Hadron production at high p_T: experimental survey

"QUARK MATTER 2004"
17th International Conference on
Ultra-Relativistic Nucleus-Nucleus Collisions

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Overview

1. Introduction:
   - The goal: study Quantum Chromo many-body Dynamics: QGP, CGC.
   - The means: compare hard scattering production in diff. colliding systems.
2. "QCD vacuum" production – high p_T spectra in p+p:
   - Baseline reference data of hard scattering in free space.
3. "Hot QCD medium" production – high p_T spectra in central A+A:
   - ➡ Light-flavor (u,d,s): Suppressed (compared to free space). $\sqrt{s}$, p_T, y, centrality, and particle species dependence.
   - ➡ Heavy-flavor (c): Unsuppressed (?).
   - ➡ Colorless particle (γ): Unsuppressed.

   } **QGP ?**
4. "Cold QCD medium" production – high p_T spectra in d+Au:
   - ➡ Light-flavor (u,d,s) : Enhanced at $y \leq 0$ (mid-rapid. & high x_2 in Au) p_T, centrality, and particle species dependence.

     Suppressed at $y \geq 1$ (small x_2 in Au) } **CGC ?**
5. What have we learnt ? Data vs. theory.
6. Summary

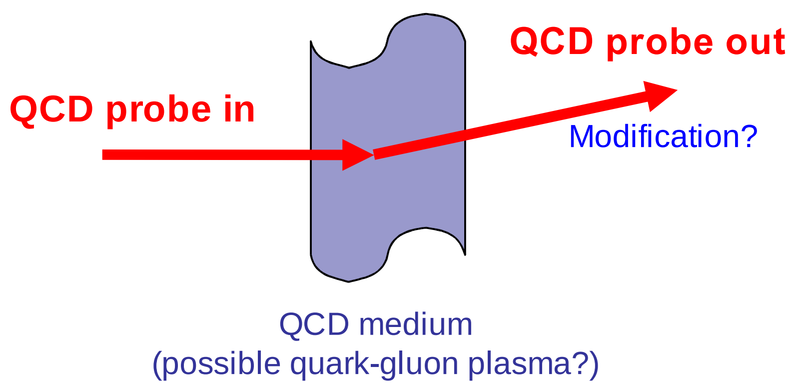
Hard QCD probes. Motivation (I)

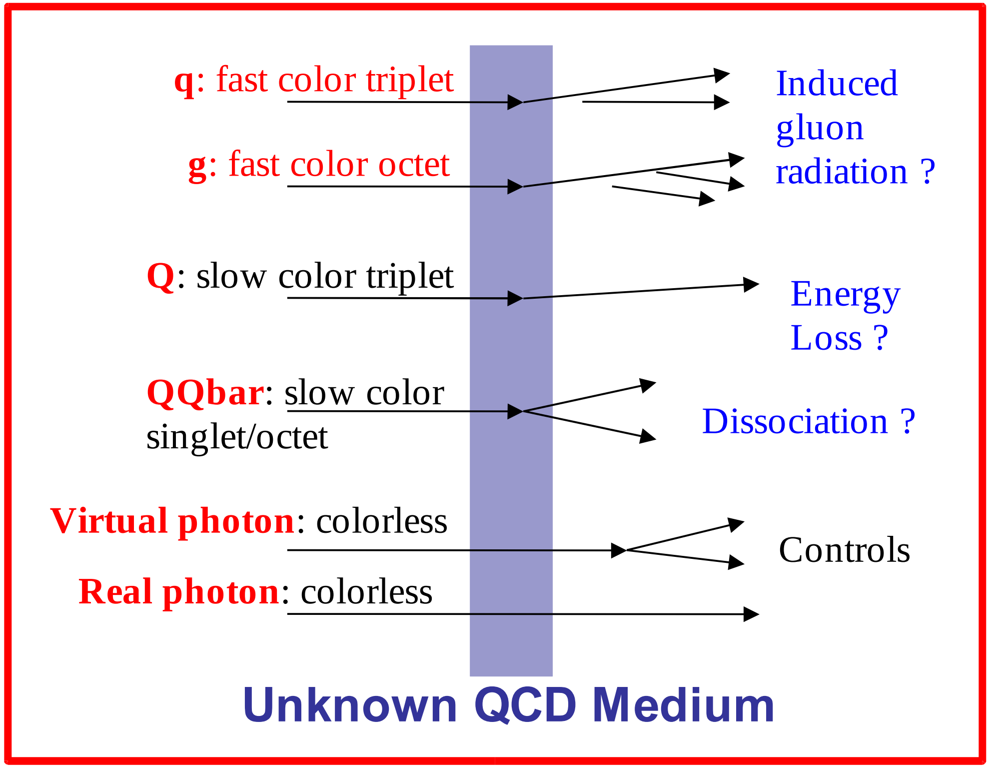
- Hard probes: High-p_T, jets, direct γ, heavy-quarks (D, B), ...

[1] Early production ($\tau \sim 1/p_T < 0.1$ fm/c) in parton-parton scatterings with large Q^2:

Closest experimental probes to underlying QCD (q,g) degrees of freedom.

[2] Direct probes of partonic phase(s) $\Rightarrow$ Sensitive to QCD medium properties:





[3] Incoherent processes: Direct comparison A+A to p+p yields via " N_{coll} scaling" :

$$d\sigma_{AB \to hard}(b) = \mathbf{T}_{AB}(b) \cdot d\sigma_{pp \to hard}$$

Nuclear overlap:

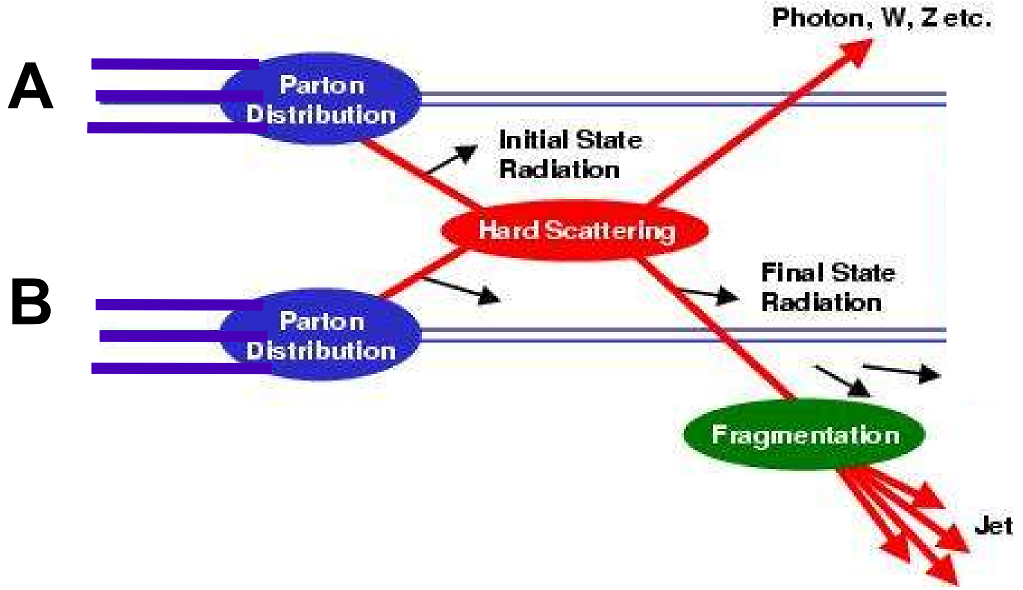
$\mathbf{T}_{AB}(b) \propto N_{coll}(b)$: number of binary inelastic *NN* colls.

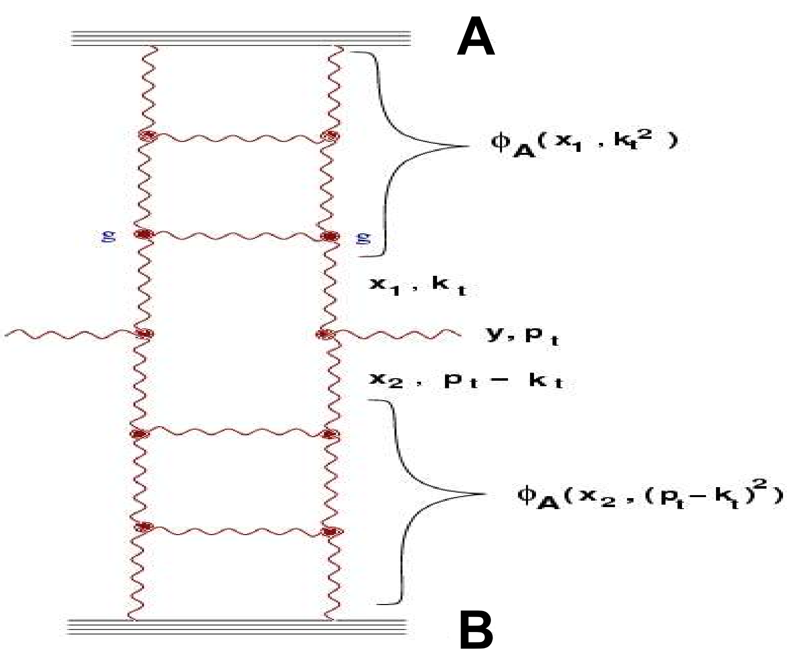
Hard QCD probes. Motivation (I)

[4] Production yields theoretically calculable via:

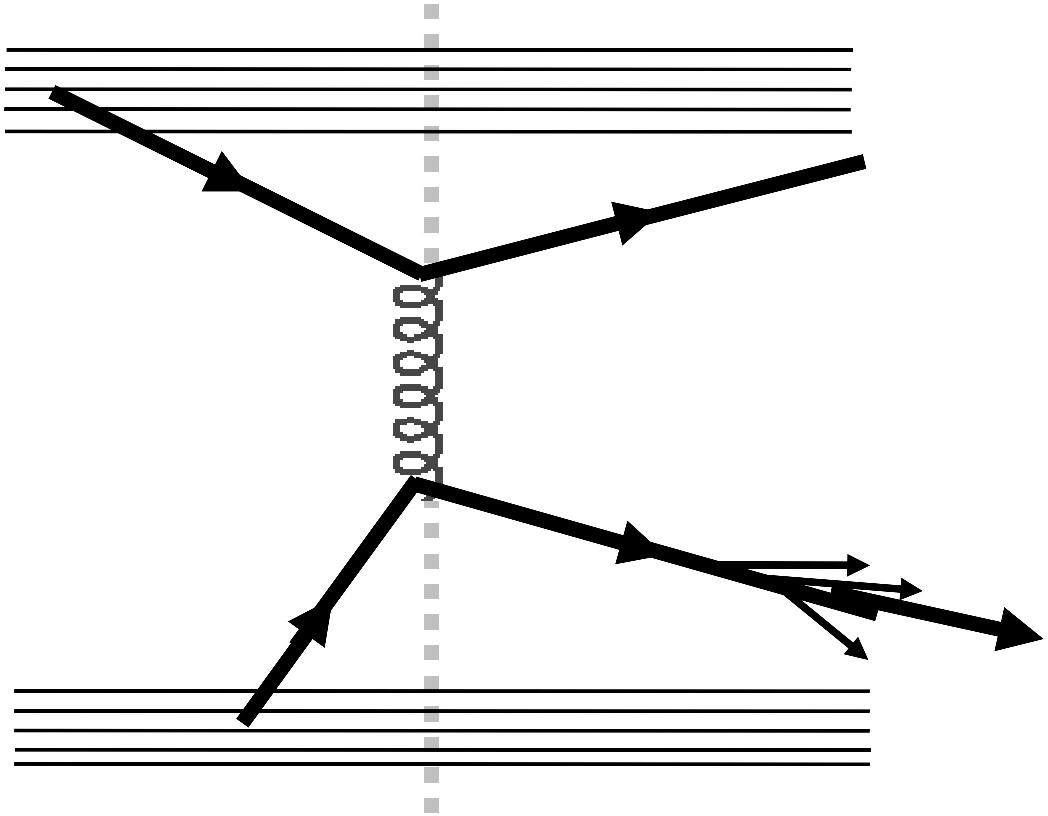
perturbative-QCD or ... classical-field QCD:

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





Hard scattering in A+A collisions



Hard scattering in A+A collisions

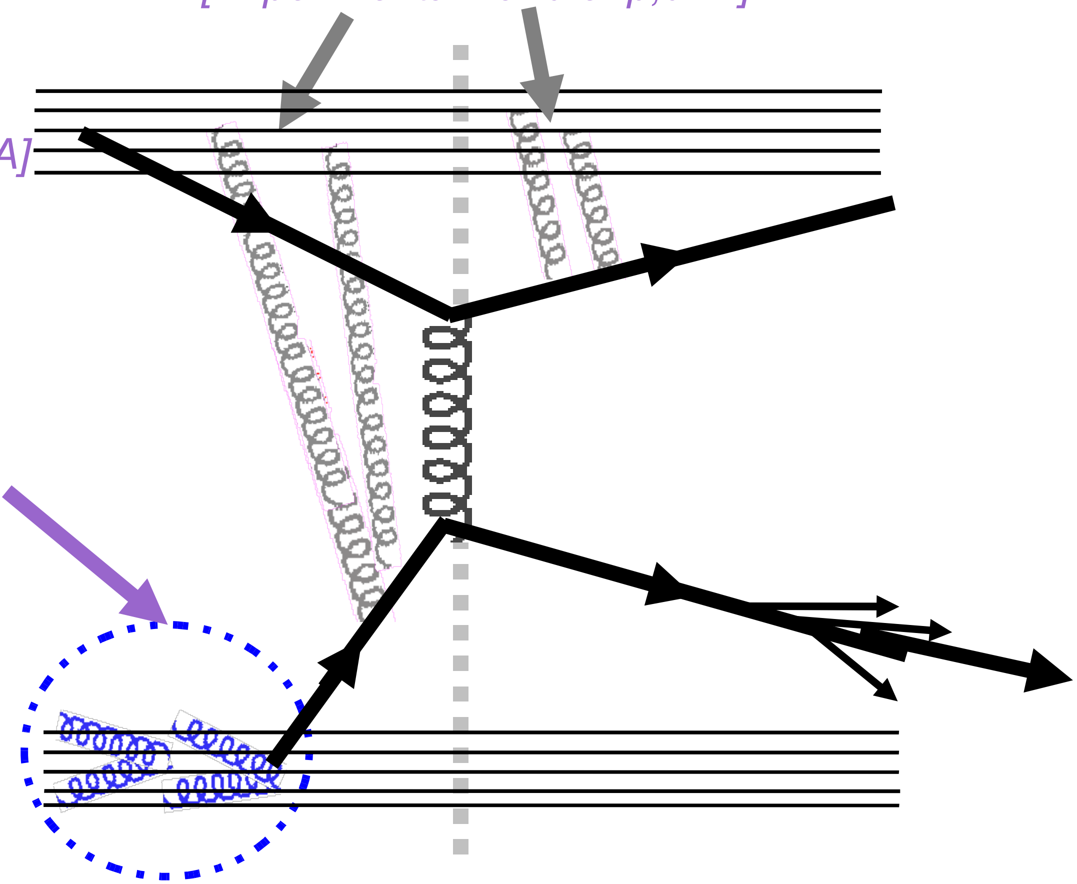
p_T broadening
(Cronin enhancement)

[Experimental handle: p,d+A]

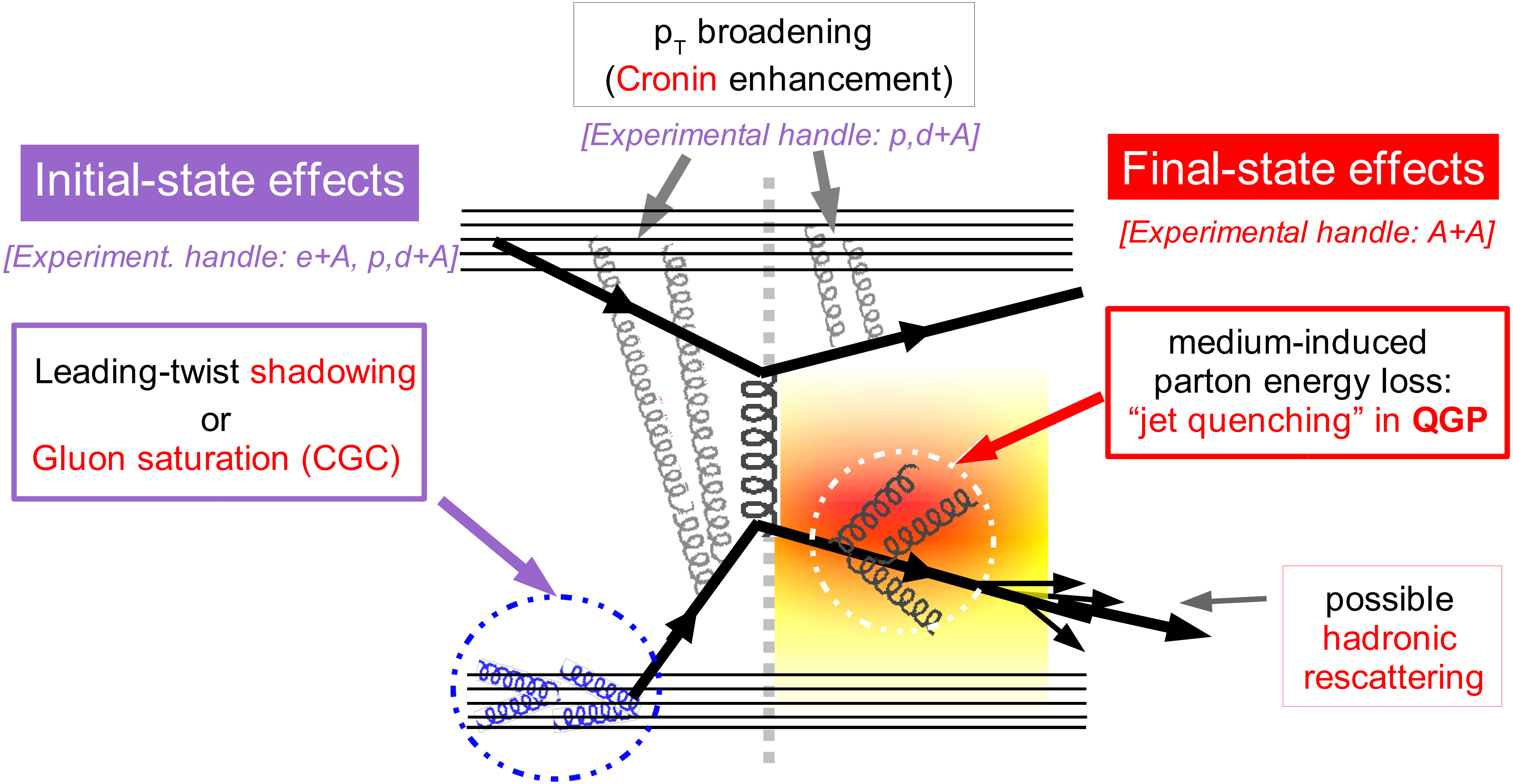
Initial-state effects

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

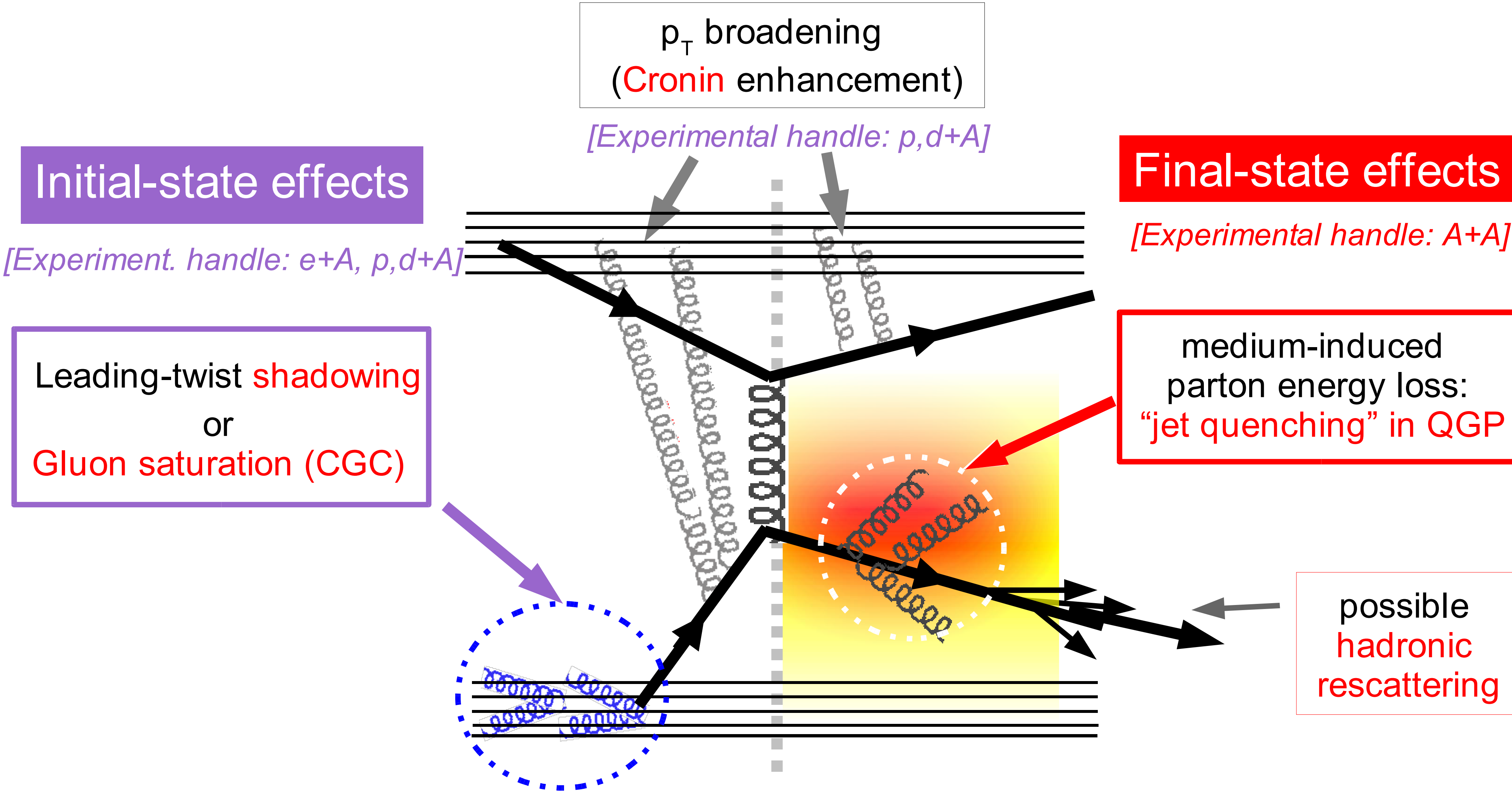
Leading-twist shadowing
or
Gluon saturation (**CGC**)



Hard scattering in A+A collisions

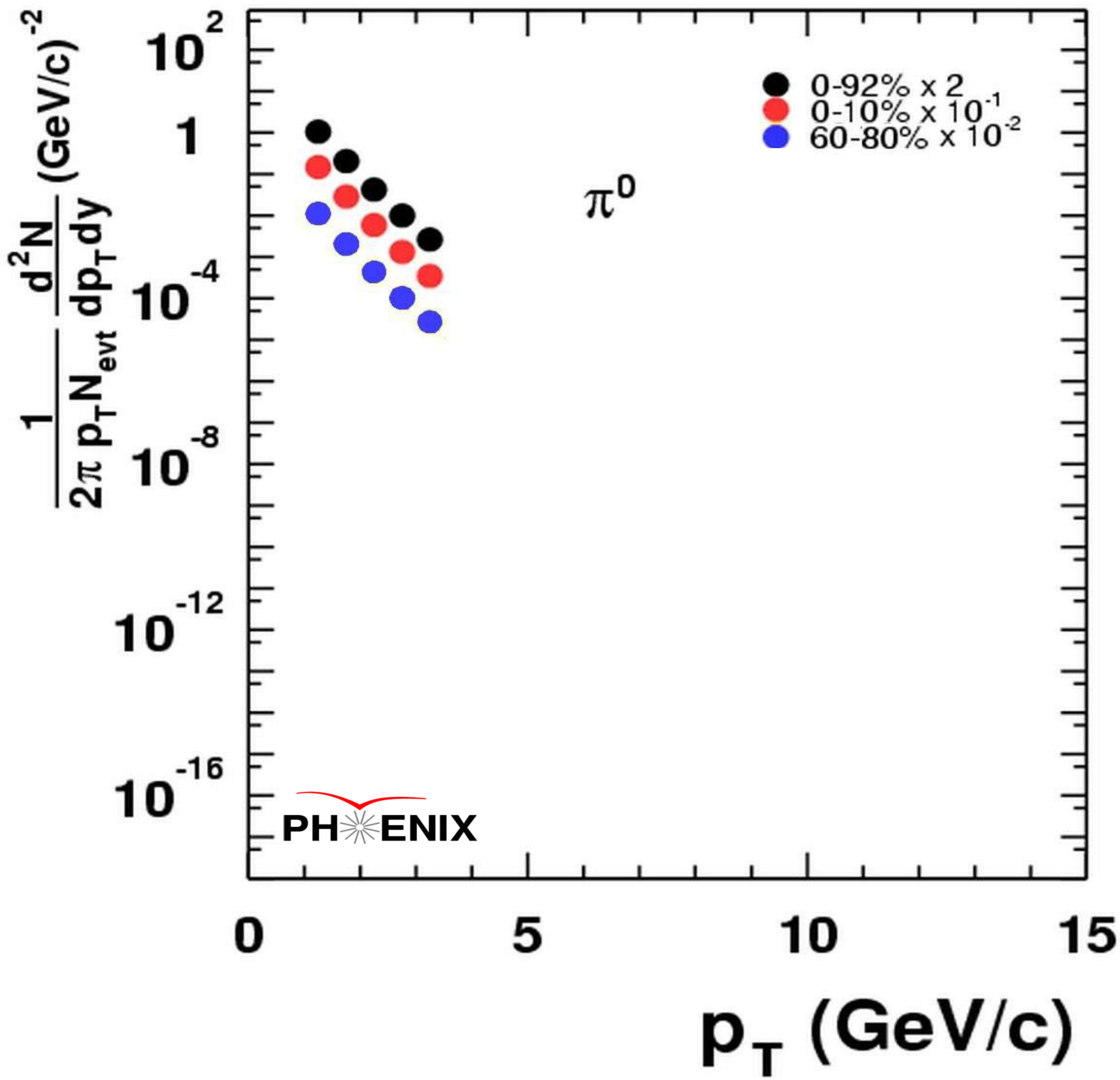


Hard scattering in A+A collisions



- Approach: Study modifs. (incl. spectra, partic. composition) of high p_T production in A+A with respect to p+p, p+A to learn about QCD many-body dynamics:
  - "Quark Gluon Plasma" (final-state A+A) and/or
  - "Color Glass Condensate" (initial-state A).

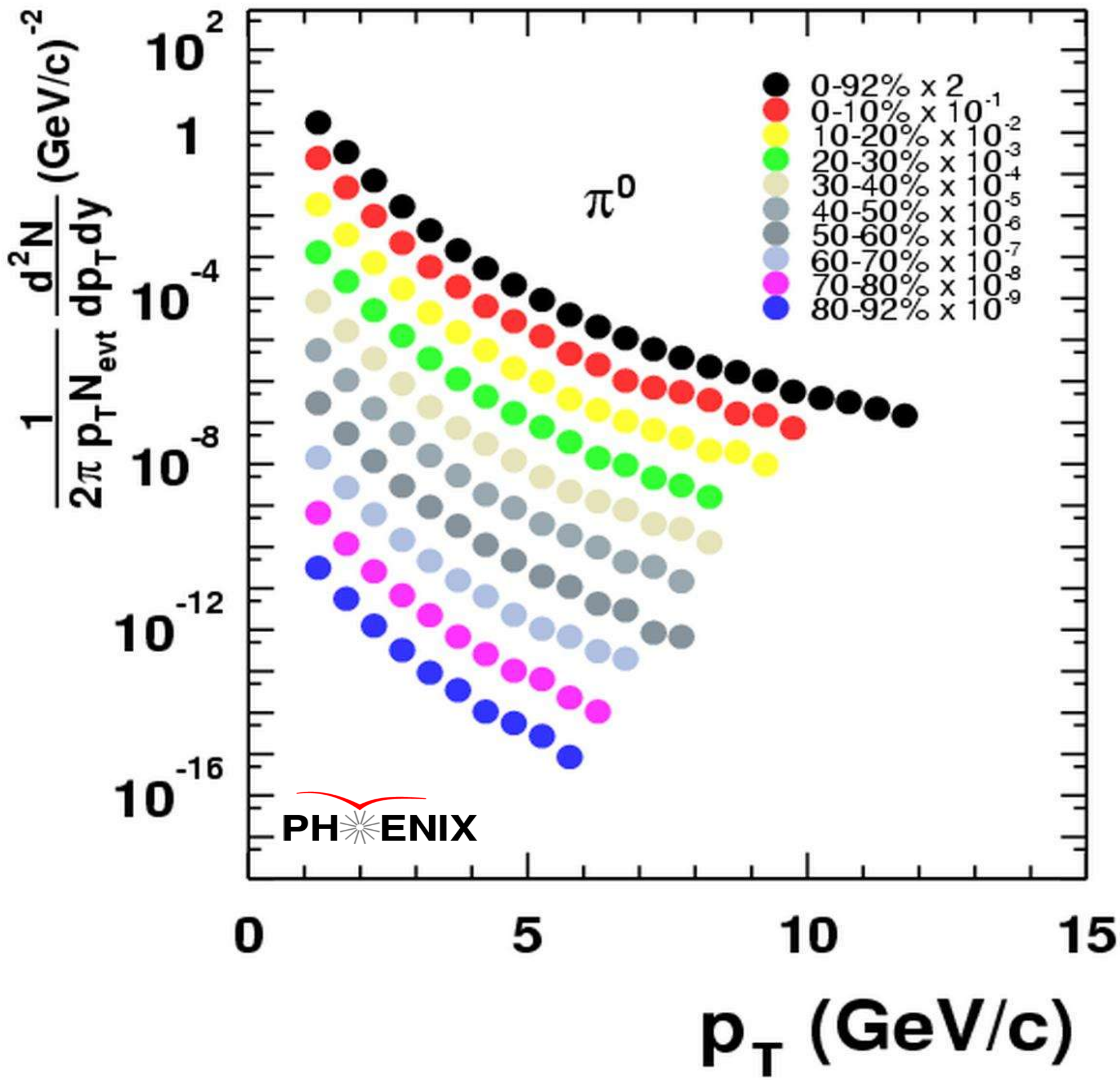
High p_T spectra @ RHIC



π^0 spectra as of QM'01

2 centralities
4 orders of magnitude
p_T^{max} = 4 GeV/c

High p_T spectra @ RHIC



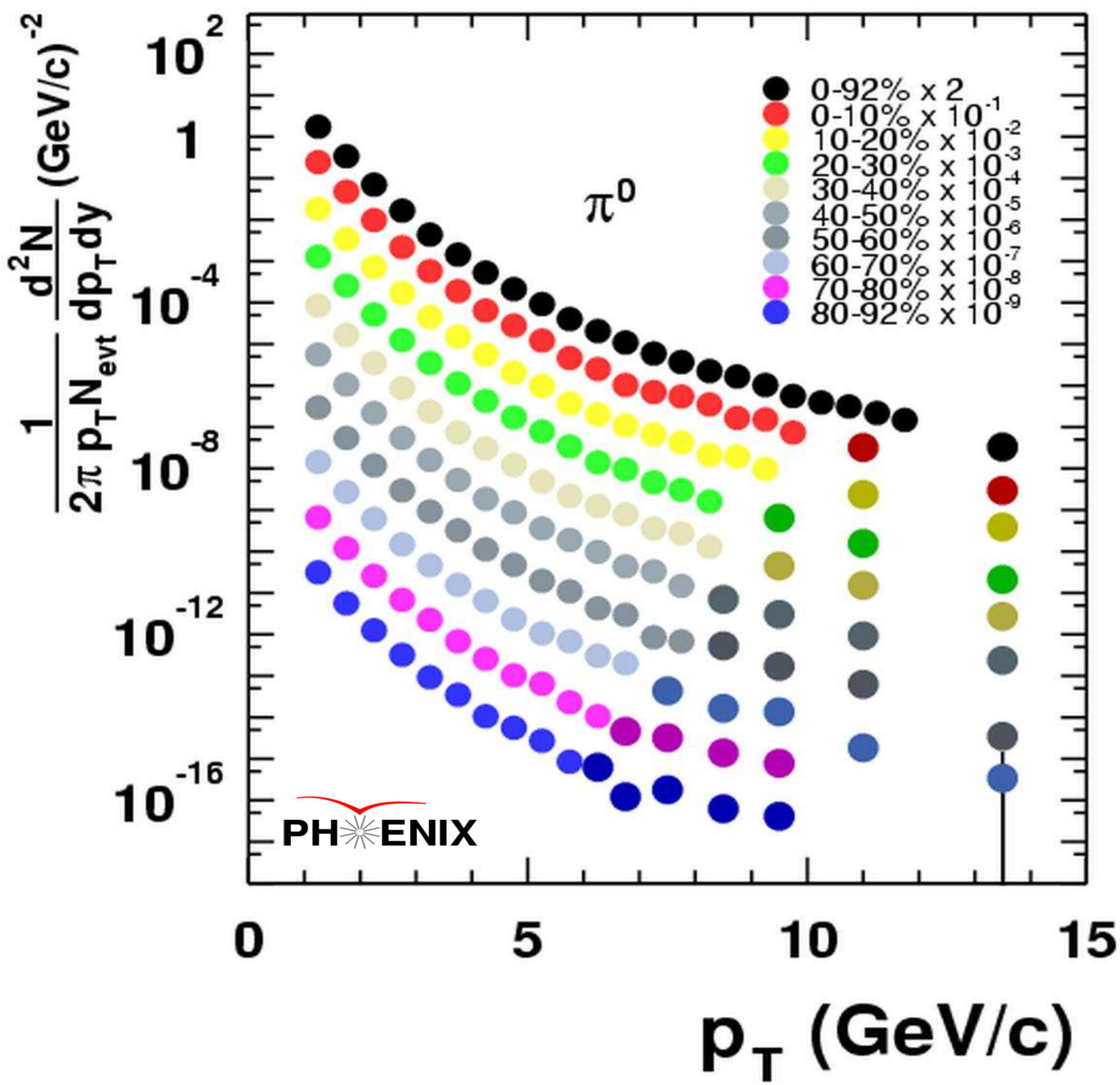
π^0 spectra as of QM'02

10 centralities

7 orders of magnitude

p_T^{max} = 12 GeV/c

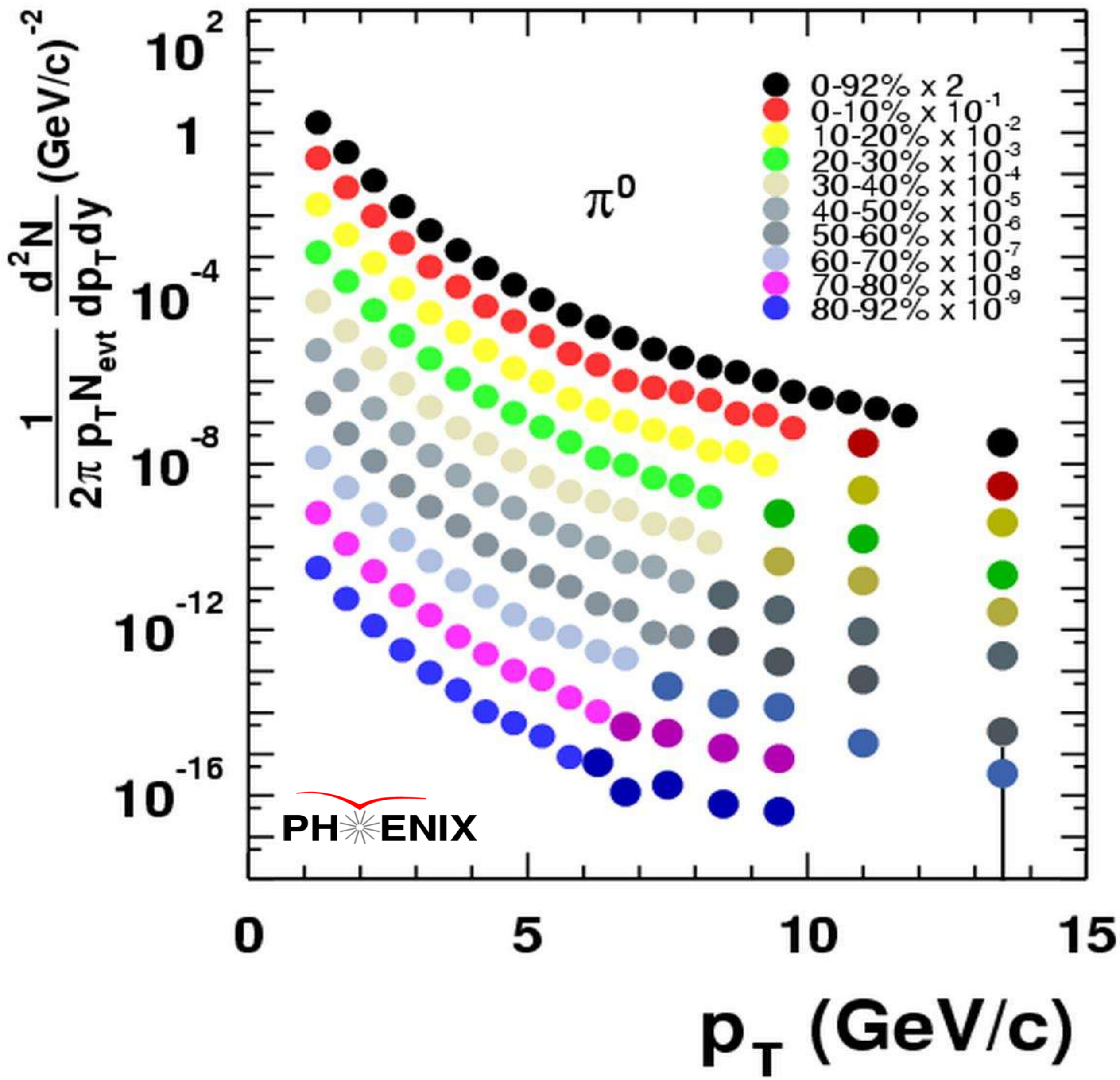
High p_T spectra @ RHIC



π^0 spectra as of QM'04

10 centralities
8 orders of magnitude
p_T^{max} = 15 GeV/c !

High p_T spectra @ RHIC



π^0 spectra as of QM'04

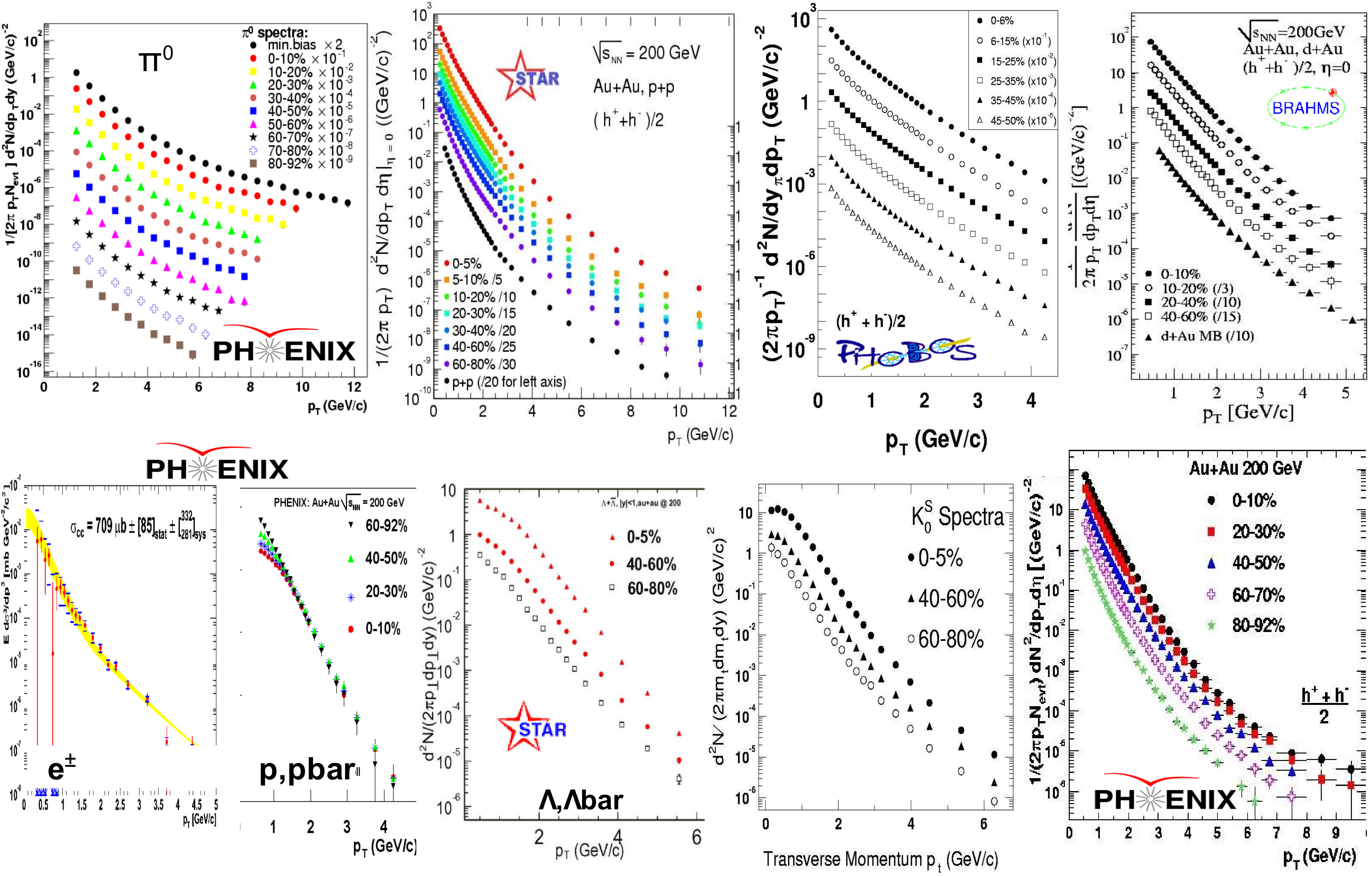
10 centralities

8 orders of magnitude

p_T^{max} = 15 GeV/c !

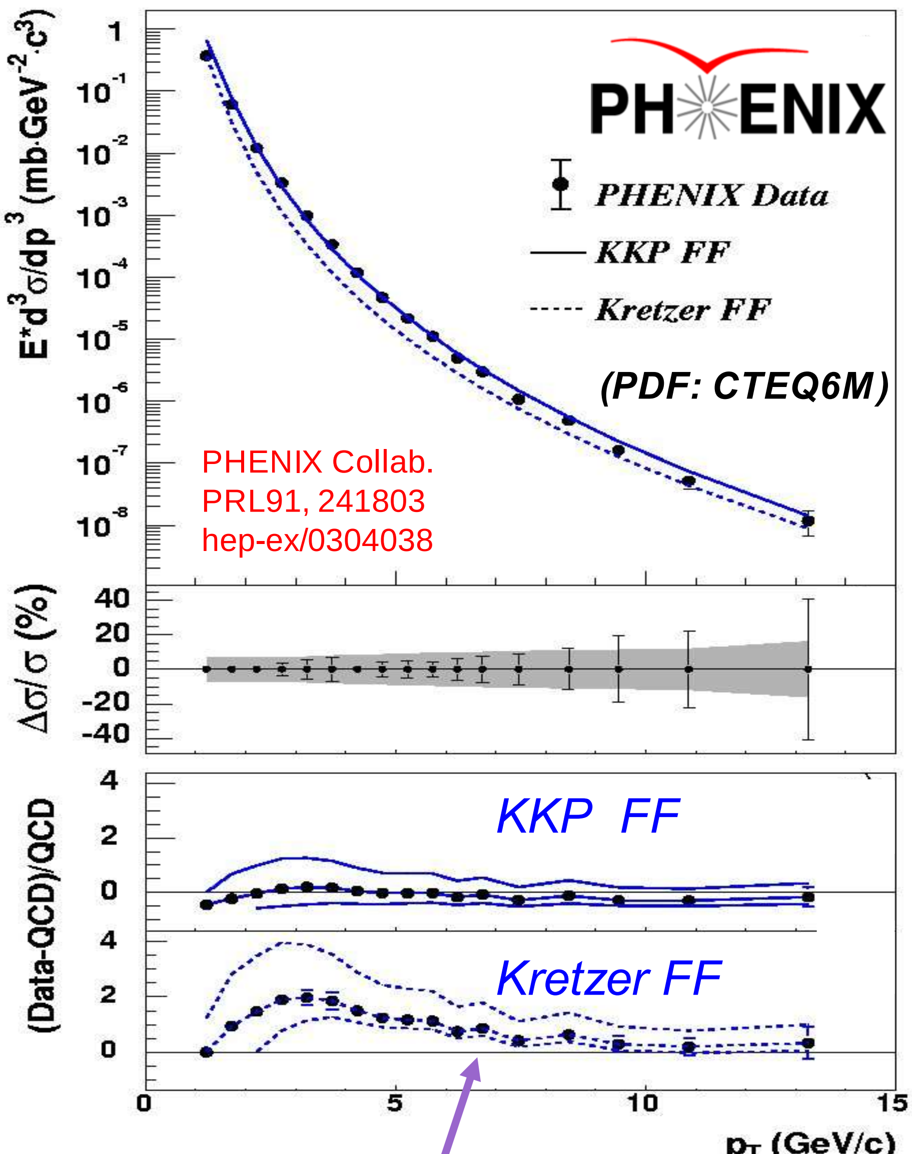
Impressive amount of high quality high p_T data !

High p_T spectra in Au+Au @ 200 GeV

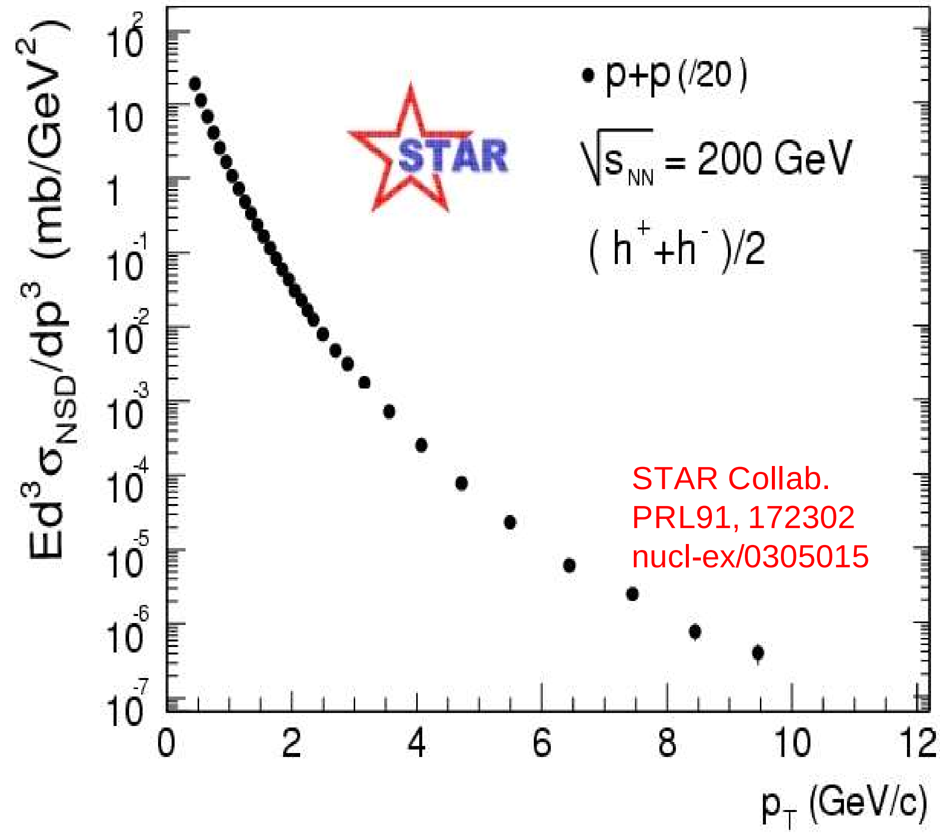


High p_T p+p @ 200 GeV: "baseline" data

p+p → π^0 X



p+p → $h^\pm$ X (Non Singly Diffractive)

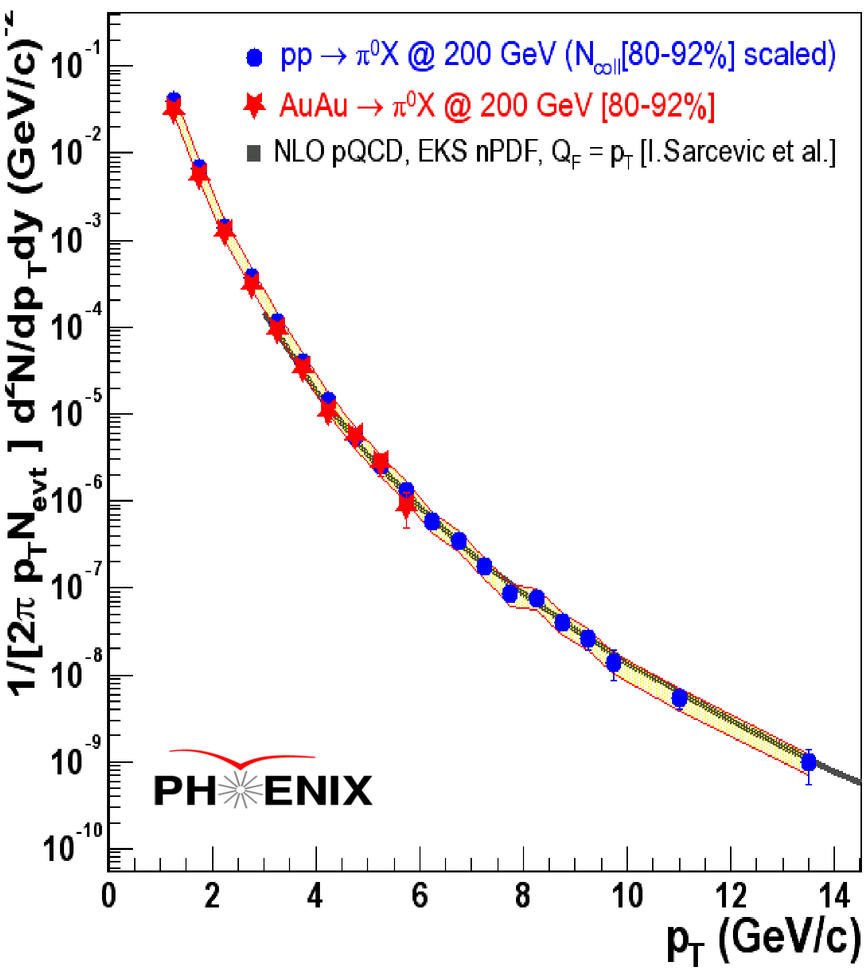


- Well calibrated (experimentally & theoretically) p+p references at hand !

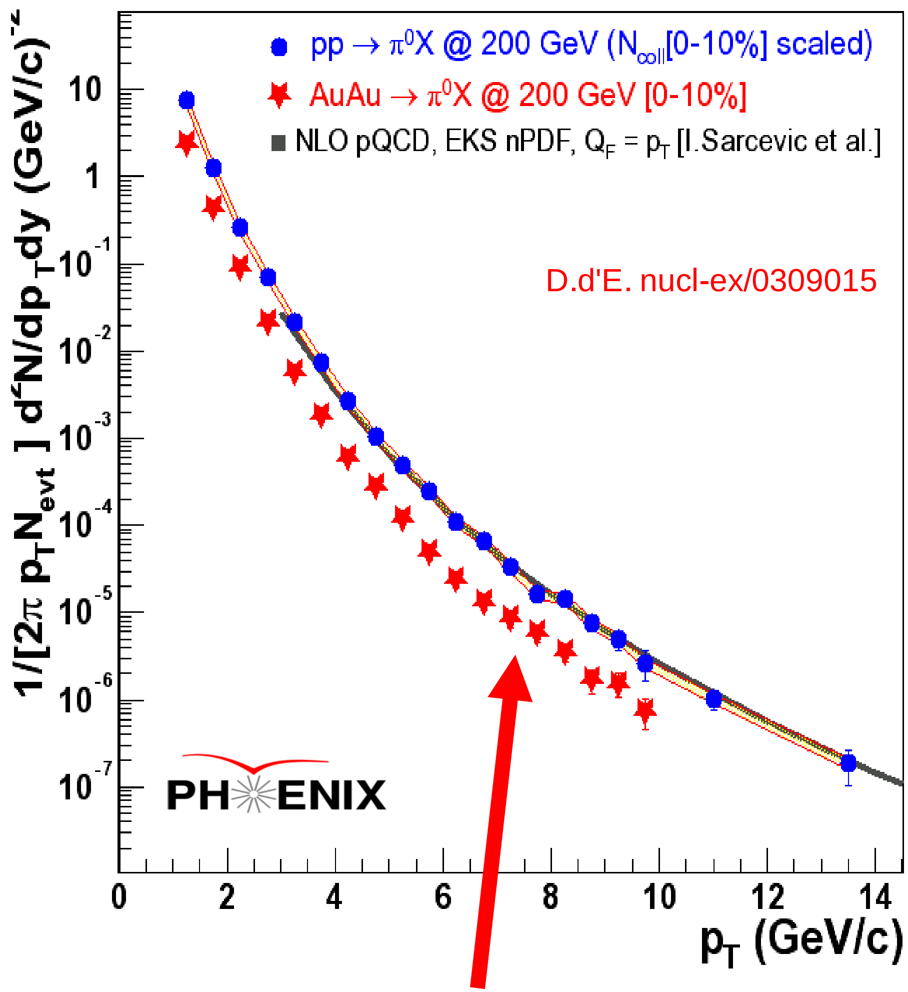
Good theoretical (NLO pQCD) description

Au+Au *vs.* p+p @ 200 GeV (π^0)

Au+Au→ $\pi^0 X$ (peripheral)



Au+Au→ $\pi^0 X$ (central)

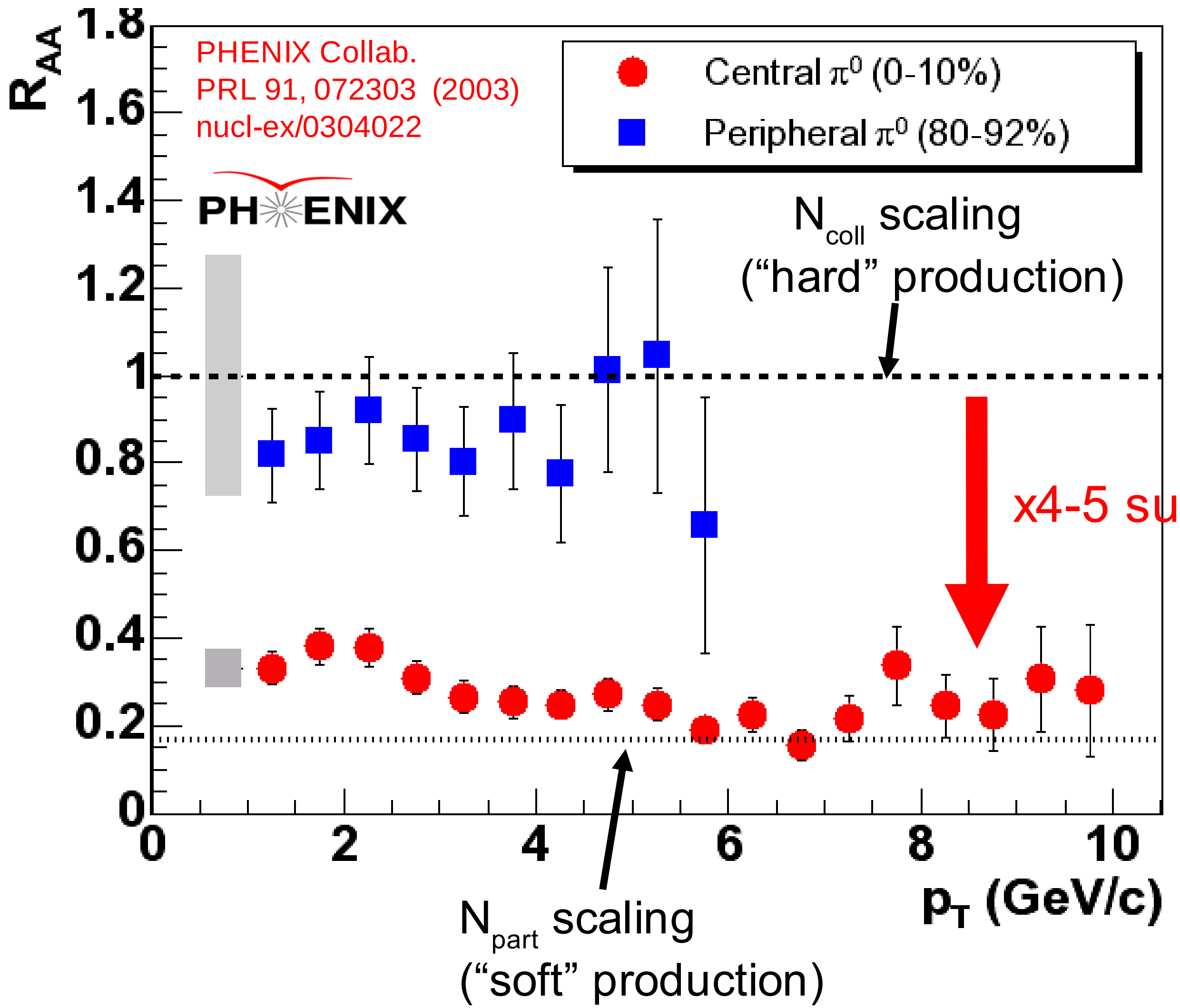


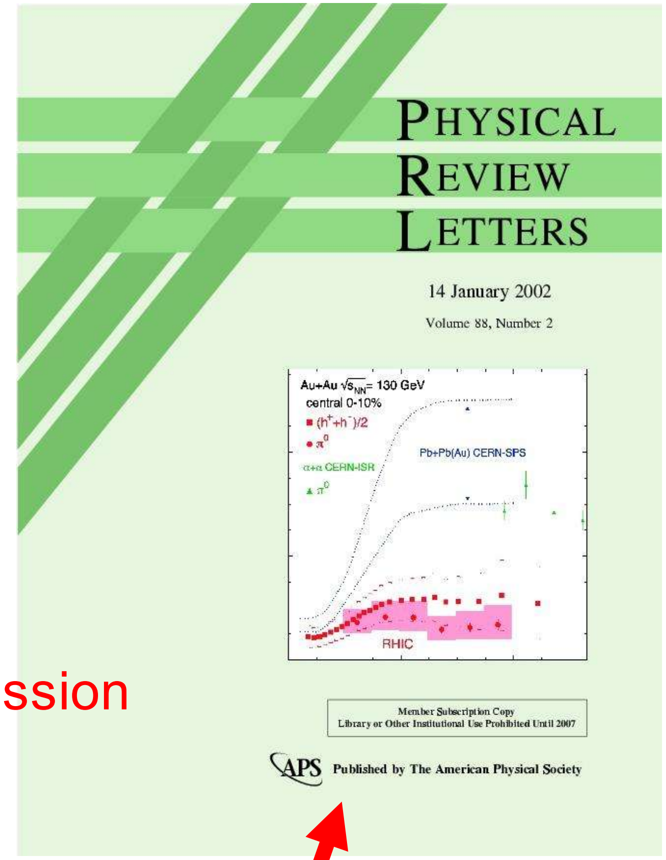
Peripheral data agree well with p+p (data&pQCD) plus collision scaling

Strong suppression in central Au+Au collisions

Nuclear modification factor (π^0)

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



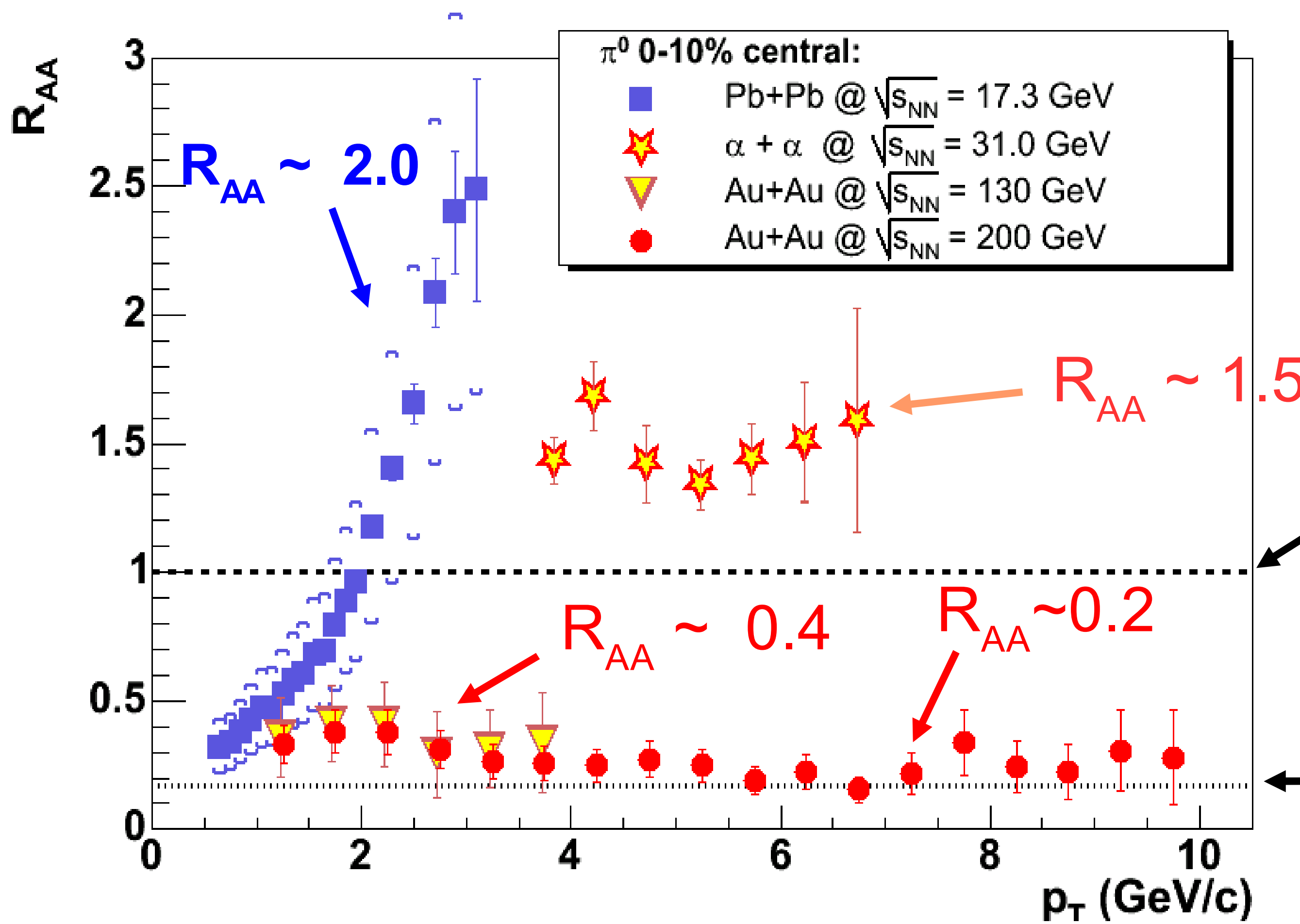


Discovery of high p_T suppression
(one of most significant results @ RHIC so far)

Nuclear modification factor: $\sqrt{s_{NN}}$ dependence

R_{AA} (π^0) compilation in nucleus-nucleus collisions:

- CERN: Pb+Pb ($\sqrt{s_{NN}}$ = 17.3 GeV), $\alpha+\alpha$ ($\sqrt{s_{NN}}$ = 31 GeV): Cronin enhancement.
- 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)
PHENIX, PRL 88 022301 (2002)
PHENIX, PRL 91, 072303 (2003)

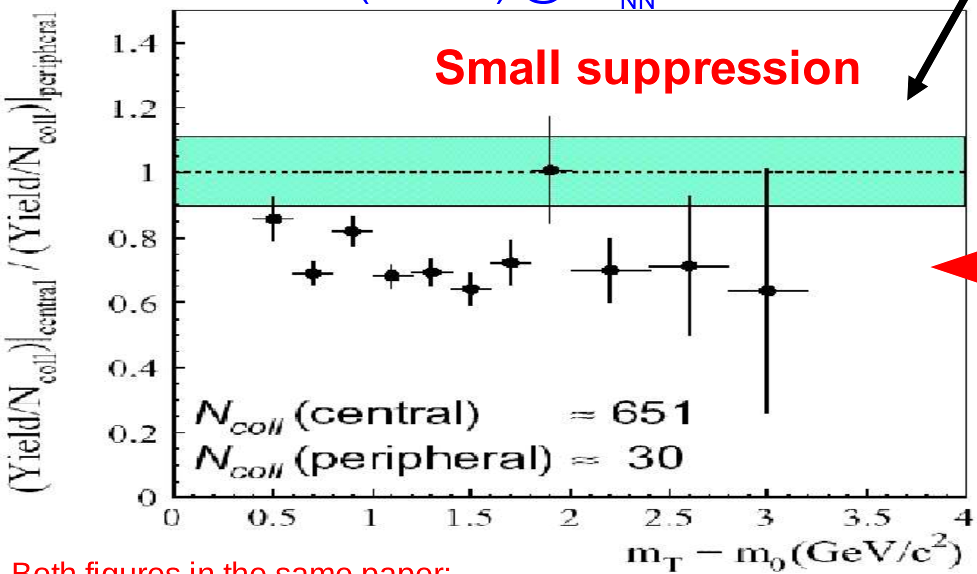
N_{coll} scaling ("hard" production)

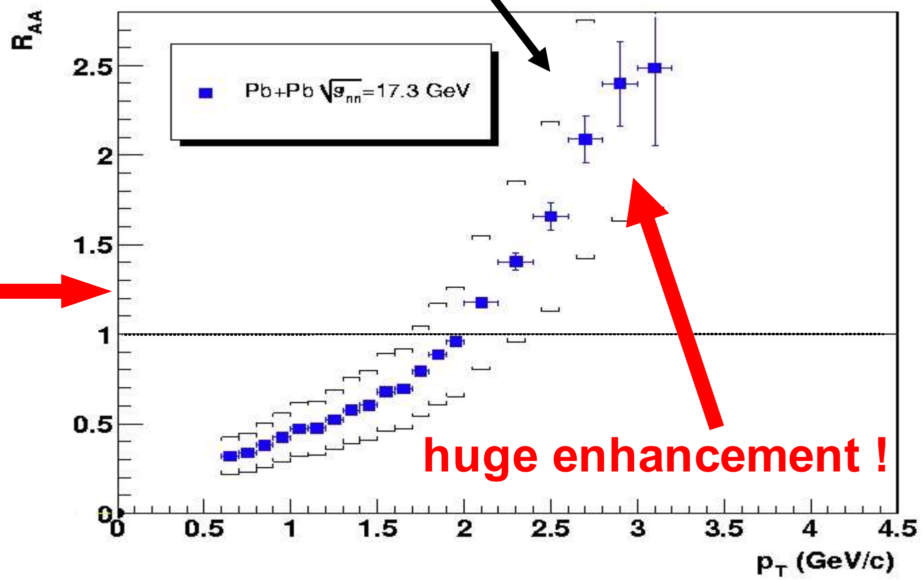
N_{part} scaling ("soft" production)

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

- However ... how does one reconcile R_{cp} ~ 0.8 with R_{AA} >> 1. for π^0 at SPS ?!

Pb+Pb (0-10%) @ $\sqrt{s_{NN}}$ = 17.3 GeV





Both figures in the same paper:
WA98, EPJ C 23, 225 (2002)

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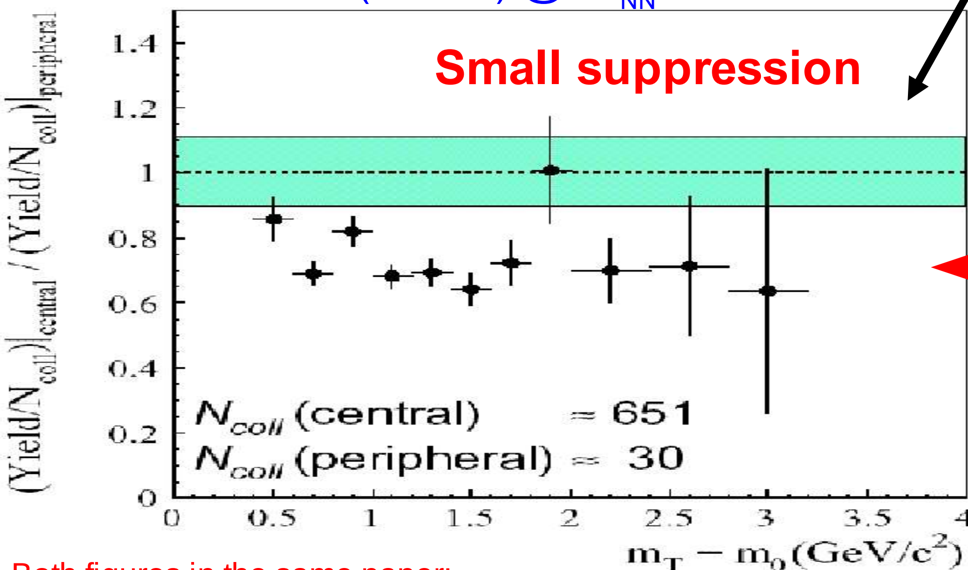

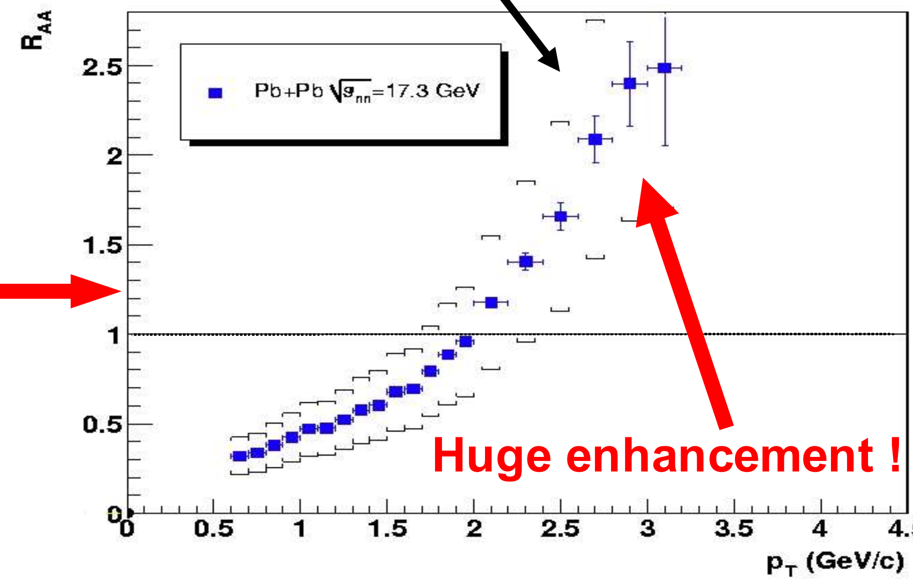

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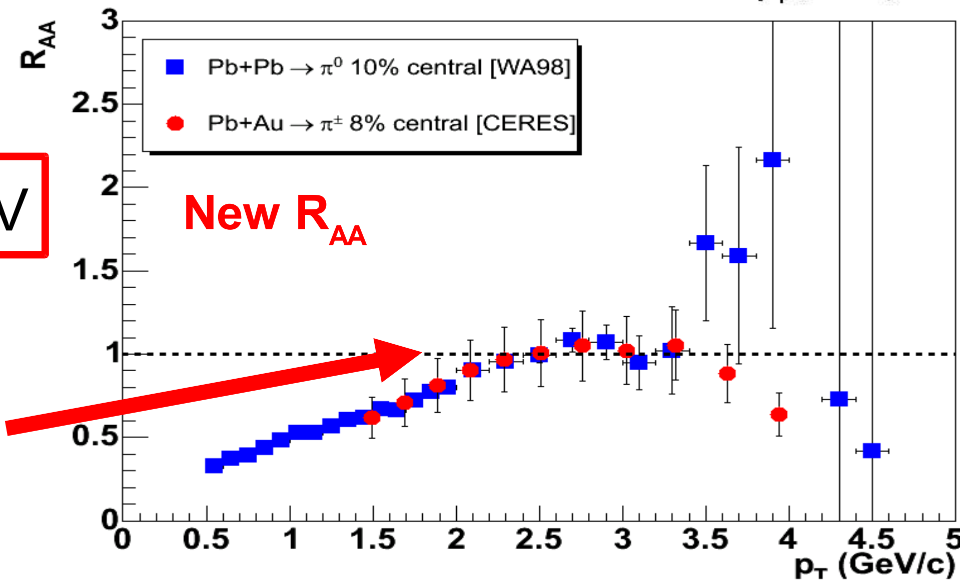
WA98, EPJ C 23, 225 (2002)

- Better p+p → π^0 ref. @ $\sqrt{s_{NN}}$ = 17.3 GeV

[details in D.d'E. poster S26].

- No "Cronin" effect ! (but N_{coll} scaling)

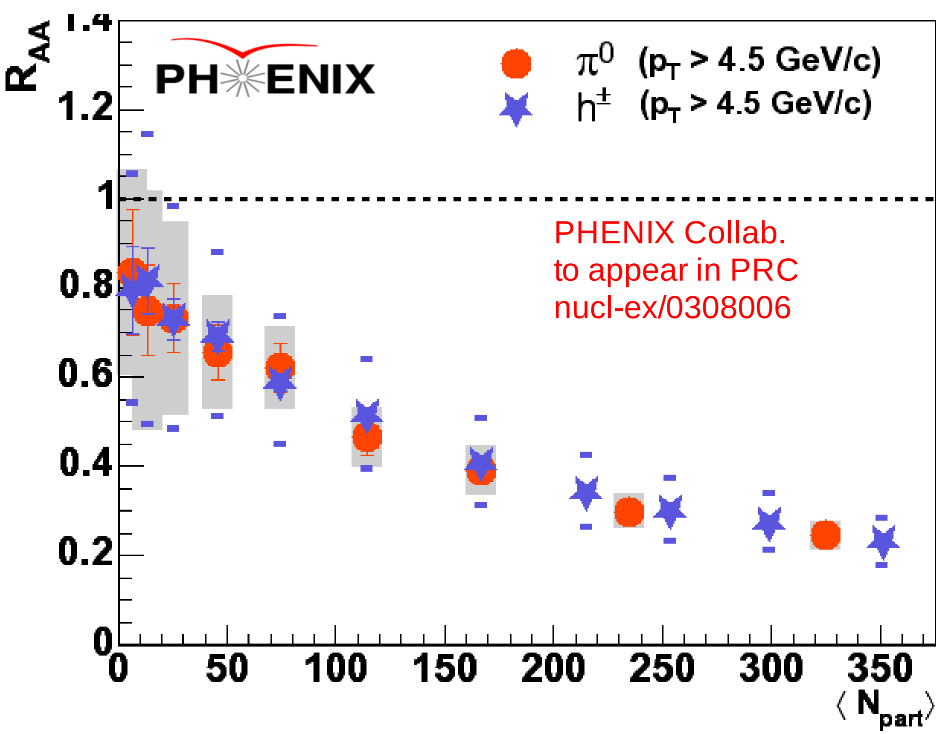


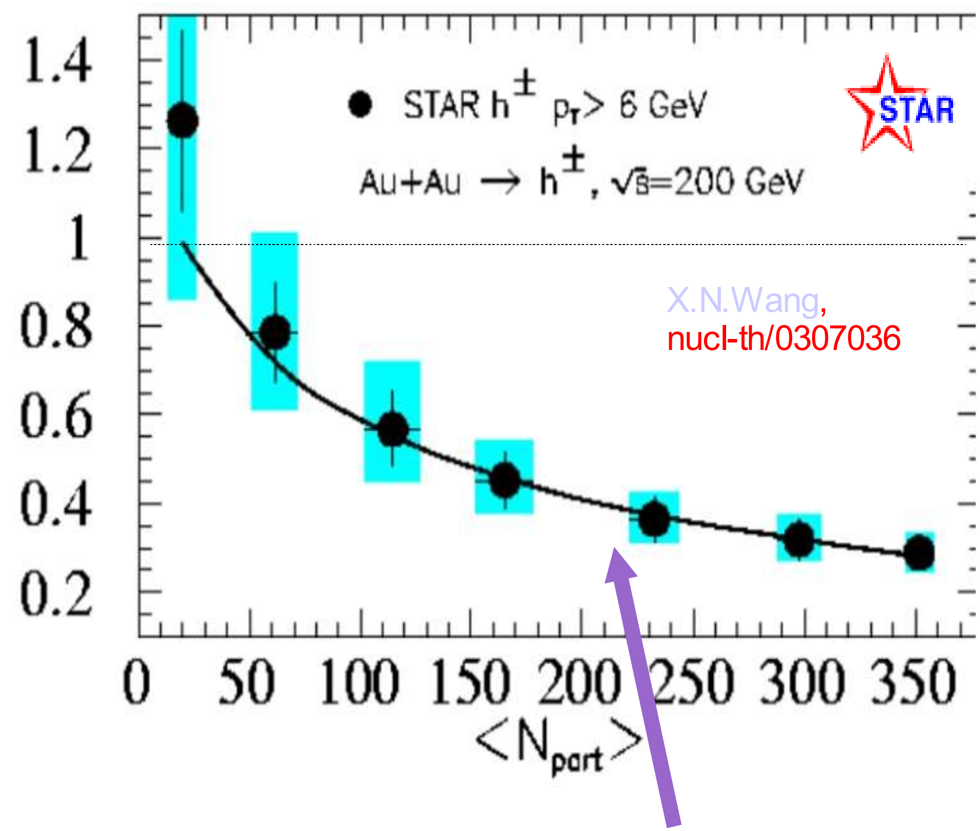
- Look for onset of suppression at RHIC Au+Au,p+p @ $\sqrt{s_{NN}} \approx$ 20 GeV ?

High p_T suppression: centrality dependence (I)

back to RHIC energies ....

- Smooth evolution of suppression w.r.t. N_{coll} scaling (in agreement with pQCD+parton energy loss expectations):



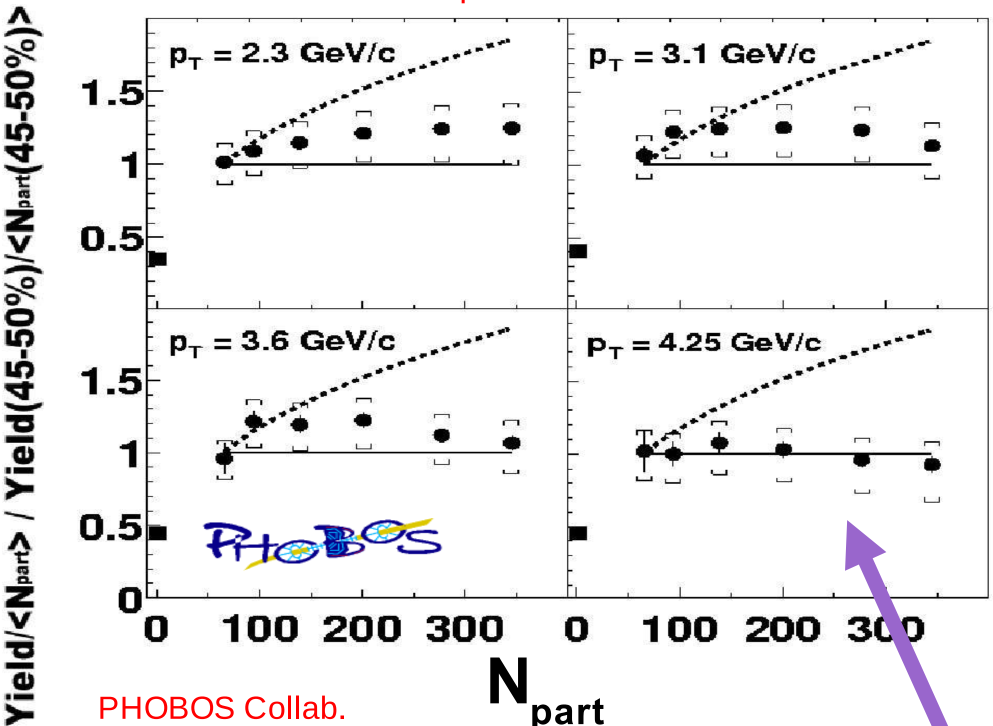


peripheral → central

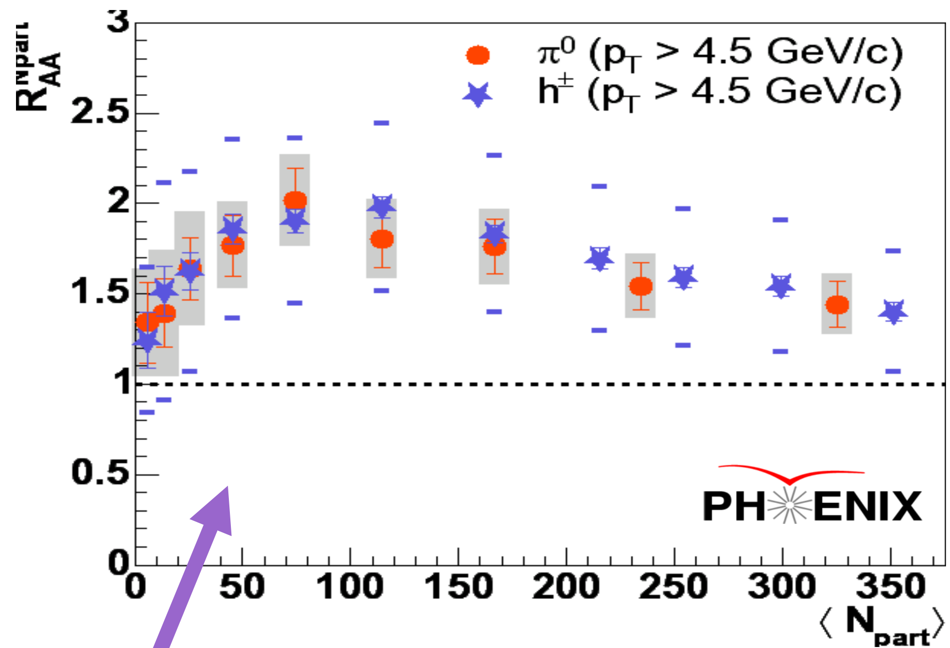
pQCD+partonic ΔE_{loss}
(1+1D expansion)

High p_T suppression: centrality dependence (II)

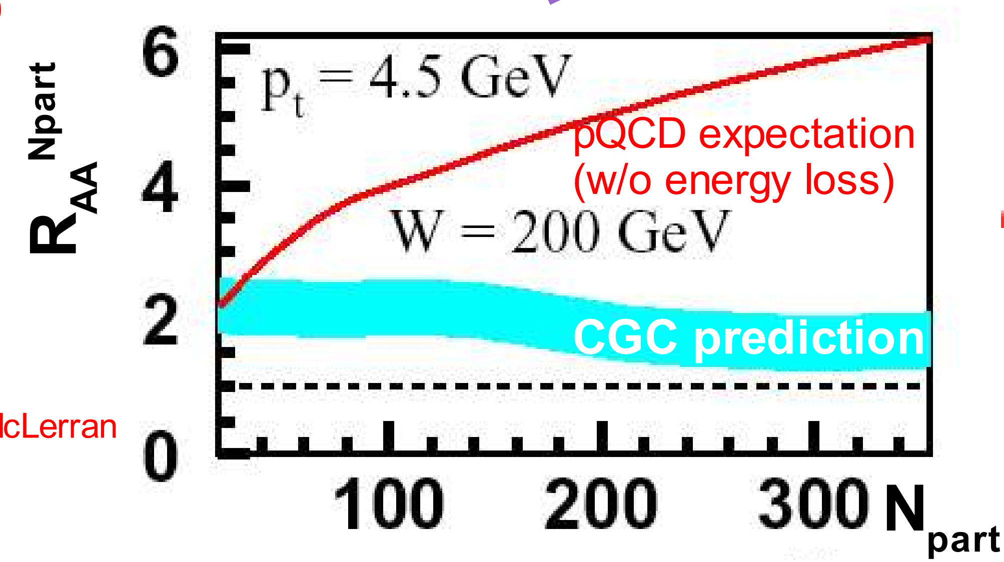
- Approx. N_{part} scaling (in accord with CGC predictions too):



PHOBOS Collab.
PLB 578, 297 (2003)
nucl-ex/0302015



PHENIX Collab.
to appear in PRC
nucl-ex/0308006

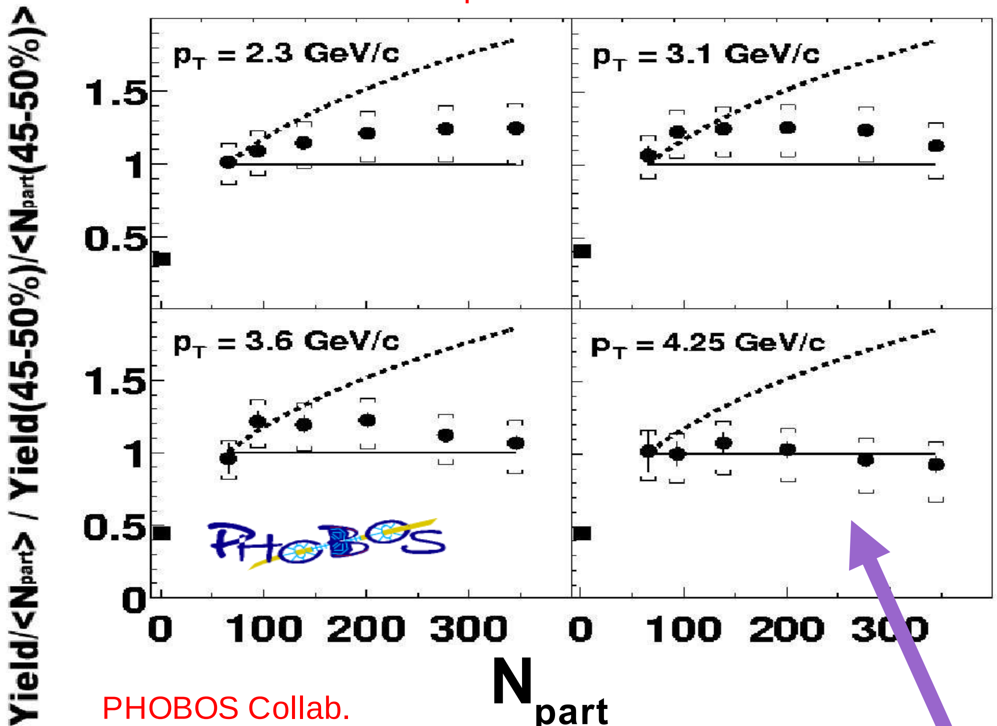


D.Kharzeev, E.Levin, L.McLerran
PLB 561, 93 (2003)

- High p_T production per participant pair ~constant in wide range of centralities

High p_T suppression: centrality dependence (II)

- Approx. N_{part} scaling (in accord with CGC predictions too):



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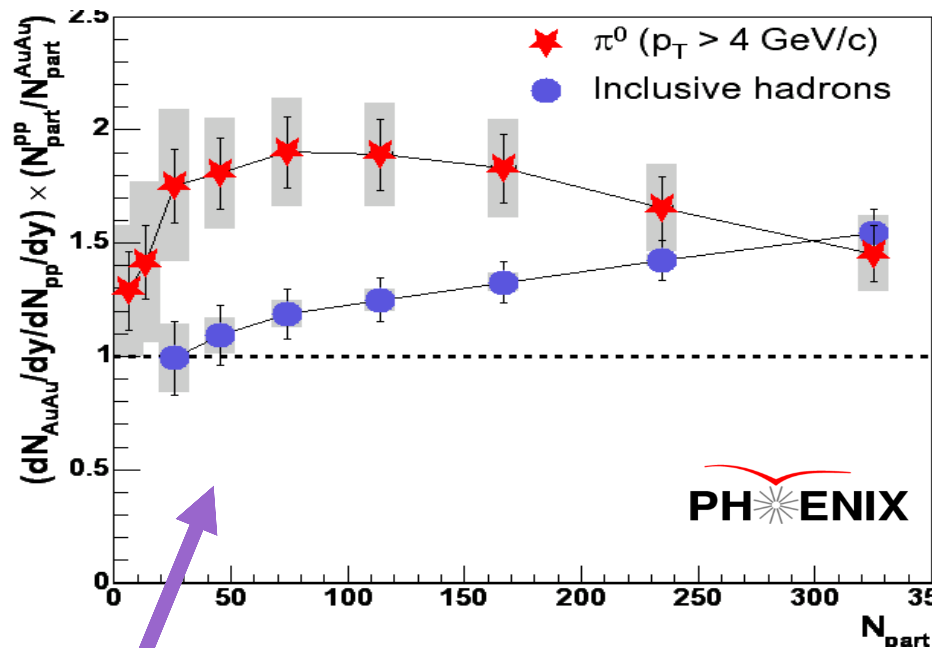

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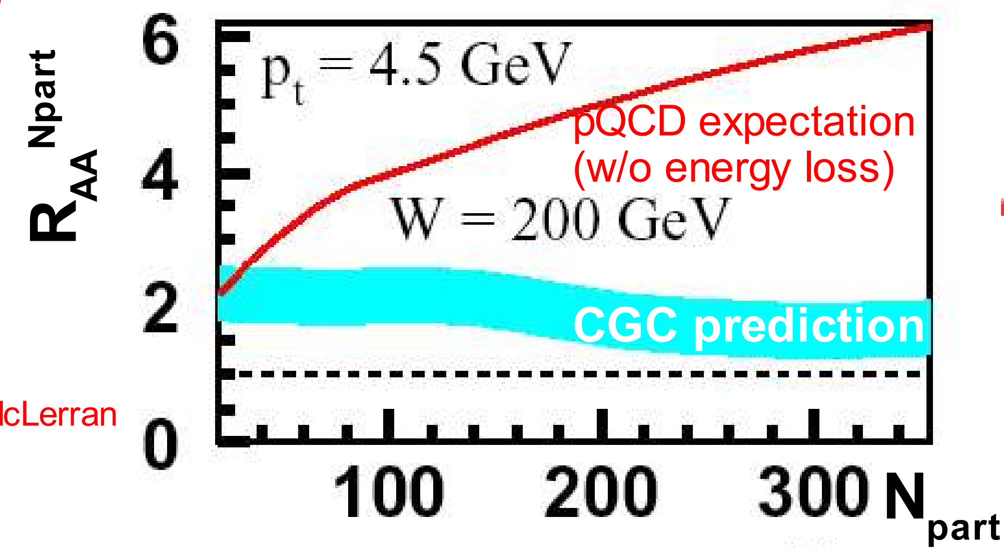

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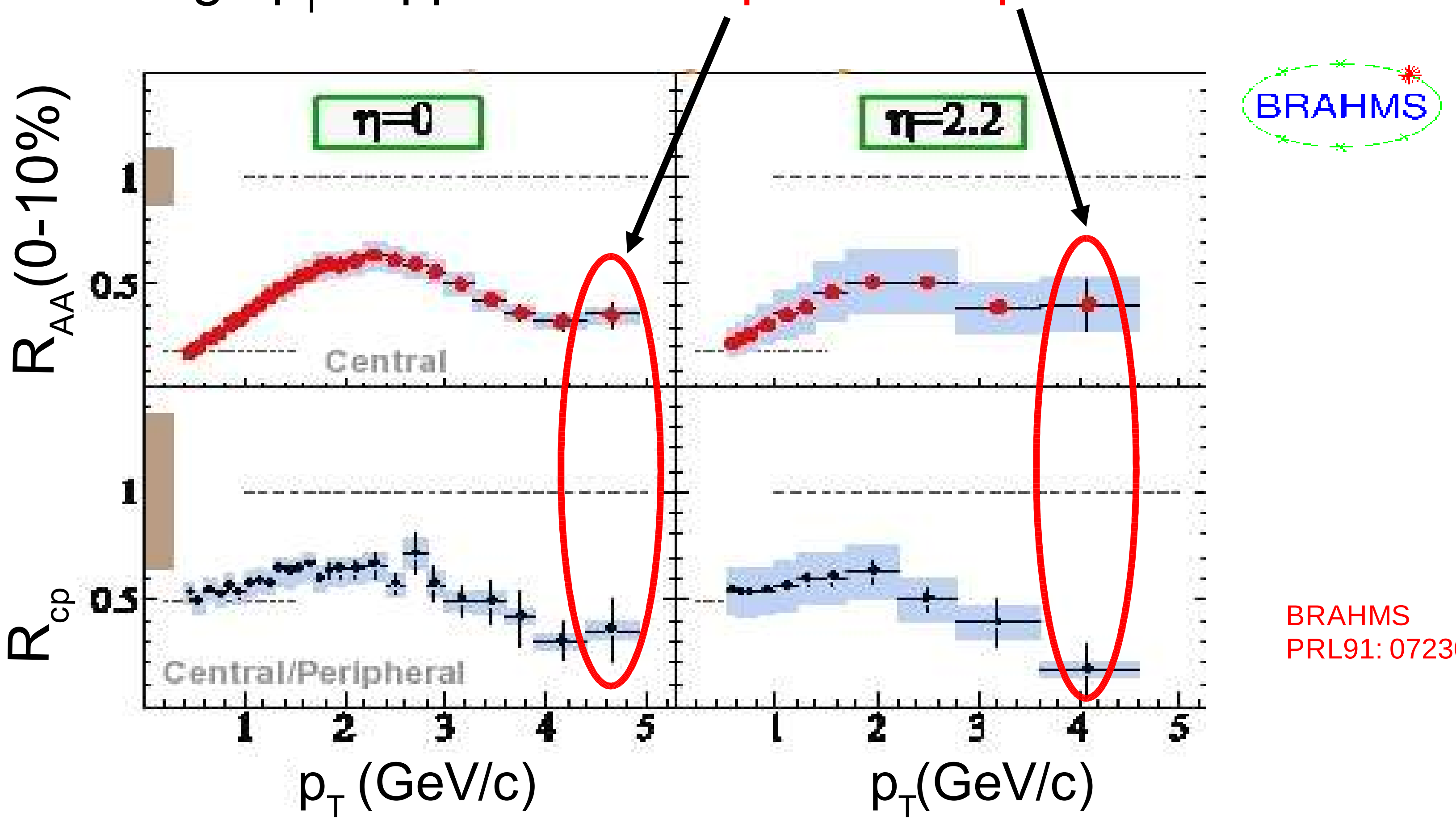
High p_T suppression: (pseudo)rapidity dependence

- Similar high p_T suppression at $\eta = 0$ and $\eta = 2.2$

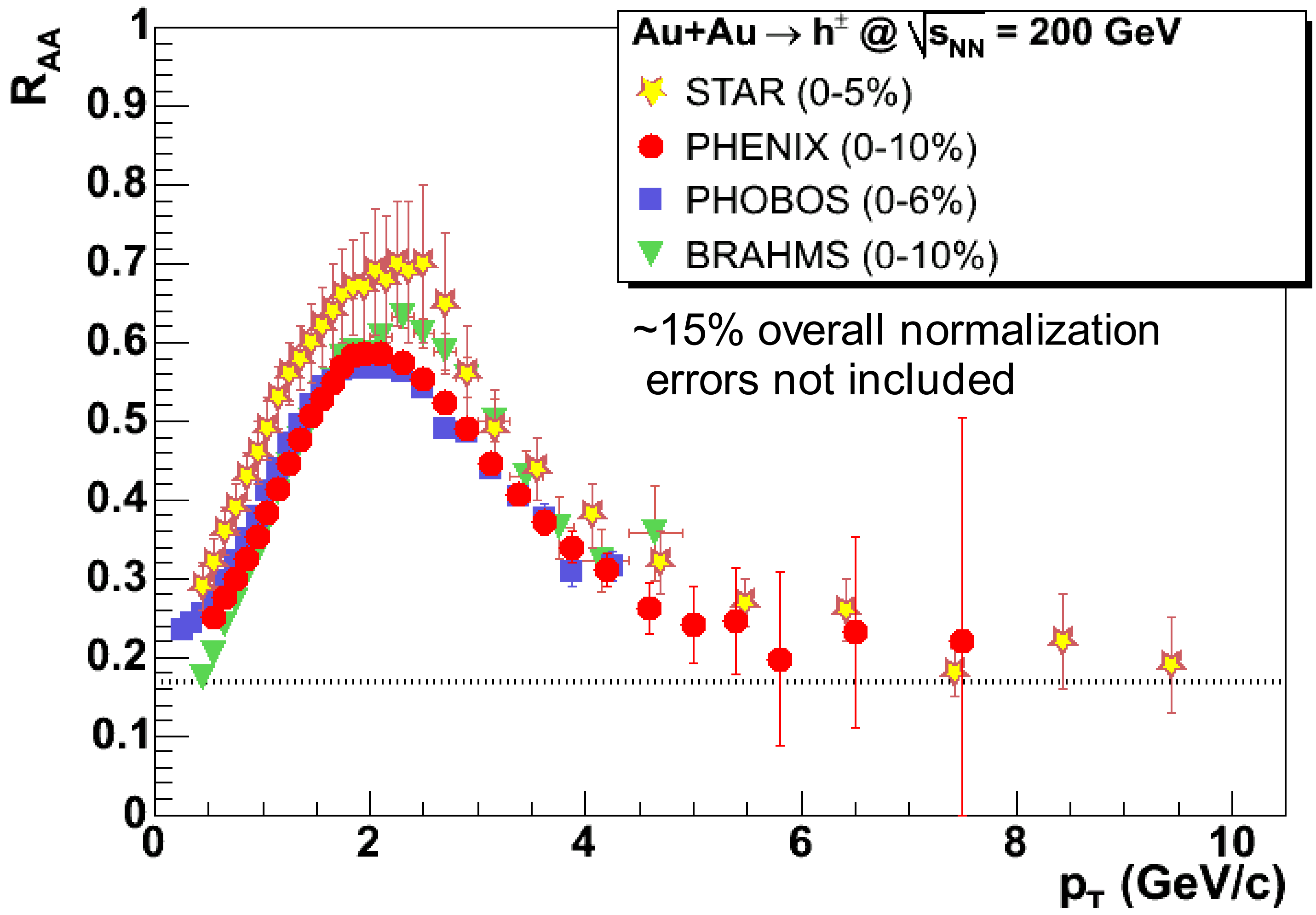


BRAHMS
PRL91: 072305(2003)

- *"The quenching medium extends also in the longitudinal direction."*
- Additional initial-state depletion at work too in this kinematic range (given the new d+Au results at forward rapidities).

High p_T suppression: particle dependence (I)

- Inclusive charged hadrons suppressed a factor ~ 4 – 5 at p_T= 5 GeV/c



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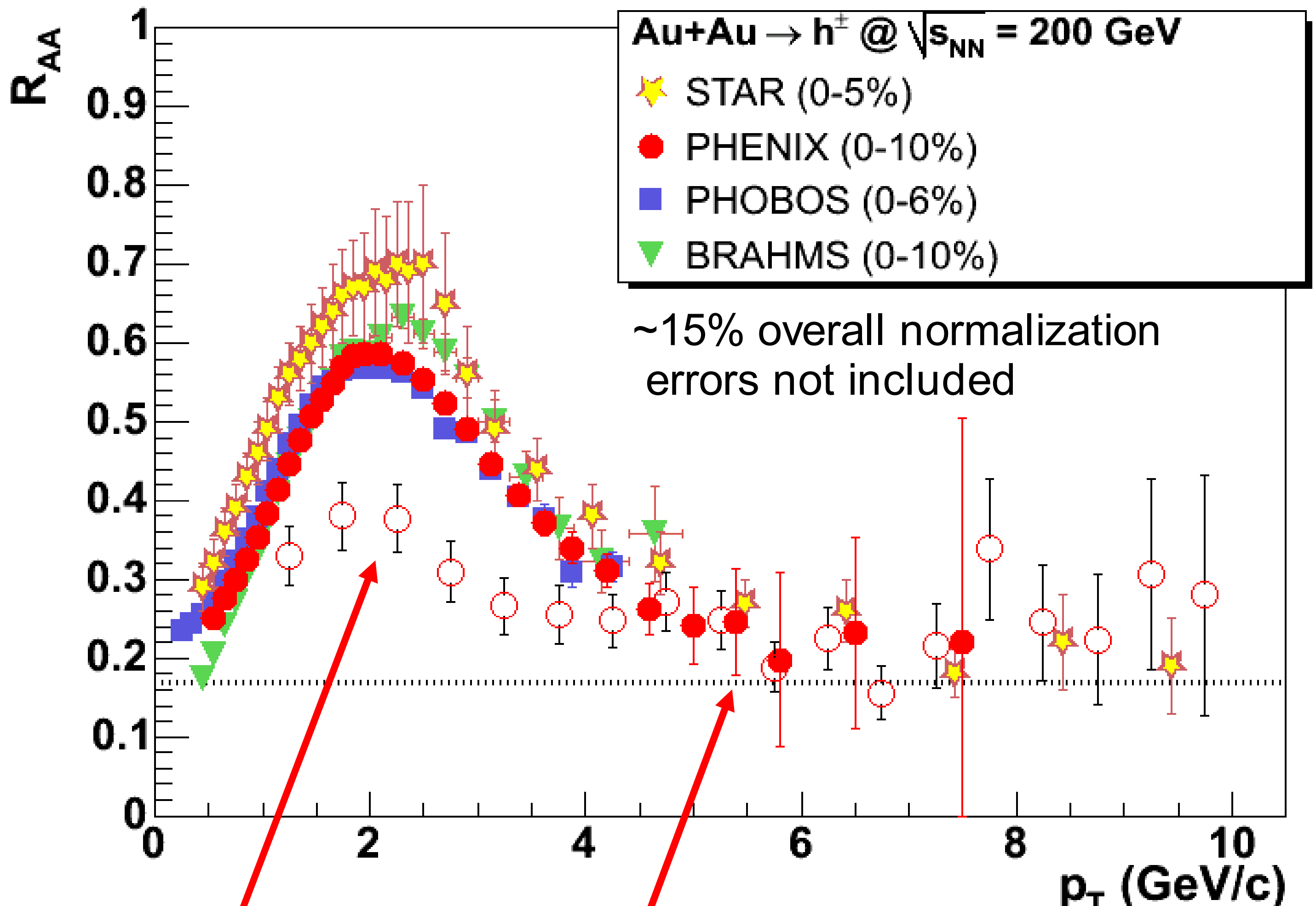
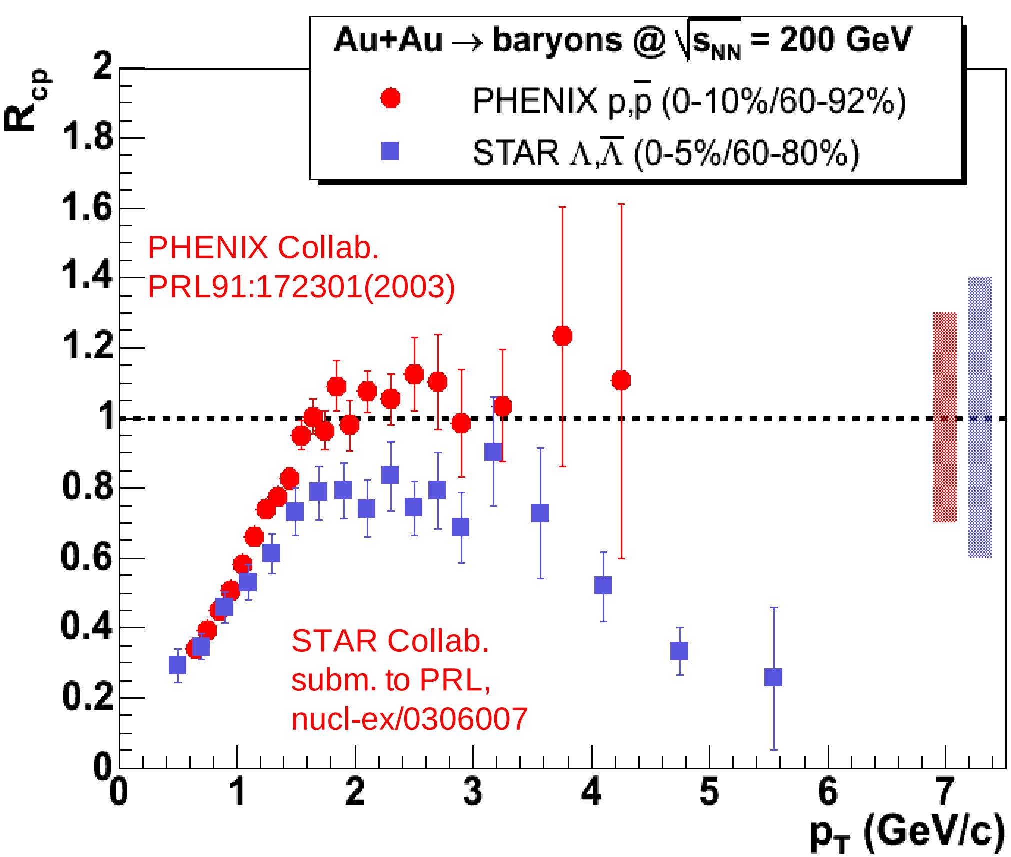
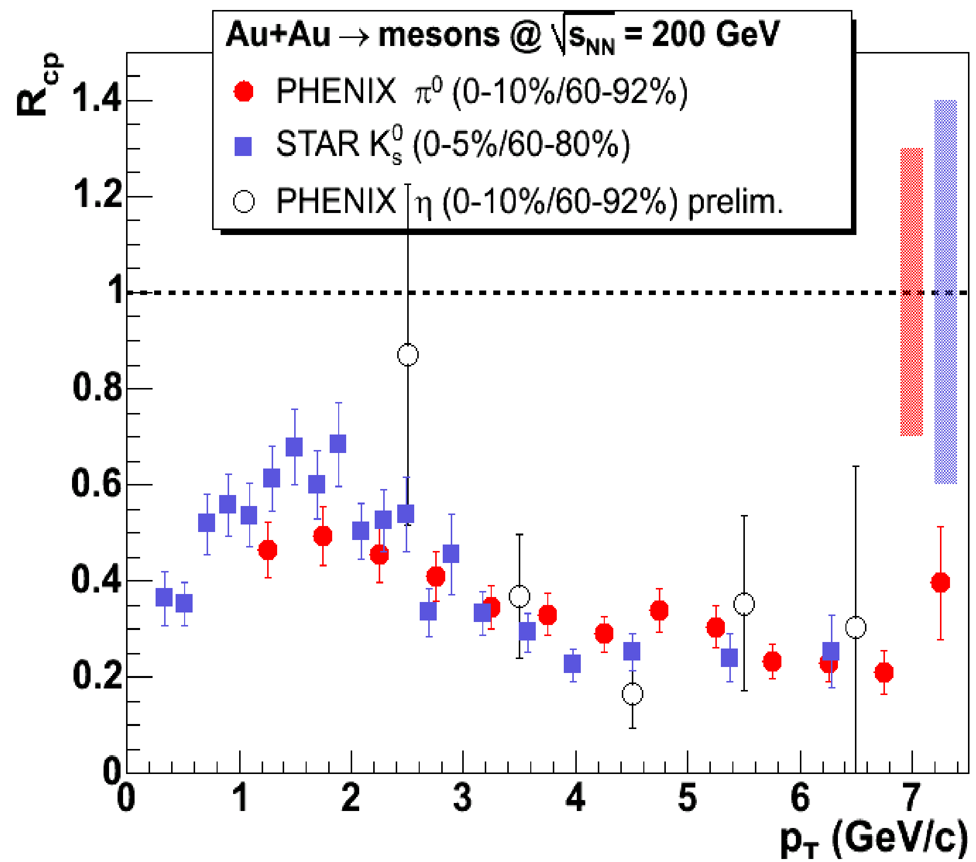


- ... but less than π^0 in the range p_T = 2 – 5 GeV/c.
- Universal (PID-wise) suppression above p_T = 5 GeV/c

High p_T suppression: particle dependence (II)

- R_{cp} (ratio central/peripheral) at intermediate p_T = 2 – 4 GeV/c:
  1. Baryons: p, $\bar{p}$, Λ, $\bar{\Lambda}$ **NOT** suppressed in central Au+Au.
  2. Mesons: π^0, k^0_s, η equally suppressed.

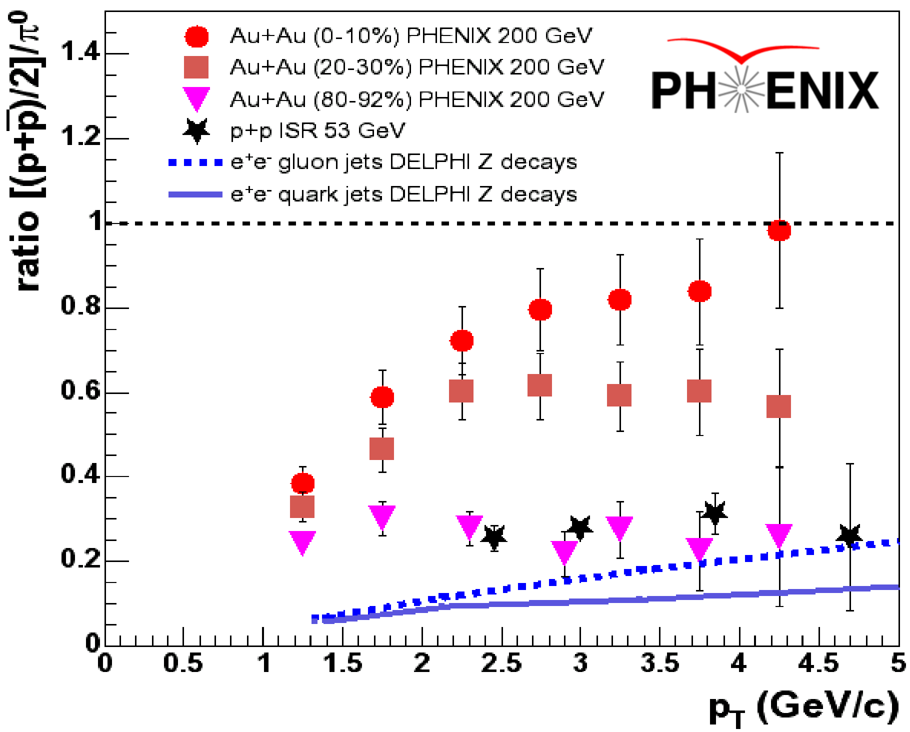


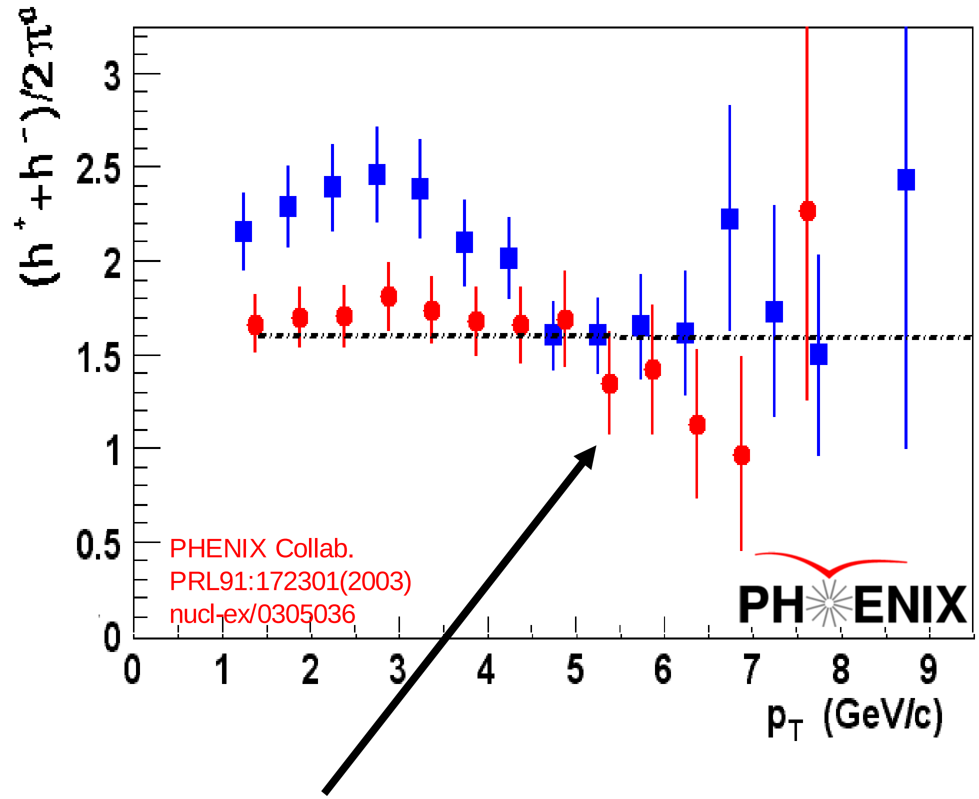


- Particle composition inconsistent with known fragmentation functions.
- Different production mechanism for baryons and mesons in the intermediate p_T range (e.g. fragmentation vs. q recombination in dense partonic medium).

High p_T suppression: particle dependence (III)

- Central colls.: $p/\pi \sim 0.8$ (at p_T = 2 - 4 GeV/c) at variance with perturbative production mechanisms (favour lightest meson).
- Periph. colls.: $p/\pi \sim 0.2$ as in p+p,p (ISR,FNAL) & in e+e- jet fragmentation

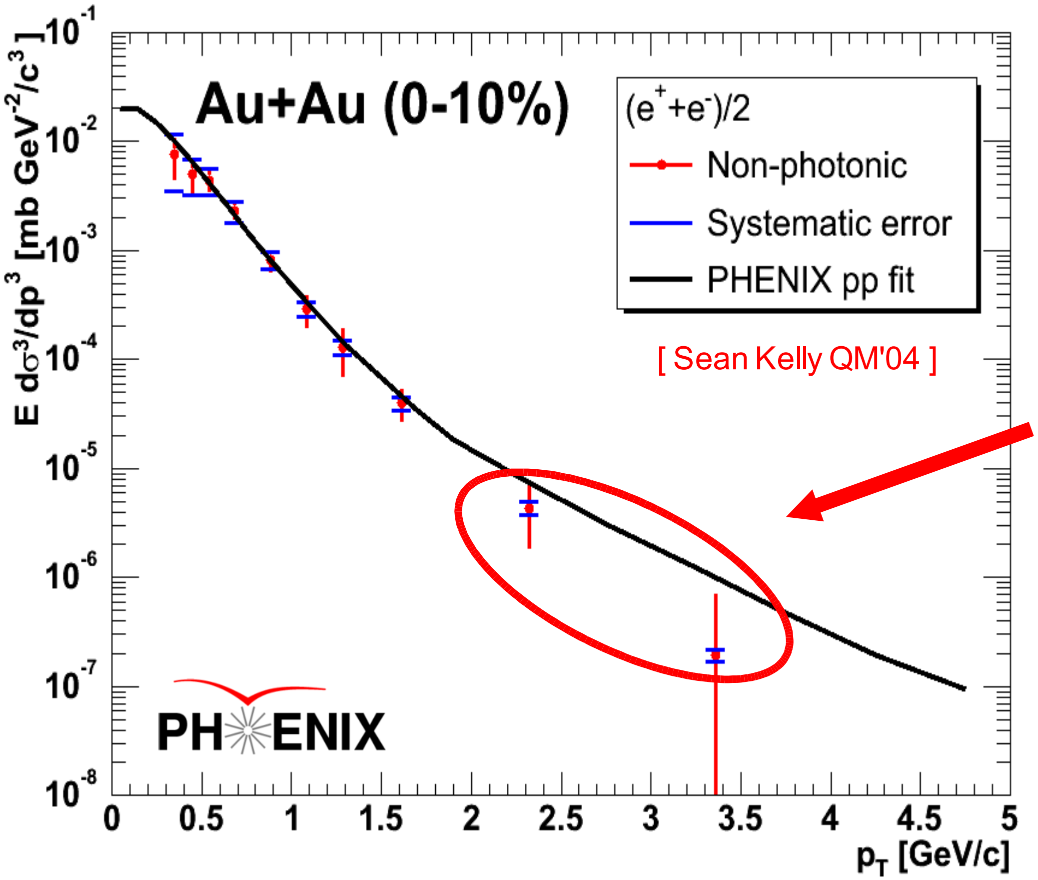




- Charged hadron and π^0 equally suppressed above $p_T \sim 5$ GeV/c: $h/\pi \sim 1.6$ as in p+p (perturbative ratio).
- Since $h^\pm = \pi^\pm + p(pbar) + K^\pm \Rightarrow$ baryon enhancement limited to $p_T < 4.5$ GeV/c

Unsuppressed (?) hard heavy-quark production

- Indirect measurement via semileptonic open-charm decays: $D \rightarrow e^{\pm}X$.
- Within uncertainties, single electron Au+Au central spectra and x-section(*) consistent with N_{coll} scaled p+p charm production:



(*) Charm production is intrinsically hard: N_{coll} scaling expected down to low p_T

- Possible reduction (1σ) at high p_T ?

factor ~2 less suppression expected for D than for π (R_{AA}=0.2) in models of medium-induced energy loss

Wait for results from hi-stat. Run-4.

- Strong(*) medium effects on heavy flavor production precluded so far.

(*) at least as strong as for light-quark mesons.

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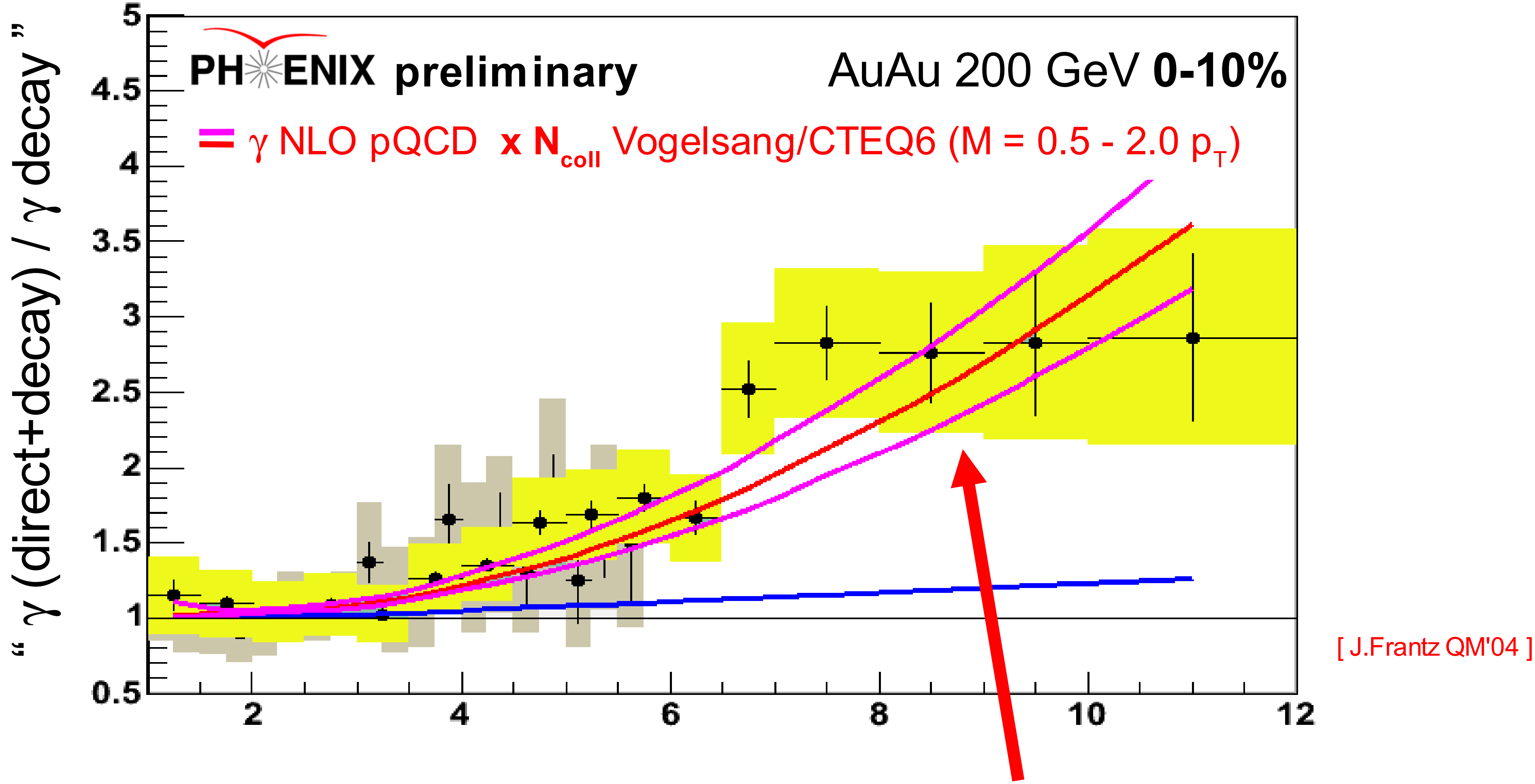
Unsuppressed hard colorless production

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

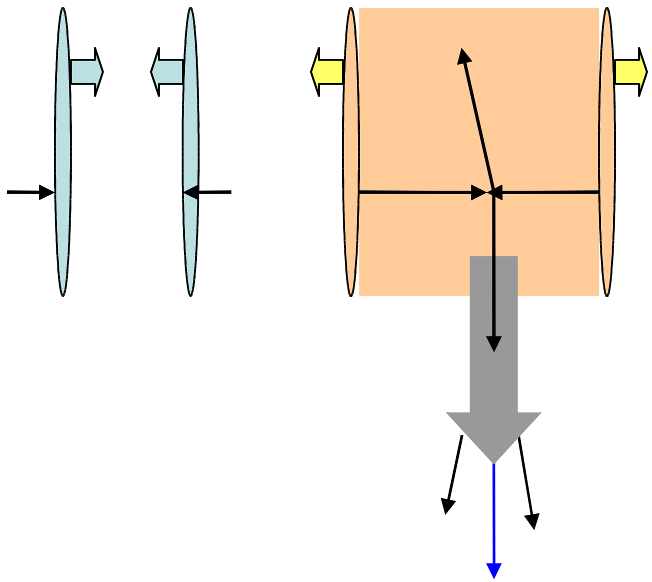


- Probes insensitive to colored final-state do show <u>collision scaling</u> at high p_T:

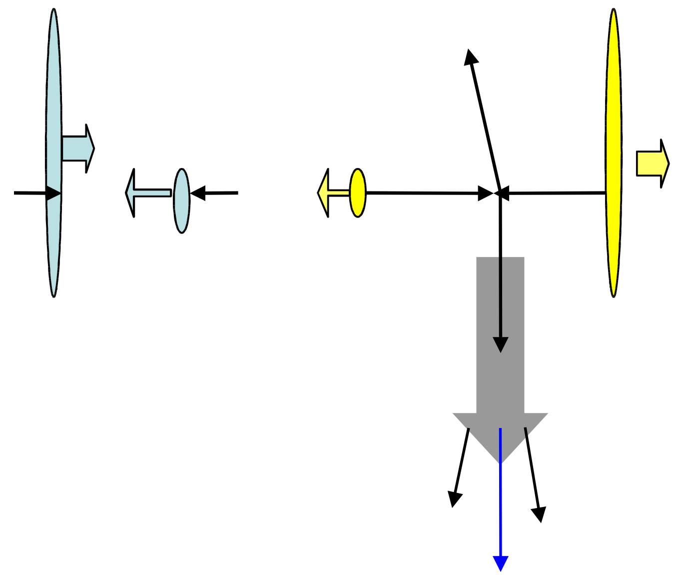
pQCD incoherent parton scattering holds for hard processes in central Au+Au !

High p_T in d+Au ("control" experiment)

A+Au collision



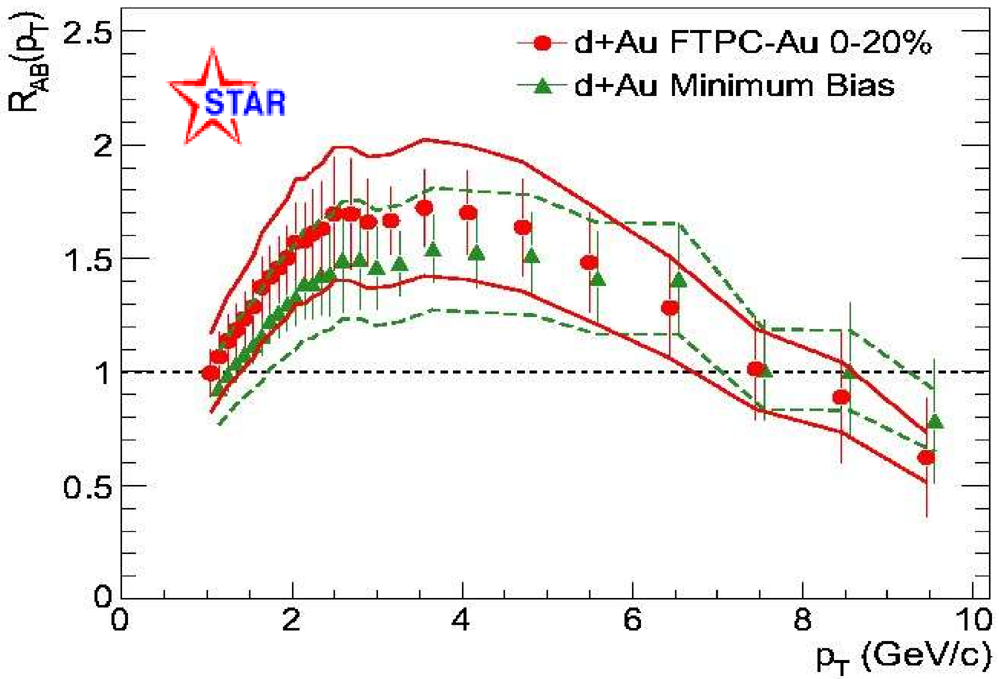
p,d+Au collision



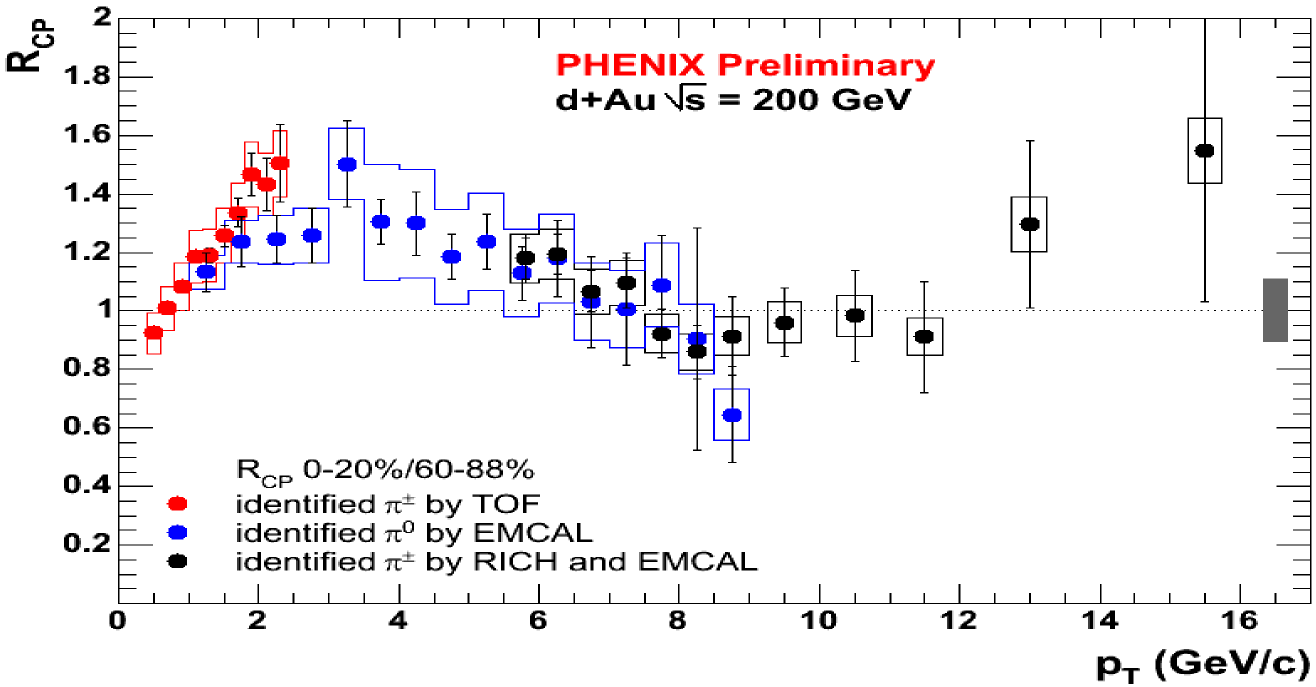
hot & dense medium
(initial+final-state effects)

cold medium
(initial- state effects only)

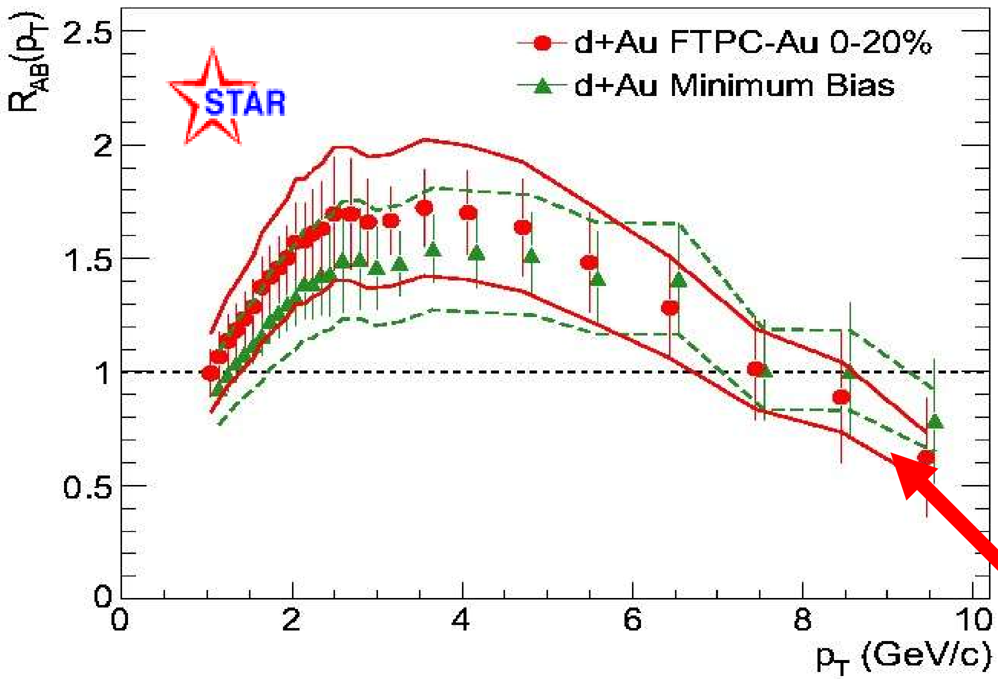
d+Au nuclear modification factor (η=0)



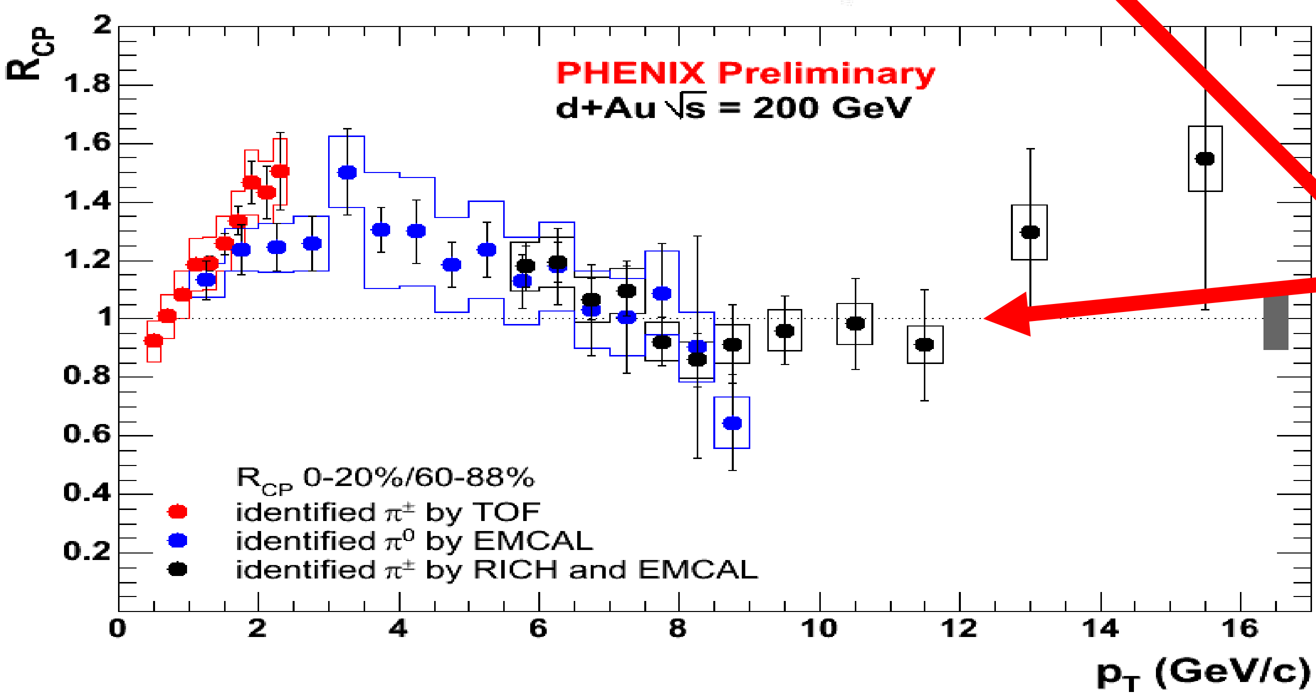
- $R_{dAu} > 1$ in min. bias, central d+Au and p+Au (neutron-tagged) colls.
- High p_T d+Au unquenched: reminiscent of p+A "Cronin enhancement" (initial-state soft & semihard scattering).
- No Au gluon saturation effects in kinematic region probed (η = 0).



d+Au nuclear modification factor (η=0)

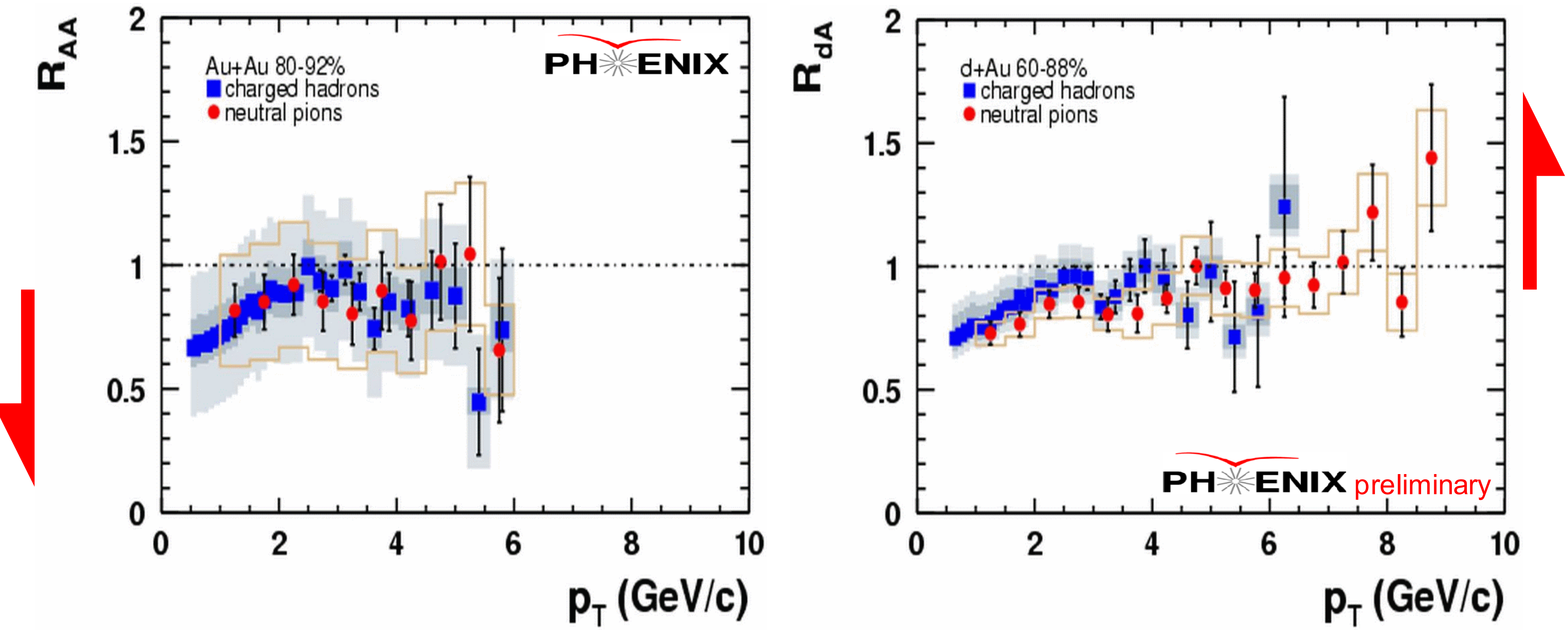


- $R_{dAu} > 1$ in min. bias, central d+Au and p+Au (neutron-tagged) colls.
- High p_T d+Au unquenched: reminiscent of p+A "Cronin enhancement" (initial-state soft & semihard scattering).
- No Au gluon saturation effects in kinematic region probed ($\eta = 0$).



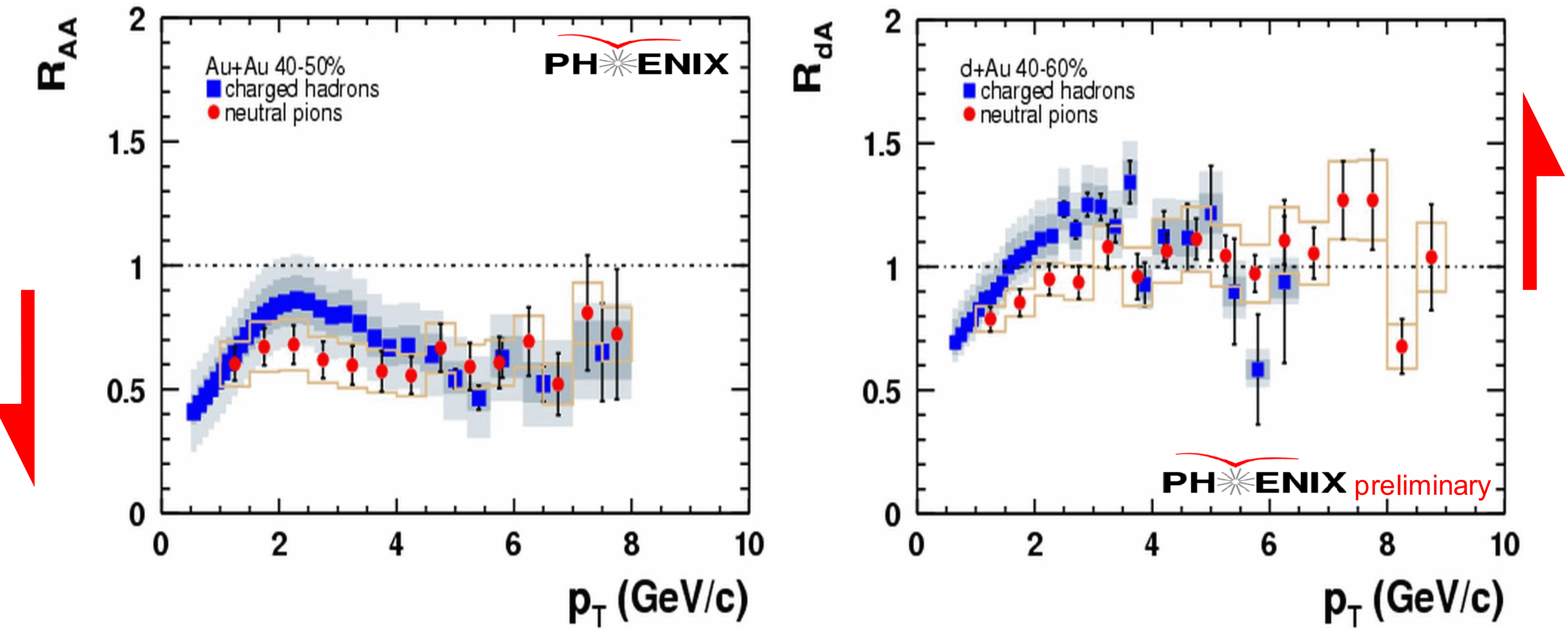
Cronin effect disappears ($R_{cp} \approx 1$) above $p_T \approx 8$ GeV/c

R_{AA} vs. R_{dA} ($\eta = 0$) : centrality dependence



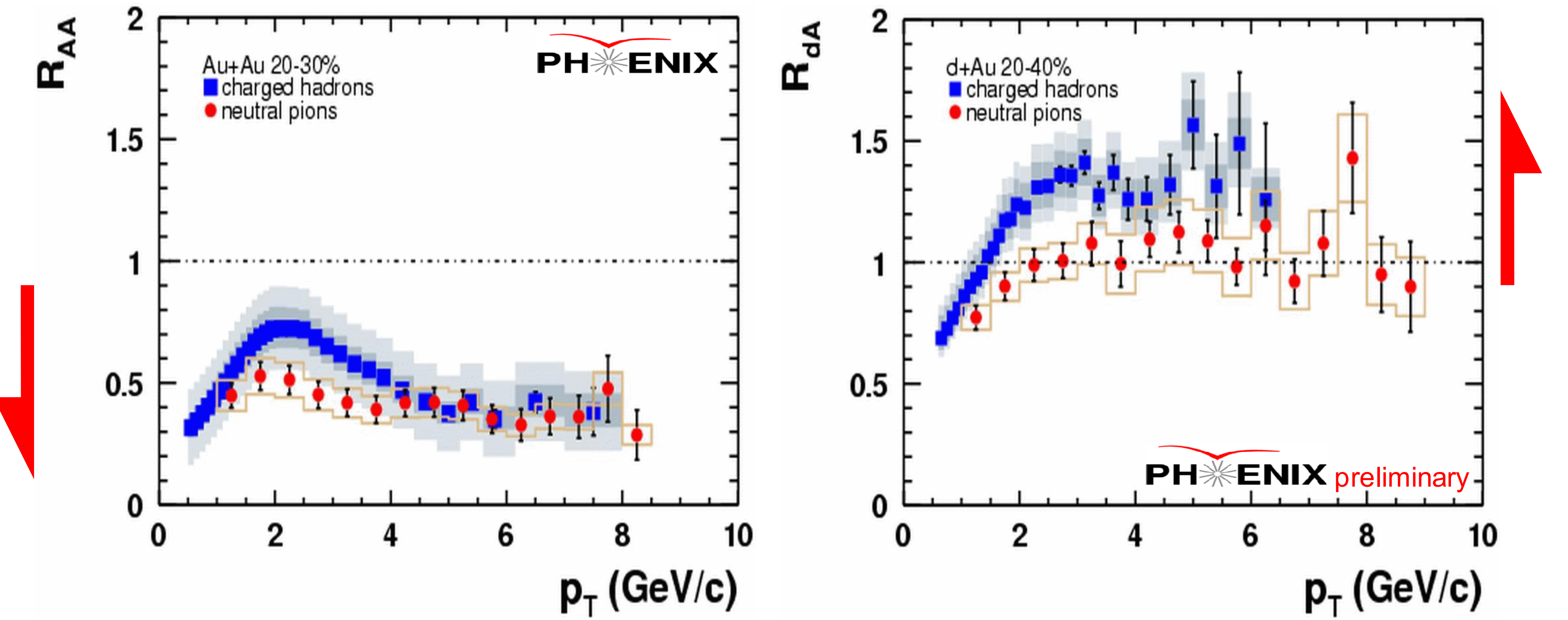
- PERIPHERAL Au+Au & d+Au

R_{AA} vs. R_{dA} (η = 0) : centrality dependence



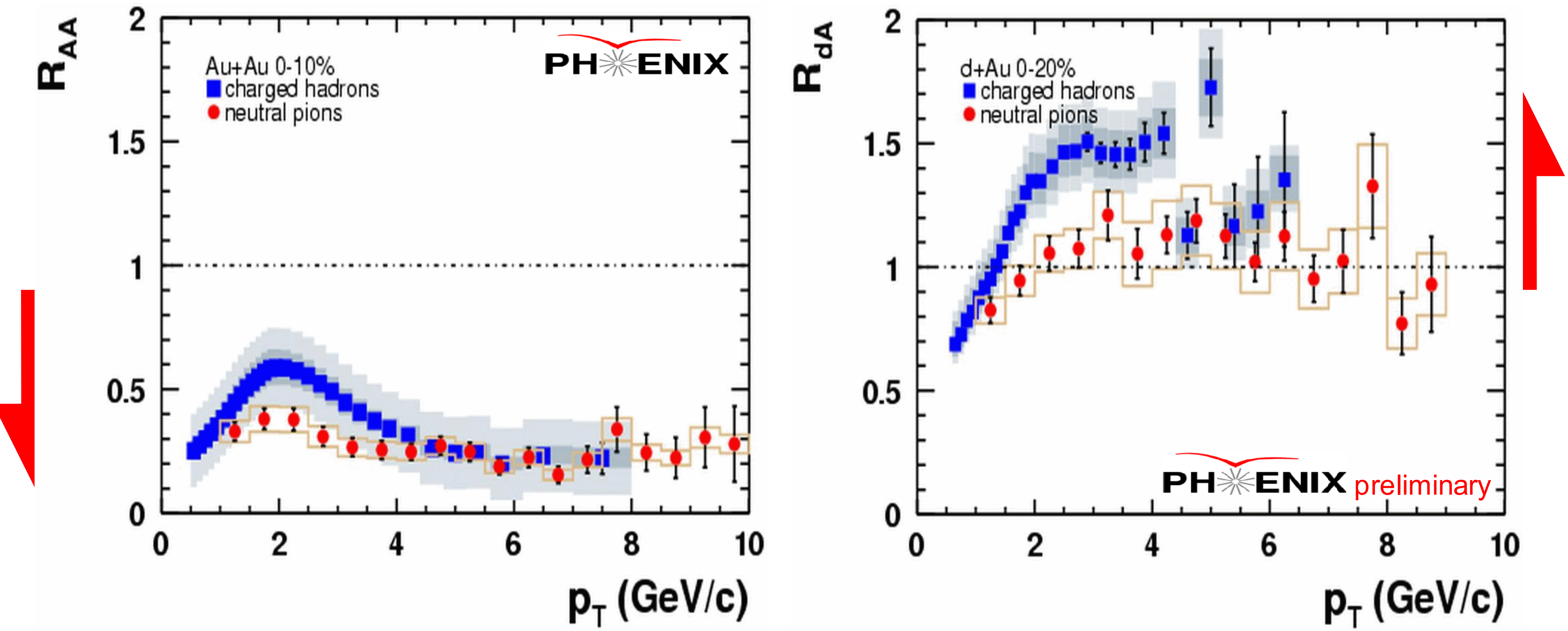
- MID-PERIPHERAL Au+Au & d+Au

R_{AA} vs. R_{dA} (η = 0) : centrality dependence



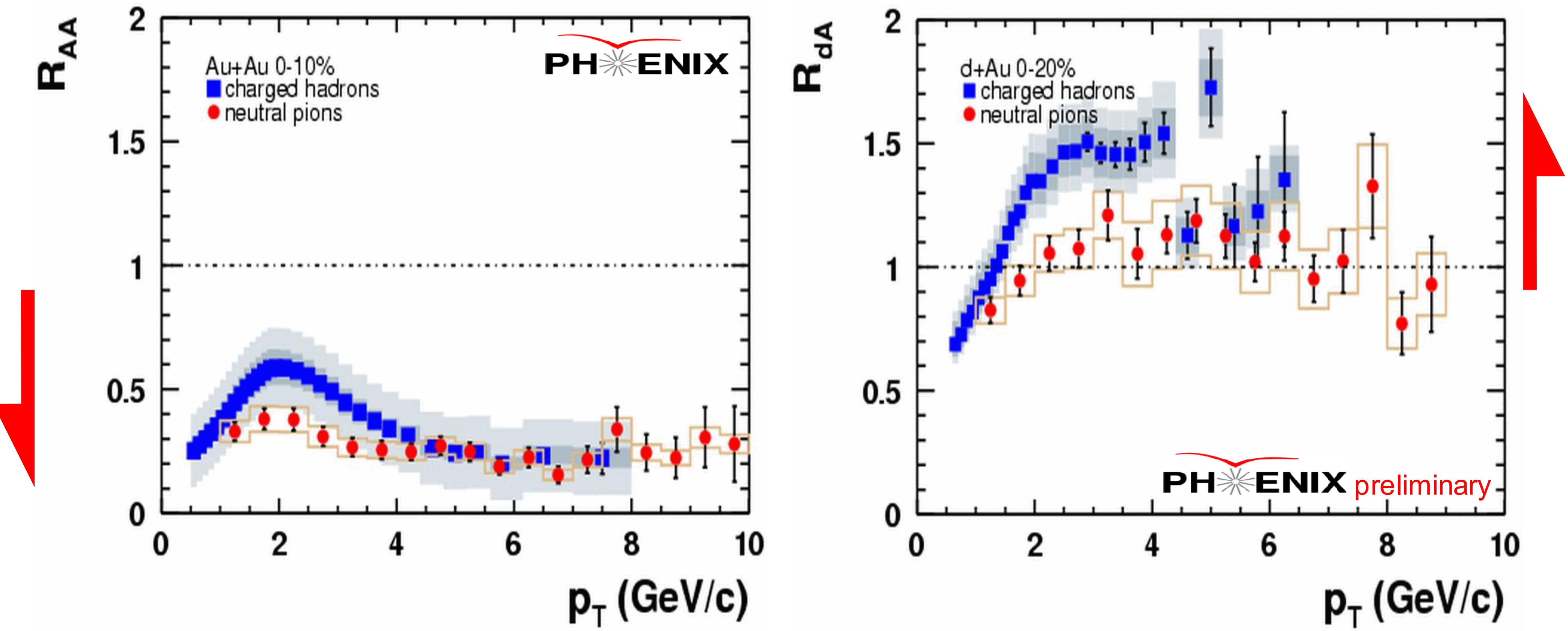
- MID-CENTRAL Au+Au & d+Au

R_{AA} vs. R_{dA} ($\eta = 0$) : centrality dependence



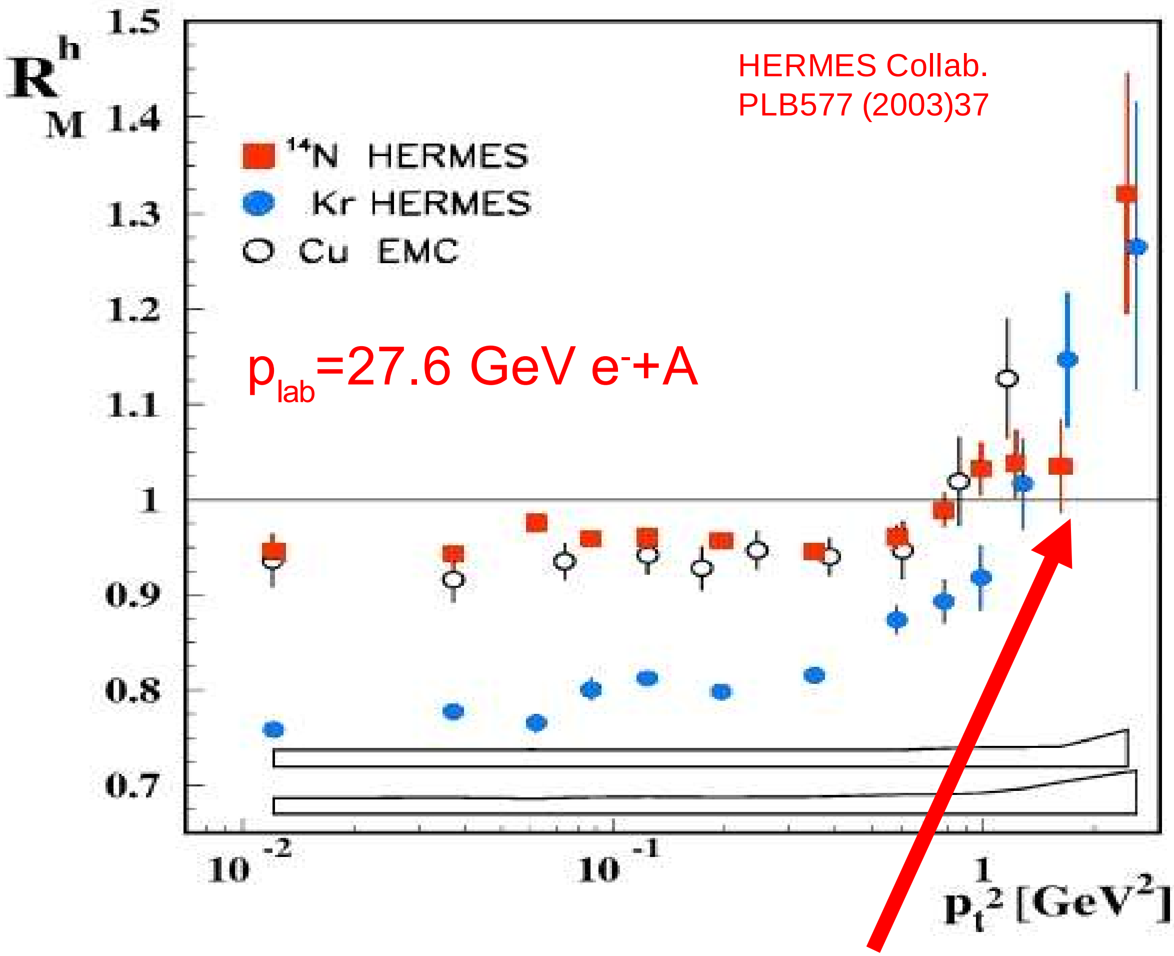
- CENTRAL Au+Au & d+Au

R_{AA} vs. R_{dA} ($\eta = 0$) : centrality dependence



- Opposite centrality dependence of d+Au nuclear enhancement compared to Au+Au nuclear suppression.
- (Model-independent) conclusion: Au+Au suppression at y = 0 not due to a “cold” (initial-state) nuclear matter effect: gluon saturation effects not relevant, final-state (QGP) interpretation favoured.

Nuclear attenuation factor in e+A

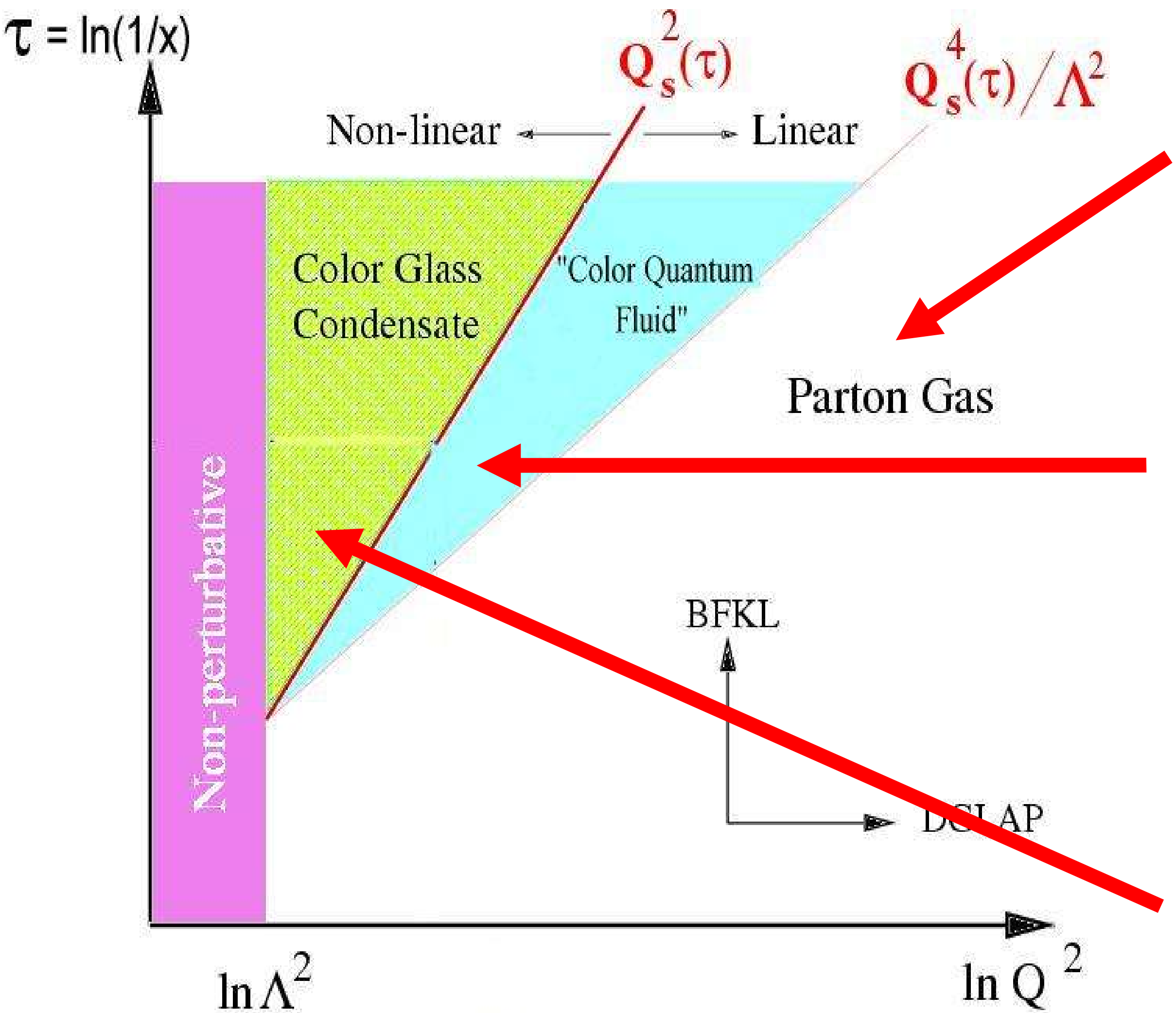


- Cronin-like p_T broadening observed in nuclear DIS too.
- Nuclear attenuation ratio is free from modified nPDF effects:

$$R_M^h(z,\nu,p_t^2,Q^2) = \frac{\left.\frac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_A}{\left.\frac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_D}$$

The quest for gluon saturation effects @ RHIC ...

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



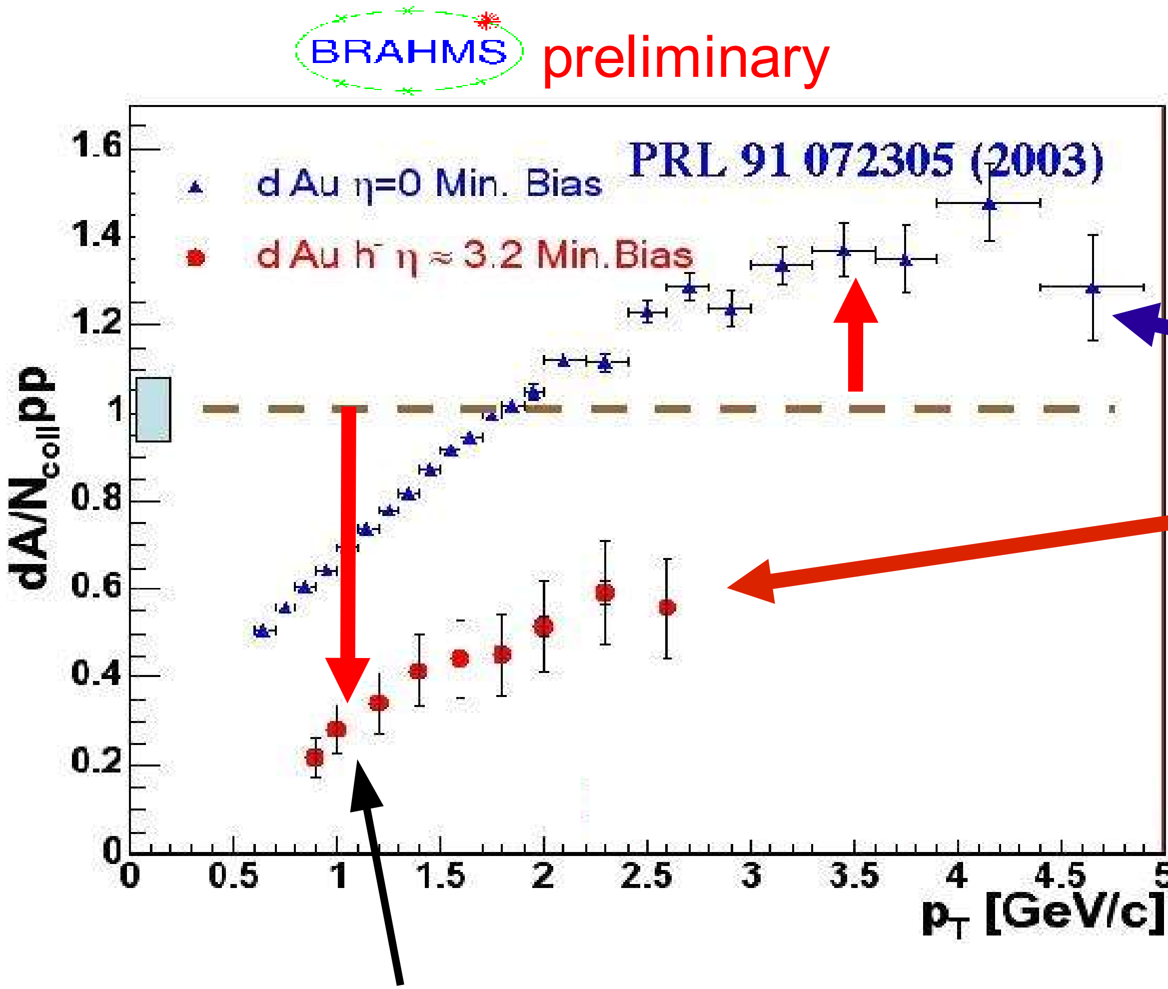
RHIC kinematical regime:

- **High p_T @ midrapidity:**
  $y = 0$, $Q^2 = 1\text{-}100$ GeV^2/c^2
  - pQCD collinear factorization
  - DGLAP evolution (g splitting)
  - small (~20%) nuclear effects in PDFs (LT shadowing).

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

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

d+Au nuclear modification factor (η = 3.2)



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

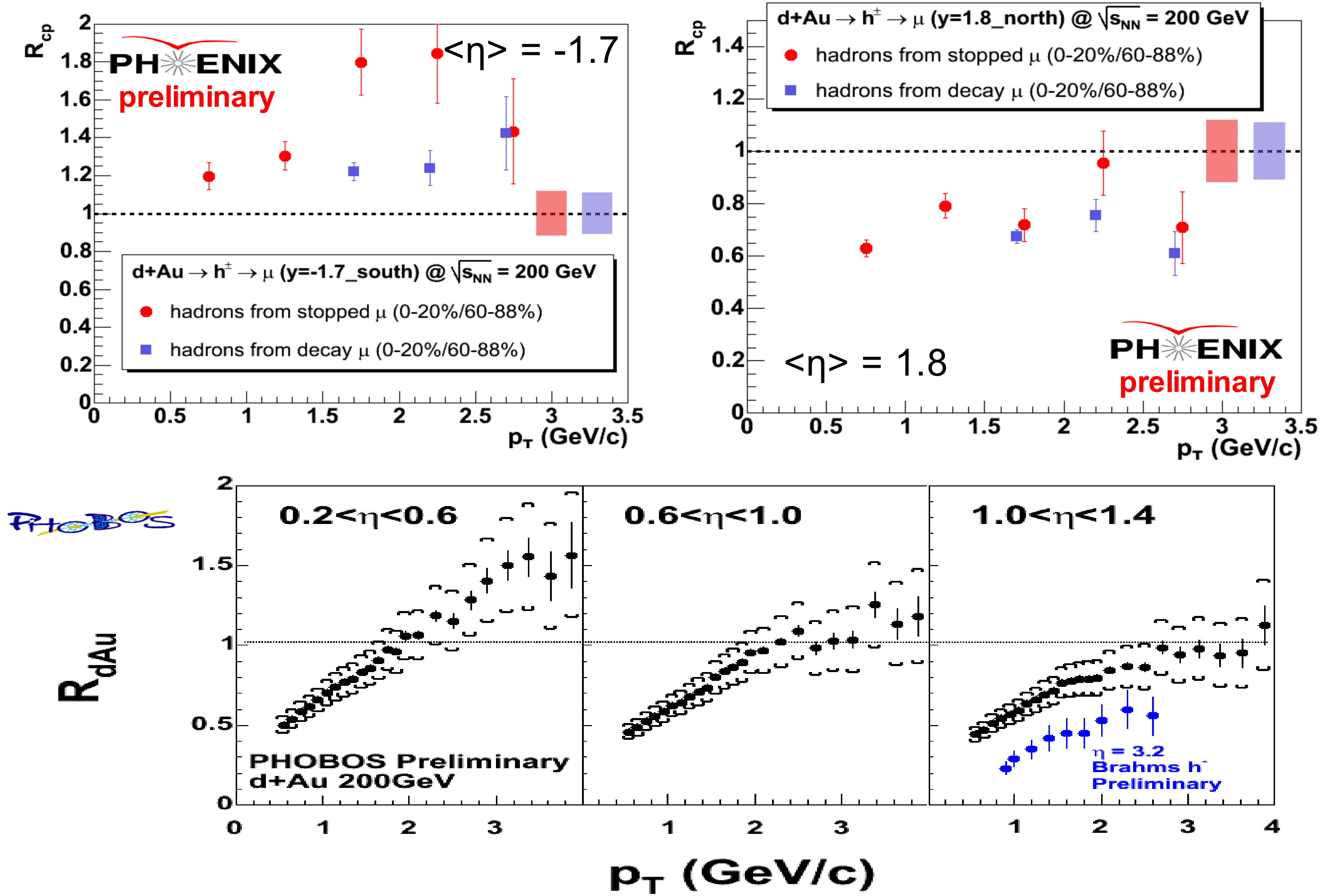
for p_T=2 GeV/c:

η = 0. (x ≈ 10^{-2})

η = 3.2 (x ≈ $5\cdot10^{-4}$)

- Significant suppression (factor ~2-3) of moderately high p_T hadro-production at η = 3.2 (small x_2 in Au).
- Qualitative agreement with gluon saturation / strong shadowing effects.

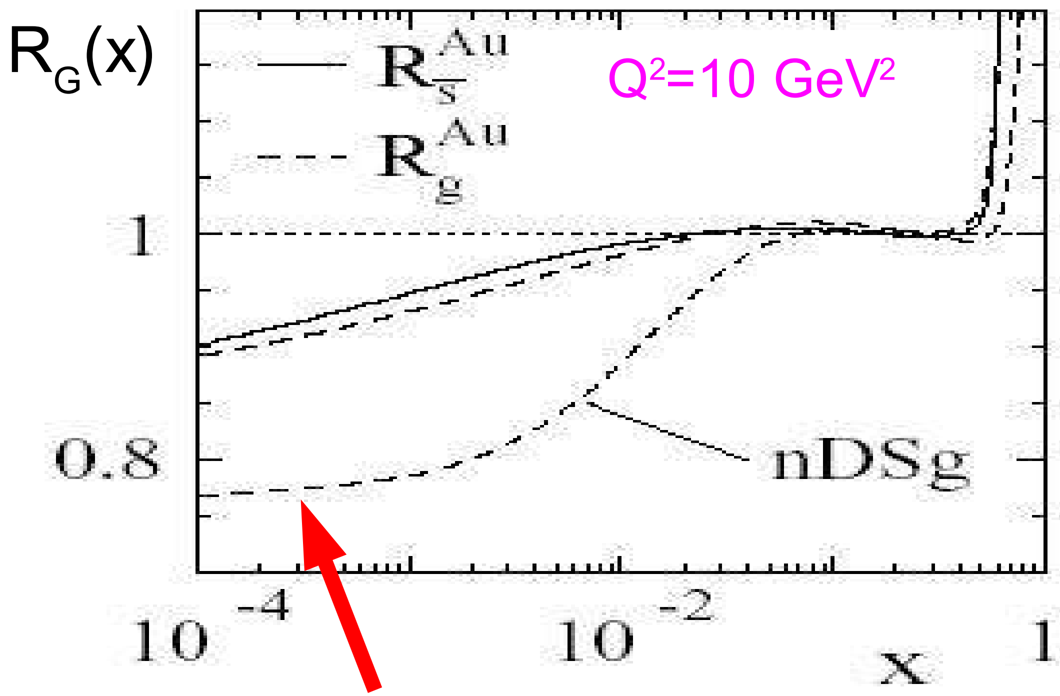
d+Au nuclear modification factor (other results @ η≠0)



- Increasing suppression with rapidity: $R_{dAu}(\eta=1)\approx 1$, $R_{dAu}(\eta\approx 2)\approx 0.7$, ...

why so much excitement ...

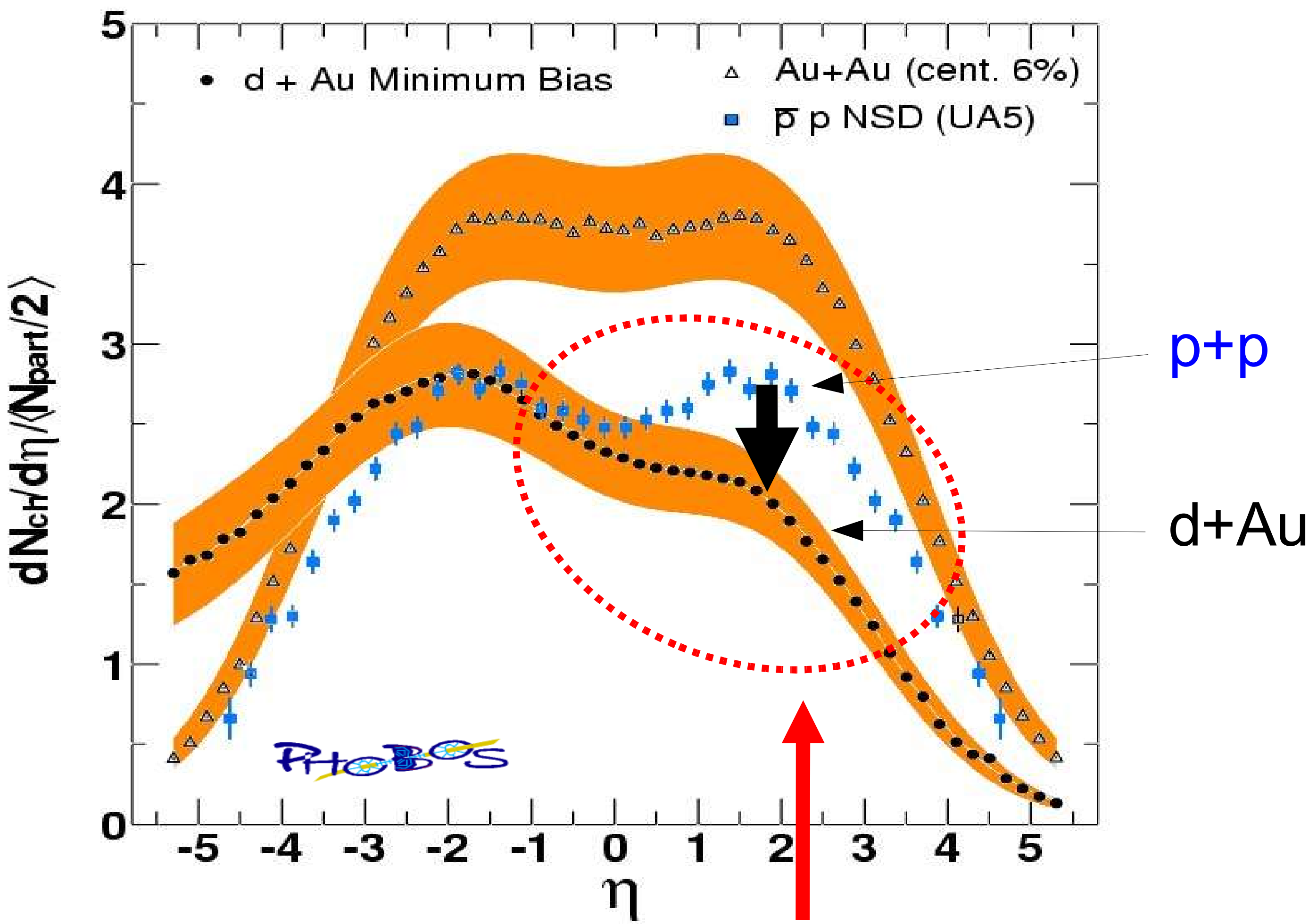
- Take the predictions of a standard "leading twist" approach ...
- NLO DGLAP global analysis of nuclear PDFs (fit to ~450 experimental points from e+A, p+A Drell-Yann data):



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

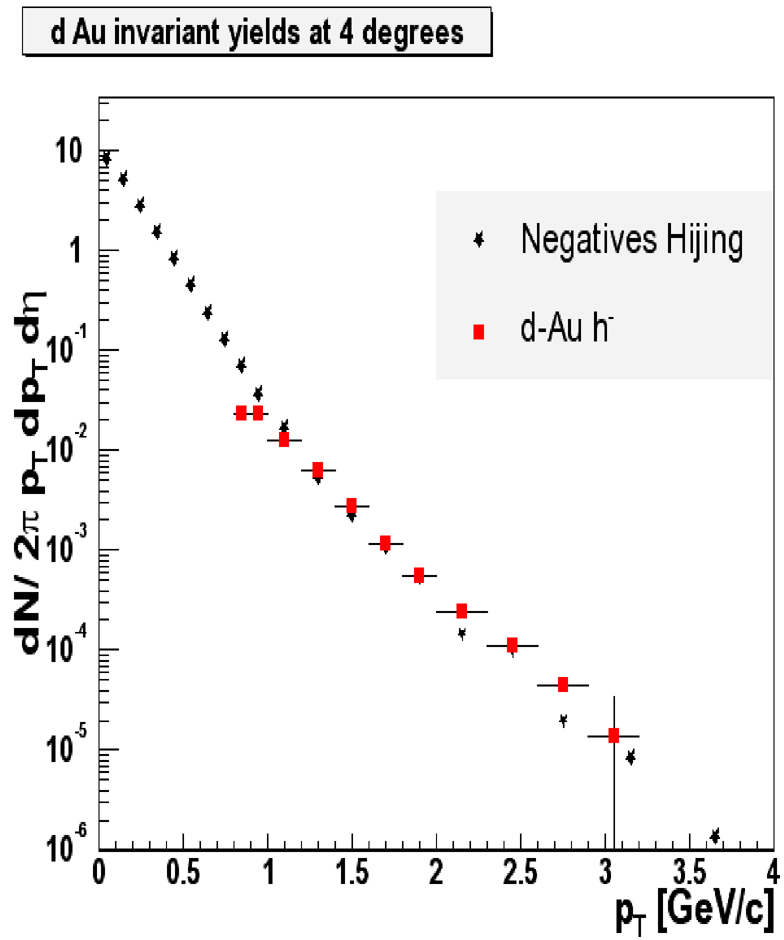
- Maximum gluon shadowing at $x \sim 10^{-4}$ (indirectly) constrained by all available DIS data on nuclear targets is ~0.8
- IF indeed $R_G(x=10^{-4}) \approx 0.2\text{-}0.4$ (as suggested by BRAHMS), this could be an evidence of breakdown of QCD factorization at high p_T (due to high twist effects at small-x).

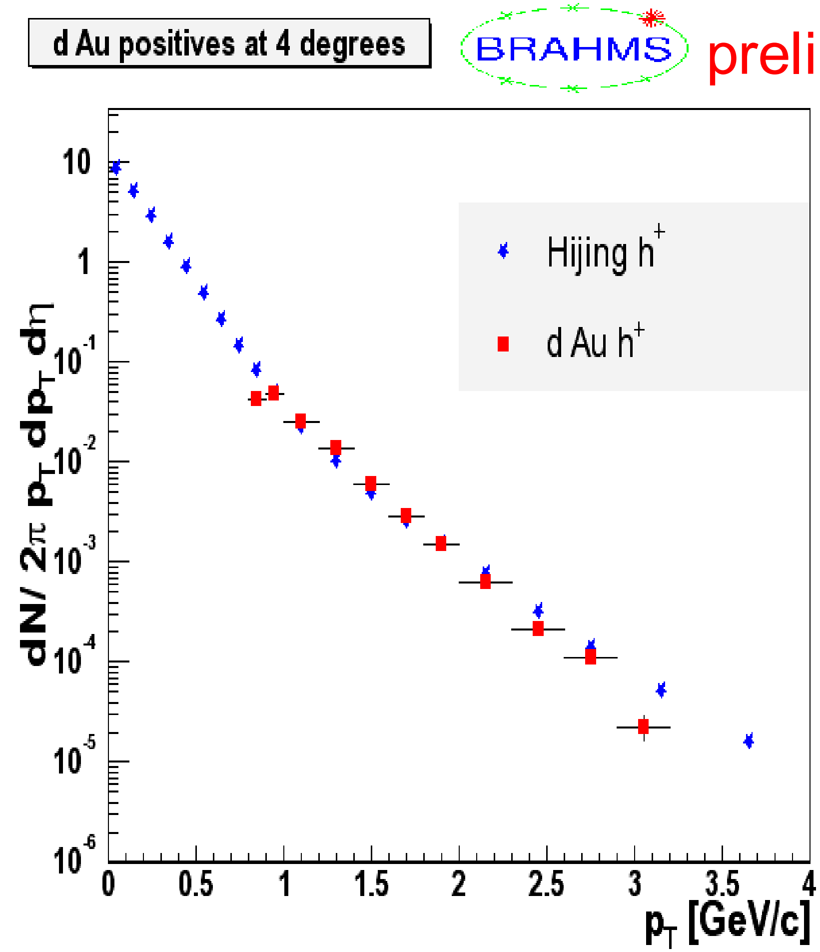
but (1) ... soft production is also suppressed in d+Au !



- Particle multiplicities (low p_T) in d+Au well below expectations from $N_{part\ tot}$ scaling compared to p+p at forward rapidities (d fragmentation) ! Well known from p+A at lower sqrt(s). How this affect high p_T production?
- Bottom line: Be careful with blind application of "usual" scaling laws for particle production at forward rapidities in asymmetric systems !

but (2) ... valence q (not g) dominate BRAHMS data





BRAHMS preliminary

- h+ > h- : deuteron valence quarks (high x_1) dominate over “wee” gluons from Au (small x_2).
- (Personal) Conclusion: It's premature to claim $R_{Gluon}(x=10^{-4}) \approx 0.2\text{-}0.4$ It's premature to claim CGC at RHIC.

What hard scattering data at RHIC tell us(*) about the properties of the underlying QCD matter ...

Summary of possible physical scenarios:

1. Dense final-state partonic medium: Parton energy loss + quark recombination.

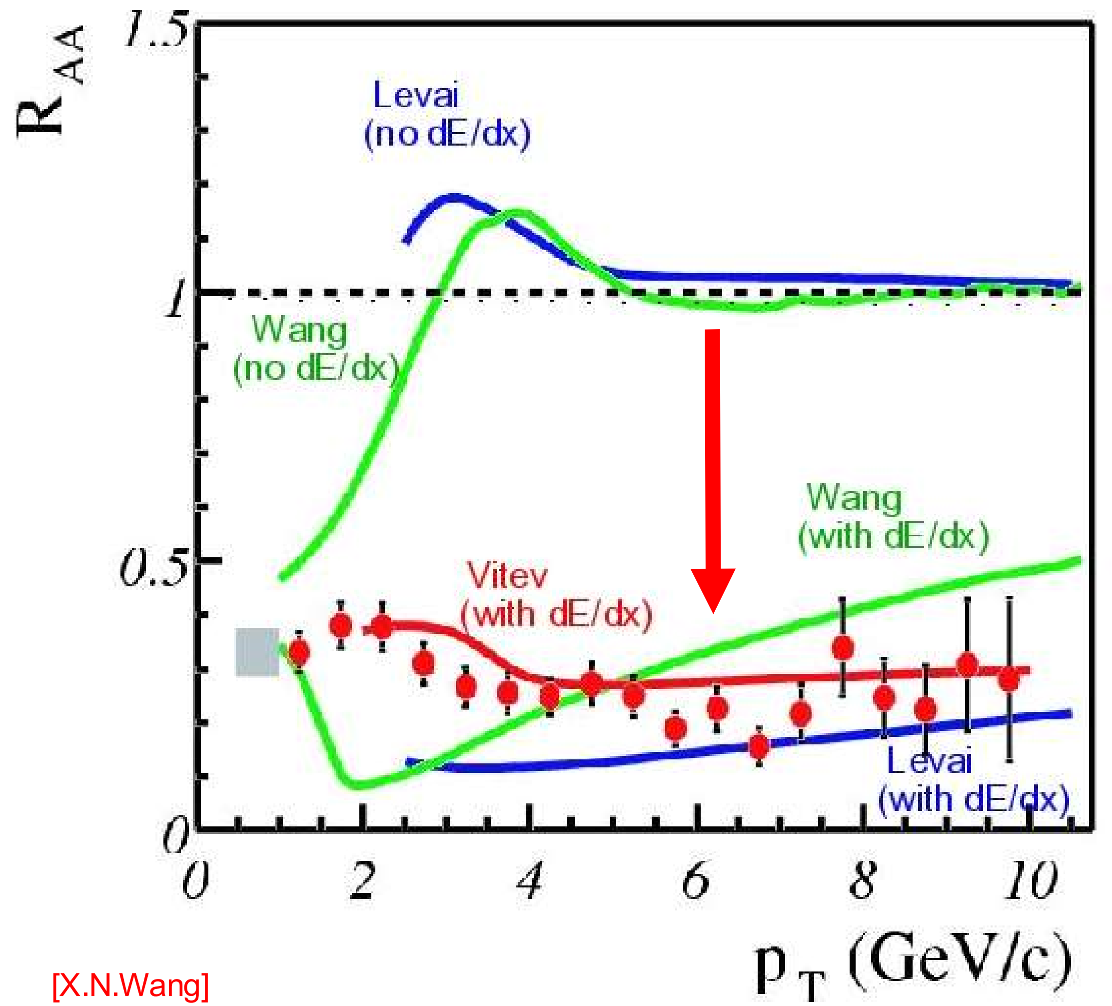
2. Dense initial-state partonic medium: Gluon saturation.

3. Dense final-state hadronic medium: hadronic energy loss.

(*) via confronting data to theory

Final-state "QGP" effects vs. data (I)

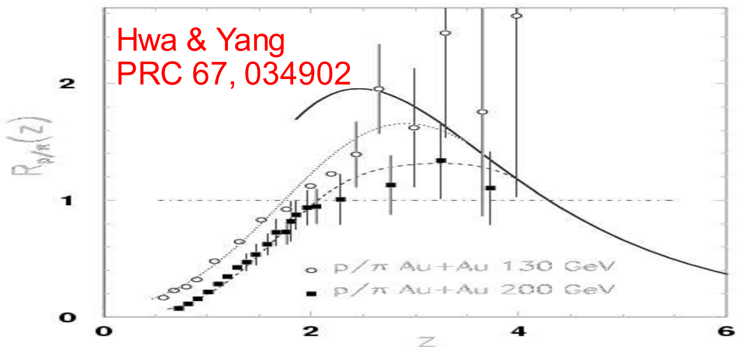
- Dense medium properties according to "jet quenching" models:
  - Initial gluon densities:
    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]
  - Opacities:
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]
  - Transport coefficients:
    $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 [BDMPS, Arleo,]
  - Plasma temperatures:
    $T \sim 0.4$ 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]

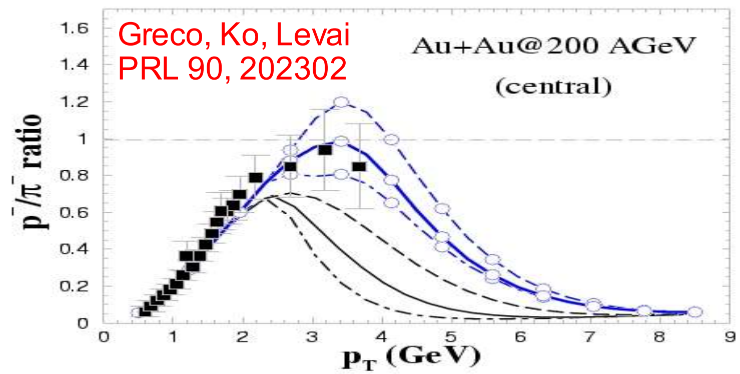


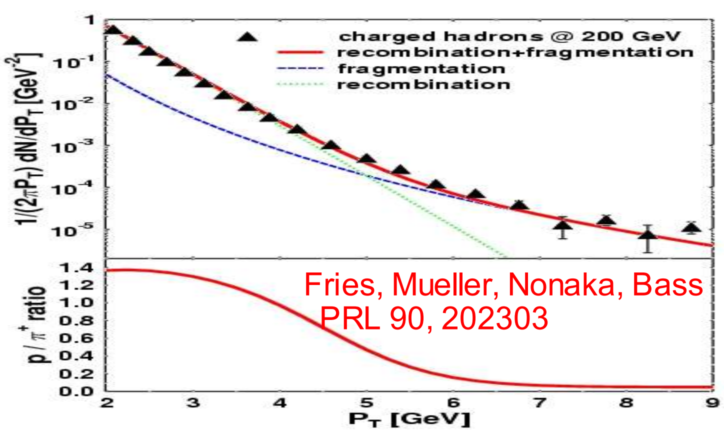
- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\epsilon_{crit\ QCD}$ in thermalized syst.

Final-state "QGP" effects vs. data (II)

- Quark recombination (coalescence) mechanisms provide a simple explanation of anomalous chemistry at intermediate p_T's (2-5 GeV/c):







- By quark momenta addition, recombination dominates for p_T ~ 1- 4 GeV/c:

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

- Fragmentation dominates for p_T > 5 GeV/c:

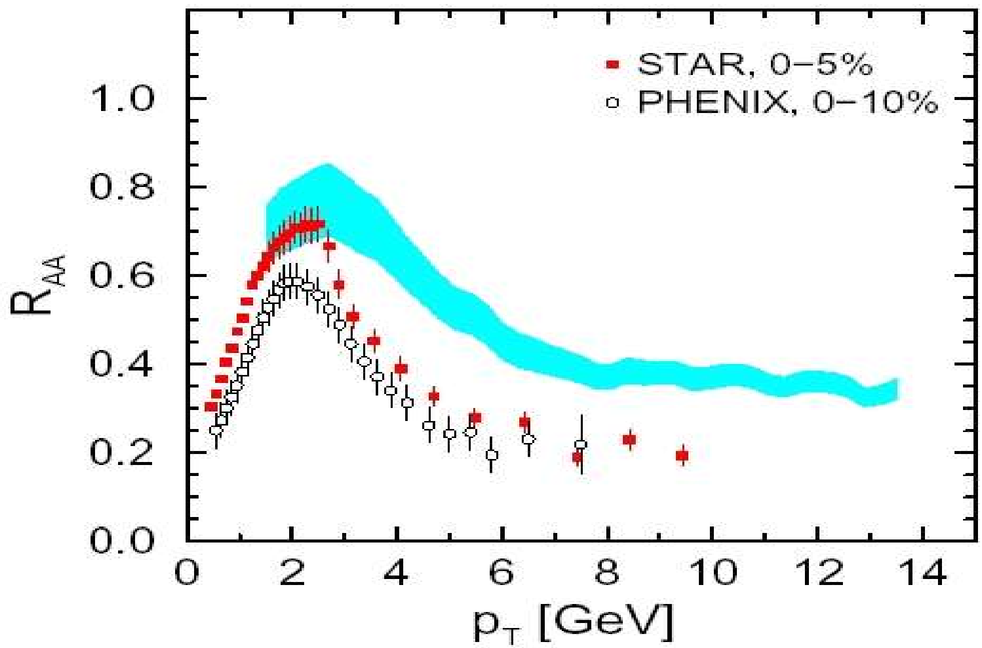
  p_T(hadrons)= z p_T(partons) , with z<1

- High parton densities in a thermal medium are required.

- *However... is recomb. consistent with (p+p-like) Au+Au dN/dφ near-side widths ?*

Final-state effects in a dense hadronic medium ?

- Assumption: fast parton hadronization time implies rescattering of "pre-hadrons" (colorless but not fully formed) inside expanding (hadronic) fireball.
- Nuclear modification factor: [expanding system with $\epsilon_{init}\approx 1$ GeV/fm^3 (*)]



(*) NB: Such a dense hadronic medium should have gone first through an (even) denser partonic phase of course ...

Cassing, Gallmeister, Bratkovskaya, Greiner, Stoecker, nucl-th/0312049

- State-of-the-art hadronic models (HSD, UrQMD) produce suppression but ...

sion of high p_T hadrons [35]. The interactions of formed hadrons are found to be negligible in central Au+Au collisions at $\sqrt{s} = 200$ GeV for $p_T \geq 6$ GeV/c and the large suppression seen experimentally is attributed to a large extent to the interactions of 'leading' pre-hadrons with the dense environment, which should be partly of partonic nature in order to explain the large attenuation seen in central Au+Au collisions.

Summary

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

➡ Observation 1: Light-flavor (u,d,s) spectra suppressed by a factor 4-5. (possible suppression already at $\sqrt{s} \approx 20$ GeV).

➡ Observation 2: Intermediate p_T light-flavor composition inconsistent with known fragmentation functions in free space.

➡ Observation 3: Heavy-flavor (c) spectra unsuppressed (?).

➡ Observation 4: Direct photon spectra unsuppressed.

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

➡ Observation 5: Spectra enhanced by a factor ~1.3

☆ "Explanation" (1,2 via 4,5): pQCD hard scattering + final-state parton energy loss + parton recombination:
$\Rightarrow$ Dense thermal QCD medium.

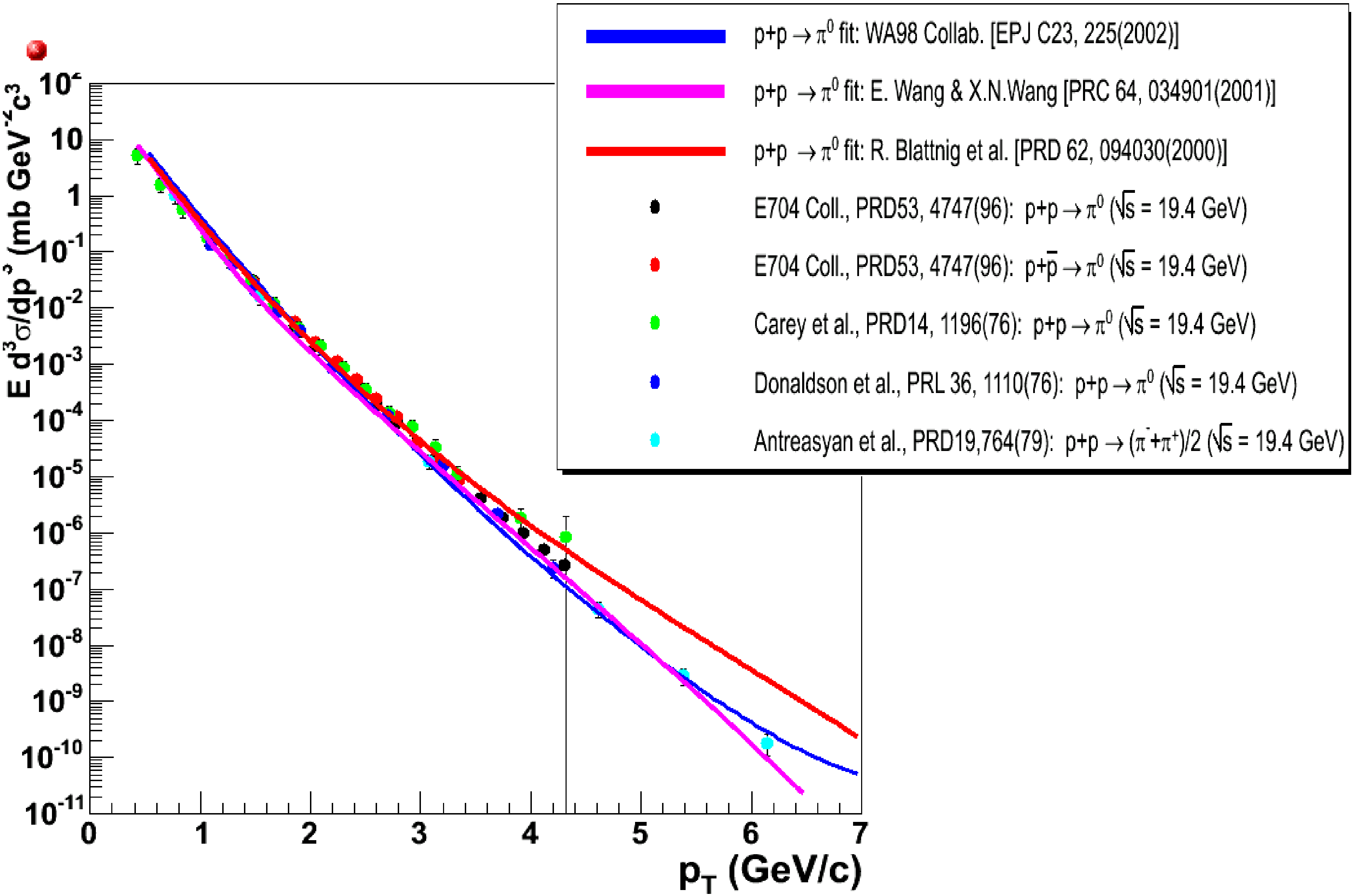
☆ High p_T in d+Au at forward rapidities at RHIC:

➡ Observation 6: Spectra suppressed by a factor ~2-3.

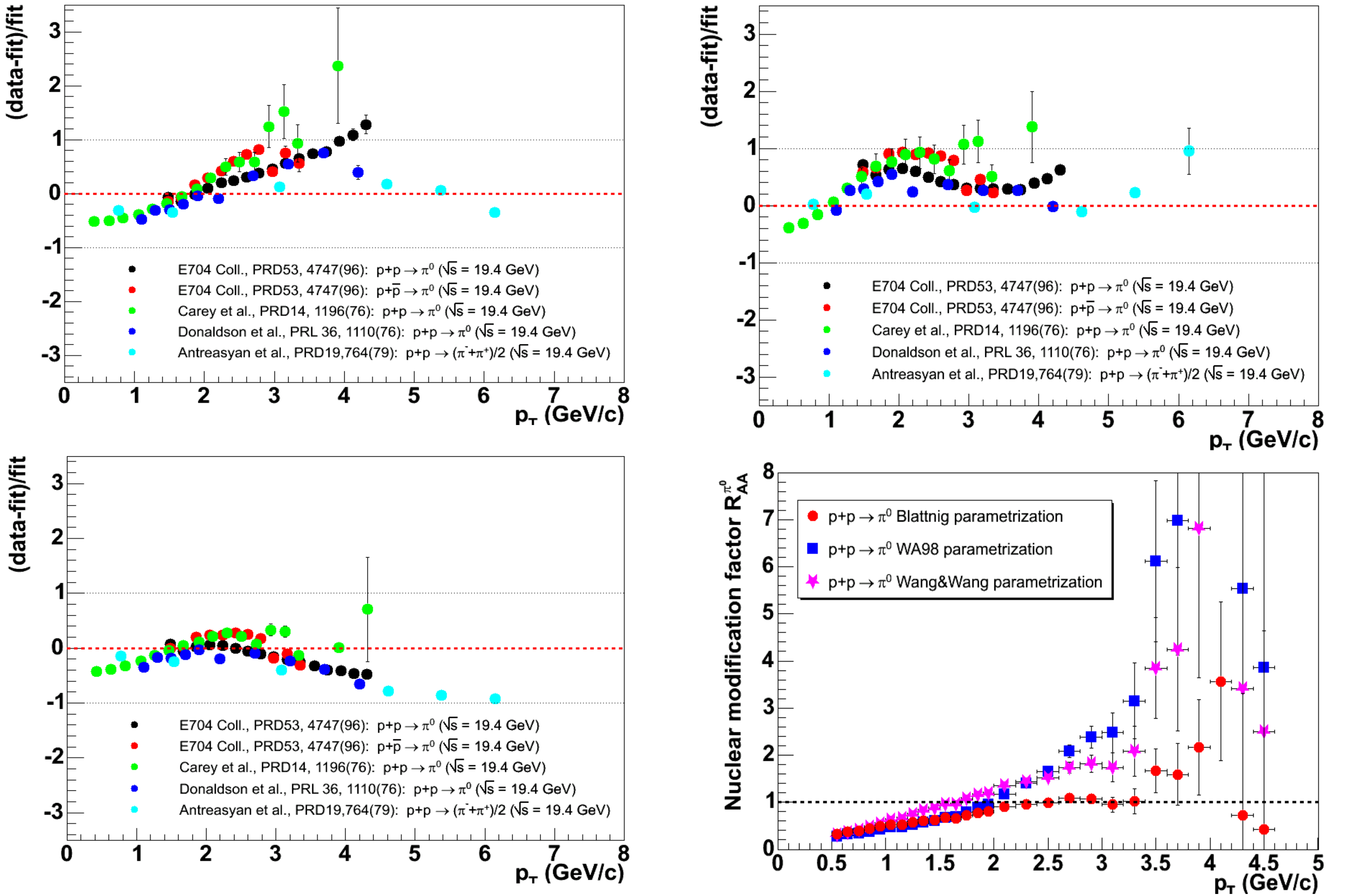
☆ "Explanation" (6): possible evidence of high twist effects at small-x.

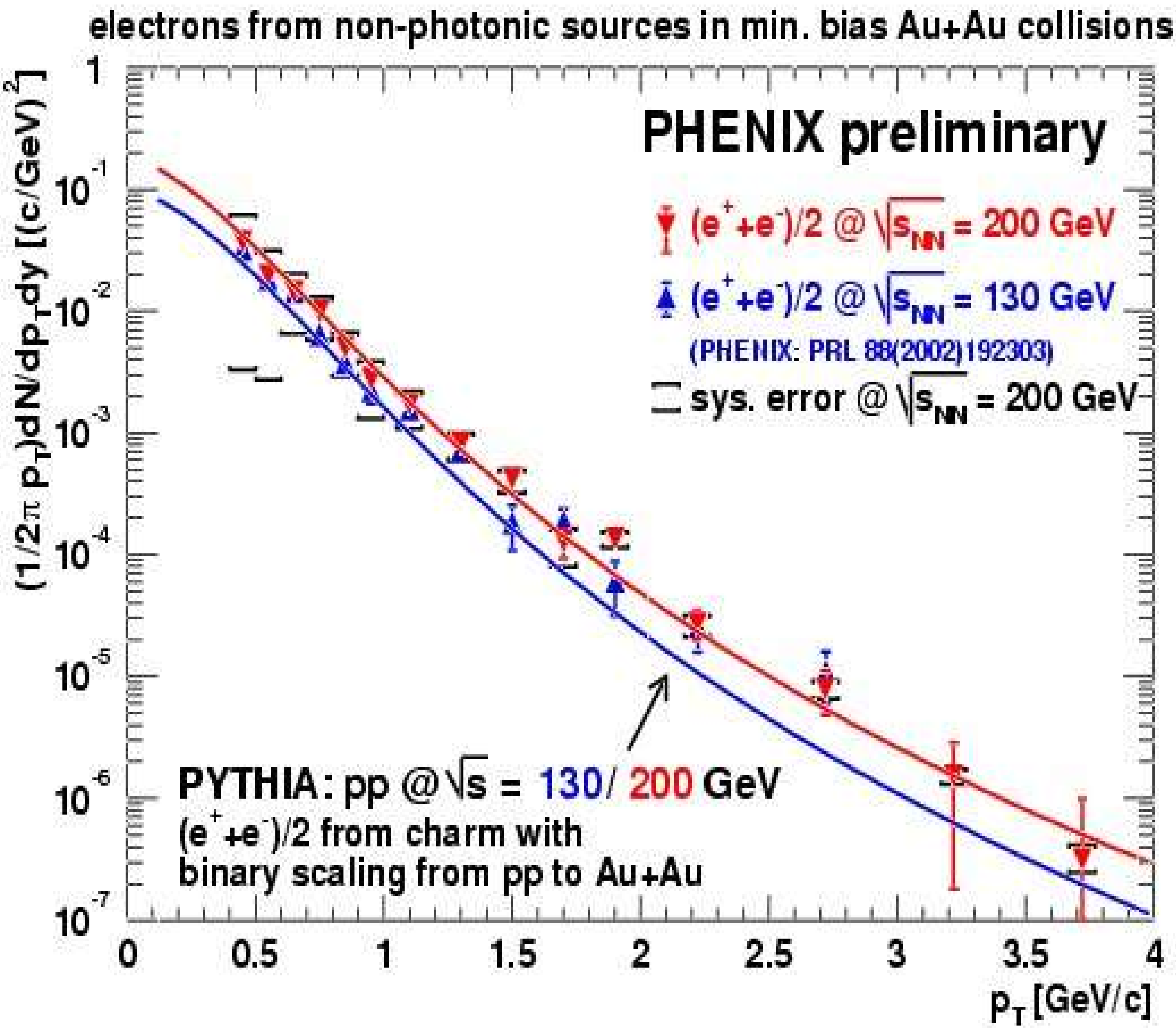
backup slides ...

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



High p_T @ SPS: “Cronin” or “quenching” ?





 David d'Enterria (Columbia Univ.)