High-p_T identified particles in PHENIX: data vs. theory

19th Winter Workshop on Nuclear Dynamics

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Overview

- 2 most significant experimental results at RHIC:
  - "High p_T π^0 suppression"
  - "Anomalous" high p_T baryon/meson ratio
- Identified π^0 and p,pbar experimental results at high p_T:
  - $\sqrt{s_{NN}}$ dependence (17 GeV, 31 GeV, 130 GeV, 200 GeV)
  - Magnitude and p_T dependence of suppression
  - Centrality dependence of suppression
  - Flavor dependence of suppression
- Theoretical descriptions of nuclear & medium effects at high p_T:
  - Nuclear shadowing. Cronin enhancement.
  - Parton energy loss (BDMPS, GLV, HSW).
  - Hadronic energy loss.
  - Gluon saturation.
  - Parton recombination.
- Summary & conclusions

High p_T particles @ RHIC. Motivation

- Products of parton fragmentation (jet "leading particle").
- Early production in parton-parton scatterings with large Q^2.
- Direct probes of partonic phases of the reaction $\Rightarrow$ Sensitive to dense medium properties: QGP energy loss, saturated CGC ...
- Info on medium effects accessible through comparison to nuclear- geometry scaled "vacuum" (*pp*) yields:

$$\sigma_{AB}^{hard} = \int d^2b \left[1 - e^{-\sigma_{NN}^{hard} T_{AB}(b)}\right] \approx \int d^2b \, \sigma_{NN}^{hard} \, T_{AB}(b) \qquad \text{or}$$

"binary scaling": $\langle N_{coll} \rangle (b) = \sigma_{NN} \cdot T_{AB}(b) \Rightarrow \boxed{\sigma_{AB}^{hard} \propto \langle N_{coll} \rangle_{C_1 - C_2}}$

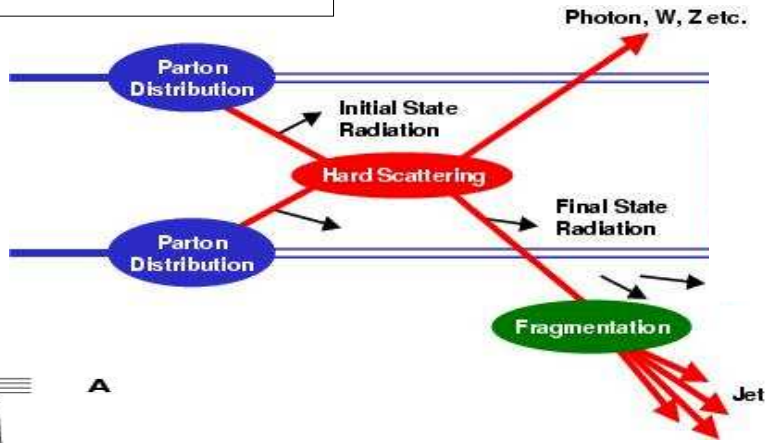
- Production yields calculable theoretically (next slide) ...

High p_T particles @ RHIC. Motivation (cont'd)

- Production yields calculable via pQCD:

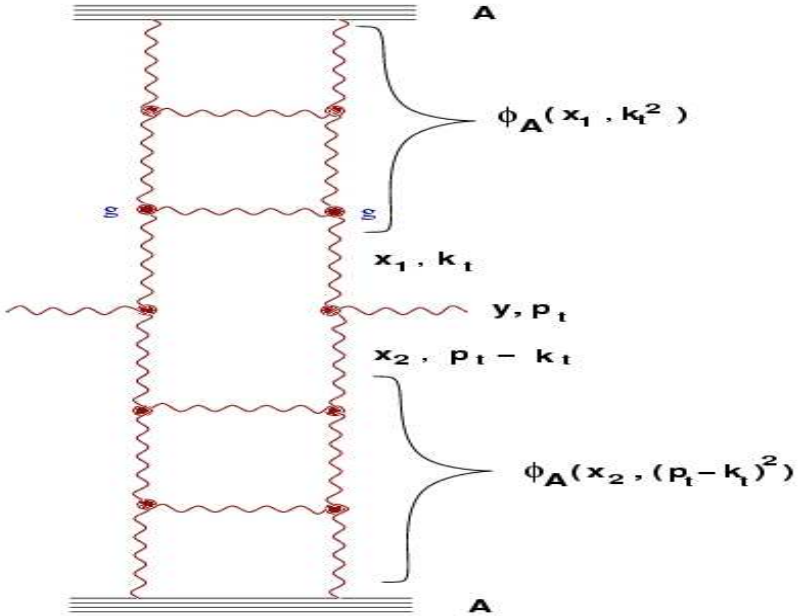
$$\sigma_{AB \to hX} \propto f_{a/A}(x_a,Q^2_a) \otimes f_{b/B}(x_b,Q^2_b) \otimes \sigma_{a\,b \to cd} \otimes D_{h/c}(z_c,Q^2_c)$$

"Factorization theorem"



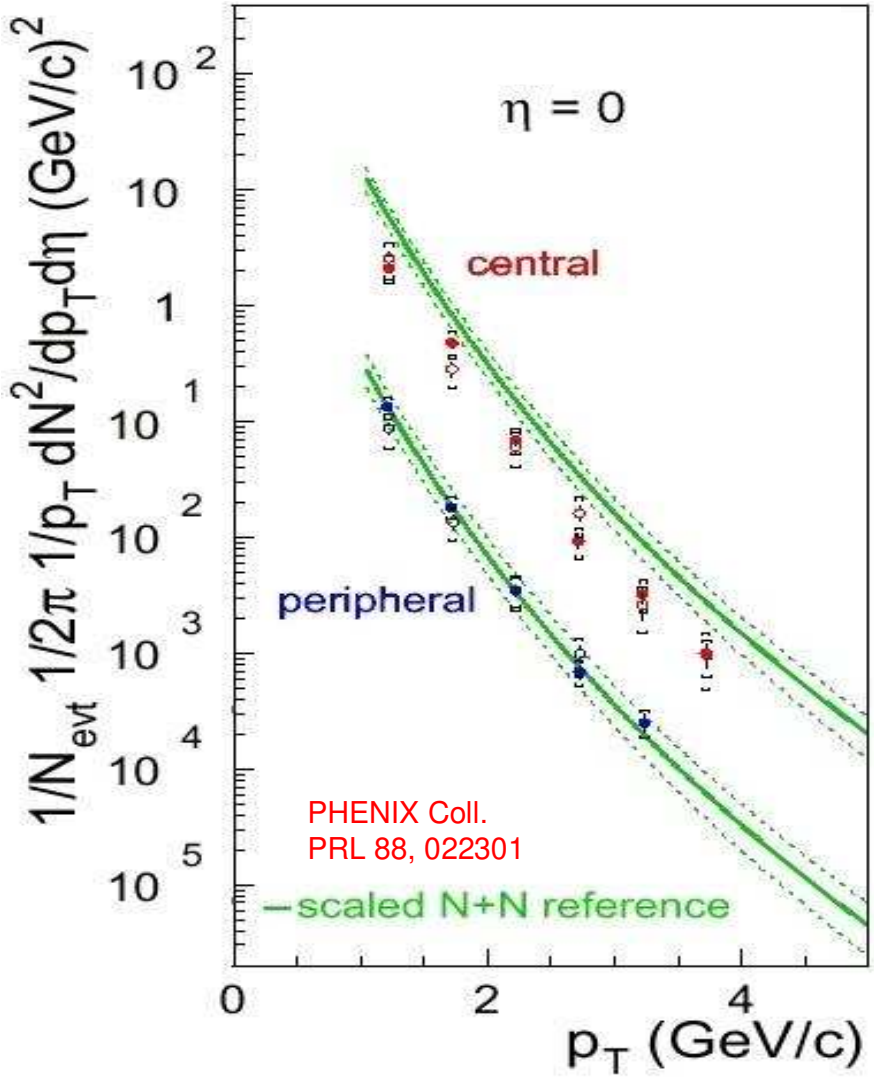
- ... or via "classical" CD:

"Mueller diagram for classical glue radiation"

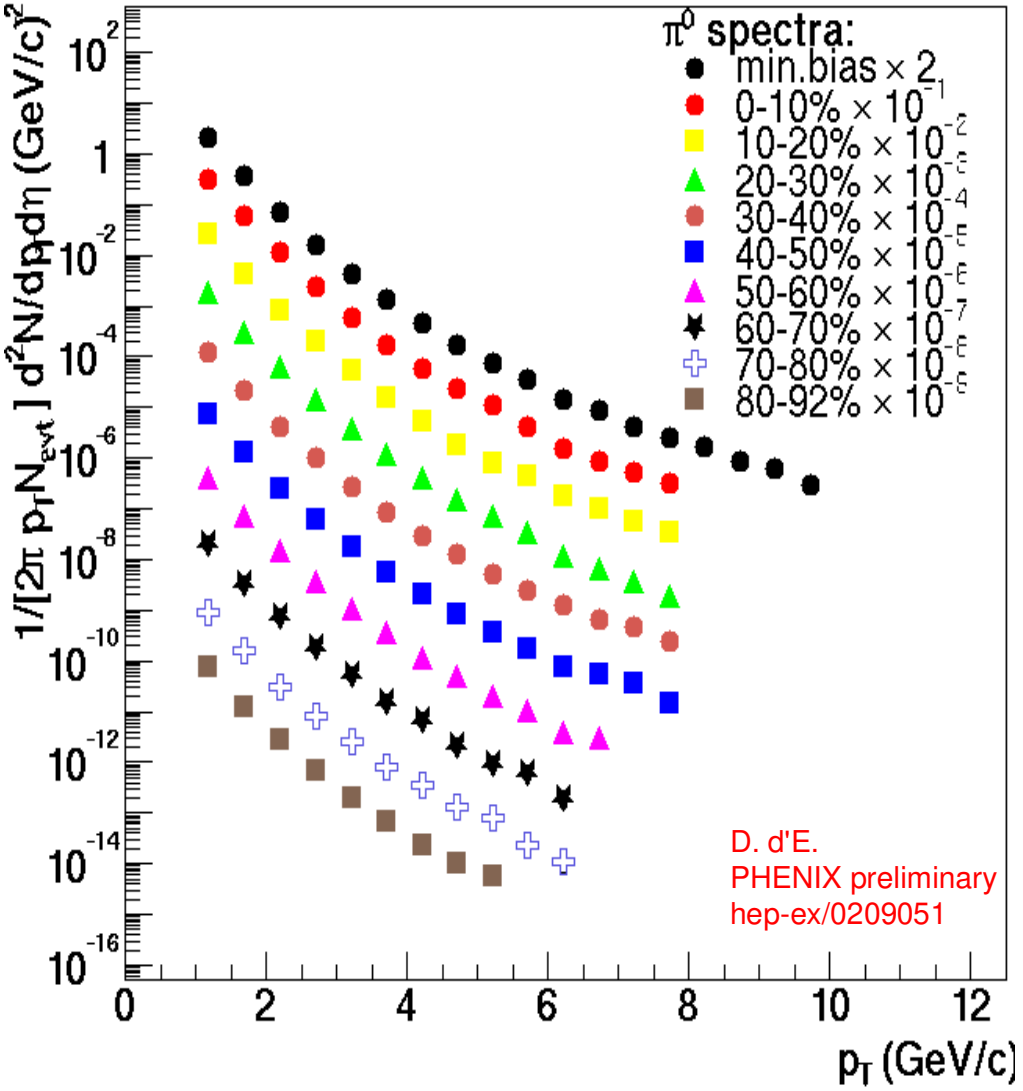


High p_T neutral pion spectra

Au+Au $\sqrt{s_{NN}}$ = 130 GeV

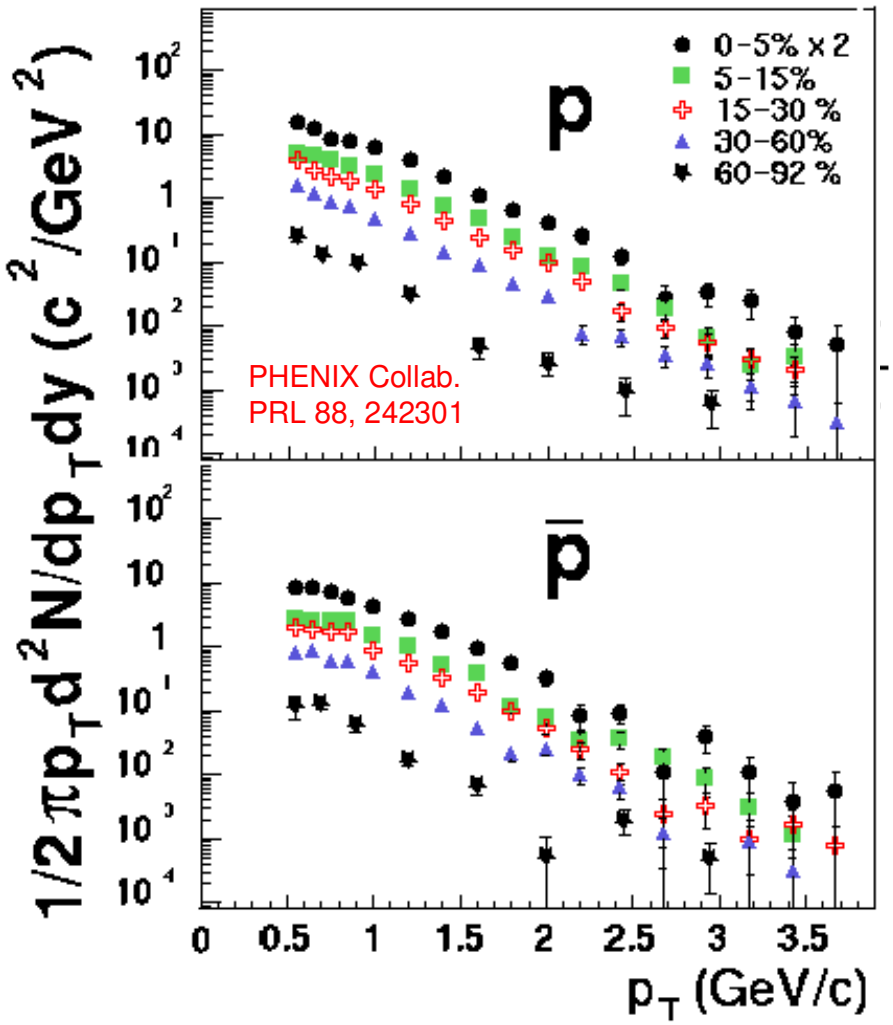


Au+Au $\sqrt{s_{NN}}$ = 200 GeV

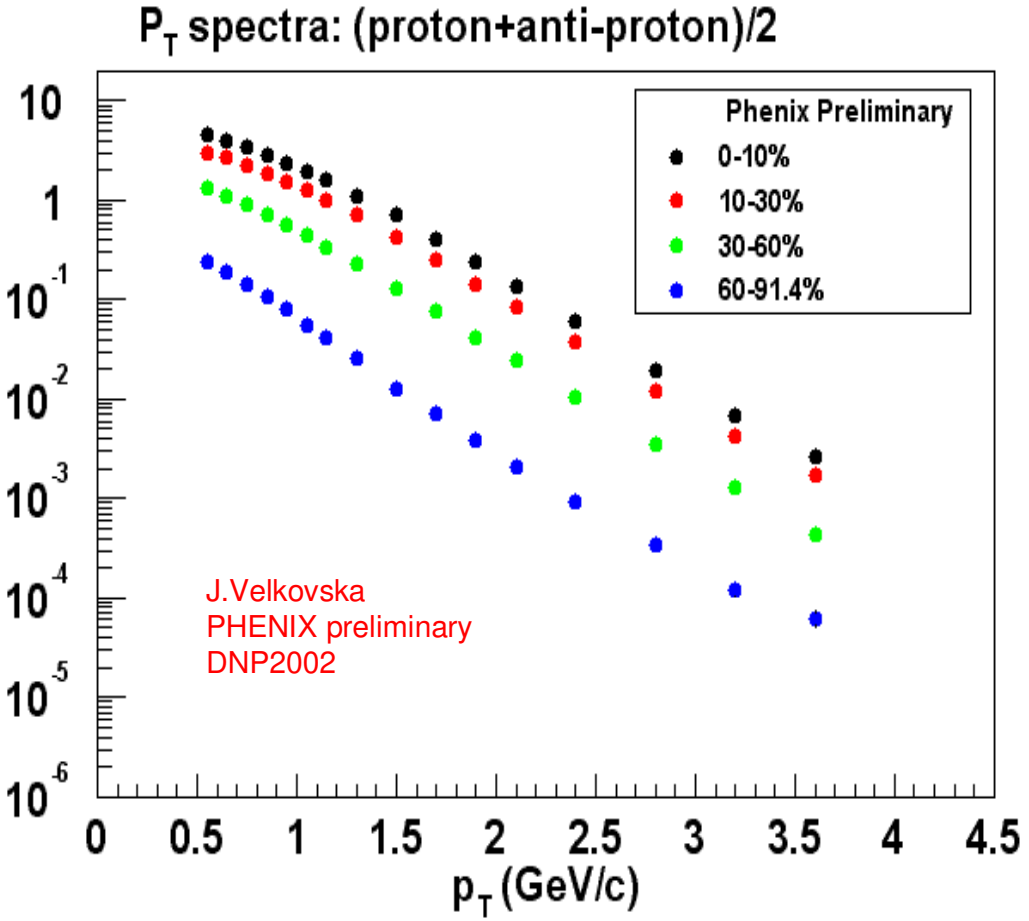


Identified p,pbar high p_T spectra

Au+Au $\sqrt{s_{NN}}$ = 130 GeV

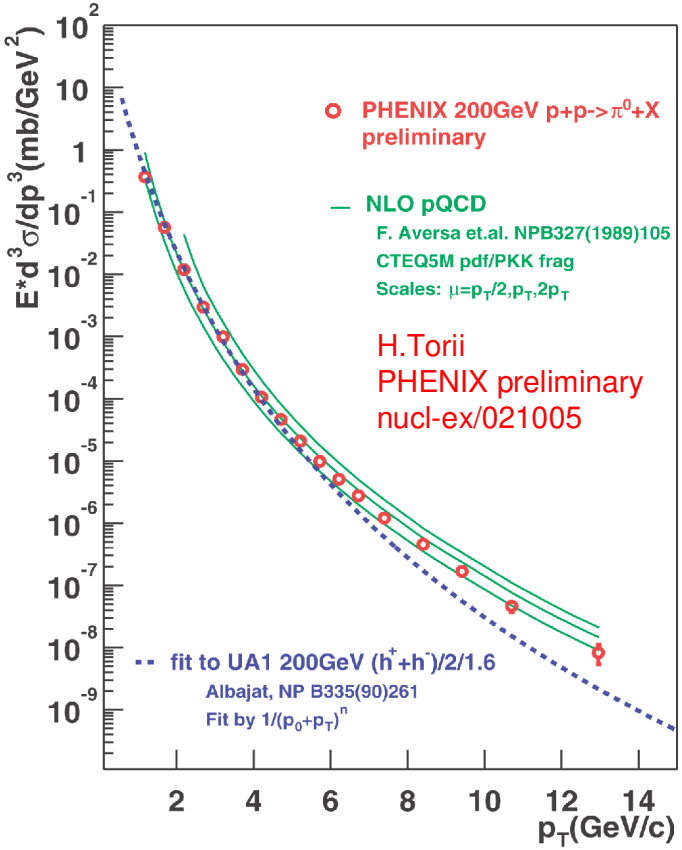


Au+Au $\sqrt{s_{NN}}$ = 200 GeV

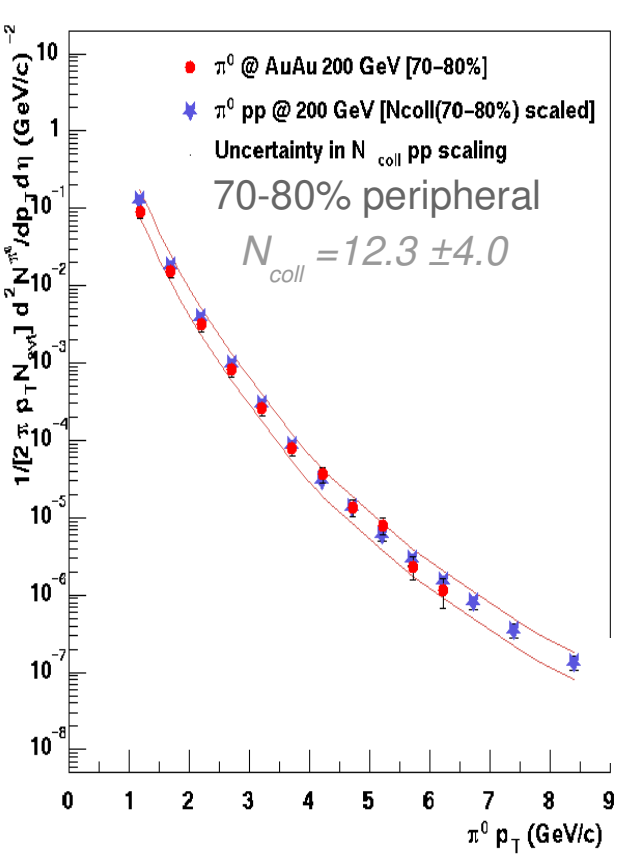


High-p_T π^0 @ 200 GeV: AuAu vs pp

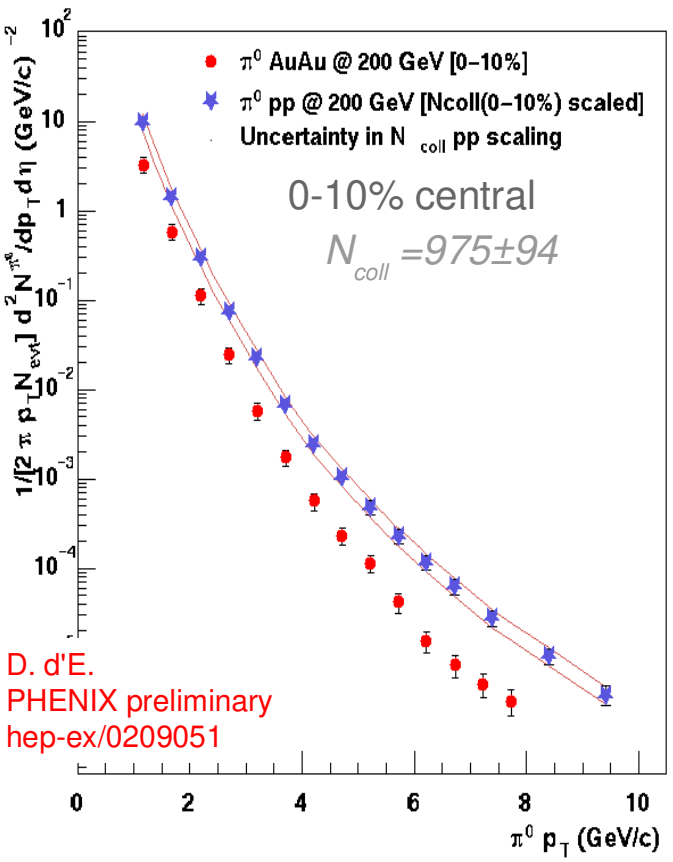
p+p→ π^0 X



Au+Au→ π^0 X (periph)



Au+Au→ π^0 X (central)



pp data agree with pQCD

Periph. data agree with pp plus collision scaling

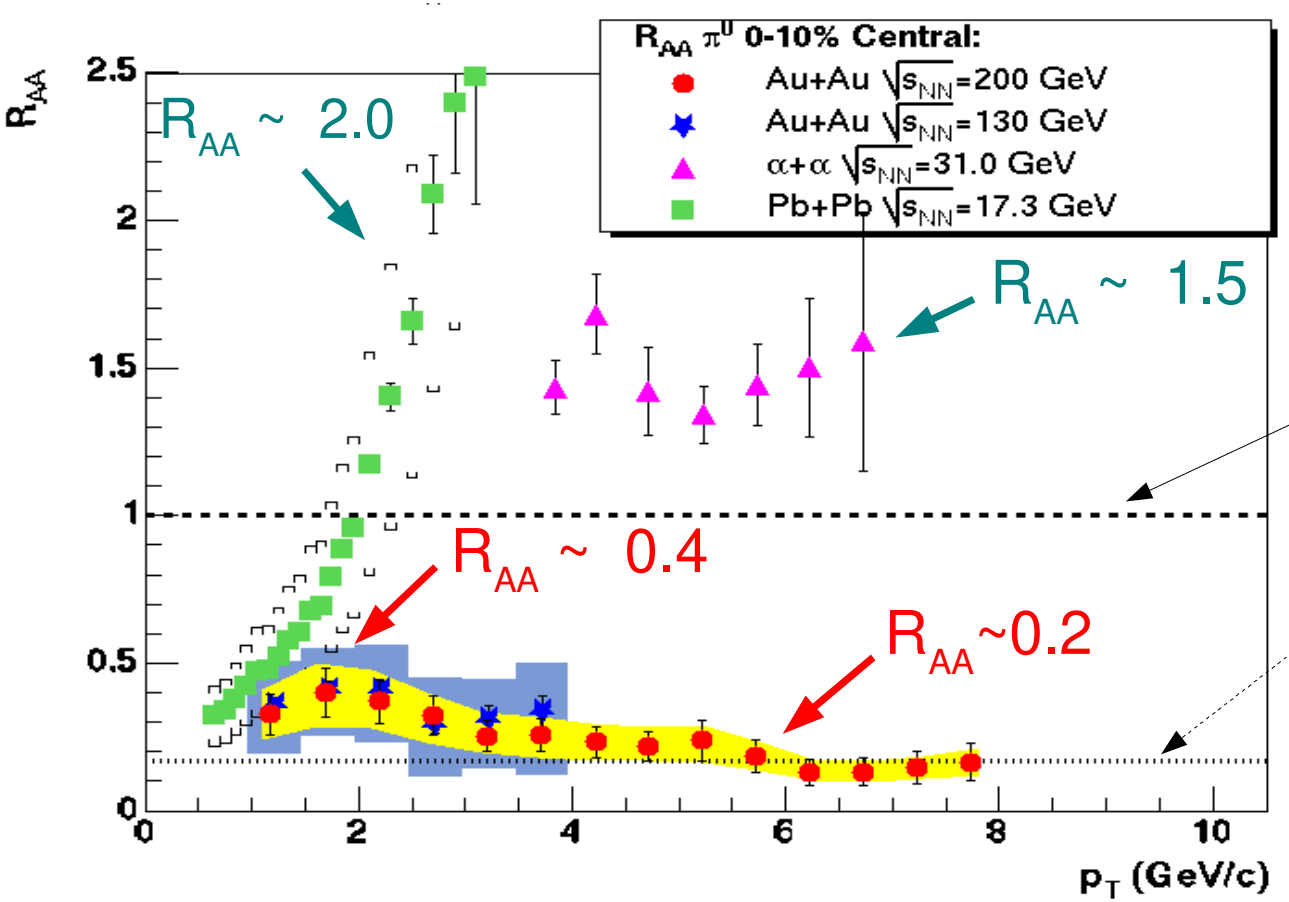
Strong suppression in central AuAu collisions

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

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

Compilation of high p_T π^0 central A+A

- CERN: Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 GeV), α+α ($\sqrt{s_{NN}}$ ~31 GeV): Cronin enhancement
- RHIC: Au+Au ($\sqrt{s_{NN}}$ ~ 130, 200 GeV): x4-5 suppression with respect to N_{coll}



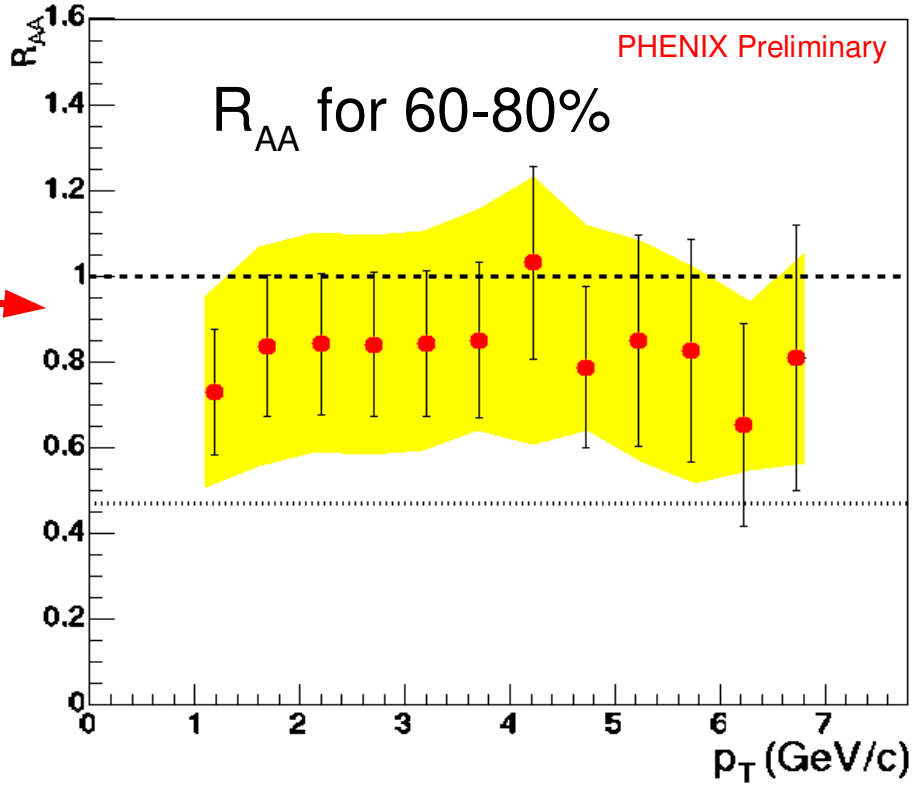
A.L.S.Angelis PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
D.d'E. PHENIX Preliminary QM2002

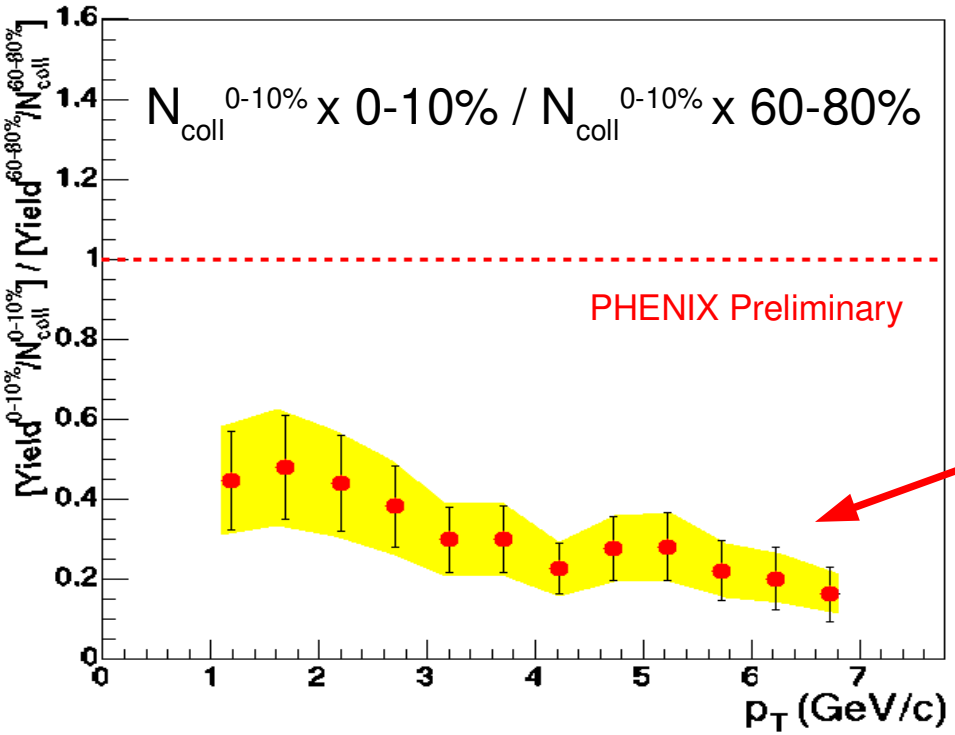
$N_{collision}$ scaling

N_{part} scaling

High-p_T suppression: Central/peripheral

- High p_T π^0 peripheral consistent with Ncoll scaling:

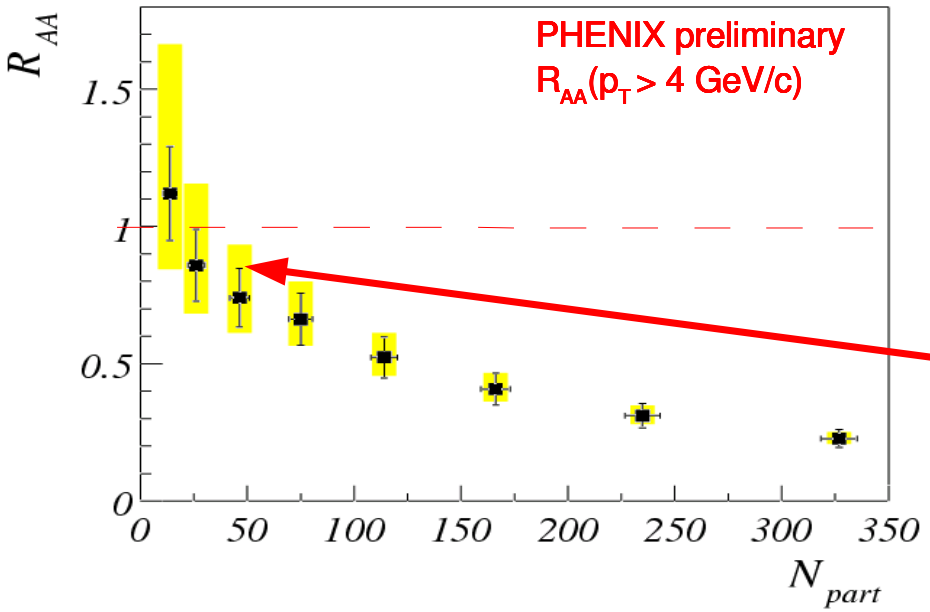


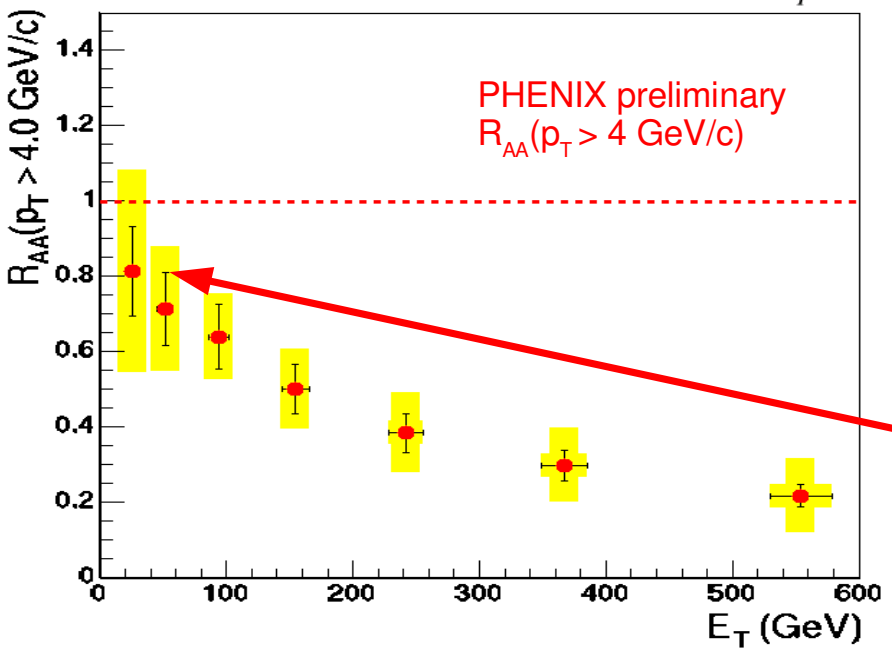


- Ratio central/periph ~ 0.2

(confirms R_{AA} result *without pp reference & part of the exp. uncertainties canceled out, but larger N_{coll} errors*)

Centrality dependence of π^0 suppression





Suppression vs N_{part}:

- Smooth suppression (no 1st order phase transition-like behavior).
- $R_{AA} < 1$ for 50-70% centrality:
  $N_{part} \sim 40 \pm 15$
  (coincidental agreement with parton percolation predictions ?)

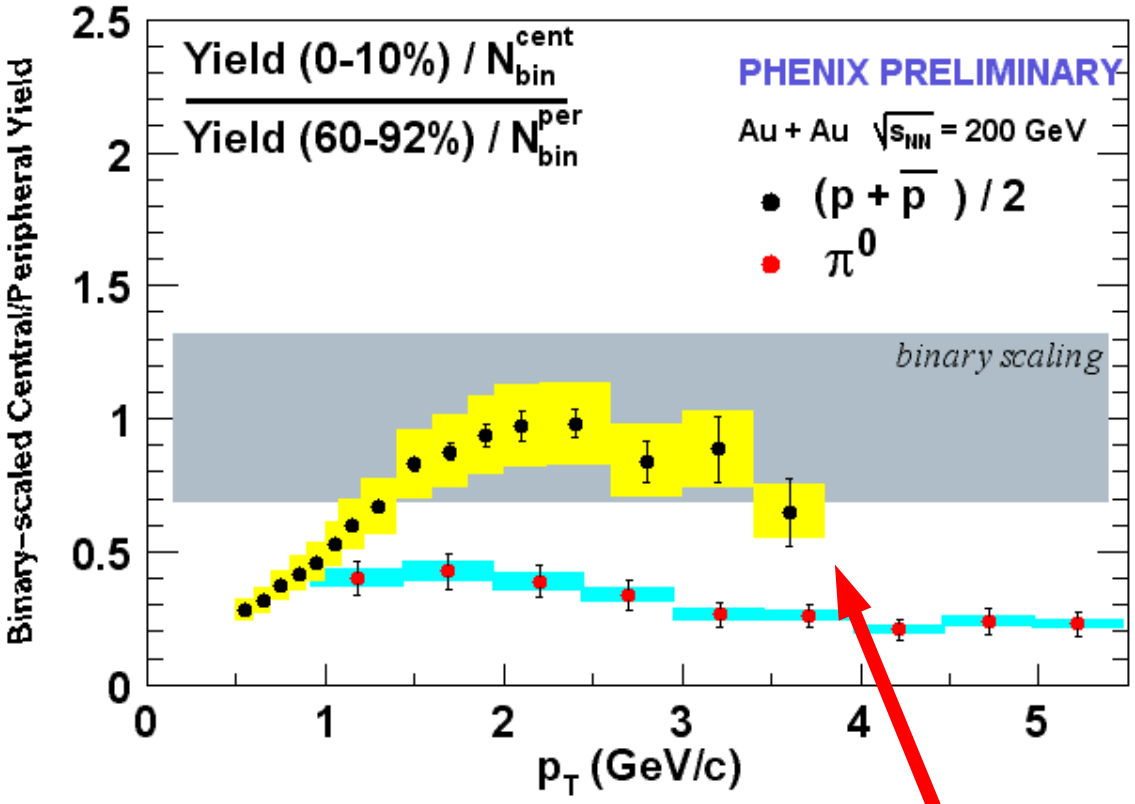
Suppression vs E_T:

- E_T measured in EMCal (*S. Bazilevsky talk*)
- Suppression apparent up to 50-60% centrality:

  $E_T \sim 20.5$ GeV

Hadron composition at high-p_T: R_{AA} (p) vs $R_{AA}(\pi)$

- Protons (antiprotons) not suppressed for p_T=1.5 – 3.5 GeV/c :
  - If p_T > 2 GeV/c particles ≈ parton fragmentation products. What makes such a difference between baryonic and mesonic products ?

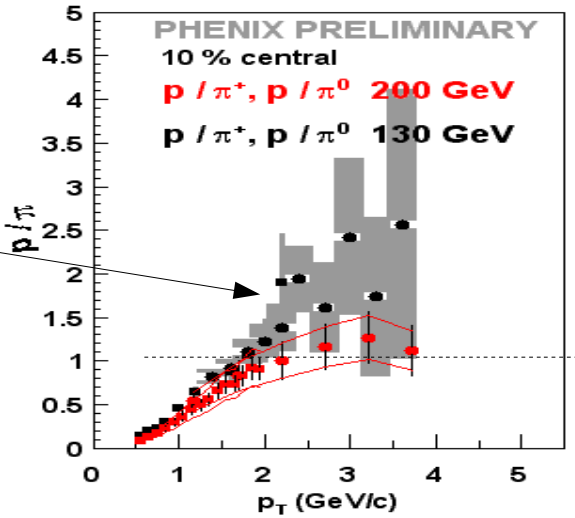


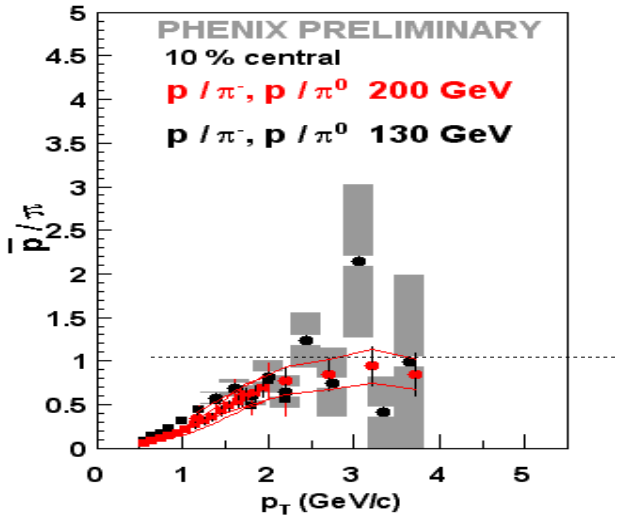
- Start of proton quenching at higher p_T ?

Hadron composition at high-p_T : p/π ratios

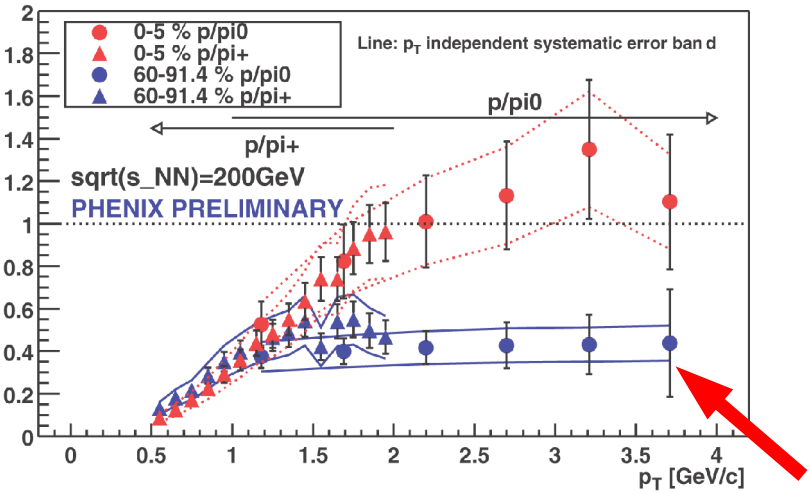
- Central colls.: Baryon yield ≈ pion yield for p_T>2 GeV/c

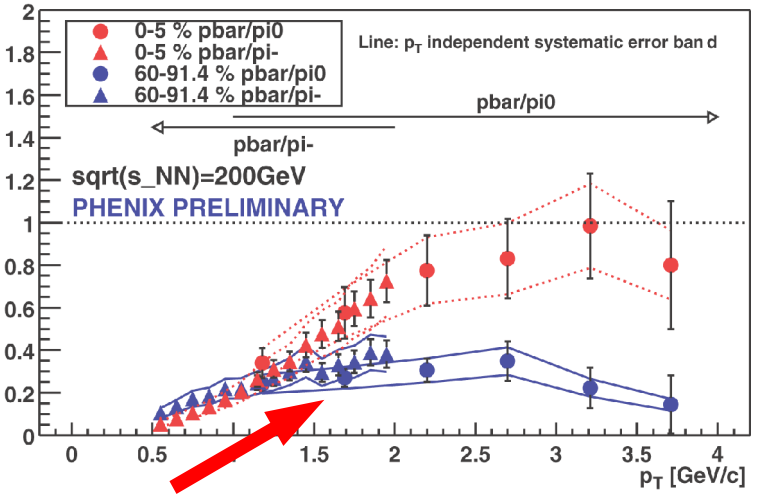
more protons @ 130 GeV than @ 200 GeV





- Very different from jet fragmentation (strong non-perturbative production).

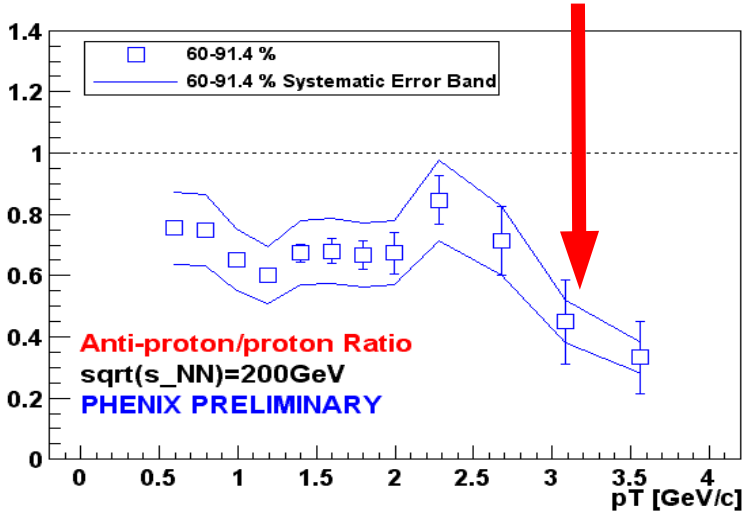


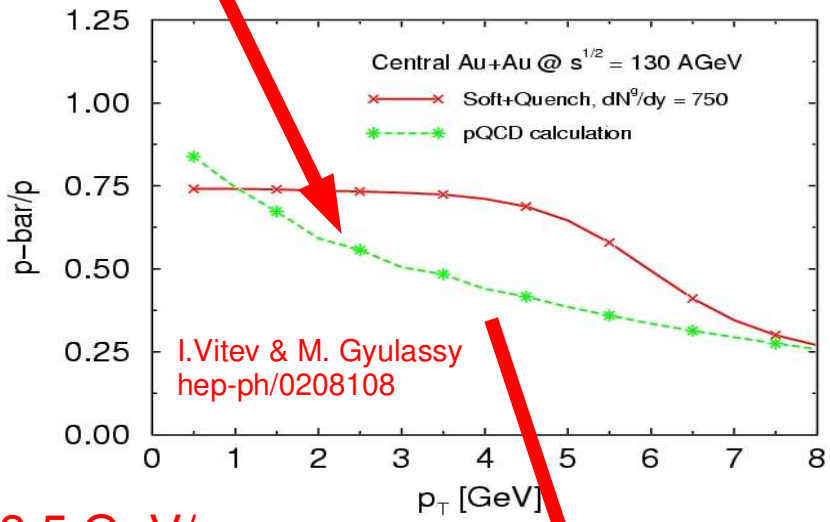


- Periph. colls.: baryon/meson ratio ~ 0.3 as in p+p,$\bar{p}$ (ISR,FNAL)

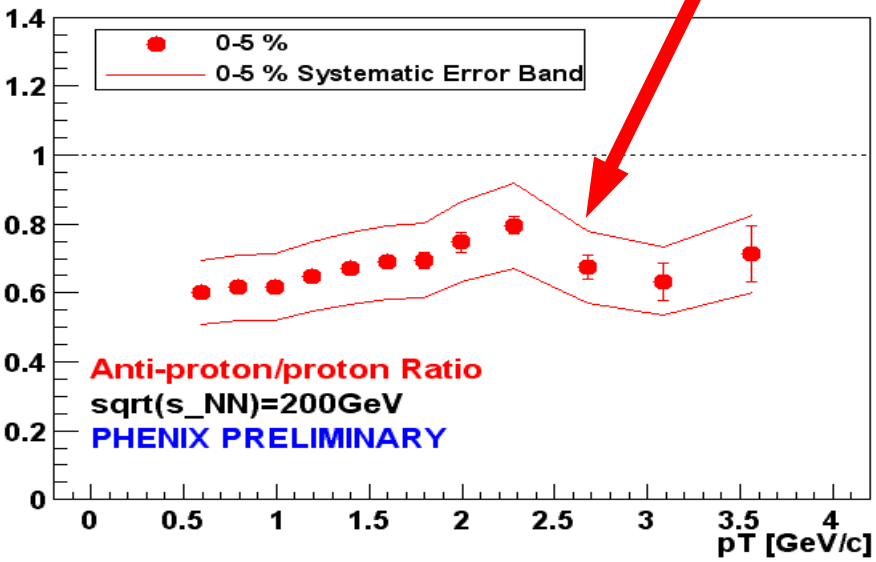
Hadron composition at high-p_T : $\bar{p}/p$ ratios

- Peripheral pbar/p: Decreases with p_T (perturbative behaviour)

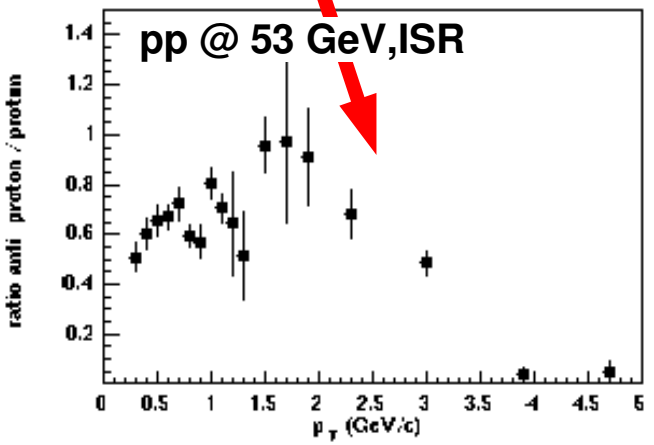




- Central pbar/p: ~ 0.7 constant up to 3.5 GeV/c



(as found in pp data)



High-p_T @ RHIC: a theorist "guide"

- **APPROACH "A"** (based on pQCD, factorization theorem):

  Step 1: pQCD *(NLO or LO+K-factor) = PDFs + scatt. matrix + FFs*
  Step 2: pQCD + nPDF (shadowing) + p_T broadening (Cronin)

  ✔ *So far one can explain peripheral data*

  Step 3: pQCD + initial-state nuclear effects + Parton energy loss

  - Energy loss 1: BDMPS (LPM, thick plasma)
  - Energy loss 2: GLV (LPM, thin plasma)
  - Energy loss 3: HSW (modified FFs), (*g* radiation + absorption)

  ✔ *So far one can ~ explain central colls. (magnitude, p_T dependence)*

  Step 4: pQCD + IS nuc. effects + Energy loss + parton recombination

  ✔ *Tries to explain flavor dependence of central colls. ...*

- **APPROACH "B"** (based in "classical" CD):

  - Step 1: CGC (gluon saturated nuclear wave function: MLV, ...)
  - Step 2: (classical) glue + glue collisions: gg $\rightarrow$ g
  - Step 3: Gluon fragmentation (FFs)

  ✔ *Tries to explain: suppression, N_{part} scaling, flavor dependence ...*

Magnitude of the suppression

- Data vs. theory: What do we learn about the medium from "jet quenching" models ?

  - High opacities:

    $\langle n \rangle = L/\lambda \approx 3 - 4$

  - Large initial gluon densities:

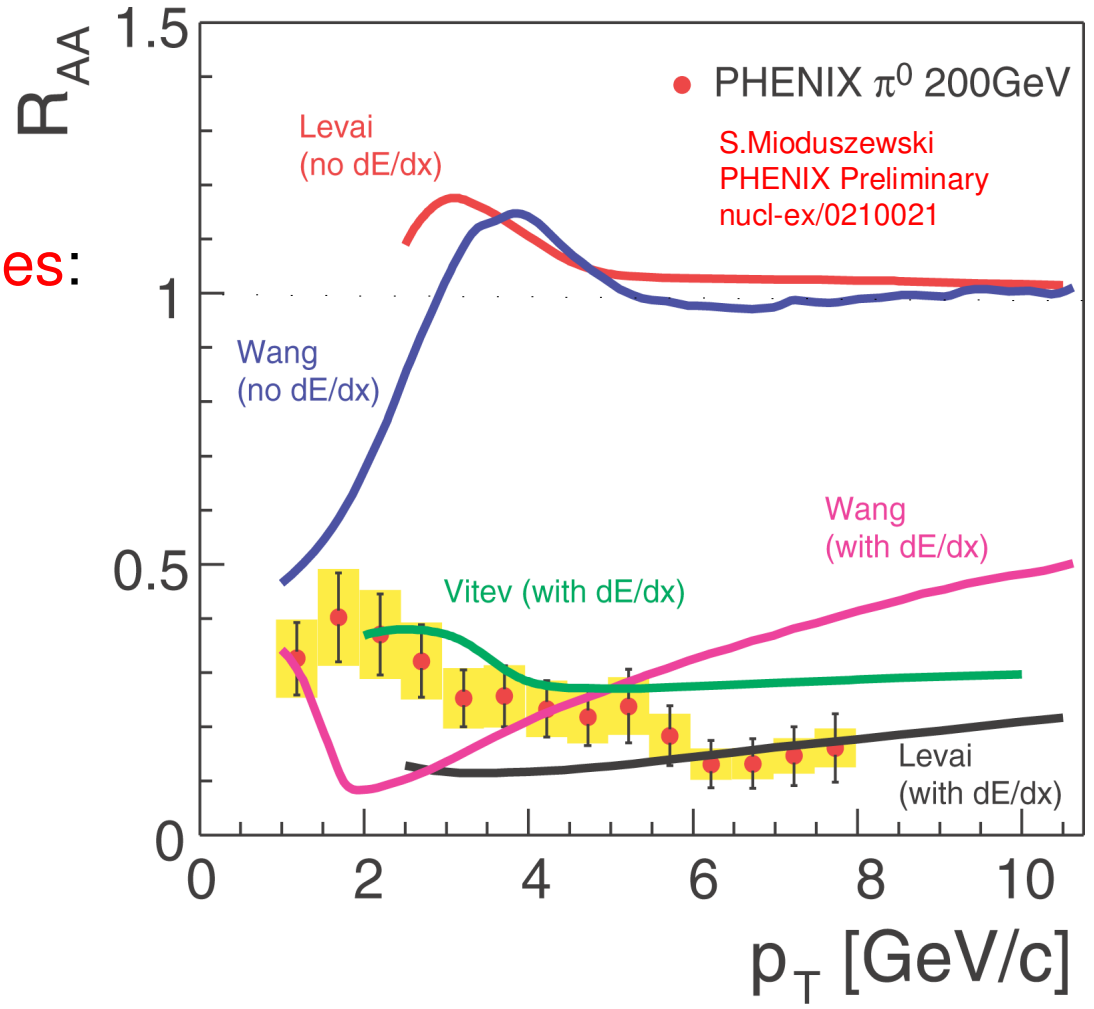
    $dN^g/dy \sim 800\text{-}1200$

  - Transport coefficients:

    $\langle q_0 \rangle \sim 3.5\ \mathrm{GeV/fm^2}$

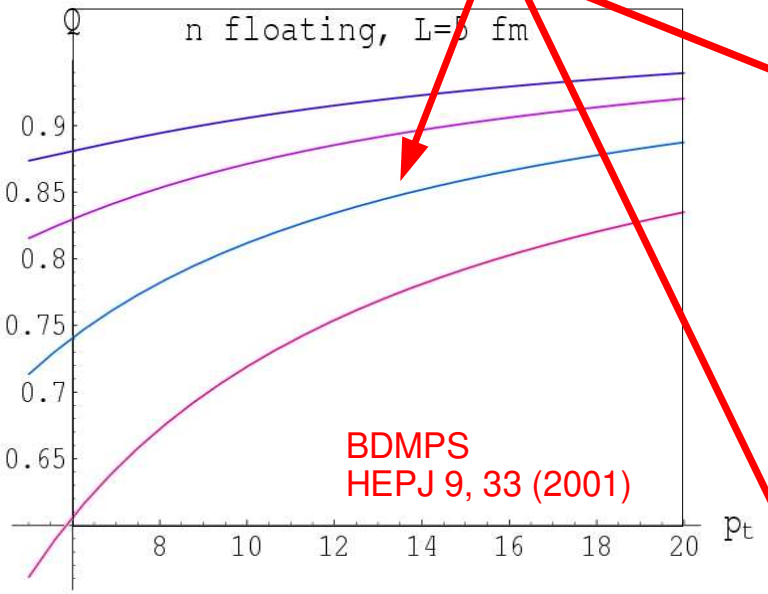
  - Medium-induced gluon radiative energy losses:

$dE/dx \approx 0.25\ \mathrm{GeV/fm}$ (expanding)
$dE/dx|_{eff} \approx 7\ \mathrm{GeV/fm}$ (static source)

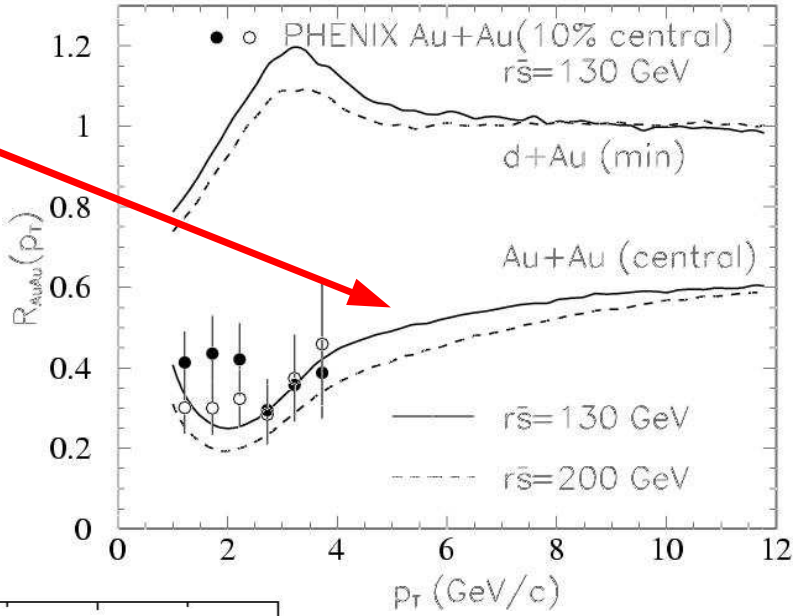


p_T dependence of the suppression (I)

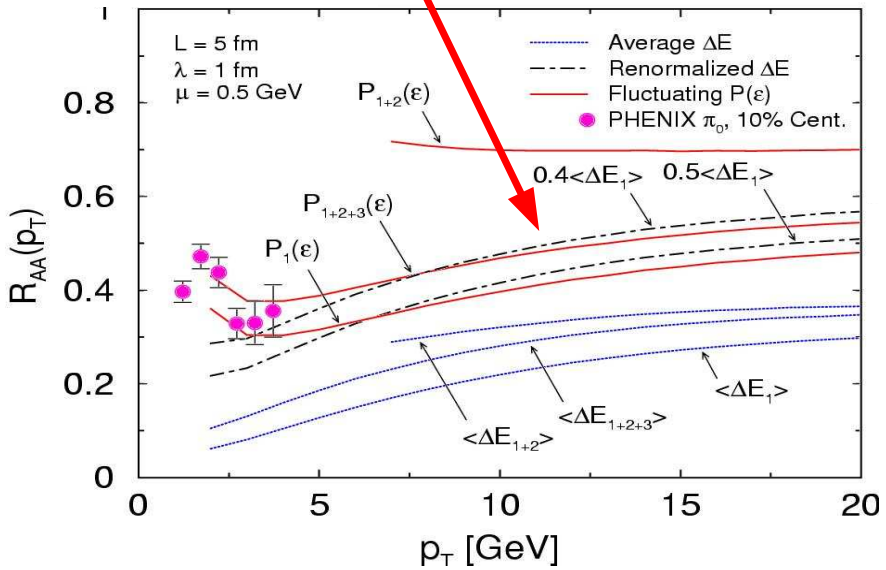
- All medium-induced (LPM) energy-loss models predict a smooth decrease of suppression ($\propto \sqrt{p_T}$) not seen in the data so far ...



BDMPS
HEPJ 9, 33 (2001)



E. Wang & X.N.Wang
PRL 89 162301 (2002)



GLV
PLB538, 282(2002)

p_T dependence of the suppression (II)

- Energy loss with LPM interference effect: (1) gives too much suppression at moderate p_T, (2) does not give the observed ~flat p_T dependence of R_{AA}
- Alternative 1: Let's test the Bethe-Heitler limit ...

Jeon, Jalilian-Marian, Sarcevic: hep-ph/0207120

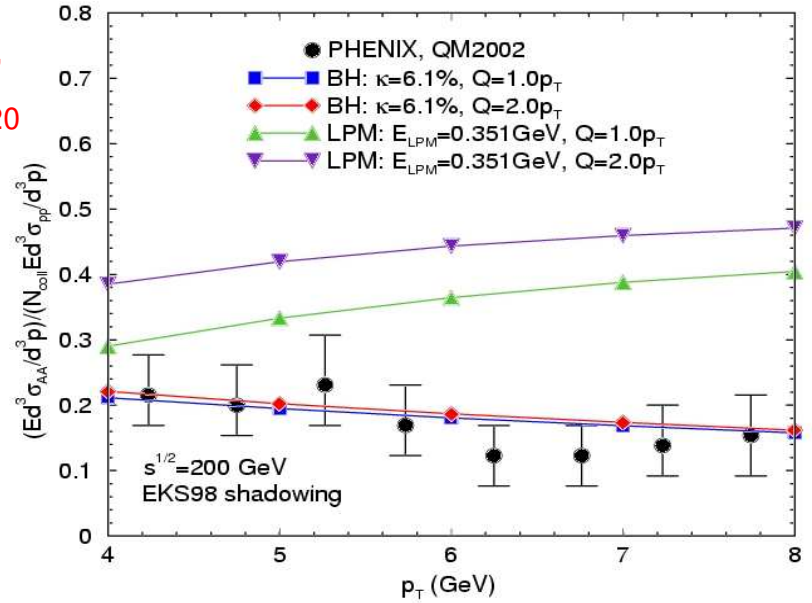
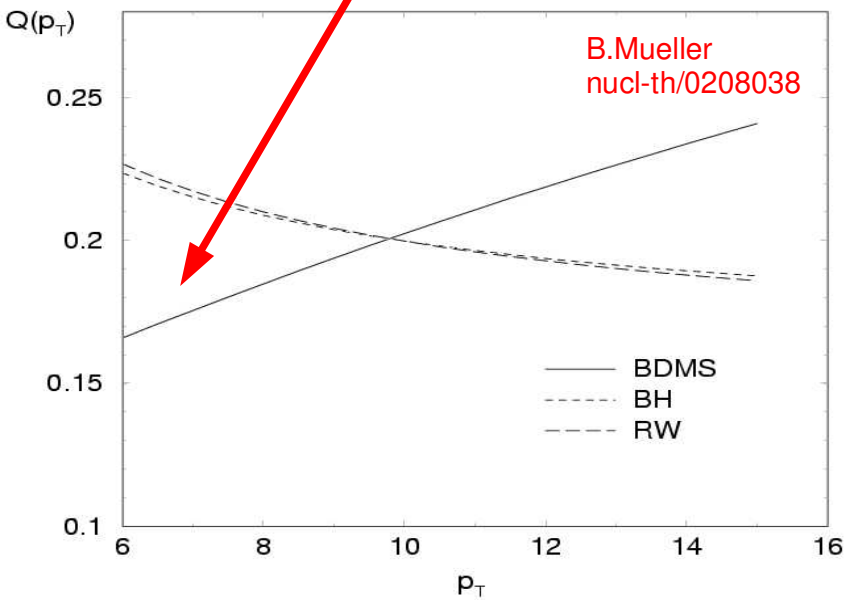


FIG. 8. Ratio of inclusive π^0 cross sections in heavy ion and p-p collisions at $\sqrt{s} = 200$ GeV, compared with PHENIX

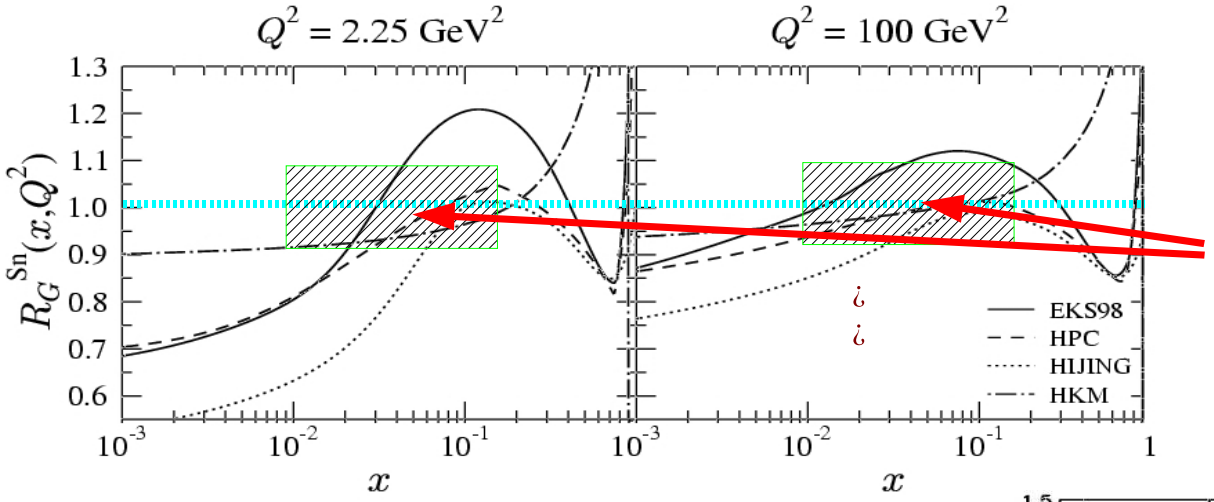


- Alternative 2: Let's add all other relevant nuclear effects ...
  - ✔ Modified nuclear PDFs (aka "shadowing")
  - ✔ Initial-state p_T broadening (aka "Cronin effect")

Parton shadowing does not seem to play a role (?)

- (x,Q^2) kinematical range relevant for RHIC (p_T ~ 2-10 GeV/c, y ≈ 0):

$$\begin{cases} x_{i,j} = (p_T/\sqrt{s})\cdot(e^{\pm y1}+e^{\pm y2}) \approx 2p_T/\sqrt{s} \approx 0.01\text{-}0.2 \quad \text{(gluons dominant !)} \\ Q^2 \approx p_T^{\,2} \approx 4 - 100\ \text{GeV}^2 \end{cases}$$



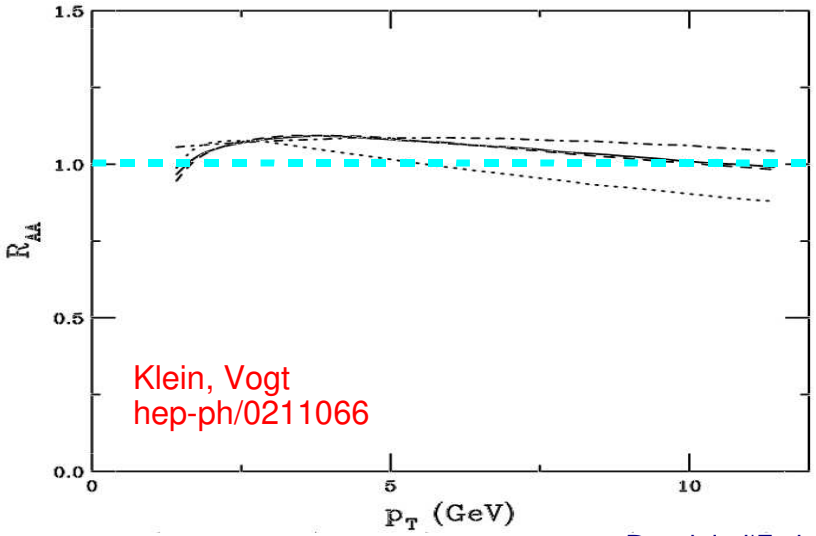
EKS98 ("state-of-the-art" nuclear PDFs):

R_{gluon} ~ 1.0 @ RHIC:

EKS hep-ph/0201256

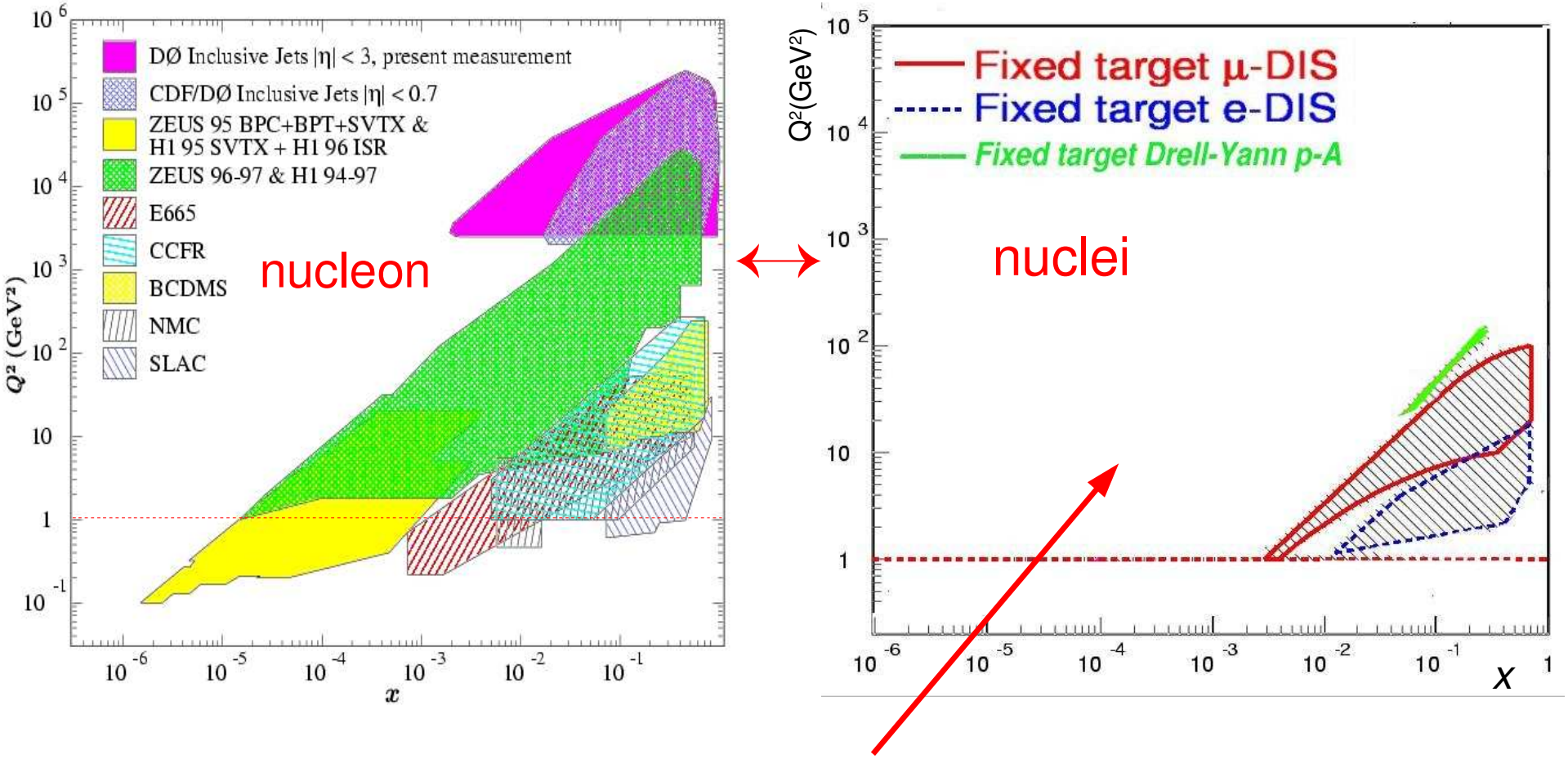
R_{AA} vs p_T due to shadowing: ~ 1

"Shadowing is a small effect at mid-rapidity"



but ... what do we <u>really know</u>(*) about gluon shadowing ?

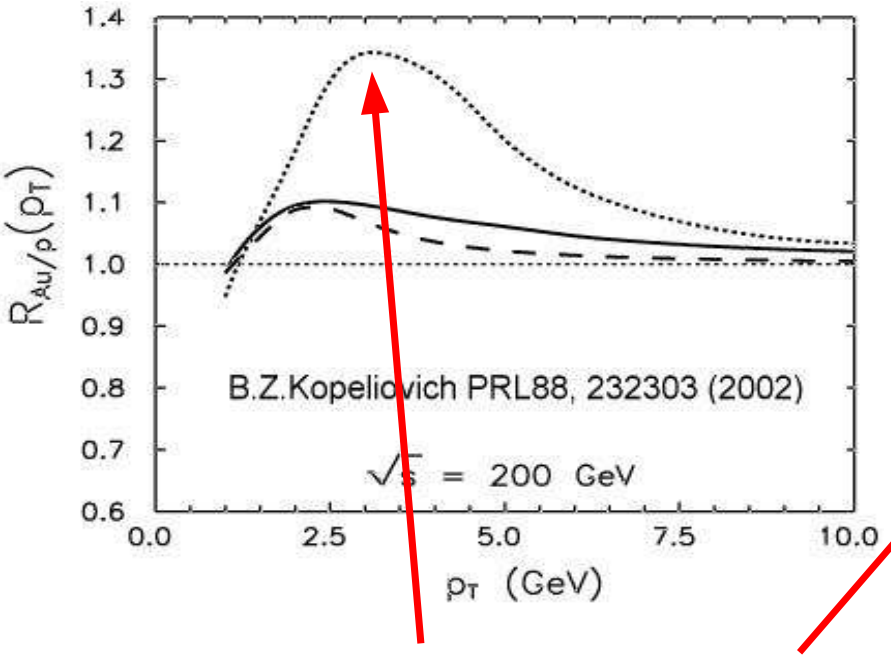
(*) = *measured in lepton-A experiments*

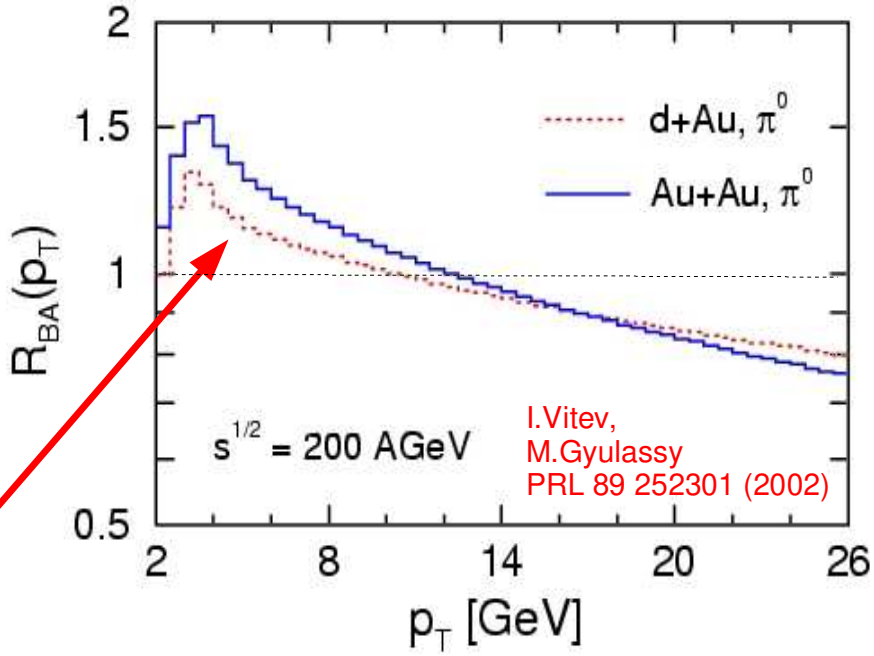


"propaganda"-plot for current dA run (and for eRHIC) ...

Nuclear (x,Q^2,A) plane is "terra incognita" compared to nucleon (x,Q^2) !

Cronin enhancement does seem to play a role

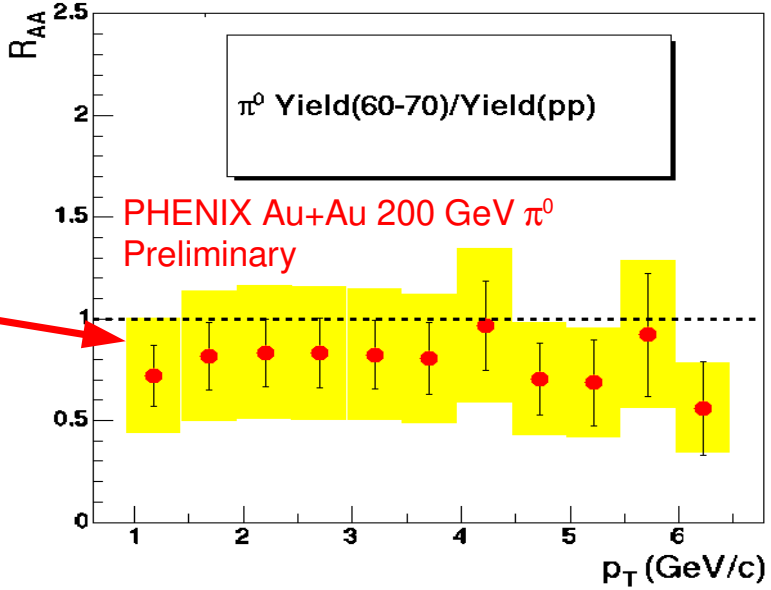




Expected k_T broadening @ RHIC

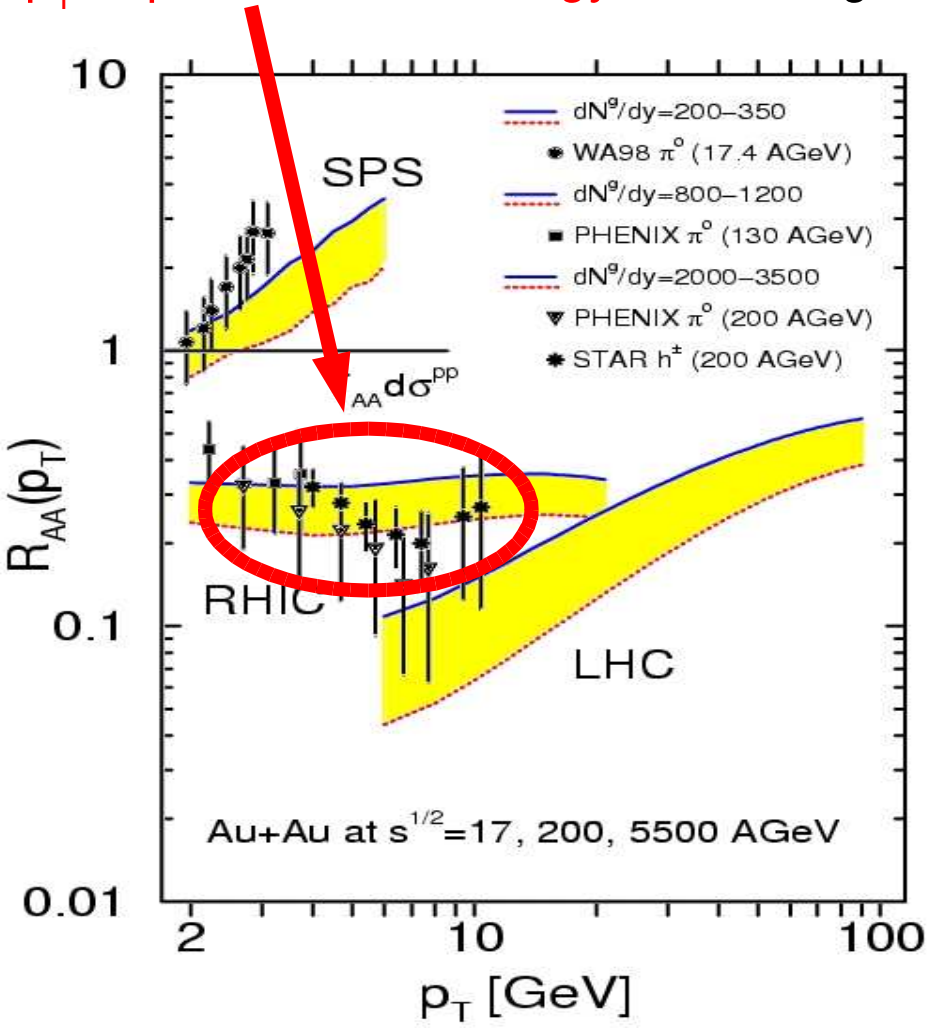
though ... are those predictions consistent with the apparent absence of Cronin enhancement in peripheral Au+Au @ 200 GeV ?

Answer soon: d+Au 2003 ...



Energy loss + Shadowing + Cronin = flat R_{AA}

- Initial state p_T broadening provides: (1) the needed enhancement at intermediate p_T , (2) the small decrease at higher p_T so as to compensate for the p_T dependence of energy loss and give the observed ~flat R_{AA} (p_T)



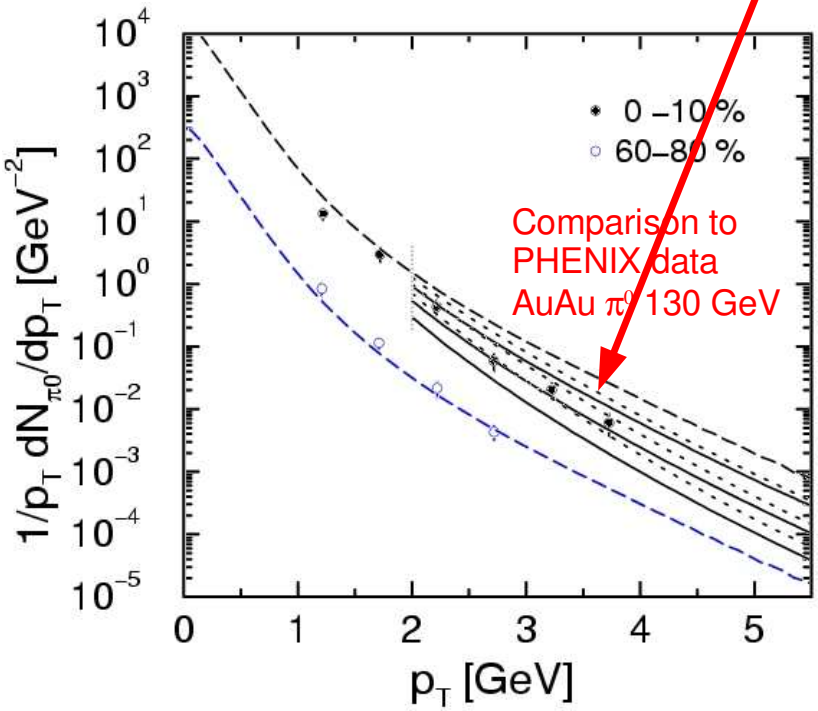
I.Vitev,
M.Gyulassy
PRL 89 252301 (2002)

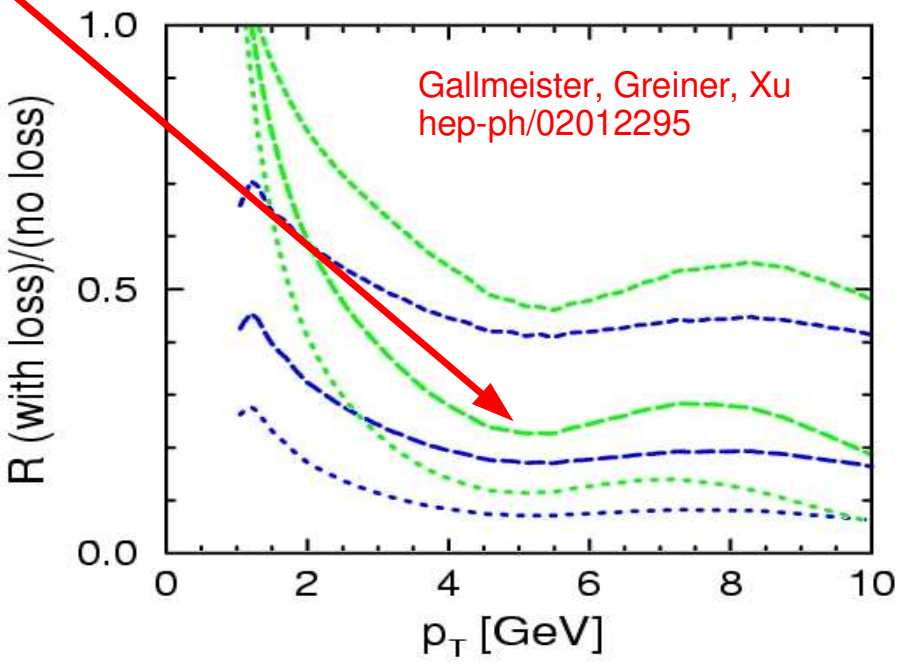
- It seems that parton energy loss can explain the data ... yet ...

High p_T suppression explainable too due to hadronic final-state interactions (*) !?

(*) "comovers"-like explanation (parentheses for the SPS J/Psi story "connaisseur")

- Dense hadronic medium: $\langle L/\lambda \rangle \sim 2\text{-}3$

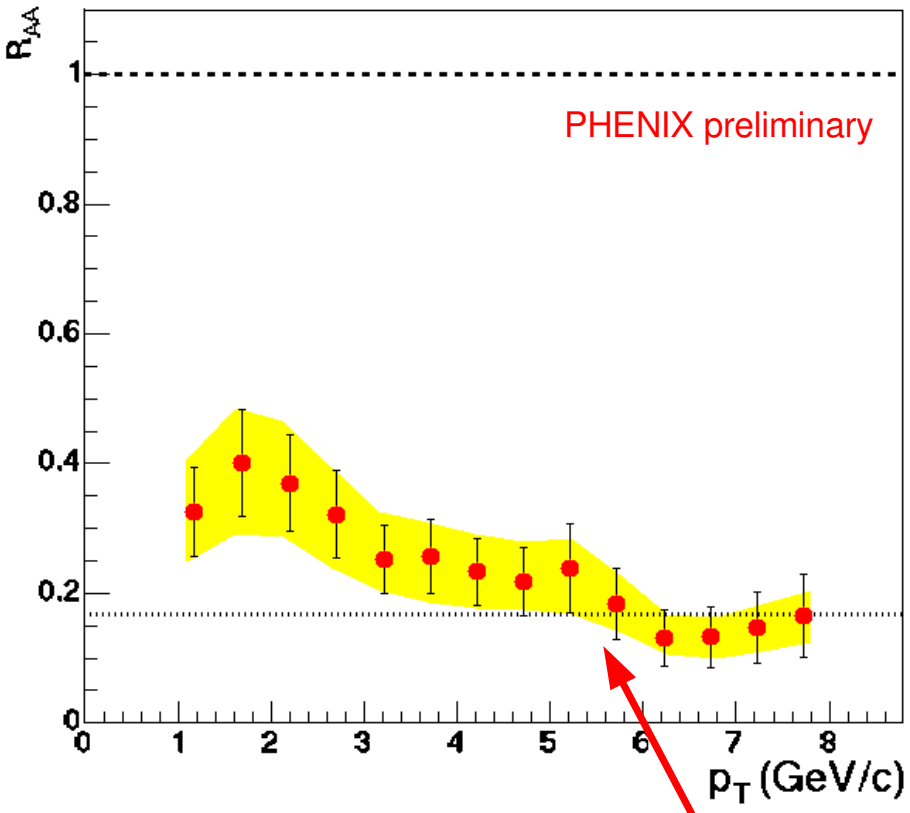


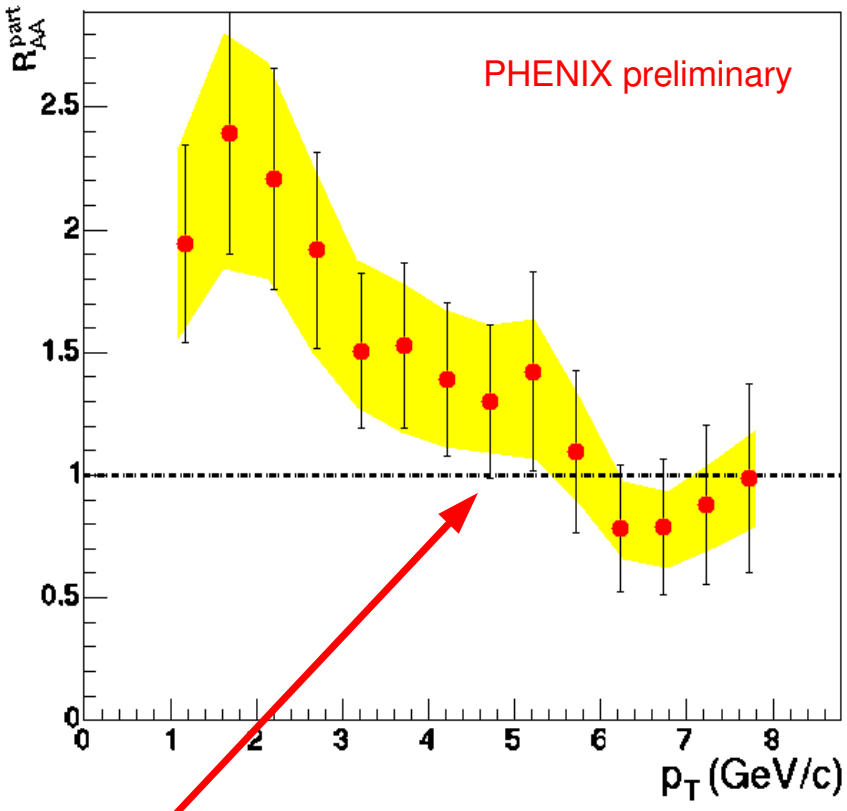


- Main justification: fast parton hadronization time (i.e. inside expanding fireball)
  But, do τ_{had} estimates in pp (vacuum) apply to hadroniz. in (colored) medium ?
- Description of scattering in the hadronic phase realistic enough ? ("... *our calculations are at best semiquantitative* ...").

p_T-dependence of π^0 suppression: N_{part} scaling ?

- R_{AA} and R_{AA}^{Npart} (0-10% central collisions):

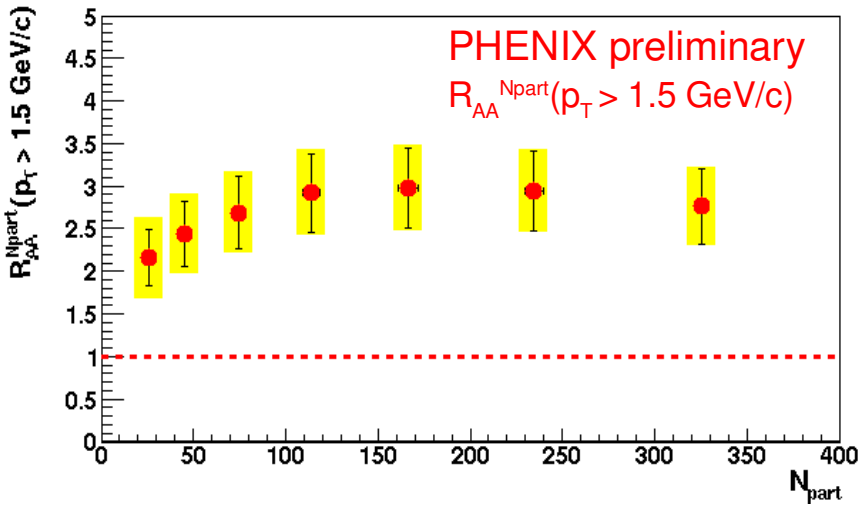


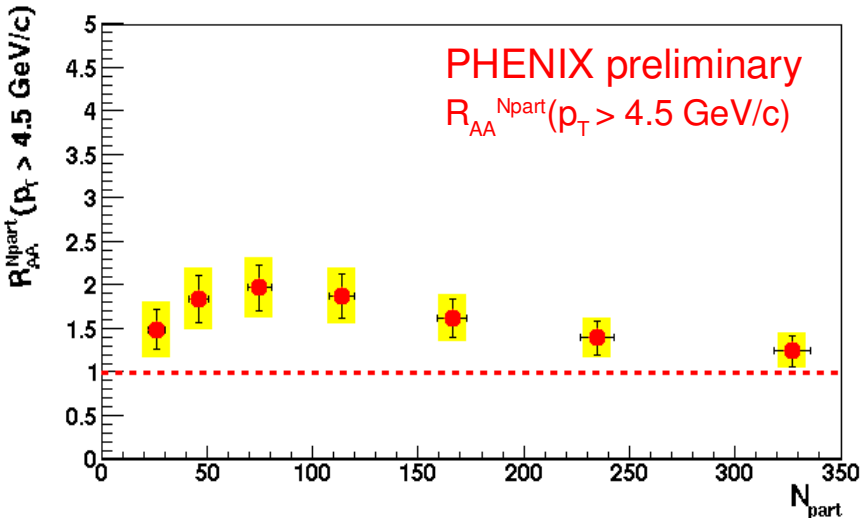


- Approx. N_{part} scaling, R_{AA} ~ 0.16 (R_{AA}^{Npart} ~ 1.) , only for $p_T > 4$ GeV/c

Centrality-dependence of π^0 suppression : N_{part} scaling ?

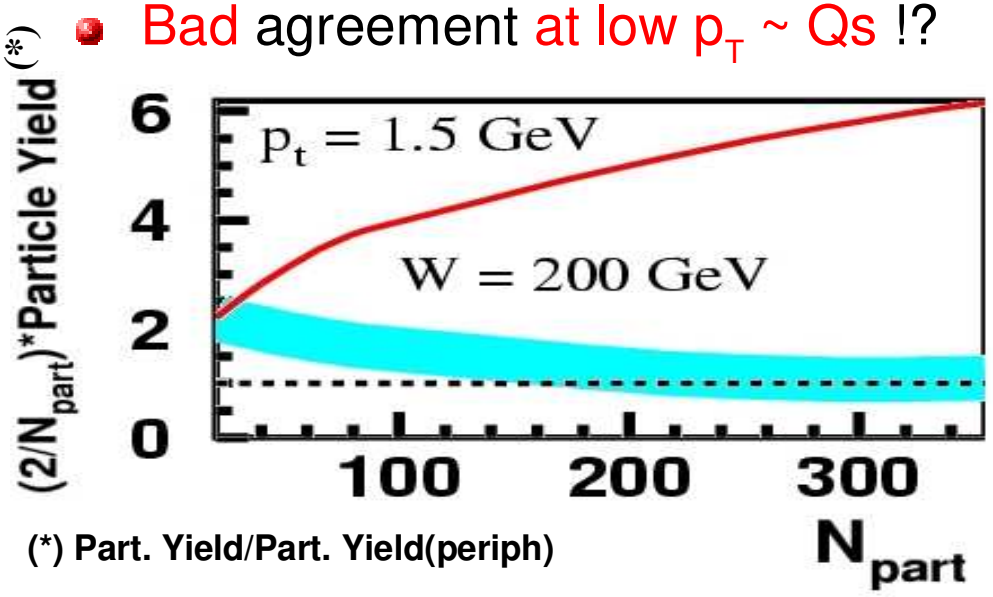
- Integrated $R_{AA}^{Npart/2}$ above a given p_T (1.5 GeV/c, 4.5 GeV/c) vs. N_{part} compared to gluon saturation predictions:



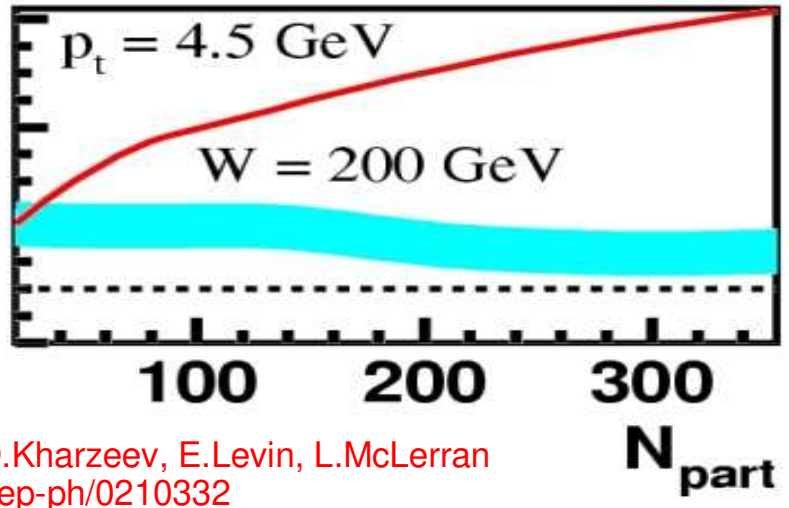


- Bad agreement at low p_T ~ Qs !?

Reasonable agreement at high p_T



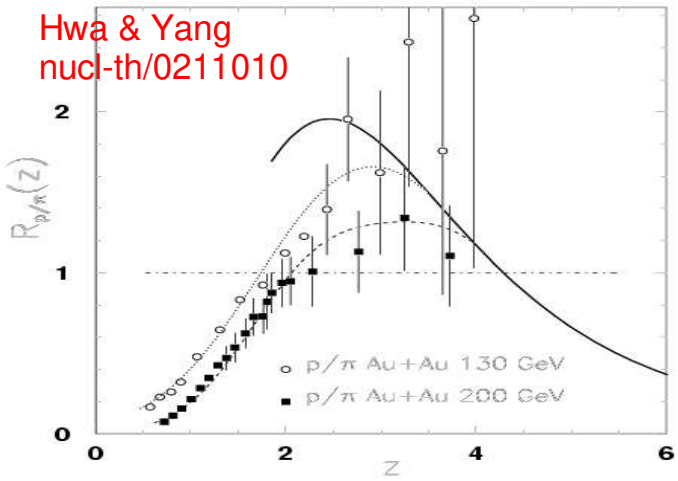
(*) Part. Yield/Part. Yield(periph)

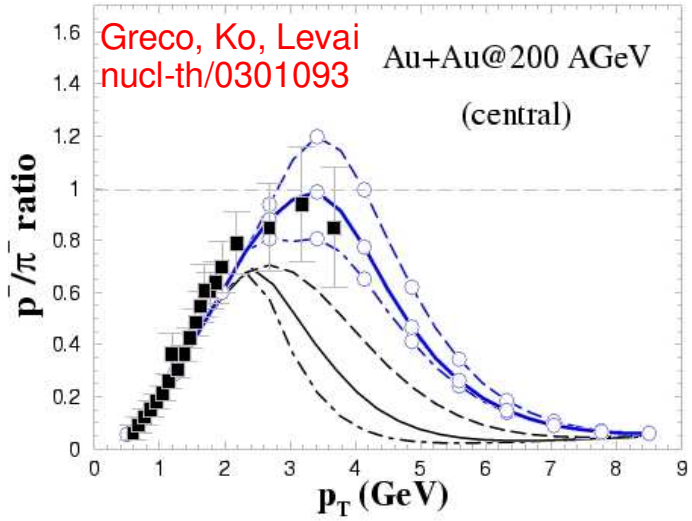


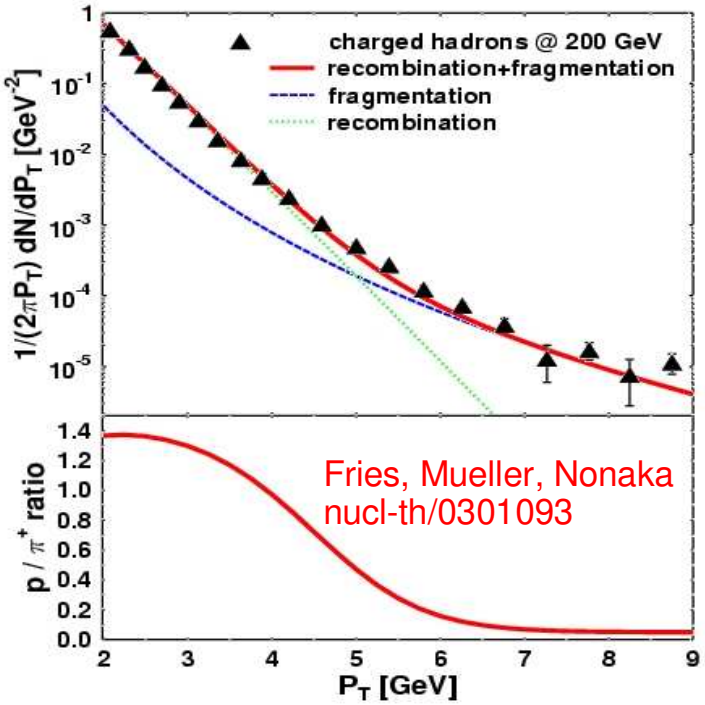
D.Kharzeev, E.Levin, L.McLerran
hep-ph/0210332

Parton recombination and high p_T "chemistry"

- Recombination/coalescence models: ~10 pre-prints in the last 2 months







- Recombination dominates for p_T ~ 1- 4 GeV/c:
  $\langle p_T(\text{baryons})\rangle > \langle p_T(\text{mesons})\rangle > \langle p_T(\text{quarks})\rangle$
  (coalescence, thermal quark distribution ...)
- Fragmentation dominates for $p_T > 5$ GeV/c:
  $p_T(\text{hadrons}) = z\, p_T(\text{partons})$, with $z<1$

High p_T identified particles @ PHENIX: Summary (I)

- Two most interesting physical "discoveries" @ RHIC:
  1. High p_T suppression.
  2. High p_T baryon/meson enhancement.

  "Clear signals of strong medium effects at work !"

- What can we learnt about the medium properties ?
  - Final-state partonic jet quenching + parton recombination ? (QGP)
  - Initial-state saturation of nuclear wave functions ? (CGC)
  - Final-state hadronic absorption ? (very dense hadron medium)

- Answers:
  - Experimental: Detailed analysis of Au+Au (d+Au) suppression pattern.
  - Theoretical: Does scenario "X" consistently explains: the magnitude, p_T dependence, centrality evolution, and flavor behaviour of RHIC high-p_T suppression ?

High p_T identified particles @ PHENIX: Summary (II)

- Experimental results:
  - Central AuAu collisions:
    - Strong suppression (factor ~ 5) of π^0 with respect to N_{coll} scaling (approx. N_{part} scaling above ~ 4 GeV/c).
    - Suppression sets in over 50-70% centrality class (N_{part} ~ 50).
    - No apparent suppression of (anti)protons up to ~4 GeV/c ("anomalous" p/π).
  - Peripheral AuAu collisions:
    - Behave effectively as pp collisions (i.e. as pQCD) for all species.
- Data vs. theory:
  - Magnitude of suppression in agreement with parton energy loss scenarios assuming opaque medium formation (dN^g/dy~900, λ/L~3-4, dE/dx~7GeV/fm). [But also with hadronic dense medium ?].
  - Flat p_T dependence (so far) of suppression not described with LPM energy loss alone. Other effects (esp. Cronin broadening) needed at intermediate p_T
  - Parton coalescence proposed to explain baryon/pion~1 ratio at intermediate p_T
  - Gluon saturation prediction of N_{part} scaling of R_{AA} vs centrality seems to work at high p_T (but not at p_T~Q_s ?).

Backup slides

Identified high p_T particles @ PHENIX

1. Mesons – π^0, ($\pi^{\pm}$):
   - 130 GeV ($p_T^{max} \approx 3.5$ GeV/c): PRL 2001
   - 200 GeV ($p_T^{max} \approx 10.$ GeV/c): QM 2002
2. Baryons – p, $\bar{p}$:
   - 130 GeV ($p_T^{max} \approx 3.5$ GeV/c): PRL 2002
   - 200 GeV ($p_T^{max} \approx 4.$ GeV/c): QM 2002
3. Particles ratios (p/π, $\bar{p}/p$, $\bar{p}/h$):
   - 130 GeV ($p_T^{max} \approx 3.5$ GeV/c): PRL 2002
   - 200 GeV ($p_T^{max} \approx 4.$ GeV/c): QM 2002

4. Electrons: 130, 200 GeV ($p_T^{max} \approx 4.$ GeV/c): PRL 2002, QM2002

Summary of published high p_T observables

1. Inclusive p_T spectra (π^0, p, $\bar{p}$, ...):
   For different AuAu centrality classes (central → periph. + min. bias)
2. Nuclear modification factor vs p_T:

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

→ p_T dependence of medium effects

Numerator : Different AuAu centrality classes.

Denominator : - NN ref.: UA1 $p\bar{p}$, PHENIX pp→ π^0X @ 200 GeV

- $\langle N_{coll}\rangle$ from Glauber

3. Central/peripheral ratio vs p_T:
   For diff. AuAu cent. class combinations.

→ p_T dependence of medium effects

4. R_{AA} (p_T-integr.) vs centrality (N_{part}).

→ Participant density dependence of medium eff.

5. Particle ratios vs p_T:
   For different AuAu centrality classes.

→ Flavor dependence of medium effects