Recent Results From PHENIX

Theme: Suppression and Enhancement

Outline:

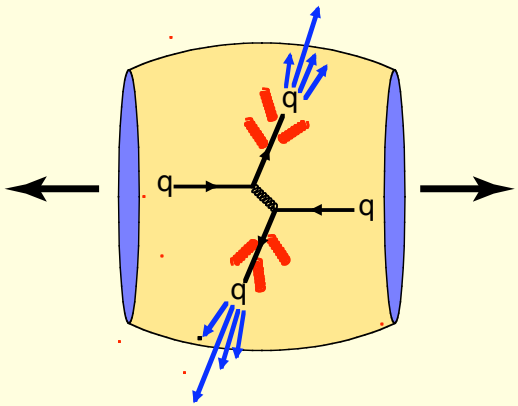
- Initial vs. Final state
- Particle type dependence
- Rapidity dependence
- Run 4 results: Au+Au 62.4A GeV
- Summary

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund

12 Countries; 57 Institutions; 460 Participants

USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

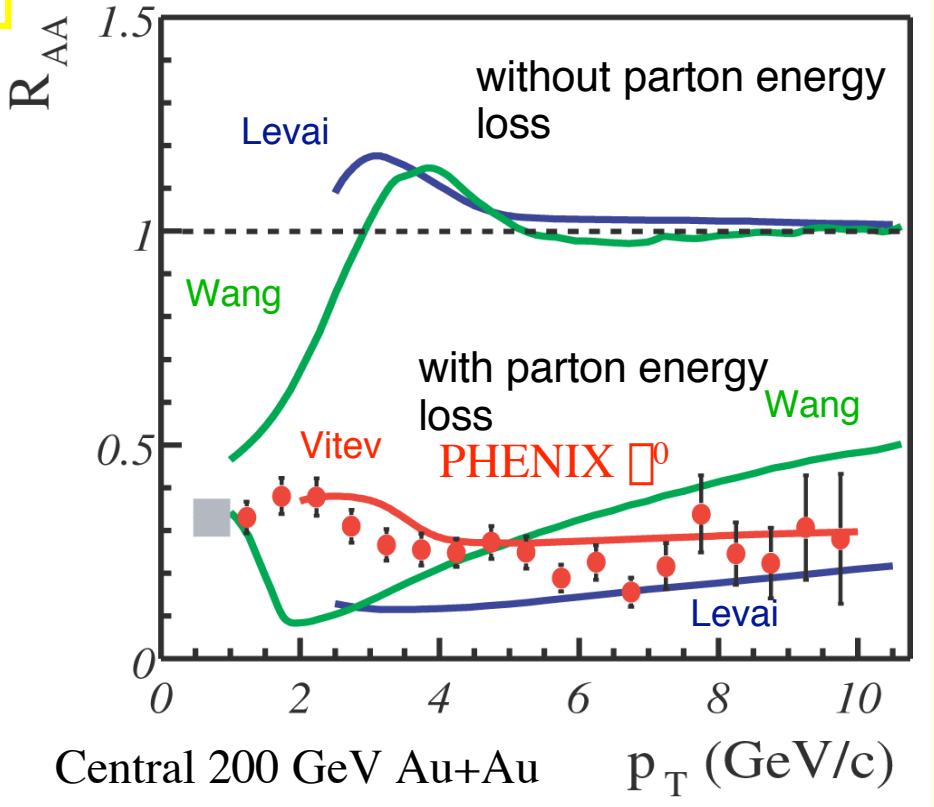
Parton Energy Loss (jet quenching)



Nuclear Modification Factor:

Compare A+A to p-p cross sections

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

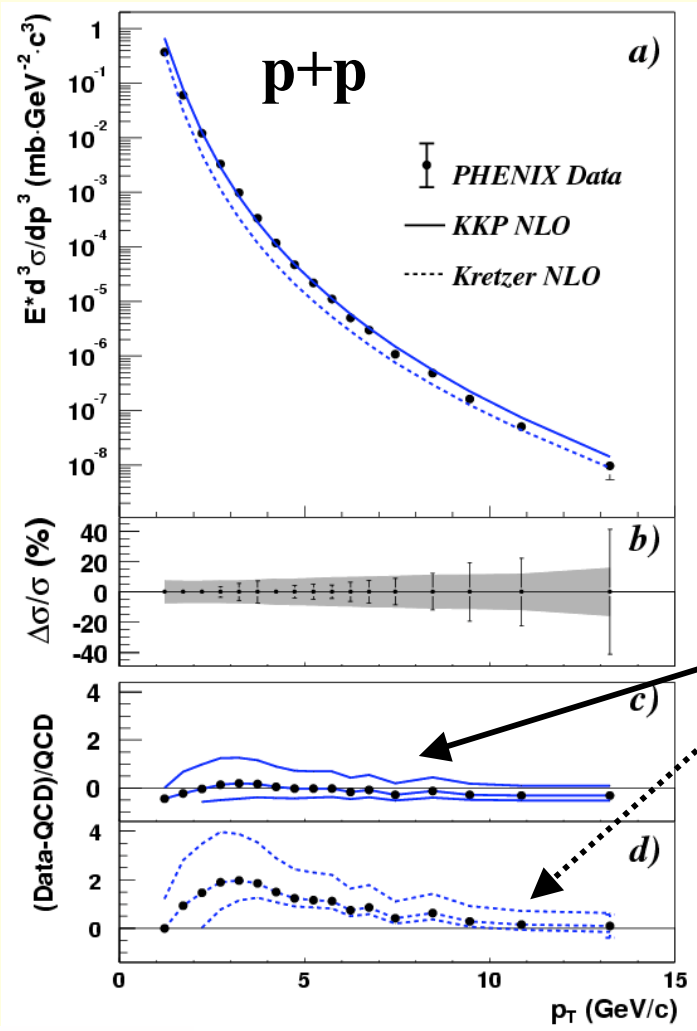


The observed suppression of high p_T particle production in central Au+Au collisions, as predicted as the result of parton energy loss in the created dense partonic matter is certainly the most spectacular result from RHIC.

Alternative explanation: Initial state effect (Gluon saturation).

Run 2: π^0 in p+p collisions at 200 GeV/c (The importance of a good Reference measurement)

PRL 91 (2003) 241803



Reference pp result for Au+Au suppression

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

Very good agreement!

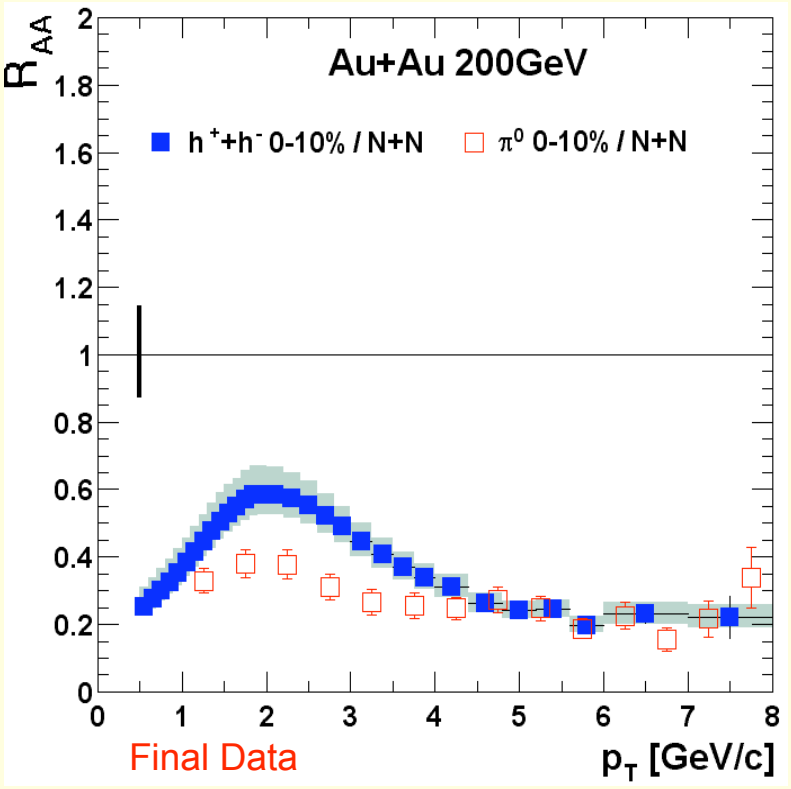
Reliable Direct γ prediction.

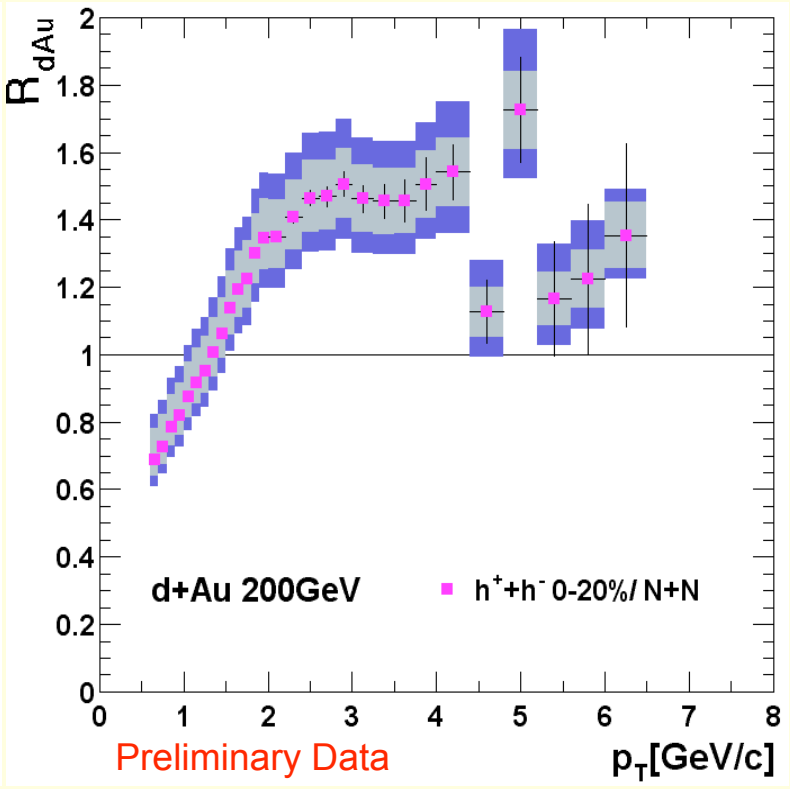
Calculations with different (gluon) FF's
-Large Gluon jet contribution - good for Spin ΔG measurement.
(Regions indicate scale uncertainty)

Run 3: Last Years Big News

The dramatic suppression of hadrons in central Au+Au collisions is **not caused by initial state effects**.

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





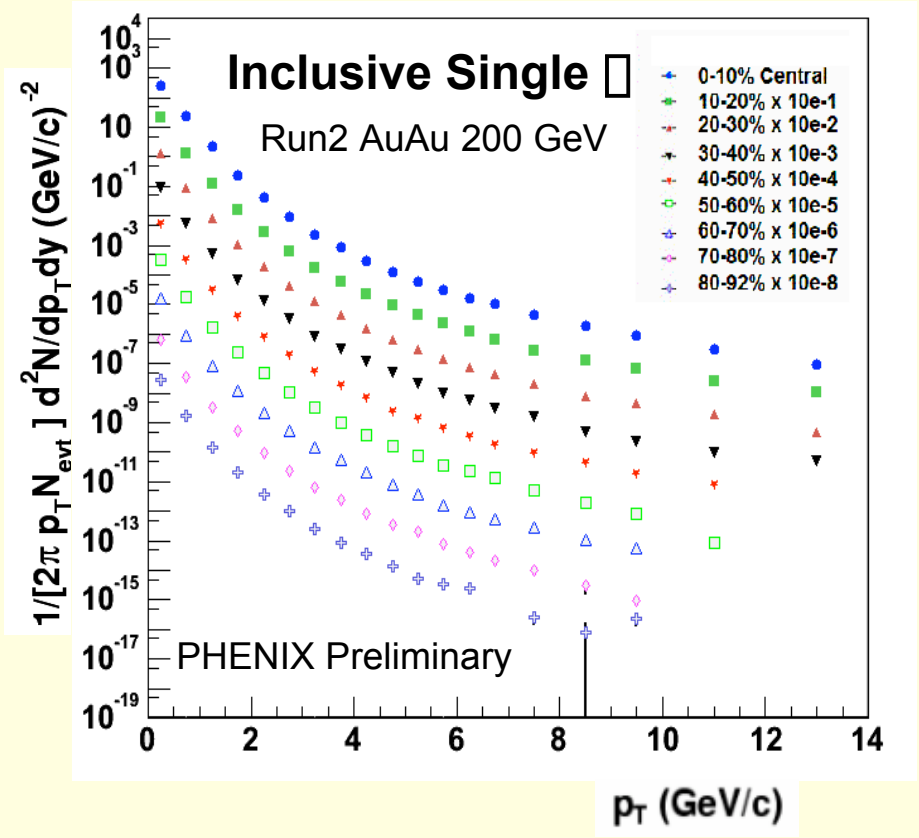
- Opposite centrality evolution of Au+Au compared to d+Au control.
- **Initial state enhancement ("Cronin effect") in d+Au is suppressed by final state effect in Au+Au.**

Direct s: Initial State probe

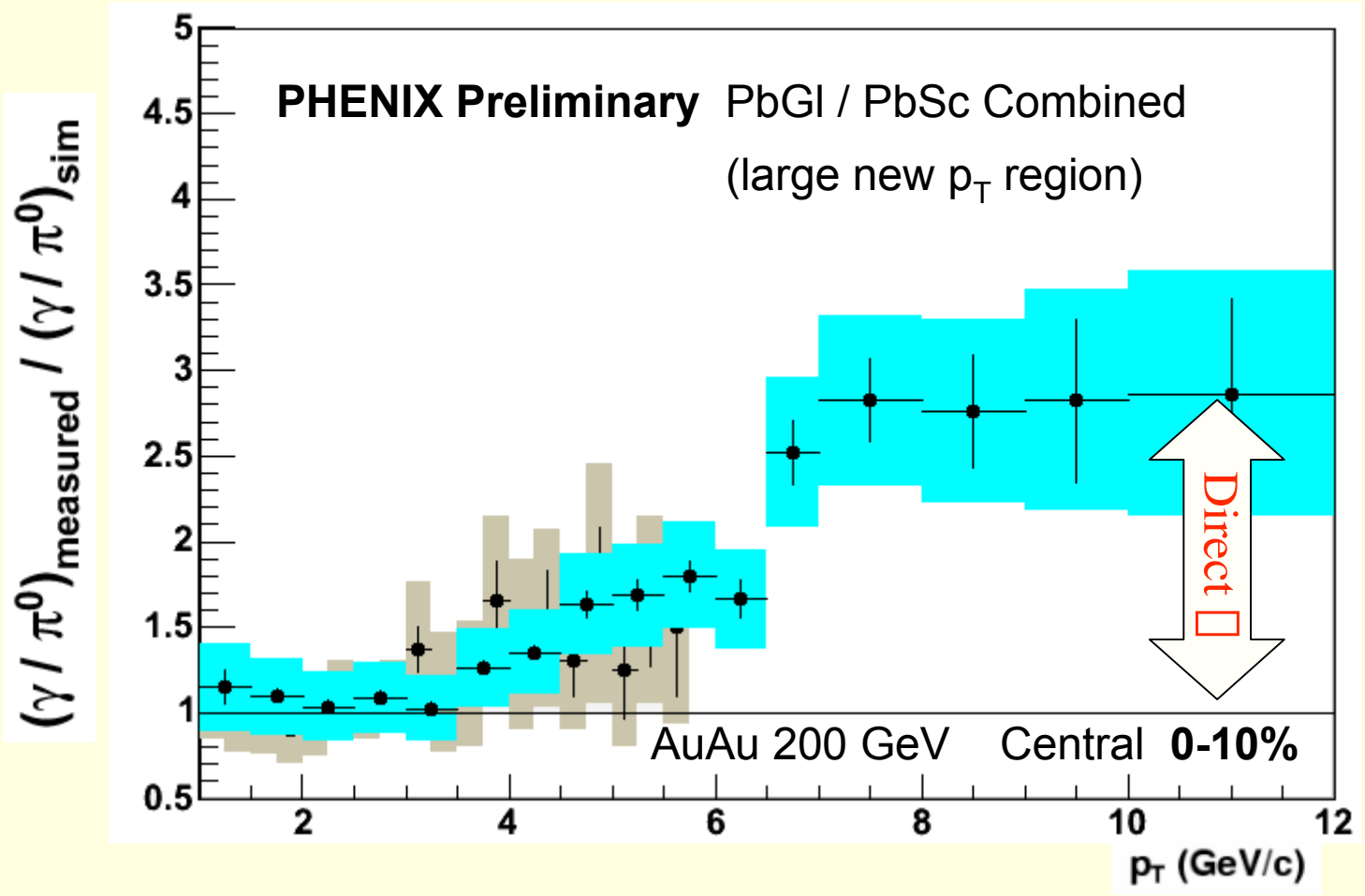
- **Further test of quenching hypothesis: Direct measurement.**

- **Direct produced in initial hard q+g-> q+ Compton**
- **Penetrating probe - should not be suppressed (unless gluon saturation).**

- **Use measured ^{0} ( ) spectra in Monte Carlo to calculate decay spectra**
- **Compare to measured inclusive spectra to search for excess**
- **$_{Meas}/_{Decay}$ >1 implies direct excess**

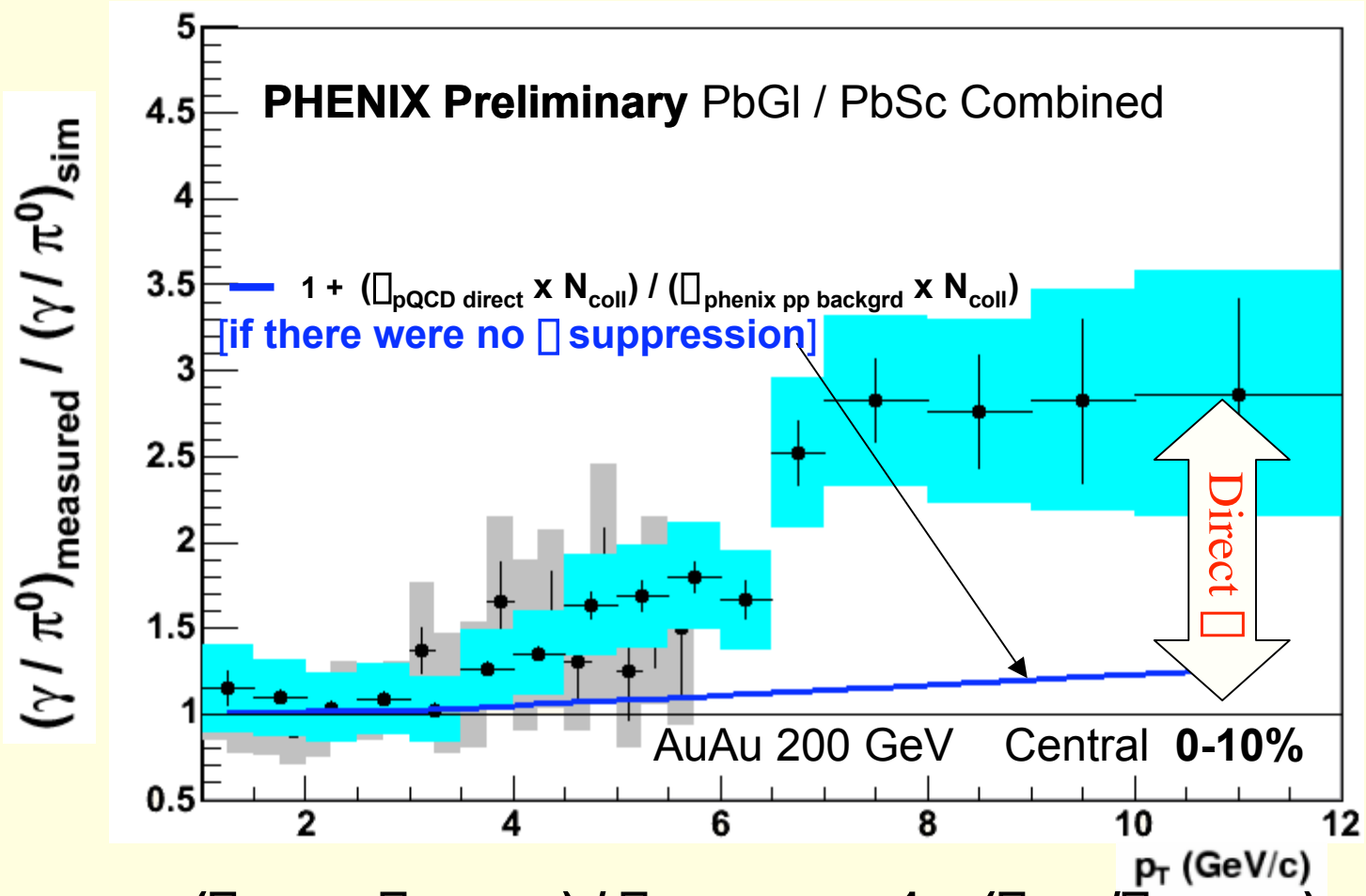


Direct Central 0-10%



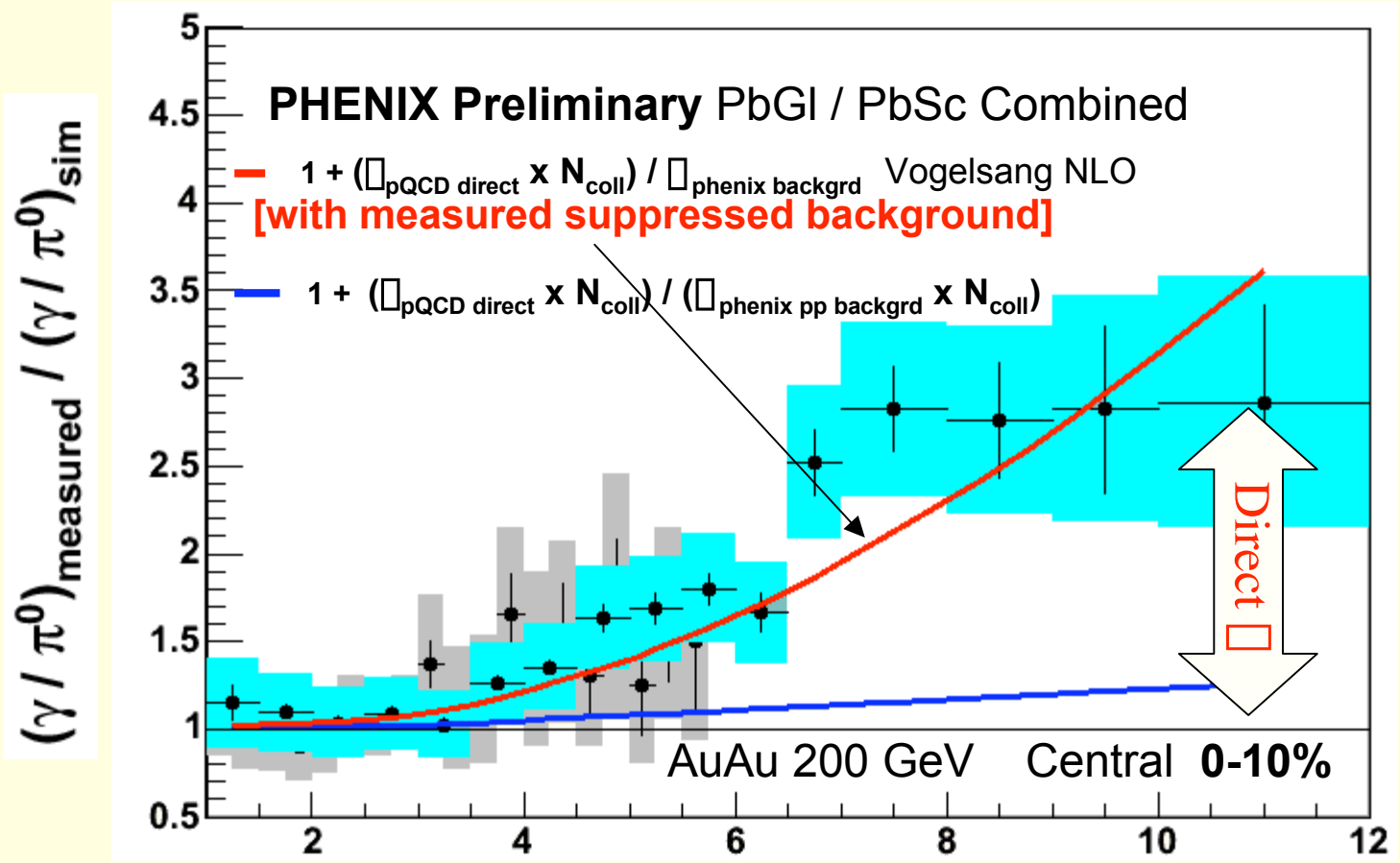
$[\gamma/\pi^0]_{measured} / [\gamma/\pi^0]_{background} = \gamma_{measured}/\gamma_{background}$

Direct Central 0-10%



$(\gamma_{direct} + \gamma_{exp.\ bkgd.}) / \gamma_{exp.\ bkgd.} = 1 + (\gamma_{direct} / \gamma_{exp.\ bkgd.})$

Direct Central 0-10%

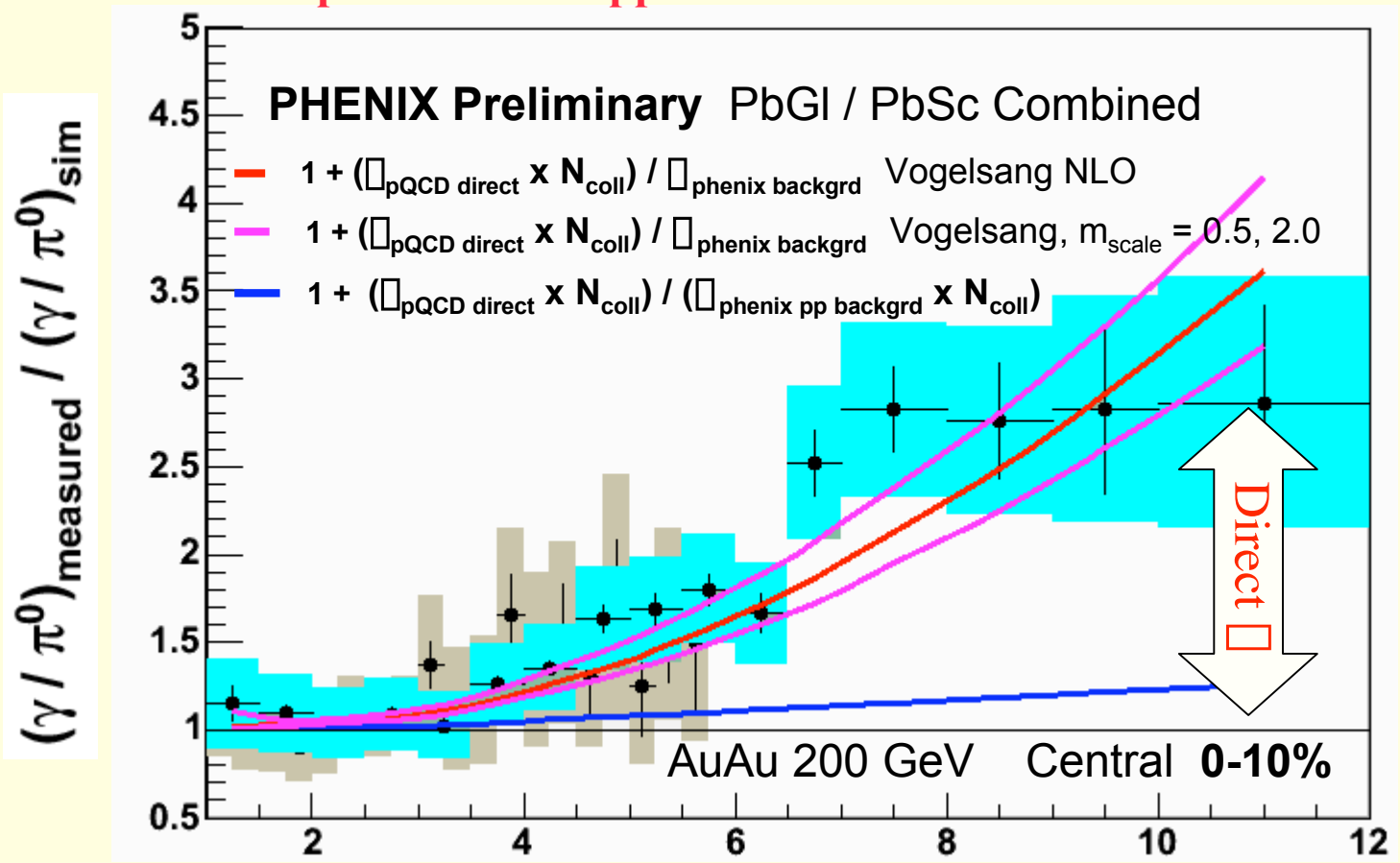


$$(\gamma_{direct} + \gamma_{exp.\ bkgd.}) / \gamma_{exp.\ bkgd.} = 1 + (\gamma_{direct}/\gamma_{exp.\ bkgd.})$$

Direct Central 0-10%

Both d+Au R_{AA} and Direct results imply that high p_T suppression is not an initial state effect.

Initial state explanation of suppression is laid to rest!



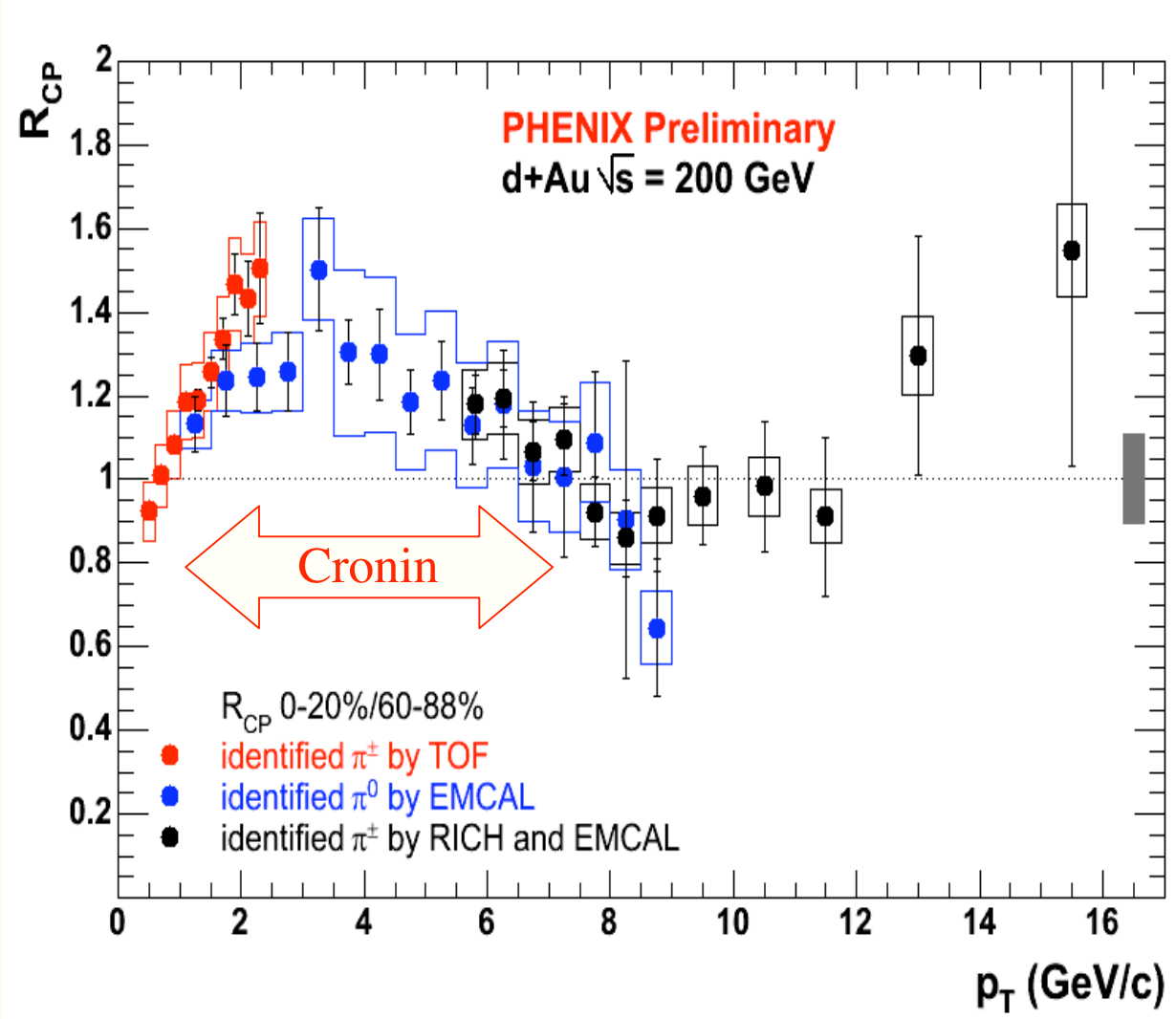
3/4 are Direct!

-Jet studies feasible!

$$(\gamma_{direct} + \gamma_{exp.\ bkgd.}) / \gamma_{exp.\ bkgd.} = 1 + (\gamma_{direct}/\gamma_{exp.\ bkgd.})$$

d+Au Pion R_{CP} to high p_T

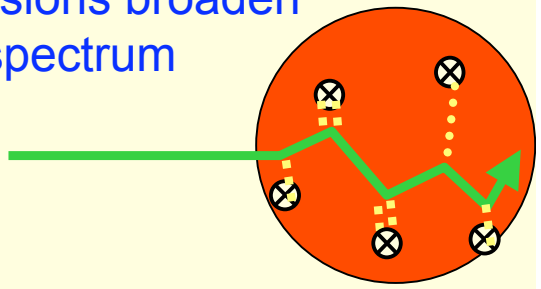
$$R_{CP} = \frac{\text{Yield}^{0\text{-}10\%} / \langle N_{coll}^{0\text{-}10\%} \rangle}{\text{Yield}^{60\text{-}92\%} / \langle N_{coll}^{60\text{-}92\%} \rangle}$$



Pion identification to high p_T to determine extent of "Cronin" effect

R_{CP} ~ 1 for p_T>7 GeV/c

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

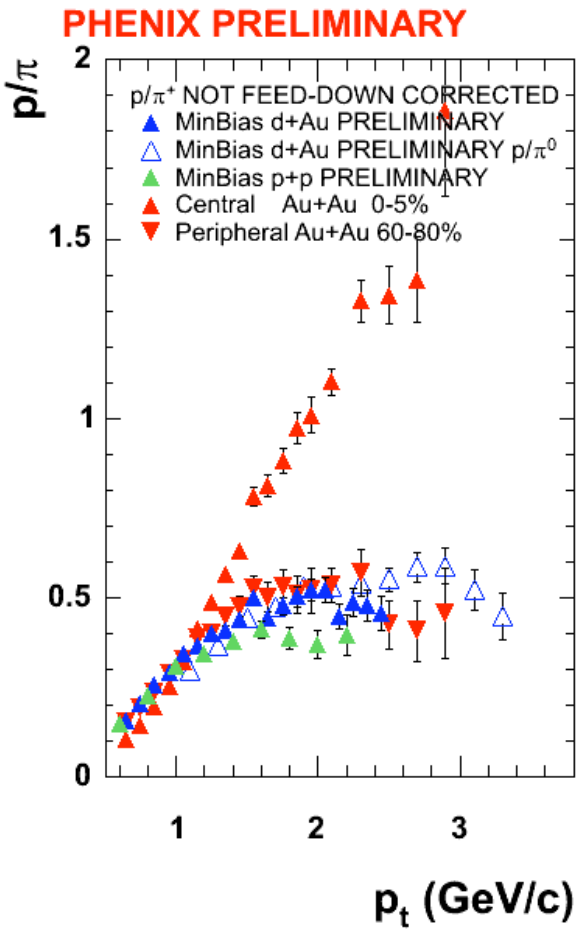


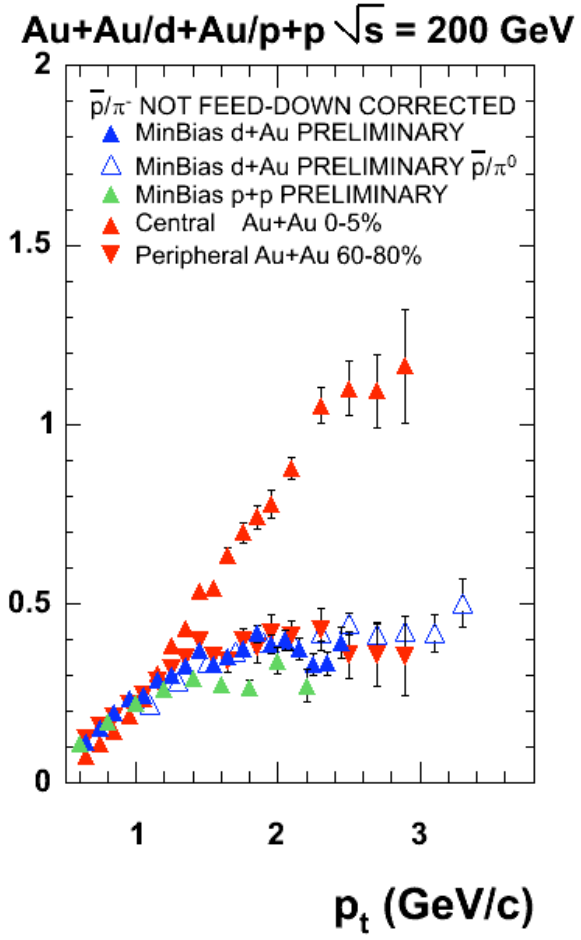
Enhanced p/π ratio in Central Au+Au

p,pbar yields strongly enhanced in central Au+Au compared to peripheral, pp, and dAu.

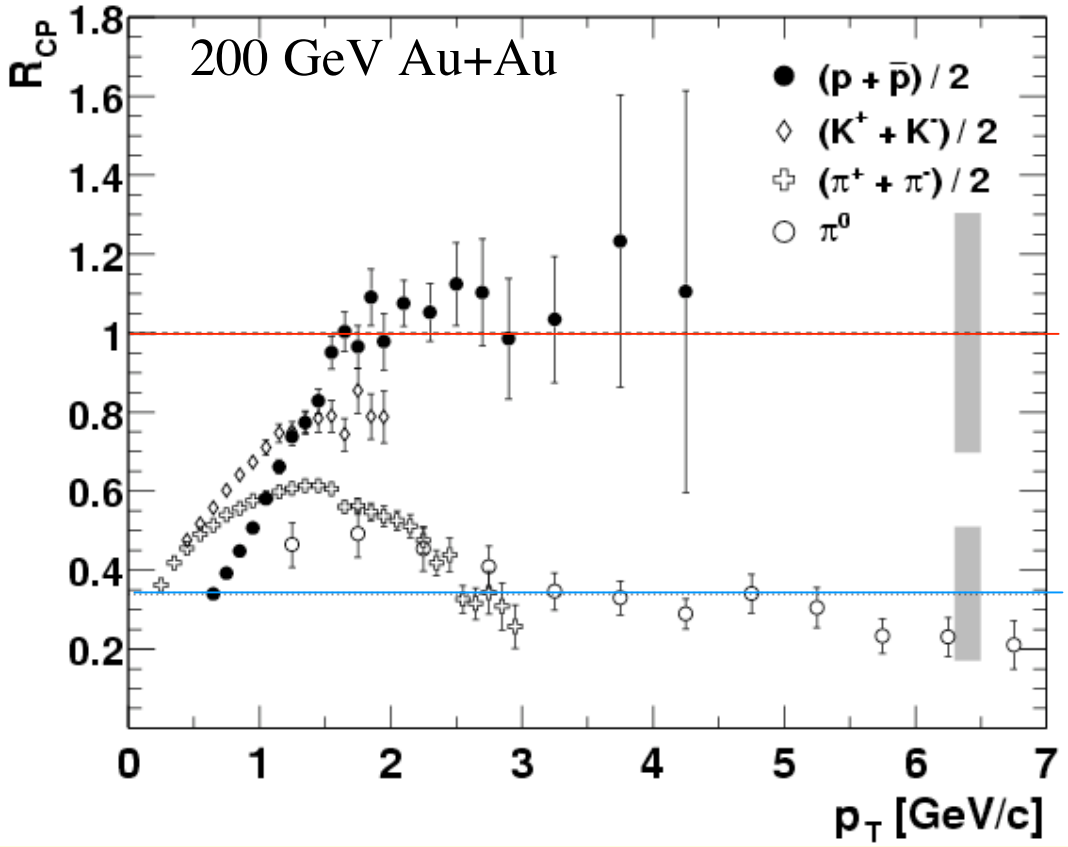
But: h/π^0 ratio shows that p enhancement ends at ~5 GeV/c

Collective flow?





R_{CP} For Identified Particles



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

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

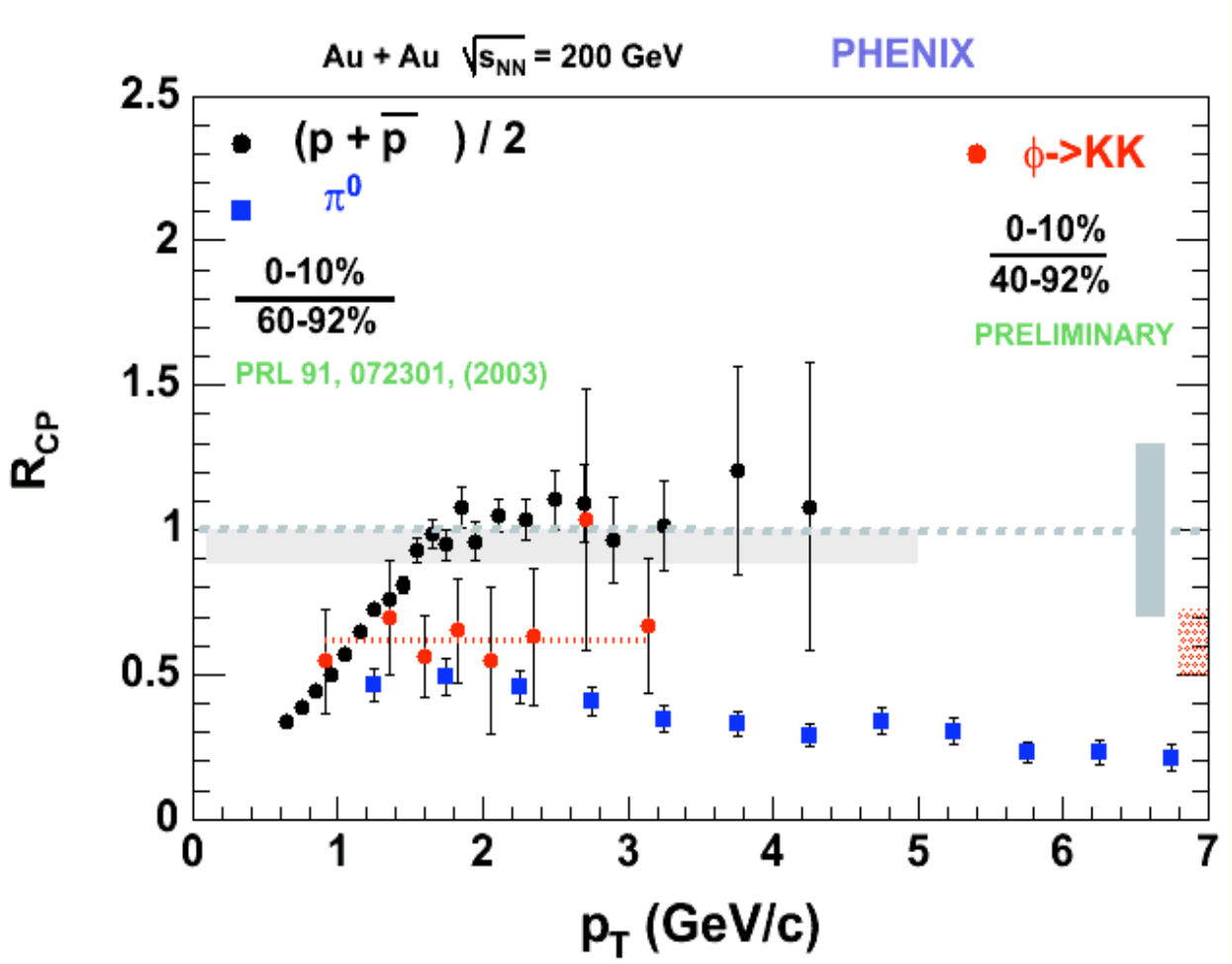
N_{coll} scaling

N_{part} scaling

π^0: Central Suppressed

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

R_{CP}: Mass vs Quark Content



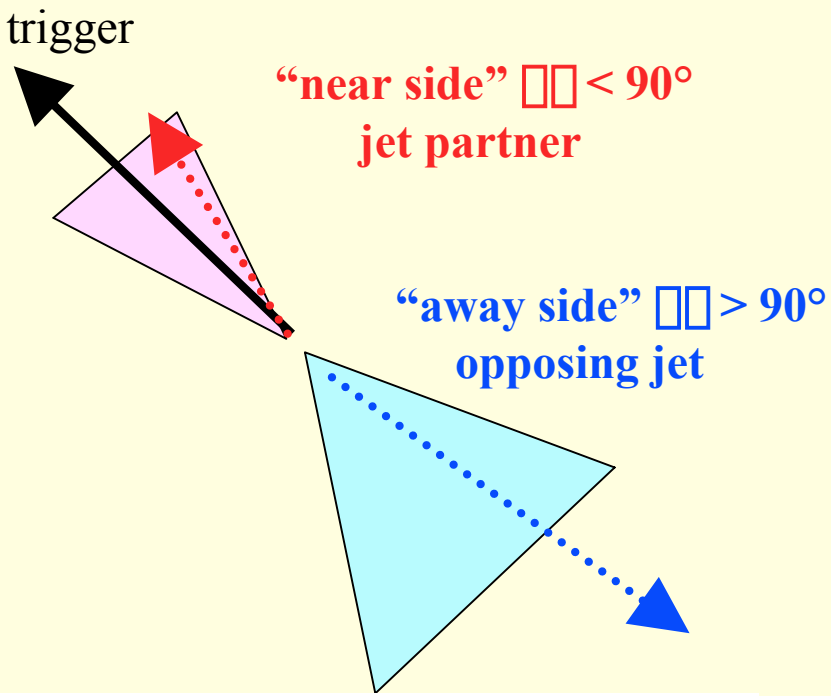
The □ is interesting as a meson with mass similar to the proton.

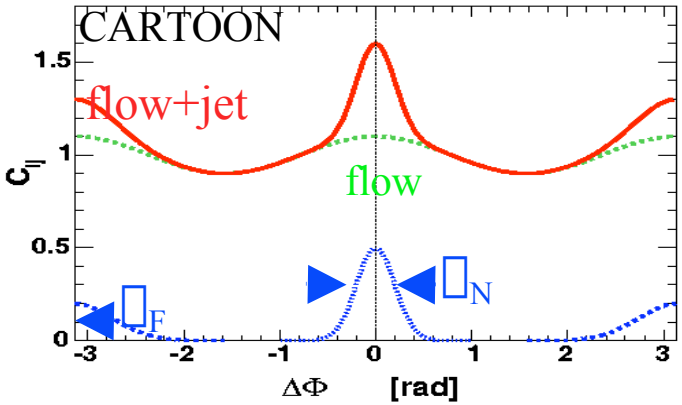
The □ is suppressed, like other mesons.

Baryons not suppressed.

Quark Coalescence a suggested explanation.

Jets in PHENIX





Trigger:
hadron with $p_T > 2.5$ GeV/c

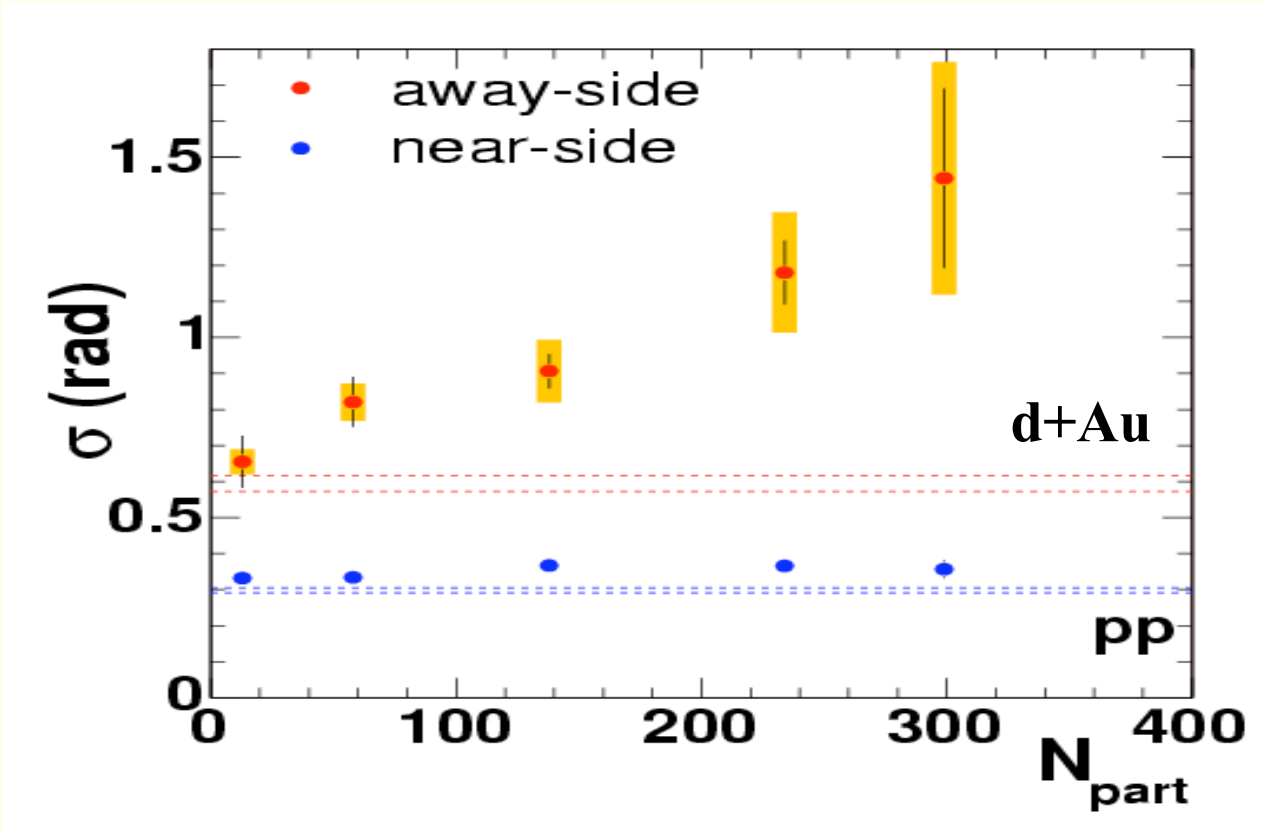
Count associated particles for each trigger at lower p_T
□ “conditional yield”

Near side yield: number of jet associated particles from same jet in specified p_T bin

Away side yield: jet fragments from opposing jet

Jet widths in Au+Au

$(2.5<p_{Ttrigg}<4.0)$@ $(1.0<p_{T\ Assoc.}<2.5)$

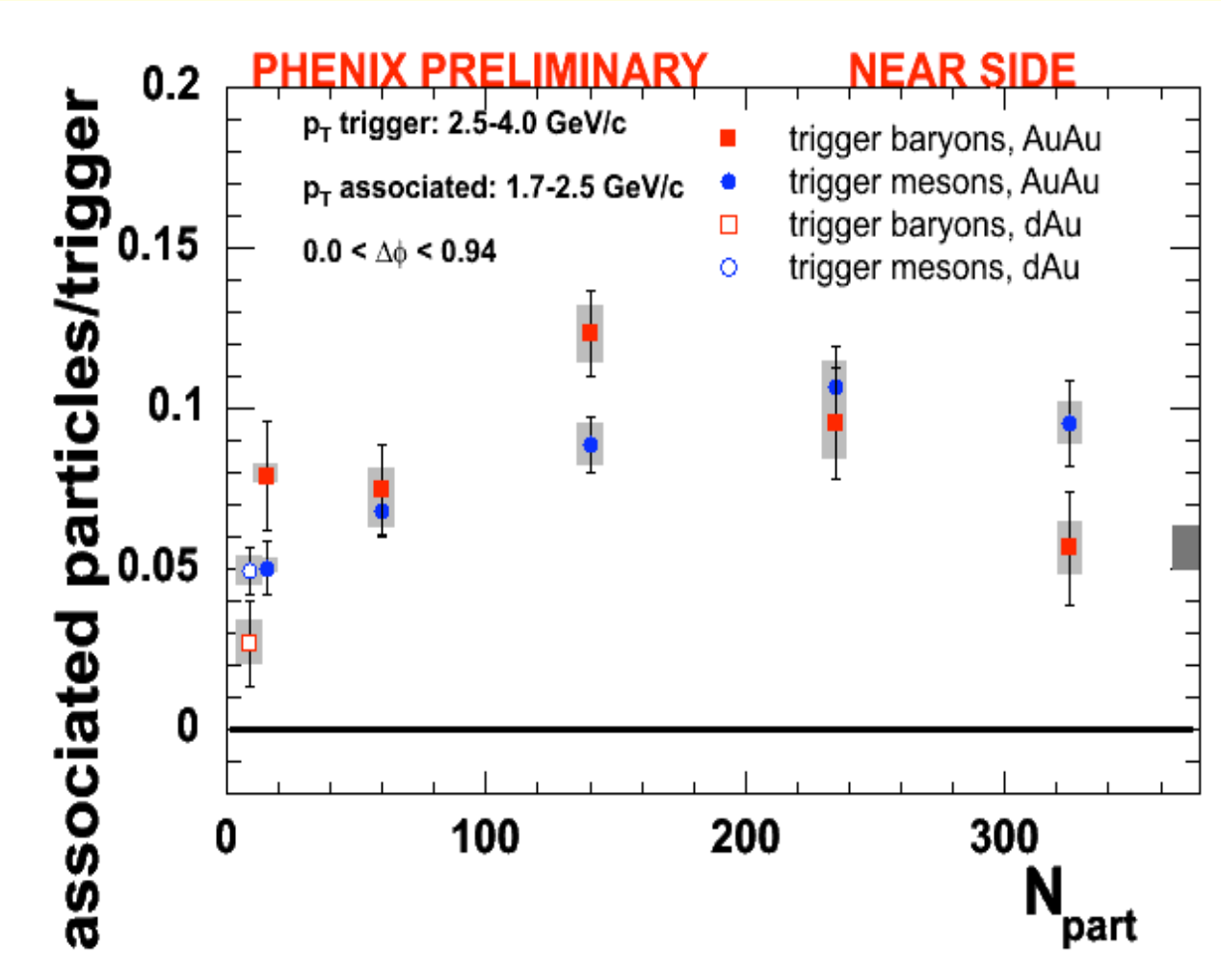


The near-side width is independent of centrality.

The away-side width increases with centrality.

These widths can be related to the standard jet correlation parameters $<|j_{Ty}|>$ and $<|k_{Ty}|>$.

Identified trigger particle associated yields



Associated particle yield for baryons is the same as for mesons.

Coalesced hadrons would not be expected to have associated particles. **Problem for thermal coalescence explanation?**

Extended R_{CP} Rapidity Measurement

Extend R_{CP} measurement using hadrons detected in muon arms
(cover **-2.4 < □ < -1.2** and **1.2 < □ < 2.2**).

This has been done in two ways:

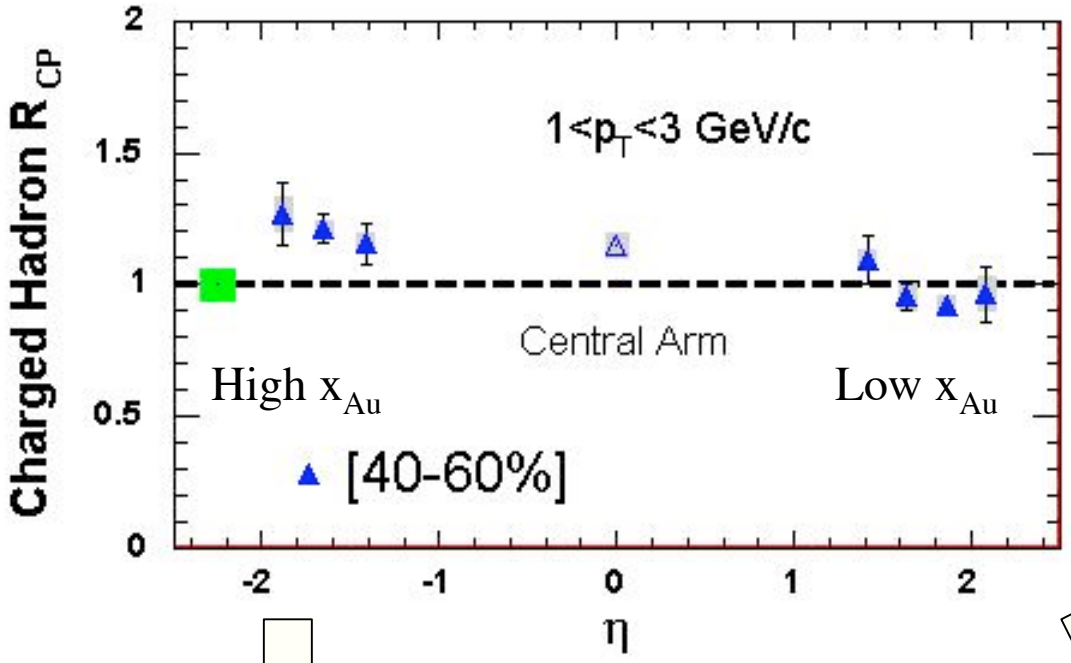
- By directly measuring hadrons that interact in the Muon Identifier (**punch-through** hadrons).

- By detecting muons from **decays** of light mesons (□, K) using z-vertex flight path information.

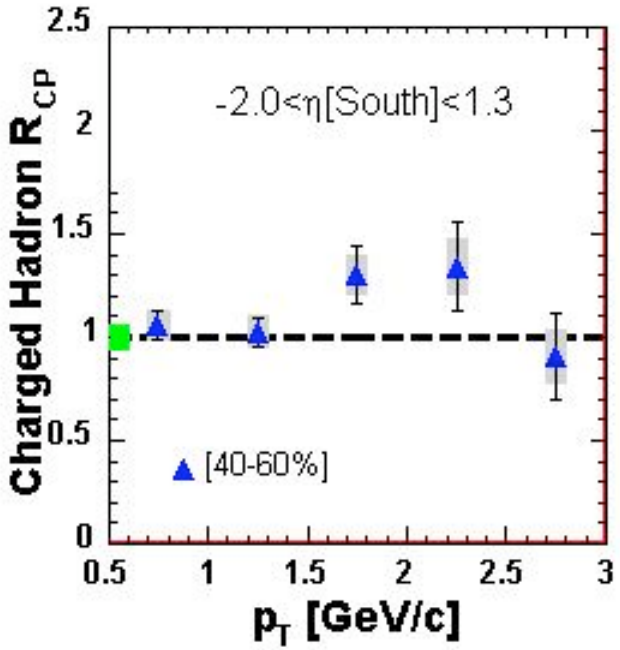
Semi-Peripheral

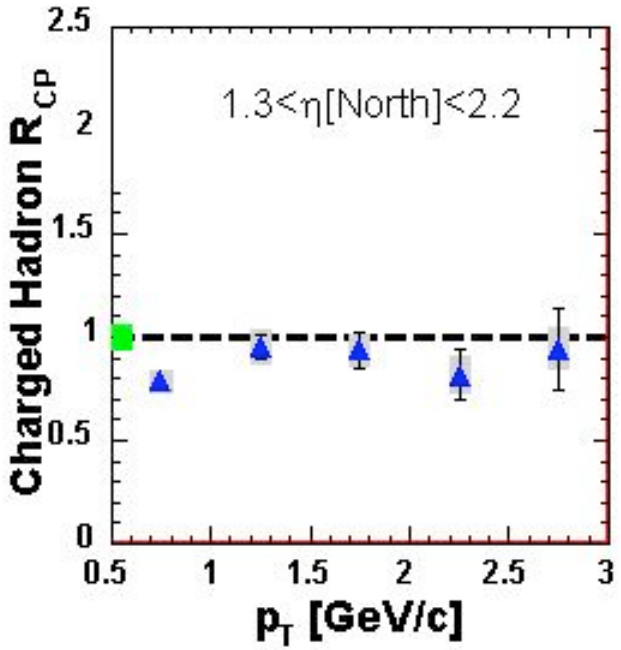
d

Au



Phenix Preliminary

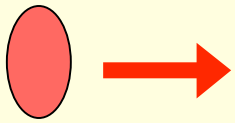




- **Low x_{Au} suppression**
- **High x_{Au} enhancement**

T.C.Awes, ORNL

Semi-Central



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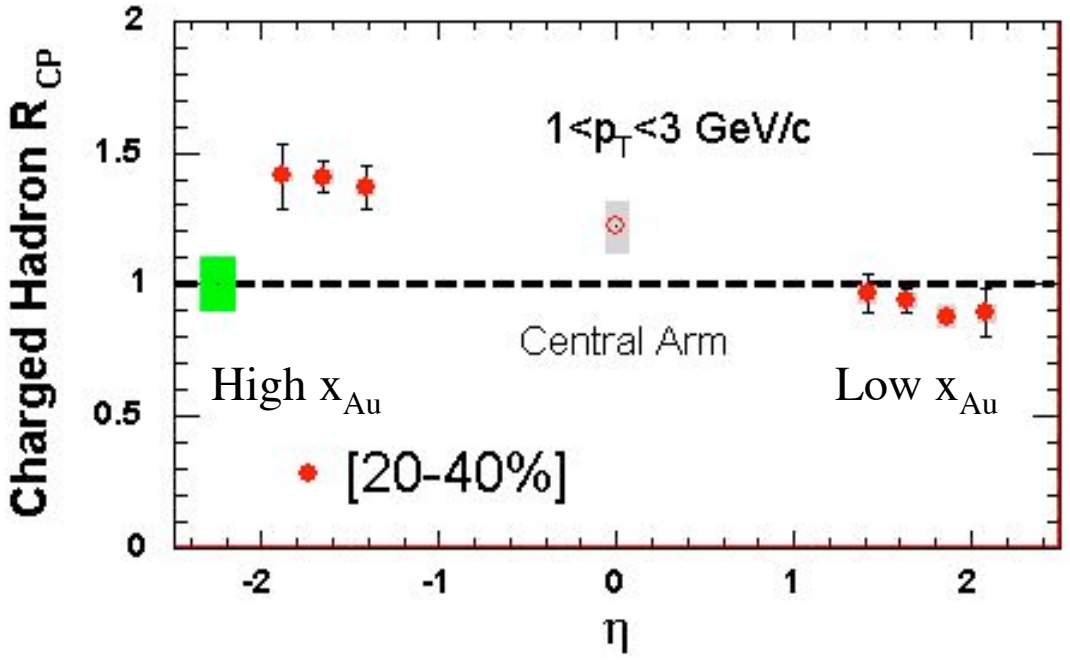
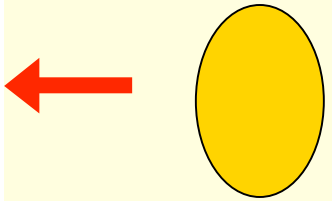
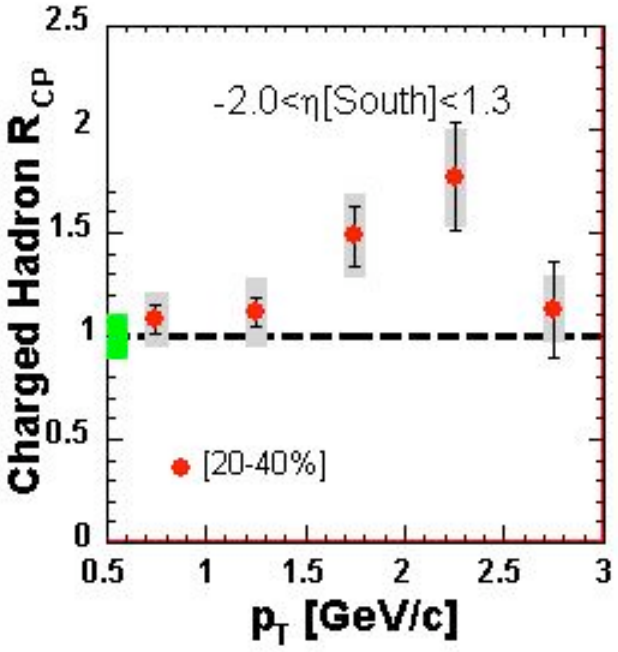


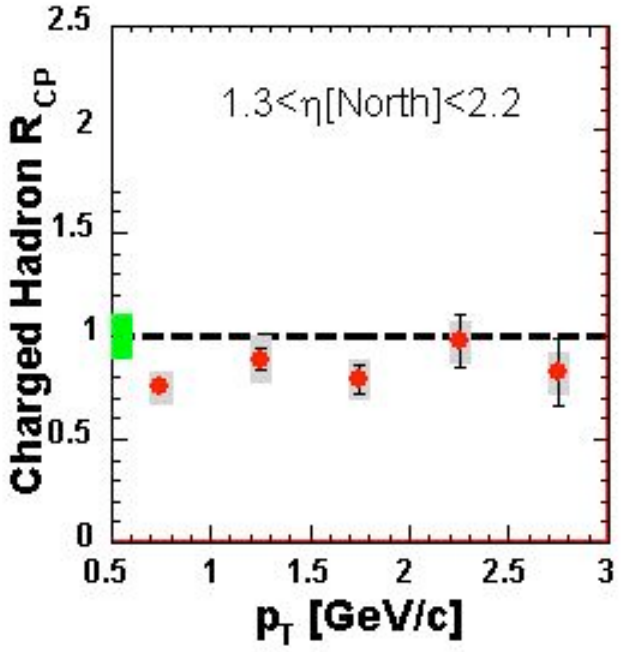


Au

PHENIX

Phenix Preliminary





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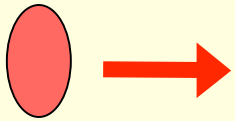
Central



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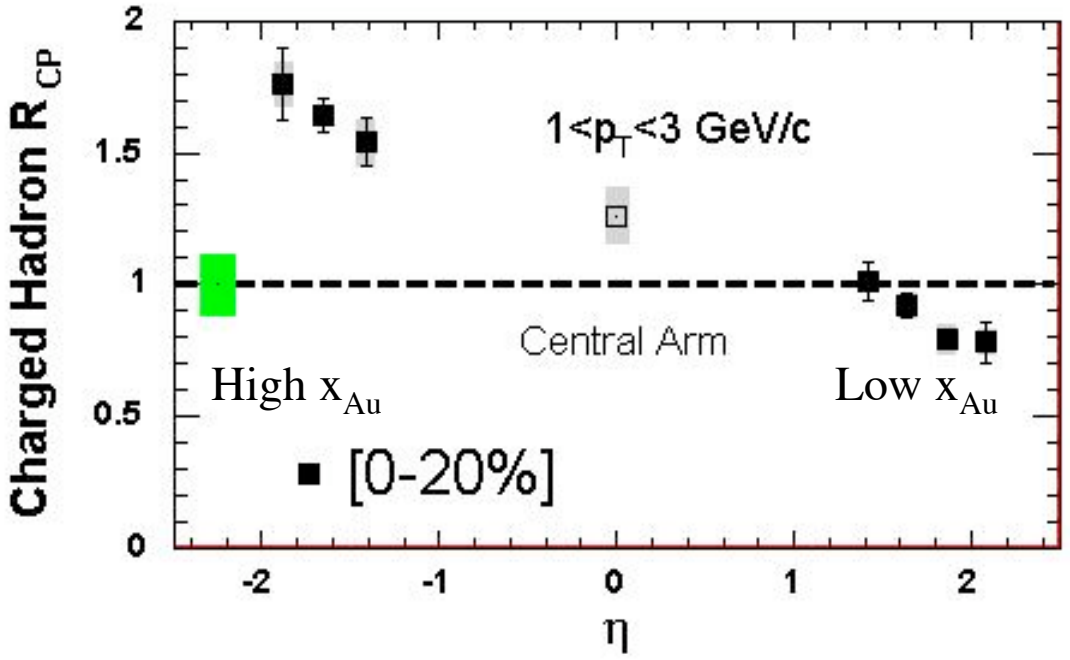
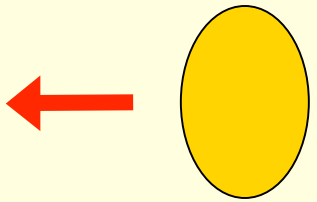
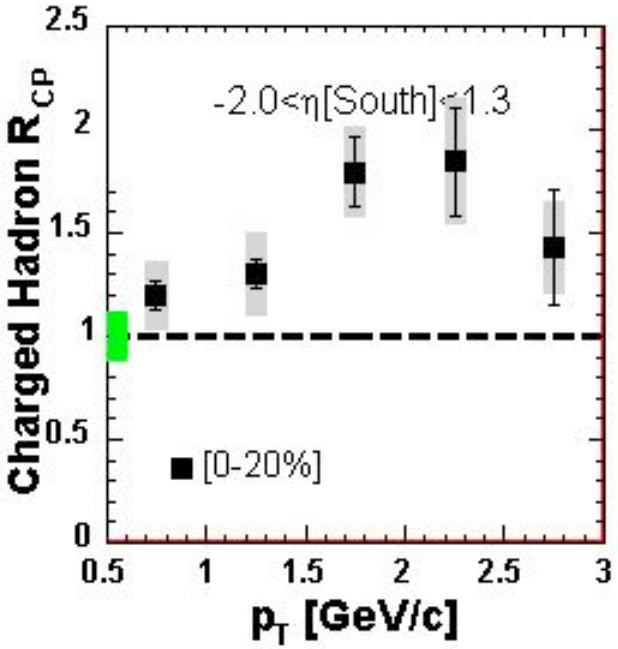


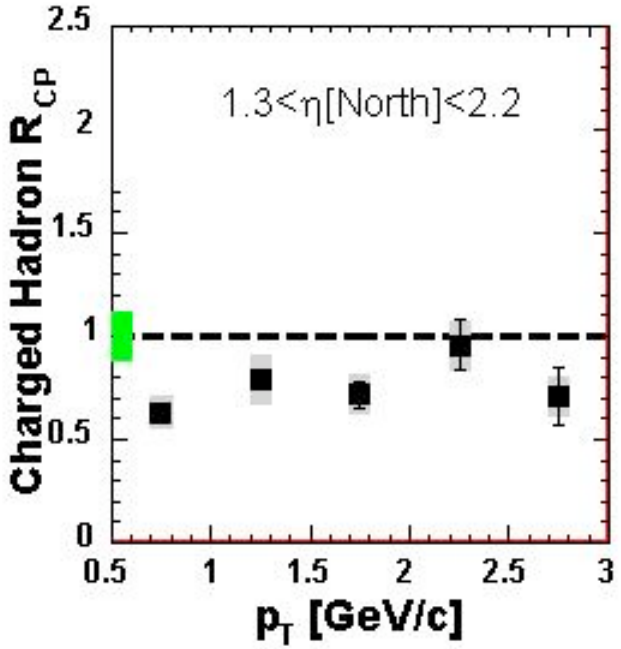


Au

Phenix Preliminary

- **Suppression or enhancement increases with rapidity, centrality, and p_T**





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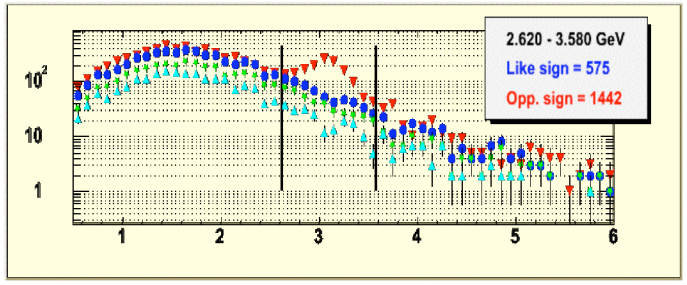
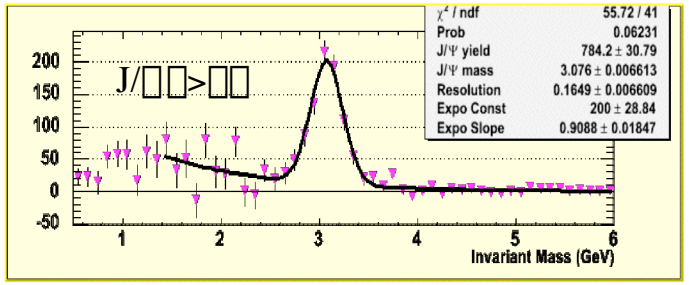
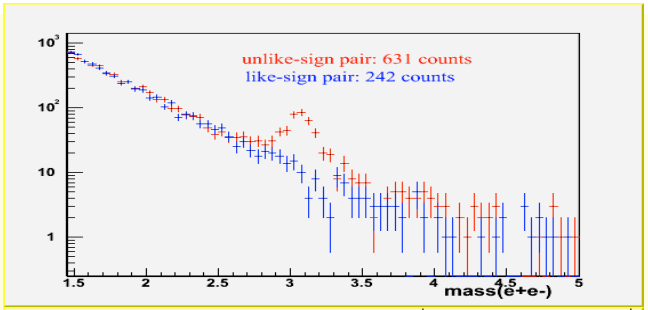
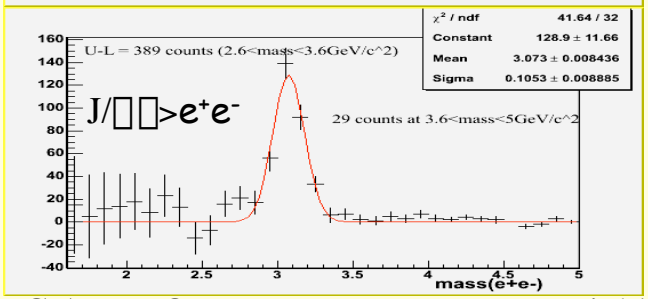
d+Au J/□ R_{CP}

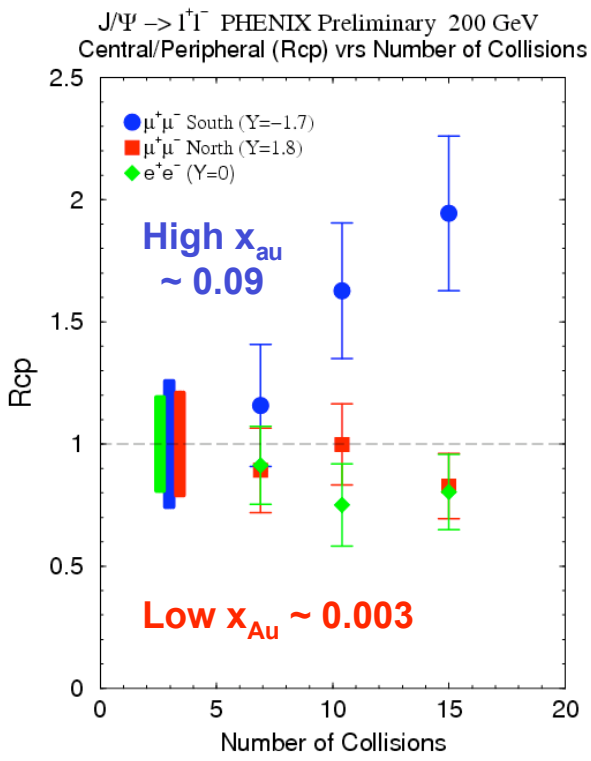






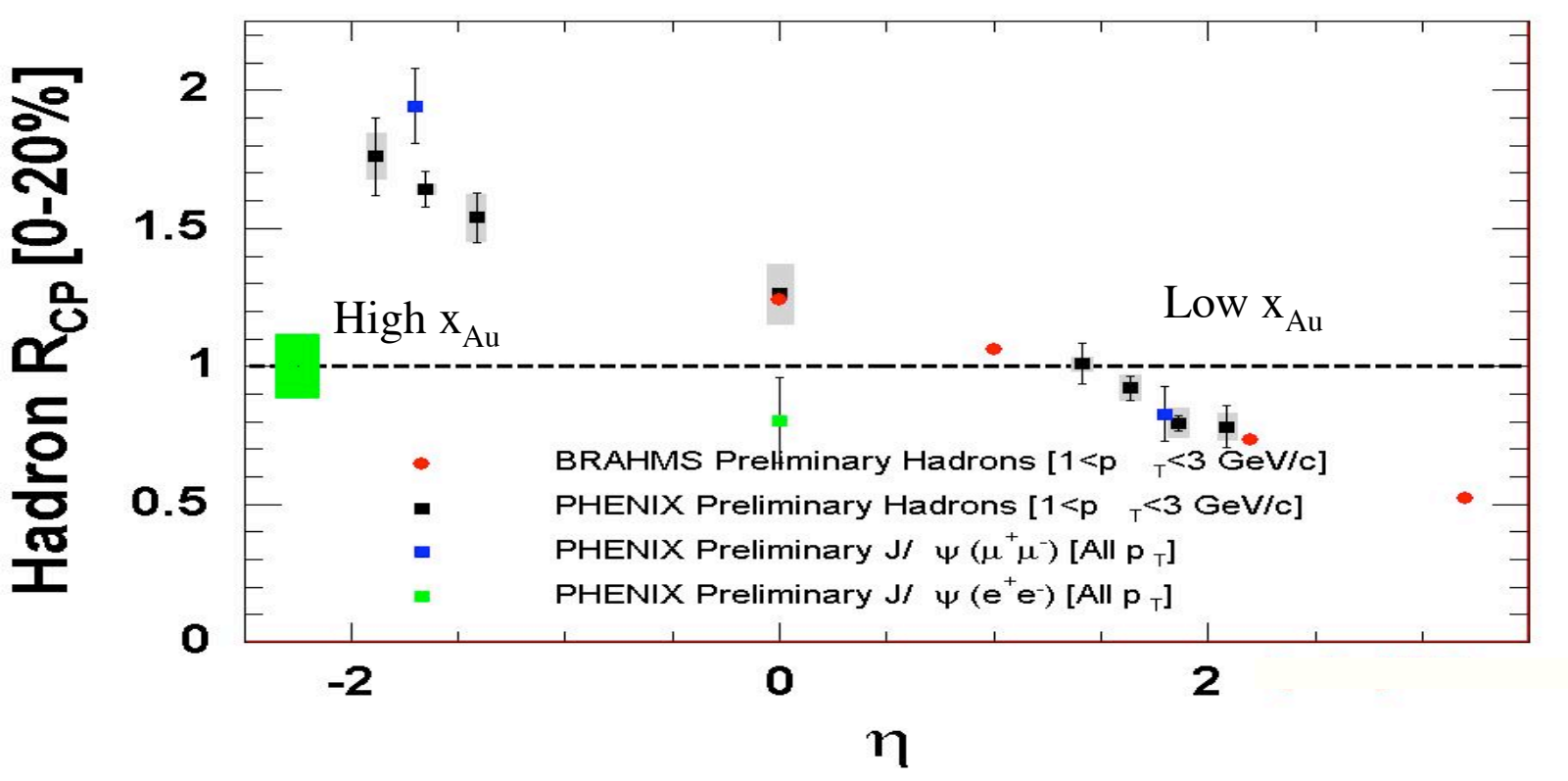


- **Low and med x_{Au} have small variations**
  - **Weak nuclear effects**
  - **Small shadowing centrality dependence**



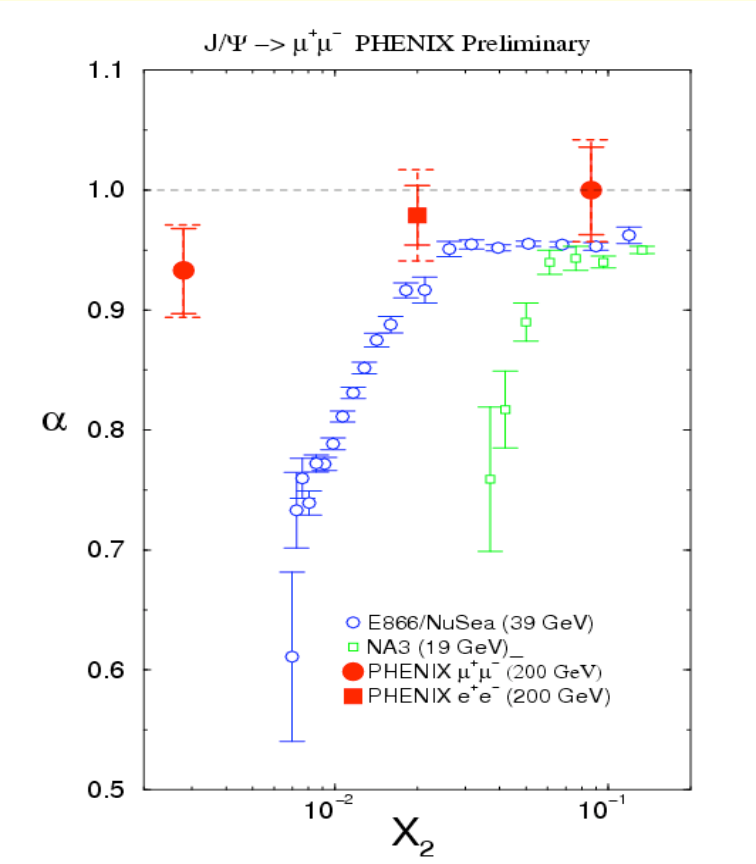
- **High x_{Au} has a steeply rising shape**
  - **Strong anti-shadowing but weak shadowing?**

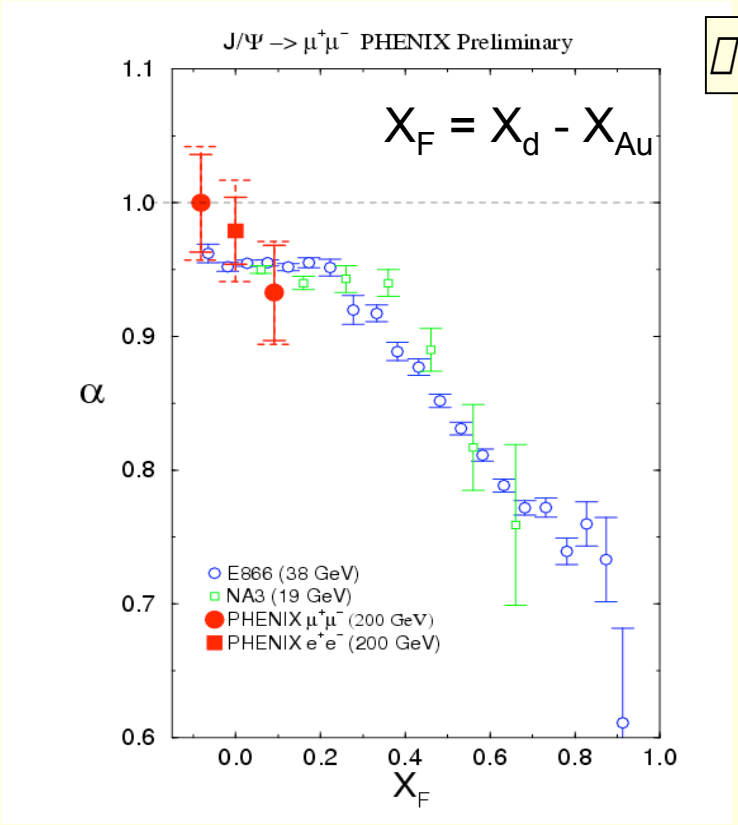
d+Au R_{CP} vs. □ Summary



- **Suppression at low x_{Au} (shadowing, saturation,…)**
- **Enhancement at high x_{Au} (Cronin, anti-shadowing,…)**
- **J/□ behaves like other mesons**

More on J/ψ d+Au x-Dependence





$$\sigma_{dA} = \sigma_{pp}(2 \times 197)$$

E866: PRL 84, 3256 (2000)
NA3: ZP C20, 101 (1983)

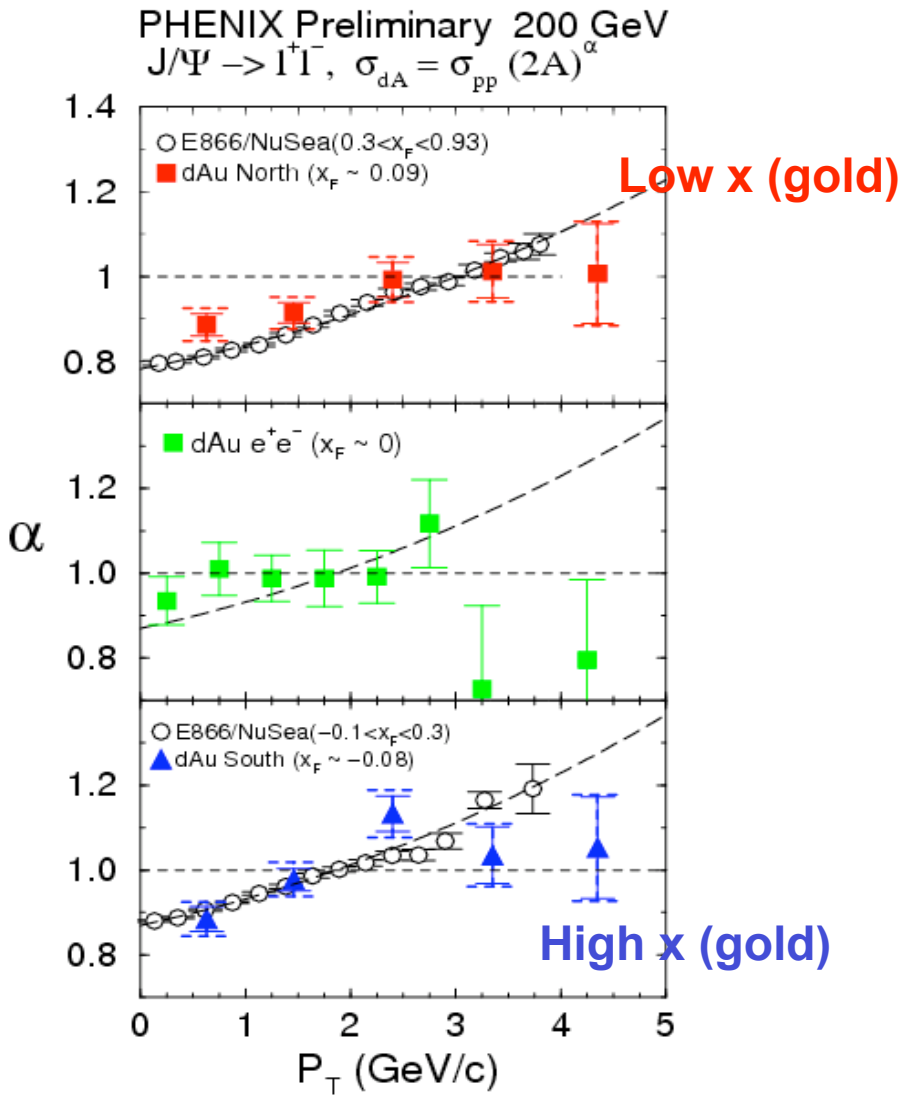
- **Not universal versus x_2 : shadowing is not the whole story.**
- **Same versus x_F for diff s. Incident parton energy loss ? (high X_d = high X_F)**

d+Au J/ P_T Broadening Observed

P_T broadening observed in both the low and high x part of the J/ spectra.

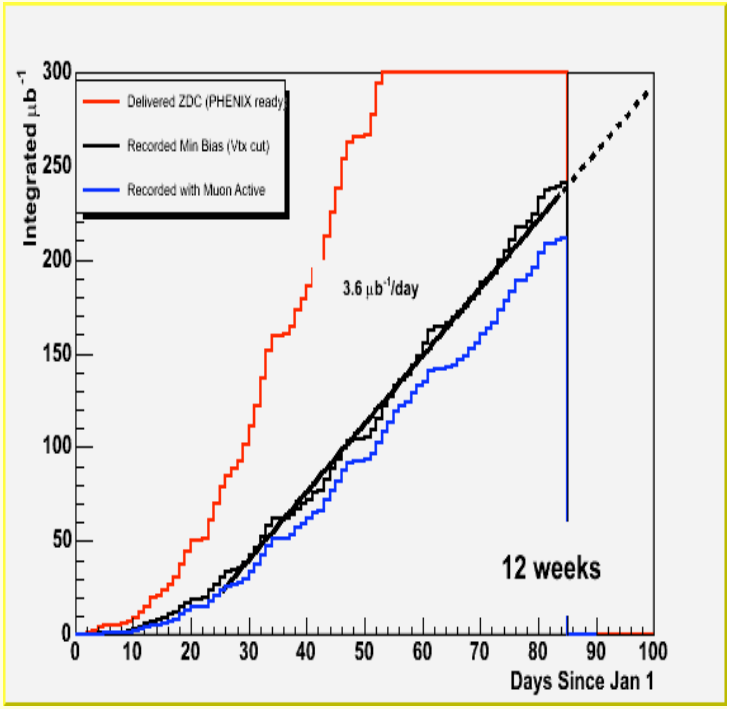
Very similar p_T enhancement as observed at lower energies.

$$\sigma_{dA} = \sigma_{pp}(2 \cdot 197)^{\alpha}$$



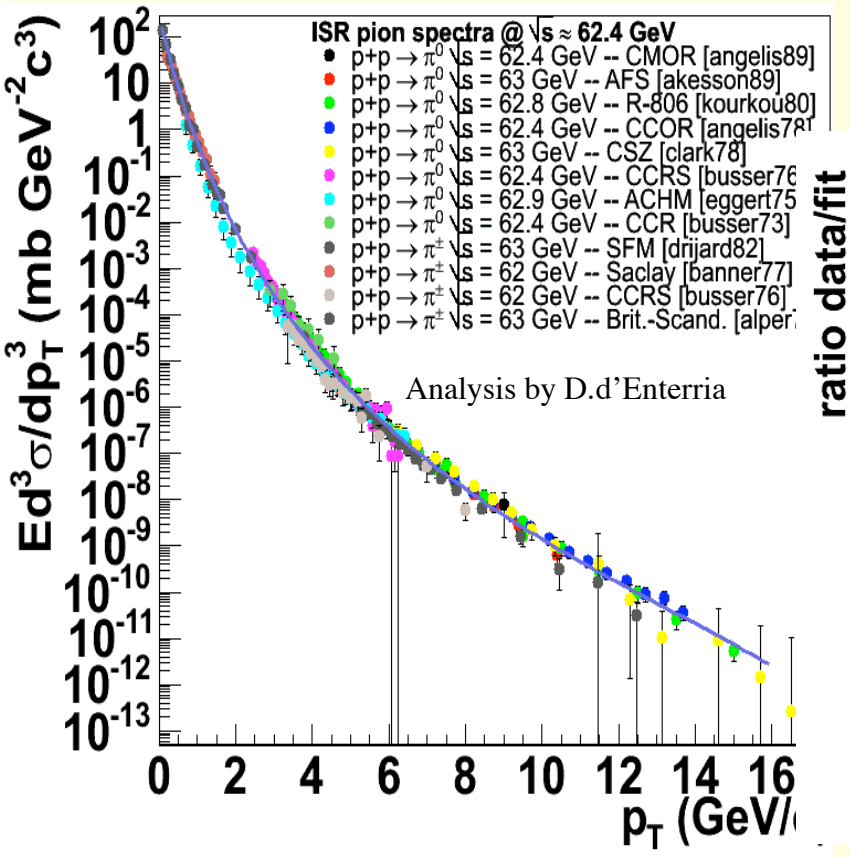
PHENIX in Run 4

- New for run 4: Aerogel for improved hadron PID, TRD for improved electron identification.
- Compared to Run 2 (200 GeV Au+Au) both muon arms. Complete central arm coverage.
- 200A GeV Au+Au data sample of 1.5×10^9 min bias events recorded, or 241 μb^{-1} integrated luminosity
  - Recorded at up to 350Mbyte/s @ 1.5kHz
  - 60 times the 24×10^6 minbias events of Run 2 used for most analyses
  - 10 times the 24 μb^{-1} sampled in Run 2 by triggered events
  - Expect J/ψ measurement, hadron spectra to higher p_T, direct γ, …

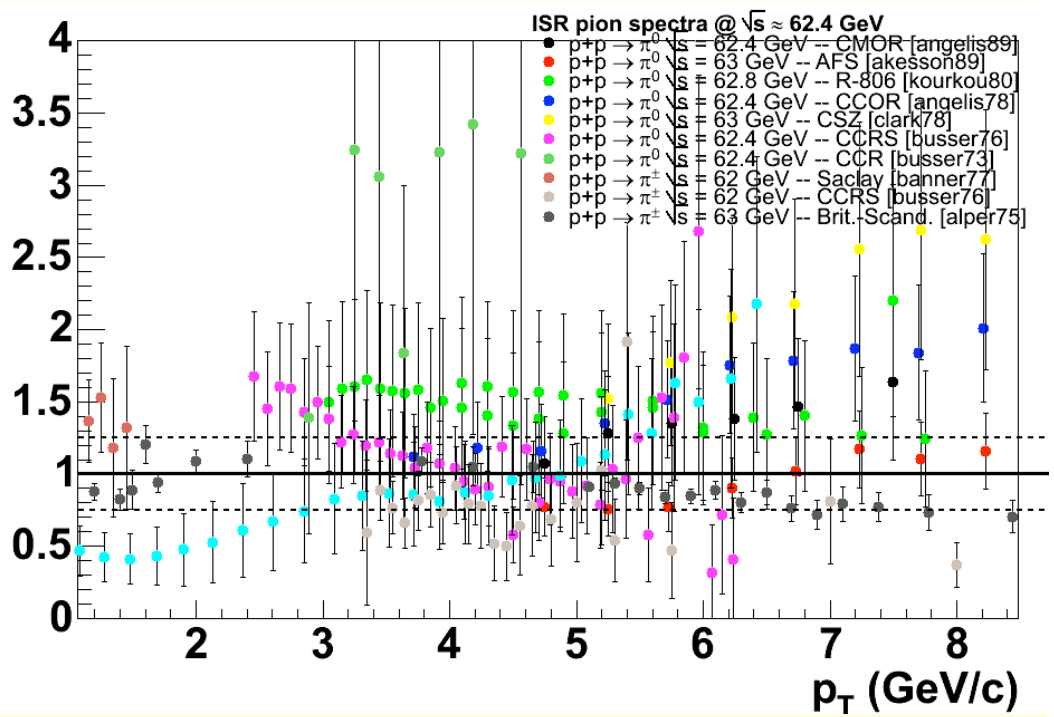


- 62.4 A GeV Au+Au data sample of 58×10^6 min bias events recorded.
  - Preliminary results shown here - Thanks to effort of (unnamed) many!
- Promising polarized pp development.

R_{AA}: p+p □> □ at $\sqrt{s}$=62.4 GeV



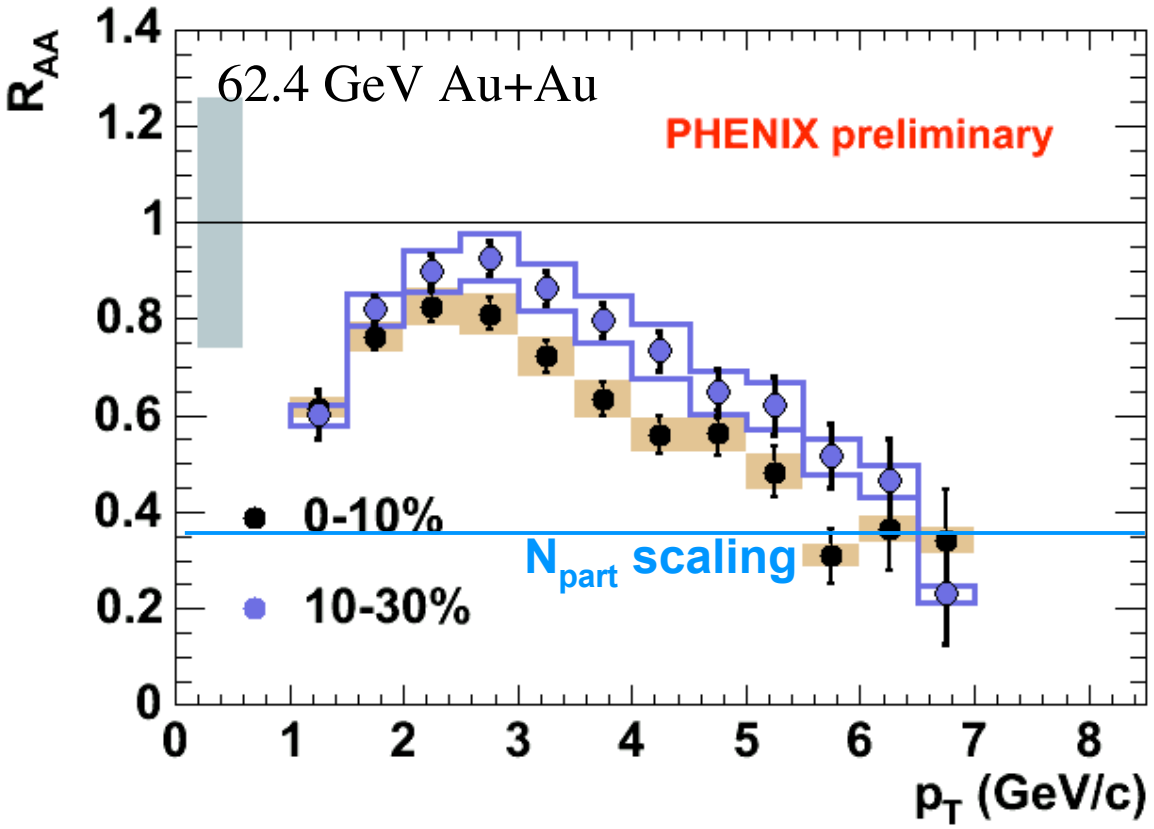
$$f(p_T) = A/(e^{a\cdot x^2+b\cdot x} + x/p_0)^n$$

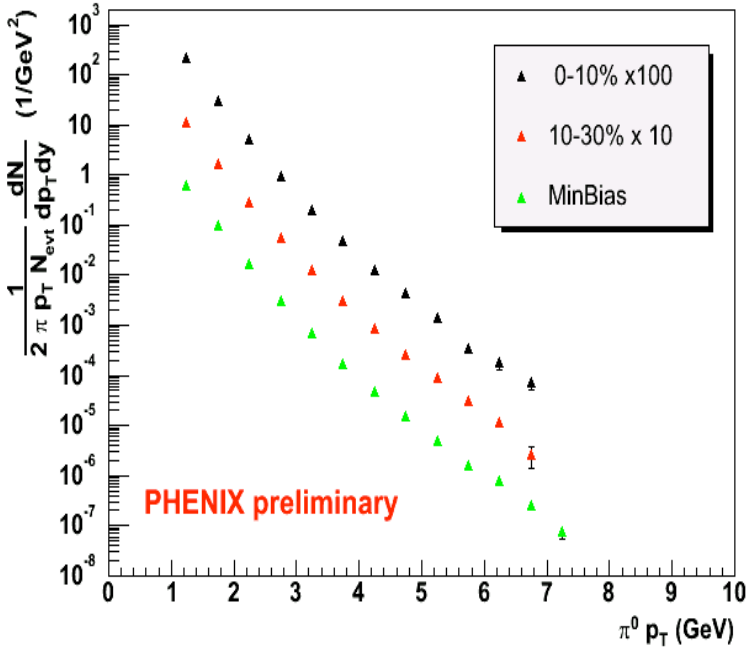


- Plenty of pp results @ 62.4 (62-63?!) GeV, but significant discrepancies!
- Assign ~25% systematic error to best fit. Note: It is a shape uncertainty, not just a scale uncertainty.

π^0 Production in Au+Au at 62.4A GeV

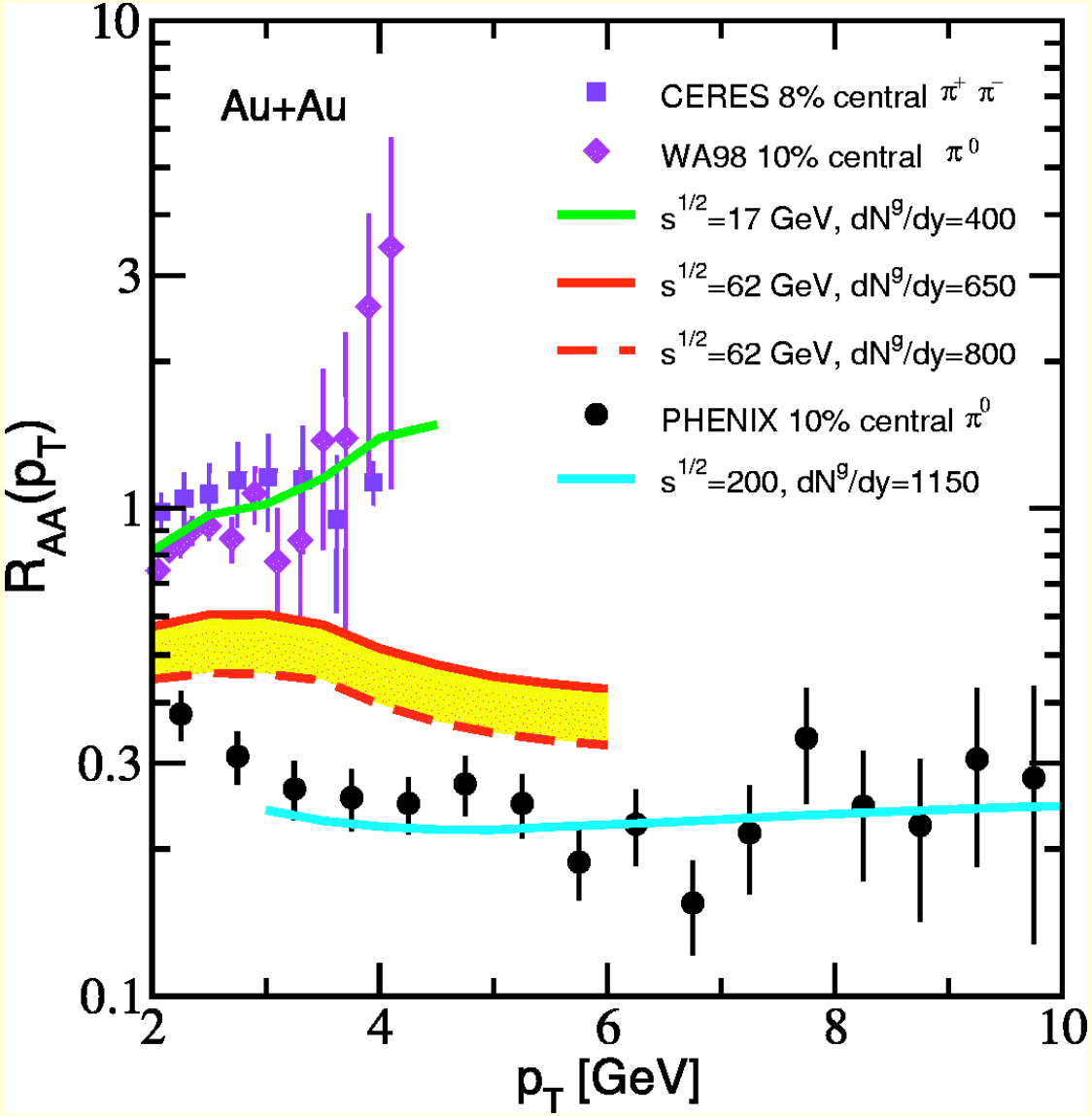
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$





- **Suppression at $p_T \sim 7$ GeV/c similar to @ 200 GeV at $p_T \sim 4$ GeV/c**
- **Cronin enhancement apparently much more significant.**

π^0 R_{AA} s Systematics: Predictions



- Cronin and parton energy loss dominant effects with different s dependences and contributions.
- The 62.4 GeV result should be a good test of models.
- Given the 17 GeV and 200 GeV results, there is not much room for error!

- Reasonable agreement with 62.4 GeV result - data suggests larger Cronin contribution.
- But systematic errors in p+p reference are large.

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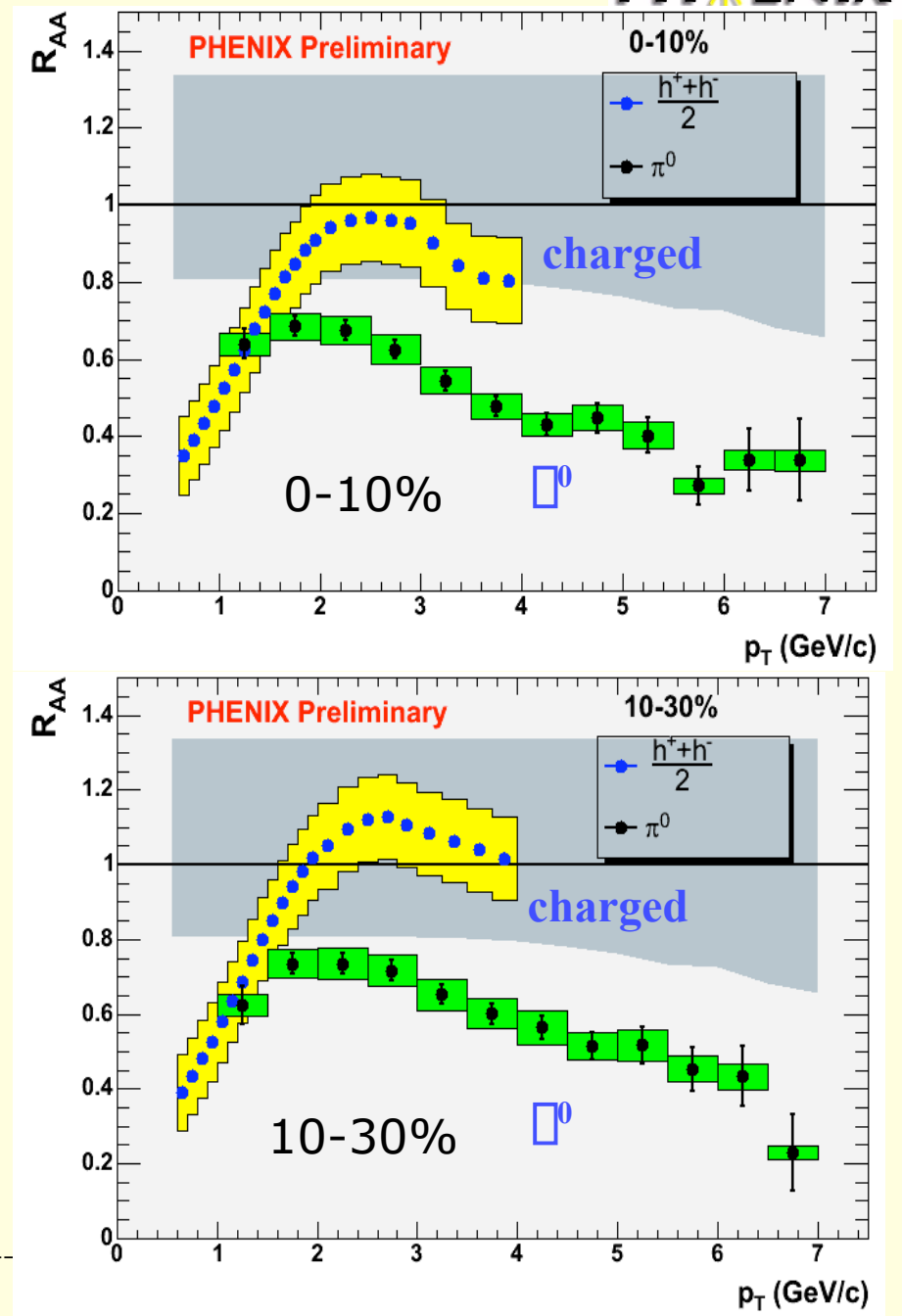
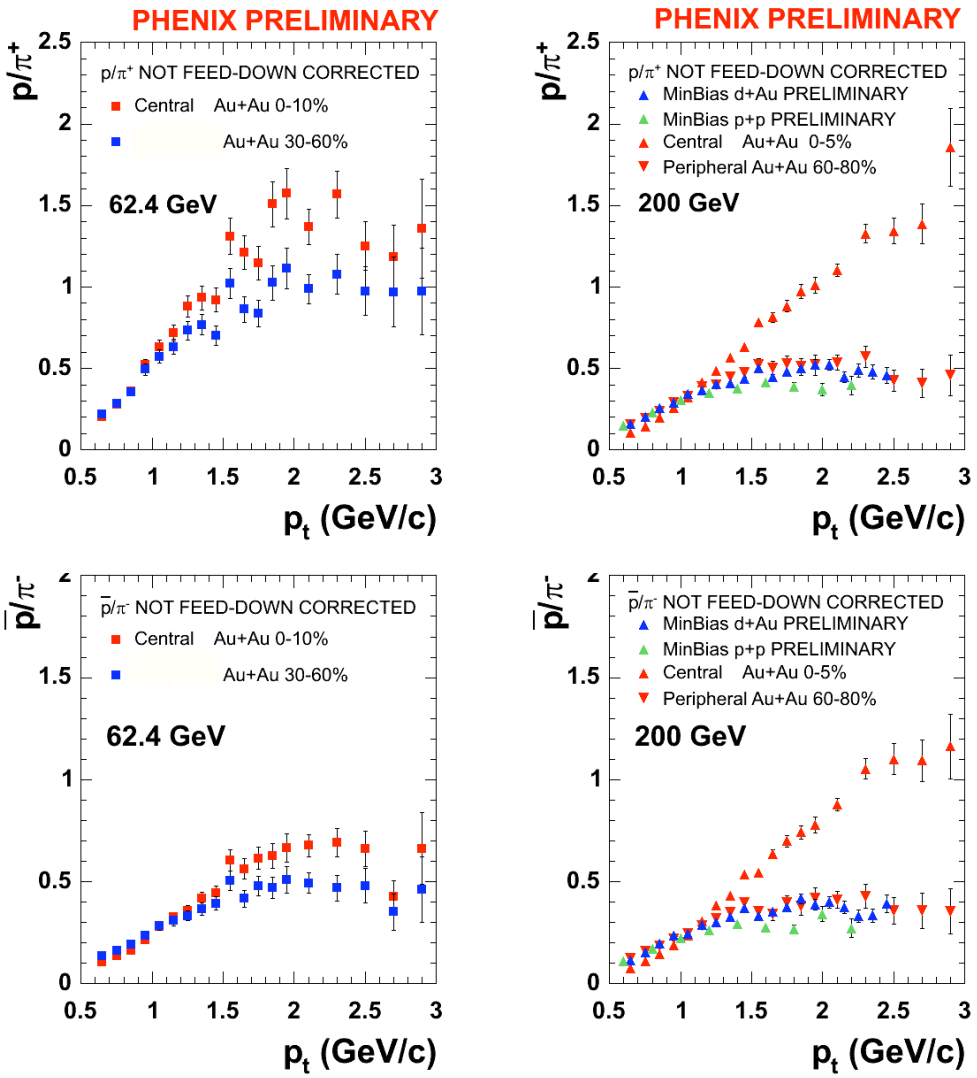
Charged Hadron R_{AA}

- Charged hadron measurements from ISR now used for p+p reference.
- π^0 yield is also divided by (charged reference)/1.6, not ISR π^0 measurement reference.
- Discrepancy between charged hadron and π^0 not surprising due to expected p, pbar contribution.

Particle ID is essential.



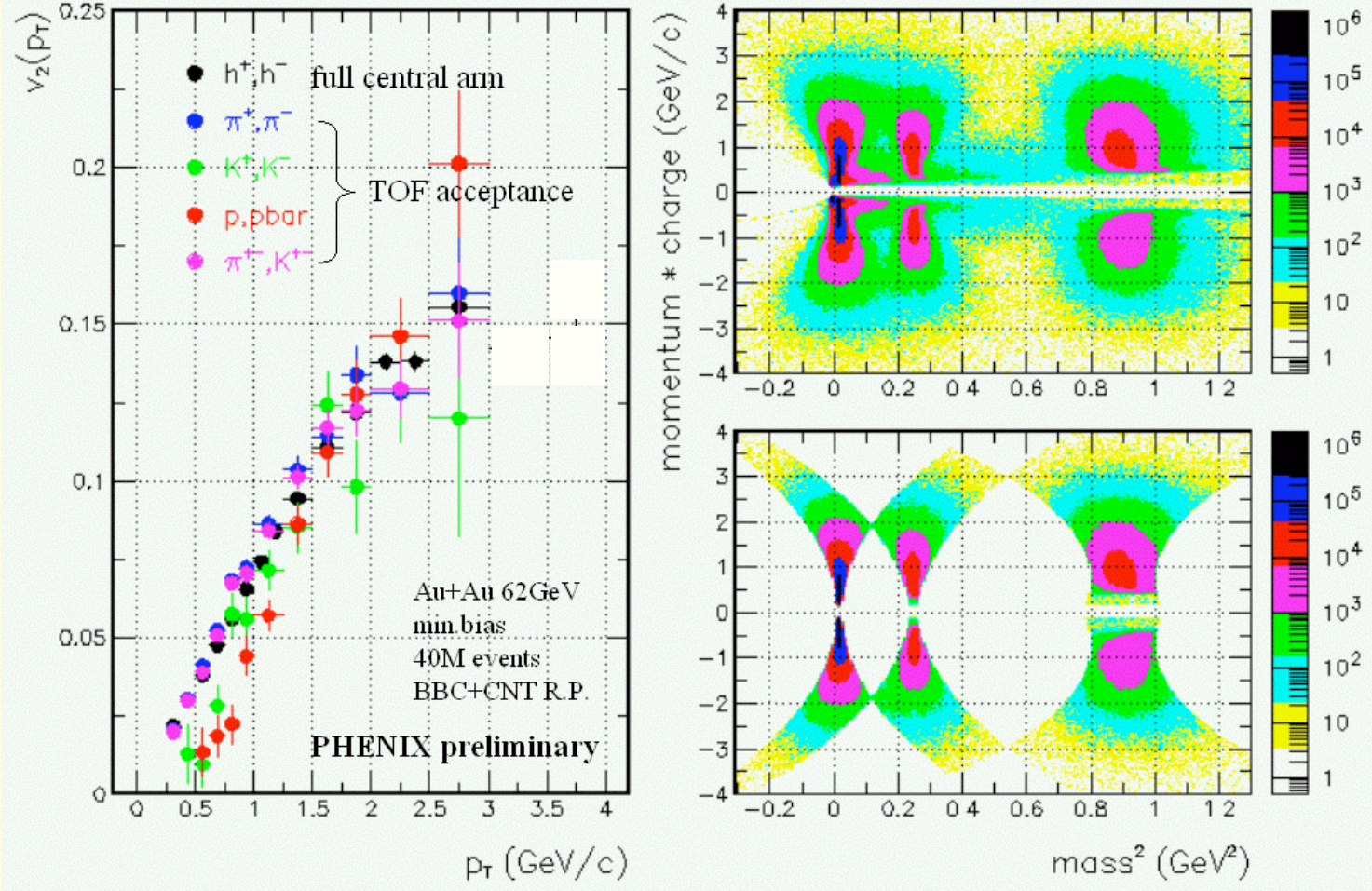
p/□ ratio in Au+Au at 62.4 GeV



- Central p/□+ ratio similar to 200 GeV Au+Au result at high p_T.
- Central pbar/□- ratio at 2-3 GeV is smaller than 200 GeV results.
- Smaller pbar/p ratio due to more baryon transport to mid-rapidity and less p-pbar production.

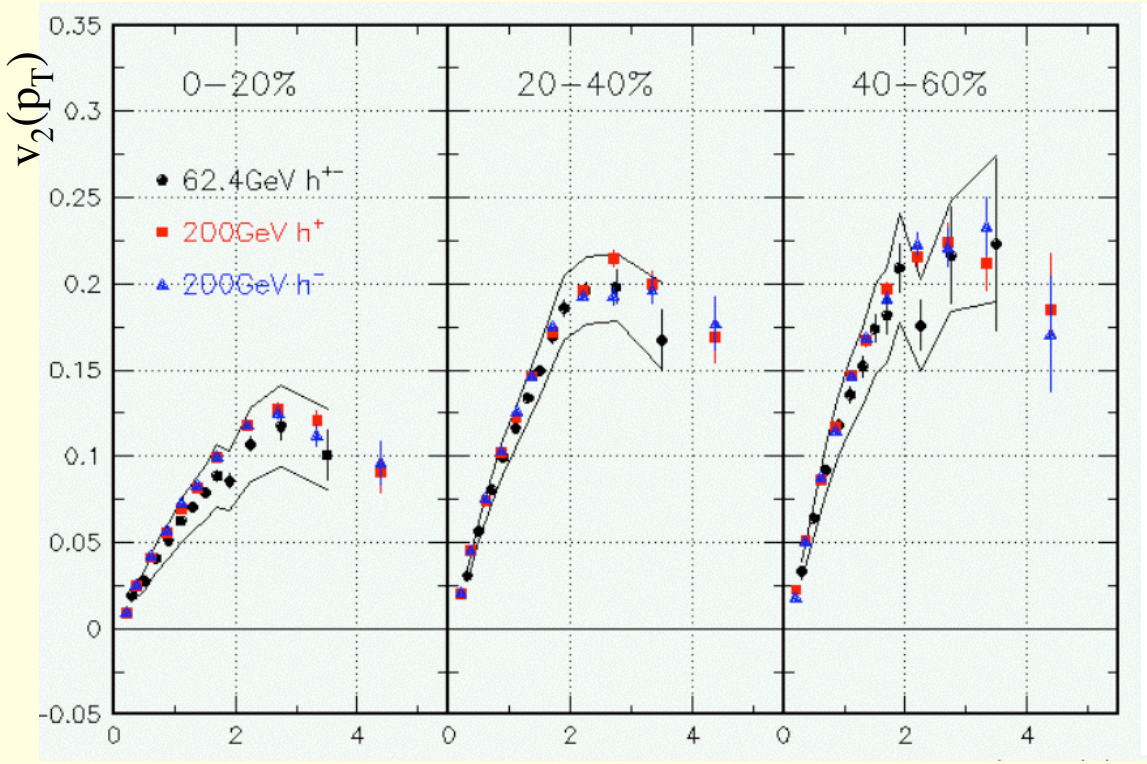
□,K,p Flow Analysis at 62.4 GeV

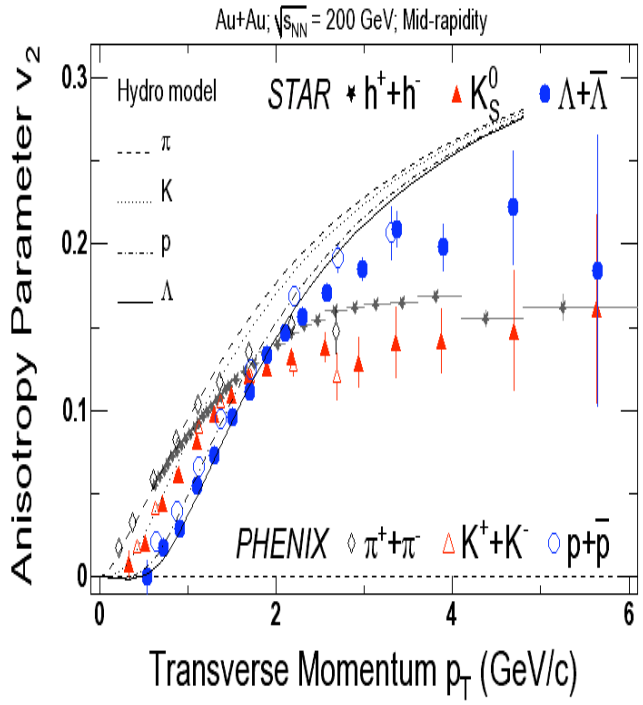
Min Bias 62.4A GeV Au+Au



Magnitude and mass ordering of v_2 similar to observed at 200 GeV

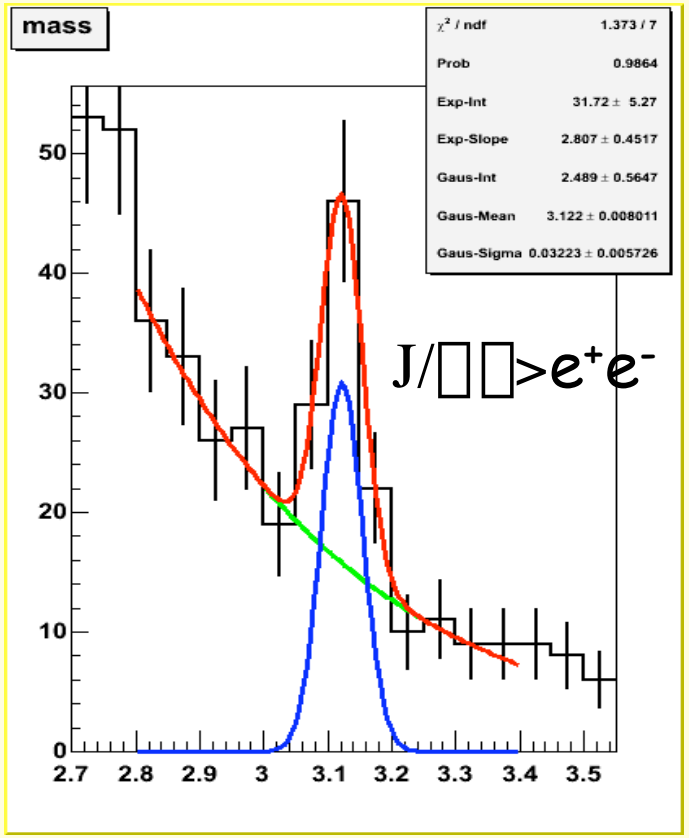
Comparison of v_2 at 62.4 and 200 GeV





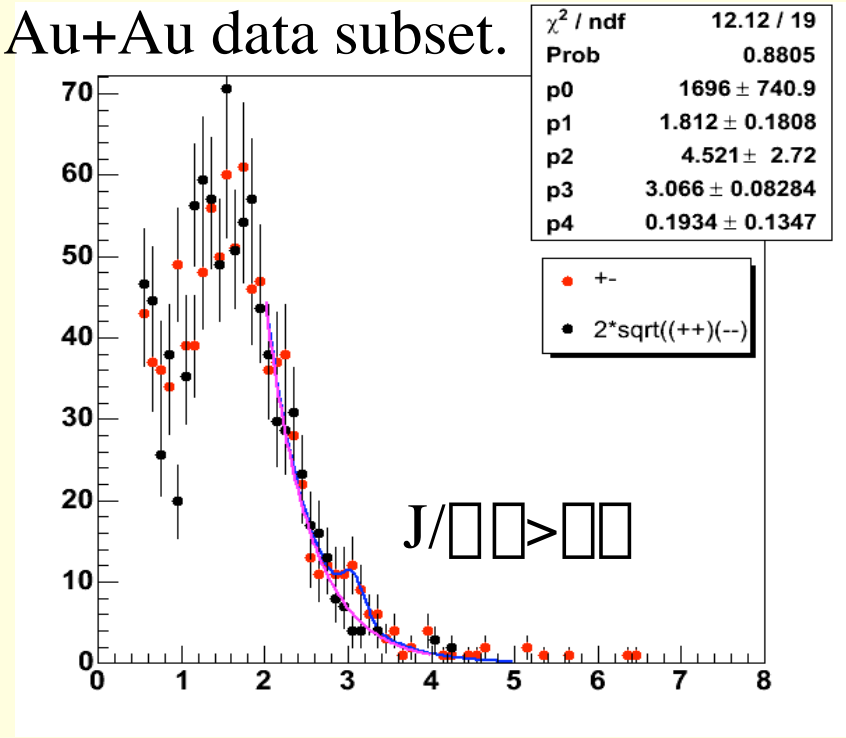
- v_2 with PID at 62.4 GeV looks like 200 GeV results where Hydro works.
- Similarly good "coalescence" scaling of $v_2(p_T)$ at 62.4 as at 200 GeV.

J/□ in Run 4 200 GeV Au+Au



Over 1. 5 billion Min Bias events or 241 □b^{-1} recorded on tape by PHENIX. Expect ~3000 J/□ muon arm.

Clear J/□ signal already observed in Au+Au data subset.



Summary

- R_{dA} enhancement for d+Au and N_{coll} scaling of direct □yield in central Au+Au imply high p_T suppression in Au+Au is a final state effect.
- Baryons apparently not suppressed with jet-like behavior similar to pions.
- Interesting suppression and enhancement effects vs. rapidity (or x) in d+Au as seen via PHENIX muon detectors. Hadrons and J/□.
  - Appears to be energy loss effect rather than saturation/shadowing.
- Results for 62.4 GeV qualitatively similar to 200 GeV
  - R_{AA} suppression weaker, larger Cronin effect. PID important.
  - $v_2(p_T)$ with PID virtually the same at 62.4 and 200 GeV
- Huge Run 4 data set will allow further detailed studies, direct □, □-jet, J/□,..

Special thanks to CA-D for an extremely successful Run 4!