High p_T spectra: Experimental overview

INT/RHIC Winter Workshop on First Two Years of RHIC: Theory versus Experiments

Seattle, December 13-15, 2002

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High p_T particles @ RHIC. Motivation

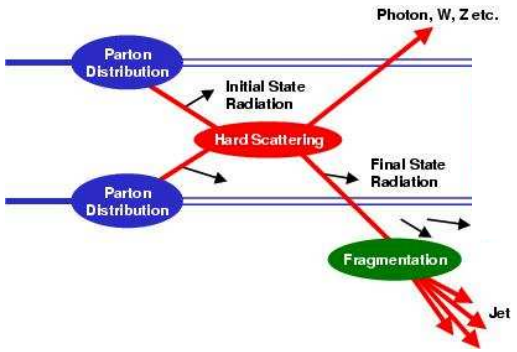
- Products of parton fragmentation (jet "leading particle").
- Early production in parton-parton scatterings with large Q^2.
- Direct probes of partonic phases of the reaction $\Rightarrow$ Sensitive to hot/dense medium: parton energy loss ("jet quenching").
- Info on medium effects accessible through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

Nucl. geom. scaling: $$\sigma_{AB}^{hard} = \int d^2b \left[1 - e^{-\sigma_{NN}^{hard} T_{AB}(b)}\right] \approx \int d^2b \, \sigma_{NN}^{hard} \, T_{AB}(b)$$

Since: $$\langle N_{coll} \rangle(b) = \sigma_{NN} \cdot T_{AB}(b) \Rightarrow \frac{(d^2\sigma_{AB}^{hard})_{C_1-C_2}}{dp_T dy} = \langle N_{coll} \rangle_{C_1-C_2} \cdot \frac{\sigma_{AB}^{geo}}{\sigma_{NN}} \cdot \frac{d^2\sigma_{pp}^{hard}}{dp_T dy}$$

- Production yields calculable via pQCD:

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



Measured Au+Au high p_T spectra @ RHIC

0. *Foreword*: " high p_T" ≡ p_T > 1.5 GeV/c @ mid-rapidity *(but y ≈ 2. BRAHMS π^-)*

1. Unidentified charged-particles:
   - 130 GeV (p_T^{max} ≈ 5. GeV/c): PHENIX, STAR (PRL 2001, PRL 2002)
   - 200 GeV (p_T^{max} ≈ 12. GeV/c): BRAHMS, PHENIX, PHOBOS, STAR (QM 2002)

2. Identified baryons – p, $\bar{p}$:
   - 130 GeV (p_T^{max} ≈ 3.5 GeV/c): PHENIX (PRL 2002)
   - 200 GeV (p_T^{max} ≈ 4. GeV/c): PHENIX (QM 2002)

3. Identified mesons – π^0, $\pi^{\pm}$:
   - 130 GeV (p_T^{max} ≈ 3.5 GeV/c): PHENIX (PRL 2001)
   - 200 GeV (p_T^{max} ≈ 10. GeV/c): PHENIX, BRAHMS (π^-<4 GeV/c) (QM 2002)

4. Particles ratios (p/π, $\bar{p}/p$, p/h):
   - 130 GeV (p_T^{max} ≈ 3.5 GeV/c): PHENIX (PRL 2002)
   - 200 GeV (p_T^{max} ≈ 4. GeV/c): BRAHMS, PHENIX, STAR (QM 2002)

5. Electrons: 130, 200 GeV (p_T^{max} ≈ 4. GeV/c): PHENIX (PRL 2002, QM2002)

Talk by R.Averbeck

Summary of published high p_T observables

1. Inclusive p_T spectra ($h^{\pm}$, 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

- $\langle N_{coll}\rangle$ ($\langle N_{part}\rangle$ for PHOBOS) from Glauber

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

➜ p_T dependence of medium effects

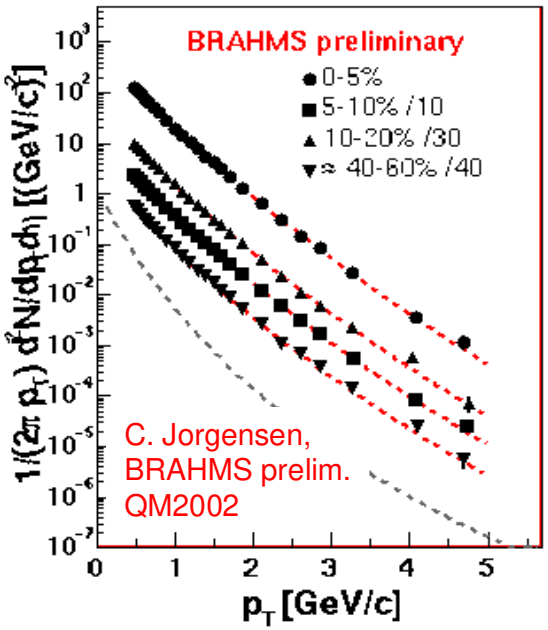
4. R_{AA} (p_T-integr.) vs centrality (N_{part}).

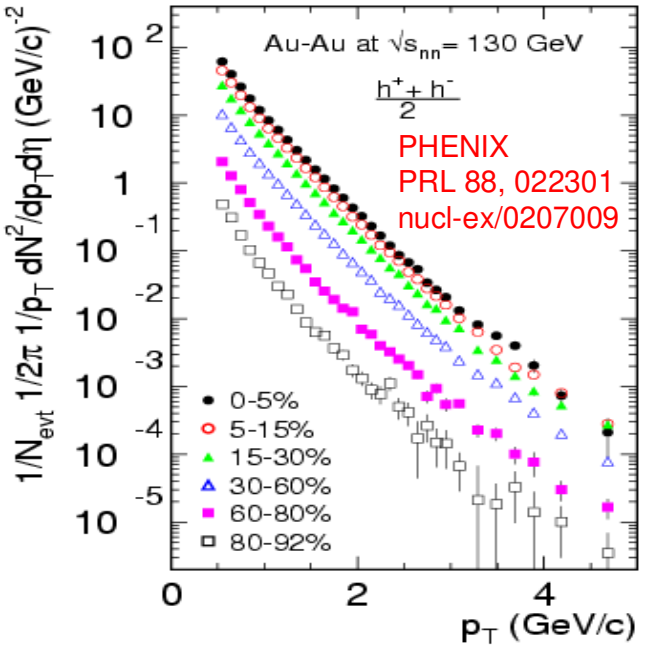
➜ Participant density dependence of medium eff.

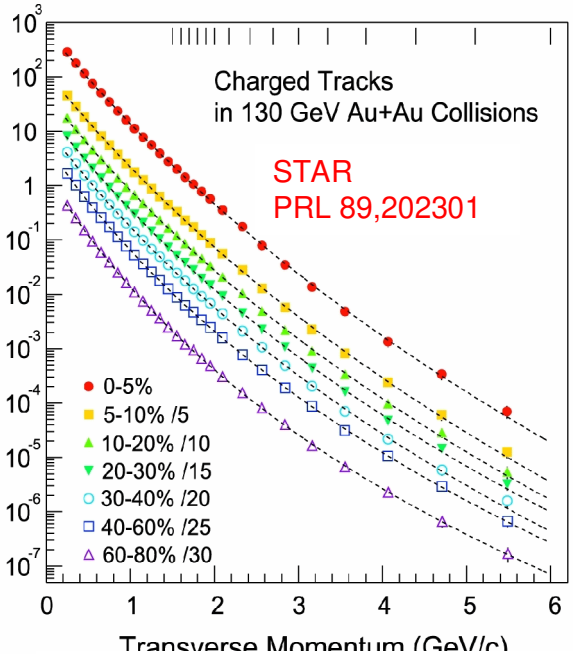
5. Particle ratios vs p_T:
   For different AuAu centrality classes.

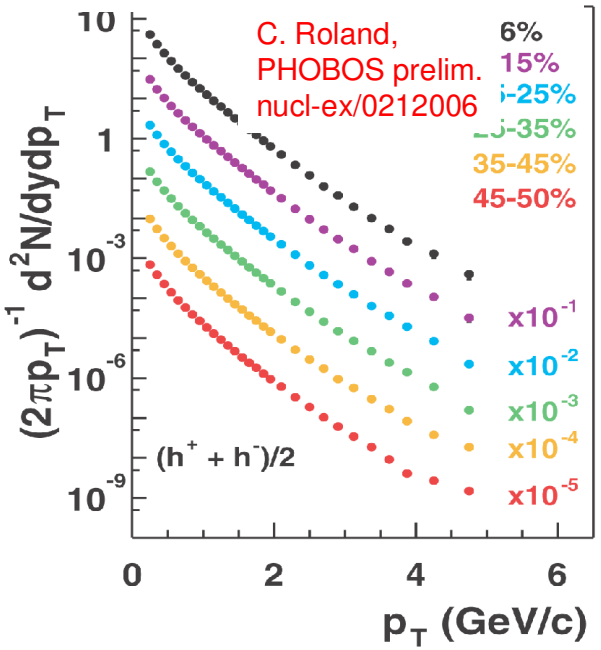
➜ Flavor dependence of medium effects

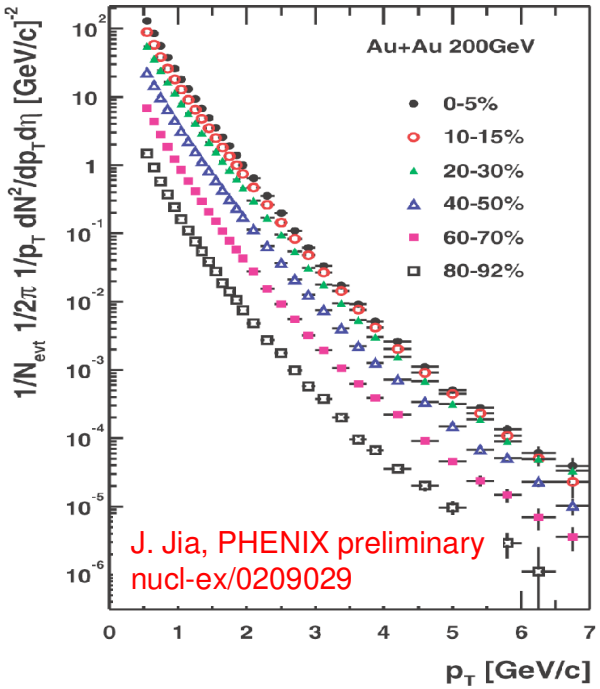
Compilation I: Inclusive charged particle spectra

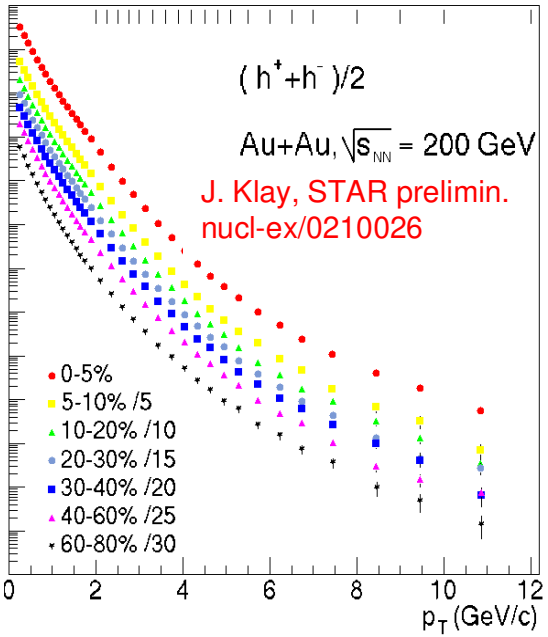




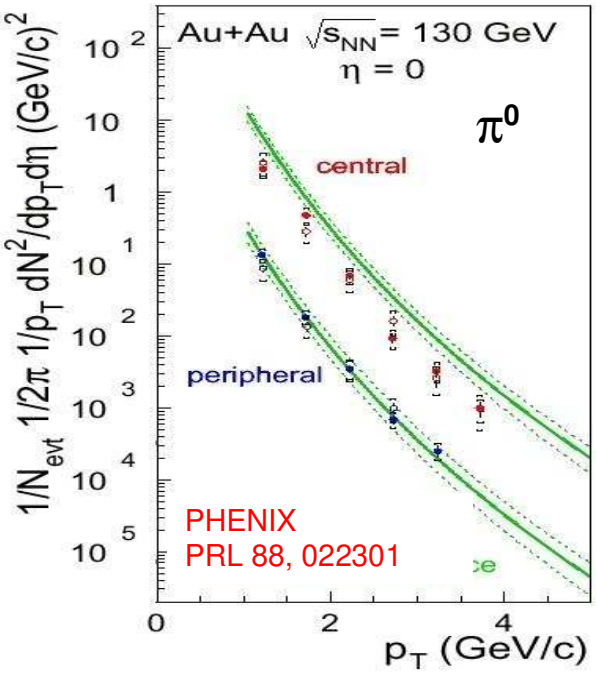


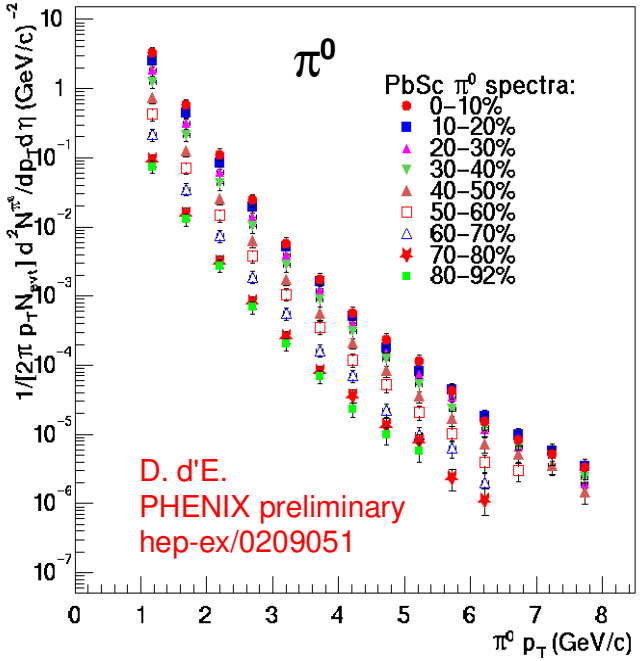


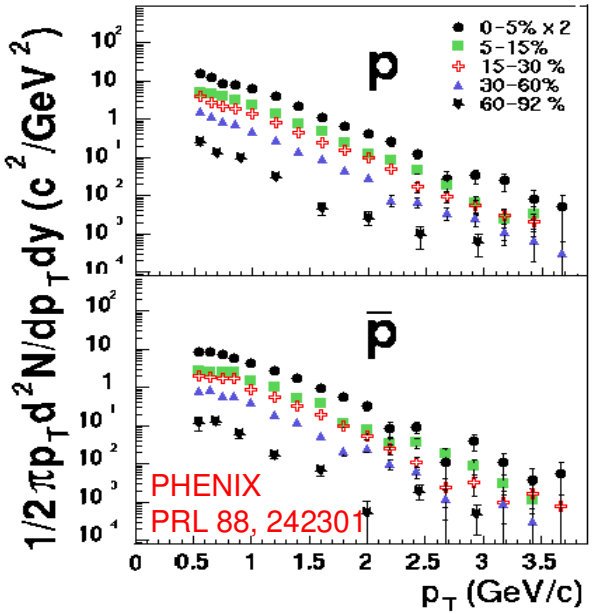


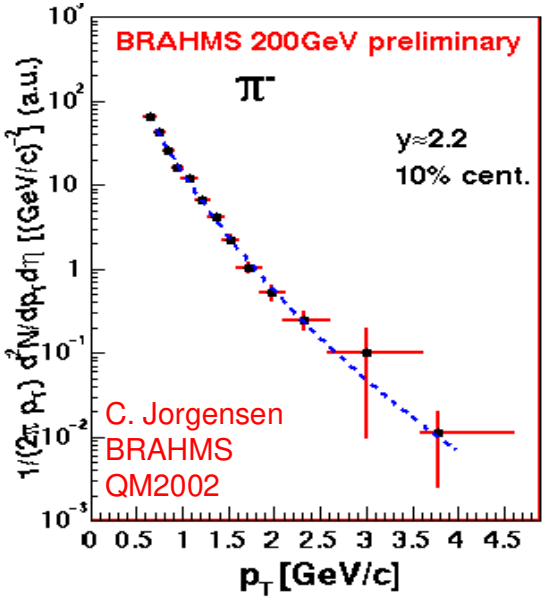


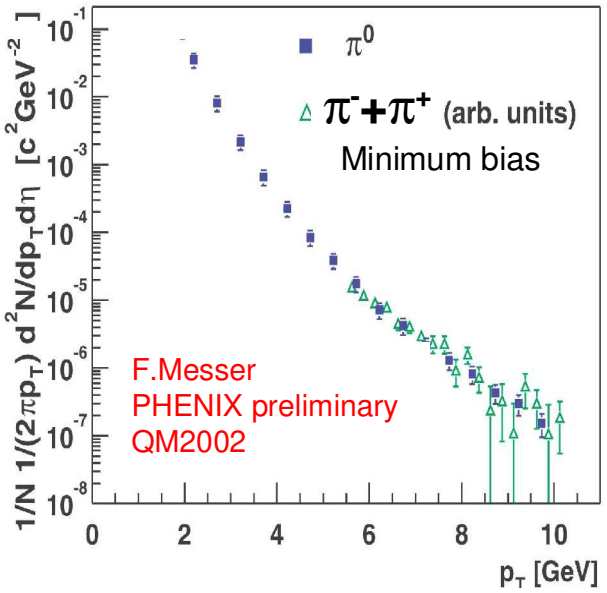
Compilation II: Identified high p_T spectra

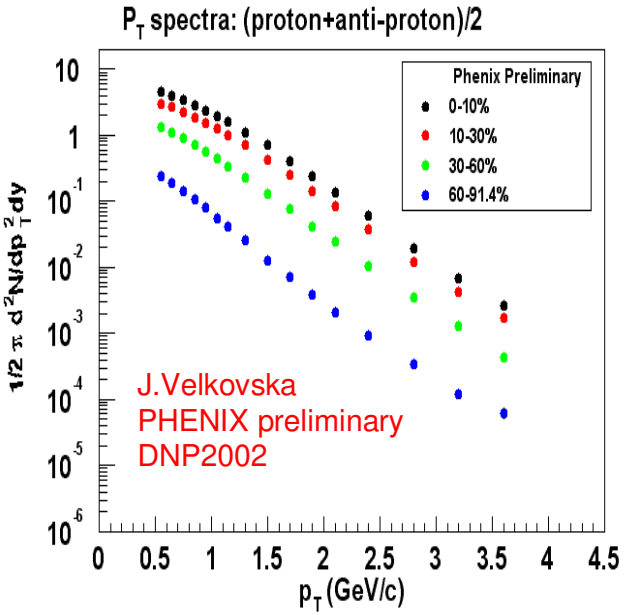






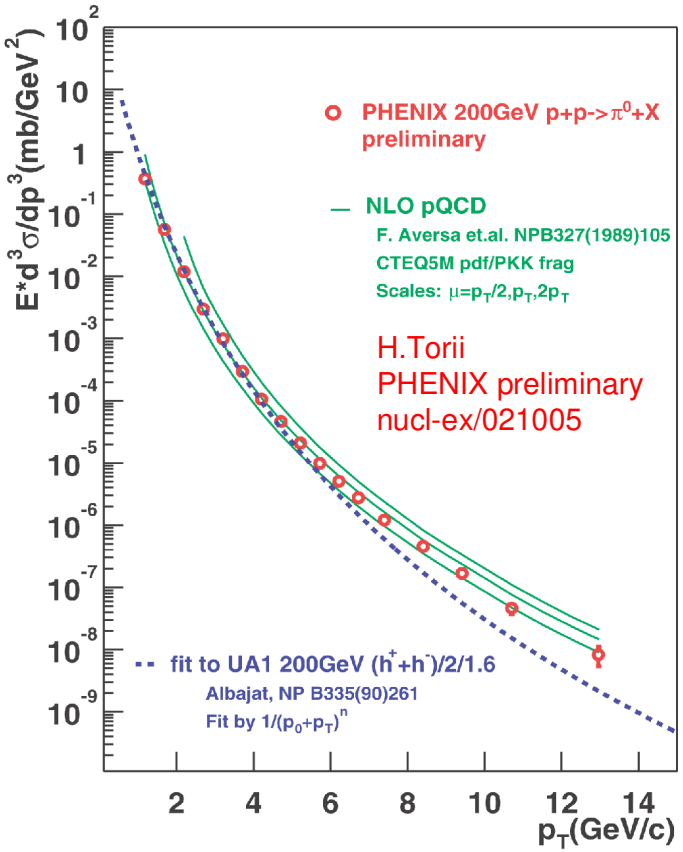




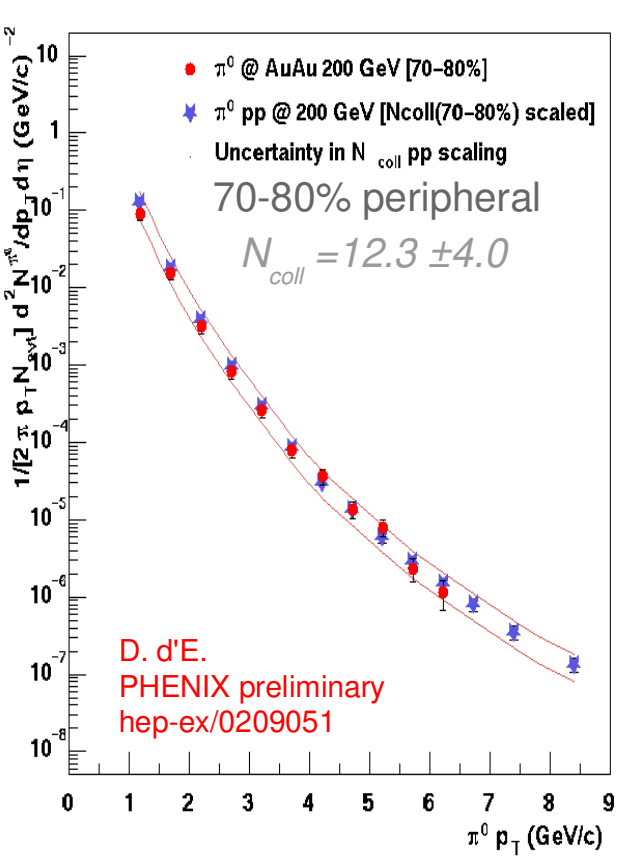


High-p_T AuAu vs pp (π^0 @ 200 GeV)

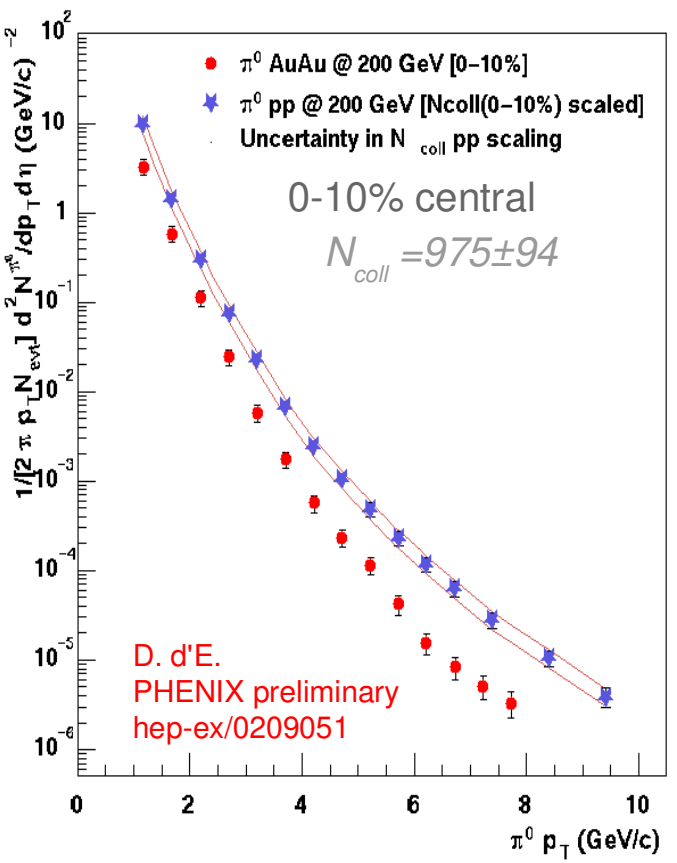
p+p→ π^0 *X*



Au+Au→ π^0 *X* (periph)



Au+Au→ π^0 *X* (central)

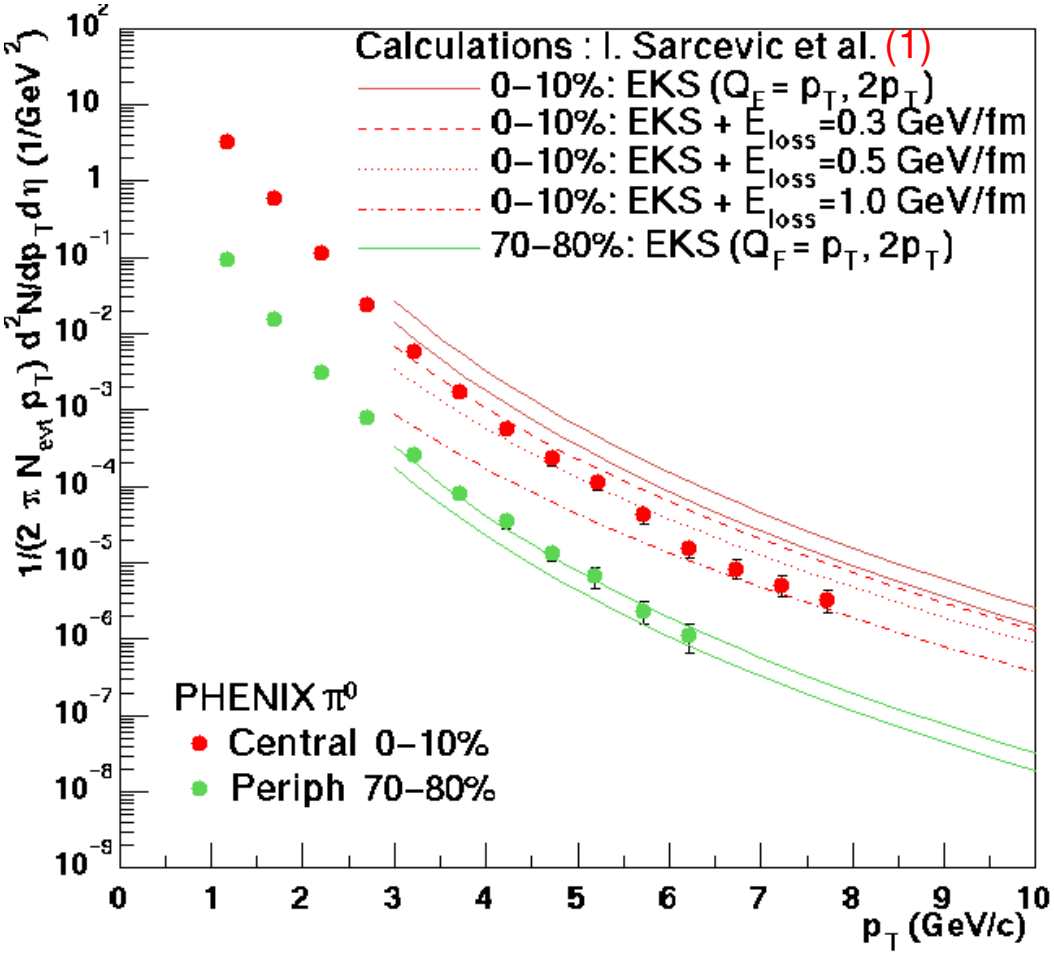


pp data agree with pQCD

Periph. data agree with pp plus collision scaling

Strong suppression in central AuAu collisions

High-p_T AuAu spectra vs pQCD (π^0 @ 200 GeV)



NLO pQCD

- PDFs: MRS99
- FFs: BKK

Medium effects:

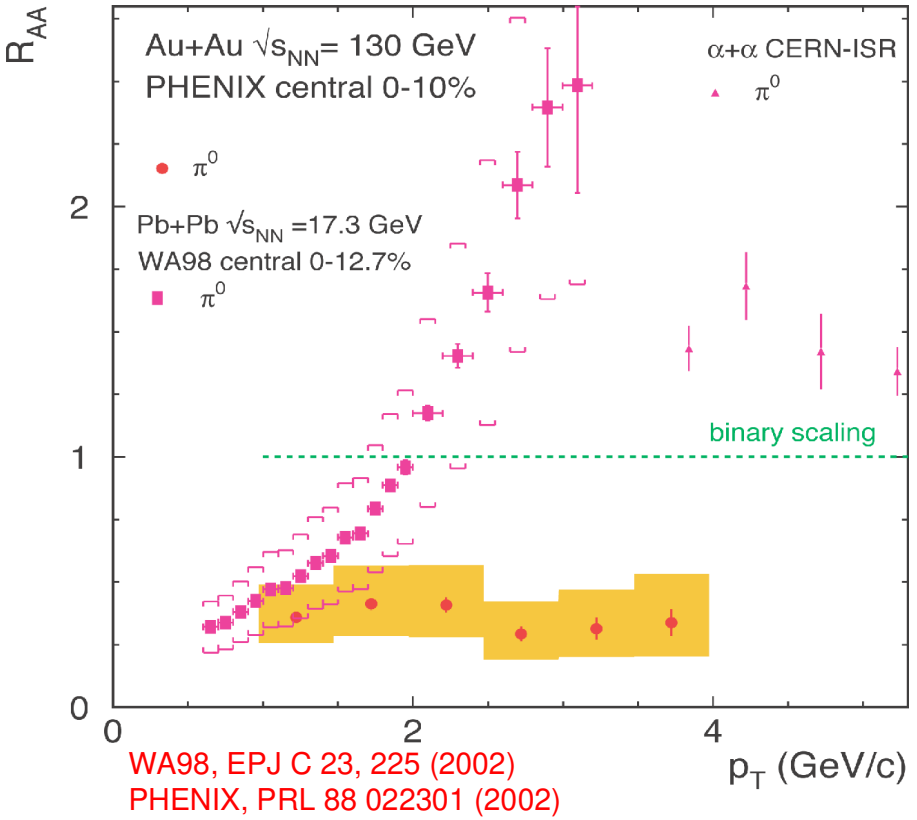
- Shadowing: EKS98
- E_{loss}: Modified FFs (Wang, Huang, Sarcevic).

(1) S.Jeon, J. Jalilian- Marian, I.Sarcevic hep- ph/0207120

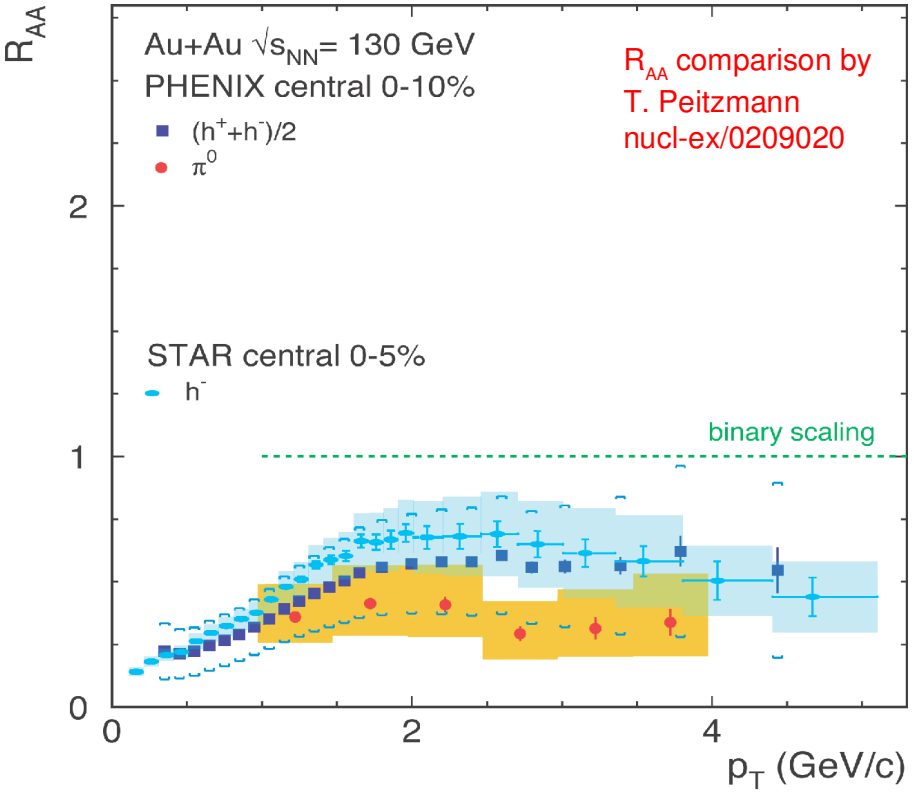
- Peripheral: Reproduced with no significant nuclear effects.
- Central: Well below predictions without energy loss.
  Increasing suppr. with p_T (inconsistent with const. ε_{loss})

Hadron suppression: central AuAu (130 GeV)

- Strong suppression (from N_{coll} scaling) in π^0: R_{AA} (p_T=3.5 GeV/c) ≈ 0.25
- Less suppression for charged hadrons: R_{AA} (p_T = 5 GeV/c) ≈ 0.4
- Significantly different behaviour than at lower energies: SPS Pb+Pb and ISR α+α (Cronin enhancement: R_{AA} > 1 for p_T > 2 GeV/c)



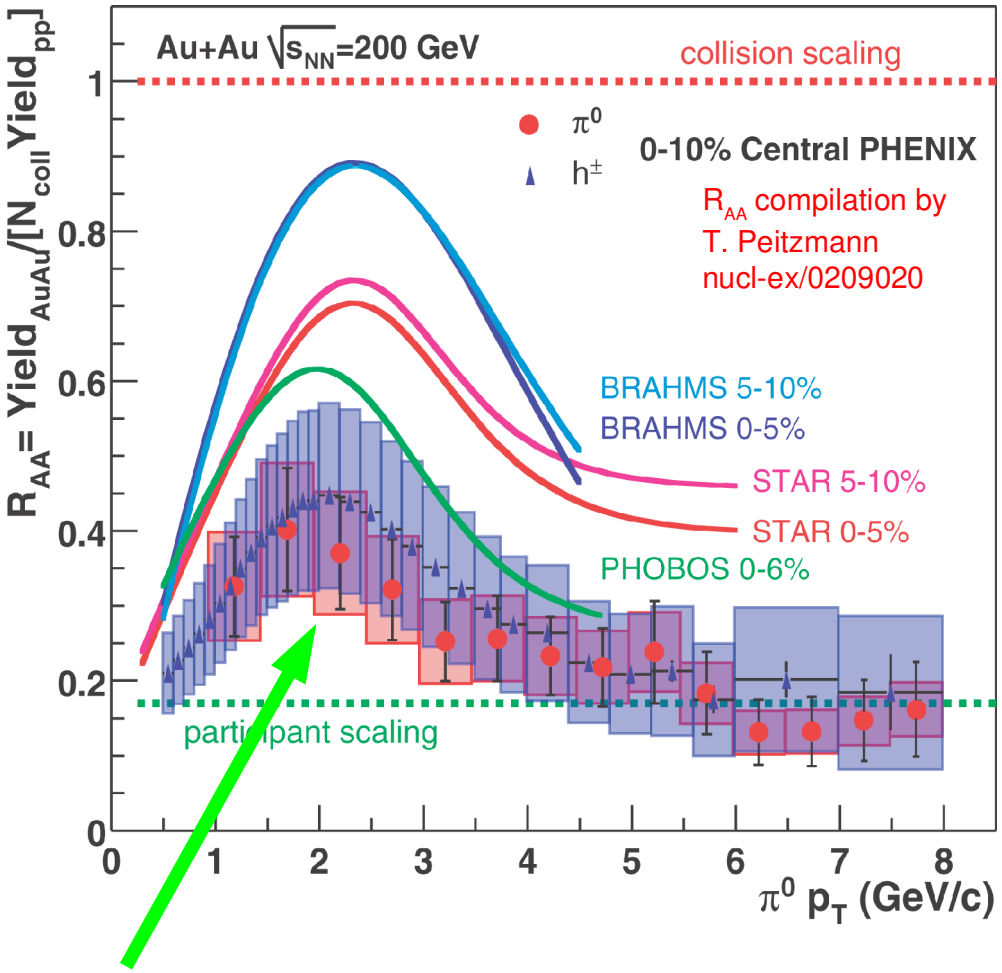
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)



Hadron suppression: central AuAu (200 GeV)

- Neutral pions :
  - Similar suppression as @ 130 GeV
  - Increasing with p_T.
  - R_{AA} saturates at ~0.2 for p_T> 5 GeV/c
  - Diff. p_T (x_T) evolution than expected for nuclear shadowing.
- Charged hadrons :
  - Increasing with p_T and saturating at high p_T too: R_{AA}~0.35
  - Less suppressed than π^0
  - BRAHMS > STAR > PHOBOS > PHENIX. Diffs. (within errors):

    Glauber + cent. trigger ~ 10%
    pp ref. ~ 10%
    Eff. corrections: ~15%

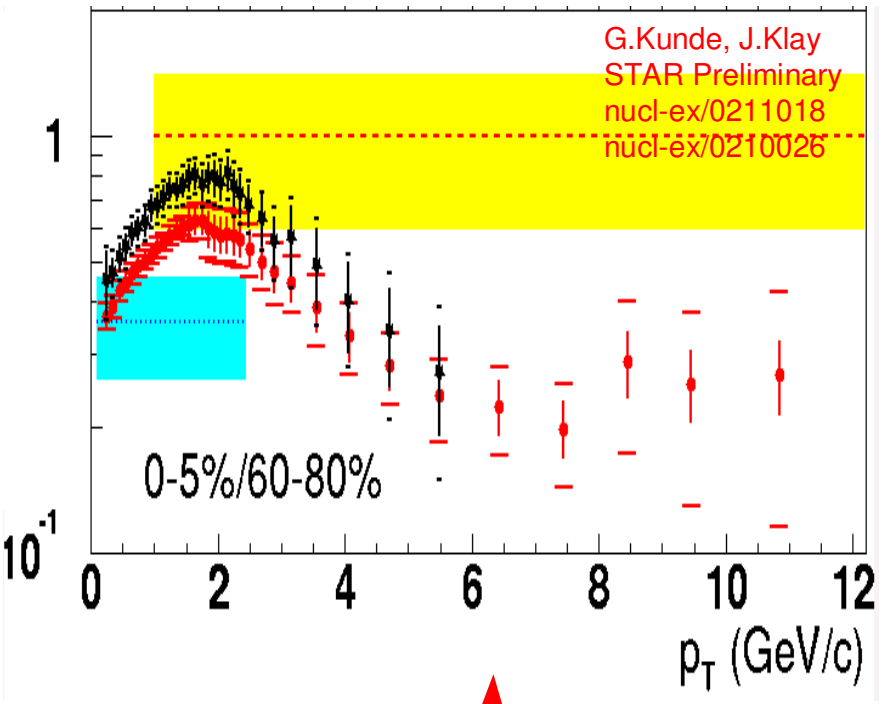


- Local maximum @ $p_T \approx$ 2 GeV/c:
  - "Cronin enhancement" on top of N_{part} scaling ?

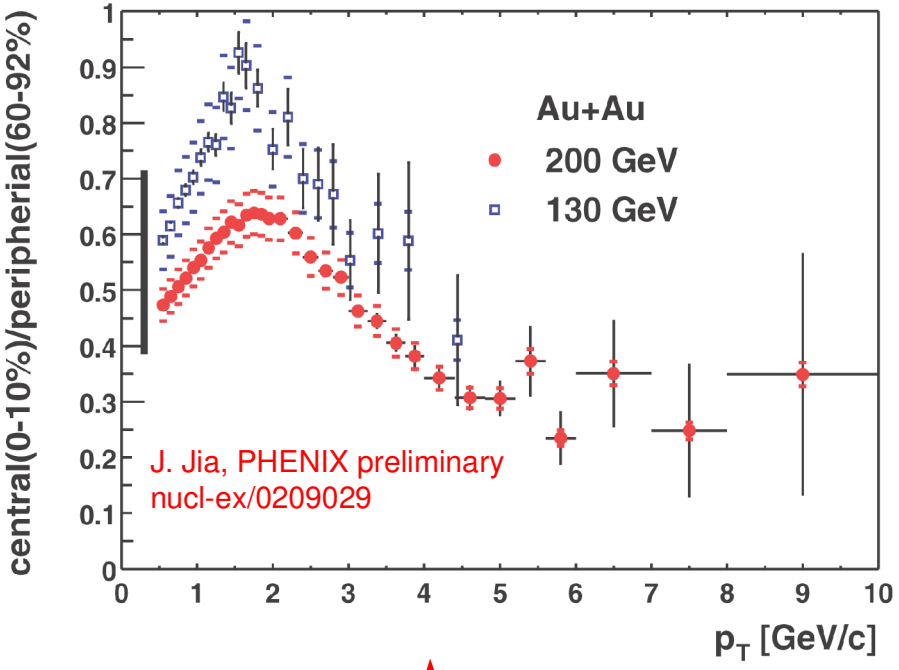
Hadron suppression: Central/peripheral

- Similar info than R_{AA}. But now: *No need of pp reference, & part of the exp. uncertainties cancels out (but larger N_{coll} errors)*.

STAR $h^{\pm}$



PHENIX $h^{\pm}$

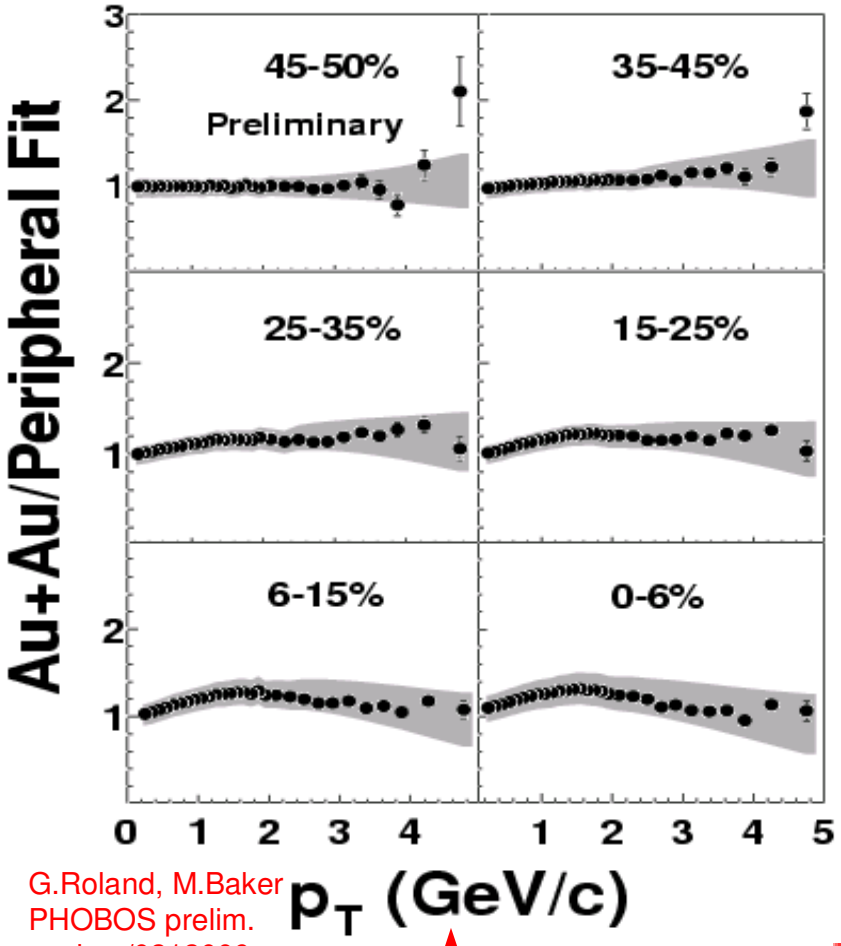


STAR ≈ PHENIX

- Stronger suppression than seen in R_{AA}
- Less suppression than seen in R_{AA}

Hadron suppression: Central/mid-central

PHOBOS $h^{\pm}$ ($R_{AA}^{Npart/2}$)



G.Roland, M.Baker
PHOBOS prelim.
nucl-ex/0212006
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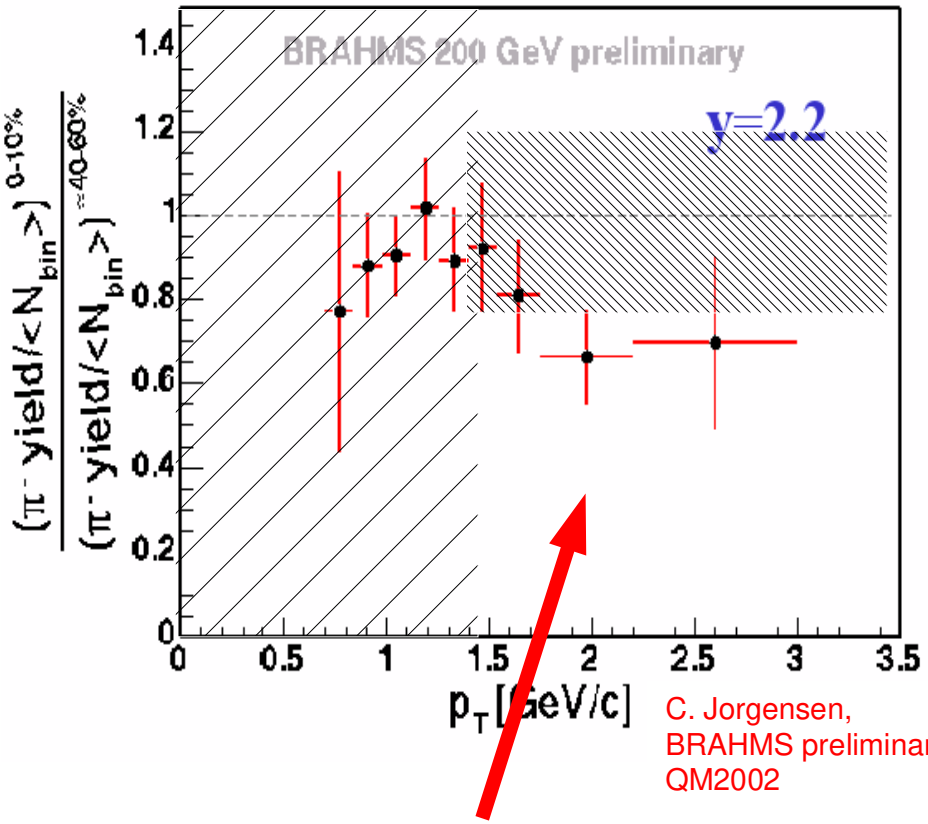
BRAHMS $h^{\pm}$



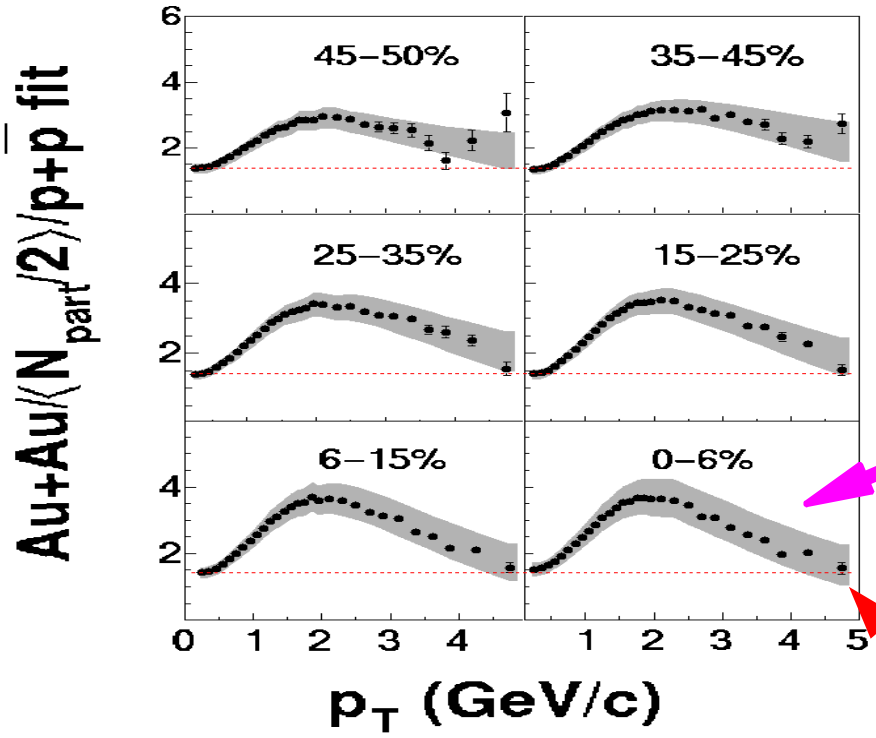
C. Jorgensen,
BRAHMS preliminary
QM2002

- First high p_T result off mid-rapidity
- Approx. $N_{part\ pairs}$ scaling (when dividing by fit to 45-50% centrality)

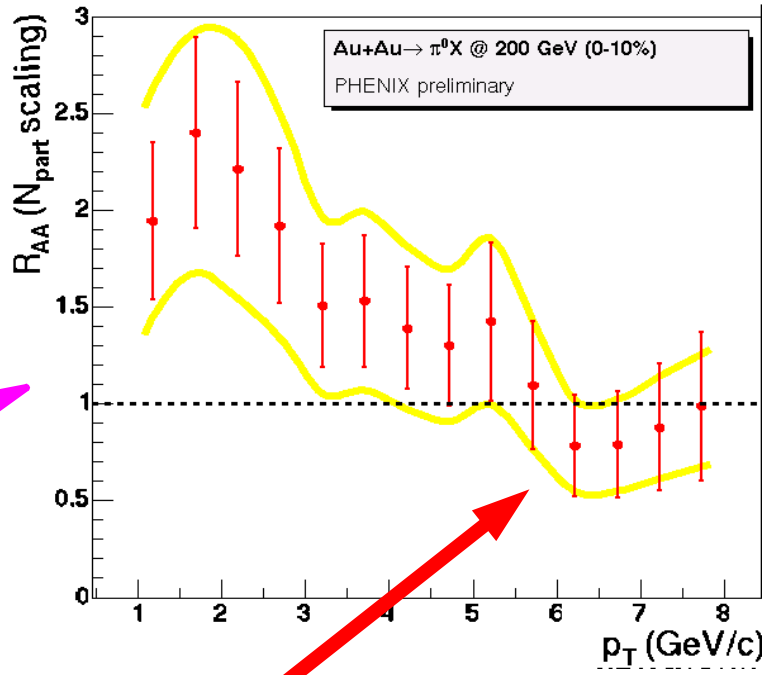
Suppression & N_{part} scaling ?

- R_{AA} using $N_{part}(/2)$ in the denominator:

PHOBOS $h^{\pm}$



PHENIX π^0



- Approx. N_{part} scaling, R_{AA}~ 1, only for p_T> 5 GeV/c ?
- "Cronin enhancement" at ~2 GeV/c ?
- Clear N_{part} scaling signal in Run-3: R_{AA} = Yield(Au+Au) / [N_{part} x Yield(d+Au)] ≈ 1

Hadron suppression: central AuAu (data vs theory)

- What does it tell us about the medium ?

  - Parton energy loss :

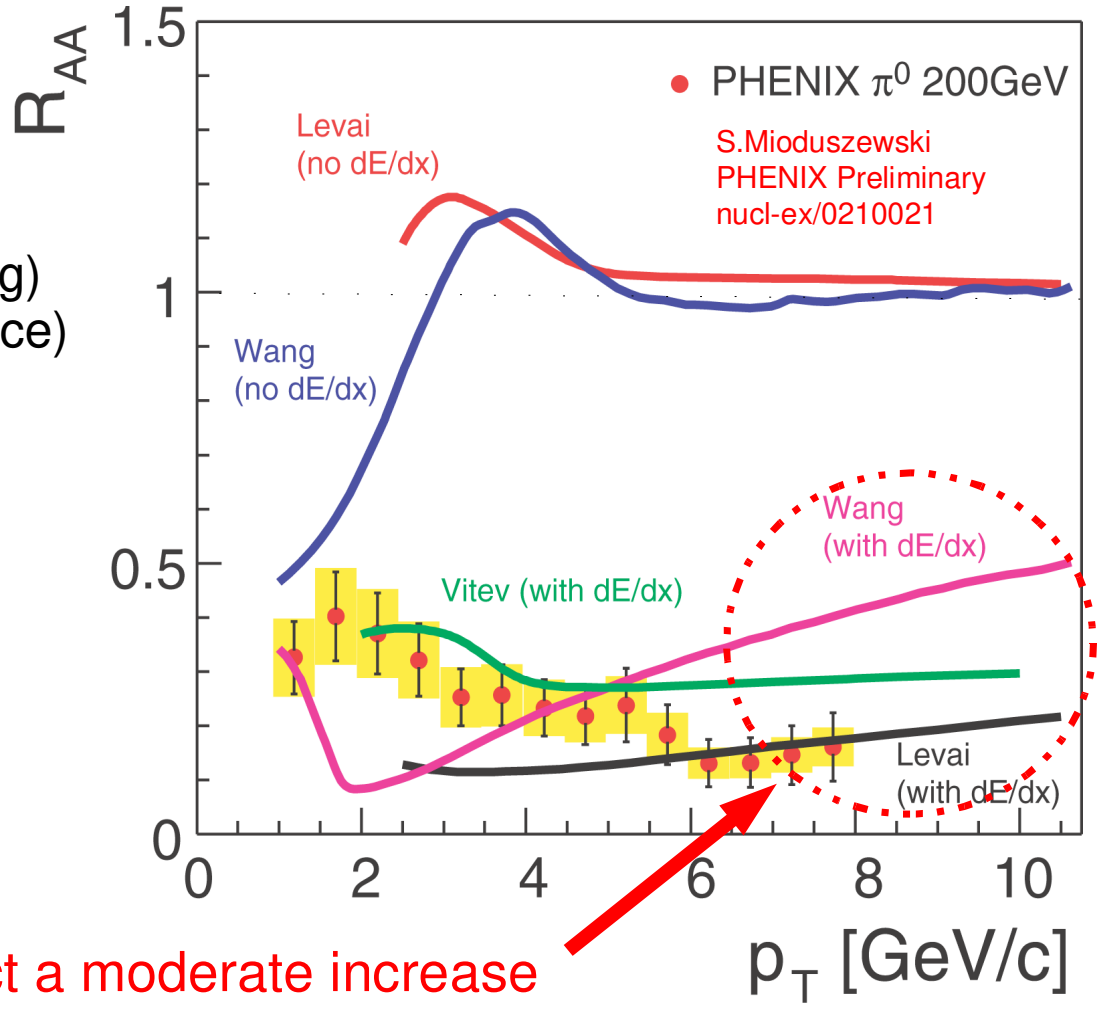
    dE/dx ≈ 0.25 GeV/fm (expanding)
    $dE/dx|_{eff}$ ≈ 7 GeV/fm (static source)

  - Opacities:

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

  - Gluon densities:

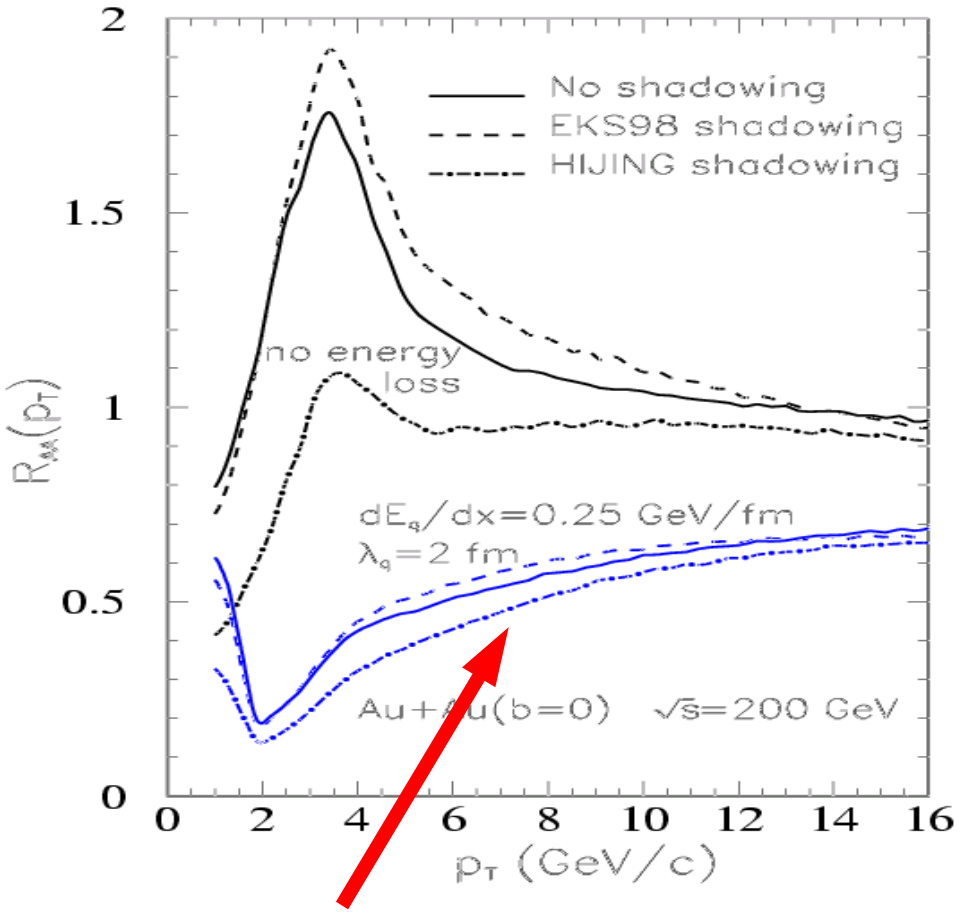
    $dN^g/dy \sim 900$



- All models (LPM ε_{loss}) expect a moderate increase of R_{AA} at higher p_T (final PHENIX Run-2 π^0 data soon)

1999 “Last Call for RHIC predictions”

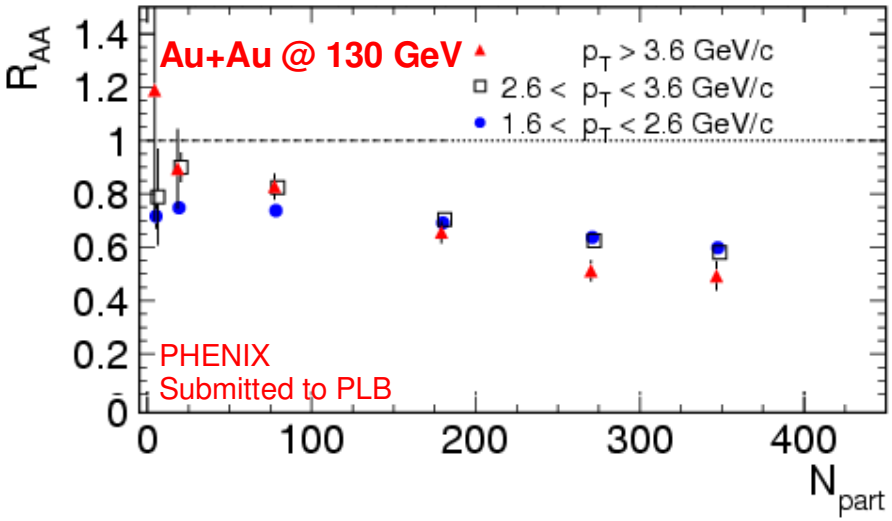
- X.N. Wang's nuclear modification factor:

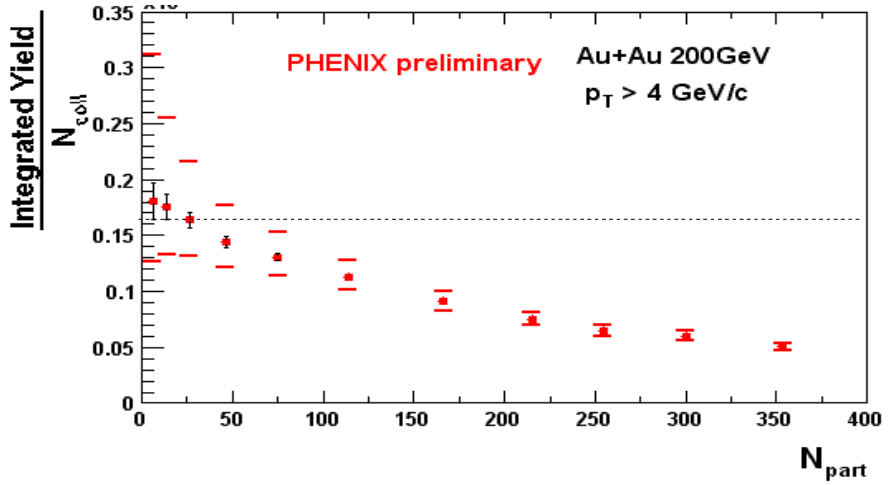


- Factor ~2 suppression @ high p_T (also prediction by I.Vitev).

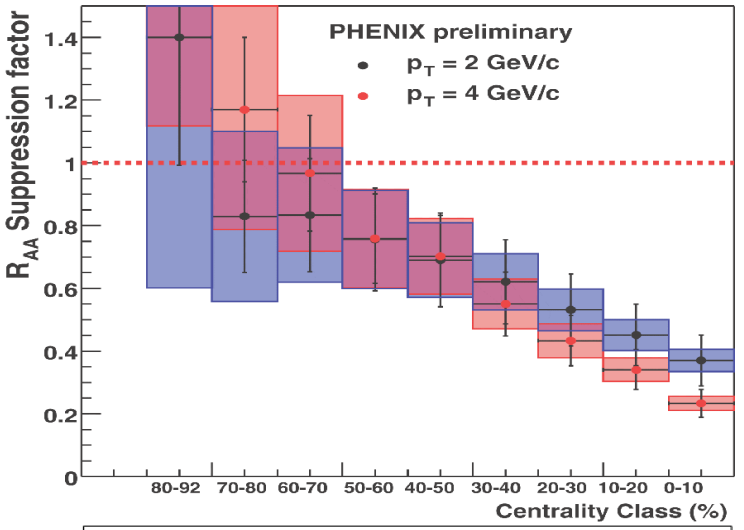
Centrality dependence of hadron suppression

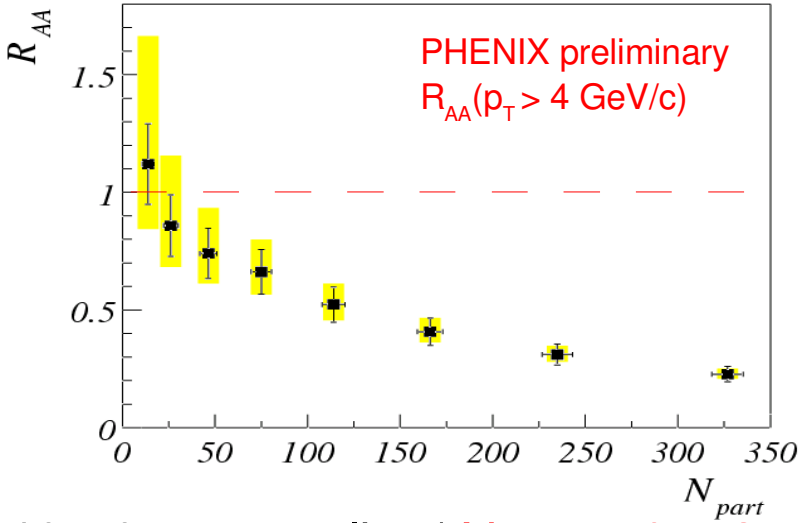
PHENIX $h^{\pm}$





PHENIX π^0





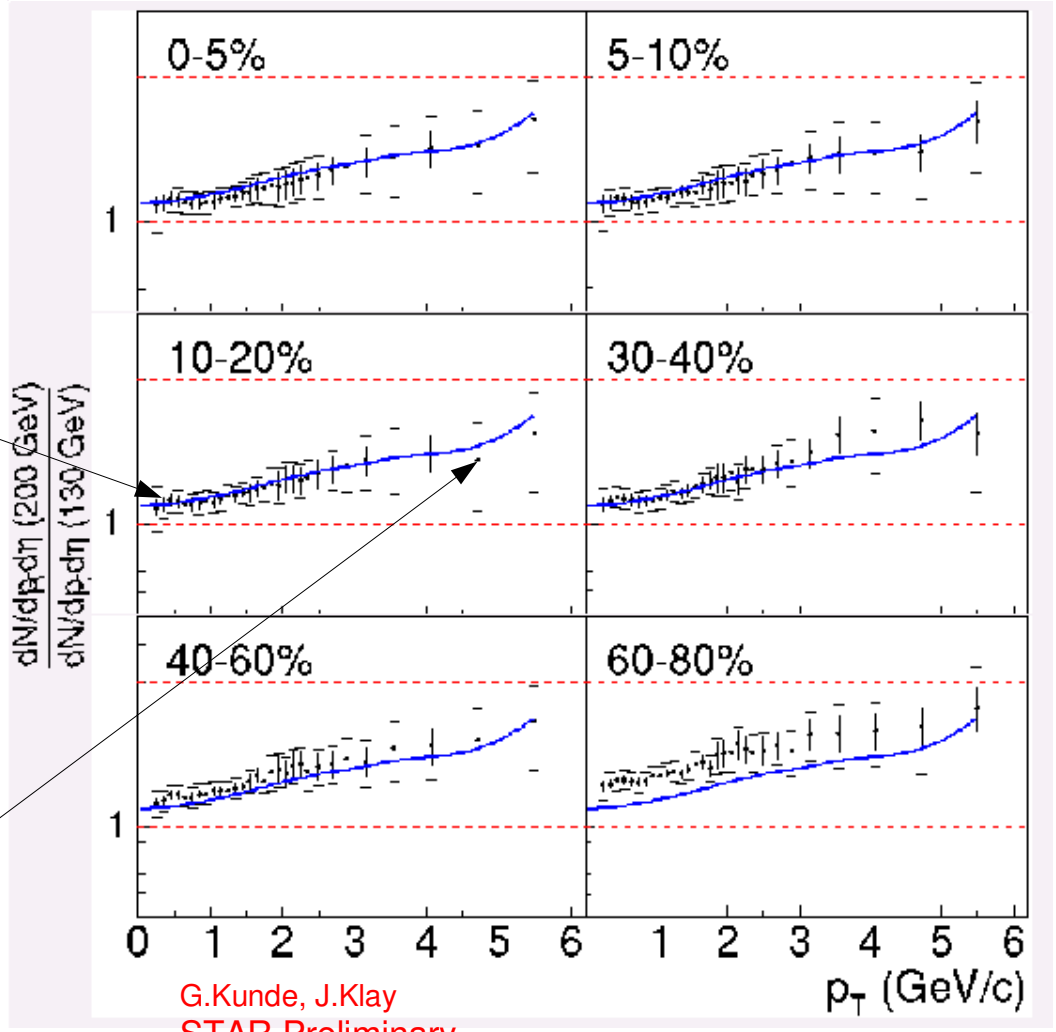
- Gradual suppression: $R_{AA} < 1$ cross for 40-70% centrality ($N_{part} \sim 50 \pm 25$)

pQCD-compatible high-p_T yield increase (130 → 200 GeV)

- N_{ch}(200/130) ~ independent of centrality: roughly the same amount suppression per centrality at both energies.

  - $\Delta N_{ch}(130 \rightarrow 200)_{soft} \approx +15\%$ at low p_T in agreement with global multiplicity increase.

  - $\Delta N_{ch}(130 \rightarrow 200)_{hard} \approx +15\%$ → +100% increase at high p_T in agreement with pQCD predictions (mini-jet production).



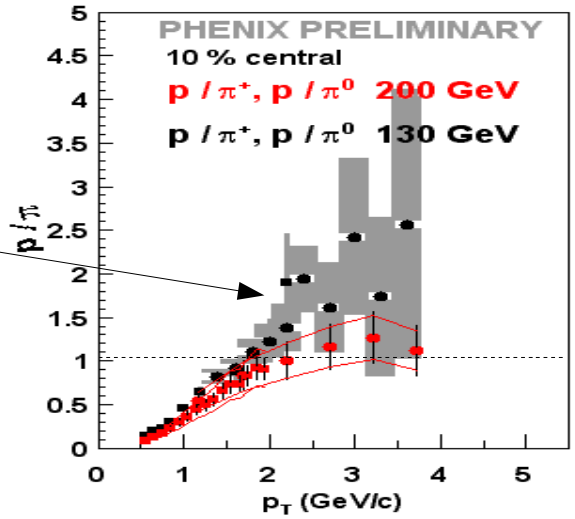
G.Kunde, J.Klay
STAR Preliminary
nucl-ex/0211018
nucl-ex/0210026

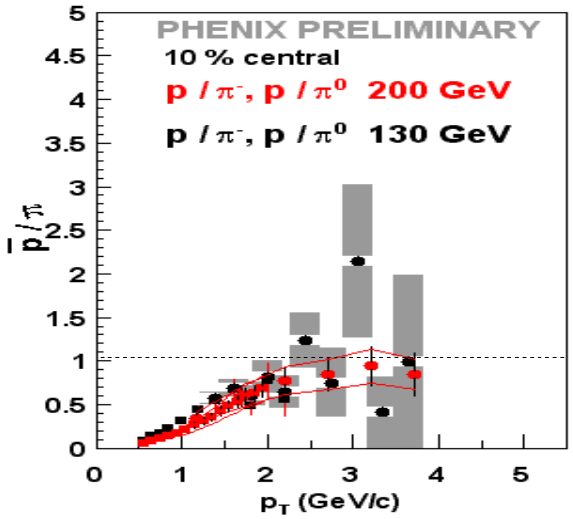
Hadron composition at high-p_T : p/π ratios

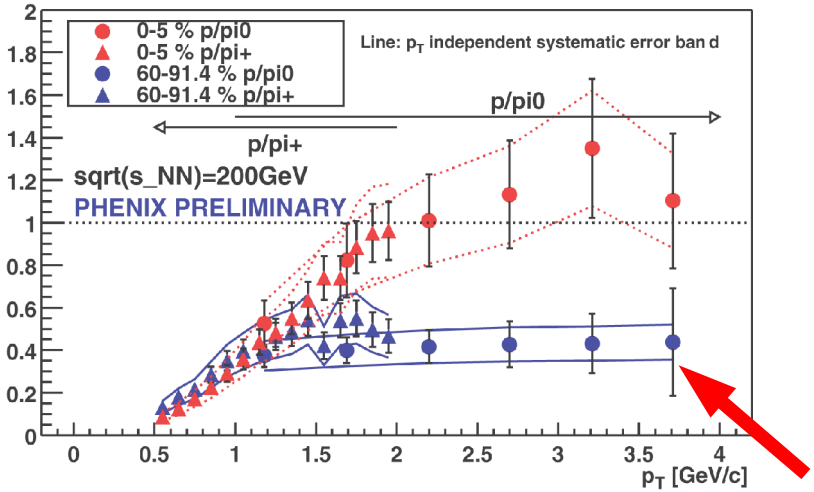
Strong non-perturbative (anti)baryon enhancement

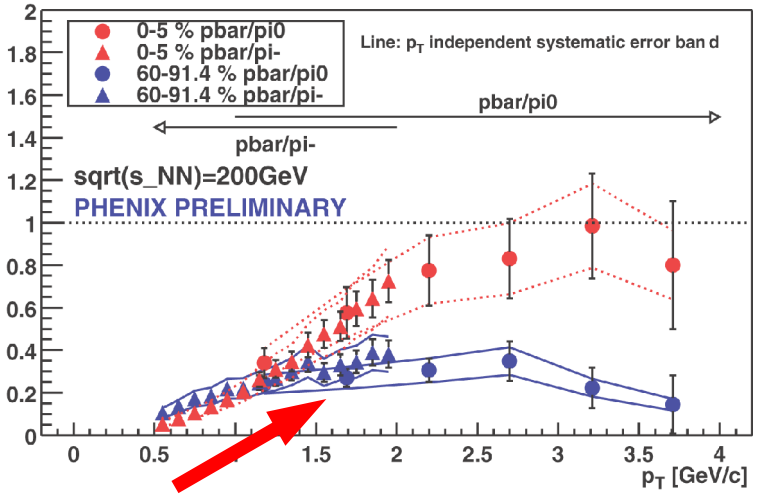
- Central colls.: Baryon yield ≈ pion yield for p_T>2 GeV/c (≠ jet fragmentation)

more protons @ 130 GeV than @ 200 GeV





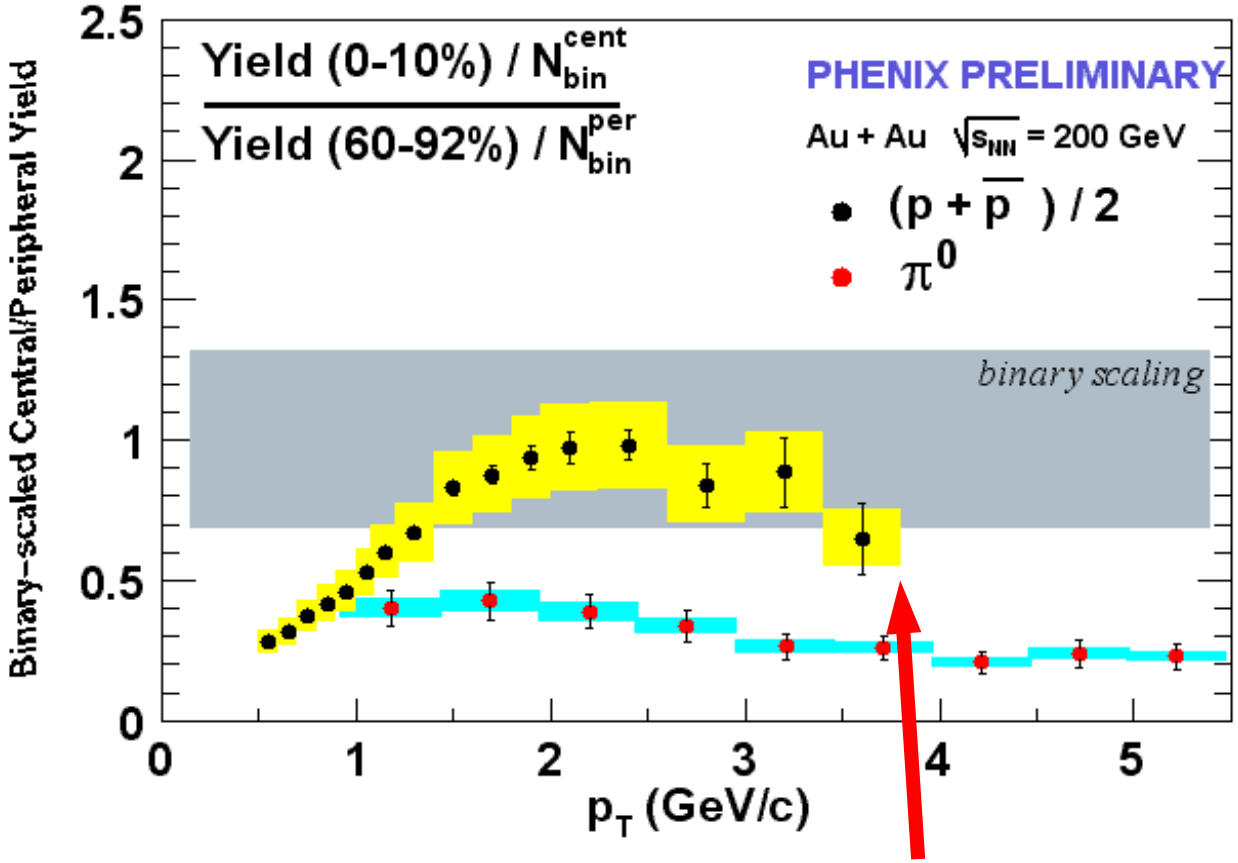




- Periph. colls.: baryon/meson ratio ~ 0.3 as in p+p,$\bar{p}$ (ISR,FNAL)

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

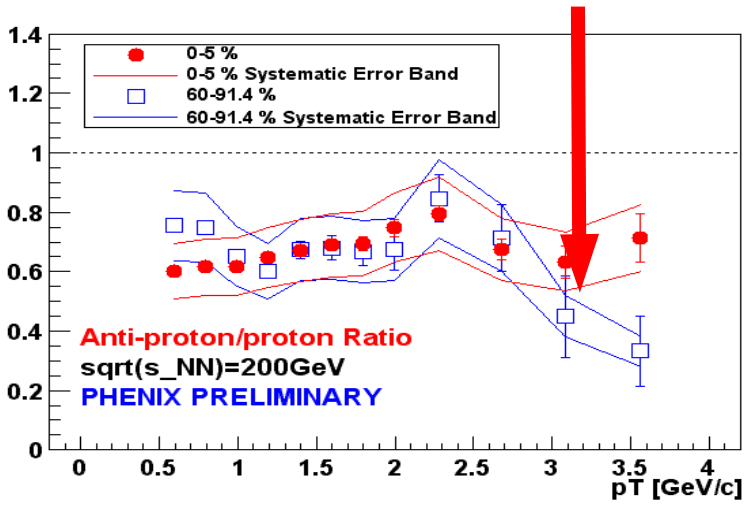
- Protons/antiprotons not suppressed for p_T=1.5 – 3.5 GeV/c :
  - Flow ? quenching+ baryon junctions ? different (medium) fragmentation for mesons than for baryons ? parton recombination ?

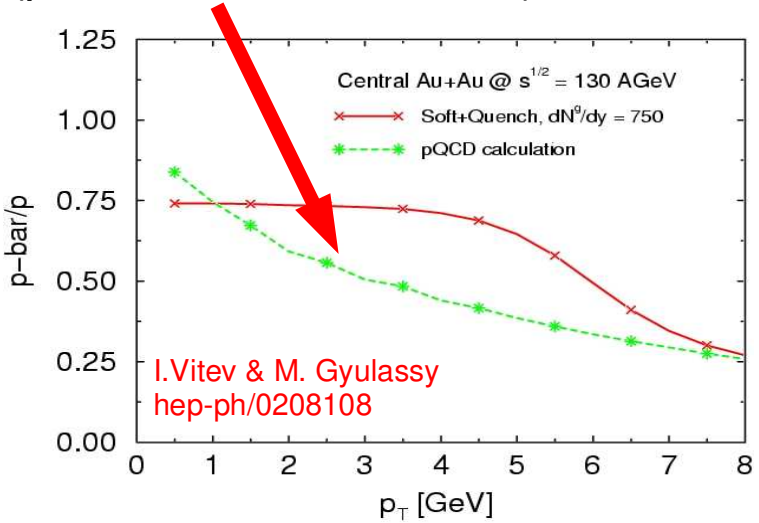


  - Start of proton quenching at higher p_T ?

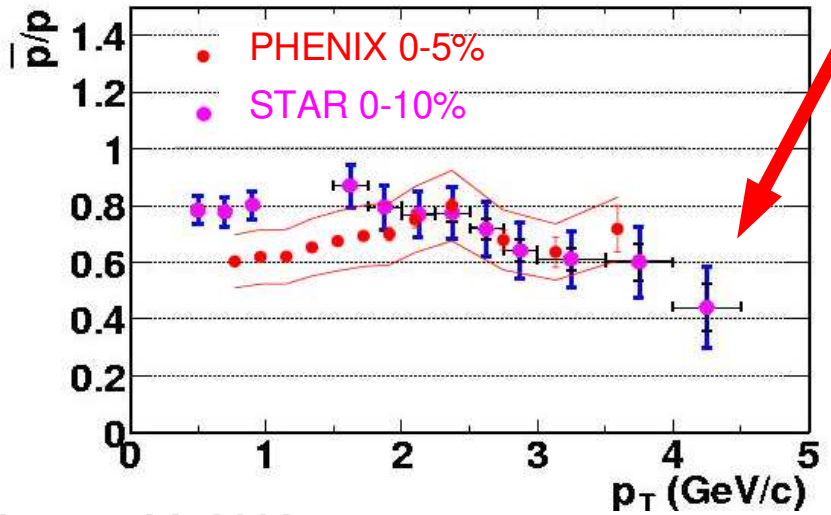
Hadron composition at high-p_T : $\bar{p}/p$ ratios

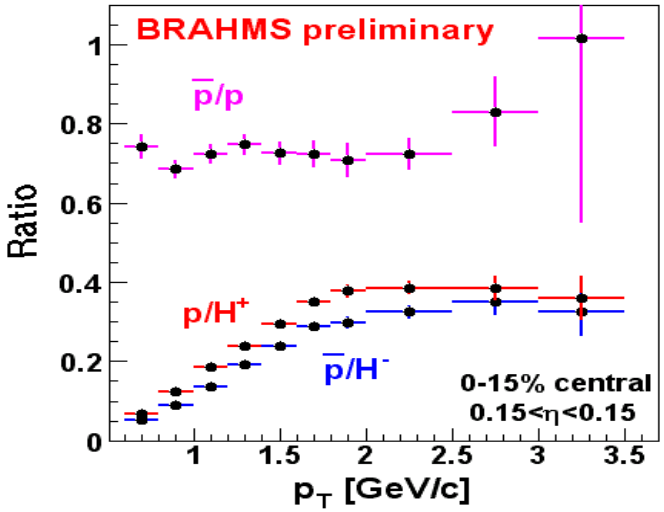
- Peripheral pbar/p: Decreases with p_T (perturbative behaviour)





- Central pbar/p: ~ 0.7 const. up to 3.5 GeV/c (PHENIX, STAR, BRAHMS)
  decreasing trend above 4 GeV/c (STAR).





High p_T @ RHIC: Summary (I)

- Large amount of high quality data after 2 years of RHIC: Results globally consistent within errors among the 4 experiments.
- Central AuAu collisions:
  - Strong suppression (factor ~5) of π^0 with respect to N_{coll} scaling.
  - Suppression (factor ~3.5) of unidentified charged hadrons.
  - No apparent suppression of (anti)protons up to ~4 GeV/c ("anomalous" p/π).
  - Approx. N_{part} scaling of hadrons above ~5 GeV/c.
  - Magnitude of suppression in agreement with parton energy loss scenarios assuming opaque medium formation ($dN^g/dy \sim 900$, $\lambda/L \sim 3\text{-}4$).
  - Flat p_T dependence (so far) of suppression not described with LPM energy loss alone.
- Peripheral AuAu collisions:
  - Behave effectively as pp collisions (i.e. as pQCD predicts) for all species.
- Suppression sets in over 40-70% centrality class ($N_{part} \sim 50$).
- Relative increase of high p_T yields (130 to 200 GeV) in agreement with pQCD: particle production from (mini)jets.

Summary (II)

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

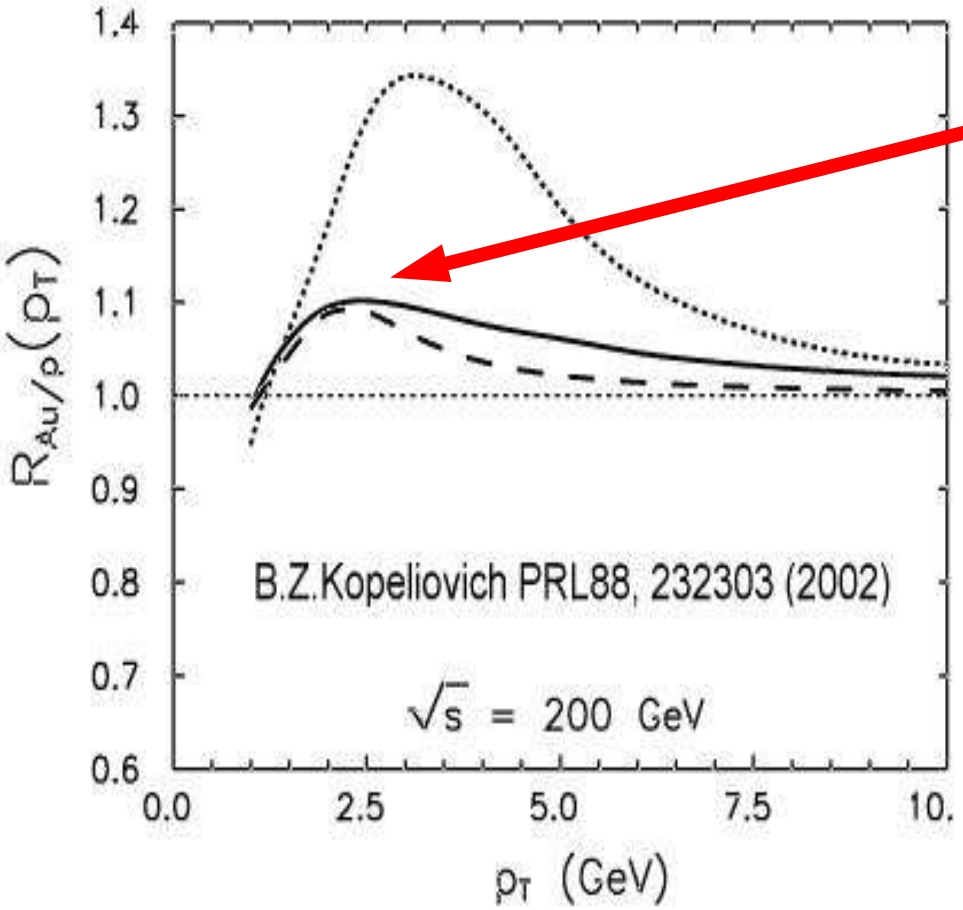
  "Clear signals of strong medium effects at work !"
- What do we learn about the medium properties ? QGP yes/no ?

  - Final-state partonic jet quenching ? (QGP)
  - Initial-state saturation of nuclear wave functions ? (CGC)
  - Final-state hadronic absorption ? (very dense hadron medium)
  - other ... ?

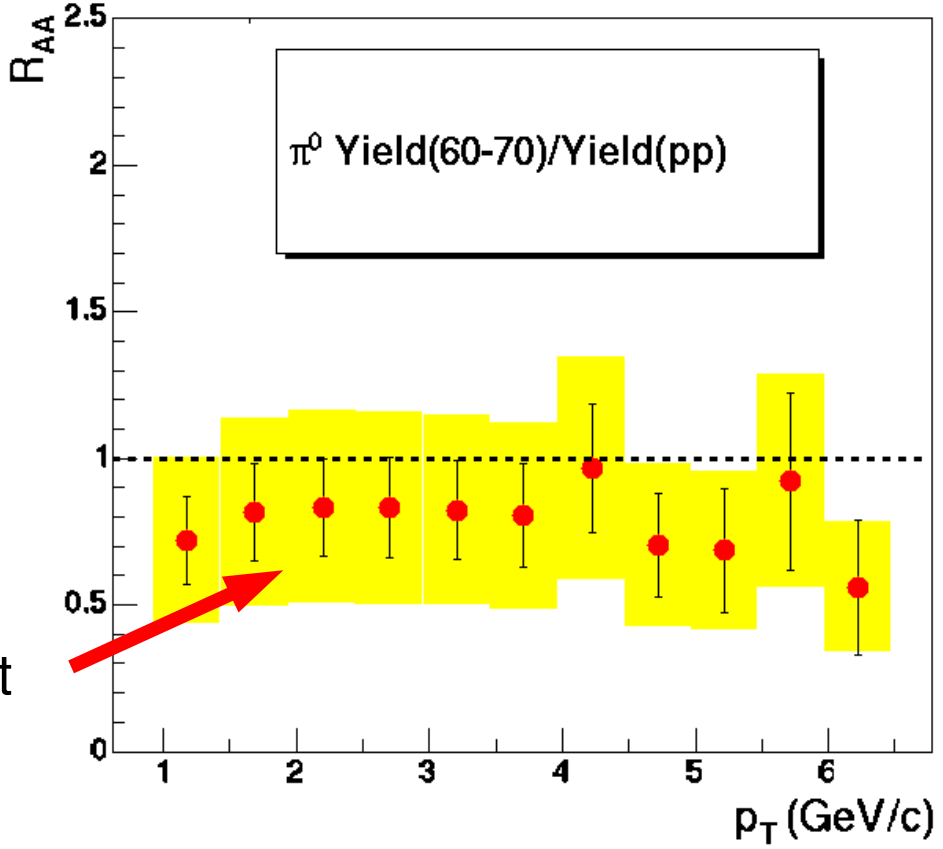
- Answers:
  - Experimental: d+Au ...
  - Theoretical: Does scenario "X" consistently explains: the magnitude, p_T dependence, centrality evolution, and flavor behaviour of RHIC high-p_T suppression ?

Backup slides

Cronin enhancement

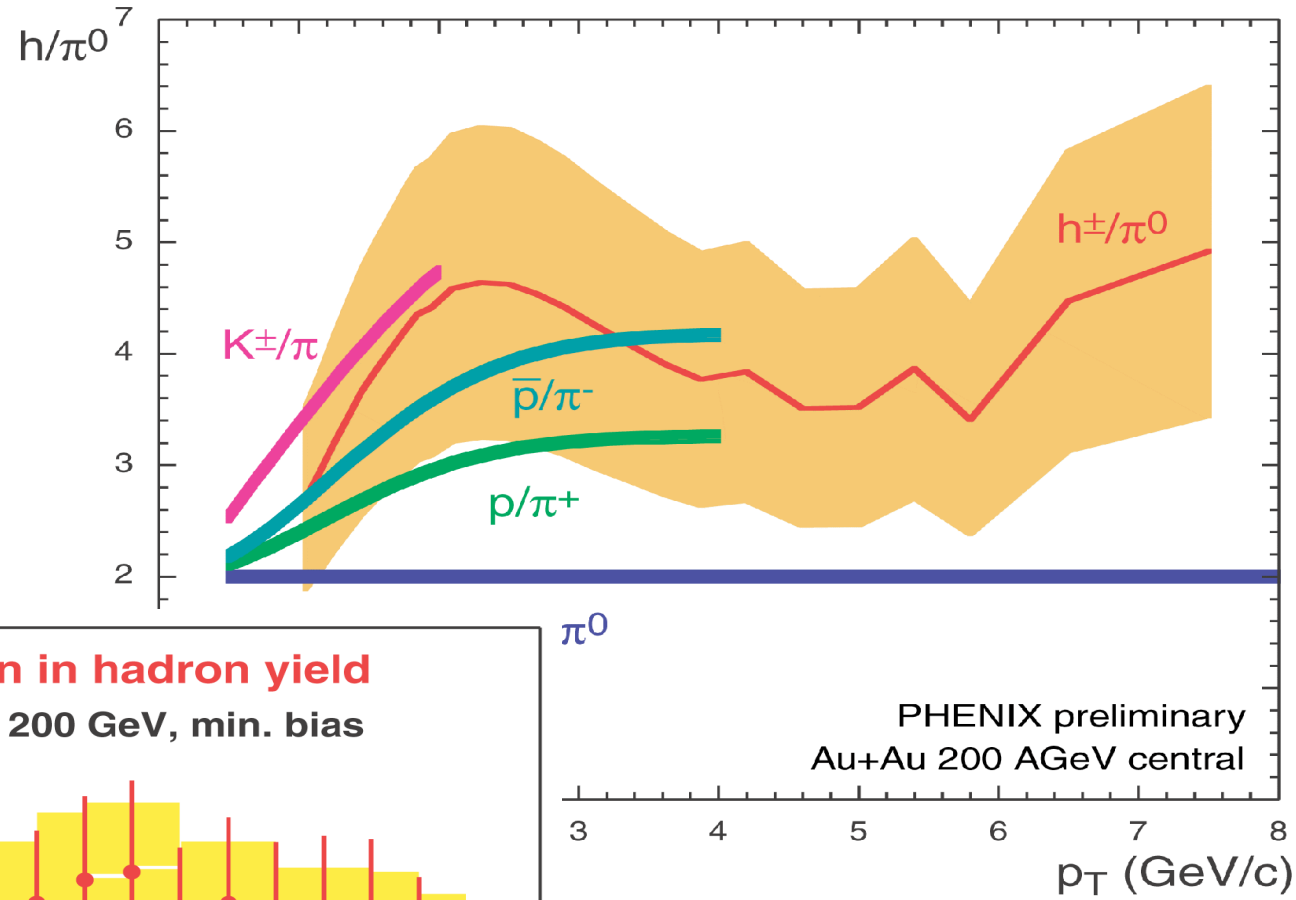


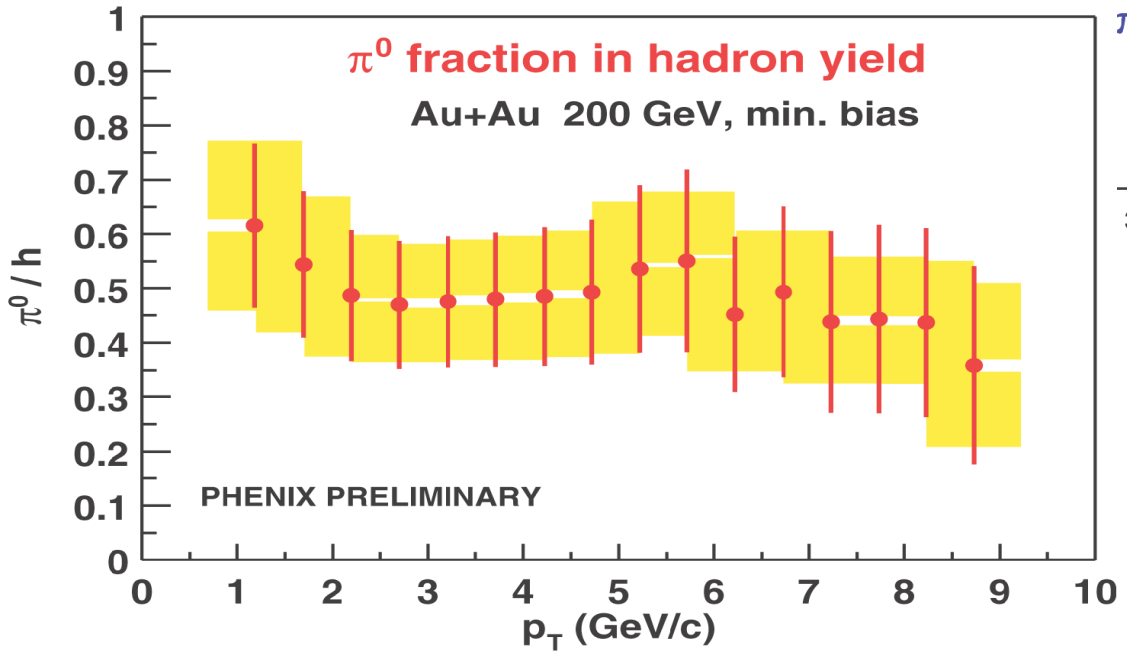
Prediction in pA @ 200 GeV:
Cronin peak @ p_T= 2.5 GeV/c



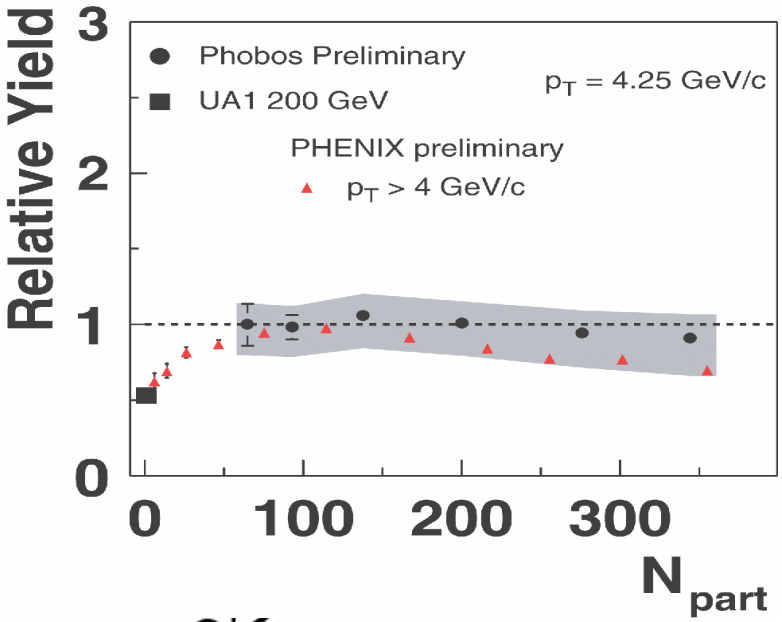
But no apparent Cronin enhancement
in most peripheral AuAu @ 200 GeV

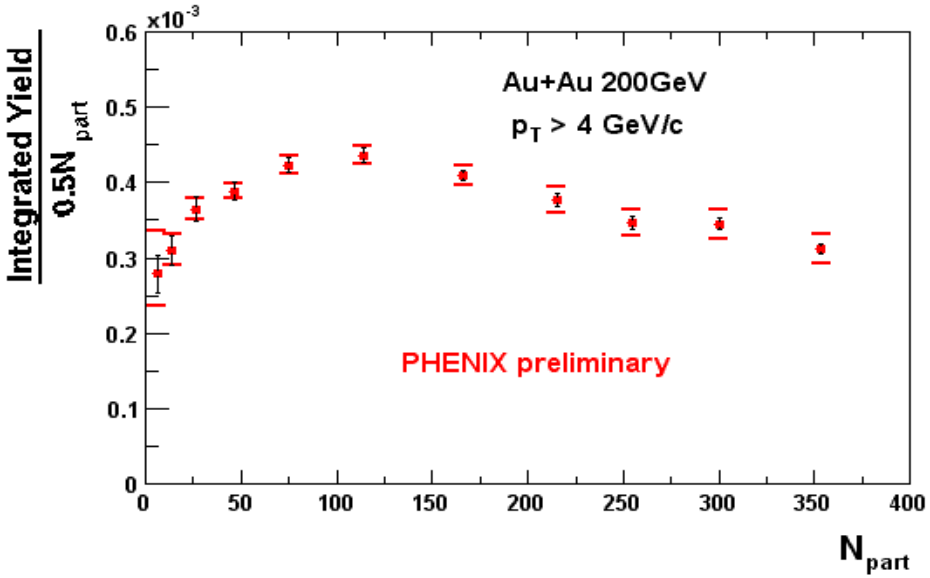
Hadron composition at high-p_T: Summary

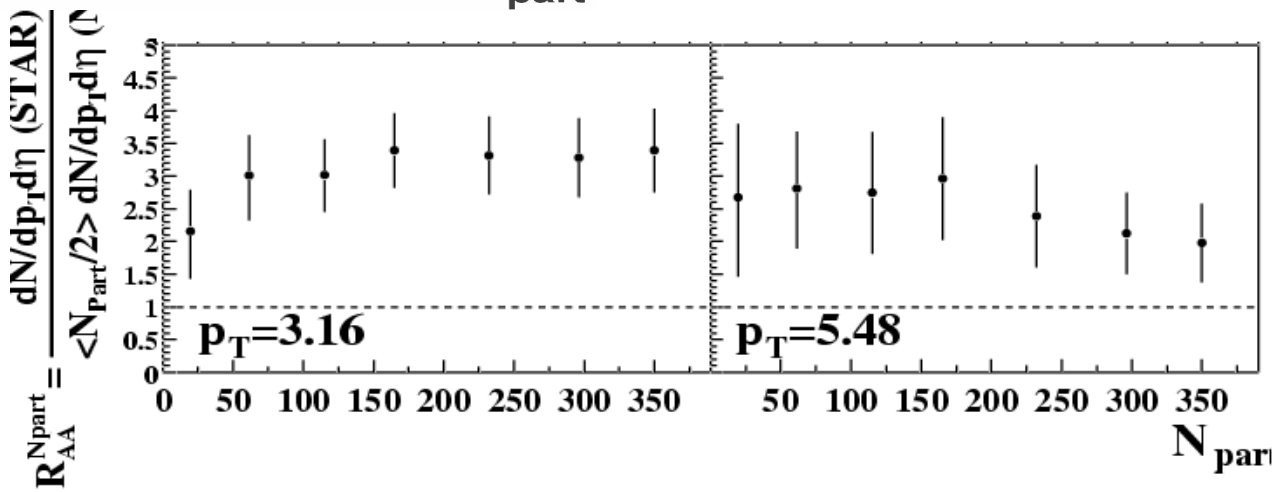




Centrality dependence of hadron suppression (R_{AA} for N_{part} scaling)

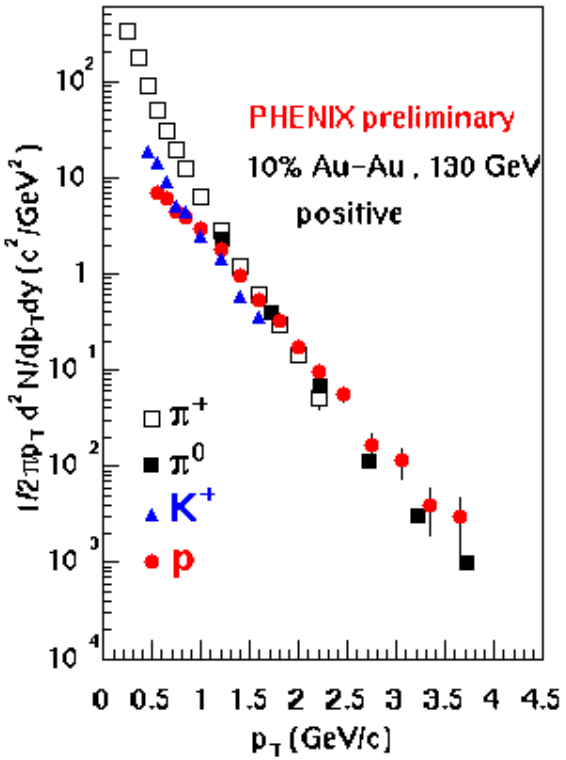


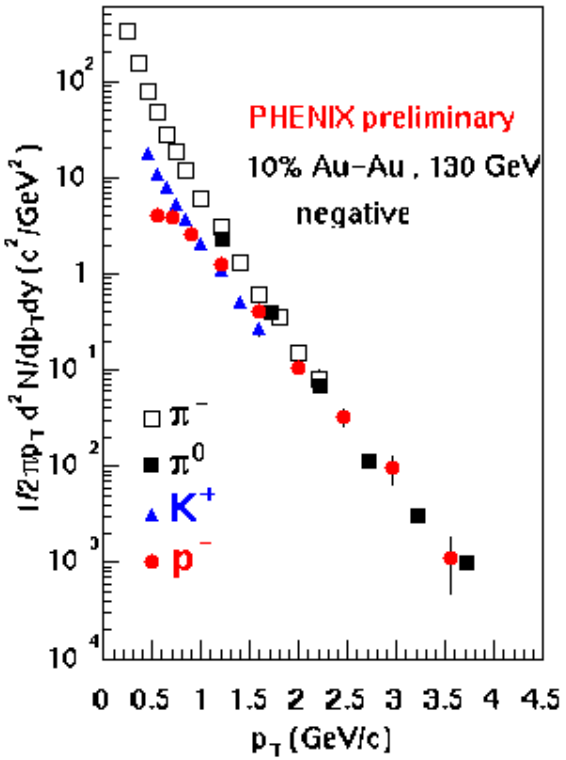


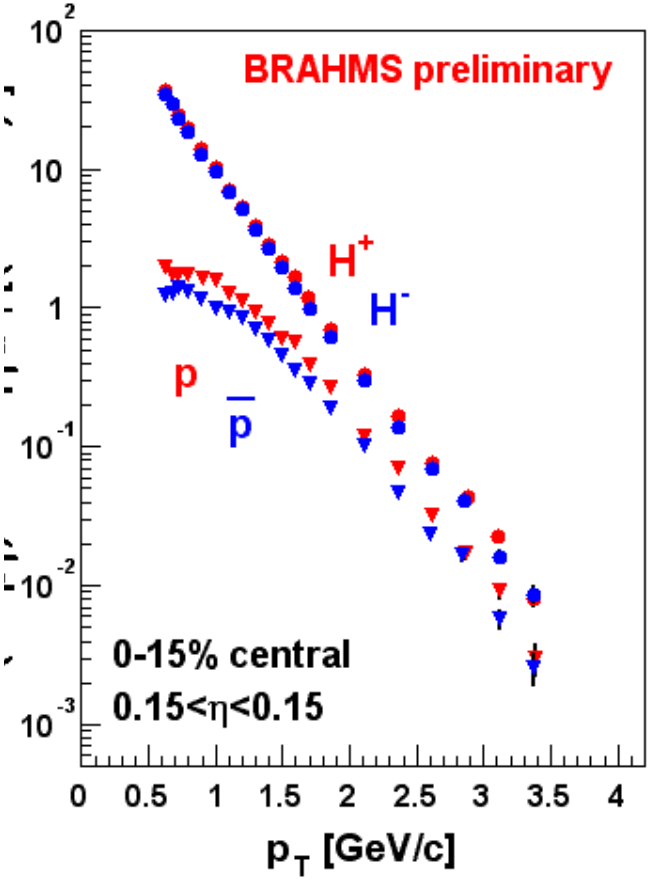


Hadron composition at high-p_T

- Baryon yield ≈ pion yield for p_T>2 GeV/c in central colls.



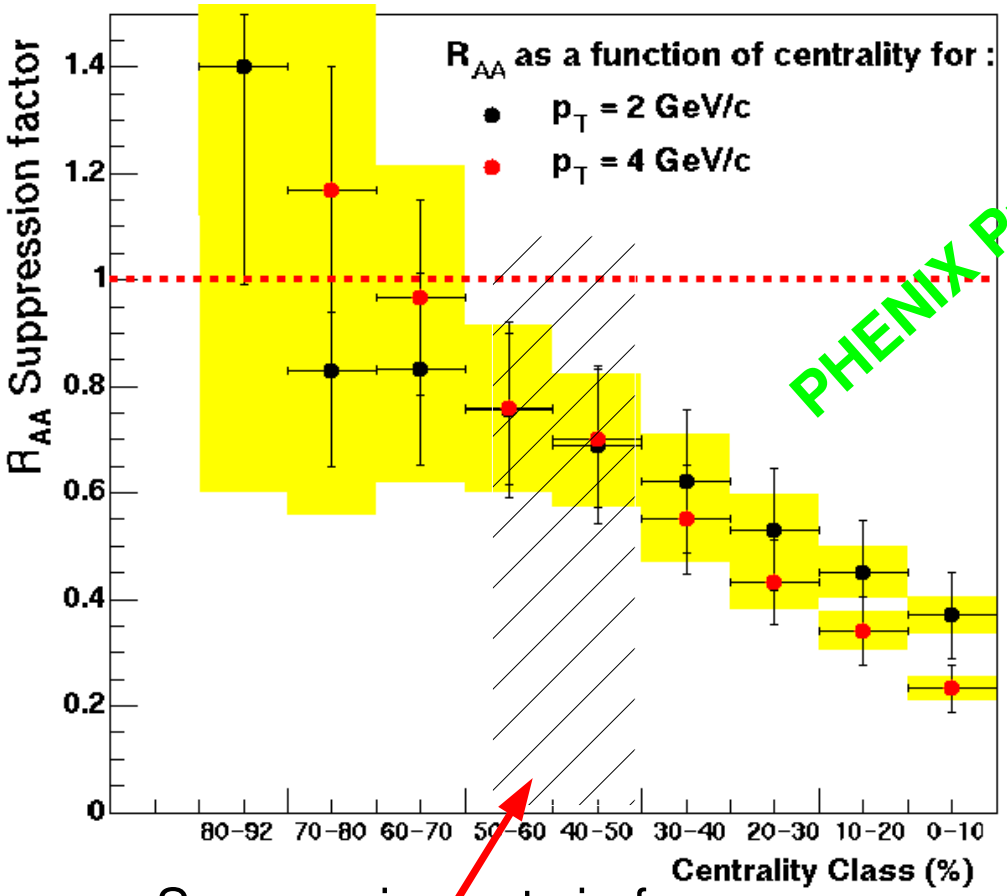




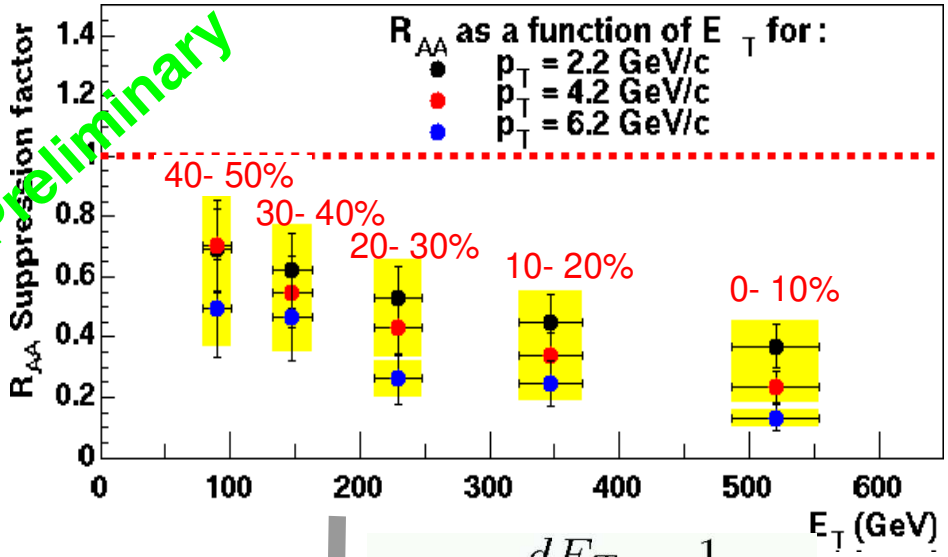
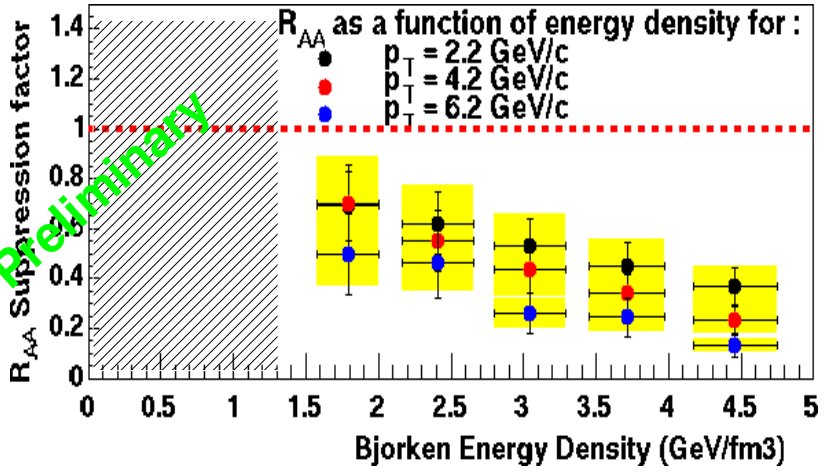
[PRL 88, 242301 (2002) & QM2002]

Onset of suppression ?

- R_{AA} plotted as a function of centrality ~ transverse energy (~ $\varepsilon_{Bjorken}$):



Suppression sets in for centrality ~40-60%



$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0\,\pi R^2}$$