High p_T experimental results @ RHIC:

Au+Au, d+Au, p+p collisions at $\sqrt{s}$ = 200 GeV

RIKEN/BNL Research Center Workshop
"High p_T physics at RHIC"

Brookhaven National Lab, NY, Dec. 2, 2003

David d'Enterria
Nevis Labs, Columbia University, NY

Overview

1. Introduction:

- Study of QCD media (QGP, CGC) via hard scattering processes.

2. High p_T results (Au+Au vs. p+p):

- dN/dp_T (light quarks u,d,s):
  - Suppression of hadron spectra: p_T, $\sqrt{s}$, centrality, & rapidity dependence.
  - "Anomalous" hadron composition (p_T = 2 – 4 GeV/c): baryon enhancement.
- dN/dp_T (heavy quark: c): Unsuppressed open charm spectra.
- $dN_{pair}/d\varphi$ azimuthal anisotropies:
  - Strong collective behaviour: large elliptic flow.
  - Disappearance of jet signals: reduced away-side dijet correlations.

4. High p_T results in d+Au ("control" experiment):

- dN/dp_T:
  - "Cronin-like" enhancement at y = 0, and suppression at y ≈ 3.
  - p_T, centrality, and particle species dependence.
- $dN_{pair}/d\varphi$: jet-like azimuthal anisotropies.

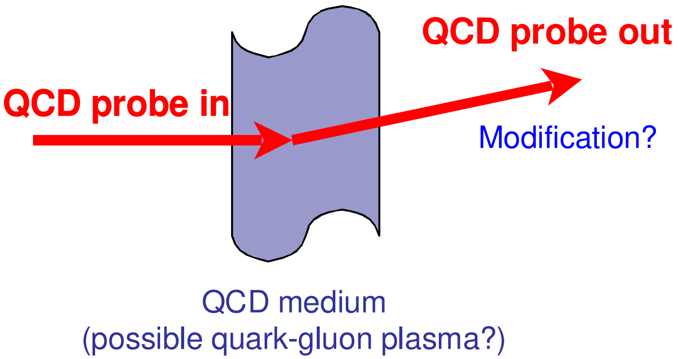
5. Data vs. theory.

6. Summary

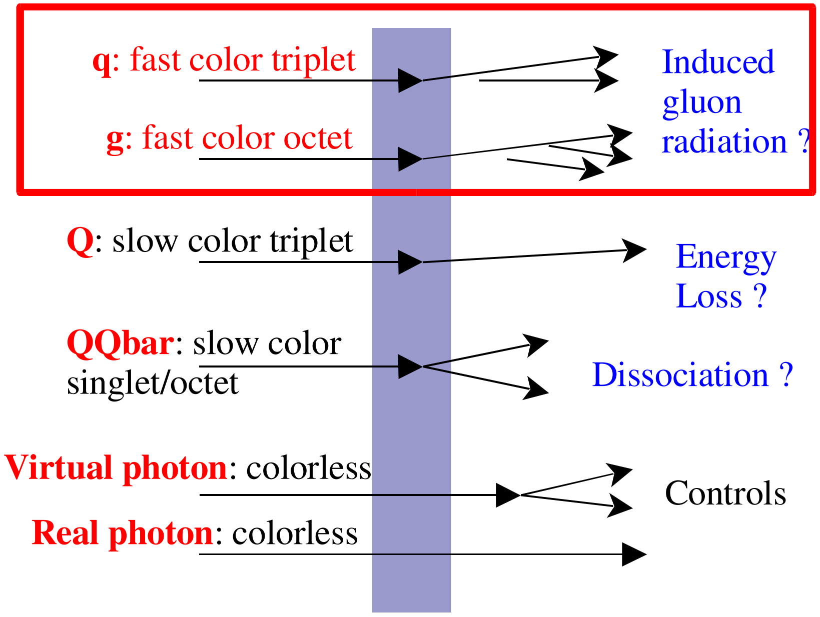
... plus my (personal) list of selected exp./phenom. "issues"

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:


QCD probe in
QCD probe out
Modification?

QCD medium
(possible quark-gluon plasma?)


q: fast color triplet
g: fast color octet
Induced gluon radiation ?
Q: slow color triplet
Energy Loss ?
QQbar: slow color singlet/octet
Dissociation ?
Virtual photon: colorless
Real photon: colorless
Controls

Unknown Medium

- Incoherent processes: Direct comparison A+A to p+p data via "collision scaling"

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

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

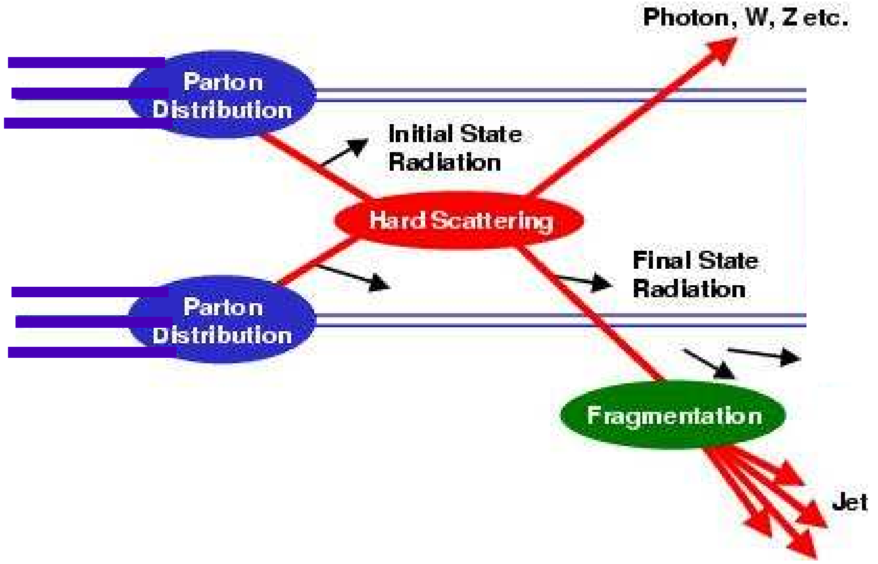
Hard QCD probes. Motivation (II)

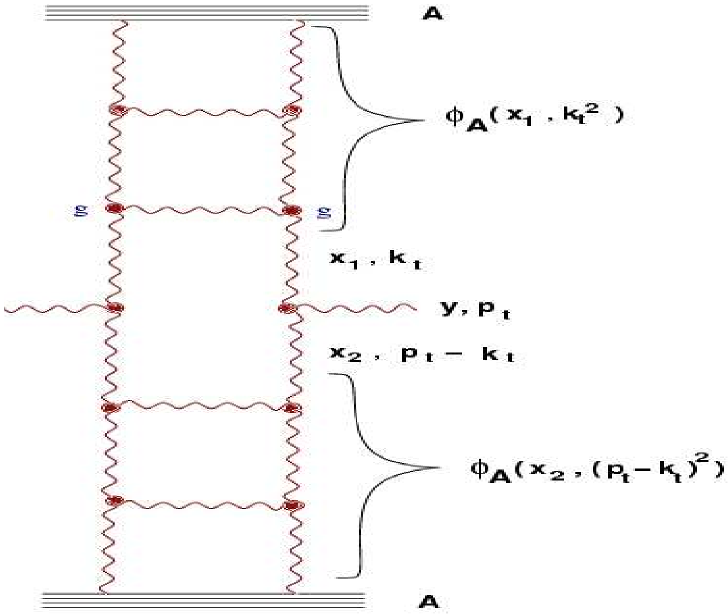
- Production yields theoretically calculable:

via perturbative QCD or ...

via classical-field QCD:

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


Photon, W, Z etc.
Parton Distribution
Initial State Radiation
Hard Scattering
Final State Radiation
Parton Distribution
Fragmentation
Jet


A
$\phi_A(x_1, k_t^2)$
g
g
x_1, k_t
y, p_t
$x_2, p_t - k_t$
$\phi_A(x_2,(p_t-k_t)^2)$
A

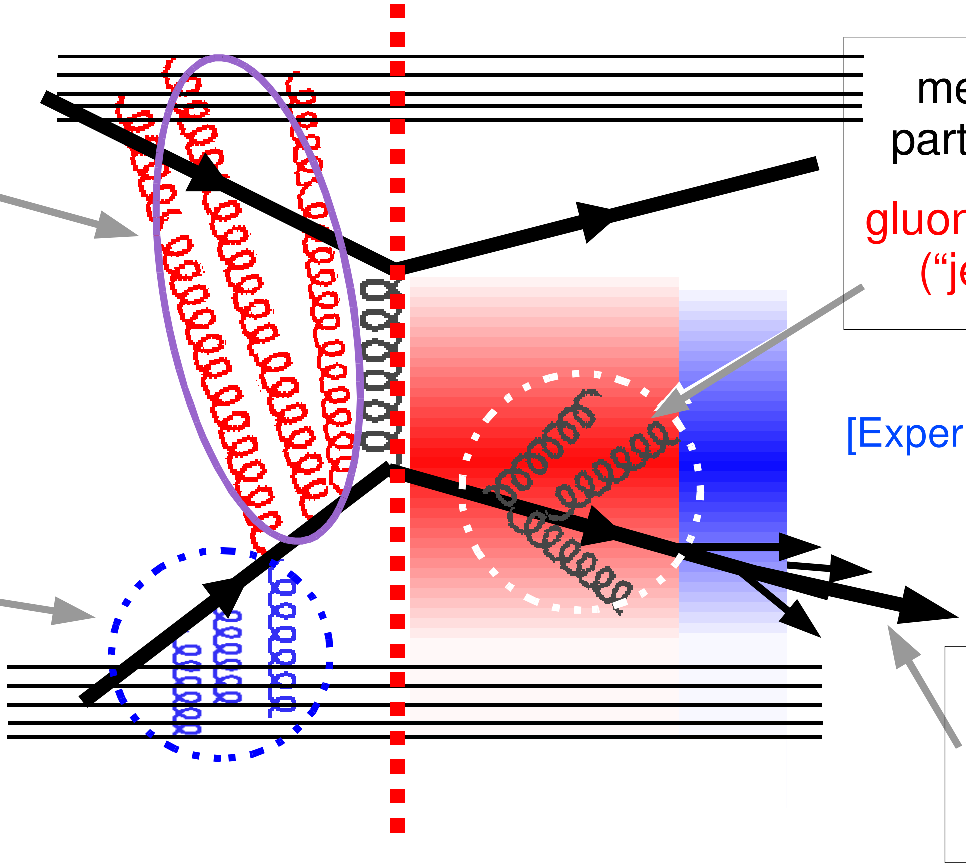
Mueller diagram for classical glue radiation

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

Hard scattering in A+A collisions

Initial-state effects:

Final-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]

medium-induced
parton energy loss:

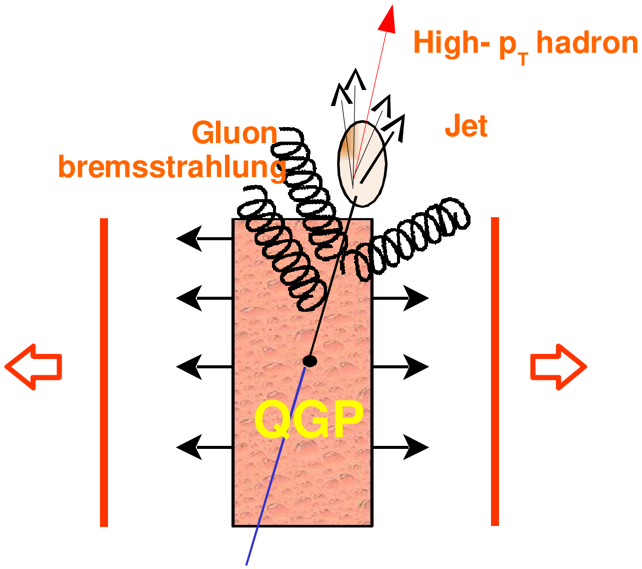
gluon bremsstrahlung
("jet quenching")

[Experimental handle: A+A]

possible hadronic
rescattering
(after/before
hadronization ?)

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

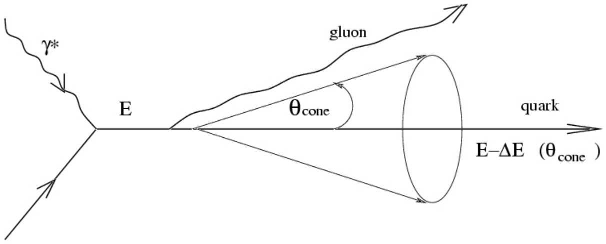
Final-state QGP effects


High- p_T hadron
Gluon bremsstrahlung
Jet
QGP

- 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)


γ^*
E
gluon
θ_{cone}
quark
$E-\Delta E \ (\theta_{cone})$

  - Energy is carried away by gluon-sstrahung outside jet cone: $dE/dx \sim \alpha_s \langle k_T^2 \rangle$
  - Formalisms: BDMPS (thick plasma), GLV (thin plasma), Wiedemann&Salgado (combined).
  - Correction for expanding plasma (1-D):

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

- Suppression of inclusive high p_T leading hadrons due to final-state radiation.

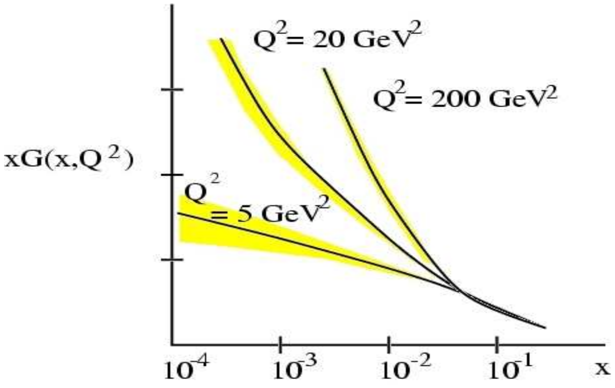
Initial-state CGC effects

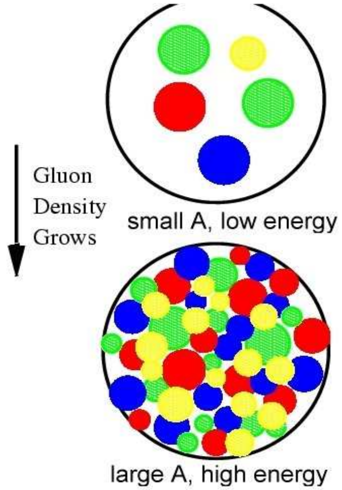
- Initial conditions at RHIC: high-energies + large nuclei
  - Values of small-x: $x_{Bj} = 2p_T/\sqrt{s} \ll 1$

High parton (gluon) densities

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

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





Gluon
Density
Grows
small A, low energy
large A, high energy

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

Saturation scale:

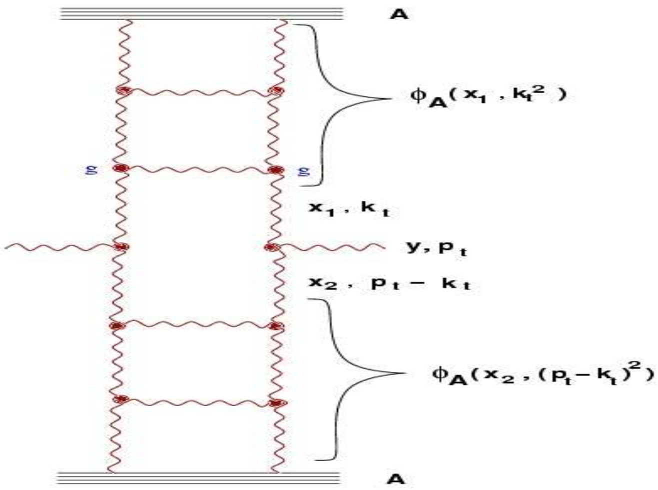
$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$ ~ 1.5 GeV^2/c^2 @ RHIC

$Q_s^2 \gg \Lambda_{QCD}^2 \Rightarrow \alpha_s \ll 1$ (weak coupling)

"Classical" (Chromo-Dynamics) methods applicable

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

- Particle production via glue-glue collisions:



A
$\phi_A(x_1, k_t^2)$
g
g
x_1, k_t
y, p_t
$x_2, p_t - k_t$
$\phi_A(x_2, (p_t - k_t)^2)$
A

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

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: $2\cdot10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)

p+p collisions @ 500 GeV

p+A collisions @ 200 GeV

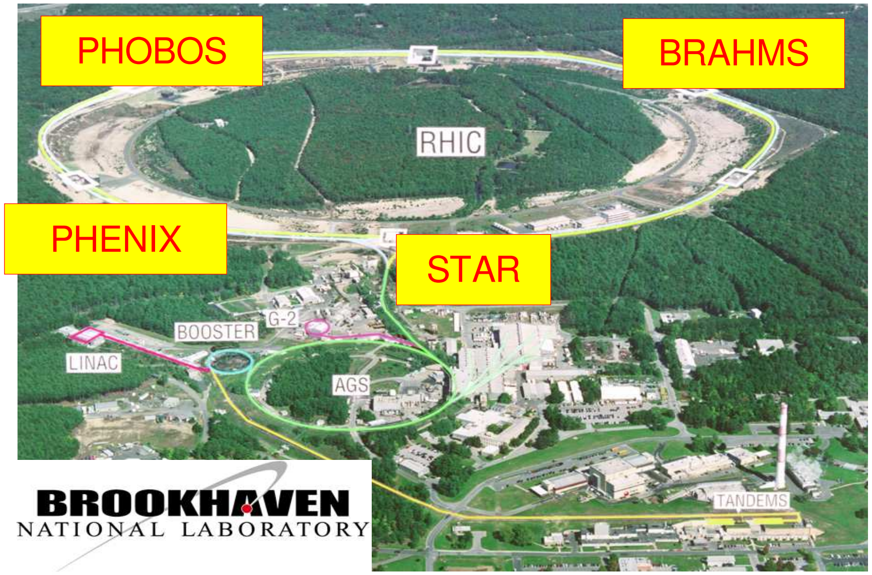
4 experiments:

BRAHMS, PHENIX, PHOBOS, STAR

Run-1 (2000): **Au+Au @ 130 GeV**

Run-2 (2001-2): **Au+Au, p+p @ 200 GeV**

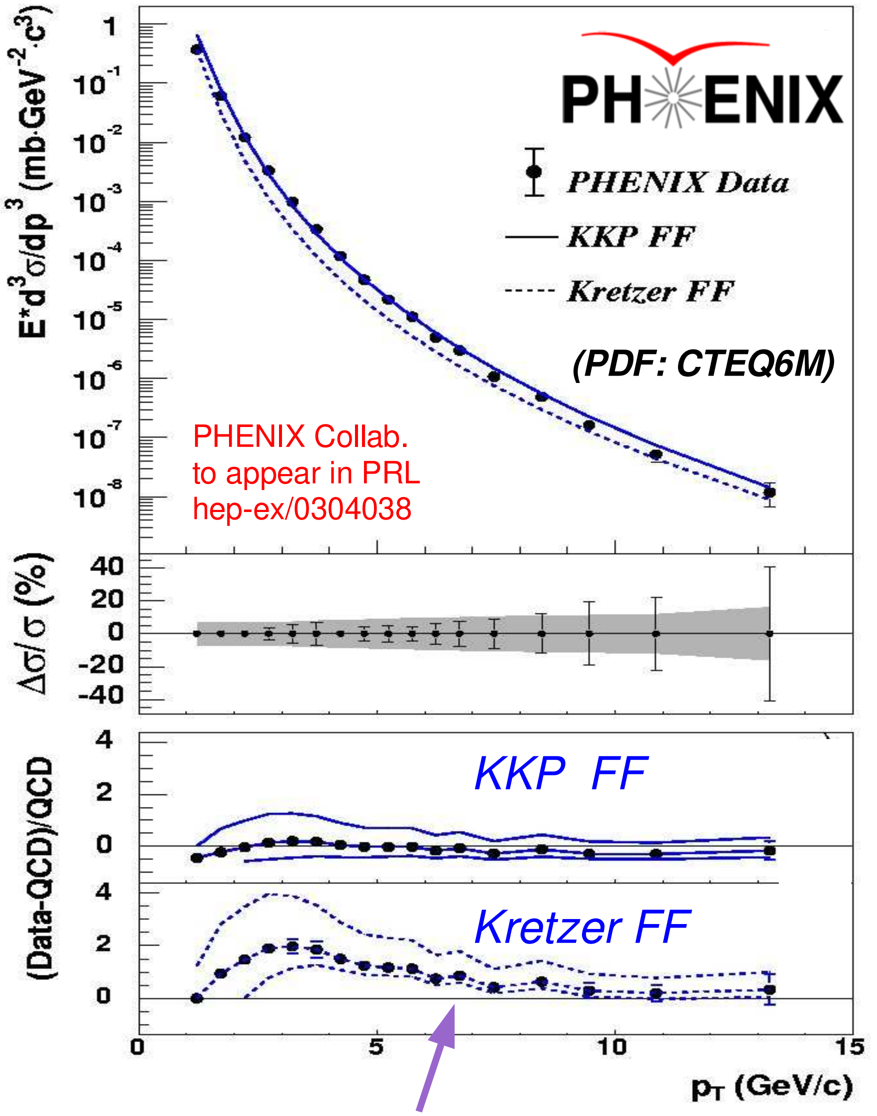
Run-3 (2002-3): **d+Au, p+p @ 200 GeV**


PHOBOS
BRAHMS
RHIC
PHENIX
STAR
BOOSTER
G-2
LINAC
AGS
TANDEMS
BROOKHAVEN
NATIONAL LABORATORY

SECTOR 5
RHIC

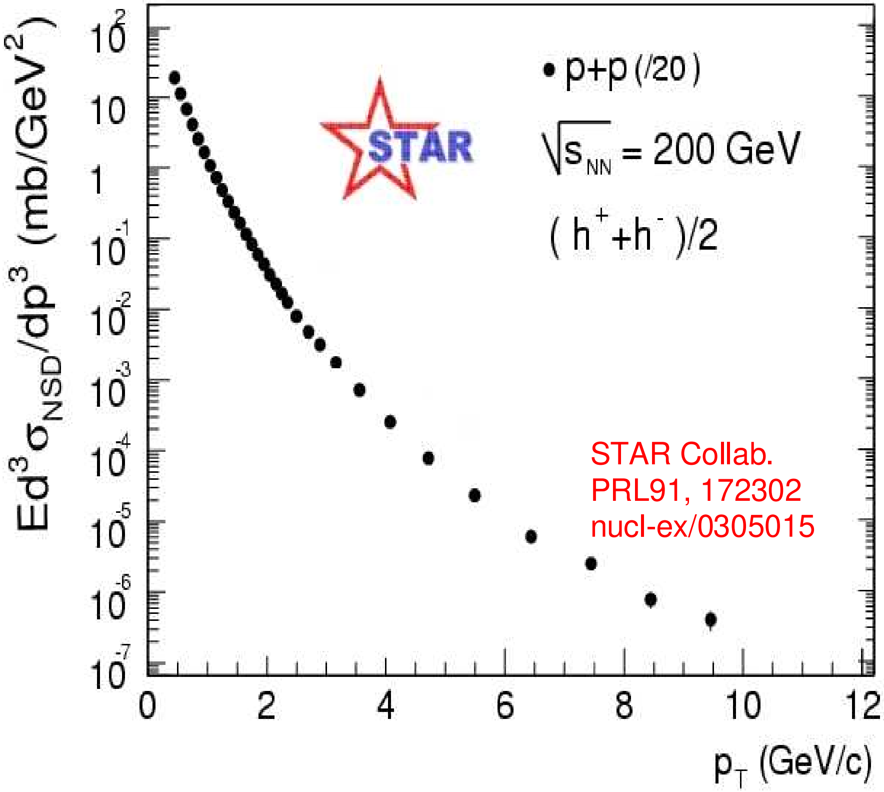
High p_T p+p @ 200 GeV: “baseline” data

p+p→ π^0 *X*



Good theoretical (NLO pQCD) description

p+p → h± *X* (Non Singly Diffractive)



Issue (1): No need of initial-state intrinsic k_T in pQCD calculations ?

Constraint of FFs ? role of PDFs ?

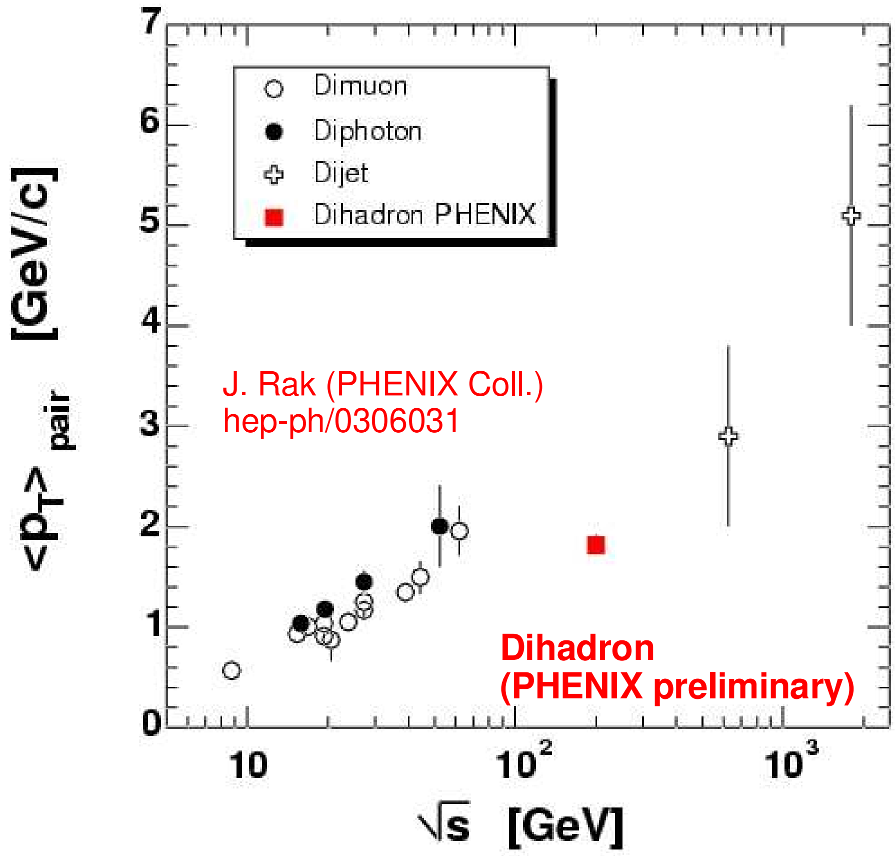
Issue (2):

σ_{SD}(STAR) ~1.3 σ_{NSD}(UA1) ~ 2. σ_{NSD}(UA5)

Parenthesis (1): p+p issues @ high p_T

p+p→ di-X

Intrinsic $\langle k_T \rangle$ = 725 ± 34 MeV/c



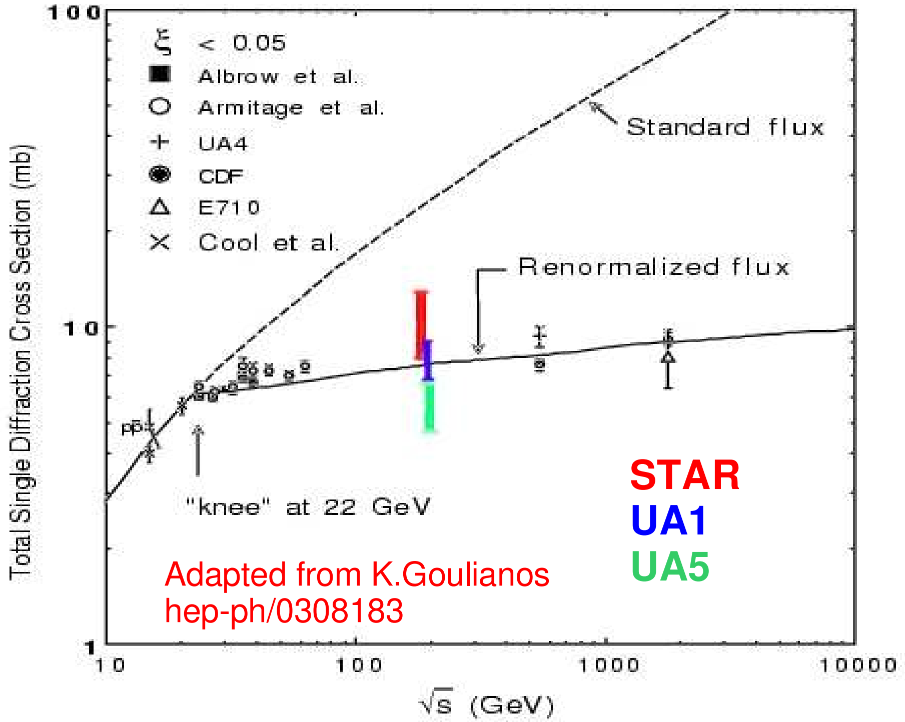
J. Rak (PHENIX Coll.)
hep-ph/0306031

Dihadron
(PHENIX preliminary)

- How well does pQCD reproduce di-hadron data @ high p_T ?

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

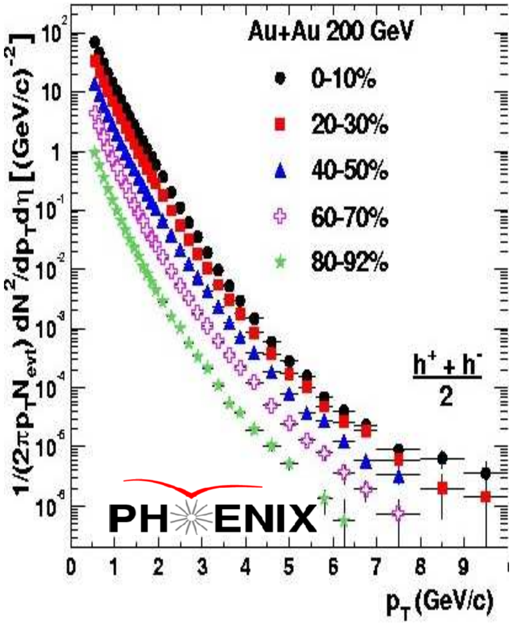
σ_{SD}(STAR) ~ 9 ± 3.5 mb
σ_{SD}(UA1) = 7 ± 1 mb
σ_{SD}(UA5) = 4.8 ± 0.9 mb

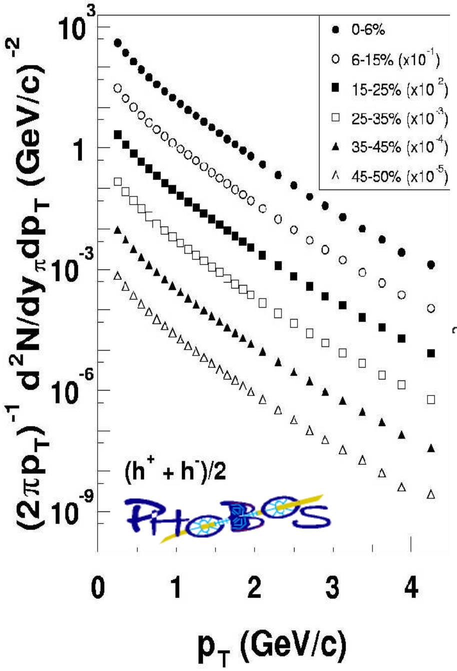


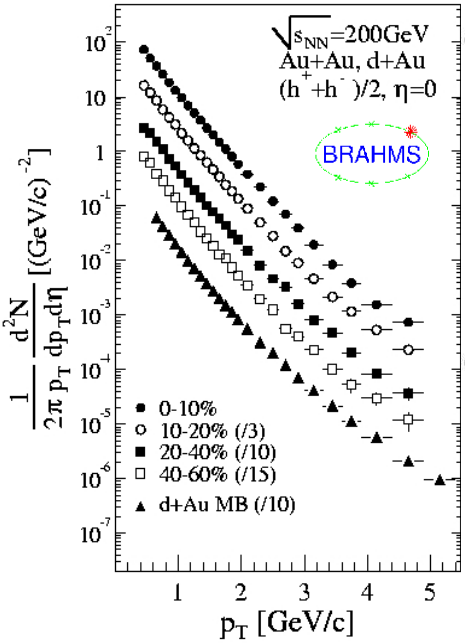
Adapted from K.Goulianos
hep-ph/0308183

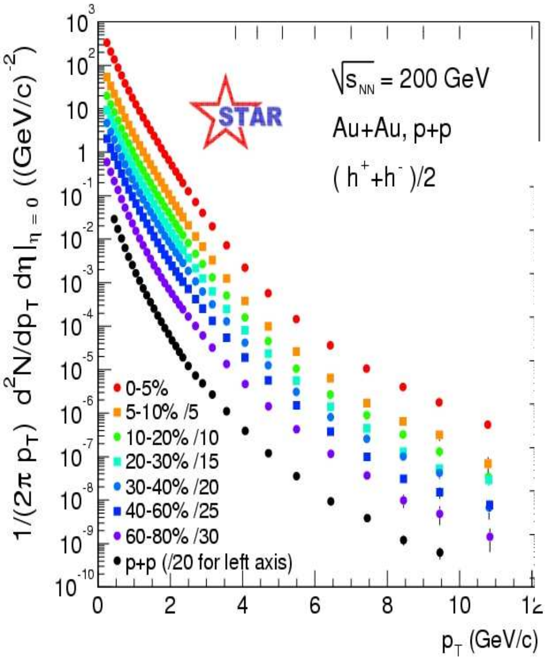
- Though a small contribution @ high p_T, it'd be good to measure the fraction of “hard” diffractive cross-section ...

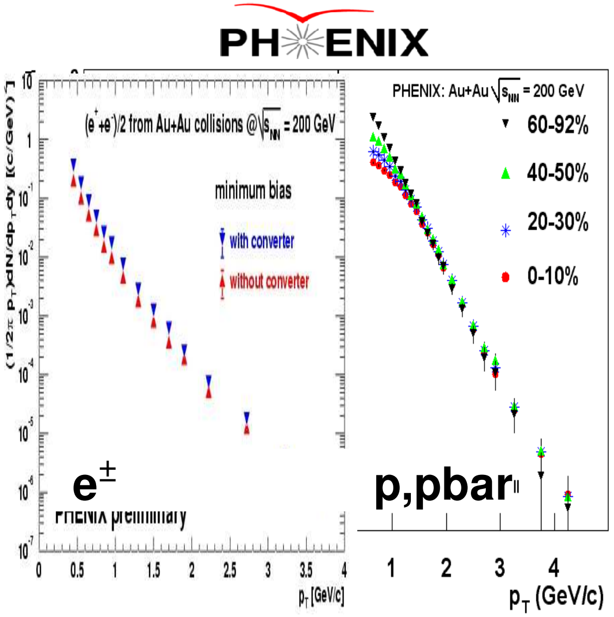
High p_T spectra in Au+Au @ 200 GeV

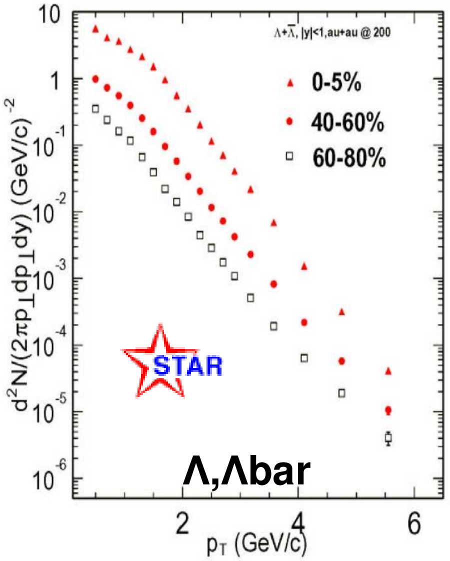


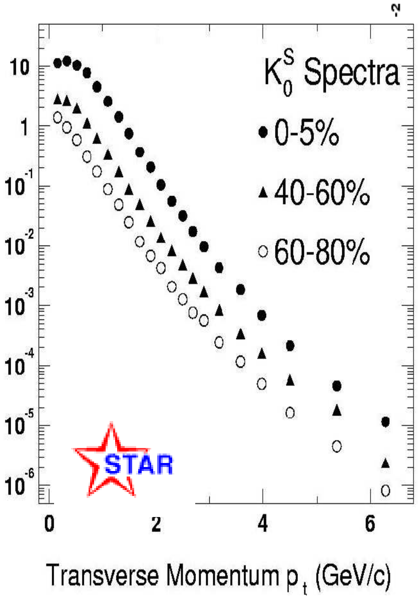


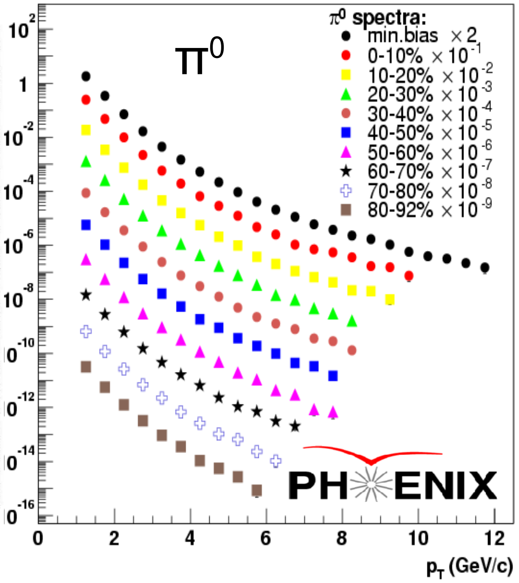






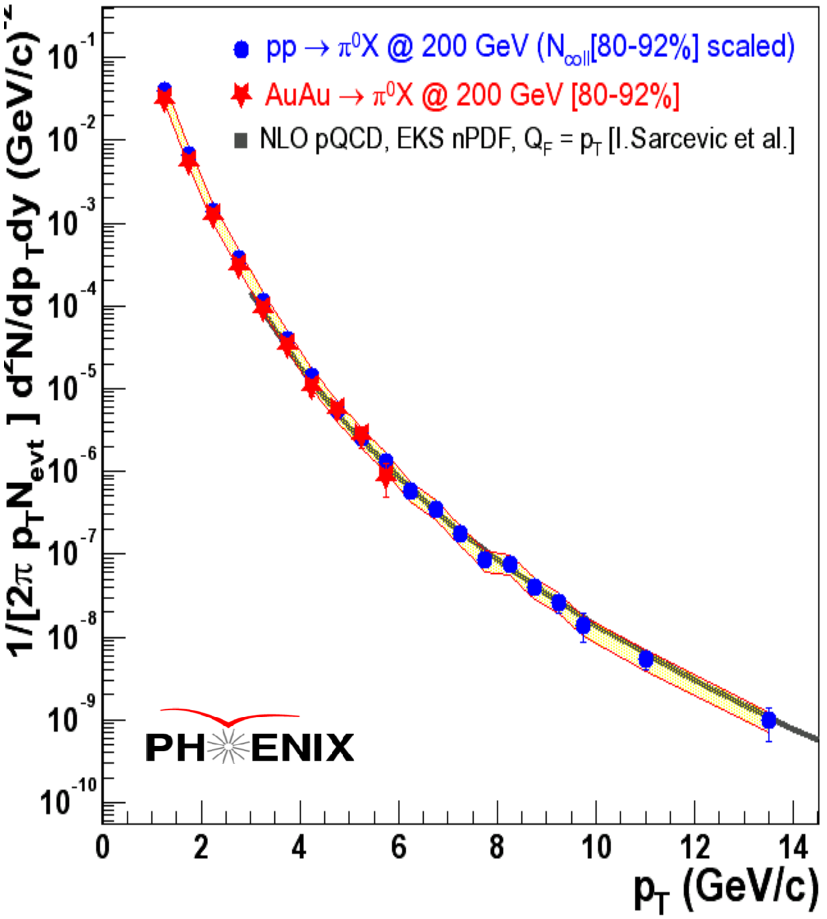




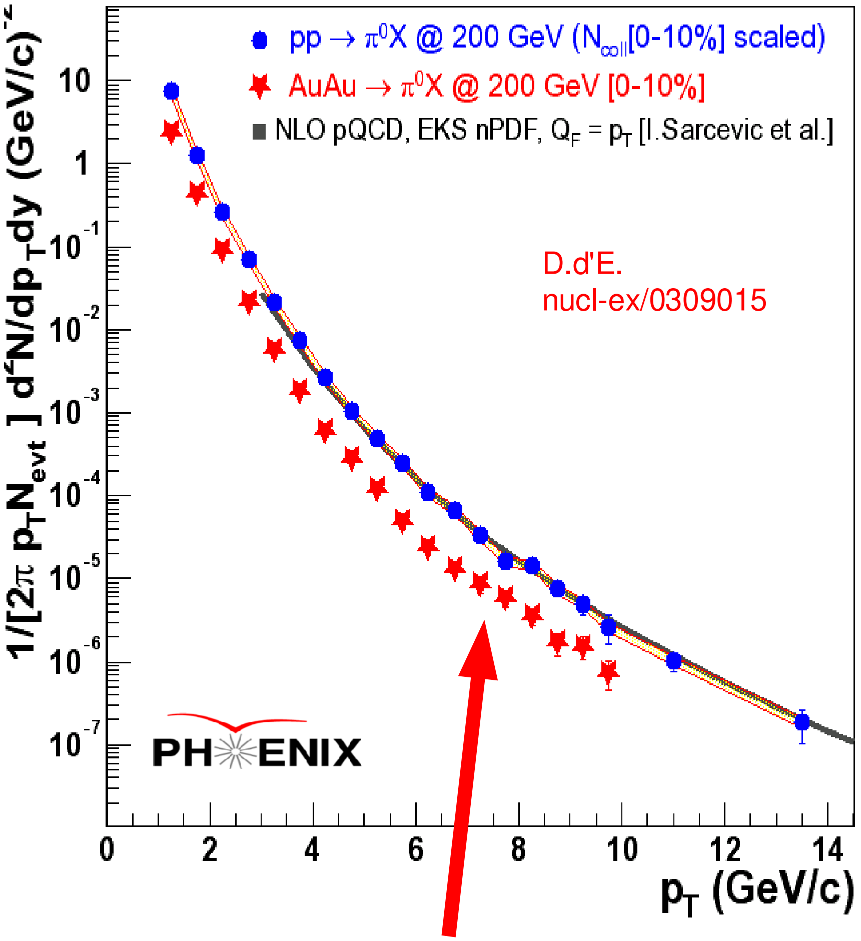


Au+Au *vs* p+p @ 200 GeV (high p_T π^0)

Au+Au→ π^0 *X* (peripheral)



Au+Au→ π^0 *X* (central)



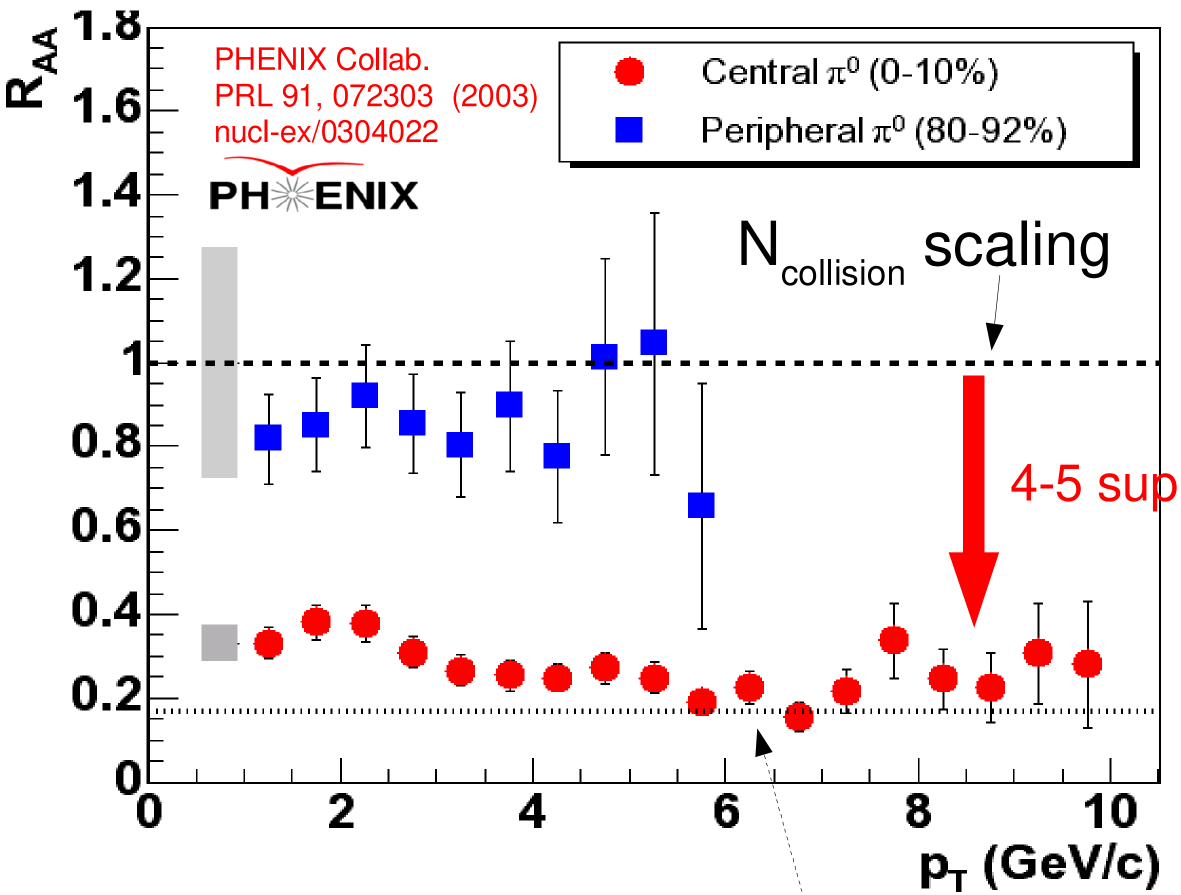
D.d'E.
nucl-ex/0309015

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

Strong suppression in
central Au+Au collisions

Nuclear modification factor (π^0)

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

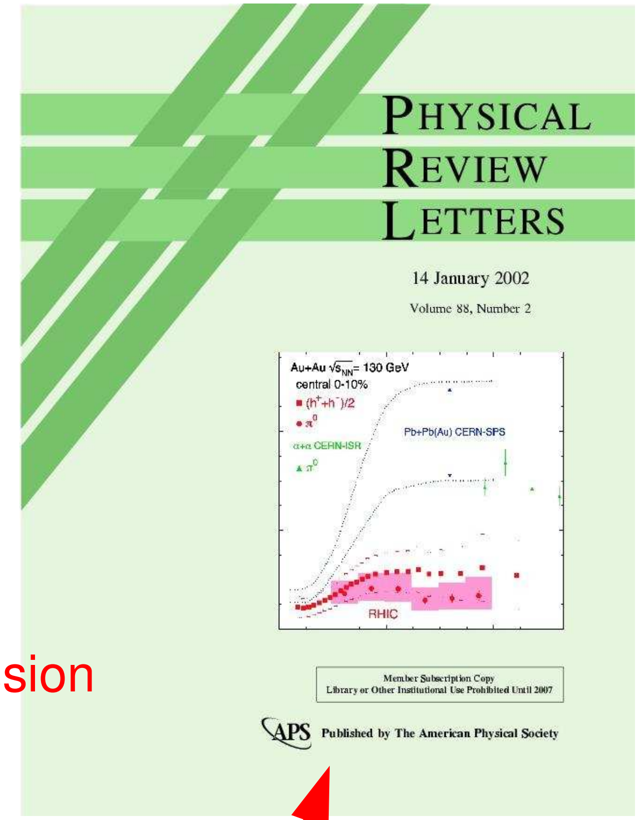


PHENIX Collab.
PRL 91, 072303 (2003)
nucl-ex/0304022

$N_{collision}$ scaling

4-5 suppression

N_{part} scaling



PHYSICAL
REVIEW
LETTERS

14 January 2002

Volume 88, Number 2

Au+Au $\sqrt{s_{NN}}$ = 130 GeV
central 0-10%
$(h^+ + h^-)/2$
π^0
α+α CERN-ISR
π^0
Pb+Pb(Au) CERN-SPS
RHIC

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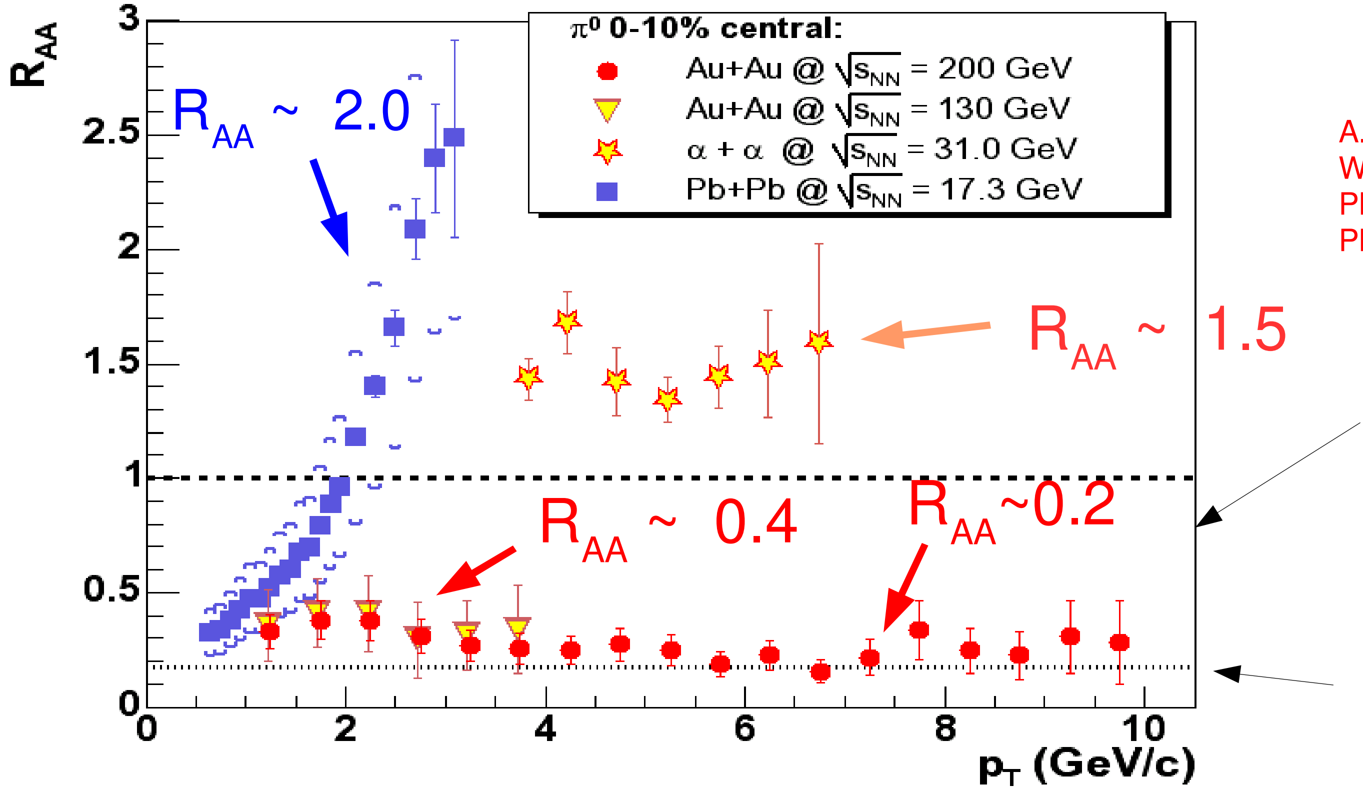
Discovery of
high p_T suppression
(one of most significant
results @ RHIC so far)

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

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

- CERN: Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 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)
PHENIX, PRL 91, 072303 (2003)

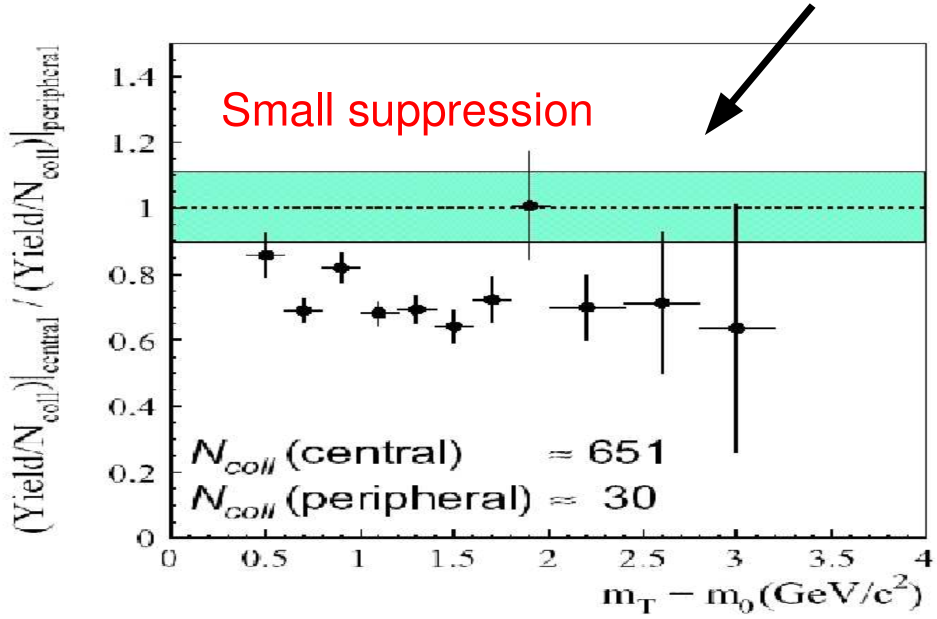
$N_{collision}$ scaling

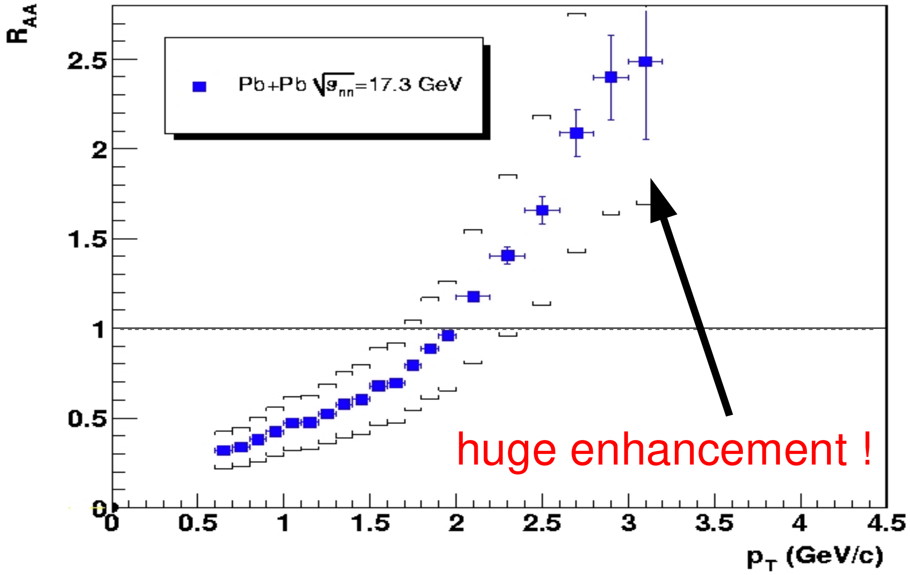
$N_{participant}$ scaling

Issue (3): Is there really such a large “Cronin enhancement” at CERN-SPS ?
Do we have p+p reference at $\sqrt{s}$~20 GeV under control ? (I don't think so ...)

Parenthesis (2a): high p_T production @ SPS ?

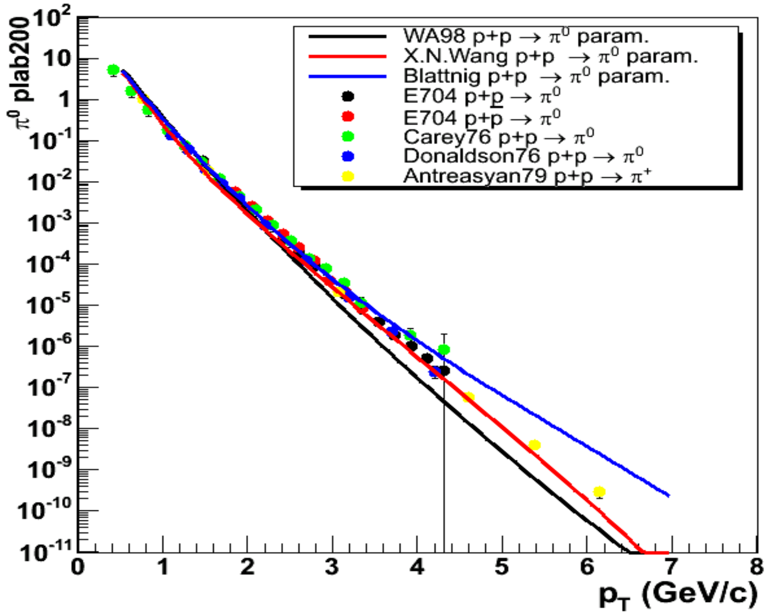
- How does one reconcile R_{cp} (π^0) ~ 0.8 with R_{AA} (π^0) >> 1. at SPS ??





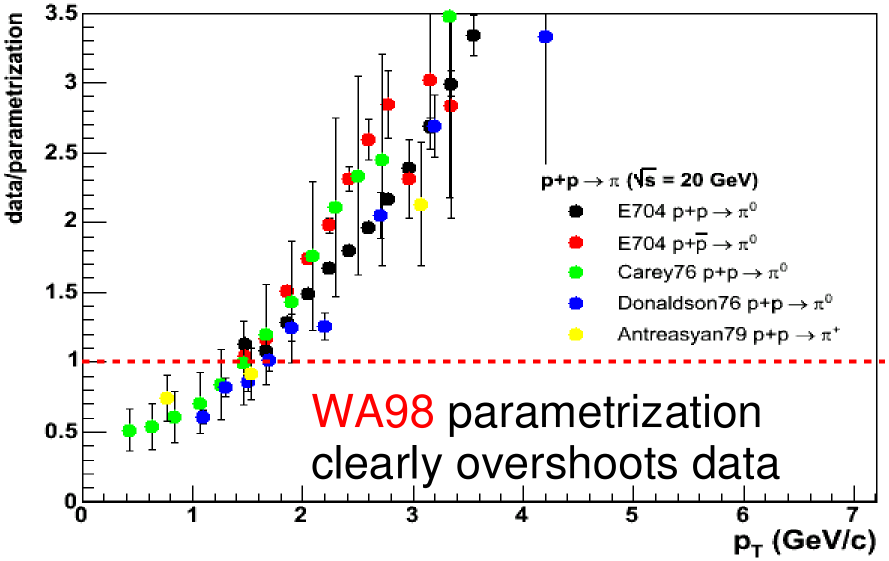
Both figures in the same paper:
WA98, EPJ C 23, 225 (2002)

- High p_T π^0 data vs. 3 different p+p parametrizations @ $\sqrt{s}$ ~20 GeV:

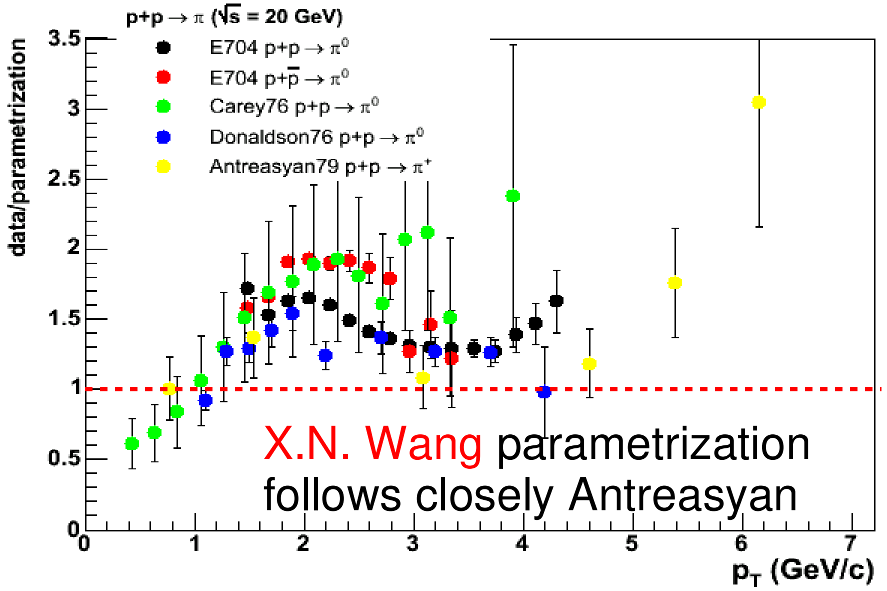


Parenthesis (2b): high p_T production @ SPS ?

- Data/parametrization (3 different $p+p \to \pi^0$ references @ $\sqrt{s}$ ~20 GeV):

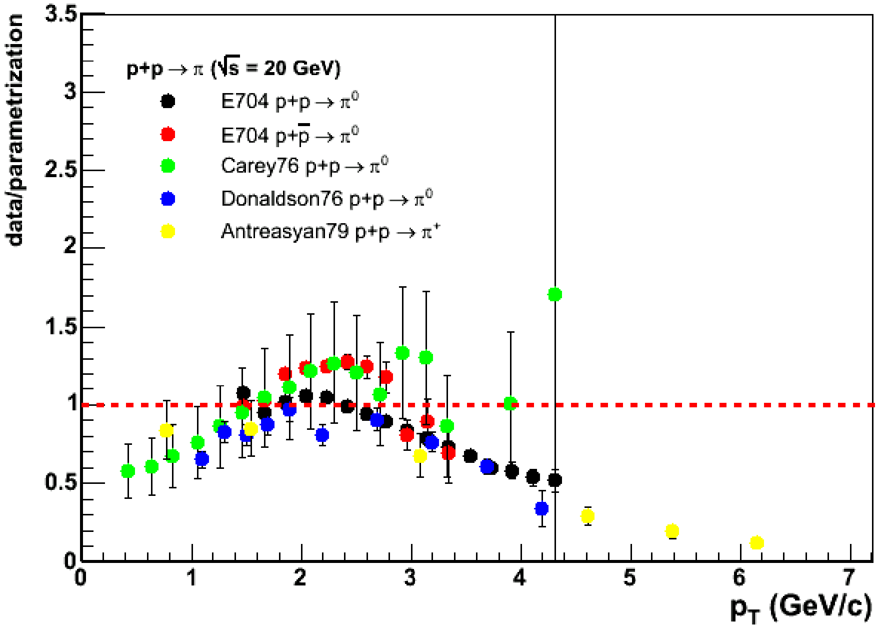


WA98 parametrization clearly overshoots data



X.N. Wang parametrization follows closely Antreasyan

Blattnig et al. parametrization has the lowest chi2



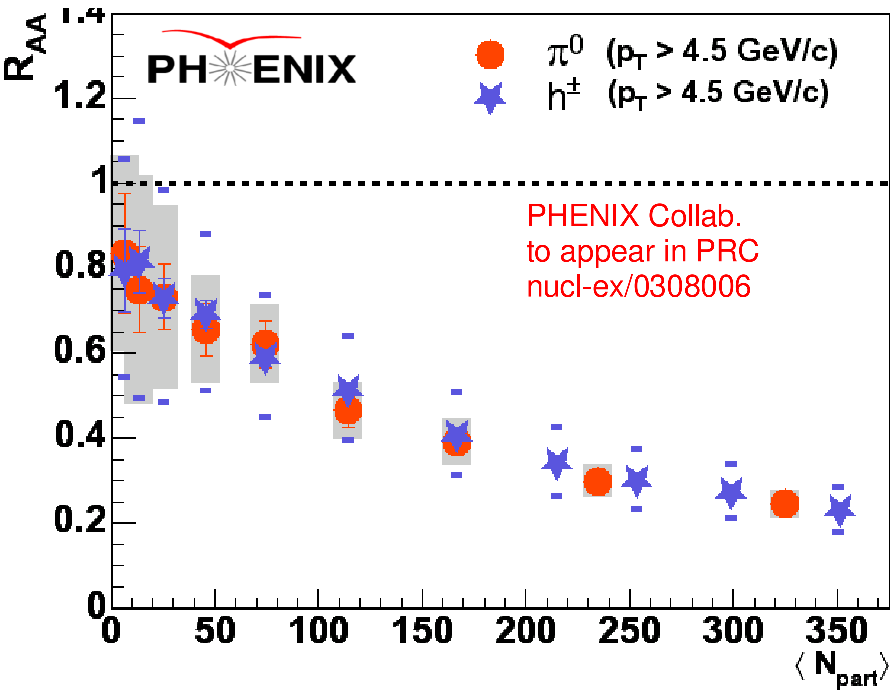
- Looking for the onset of hi p_T suppression ?

Measure p+p, Au+Au @ 20 GeV @ RHIC !

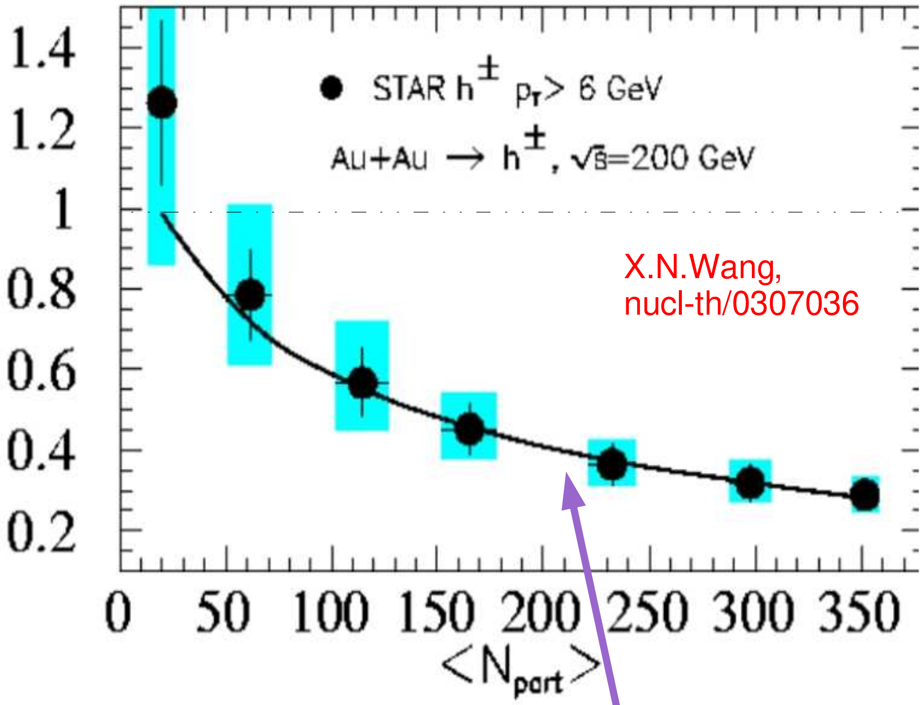
High p_T suppression: centrality dependence (I)

Let's go back to RHIC energies ....

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



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



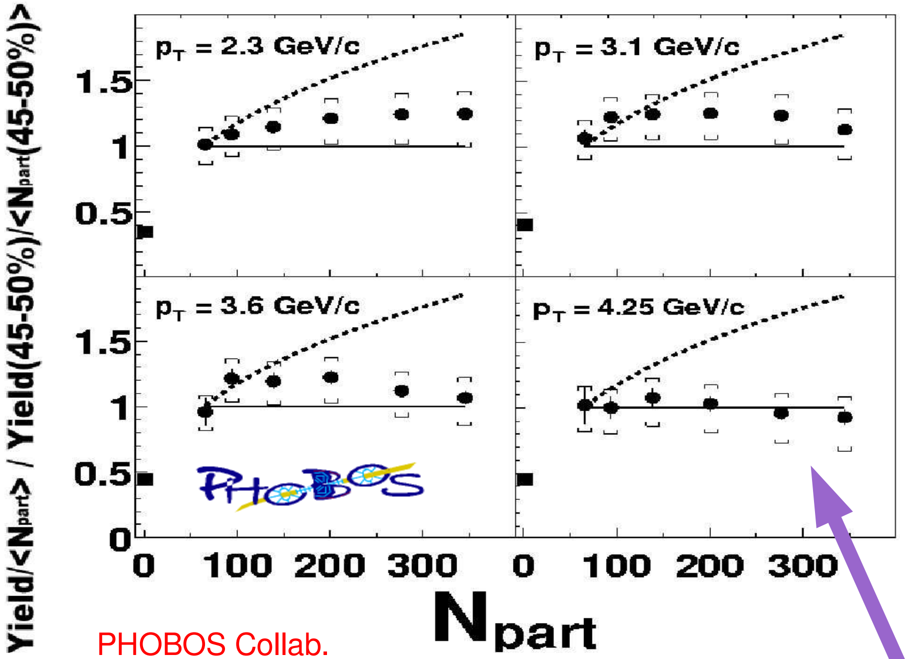
X.N.Wang,
nucl-th/0307036

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

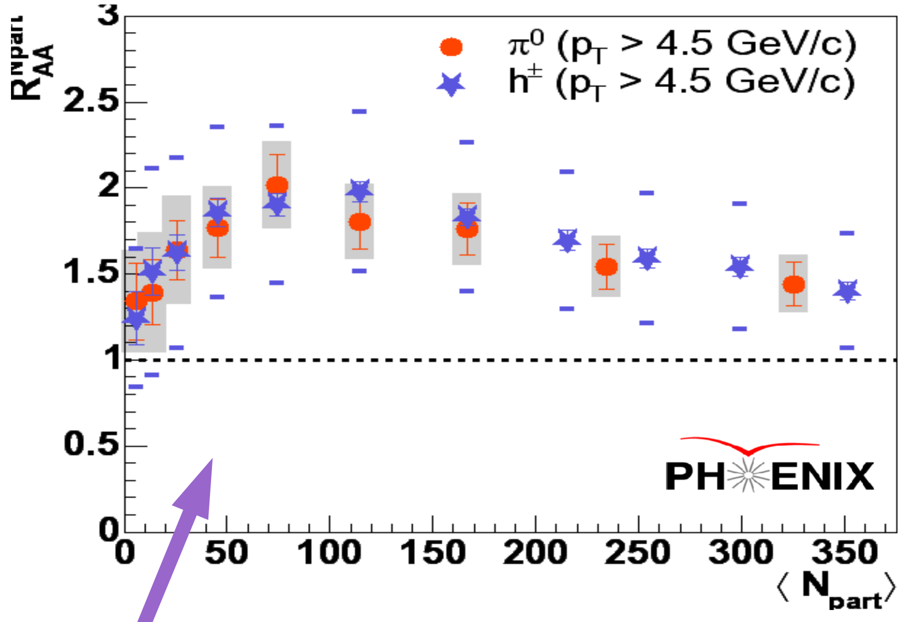
peripheral → central

High p_T suppression: centrality dependence (II)

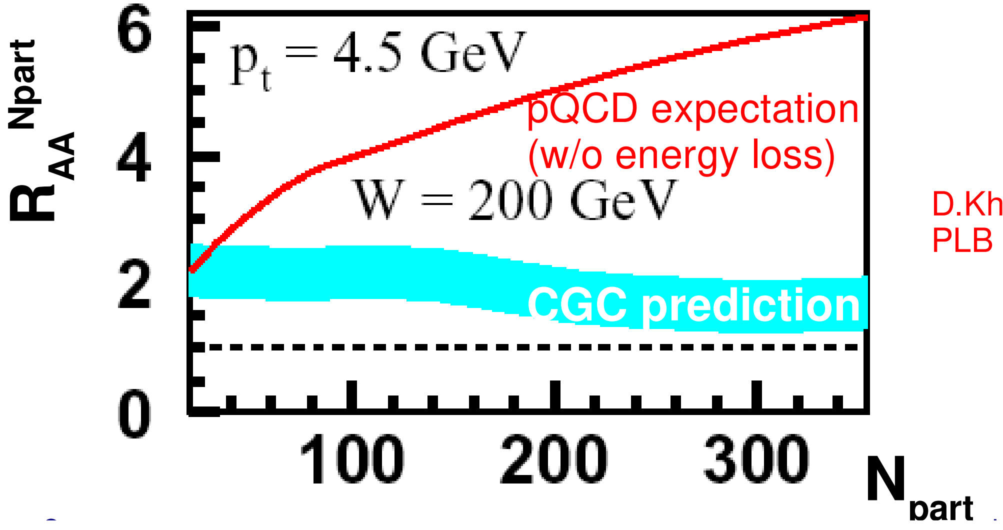
- Approx. N_{part} scaling (in accord with CGC predictions too):



PHOBOS Collab.
submitted to PLB
nucl-ex/0302015



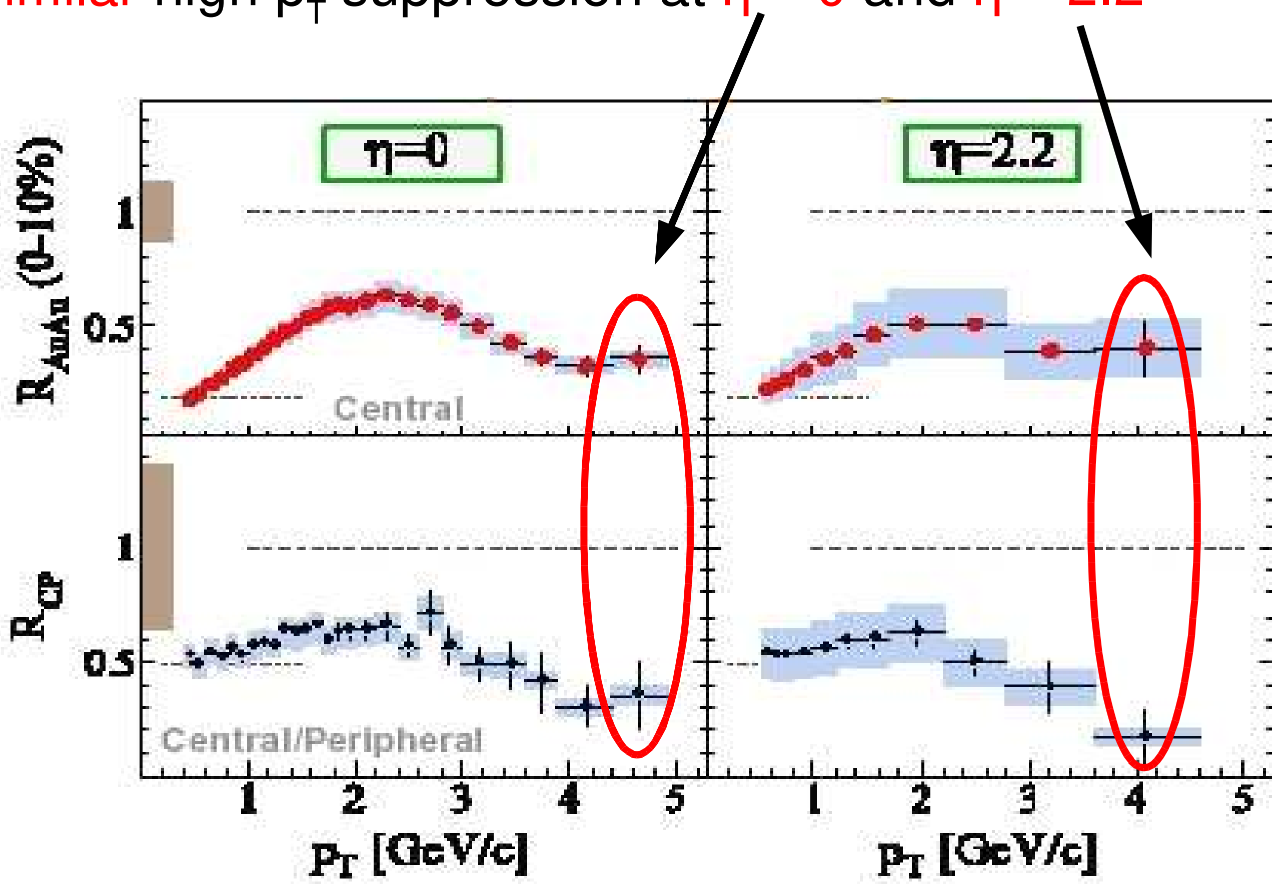
PHENIX Collab.
to appear in PRC
nucl-ex/0308006



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

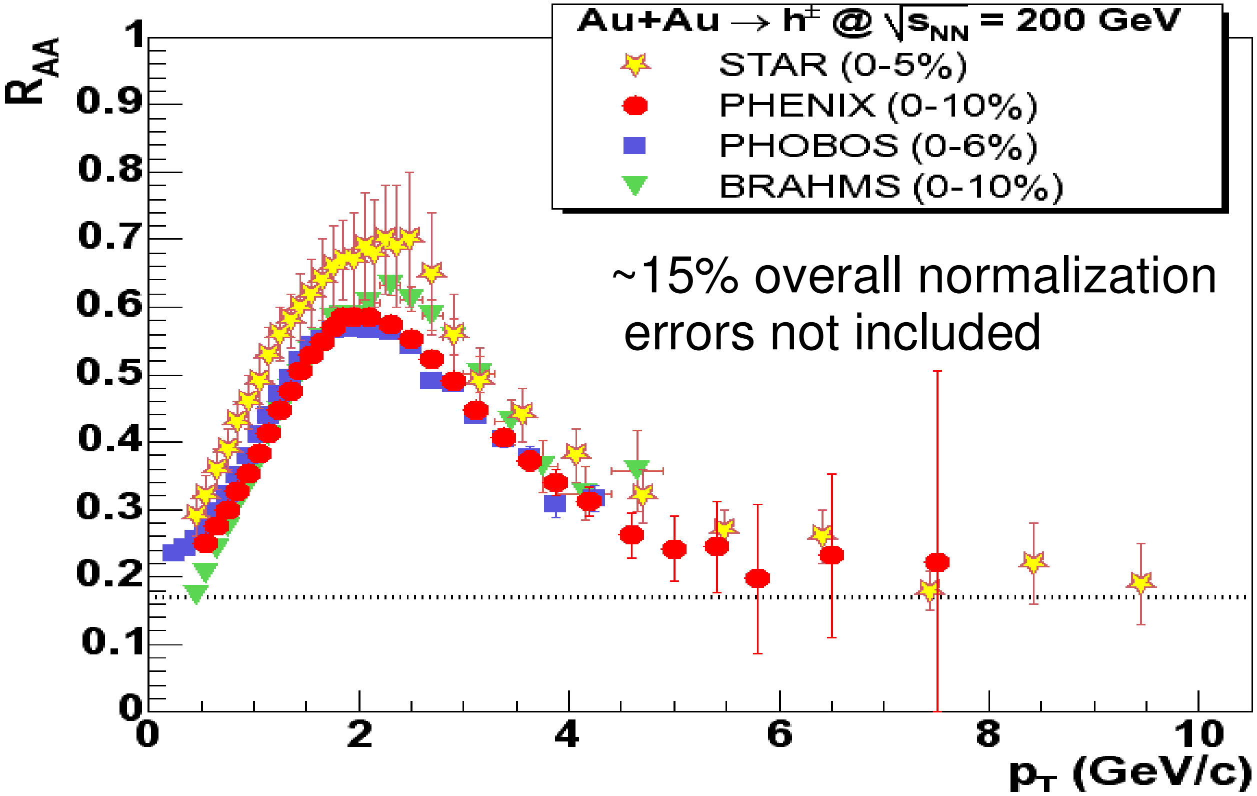
BRAHMS
PRL91: 072305(2003)

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

Issue (4): In view of the d+Au suppression at $\eta = 2.2$ ... Is there a single "medium" responsible of this effect in Au+Au ? (or a combination of final&initial state effects)

High p_T suppression: particle dependence (I)

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



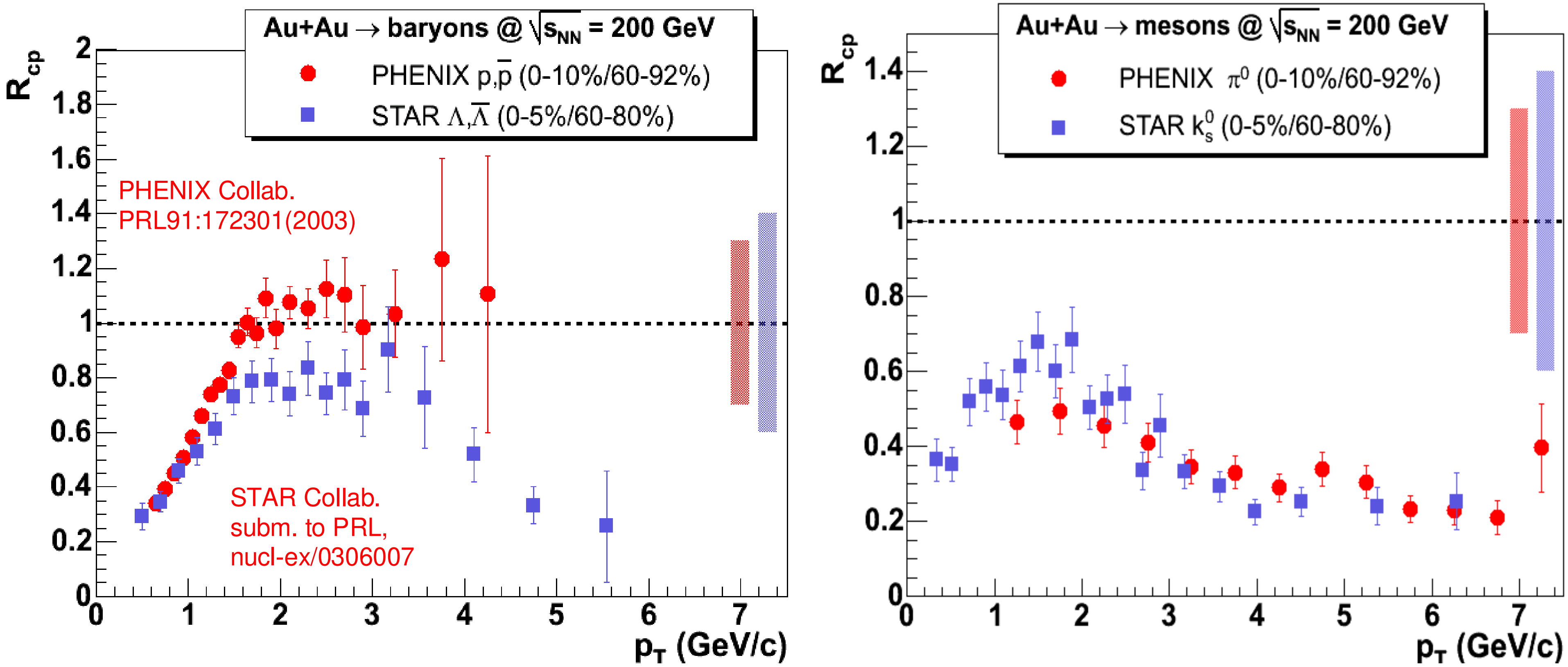
~15% overall normalization errors not included

Issue (5): Different p+p refs. : UA1 param., PHENIX π^0, STAR NSD $h^\pm$.
Issue (6): Different Glauber calculations (nuclear geometry scaling).

- Yet ... good general agreement among experiments !

High p_T suppression: particle dependence (II)

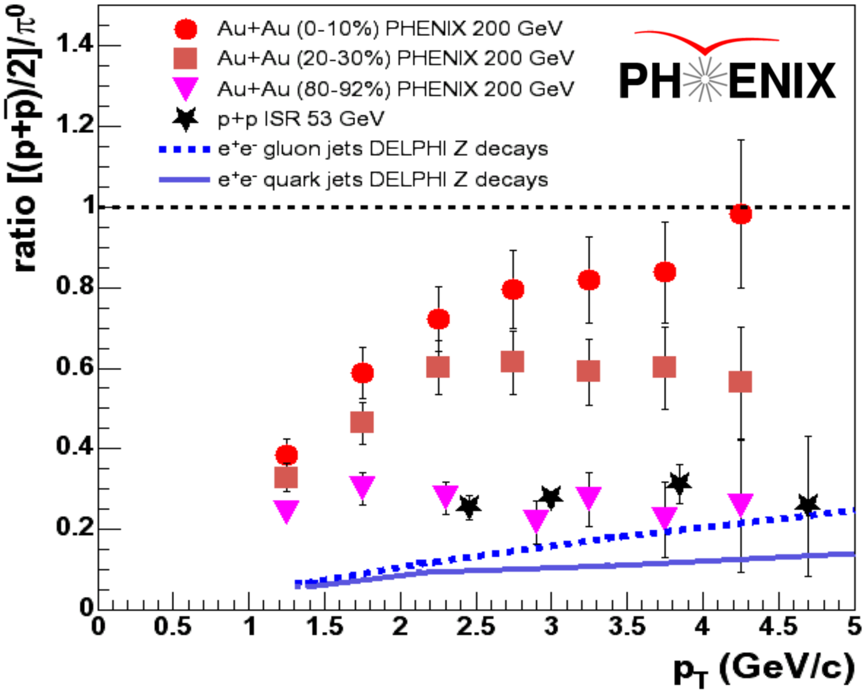
- R_{cp} (ratio central/peripheral) at intermediate p_T = 2. – 4. GeV/c:
  (i) (anti)baryons: p, pbar, Λ, Λbar **NOT** suppressed in central Au+Au.
  (ii) mesons: π^0, k^0_s equally suppressed.

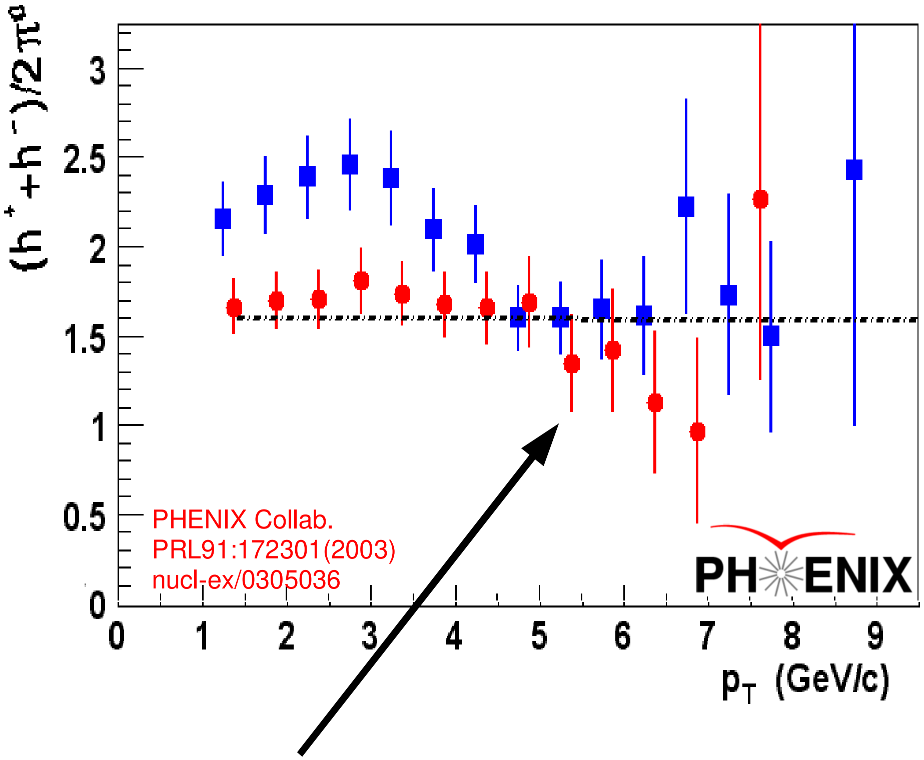


- Different production mechanisms for baryons & mesons in the intermediate p_T range (e.g. quark recombination vs. fragmentation).

High p_T suppression: particle dependence (III)

- 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

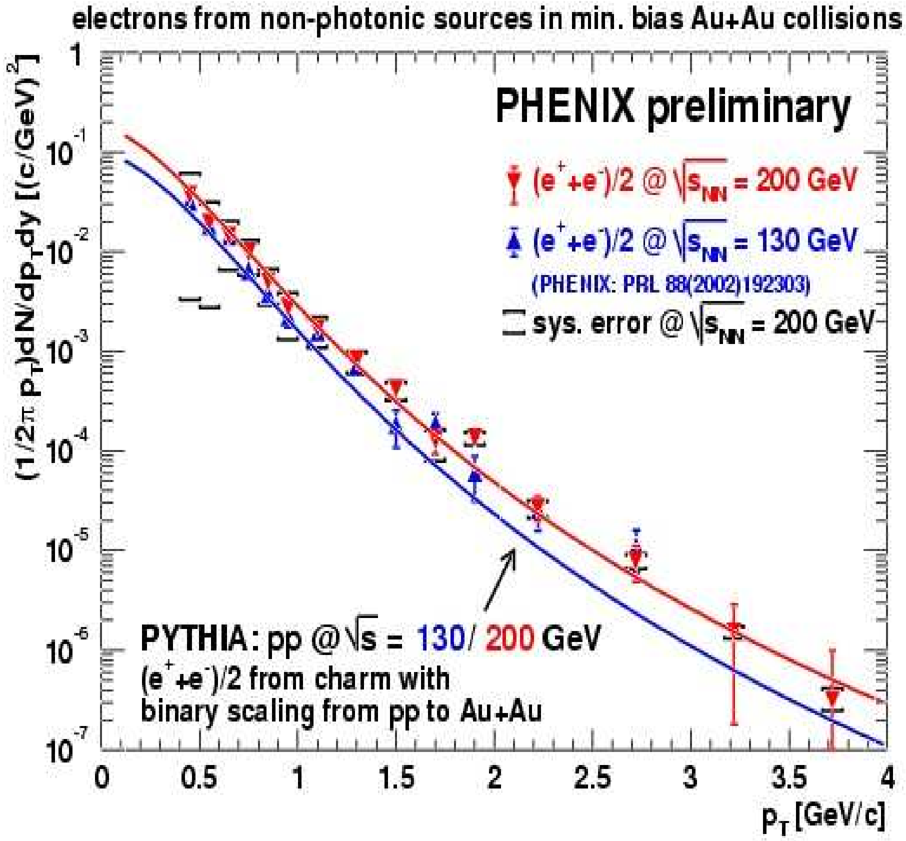




- Charged hadron and π^0 equally suppressed above $p_T \sim 5$ GeV/c: $h/\pi \sim 1.6$ as in p+p (perturbative ratio).
- Since $h^\pm = \pi^\pm + p(pbar) + K^\pm \Rightarrow$ baryon enhancement limited to $p_T < 4.5$ GeV/c

High p_T suppression of heavy-quarks ?

- Within uncertainties, single electron Au+Au spectra (and cross-section) consistent with N_{coll} scaled p+p charm production (as given by PYTHIA):



***Assuming** all $e^{\pm}$ above bckgd are from open charm decays and **neglecting** modifications of nuclear PDFs (shadowing).*

- Open charm contribution (PYTHIA 6.152 p+p):

CTEQ5L, Mc=1.25 GeV, K=3.5, $<k_T>$=1.5 GeV/c
$\sigma(pp \rightarrow cc)$ =330(650) μb @ $\sqrt{s}$ = 130 (200) GeV

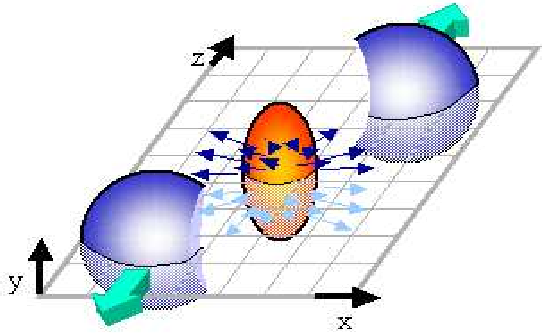
Fixed target charm data (SPS, FNAL) & ISR single electron data reproduced.

- Strong medium effects on heavy flavor production precluded.

Issue (7): How does PHENIX indirect charm measurement from single electron data compare with preliminary identified D mesons from STAR ?

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

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

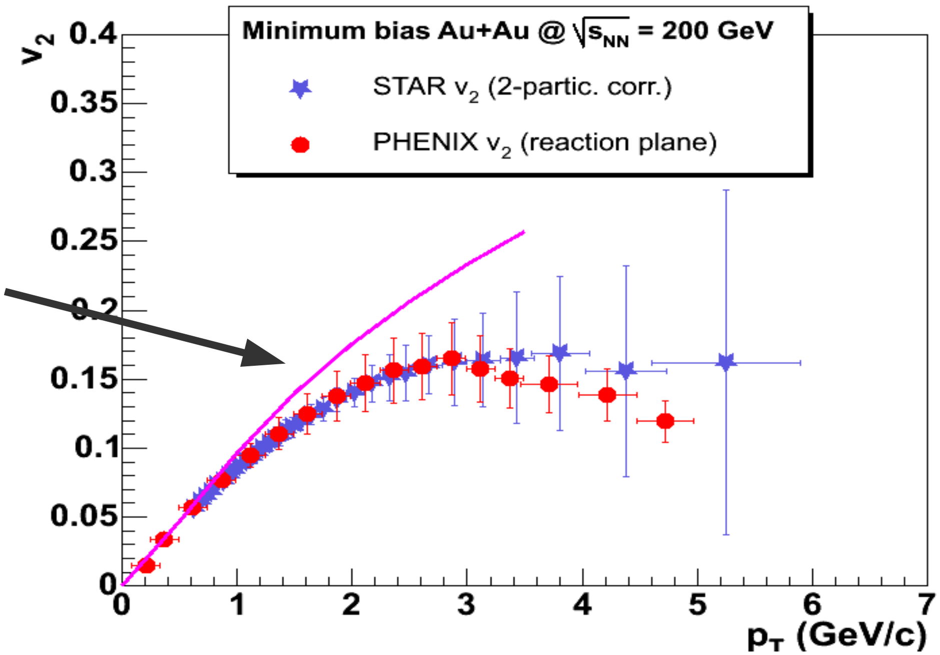
1. Truly collective effect (absent in p+p colls.).
2. "Hard" probe: develops exclusively in first instants of the reaction (t<3 fm/c).

- Large v_2 signal (saturating @ high p_T):

Exhausting hydro limit for p_T<1.5 GeV/c

⇒ Strong (collective) pressure grads.

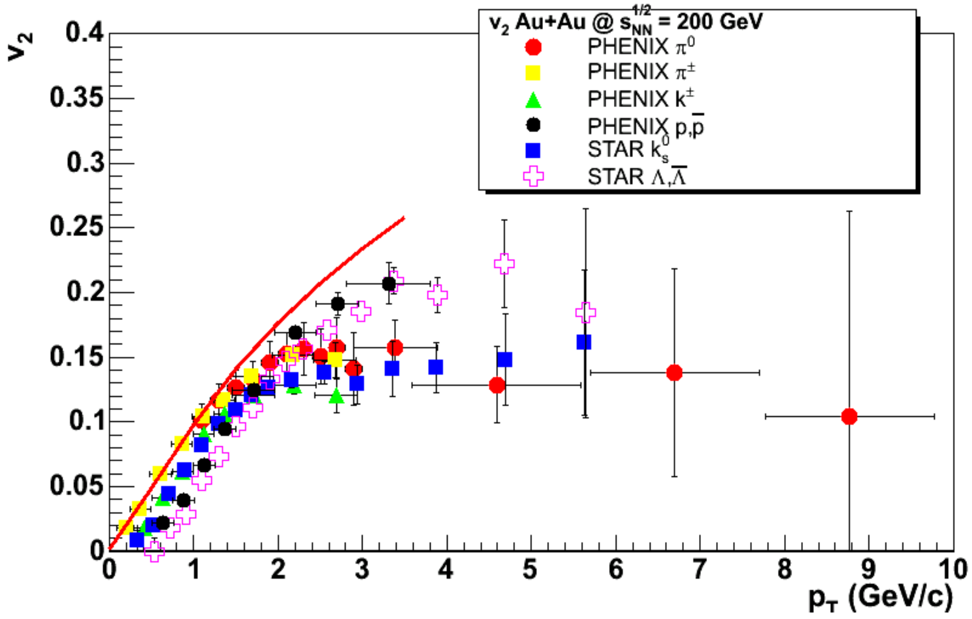
⇒ Large and fast (t<1.0 fm/c) parton rescattering (early thermalization).



High p_T azimuthal correlations: Elliptic flow (II)

- Particle species
  hierarchy of flow values:

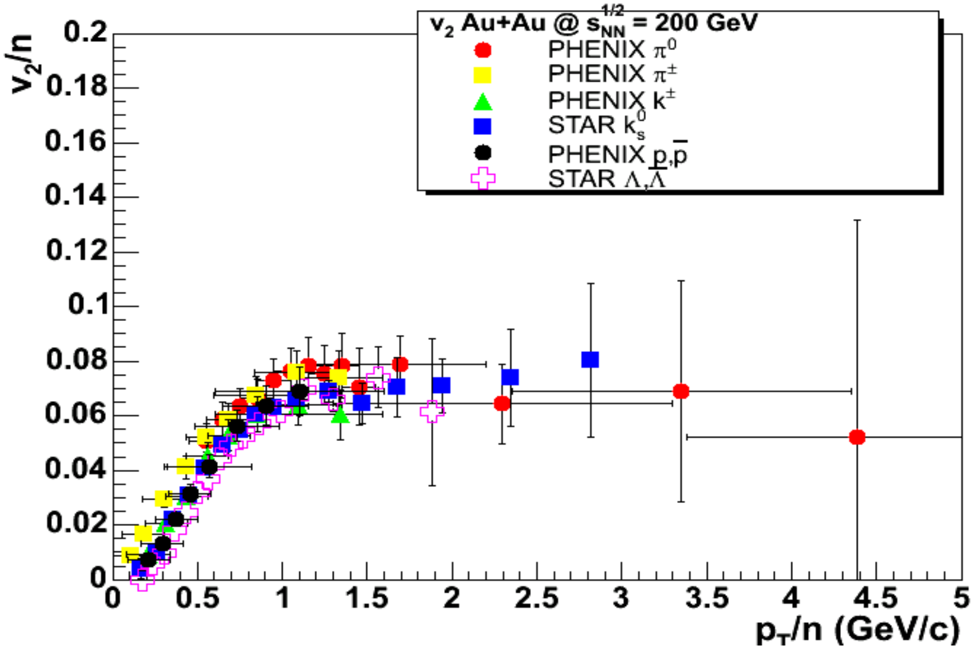
  $v_2^{meson} > v_2^{baryon}$ at low p_T
  $v_2^{meson} \approx v_2^{baryon}$ at $p_T \approx 2.$ GeV/c
  $v_2^{meson} < v_2^{baryon}$ at higher p_T



- Simple v_2 scaling behaviour predicted by quark recombination models:

  v_2 and p_T normalized by # of constituent quarks:

  n = 2 mesons
  n = 3 baryons



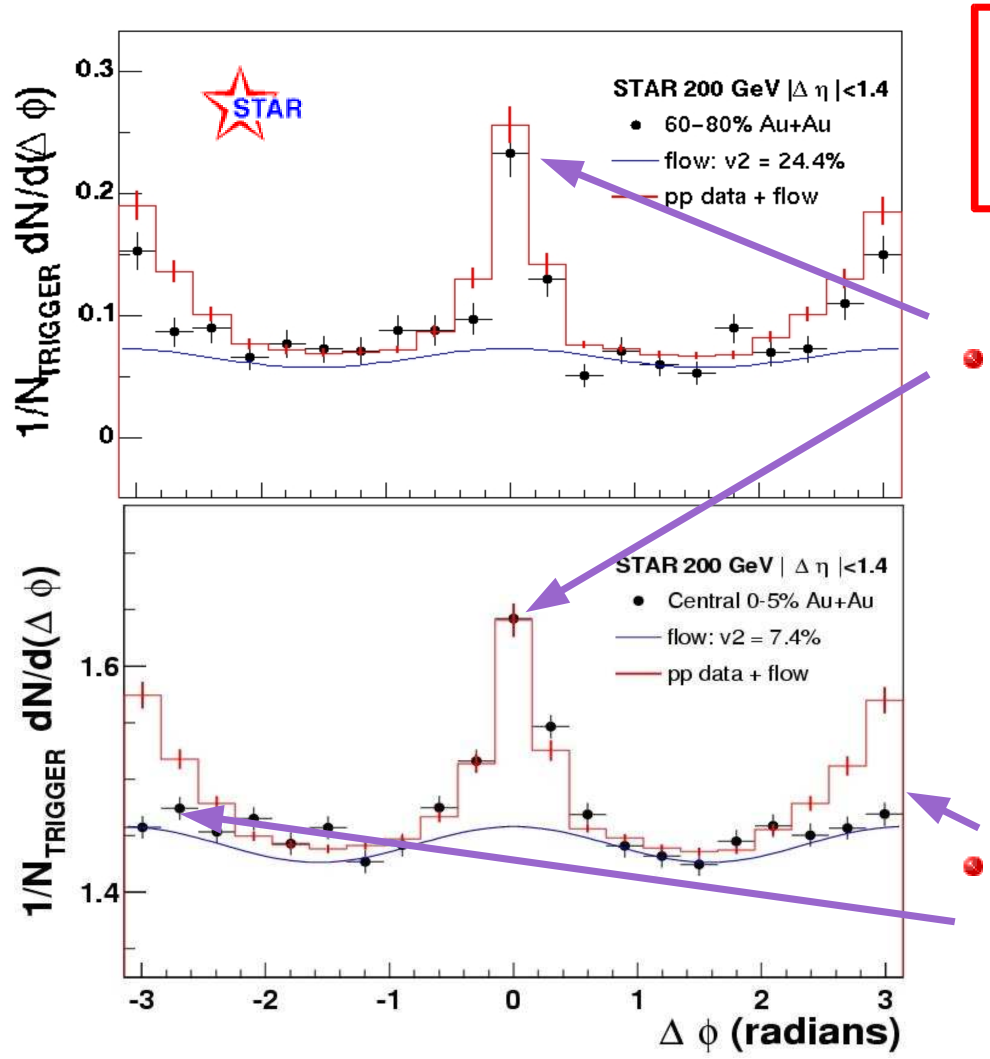
High p_T azimuthal correlations: Jet signals in Au+Au & p+p

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

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

Periph.:

Central:



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

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

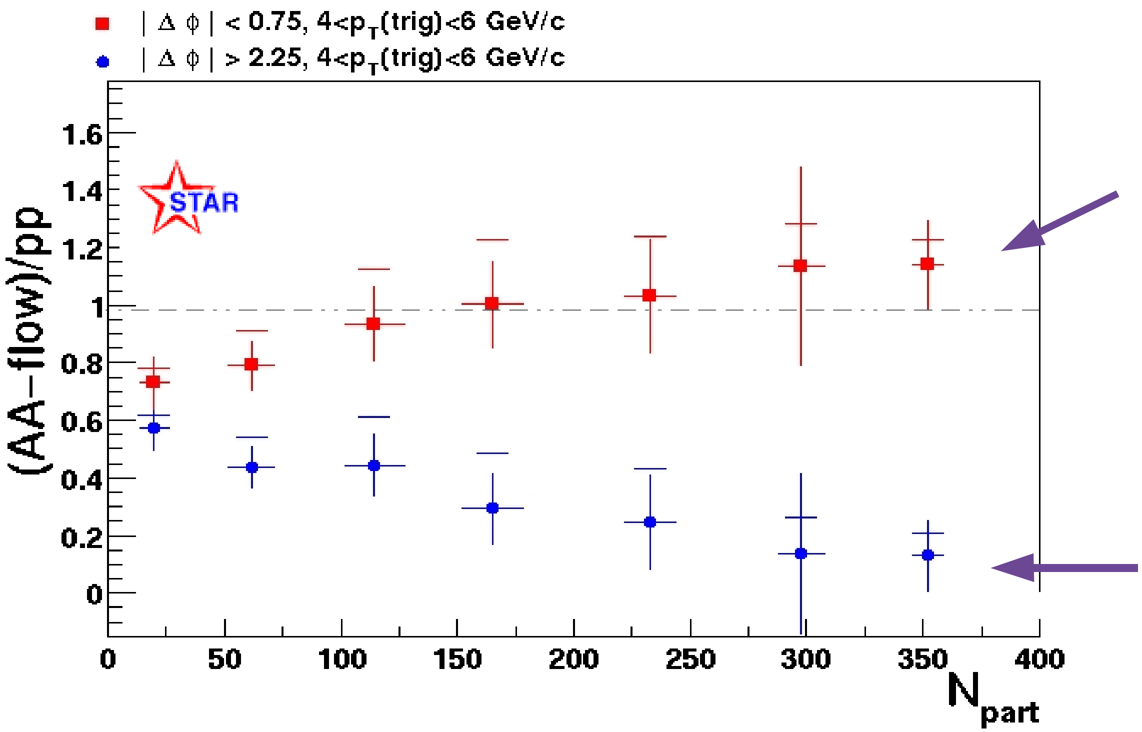
- Away-side peak: Au+Au << p+p.

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

High p_T azimuthal correlations: Au+Au 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

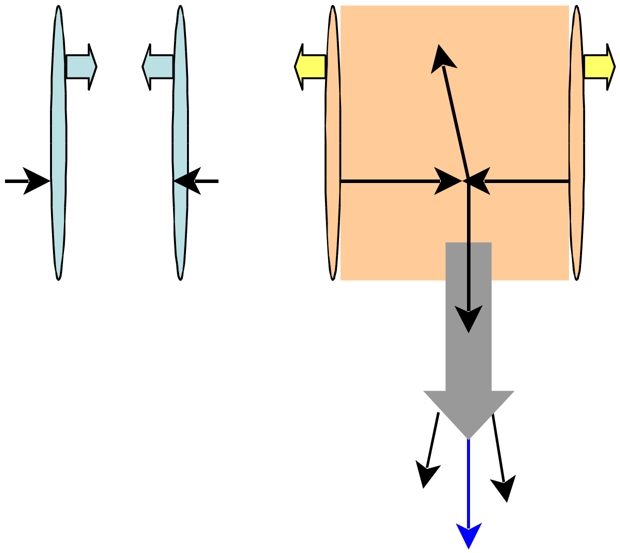
Away-side peak: I_{AA}~ 0

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

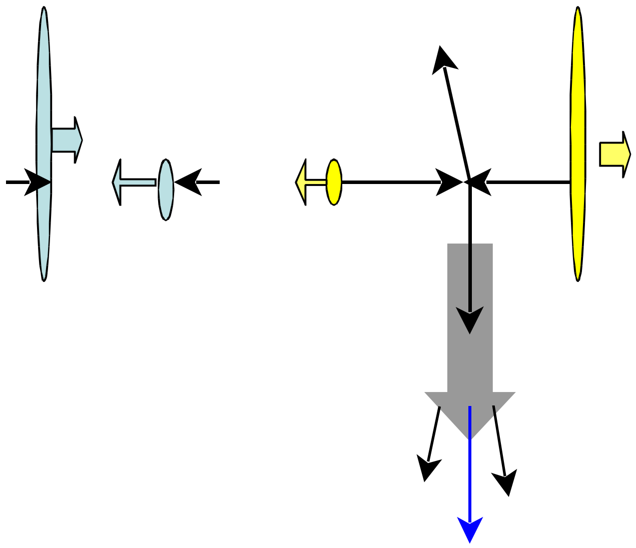
Issue (8): I_{AA}(periph)<1 ... is this physics ? an experimental bias ?
(Other independent measurements of correlation functions needed !)

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

A+Au collision



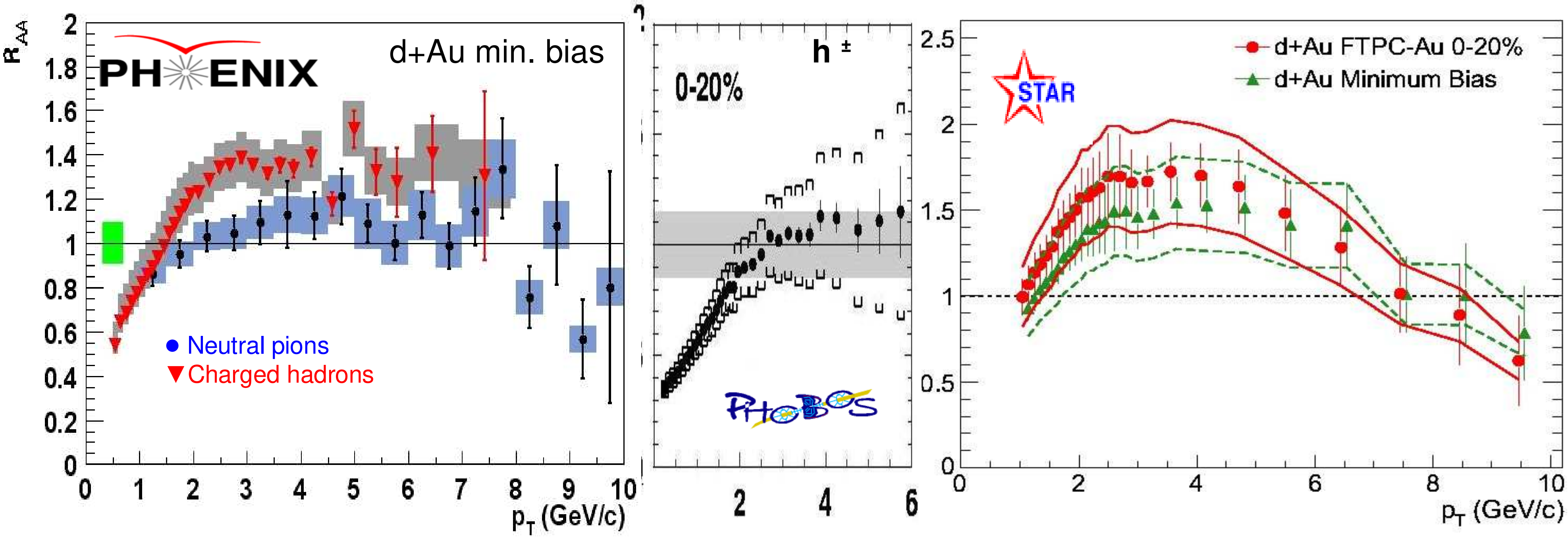
p,d+Au collision



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

cold medium
(initial- state effects only)

d+Au nuclear modification factor (η=0)

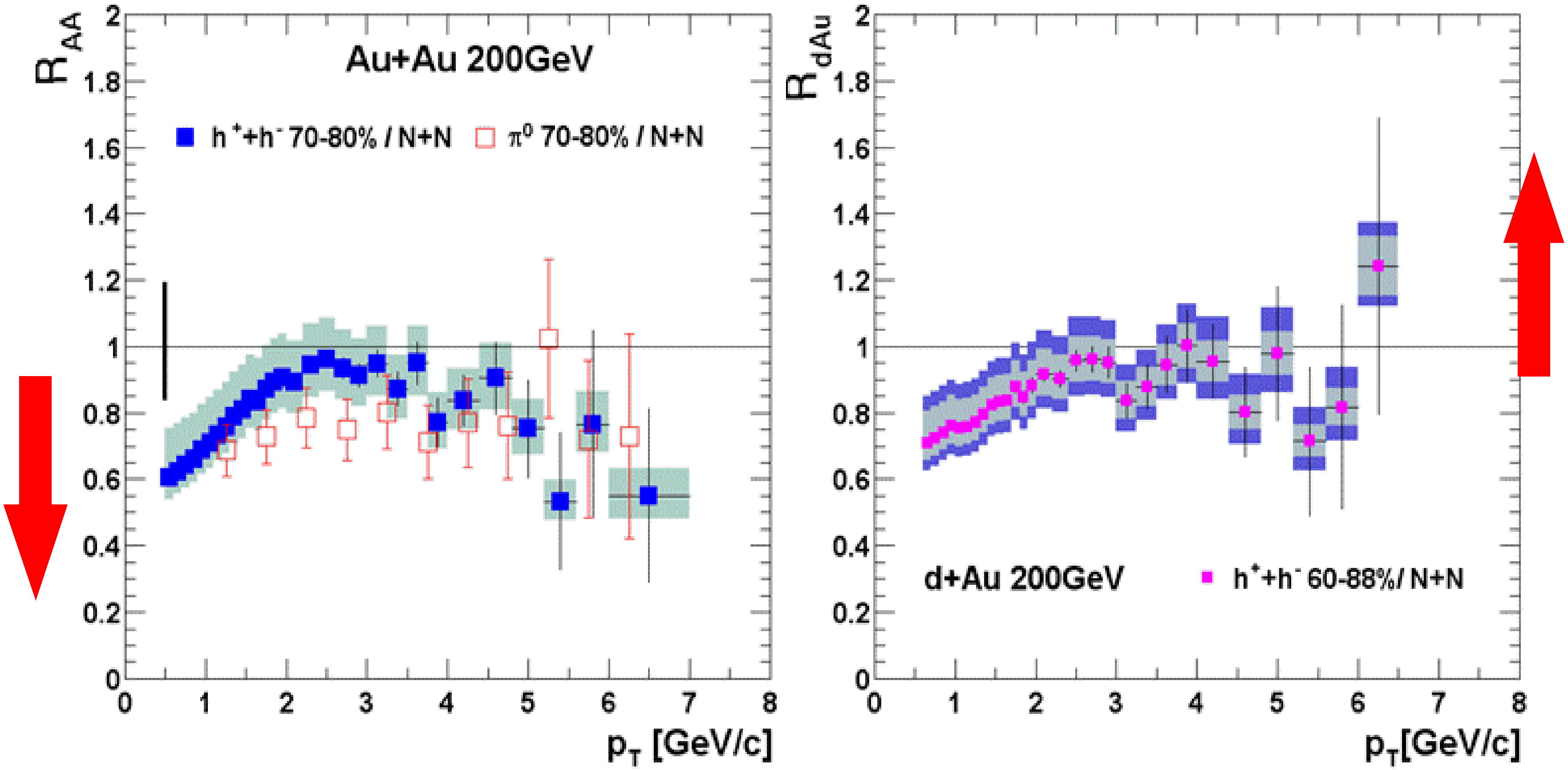


- $R_{dAu} > 1$ in min. bias, central, and p+Au (neutron-tagged) collisions.
- High p_T d+Au unquenched: clearly reminiscent of p+A "Cronin enhancement" (initial-state soft & semihard scattering).
- No apparent Au gluon saturation effects in kinematic region probed (y=0).

Issue (9): Particle-species dependence of Cronin: $R_{dAu}(h^{\pm}) \sim 1.4$ and $R_{dAu}(\pi^0) \sim 1.1$ lacks a clear phenomenological explanation so far

R_{AA} vs. R_{dA} : centrality dependence

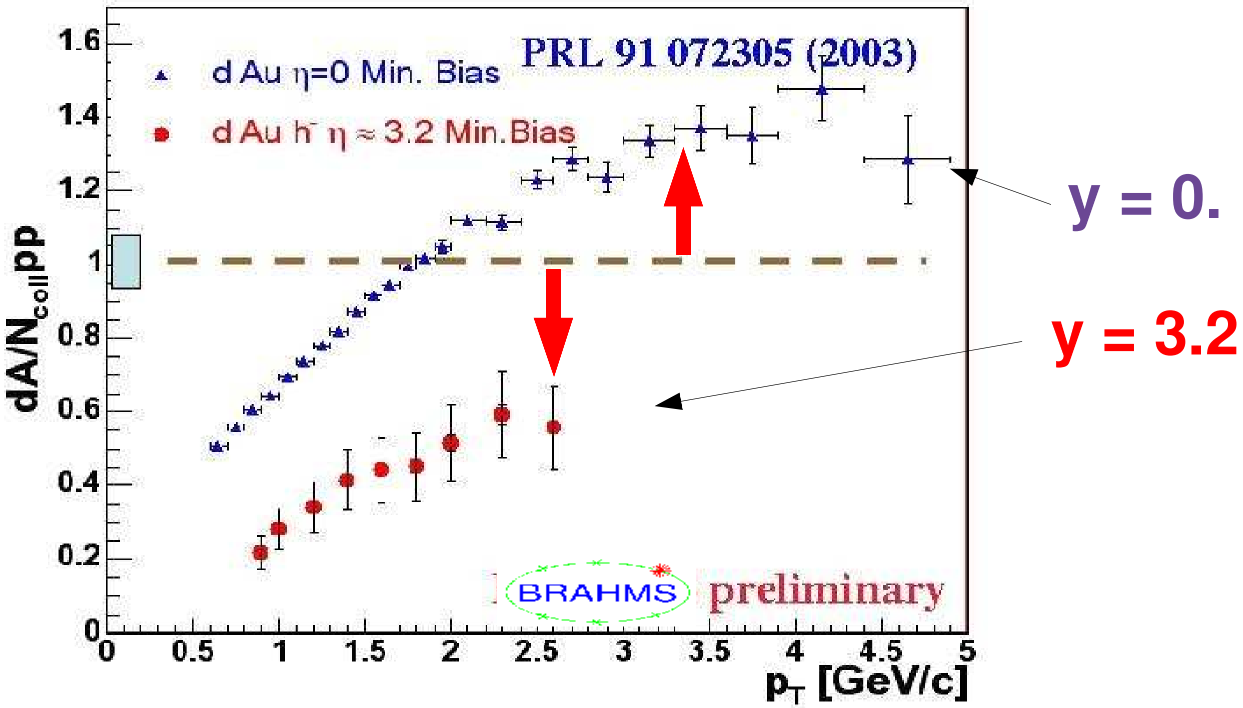
PHENIX preliminary



- Opposite centrality dependence of d+Au nuclear enhancement compared to Au+Au nuclear suppression.
- Conclusion: Au+Au suppression at y=0 not due to a “cold” nuclear matter (initial-state) effect. (CGC effects small, QGP favoured).

d+Au nuclear mod. factor: (pseudo)rapidity dependence

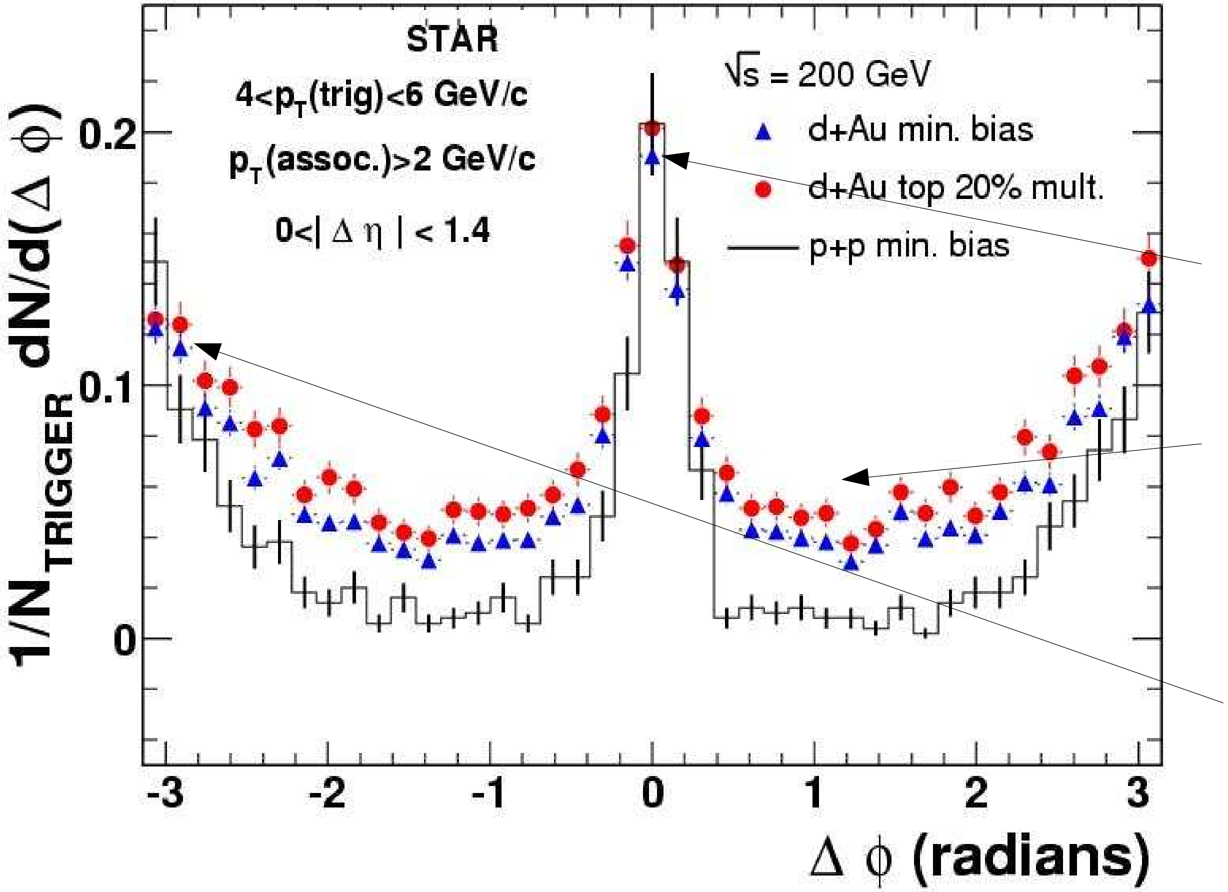
BRAHMS preliminary



- Significant suppression (factor ~2-3) of moderately high p_T hadro-production at y = 3.2 (deuteron direction): small-x~10^{-3} !
- Consistent with predicted gluon saturation effects ... CGC “strikes back” !

Issue (10): ... but probably also with “standard” leading-twist nuclear shadowing. Are we talking about the same physics “process” as described by 2 models ? or this is truly the 1st evidence of the breakdown of pQCD factorization at small x ...

High p_T azimuthal correlations: jets in d+Au and 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 !

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. (R_{cp}, v_2) 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 vs. data (I)

- Dense medium properties according to “jet quenching” models:

  - ✯ High opacities:

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

  - ✯ Large initial gluon densities:

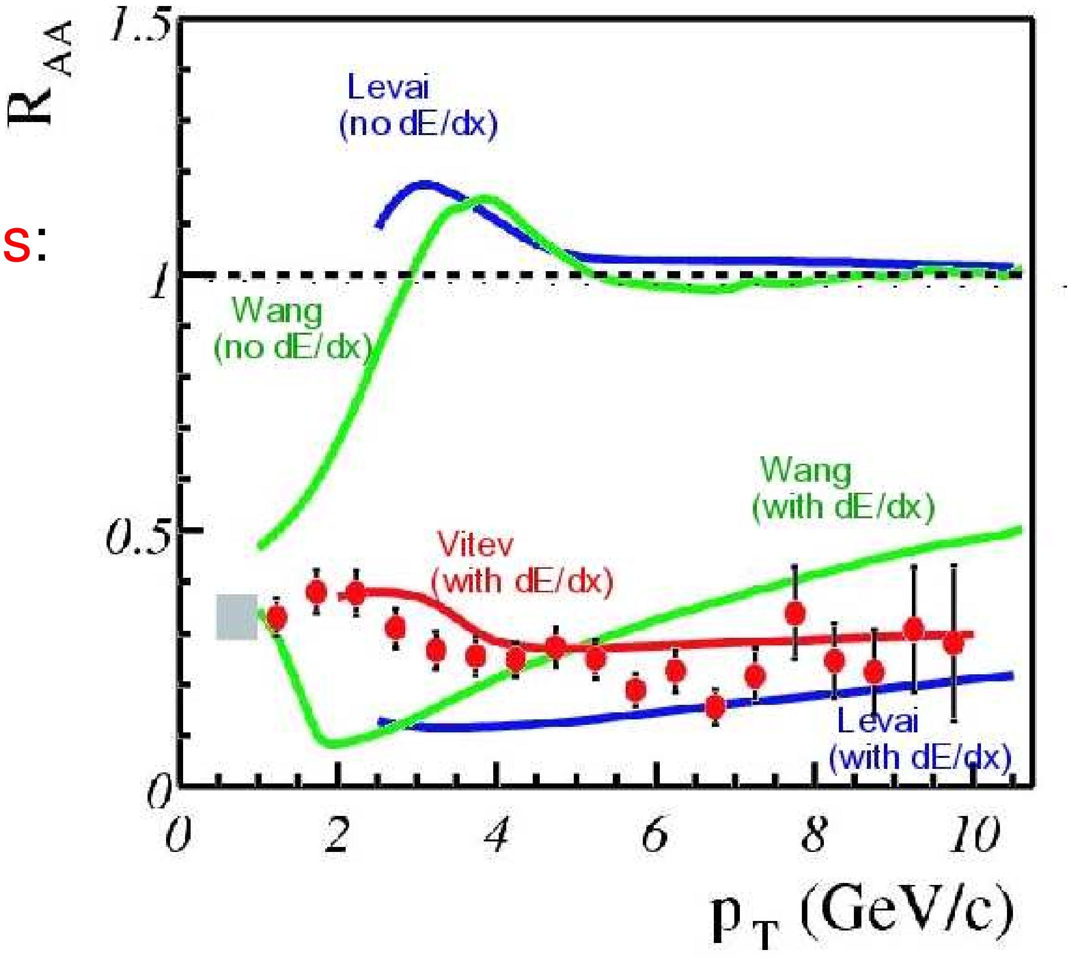
    $dN^g/dy \sim 800\text{-}1200$

  - ✯ Transport coefficients:

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

  - ✯ Medium-induced gluon radiative energy losses:

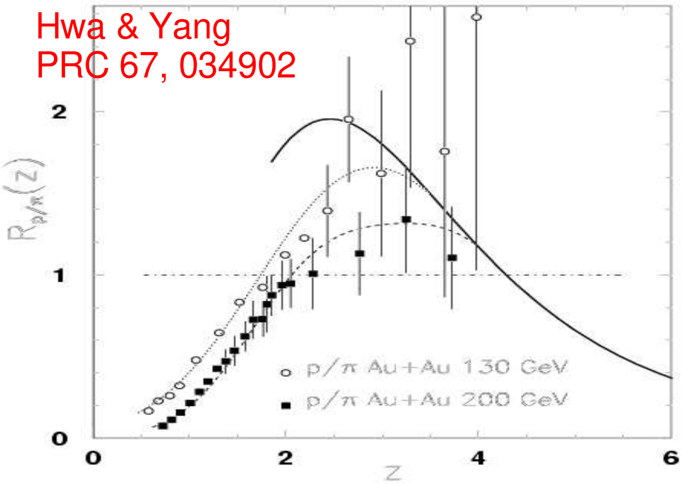
    $dE/dx \approx 0.25$ GeV/fm (expanding)
    $dE/dx|_{eff} \approx 14$ GeV/fm (static source)

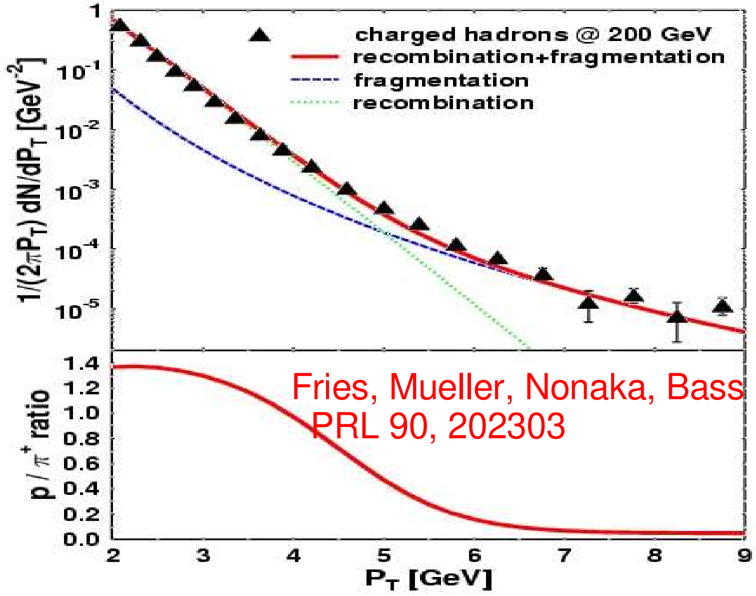


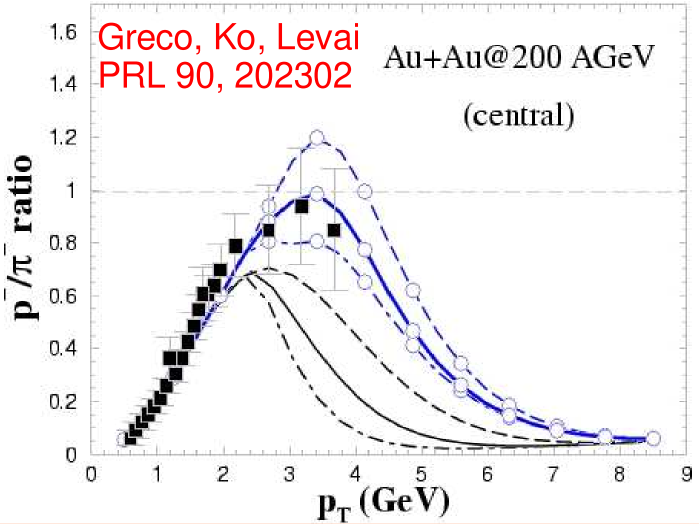
Issue (11): What is the (theor., exp.) evolution of R_{AA} at higher p_T values ?

Final-state QGP effects vs. data (II)

- Quark recombination/coalescence mechanisms are needed to explain the anomalous high p_T “chemistry” at intermediate p_T's:


Hwa & Yang
PRC 67, 034902


Fries, Mueller, Nonaka, Bass
PRL 90, 202303


Greco, Ko, Levai
PRL 90, 202302

- 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 $z<1$

Issue (12): Is recomb. consistent with (p+p-like) Au+Au dN/dφ near-side widths ?

“QGP” models vs. data: summary

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

- $\langle n \rangle = L/\lambda \approx 3 - 4$ or $dN^g/dy \sim 1000$ or $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 or $dE/dx \approx 14$ GeV/fm.

✔ Centrality dependence of Au+Au suppression.

✔ Dissapeareance of away-side dijet angular correlations.

✔ Unquenching in d+Au collisions at $y = 0$.

"Issues":

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

- Additional nuclear effects needed to "flatten" LPM [$\propto \log(p_T)$] R_{AA} (probably justified now given the d+Au results). Let's see at higher p_T.

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

- No jet quenching observed in Pb+Pb @ SPS with $dN^g/dy \sim 500$?

  Usual explanations: short plasma τ, quark-dominated plasma, very small hard cross-sections (Cronin-effect dominates) ...

  (Perhaps just a problem in the p+p reference @ $\sqrt{s} \approx 17$ GeV ?)

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

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

“CGC” models vs. data

- ✗ Foreword: High p_T Au+Au at y = 0 at RHIC is above Q_s ~ 1-2 GeV/c (straight application of CGC arguable in 1st instance): Need of “evolved” approaches: MLV (“pure” CGC) → KLM (extension into “DGLAP” region).
- ✔ Magnitude of Au+Au suppression at y = 0 → saturated (evolved) Au wave function (KLM). But: no suppression expected in other calculations (e.g. Baier, Wiedemann *et al.*).
- ✔ Centrality dependence of Au+Au suppr. → N_{part} -like scaling observed.
- ✔ Dissapeareance of away-side angular correlations (monojet prod.).

- ✗ Some deficit (R_{dA}~ 0.75) in d+Au collisions at y = 0 expected in “evolved CGC” models (which described the Au+Au case).
- ✔ Cronin enhancement in d+Au at y ~ 0 in MLV-based models (J.Jalilian-Marian, and Baier, Wiedemann *et al.*).
- ✔ Suppression of high p_T hadro-production in d+Au at y ≈ 3. (x~10^{-3}) in all CGC aproximations (kinemat. regime where CGC can be safely applied).

Summary (I)

- Vast amount of high p_T data: dN/dp_T, $dN/d\varphi$ for many different species ($h^{\pm}$, π^0, K^0_s, $\bar{p}$,p, $\bar{\Lambda}$,Λ, $e^{\pm}$ ...) and 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 u,d,s 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).
  - "Anomalous" particle composition at intermediate p_T~2-5 GeV/c: baryon/meson ≈ 0.8 ratio >> baryon/meson ≈ 0.2 in p+p and e^+e^-.
  - Same suppression at $y \approx 0$ and $y \approx 2$.
  - No suppression of charm mesons observed (within exp. uncertainties).
  - 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:

- ✯ Within errors, 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, central d+Au, “p”+Au) at y = 0.
- ✯ Cronin-like enhancement for π^0 (small) and $h^\pm$ (larger) at y = 0.
- ✯ Opposite behaviour of the centrality dependence of high p_T production compared to Au+Au (y=0).
- ✯ No dissapearance of away-side dijet correlations.
- ✯ Factor ~2 suppression observed at forward rapidities y ≈ 3.

Data vs. theory:

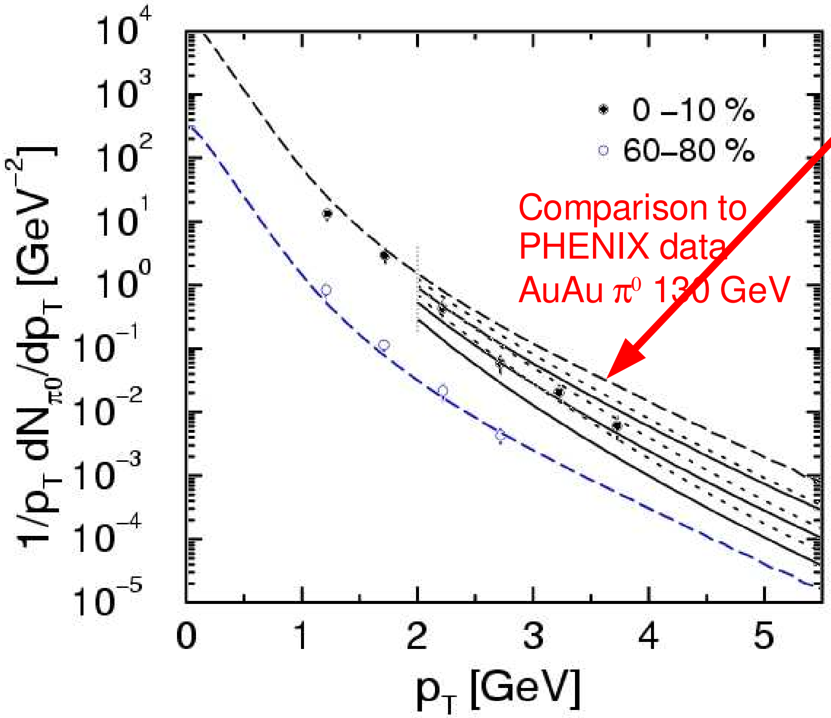
- ✯ pQCD-based final-state parton energy loss (“QGP”) models are clearly consistent with Au+Au, d+Au data at y=0 (though non-perturbative effects, e.g. quark recombination, are needed at intermediate p_T).
- ✯ Gluon saturation (“CGC”) effects may start to show up clearly at forward rapidities in d+Au (first insight of pQCD factorization breakdown at small-x ?)

The wealth of (high quality) high p_T data at RHIC is at the root of the most significant advances in the knowledge of Quantum Chromo Dynamics in years !

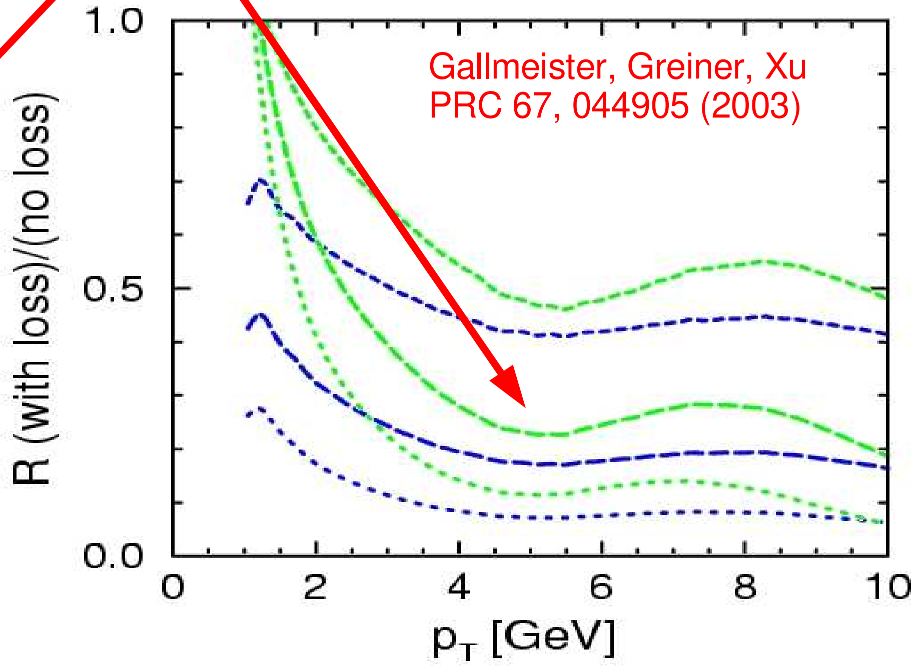
backup slides ...

Final-state effects in a dense hadronic medium ?

- Energy loss in a dense hadronic medium ($<L/\lambda> \sim 2\text{-}3$) seems to provide a (flat ?) suppression too ...



Comparison to PHENIX data AuAu π^0 130 GeV



Gallmeister, Greiner, Xu
PRC 67, 044905 (2003)

- 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*)

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 !