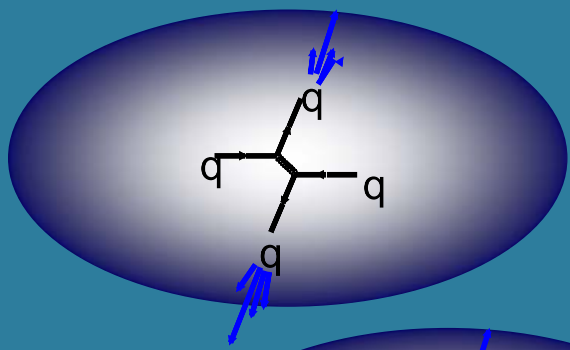
Medium Effects on Jets and their Energy Dependence

Henner Büsching

Brookhaven National Laboratory
for the PHENIX Collaboration

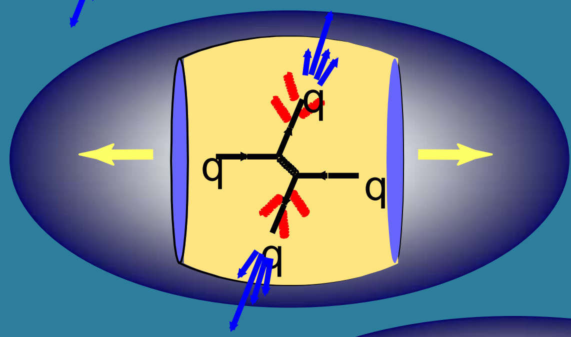
Hard Probes - Ericeira , Nov. 8 2004

Outline



p+p 200 GeV

Initial conditions



Au+Au 200 GeV

Probe hot and dense nuclear matter with high pT partons

d+Au 200 GeV

Au+Au 62.4 GeV

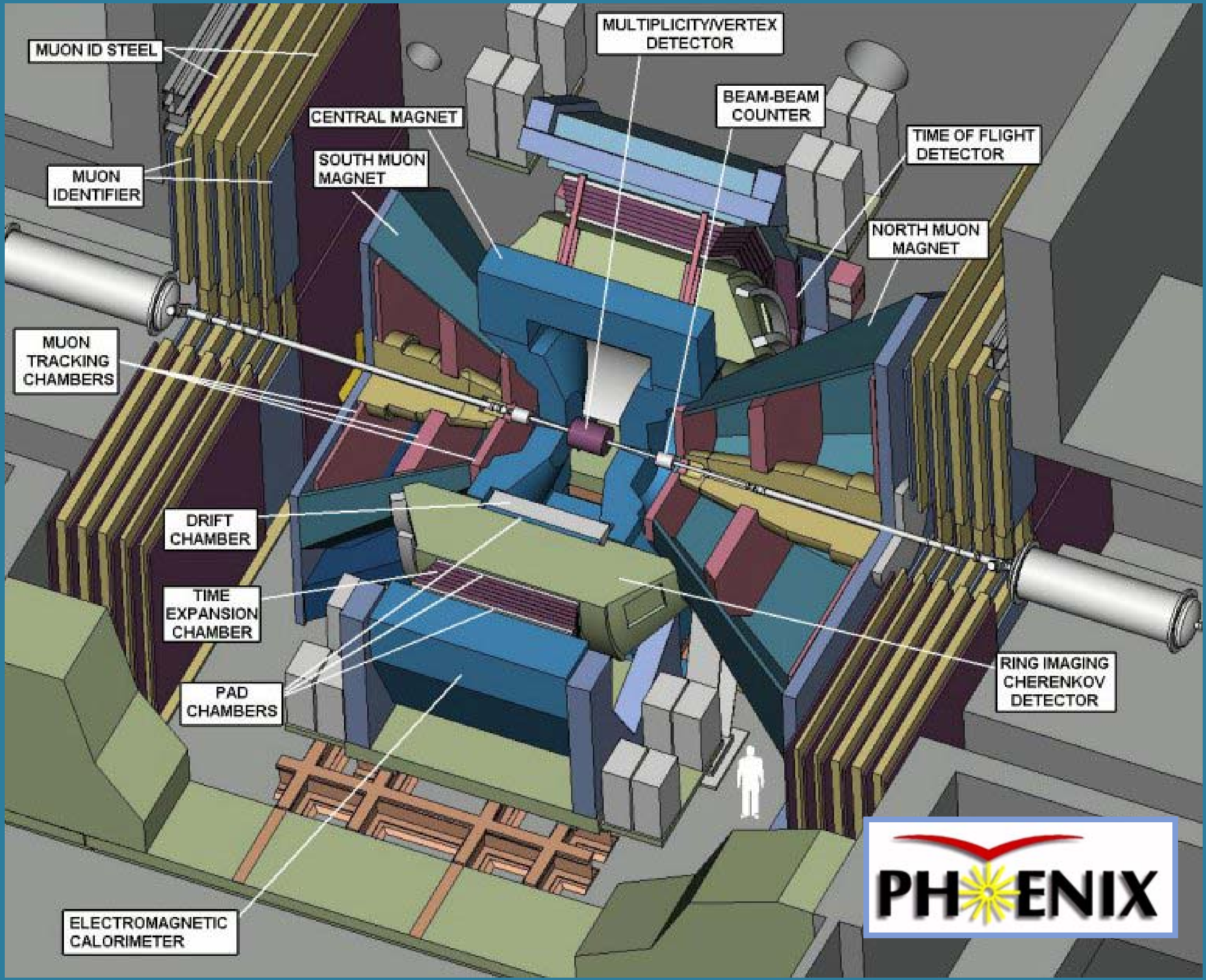
Particle species

PHENIX at RHIC

2 central spectrometers

2 forward spectrometers

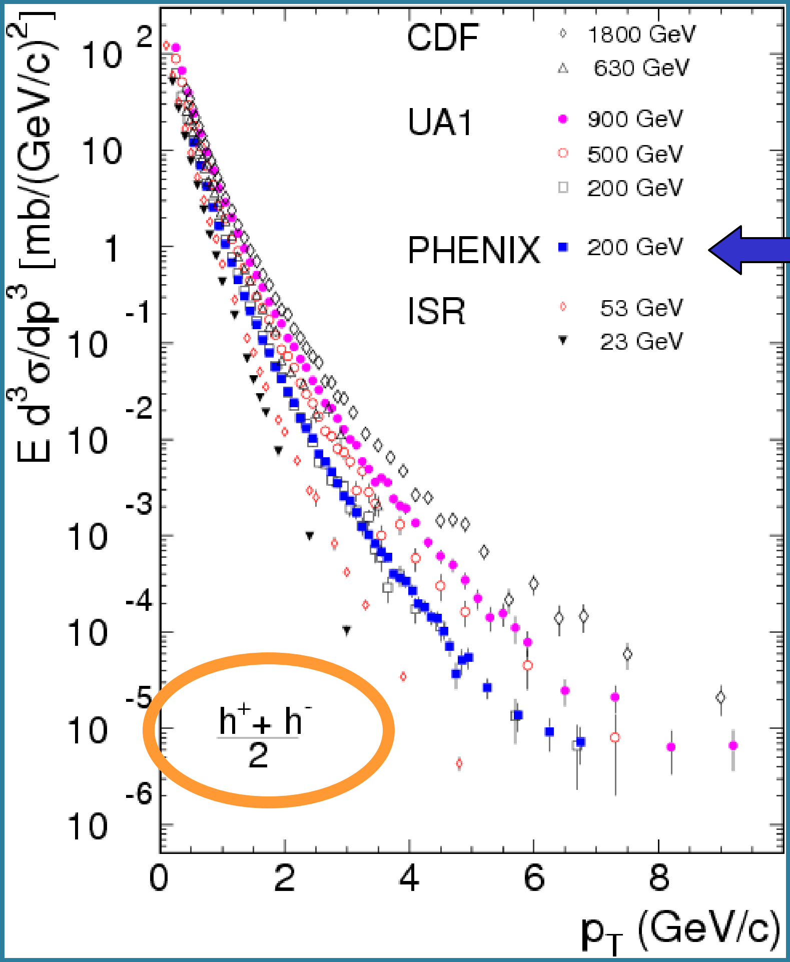
3 global detectors

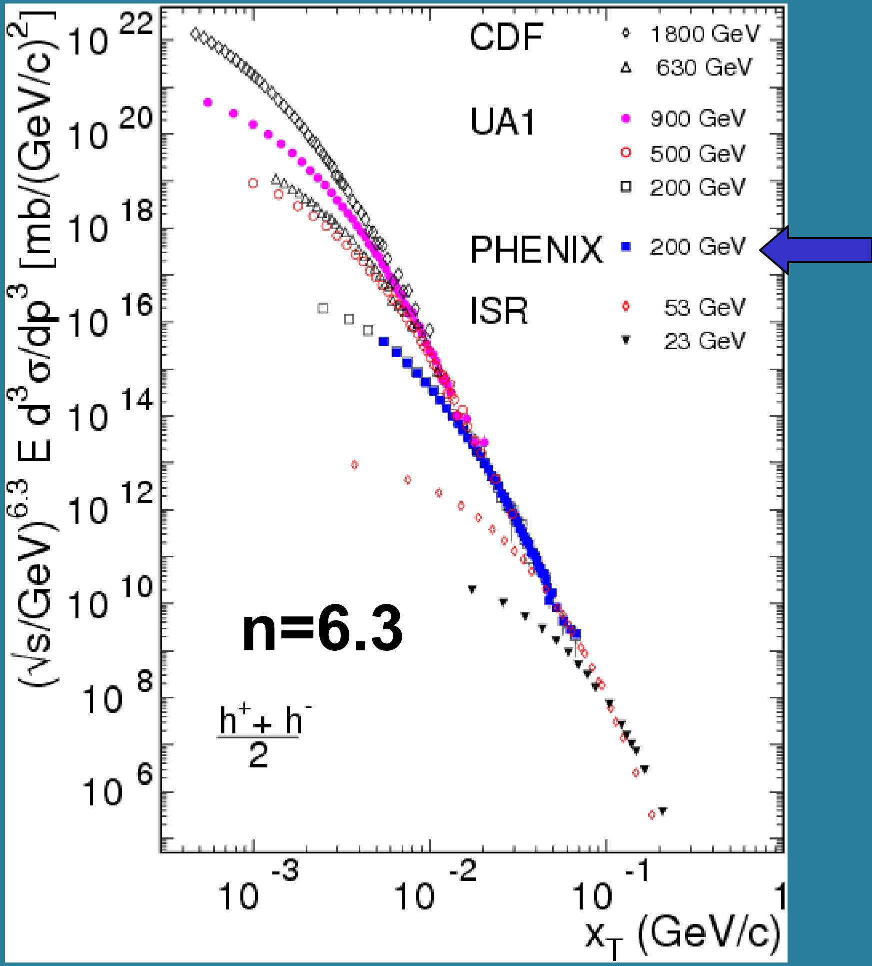


Initial Conditions

p+p at 200 GeV

Do we understand our p+p data?



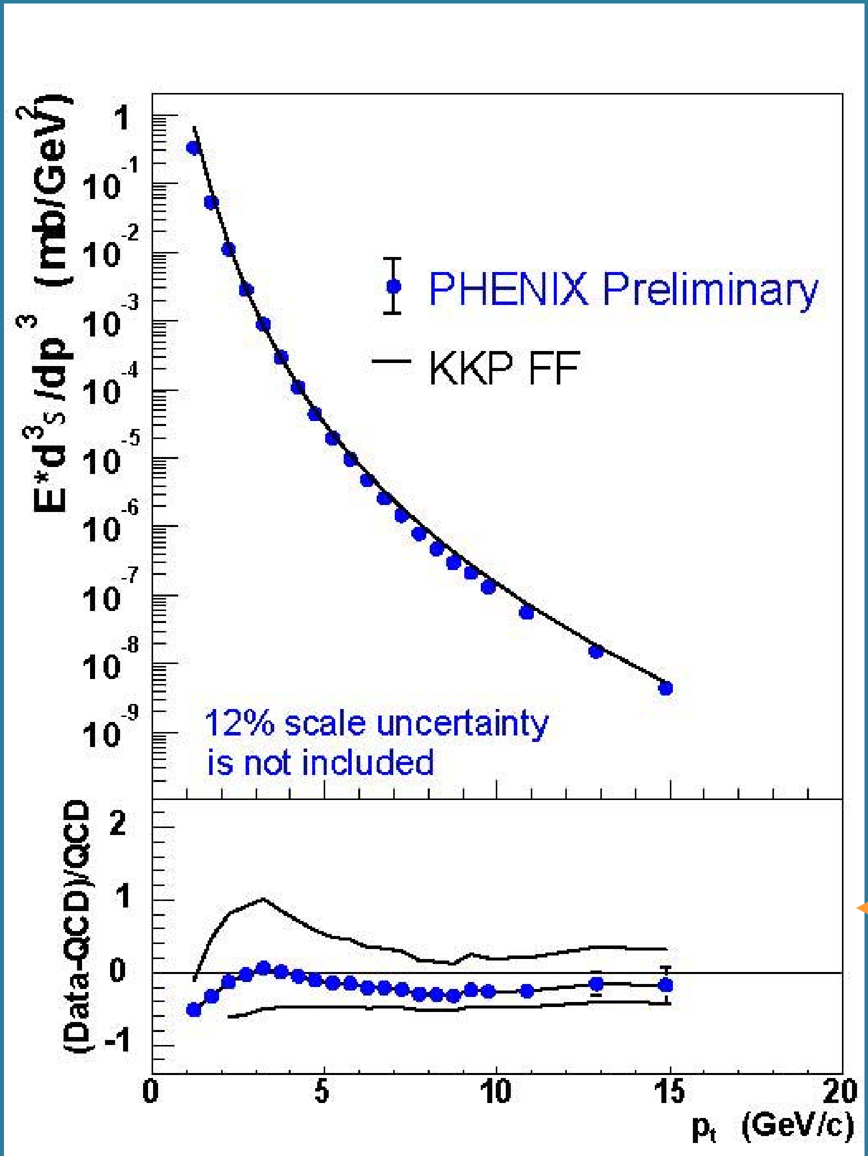


$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n}F(x_T) = \frac{1}{\sqrt{s}^n}G(x_T)$$

$$x_T = 2\,p_T/\sqrt{s}$$

x_T scaling at high pT

pQCD works – π^0



- **Good agreement with NLO pQCD**
  - Factorization theorem:

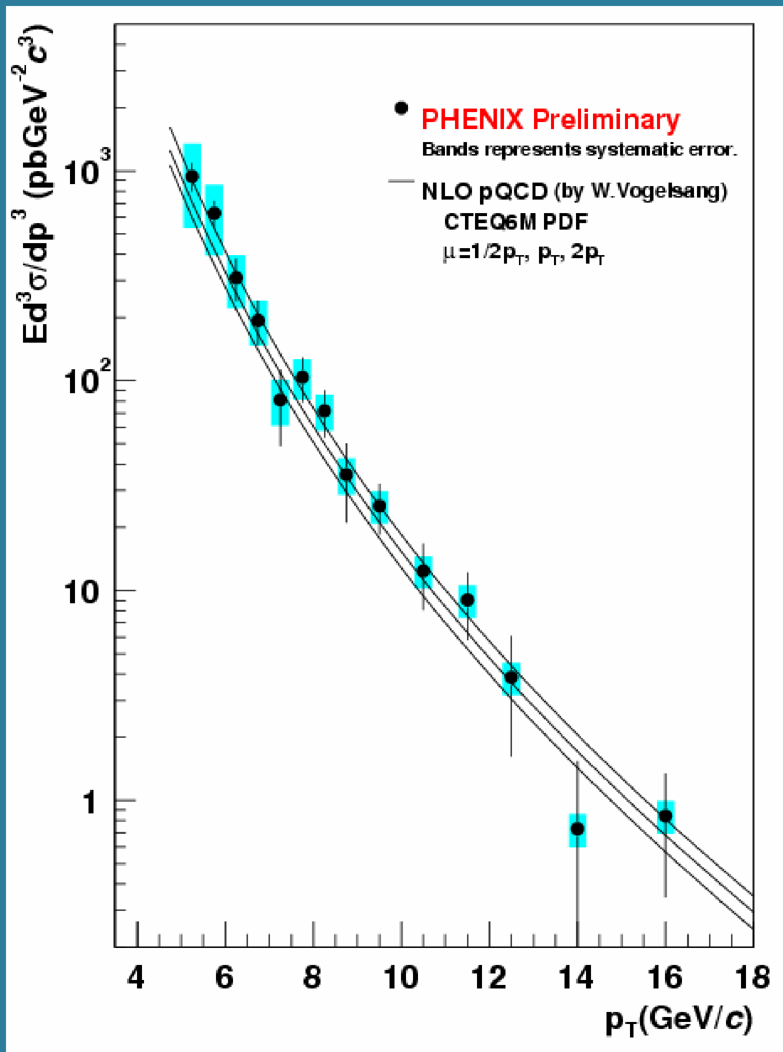
$$\sigma_{AB \to hX} \propto f_{a/A}(x_a,Q^2_a) \otimes f_{b/B}(x_b,Q^2_b) \otimes \sigma_{a\,b \to cd} \otimes D_{h/c}(z_c,Q^2_c)$$

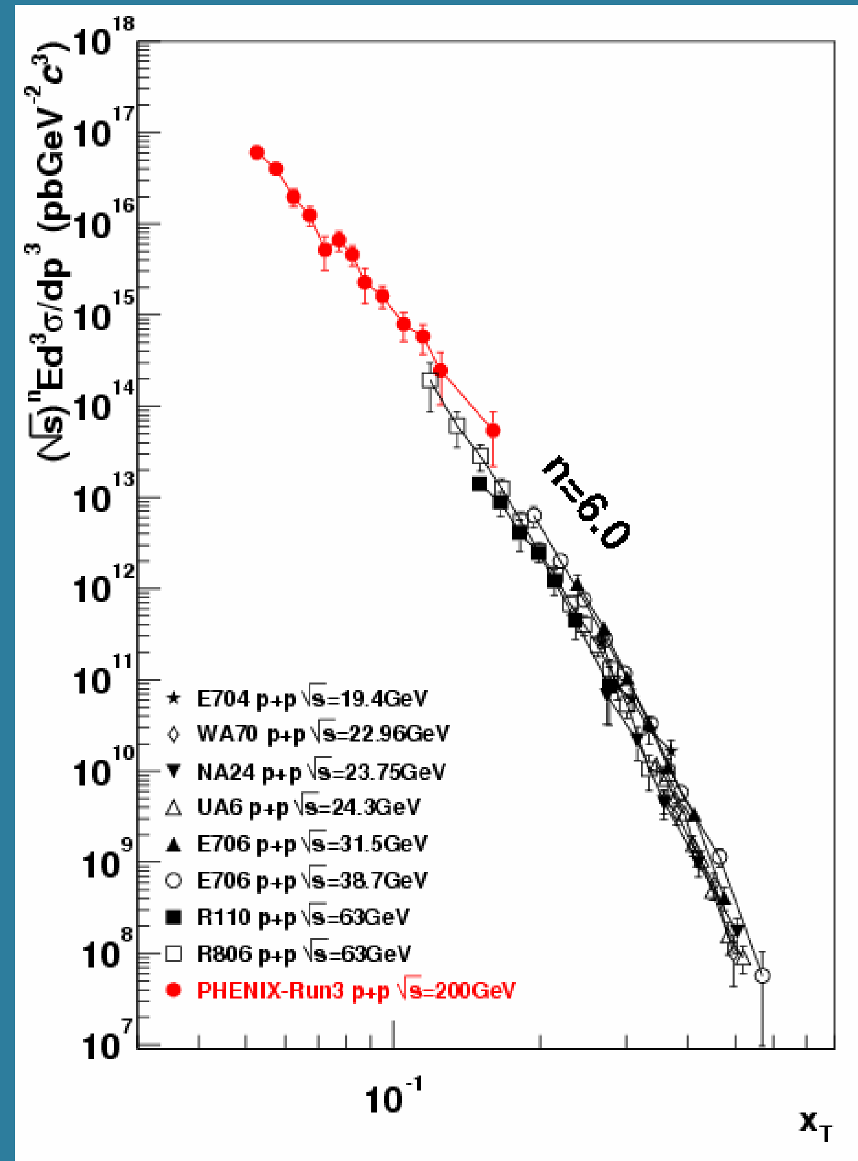
- **Constrains Fragmentation Function D(Gluon-pi)**
- **Reference for Au+Au spectra**
- **Especially good reference if measured together with heavy ion data : reduced syst. errors**

Run3 : preliminary

Run2:
Phys. Rev. Let 91, 241803 (2003)

pQCD works – direct photons





Nuclear Modification Factor R_{AA}

- **Hard processes**
  - yield scales with N_{coll}
  - reason:
    - small cross section
    - incoherent superposition
- **Nuclear Modification Factor R_{AA}**

$$R_{AB} = \frac{\left(1/N_{AB}^{evt}\right)\, d^2N_{AB}/dydp_T}{\langle T_{AB}\rangle\, d^2\sigma_{pp}/dydp_T}$$

$$\langle N_{coll}\rangle / \sigma_{NN}$$

Nuclear overlap function

$$T_{AB} = \int d^2\mathbf{r}\, T_A(\mathbf{r})\, T_B(\mathbf{b}-\mathbf{r})$$

Nuclear thickness function

$$T_A(b) = \int dz\, \rho_A(b,z)$$

from Glauber model

Geometrical factor from nuclear overlap

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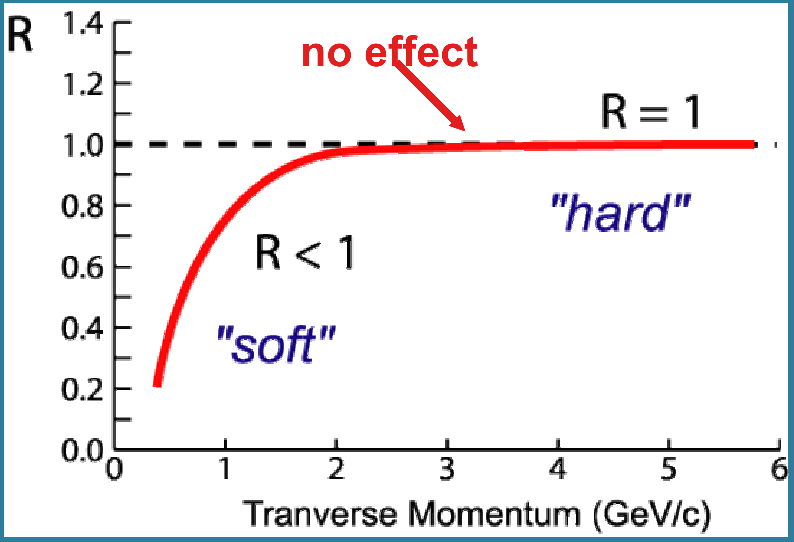

$$R_{AB} = \frac{\left(1/N_{AB}^{evt}\right)\, d^2N_{AB}/dydp_T}{\langle T_{AB}\rangle\, d^2\sigma_{pp}/dydp_T}$$

- **In the absence of nuclear effects: R_{AA}=1 at high p_T**

Nuclear Modification Factor R_{AA}

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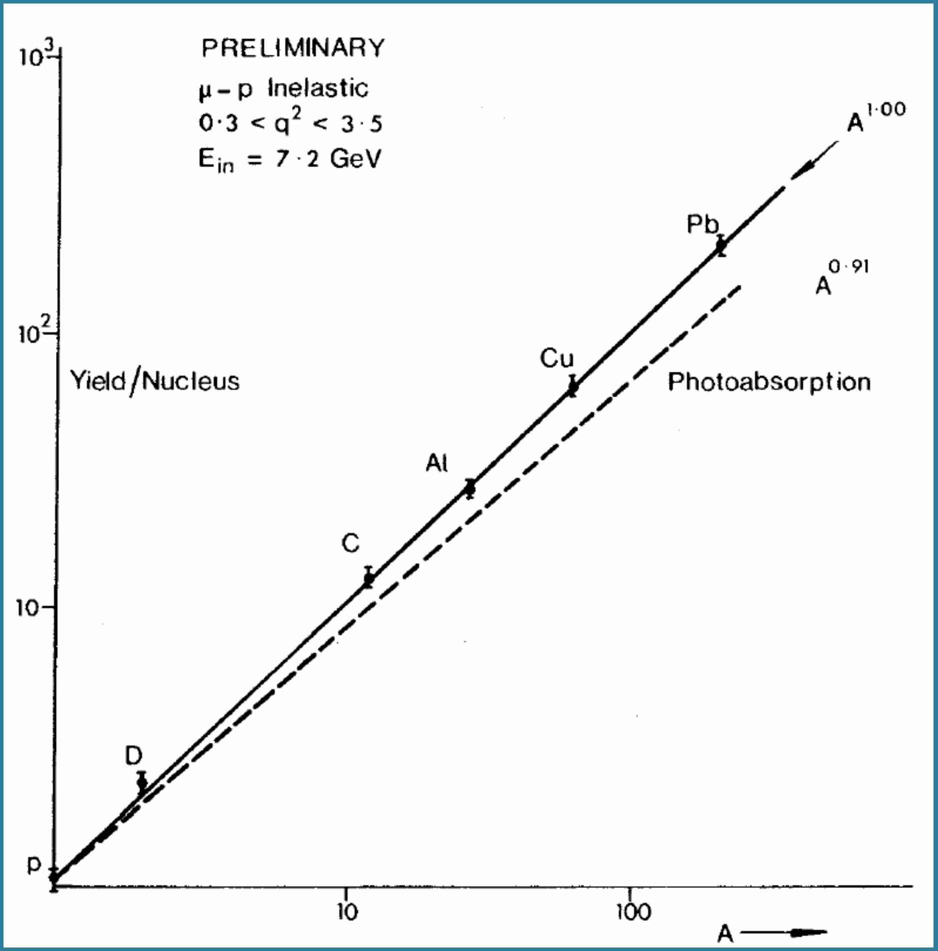
7.2 GeV muons on various targets scale as α=1.0 in μ+A



Phys. Rev. Lett. 35, 407 (1975)

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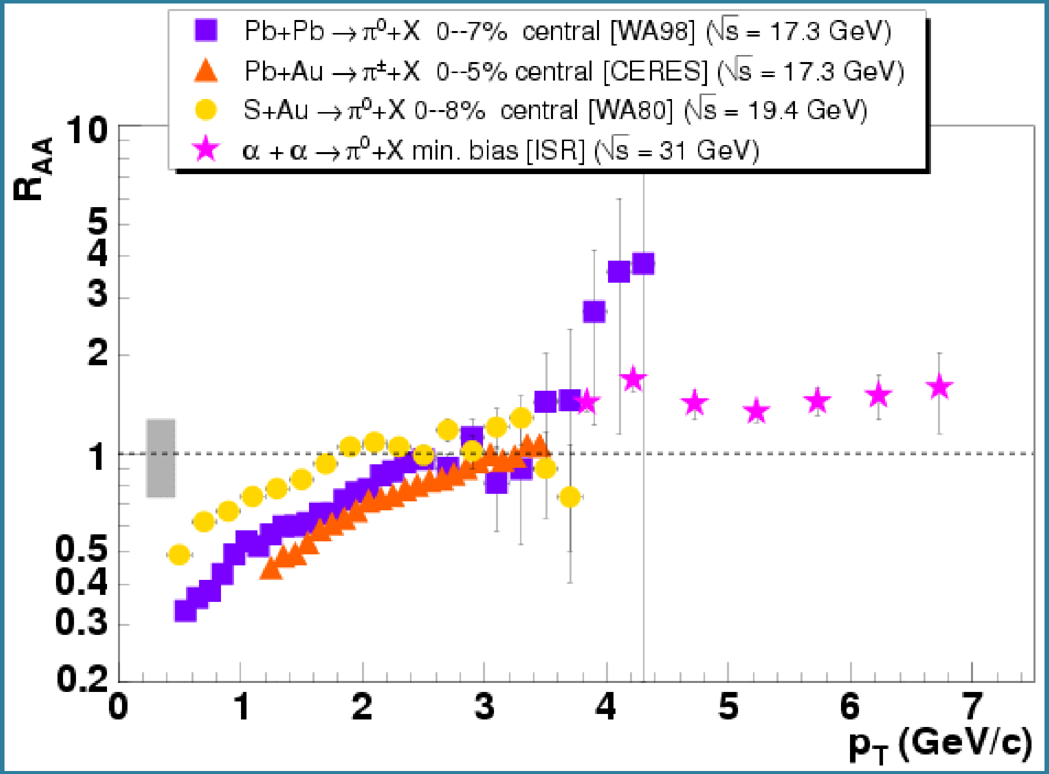
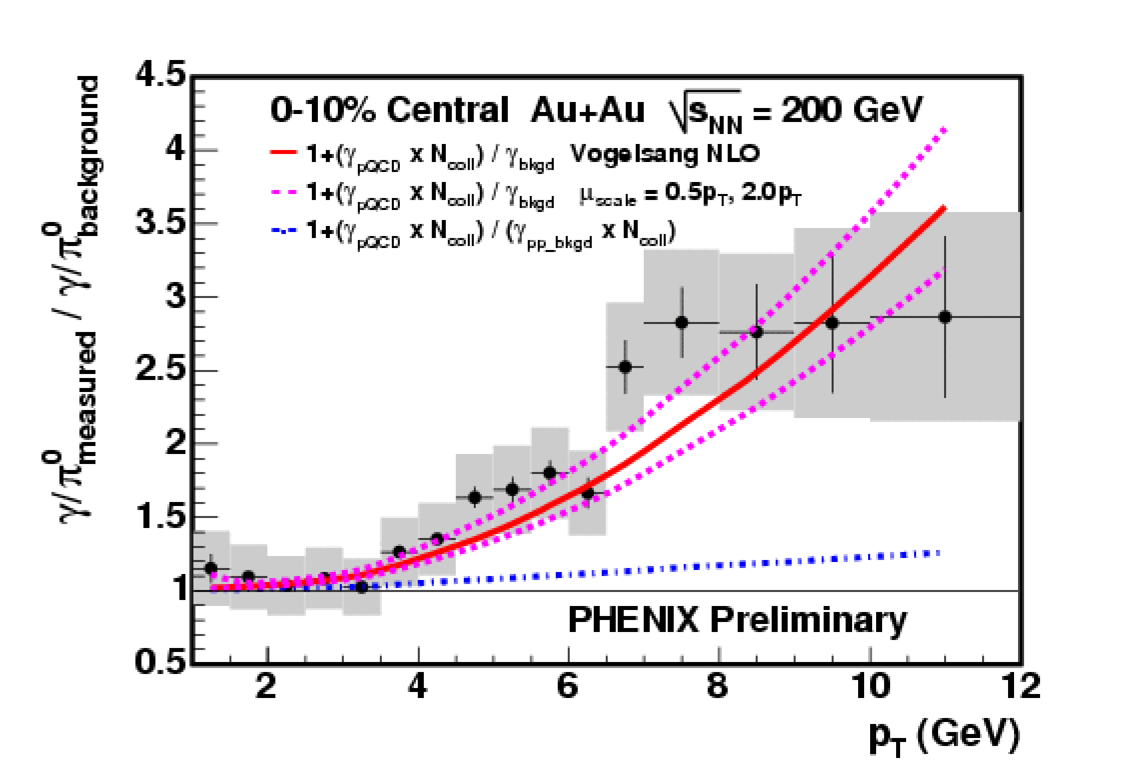


Cronin effect:
$\alpha(p_T) > 1$
Multiple scattering of incident partons

Au+Au

200 GeV

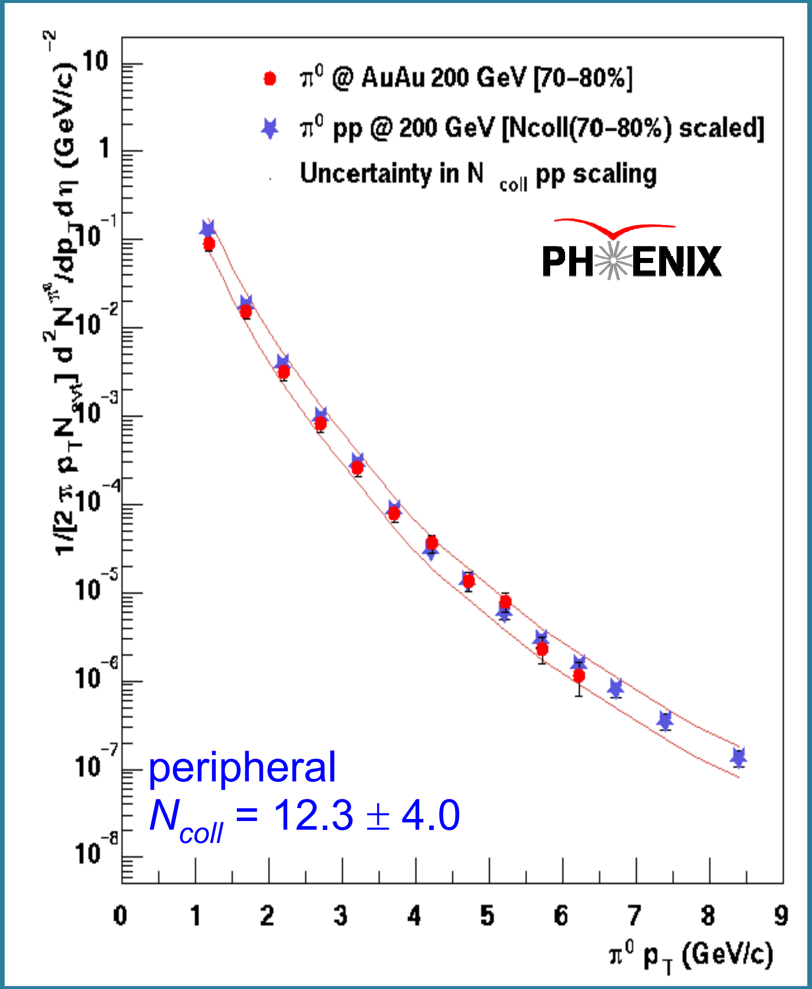
Binary scaling - direct photons

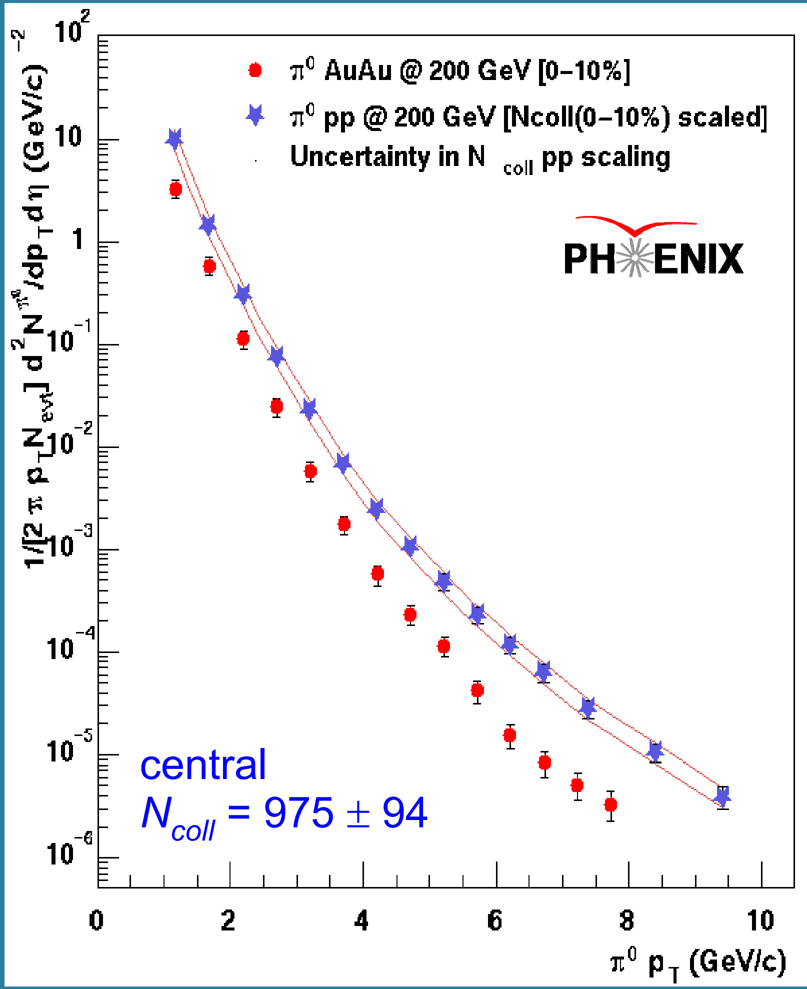


- **Important test of QCD and initial state**
  - Only interact electromagnetically
  - No interaction with medium
- **Observation:**
  - Pure N_{Coll} scaling relative to pQCD calculation

Talk by K. Reygers

π^0-Production

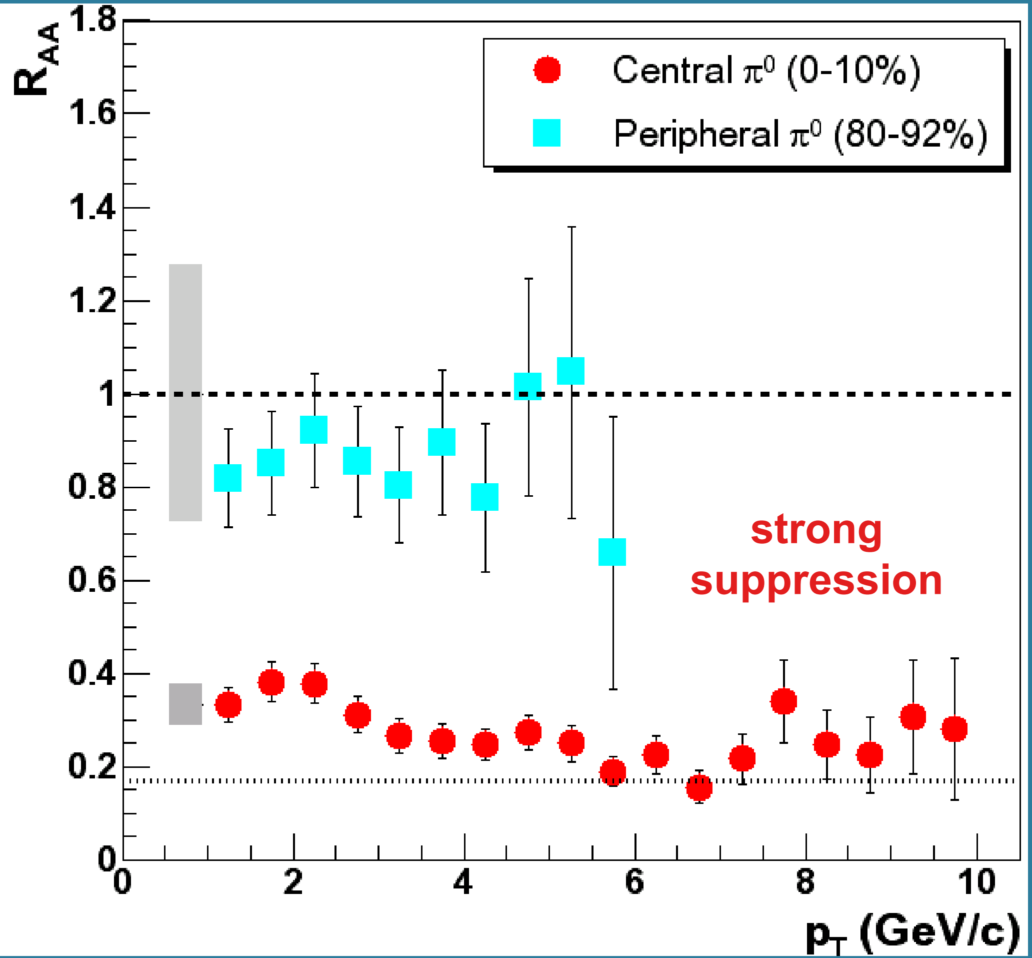




N_{coll}-scaling works in peripheral Au+Au, but strong suppression in central Au+Au

Phys. Rev. Lett. 91, 072301 (2003)

Nuclear Modification Factor R_{AA}



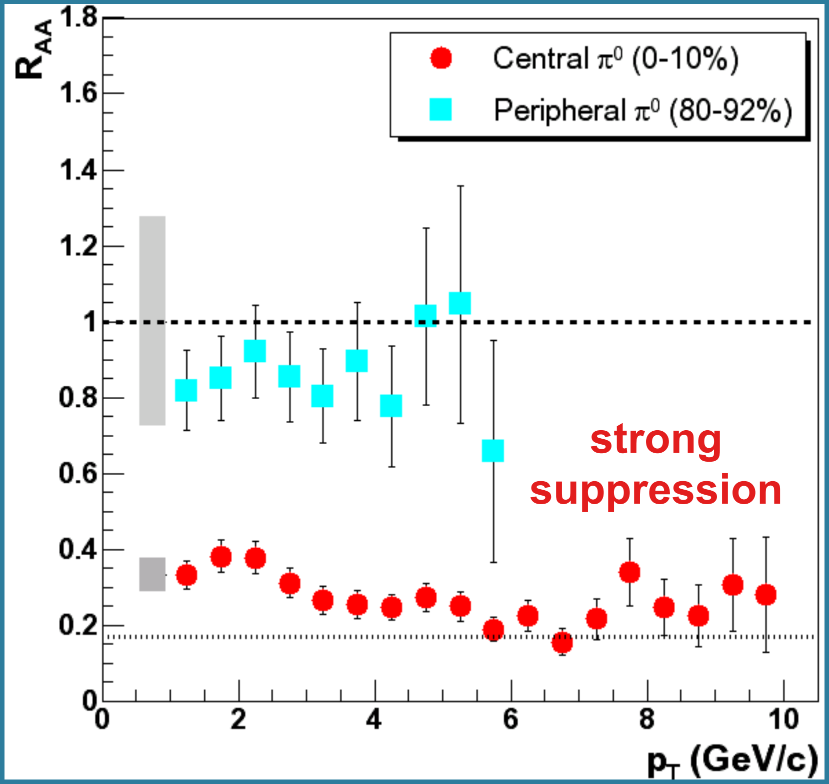
- RAA at higher pT ?
- Run4 higher statistics

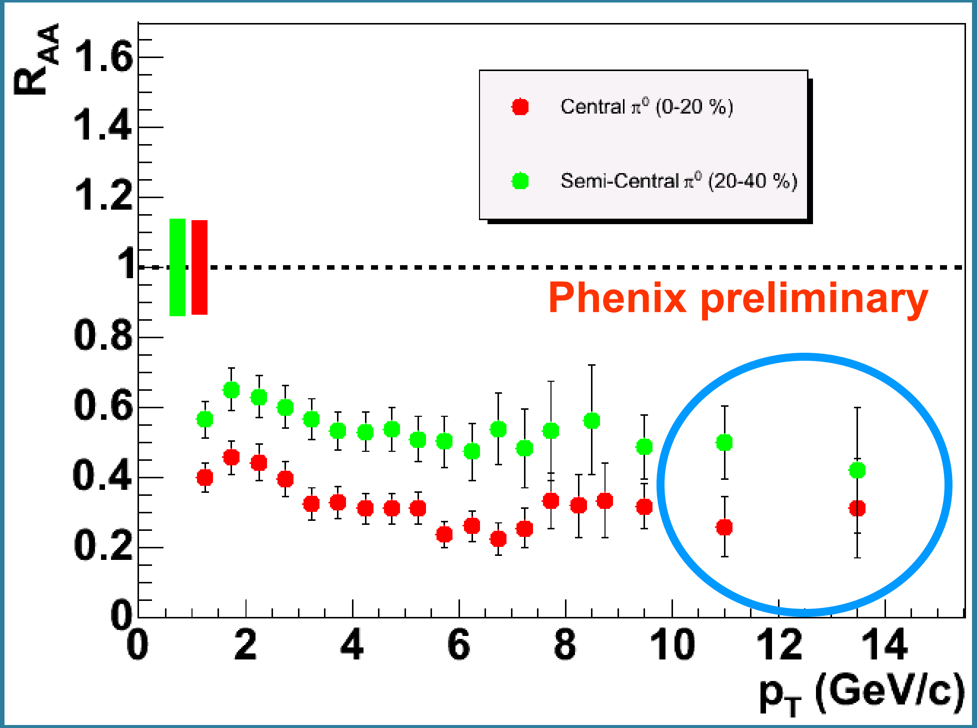
$$R_{AB} = \frac{\left(1/N_{AB}^{evt}\right)\ d^2N_{AB}/dydp_T}{\langle T_{AB}\rangle\ d^2\sigma_{pp}/dydp_T}$$

Phys. Rev. Lett. 91, 072301 (2003)

Nuclear Modification Factor R_{AA}

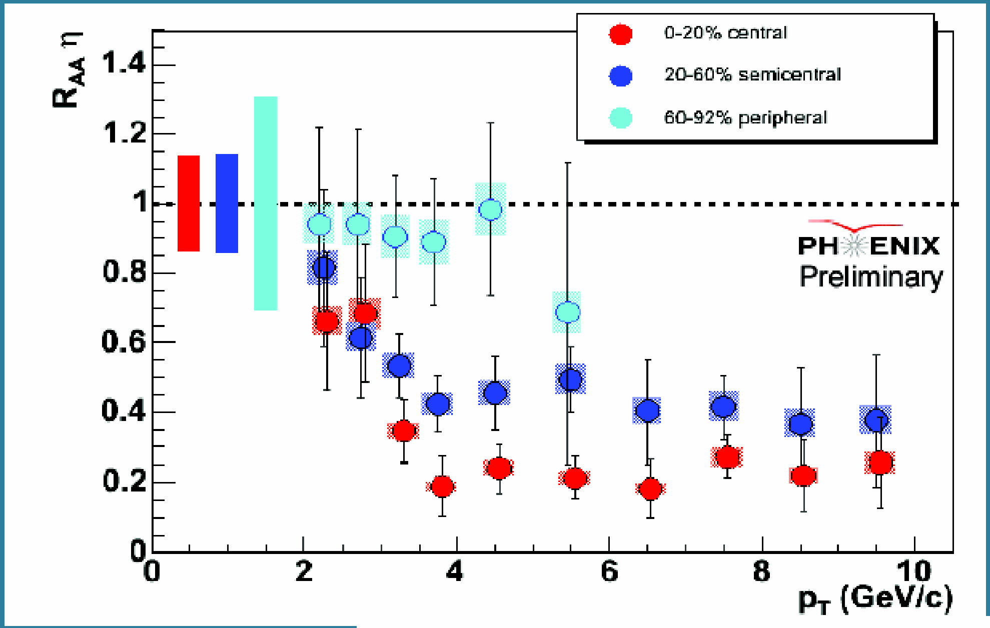
- RAA at higher p_T ?
- Run4 higher statistics
- New run3 pp reference
- Reduced stat. errors
- Reach to higher p_T



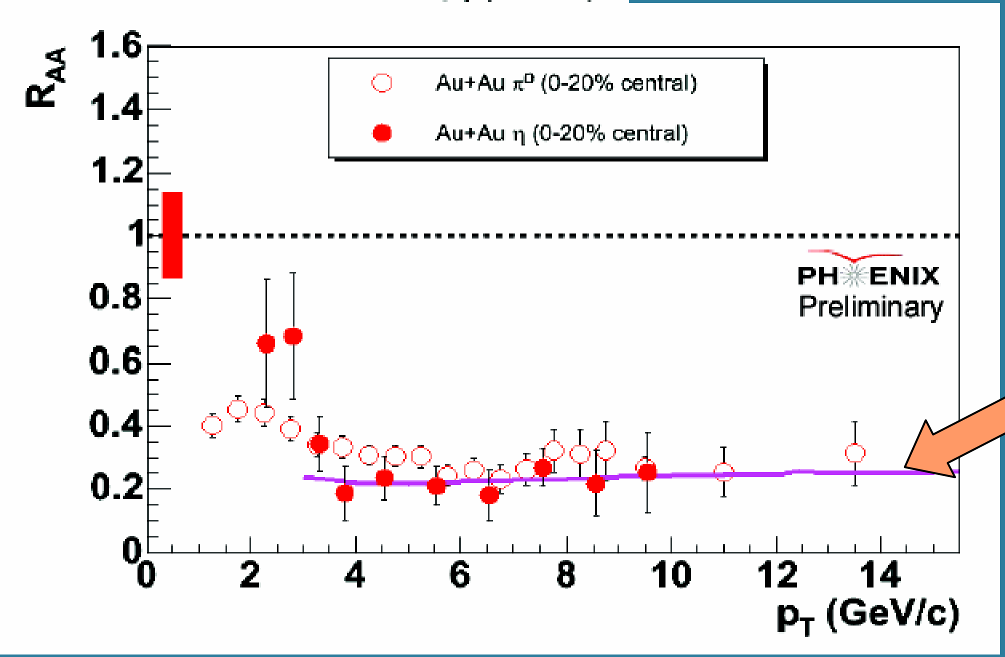


$$R_{AB} = \frac{\left(1/N_{AB}^{evt}\right)\, d^2N_{AB}/dydp_T}{\langle T_{AB}\rangle\, d^2\sigma_{pp}/dydp_T}$$

η Production



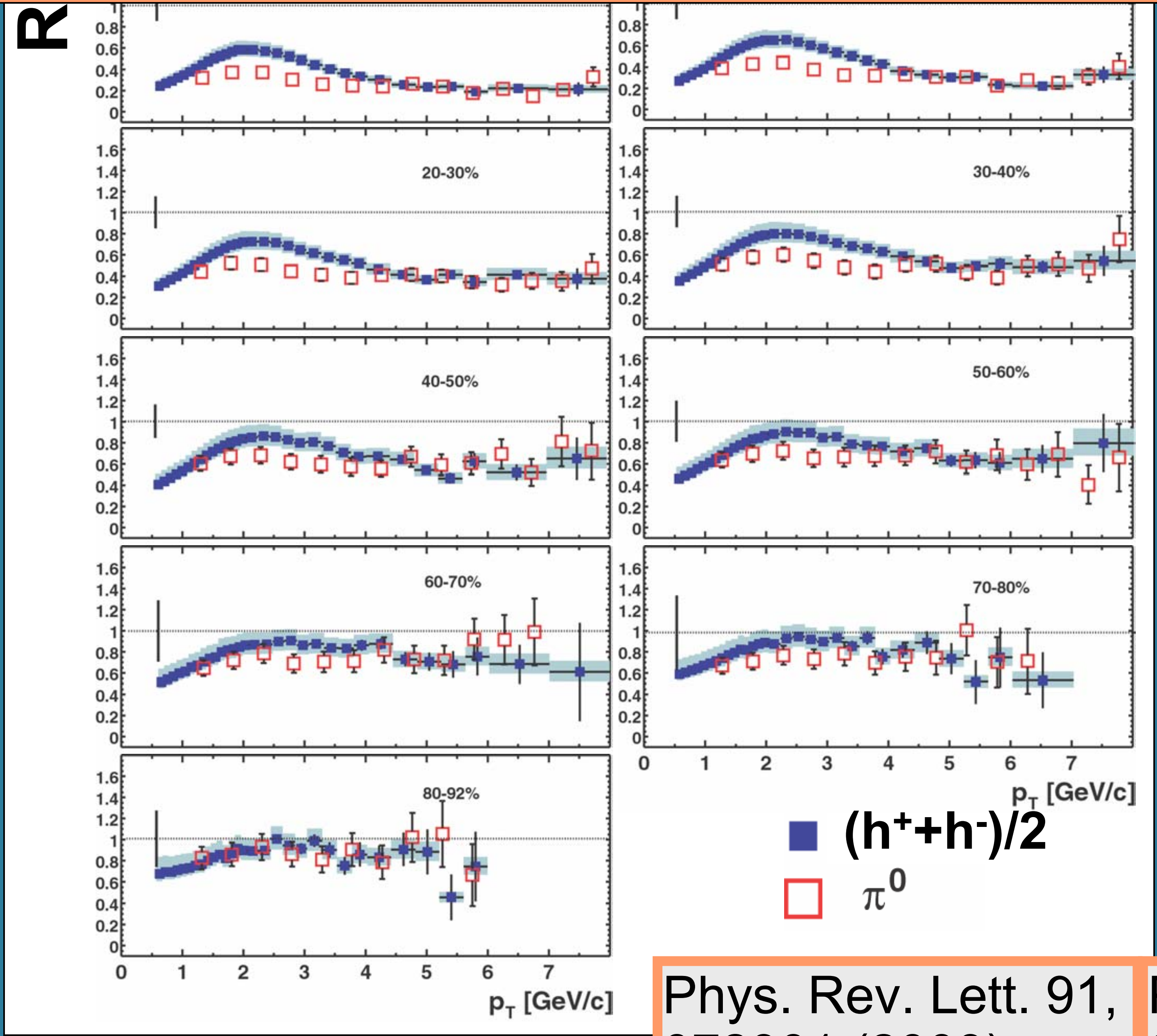
- π^0 and η suppression consistent in magnitude and p_T dependence
- Suppression of factor 5 in central collisions
- Agreement with parton energy loss predictions up to highest pT measured so far



GLV R_{AA}
$dN^g/dy = 1100$

charged hadrons less suppressed at medium pT

later in talk



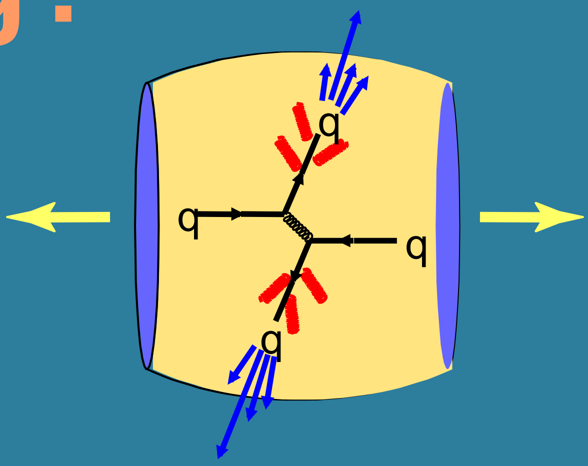
Centrality Dependence

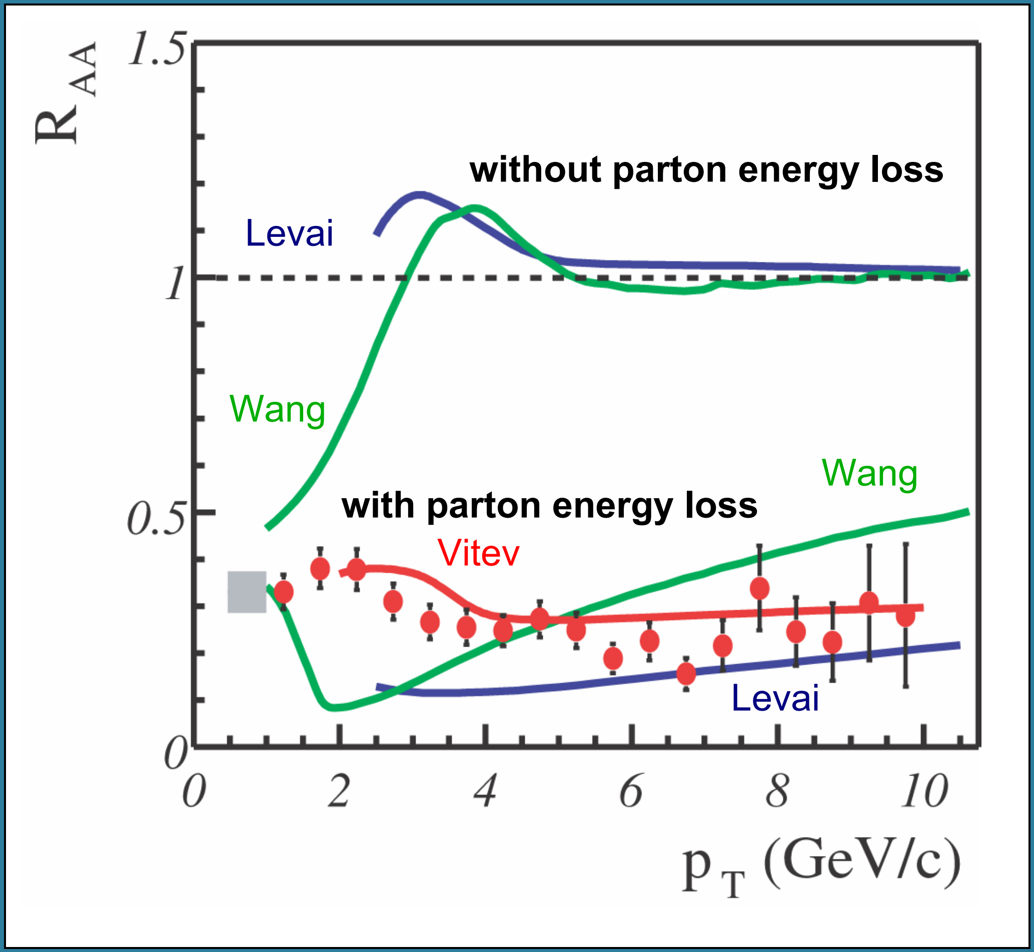
Phys. Rev. Lett. 91, 072301 (2003)

Phys. Rev. C 69, 034910 (2004)

Jet Quenching?

Comparison with model calculations
with and without parton energy loss:

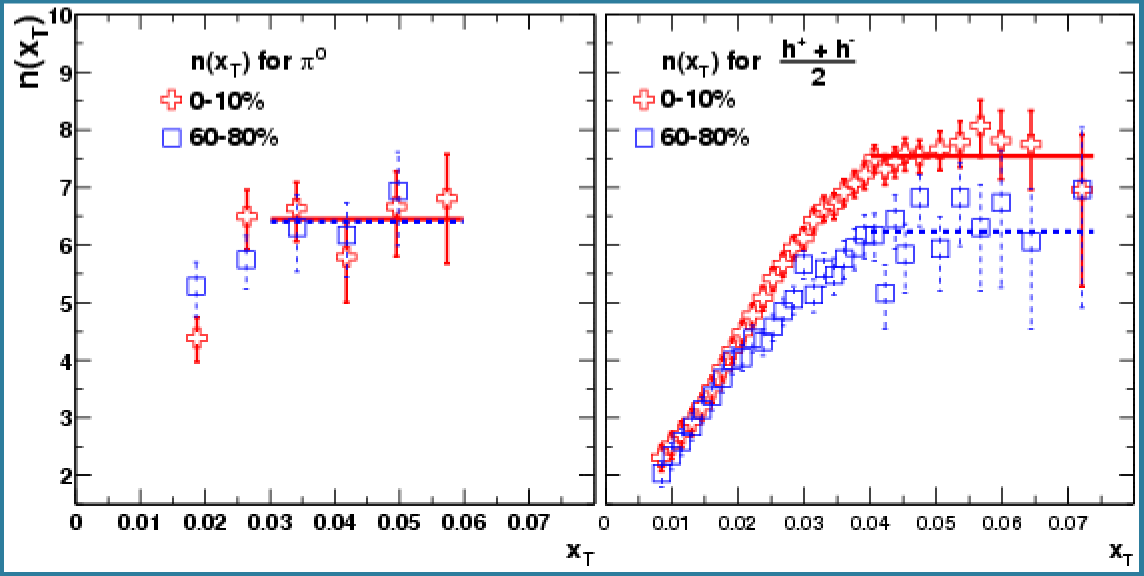




- π^0 suppression described by models with parton energy loss
- Additional nuclear effects needed to describe p_T dependence
- Other explanations not ruled out at this stage

x_T scaling in Au+Au

$$\sqrt{s}^{\,n} \times E\frac{d^3\sigma}{d^3p} = G(x_T)$$



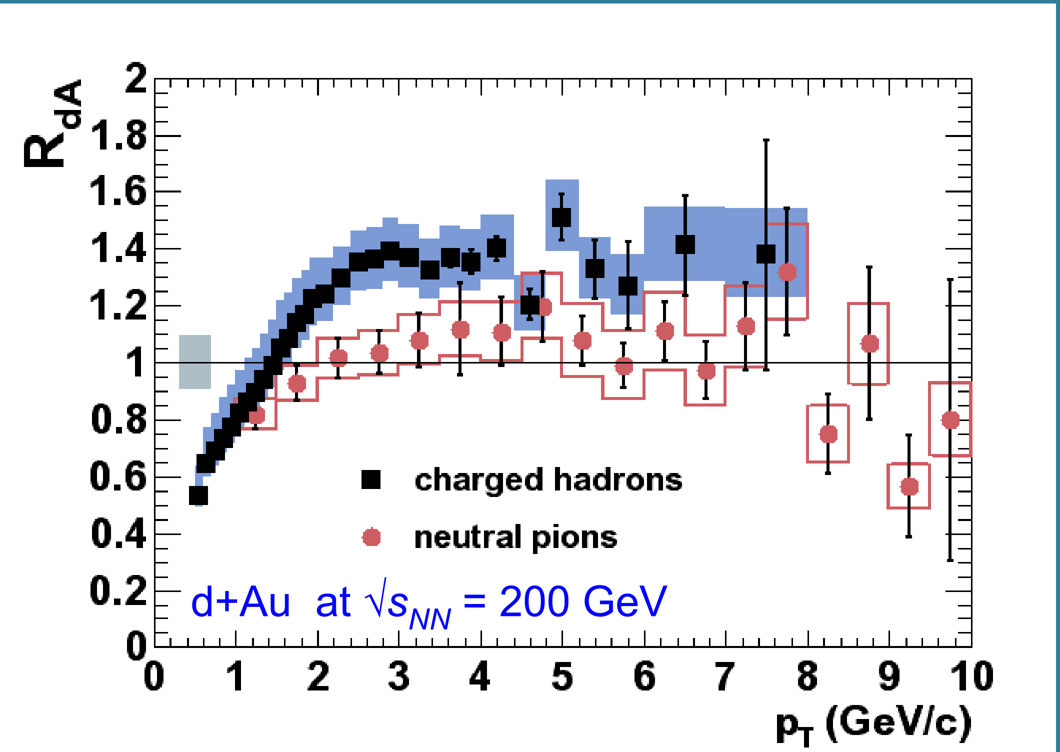
- **If** **high p_T particle production in Au+Au result of hard scattering:**
  - x_T scaling should work
- **Assumption: structure and fragmentation functions should scale**
- **n(xT, $\sqrt{s_{NN}}$) in AuAu:**
  - Compare 130 GeV and 200 GeV data
  - Central and peripheral
- **π^0 and peripheral charged particles scale**
- **Central charged particles do not scale**

Follow pQCD as in pp

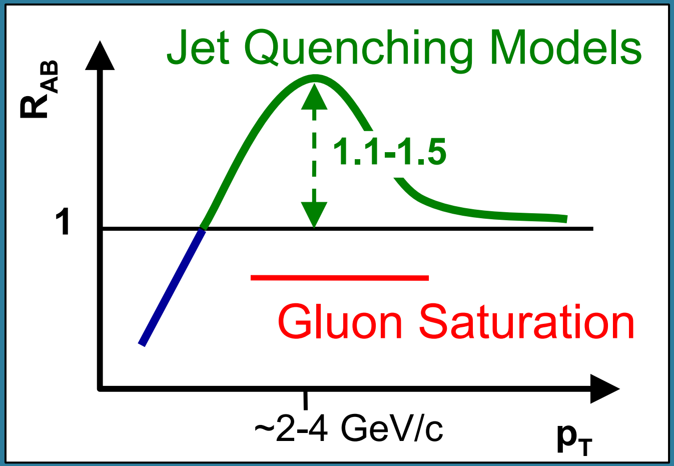
d+Au

200 GeV

The Control Experiment: d+Au



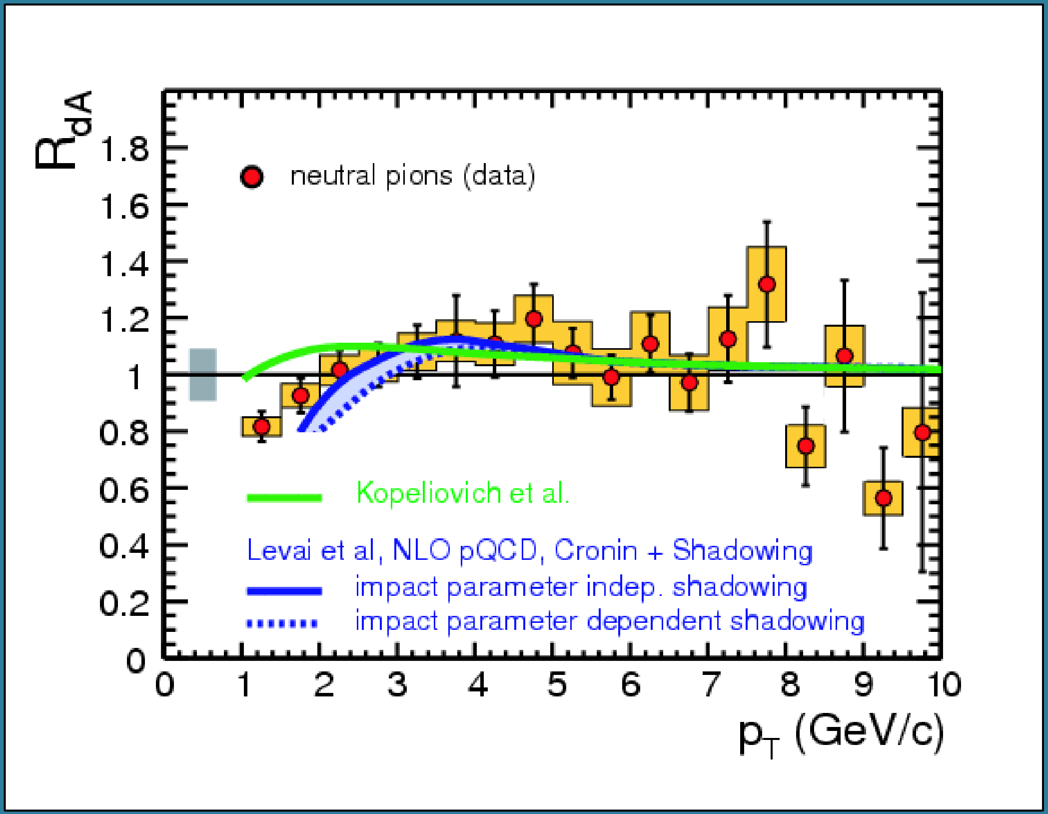
Phys. Rev. Lett. 91, 072303 (2003)



Kharzeev, Levin, McLerran, hep-ph/0210332

- No suppression in d+Au
- Initial-state effects ruled out as explanation for suppression in Au+Au at mid rapidity

π^0's in d+Au: Data vs. pQCD



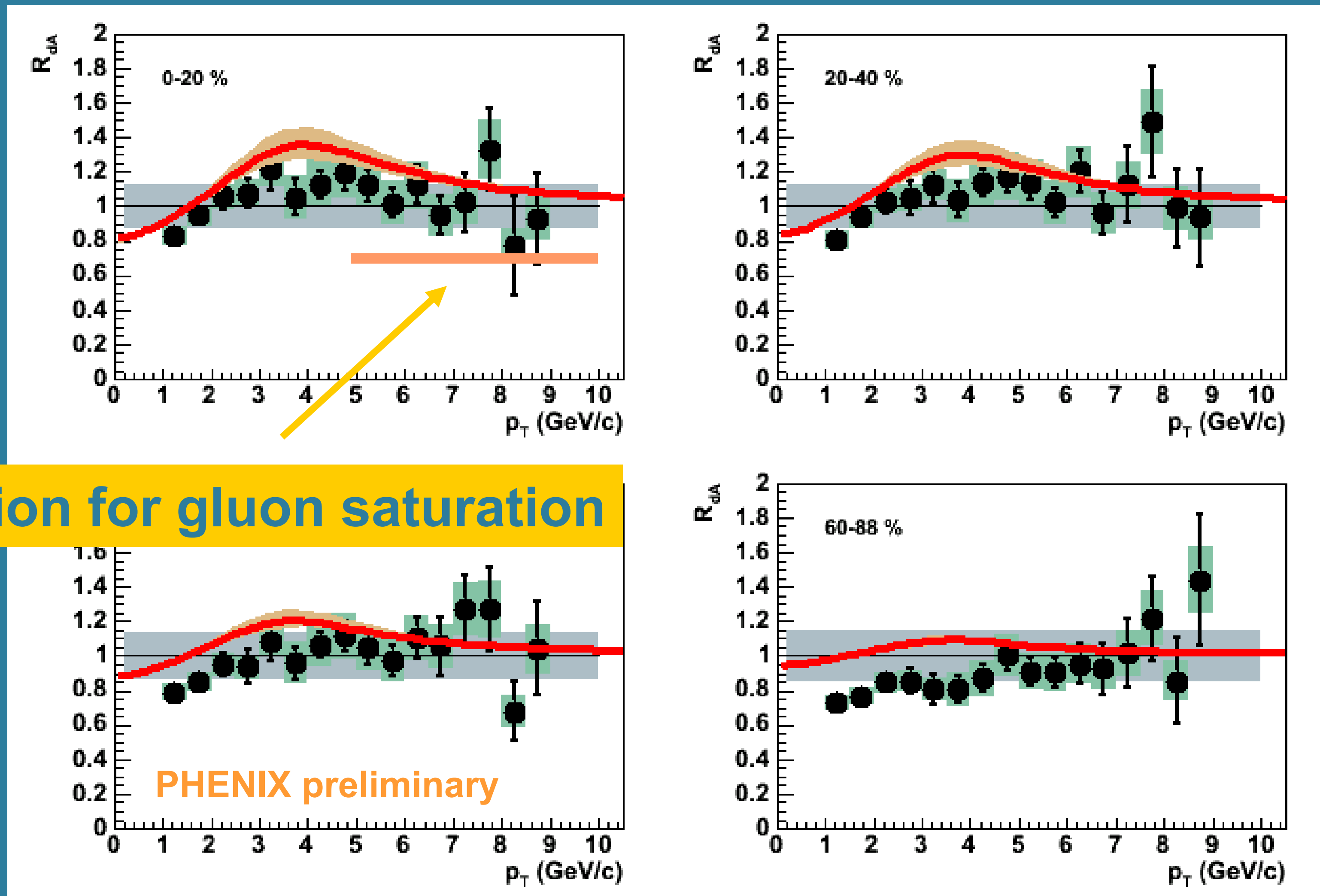
- **Data well reproduced by**
  - **NLO pQCD calculation, plus**
  - **Phenomenological model of Cronin-Effect, plus**
  - **Shadowing**

Levai et al., nucl-th/0306019

Kopeliovich et al., Phys. Rev. Lett. 88, 232303 (2002)

R_{dAu} for different centralities

$<k_T>=$ 0.52 GeV^2



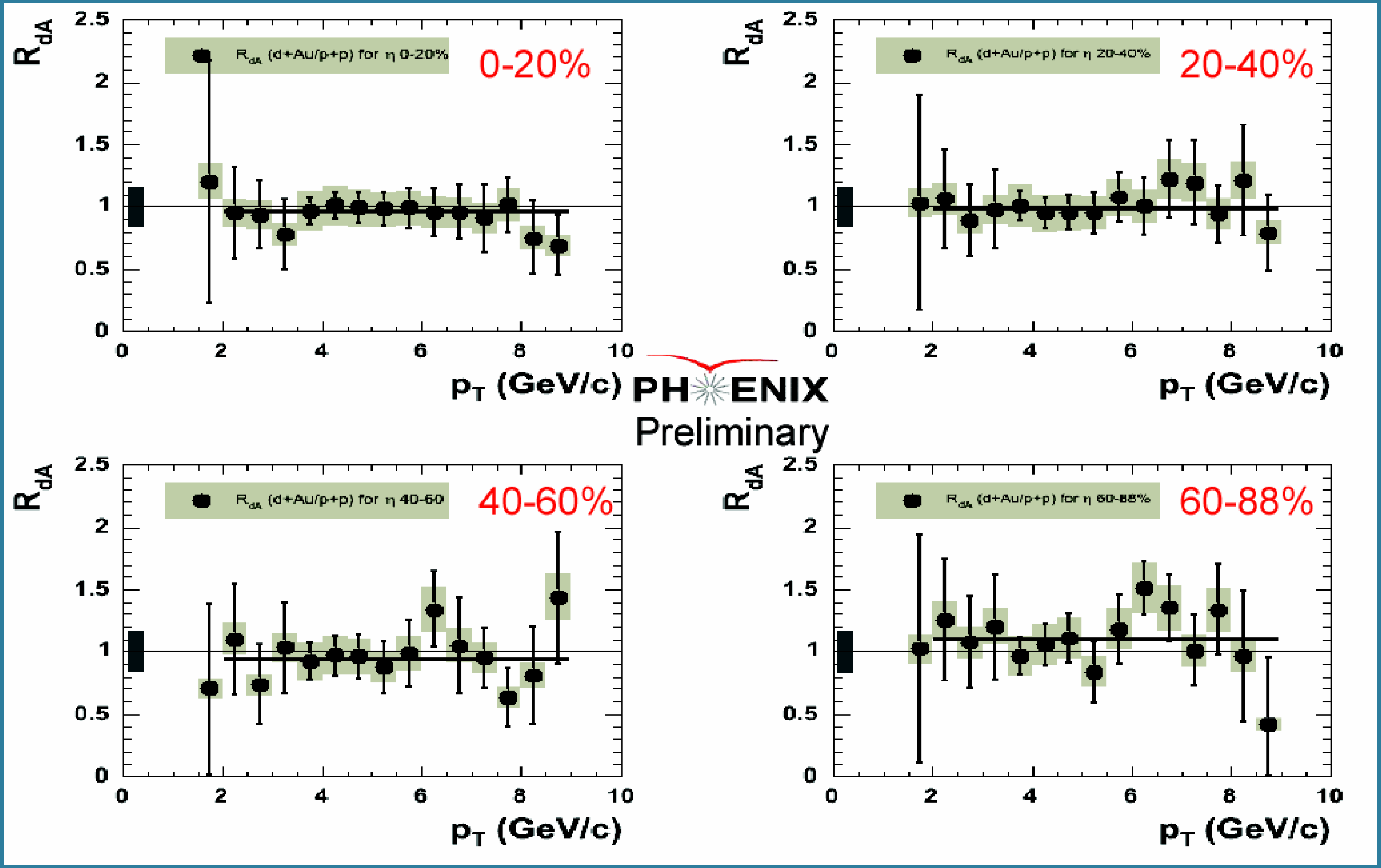
Prediction for gluon saturation

Kharzeev, Levin, McLerran, hep-ph/0210332

$(N_{part, Au})^{1/2}$ scaling

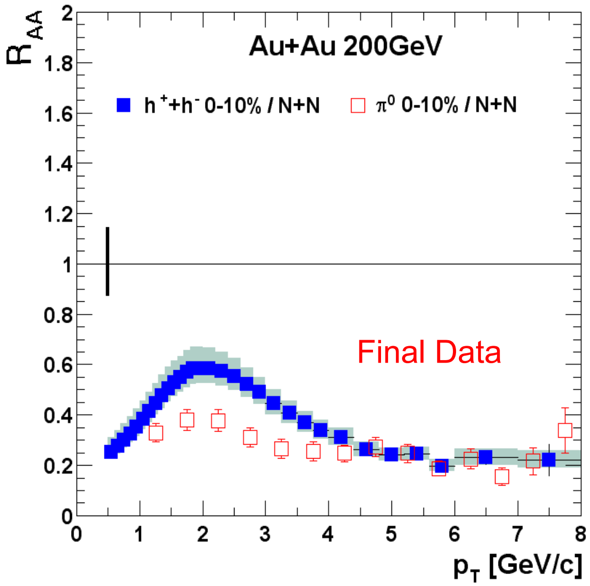
$R_{AA} \approx 0.7$ in central d+Au

η Production in dAu

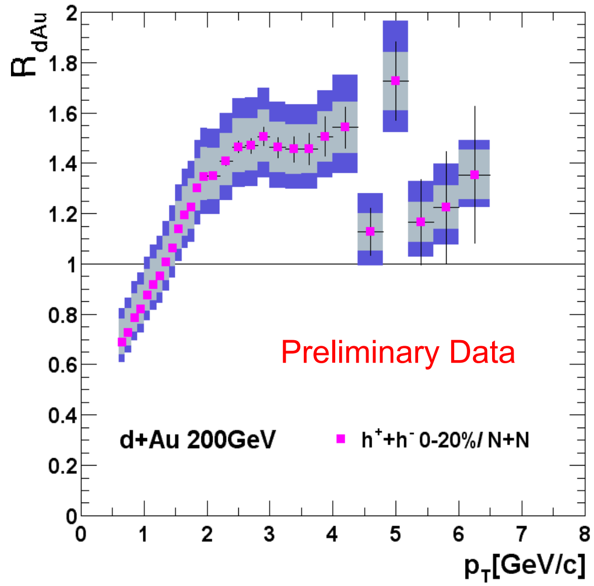


Centrality Dependence

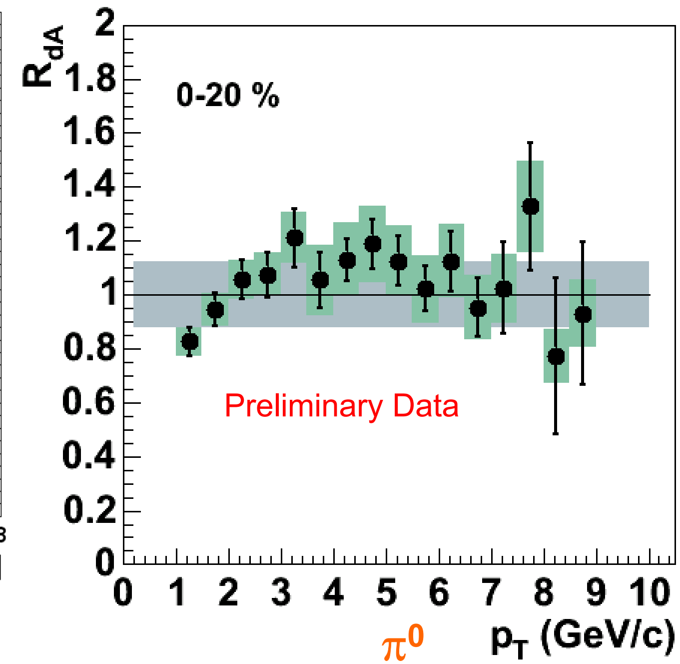
Au + Au Experiment



d + Au Control Experiment



charged



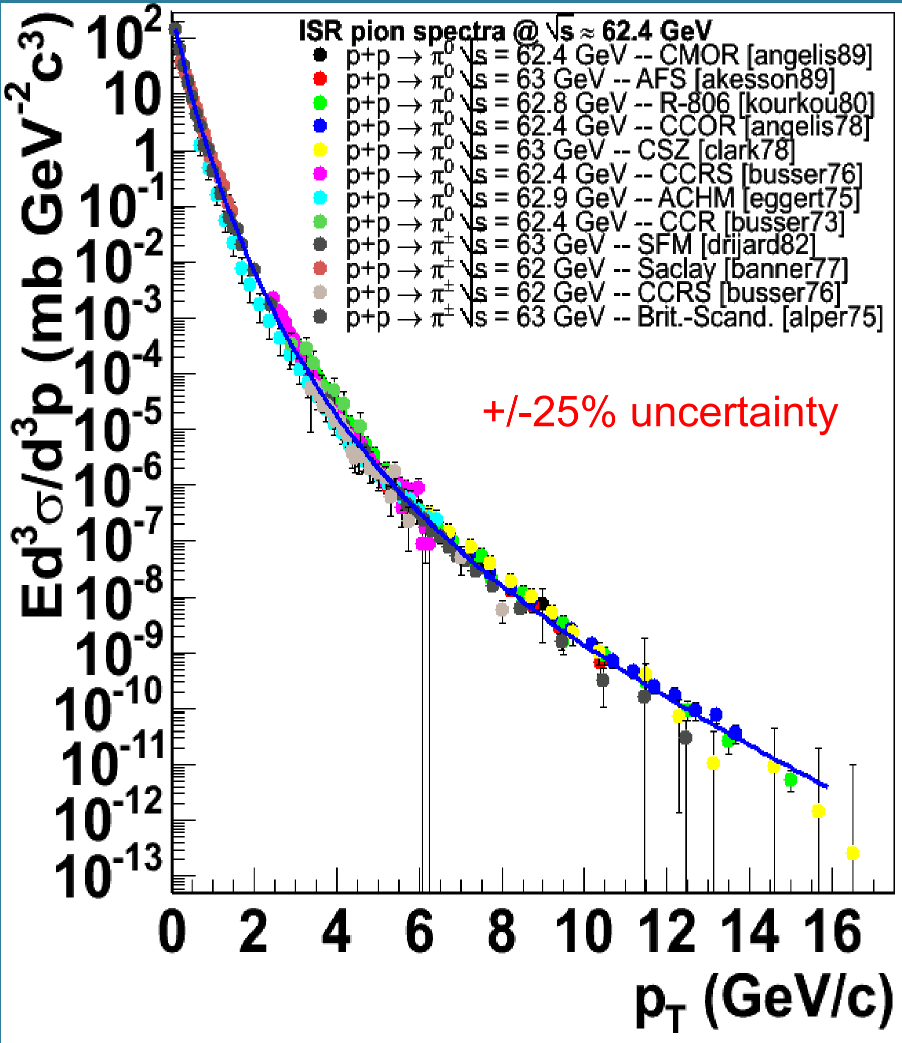
π^0

- Different behavior with increasing centrality in Au+Au and d+Au
  - R_{AuAu} decreases
  - R_{dAu} charged increases
  - R_{dAu} π^0 increases slightly

Au+Au

62.4 GeV

62.4 GeV p+p π^0 Reference



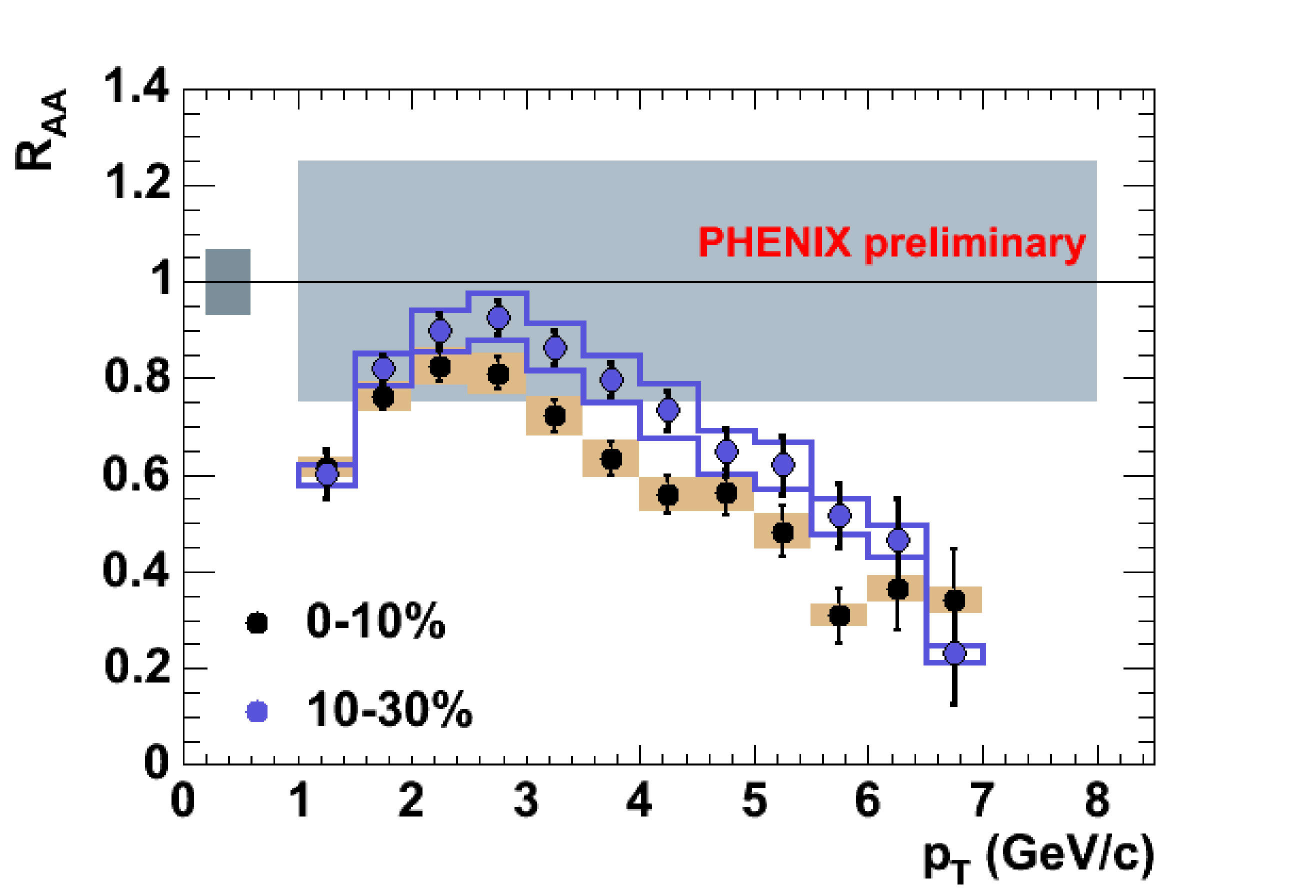
- π^0 data from ISR
- Corrected for (when necessary)
  - hadronic decay
  - direct photons
- Global fit:

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

- Fit and data cross-checked by NLO calculation
- ±25% systematic uncertainty

Talk by D. d'Enterria

R_{AA} for π^0 at 62.4 GeV

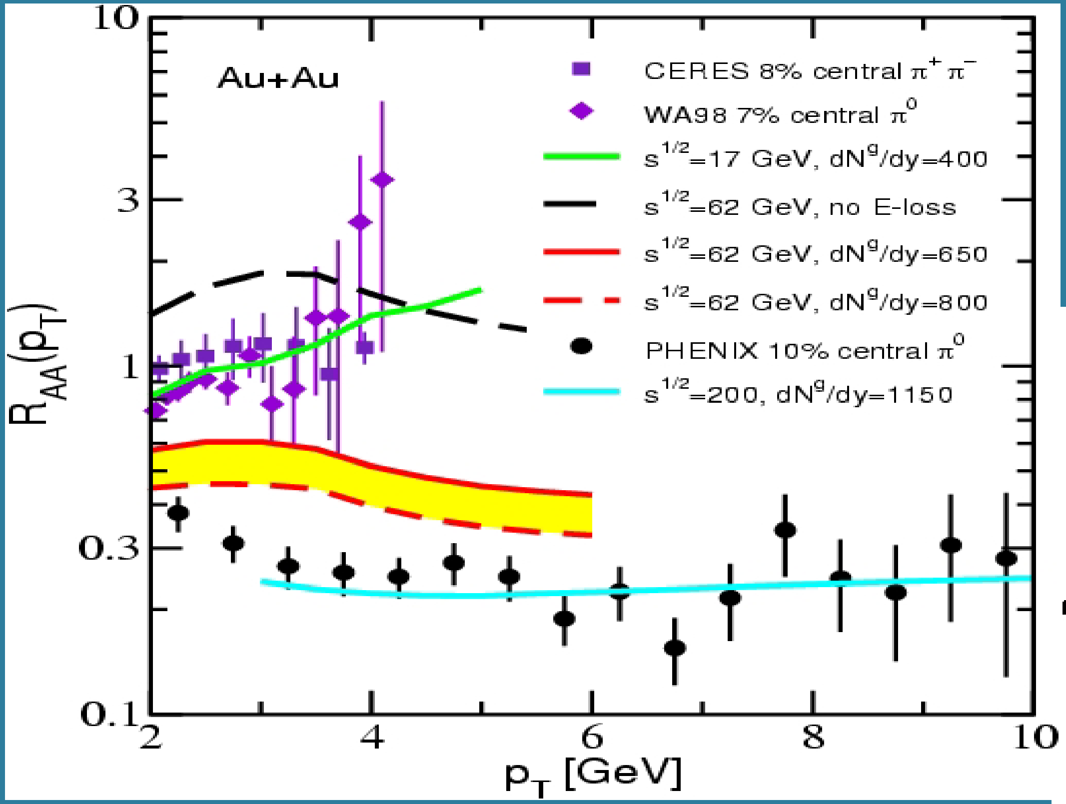


N_{coll} for peripheral events not yet understood

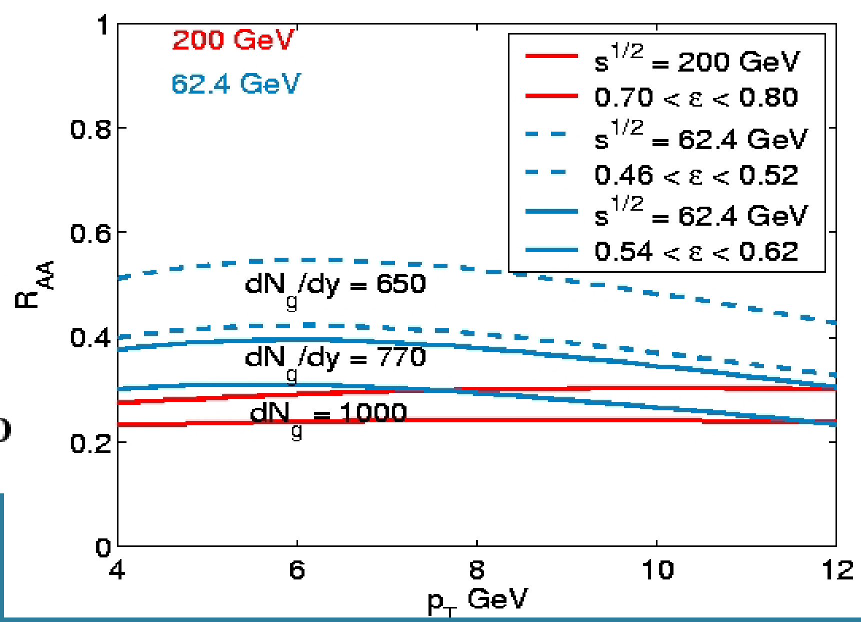
- Ratios close to unity at $p_T \sim 2.5$ GeV/c, then decreasing
- Same tendency as 200 GeV Au+Au
- Less suppression at intermediate p_T (compared to 200 GeV)

R_{AA} for π^0 at 62.4 GeV: Predictions

I. Vitev nucl-th/0404052



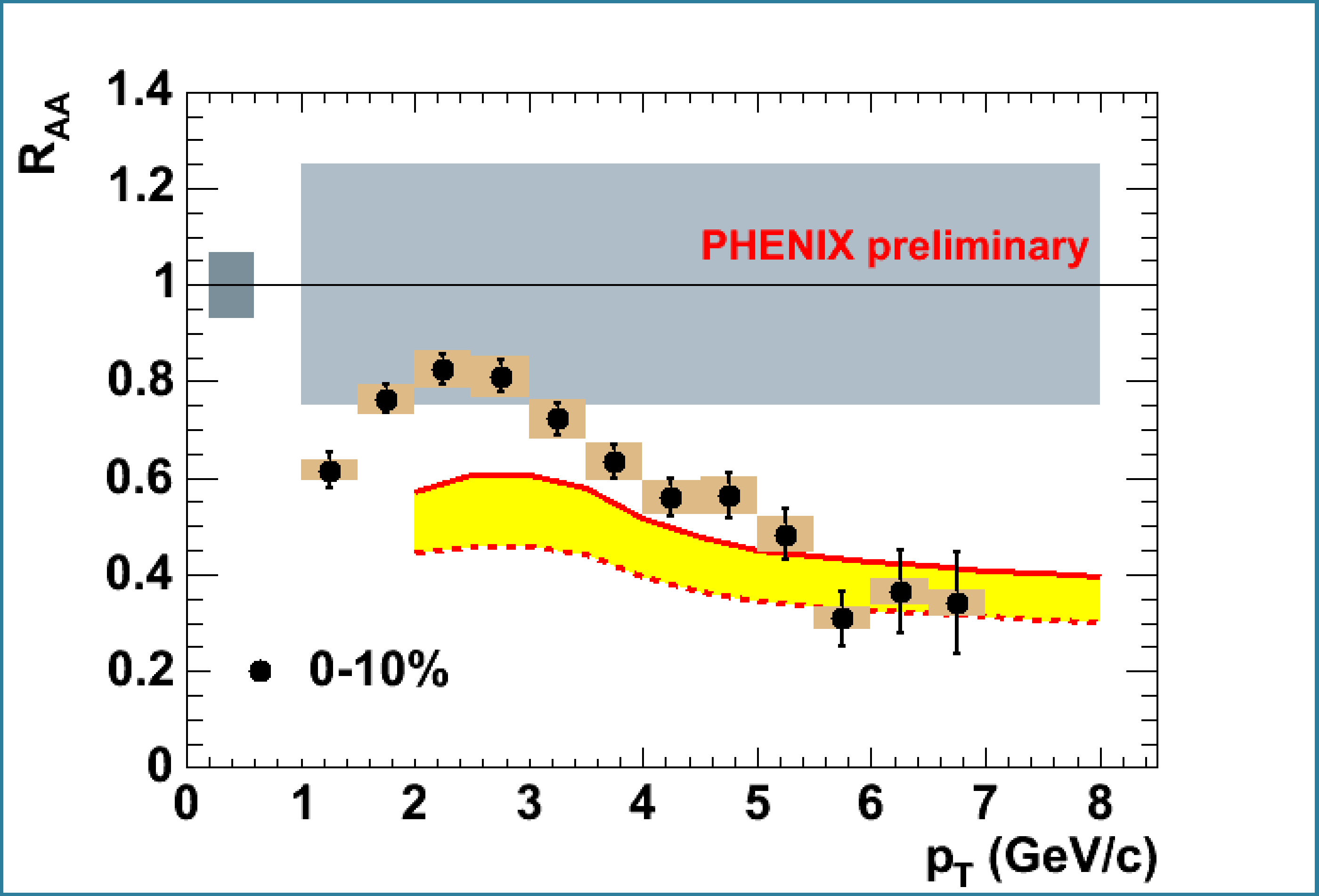
Adil & Gyulassy nucl-th/0405036



R_{AA} (π^0) ~ 0.5 - 0.3

R_{AA} for π^0 at 62.4 GeV

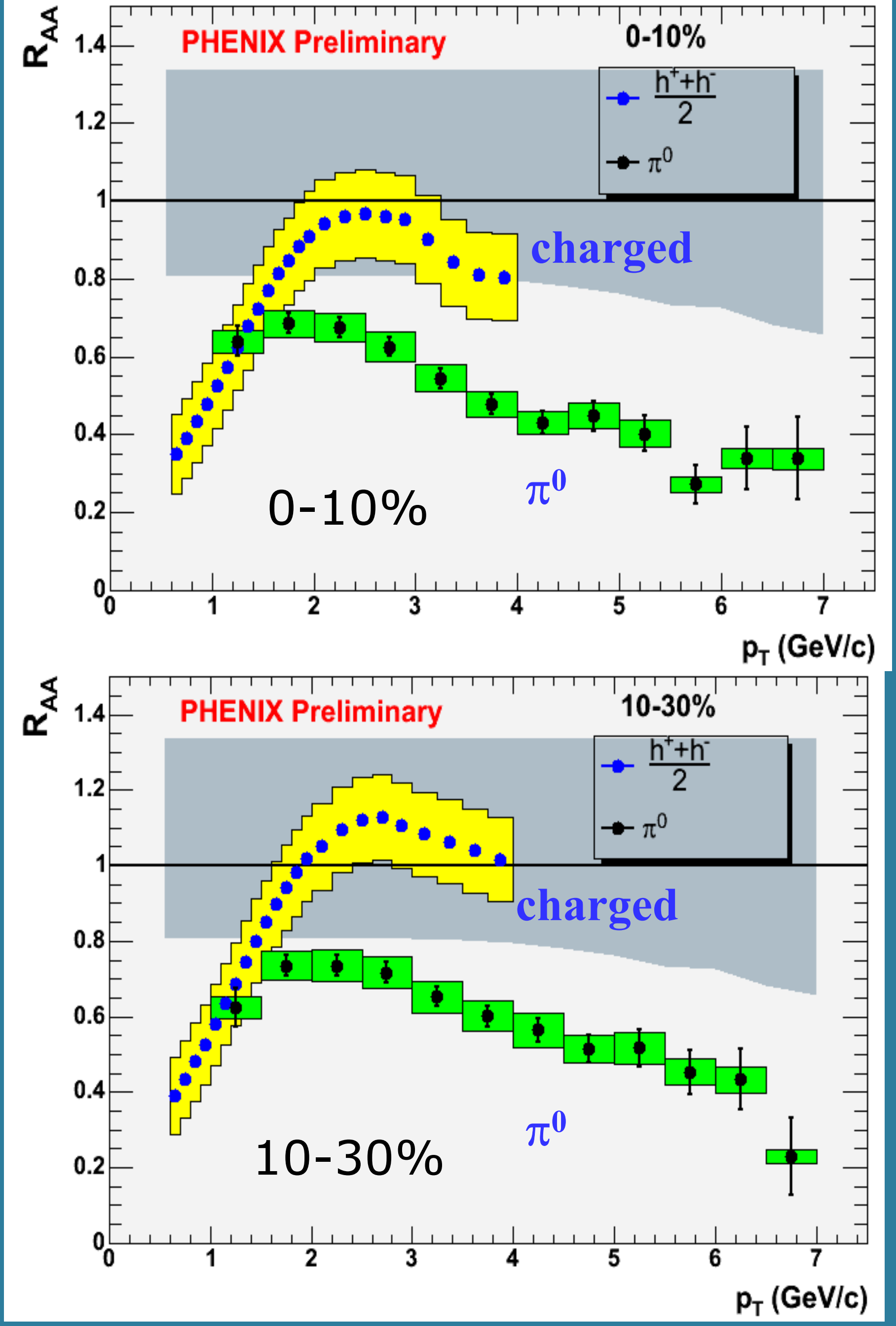
Vitev
nucl-th/0404052



- **Reasonably good agreement (esp. high p_T) within uncertainties**
- **Uncertainty in the p_T shape (esp. low p_T) of p+p reference ...**

R_{AA} for Charged Hadrons

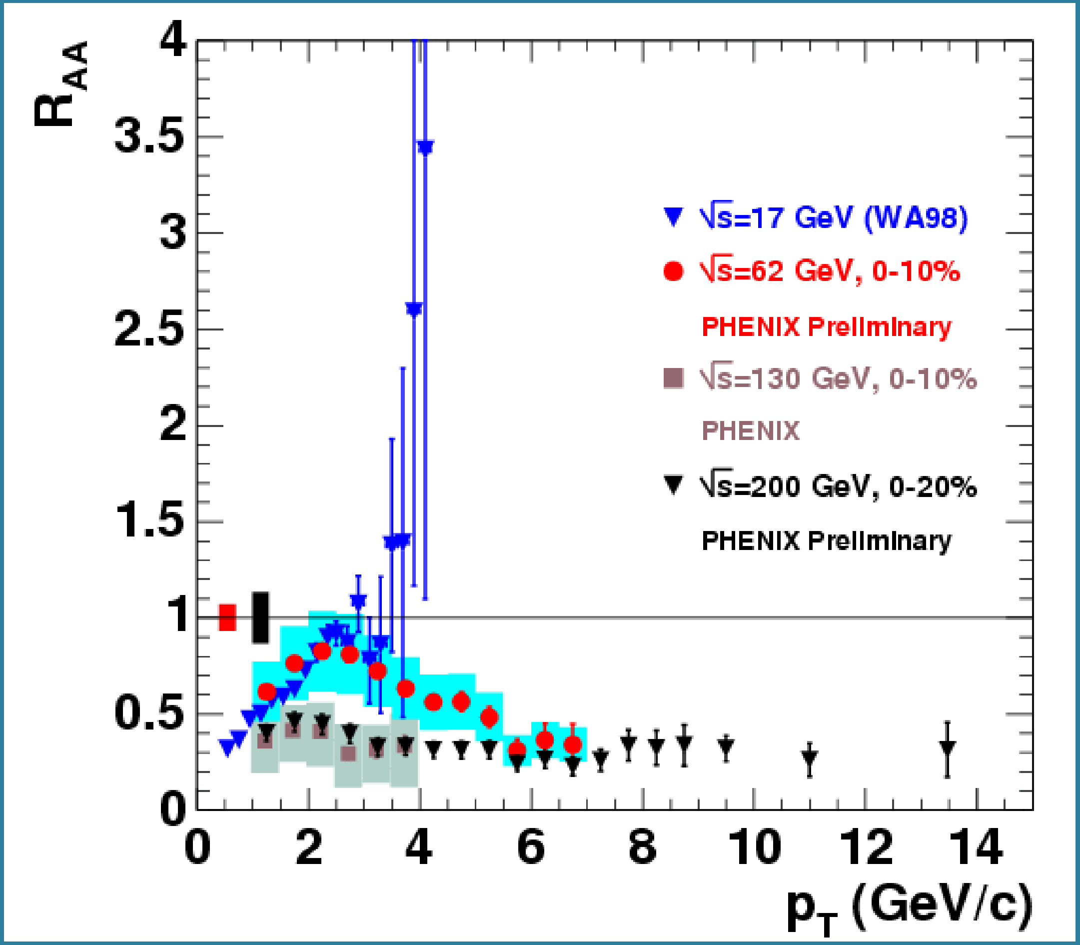
- π^0 yield is multiplied by 1.6
- Discrepancy between charged and π^0
- Pions more suppressed than h+/- at intermediate pT
- Large proton contribution up to at least 4 GeV/c



62.4 GeV

charged reference is used here

π^0 R_{AA}, Central Events,Different $\sqrt{s}$



WA98, EPJ C 23, 225 (2002)

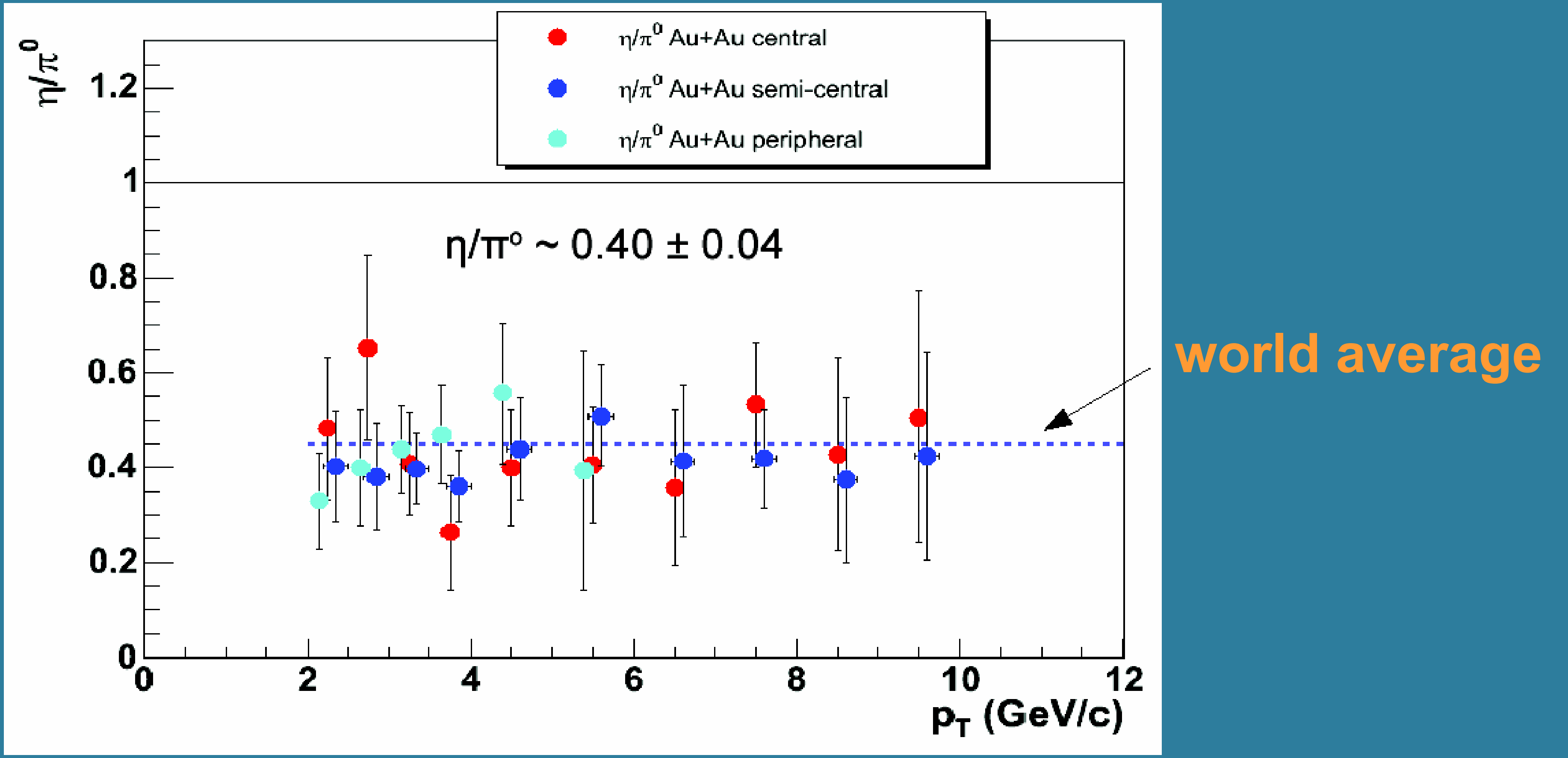
[new reference compiled by D.d'Enterria nucl-ex/0403055]

PHENIX, PRL 88 022301 (2002)

- **Suppression at 17 GeV and 62.4 GeV similar at medium p_T**
- **62.4 GeV expected lower**
- **Better reference needed!**

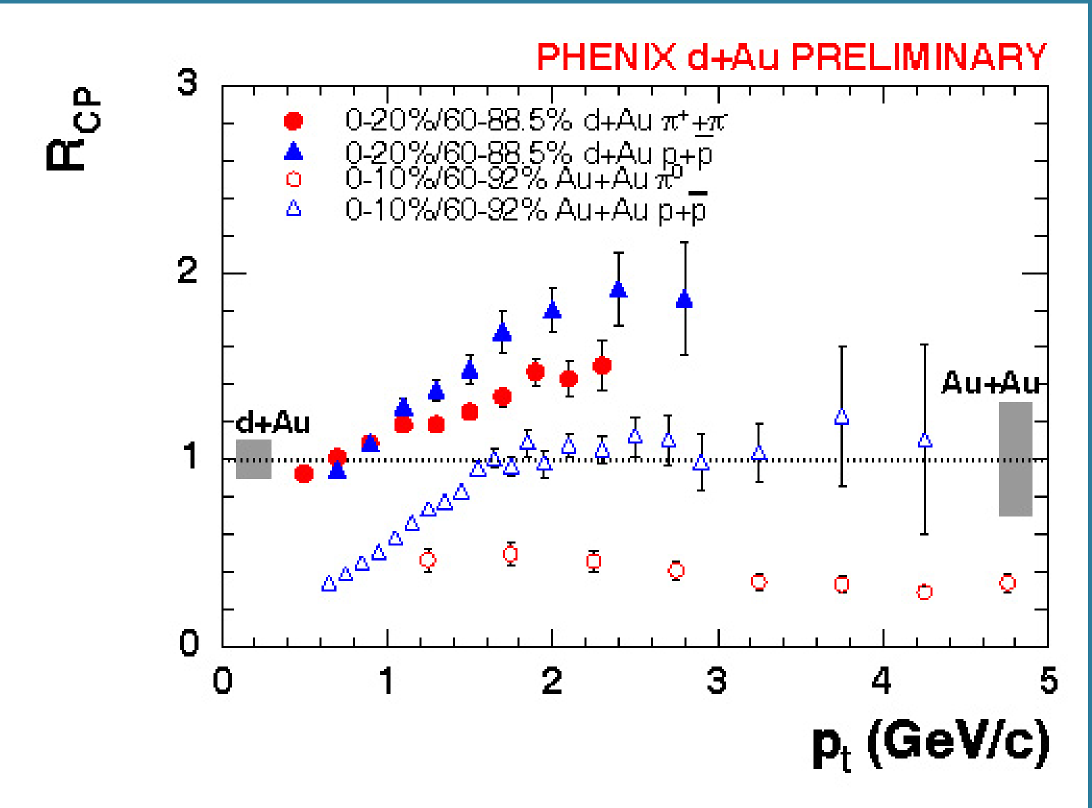
Particle ratios

η to π^0 Ratio

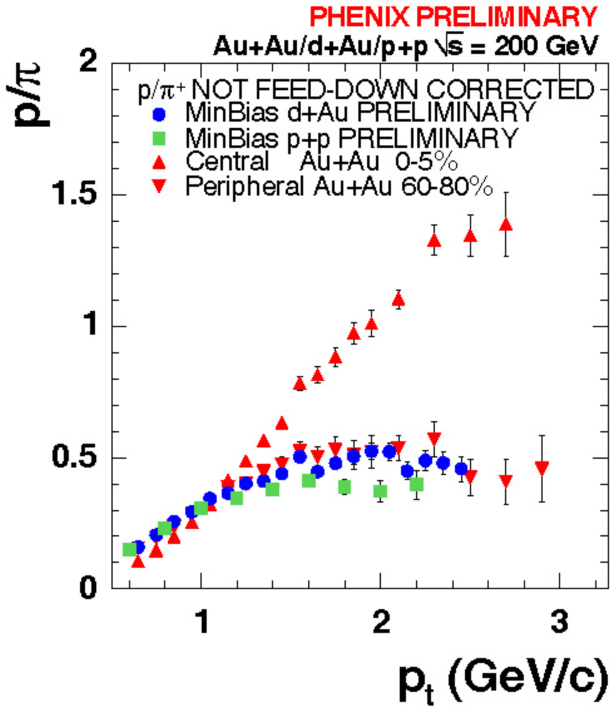


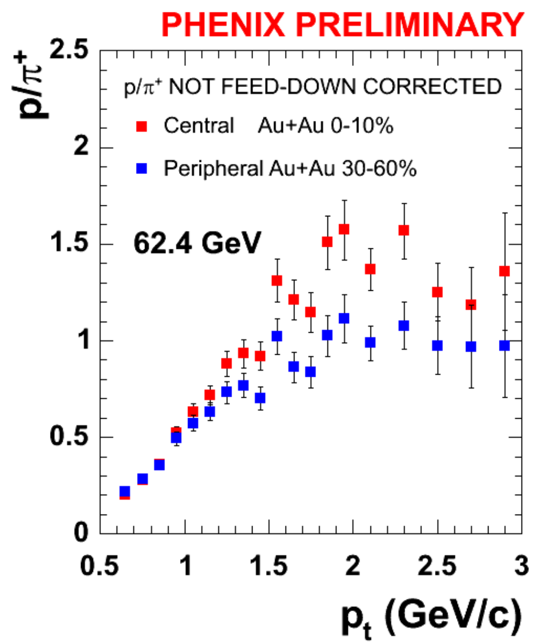
- Flat η/π^0 ratio as function of pT
- No centrality dependence
- η/π^0 ratio in AuAu consistent with world average

Proton-Scaling



- Proton/anti-proton-yield **scales with N_{coll}** in the range 2 GeV < p_T < 3 GeV
- Why are protons/anti-protons not suppressed?

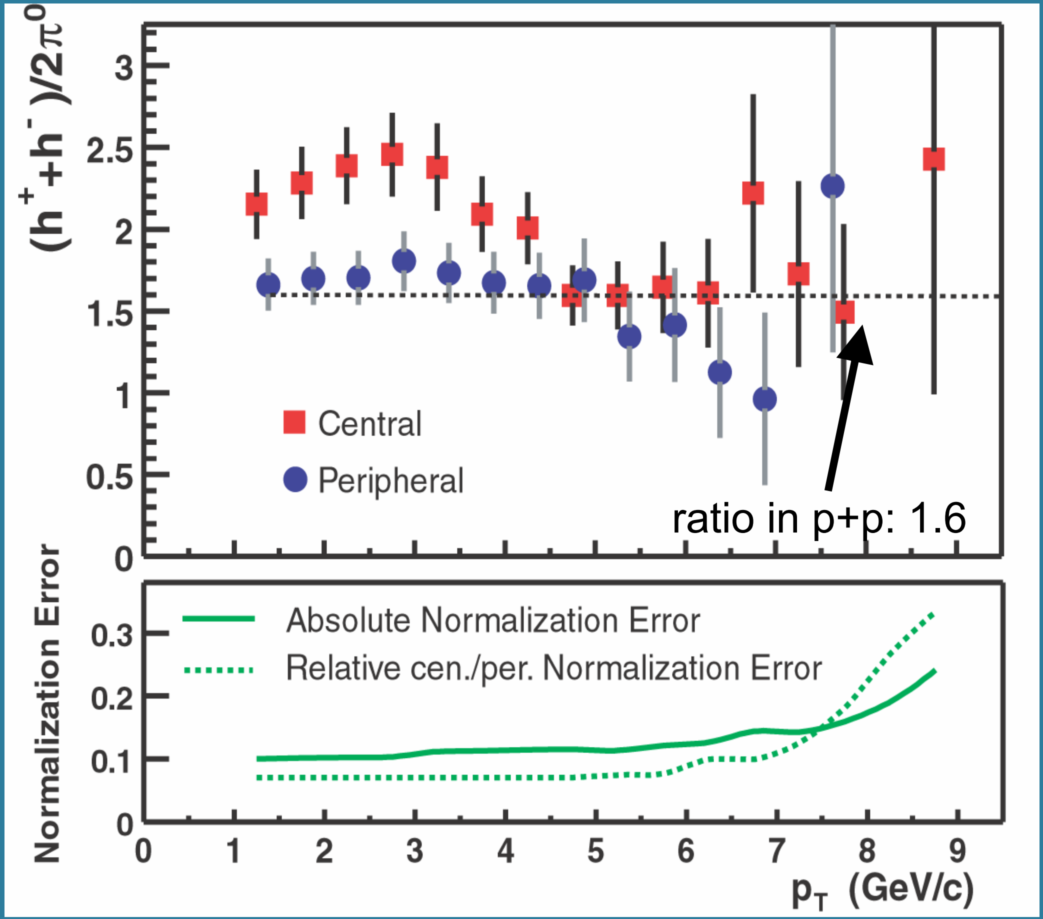




p/π – Ratio

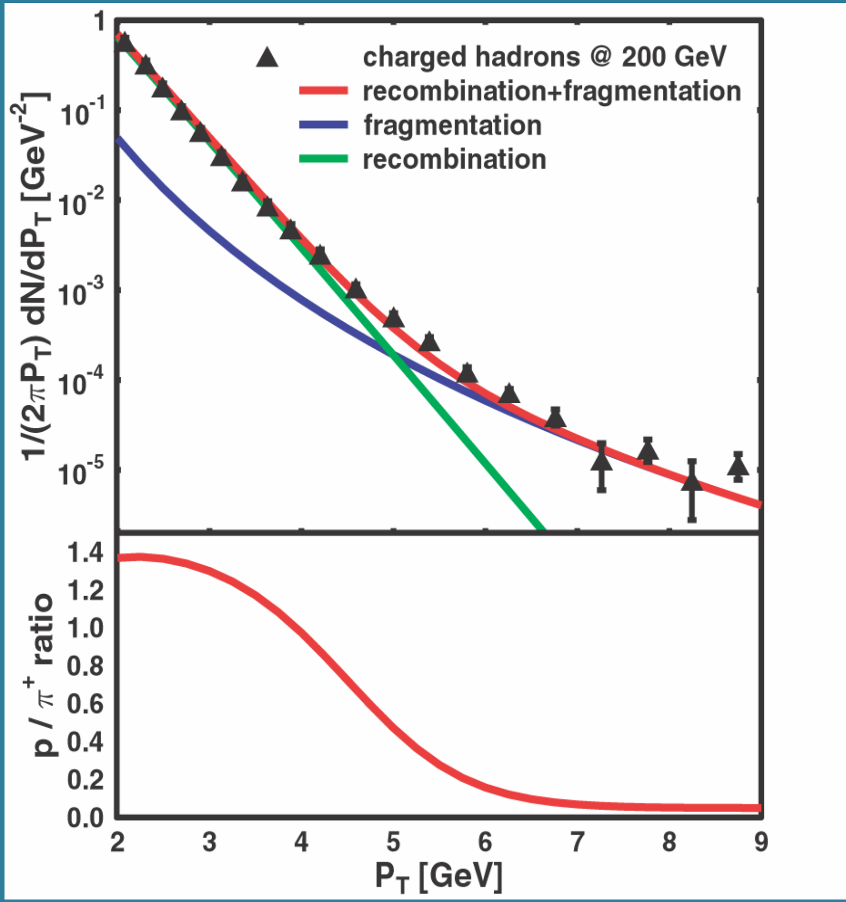
- Expectation for particle production from jet-fragmentation: p/π less than ≈0.25 at high p_T
- p/π+ > 1 at intermediate pT
- less for antiproton (pbar/π- ~ 0.7).
- Weaker centrality dependence than at 200 GeV

Charged Hadron / π^0



- **Unidentified charged hadrons can be measured up to p_T = 9 GeV/*c***
- ***Ratio above 5 GeV/c similar for***
  - *central Au+Au*
  - *peripheral Au+Au*
  - *p+p*
- ***This implies that p/π ratio goes back to "normal" value at high p_T***

A Possible Explanation: Quark Recombination



Fries, et al, nucl-th/0301087

also, Greco, Ko, Levai, nucl-th/0301093

- Two competing processes for hadron production
  - Jet-Fragmentation in the vacuum
  - Recombination of 3 quarks or a quark/anti-quark pair in a densely populated phase space
- Fries et al.
  - In case of thermalized partons at RHIC, fragmentation wins over recombination only above p_T = 5 GeV/c
  - This explains p/π ratio
  - "Such a phase phase may be appropriately called a QGP"

Talk by J. Velkovska

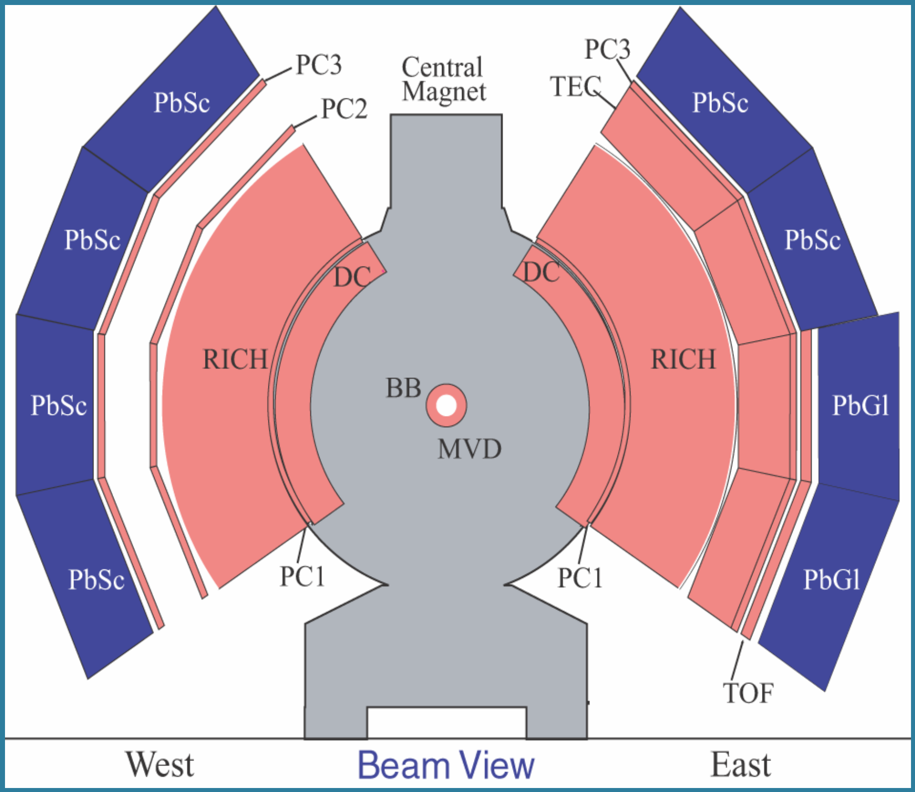
Summary

- **p+p reference well under control at 200 GeV**
  - x_T scaling works
  - binary scaling works for direct photons
- **suppression of π^0's and charged hadrons in central Au+Au**
  - charged hadrons less suppressed at medium p_T
  - x_T scaling
    - works for pions:
      - hard scattering
    - breaks for charged hadrons in central Au+Au:
      - not only hard scattering
- **non-suppression in d+Au**
  - suppression in Au+Au must be final-state effect
- **suppression also in 62.4 GeV Au+Au**
  - evidence for smooth sqrt(s) dependence
  - better reference needed to say more
- **high p/π ratio in central Au+Au**
  - possibly recombination from thermalized partons


PHENIX
OVER ONE BILLION SERVED

backup

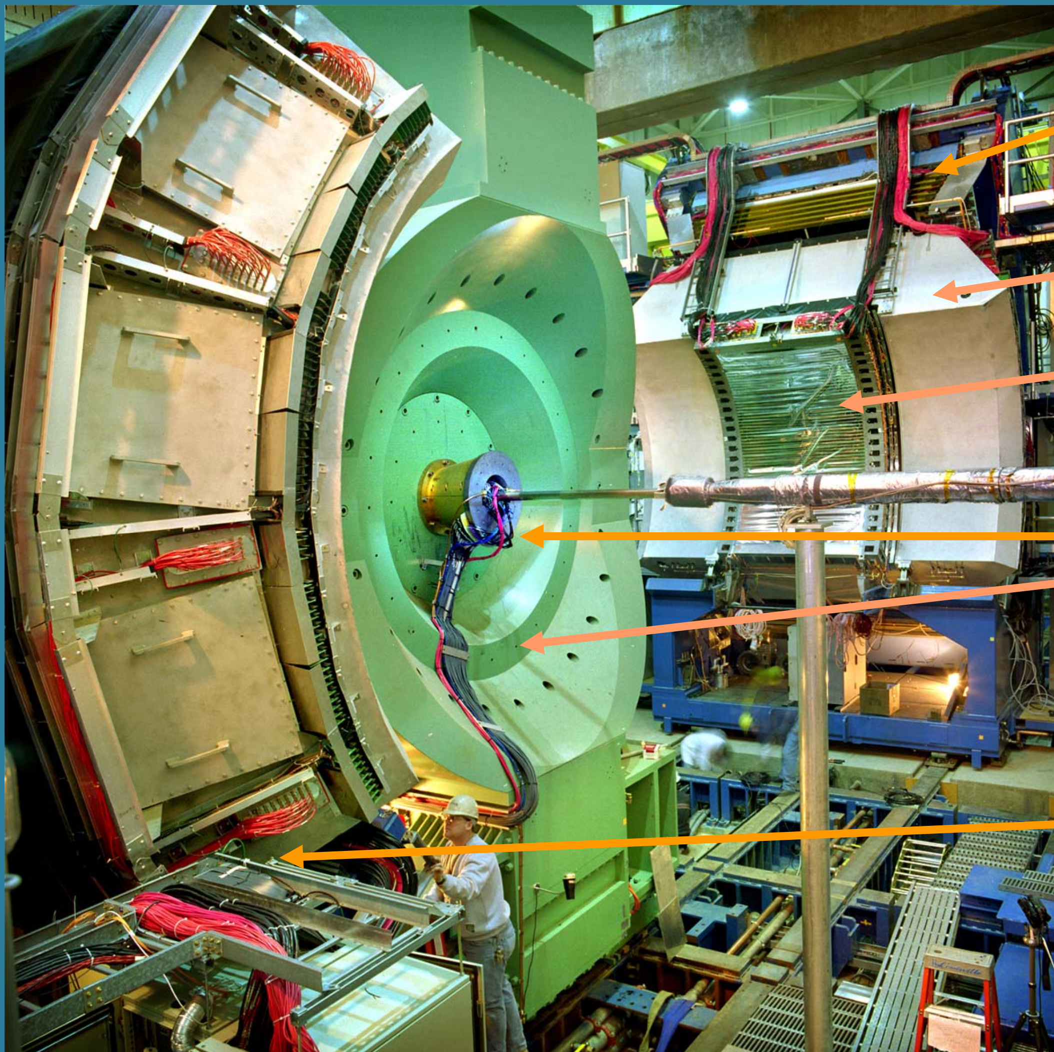
PHENIX-Setup



- Relevant for this talk:
- Detectors in the central spectrometer arms
  - π^0 via $\pi^0 \rightarrow \gamma\gamma$:
    - Lead scintillator calorimeter (PbSc)
    - Lead glass calorimeter (PbGl)
- Centrality , vertex
  - Beam Beam Counter (BBC) $3.0 < |\eta| < 3.9$
  - Zero Degree Calorimeter (ZDC)

(pseudorapidity $|\eta| < 0.35$)

PHENIX Detector at Collision Point



East Carriage
(Moved in Place)

Ring Imaging
Cerenkov

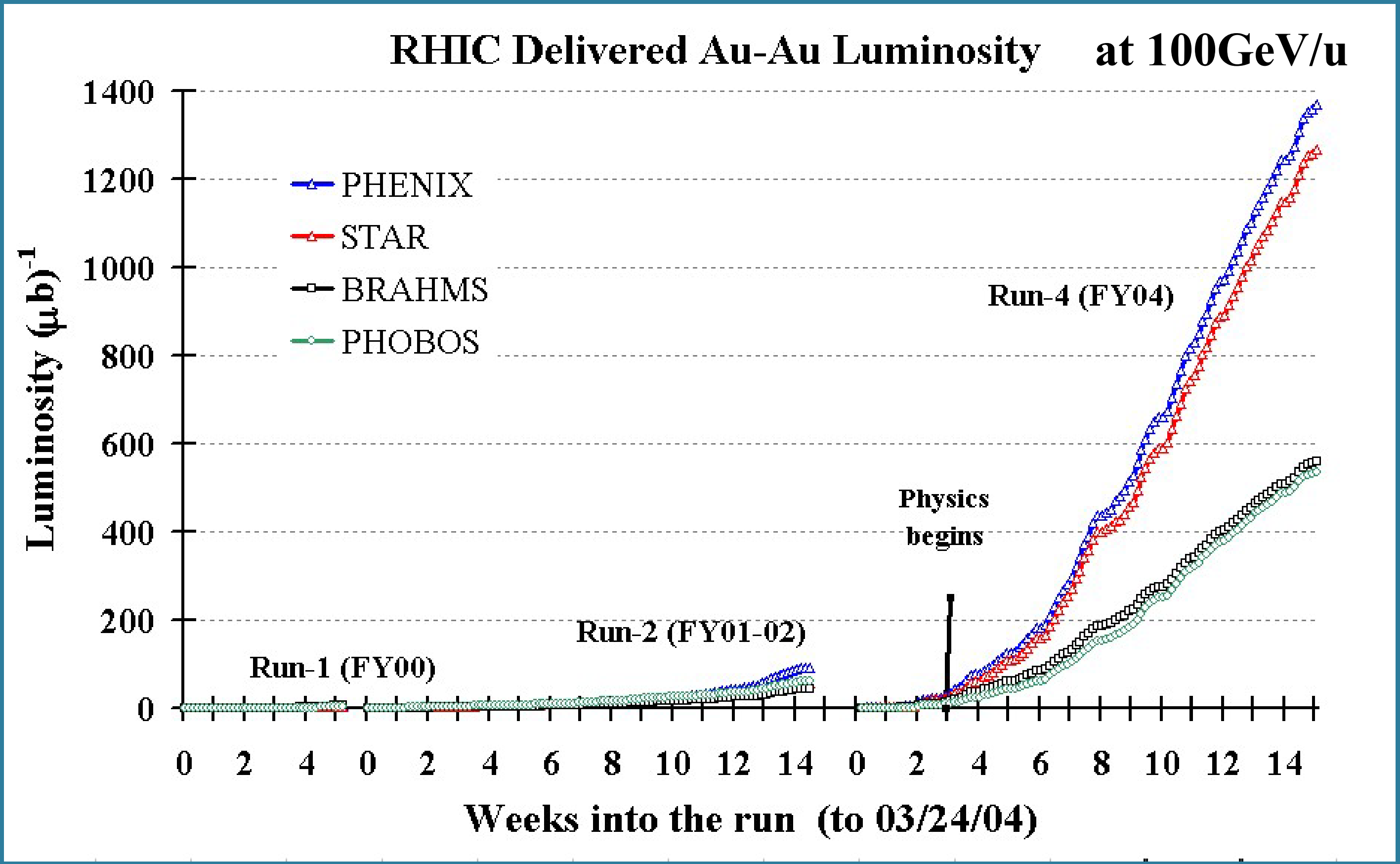
Drift Chamber

Beam-Beam Counter

Central Magnet

West Carriage

PHENIX in Run 4

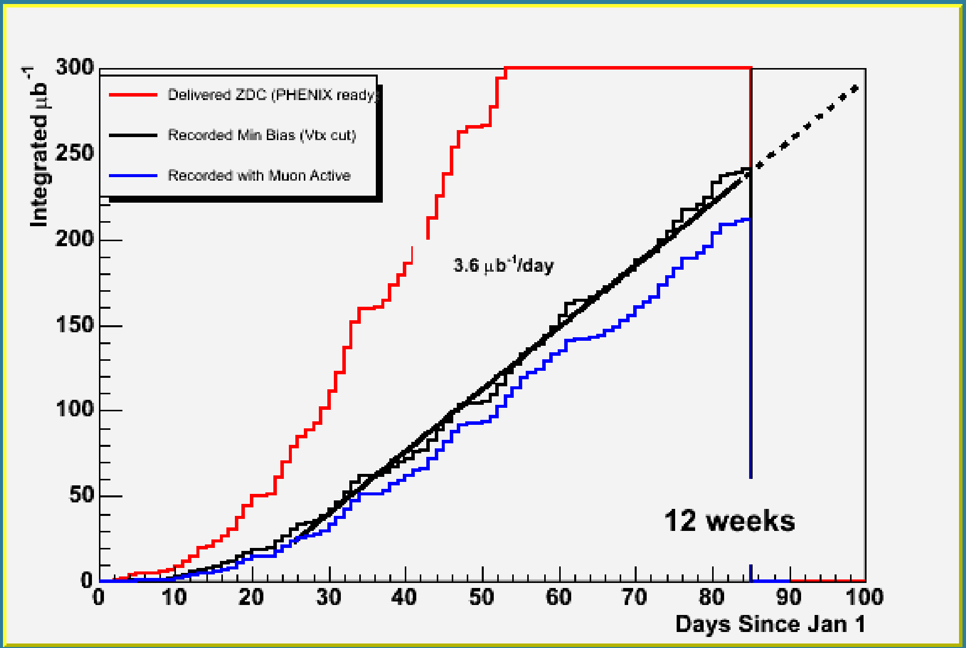


	100GeV/u (mb)$^{-1}$	Relative to Run-2	31.2GeV/u (mb)$^{-1}$
PHENIX	**1370**	**15x**	**21.8**
STAR	**1270**	**21x**	**20.7**
BRAHMS	**560**	**13x**	**12.2**
PHOBOS	**540**	**7x**	**12.3**

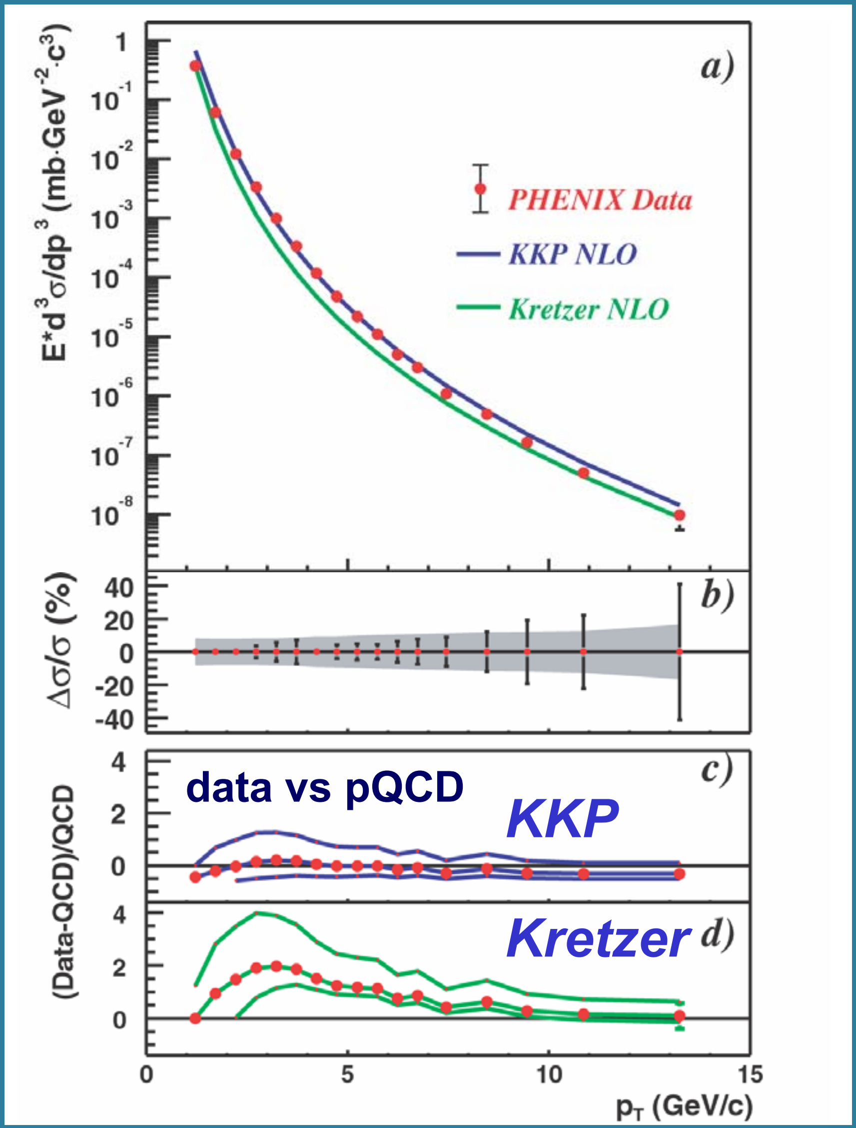
PHENIX in Run 4

- 200 GeV Au+Au data sample:
  - $1.5x10^{9}$ min bias events recorded,
  - $241mb^{-1}$ integrated luminosity
  - 60 times the $24x10^{6}$ minbias events of Run 2
  - 10 times the $24mb^{-1}$ sampled in Run 2 by triggered events

- 62.4 GeV Au+Au data sample:
  - 58x106 min bias events recorded

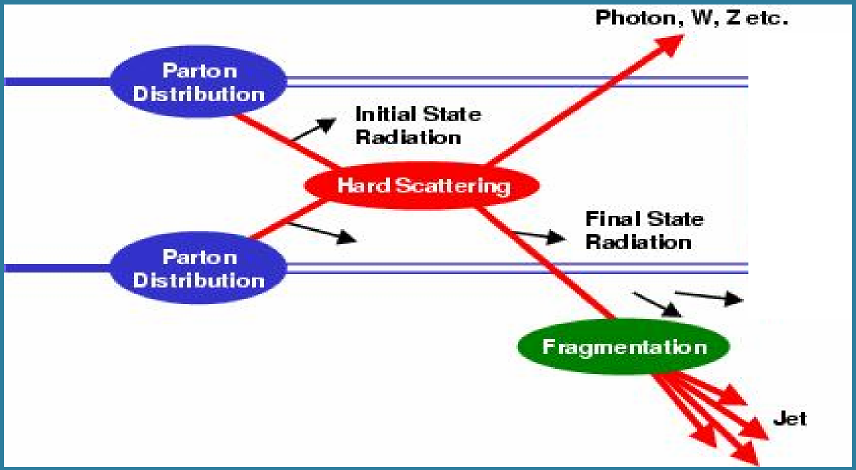


π^0 production in p+p



- **Good agreement with NLO pQCD**
  - Factorization theorem:

$$\sigma_{AB \to hX} \propto f_{a/A}(x_a,Q^2_a) \otimes f_{b/B}(x_b,Q^2_b) \otimes \sigma_{a\,b \to cd} \otimes D_{h/c}(z_c,Q^2_c)$$

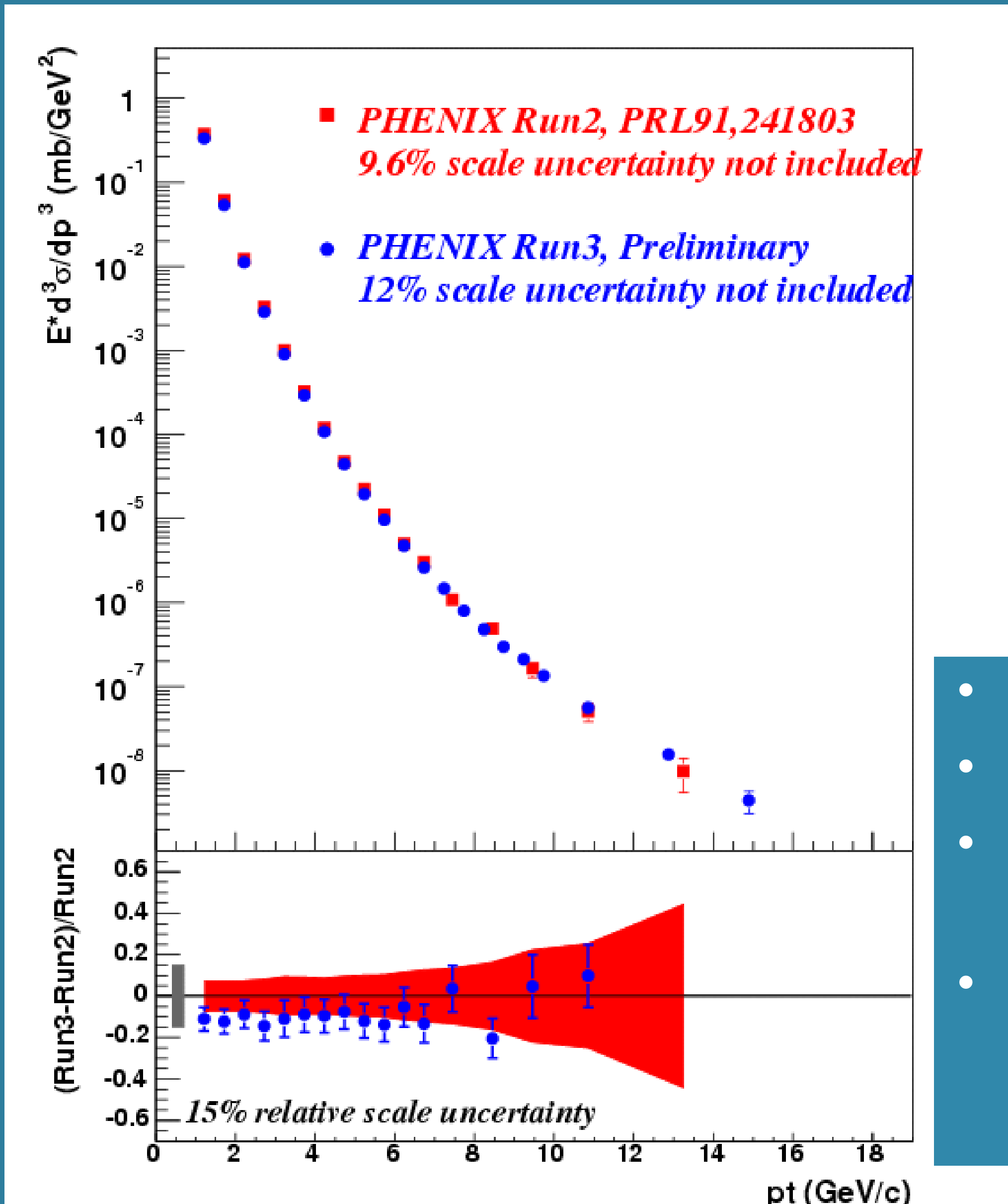


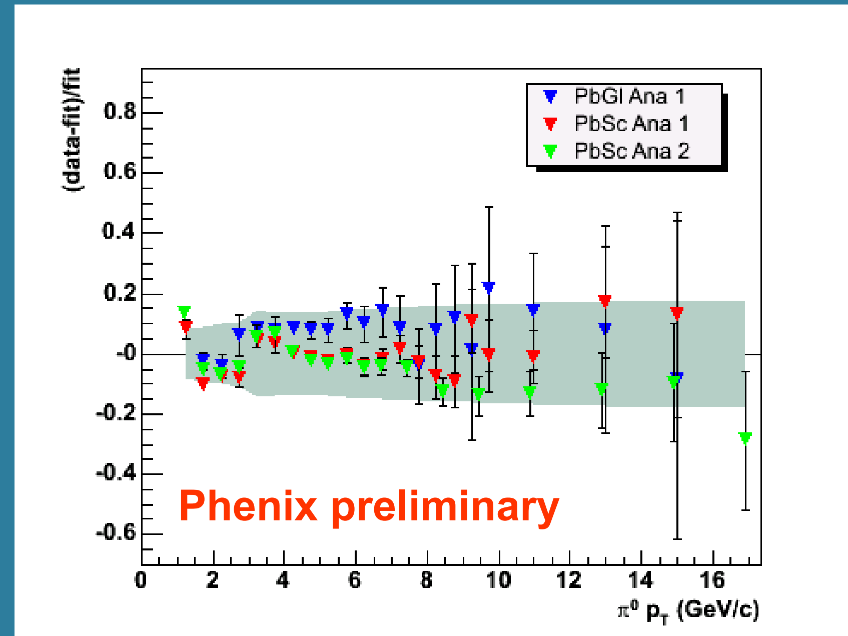
- **Constrains Fragmentation Function D(Gluon-pi)**
- **Reference for Au+Au spectra**

Phys. Rev. Let 91, 241803 (2003)

200 GeV - Run2

π^0 production in p+p

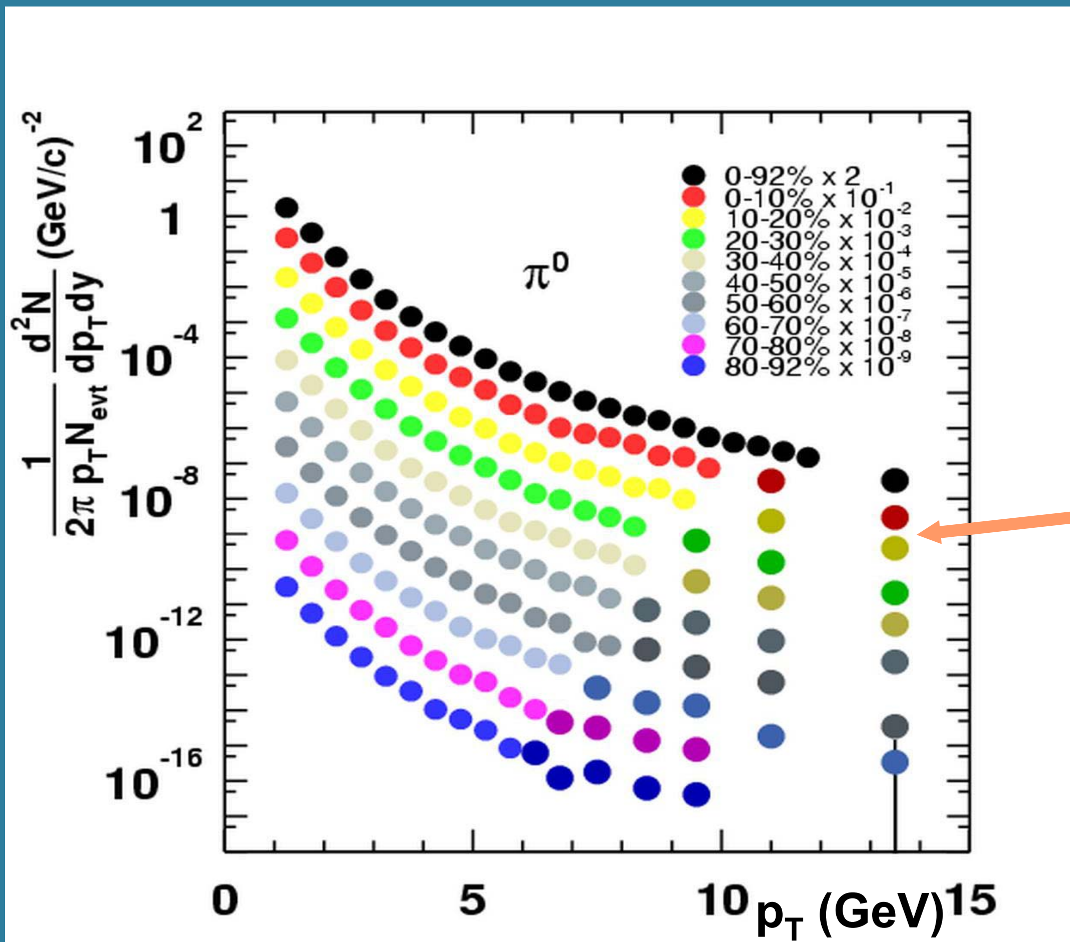




- New run3 pp data
- Reach out to pT > 16 GeV
- Good reference for run3 dAu data – reduced syst. errors
- Cross section determination under investigation

200 GeV – Run3

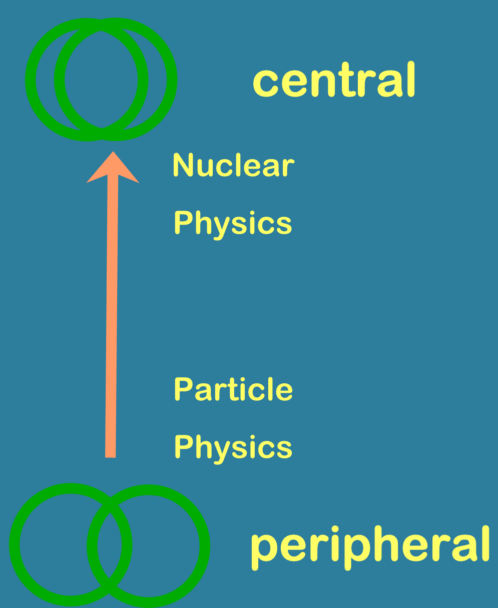
π^0 Spectra in Au+Au at 200 GeV



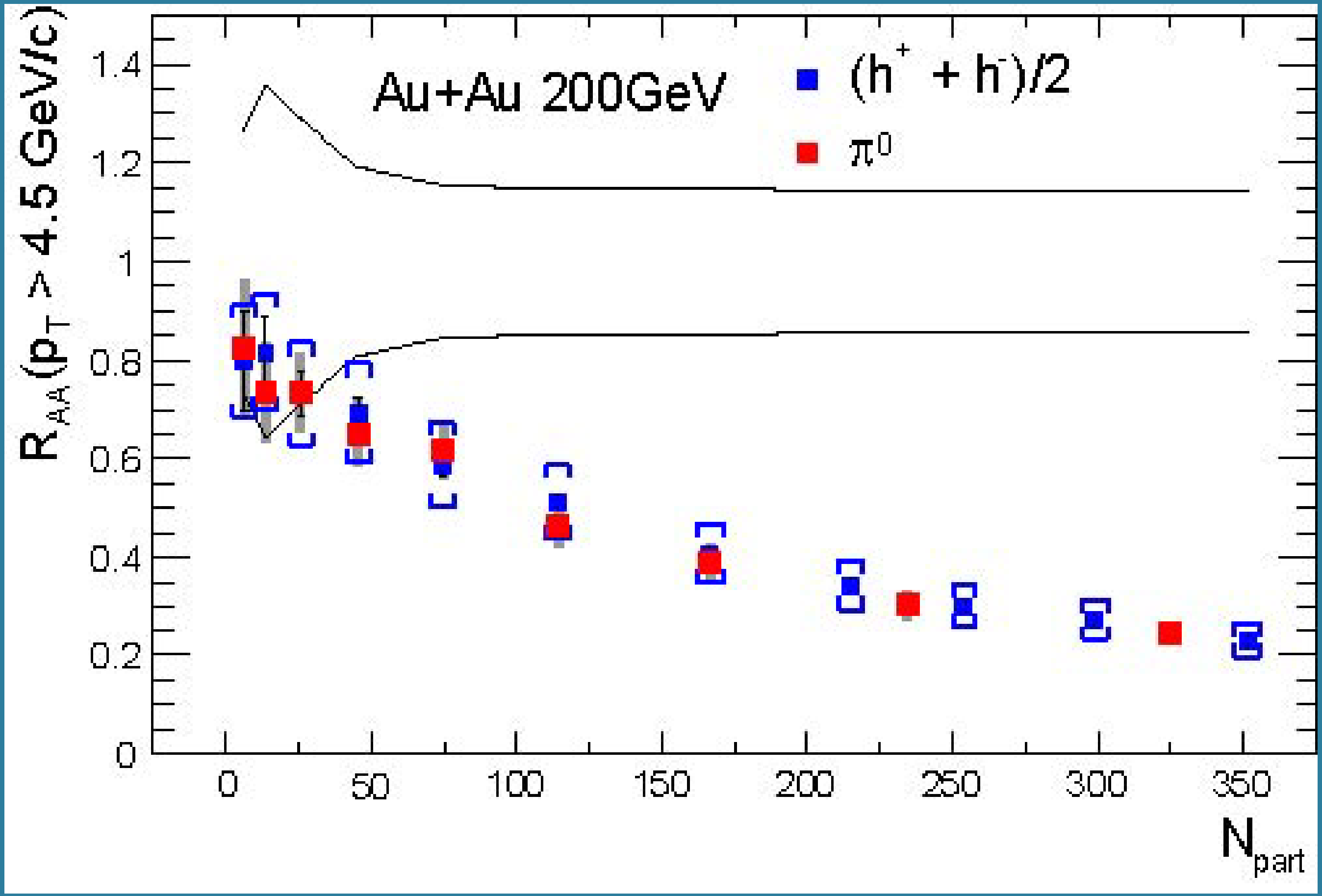
Phys. Rev. Lett. 91, 072301 (2003)

- Use p+p as base line measurement

spectra up to 15 GeV/c

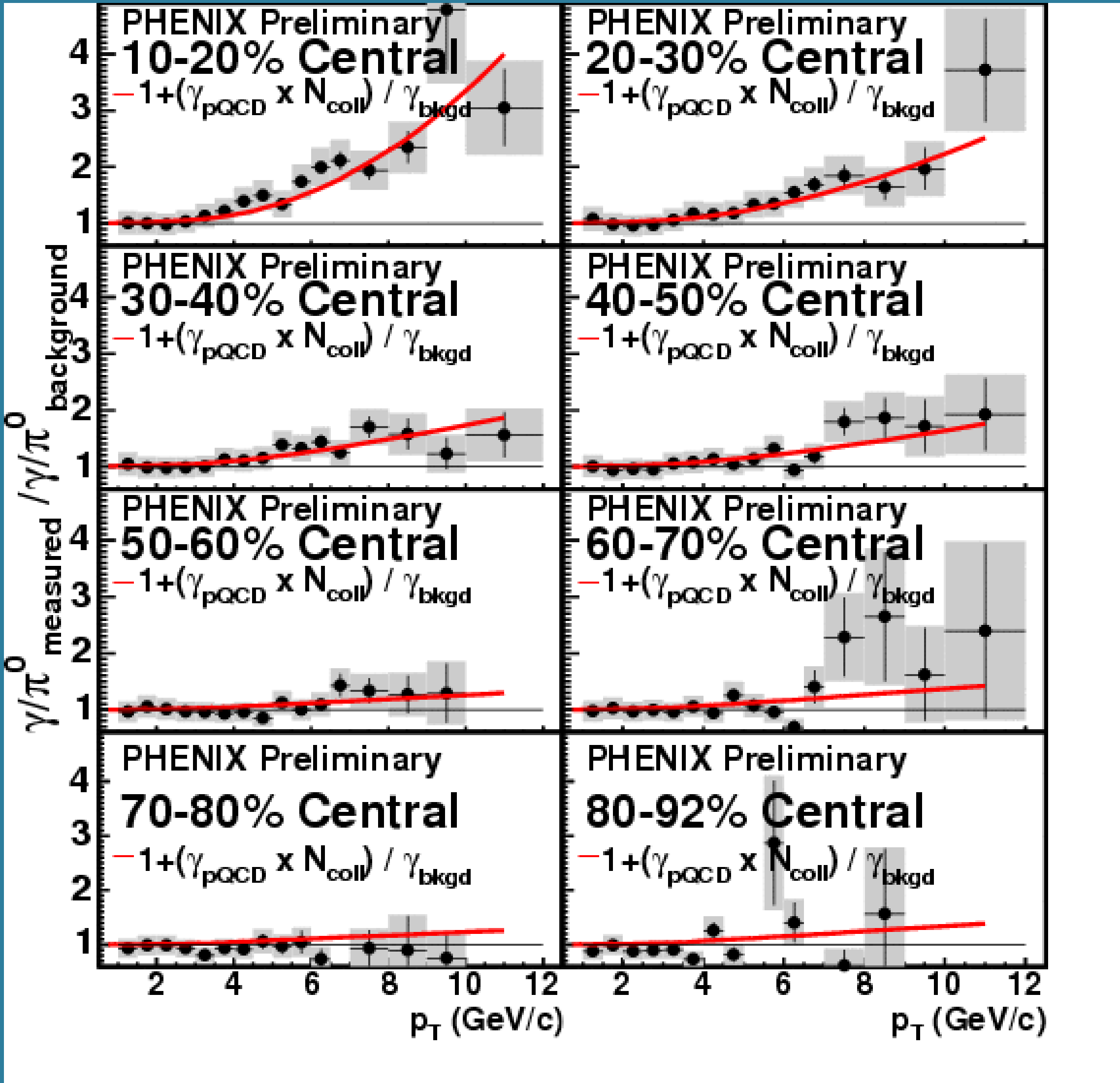


Centrality dependence



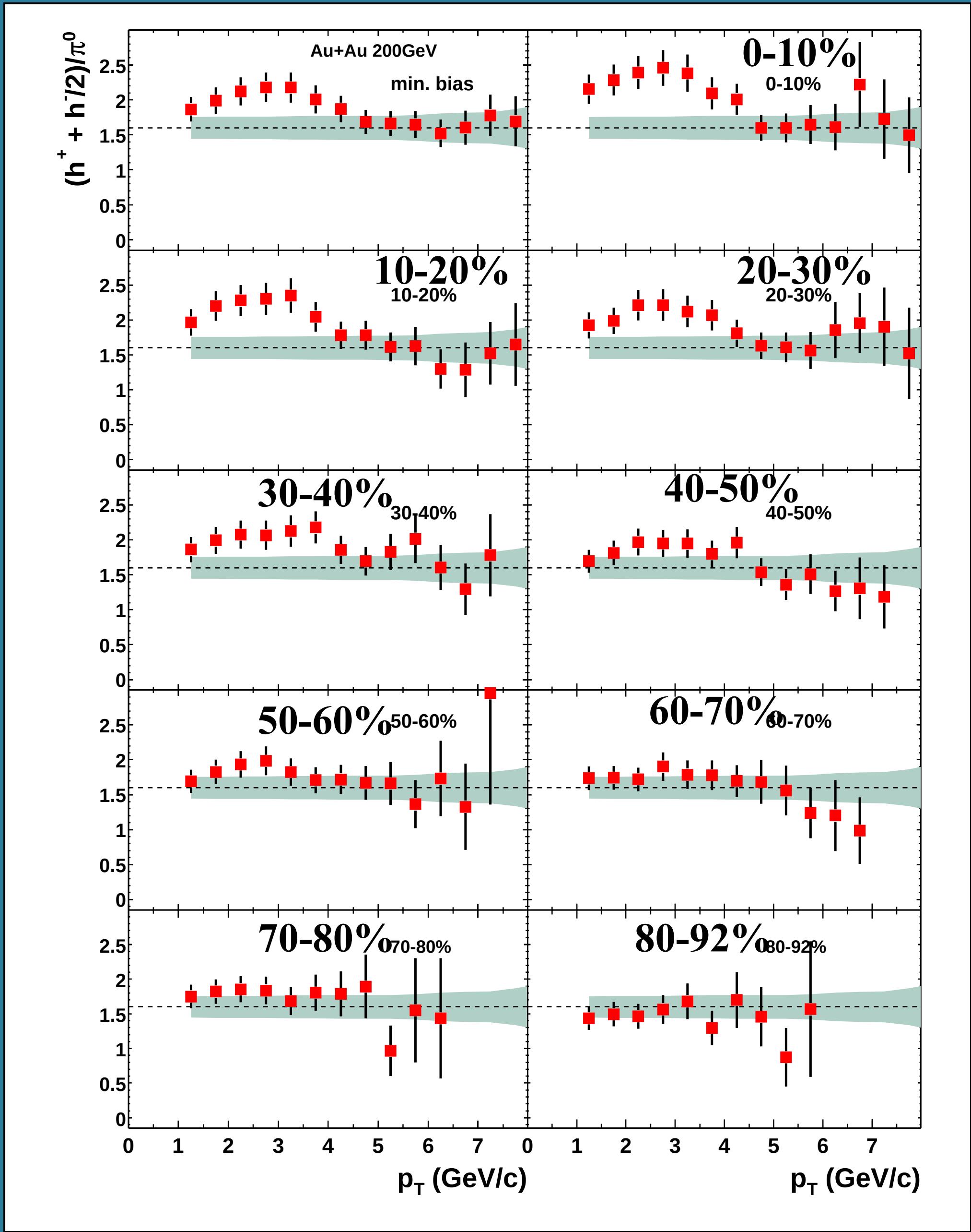
integrated π^0 yield above p_T = 4 GeV/*c*

Direct photons centrality



$(h^{+}+h^{-})/2$ to π^0 ratio in 200GeV Au-Au

- Averaged charged hadrons to π^0 ratios.
- Lines are drawn at $h/\pi^0 = 1.6$, which is predicted by results from past experiments
- At high pT, ratio reaches the asymptotic values of 1.6
- In the intermediate pT region, excess is seen
  - Consistent with the p/π^0 ratio data showing that more protons are produced
  - Strong centrality dependence



Initial ⟷ Final State Effects

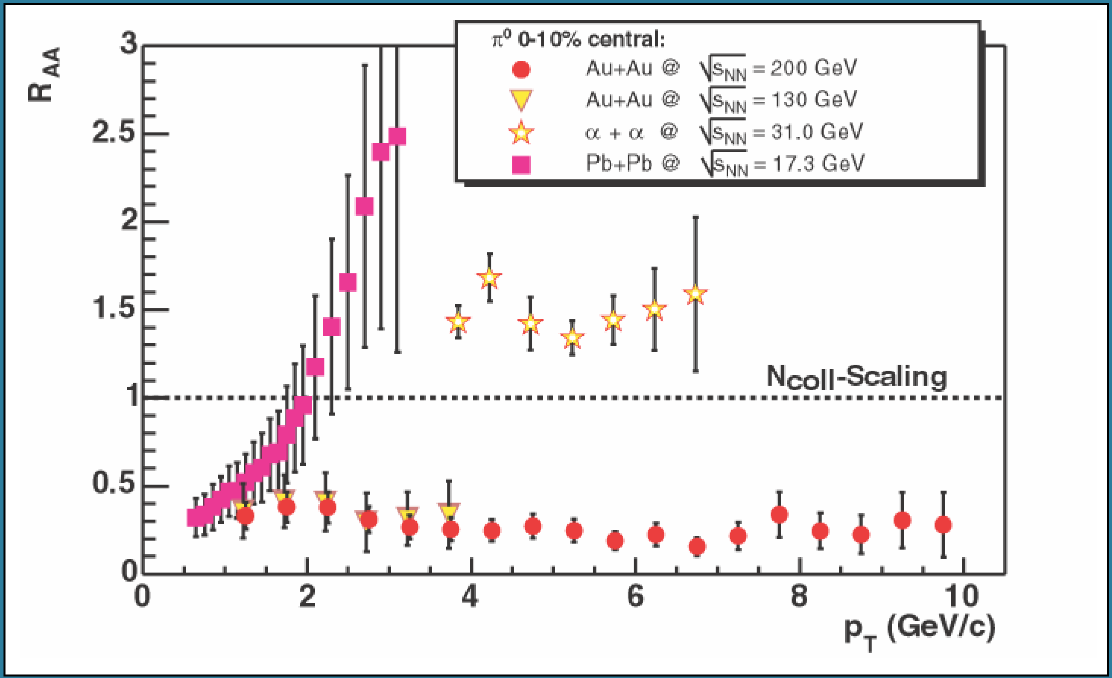
- **Initial state effects**
  - **lead to $R_{AA} \neq 1$ at high p_T**
  - **but are not related to properties of hot and dense nuclear matter**
- **Possible initial state effects:**
  - **Initial state multiple soft scatterings (Cronin effect) $R_{AA} > 1$**
  - **Modifications of nuclear structure functions in nuclei (Shadowing) $R_{AA} < 1$**
  - **gluon saturation (Color Glass Condensate) $R_{AA} < 1$?**

- Final state effects
  - dense partonic medium parton energy loss (and recombination)
  - dense hadronic medium hadronic energy loss

The Control Experiment: d+Au

- **Initial state nuclear effects present in both A+A and N+A collisions**
- **Final state medium effects only present in A+A collisions**

R_{AA} for π^0 in Central Collisions Different Energies

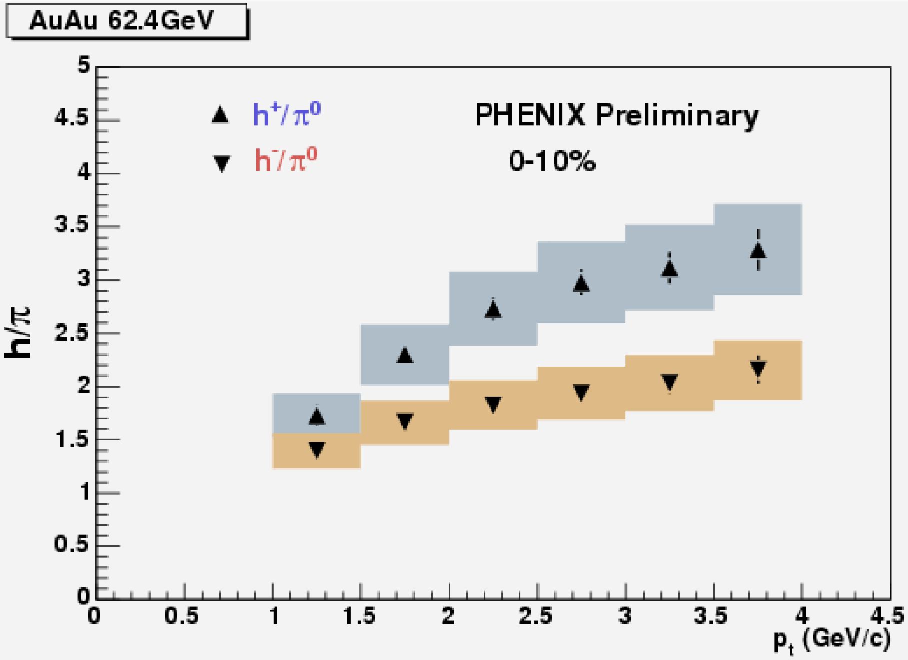


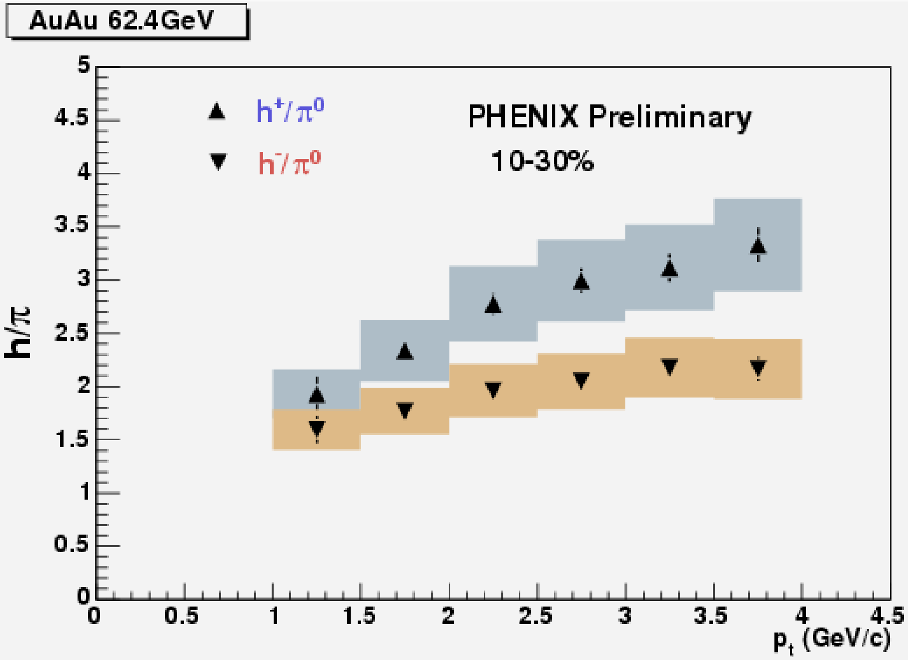
- **Cronin Effect at lower energies**
- **Expectation**
  - $R_{AA} > 1$
- **Observed**
  - factor 4-5 suppresion at 130 and 200 GeV

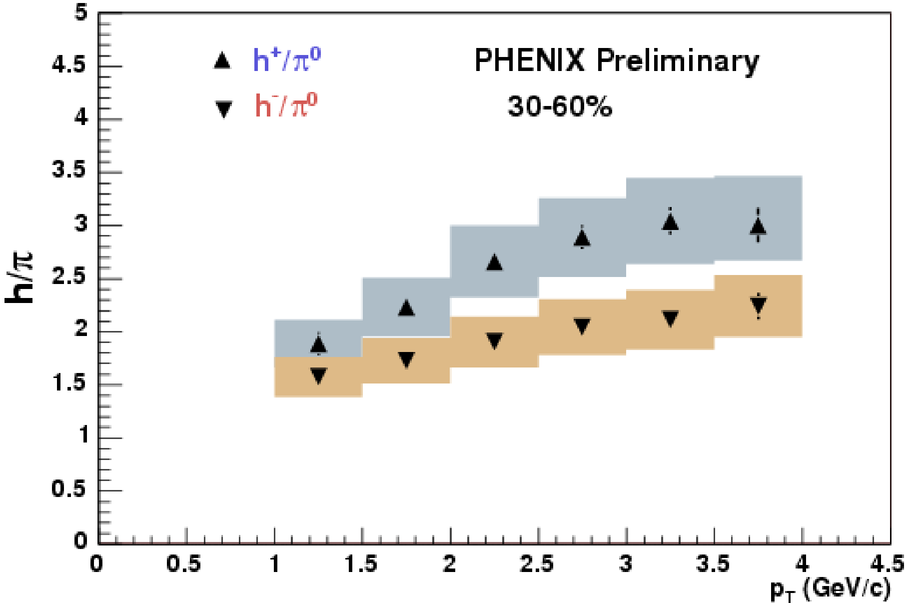
A.L.S.Angelis PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
PHENIX submitted to PRL, nucl-ex/0304022

Explanation ??

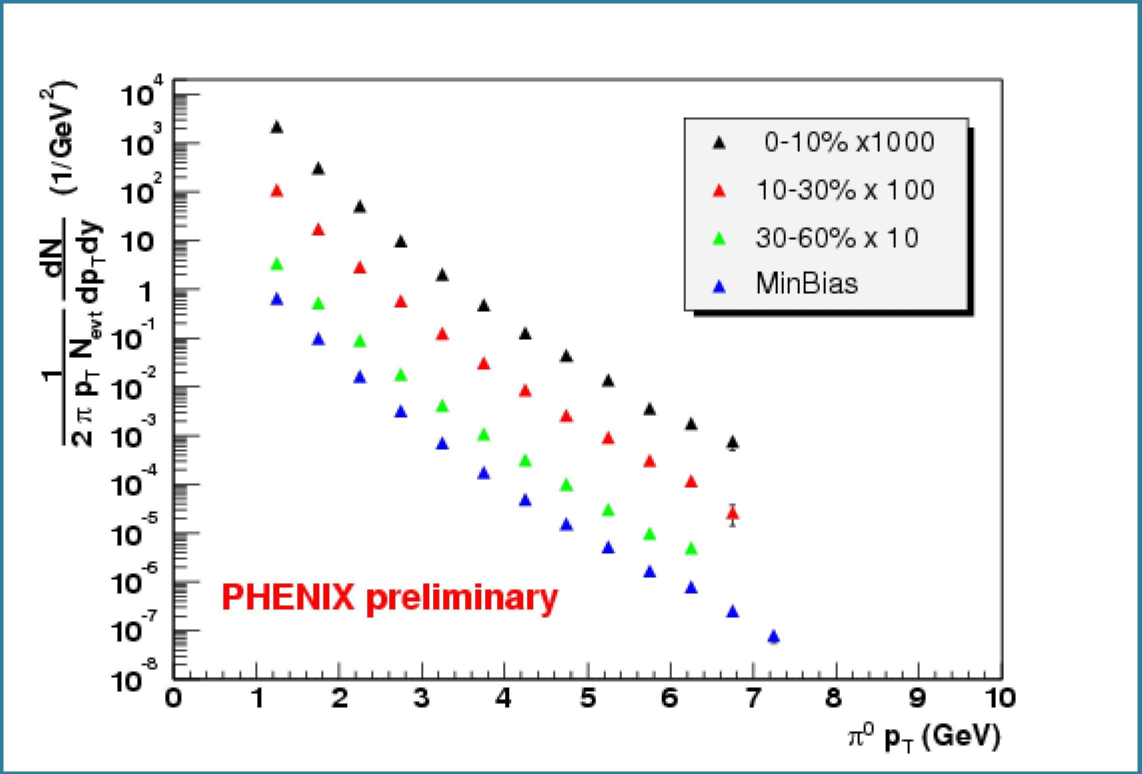
h/pi ratio


AuAu 62.4GeV
PHENIX Preliminary
0-10%
h⁺/π⁰
h⁻/π⁰
h/π
p_t (GeV/c)


AuAu 62.4GeV
PHENIX Preliminary
10-30%
h⁺/π⁰
h⁻/π⁰
h/π
p_t (GeV/c)


PHENIX Preliminary
30-60%
h⁺/π⁰
h⁻/π⁰
h/π
p_T (GeV/c)

π^0 Spectra at 62.4 GeV



- π^0 data in min. bias, 0-10%, and 10-30%, and 30-60% most central collisions up to p_T = 7GeV/c
- Small systematic uncertainty : 9~12%

Charged hadron reference

- π,k,p data from ISR are first combined to obtain charged hadron data at low $\sqrt{s}$
- Charged hadron data are then interpolated between ISR, UA1 and PHENIX to obtain the reference data at $\sqrt{s}$ 62.4 GeV
- A fit using modified hagedon functional form is used to obtain parameterization for charged hadrons

- Right Fig. shows the charged reference/1.6 and compared with π^0 and Breakstone which is not used in the fit. ($(h^{+}+h^{-})/2\pi^{0}$ = 1.6±0.16 measured in ISR and RHIC)
- Charged hadron have ±25% systematic errors and the upper error increase to about 50% at 7 GeV/c