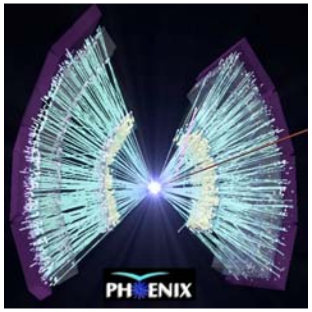


Particle Species Dependence of Yield Suppression in Au+Au @ RHIC

Tatsuya Chujo (RIKEN)

From our recent publications

- **S.S. Adler *et al.* (PHENIX), nucl-ex/0305036 [Accepted, PRL, 09/23/2003].**
- **S.S. Adler *et al*. (PHENIX), nucl-ex/0307022 [Accepted, PRC, 08/21/2003].**

First Three Years of RHIC Run

- **High quality hadron data from RHIC!**

$\pi^{\pm}$, π^0, $K^{\pm}$, K^{*0}, K_s^0, p, d, ρ^0, ϕ, Λ, Ω, Ξ (+ anti-particles)

- ***Hadron Measurements***
  - p_T distribution (soft and hard process).
  - Particle ratio, yield, $<p_T>$.
  - HBT correlations.
  - Event anisotropy (v_2).
  - Jet physics.

2000 summer:	**Au+Au**	**130 GeV**
2001/2002:	**Au+Au**	**200 GeV**
	p+p	**200 GeV**
2002/2003:	**d+Au**	**200 GeV**
	p+p	**200 GeV**

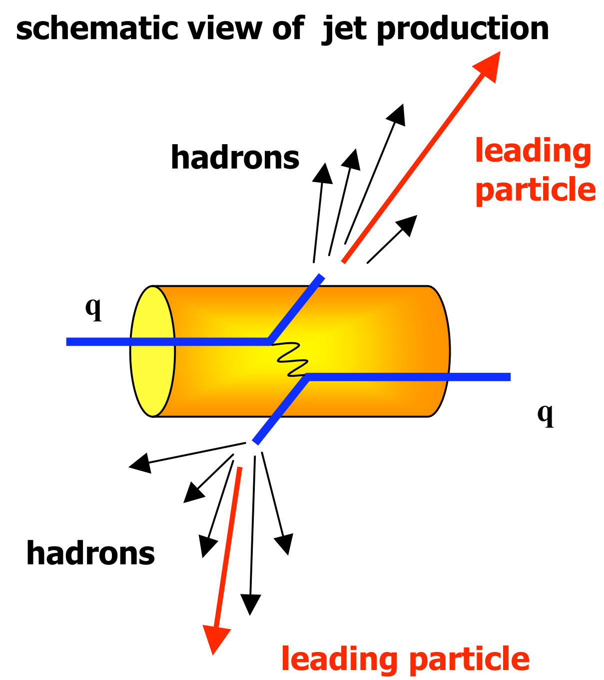
≈ BNL post-doc

Hard Scattered Partons

- Used **"calibrated"** probe (p+p data).
- Hard scatterings in nucleon collisions produce jets of particles.
  - hadron structure function
  - hard scattering parton (pQCD)
  - fragmentation of partons
- In the presence of a color-deconfined medium, the partons lose their energy (~GeV/fm) via gluon bremsstrahlung.

  - **"Jet Quenching"**
    $\propto$ Color Charge Density

"gluonometer"



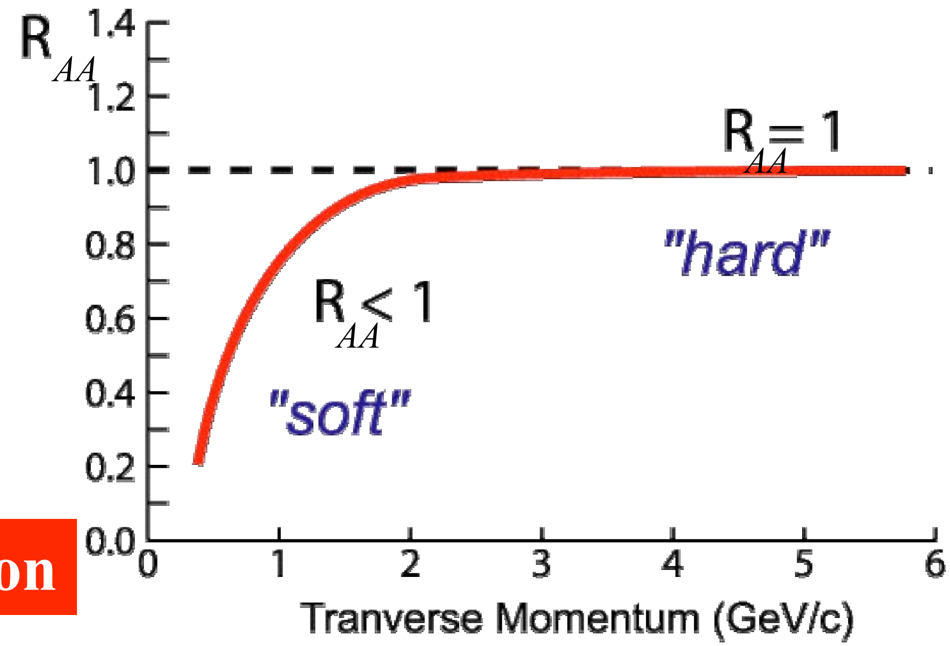
How Quantify the Nuclear Modification

Nuclear Modification Factor

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

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$

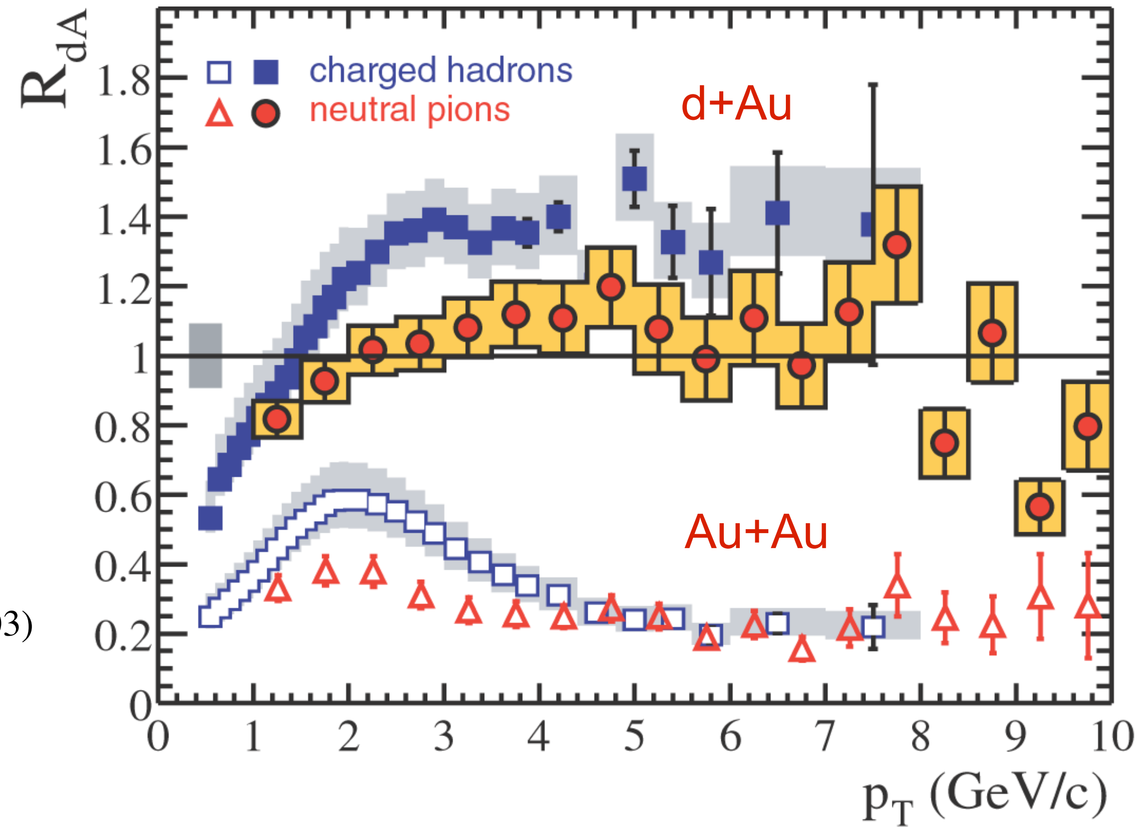
NN cross section



- **Scenario 1 : R_{AA} =1 : Scale with # of binary collisions (N_{coll}).**
- **Scenario 2 : R_{AA} >1 : Cronin effect (observed in ISR and SPS).**
- **Scenario 3 : R_{AA} <1 : Suppression.**

- Any departures from the expected binary collision scaling (N_{coll}) behavior provide the information on the strong interacting medium in *AA* collisions.

R_{AA} vs. R_{dA} for $h^{\pm}$ and π^0



PHENIX (d+Au)
PRL 91, 072303 (2003)
hep-ex/0306021

d+Au

Initial State Effects Only

Au+Au

Initial + Final State Effects

- π^0 and charged are largely suppressed in central Au+Au at high p_T.
- No Suppression in d+Au, instead small enhancement observed !
- d-Au results rule out CGC (initial sate effect) as the explanation for high p_T suppression of hadrons in AuAu central.

RHIC High p_T Results

π^0 and $h^{\pm}$

1. High p_T yield suppression in central Au+Au.
2. Disappearance of away-side jet in central Au+Au (STAR publication).
3. Absence of high p_T suppressions in d+Au (cold matter).

→ **Suppression in AuAu is the final state effect!**

Baryons are also suppressed in central Au+Au?

IN THIS TALK …

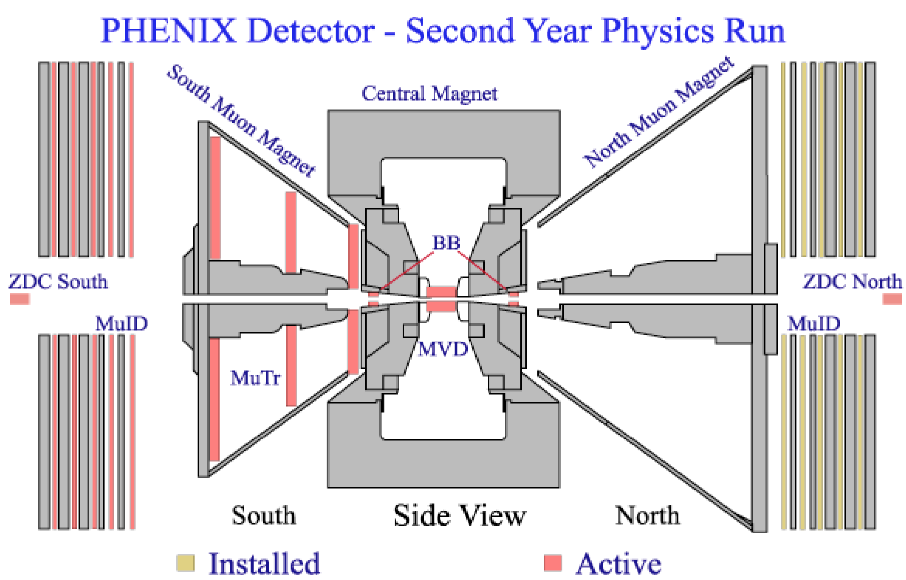
- **Focused on proton and anti-proton production in Au+Au @ measured by PHENIX experiment @ $\sqrt{s_{NN}}$ = 200 GeV.**

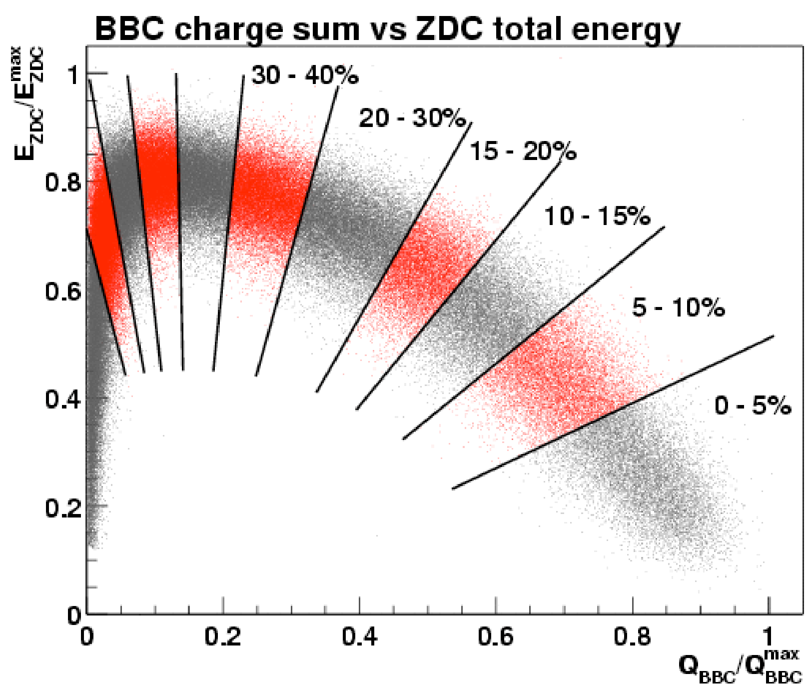
1. **Data Analysis**
2. **Experimental Results**
   - Proton p_T spectra vs. centrality.
   - p/π ratio.
   - Scaling behavior and suppression factor (R_{CP}).
   - Comparison with results for π^0 and inclusive charged hadrons.
3. **Discussion**
   - Parton Recombination and Fragmentation Model.
   - Hydrodynamics + Jet Model.
   - Cronin effect from d+Au data.
4. **Summary**

Part I

Identified Charged Particle Data Analysis

Collision Centrality Determination





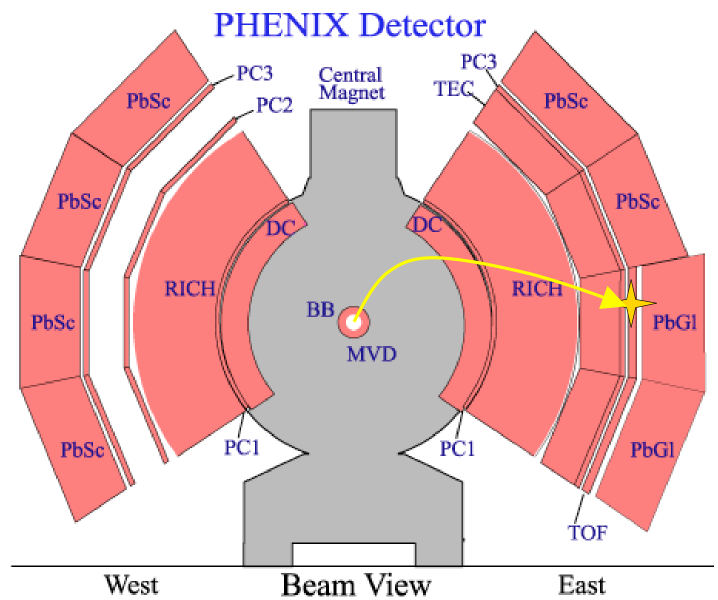
- Centrality selection : Used charge sum of Beam-Beam Counter (**BBC**, |η|=3~4) and energy of Zero-Degree Calorimeter (**ZDC**) in minimum bias events (92% of total inelastic cross sections).
- Extracted $\mathbf{N_{coll}}$ and $\mathbf{N_{part}}$ based on Glauber model.

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
  - $\Delta\phi = \pi/8$, $-0.35 < \eta < 0.35$

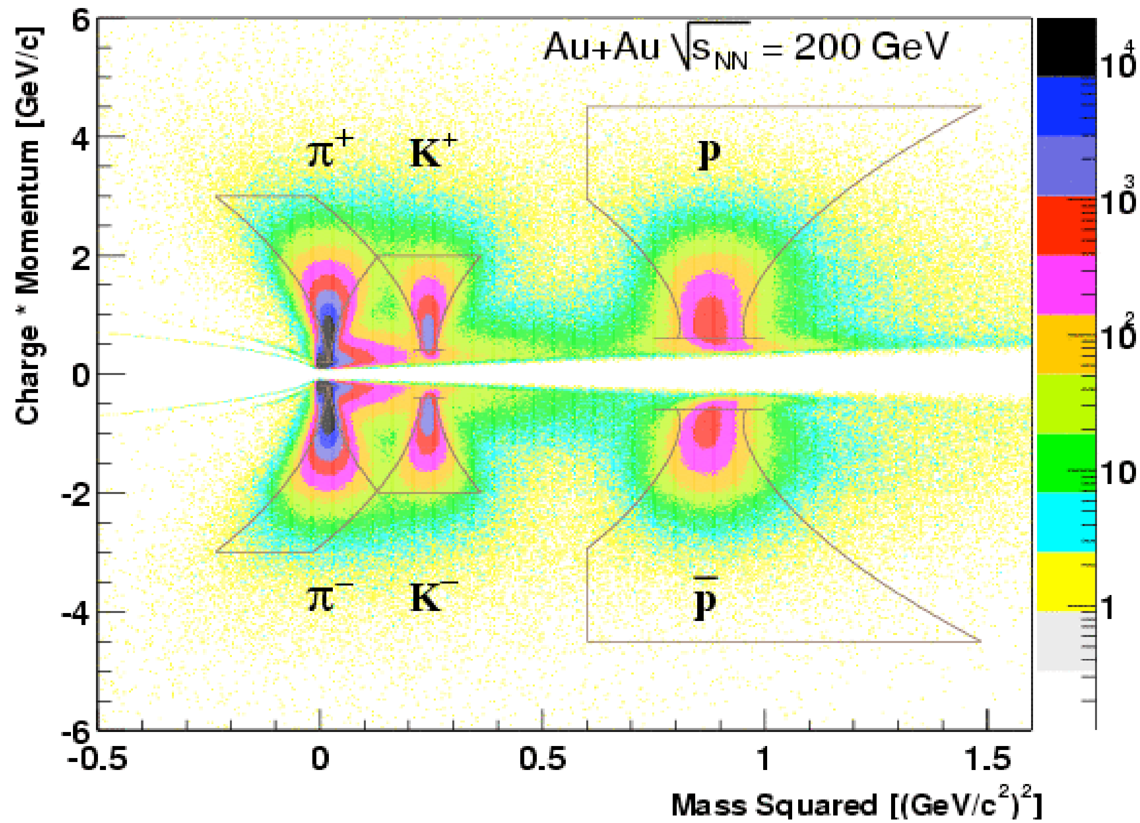
- **Momentum Resolution**

$$\delta p / p \approx 0.7\% \oplus 1.0\% \times p \text{ (GeV/}c\text{)}$$

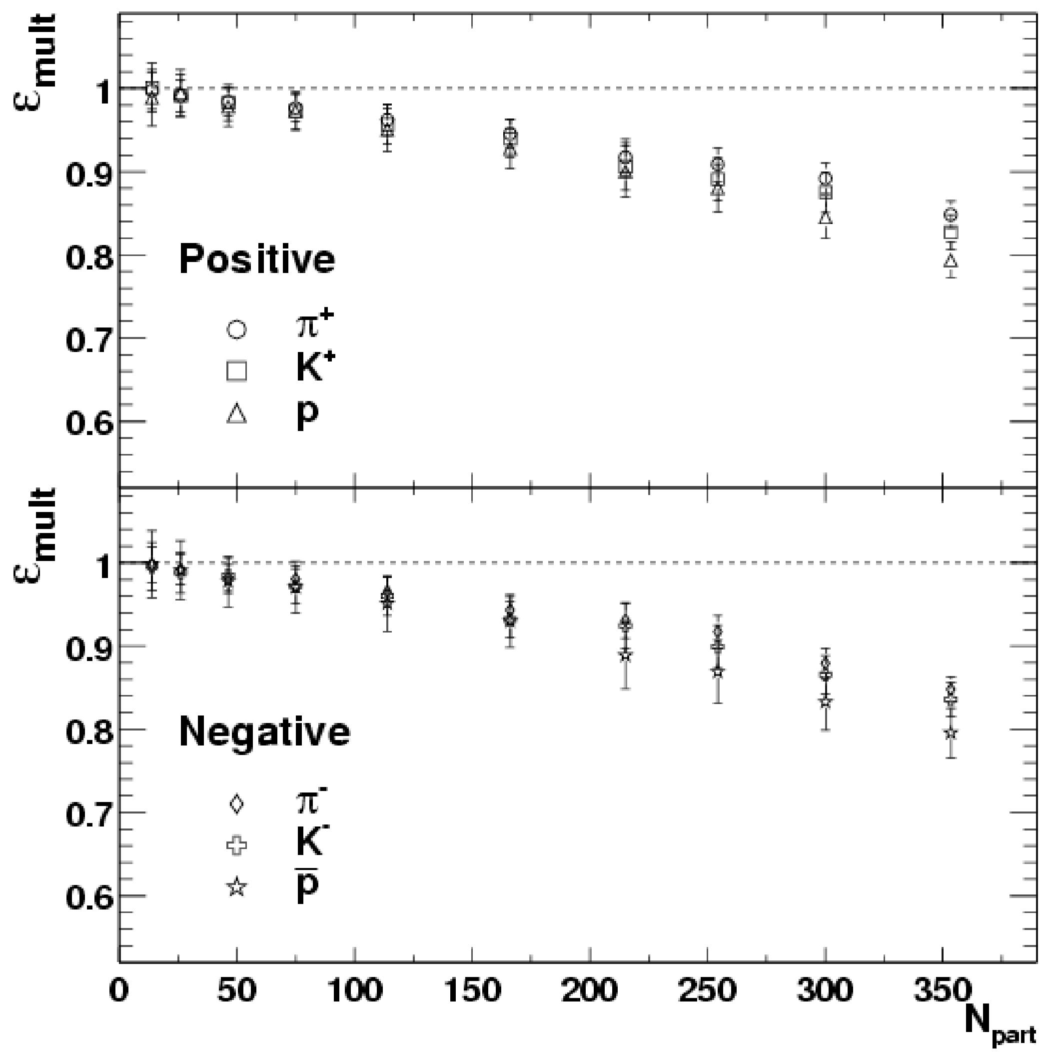
- **TOF resolution** σ_{TOF} ~ 115 ps.

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

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



Detector Occupancy Correction



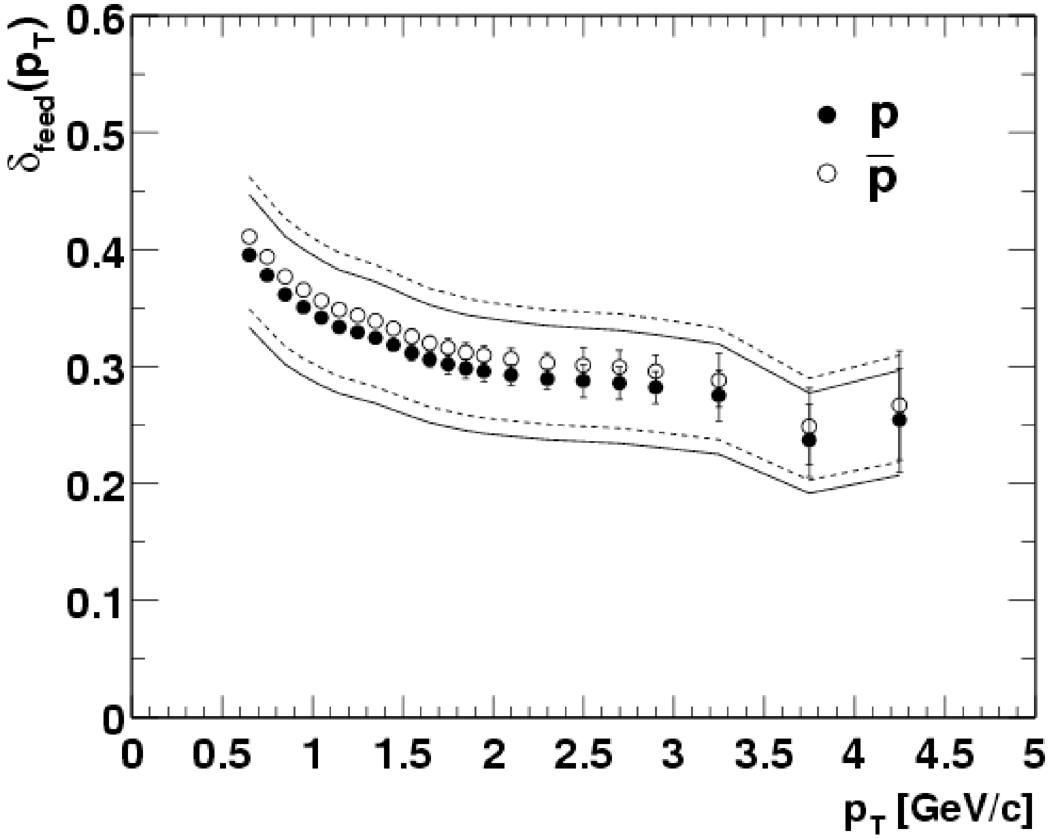
- Due to the high multiplicity environment in Au+Au, corrections for detector occupancy is necessary.

- **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



$$C_{feed}(j, p_T) = 1 - \delta_{feed}(j, p_T)$$

~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, Λbar/Λ 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 Λ/p (Λbar/pbar) measured ratio at 130 GeV AuAu.

Estimate fractional contributions of p (pbar) from Λ (Λbar) decay in all measured p (pbar).

Final p_T Spectra

Invariant Yield

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

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

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.

PHENIX

Part II

Experimental Results on Identified Particles

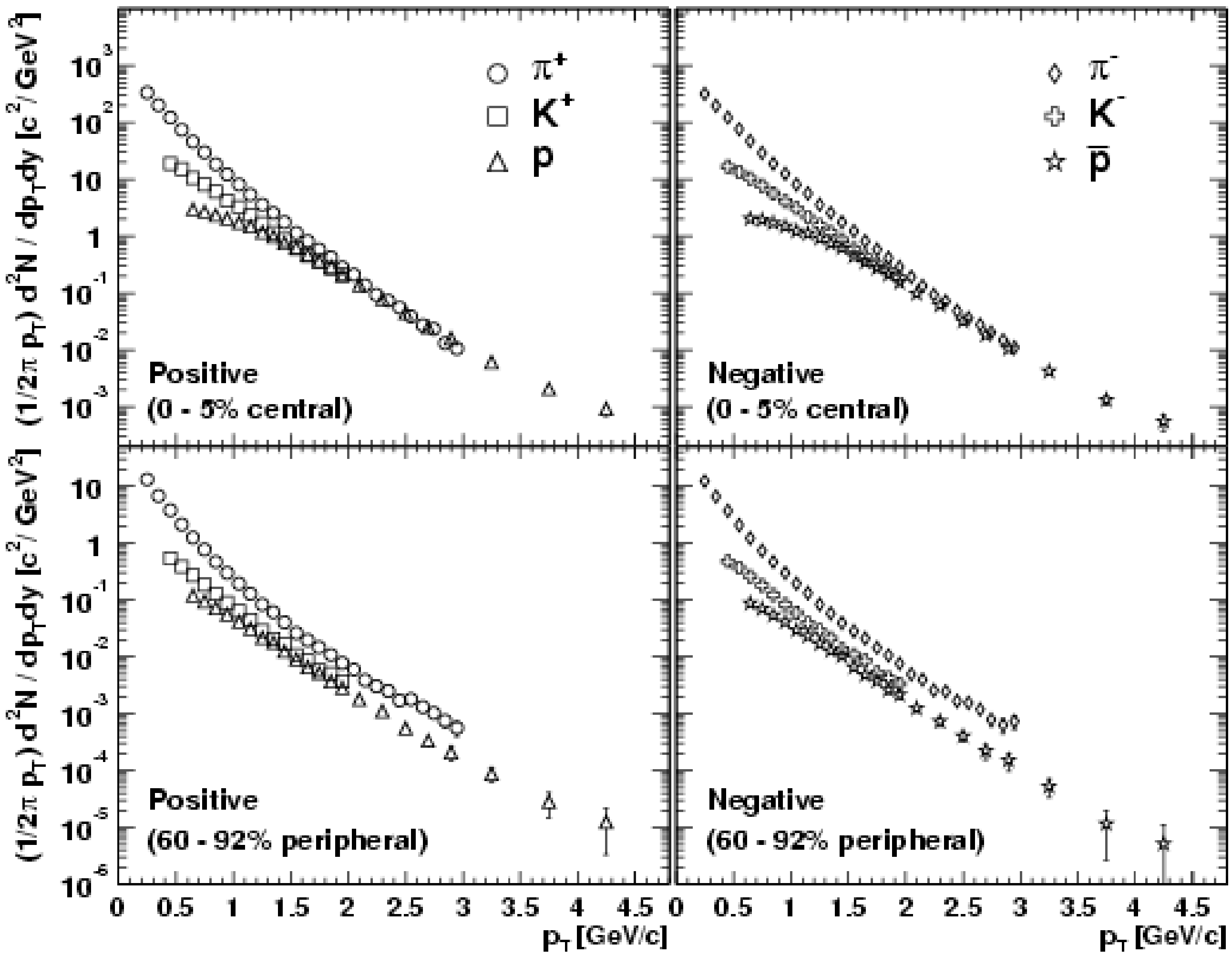
p_T Spectra (central vs. peripheral)

Central

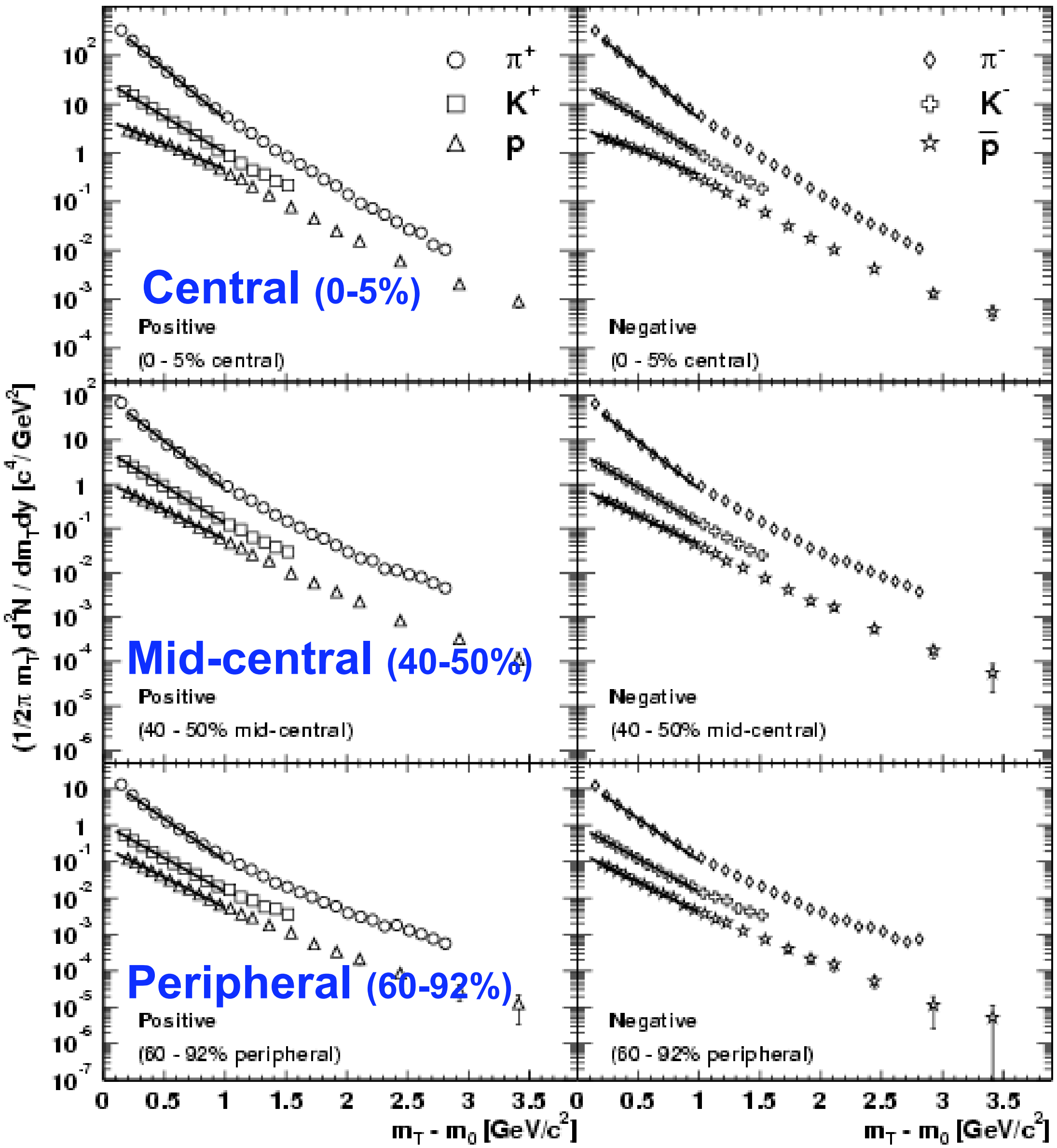
- low p_T slopes increase with particle mass
- proton and anti-proton yields equal the pion yield at high p_T.

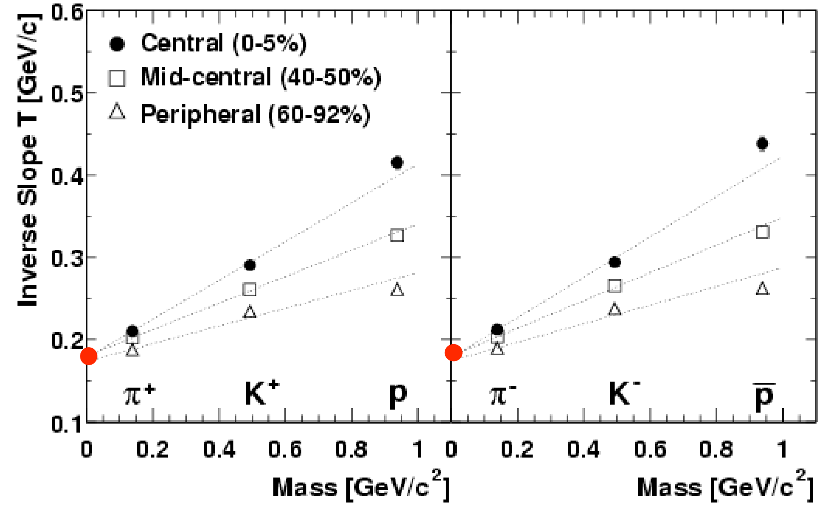
Peripheral

- mass dependence is less pronounced
- similar to pp



m_T - m_0 Spectra





Fit Functional Form

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

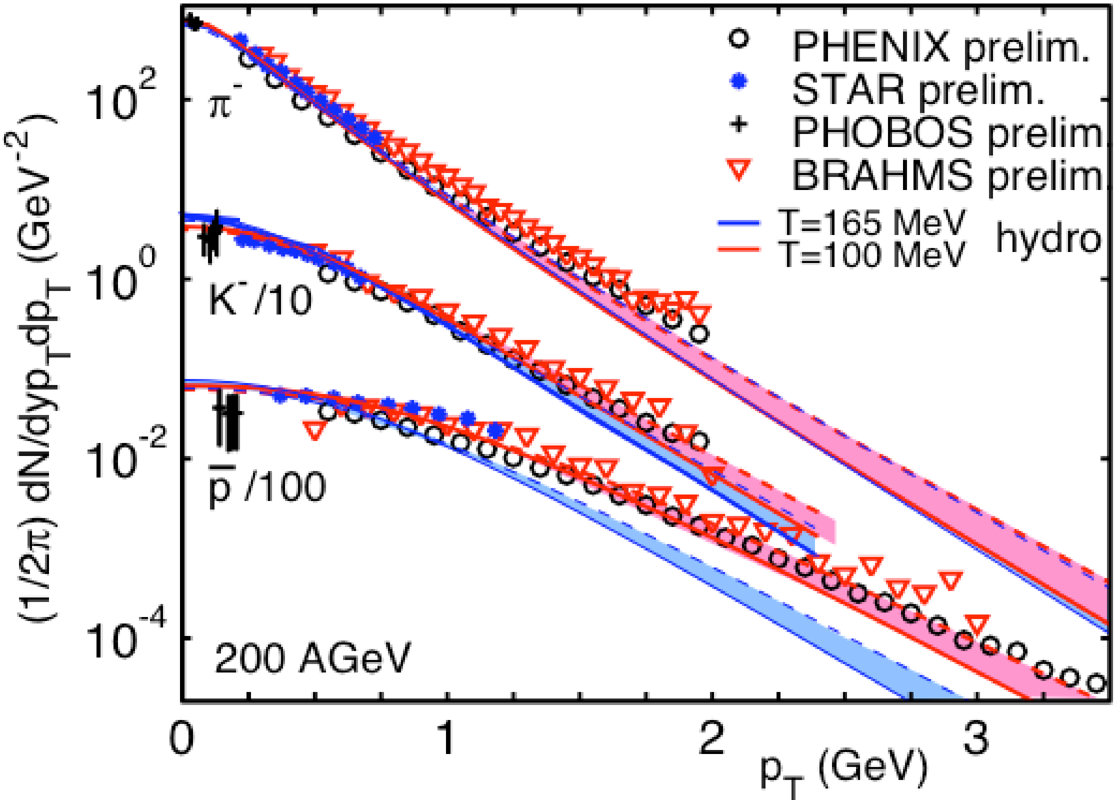
- **Clear mass and centrality dep. in slope parameter *T*.**
- **Freeze-out temperature T_0 ~ 175 MeV for all centralities.**

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

Consistent with collective flow picture.

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

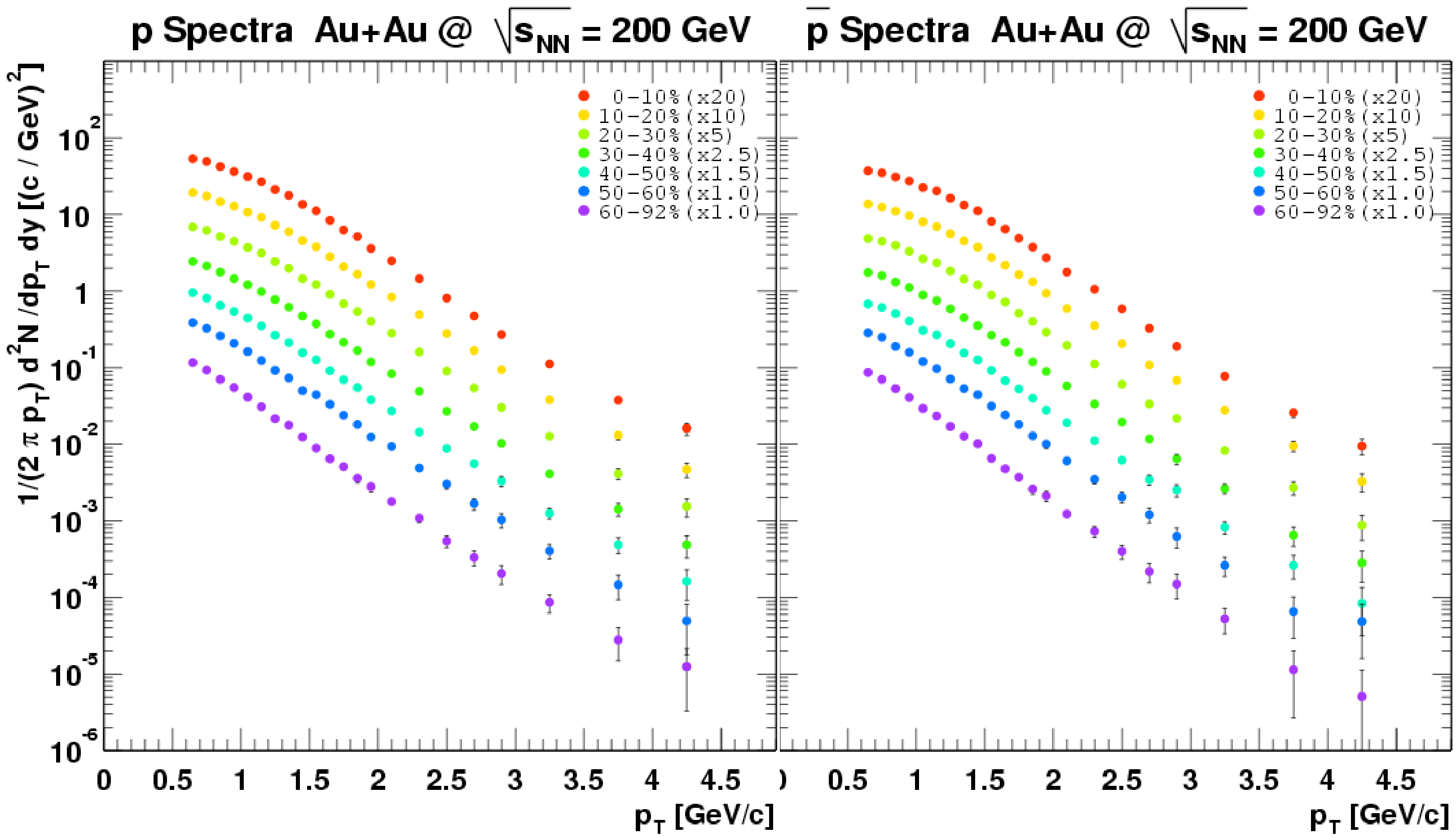


* Note: all data points are preliminary results (QM02).

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

Hydrodynamics describes all pT spectra up to 2 GeV/c.

Proton and anti-proton spectra in AuAu 200 GeV

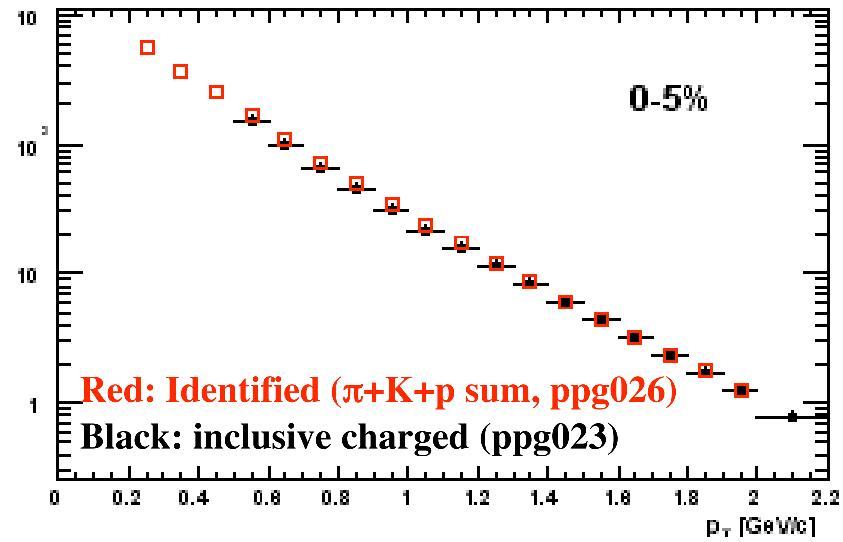


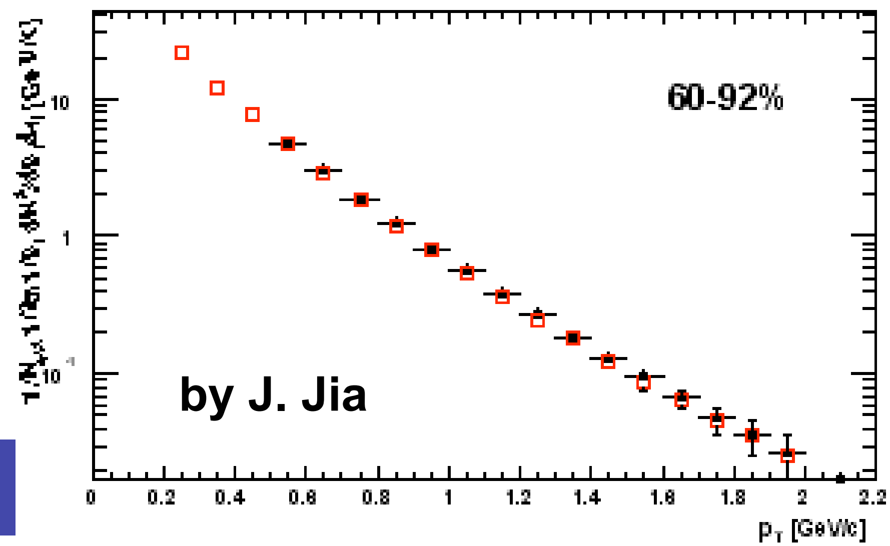
- Corrected for weak decay feed-down effect (~40% at 0.6 GeV/c, ~25% at 4 GeV/c).
- **Strong centrality dependence in spectra shape at low p_T (< 1.5 GeV/c).**

Consistency Check (Charged vs. PID Spectra)

PHENIX

- Identified spectra were converted from y→ η.
- Compared to 2 GeV/c where kaon runs out.

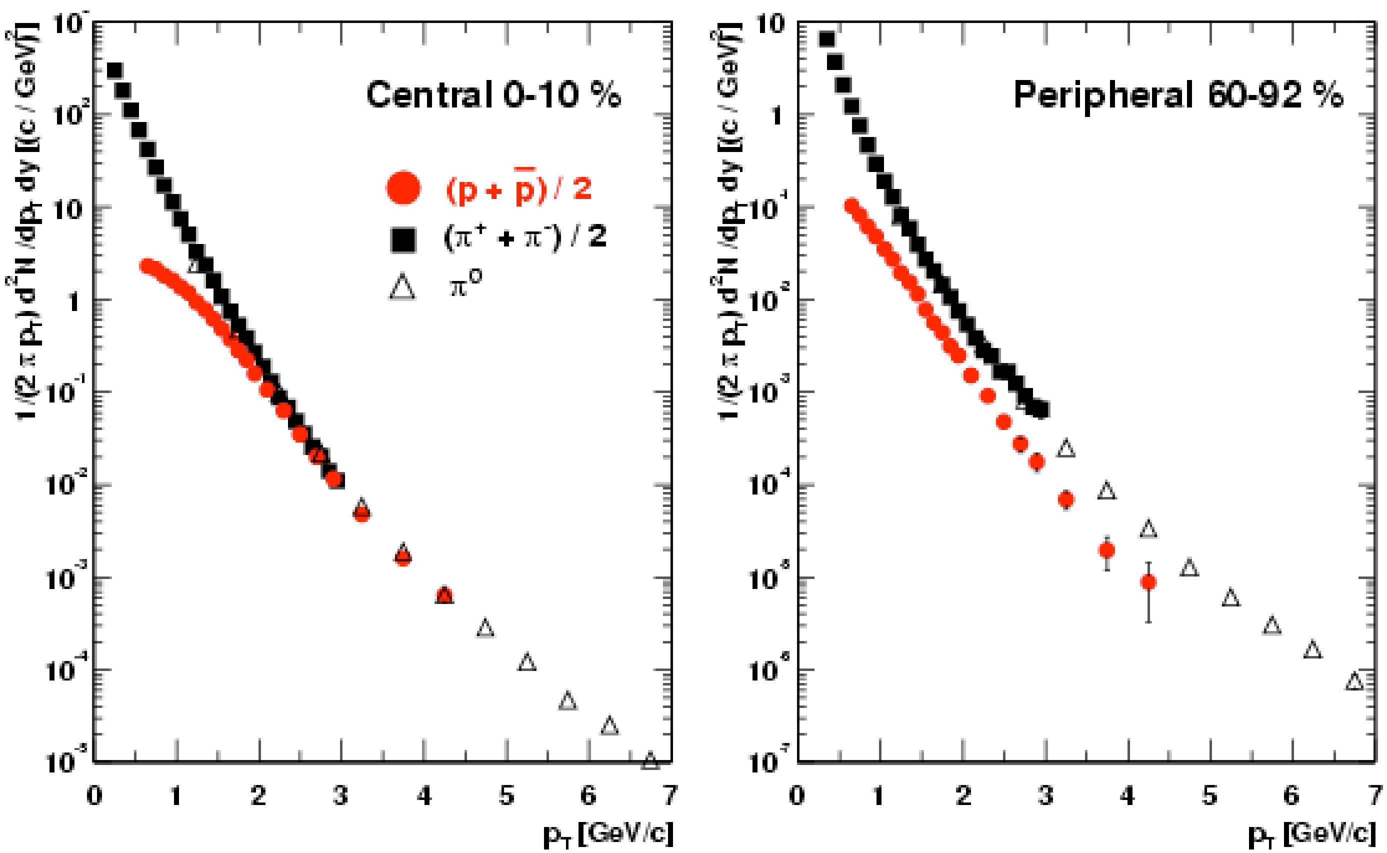




Good agreement within ±10%

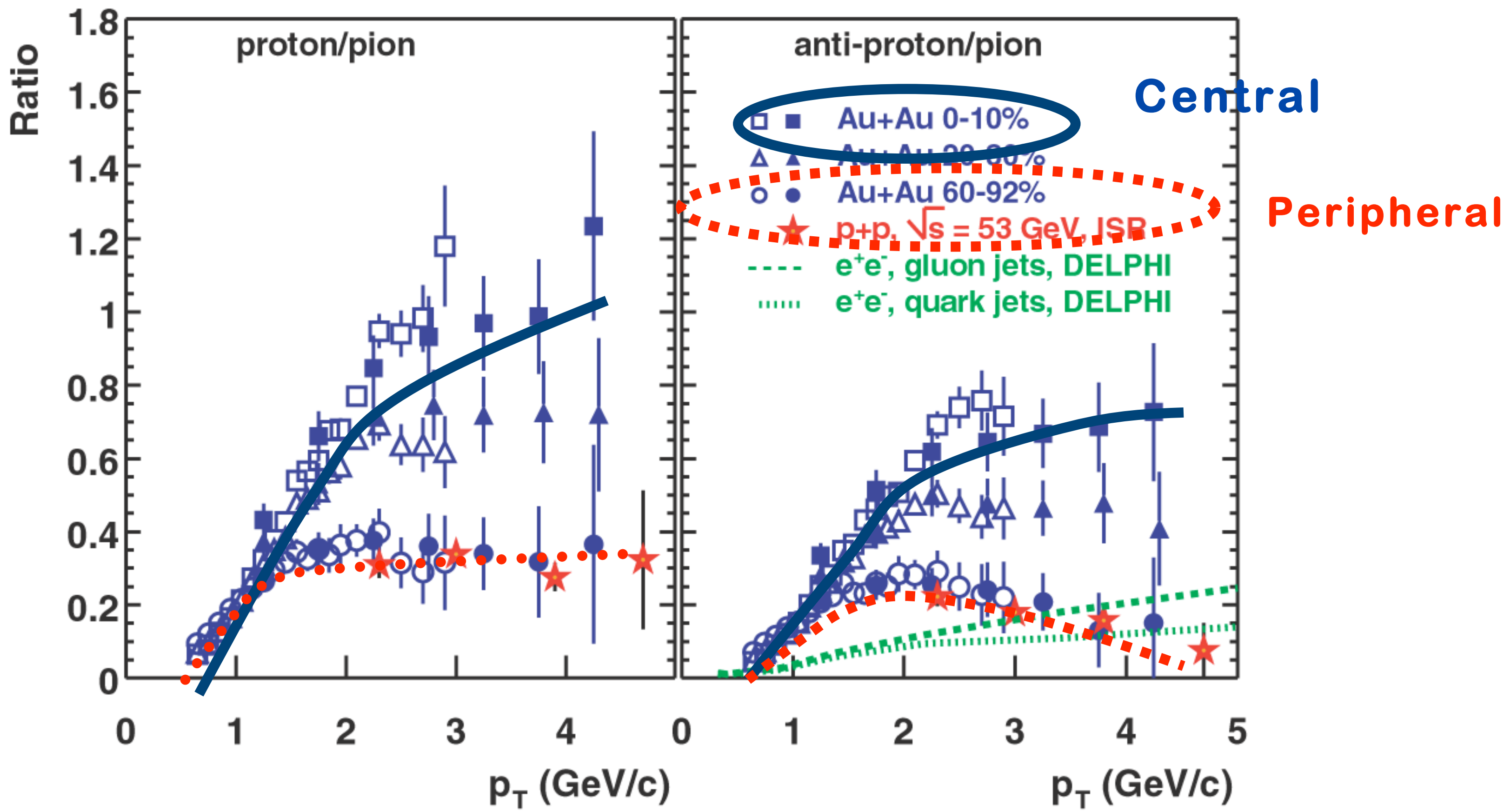
p vs. π Spectra in Au+Au @ 200 GeV

$\pi^{\pm}$ vs. π^{0}: Good agreement within 5-15%



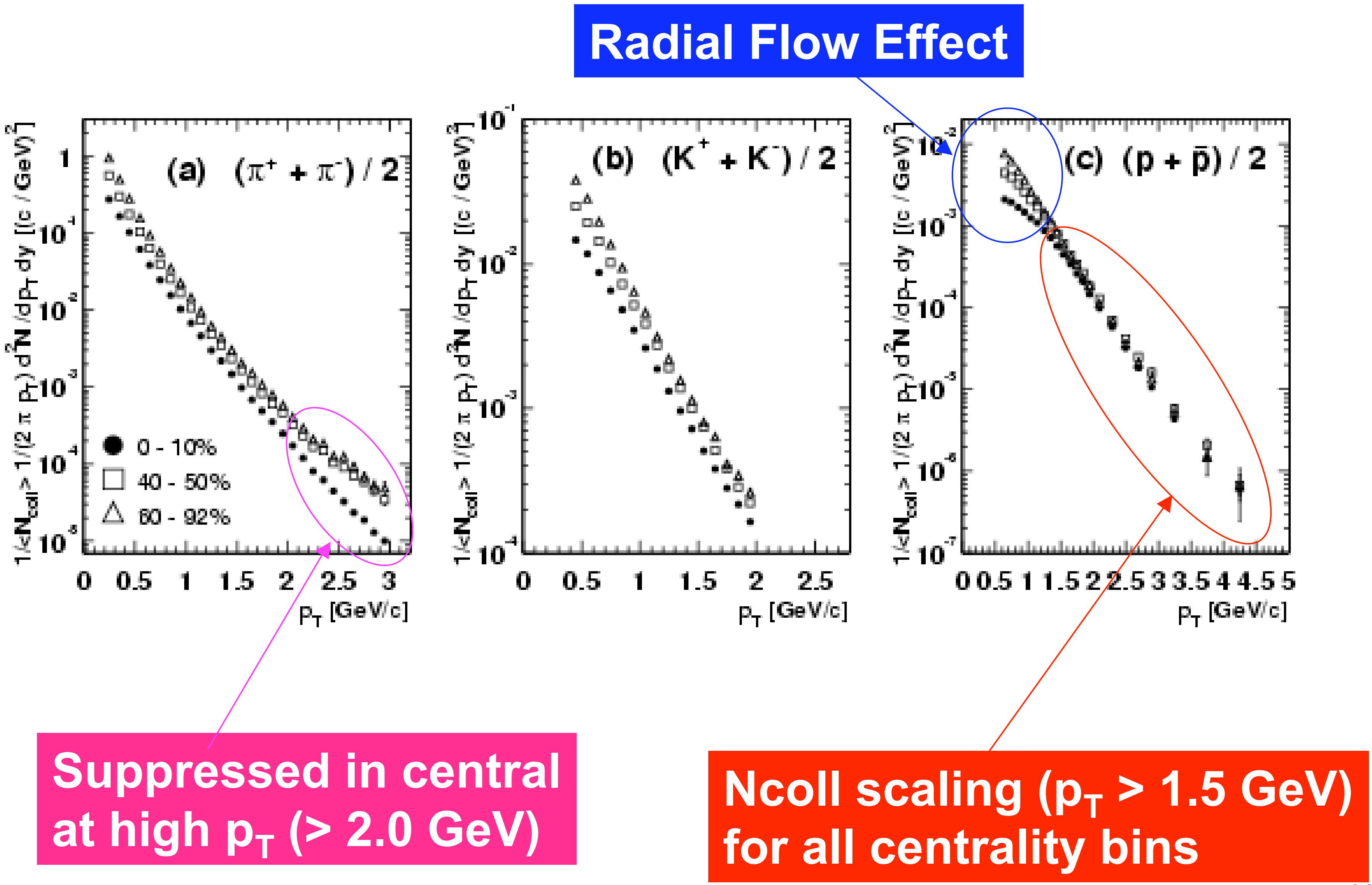
- Clearly seen p-π merging at p_T ~ 2 GeV/c in central.
- No p-π merging in peripheral.
- Suggested significant fraction of p, pbar at pt = 1.5 - 4.5 GeV/c in central.

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).**

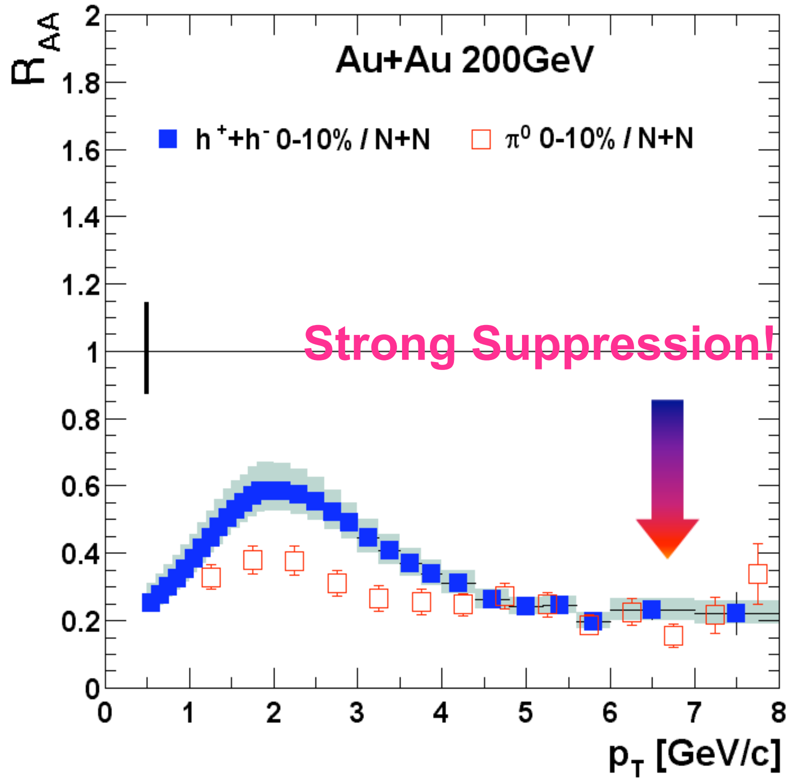
N_{coll} scaled p_T spectra



Centrality dep. of R_{AA} for π^0 and h

PHENIX

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



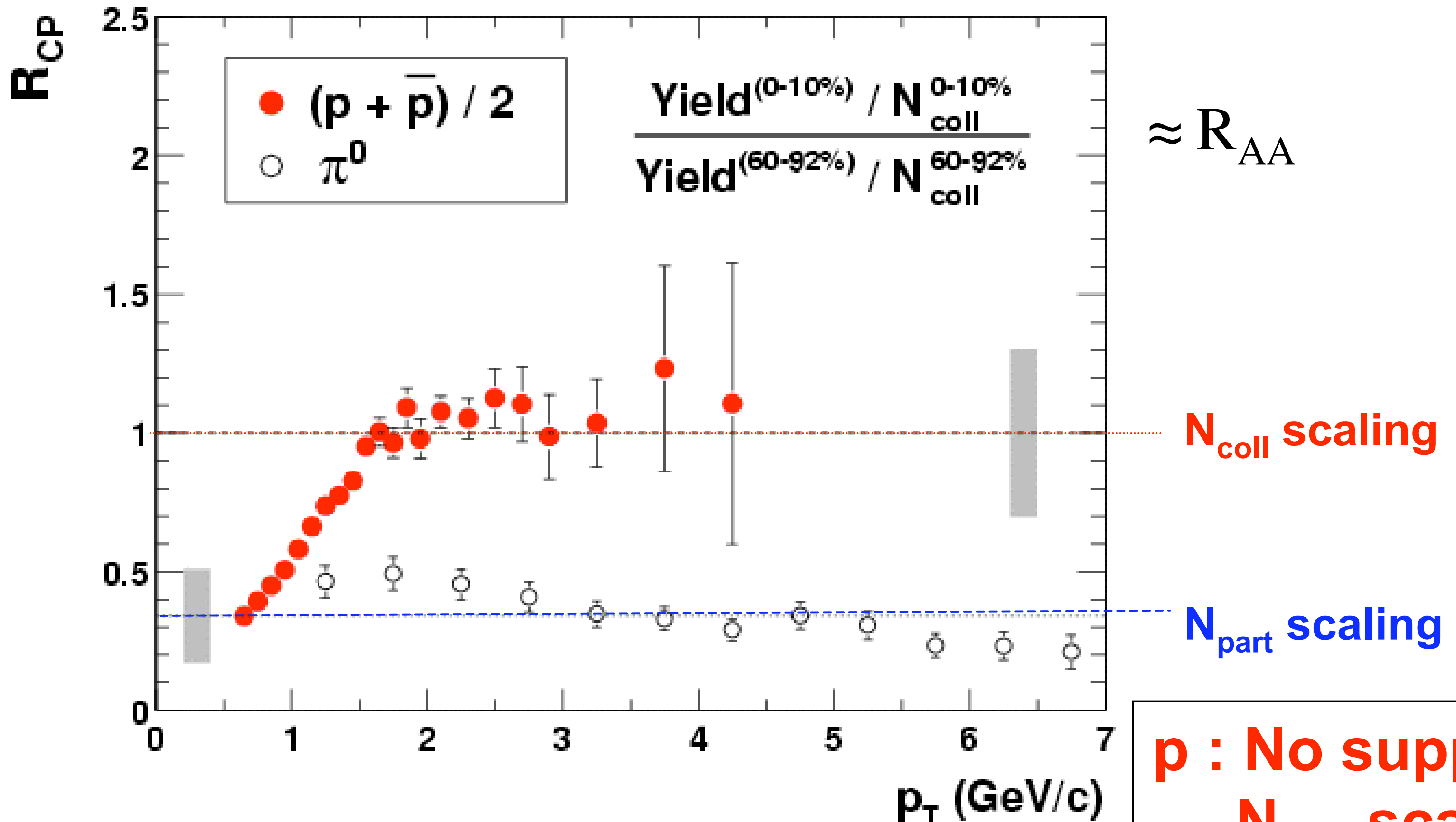
- R_{AA} is **well below 1** for both charged hadrons and neutral pions in central.
- Suppression is larger in central events.
- The neutral pions fall below the charged hadrons since they do not contain contributions from protons and kaons.

PHENIX AuAu 200 GeV

π^0 data: PRL 91 072301 (2003), nucl-ex/0304022.

charged hadron (preliminary) : NPA715, 769c (2003).

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



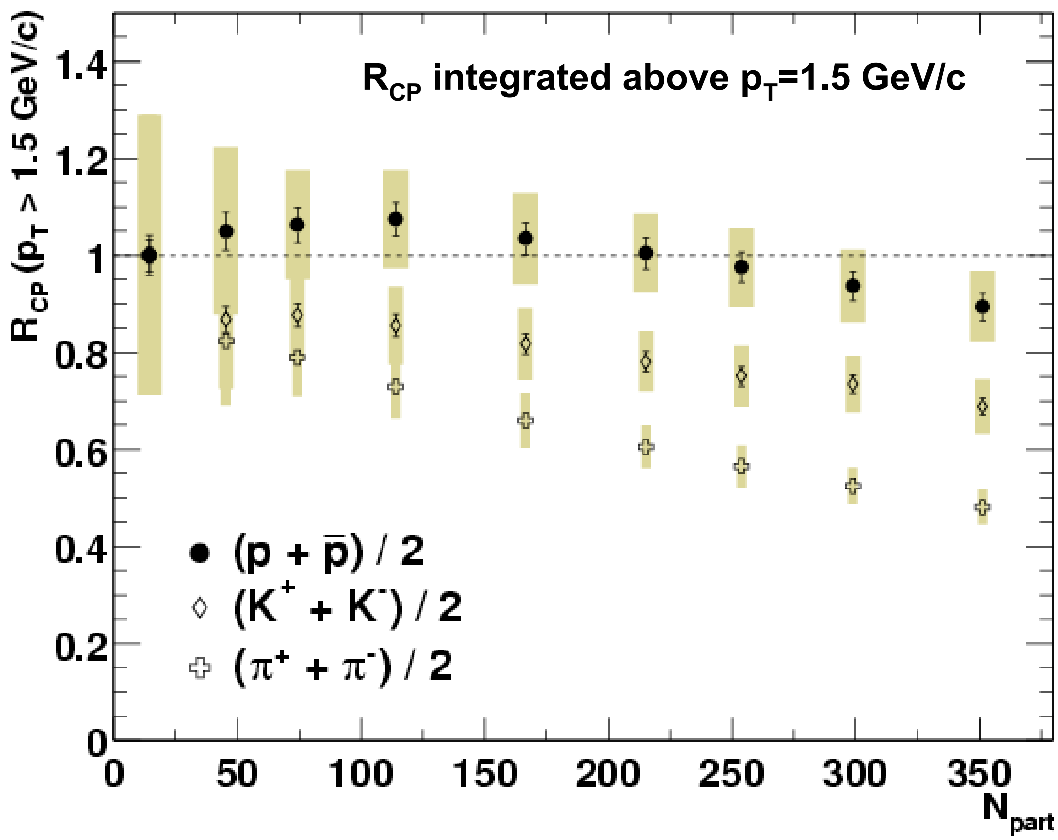
nucl-ex/0305036
nucl-ex/0307022

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

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

π^0: Suppression (central > peripheral)

Centrality Dependence of R_{CP}

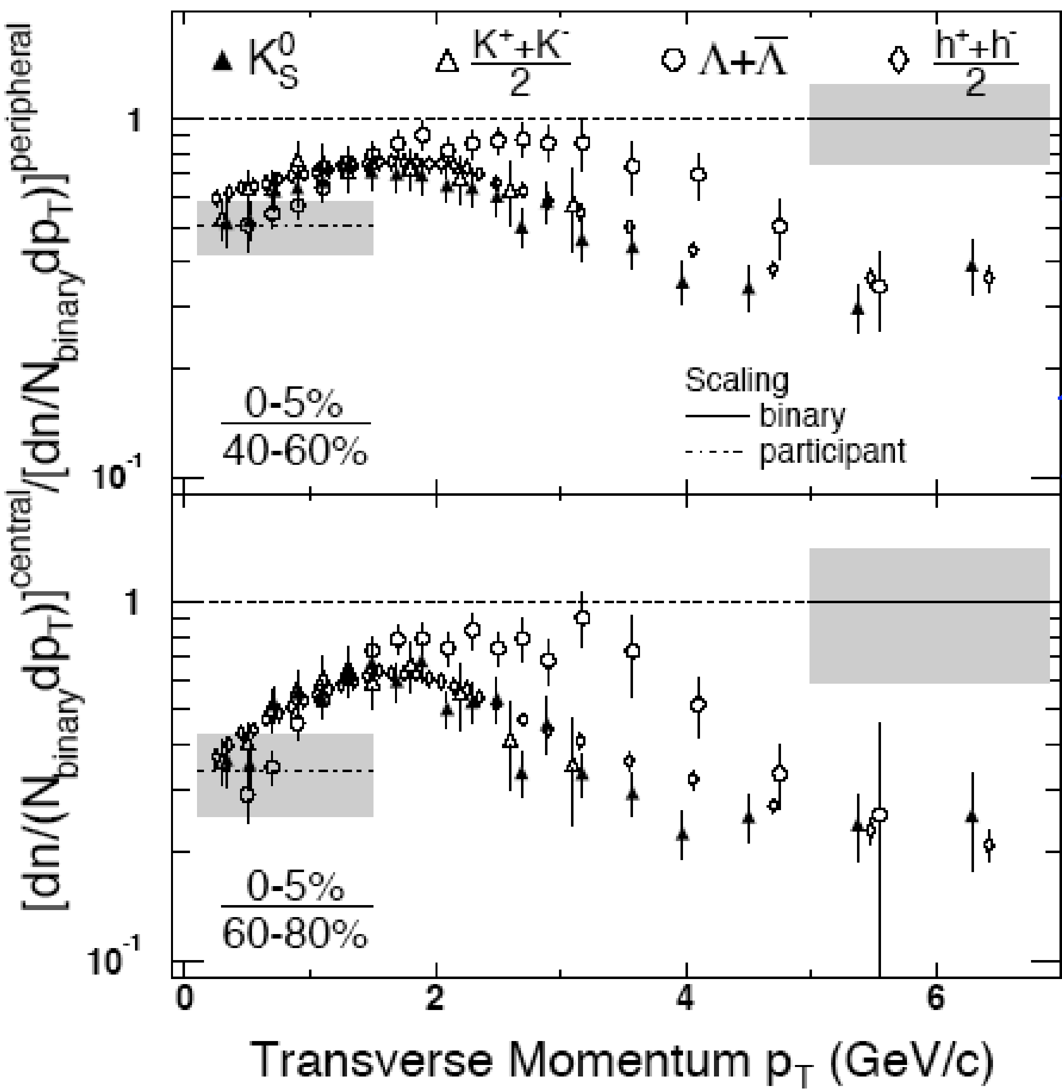


* Data points are normalized to the most peripheral data point.

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

STAR Results

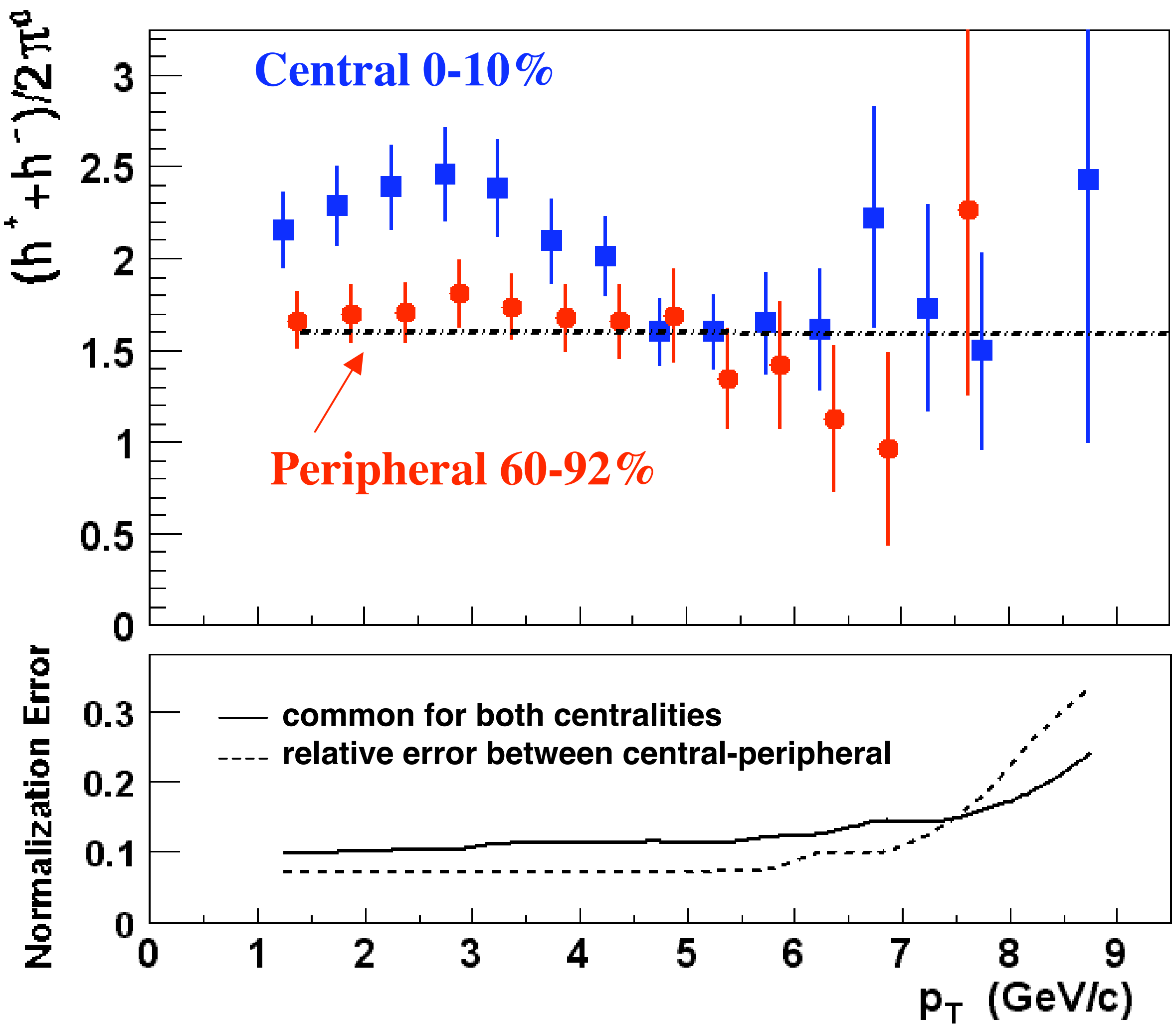
STAR nucl-ex/0306007



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

Particle Composition at p_T > 5 GeV

PHENIX (Au+Au) nucl-ex/0305036



~1.6 (p+p data at $\sqrt{s_{NN}}$ = 53 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.**

Part III

Interpretations (Recombination vs. Hydro)

Recombination/Fragmentation Model

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

- Quarks and anti-quarks recombine into hadrons locally "at an instant"
  - qq-bar → Meson
  - qqq → Baryon
- Thermal part (quark only) and power law tail (quarks and gluons) from pQCD.
- Modification of fragmentation function "$D_{i \to h}(z)$" by energy loss of partons.
- Competition between recombination and fragmentations mechanism.
- **Quark degrees of freedom** play an important role.

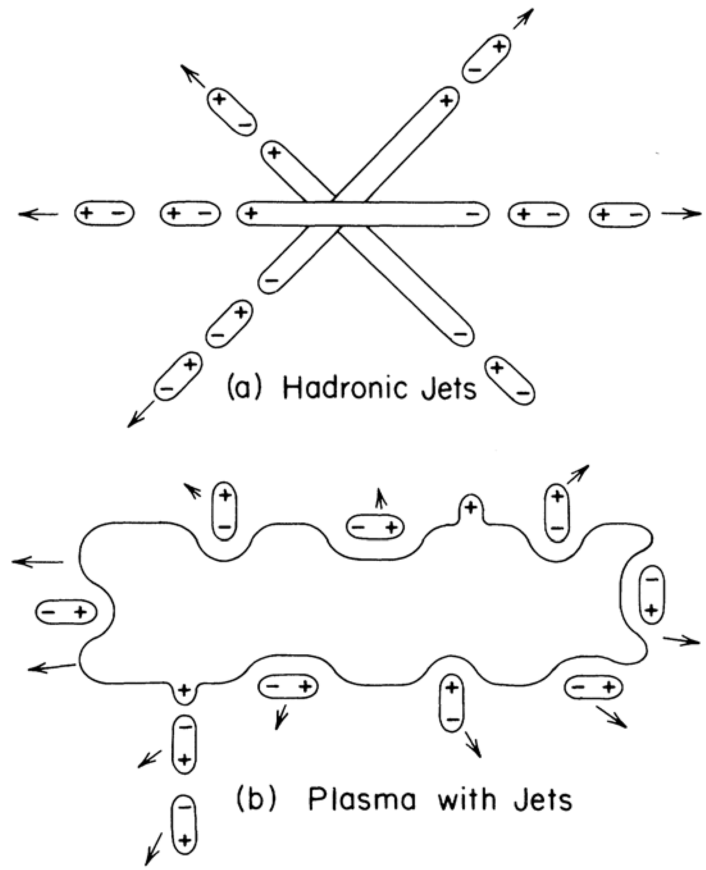


FIG. 1. Schematic conception of contrasting hadronization mechanisms for (a) a superposition of hadronic jets and (b) a plasma with a jet caused by a fast quark escaping.

Lepez, Parikh, Siemens, PRL 53 (1984) 1216

Recombination Tested

The *complicated* observed flow pattern in $v_2(p_T)$

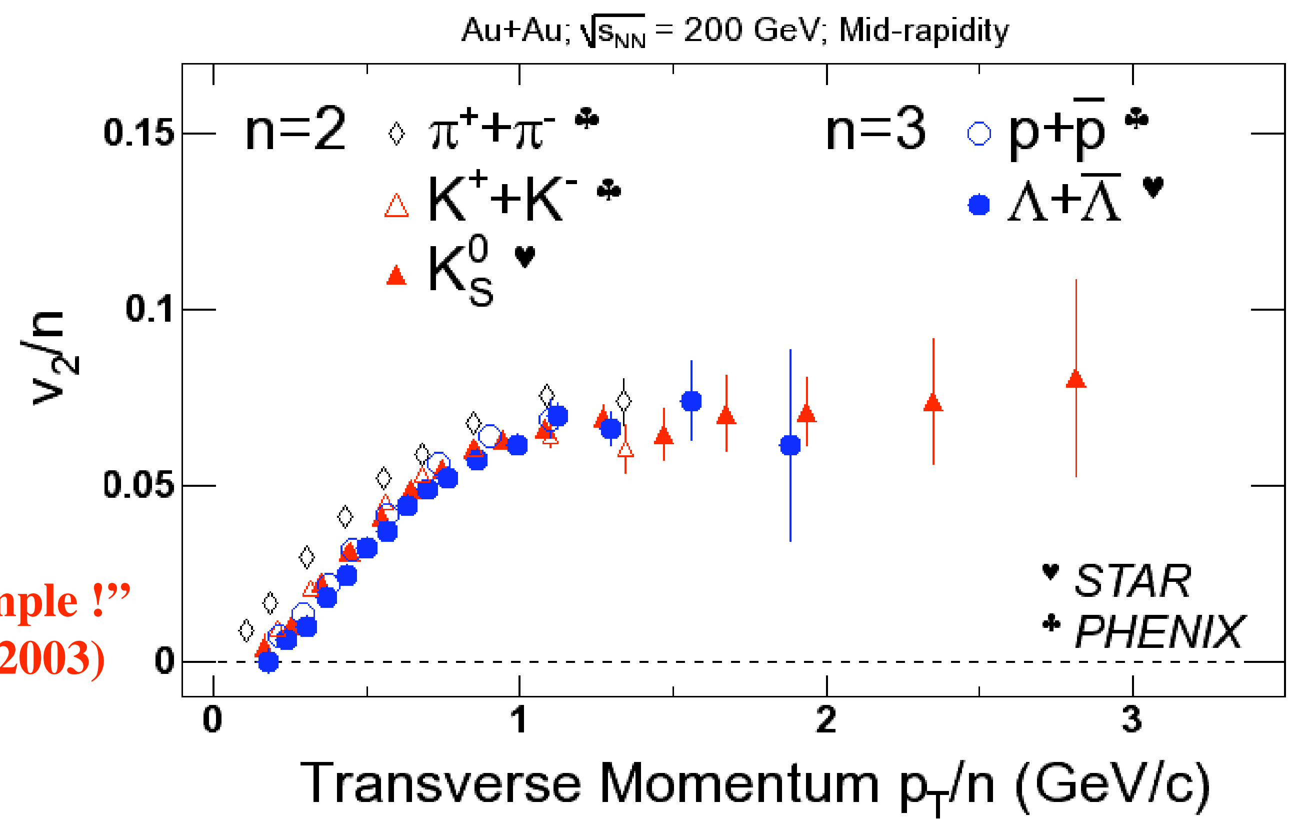
$$d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi)$$

is predicted to be *simple* at the quark level under

$p_T \rightarrow p_T / n$, $v_2 \rightarrow v_2 / n$, n = 2,3 for meson,baryon

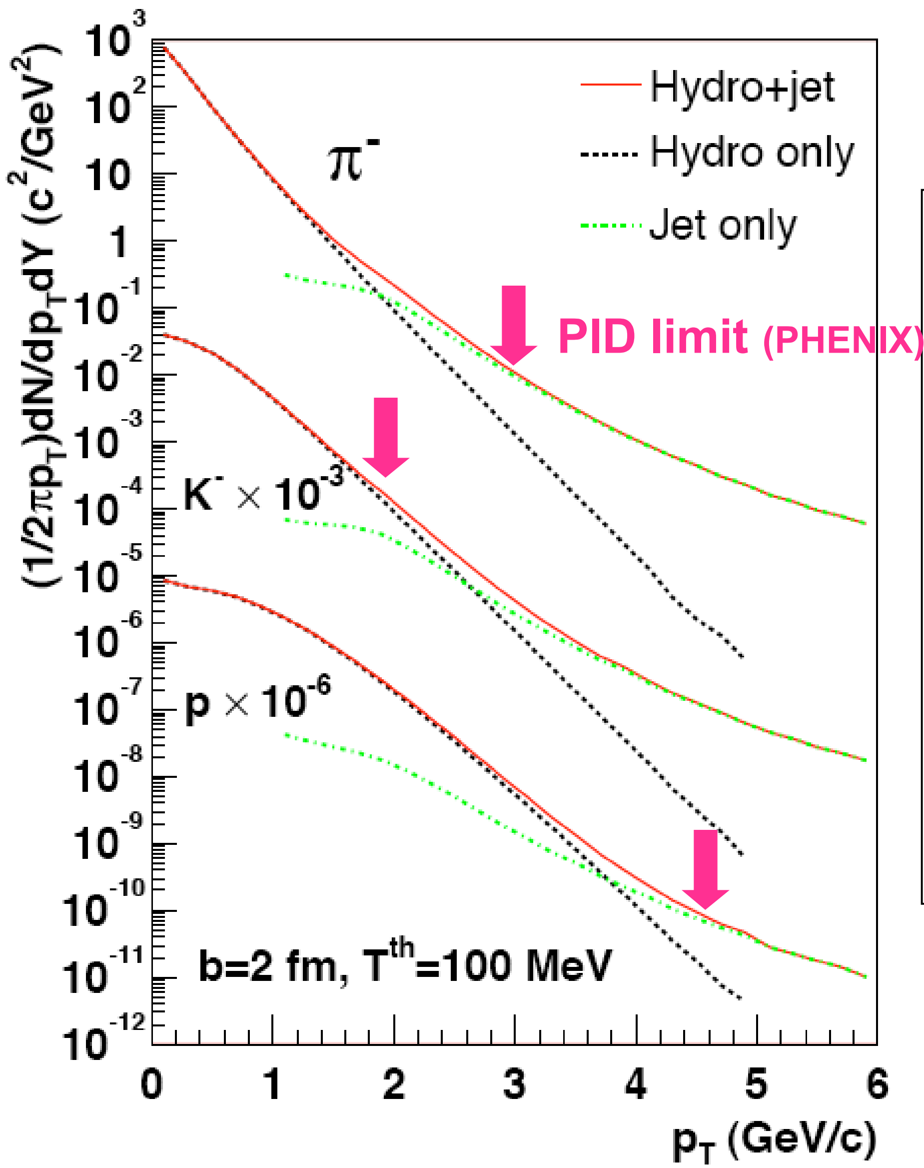
if the flow pattern is established at the quark level

Compilation courtesy of H. Huang



"RHIC Physics is simple !"
(B. Muller, CIPANP2003)

Another Approach (Hydro + Jet Model)

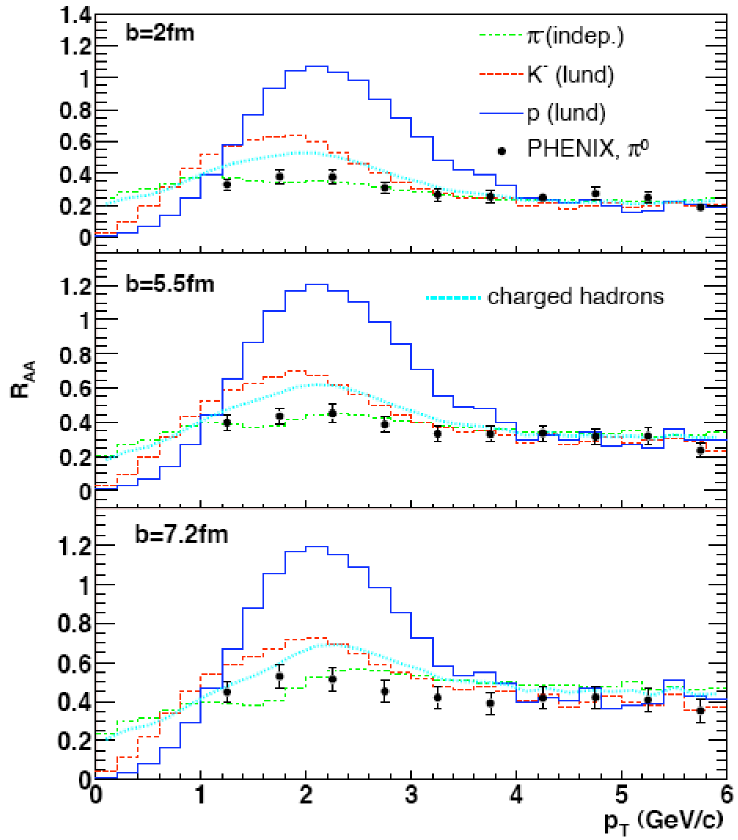


Hirano, Nara (Hydro + Jet Model)
nucl-th/0307015

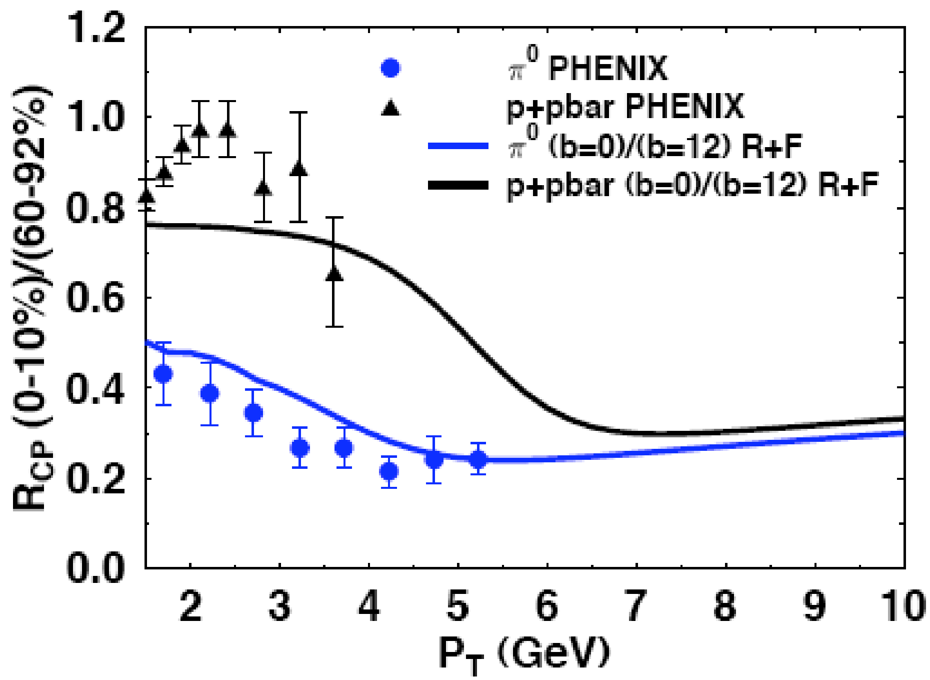
- **Explicit 3D Hydrodynamical calculations (including QGP in EOS).**
- **Tuned jet quenching effect to reproduce the suppression factor in π^0 data.**

- Hydrodynamics can describe p_T spectra up to ~ 2 GeV/c.
- Well described $dN/d\eta$ distributions and v_2 vs. p_T at RHIC.
- **Jet contributions from 2 GeV/c.**

Model Comparison (1) - R_{CP} -



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



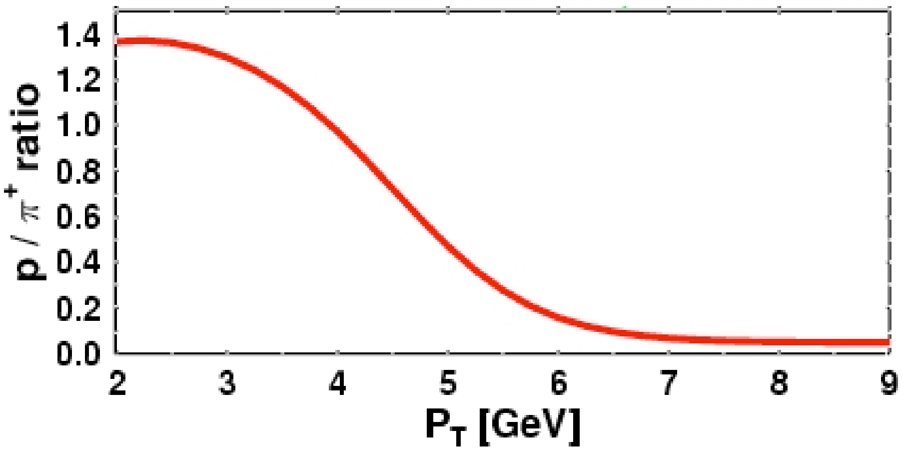
Fries, Muller, Nonaka, Bass
(Fragmentation/Recombination model)
nucl-th/0306027

- **Recombination model, Hydro-jet model**
  ⇒ Predicted baryon enhancement is limited up to ~ 4-5 GeV/c.
- **Qualitative agreement with data for both models.**

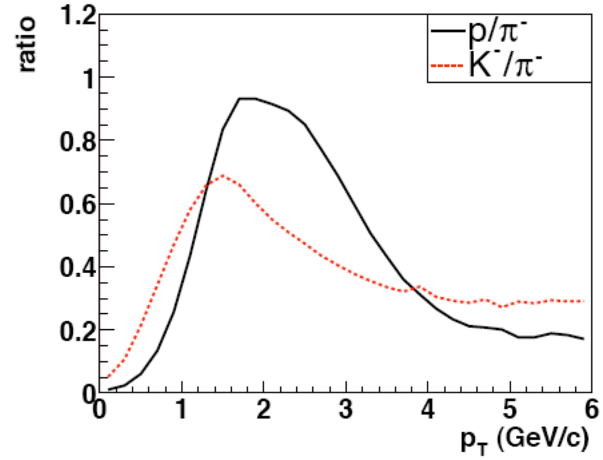
Model Comparison (2) - p/π vs. p_T -

Parton recombination/fragmentation

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



Hydro+Jet Hirano, Nara
nucl-th/0307015



- Both **Parton Recombination** and **Hydro+Jet** 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 ?

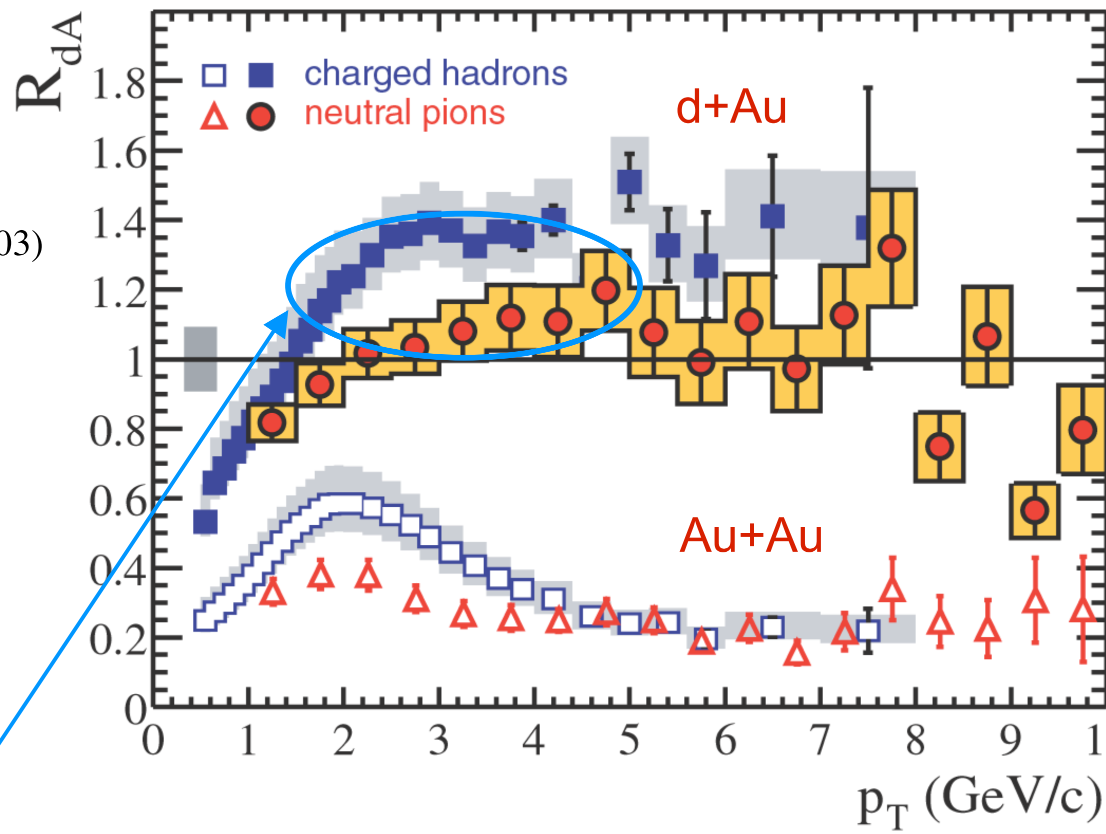
  or Baryon Junction Mechanism ?

  (Vitev, Gyulassy PRC 65, 041902, 2002)

How about the Cronin effect ? → dAu results.

R_{dA} for charged hadrons and π^0

PHENIX
PRL 91 072303 (2003)
nucl-ex/0306021

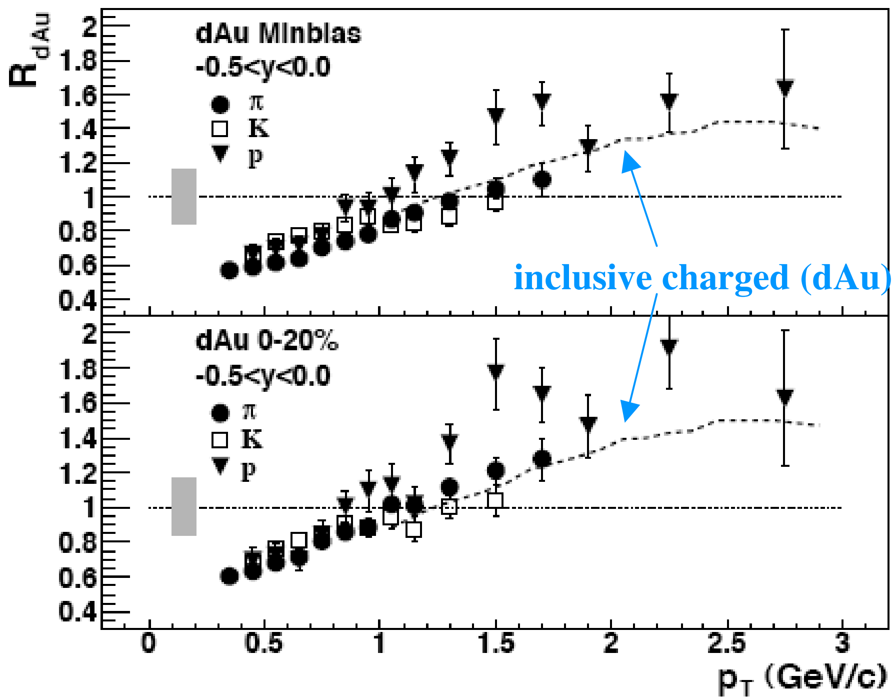


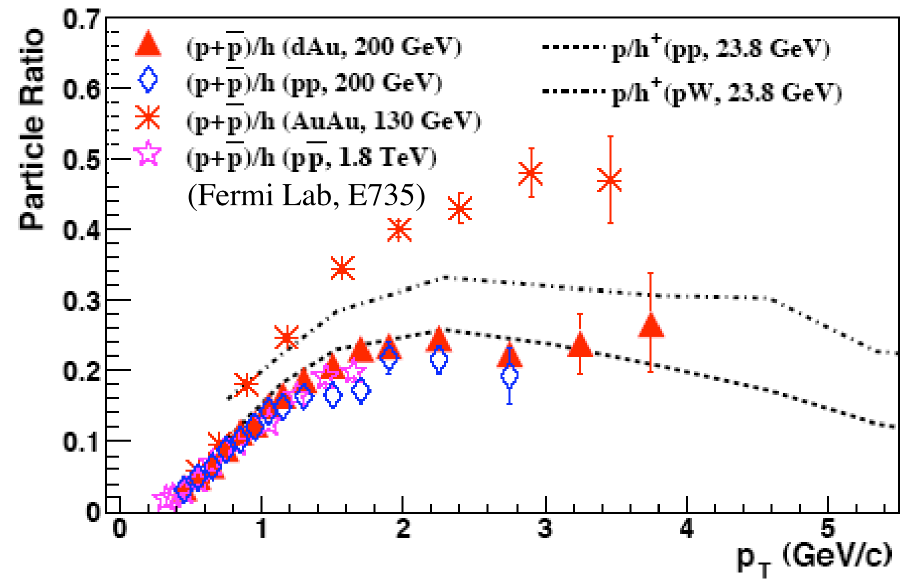
Initial State Effects Only

Initial + Final State Effects

- **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.**

R_{dAu} and p/h for π, K, p in d+Au (STAR)





STAR nucl-ex/0309012

- Small particle species dependence of Cronin effect, compared to lower energies.
- Same (p+pbar)/h ratio in dAu as p+p.
- **Indicated the Cronin effect alone is not enough to account for the relative baryon enhancement in AuAu central.**

Summary

Proton and anti-proton (Λ)

1. **Observed baryon enhancement relative to pion in central Au+Au at intermediate p_T (2 - 4 GeV/c).**

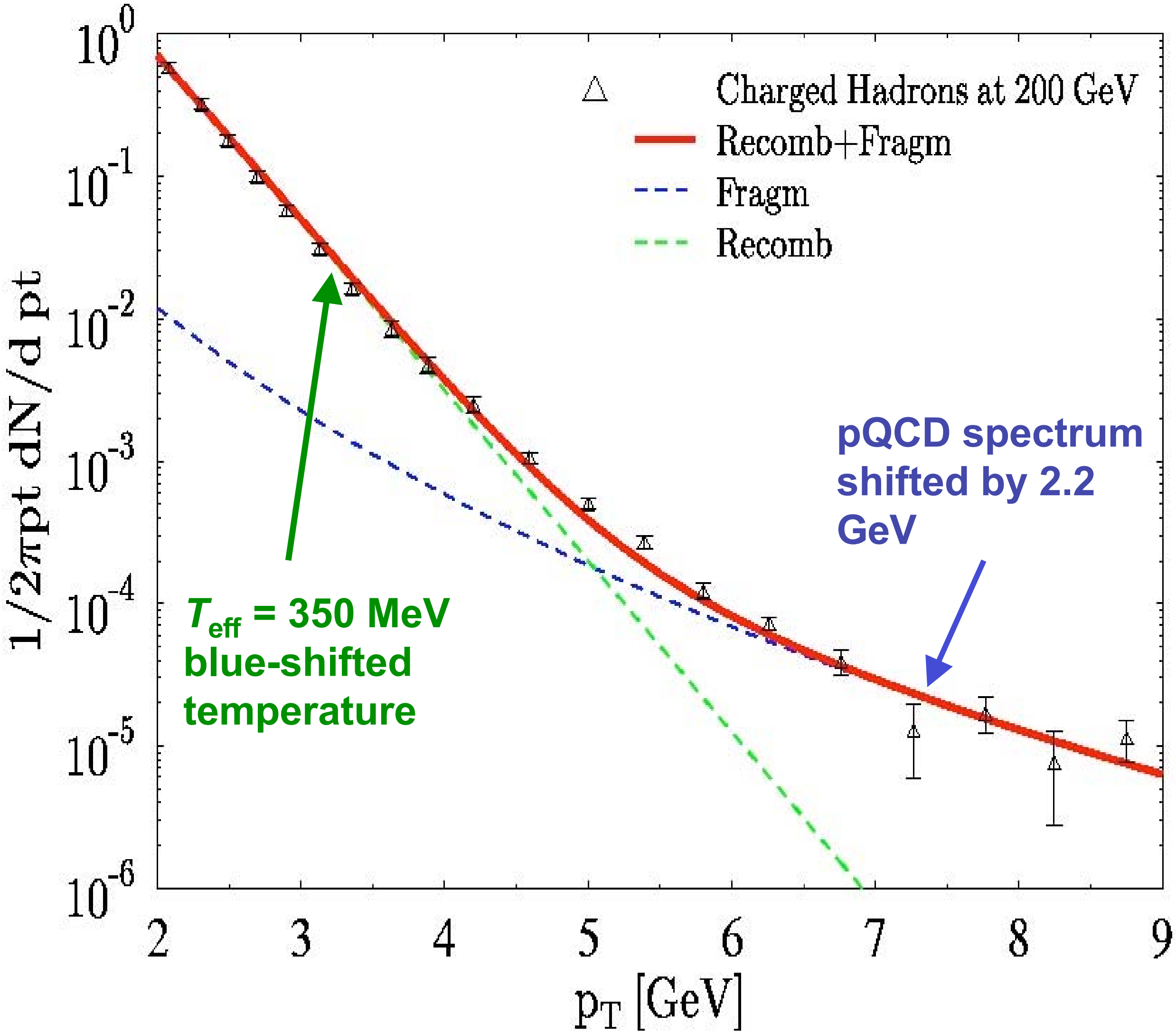
2. **Absence of yield suppression for p and pbar (Λ) at intermediate p_T.**

3. **dAu results suggest that the Cronin effect alone is not enough to account for the relative baryon enhancement in AuAu central.**

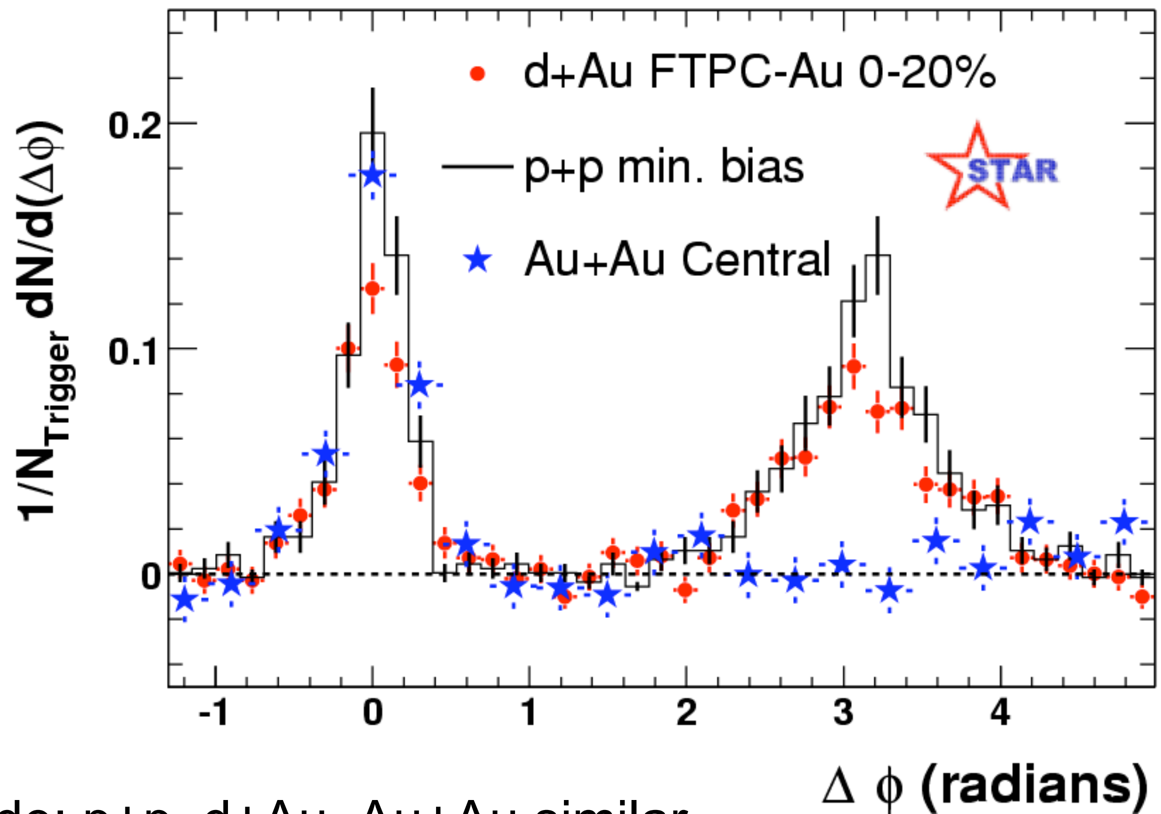
4. **Both Parton Recombination and Hydro+Jet models reproduce p/π ratio (p_T and centrality dep.) qualitatively and predicted that enhancement is limited < 5 GeV/c.**

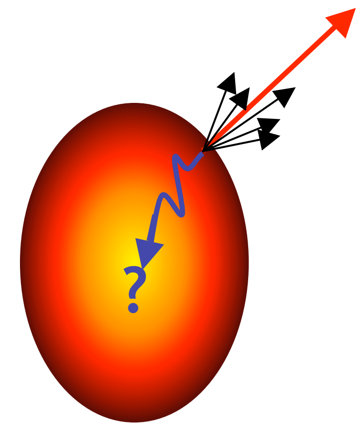
Partonic Flow

Nonaka et al., nucl-th/0306027



Azimuthal Distributions in d+Au (STAR)



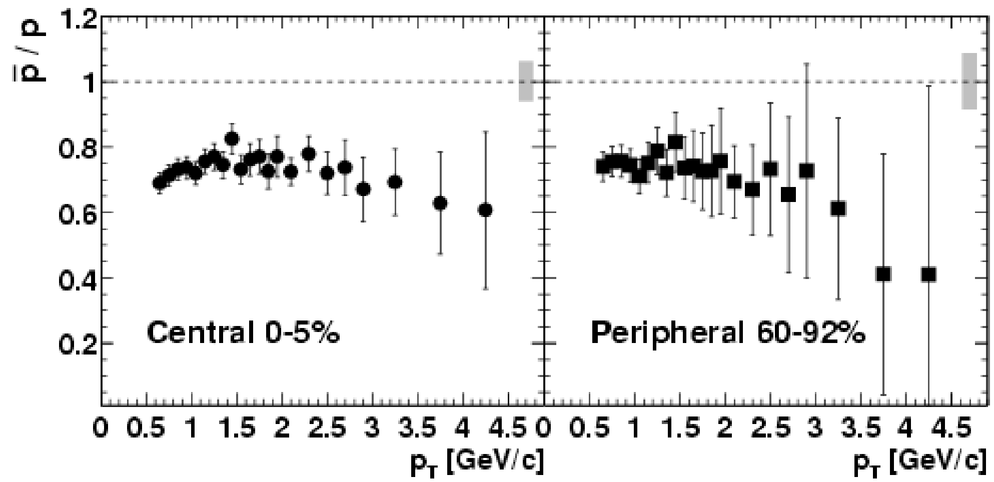


* Pedestal and flow subtracted

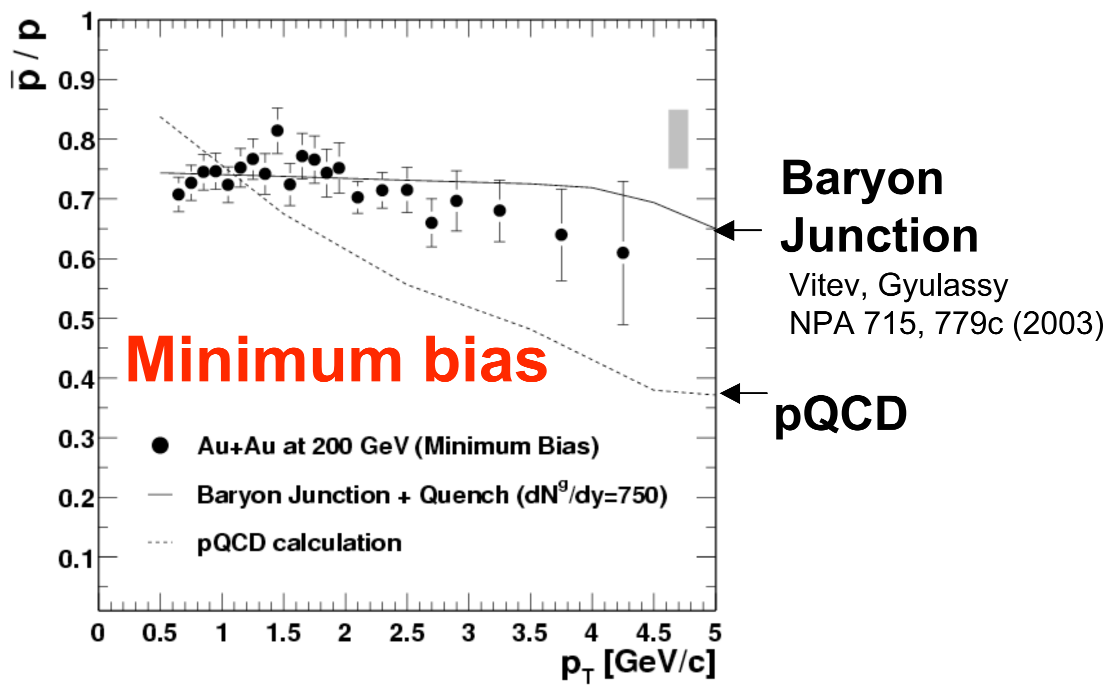
- Near-side: p+p, d+Au, Au+Au similar
- Back-to-back: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the back-to-back correlation in central Au+Au is a final-state effect

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



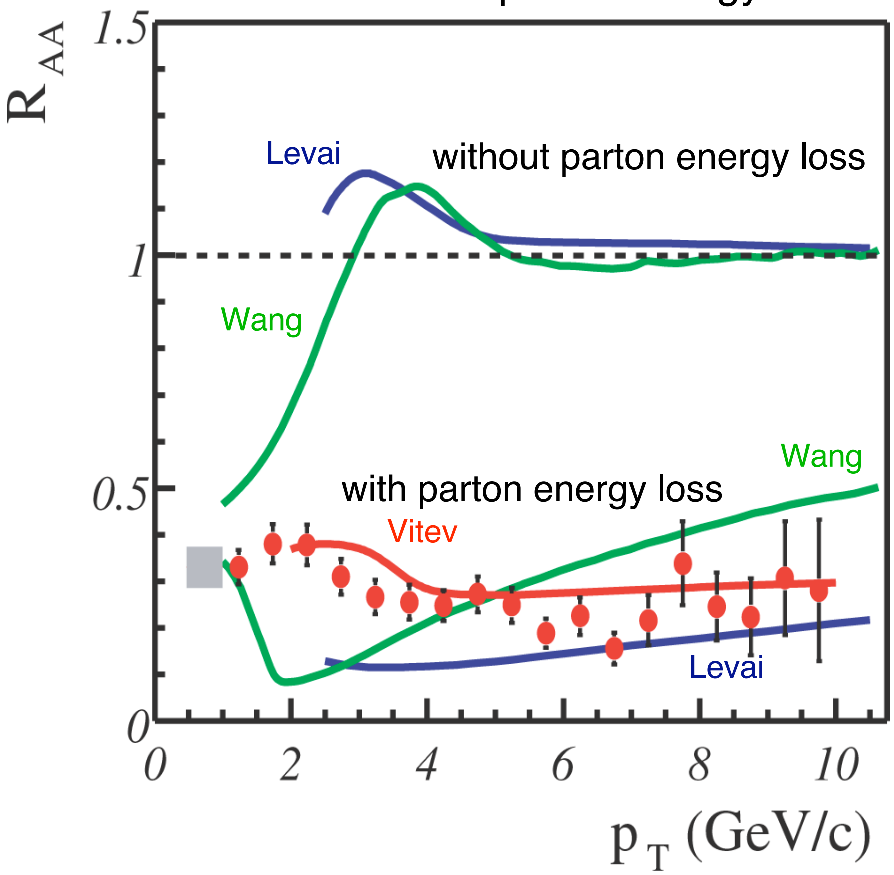
Constant within the experimental errors



- **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.

Jet Quenching Effect

Comparison with model calculations
with and without parton energy loss



Au+Au→π^0+X at $\sqrt{s_{NN}}$ = 200 GeV

CGC Model: Initial Effects

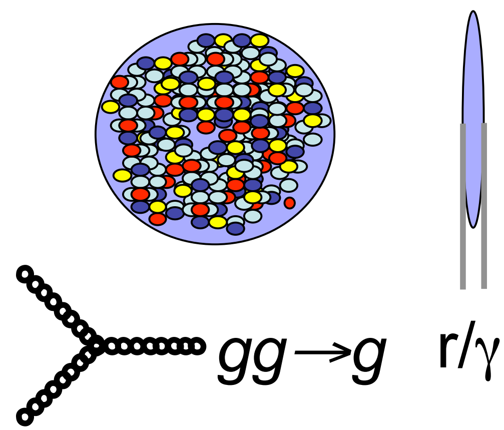
- **Gluon Saturation**
  - **(Color Glass Condensate: CGC)**

Wave function of low x gluons overlap; the self-coupling gluons fuse, **saturating** the density of gluons in the initial state.

Braking QCD factorization!

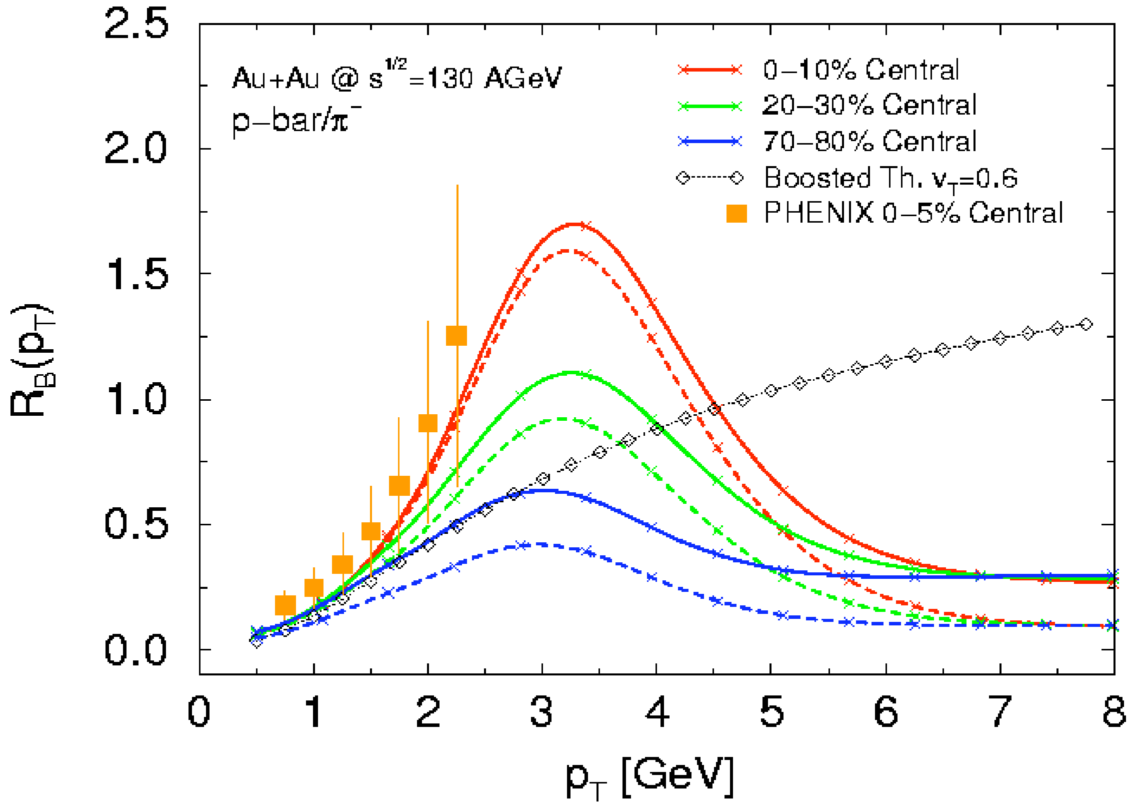
→gets N_{ch} right!

hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi



D.Kharzeev et al., PLB 561 (2003) 93

Baryon Junction

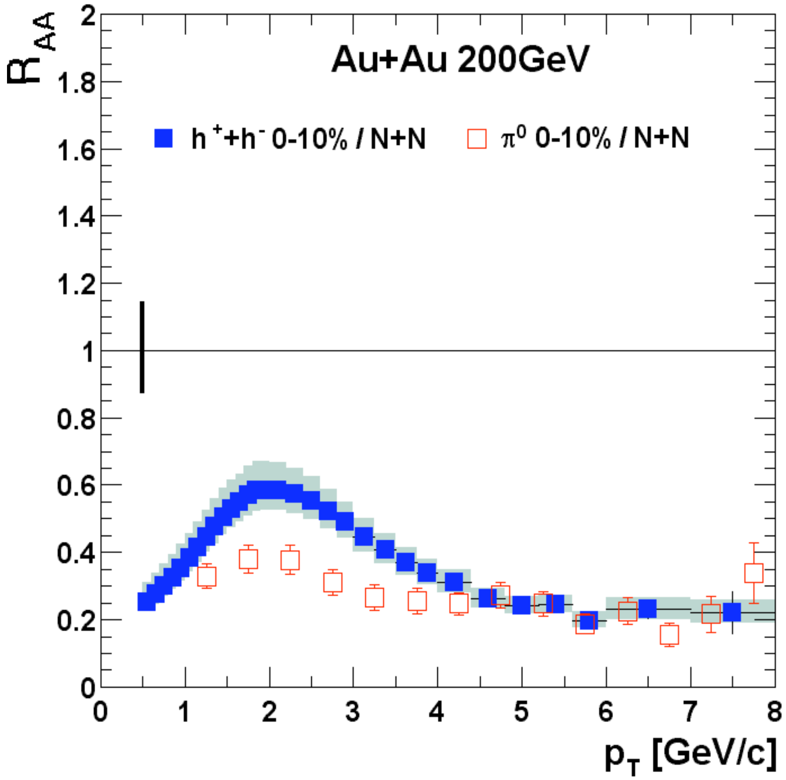


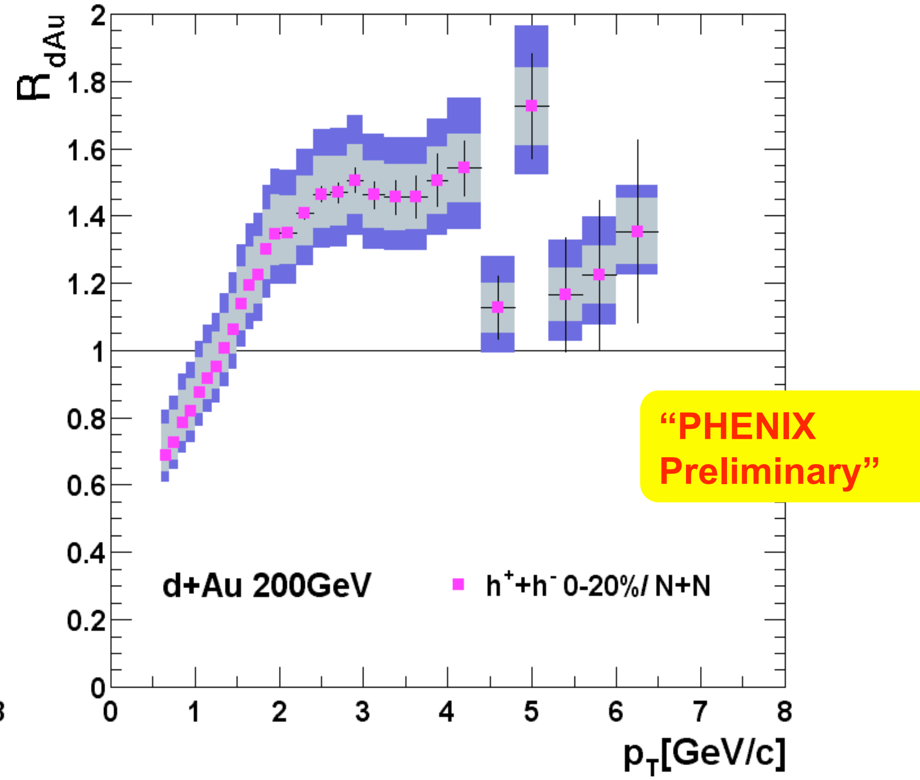
Baryon Junction
Vitev, Gyulassy
PRC 65, 041902, 2002

Centrality Dependence

Au + Au Experiment

d + Au Control Experiment





- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au.
- High p_T hadron suppression in AuAu is <u>**clearly a final state effect.**</u>