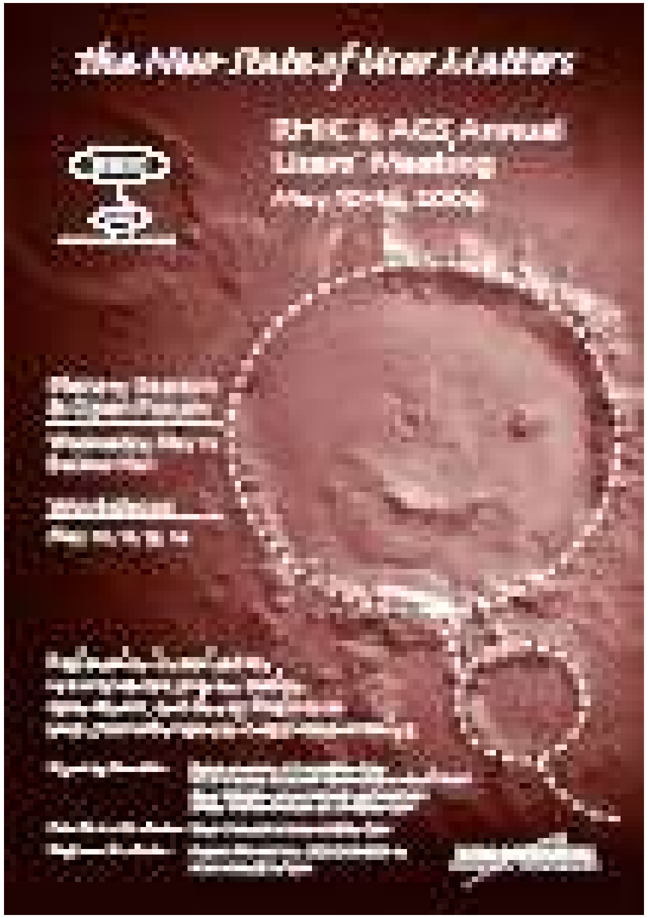


High p_T at RHIC: Highlights.

AGS&RHIC Users Meeting

BNL, NY - May 12, 2004

David d'Enterria
Nevis Labs, Columbia University, NY

QGP & CGC search @ RHIC in the high p_T sector

NEW

➡ "QCD vacuum" reference results – p+p @ 200 GeV

1. Inclusive hadron spectra: $Ed^3\sigma/d^3p$
2. Jet properties $(dN_{pair}/d\varphi)$: $\langle j_T \rangle$, $\langle k_T \rangle$

Comparison to pQCD (NLO) expectations

➡ "Hot QCD medium" highlights – central Au+Au @ 200, 62 GeV

1. Suppressed hadron spectra: dN/dp_T
   $\sqrt{s}$, p_T, centrality dependence
2. Suppressed di-jet correlations $(dN_{pair}/d\varphi)$
   reaction-plane dependence, low p_T assoc. correlations ...
3. Baryon "anomalies" @ intermediate p_T
   enhanced dN/dp_T and v2, jet-like $dN_{pair}/d\varphi$

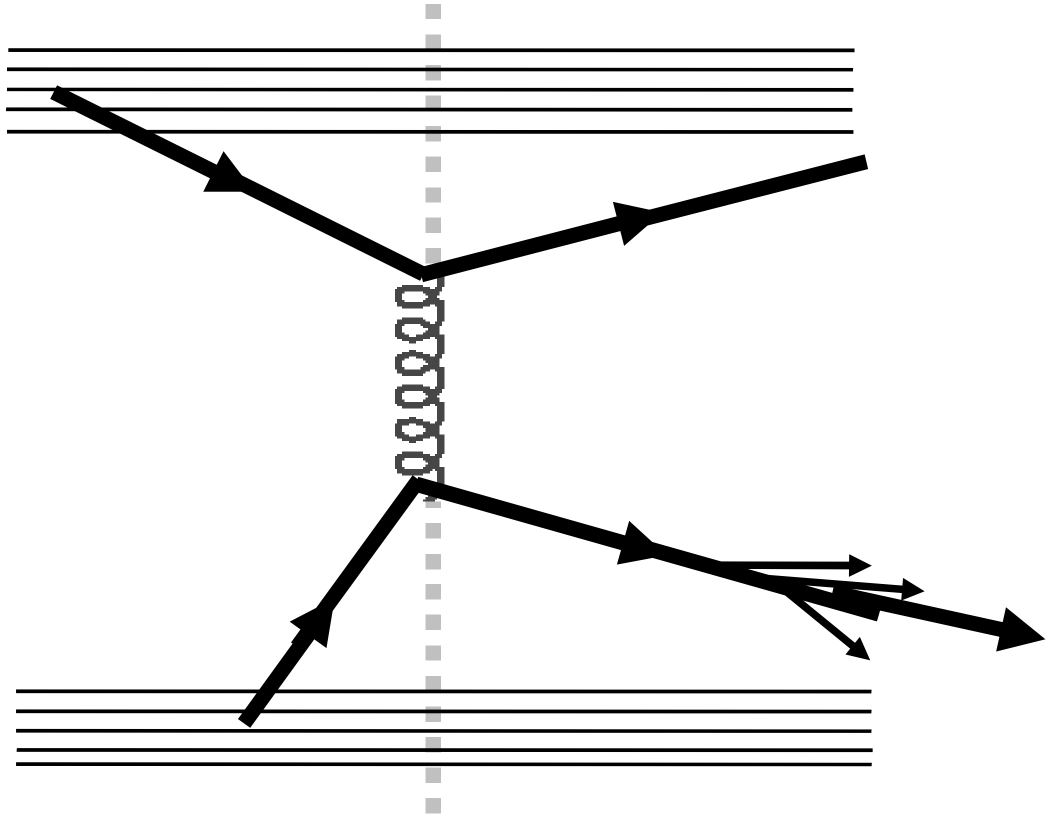
Comparison to QGP expectations ("jet quenching" & "q recomb.")

➡ "Cold QCD medium" highlights – d+Au @ 200 GeV

1. Inclusive hadron dN/dp_T enhancement at $y \leq 0$
2. Inclusive hadron dN/dp_T suppression at $y \geq 1$

Comparison to "Color-Glass-Condensate" expectations

Hard scattering in A+A collisions



Hard scattering in A+A collisions

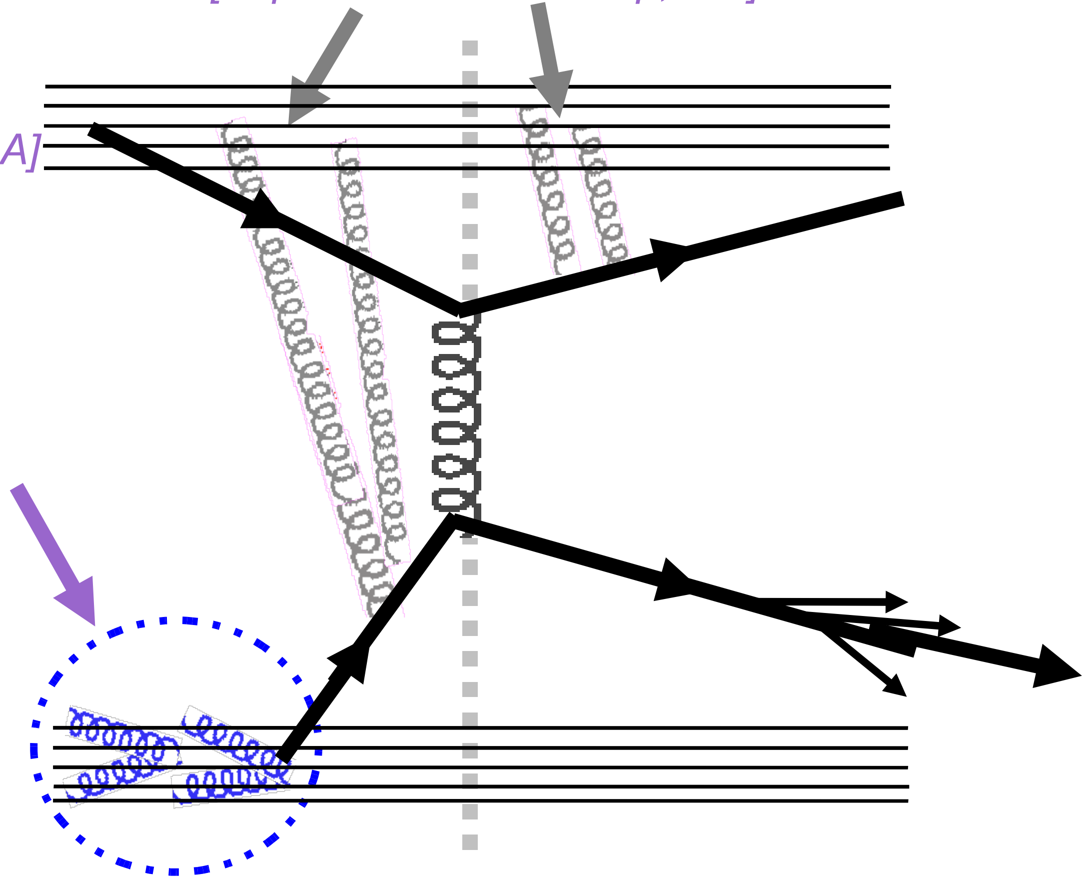
p_T broadening
(Cronin enhancement)

[Experimental handle: p,d+A]

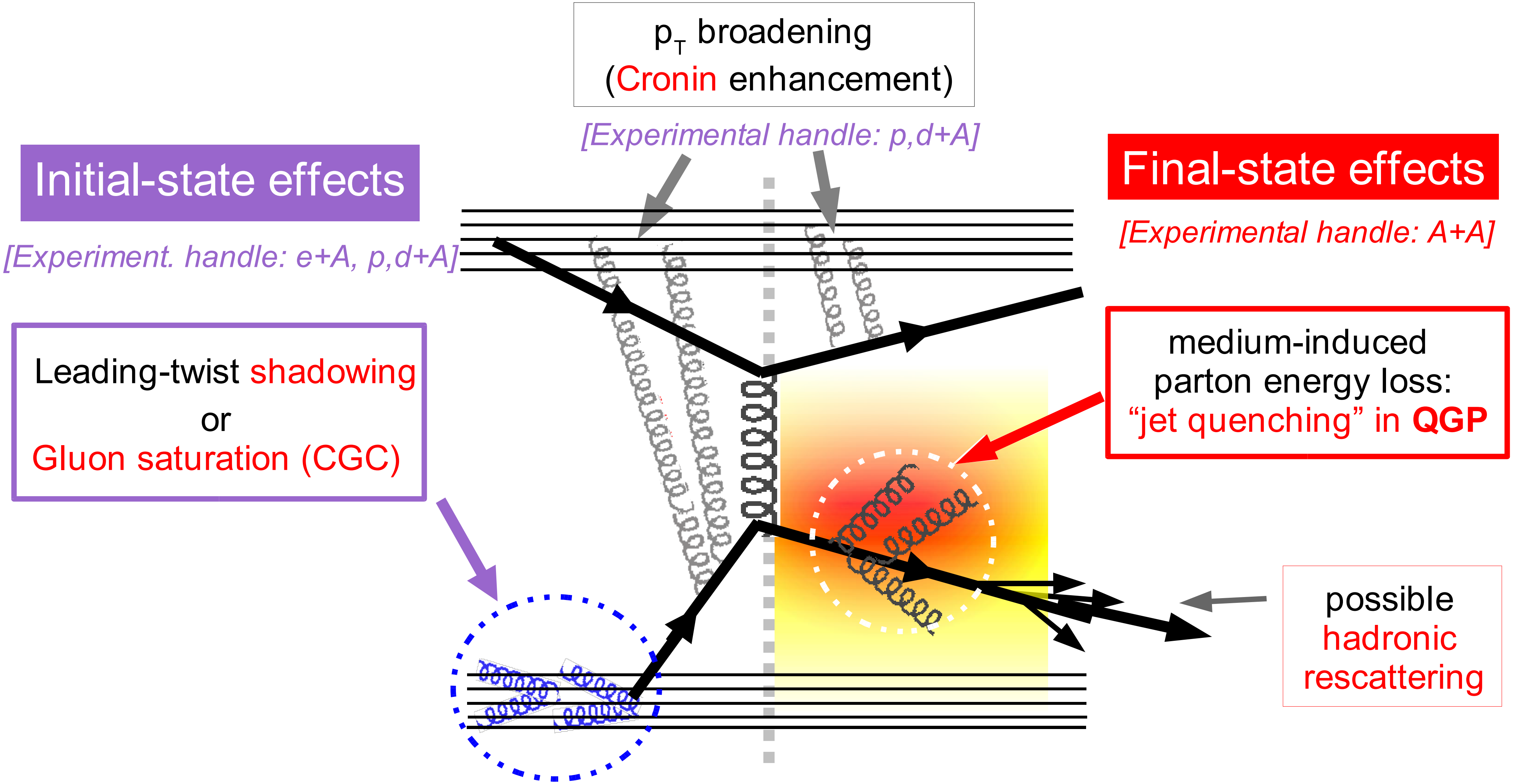
Initial-state effects

[Experiment. handle: e+A, p,d+A]

Leading-twist shadowing
or
Gluon saturation (**CGC**)

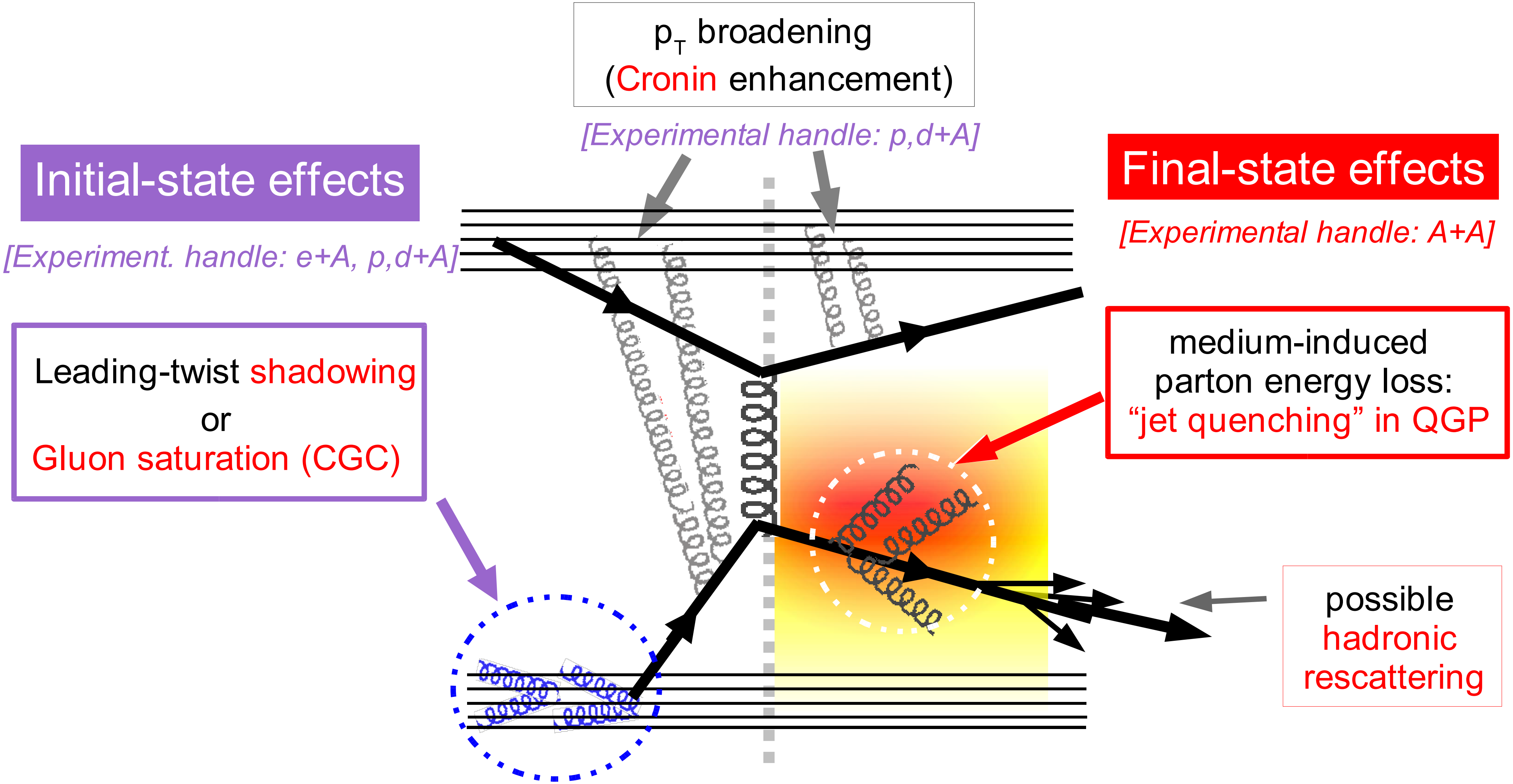


Hard scattering in A+A collisions



David d'Enterria (Columbia Univ.)

Hard scattering in A+A collisions



- Approach: Study modifications (dN/dp_T, particle composition, $dN_{pair}/d\varphi$, ...) of high p_T in A+A with respect to p+p, d+A to learn about QCD many-body dynamics:
  - "Quark Gluon Plasma" (final-state A+A) and/or
  - "Color Glass Condensate" (initial-state A).

Part I:

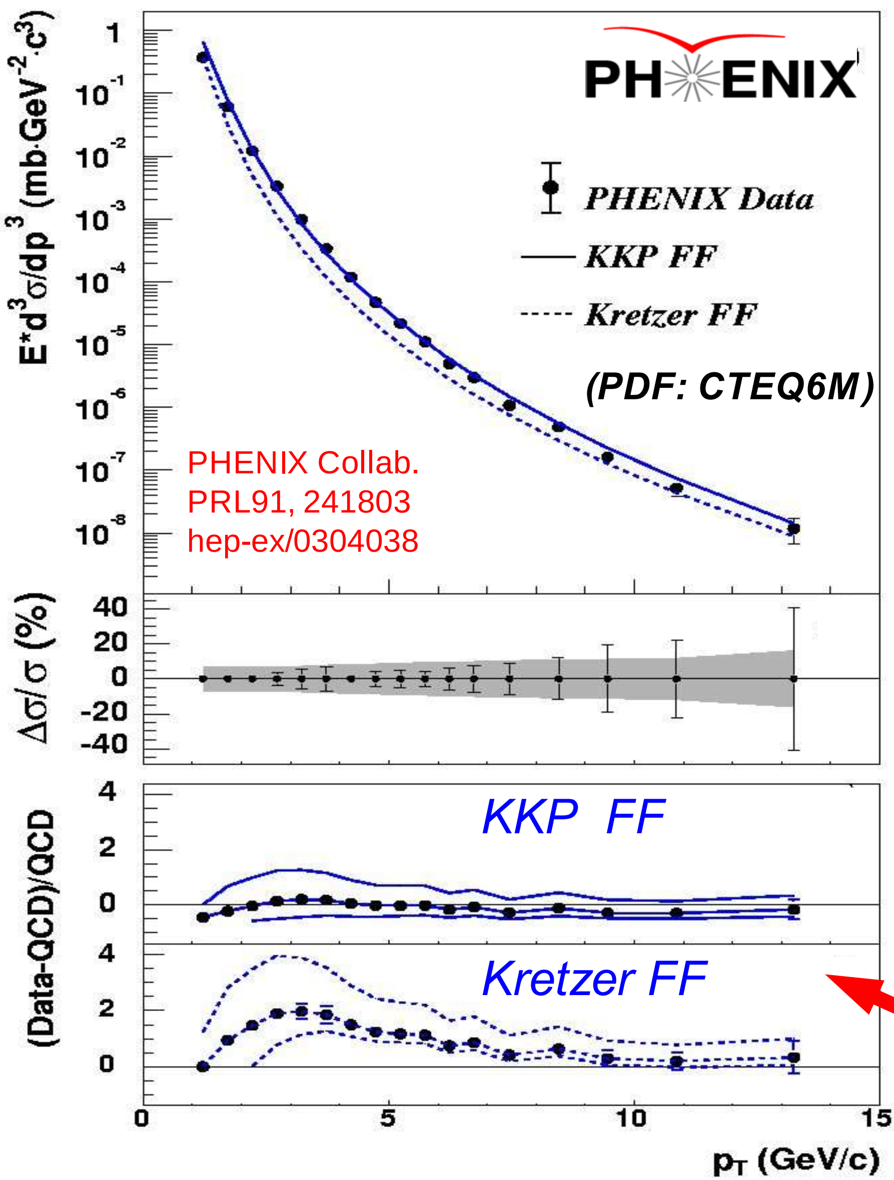
p+p @ 200 GeV

"Calibrating" the QCD vacuum

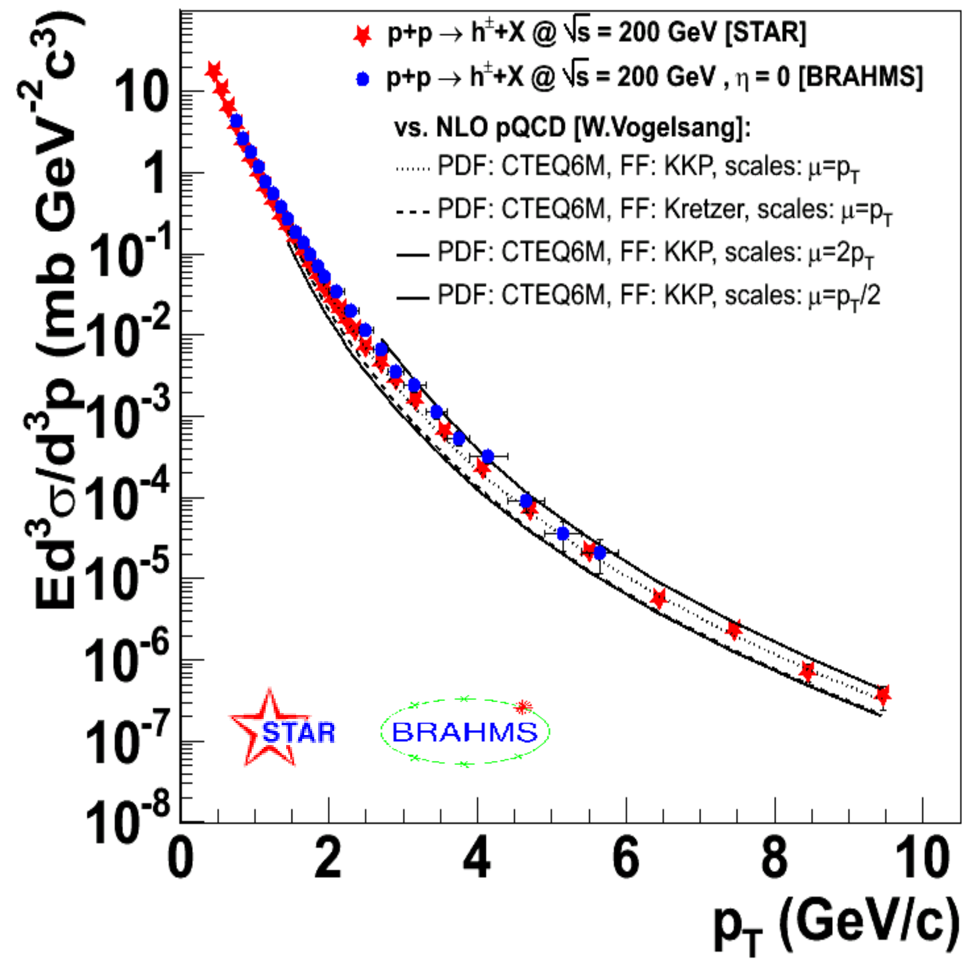
p+p @ 200 GeV: “baseline” spectra

- Good theoretical (NLO pQCD) description ...

$p+p \rightarrow \pi^0 X$



$p+p \rightarrow h^{\pm} X$ (non singly diffractive)

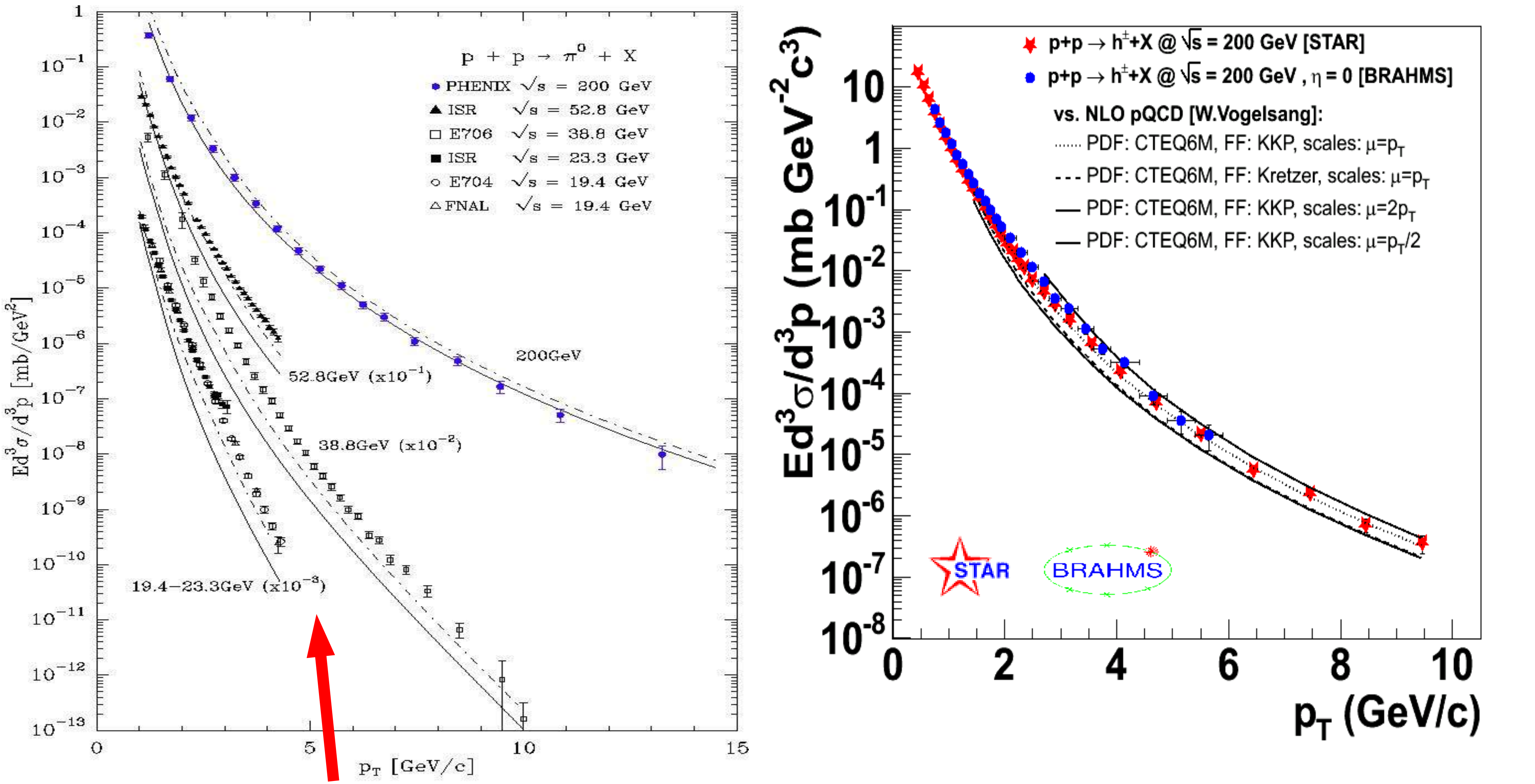


- High quality data: sensitive to different parametrizations of gluon FF

p+p @ 200 GeV: "baseline" spectra

- Good theoretical (NLO pQCD) description ...

p+p → π^0 X   p+p → $h^{\pm}$ X (non singly diffractive)

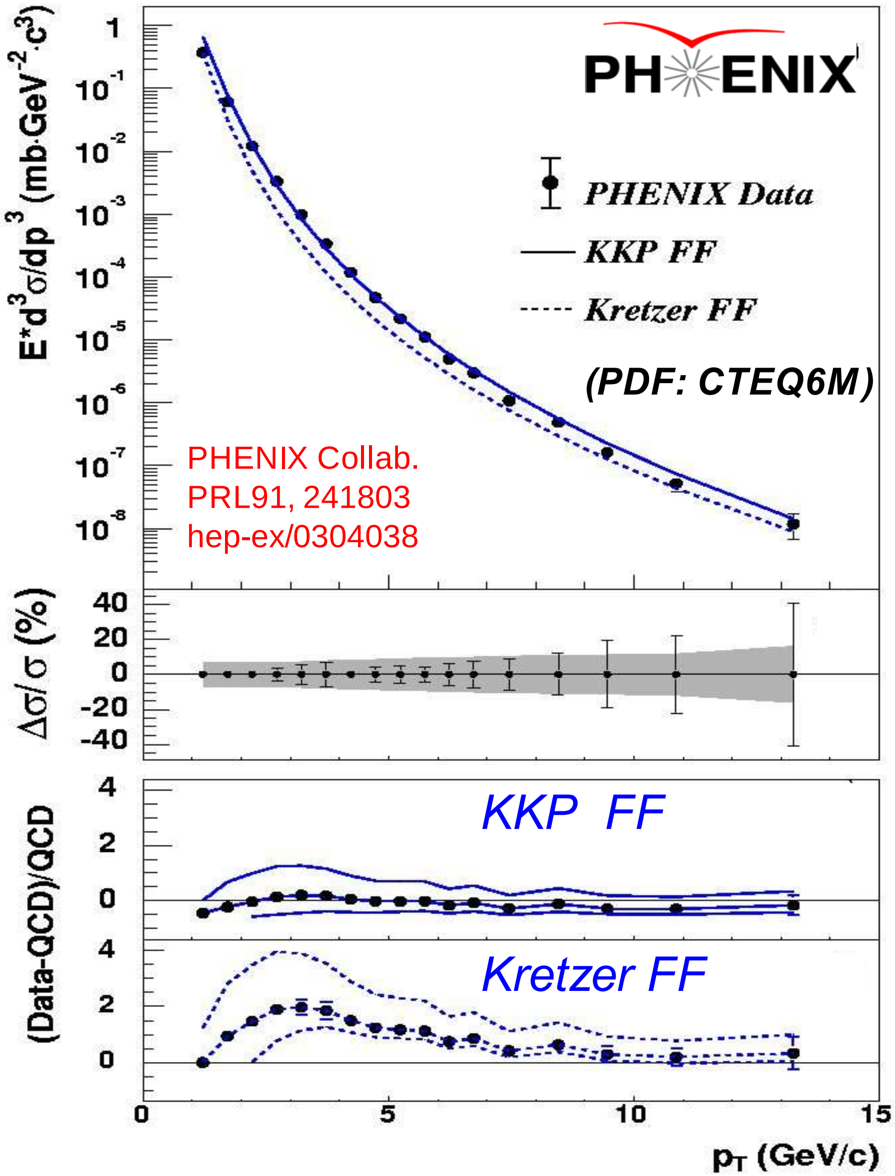


... at variance with lower sqrt(s) results (factors of ~2-4 discrepancy): non-perturbative effects (intrinsic k_T), partly cured by NLL soft g resummation

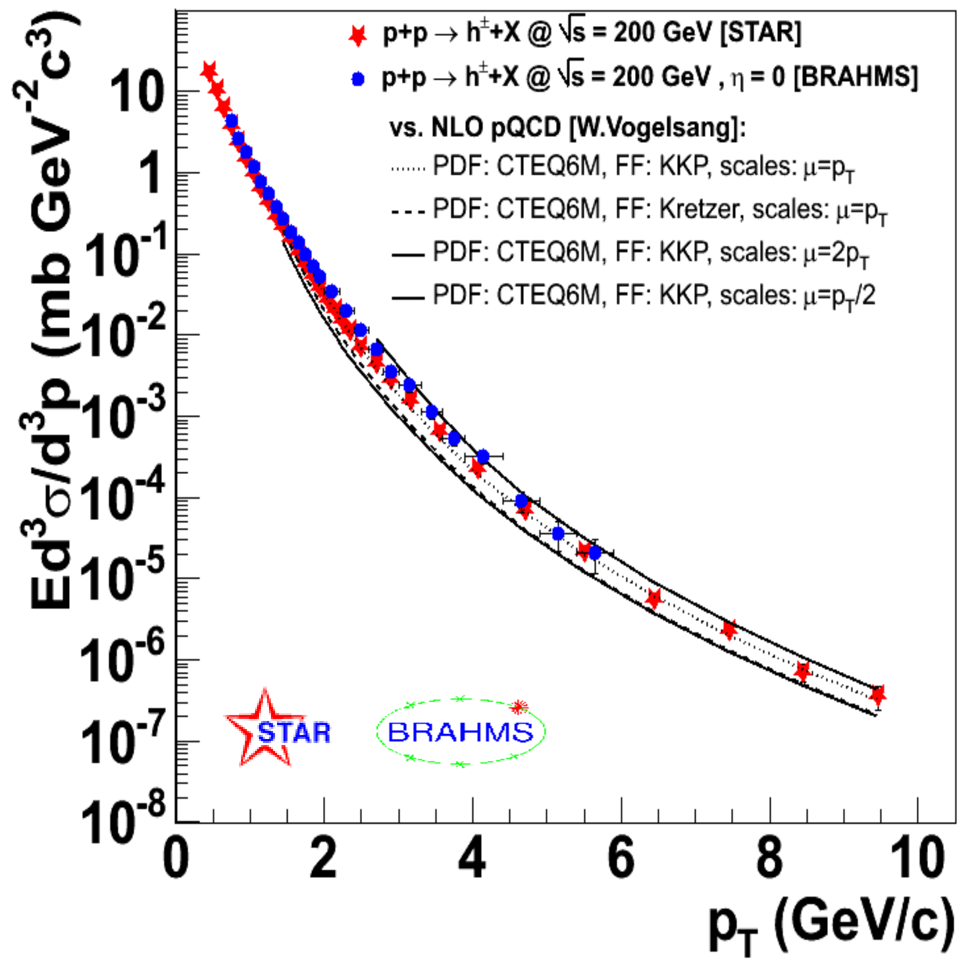
p+p @ 200 GeV: "baseline" spectra

- Good theoretical (NLO pQCD) description:

$p+p \to \pi^0 X$



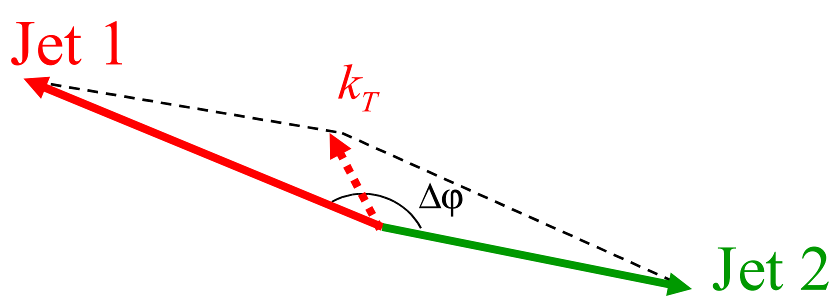
$p+p \to h^\pm X$ (non singly diffractive)

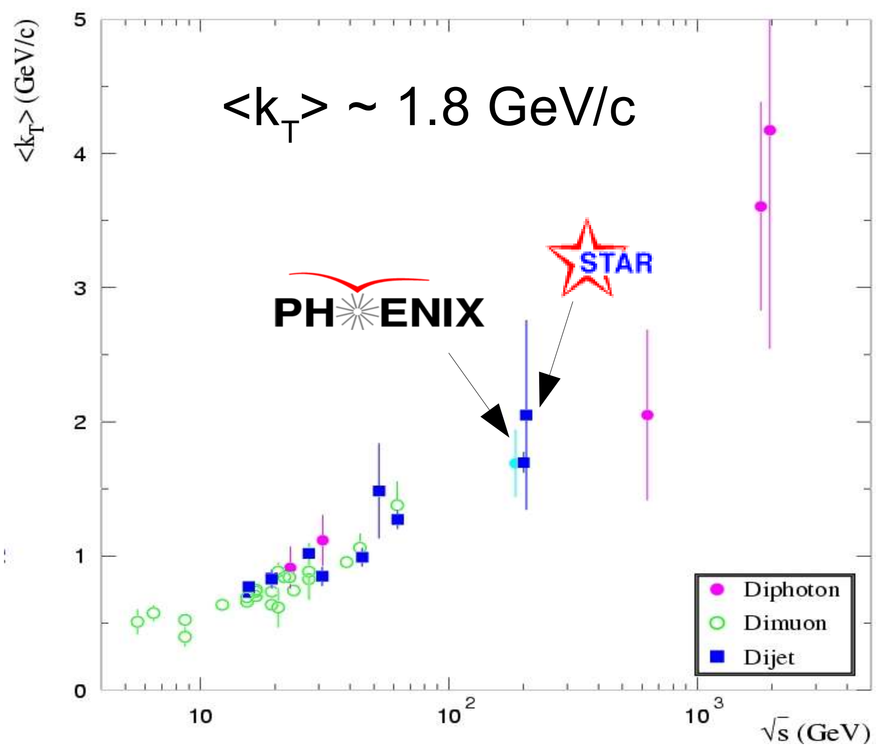


- Well calibrated (experimentally & theoretically) p+p references at hand !

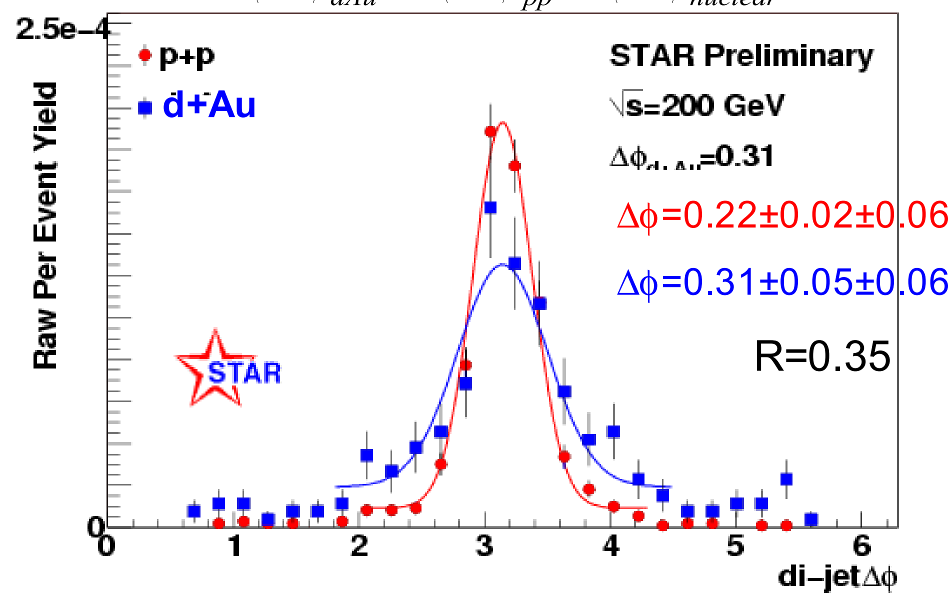
p+p @ 200 GeV: jet properties (I)

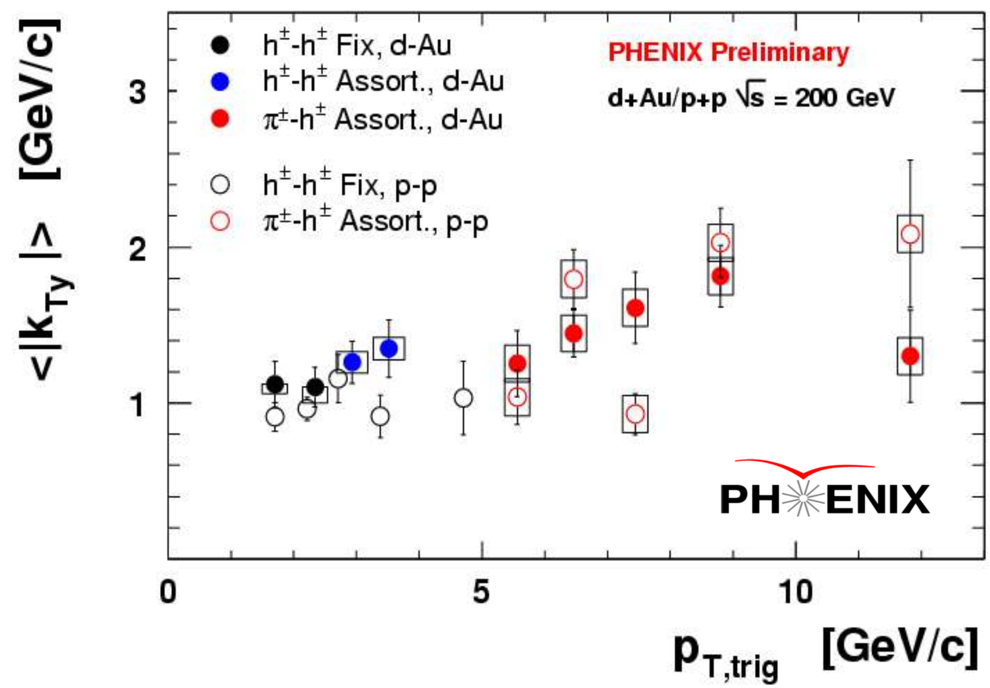
- Intrinsic k_T (di-jet acoplanarity):





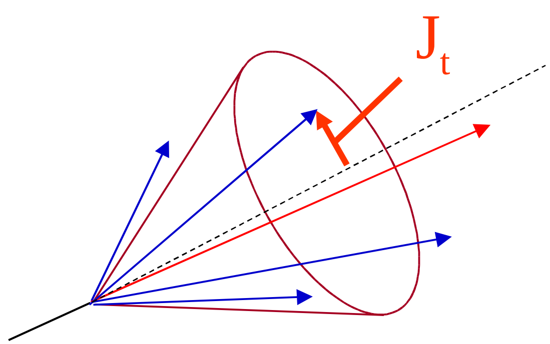
$$\langle k_T^2 \rangle_{dAu} \equiv \langle k_T^2 \rangle_{pp} + \langle k_T^2 \rangle_{nuclear}$$

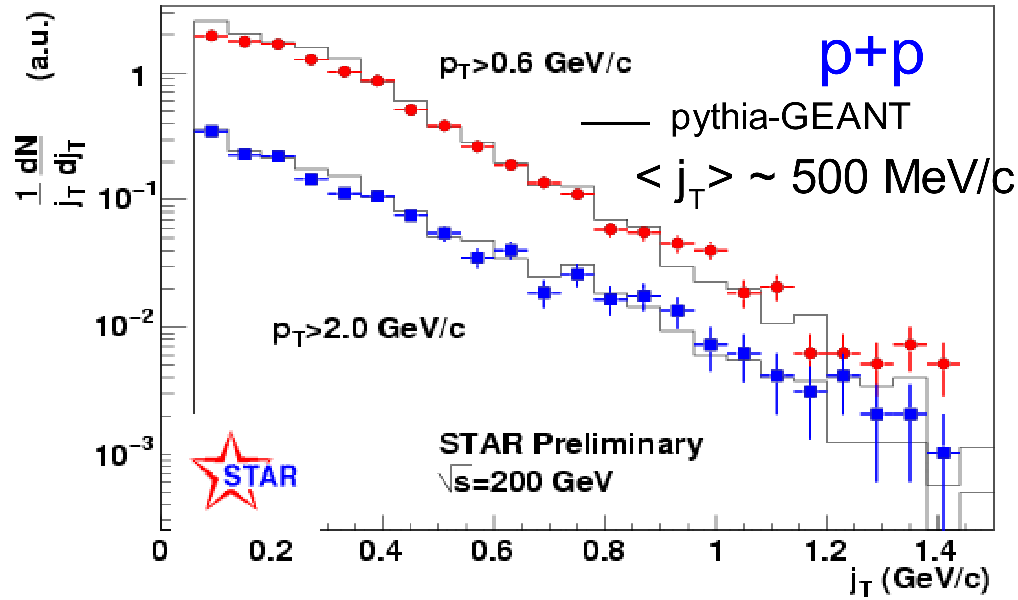


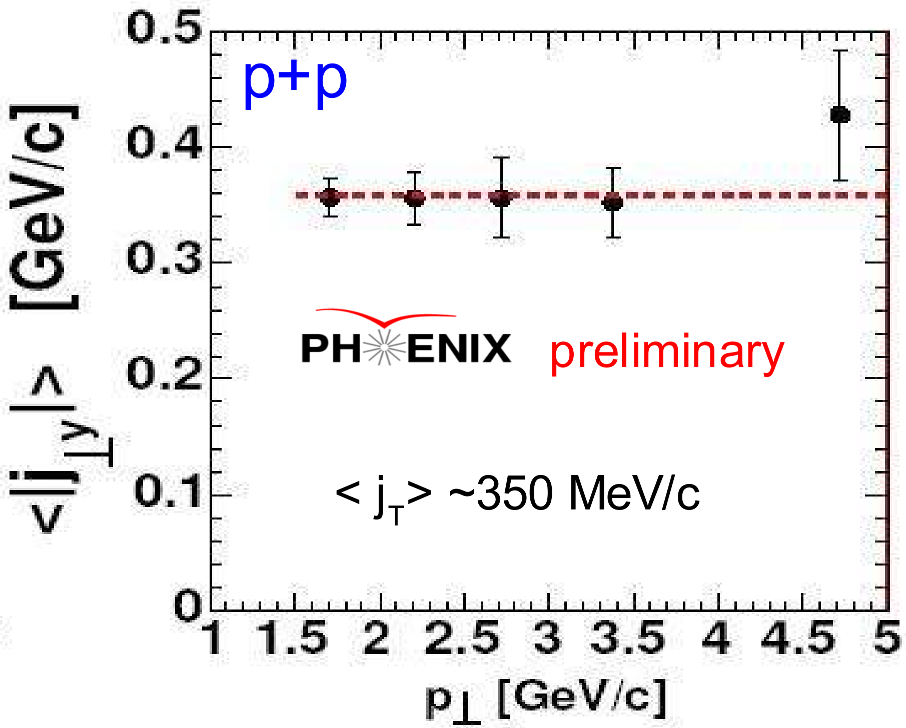


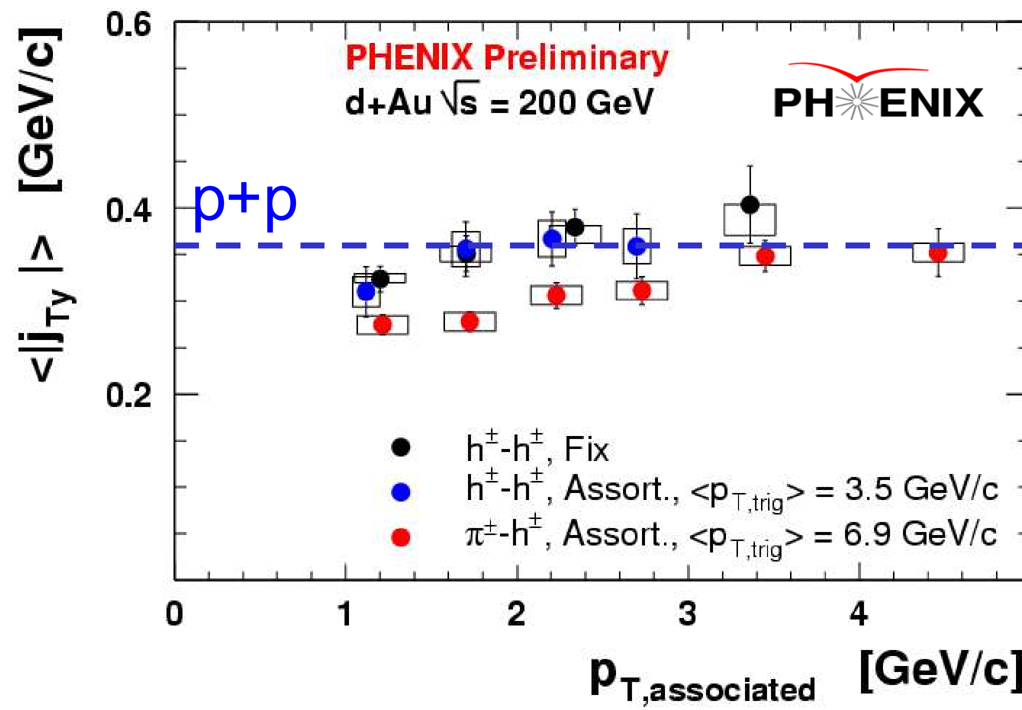
p+p @ 200 GeV: jet properties (II)

- Jet "width" j_T :







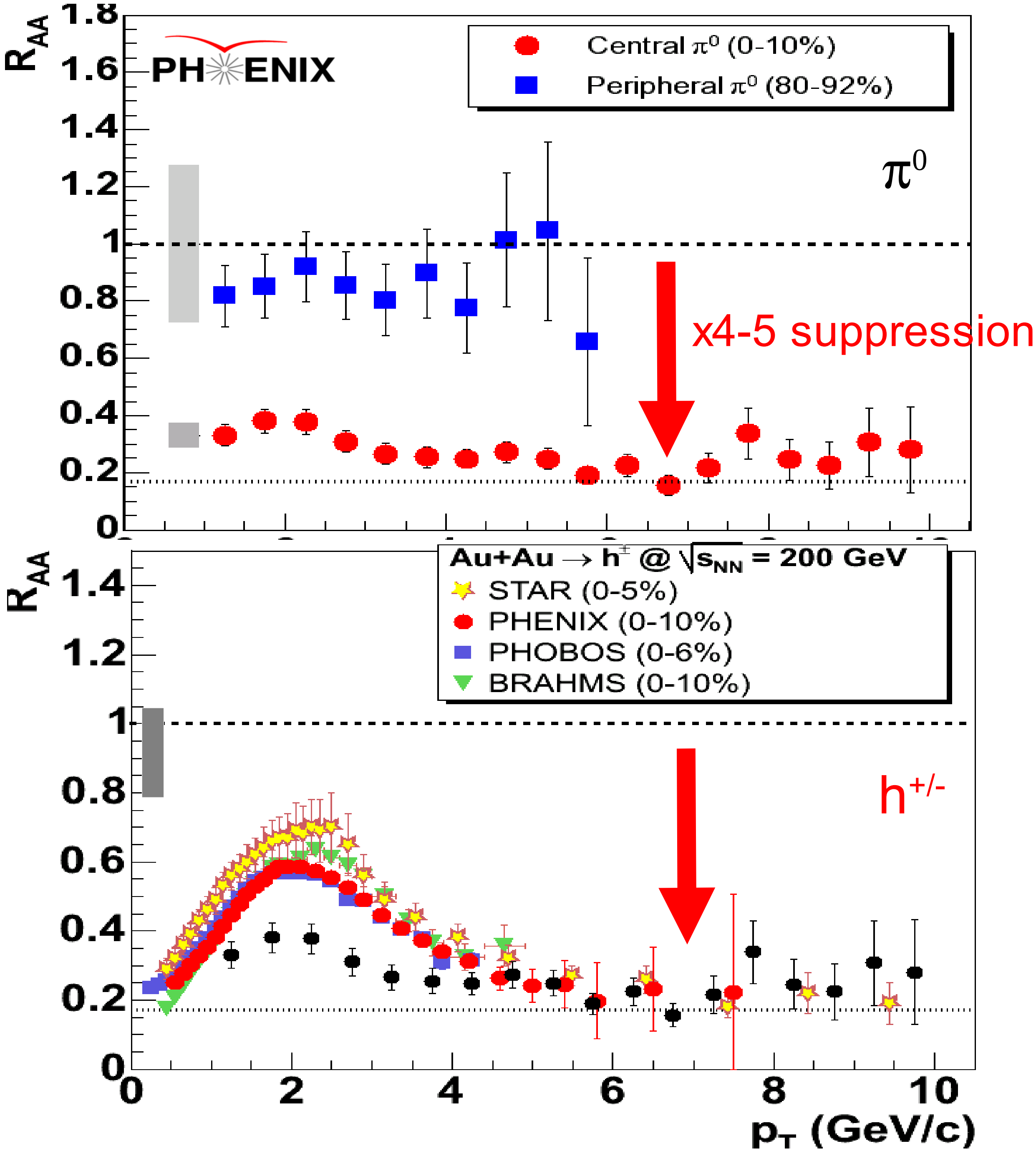


Part II:

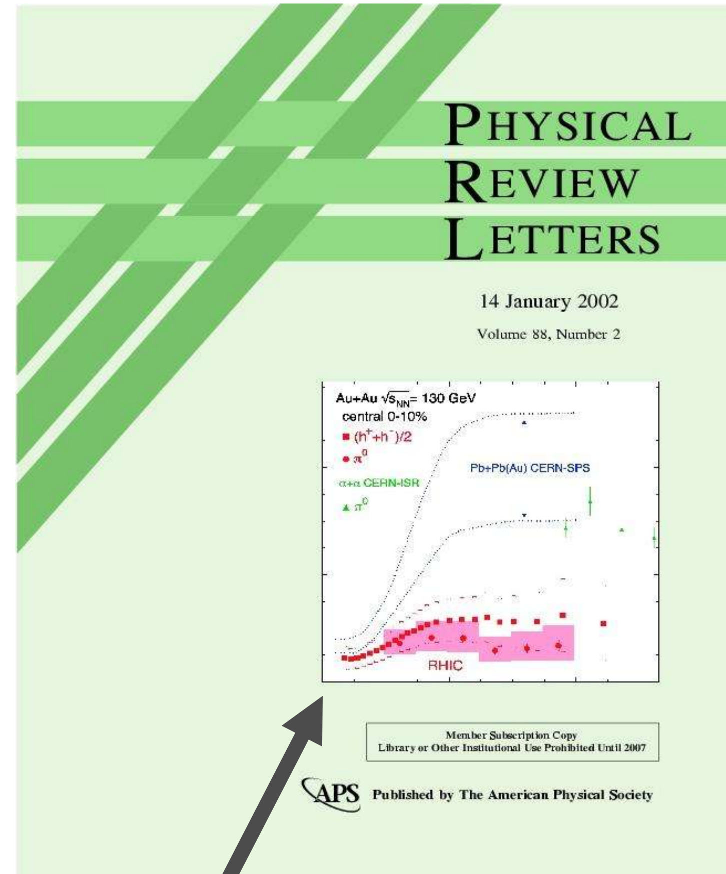
Au+Au @ 200 GeV

Probing the hot & dense QCD medium

Au+Au @ 200 GeV (central): suppression !



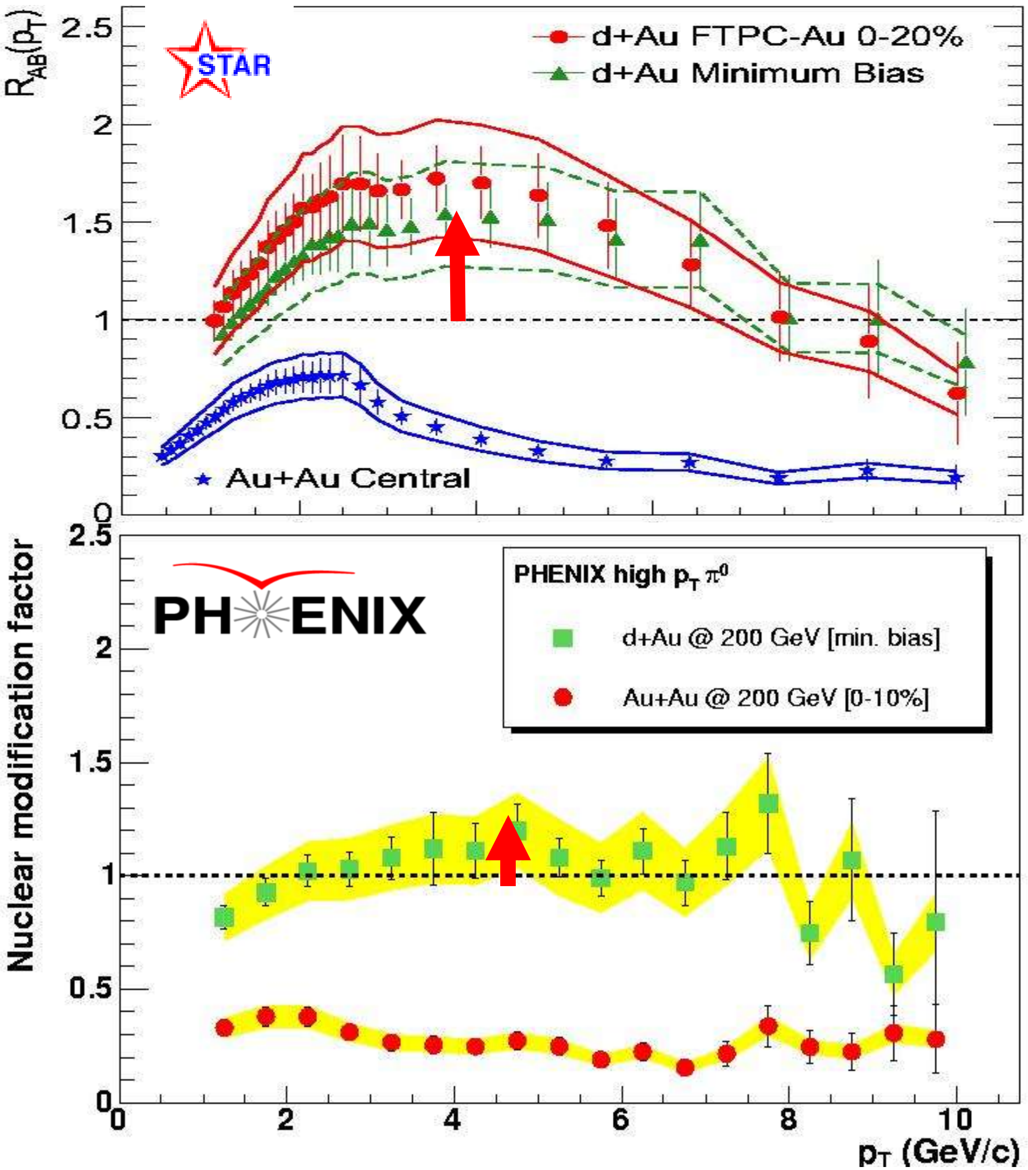
R_{AA} << 1: well below pQCD (collinear factorization) expectations for hard scattering cross-section

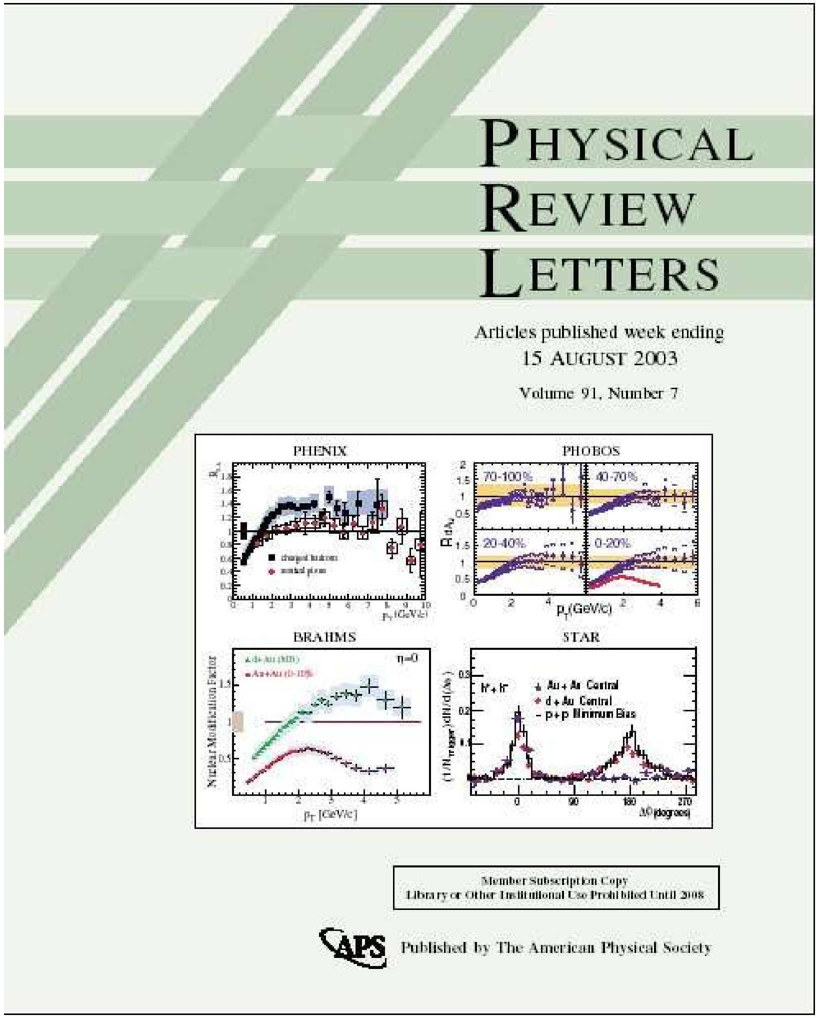


Discovery of high p_T suppression

(one of most significant results @ RHIC so far)

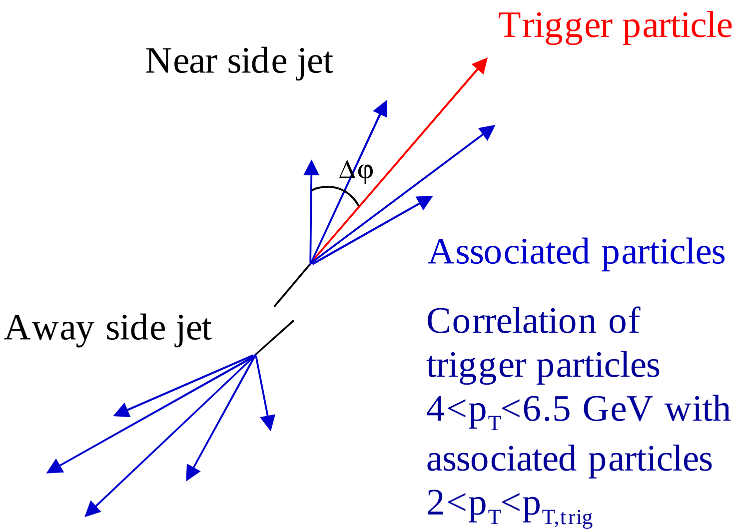
d+Au @ 200 GeV: enhancement !

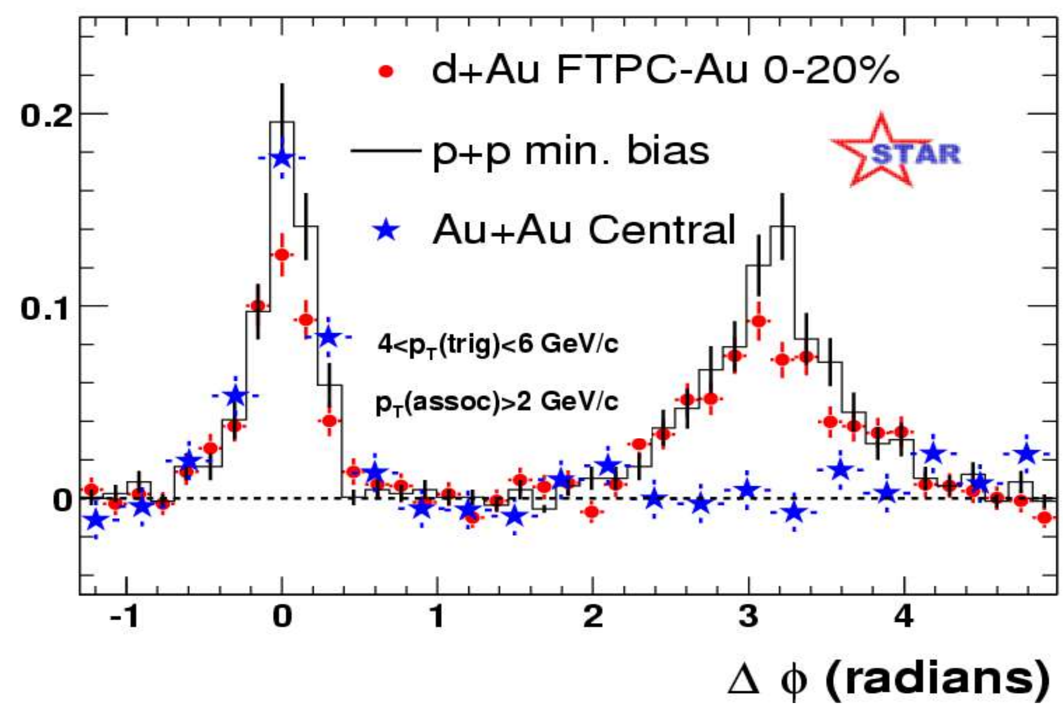




- Suppression in central Au+Au due to final-state effects

Au+Au @ 200 GeV (central): mono-jet correlations !

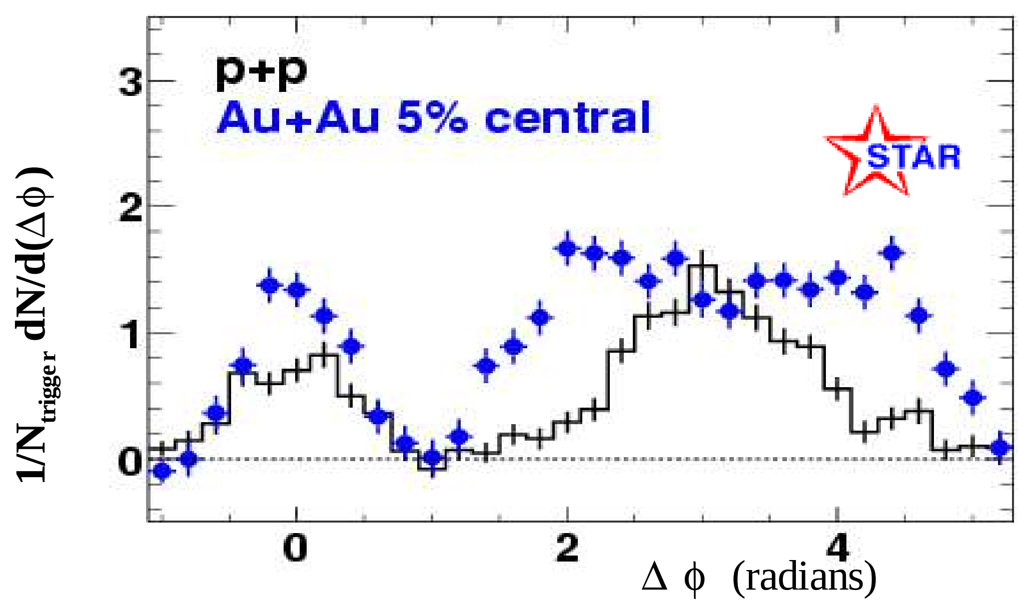




p+p, peripheral Au+Au: 2 jets

Central Au+Au: no away-side jet

d+Au control: 2 jets



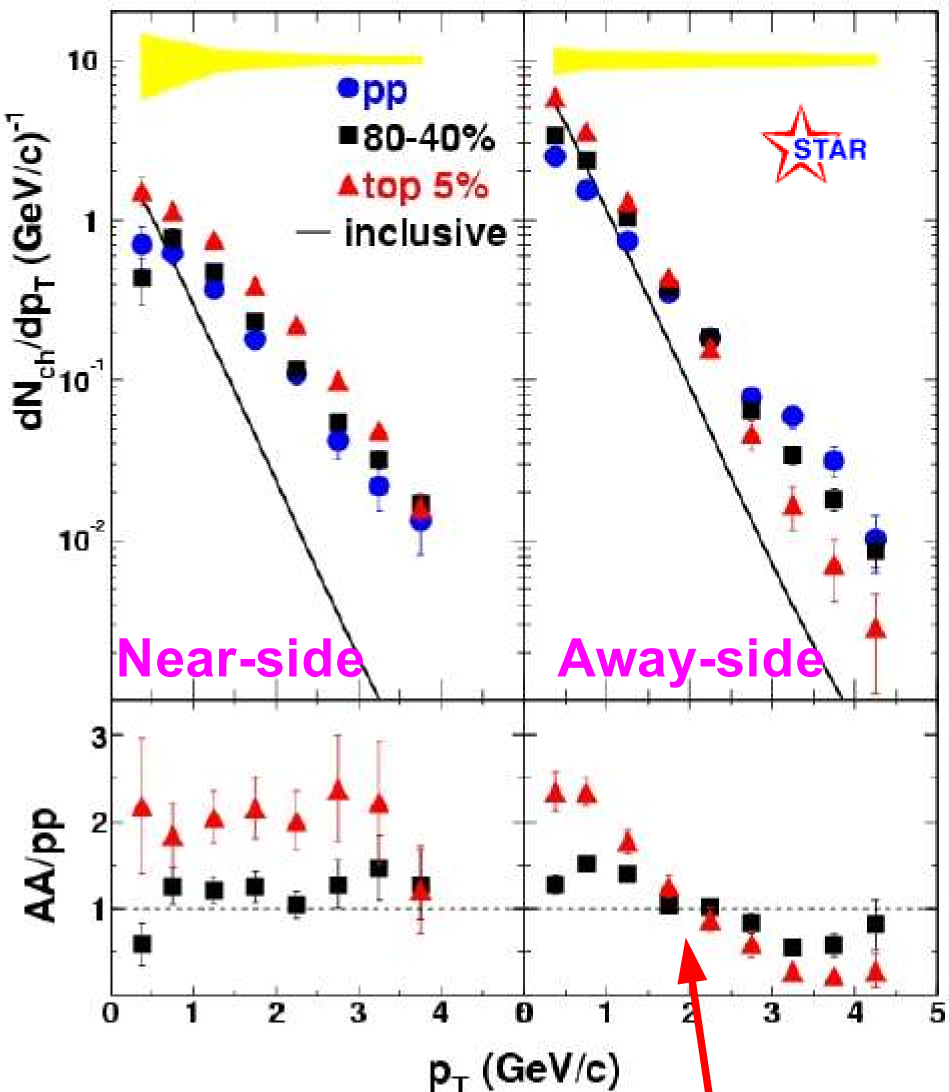
Associated low-p_T yield ("jet remnants"):

near-side: jet-like

away-side: broad cos($\Delta\phi$)-like from momentum conservation

Au+Au @ 200 GeV (central): jet properties

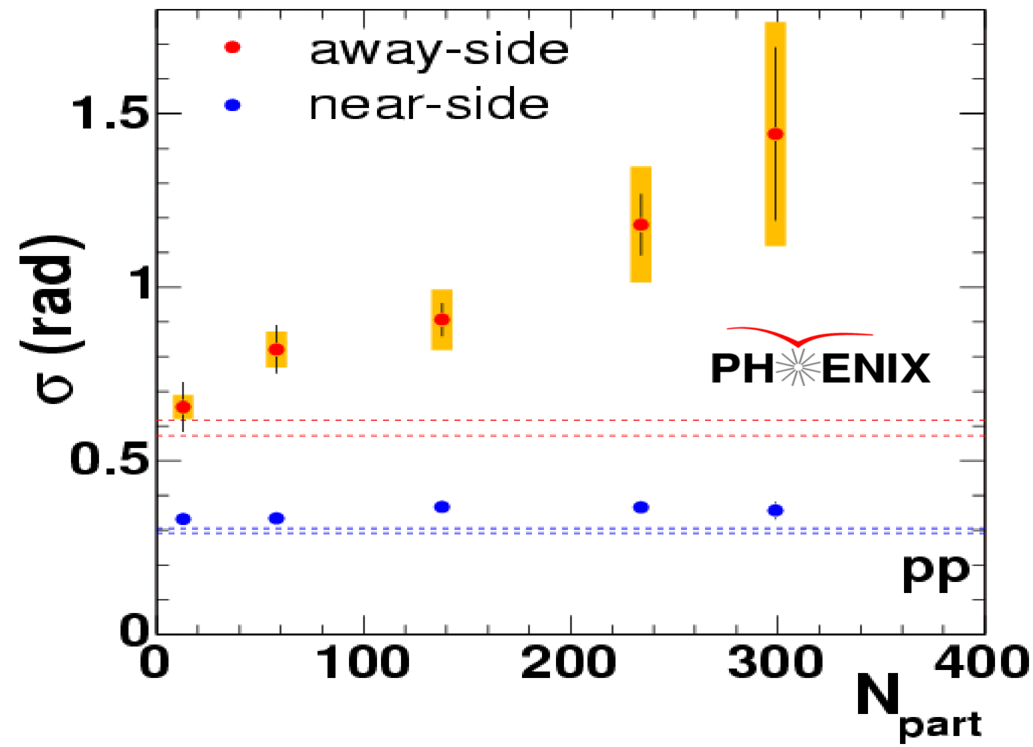
- Associated hadron p_T spectra:



- Jets widths:

$2.5 < p_{Ttrigg} < 4.0$ GeV/c

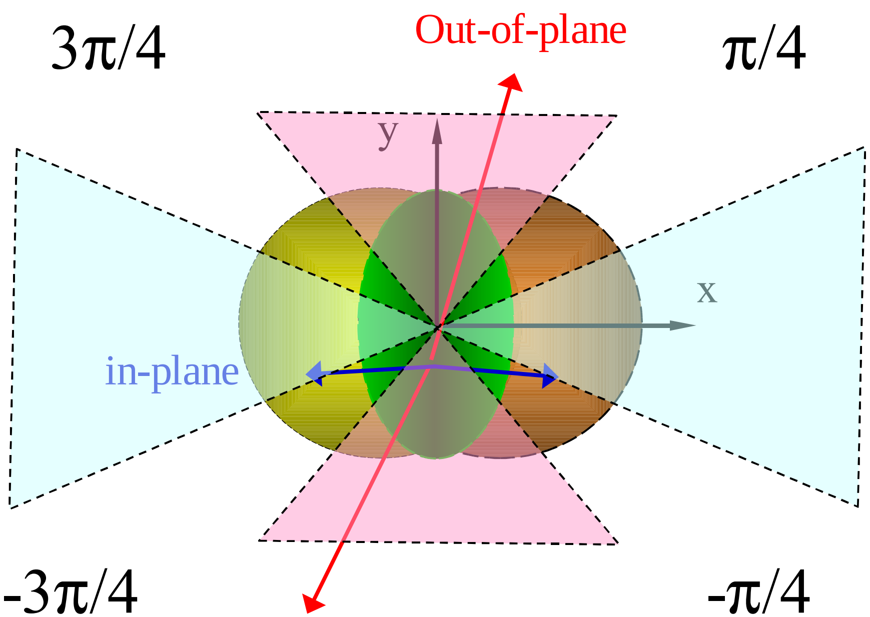
$1.0 < p_{T\ Assoc.} < 2.5$ GeV/c

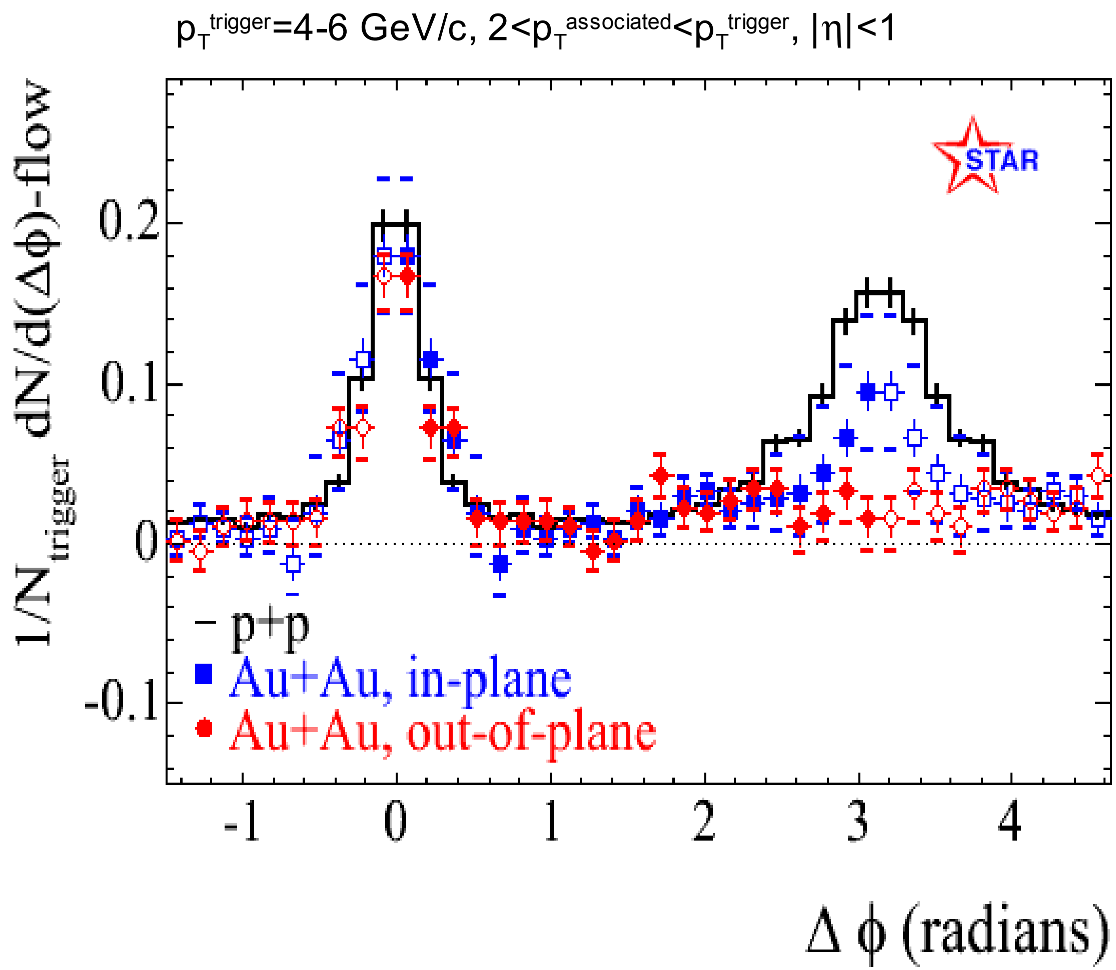


- The near-side width independent of centrality.
- The away-side width increases with centrality.

- Central Au+Au: Associated away-side yields are "moved down" in p_T

Au+Au @ 200 GeV (central): reaction-plane dependence of monojet topologies



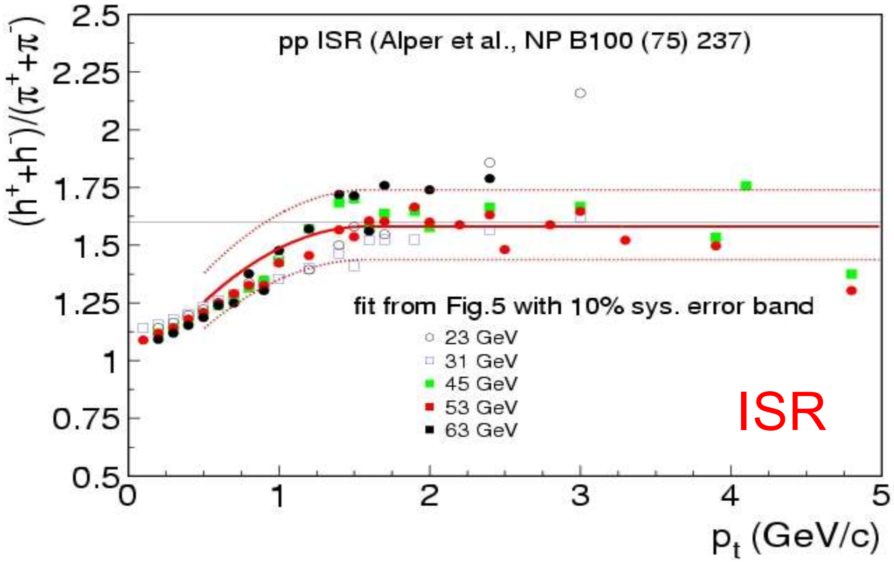


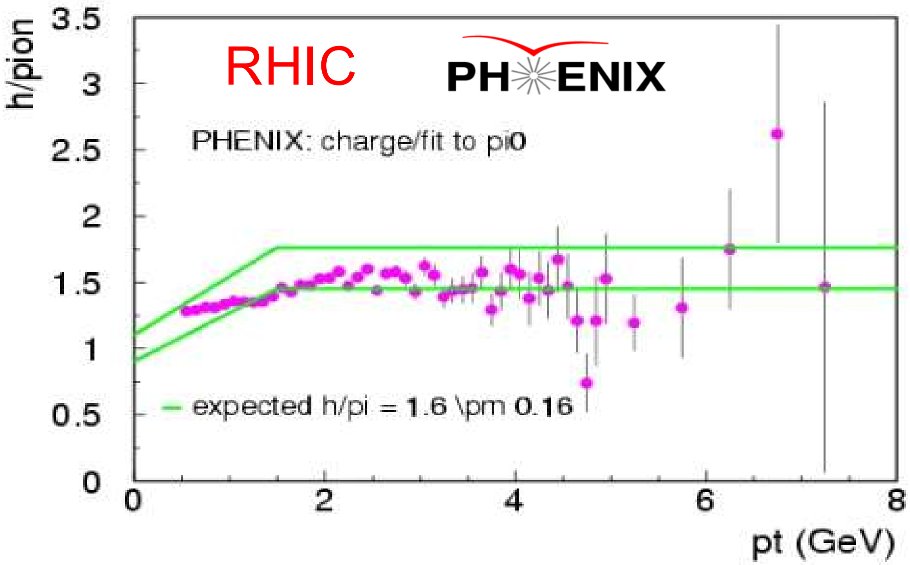
Back-to-back suppression out-of-plane stronger than in-plane

Effect of path length on suppression is experimentally accessible

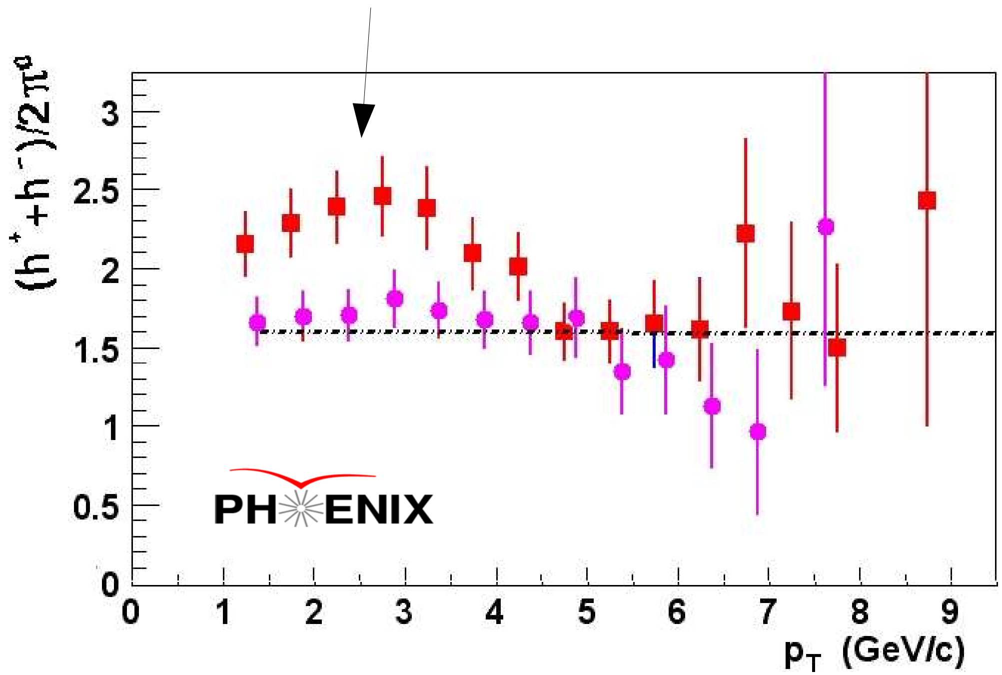
Au+Au @ 200 GeV: "anomalous" hadron composition

- p+p collisions: hadron/meson ~ 1.6





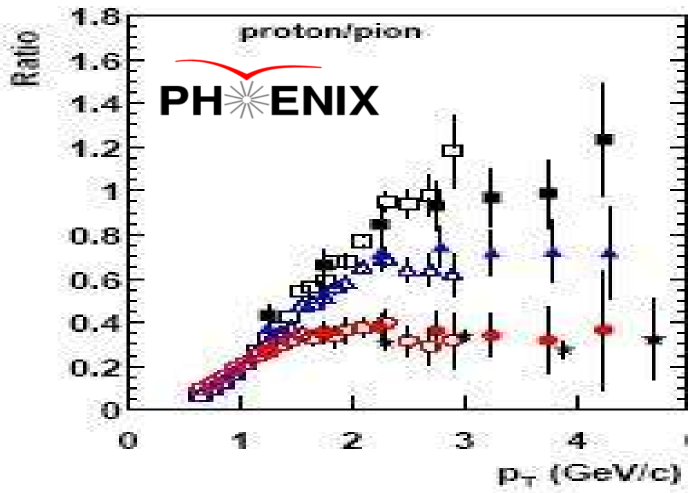
- Au+Au (central): Baryon/meson ~ 2.5 within p_T = 1 - 4 GeV/c

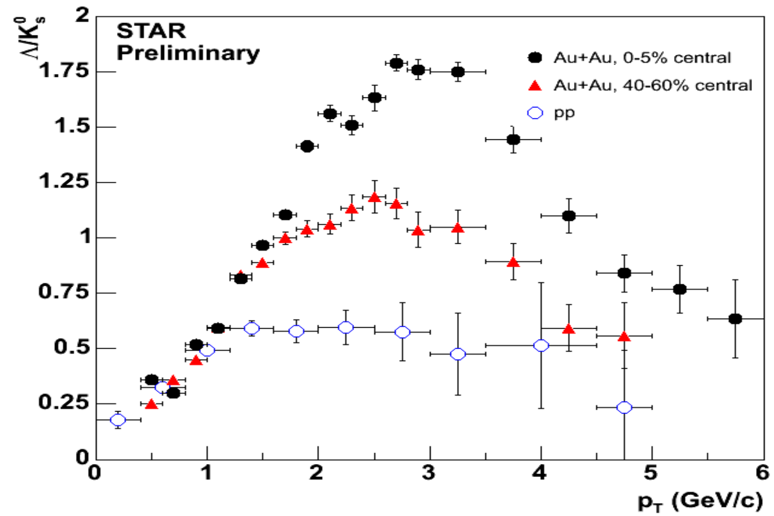


- Particle composition inconsistent with known fragmentation functions.

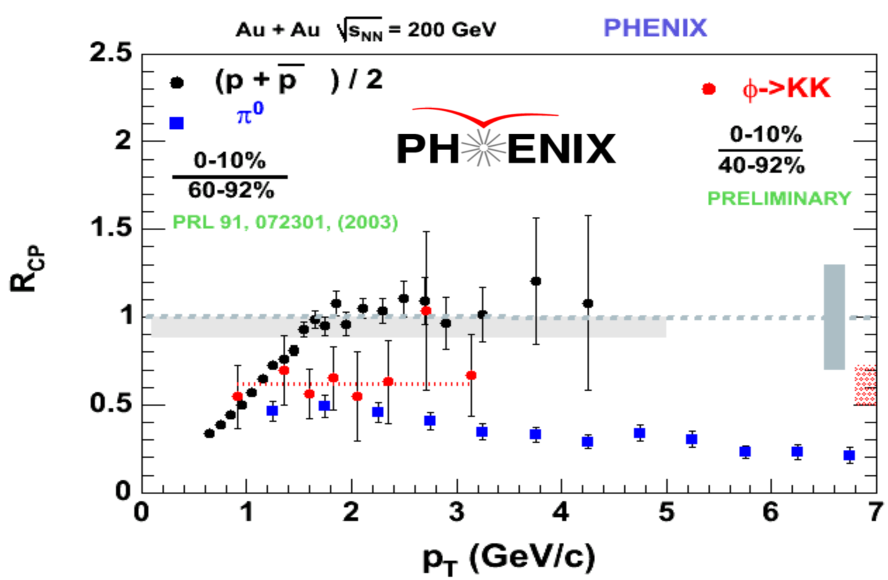
Au+Au @ 200 GeV (central): baryons > mesons !

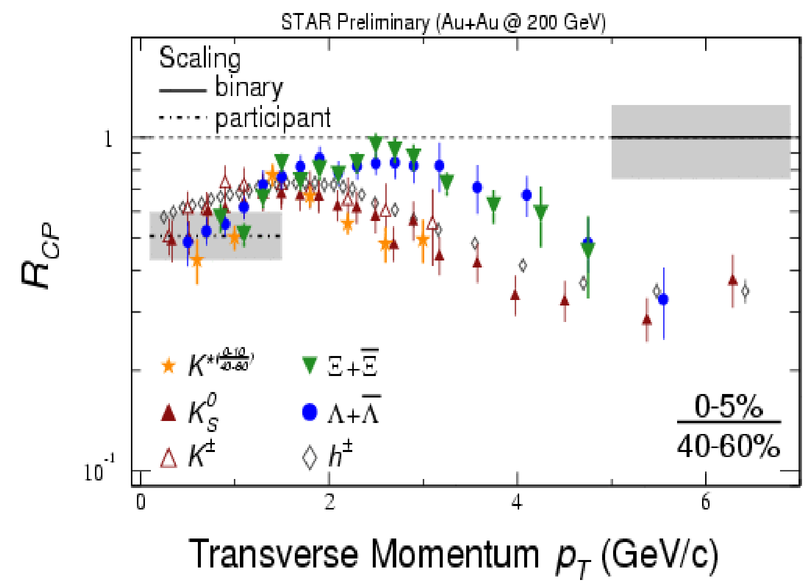
- Baryon/meson ratios: ~1 !





- Rcp baryons vs. mesons: very heavy mesons (ϕ ,k*) =! baryons

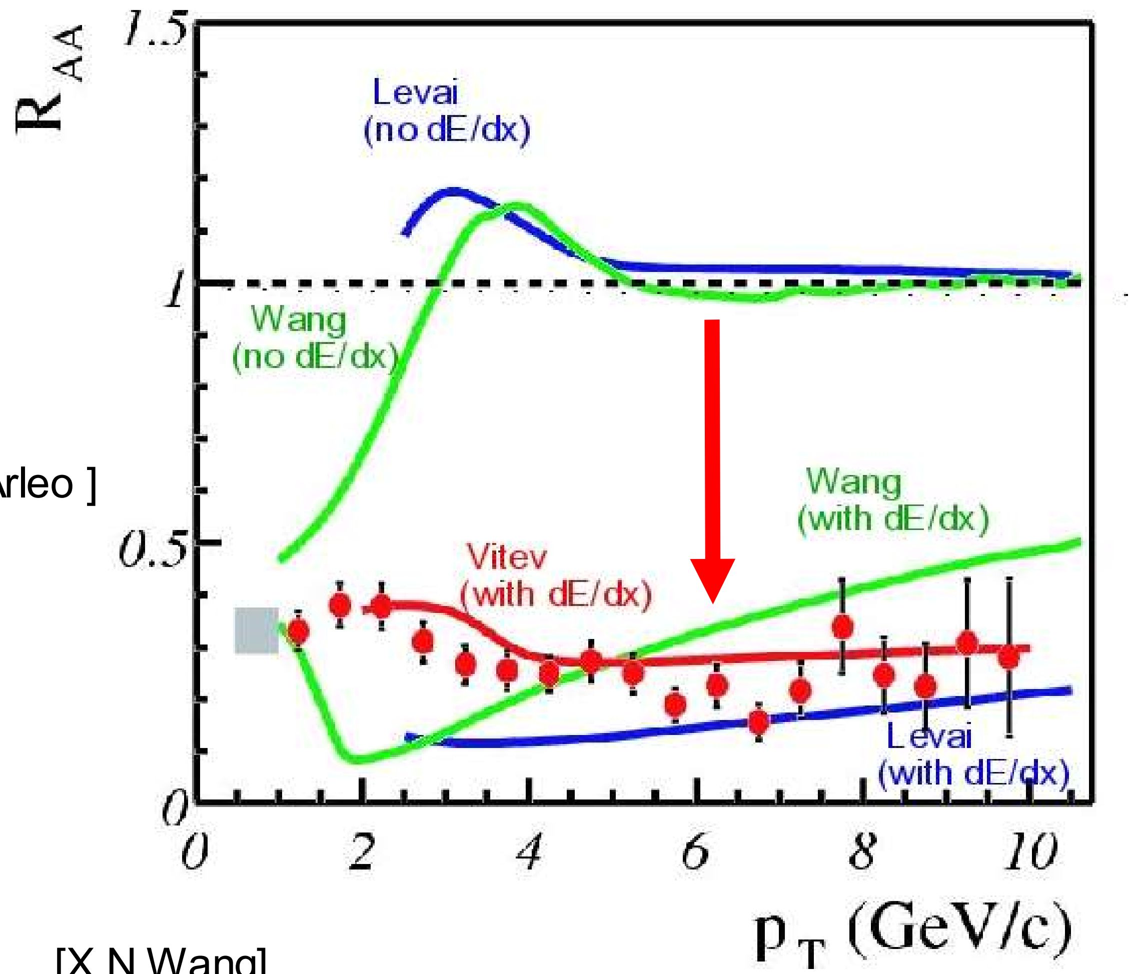




- Additional production mechanism for baryons in the intermediate p_T range

Theory vs. data (I): final-state very dense medium

- Medium properties according to "jet quenching" models:
  - Initial gluon densities:
    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]
  - Opacities:
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]
  - Transport coefficients:
    $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 [BDMPS, F.Arleo]
  - Plasma temperatures:
    T ~ 0.4 GeV [G. Moore]
  - Medium-induced radiative energy losses:
    $dE/dx \approx 0.25$ GeV/fm (expanding)
    $dE/dx|_{eff} \approx 14$ GeV/fm (static source) [X.N.Wang]



- Such large opacities imply:
  (i) large rescattering: thermalization, (ii) energy densities $\epsilon_{crit\ QCD}$ >> 1 GeV/fm3

Theory vs. data (II): partonic or hadronic medium ?

- Energy loss in Dual-Parton-Model based approaches ...

Final state interactions: Partons or hadrons?

We can divide our suppression factor

$$\widetilde{S}_{\pi^0}(b,s,y,p_T) = \exp\left\{-\tilde{\sigma}\left[1 - \frac{N_{\pi^0}(b,s,y,p_T+\delta p_T)}{N_{\pi^0}(b,s,y,p_T)}\right] N(b,s,y)\ell n\left(\frac{N(b,s,y)}{N_{pp}(y)}\right)\right\}$$

where the log term corresponds to:

$$\ell n\left(\frac{N(b,s,y)}{N_{pp}(y)}\right) = \ell n\left(\frac{\tau_f}{\tau_0}\right)$$

in two parts:

Partonic: From initial density $N(b,s,y) = \frac{dN/dy}{\pi R_A^2} \sim \frac{1000}{\pi R_A^2}$ to $\frac{dN/dy}{\pi R_A^2} \sim \frac{300}{\pi R_A^2}$, or equivalently from $\tau_0 = 1$ fm to $\tau_p = 3.6$ fm

Hadronic: From partonic density $\frac{dN/dy}{\pi R_A^2} \sim \frac{300}{\pi R_A^2}$ to $N_{pp}(y) = 2.24$ fm^{-2}, or equivalently from $\tau_p = 3.6$ fm to $\tau_f = \infty(5-7)$ fm

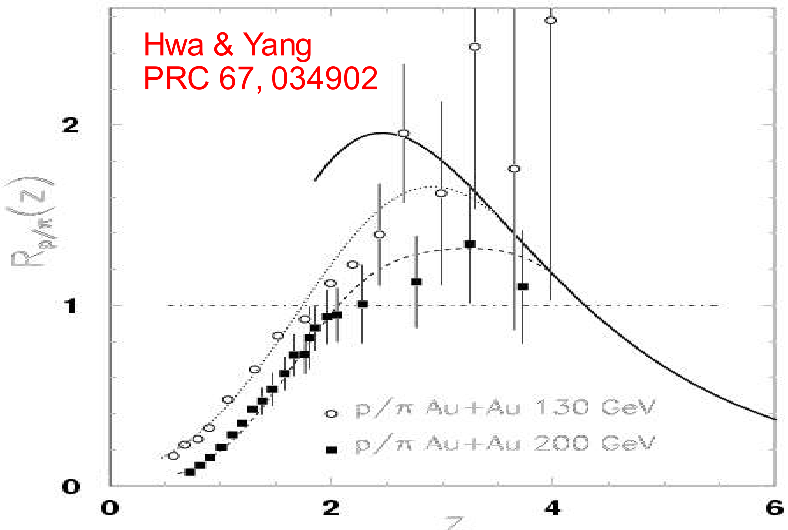
We find that:
78% of the effect takes place in the partonic phase
22% of the effect takes place in the hadronic phase

(Elena Ferreiro)

... Mostly partonic

Theory vs. data (III): final-state "quark" medium

- Quark recombination (coalescence) mechanisms provide an additional mechanism for baryon production at intermediate p_T's (2-5 GeV/c):



Via quark momenta addition:

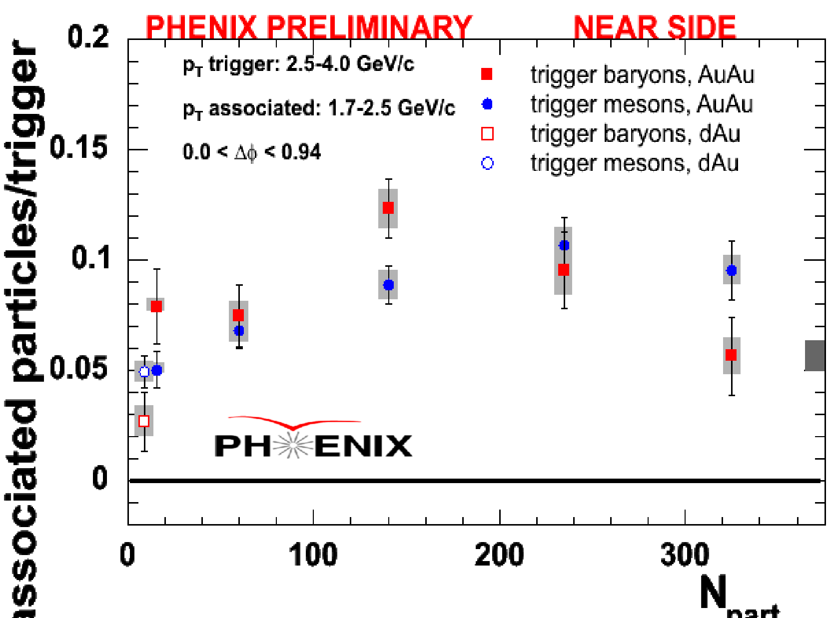
p_T(baryons) > p_T(mesons) > p_T(quarks)

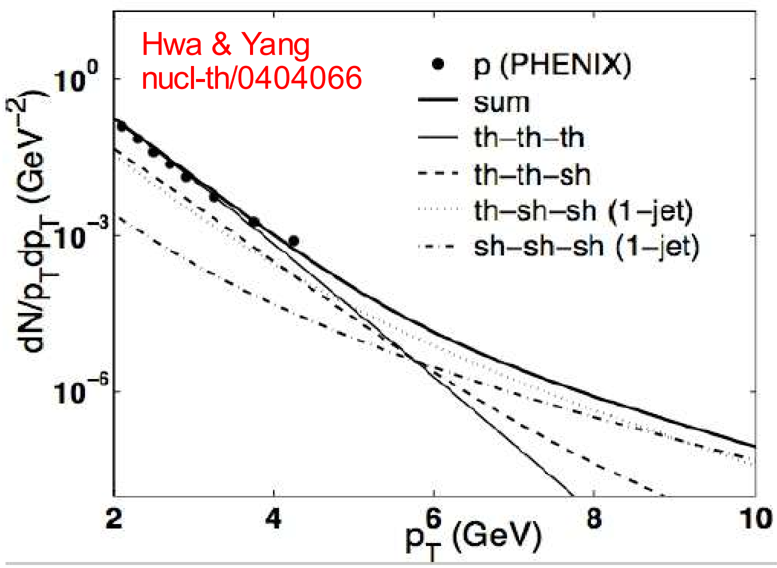
Fragmentation dominates for p_T > 5 GeV/c:

p_T(hadrons)= z p_T(partons) , with z<1

Large quark densities in thermal medium required

- *However ... thermal + shower parton recombination needed to explain jet-like baryon near-side azimuthal correlations*





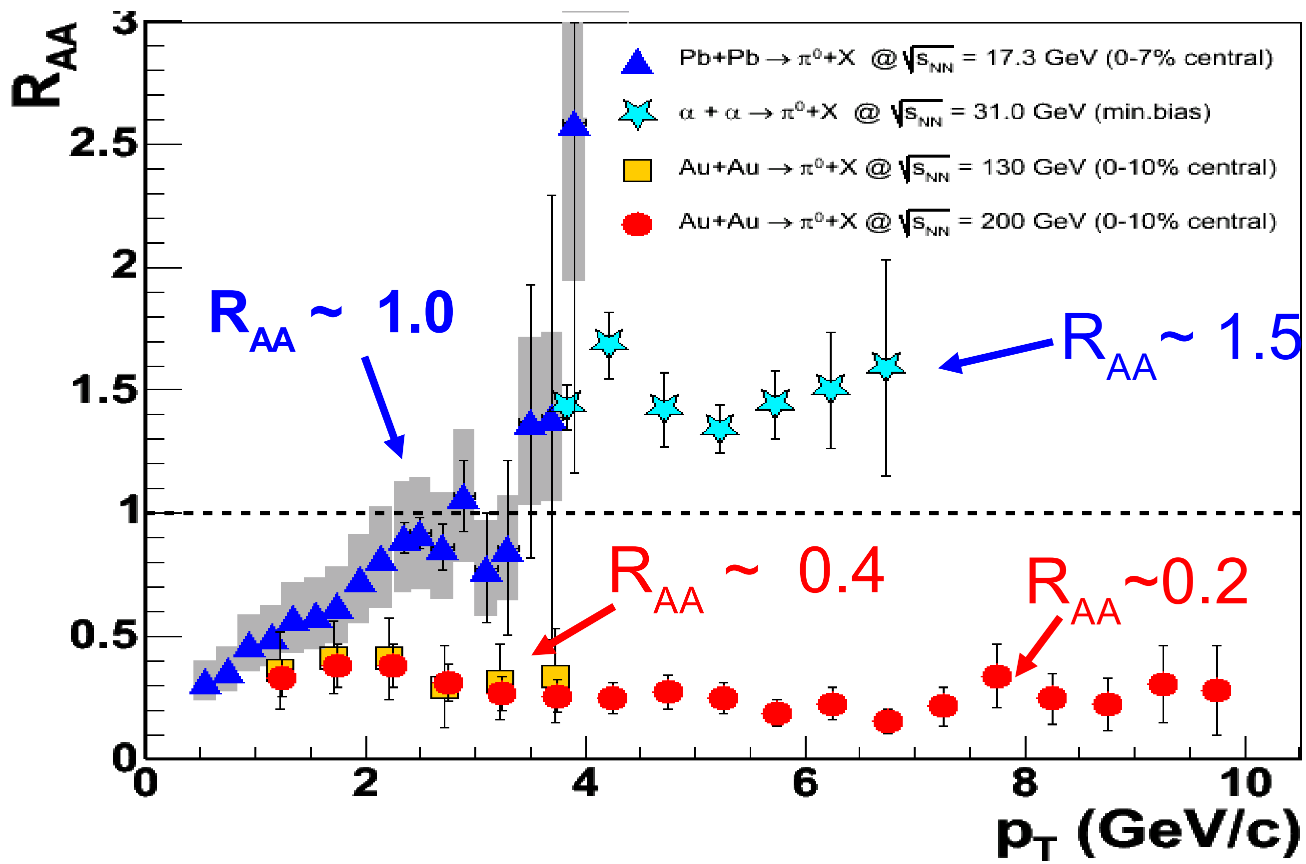
Part II$_b$:

Au+Au @ 62.4 GeV

Probing the (sligthly less) hot & dense QCD "medium"

Nuclear modification factor (π^0): $\sqrt{s_{NN}}$ dependence

- CERN-SPS: Pb+Pb central ($\sqrt{s_{NN}}$ = 17.3 GeV): small suppression (?) (*)
- CERN-ISR: $\alpha+\alpha$ ($\sqrt{s_{NN}}$ = 31 GeV): Cronin enhancement (too small system).
- RHIC: Au+Au ($\sqrt{s_{NN}}$ = 130, 200 GeV): x 4-5 suppression.



A.L.S.Angelis, PLB 185, 213 (1987)

WA98, EPJ C 23, 225 (2002)

(*) Reanalysis: D.d'E. nucl-ex/0403055

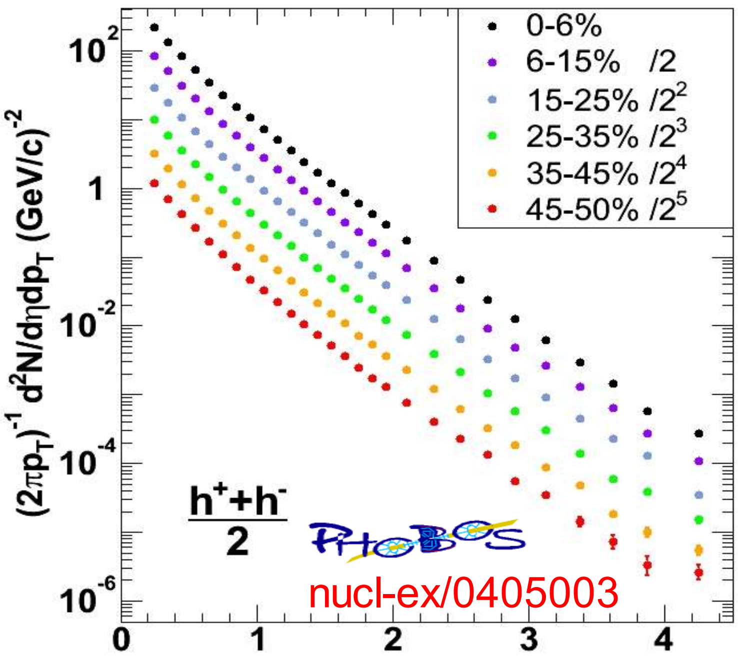
PHENIX, PRL 88 022301 (2002)

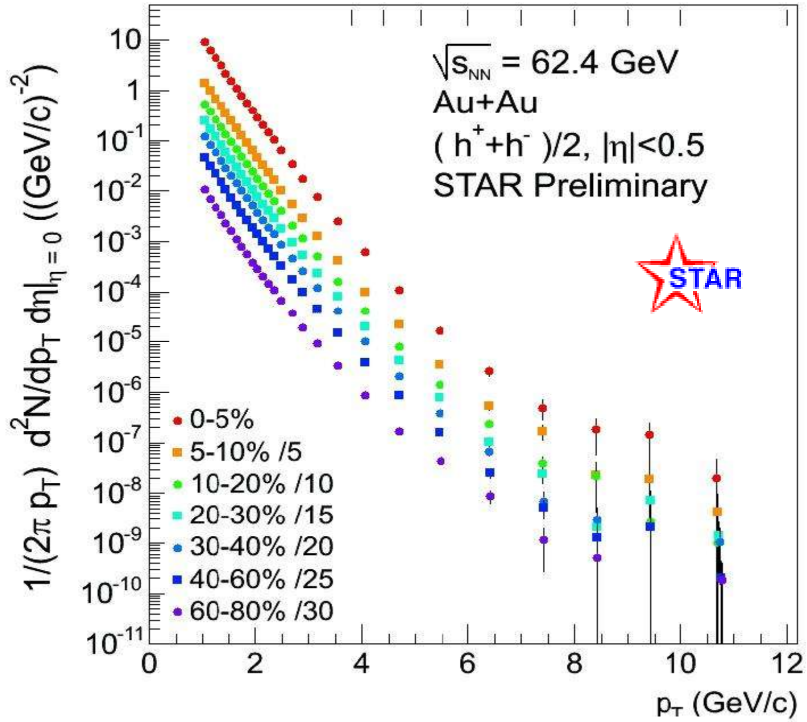
PHENIX, PRL 91, 072303 (2003)

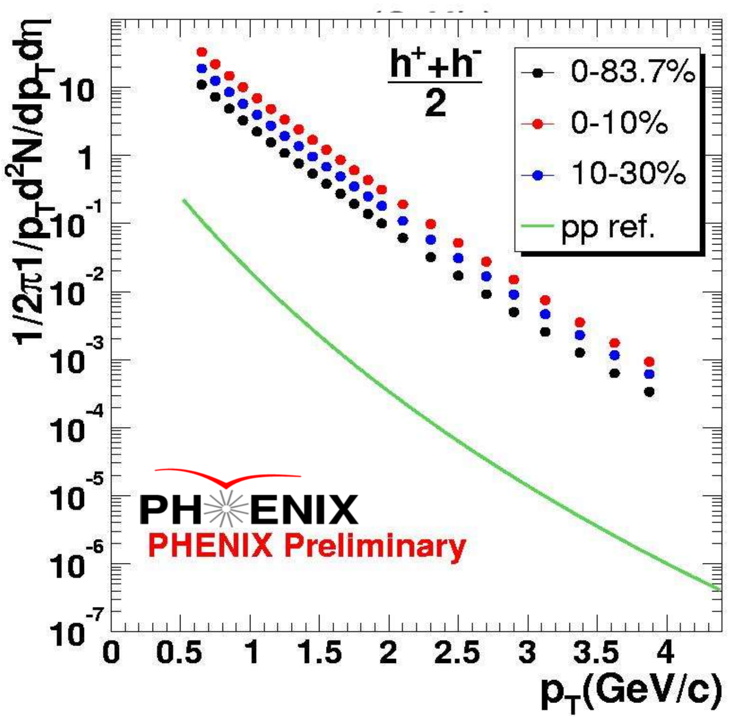
(*) RHIC should run Au+Au and p+p @ $\sqrt{s_{NN}}$ ~ 20-30 GeV

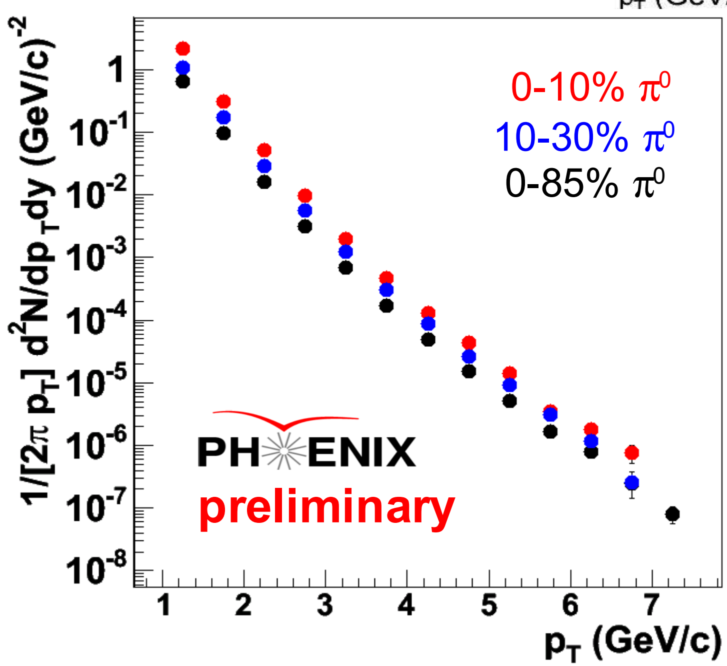
- RHIC Au+Au ($\sqrt{s_{NN}}$ = 62.4 GeV): (i) probe suppression excitation function, (ii) confirm/constraint models of (partonic) energy loss

Au+Au @ 62.4 GeV: p_T spectra



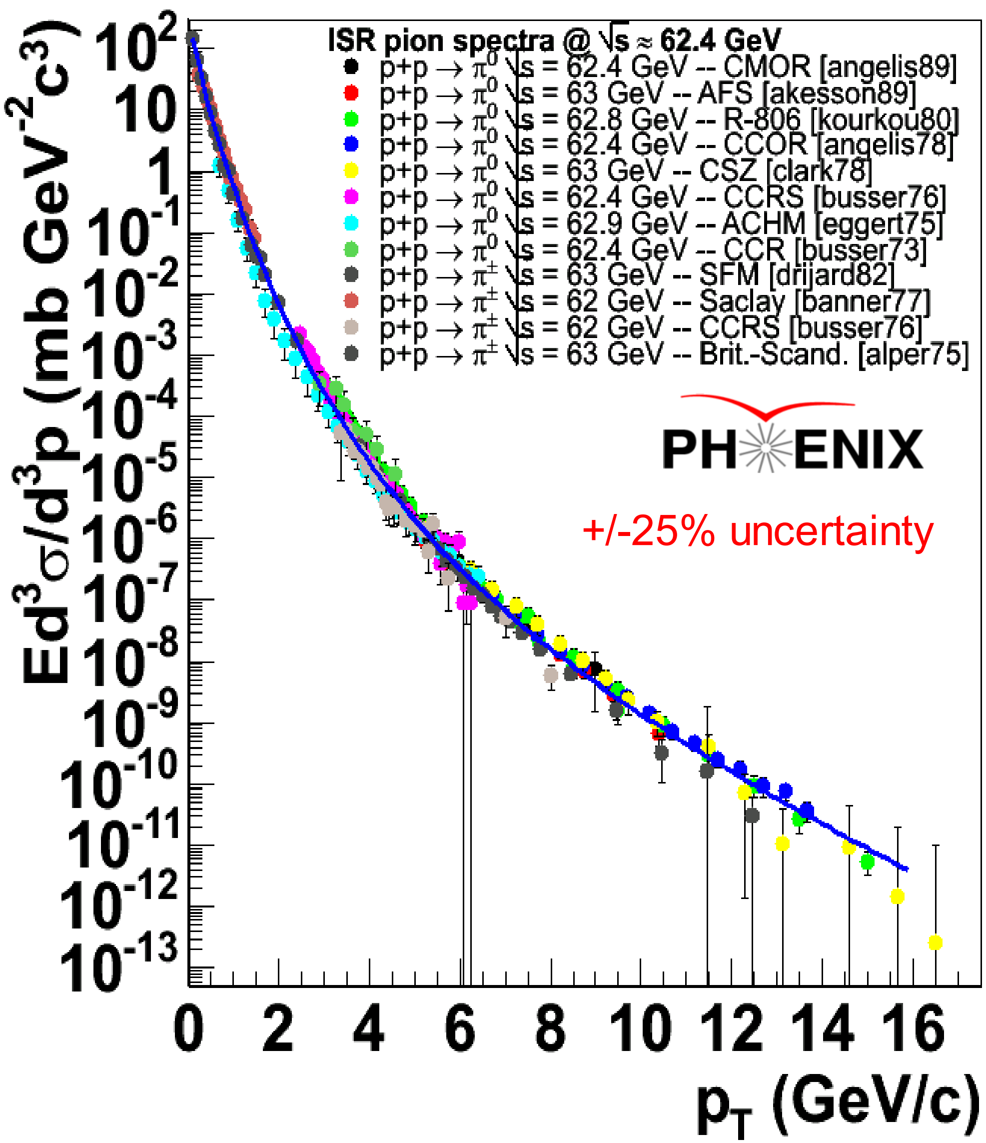


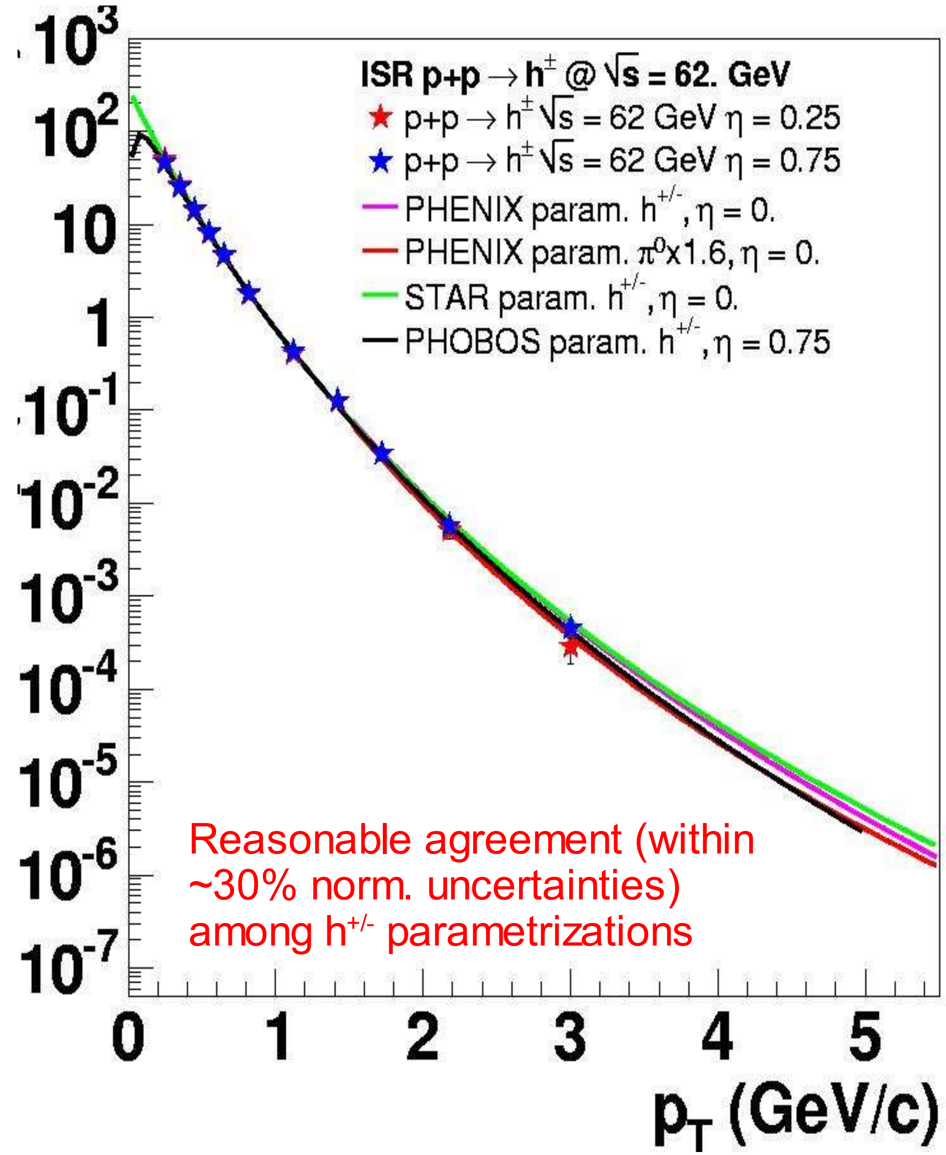




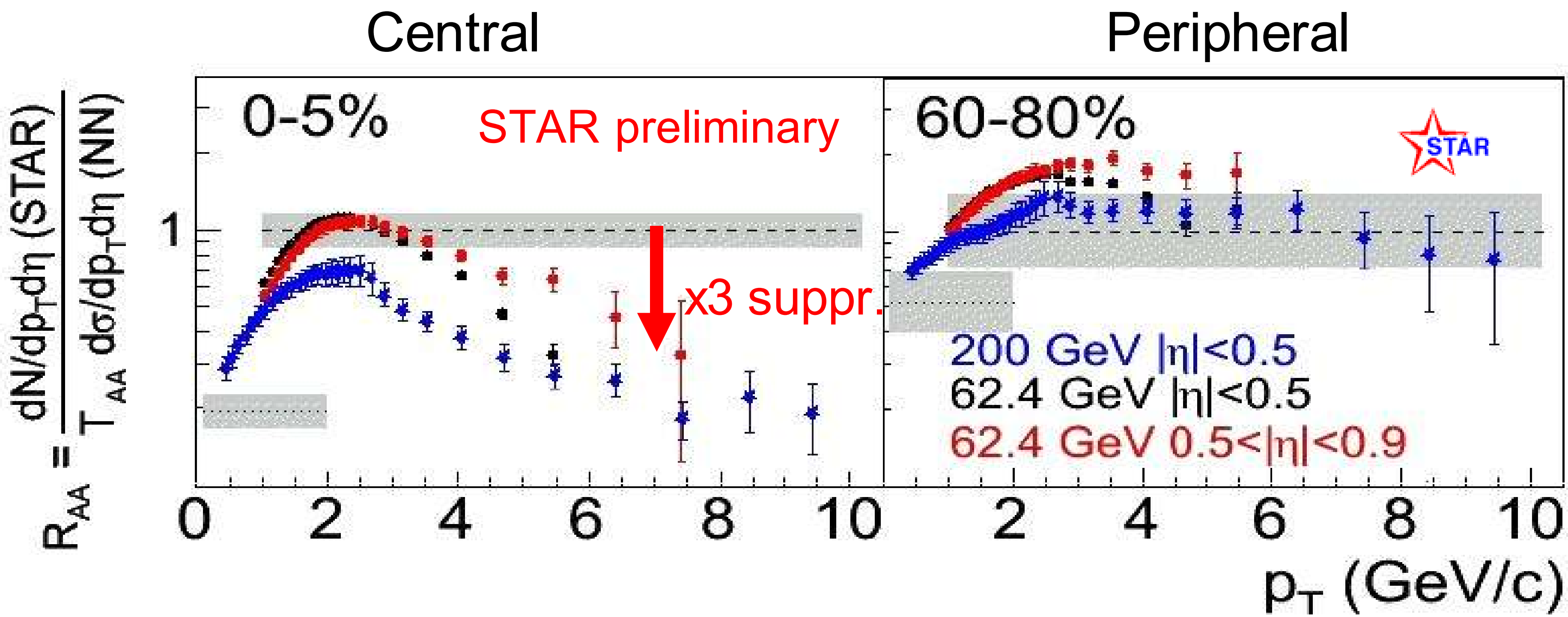
p+p @ 62.4 GeV: reference p_T spectra

- No concurrent p+p measured at RHIC. Have to rely on ISR measurements ...



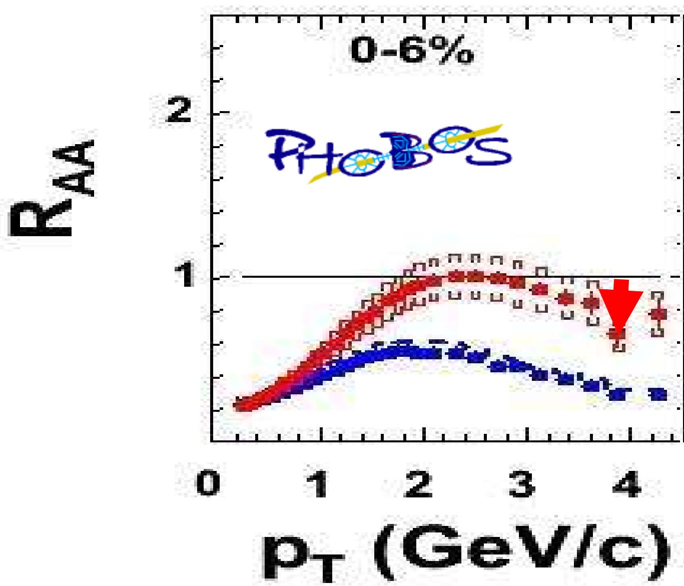


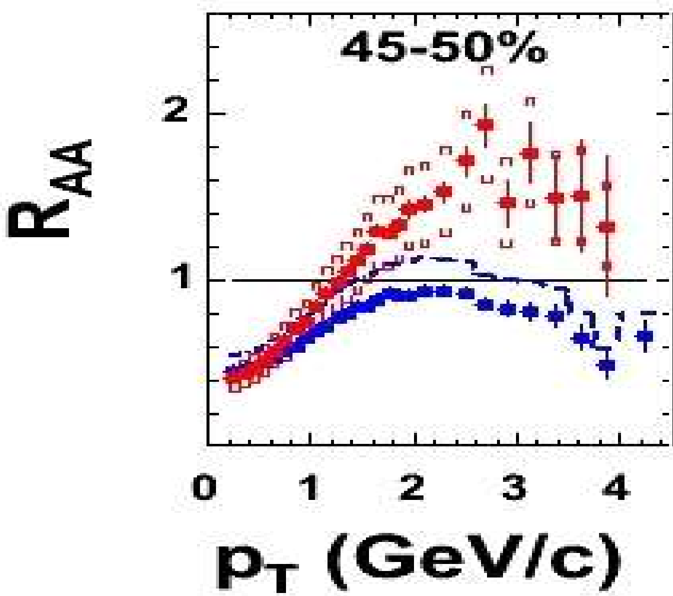
Au+Au @ 62.4 GeV (R_{AA} central): $h^{\pm}$ suppression !



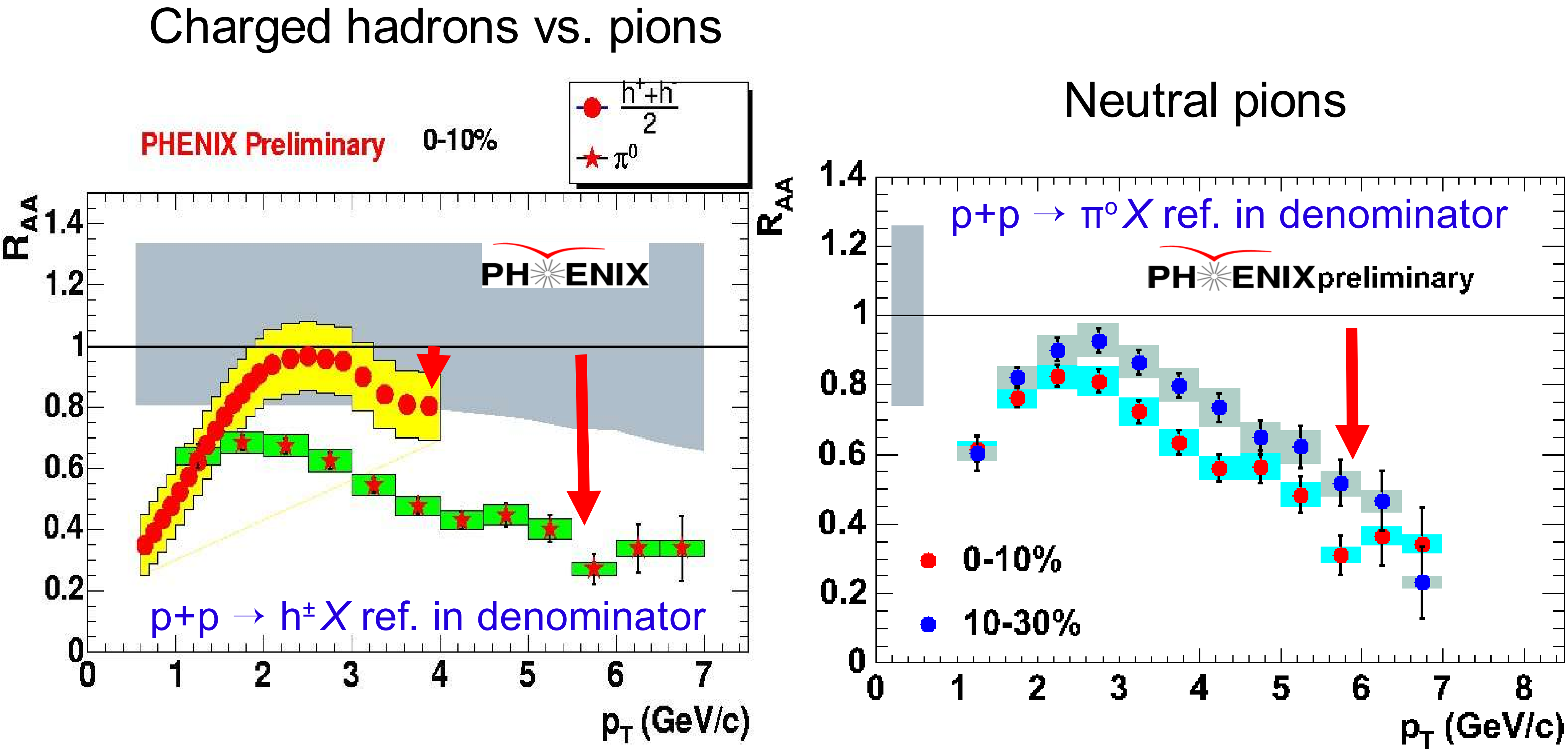
p_T~2-3 GeV/c:
R_{AA} ~ 1

p_T >6 GeV/c:
R_{AA} ~ 0.3



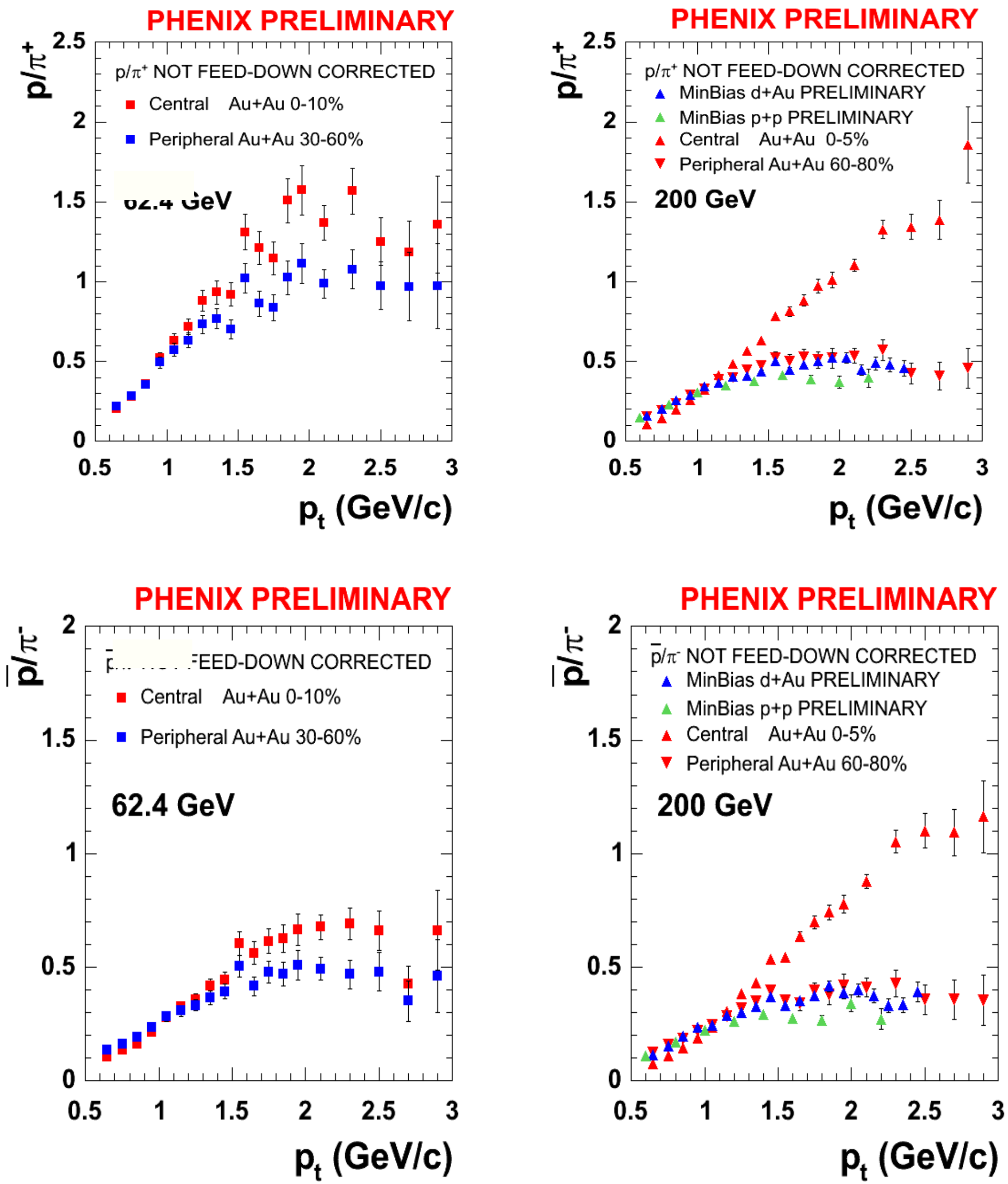


Au+Au @ 62.4 GeV (R_{AA} central): π^0 suppression !



- Pions more suppressed than $h^{+/-}$ at intermediate p_T (also found at 200 GeV): R_{AA} ~ 0.6 at p_T~2 GeV/c
- "Universal" (PID) and constant suppr. at high p_T: R_{AA} ~ 0.3 for p_T > 6 GeV/c

Au+Au @ 62.4 GeV (R_{AA} central): baryons again !



- Central p/π^+ ratio similar to 200 GeV Au+Au result at high p_T.

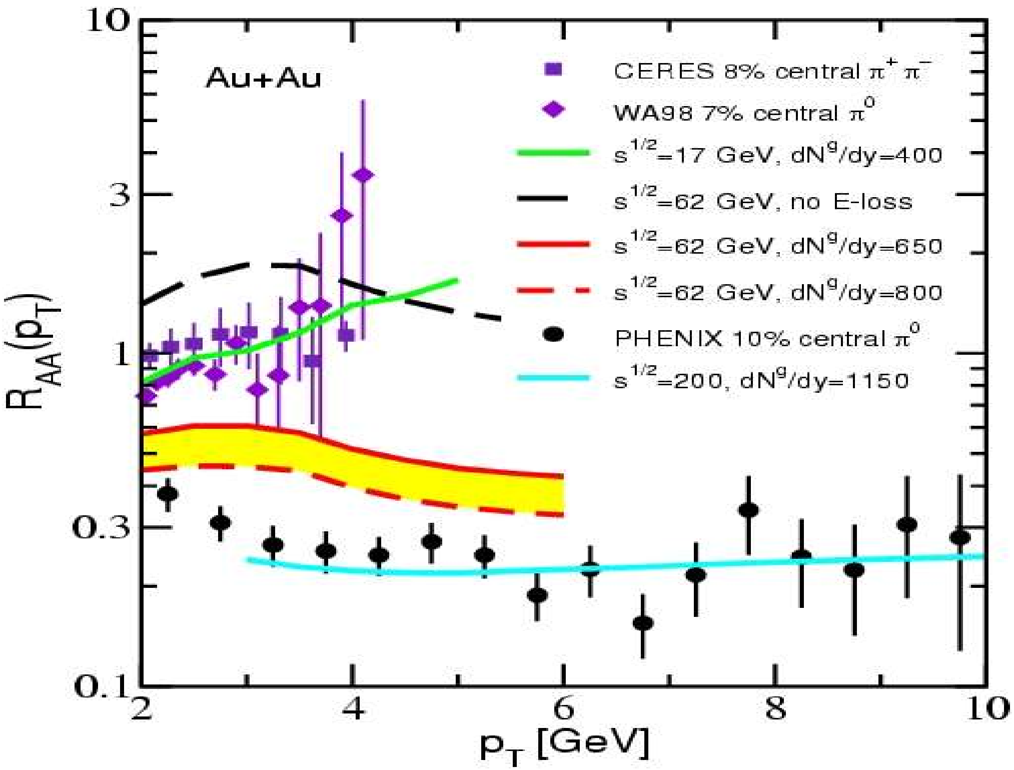
- Central pbar/π^- ratio at 2-3 GeV is smaller than 200 GeV results.

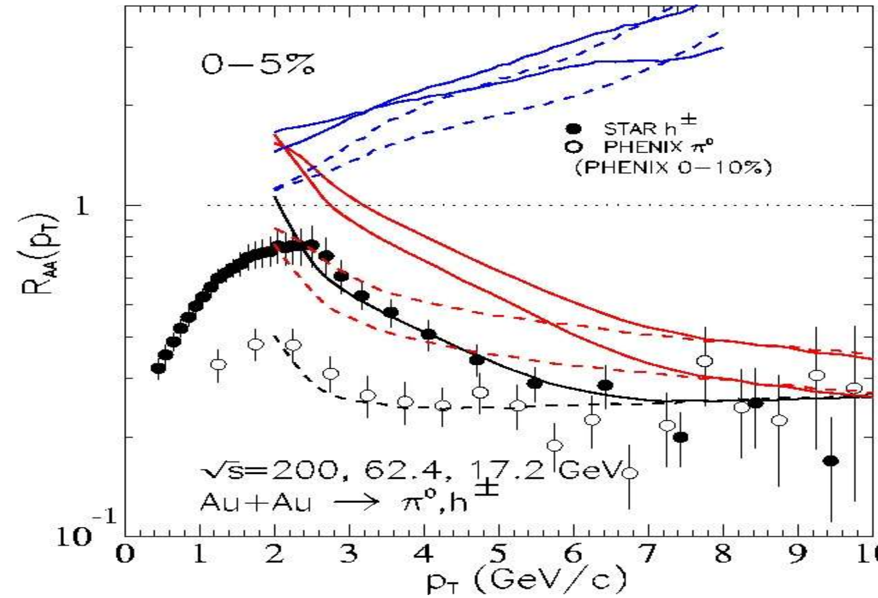
- Smaller pbar/p ratio due to more baryon transport to mid-rapidity and less pbar production.

Au+Au @ 62.4 GeV (central): suppression predictions

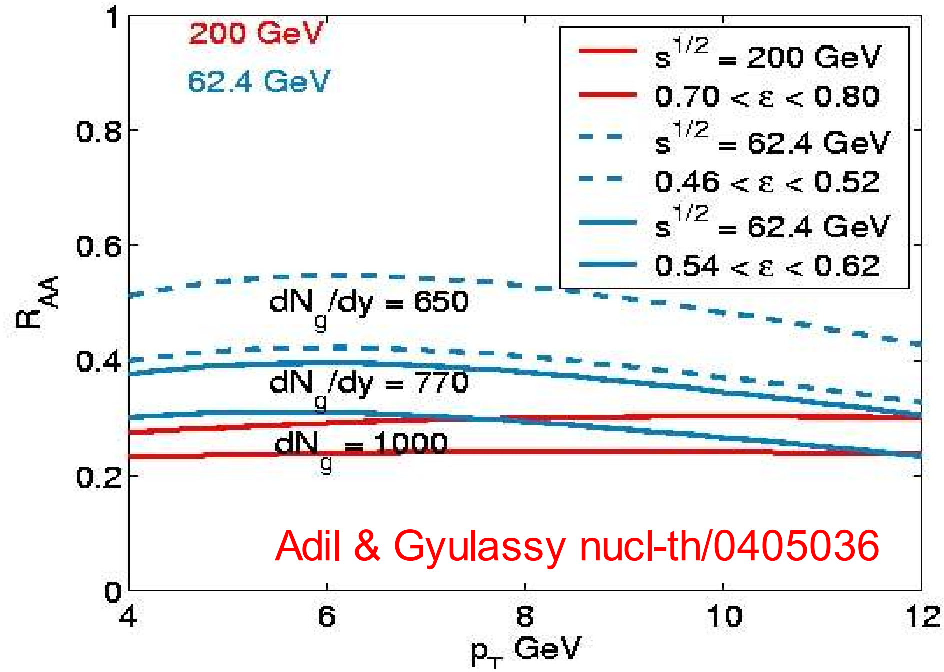
$R_{AA}(\pi^0) \sim 0.5 - 0.3$

I. Vitev nucl-th/0404052



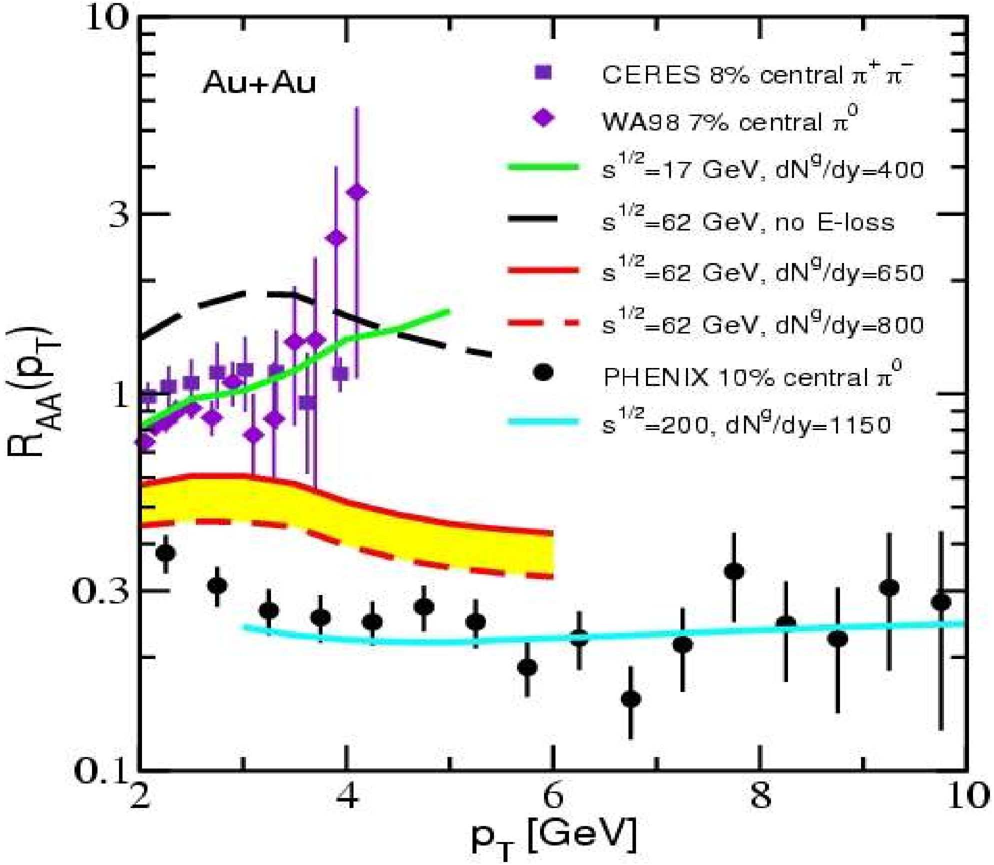


X.N. Wang nucl-th/0405029

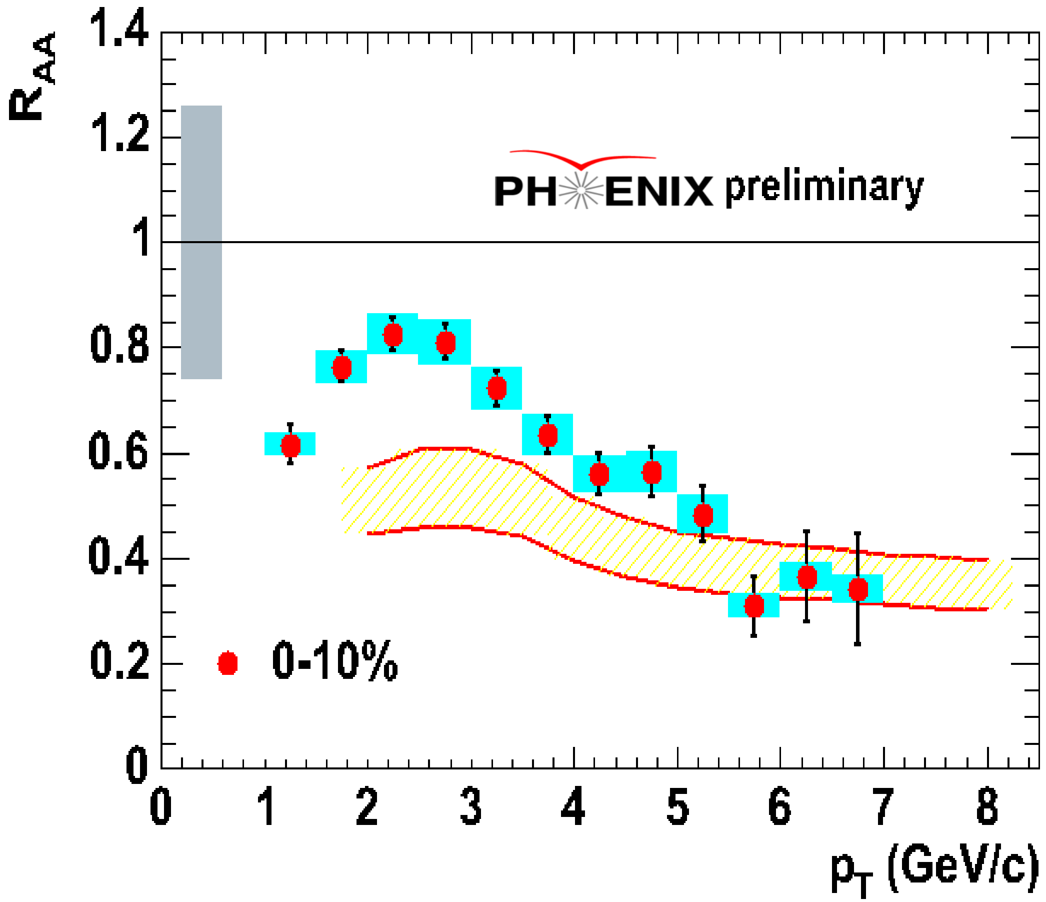


Au+Au @ 62.4 GeV (central): data vs. theory

I. Vitev nucl-th/0404052



Comparison by Saskia Mioduszewski



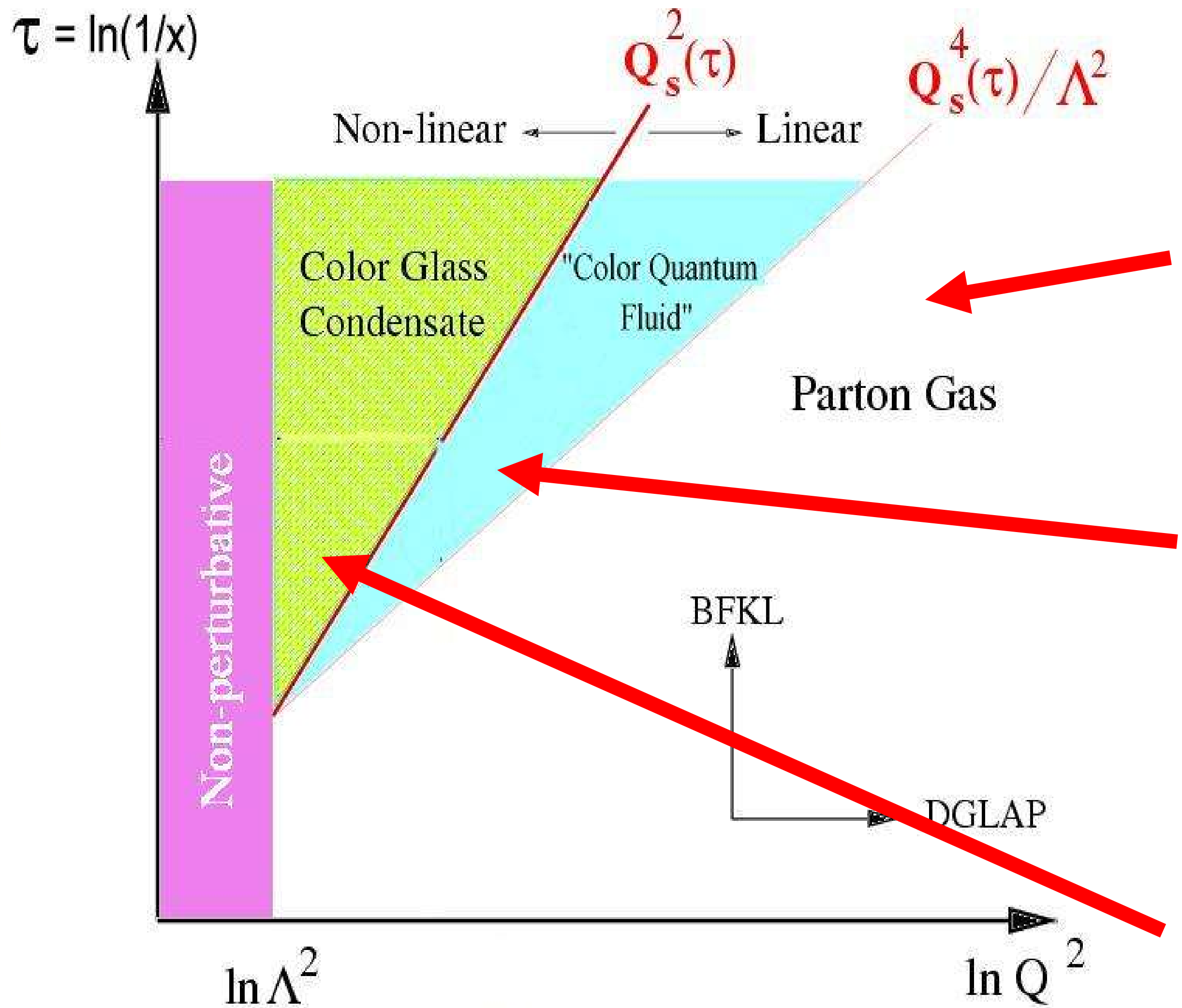
- Reasonably good agreement (esp. high p_T) within uncertainties
- Caveat: uncertainty in the p_T shape (esp. low p_T) of the p+p reference ...

Part III:

d+Au @ 200 GeV at y~3

Probing the QCD cold "medium"

The quest for gluon saturation effects @ RHIC ...



(2 → 2) $x_T = p_T/\sqrt{s}\,(e^{-y}+e^{y})$

x small: Look forward in rapidity !

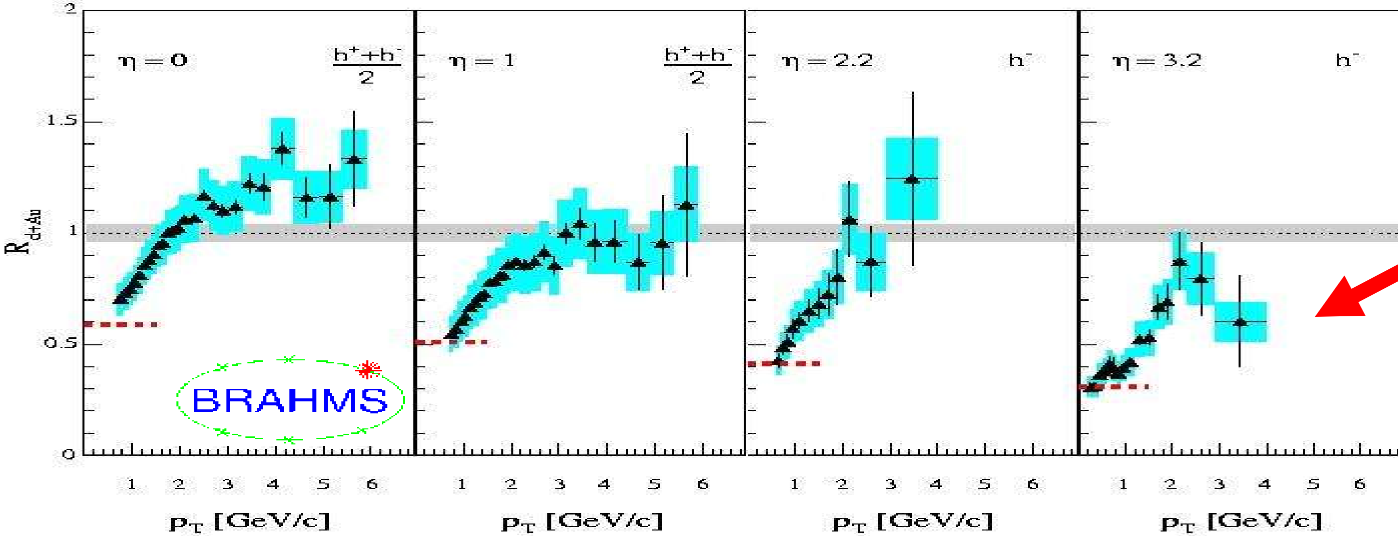
RHIC kinematical regime:

- **High p_T @ midrapidity:**
  $y = 0$, $Q^2 = 1\text{-}100\ \mathrm{GeV^2/c^2}$
  - pQCD collinear factorization
  - DGLAP evolution (g splitting)
  - small nuclear effects in PDFs (LT shadowing).

- **Moderate p_T, rapidities:**
  $y \approx 1\text{-}3$, $Q^2 \approx 10\ \mathrm{GeV^2/c^2}$
  - k_T factorization
  - linear BFKL evolution (g splitt.)
  - "moderate" nuclear effects (LT shadowing).

- **Low p_T @ large rapidities:**
  $y > 3$, $Q^2 < Q_s^2 \approx 5\ \mathrm{GeV^2/c^2}$
  - pQCD factorization breakdown
  - non-linear evolution (g fusion)
  - strong nuclear effects in the initial-state

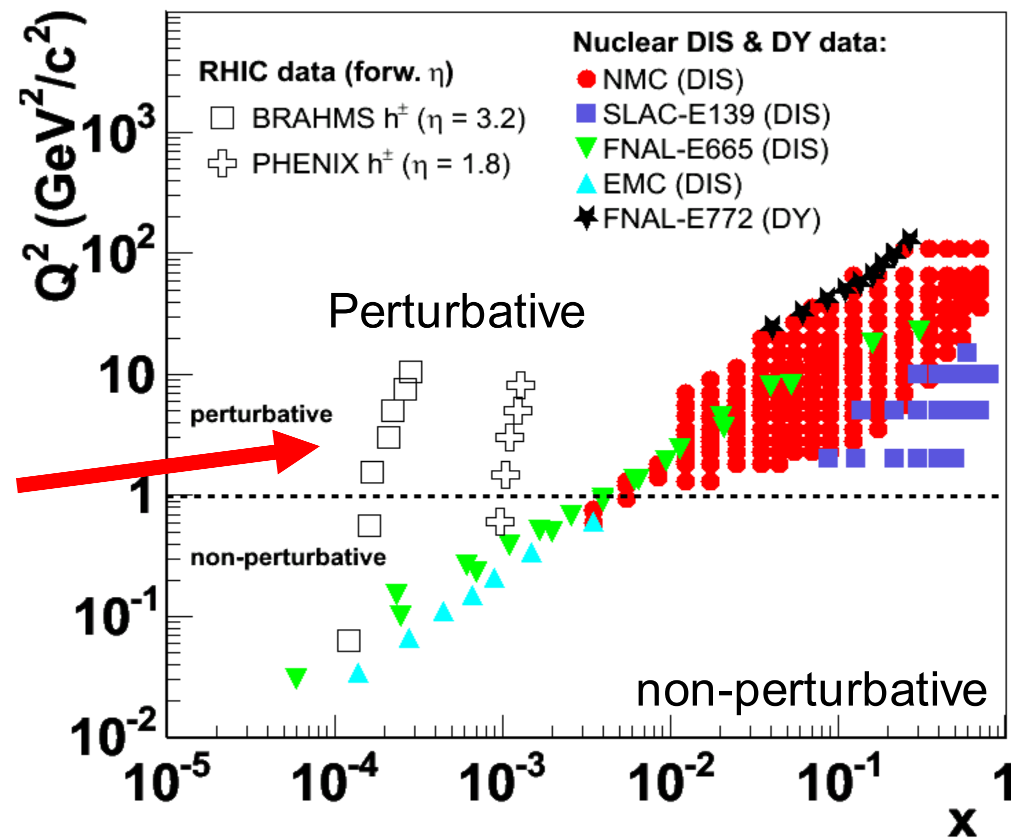
d+Au @ 200 GeV (η = 3.2): forward suppression !



- Factor ~2 suppression p_T = 1-3 GeV/c hadron production at η = 3.2 ($x_2 \sim 10^{-4}$ in Au).

- First time a large "shadowing" is seen at small-x and high p_T in nuclear syst.

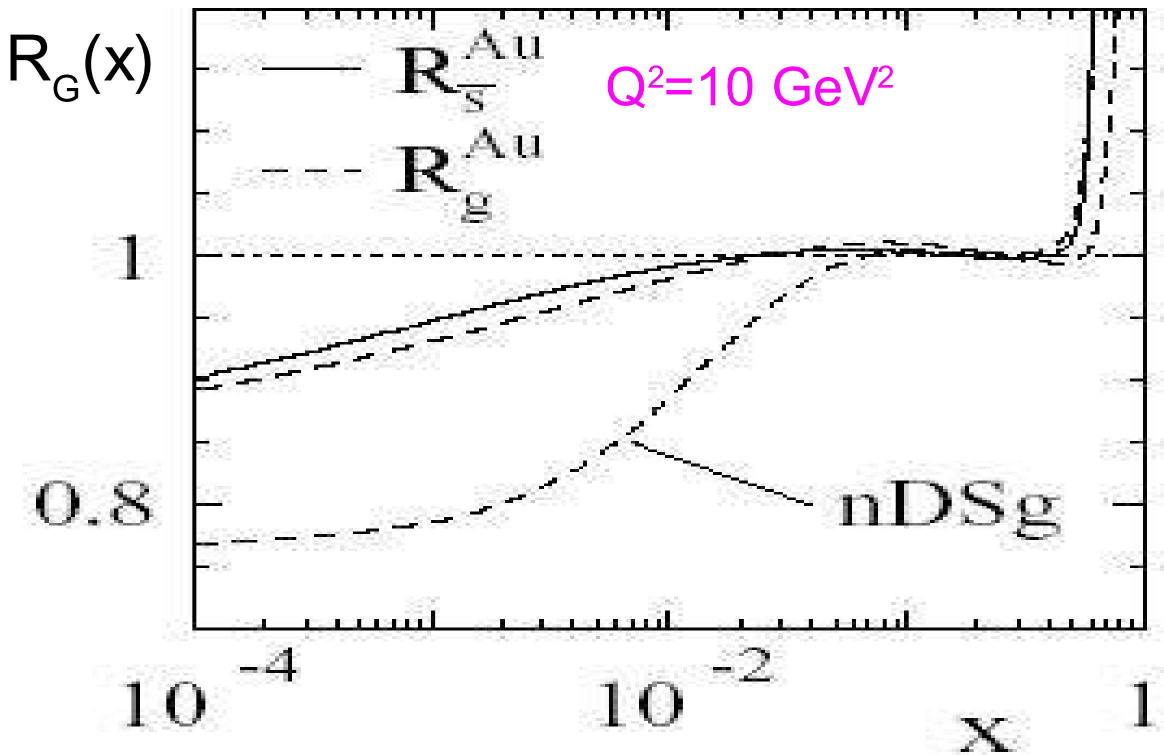
- So far unexplored perturbative region of nuclear (x,Q^2) plane.



David d'Enterria (Columbia Univ.)

Is this "standard" nuclear shadowing ?

- Maximum gluon shadowing at $x \sim 10^{-4}$ (indirectly) constrained by leading-twist approaches fitted to available DIS data on nuclear targets is ~0.8

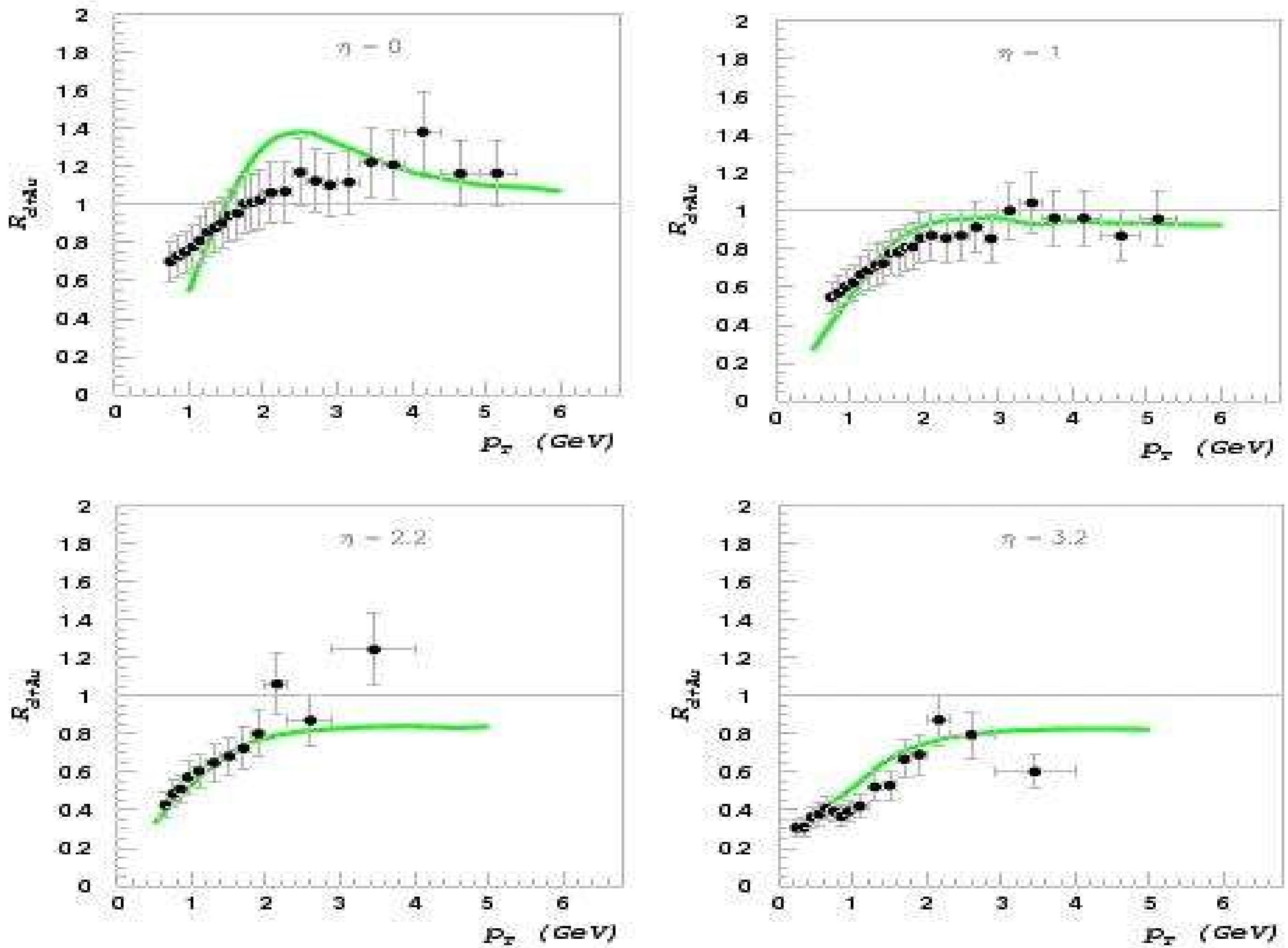


NLO DGLAP global analysis of nuclear PDFs

D. de Florian & R.Sassot
hep-ph/0311227

Is this “Color Glass Condensate” ?

- CGC + quantum evolution seem to reproduce data:



(K. Tuchin)

- Possible hint of extra higher-twist effects at small-x (breakdown of QCD factorization). But, soft physics effects can still be playing a role here ...

Summary

High p_T central Au+Au vs p+p at midrapidity at RHIC:

(1) Inclusive spectra suppressed by a factor of 4-5 at 200 GeV and by a factor of ~3 at 62.4 GeV

(2): Intermediate p_T hadron composition inconsistent with known fragmentation functions in free space.

(3) Disappearance of away-side jet correlations. Enhanced mono-jet pattern following line of longest path.

High p_T d+Au vs p+p at midrapidity at RHIC:

(4) Spectra enhanced by a factor ~1.3

"Explanation" (1,2 via 4): pQCD hard scattering + final-state parton energy loss + quark recombination in dense thermal QCD medium.
QGP ? : thermal γ ?, J/Ψ suppression ? (Run-4 AuAU @ 200 GeV)

High p_T in d+Au at forward rapidities at RHIC:

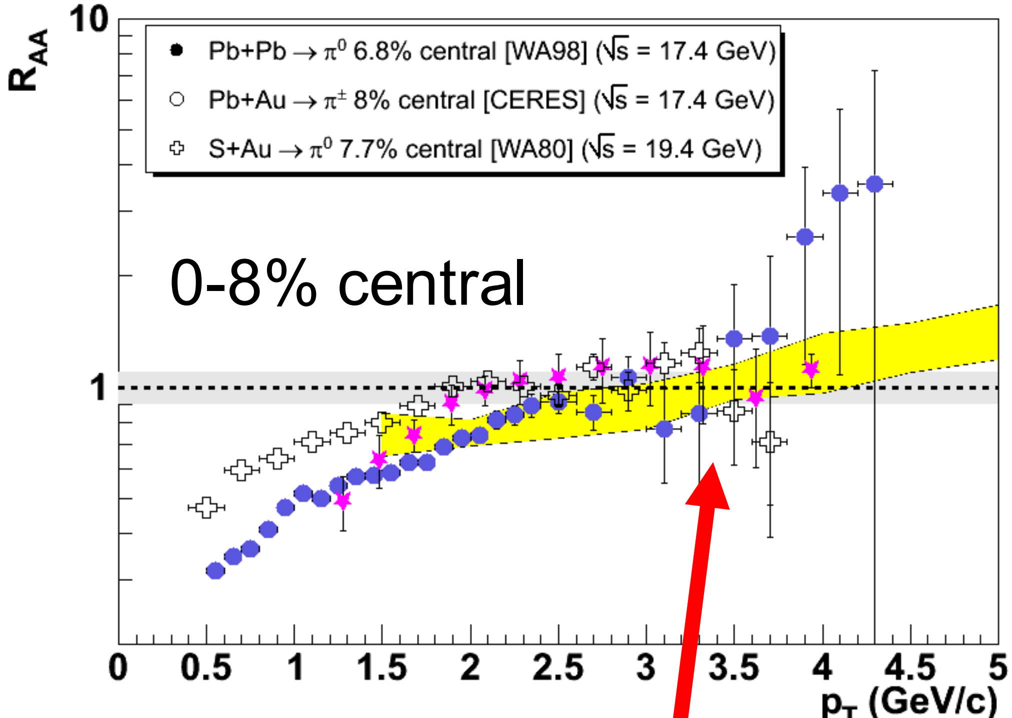
(5) Spectra suppressed by a factor ~2.

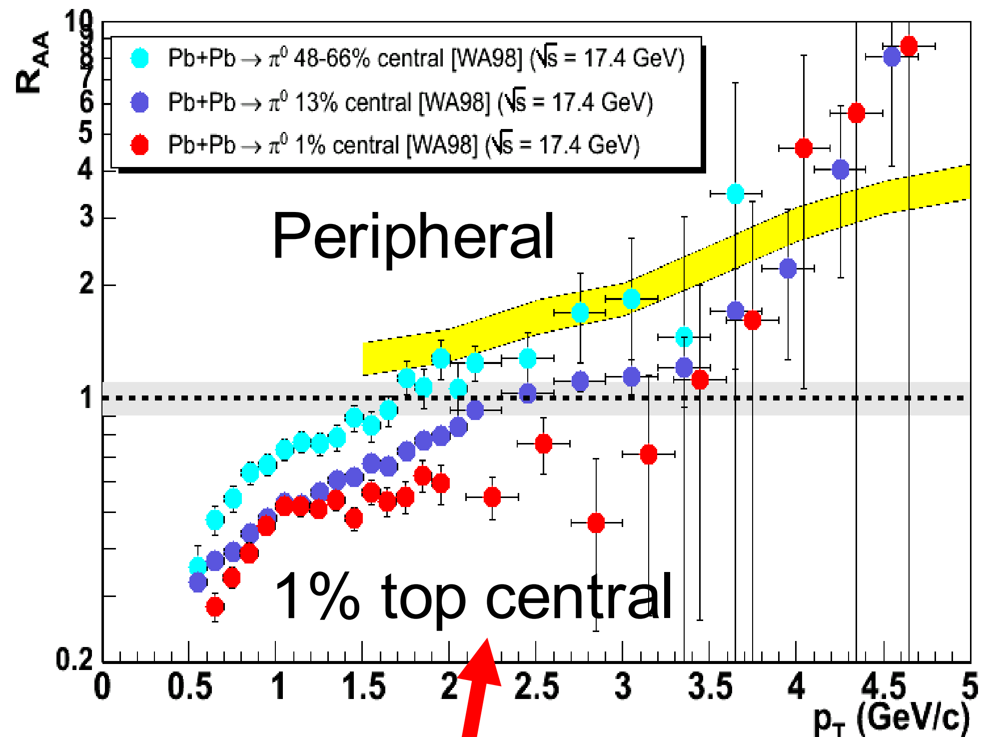
"Explanation" : possible evidence of higher twist effects at small-x.

backup slides ...

High p_T @ CERN-SPS: "Cronin" or "quenching" ?

- New nuclear modification factor (better p+p → π^0 ref. @ $\sqrt{s_{NN}}$ = 17.3 GeV)



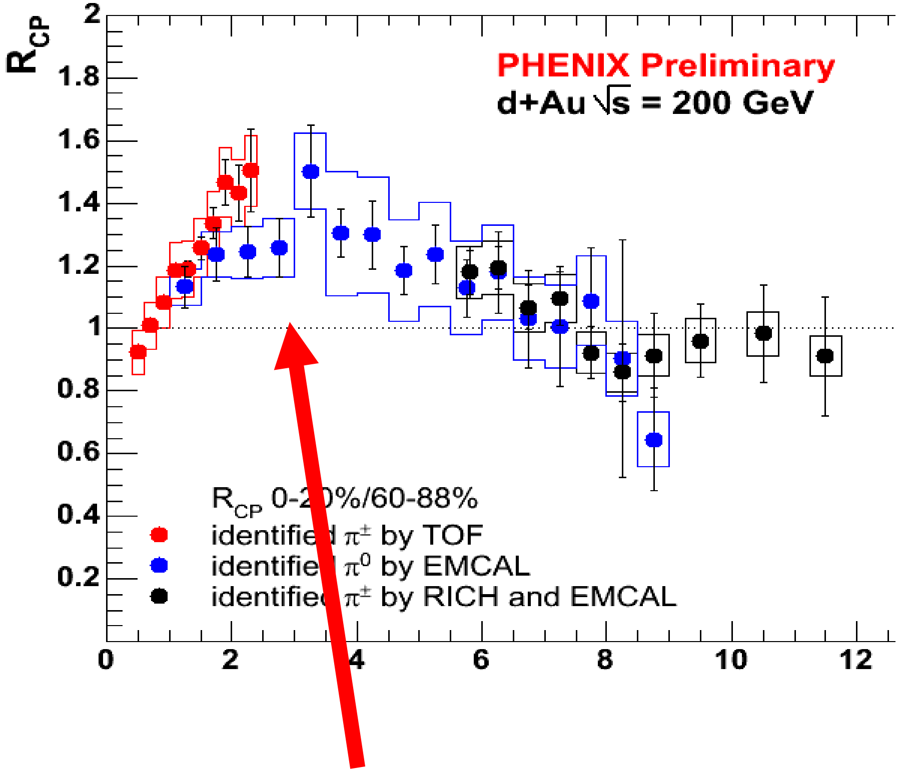


[D.d'E. to be submitted]

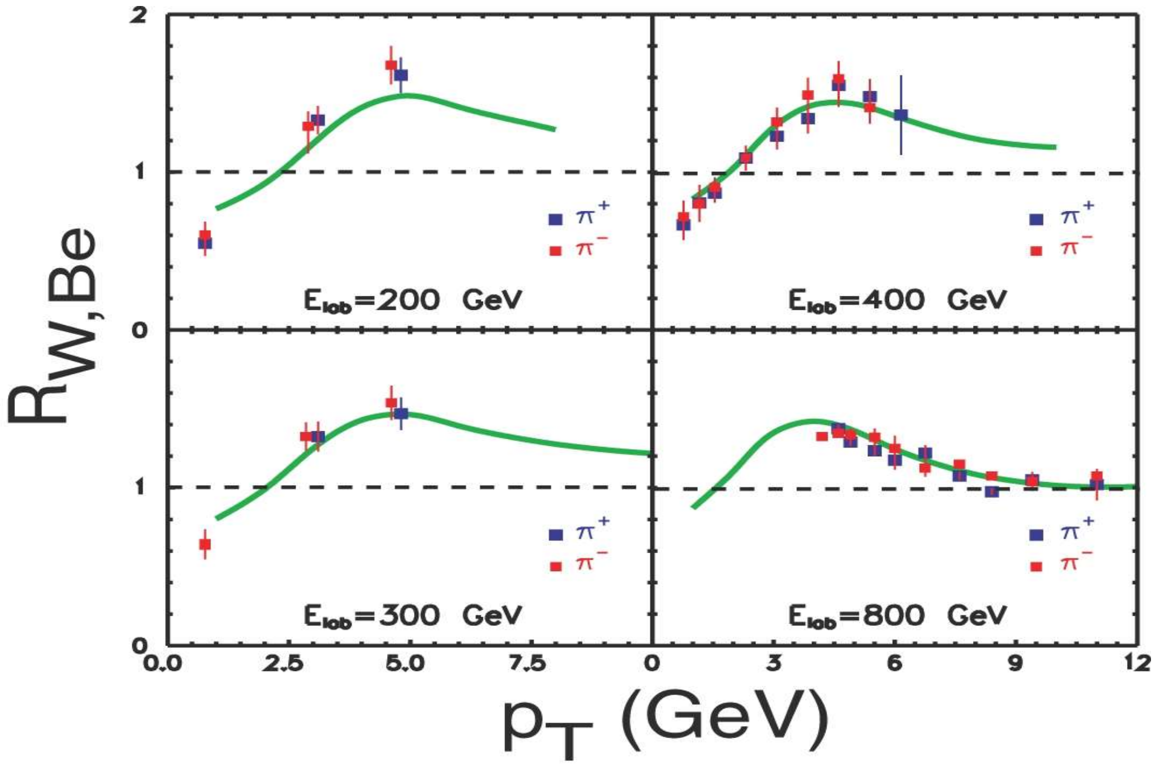
- No "Cronin" effect in central collisions (R_{AA} ~ 1).
- "Cronin" enhancement in peripheral ... and suppression in top central ?
- Look for onset of suppression at RHIC Au+Au, p+p @ $\sqrt{s_{NN}} \approx$ 20 GeV ?

d+Au nuclear modification factor (at y=0)

d+Au @ $\sqrt{s_{NN}}$ = 200 GeV



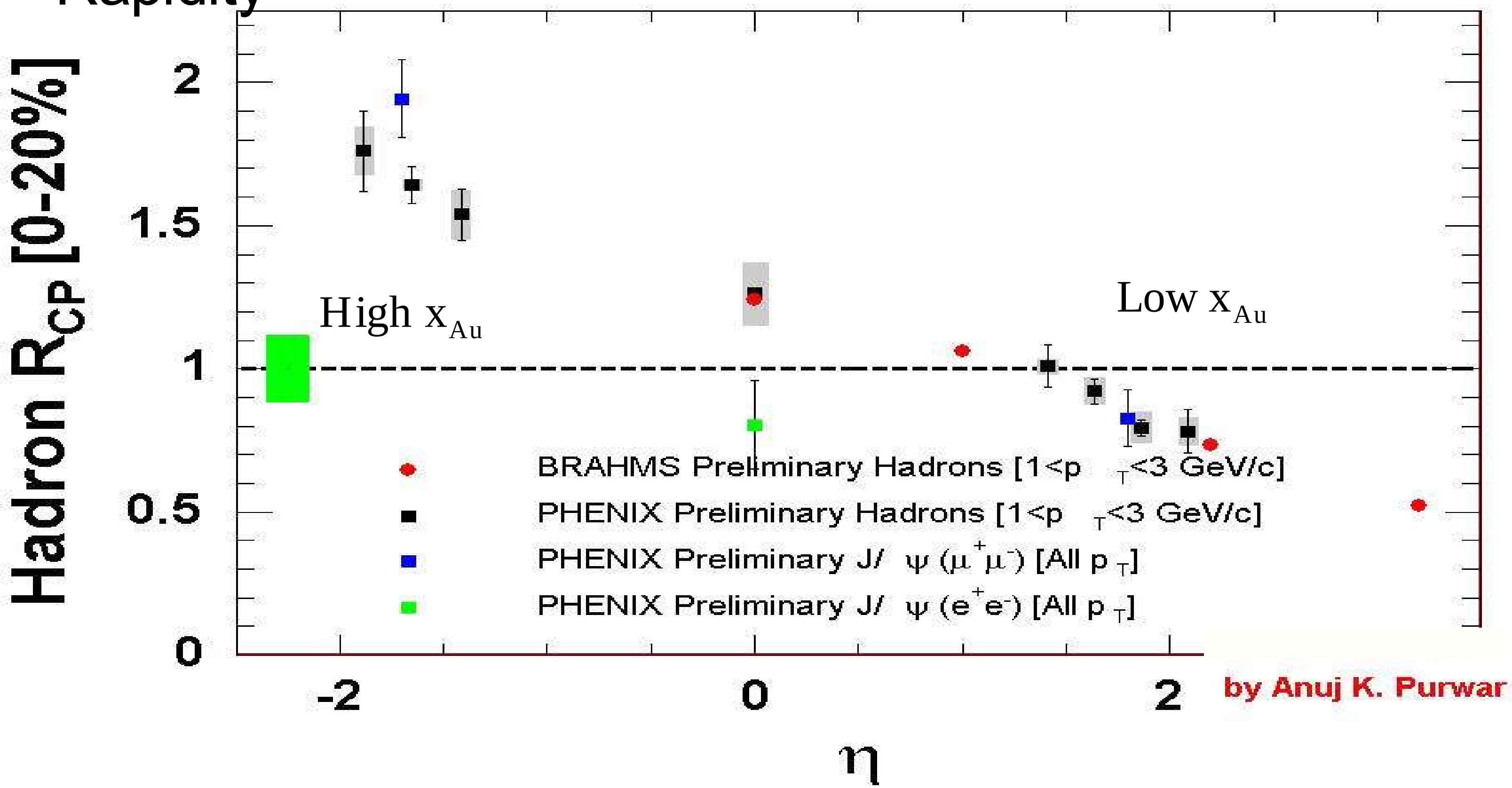
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



- High p_T production in d+Au not suppressed but enhanced ! $R_{dAu} > 1$ as in p+A "Cronin enhancement": p_T broadening due to initial-state soft & semihard scattering.
- "pQCD" cross-sections (R_{AA}~1) recovered at $p_T > 8$ GeV/c
- No Au shadowing effects in kinematic region probed (y= 0).

d+Au @ 200 GeV : rapitidy dependence of suppression

- Rapidity



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

QCD factorization in A+B collisions

pQCD (factorization theorem) expectation for inclusive A+B hard cross-sections:

Independent scattering of “free” partons: $f_{a/A}(x,Q^2) = A\, f_{a/p}(x,Q^2)$

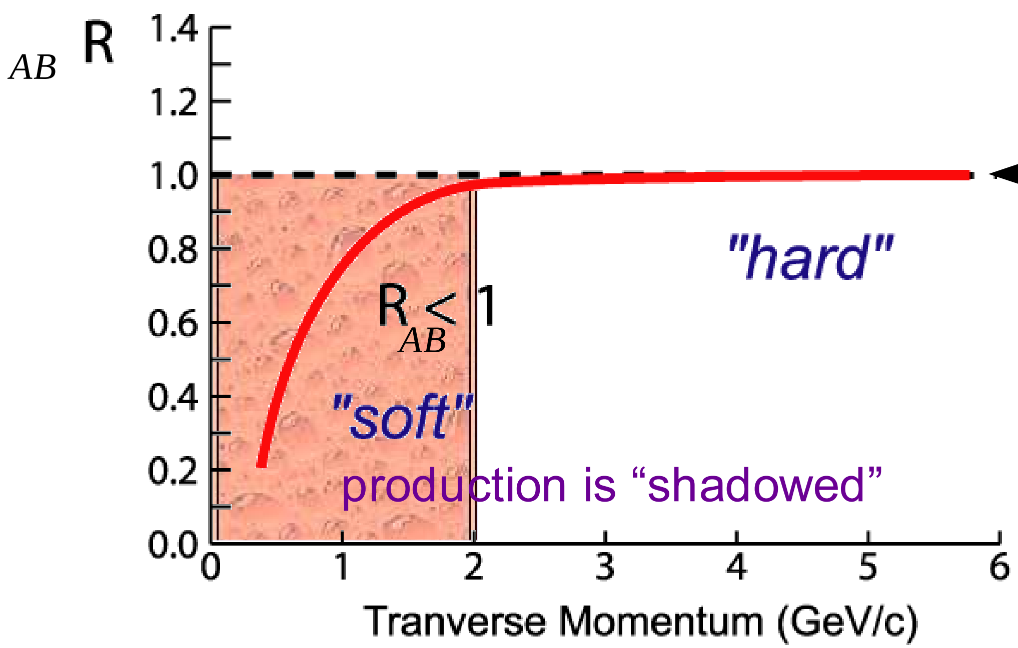
$d\sigma_{AB \to hard} = A \cdot B \cdot d\sigma_{pp \to hard}$

At imp. param. b: $dN_{AB \to hard}(b) = T_{AB}(b) \cdot d\sigma_{pp \to hard}$

geom. nuclear overlap at b

Nuclear Modification Factor:

$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$



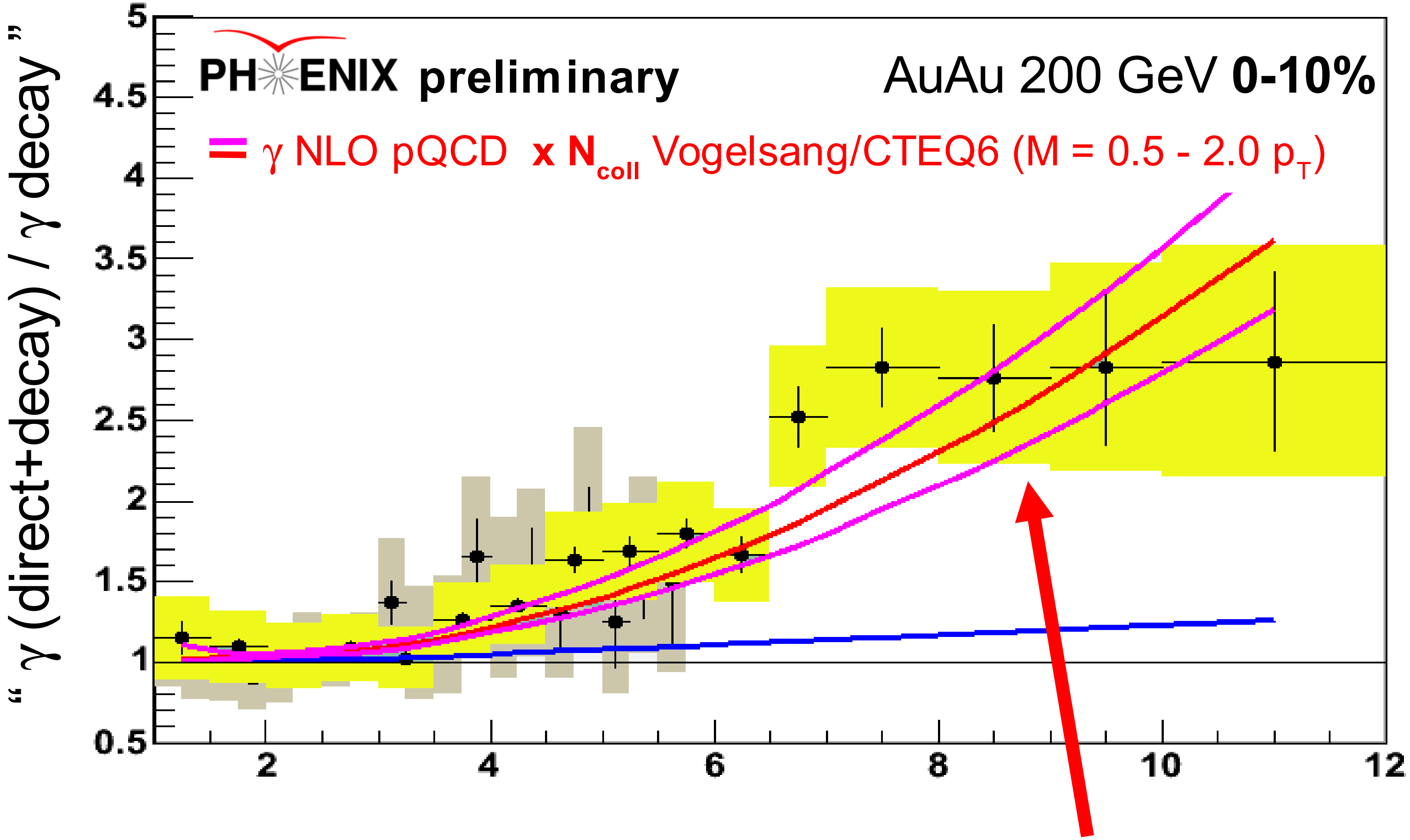
T_{AB} ~ # NN colls. (“N_{coll} scaling”)

$R_{AA} = 1$

A+A = “simple superposition of p+p collisions” at high-p_T where hard scattering dominates

Confirmation... unsuppressed hard colorless production in Au+Au central

- "Control" observable: direct photons (clean, penetrating = directly coupled to partonic vertex, no fragmentation) non-hadronic hard probes.



[J.Frantz QM'04]

Photons (insensitive to final-state effects) show collision scaling at high p_T:

- pQCD parton scattering holds for hard processes in central Au+Au !