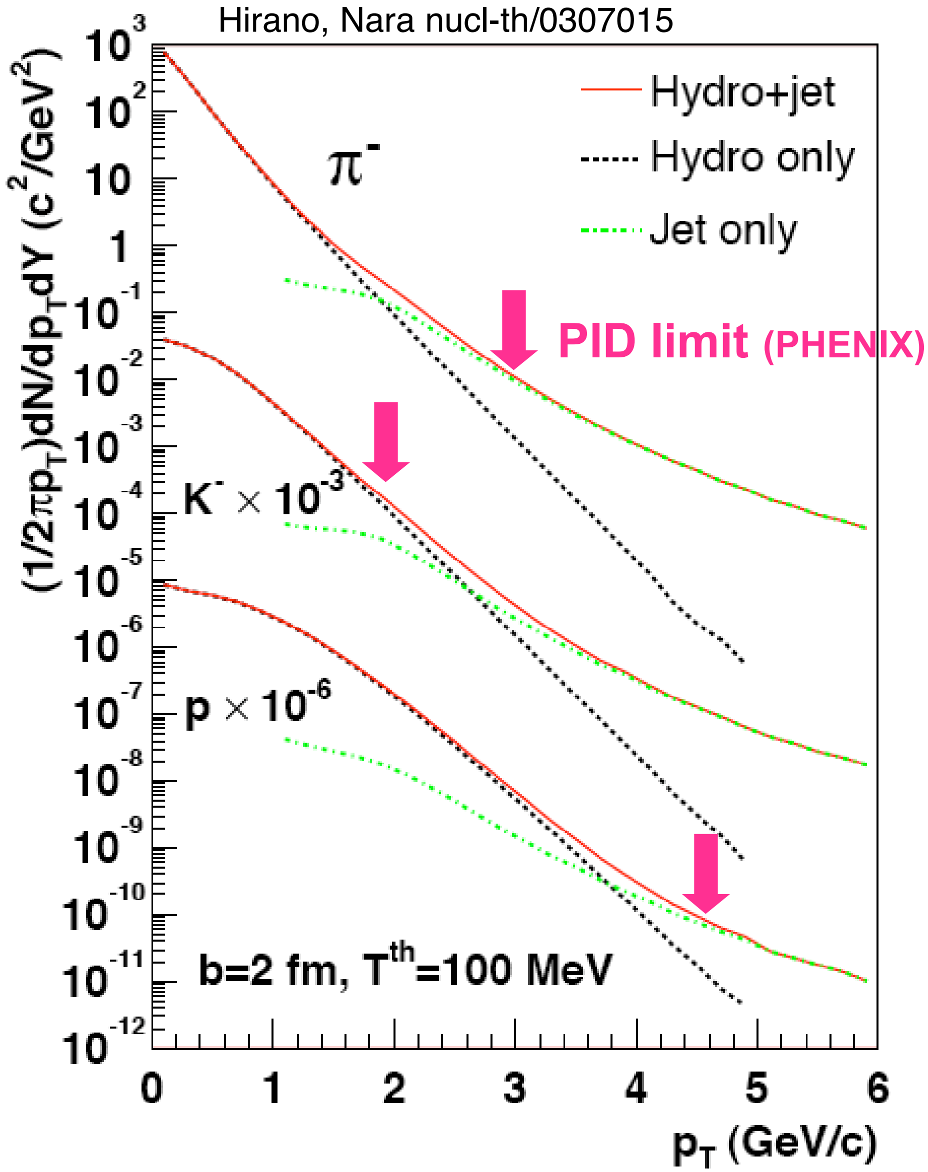


* Note: all data points are preliminary results (QM02).

Calculations → too long a system lifetime
Enormous initial pressure, but decouples quickly (~10 fm/c)

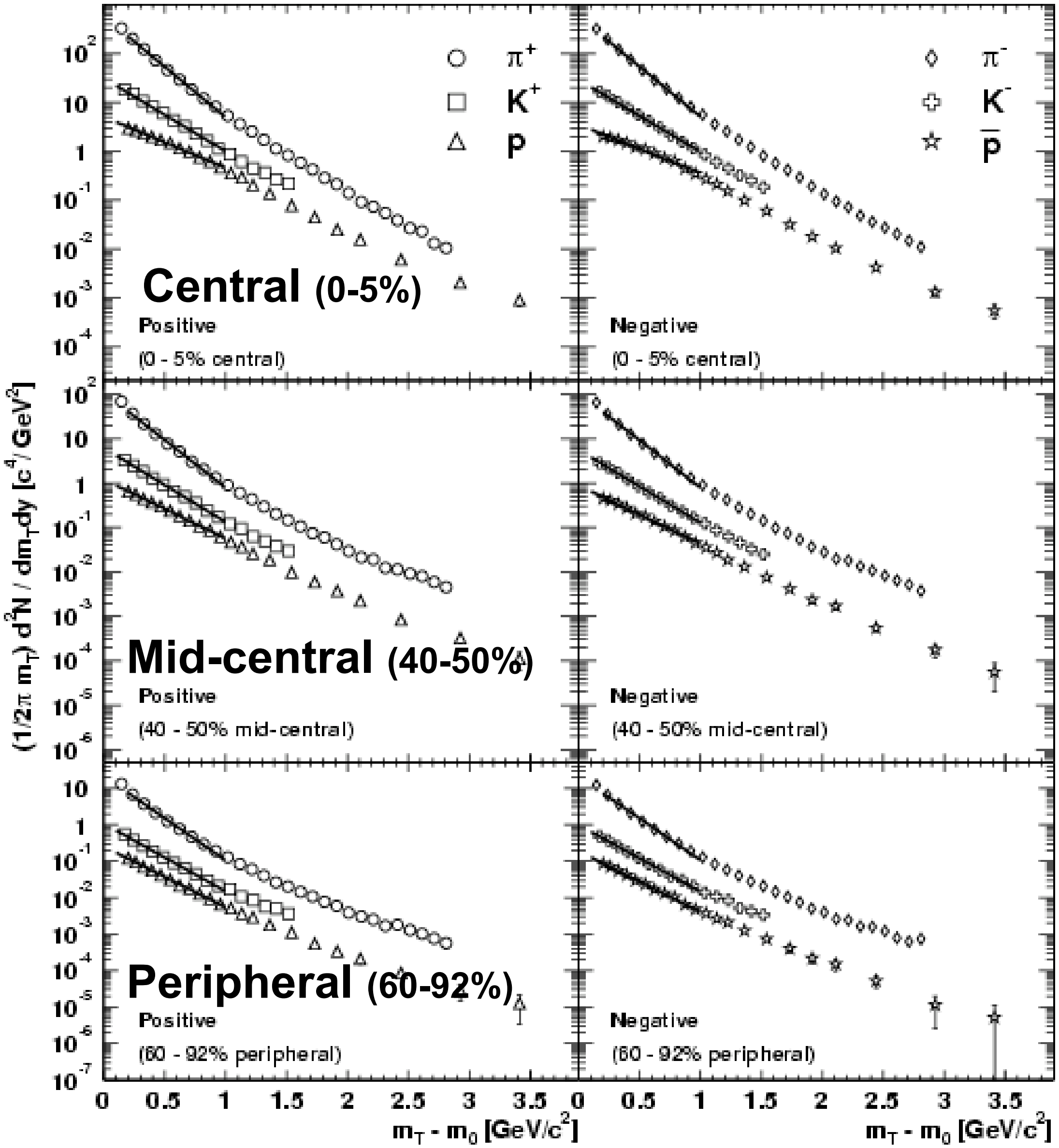
Hydrodynamics describes bulk particle momentum distributions.

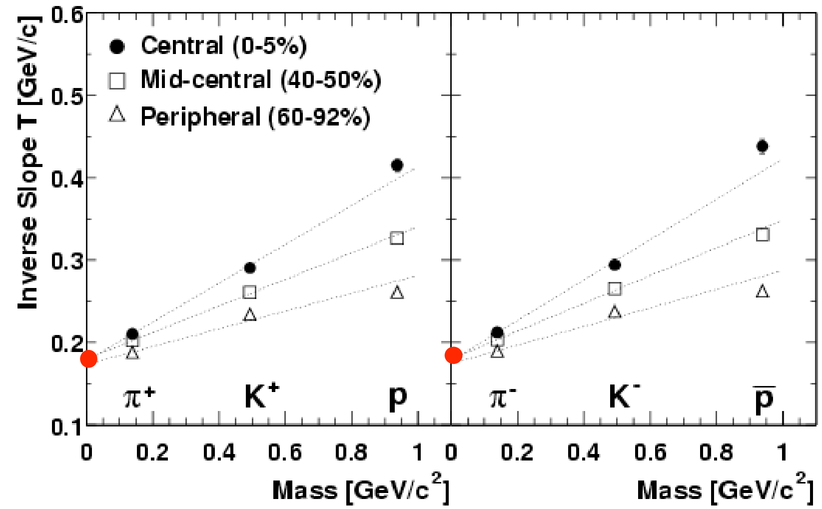
Hydro + Jet Model



- Hydrodynamics can describe the spectra up to ~ 2 GeV/c.
- **Jet contributions > 2 GeV/c.**
- Needed detailed comparison with data (e.g. centrality dependence) .

m_T - m_0 Spectra





Fit Function

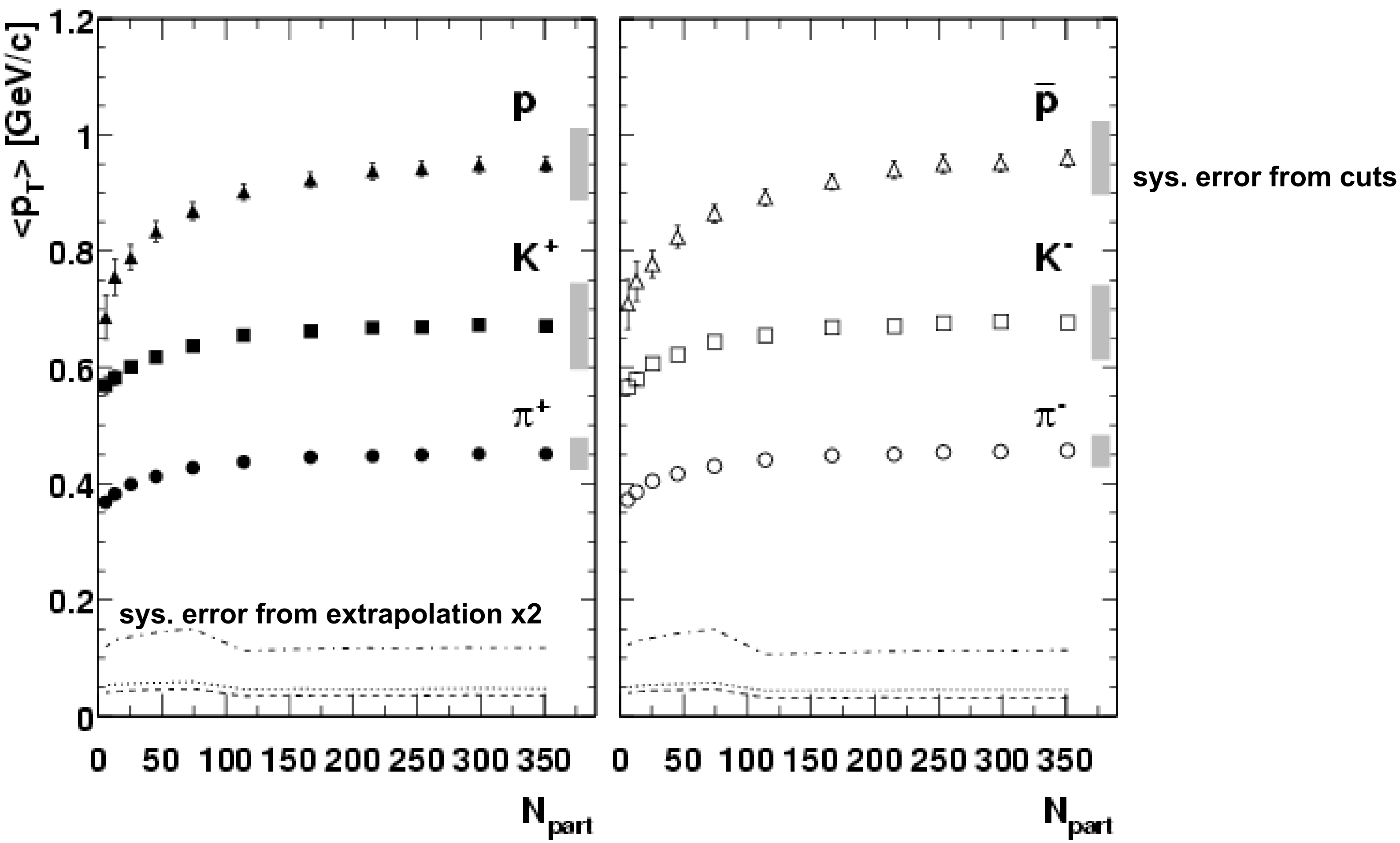
$$\frac{1}{2\pi T(T+m_0)} \cdot A \cdot \exp\left[-\frac{m_T - m_0}{T}\right]$$

- **Clear mass and centrality dep. in slope parameter *T*.**
- **Freeze-out temperature T_0 ~ 175 MeV for all centralities.**

$$T = T_0 + m\langle u_t \rangle^2$$

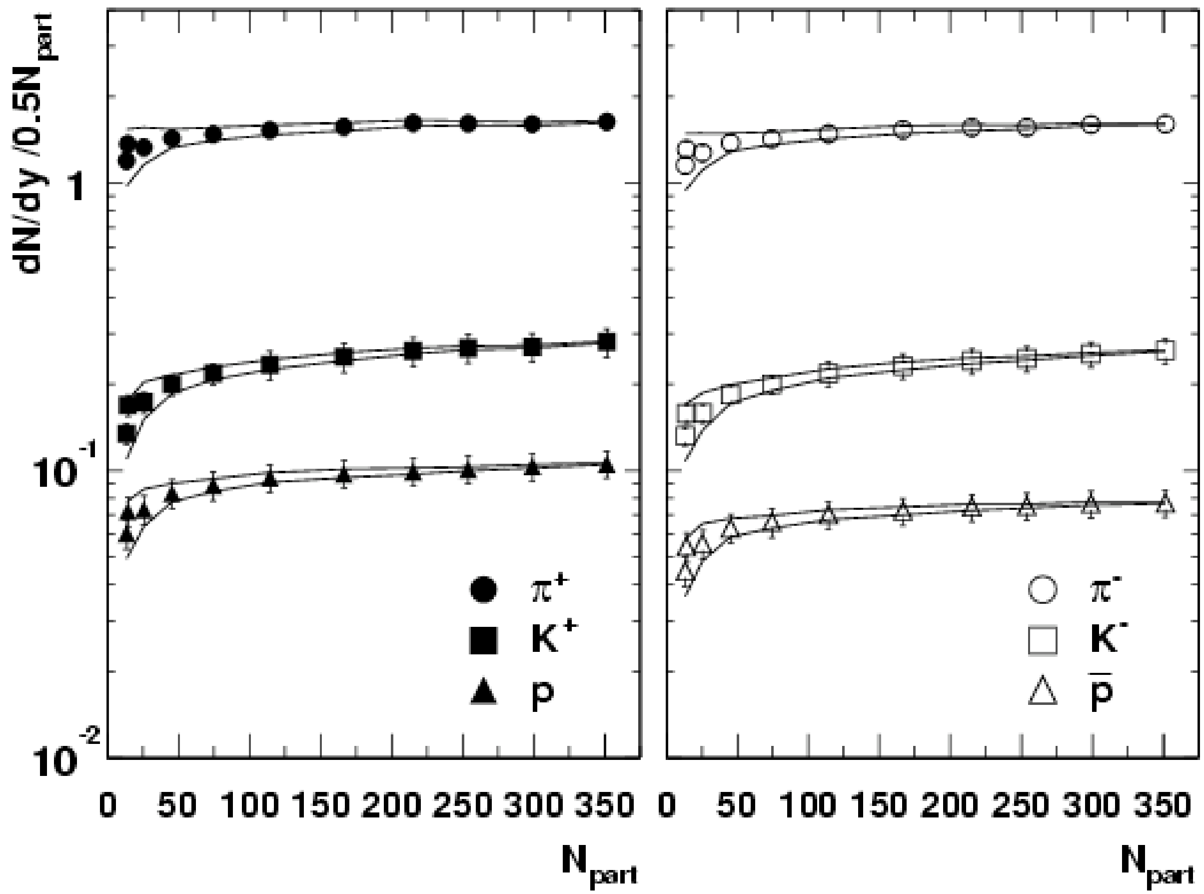
(2) Yields and <p_T>

Mean p_T vs. N_{part}



- Increase from peripheral to mid-central, and then saturate from mid-central to central for all particle species.
- **Observed clear mass dependence (consistent with hydro picture).**

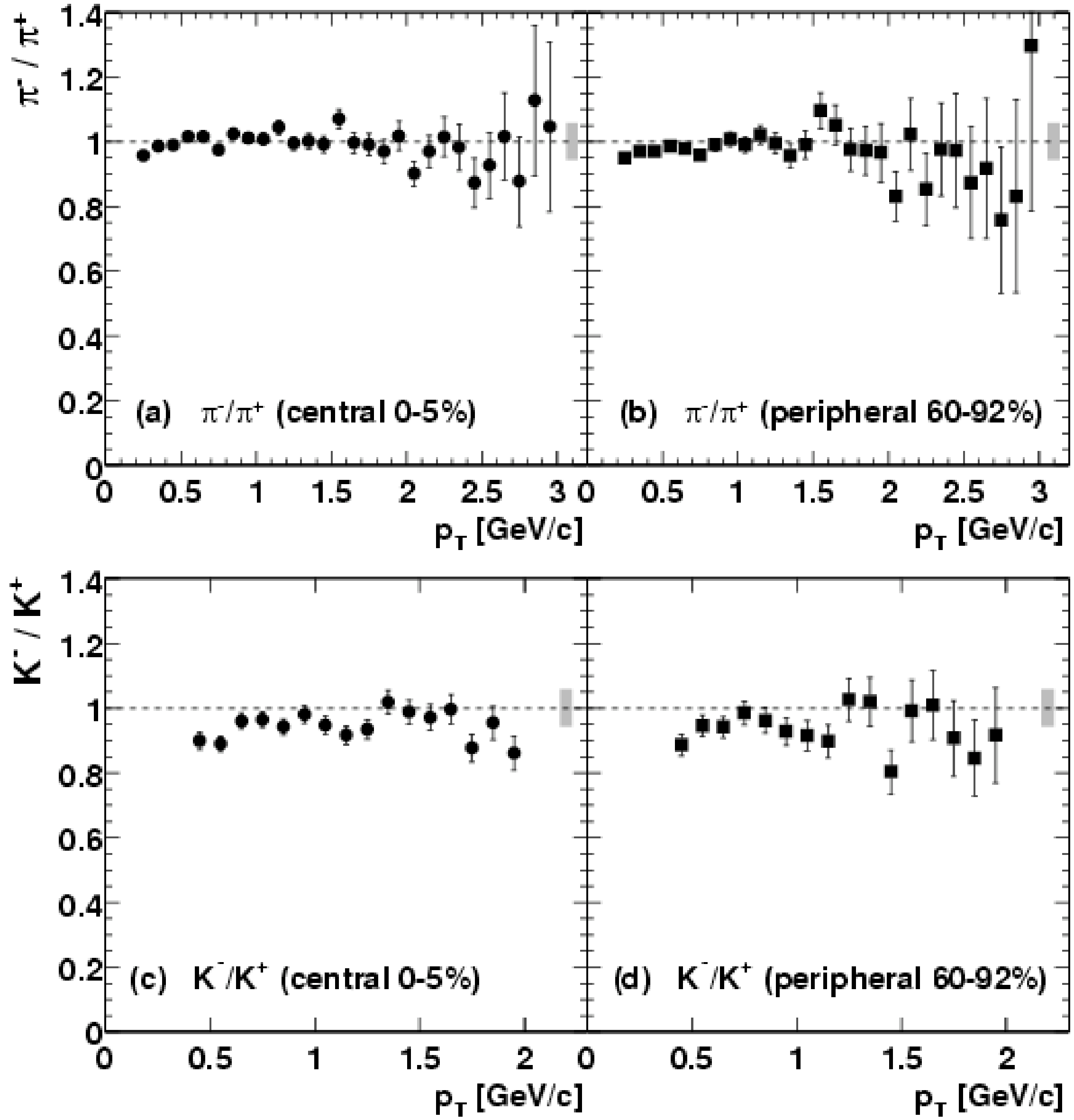
dN/dy vs. N_{part}



- dN/dy per participant pair increases for all particle species with Npart up to ~ 100 and saturates from the mid-central to the most central.
- **Net proton : $dN/dy|_p$ - $dN/dy|_{pbar}$ = 4.95 ± 2.74 (most central AuAu).**

(3) Particle Ratios

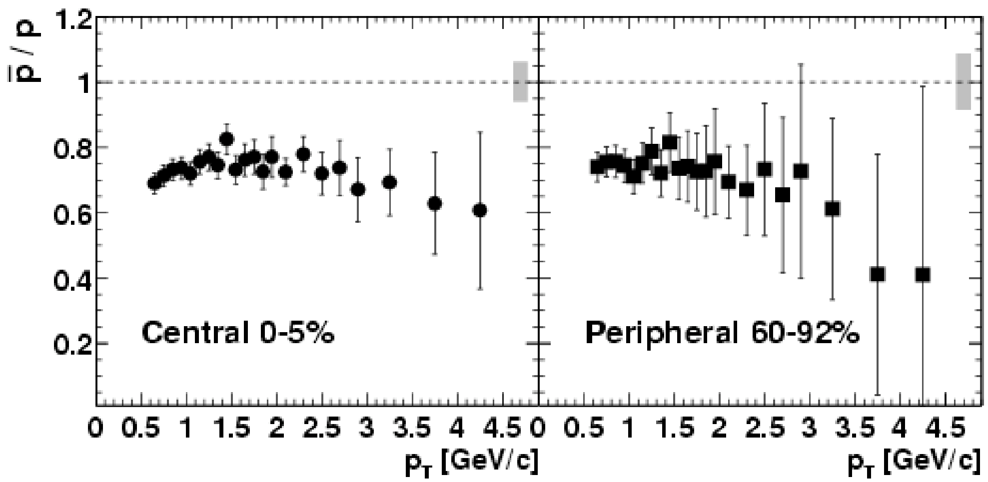
π^-/π^+ and K^-/K^+ vs. p_T



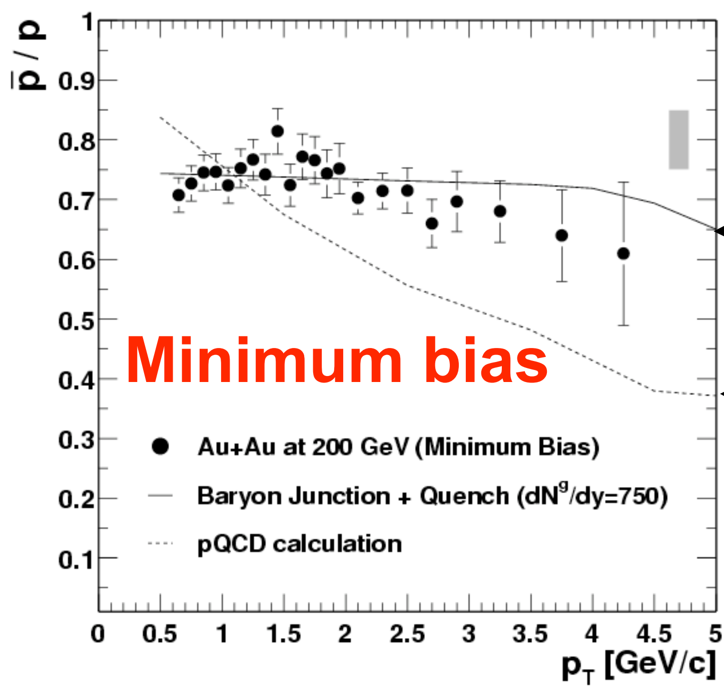
- For each of these particle species and centralities, the particle ratios are constant within the experimental errors over the measured p_T range.

$\bar{p}/p$ ratio vs. p_T

PHENIX



Constant within the experimental errors



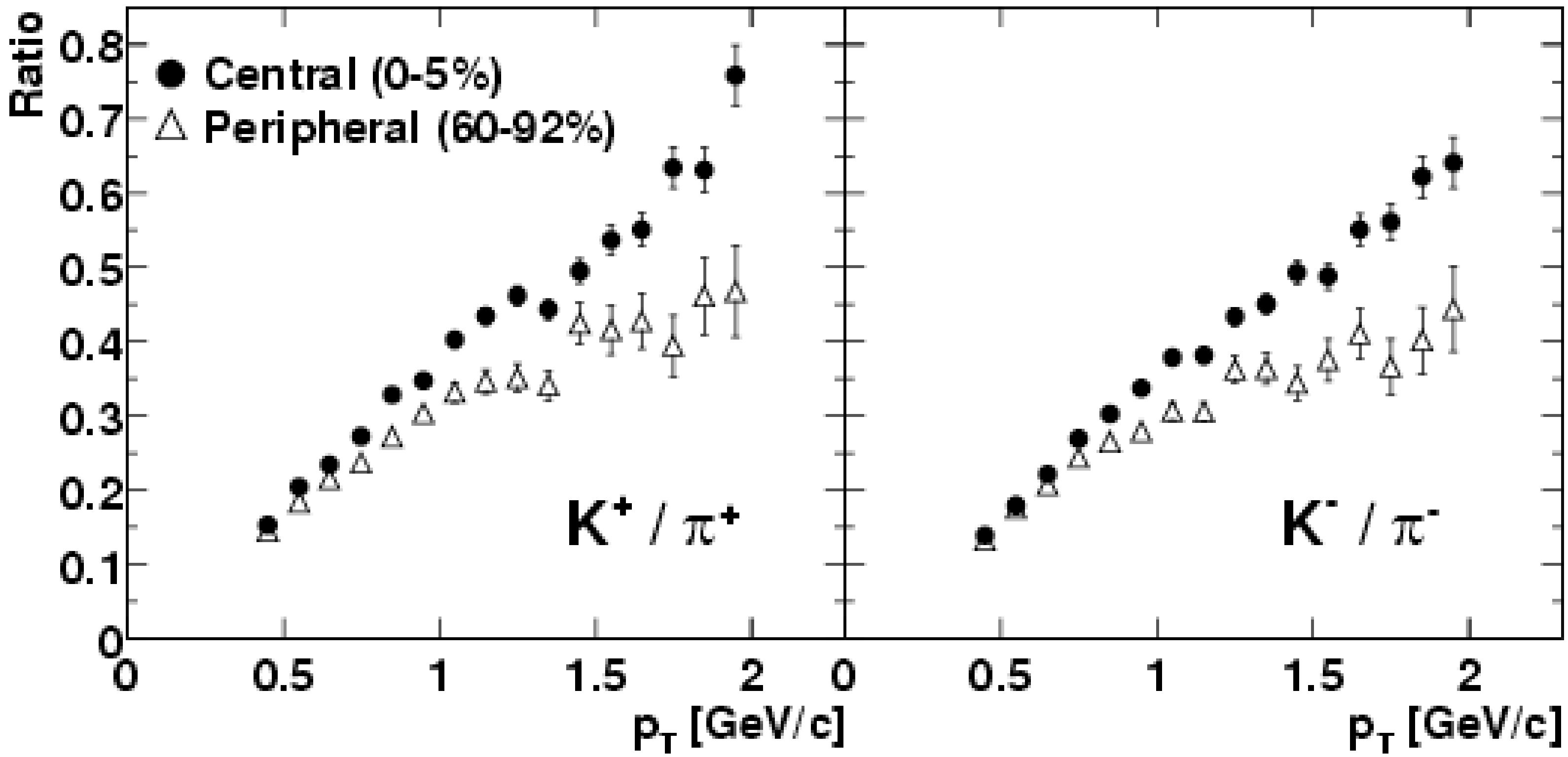
Baryon Junction

Vitev, Gyulassy
NPA 715, 779c (2003)

pQCD

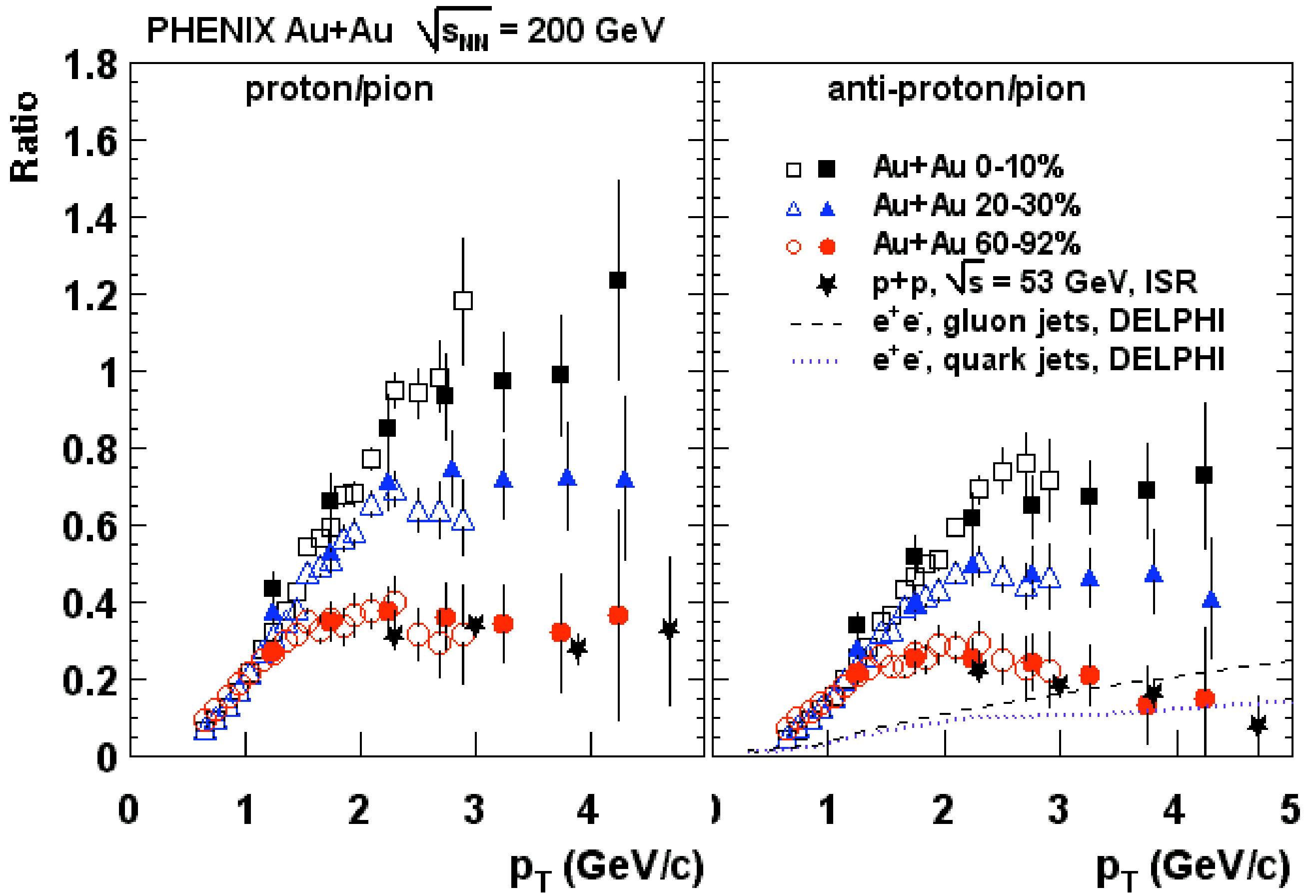
- **Baryon Junction model** agrees well with the measured p_T dependence of pbar/p ratio.
- **Parton recombination model** also reproduce the ratio and its flat p_T dependence.

K/π ratio vs. p_T



- Both K^+/π^+ and K^-/π^- ratios increase with p_T.
- Increase is faster in central collisions in peripheral one.

p/π ratio vs. p_T and centrality

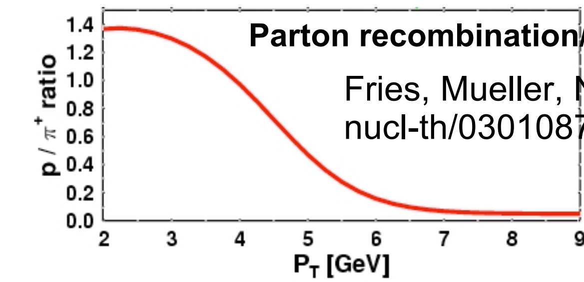


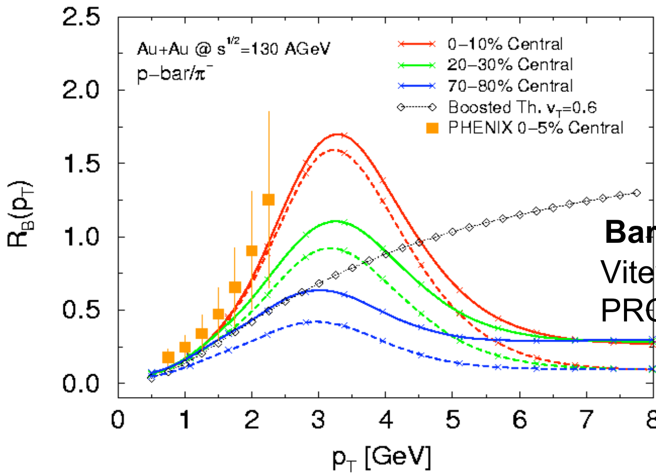
- Both p/π and pbar/π ratios are enhanced compared to peripheral Au+Au, p+p and e^+e^- at p_T = 1.5 ~ 4.5 GeV/c.
- Consistent with gluon/quark jet fragmentation in peripheral AuAu (> 3 GeV/c).

What is the PHYSICS behind?

Parton recombination/fragmentation

Fries, Mueller, Nonaka,Bass
nucl-th/0301087

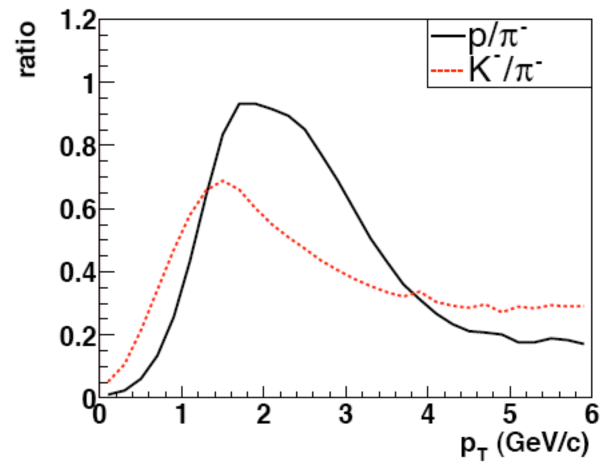




Baryon Junction
Vitev, Gyulassy
PRC 65, 041902, 2002

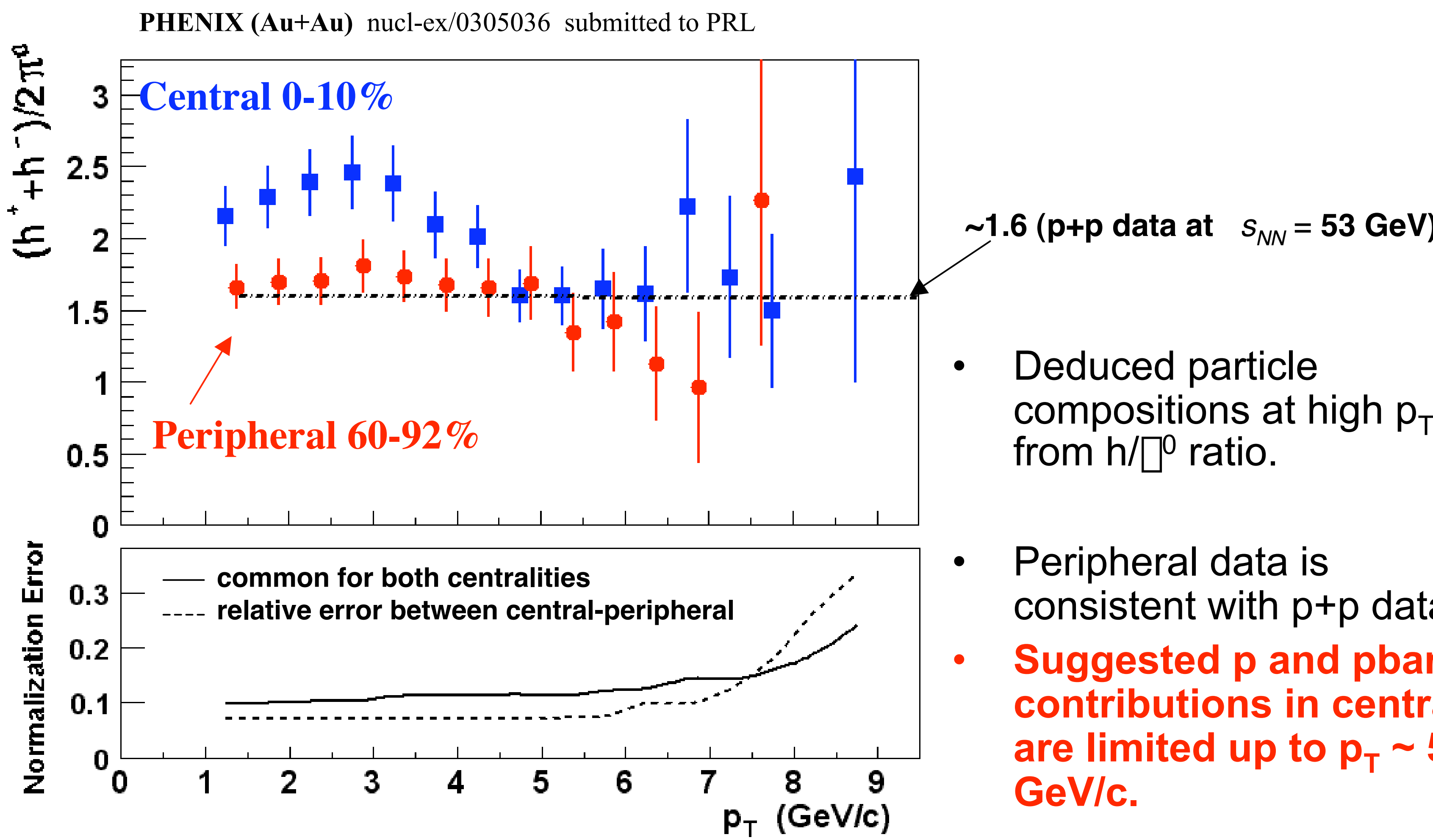
Hydro+Jet

Hirano, Nara
nucl-th/0307015



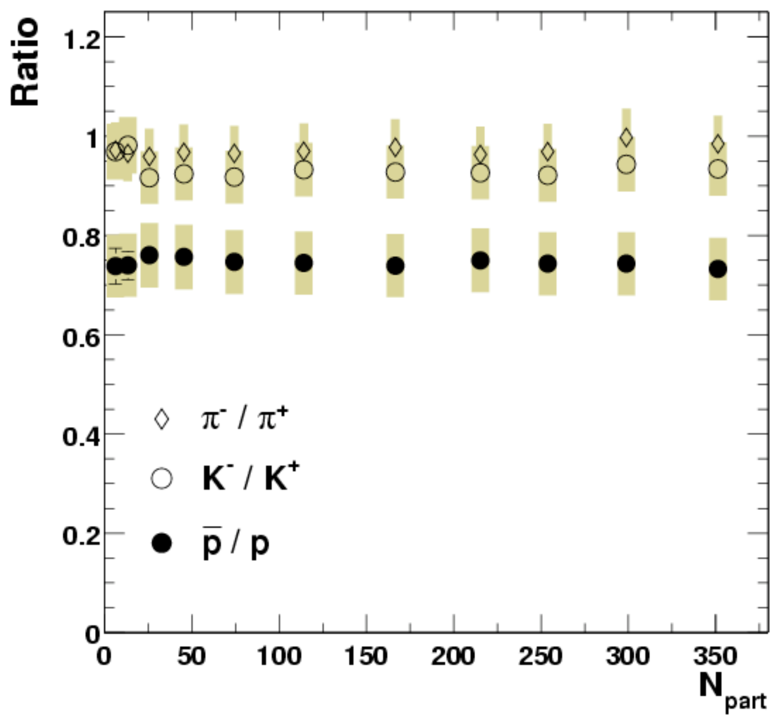
- Both **Parton Recombination/Coalescence** and **Baryon Junction** models reproduce p/π ratio (p_T and centrality dep.) qualitatively.
- **Both models predict p/π enhancement is limited < 5 GeV/c.**
- Another scenarios: Different formation time between baryons and mesons ?
  or Strong radial flow + hard scattering ?

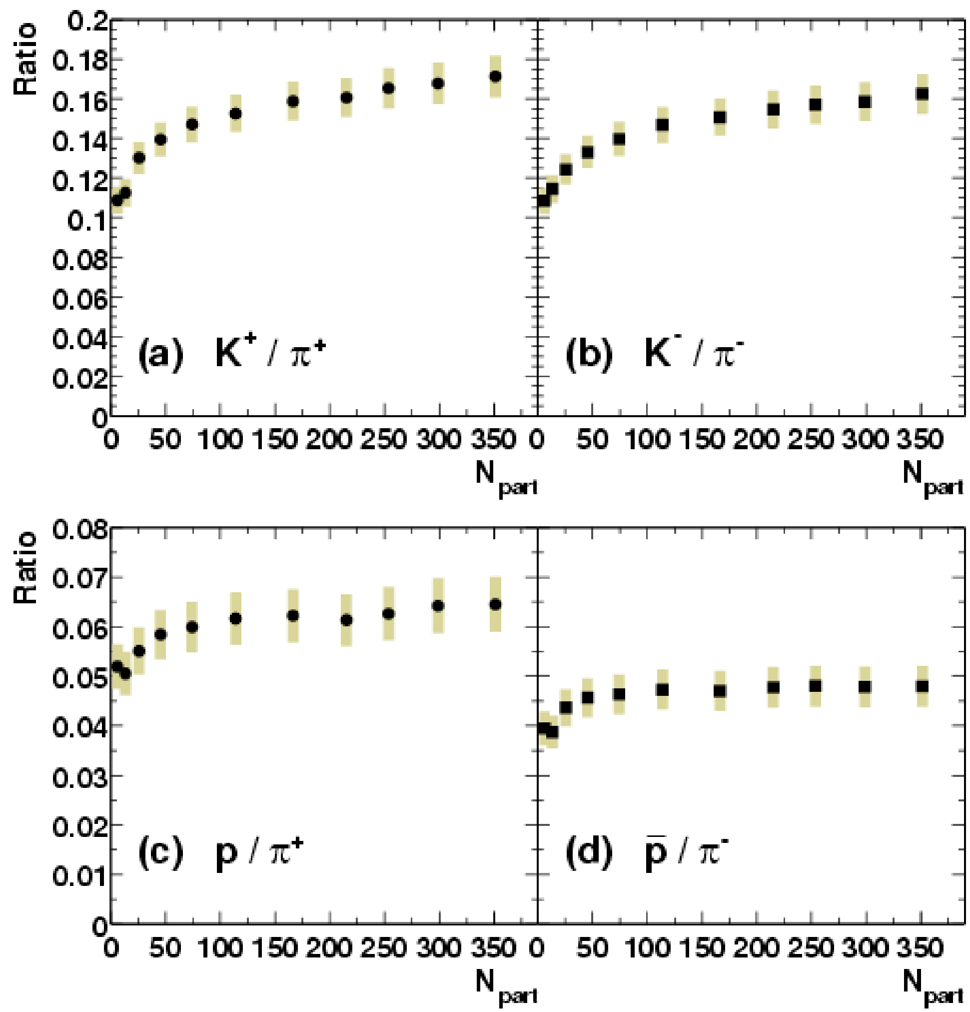
Particle composition beyond 5 GeV …



- Deduced particle compositions at high p_T from h/π^0 ratio.
- Peripheral data is consistent with p+p data.
- **Suggested p and pbar contributions in central are limited up to p_T ~ 5 GeV/c.**

Particle Ratio vs. N_{part}



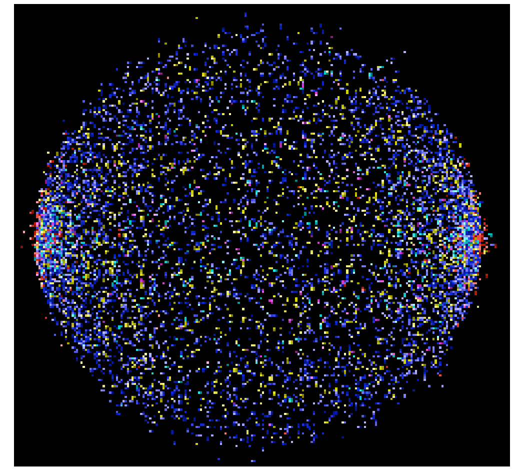


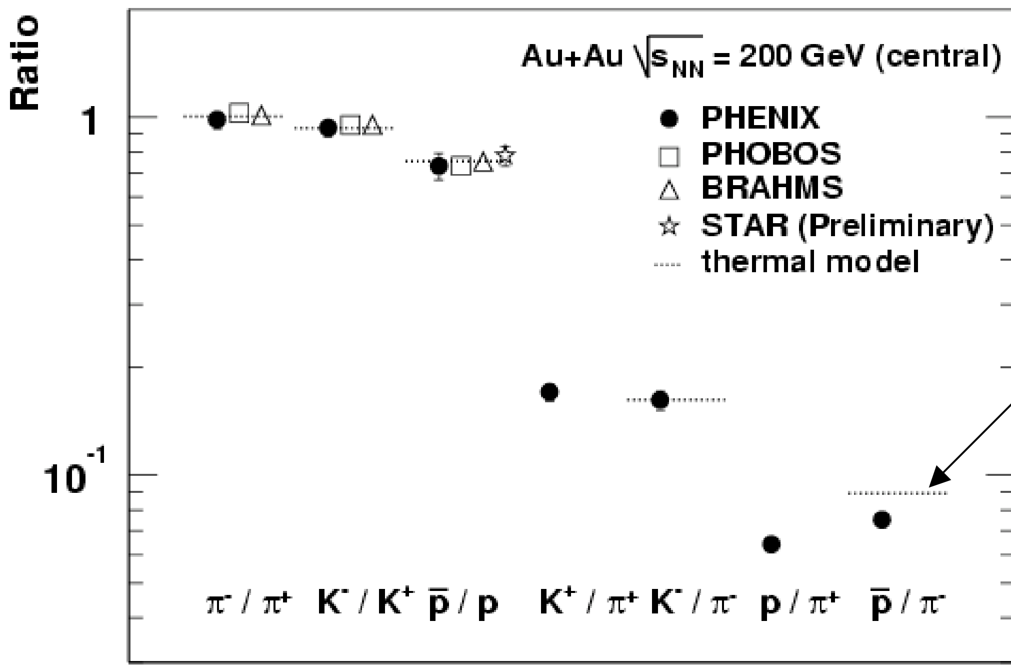
- Ratios for equal mass particle are independent of N_{part}.
- K/□ : increase rapidly for peripheral and then saturate (or rise slowly to central).
- p/□ : similar to these of K/□.

Statistical Thermal Model

- **Almost complete reconstruction of particle ratios by the statistical thermal model.**
- **Thermal model prediction in AuAu 200 GeV central.**

$$T_{ch} = 177 \text{ MeV}, \mu_B = 29 \text{ MeV}$$





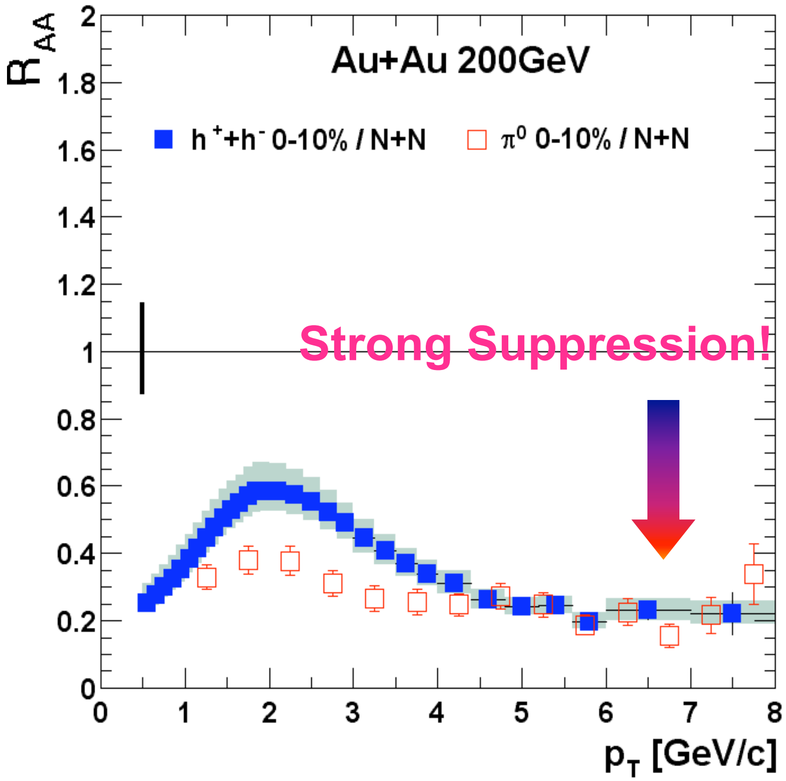
* feed-down effect is not included in the model.

- Thermal model: P.Braun-Munzinger et al., PLB 518, 41 (2001).
- PHOBOS: B.B.Back et al., PRC 67, 021901(R) (2003).
- BRAHMS: I.G.Bearden et al., PRL 90, 102301 (2003).
- STAR: G.V.Buren, NPA 715, 129c (2003).
- PHENIX : nucl-ex/0307022.

(4) Scaling Properties of Hadrons

R_{AA} for π^0 and charged hadron

$$R_{AA} = \frac{Yield_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{Yield_{pp}}$$

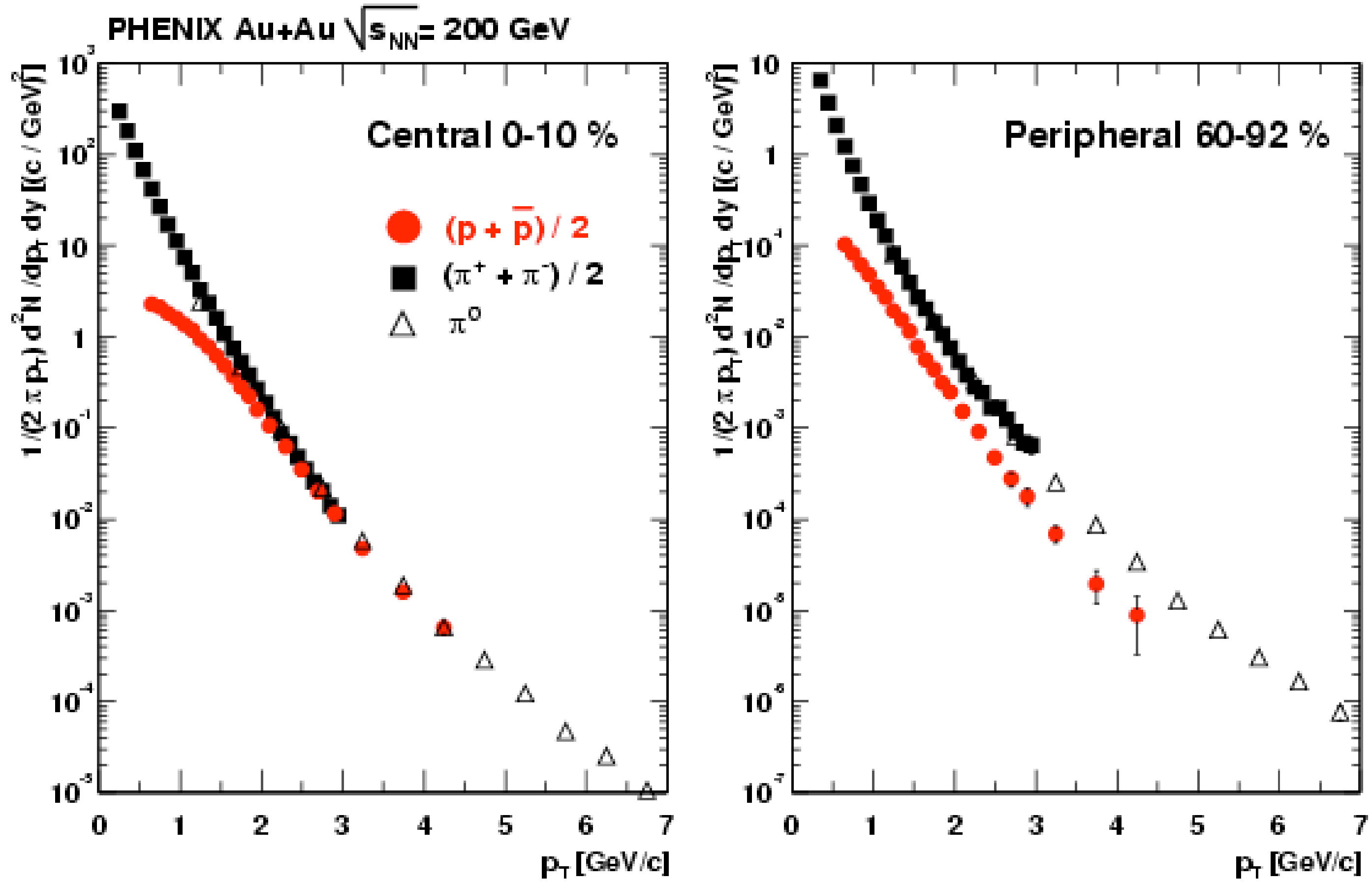


- R_{AA} is **well below 1** for both charged hadrons and neutral pions.
- The neutral pions fall below the charged hadrons since they do not contain contributions from protons and kaons.

PHENIX AuAu 200 GeV
π^0 data: PRL 91 072301 (2003), nucl-ex/0304022.
charged hadron (preliminary) : NPA715, 769c (2003).

p_T spectra (p vs. π) in Au+Au @ 200 GeV

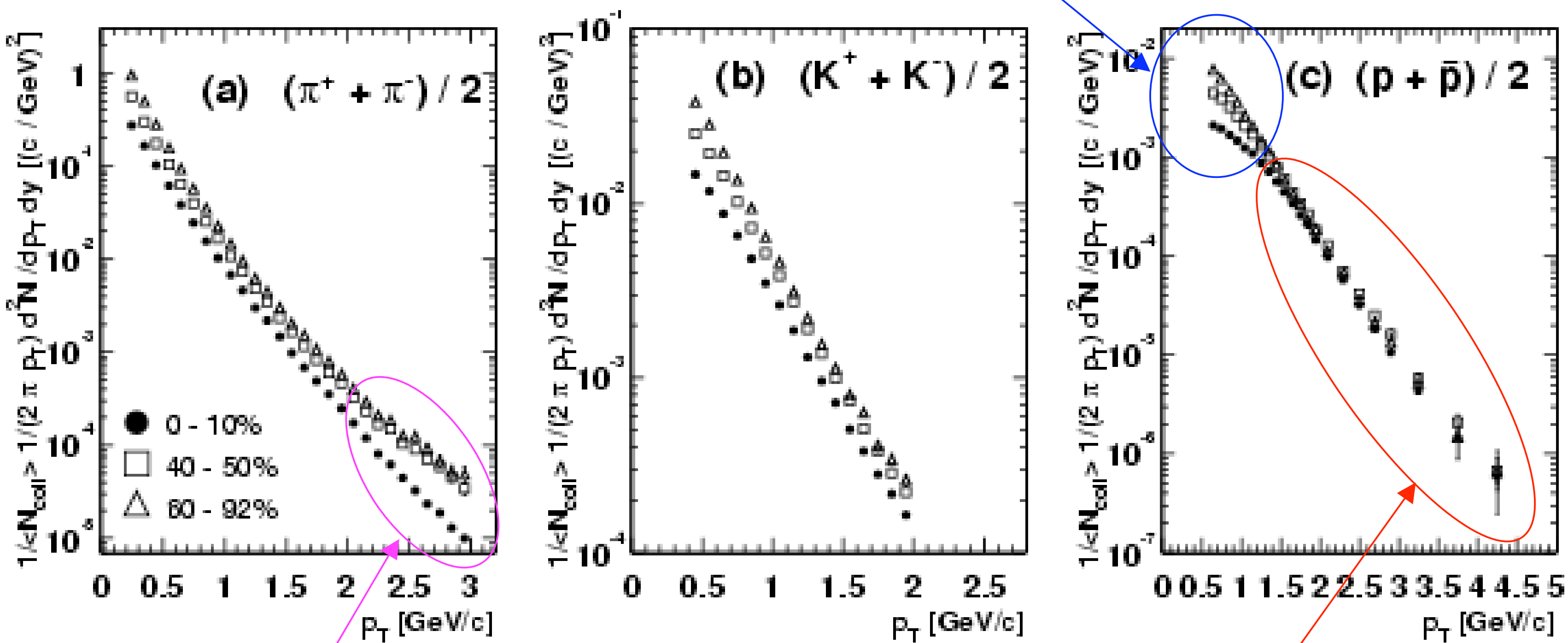
PHENIX



- Clearly seen p-π merging at $p_T \sim 2$ GeV/c in central.
- No p-π merging in peripheral.
- Suggested significant fraction of p, pbar at pt = 1.5 - 4.5 GeV/c in central.

N_{coll} scaled p_T spectra

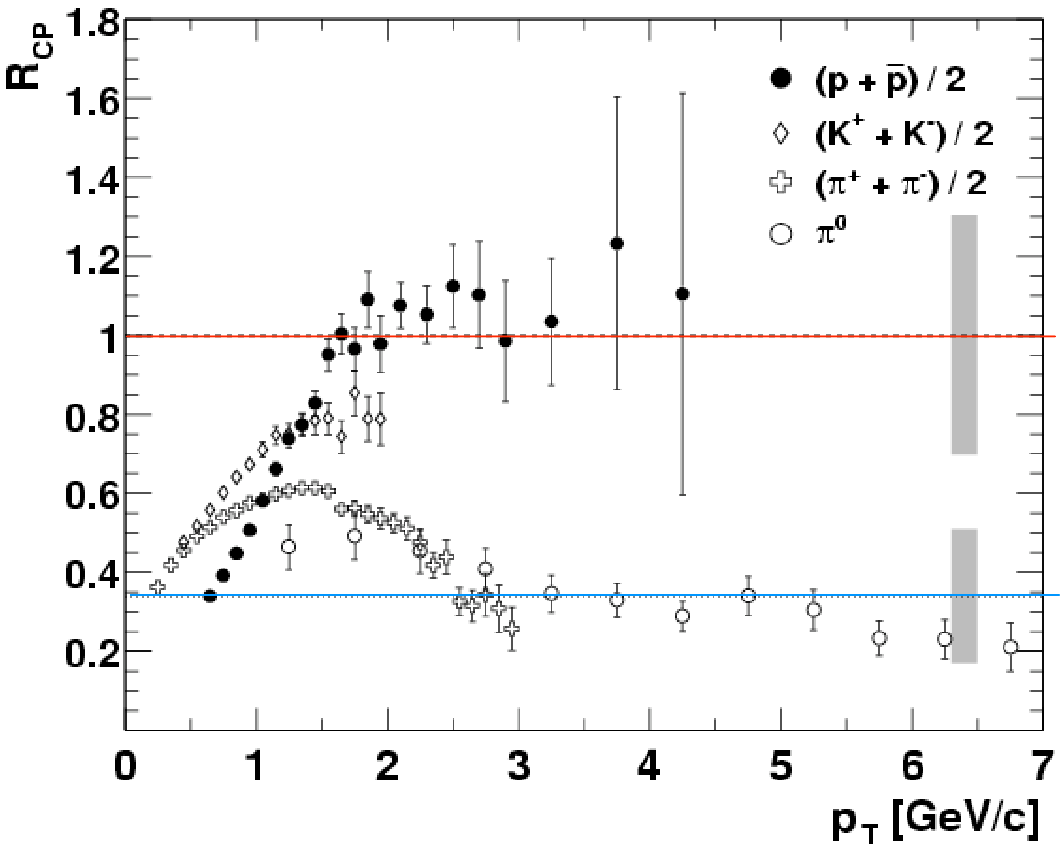
Radial Flow Effect



Suppressed in central at high p_T (> 2.0 GeV)

Ncoll scaling (p_T > 1.5 GeV) for all centrality bins

Central-to-Peripheral Ratio (R_{CP}) vs. p_T



N_{coll} scaling

N_{part} scaling

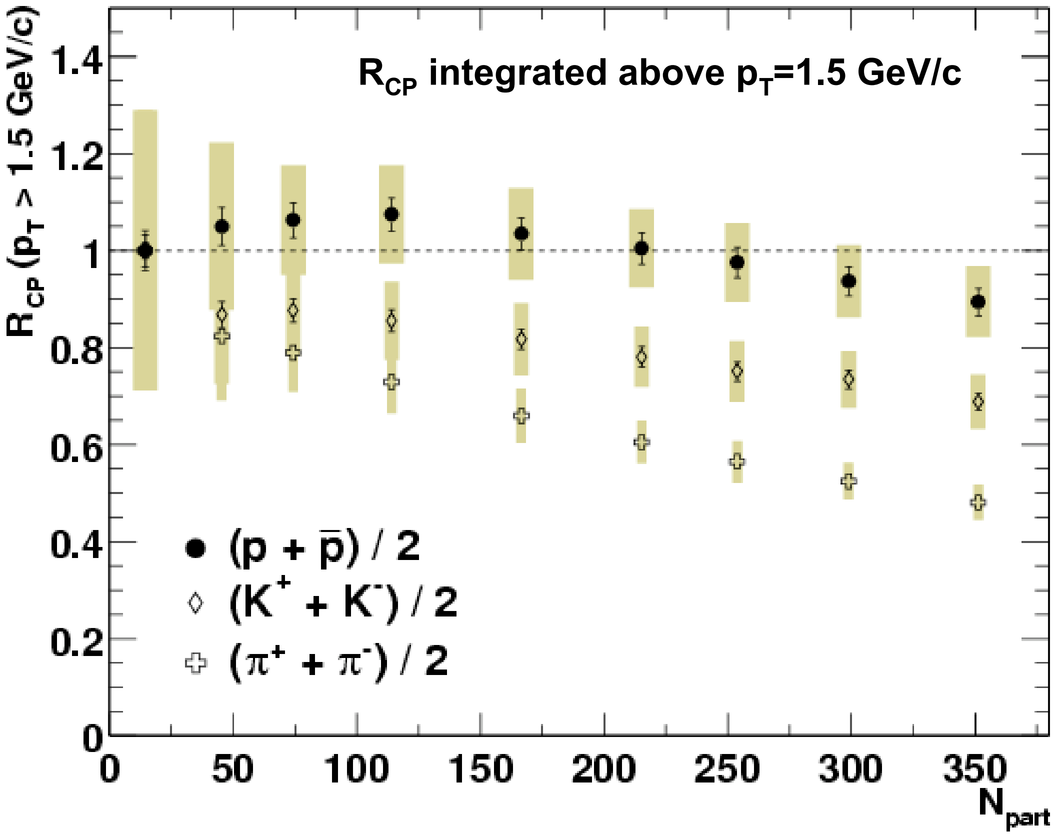
* Shaded boxes : N_{part}, N_{coll} determination errors.

$$R_{CP} = \frac{\text{Yield}^{0\text{-}10\%} / \langle N_{coll}^{0\text{-}10\%} \rangle}{\text{Yield}^{60\text{-}92\%} / \langle N_{coll}^{60\text{-}92\%} \rangle} \approx R_{AA}$$

p : No suppression,
N_{coll} scaling at
1.5 GeV - 4.5 GeV

π^0: Suppression
(central > peripheral)

Centrality Dependence of R_{CP}

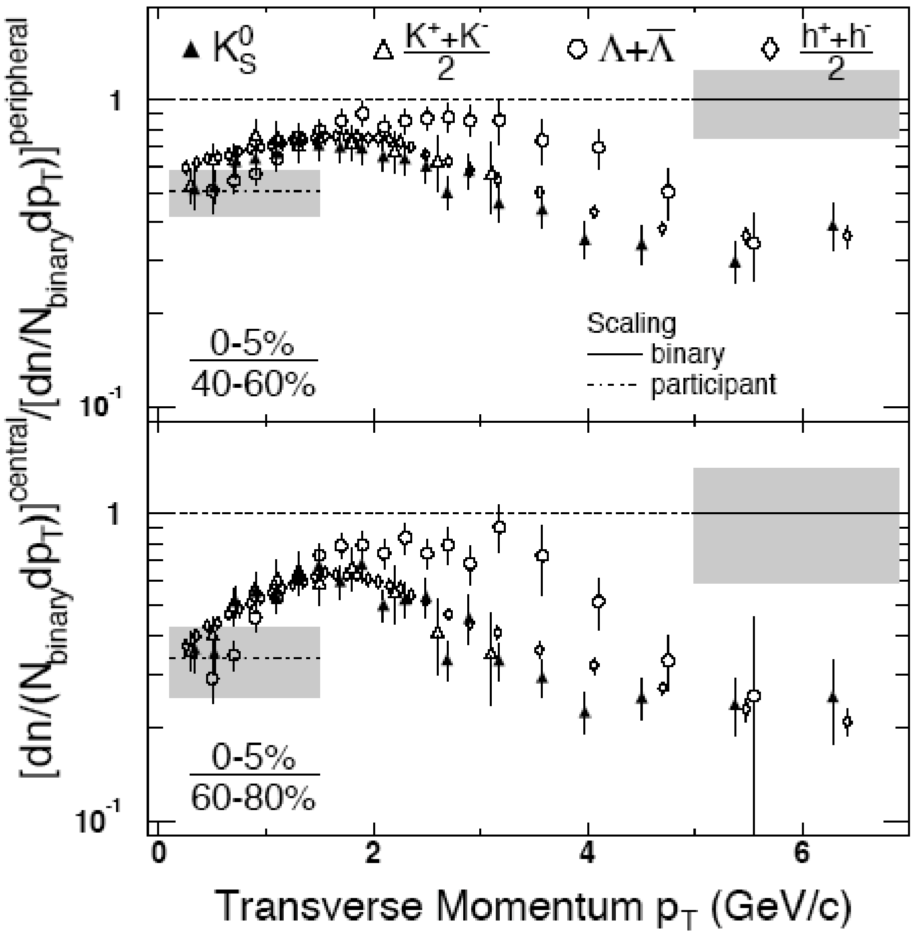


* Data points are normalized to the most peripheral data point.

- **Proton data scales with N_{coll} for all centrality bins.**
- **Charged pions: decrease with N_{part}, kaons: between pions and protons.**

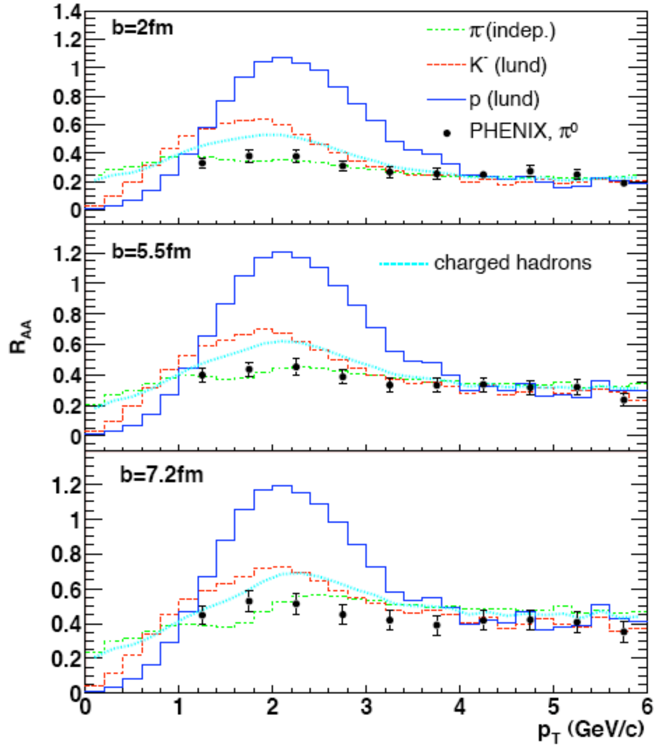
STAR Results

STAR nucl-ex/0306007

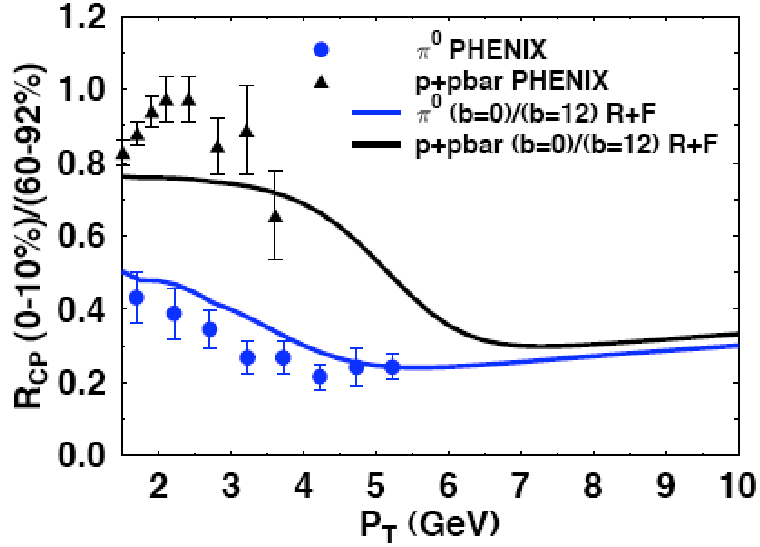


- Similar behavior has been observed in □.
- Limitted behavior of baryon enhancement (< ~4 GeV/c).

Model Comparison



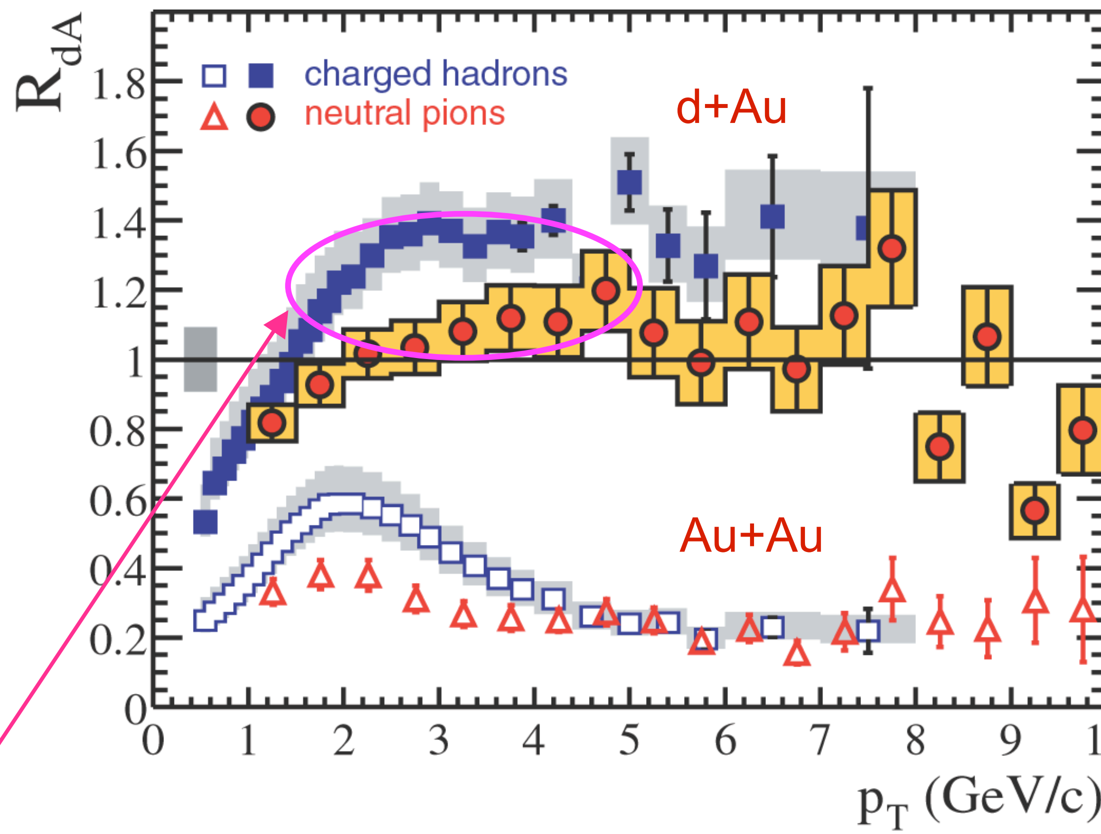
Hirano, Nara (Hydro+Jet model)
nucl-th/0307015



Fries, Muller, Nonaka, Bass
(Fragmentation/Recombination model)
nucl-th/0306027

- **Baryon Junction model, Recombination model, Hydro-jet model**
  ⇒ Predicted baryon enhancement is limitted up to ~ 4-5 GeV/c.
- **Qualitative agreement with data for all these models.**

R_{dA} for charged hadrons and π^0



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nucl-ex/0306021

- **Different behavior between π^0 and charged again at p_T = 1.5 - 5.0 GeV/c!**
- **d+Au data suggests the flavor dependent Cronin effect.**
- **New results will come soon!**

Summary and Conclusions

We presented the high statistics identified charged hadron p_T spectra, ratios and yields in Au+Au collisions at s_{NN} = 200 GeV from the PHENIX experiment.

1. In low p_T region (< 2 GeV/c) in central collisions, the p_T spectra show a clear mass dependence in their shape (p: shoulder-arm shape, π: concave shape).
2. Inverse slope parameters show clear mass and centrality dependence.
3. These observations are consistent with **hydro-dynamic picture**.
4. In central events, **p and pbar comprise a significant fraction of hadron yields** in the intermediate p_T range (2 ~ 4 GeV/c).
5. Particle ratios in central AuAu are well reproduced by the statistical thermal model with **μ_B=29 MeV and T_{ch}=177 MeV**.
6. Net proton number in AuAu central is ~5 at mid-rapidity.
7. At the intermediate p_T, **p and pbar spectra show the different scaling behavior** from pions (N_{coll} scaling), and a strong centrality dependence of p/π ratio has been observed.
   – Various theoretical models (recombination, baryon junction, hydro+jet) reproduce the data qualitatively.

PHENIX

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PHENIX Publications
~ single particle spectra (hadron) only ~

- K. Adcox *et al*., PHENIX Collaboration, “Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at s_{NN}=130 GeV”, Phys. Rev. Lett. 88, 022301 (2002).
- K. Adcox *et al*., PHENIX Collaboration, “Centrality dependence of $\pi^{\pm}$, $K^{\pm}$, p and p-bar production from s_{NN}=130 GeV Au+Au collisions at RHIC, Phys. Rev. Lett. 88, 242301 (2002).
- K. Adcox *et al*., PHENIX Collaboration, “Measurement of Lambda and Lambda-bar particles in Au+Au collisions at s_{NN} =130 GeV”, Phys. Rev. Lett. 89, 092302 (2002).
- K. Adcox *et al*., PHENIX Collaboration, “Centrality Dependence of the High p_T Charged Hadron Suppression in Au+Au collisions at s_{NN} =130 GeV”, Phys. Lett. B 561, 82-92 (2003).
- S.S. Adler *et al*., PHENIX Collaboration, “Suppressed □^{0} Production at Large Transverse Momentum in Central Au+Au Collisions at s_{NN}=200 GeV”, Phys. Rev. Lett. 91, 072301 (2003) [nucl-ex/0304022].
- S.S. Adler *et al*., PHENIX Collaboration, “Scaling properties of proton and anti-proton production in =200 GeV Au+Au collisions”, to be appeared in Phys. Rev. Lett., nucl-ex/0305036.
- S.S. Adler *et al*., PHENIX Collaboration, “Midrapidity Neutral Pion Production in Proton-Proton Collisions at s = 200 GeV”, to be appeared in Phys. Rev. Lett., hep-ex/0304038.
- S.S. Adler *et al*., PHENIX Collaboration, “Absence of Suppresion in Particle Production at Large Transverse Momentum in s_{NN} = 200 GeV d+Au Collisions”, Phys. Rev. Lett. 91, 072303 (2003) [nucl-ex/0306021].
- K. Adcox, et al, PHENIX Collaboration, “Single Identified Hadron Spectra from s_{NN} = 130 GeV Au+Au Collisions”, to be appeared in Phys. Rev. C, nucl-ex/0307010.
- S.S. Adler *et al*., PHENIX Collaboration, “Identified Charged Particle Spectra and Yields in Au+Au Collisions at s_{NN} = 200 GeV”, to be appeared in Phys. Rev. C, nucl-ex/0307022.
- S.S. Adler *et al*., PHENIX Collaboration, “High p_T Charged Hadron Suppression in Au+Au Collisions at s_{NN} = 200 GeV”, to be appeared in Phys. Rev. C, nucl-ex/0308006.

Backup Slides

Hard Scattered Partons

- Hard scatterings in nucleon collisions produce jets of particles.
- In the presence of a color-deconfined medium, the partons strongly interact (~GeV/fm) losing much of their energy.
- **"Jet Quenching"**