Probing QCD media with hard scattering processes @ RHIC

[High p_T in Au+Au, d+Au, and p+p collisions at $\sqrt{s}$ = 200 GeV]

DNP/APS 2003 Fall Meeting
"QCD, confinement and HI physics" Workshop

Tucson, AZ, Oct. 29, 2003

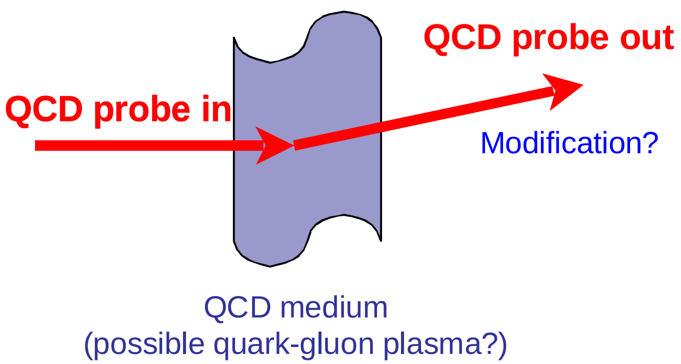
David d'Enterria
Nevis Labs, Columbia University, NY

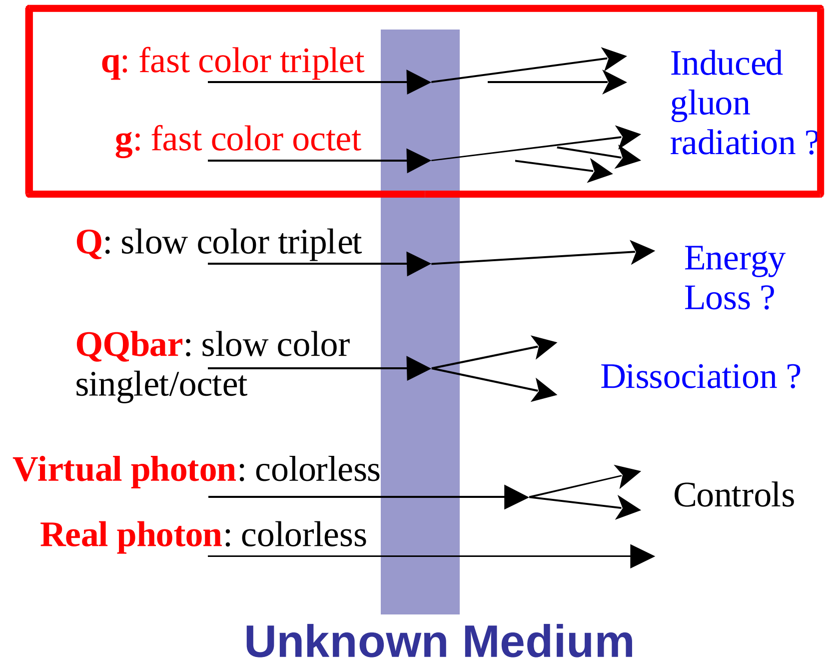
Overview

1. Introduction:
   - Hard scattering in QCD ("in vacuum" and "in medium").
2. High p_T in p+p @ 200 GeV ("baseline" data)
3. High p_T in Au+Au @ 200 GeV
   - dN/dp_T: suppression in central Au+Au:
     - p_T, $\sqrt{s}$, centrality, and (pseudo)rapidity dependence.
     - particle species dependence: baryon enhancement.
   - $dN_{pair}/d\varphi$: azimuthal anisotropies:
     - Collective behaviour: strong elliptic flow.
     - Jet signals: disappearance of away-side dijet correlations.
4. High p_T in d+Au @ 200 GeV ("control" experiment)
   - dN/dp_T: "Cronin-like" enhancement:
     - p_T, and centrality dependence.
   - $dN_{pair}/d\varphi$: jet azimuthal anisotropies.
5. Summary

Hard QCD probes. Motivation (I)

- Hard probes: high-p_T (jets, prompt γ), heavy-quark (D, B, ..).
- Early production ($\tau \sim 1/p_T < 0.1$ fm/c) in parton-parton scatterings with large Q^2.
- Direct probes of partonic phase(s) $\Rightarrow$ Sensitive to dense medium properties:





- Incoherent processes: Direct comparison to baseline "vacuum" (*pp*) data via "collision scaling":

$$\sigma_{AB\,(hard)} = \int d^2b\,[1-e^{-\sigma_{pp}T_{AB}(b)}] \propto \mathbf{T}_{AB} \times \sigma_{pp\,(hard)}$$

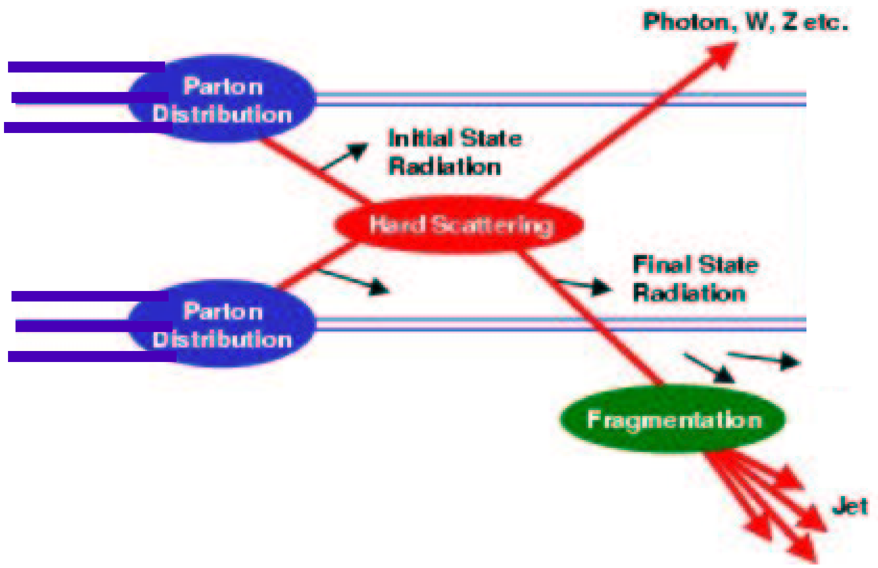
$\mathbf{T}_{AB} \propto$ # of binary inelastic *NN* colls .

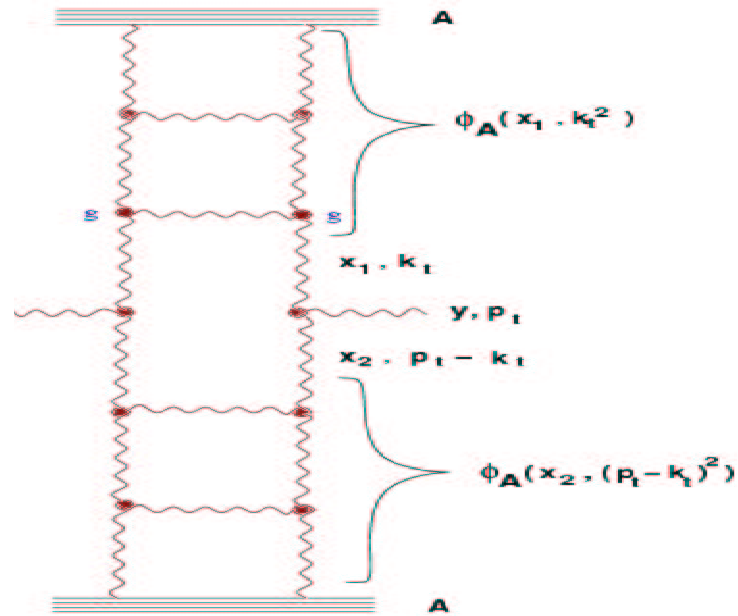
Hard QCD probes. Motivation (II)

- Production yields theoretically calculable:

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

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





"Mueller diagram for classical glue radiation"

- Hard probes allow us the study of QCD medium properties via sensitive & well calibrated (experimentally & theoretically) observables.

Hard scattering in QCD media

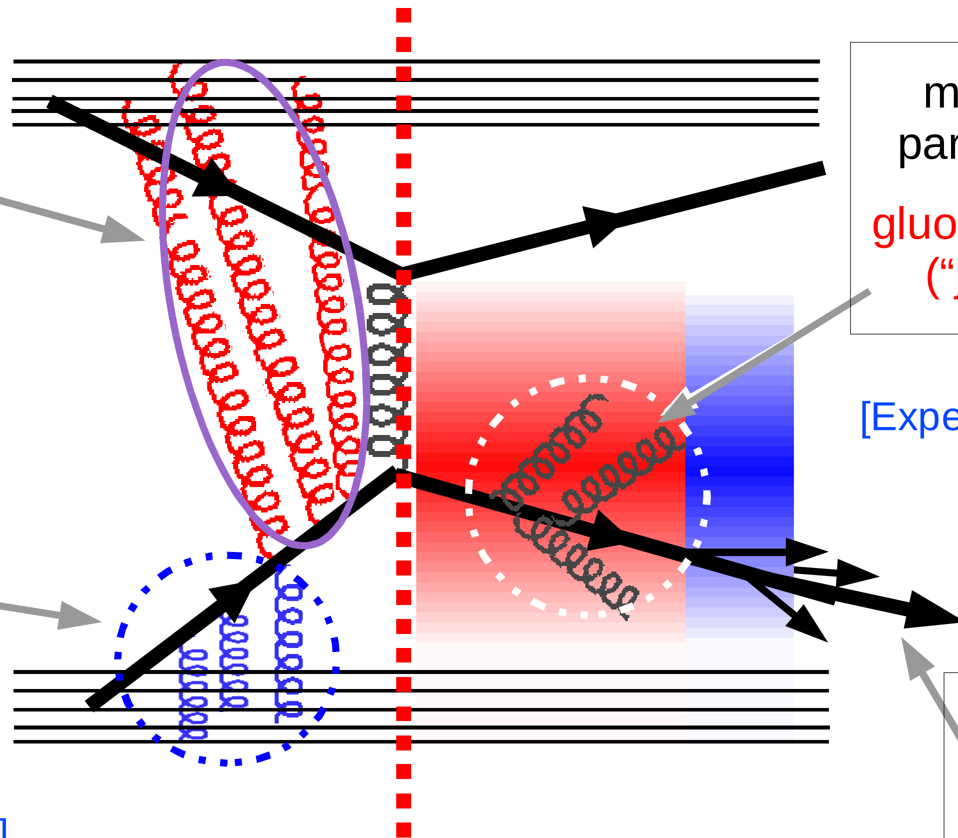
Initial-state effects:

p_T broadening:
("Cronin enhancement")
Soft & semi-hard extra k_T

[Experimental handle: p,d+A]

Leading-twist shadowing
(modified nuclear PDF)
OR
Gluon saturation in the highly non-linear regime of small-x

[Experimental handle: e+A, p,d+A]



Final-state effects:

medium-induced parton energy loss:
gluon bremsstrahlung
("jet quenching")

[Experimental handle: A+A]

possible hadronic rescattering
(after/before hadronization ?)

- If (vacuum) high p_T hadroproduction is modified in the medium, is it due to initial-state ("Color Glass Condensate") and/or final-state (Quark Gluon Plasma) effects ?

Relativistic Heavy-Ion Collider (RHIC) @ BNL

Specifications:

3.83 km circumference

2 independent rings:

- 120 bunches/ring
- 106 ns crossing time

A + A collisions @ $\sqrt{s}$ = 200 GeV

Luminosity: $2 \cdot 10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)

p+p collisions @ 500 GeV

p+A collisions @ 200 GeV

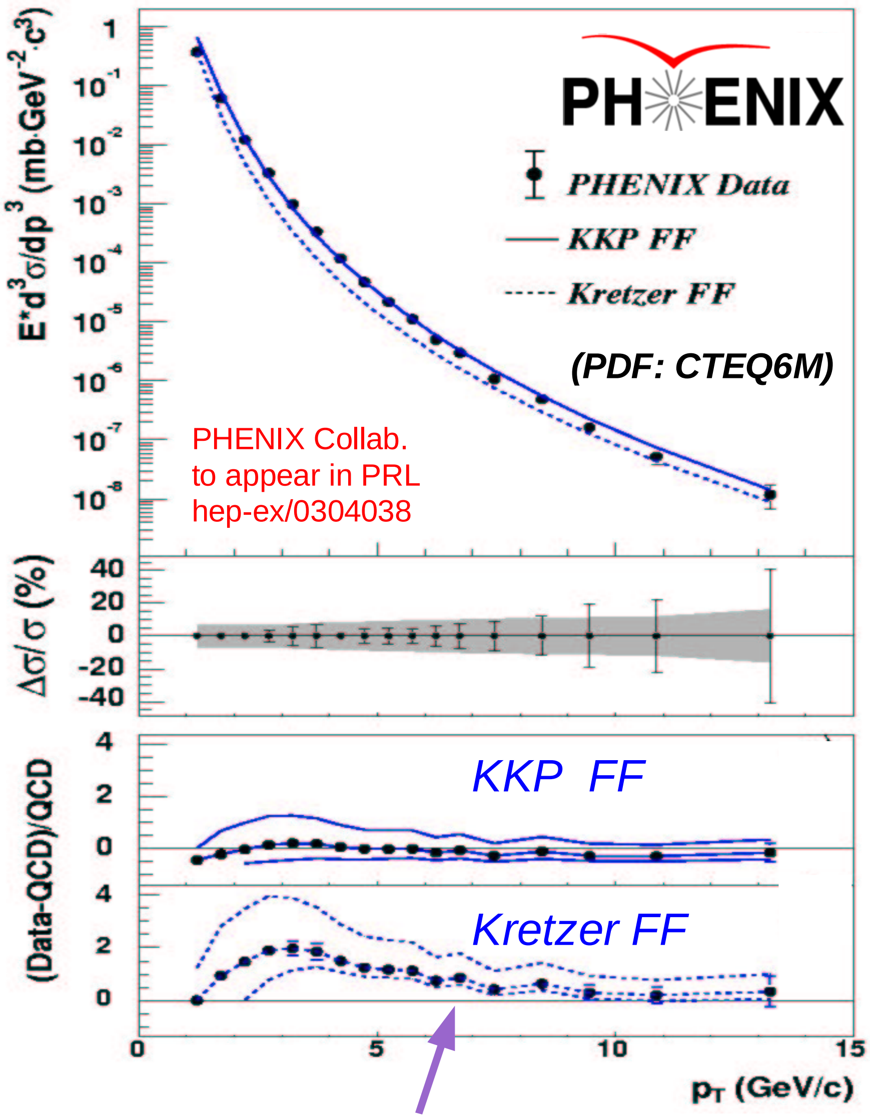
4 experiments:

BRAHMS, PHENIX, PHOBOS, STAR

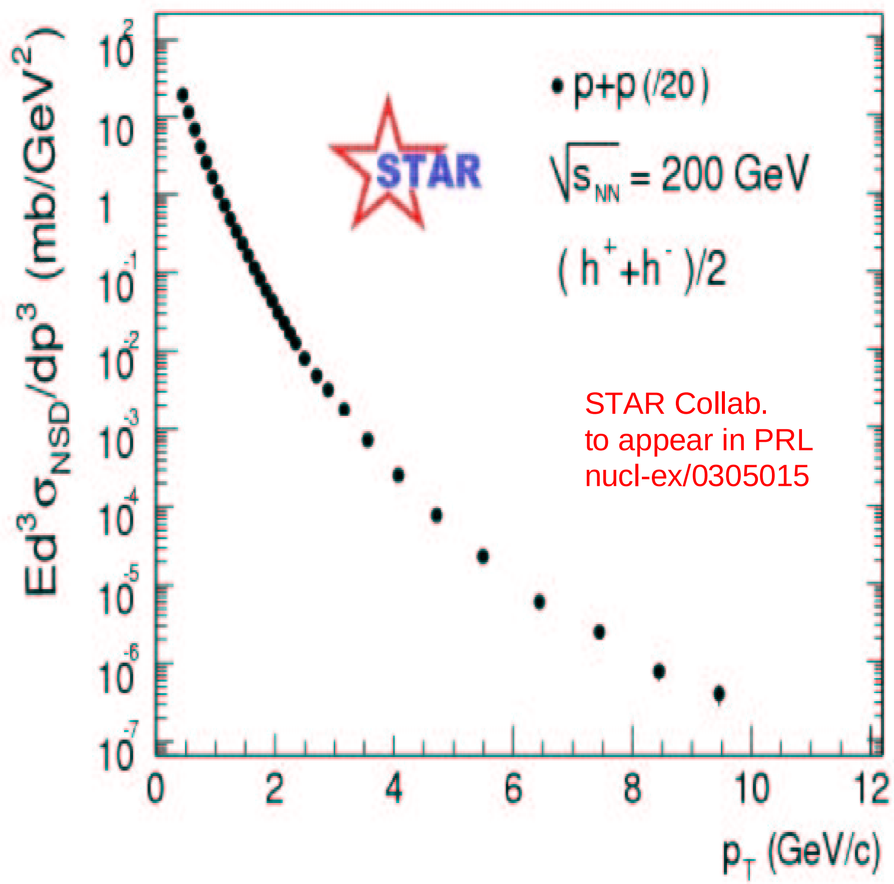
Run-1 (2000): **Au+Au @ 130 GeV**
Run-2 (2001-2): **Au+Au, p+p @ 200 GeV**
Run-3 (2002-3): **d+Au, p+p @ 200 GeV**

High p_T p+p @ 200 GeV ("baseline")

p+p→ π^0 X

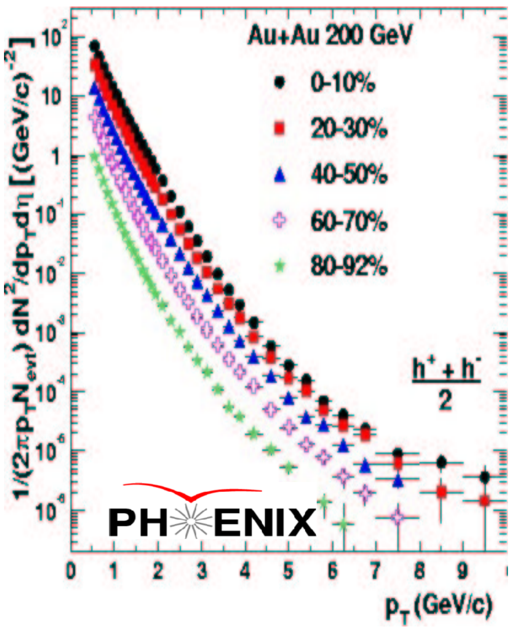


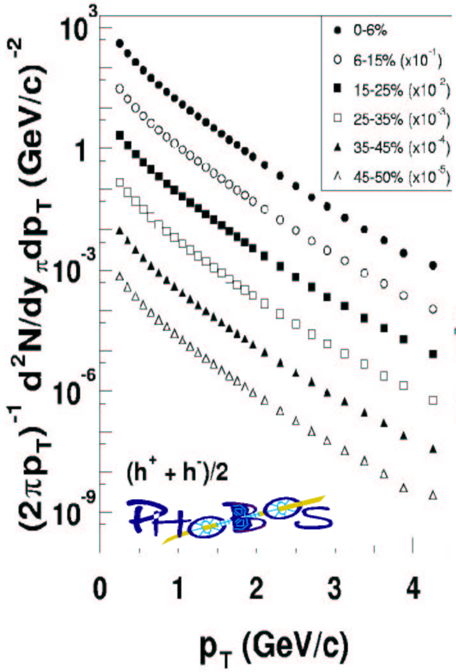
p+p → $h^{\pm}$ X (Non Singly Diffractive)

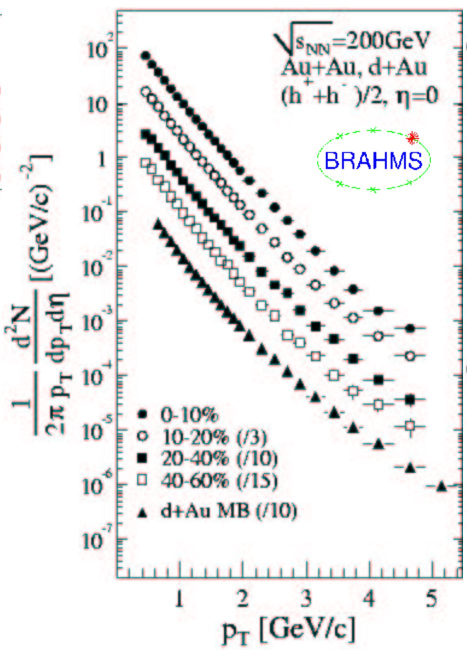


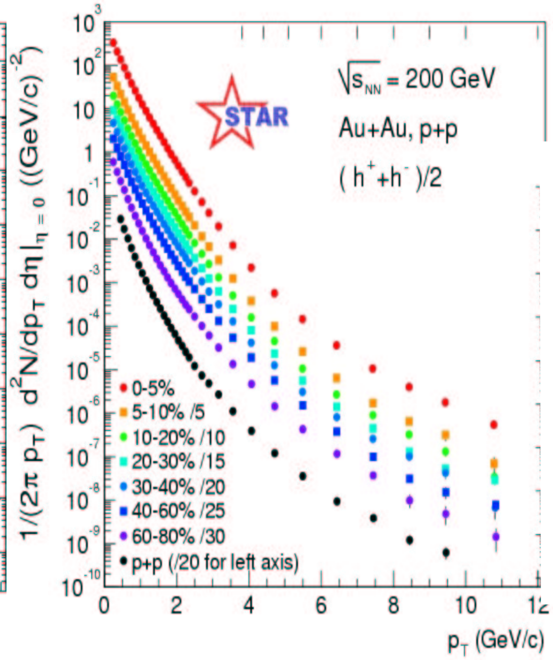
Good theoretical (NLO pQCD) description

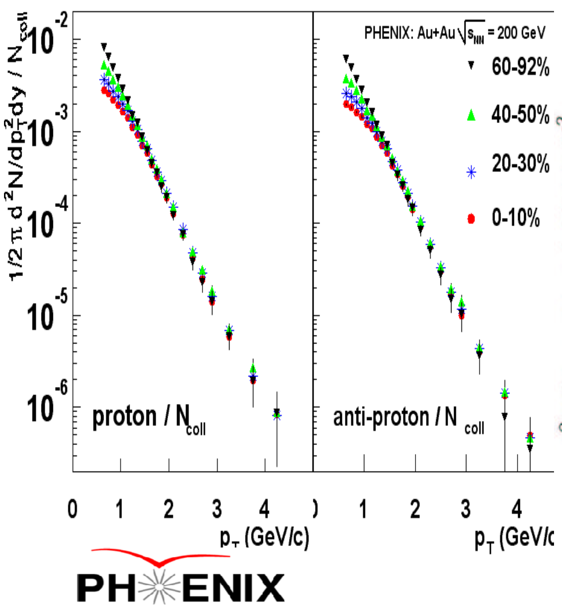
High p_T spectra in Au+Au @ 200 GeV

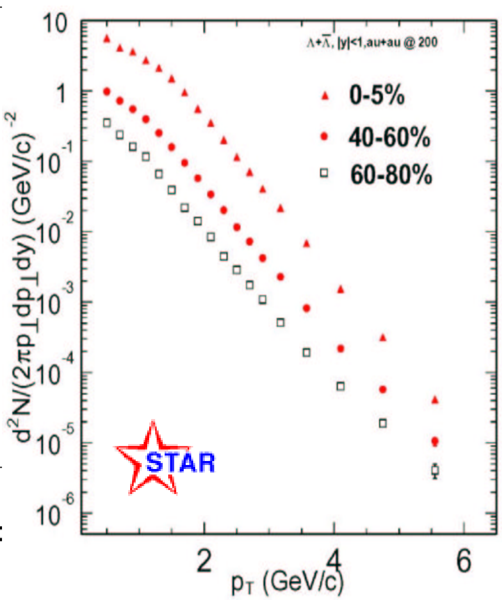


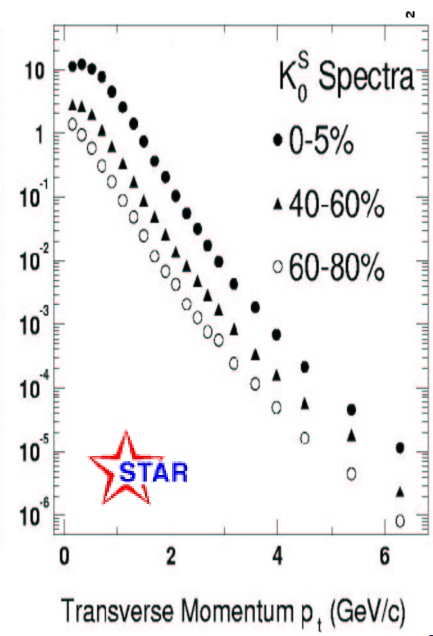


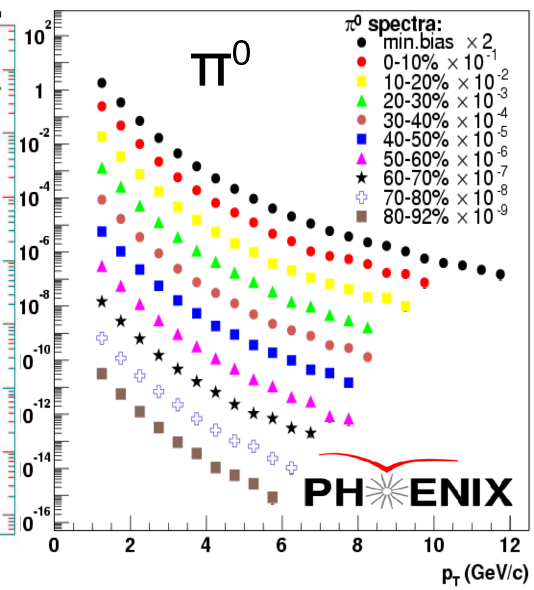






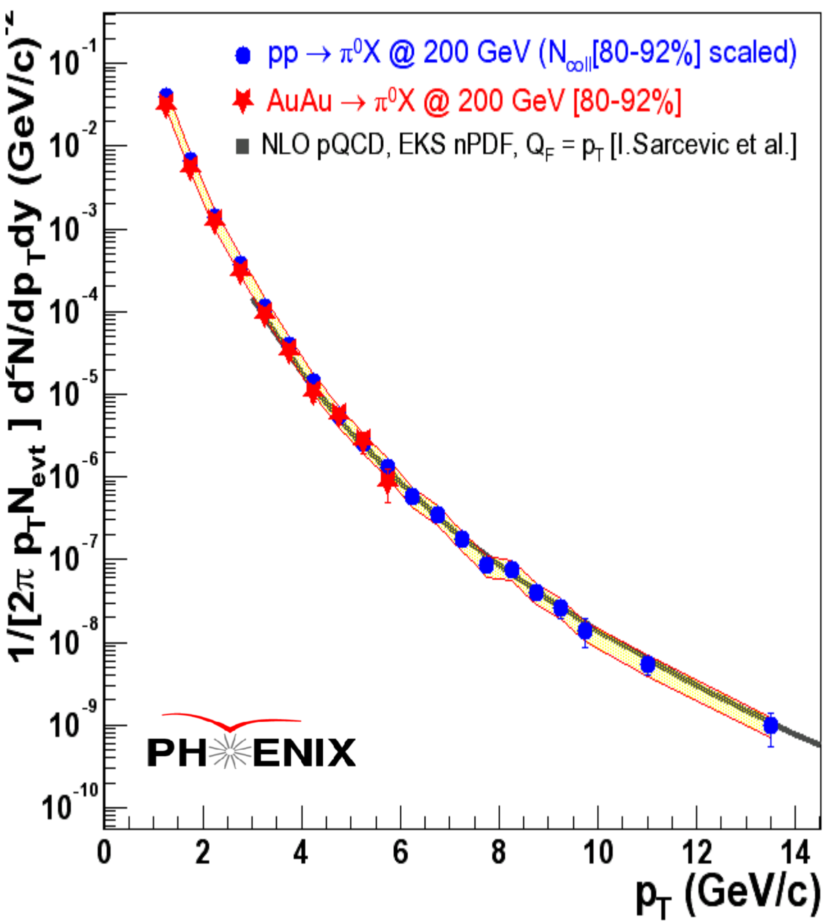




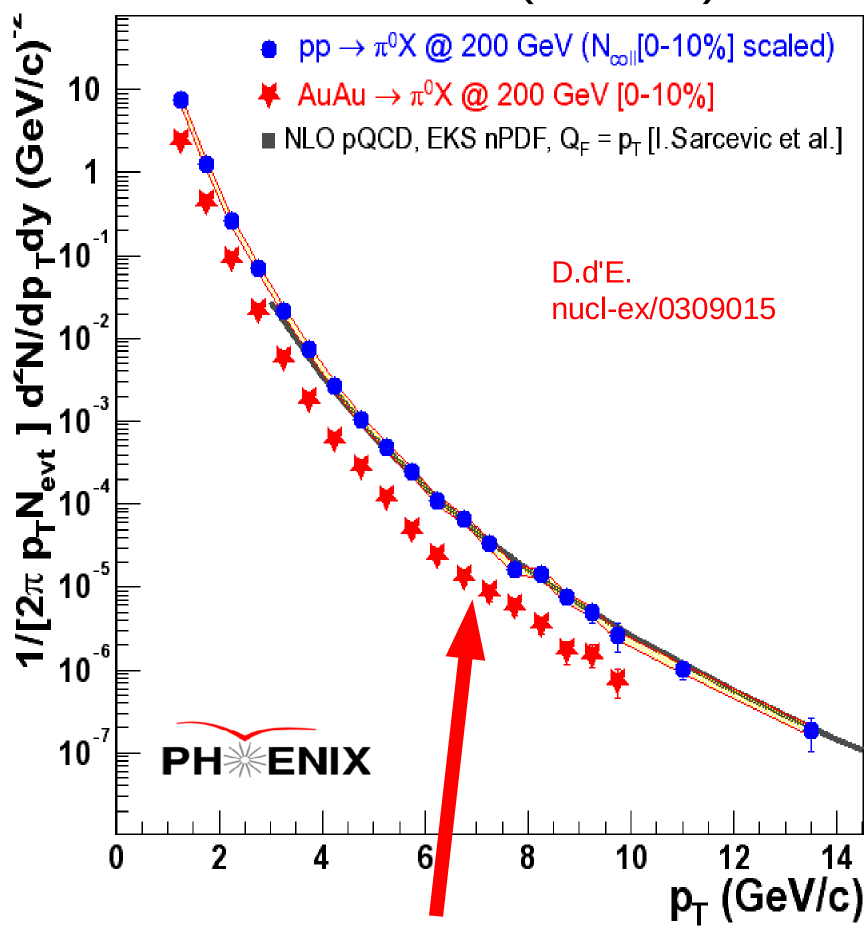


AuAu *vs* pp @ 200 GeV: high p_T π^0

Au+Au→ π^0 *X* (peripheral)



Au+Au→ π^0 *X* (central)

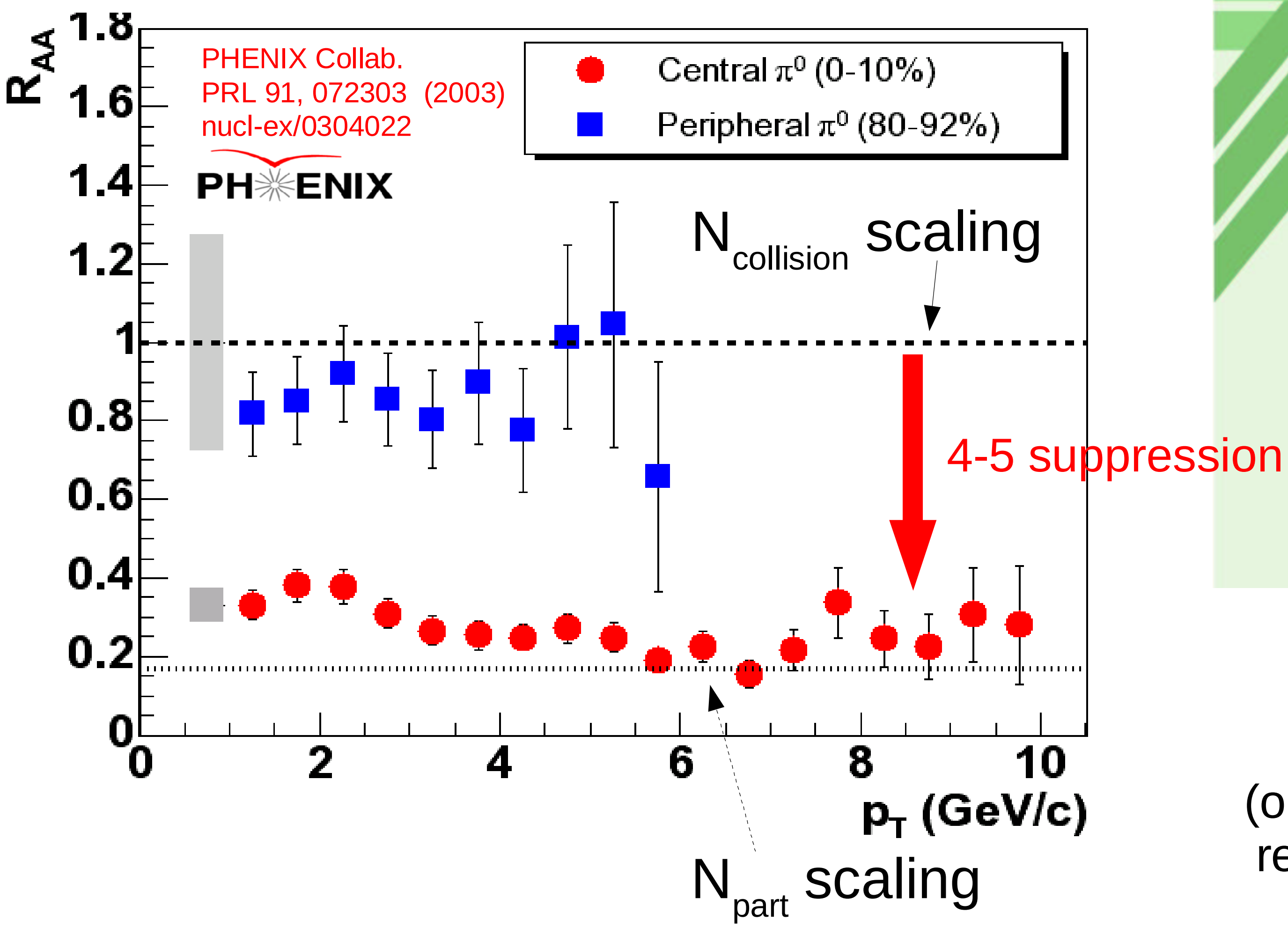


Peripheral data agree well with pp plus collision scaling and w/ pQCD

Strong suppression in central AuAu collisions

Nuclear modification factor (π^0)

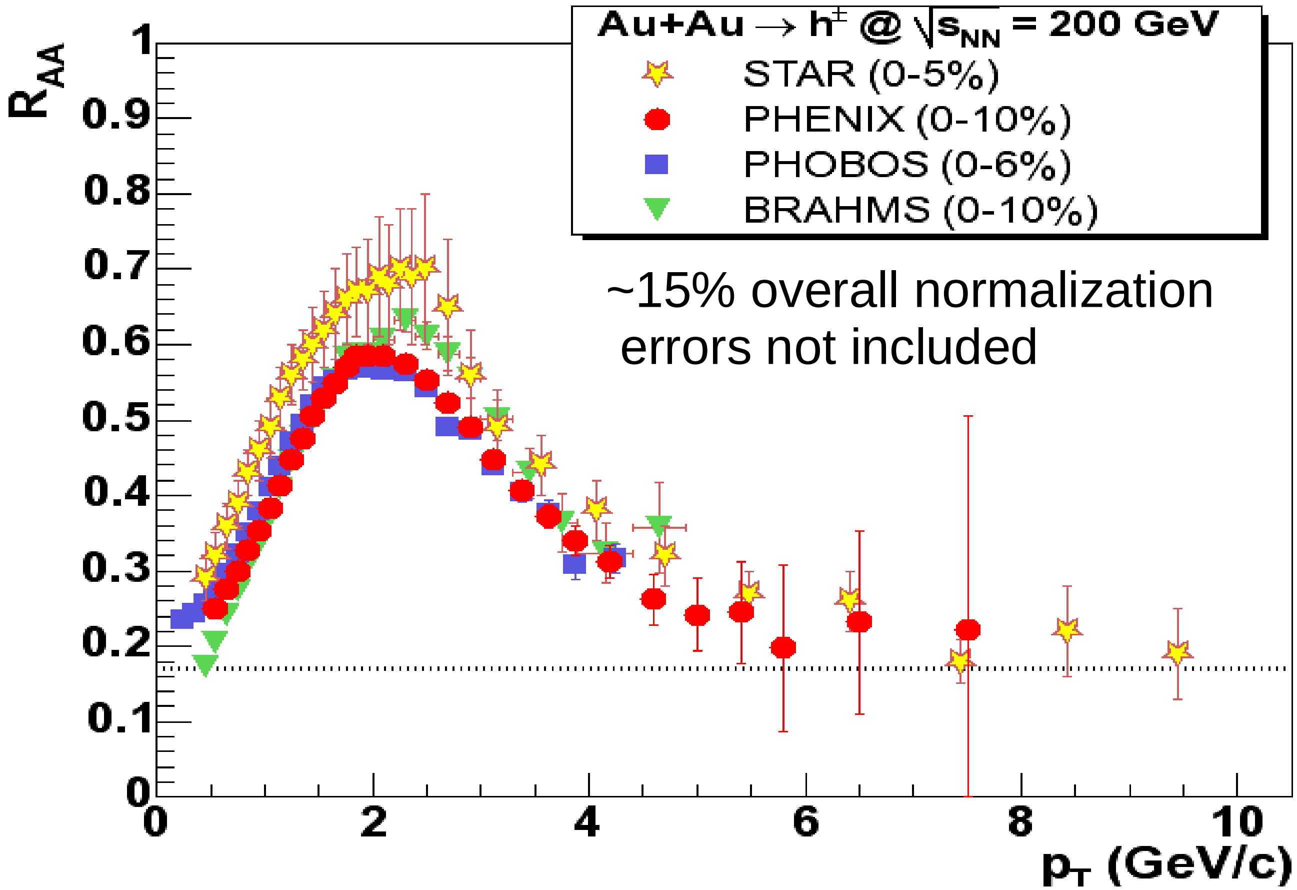
$$R_{AA}(p_T) = \frac{d^2N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle d^2N_{pp}/d\eta dp_T}$$



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

Nuclear modification factor ($h^{\pm}$)

- Inclusive charged hadrons suppressed too a factor ~4-5 above p_T= 5. GeV/c (but less suppressed than π^0 in p_T = 2 – 5 GeV/c)

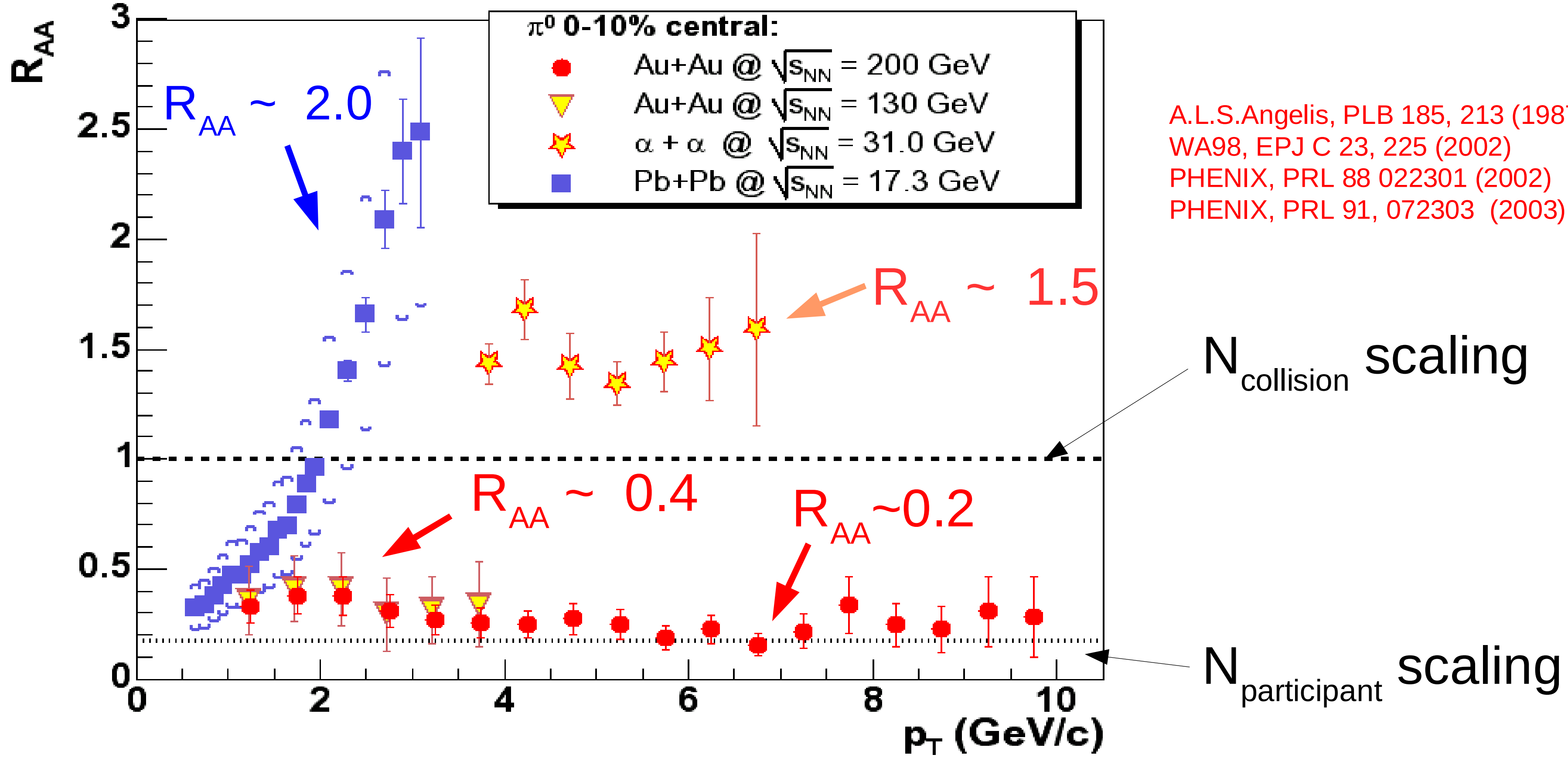


- Good general agreement among experiments.

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

R_{AA} compilation for π^0 in central A+A:

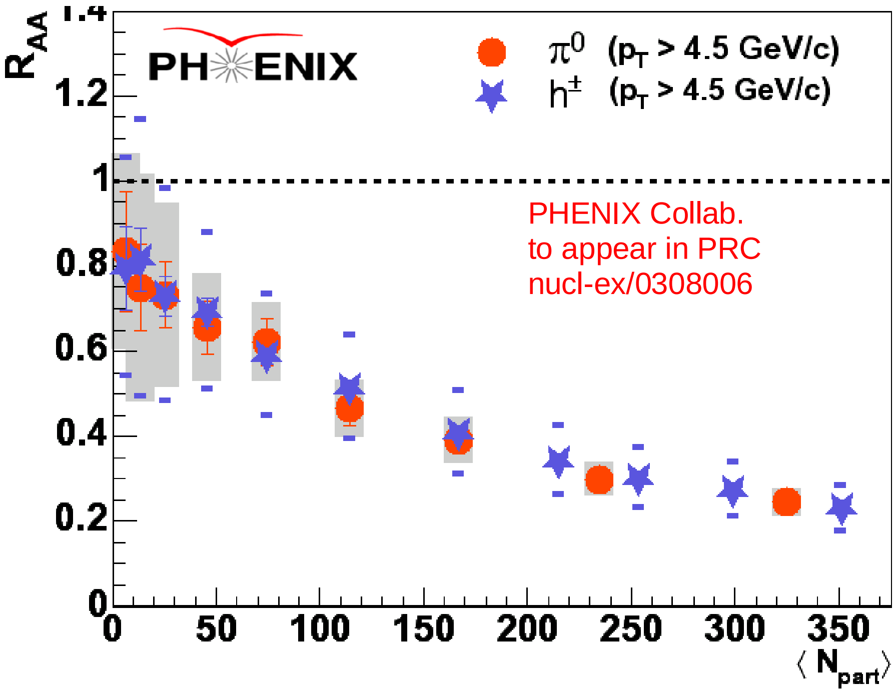
- CERN: Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 GeV), $\alpha+\alpha$ ($\sqrt{s_{NN}}$ ~31 GeV): Cronin enhancement
- RHIC: Au+Au ($\sqrt{s_{NN}}$ ~ 130, 200 GeV): x4-5 suppression with respect to N_{coll}

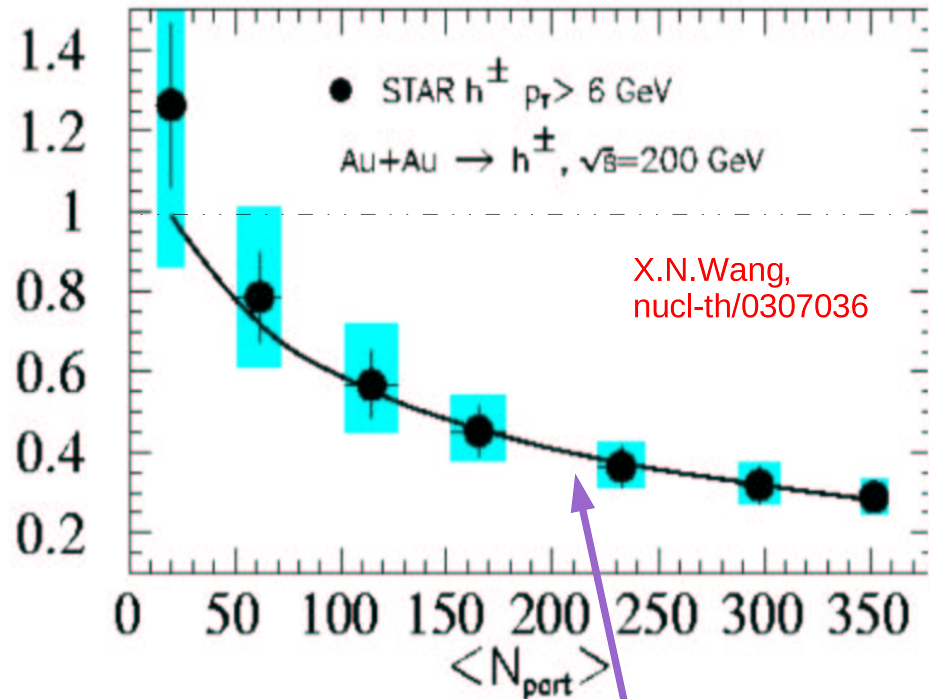


A.L.S.Angelis, PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
PHENIX, PRL 91, 072303 (2003)

High p_T suppression: centrality dependence (I)

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



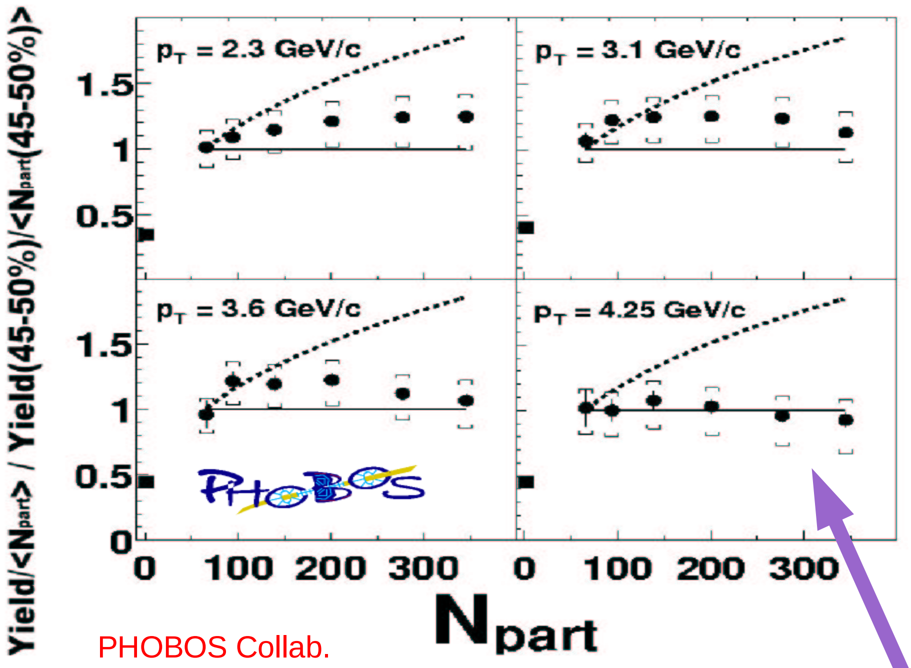


peripheral → central

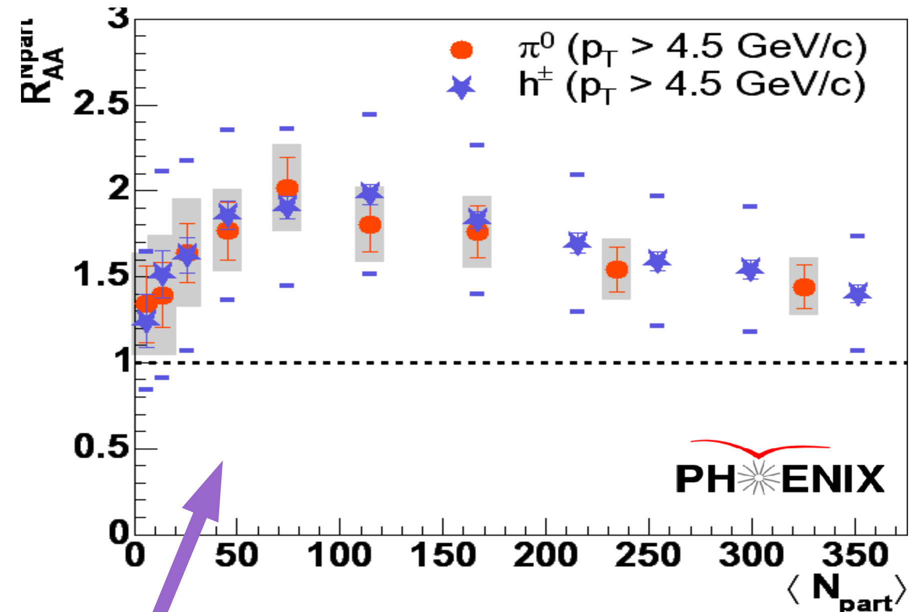
pQCD+parton ΔE_{loss}
(1+1D expansion)

High p_T suppression: centrality dependence (II)

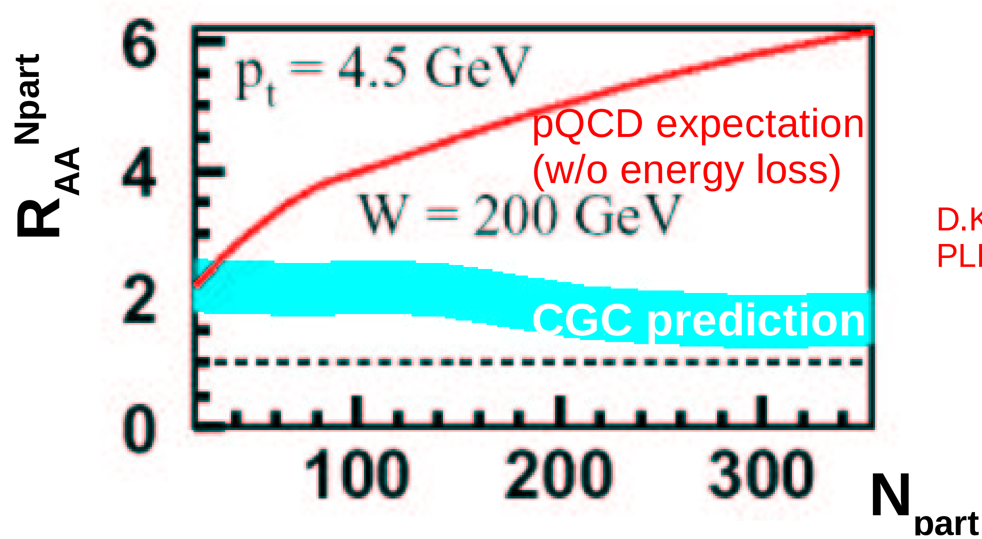
- Approx. N_{part} scaling (in accord with CGC predictions too):



PHOBOS Collab.
submitted to PLB
nucl-ex/0302015



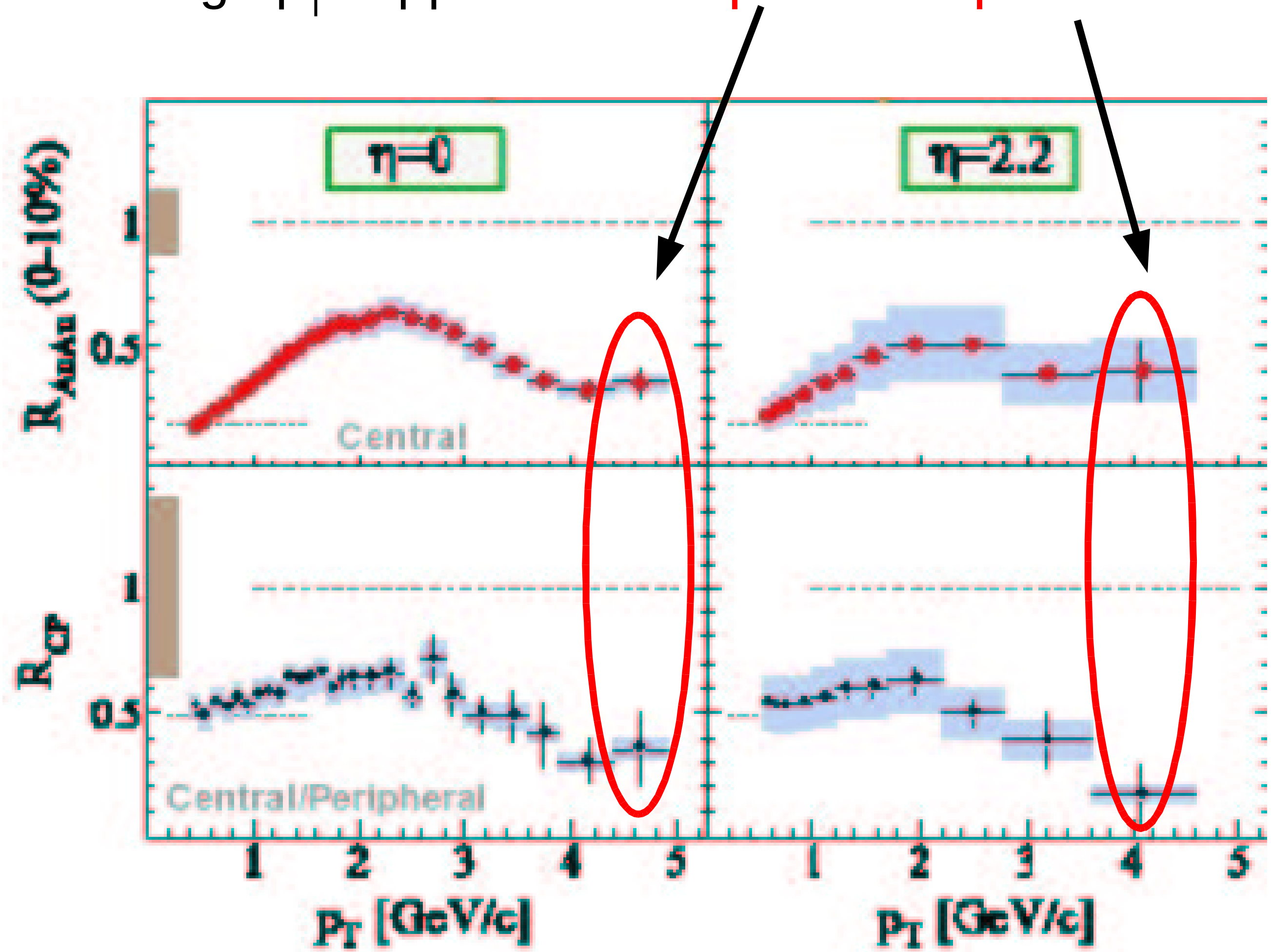
PHENIX Collab.
to appear in PRC
nucl-ex/0308006



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

High p_T suppression: (pseudo)rapidity dependence

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



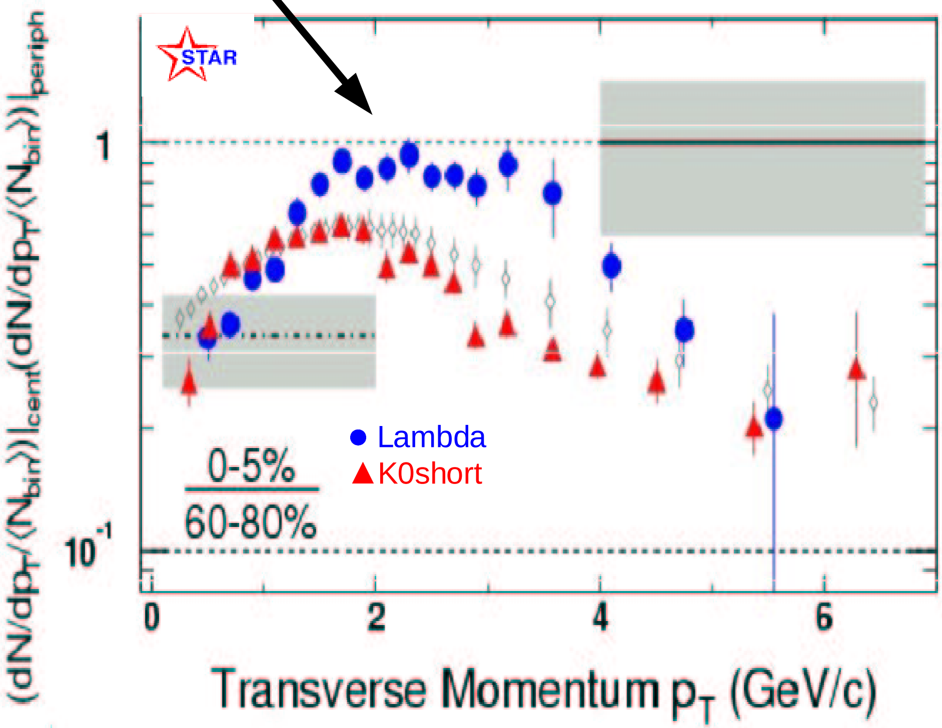
BRAHMS

BRAHMS
PRL91: 072305(2003)

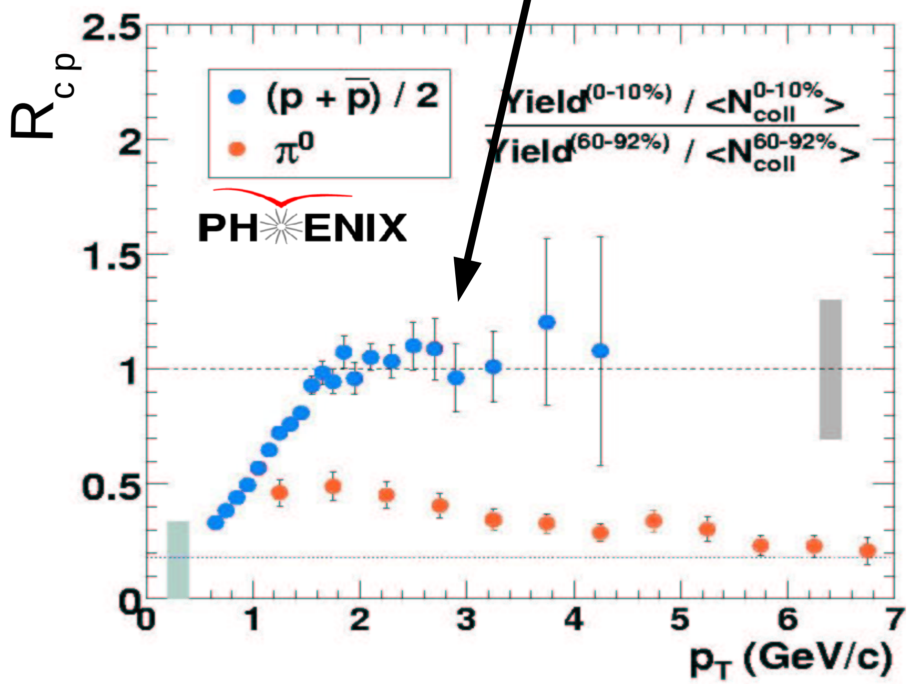
- The "quenching" medium extends also in the longitudinal direction.

High p_T suppression: particle dependence (I)

- At intermediate p_T = 2. – 4.5 GeV/c, baryons (antibaryons): p, pbar and Λ, Λbar are **NOT** suppressed in central Au+Au :



STAR Collab.
subm. to PRL, nucl-ex/0306007

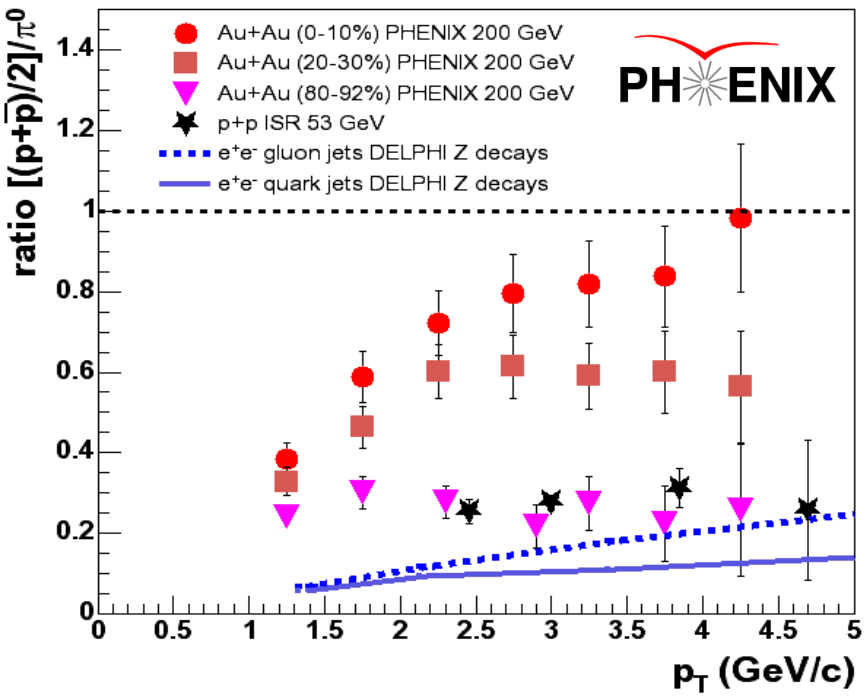


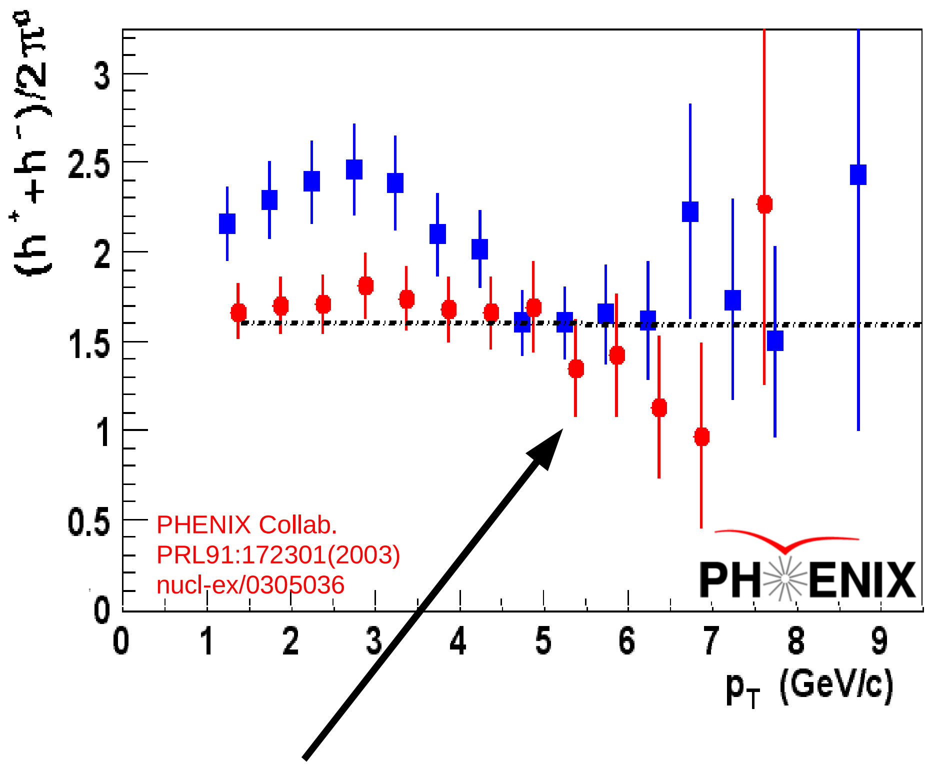
PHENIX Collab.
PRL91:172301(2003)

- Different production mechanisms for baryons & mesons in the intermediate p_T range (e.g. quark recombination vs. fragmentation).

High p_T suppression: particle dependence (II)

- Central colls.: $p/\pi \sim 0.8$ (at p_T = 2 - 4.5 GeV/c) at variance with perturbative production mechanisms (favour lightest meson).
- Periph. colls.: $p/\pi \sim 0.2$ as in p+p,pbar (ISR,FNAL) & in e+e- jet fragmentation

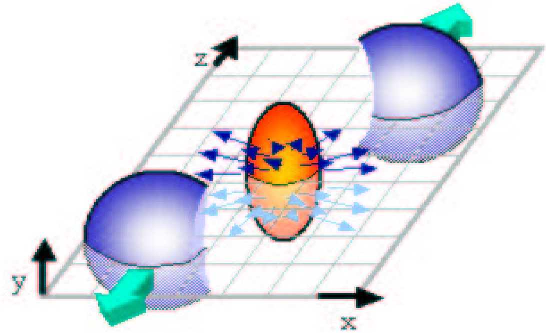




- Charged hadron and π^0 equally suppressed above $p_T \sim 5$ GeV/c: $h/\pi \sim 1.6$ as in p+p (perturbative ratio).
- Since $h^{\pm} = \pi^{\pm} + p(pbar) + K^{\pm} \Rightarrow$ baryon enhancement limited to $p_T < 4.5$ GeV/c

High p_T azimuthal correlations: Elliptic flow (I)

- Initial anisotropy in coord. space (overlap) in non-central collisions translates into final azimuthal asymmetry in momemtum space (transverse to react. plane)



Elliptic flow = v_2 second Fourier coefficient

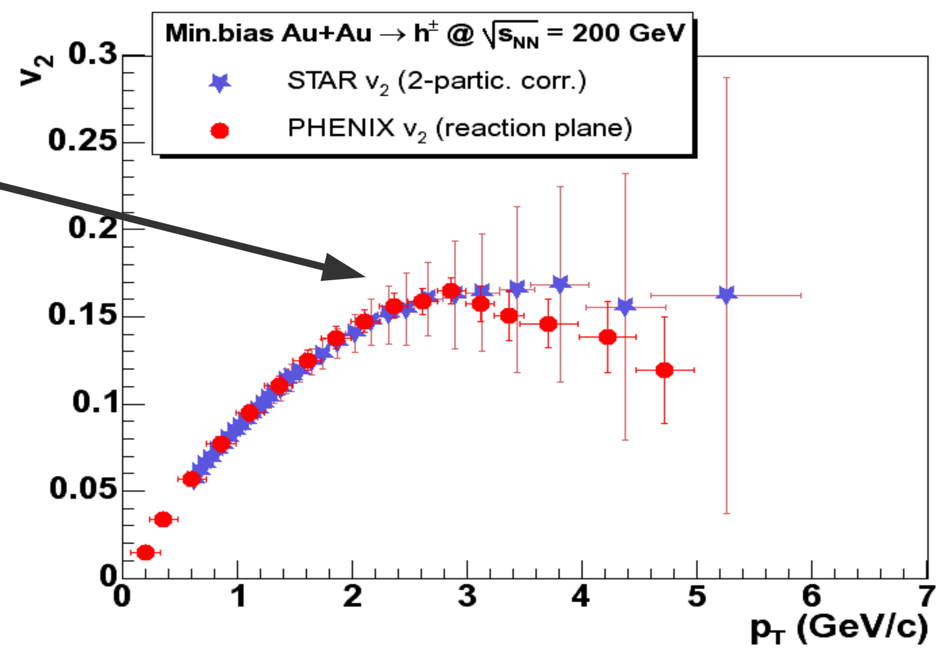
$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2(\phi - \Phi_{RP})$$

1. Truly collective effect (absent in p+p colls.).
2. "Hard" probe: develops exclusively in first instants of the reaction (t<3 fm/c).

- Large v_2 signal (saturating @ high p_T)

$\Rightarrow$ strong (collective) pressure grads.

$\Rightarrow$ large and fast (t<1.0 fm/c) parton rescattering (early thermalization).



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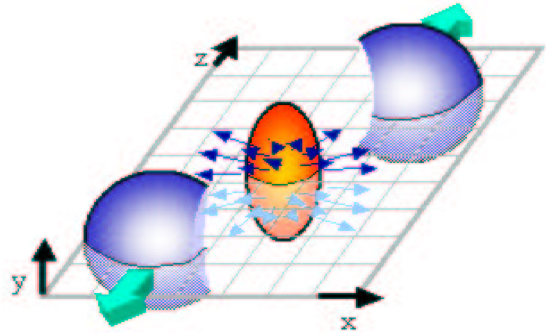

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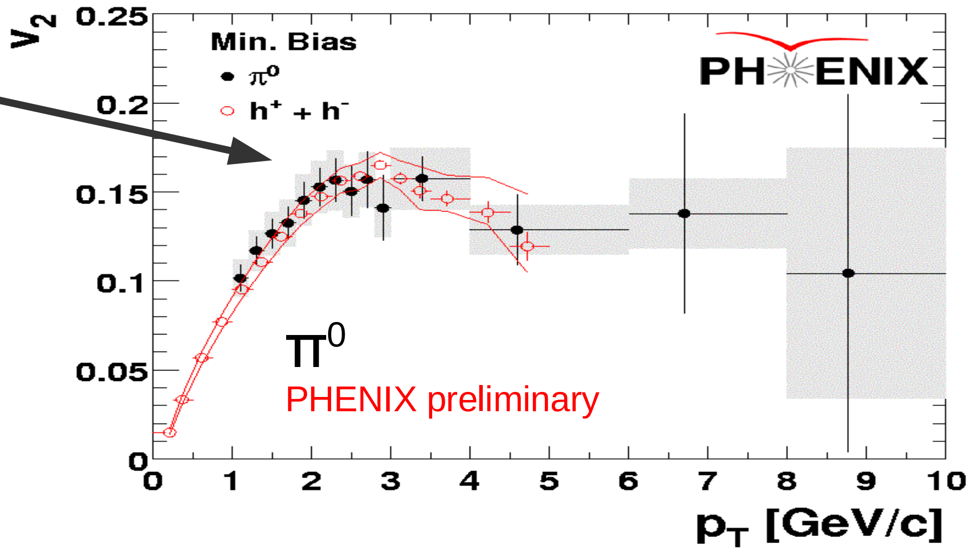
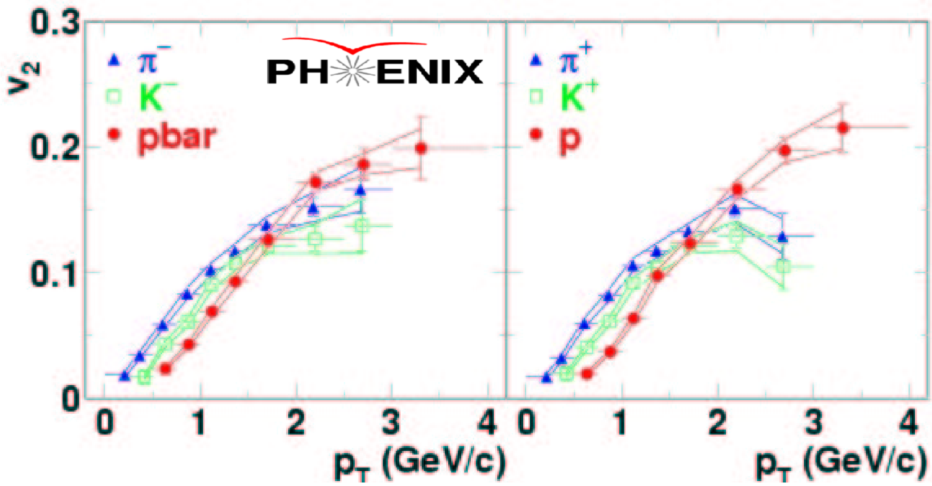
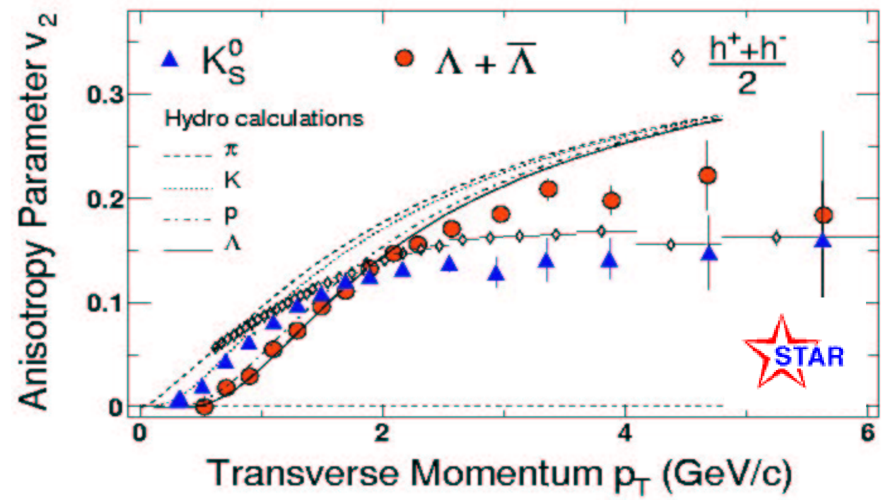


High p_T azimuthal correlations: Elliptic flow (II)

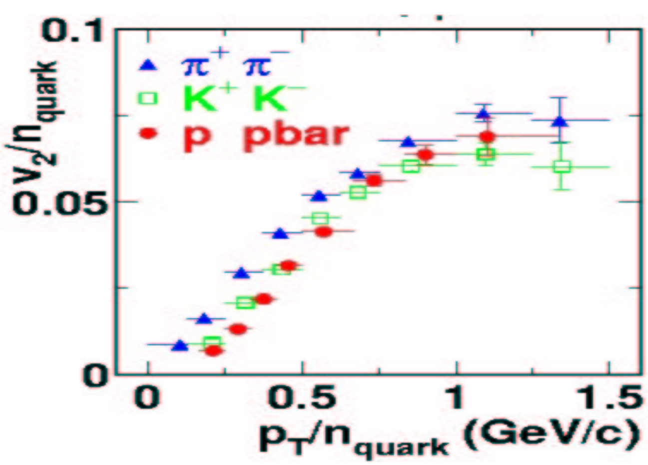
- Particle species dependence of flow:

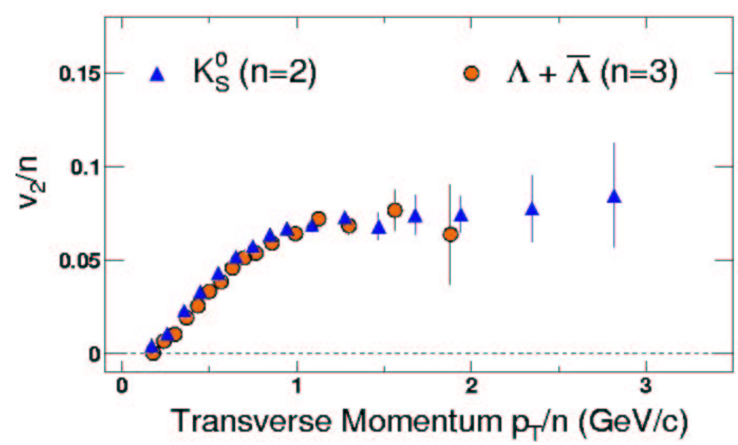




$$v_2^m > v_2^b \text{ at low } p_T,\ v_2^m \approx v_2^b \text{ at } p_T \approx 2\ \text{GeV}/c, \text{ and } v_2^m < v_2^b \text{ at higher } p_T\text{'s}$$

- Well explained by quark recombination (v_2 scaled by # of constituent quarks):



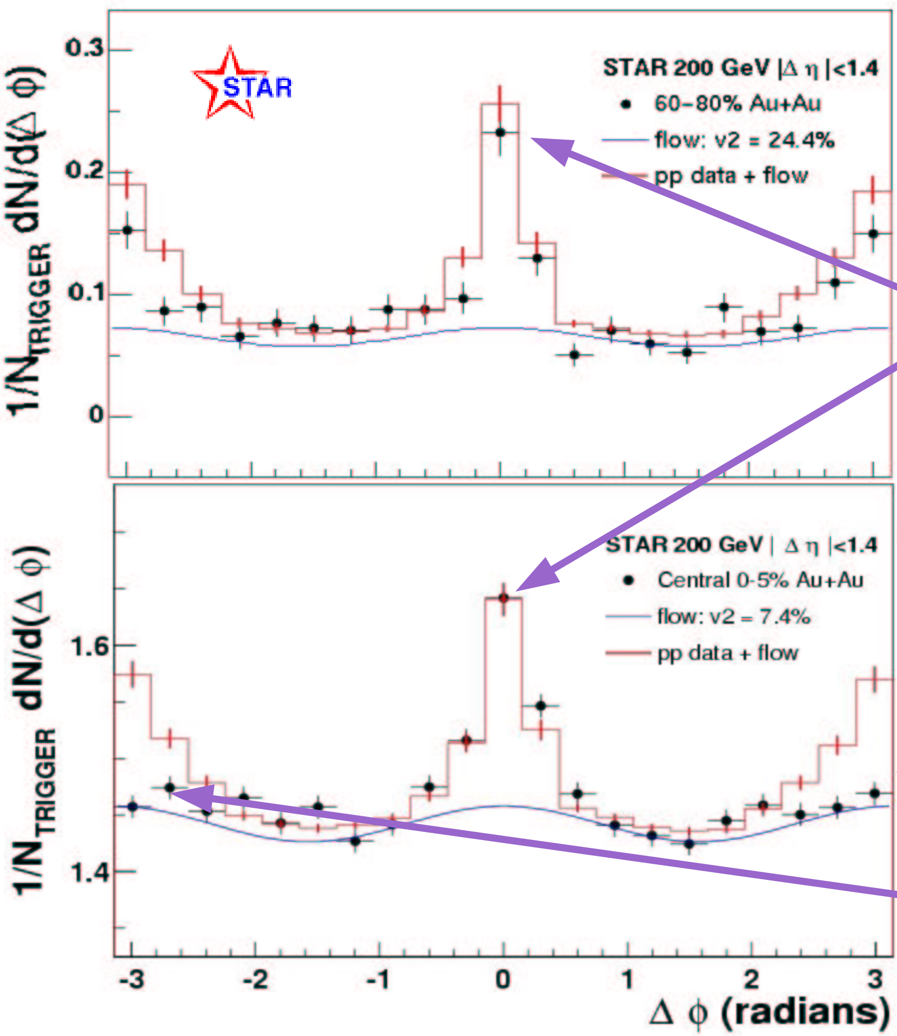


High p_T azimuthal correlations: Jet signals in Au+Au vs p+p

- $dN_{pair}/d\Delta\phi$ for "trigger" (p_T > 4GeV/c) & associated (p_T = 2- 4 GeV/c) charg. hadrons:

Periph.:

Central:



Red histogram: p+p (+flow)
Black points: Au+Au
Blue curve: flow contribution

- Near-side peak: Au+Au = p+p.

  Trigger hadrons (p_T > 4GeV/c) come from jets.

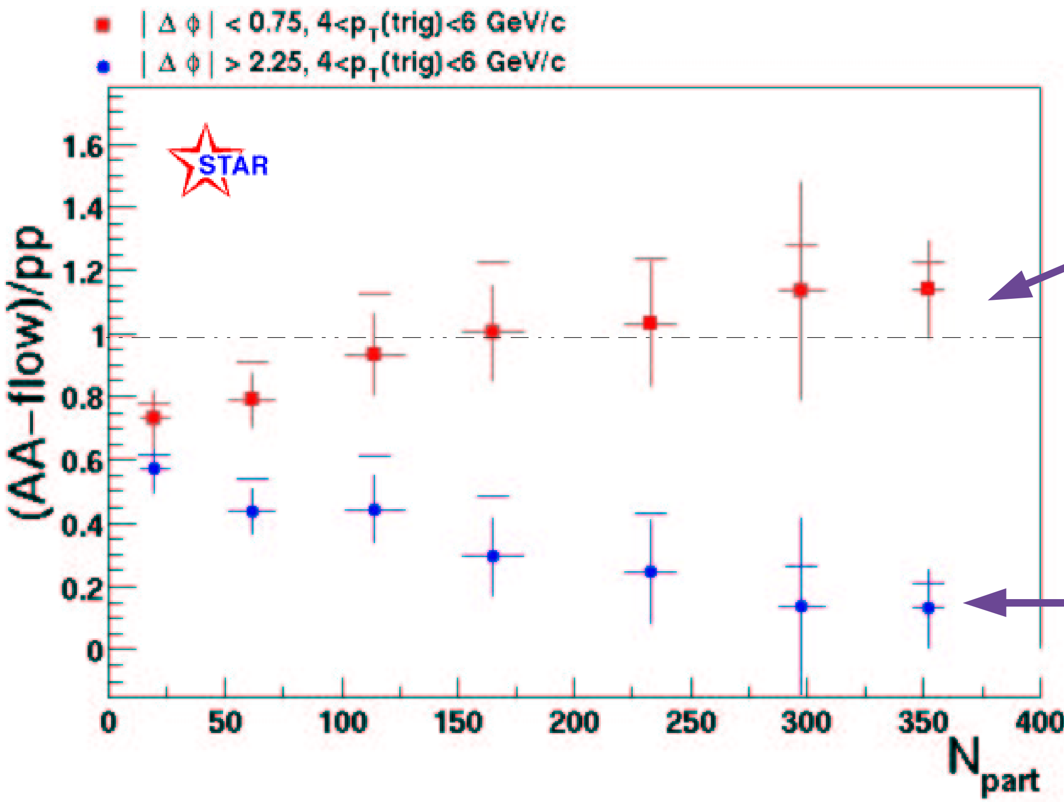
- Away-side peak: Au+Au << p+p.

  Back-to-back jets suppressed in central Au+Au !

High p_T azimuthal correlations: dijet signal disappearance

- Ratio of Au+Au (- flow) over p+p azimuthal correlation "strengths":

$$I_{AA}(\Delta\phi_1, \Delta\phi_2) = \frac{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi)[D^{\mathrm{AuAu}} - B(1 + 2v_2^2\cos(2\Delta\phi))]}{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi) D^{\mathrm{pp}}}$$

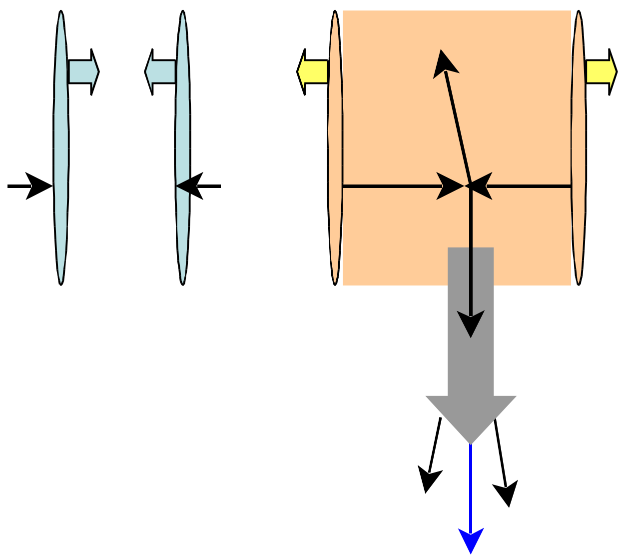


- Near-side peak: I_{AA}~1
- Away-side peak: I_{AA}~0

- Increasing dissapearance of back-to-back correlation as a function of centrality.

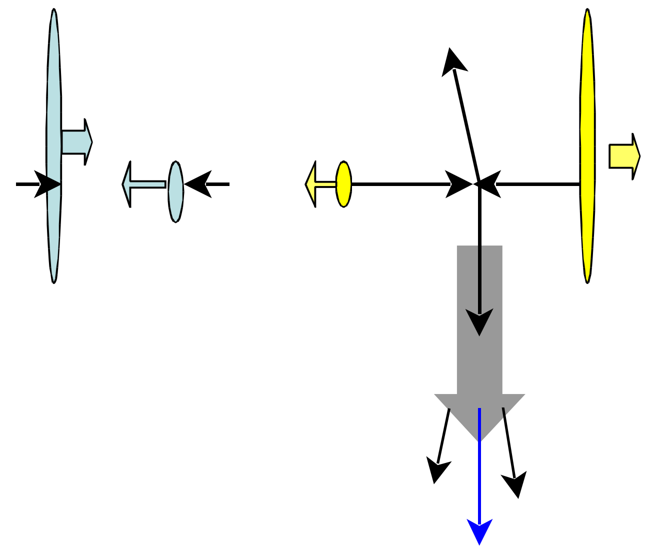
High p_T in d+Au (“control” experiment)

A+Au collision



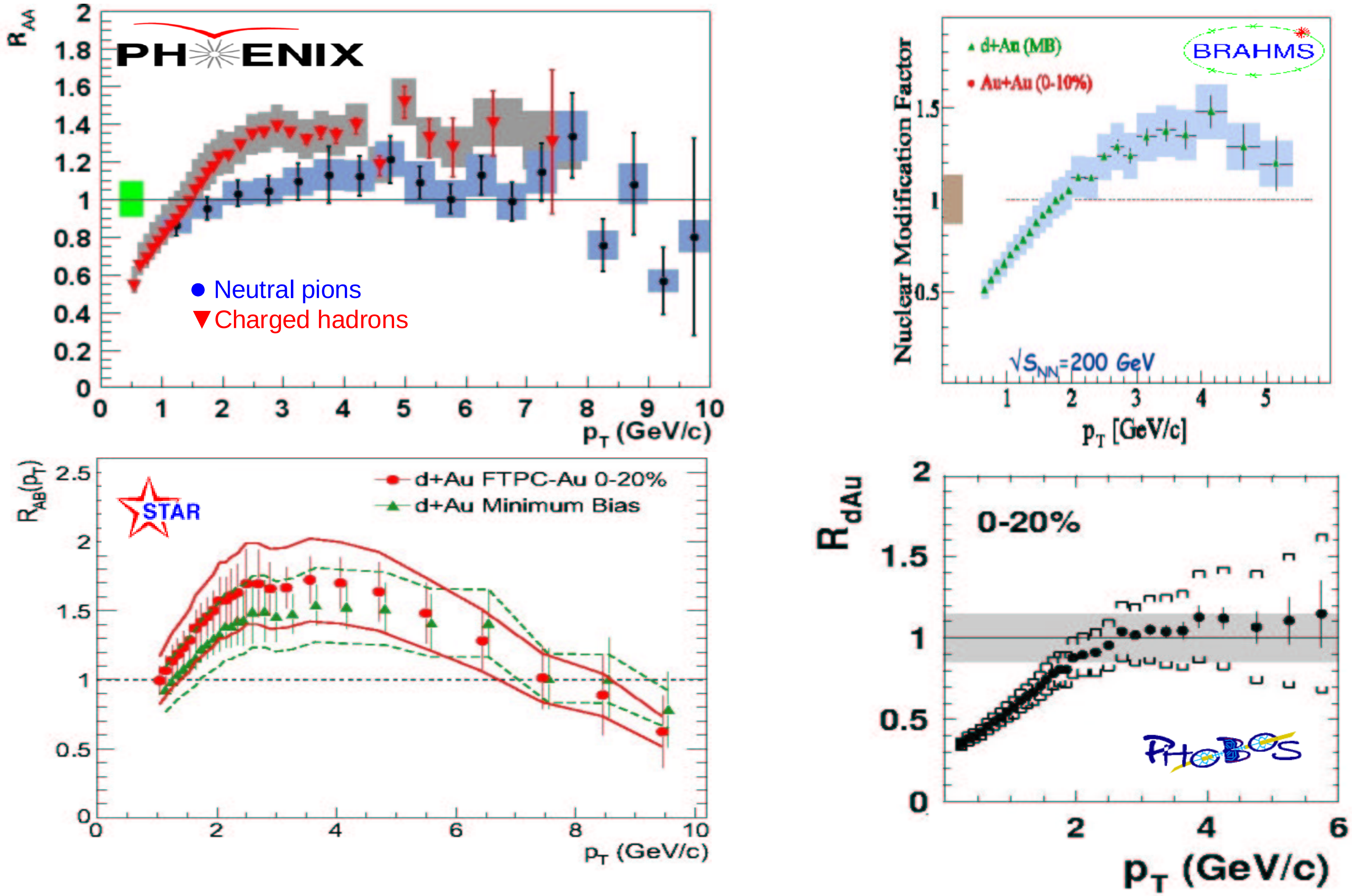
hot & dense medium
(initial+final-state effects)

p,d+Au collision



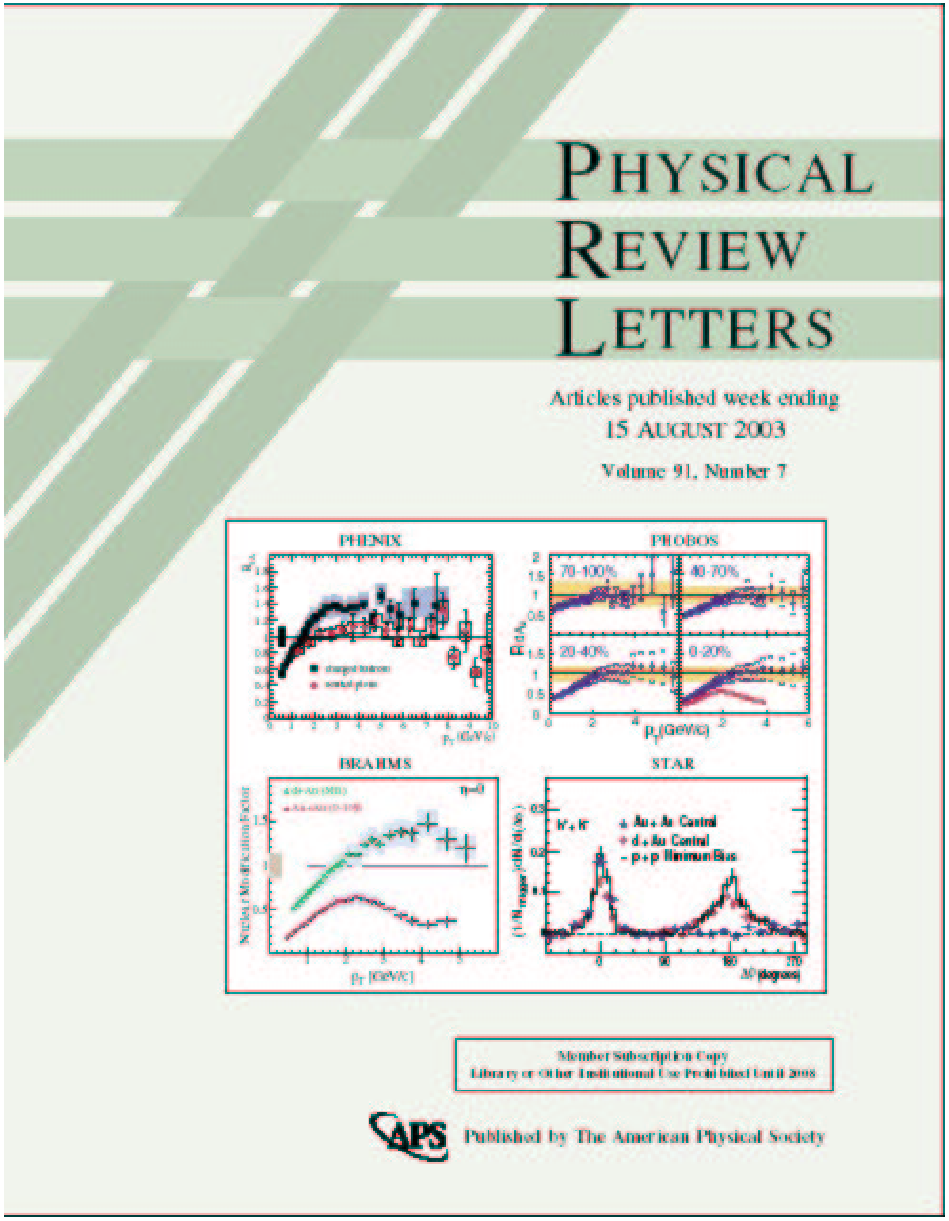
cold medium
(initial- state effects only)

d+Au nuclear modification factor

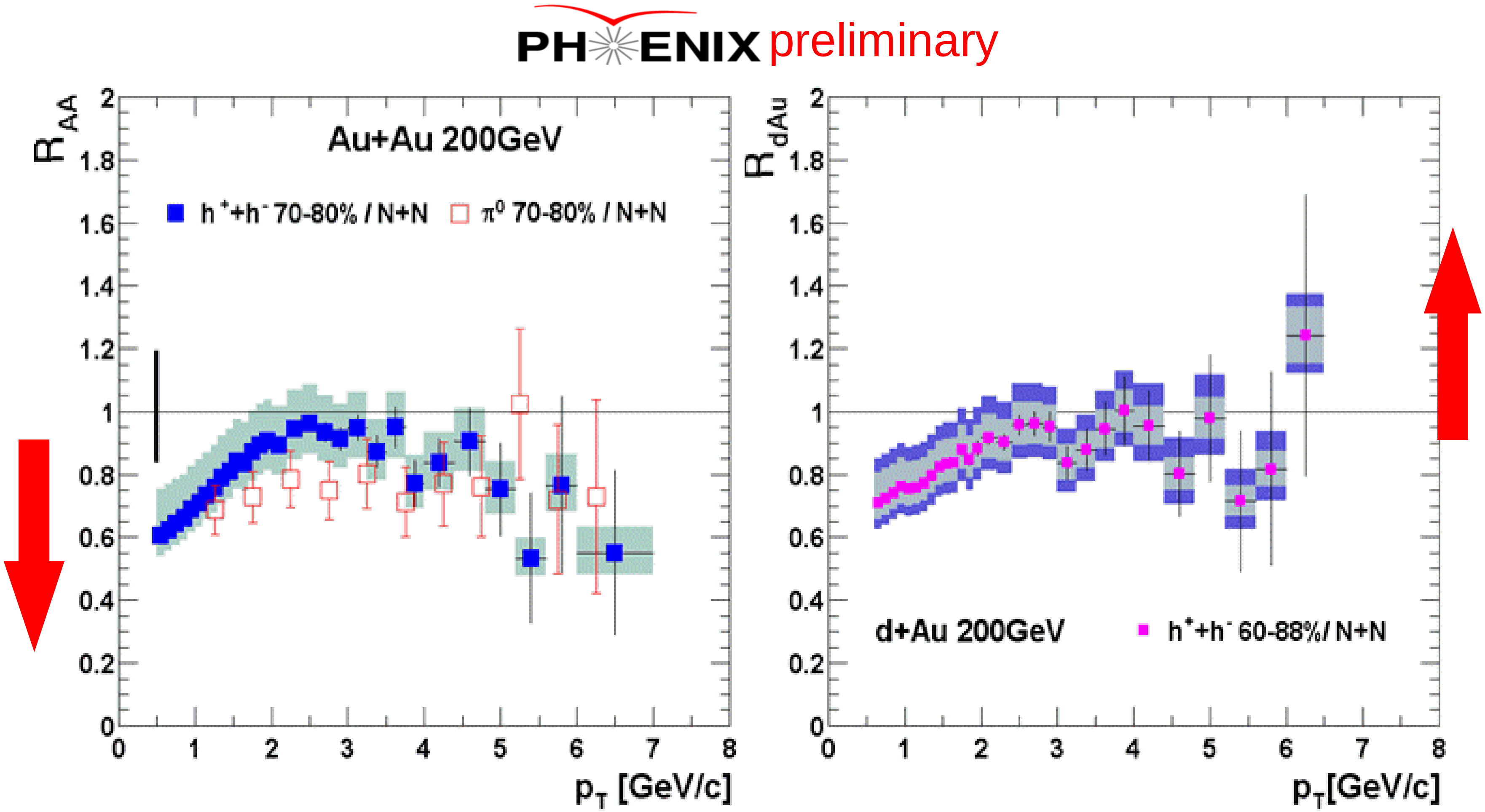


- High p_T not quenched: $R_{dAu}(h^{\pm}) \sim 1.4$ and $R_{dAu}(\pi^0) \sim 1.1$: d+Au clearly reminiscent of p+A “Cronin enhancem.” (initial-state soft & semihard scatt.).
- No apparent strong shadowing or saturation of Au PDF.

d+Au nuclear modification factor

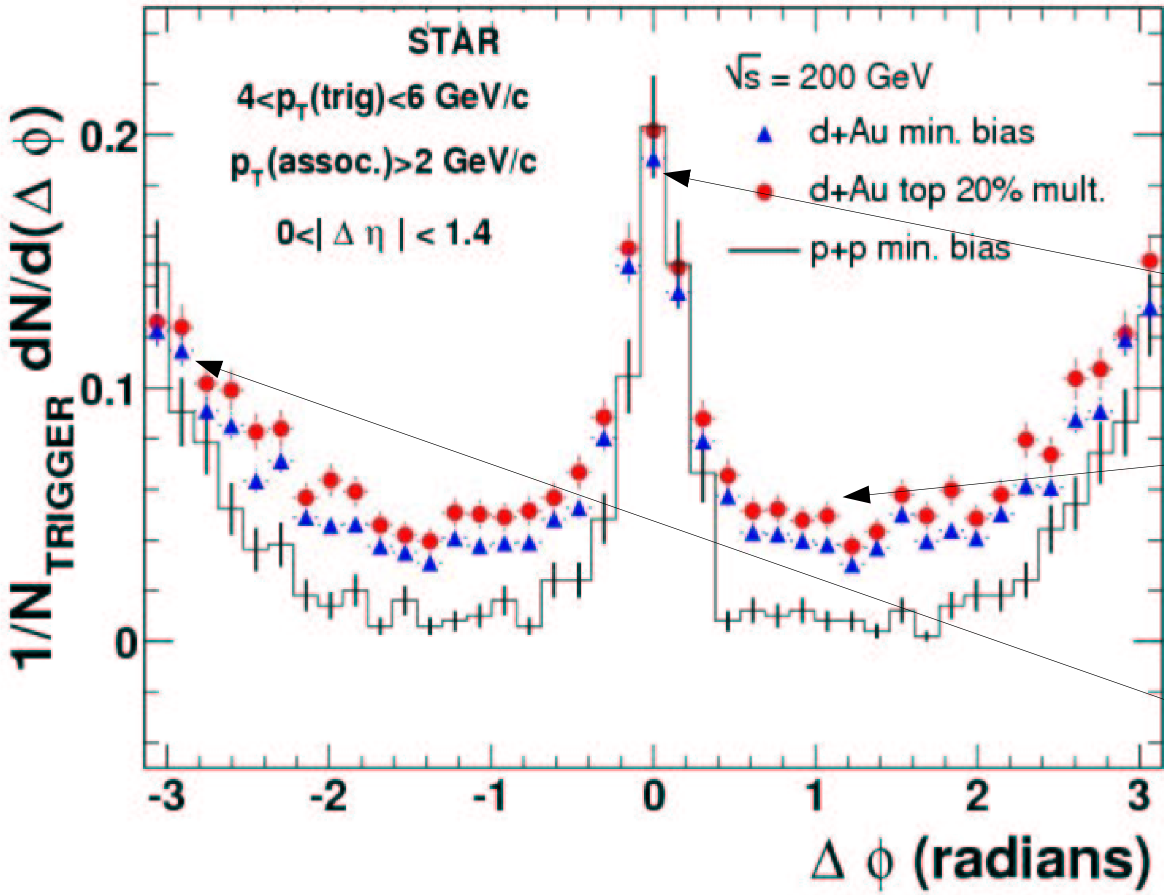


Nuclear modification factor: Au+Au vs d+Au



- Opposite centrality dependence of nuclear enhancement (in p+Au) compared to nuclear suppression (in Au+Au) !
- Conclusion: Au+Au suppression not due to a "cold" nuclear matter (initial-state) effect !

High p_T azimuthal correlations: d+Au vs p+p



- Near- side: d+Au correlation strength and width similar to p+p (and Au+Au)
- Increasing "underlying event": p+p < d+Au(min.bias) < d+Au(central)
- Away-side: d+Au peak broadens but small centrality dependence

- Back-to-back jets do not disappear in central d+Au !

Summary (I)

- Vast amount of high p_T data (dN/dp_T, $dN/d\varphi$ for $h\pm,\pi^0,K^0_s,p,\bar{p},\Lambda,\bar{\Lambda}$, diff. centrality classes...) in Au+Au, d+Au, and p+p collisions @ $\sqrt{s}$ = 200 GeV

- Central Au+Au collisions :
  - Strong suppression (factor ~ 4-5) of all hadrons (with respect to N_{coll} scaling) above p_T~ 5 GeV/c.
  - Flat and universal (pid-wise) p_T dependence of suppression >5 GeV/c.
  - Very different behaviour than at lower $\sqrt{s}$ (“Cronin” enhancement).
  - Smooth centrality dependence of suppression (weak N_{part} scaling).
  - No apparent suppression of baryons in p_T~2-5 GeV/c: “anomalous” p/π ~ 0.8 ratio >> p/π ~ 0.2 in p+p and e+e- jet fragmentation.
  - Strong elliptic flow signal (early collective rescattering).
  - Jet-like signal in near-side azimuthal correlations.
  - Disappearance of jet away-side azimuthal correlations.

Summary (II)

- Peripheral Au+Au collisions:
  - Behave effectively as p+p collisions plus N_{coll} scaling (expected pQCD behaviour) for all species and for all observables !
- d+Au collisions:
  - No suppression observed (min.bias, nor central d+Au).
  - Cronin-like enhancement for π^0 (small) and $h^{\pm}$ (larger).
  - Opposite behaviour of the centrality dependence of high p_T production compared to Au+Au.
  - No dissapearance of away-side dijet correlations.
  - No "cold" nuclear matter effects (strong saturation of nuclear PDFs) seem to explain high p_T Au+Au suppression.
- Data vs. theory:
  - pQCD-based final-state parton energy loss models ("QGP" models) seem to reproduce more aspects of the data (Au+Au, d+Au) than other approaches (though non-perturbative effects, e.g. q recombination, needed at interm. p_T).
- *Final evidence of QGP @ RHIC requires yet to see medium effects on 2 other hard QCD probes: J/ψ & (thermal) photon signals. Stay tuned !*

backup slides ...

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

High-p_T @ RHIC: theory confronting data

- **APPROACH "A"** (pQCD + parton energy loss):

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

✔ *Peripheral data explained*

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

- Energy loss 1: BDMPS, Wiedemann & Salgado (LPM, thick plasma)
- Energy loss 2: Gyulassy-Levai-Vitev (LPM, thin plasma)
- Energy loss 3: HSW (modified FFs), (*g* radiation + absorption)

✔ *Goal: explain central colls. (quenching, p_T dependence, away-side suppr.)*

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

✔ *Goal: explain baryon-meson diff. in central colls.*

- **APPROACH "B"** ("classical" QCD):

Step 1: CGC → gluon saturated nuclear wave function (MLV)
+ geometric scaling (KLN)
Step 2: glue + glue collisions: gg → g
Step 3: Gluon fragmentation (FFs)

✔ *Goal: explain high p_T deficit, away-side suppression, N_{part} scaling ...*

Final-state QGP effects (I)

- Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium:

  - Mean parton energy loss probes medium properties:

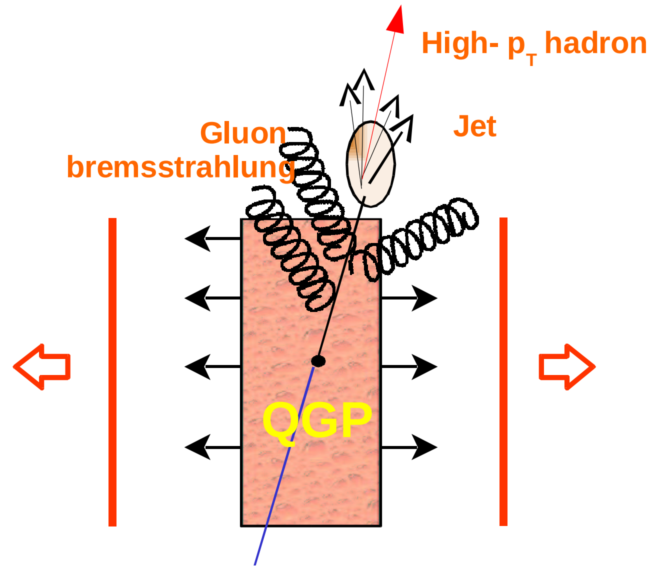
    $\Delta E \sim \rho_{gluon}$ (gluon density)

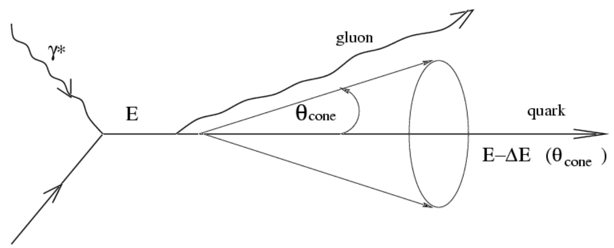
    $\Delta E \sim \Delta L^2$ (medium length)

  - Energy is carried away by gluon bremsstrahung outside jet cone: $dE/dx \sim \alpha_s \langle k_T^2 \rangle$

  - Formalisms: BDMPS (thick plasma), GLV (thin plasma), Wiedemann (combined).

  - Correction for expanding plasma:
    $\Delta E_{1-D} = (2\tau_0/R_A) \cdot \Delta E_{stat} \sim 15 \cdot \Delta E_{stat}$ (τ_0=0.2 fm/c, R_A=6 fm)





"QGP" models vs. data

✔ Magnitude of Au+Au suppression → dense partonic medium:

- High opacities: $\langle n \rangle = L/\lambda \approx 3 - 4$
- Large initial gluon densities: $dN^g/dy \sim 800\text{-}1200$
- " transport coefficients: $\langle q_0 \rangle \sim 3.5$ GeV/fm^2
- Radiative energy losses: $dE/dx \approx 0.25$ GeV/fm (expand.) ≈ 14 GeV/fm (static)

✔ Centrality dependence of Au+Au suppression.

✔ Dissapeareance of away-side dijet angular correlations.

✔ No quenching in d+Au collisions.

✗ p_T dependence of Au+Au suppression → not described in 1st instance:

- Additional nuclear effects needed to "flatten" LPM R_{AA} (probably justified given the d+Au results)

✗ $\sqrt{s}$ dependence of Au+Au suppression clear ?

- no jet quenching observed in Pb+Pb @ SPS with $dN^g/dy \sim 500$?
  (*usual explanations: short plasma life-time, quark-dominated plasma, very small hard cross-sections: Cronin-effect dominates ...*)

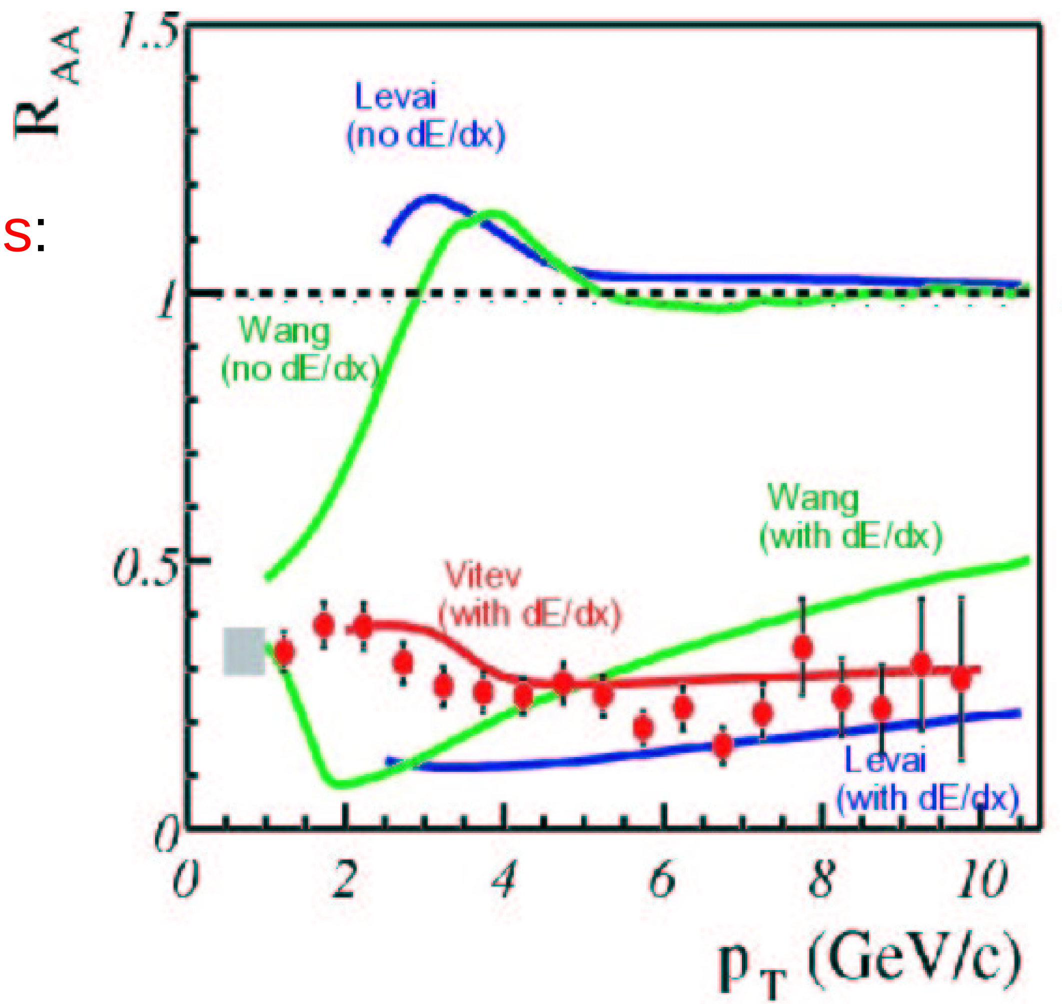
✗ Particle species dependence of Au+Au suppression ("baryon enhancement") → not perturbative !

- Additional final state effects: q recombination (or baryon junctions, ... ?) needed.

Final-state QGP effects (II)

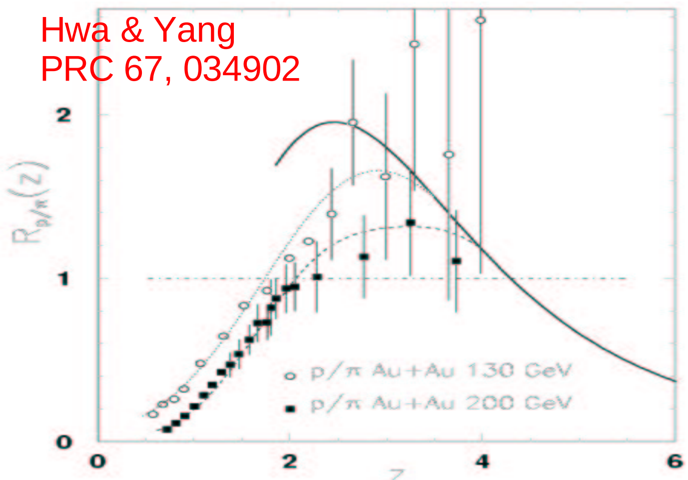
- Dense medium properties according to "jet quenching" models:
  - High opacities:
    $<n> = L/\lambda \approx 3 - 4$
  - Large initial gluon densities:
    $dN^g/dy \sim 800\text{-}1200$
  - Transport coefficients:
    $<q_0> \sim 3.5$ GeV/fm^2
  - Medium-induced gluon radiative energy losses:

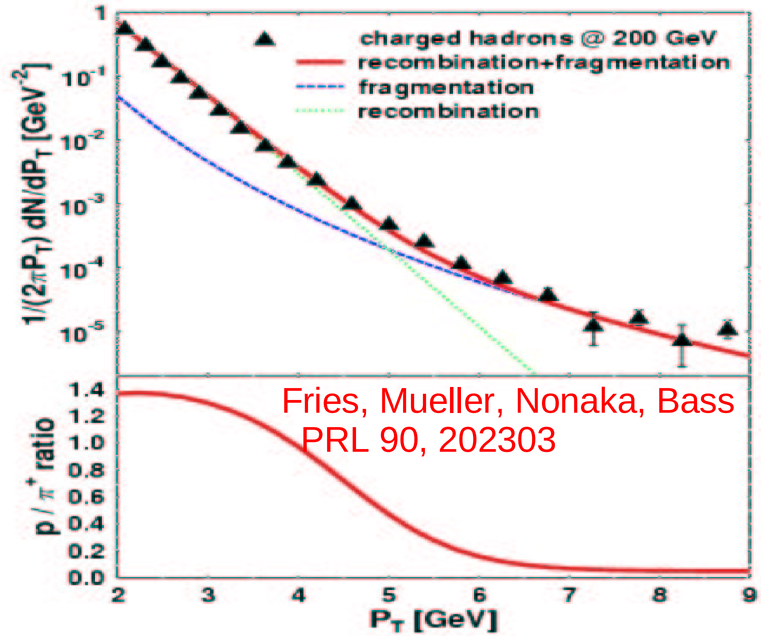
$dE/dx \approx 0.25$ GeV/fm (expanding)
$dE/dx|_{eff} \approx 14$ GeV/fm (static source)

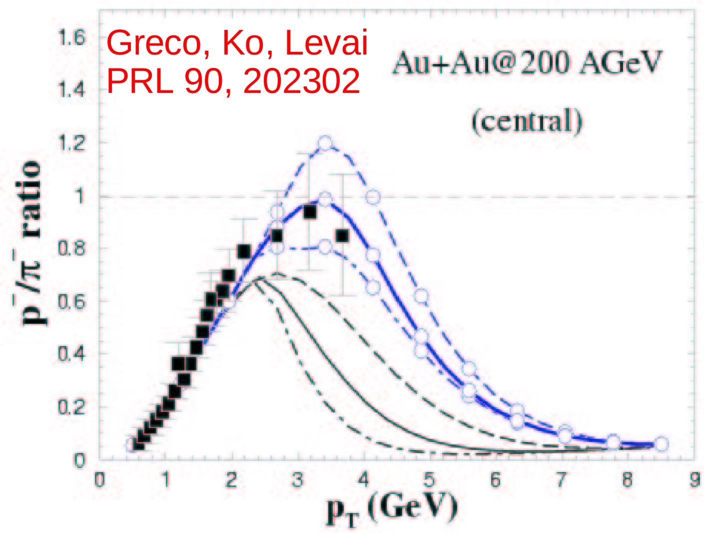


Final-state QGP effects (III)

- Quark recombination/coalescence explains the anomalous high p_T "chemistry" at intermediate p_T's:







- High parton densities in a thermal medium favour quark coalescence
- Recombination dominates for p_T ~ 1- 4 GeV/c:

  $\langle p_T(\text{baryons})\rangle > \langle p_T(\text{mesons})\rangle > \langle p_T(\text{quarks})\rangle$

- Fragmentation dominates for p_T > 5 GeV/c:

  $p_T(\text{hadrons}) = z\ p_T(\text{partons})$, with z<1

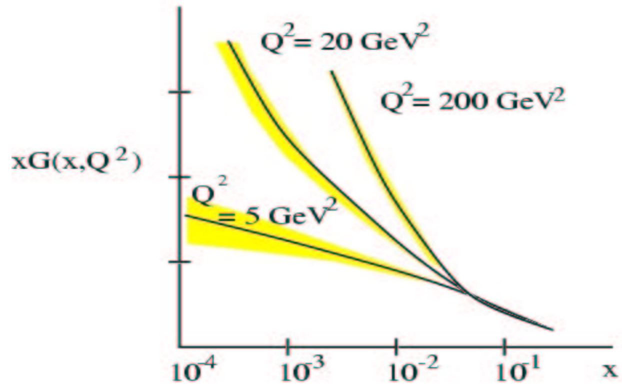
Initial-state effects in a Color Glass Condensate

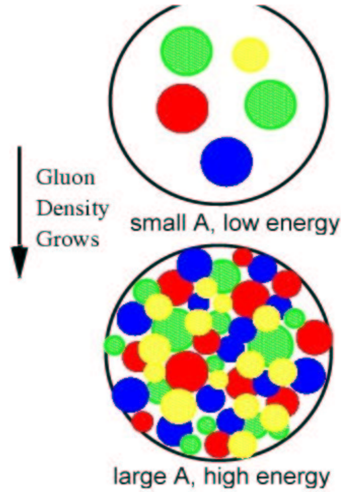
- Initial conditions at RHIC: high-energies + large nuclei
  - Values of small-x: $x_{Bj} = 2p_T/\sqrt{s} \ll 1$

High parton (gluon) densities

$$\rho_A \simeq \frac{xG_A(x,Q^2)}{\pi R_A^2} \sim A^{1/3}$$

RHIC ~ HERA x $A^{1/3}$





- Colliding nuclei described with a colored highly saturated and gluonic wave-function ("Color Glass Condensate"):

Saturation scale:

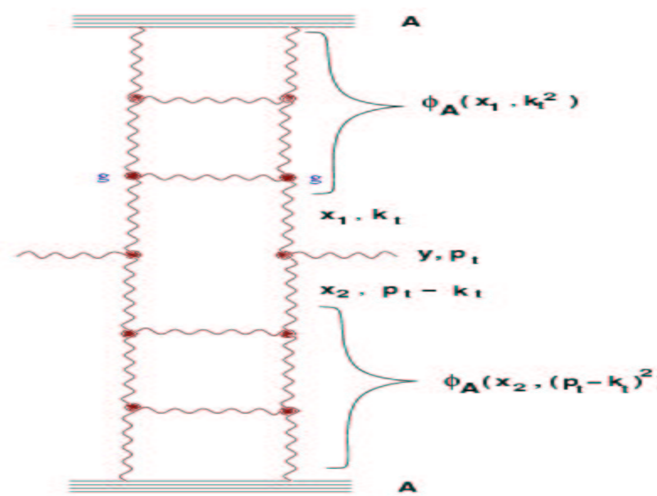
$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2} \sim 1.5 \text{ GeV}^2/c^2 \text{ @ RHIC}$$

$Q^2_s \gg \Lambda^2_{QCD} \Rightarrow \alpha_s \ll 1$ (weak coupling)

"Classical" (Chromo-Dynamics) methods applicable

Extension to $p_T > Q_s$ via "geometric scaling"

- Particle production via glue-glue collisions:



- Suppression due to reduced # of partonic scattering centers in the initial-state

"CGC" models vs. data

✗ Foreword: High p_T at midrapidity at RHIC is above Q_s ~ 1-2 GeV/c (straight application of CGC arguable in 1st instance).

✔ Magnitude of Au+Au suppression → saturated (evolved) Au wave function (KLM). But: no suppression expected in other calculations (e.g. Baier, Wiedemann *et al.*).

✔ Centrality dependence of Au+Au suppression → N_{part} scaling -like observed.

✔ Dissapeareance of away-side angular correlations (monojet production)

✗ Some deficit (R_{dA}~ 0.75) expected in d+Au collisions (Kharzeev *et al.*). However: Cronin enhancement built in the initial wave function (Baier, Wiedemann *et al.*). Similar conclusions by J.Jalilian-Marian too (though no calculations y < 1), but missing in KLM.

More converging agreement needed between diff. calculations ...
(seem to describe either Au+Au or d+Au, but not both consistently)

Hadronic model vs. data

✗ Foreword: Very dense hadronic medium scenarios should have gone first through an (even) denser partonic phase.

✔ Magnitude of Au+Au suppression → dense hadronic medium:

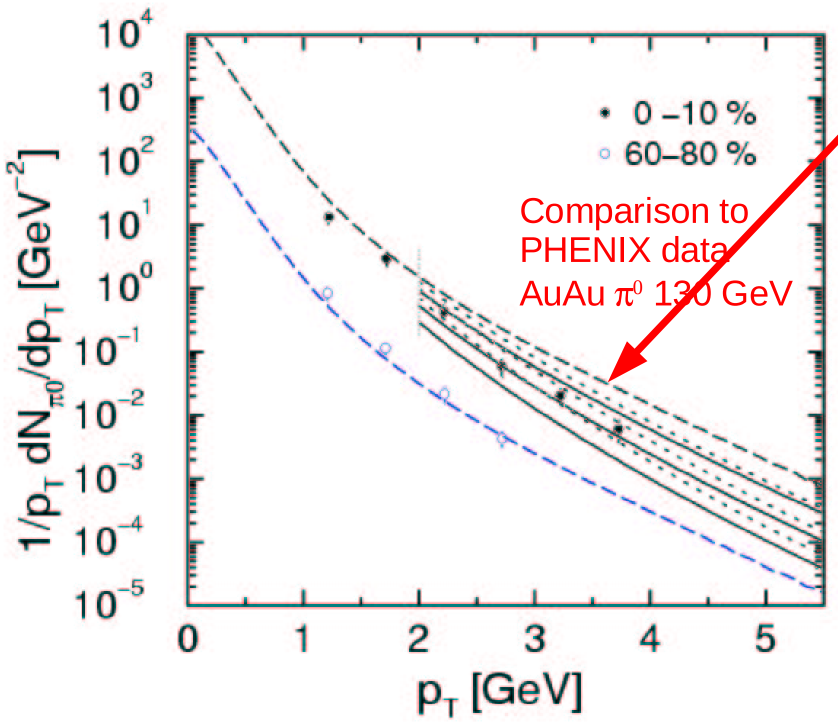
- High opacities: $\langle n \rangle = L/\lambda \approx 2$

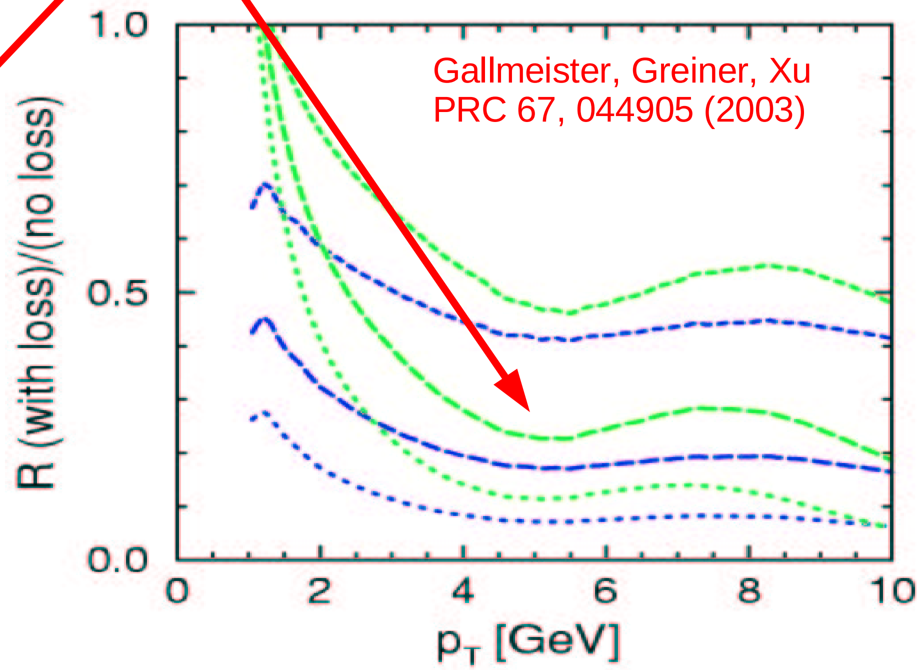
- p_T dependence of Au+Au suppression → apparently described **but** with counter-intuitive arguments (in apparent contradiction to the assumed hadron formation time ansatz).
- Possible "control" calculations (not observed in data but expected in hadronic medium description): charm meson energy loss, suppressed near-side jet correlation, ...

Estimates are only "semiquantitative".
More realistic model calculations (badly) needed !

Final-state effects in a dense hadronic medium ?

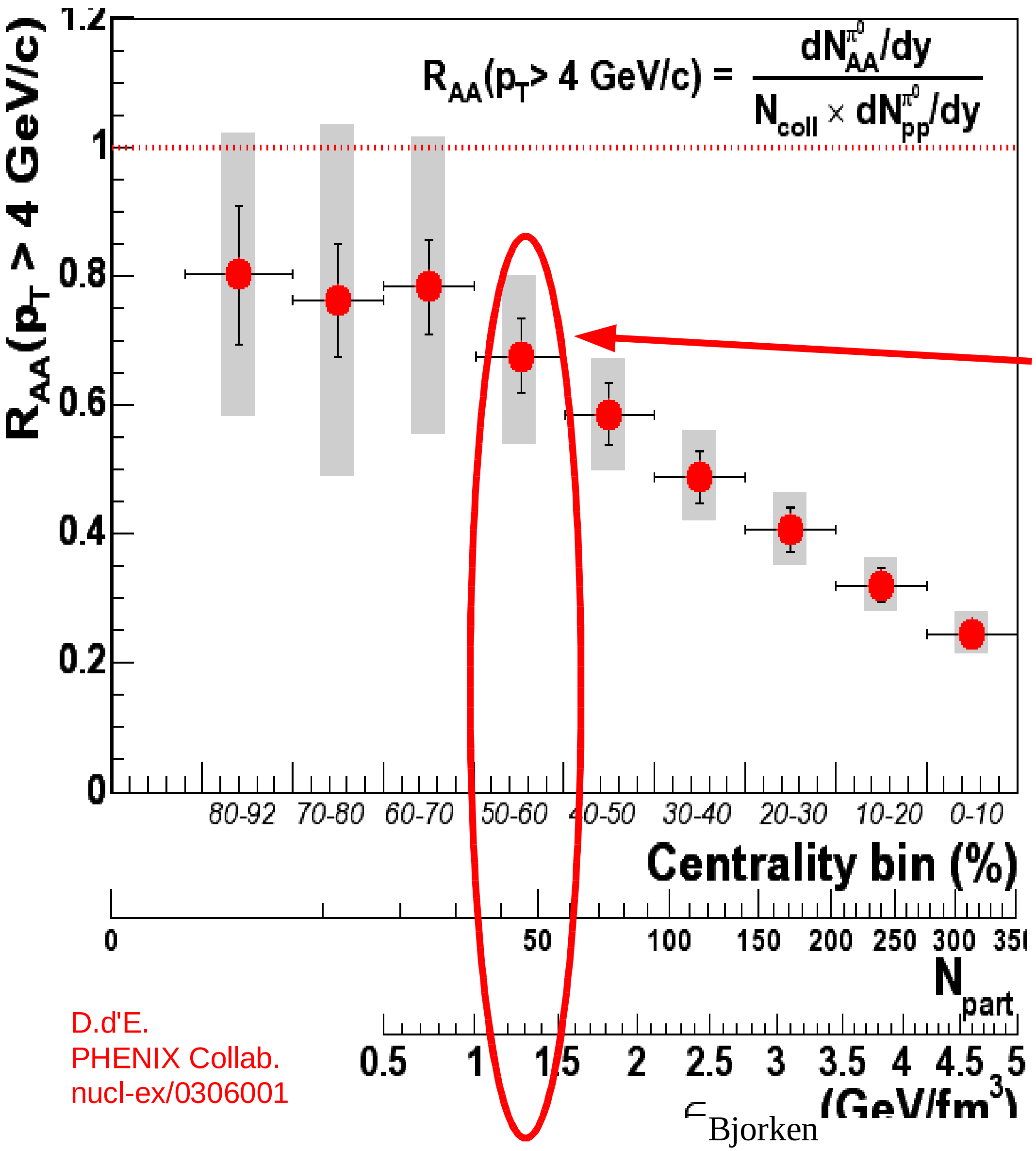
- Energy loss in a dense hadronic medium (<L/λ> ~ 2-3) seems to provide a (flat ?) suppression too ...





- Main argument: fast parton hadronization time implies rescatering of hadronic jet fragments ("pre-hadrons") inside expanding fireball.
- Description of scattering in the hadronic phase realistic enough ?
("... *our calculations are at best semiquantitative* ...").
- New results (within HSD transport code) very soon (C. Greiner *dixit*)

Centrality dependence of suppression (II)



D.d'E.
PHENIX Collab.
nucl-ex/0306001

π^0 suppression vs N_{part}:

- Peripheral (60-92%) consistent with collision scaling.
- Gradual or abrupt suppression pattern not conclusive at this point.
- $R_{AA} < 1$ (2σ) for 50-60% centrality:
  $N_{part} \sim 50 \pm 15$
  (ball-park of parton percolation predictions ?)

π^0 suppression vs $\varepsilon_{Bjorken}$:

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

(τ_0 = 1 fm/c)

- E_T measured in EMCal. Overlap area from Glauber.
- Suppression at 50-60% centrality:
  $\varepsilon_{Bjorken} \sim 1.2$ GeV/fm^3