Recent Results from PHENIX: High p_T hadron Suppression

T.C. Awes, ORNL

XXVIII Mazurian Lakes Conference on Physics
"Atomic Nucleus as a Laboratory for Fundamental Processes"
Krzyze, Poland, August 31 - September 7, 2003


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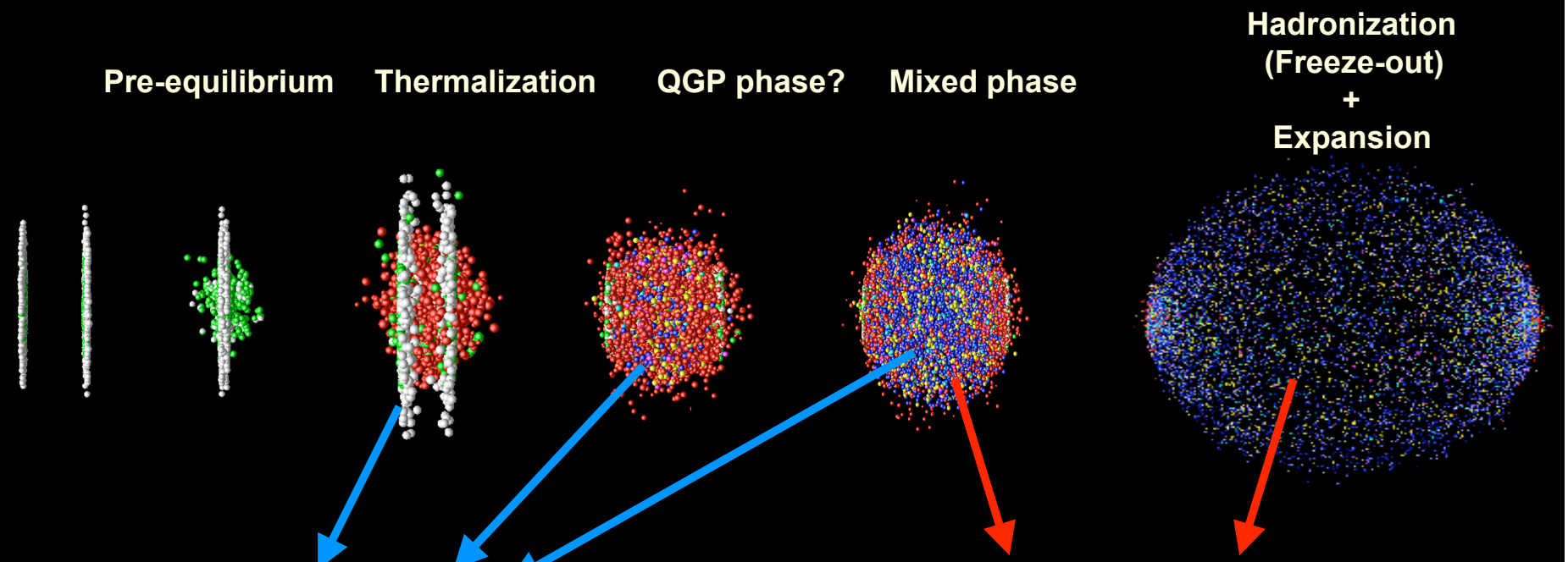
Evolution of Heavy Ion Collisions



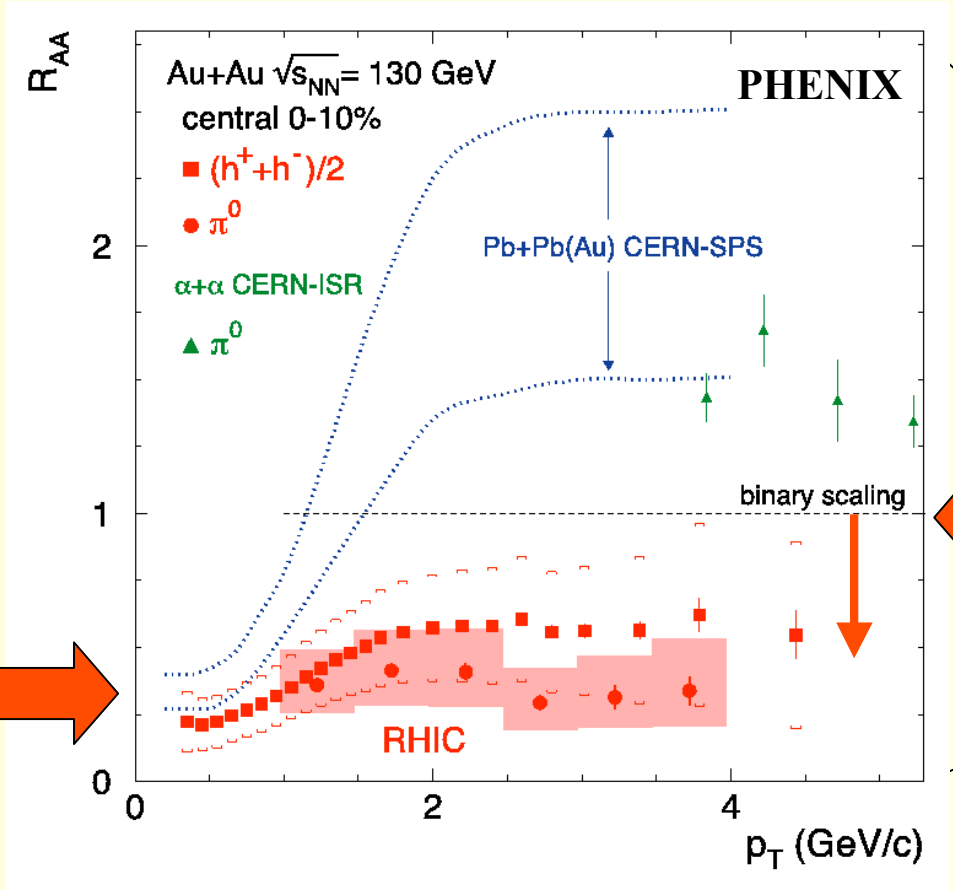
□, □□□ e^+e^-, □$^+$□$^-$

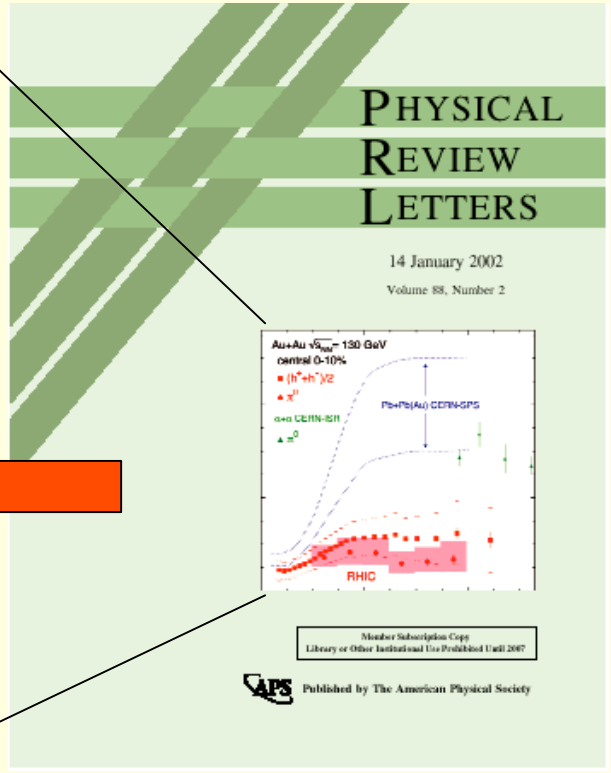
□, K, p, n, □, □, □, □, □ , d,…

Hard processes (early stages): Real and virtual photons, high p_T particles.
PHENIX emphasis

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

RHIC Headline News… January 2002





PHENIX PRL 88, 022301 (2002)

First observation of *large* suppression of high p_T hadron yields

"Jet Quenching''? == Quark Gluon Plasma?

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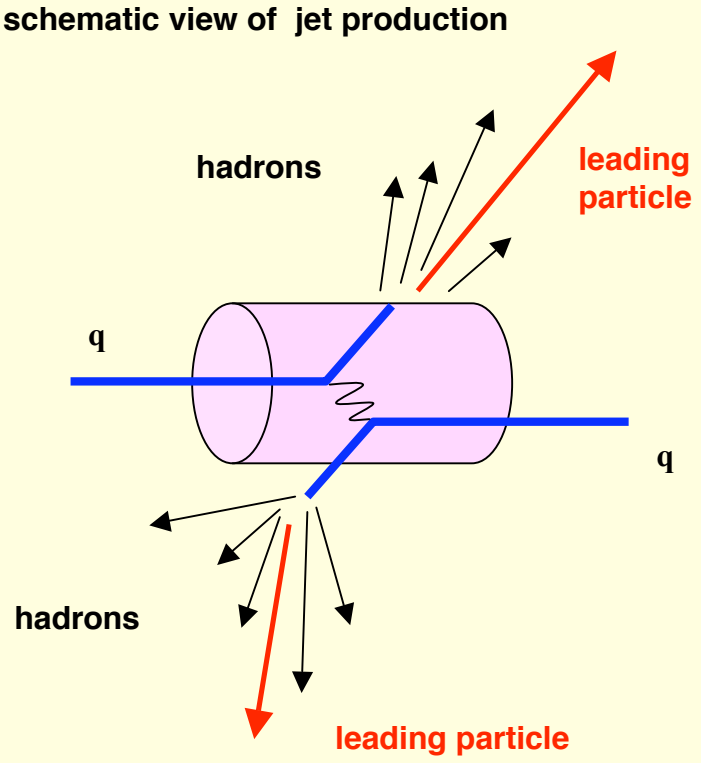
Quenching of Hard Scattered Partons

- **Hard parton scatterings in nucleon collisions produce jets of particles.**
- **In the presence of a dense strongly interacting medium, the scattered partons will suffer soft interactions losing energy (dE/dx~GeV/fm).**
- **"Jet Quenching"**



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High p_T Suppression: Outline of Talk

- The PHENIX experiment
- High p_T hadron suppression in Au+Au
- High p_T hadron suppression in d+Au (the control experiment)
- Particle type dependence of suppression
- Future investigations: Direct γ's
- Conclusions

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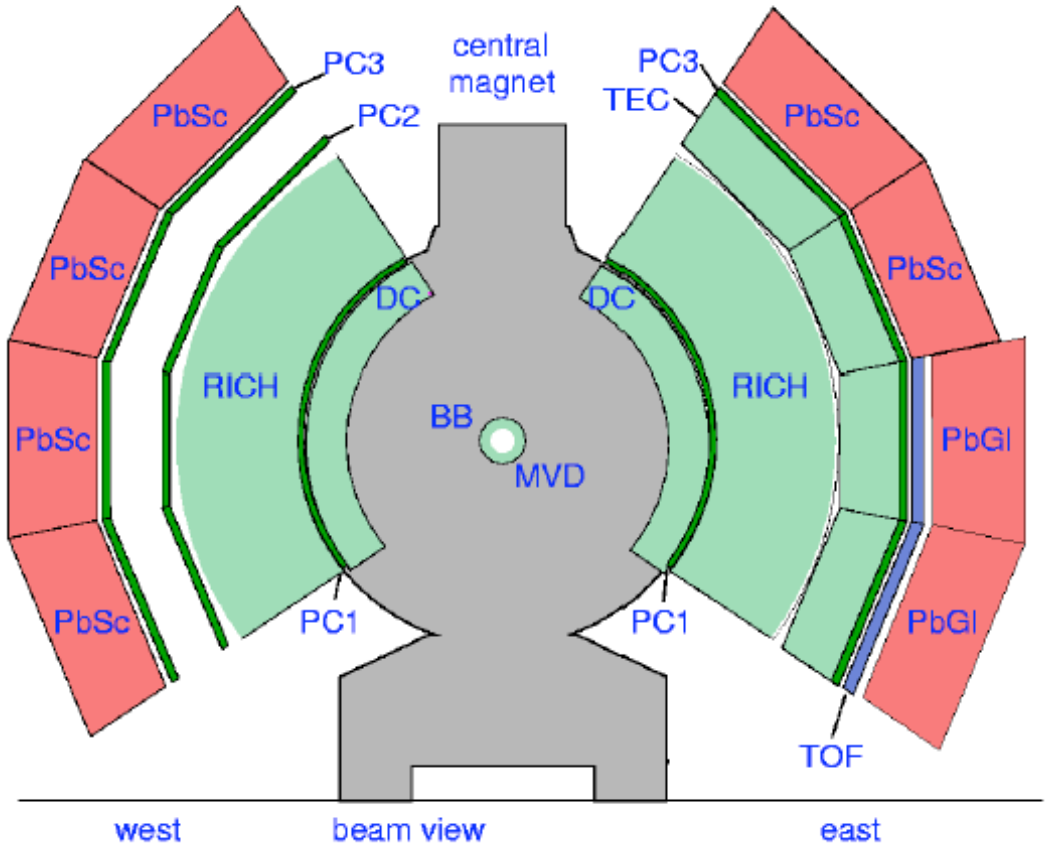
PHENIX Electromagnetic Calorimeter



PbSc

• Highly segmented lead **scintillator** sampling Calorimeter

• Module size: 5.5 cm x 5.5 cm x 37 cm

PbGl

•Highly segmented lead glass **Cherenkov** Calorimeter

• Module size: 4 cm x 4 cm x 40 cm

Two Technologies - very important for systematic error understanding!

Differences:

•Different response to hadrons

•Different corrections to get linear energy response

•Different shower overlap corrections

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"The virtue of π^0 and γ Measurements"

To determine if we have produced deconfined QGP we must separately distinguish initial state effects from final state effects.

Once produced, γ's do not interact -> sensitive to: (yield goes ↓↑)

- **initial parton distributions: Intrinsic k_T, k_T Broadening, Shadowing, Anti-shadowing, Saturation, …**
- **final state parton/hadron rescatterings: Thermal, Jet/Parton Radiation,…**

π^0's will suffer additional final state effects: Rescattering (low p_T), Absorption, k_T Broadening, Jet/Parton Energy Loss ,…

Experimental virtues (calorimeter measurement):

- **Measure γ and π^0 in same detector (get 2 for the price of 1!)**
- **Identified particles to very high p_T**
- **π^0's abundantly produced**
- **π^0 mass provides calibration check**

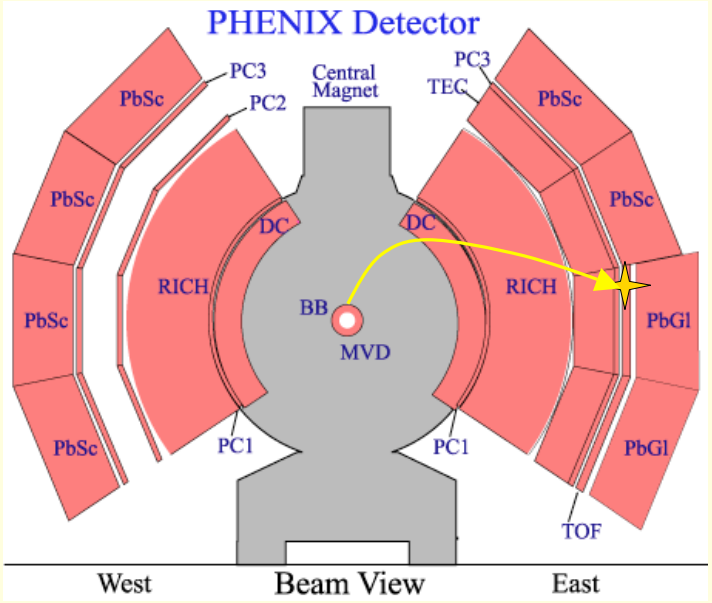
Highlighted here

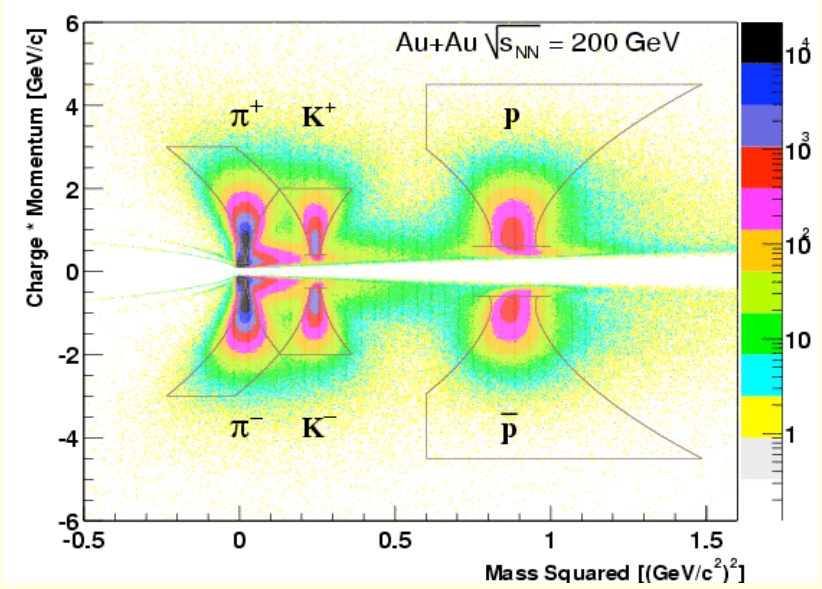
Identified Charged Tracking

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

$$\Box p/p \Box 0.7\% \oplus 1.0\% \Box p\ (\mathrm{GeV}/c)$$

- **TOF resolution** $\Box_{TOF}$ ~ 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.





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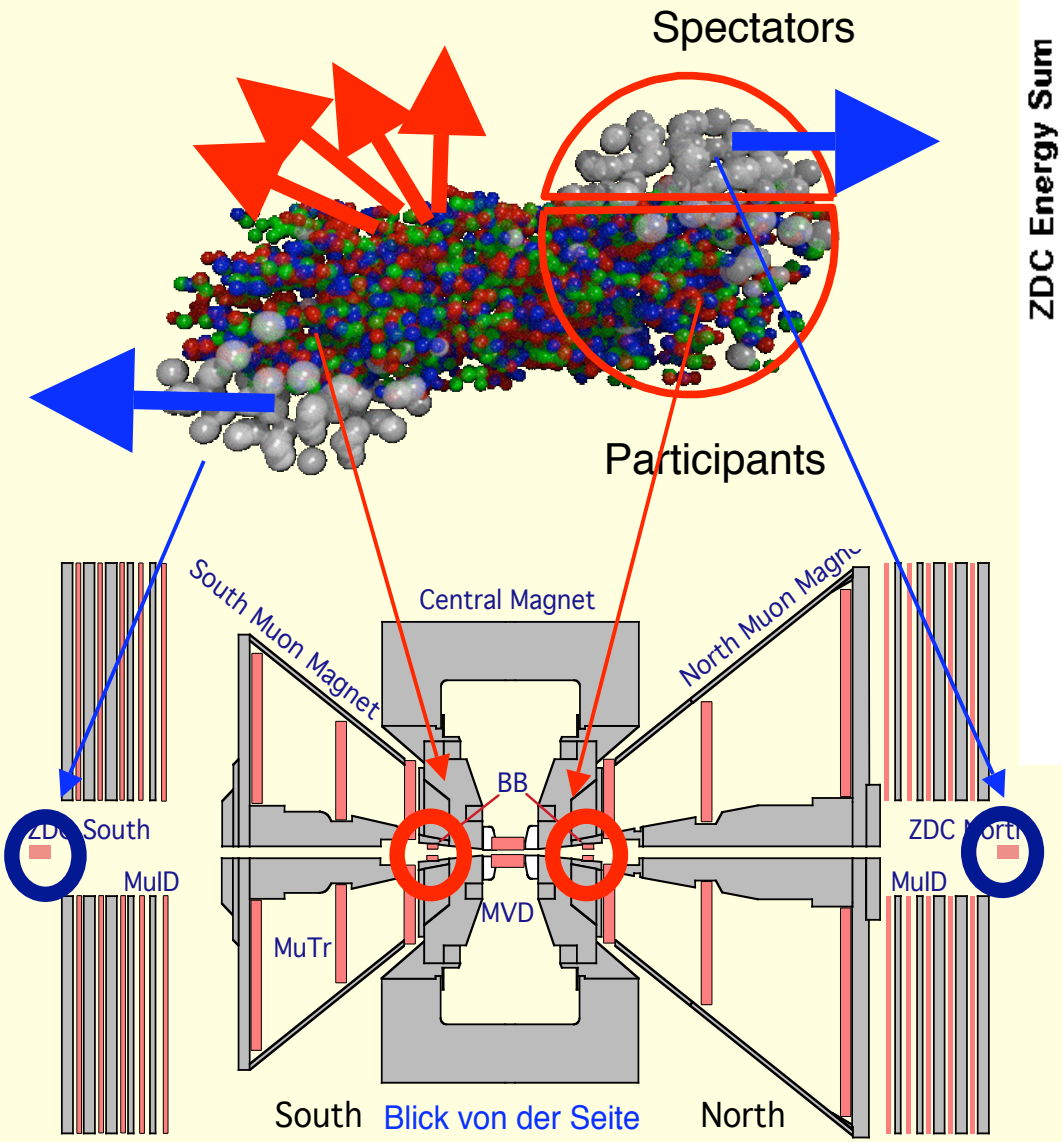
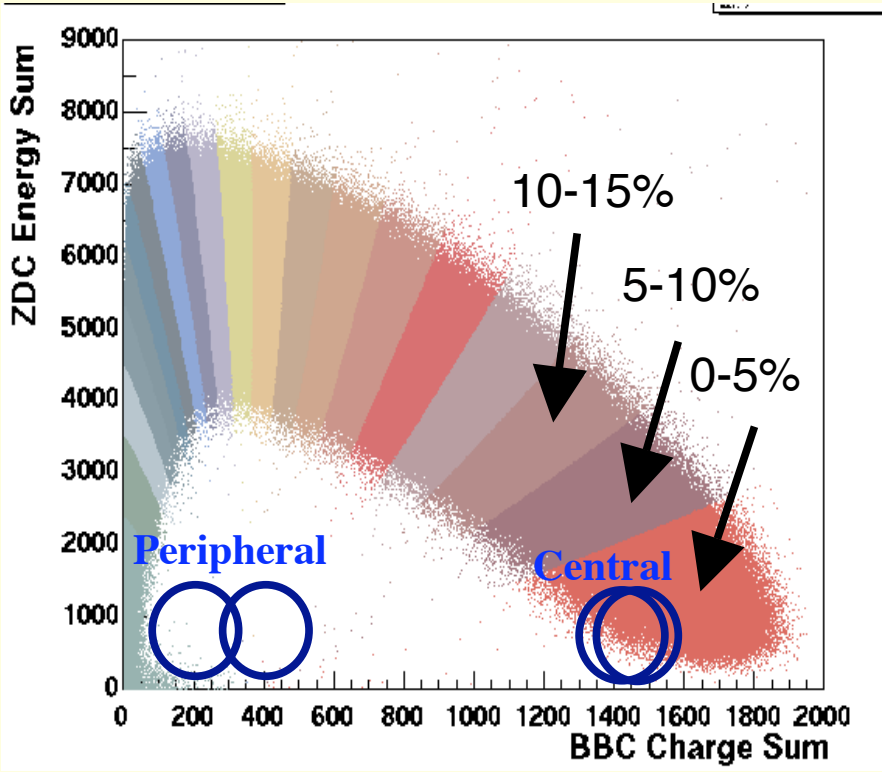
Collision Centrality Determination





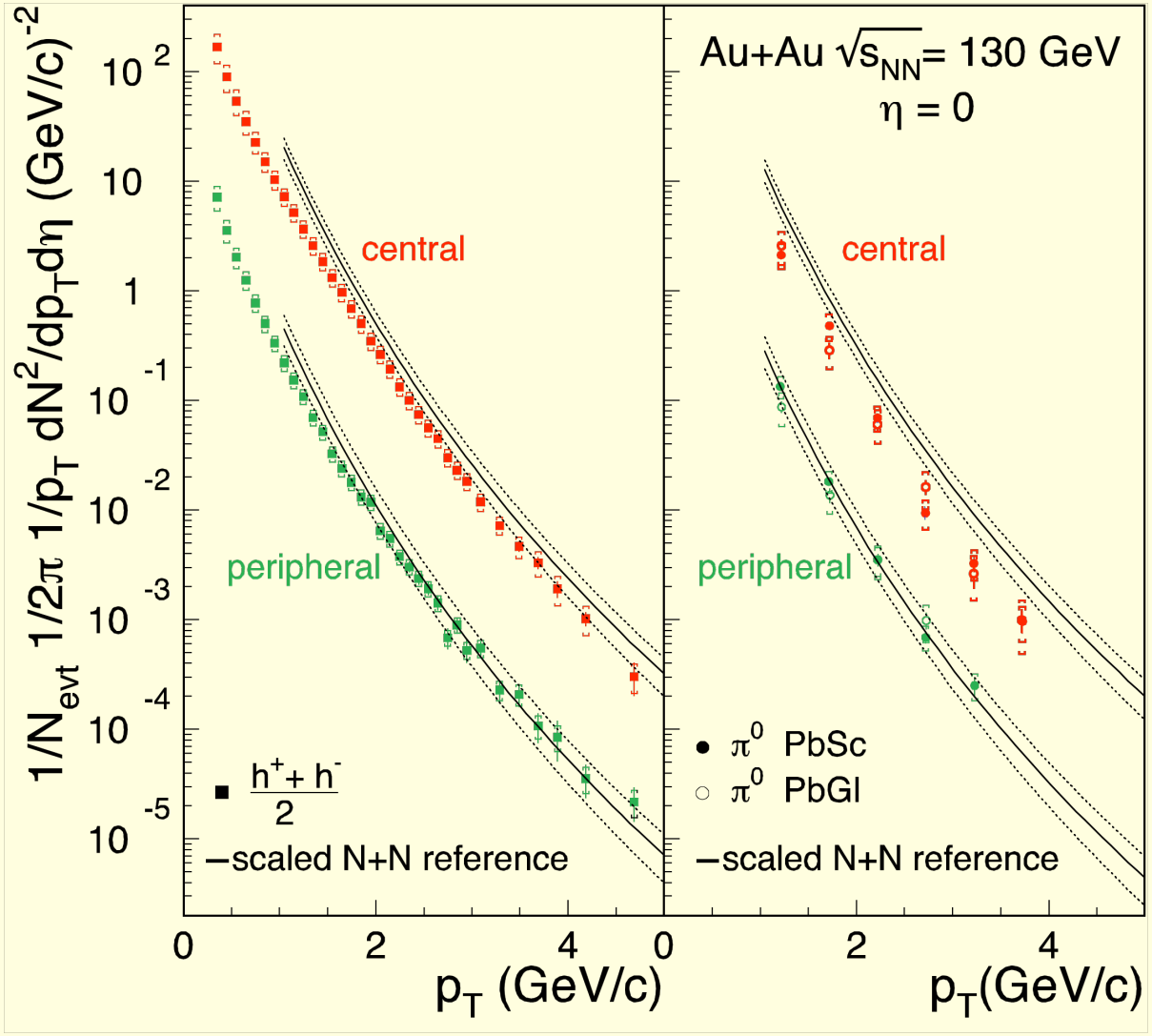
- **Centrality selection : Sum of Beam-Beam Counter (BBC, |□|=3~4) and energy of Zero-degree calorimeter (ZDC)**
- **Extracted N_{coll} and N_{part} based on Glauber model.**

RHIC Year-1 High-P_T Hadrons

Hadron spectra out to p_T~4-5 GeV/c

Nominally expect production through hard scattering, scale spectra from N+N by number of binary collisions

Peripheral reasonably well reproduced; but central significantly below binary scaling



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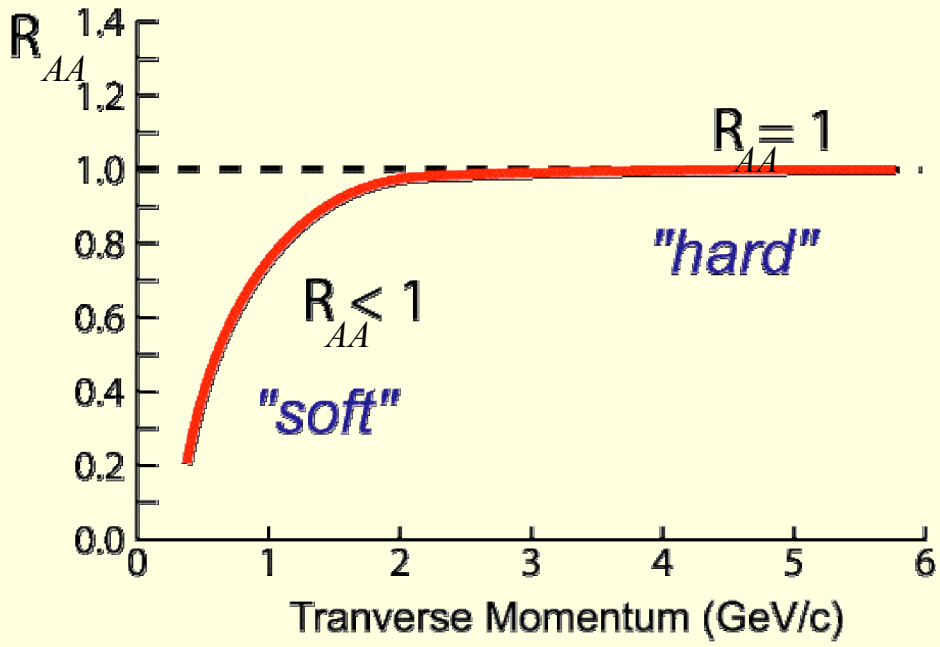
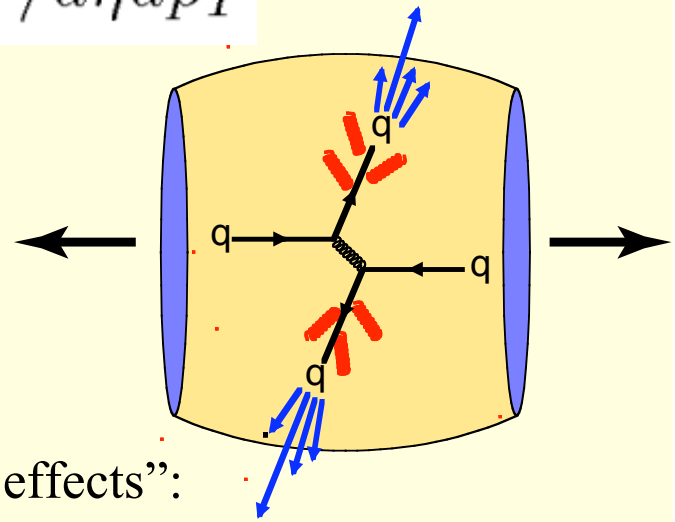
Closer look using the Nuclear Modification Factor R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2 N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, d^2 N_{pp}/d\eta dp_T}$$

Compare A+A to p-p cross sections





"Nominal effects":

$R_{AA} < 1$ in regime of soft physics

$R_{AA} = 1$ at high-p_T where hard scattering dominates

$R_{AA} > 1$ due to k_T broadening (Cronin)

Suppression:

$R_{AA} < 1$ at high-p_T

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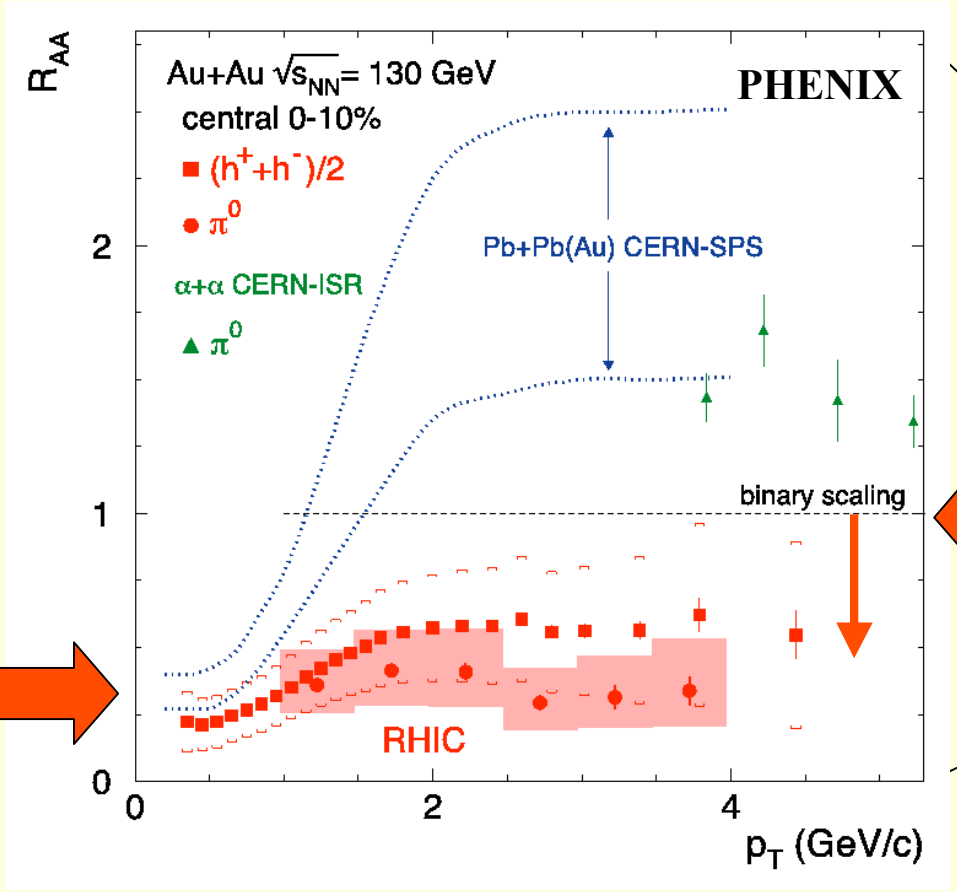
RHIC Headline News… January 2002



PHENIX PRL 88, 022301 (2002)

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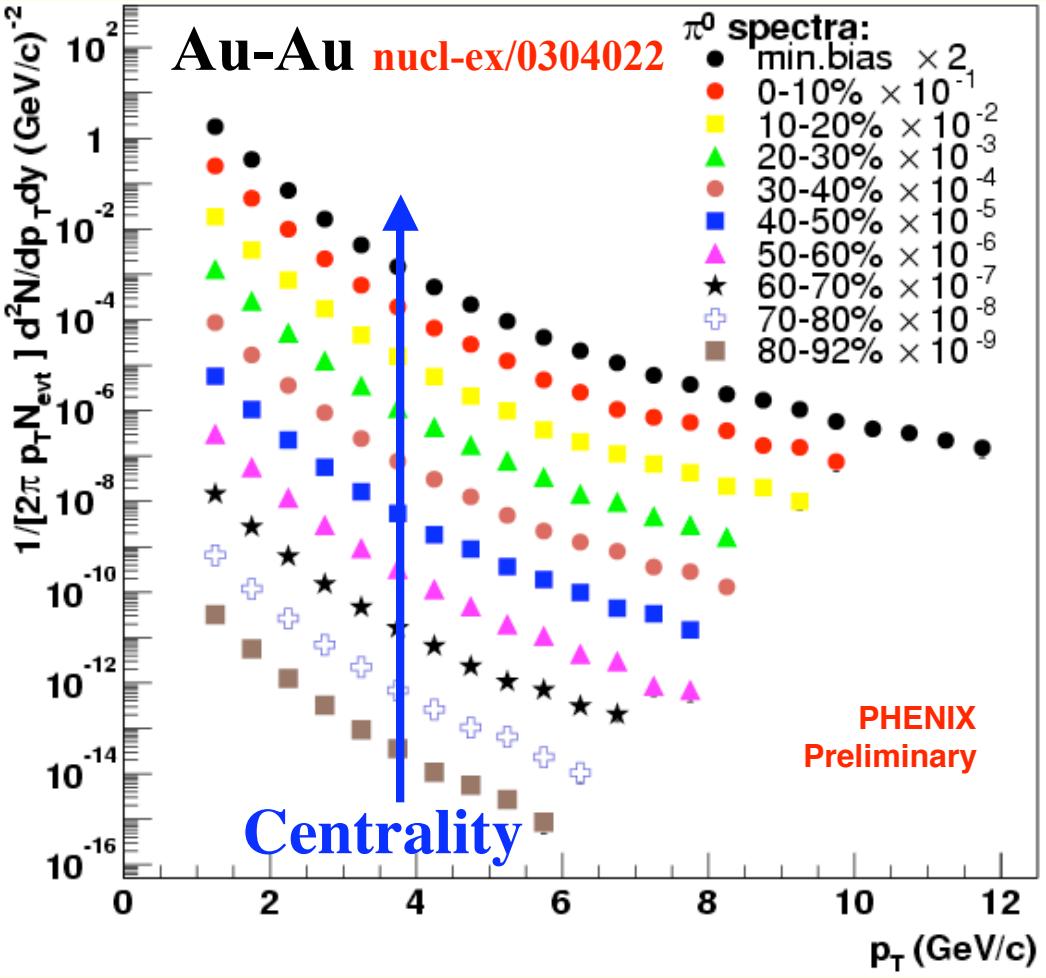
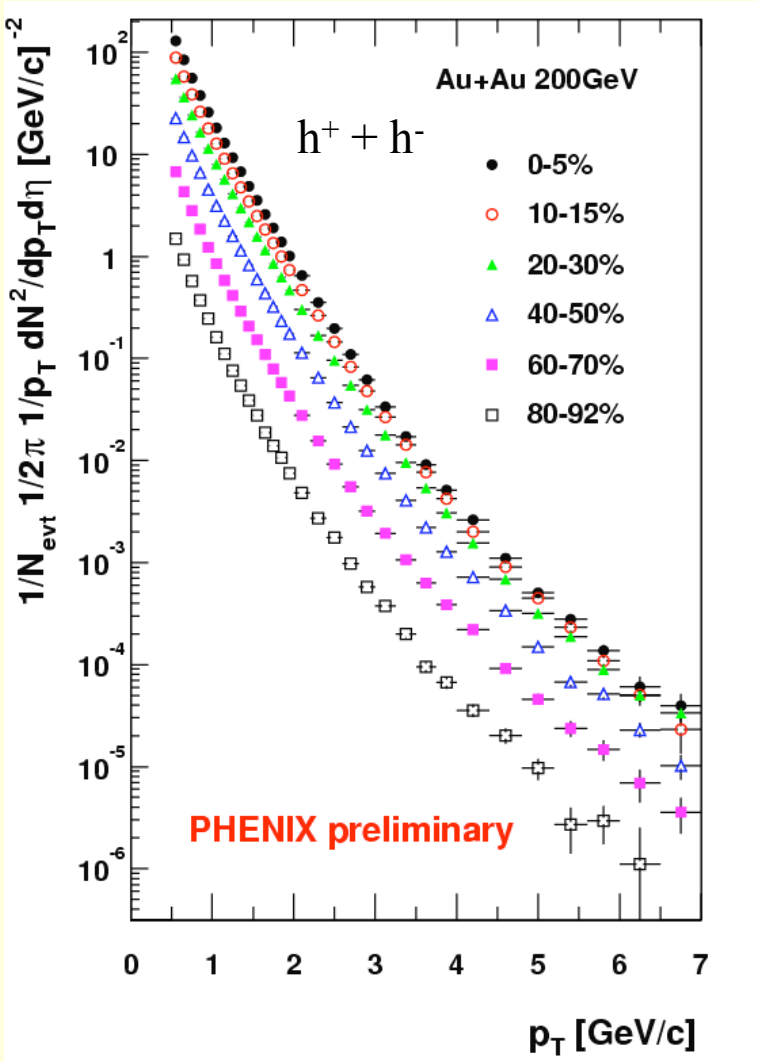
RHIC Run 2: s=200 GeV/c Au+Au collisions now extend to higher P_T





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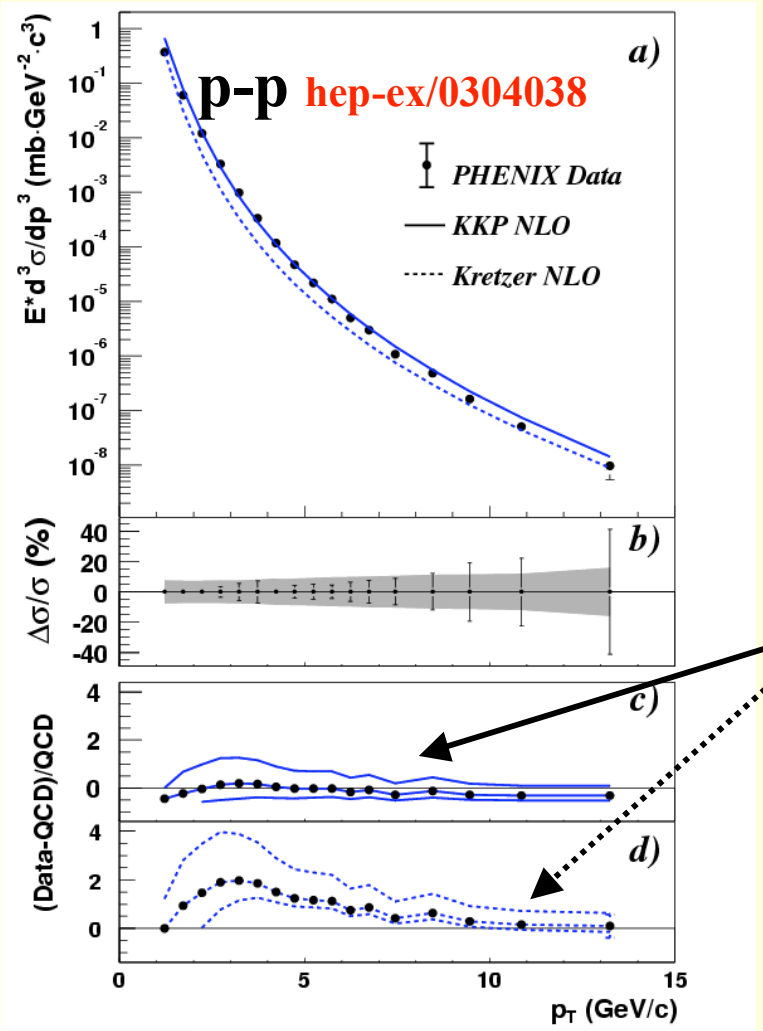
Also measured high-P_T π^0 spectra in p+p collisions at 200 GeV/c (Reference measurement)



Spectra for π^0 out to 12 GeV/c compared to NLO pQCD predictions.

Very good agreement!

(Good news for Direct γ measurement!)

No intrinsic k_T included.

Calculations with different (gluon) FF's (Regions indicate scale uncertainty)

Reference pp result for AuAu suppression

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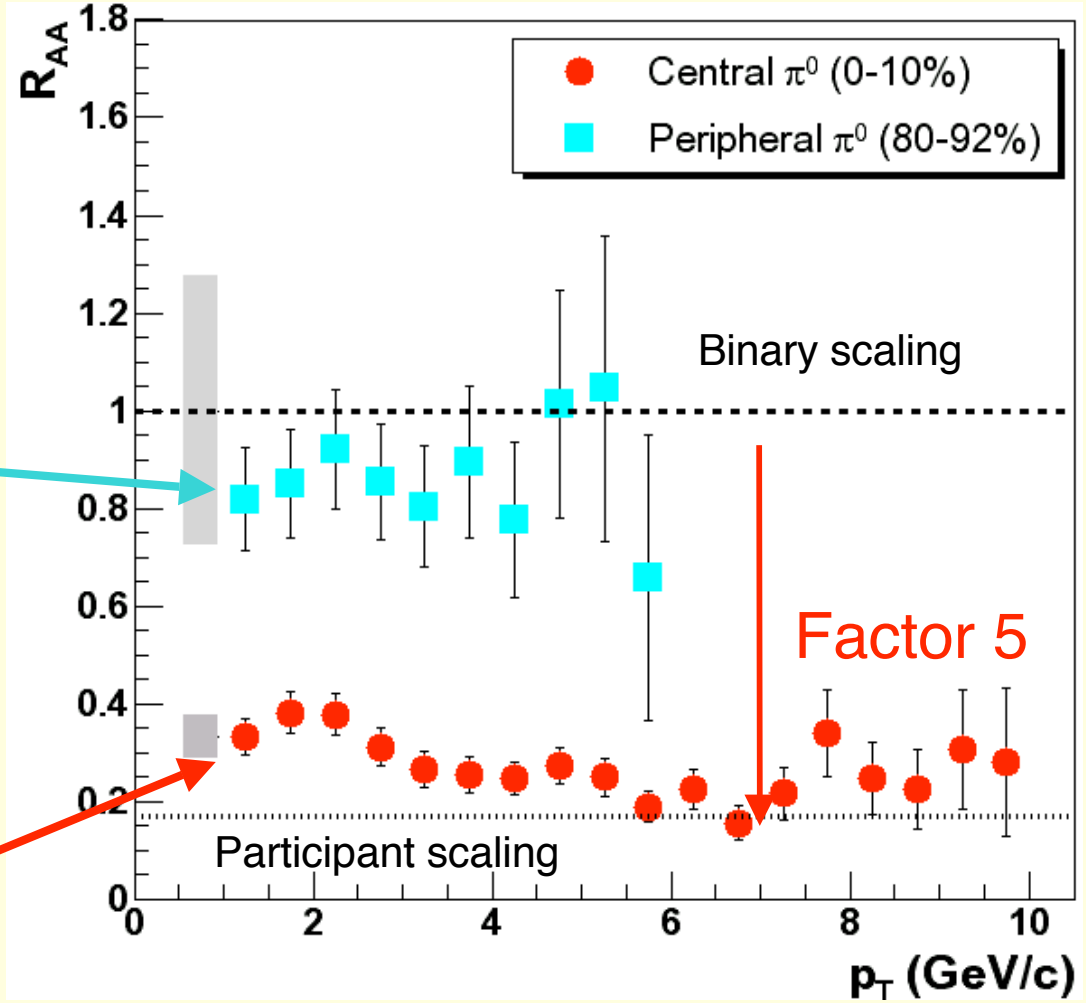
R_{AA} : High P_T Suppression to at least 10 GeV/c

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

Peripheral AuAu - consistent with N_{coll} scaling (large systematic error)

Large suppression in central AuAu - close to participant scaling at high P_T



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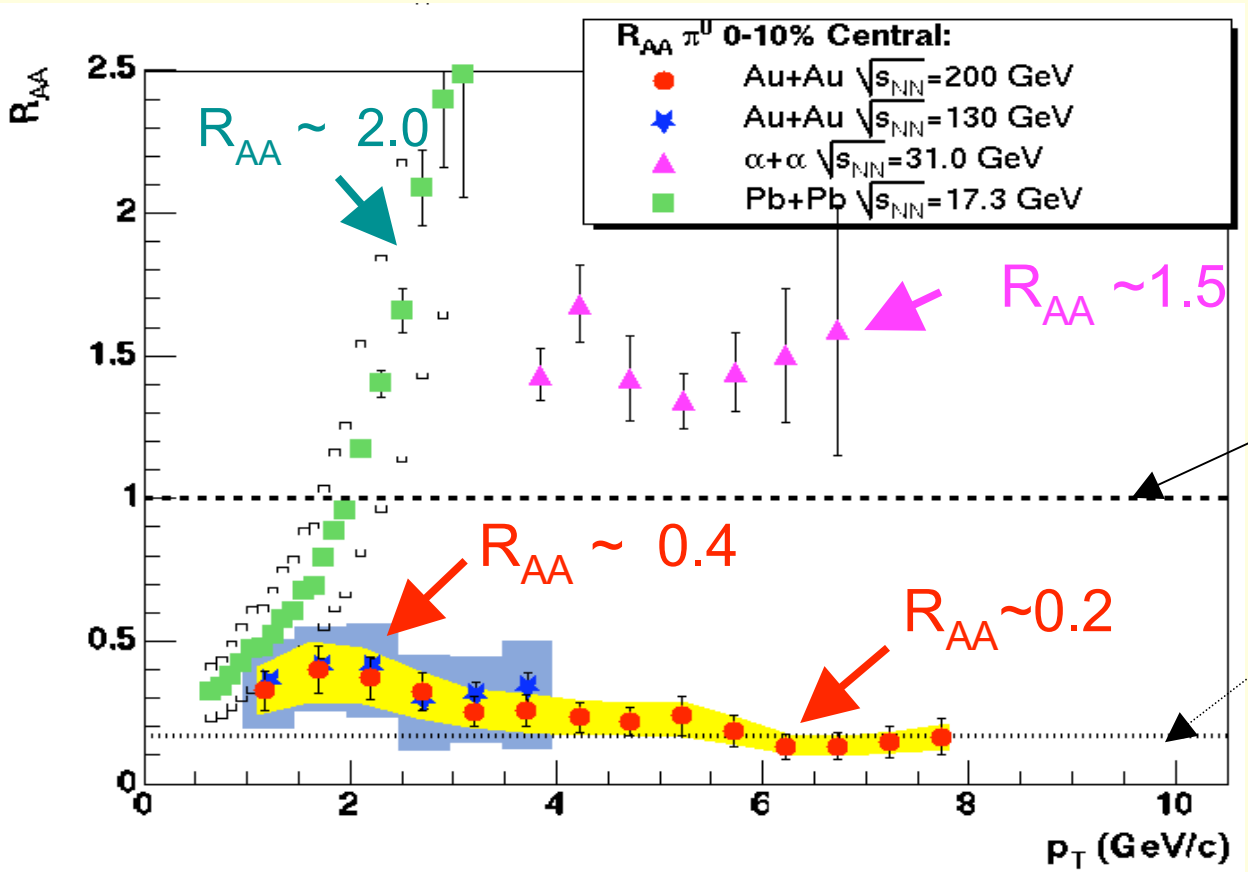
PRL 91 (2003) 072301

Nuclear modification factor: s_{NN} dependence

RHIC: Au+Au (s_{NN} ~ 130, 200 GeV): ~x5 suppression with respect to N_{coll}

CERN: Pb+Pb (s_{NN} ~ 17 GeV), □+□ (s_{NN} ~31 GeV): Cronin enhancement

Is there no energy loss at SPS energies? □$_{SPS}$ ~ 0.5*□$_{RHIC}$



A.L.S.Angelis PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
D.d'E. PHENIX Preliminary QM2002

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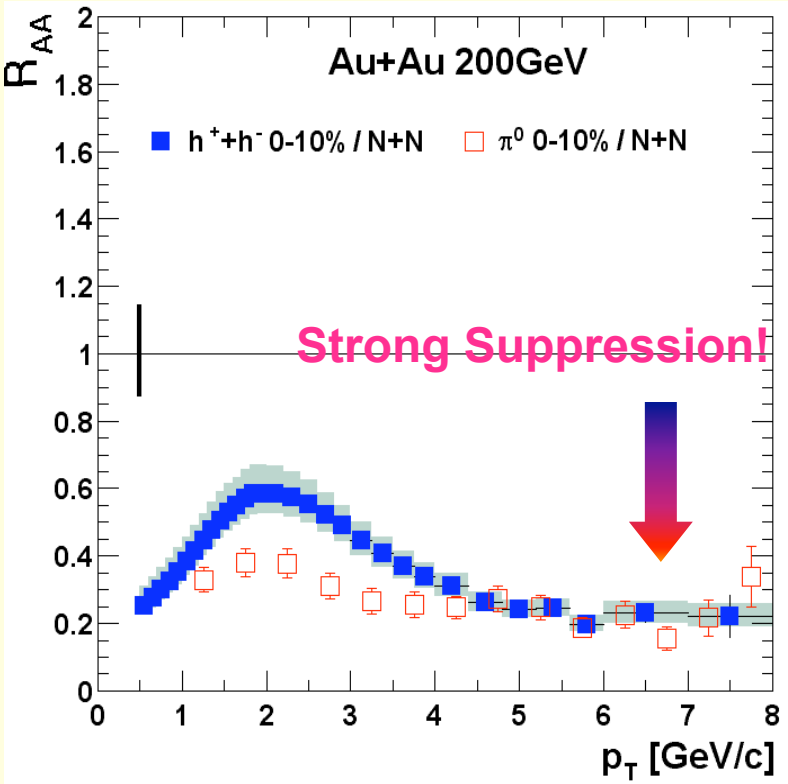
Centrality Dependence R_{AA} for π^0 and charged hadron

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$



- R_{AA} is well below 1 for both charged hadrons and neutral pions.
- The neutral pions fall below the charged hadrons.
- Difference due to 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).

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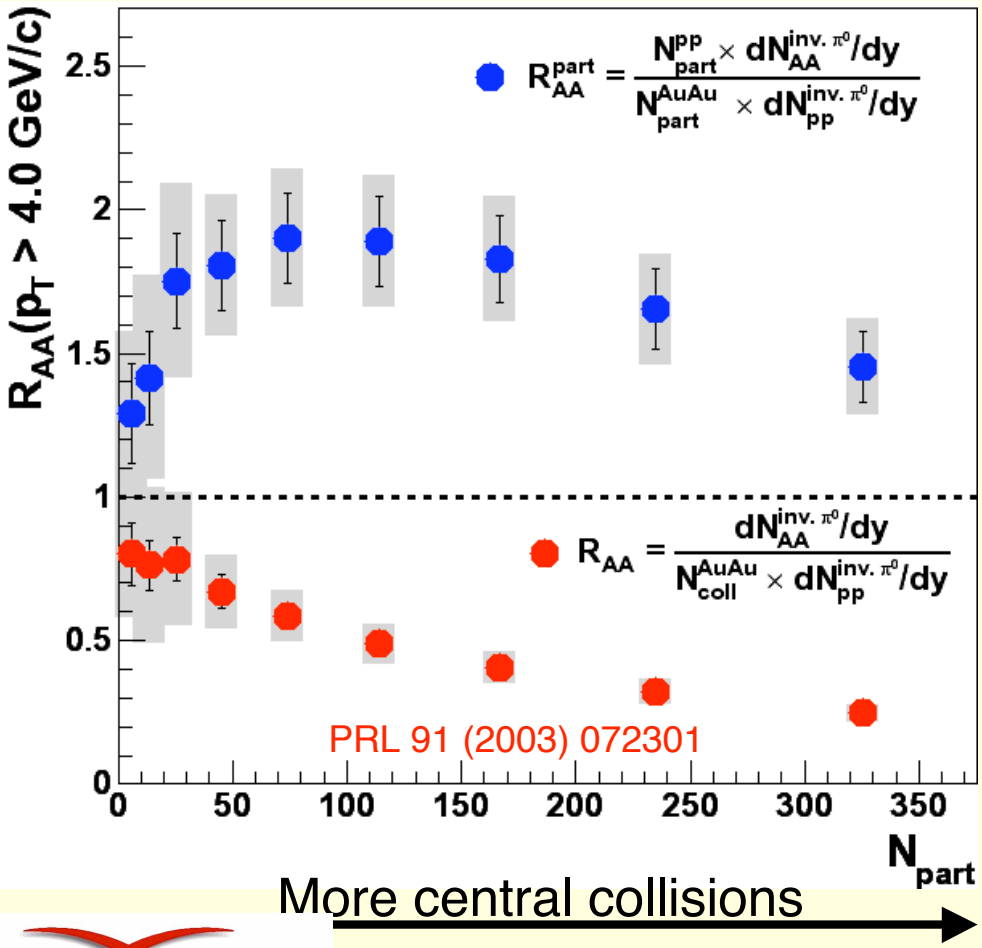
Centrality Dependence of R_{AA}

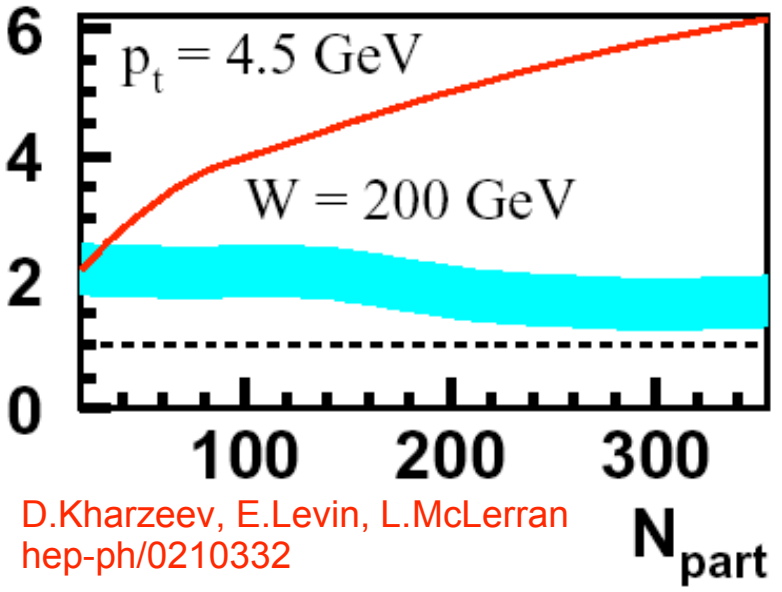
The suppression increases smoothly with centrality
- approximate N_{part} scaling.



More central collisions

Centrality dependence similar to predictions of Color Glass Condensate (AKA Gluon Saturation)

- Suggests Initial state effect!?!



D.Kharzeev, E.Levin, L.McLerran
hep-ph/0210332

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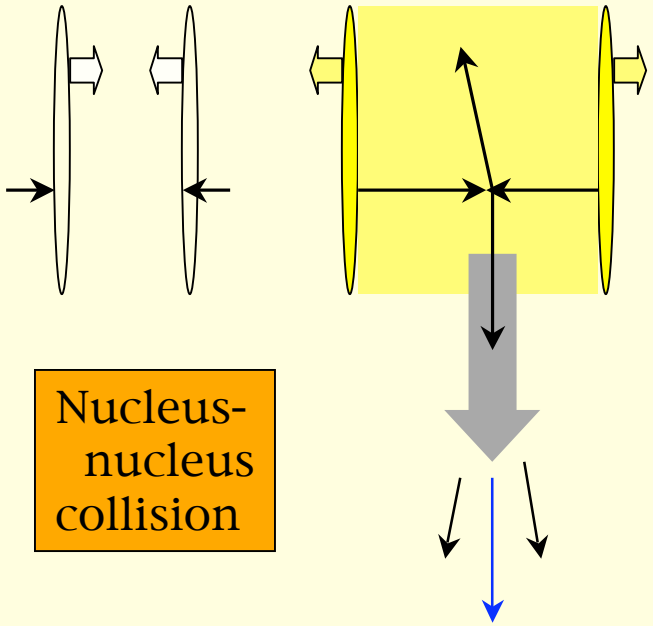
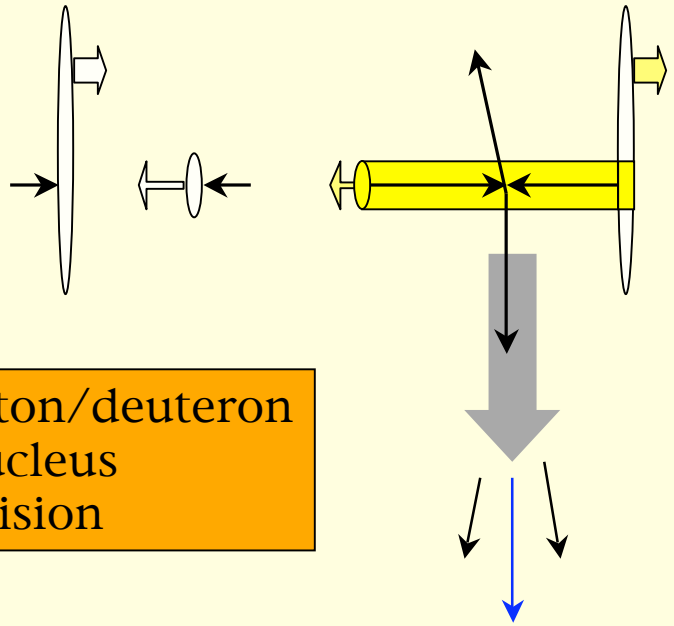
p+A (or d+A): The control experiment



Nucleus-nucleus collision



Proton/deuteron nucleus collision

- **In Jet Quenching .interpretation - interaction with medium produced in final state suppresses jet. In Gluon Saturation interpretation, gluons are suppressed in initial state resulting in suppression of initial jet production rate.**
- **Could these initial state effects be causing the suppression of high-P_T hadrons in Au+Au collisions?**
- **If so, then we should see suppression of high-P_T hadrons in d+Au collisions.**

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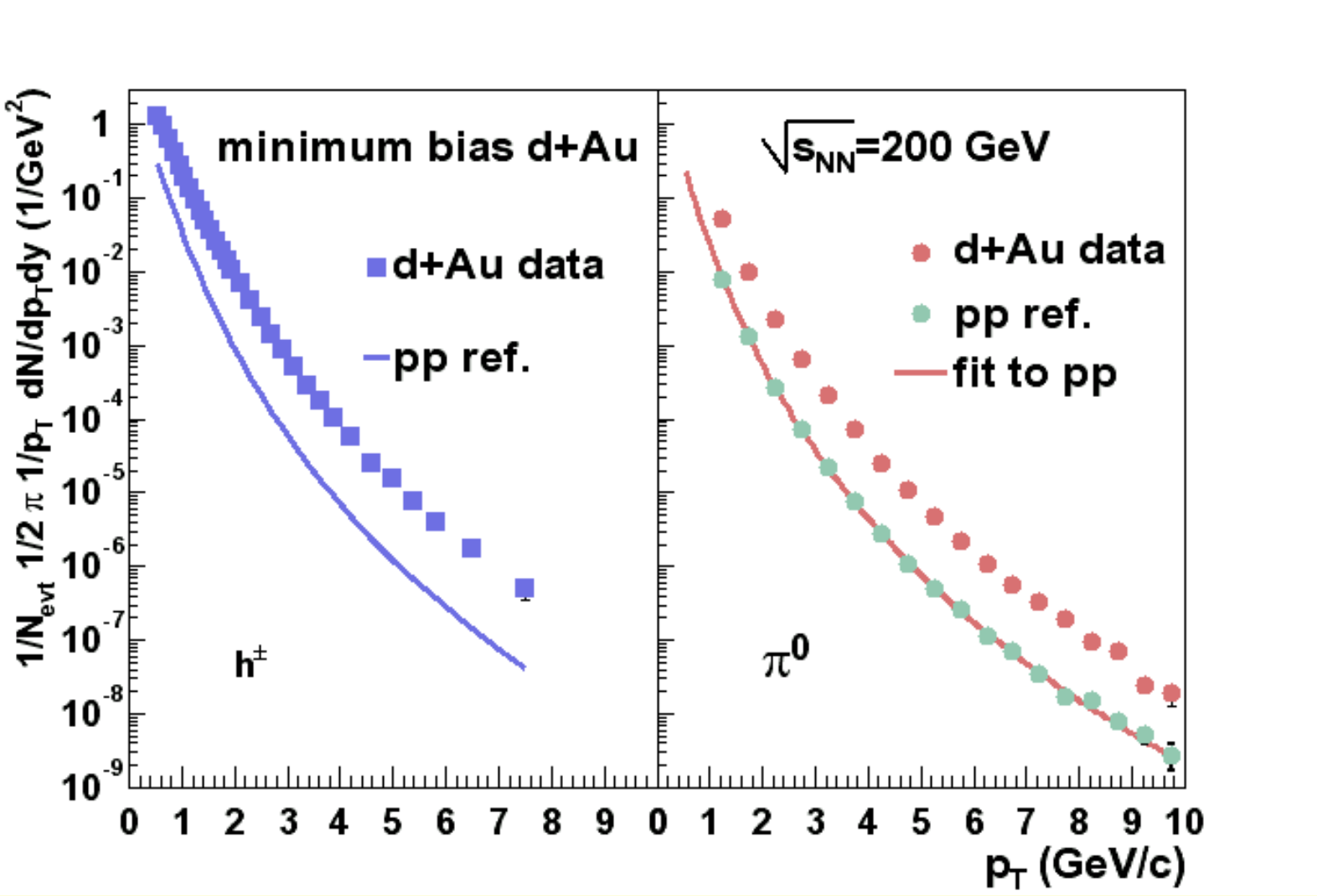
RHIC Run 3: High P_T Spectra in d+Au Collisions



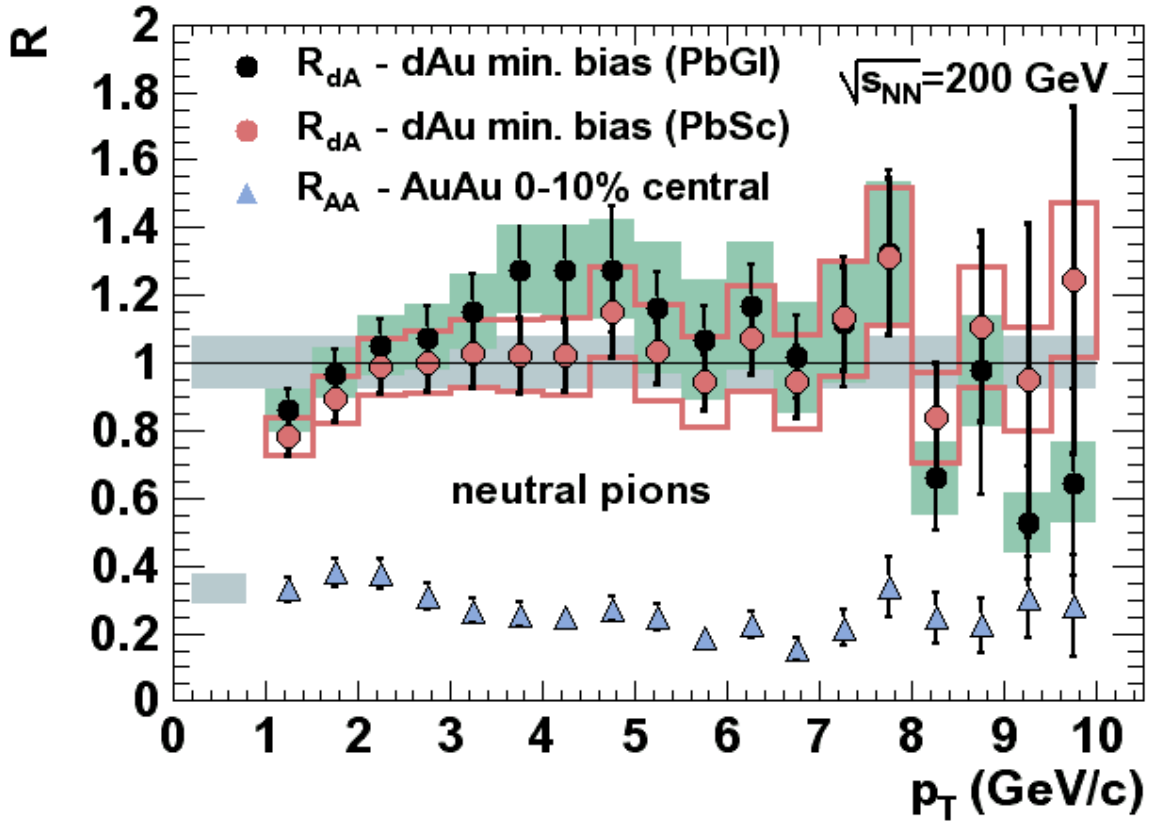
Final spectra for charged hadrons and identified pions.
PHENIX, PRL91 (2003) 072303.

R_{AA} vs. R_{dA} for Identified π^0

Neutral pions are measured with 2 independent Calorimeters – PbSc and PbGl: Consistency check.

d+Au

Au+Au

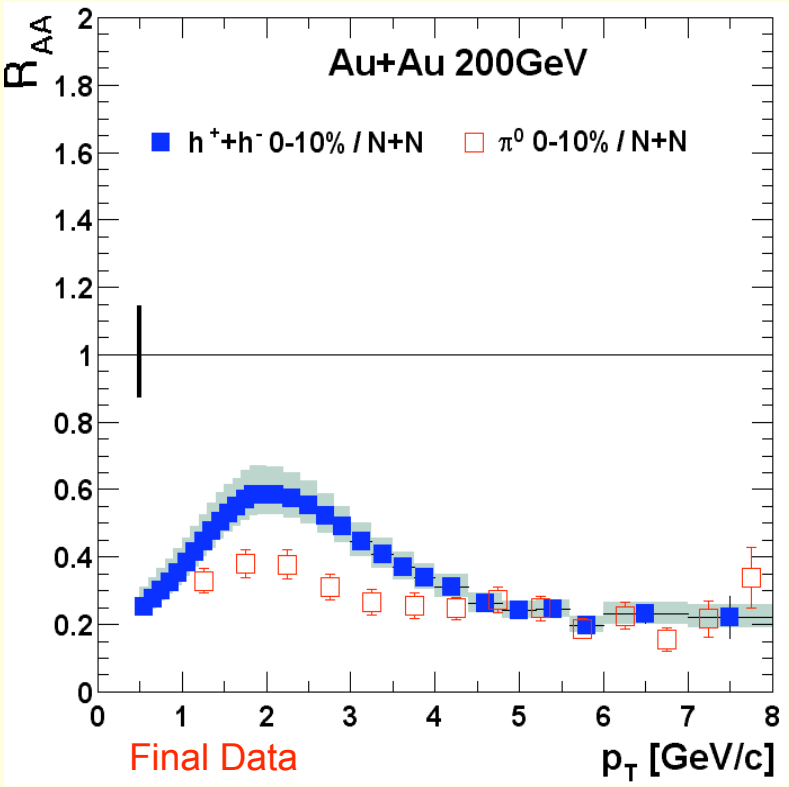


The dAu results (initial state effects only) suggest that the created medium is responsible for high p_T suppression in Au+Au.

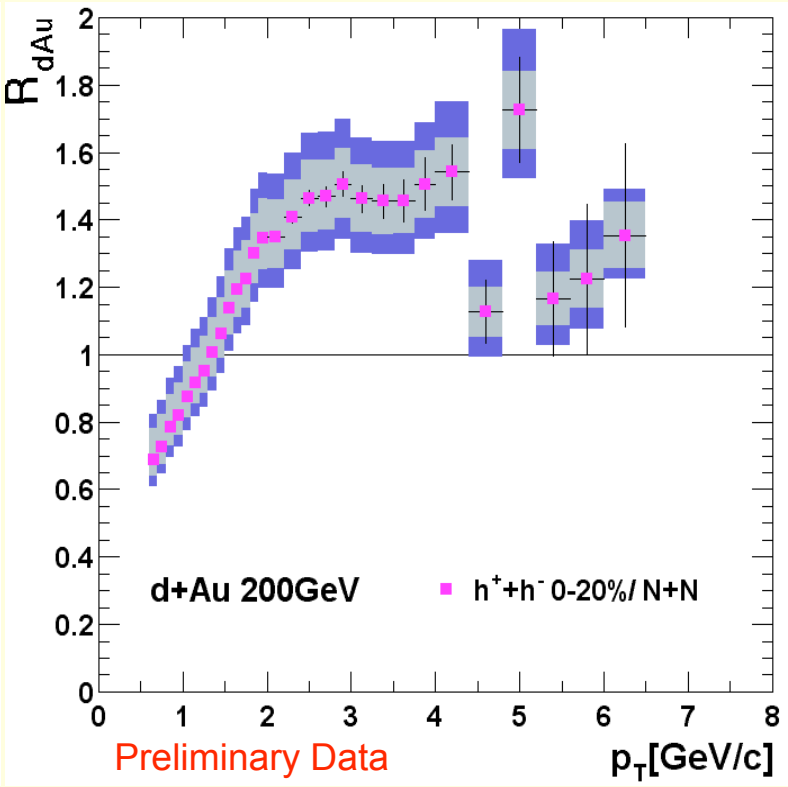
PHENIX, PRL91 (2003) 072303.

Centrality Dependence

Au + Au



d + Au Control



- Opposite centrality evolution of Au+Au compared to d+Au control.
- **Initial state enhancement ("Cronin effect") in d+Au is suppressed by final state effect in Au+Au.**
- **Notice difference between π^0 and $h^+ + h^-$ (more later).**

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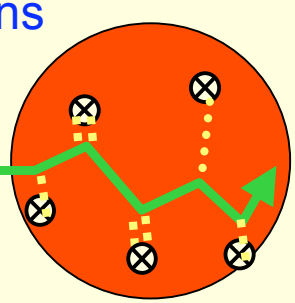
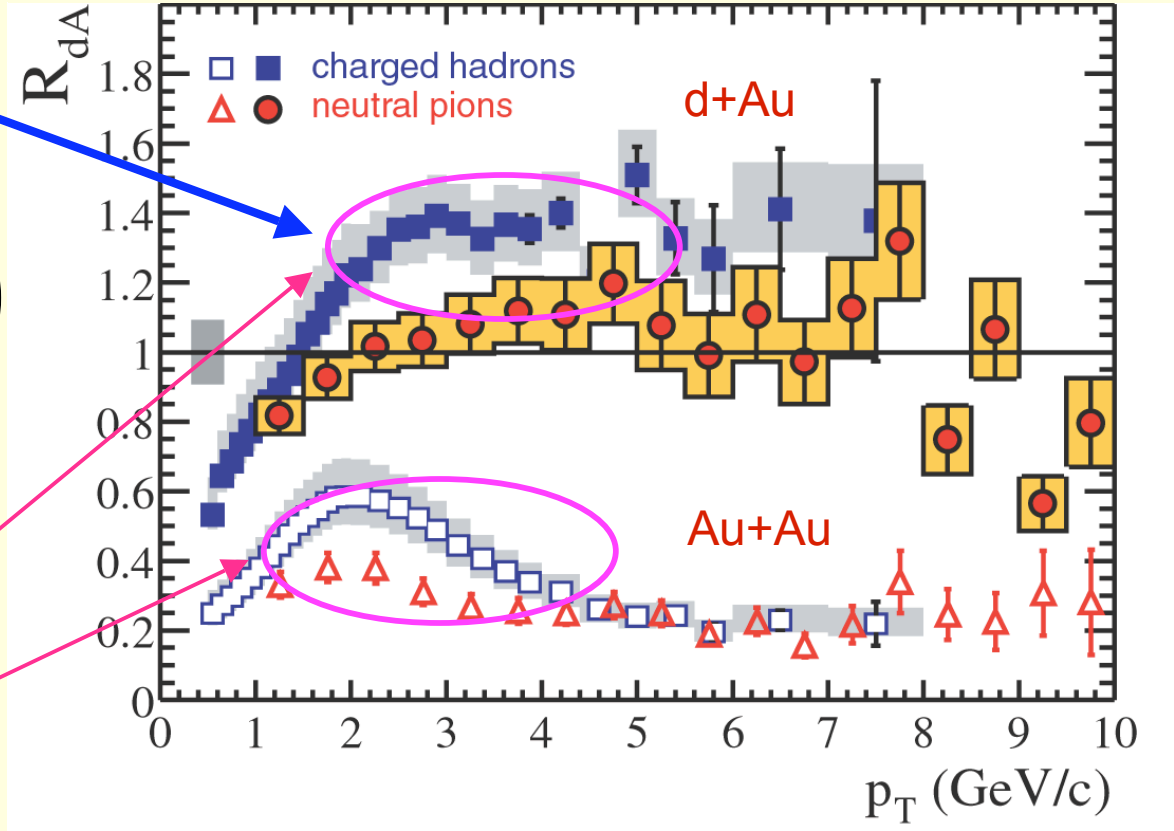
Cronin Effect:(R_{AA}>1) Charged hadrons vs. π^0

d+Au: Cronin Effect (R_{dA}>1): Initial Multiple Collisions broaden P_T spectrum





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

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

Particle ID is important!

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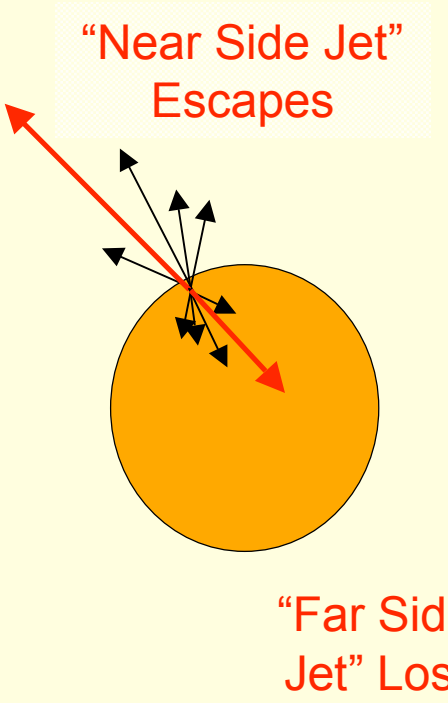
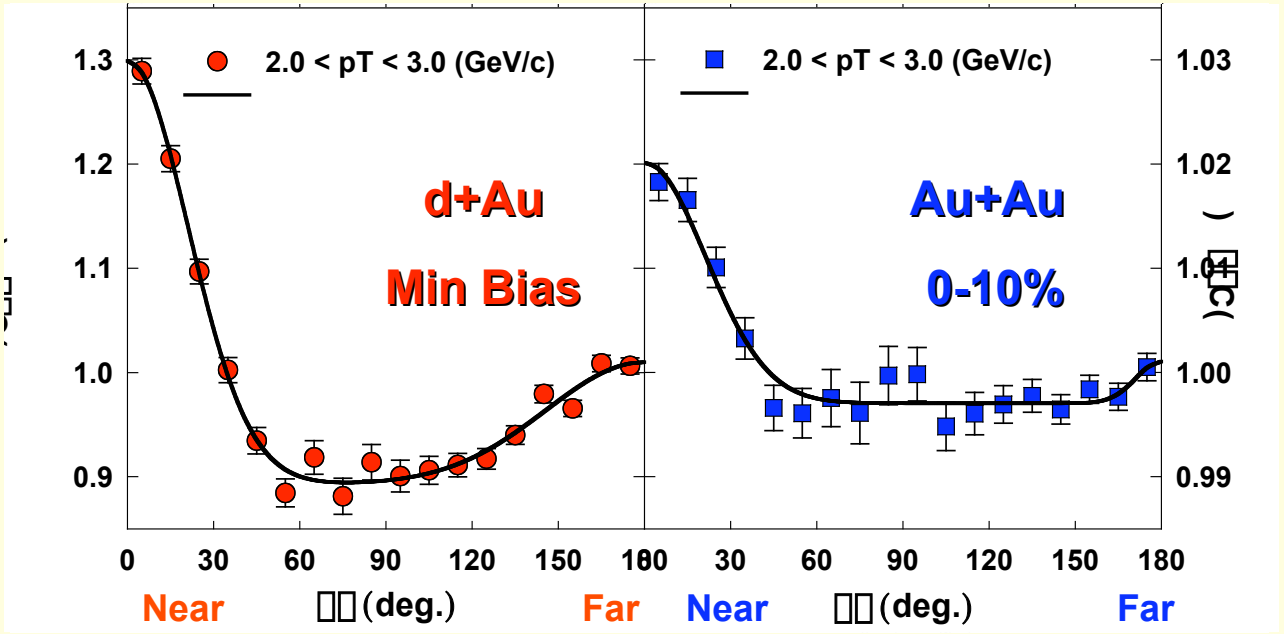
The "Away-Side" Jet: 2-Particle Correlations





PHENIX Preliminary PHENIX Preliminary

Parton exiting on the periphery of the collision zone should survive while partner parton propagating through the collision zone is more likely to be absorbed.

- Peripheral Au+Au similar to d+Au
- Central Au+Au shows distinct reduction in far side correlation.
- **Away-side Jet is suppressed in Central Au+Au - Further indication of suppression by produced medium.**

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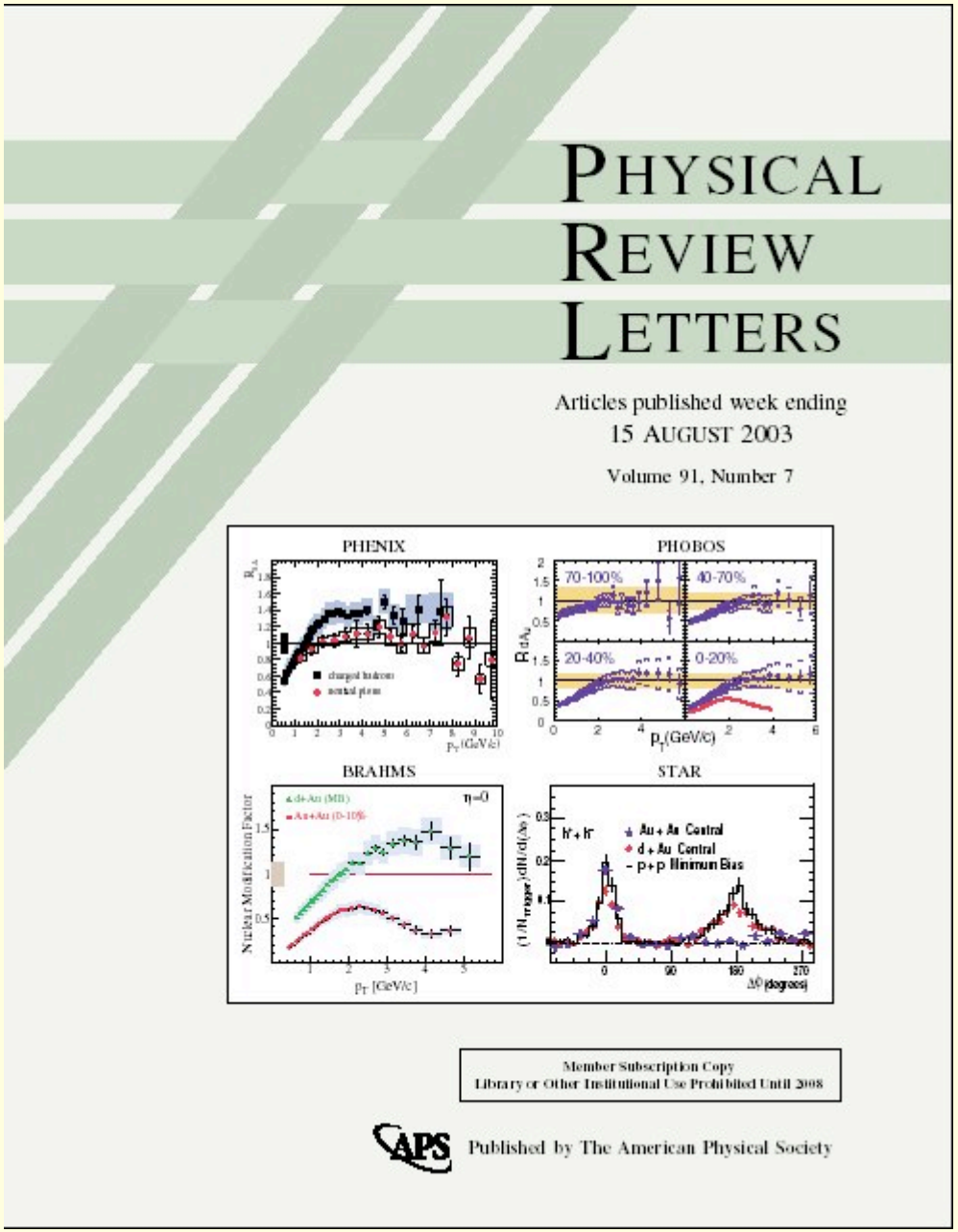

RHIC headline news… August 2003

BNL Press Release, June 2003:

Lack of high p_T hadron suppression in d+Au strongly suggests that the large suppression in Au+Au is a final state effect of the produced matter (QGP?!)

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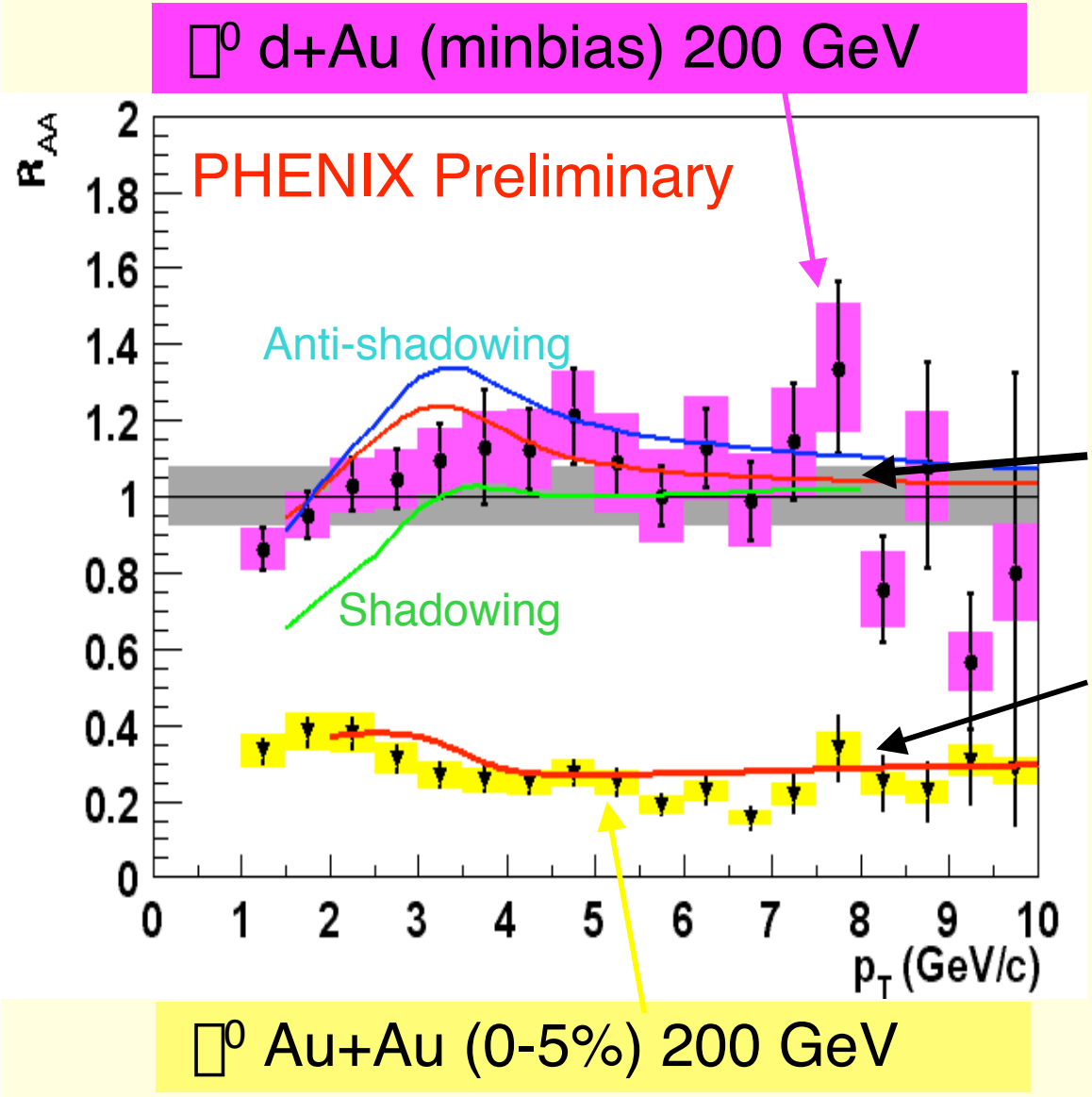
Data vs Theory : π^0



Energy loss + Shadowing + Cronin explains both Au+Au and d+Au!

Can dAu and AuAu centrality dependence also be explained?

d+Au: I. Vitev, nucl-th/0302002 and private communication.

Au+Au: I. Vitev and M. Gyulassy, hep-ph/0208108, to appear in Nucl. Phys. A; M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, p. 371 (2001).

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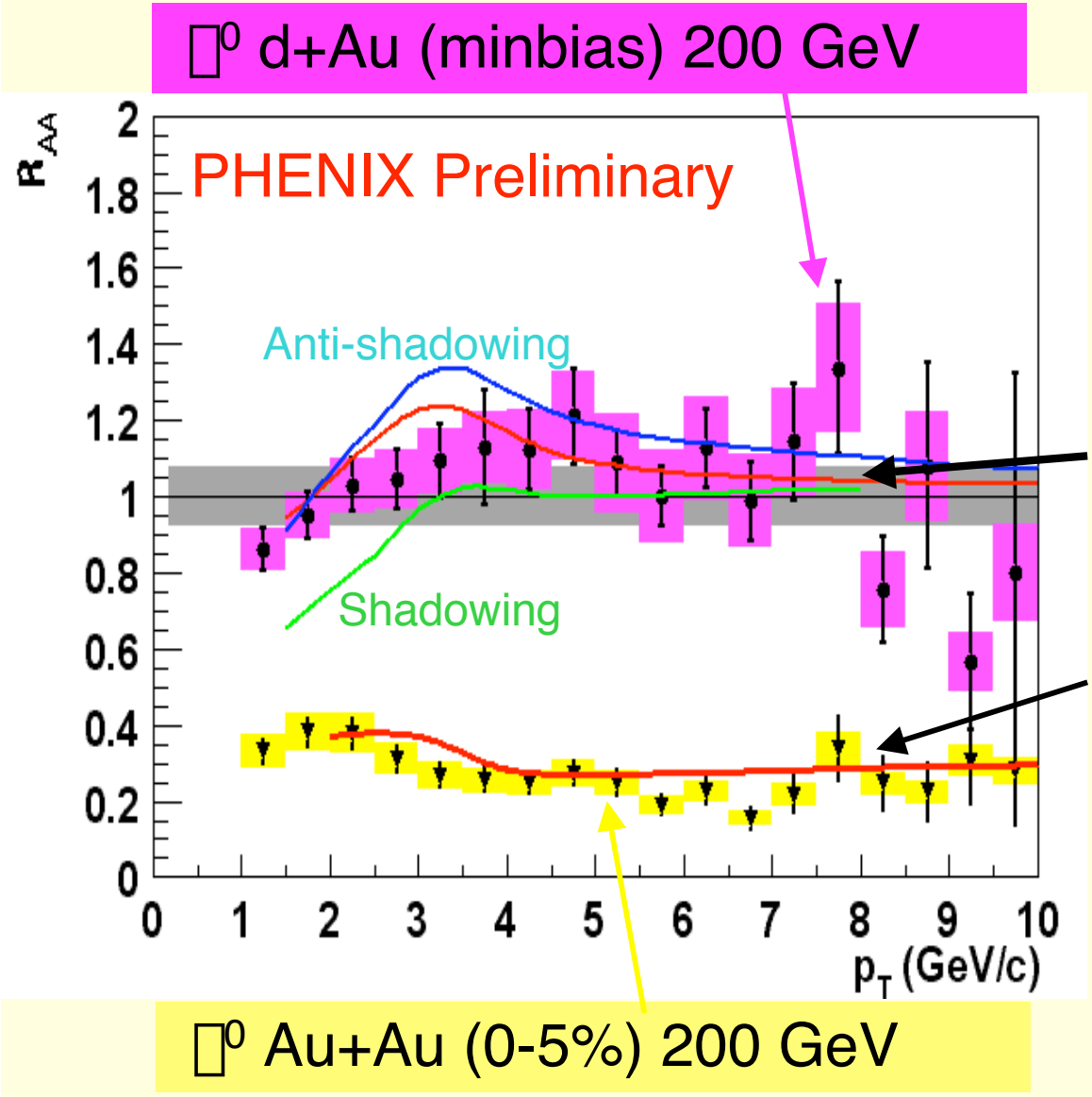

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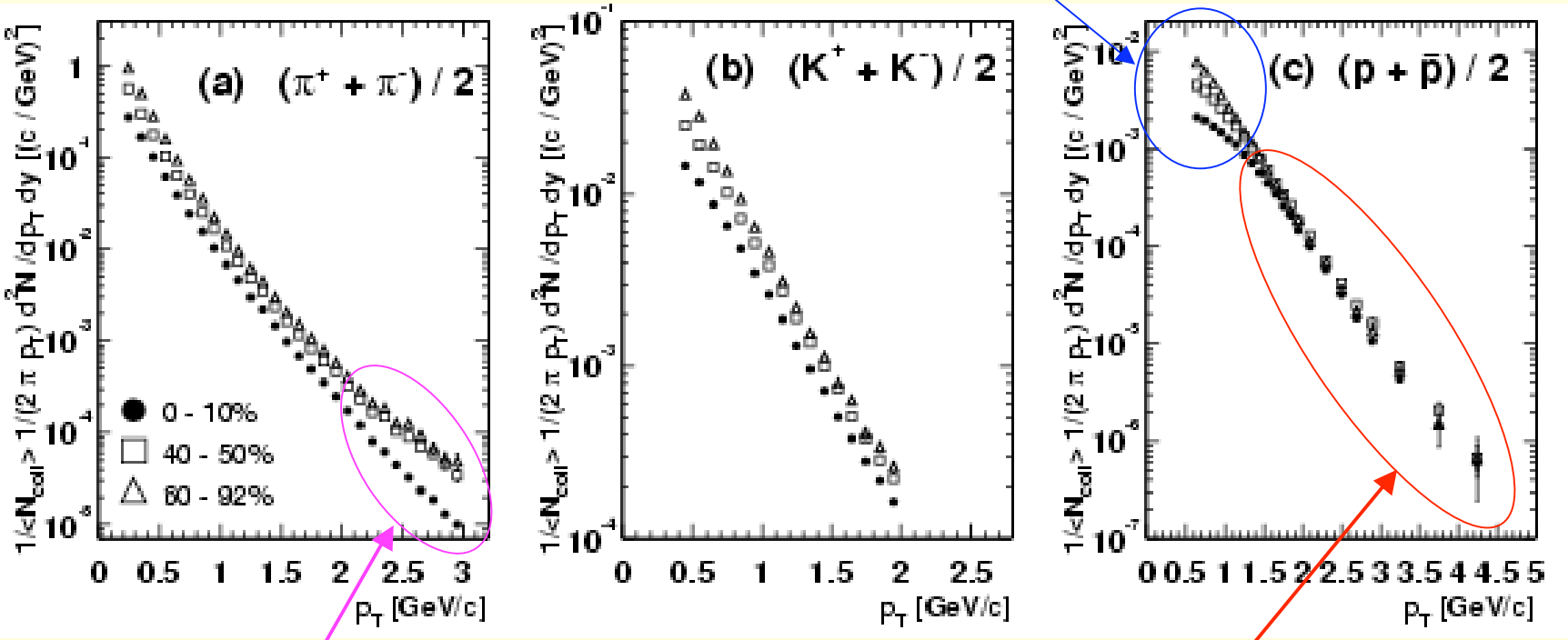
π^0 vs $h^+ + h^-$?: N_{coll} scaled p_T spectra of π, K, p

Radial Flow Effect



Suppressed in central at high p_T (> 2.0 GeV) i.e. same as π^0

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

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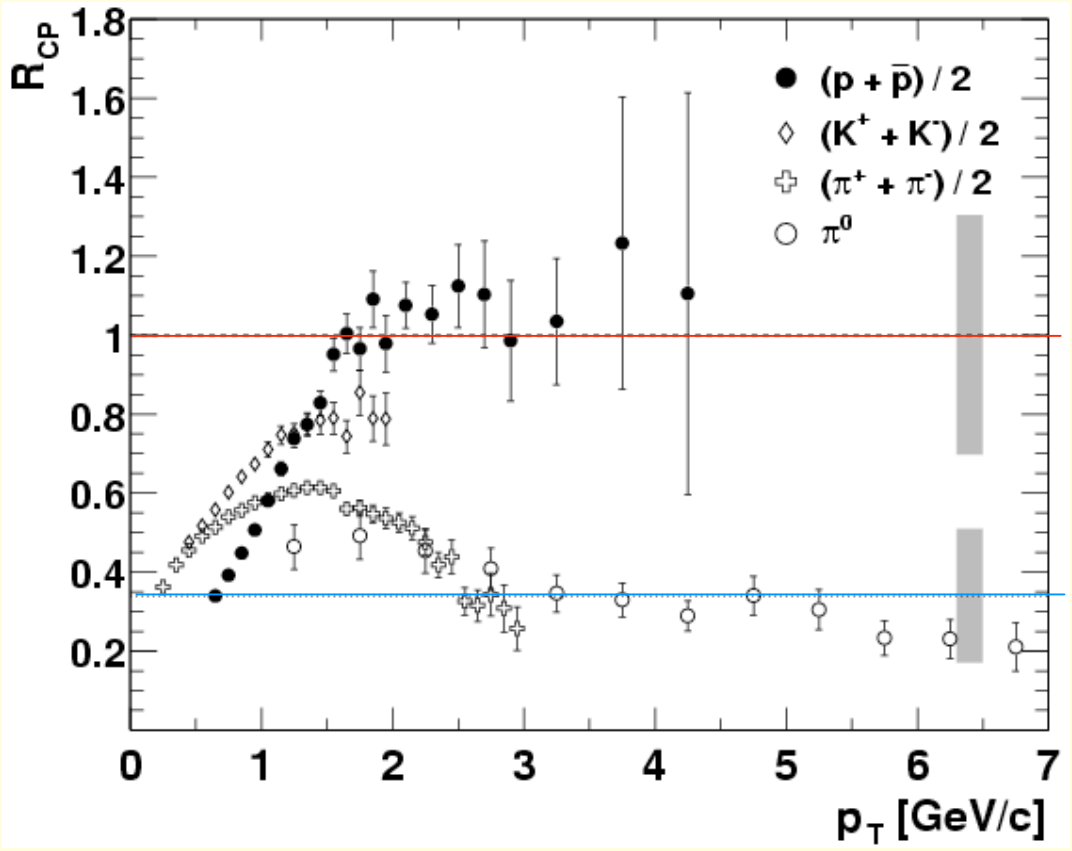
Central-to-Peripheral Ratio (R_{CP}) vs. p_T



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

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

N_{coll} scaling

N_{part} scaling

π^0: Central Suppressed

p : N_{coll} scaling (no suppression!?) at 1.5 GeV - 4.5 GeV

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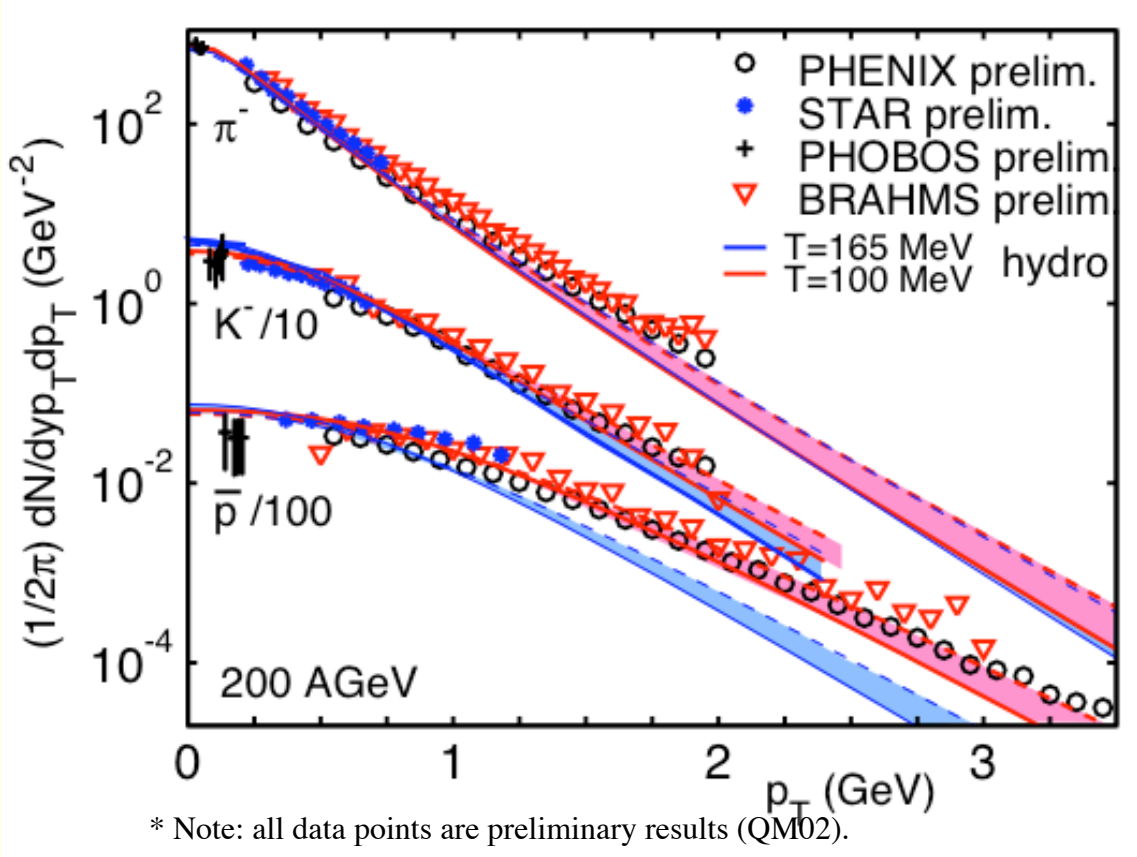
p_T Spectra for All 4 Experiments and Hydrodynamical Model

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).

Hydrodynamics describes bulk particle momentum distributions.

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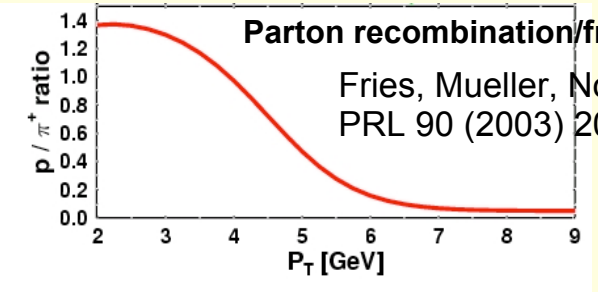
Possible explanations of the proton "non-suppression"… Theory vs Central p/π Ratio

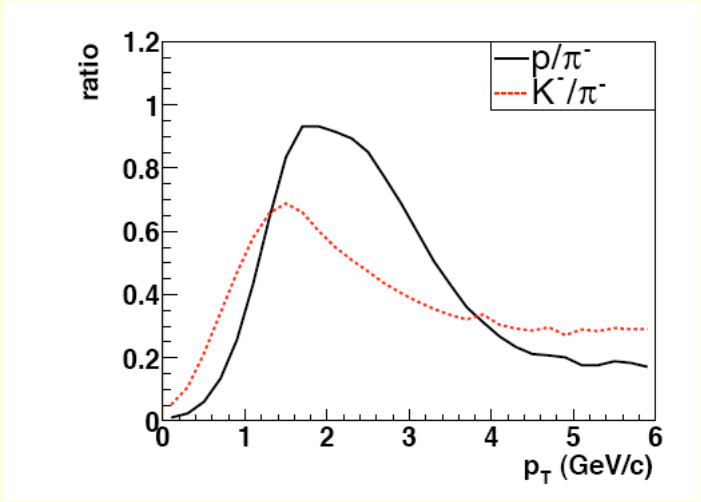
Parton recombination/fragmentation

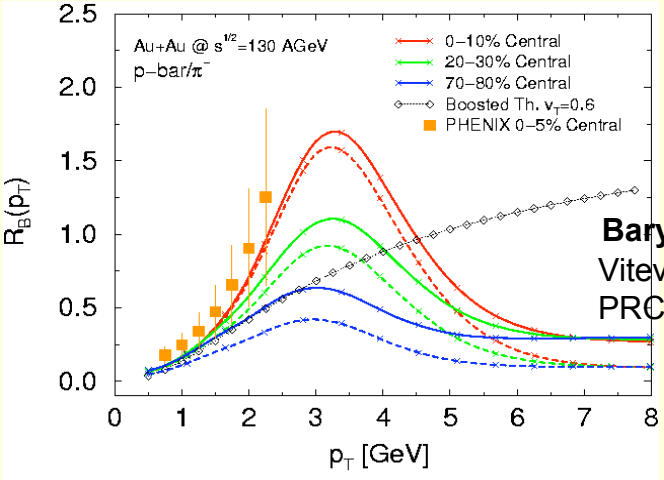
Fries, Mueller, Nonaka,Bass
PRL 90 (2003) 202303



Hydro+Jet

Hirano, Nara
nucl-th/0307015





Baryon Junction

Vitev, Gyulassy
PRC 65, 041902, 2002

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

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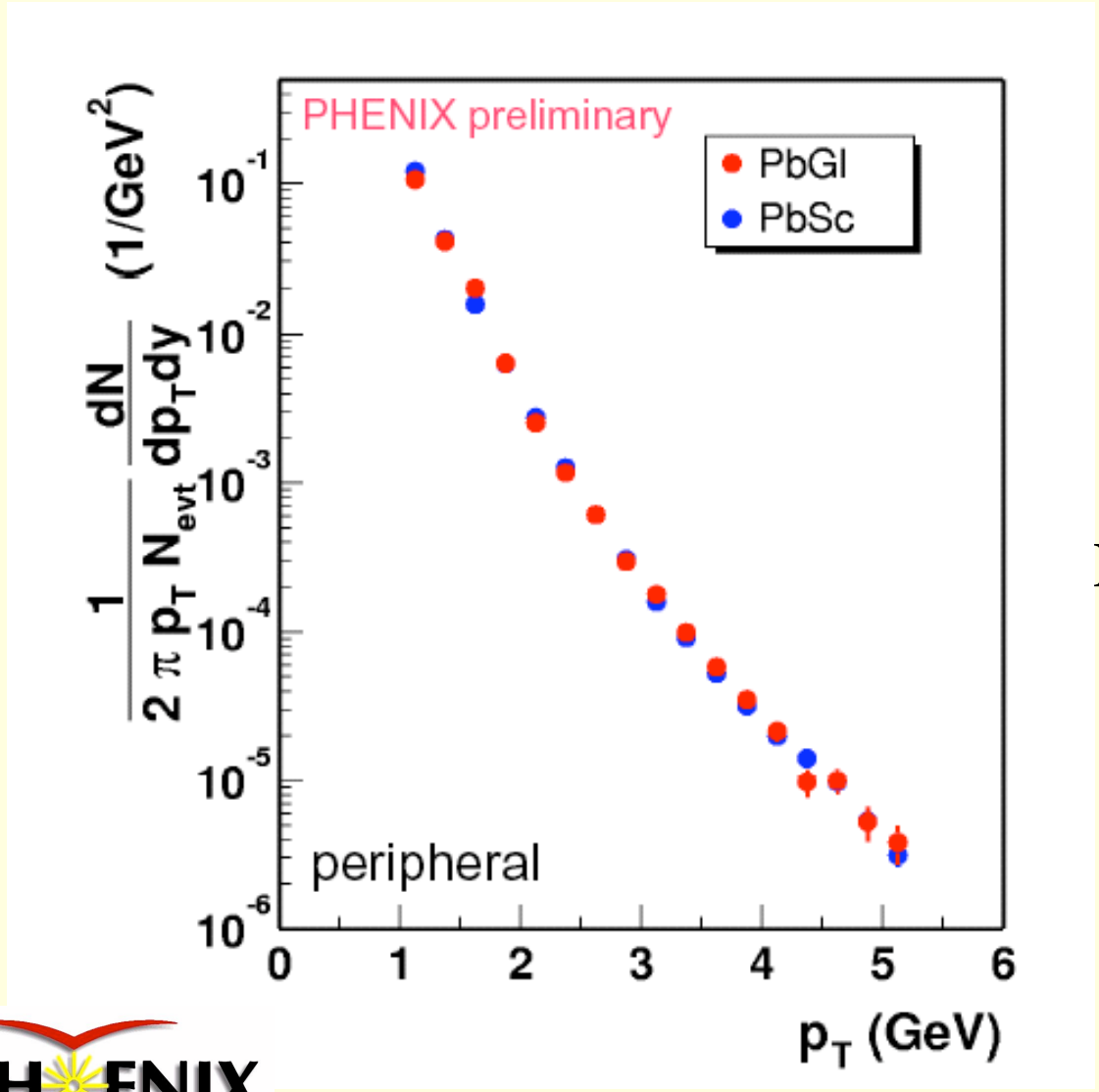
Inclusive □ : Peripheral Au+Au @ s=200 GeV/c



Further test of quenching hypothesis: Direct □measurement. Direct □produced in initial hard q+g-> q+□Compton should not be suppressed (unless gluon saturation).

PbGl and PbSc consistent

Compare with inclusive □ spectrum calculated via Monte Carlo with measured □^{0} cross section as input…

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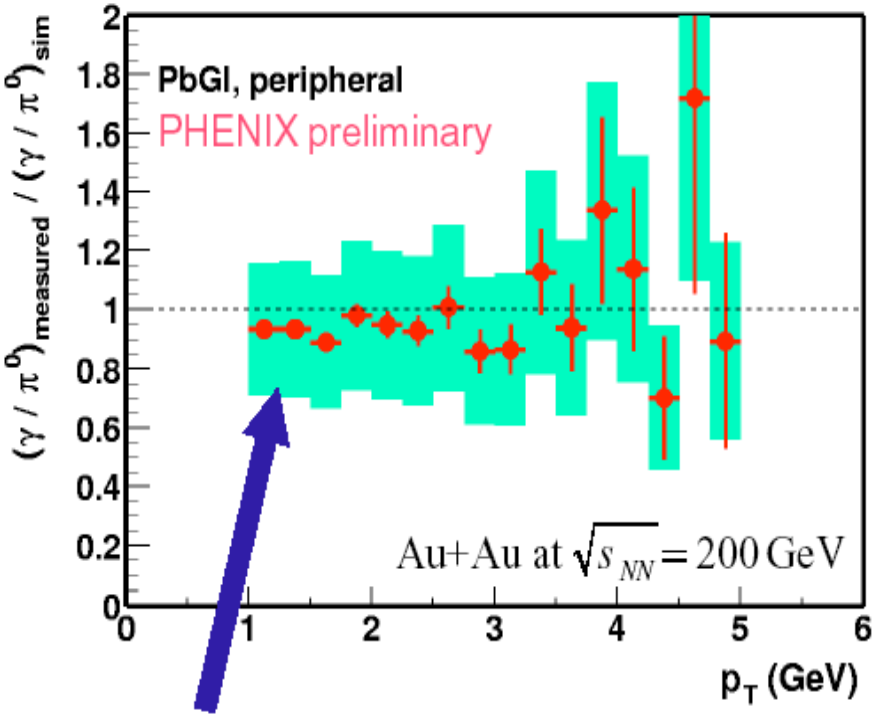
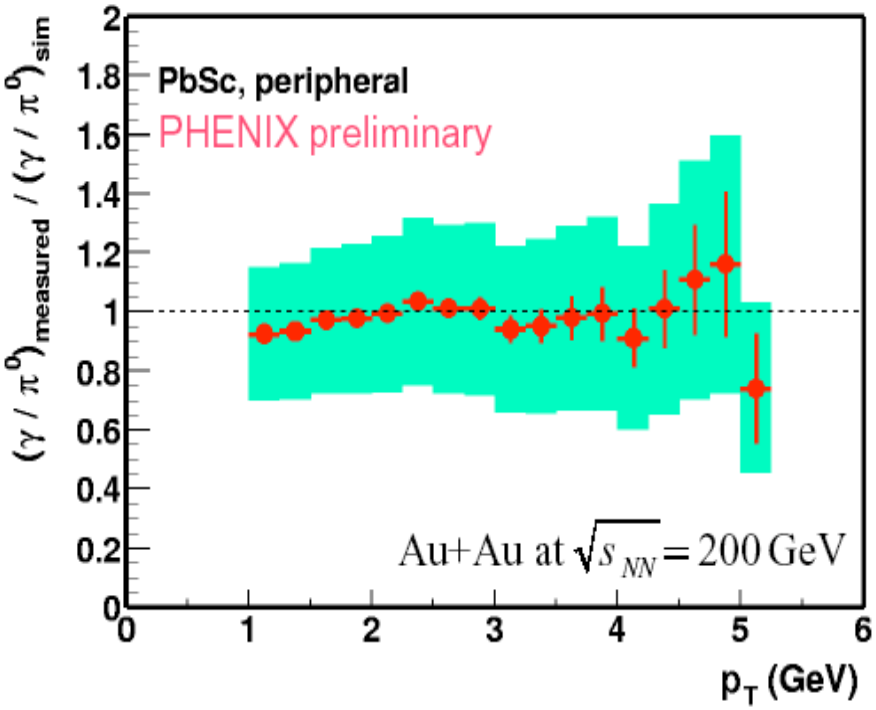
(□/□⁰)measured / (□/□⁰)simulated : Peripheral

PbGl and PbSc consistent with no □excess in peripheral





Boxes: 1σ systematic error

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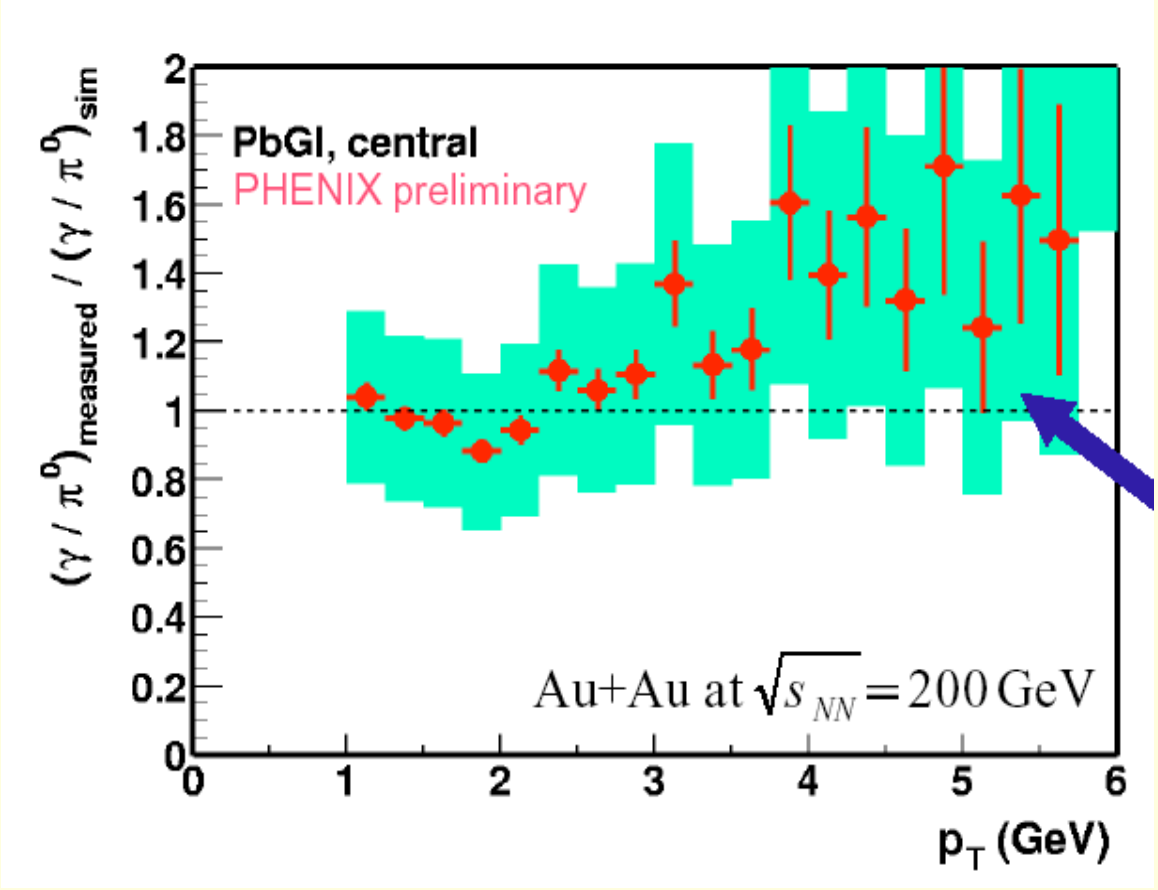
(□/□⁰)measured / (□/□⁰)simulated : Central



1□ systematic errors

No photon excess seen within errors

Working on better understanding of systematics

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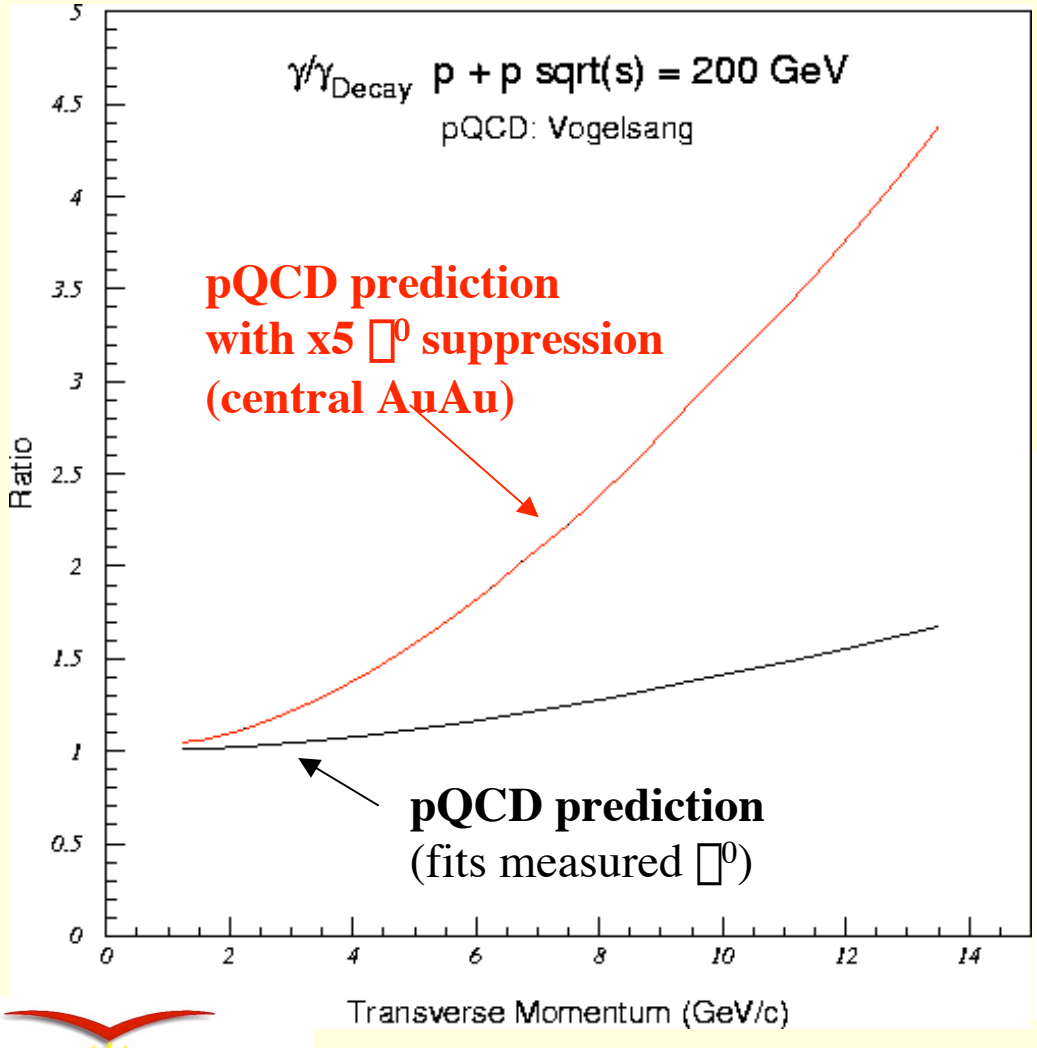
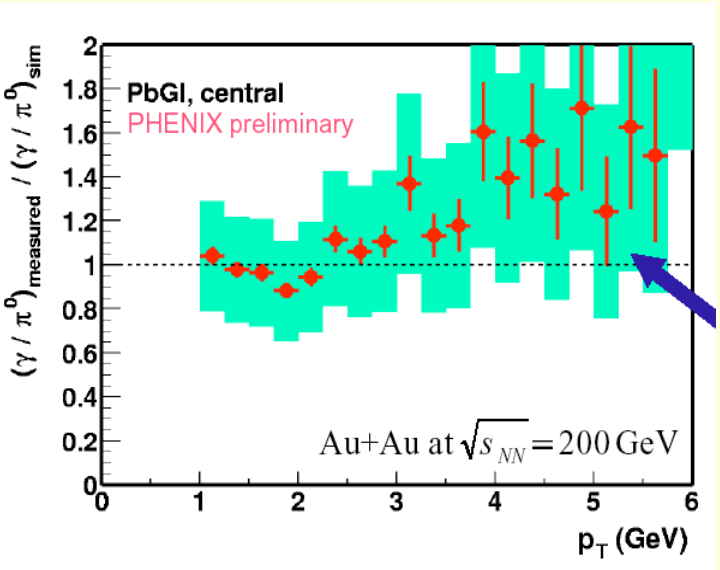
pQCD Direct □ predictions for RHIC



Plotted here as □/□Decay

(as with data)

Expect to see large direct □signal, unless □also suppressed (CGC)!



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Summary and Conclusions

• A strong suppression of hadron production is observed in central Au+Au collisions at RHIC possibly due to parton energy loss in medium (result is not conclusive in itself).

• The hadron production in d+Au collisions shows no strong suppression of high-P_T hadrons (enhancement in d+Au, in fact). Strongly indicative that suppression effect in Au+Au is due to created QCD medium.

• But protons not suppressed? Various explanations - many require thermalization (hydro), quark recombination requires thermalization of quarks and gluons, i.e. QGP.

•Due to π^0 suppression, direct γ signal at RHIC should be "easy"!

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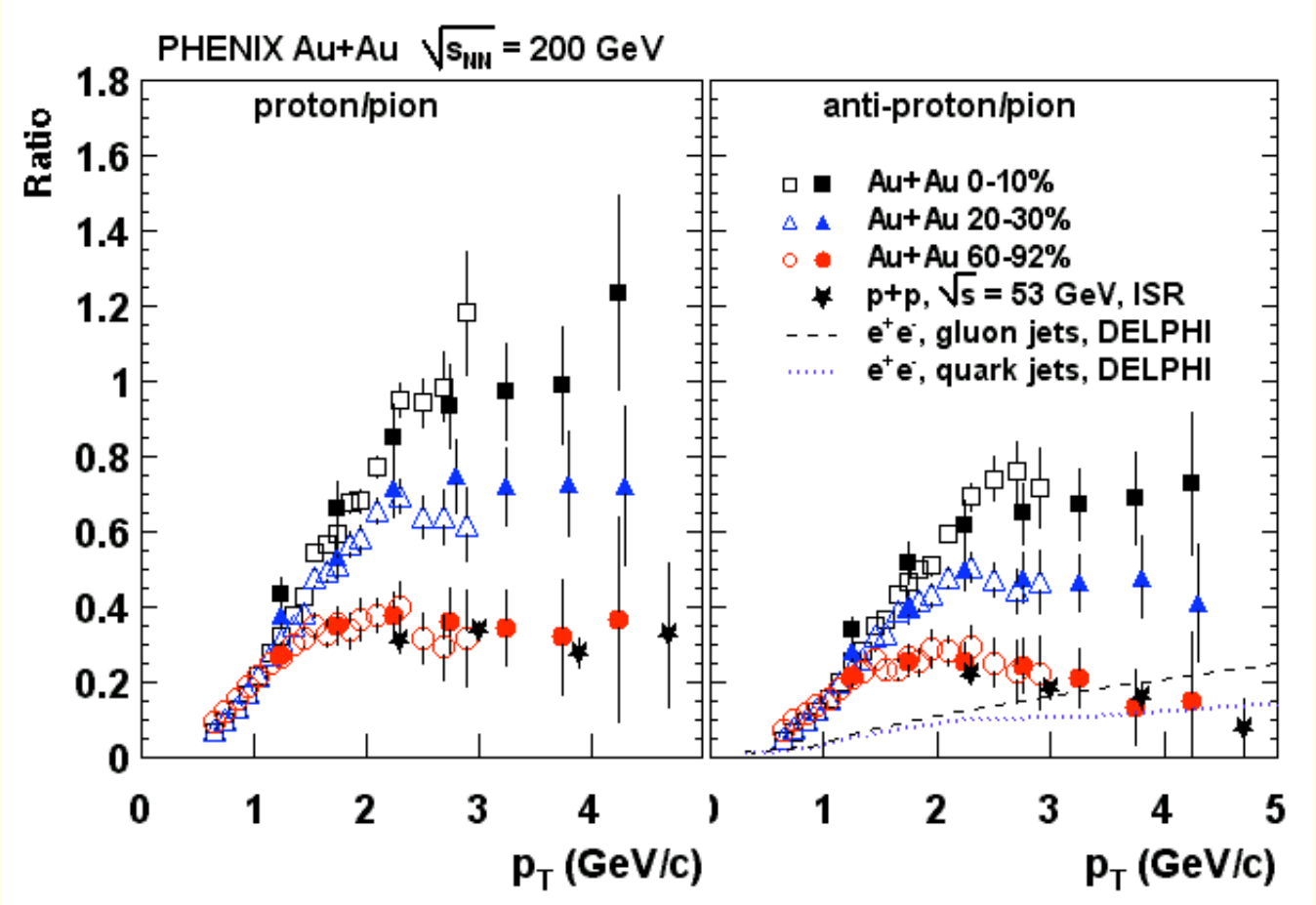
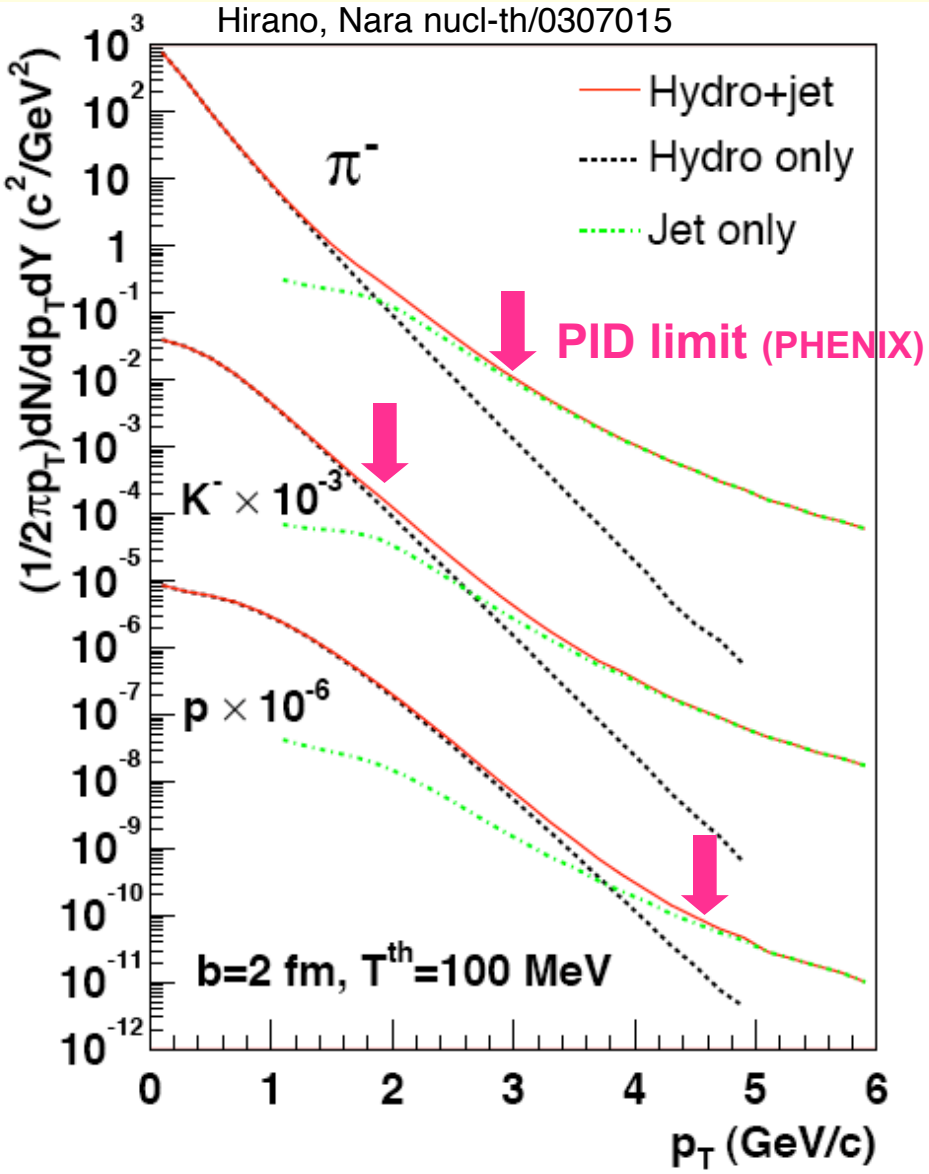
BACKUP SLIDES

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).**

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) .