Hard scattering in Au+Au, p+p and d+Au at $\sqrt{s}$ = 200 GeV : Latest results from PHENIX @ RHIC

CERN Heavy Ion Forum

Genève, July 1, 2003

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(PHENIX Collaboration)

Overview

1. Introduction:

- High-energy heavy-ion physics topics.
- Hard scattering probes.
- PHENIX experiment at RHIC.
- Run history: Au+Au @130 GeV, 200 GeV,
  p+p @ 200 GeV, d+Au @ 200 GeV

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

- Suppression of hadron spectra (central colls.)
- "Anomalous" hadron composition (central colls.)
- Collective elliptic flow, away-side jet suppression.

3. Theory vs. data:

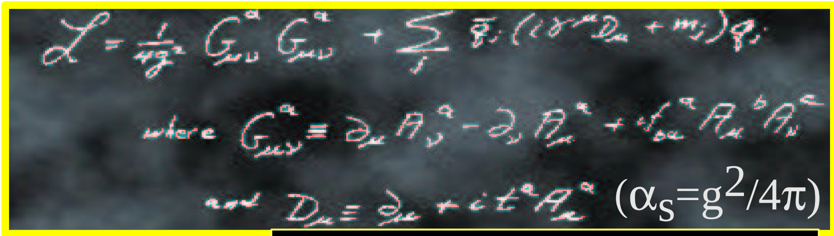
- QGP- and CGC- models vis-à-vis data.

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

- Cronin-like enhancement

5. Summary

High-energy heavy-ion physics program (in 4 plots)

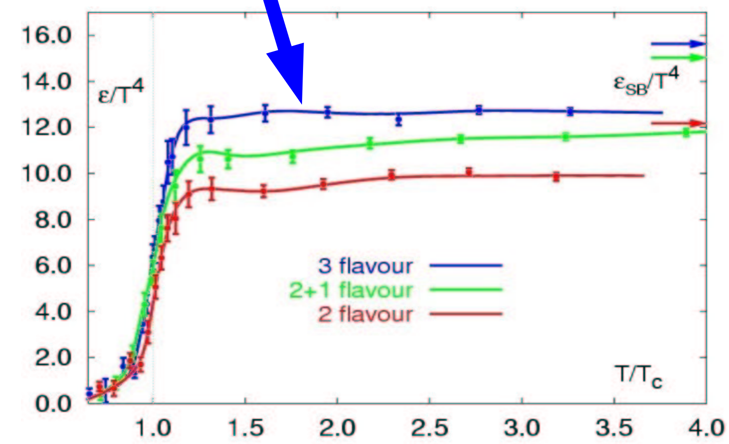


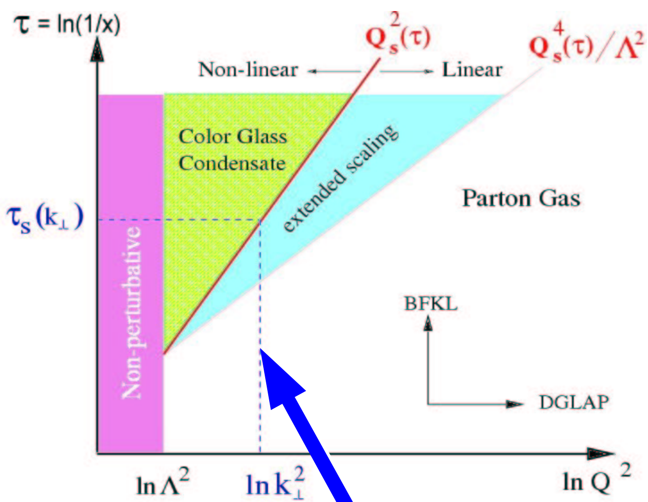
$(\alpha_S = g^2/4\pi)$

$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

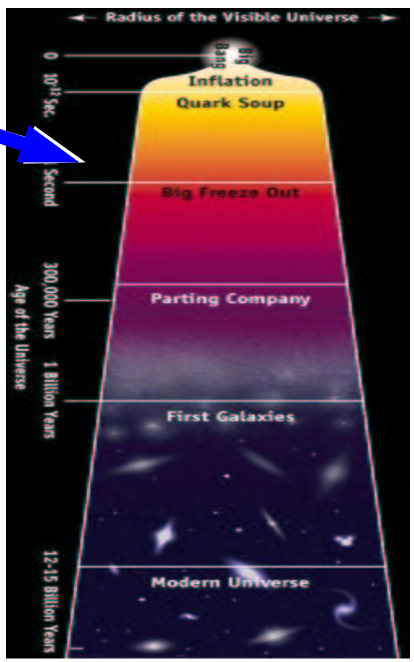
1. Learn about 2 (so far unexplained) properties of the strong interaction: confinement, chiral symmetry breaking

2. Study the phase diagram of QCD matter (esp. produce & study the QGP)





3. Probe the properties of the primordial Universe (few μsec after the Big Bang).



4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC).

Hard QCD probes (I)

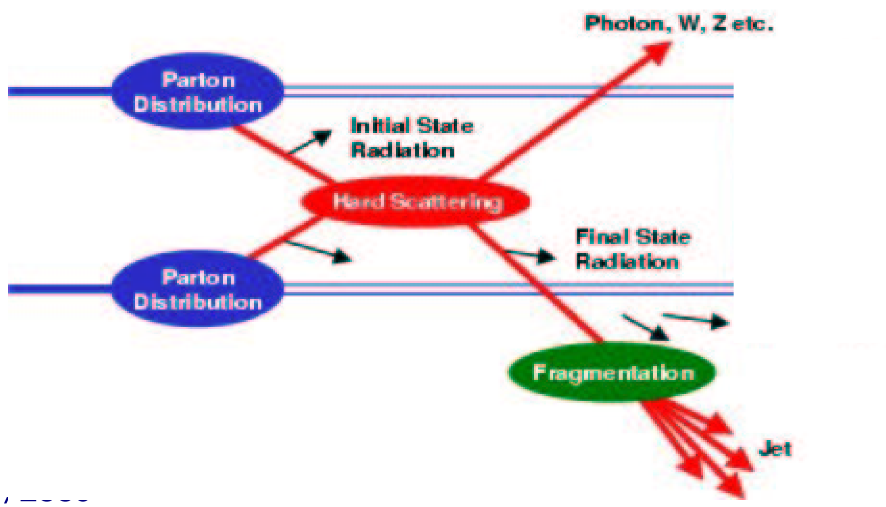
- Hard probes: High-p_T (jets, prompt γ), heavy-flavor (D, B, J/Ψ, ...)
- Early production ($\tau \sim 1/p_T \sim$ 0.1 fm/c) in parton-parton scatterings with large Q^2
- Direct probes of partonic phases $\Rightarrow$ Sensitive to dense medium properties: parton energy loss ("jet quenching"), color screening ("onia" suppression), ...
- Direct comparison to baseline "vacuum" (*pp*) data via "collision scaling":

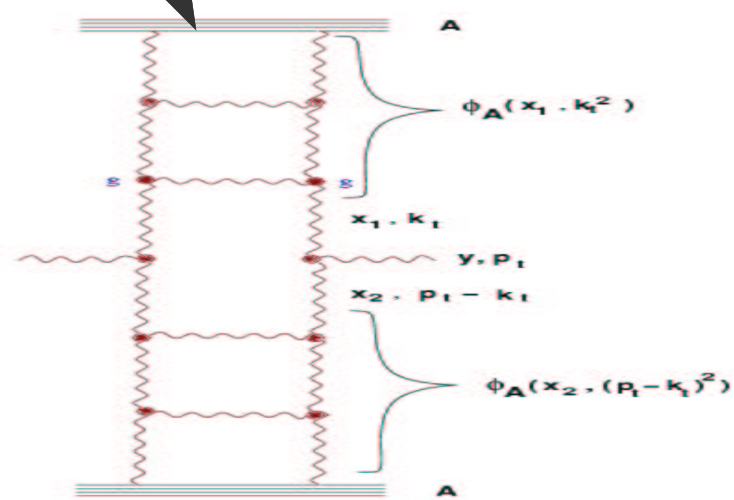
$$\sigma_{AB\,(hard)} = \int d^2b\,[1-e^{-\sigma_{pp}T_{AB}(b)}] \approx A\cdot B \times \sigma_{pp\,(hard)}$$

A·B $\propto$ # of binary inelastic *NN* colls .

- Production yields calculable via perturbative or classical-field QCD:

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



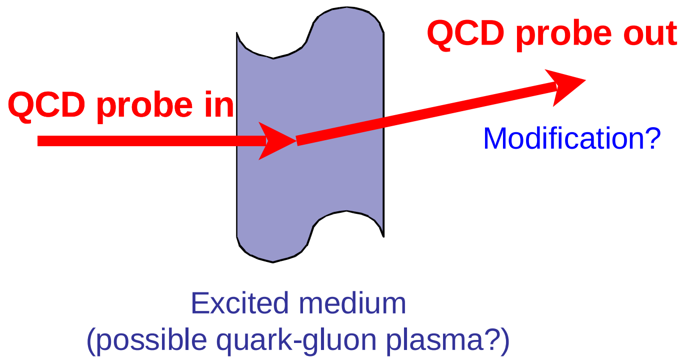


"Mueller diagram for classical glue radiation"

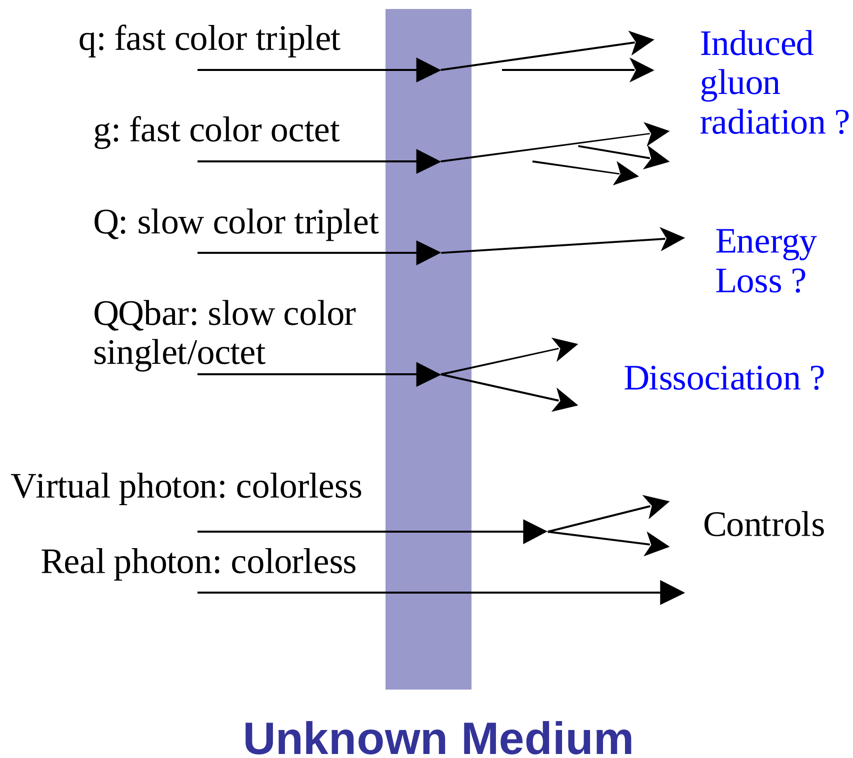
Hard QCD probes (II)

- Allow us the study of QCD medium properties via sensitive and well calibrated(*) observables:

(*) experimentally & theoretically

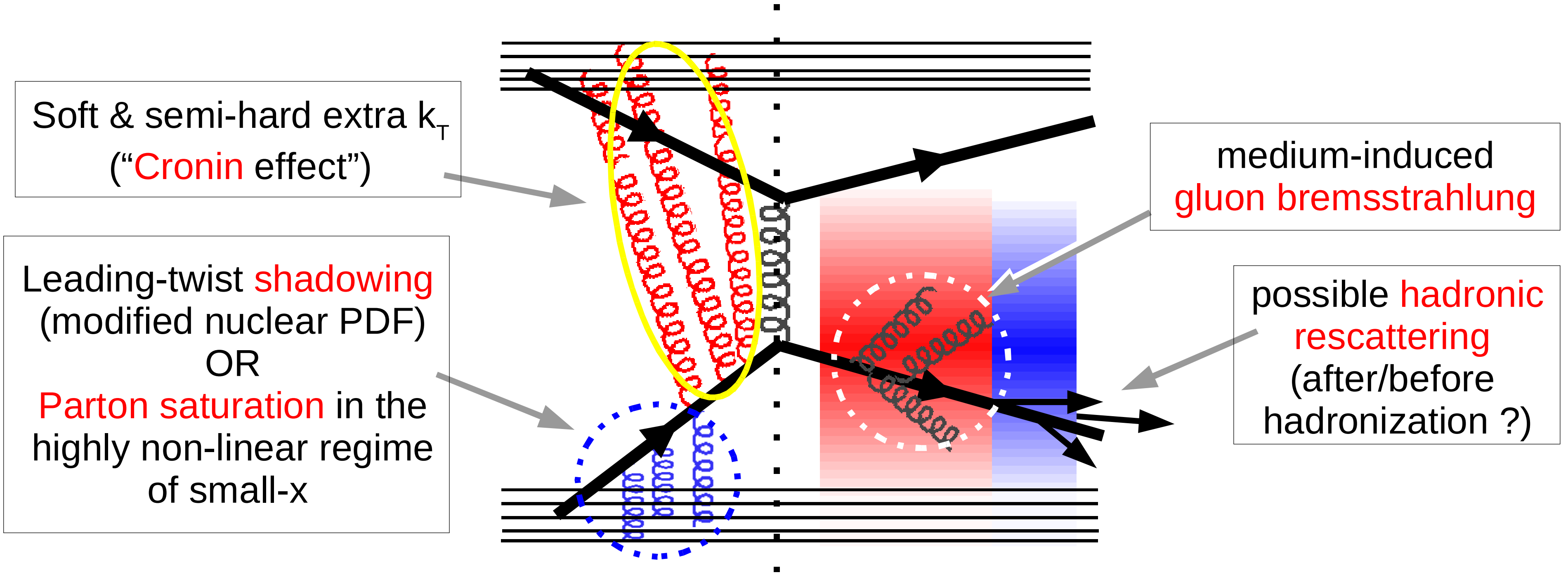


- The full pallet of QCD probes created at RHIC can be measured in the PHENIX experiment:



High p_T in a strongly interacting medium

- Hard scattering processes – Initial- vs final-state effects:



- Experimental handles on high p_T particle production:

[Standard jet finding algorithms not applicable in HI reactions due to large bckgd].

1. Depletion of high p_T inclusive hadrons (jet leading particles)
2. Attenuation / absorption of jets ("jet quenching"): photon-tagged jets, modification of angular correlations between jet products
3. Changes in particle composition

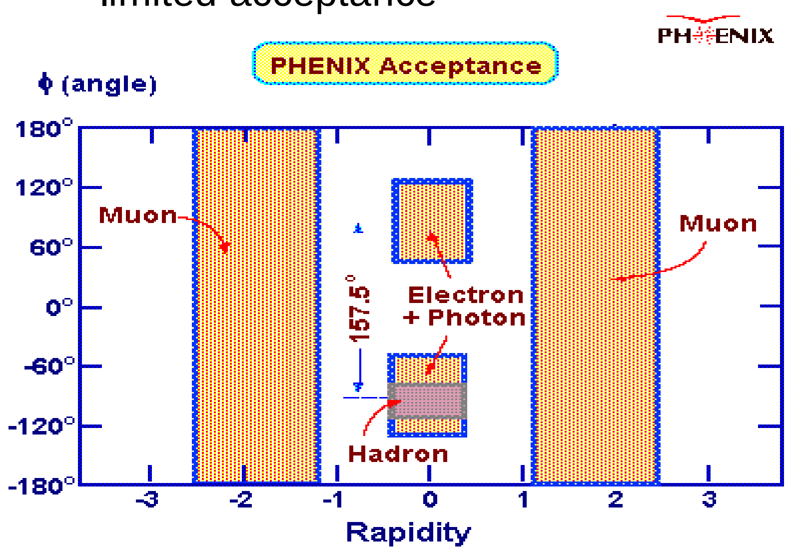
PHENIX @ RHIC

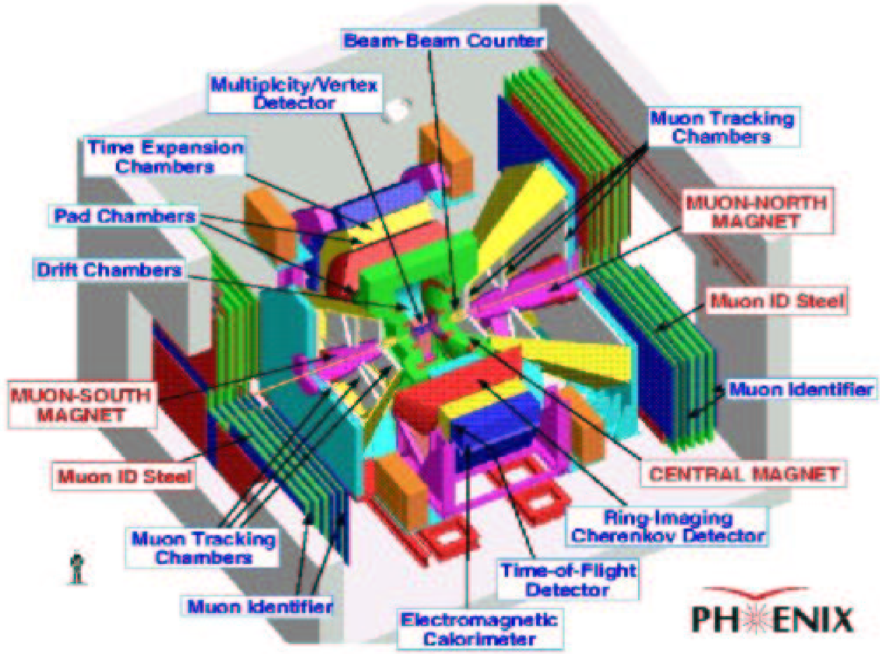
- 11 detector sub-systems
- 2 Arm central spectrometers:
  - $|\eta| < 0.35$, $\Delta\phi = \pi$ (e, γ, hadrons)
  - Open geometry axial field
- 2 forward spectrometers:
  - $1.2 < |\eta| < 2.5$, $\Delta\phi = 2\pi$ (muons)
  - Radial magnetic field
- 3 global (inner) dets.: trigger, centrality
- Designed to measure rare probes:

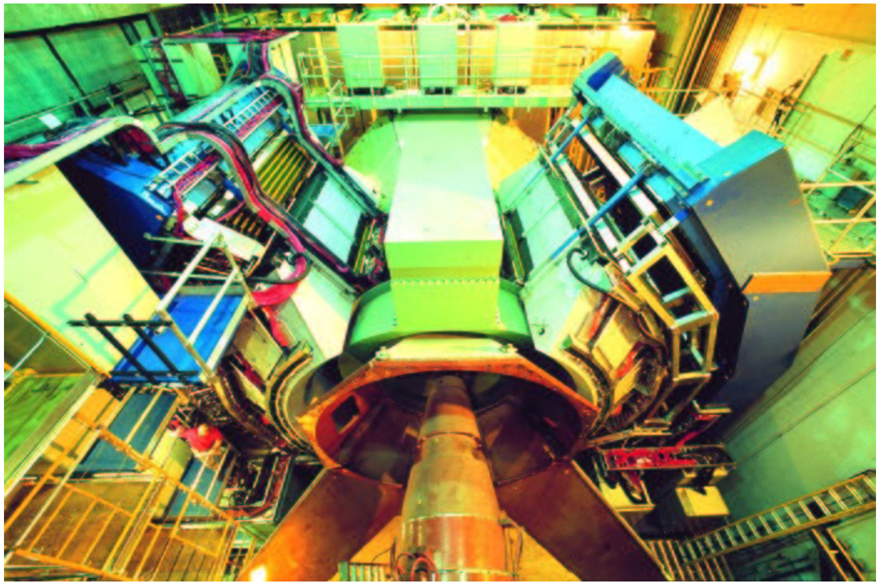
  \+ high rate capability & granularity

  \+ good mass resolution and PID

  \- limited acceptance



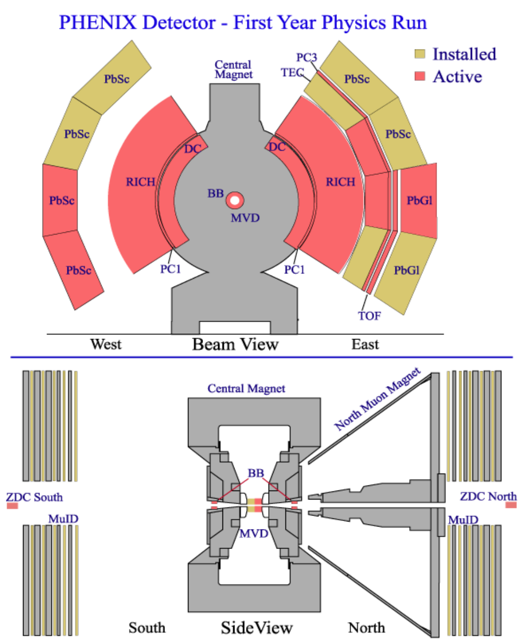




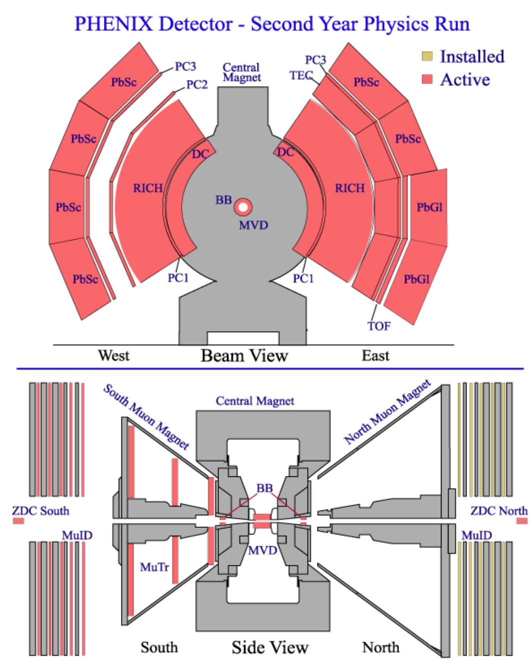
PHENIX run history

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{tot}	tot. data
01	2000	Au - Au	130	1 μb^{-1}	10M	3 TB
02	2001/2002	Au - Au	200	24 μb^{-1}	170M	~20 TB
		p- p	200	0.15 pb^{-1}	3.7G	~10 TB
03	2002/2003	d - Au	200	2.74 nb^{-1}	5.5G	46 TB
		p - p	200	0.35 pb^{-1}	4.0G	35 TB

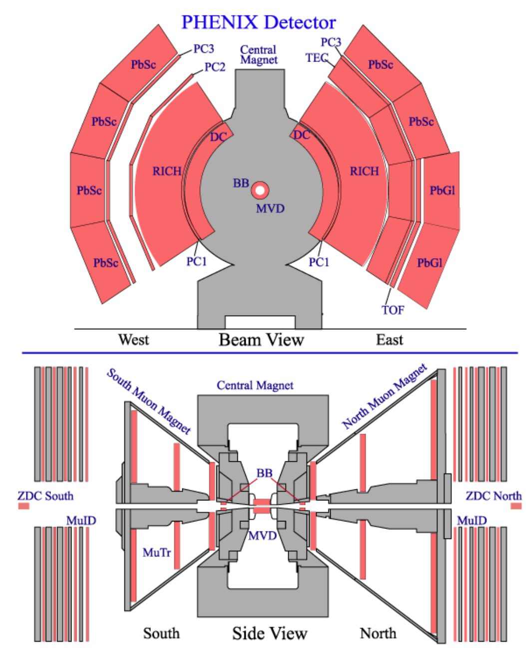
2000



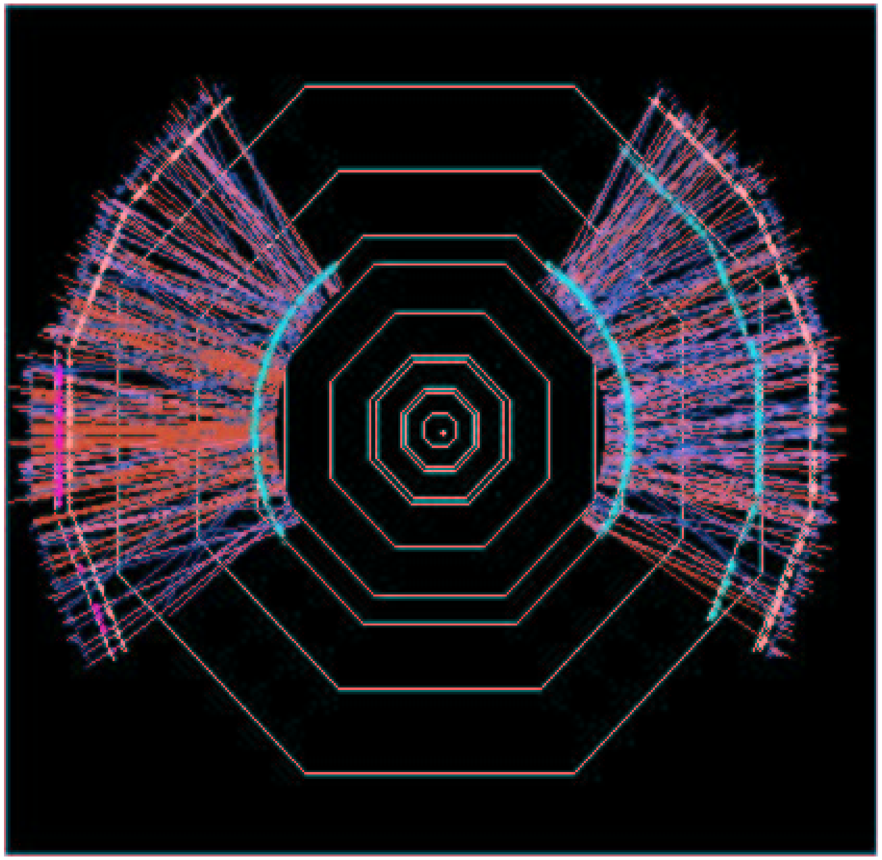
2001/2002

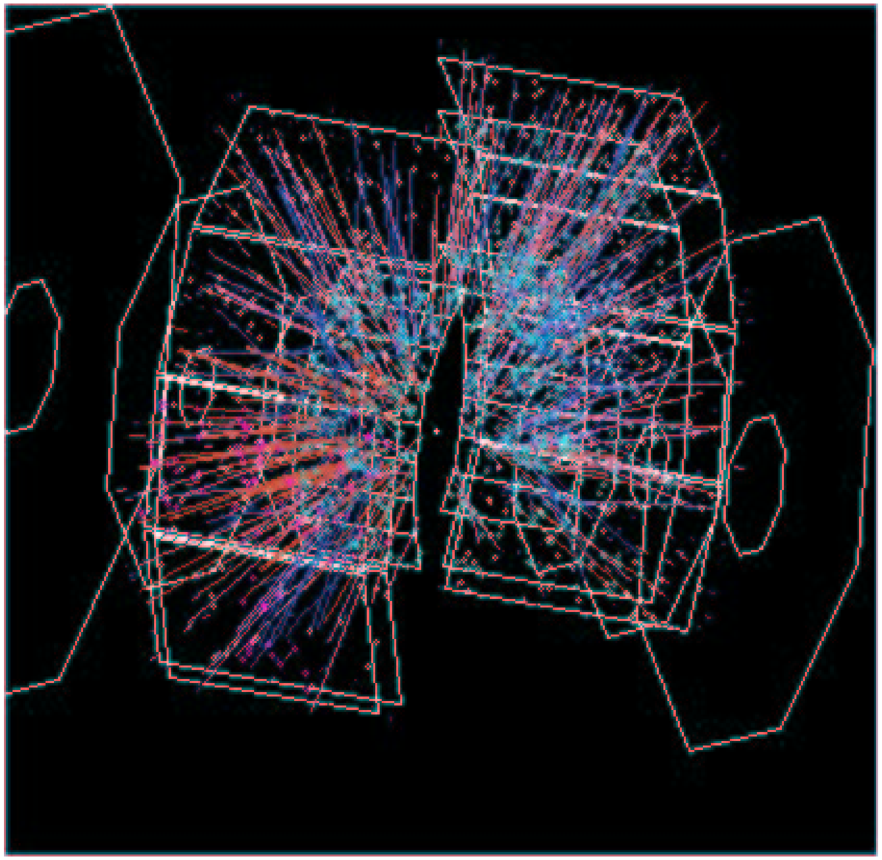


2002/2003



Au+Au in PHENIX

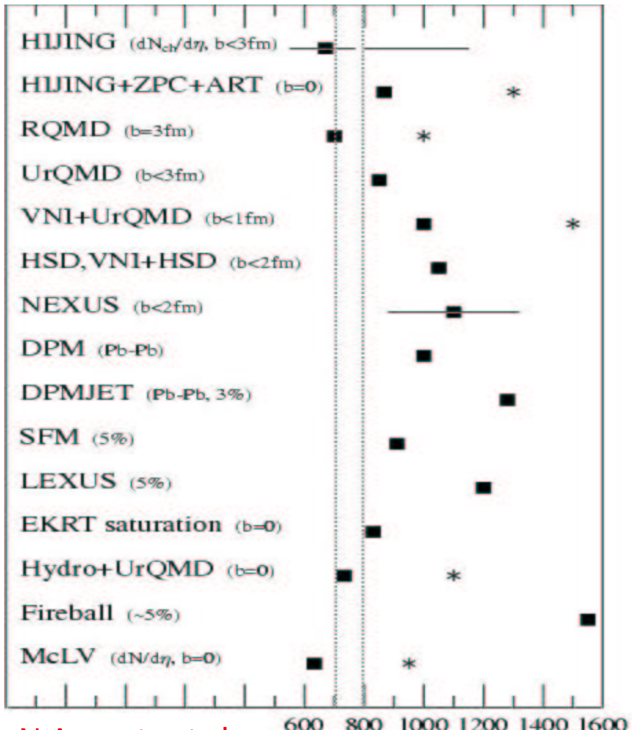




~600 charged particles per unit rapidity at mid-rapidity (5% most central)

Foreword: central rapidity densities in Au+Au

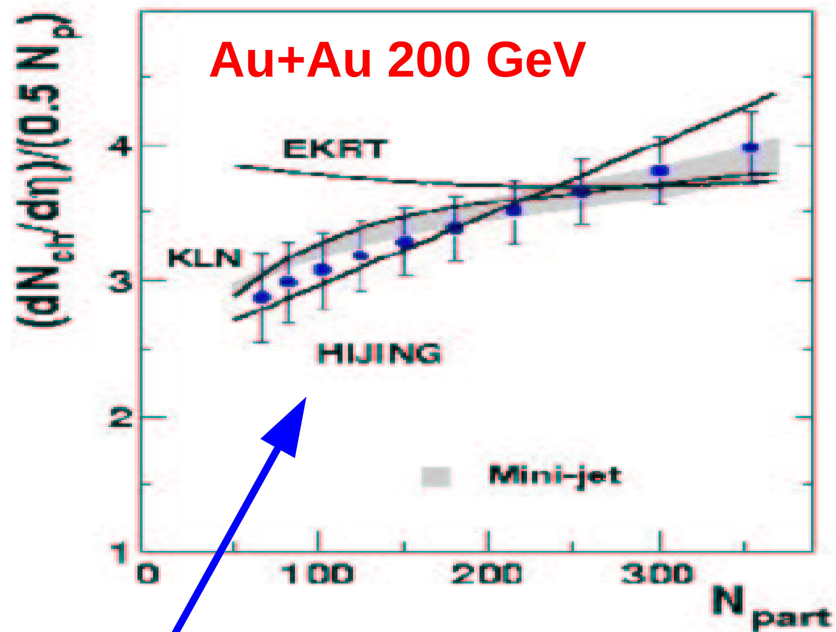
- dN_{ch}/dy constraints mechanisms of initial multi-particle production:



N.Armesto et al.
Int.J.Mod.Phys. A15, 2019

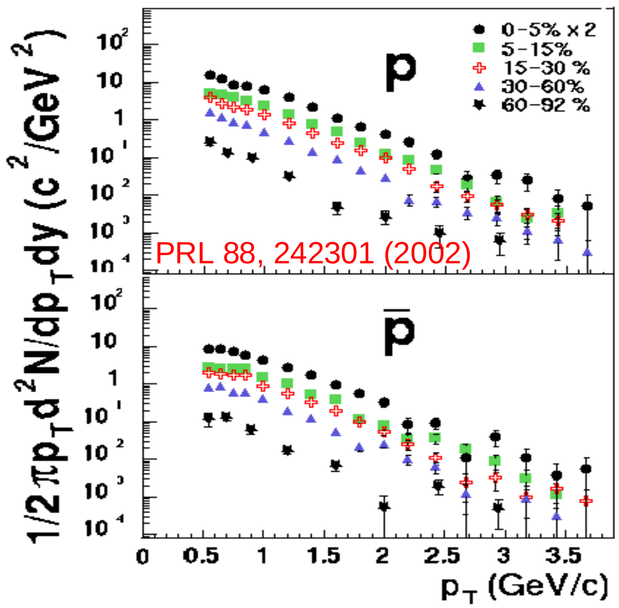
dN_{ch}/dy

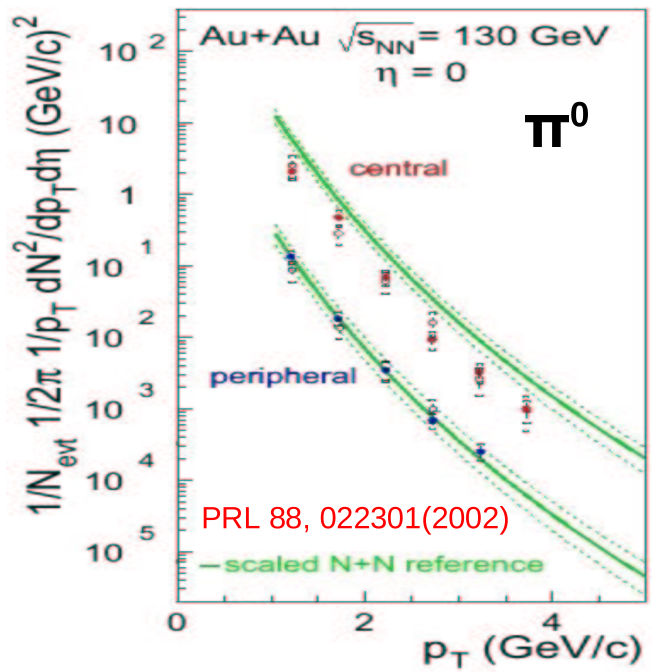
centrality dependence:

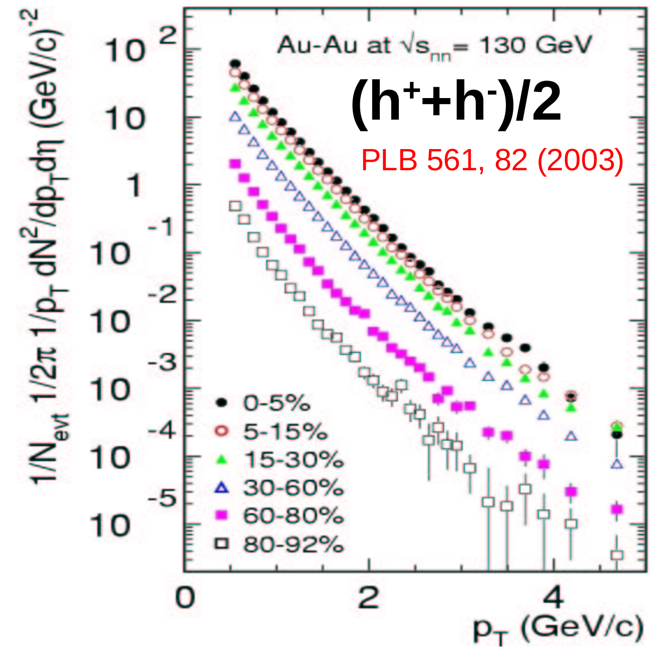


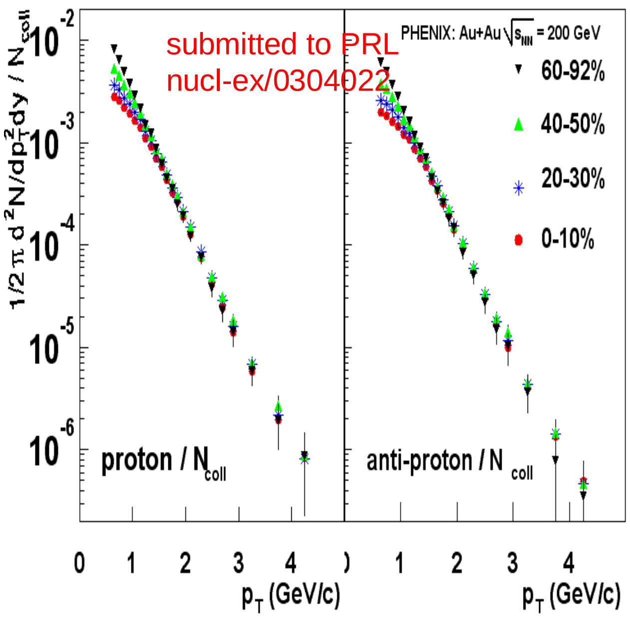
- dN_{ch}/dy (per participant pair) increases faster than linearly with N_{part} :
- Global particle density at y=0 well described by pQCD- & CGC- based models:
  - ✔ "Soft + hard" (string + pQCD “minijet”): increased hard contribution ($\propto N_{coll}$)
  - ✔ Initial-state gluon saturation (CGC): dN_{ch}/dy ~ dN_{gluon}/dy ~ $1/\alpha_s$ ~ $N_{part} \ln(N_{part})$

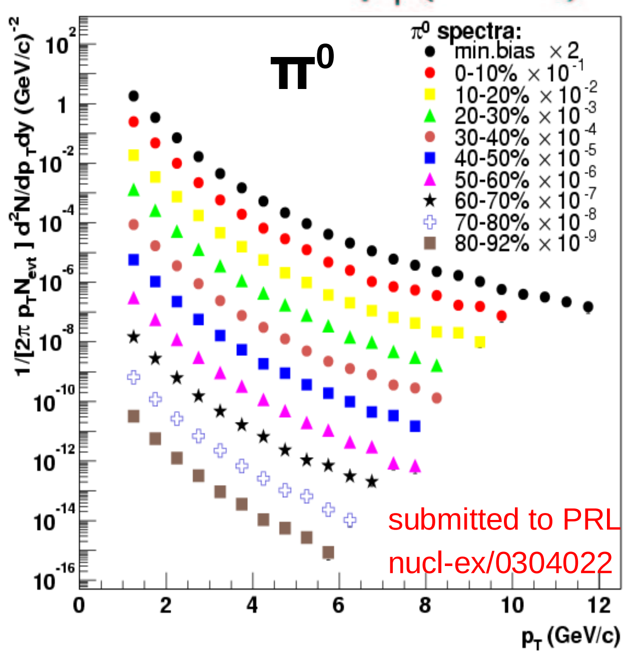
Au+Au: high p_T spectra

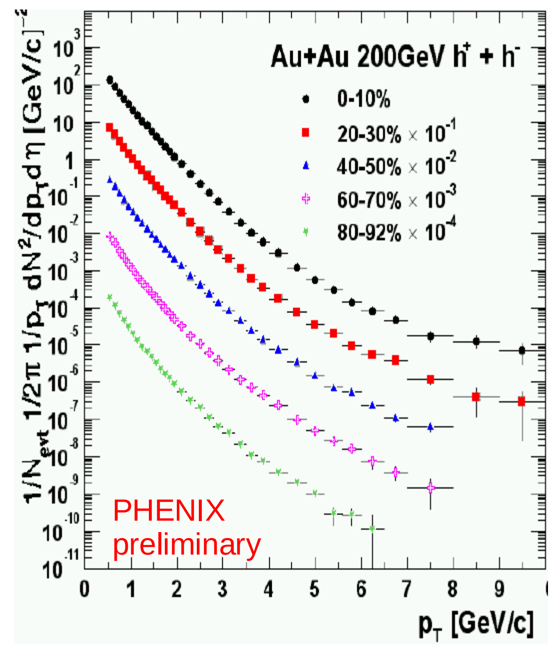




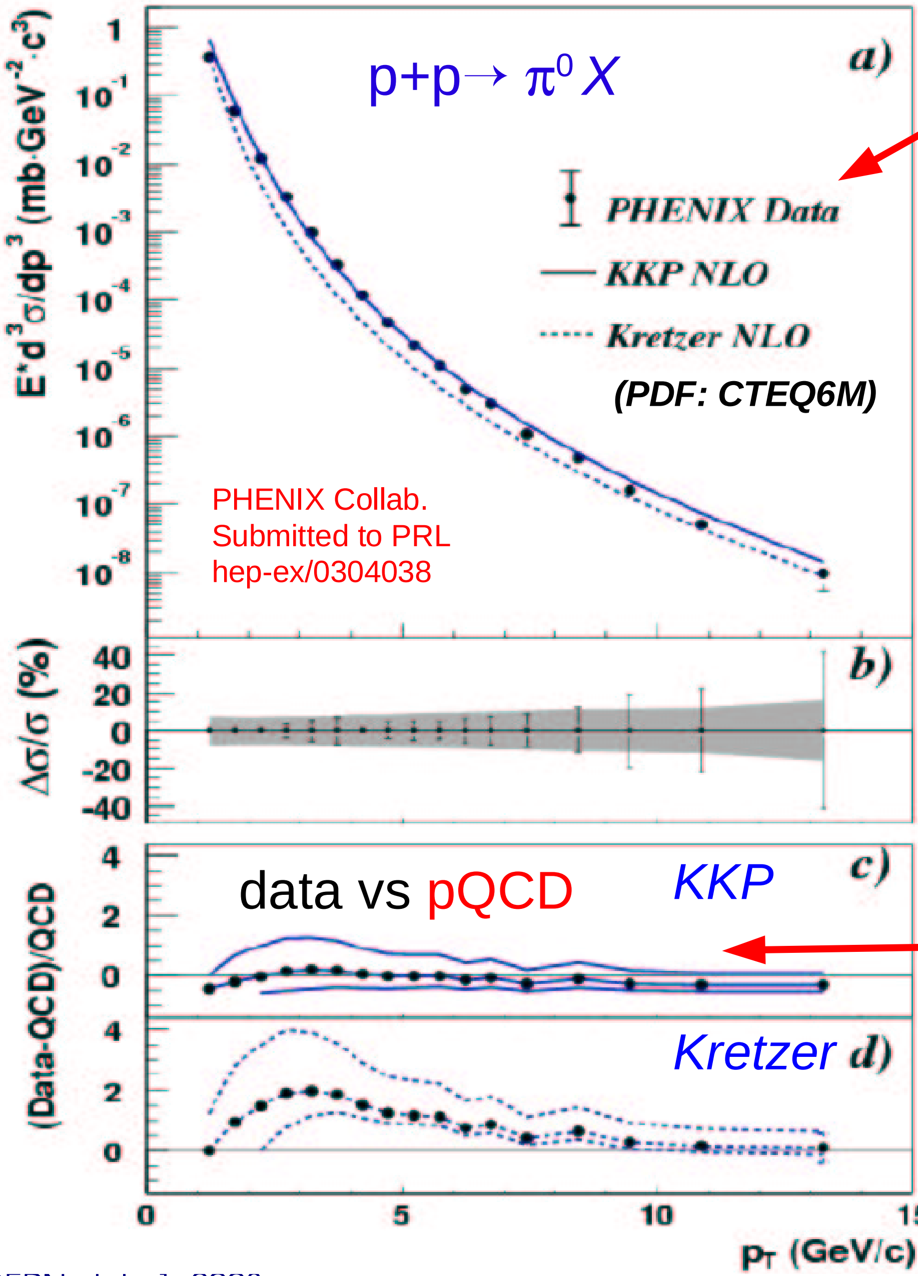




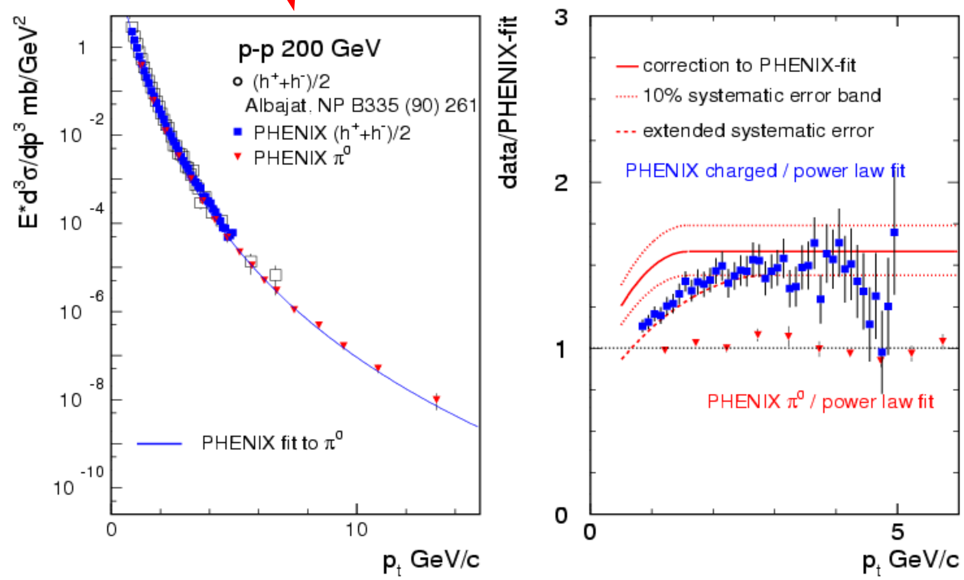




p+p reference @ 200 GeV: high-p_T π^0



- "Unbiased" ref. for Au+Au → π^0
- "Auxiliary" ref. for Au+Au → $h^\pm$

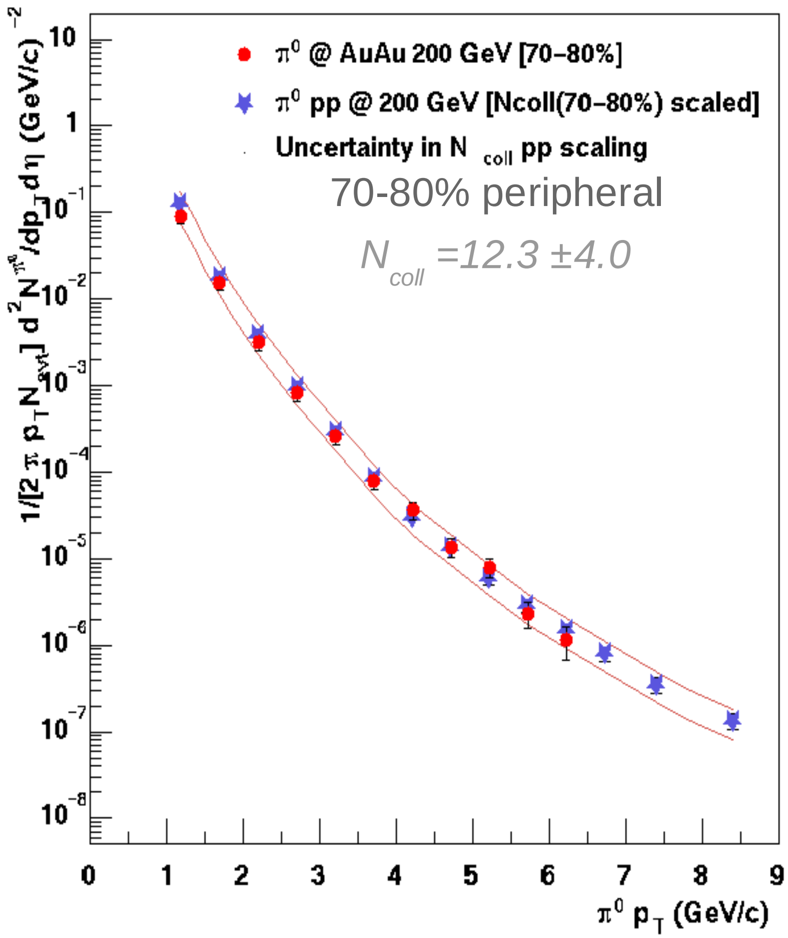


- Good NLO pQCD description

(down to p_T~ 1 GeV/c,
no intrinsic k_T needed,
sensitivity to gluon→π^0 FF)

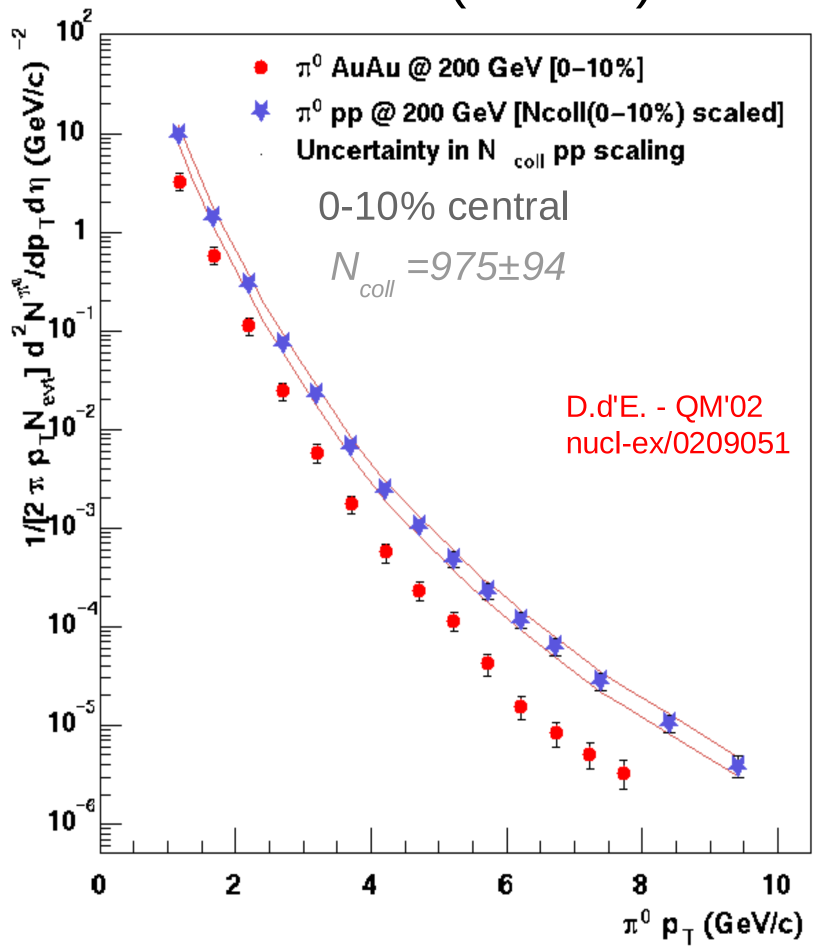
AuAu *vs* pp (neutral pions)

Au+Au→ $\pi^0 X$ (periph)



Peripheral data agree with pp plus collision scaling

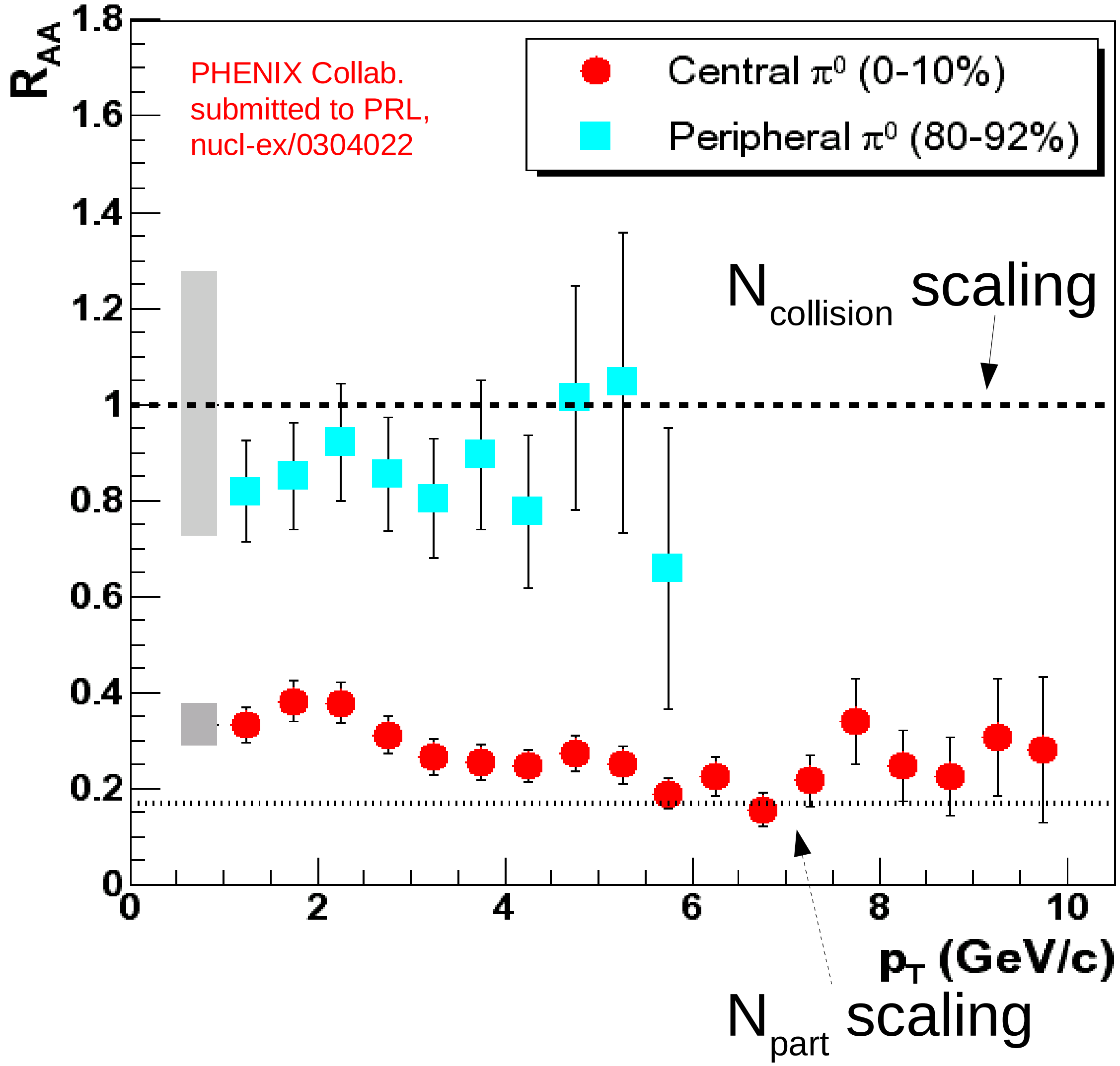
Au+Au→ $\pi^0 X$ (central)

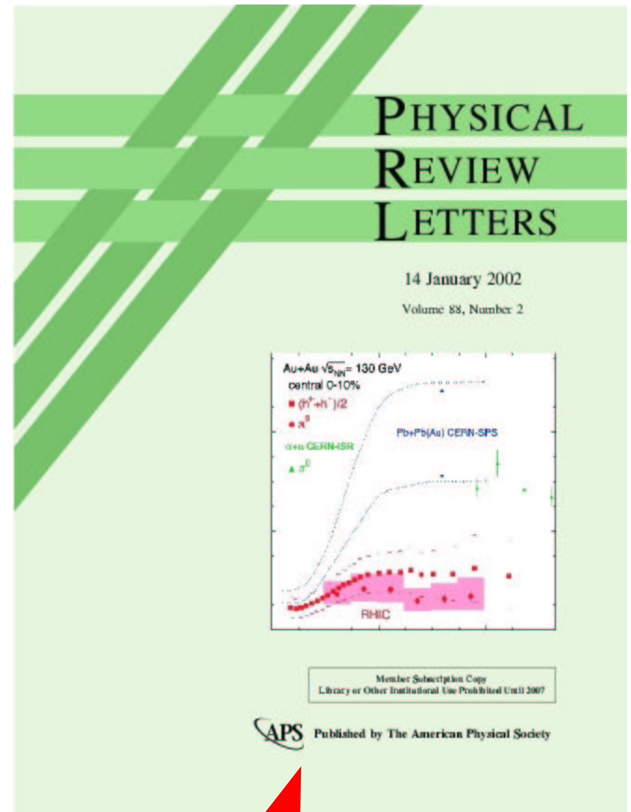


Strong suppression in central AuAu collisions

Nuclear modification factor (π^0)

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



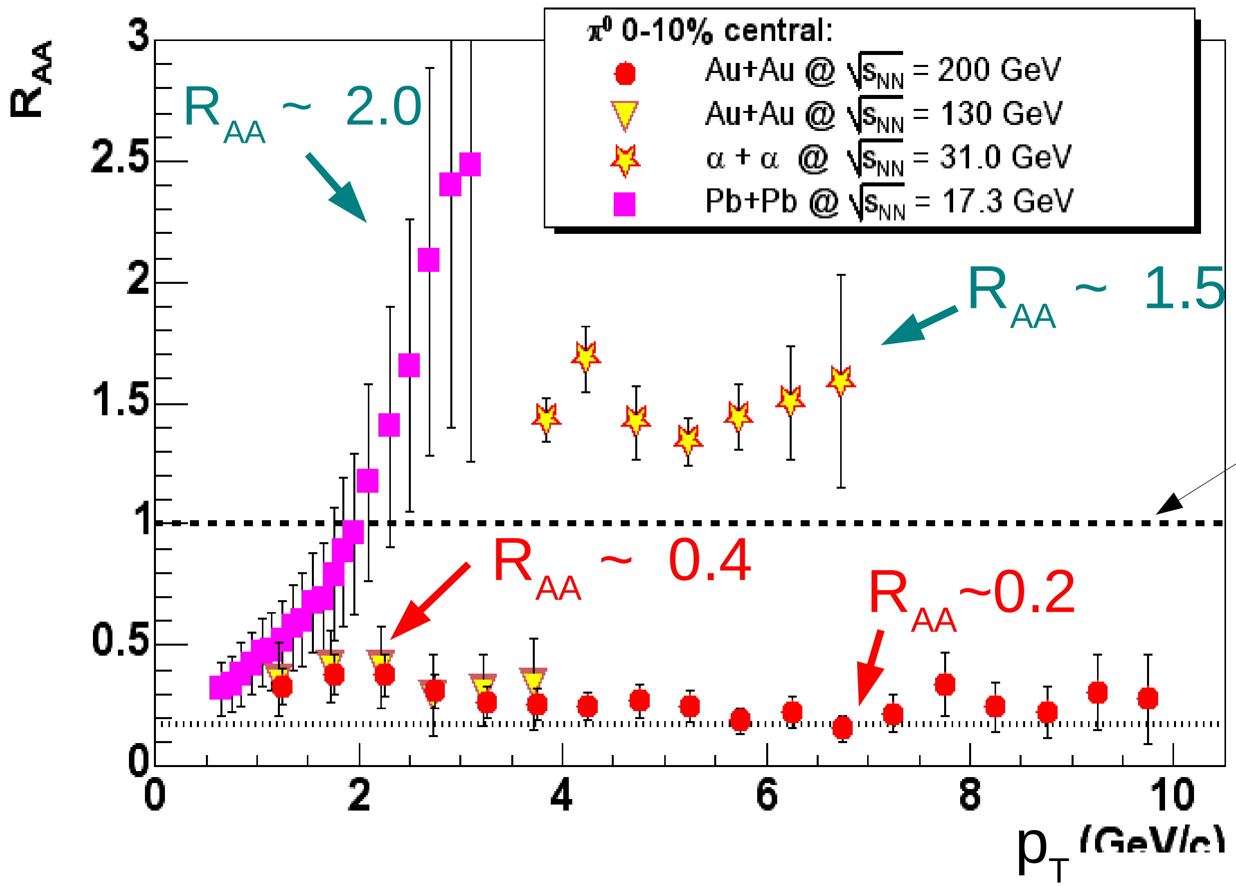


Discovery of
high p_T suppression
(most significant
result @ RHIC)

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

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

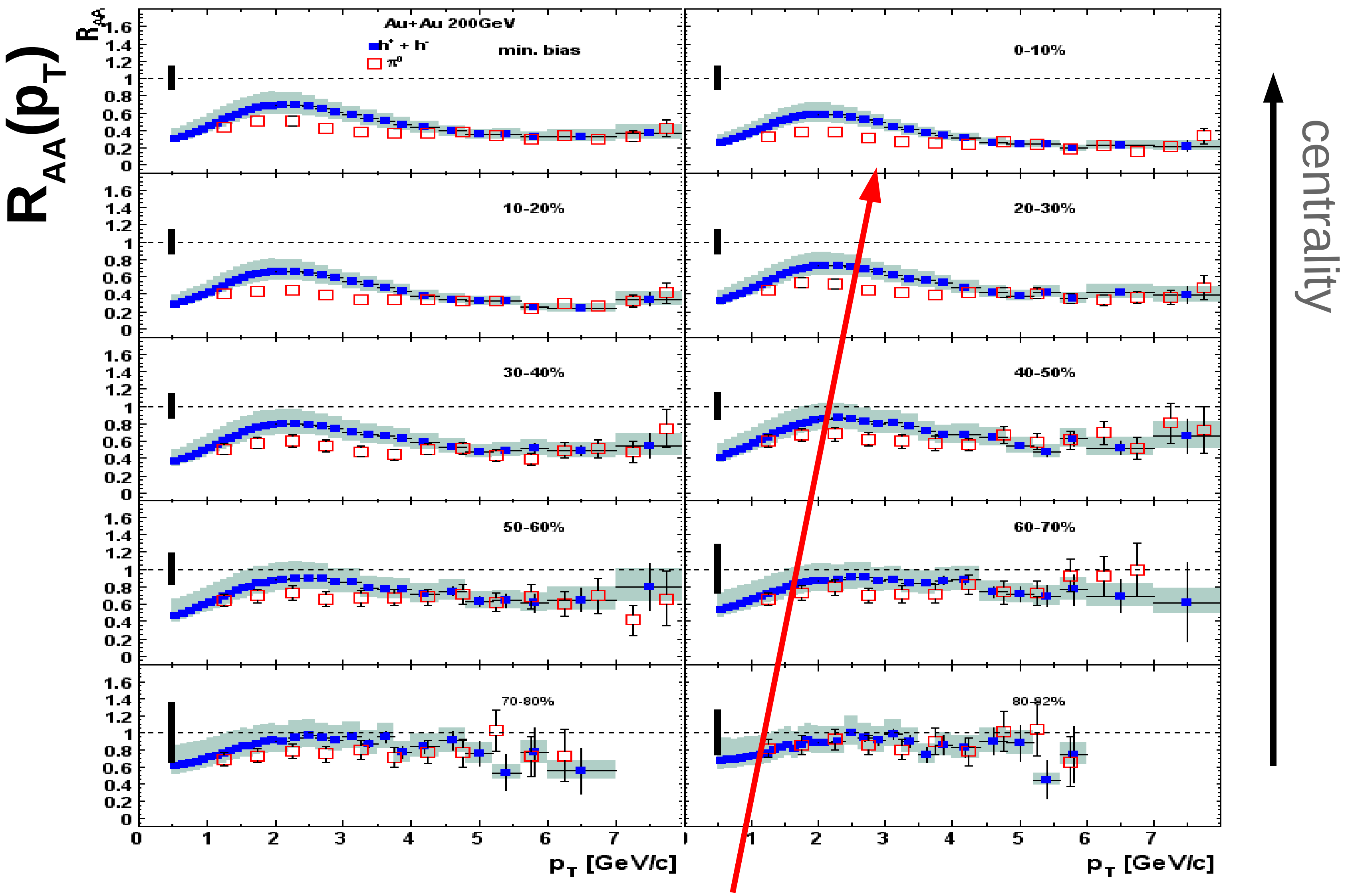
- CERN: Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 GeV), α+α ($\sqrt{s_{NN}}$ ~31 GeV): Cronin enhancement
- RHIC: Au+Au ($\sqrt{s_{NN}}$ ~ 130, 200 GeV): x4-5 suppression with respect to N_{coll}



A.L.S.Angelis PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
PHENIX submitted to PRL, nucl-ex/0304022

$N_{collision}$ scaling

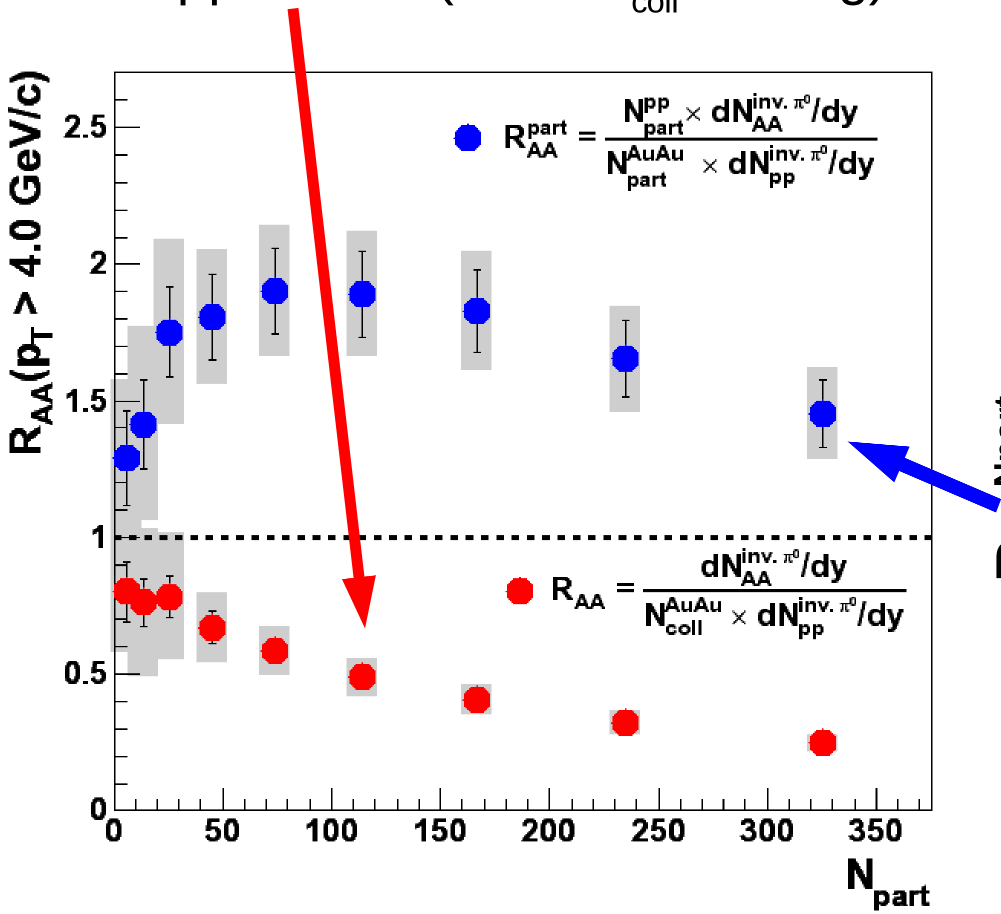
Nuclear modification factor (charged hadrons)



- Less suppression for $h^\pm$ than for π^0 at p_T ~ 2. GeV/c
- Equal suppression (R_{AA}~ 0.2) above p_T ~ 4-5 GeV/c

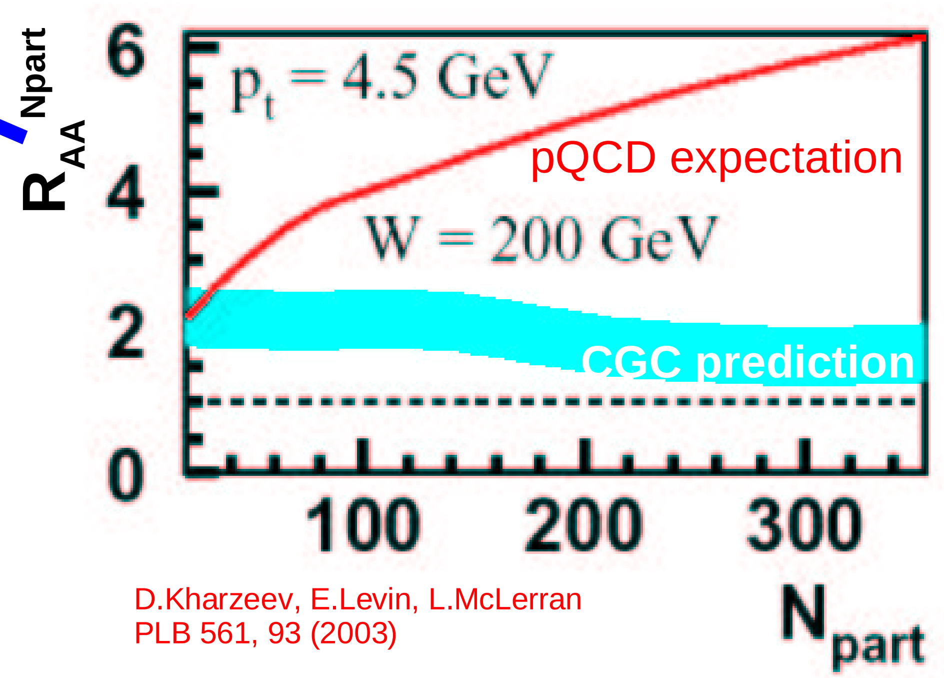
Centrality dependence of suppression (I): N_{part} scaling ?

- Suppression (w.r.t. N_{coll} scaling) increases smoothly with centrality:



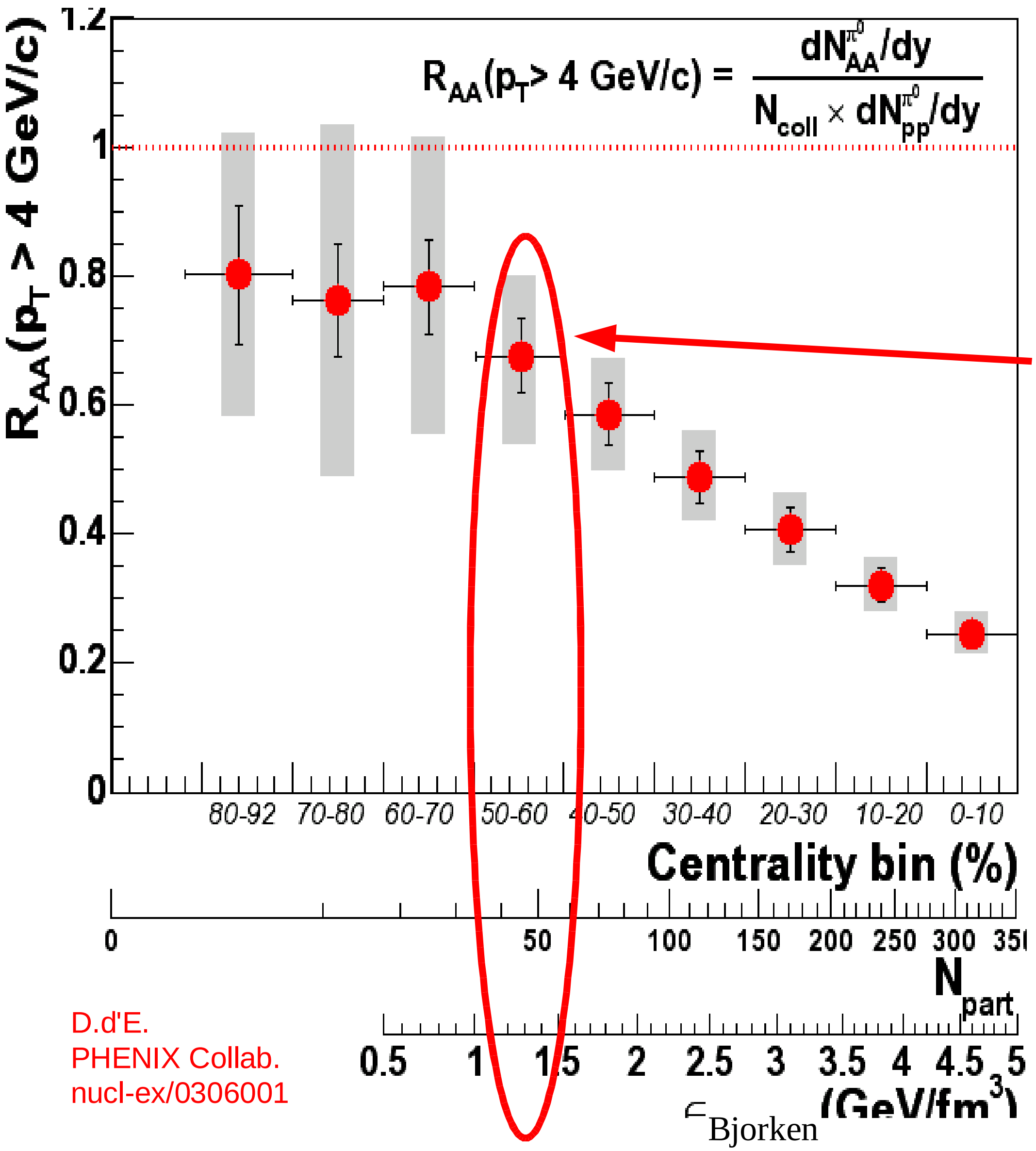
PHENIX
nucl-ex/0304022,
submitted to PRL

- Approximate N_{part} scaling in semiquantitative agreement with Color Glass Condensate prediction



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

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.
- $R_{AA} < 1$ (2sigma) for 50-60% centrality: $N_{part} \sim 50 \pm 15$
  (ball-park of parton percolation predictions ?)

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

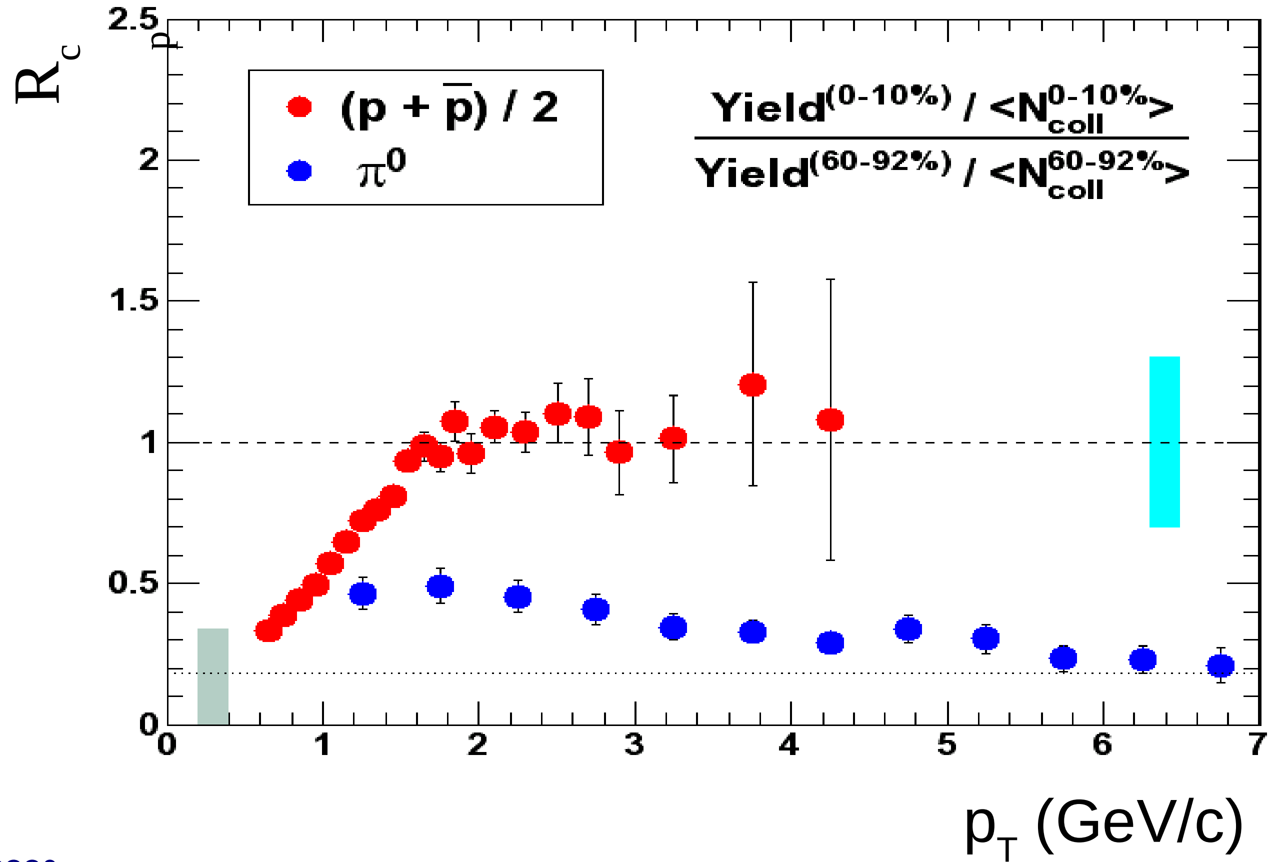
$$\epsilon_{Bj} = \frac{dE_T}{dy} \frac{1}{\tau_0\, \pi R^2}$$

(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

Hadron composition at high-p_T (1): R_{AA} (p,pbar)

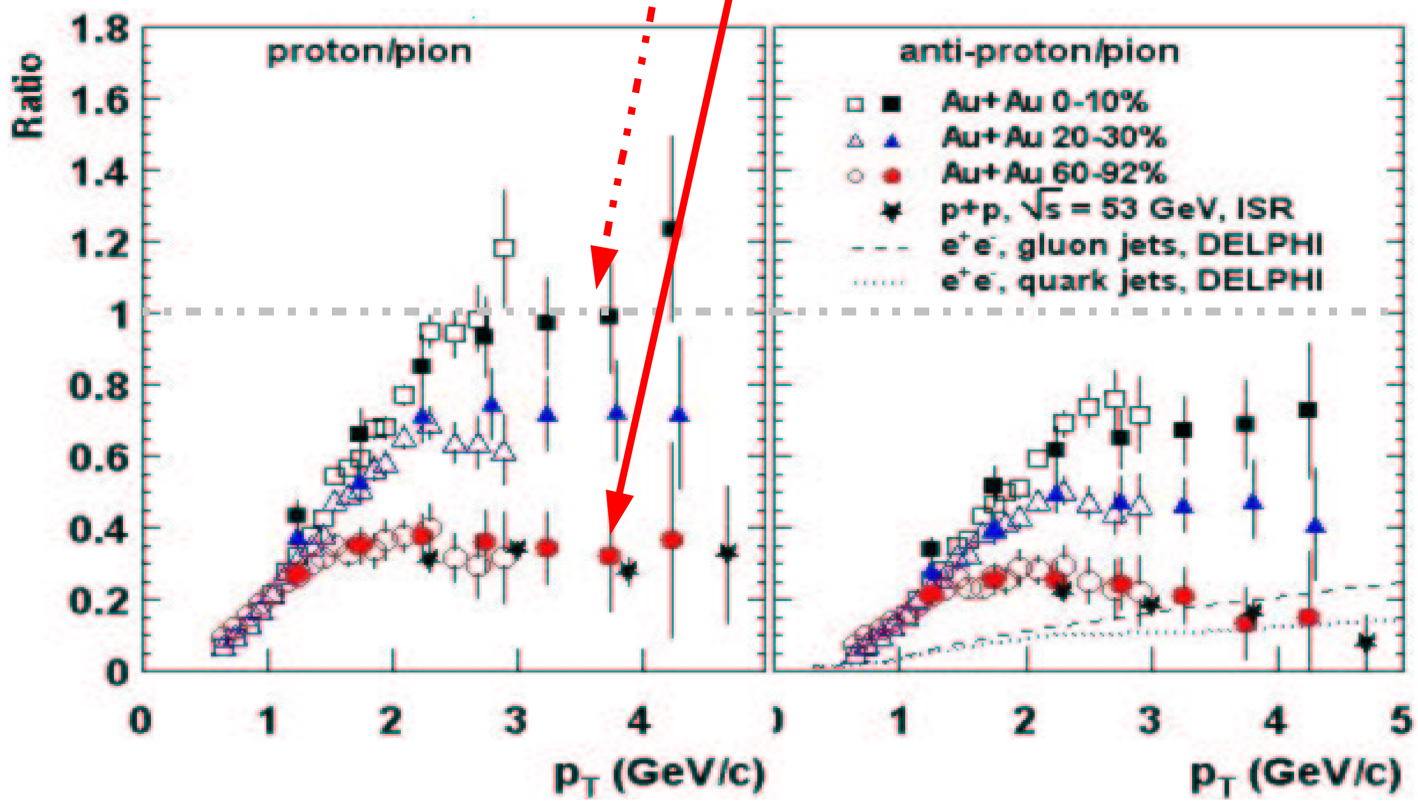
- Protons (antiprotons) **NOT** suppressed in central Au+Au (p_T < 4.5 GeV/c)
- Ratio central/periph ~ $R_{AA} \approx 1$ → N_{coll} scaling holds for baryons.
  - *(Consistent with observed $R_{AA}(h^{\pm}) > R_{AA}(\pi^0)$ in the same p_T range).*
  - Points to different production mechanisms for baryons and mesons in the intermediate p_T range ...



PHENIX Collab.
Submitted to PRL
nucl-ex/0305036

Hadron composition at high-p_T (2): p/π ratio

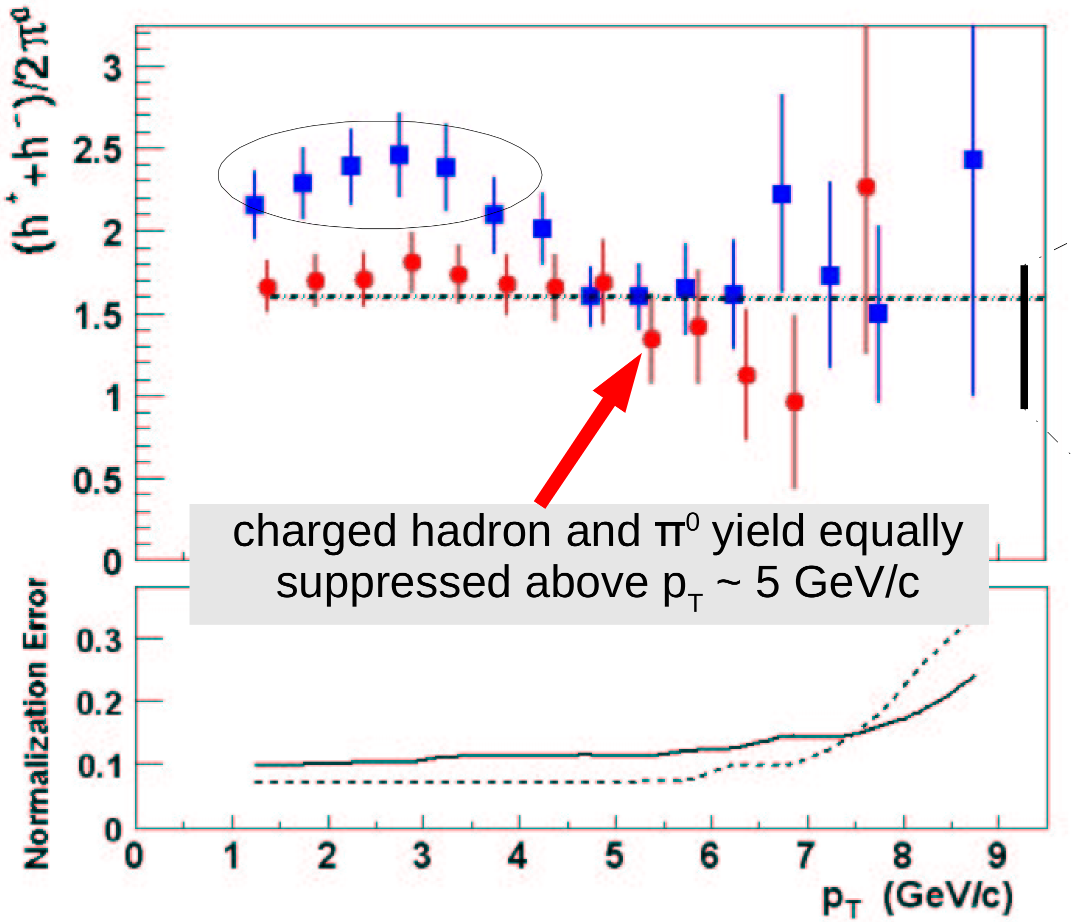
- Pronounced centrality dependence of p/π ratio.
- Central colls.: baryon/meson ~ 1.0 for p_T > 2 GeV/c at variance with perturbative production mechanisms (favour lightest meson).
- Peripheral colls. baryon/meson ~ 0.3 as in p+p,pbar (ISR,FNAL) and in e+e- jet fragmentation

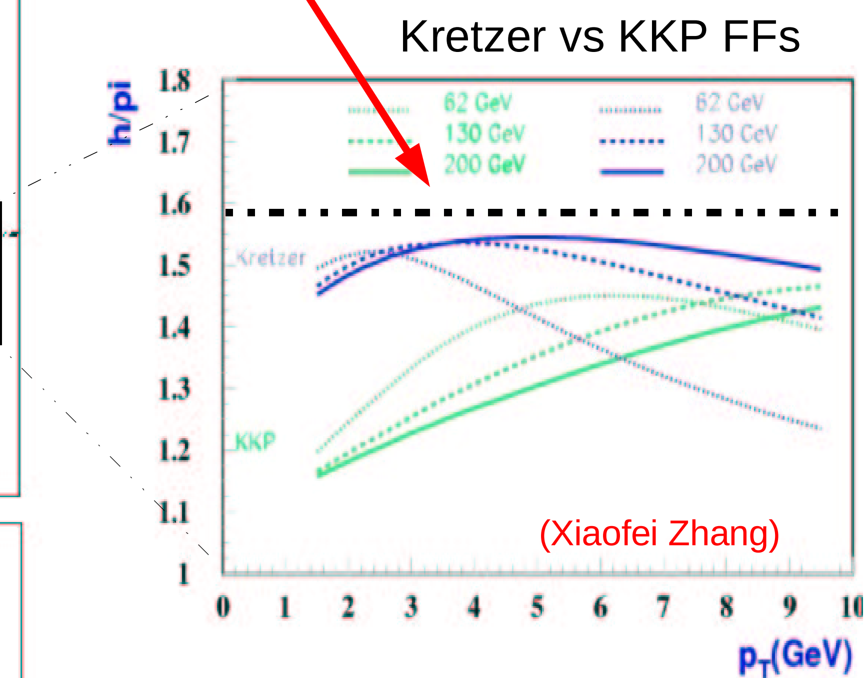


PHENIX Collab.
Submitted to PRL
nucl-ex/0305036

Hadron composition at high-p_T (3): h/π ratio

- Central colls.: $h/\pi \sim 2.5$ at intermediate p_T's (enhanced baryon production)
- Peripheral colls.: $h/\pi \sim 1.6$ as in p+p (perturbative ratio)



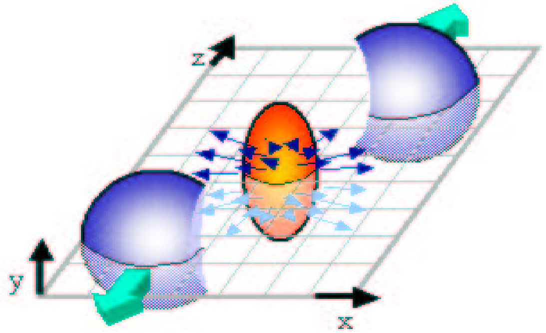


PHENIX Collab.
Submitted to PRL
nucl-ex/0305036

- Since $h^\pm = \pi^\pm + p(\bar{p}) + K^\pm \Rightarrow$ baryon non perturbative enhancement limited to $p_T < 5$ GeV/c

High p_T azimuthal correlations: Elliptic flow

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



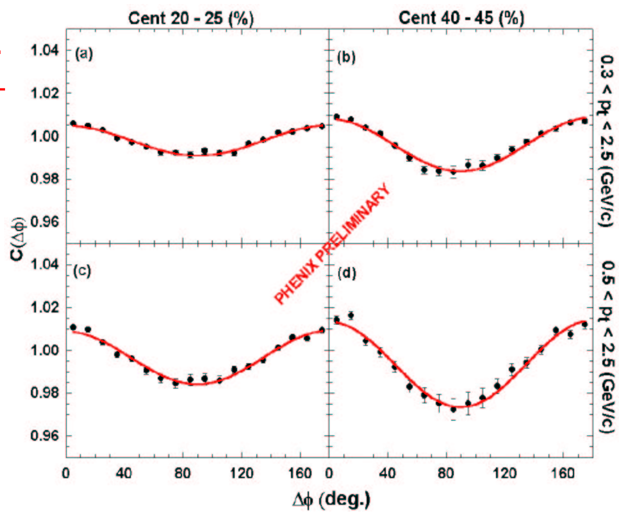
$$\frac{dN}{d\Delta\phi} \propto (1 + v_2 \cos(n\Delta\phi))$$

Flow = v_2 second Fourier coefficient

Truly collective effect: absent in p+p colls.

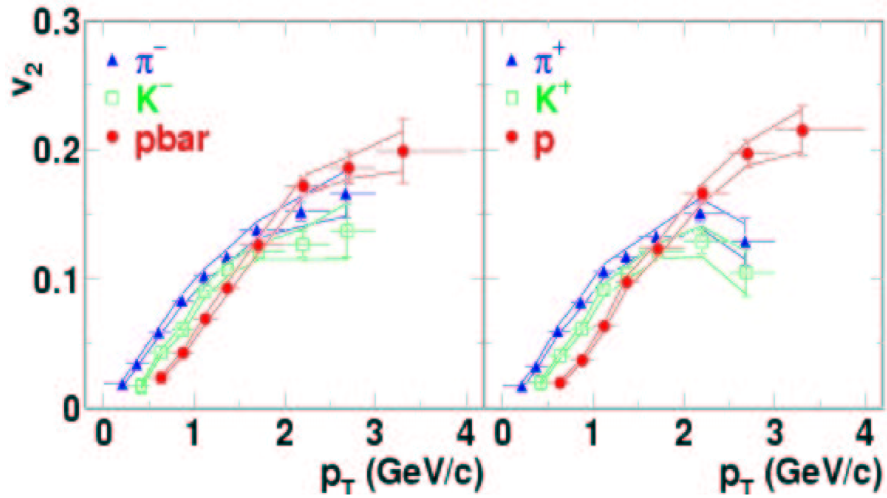
- Exp. correlation functions:

PHENIX Collab.
PRL 89, 212301



- v_2 saturation at high p_T:

PHENIX Collab.
Submitted to PRL
nucl-ex/0305013



- Strong elliptic flow signal $\Rightarrow$ strong (collective) pressure gradients $\Rightarrow$ large and fast (t<1.0 fm/c) parton rescattering (early thermalization).

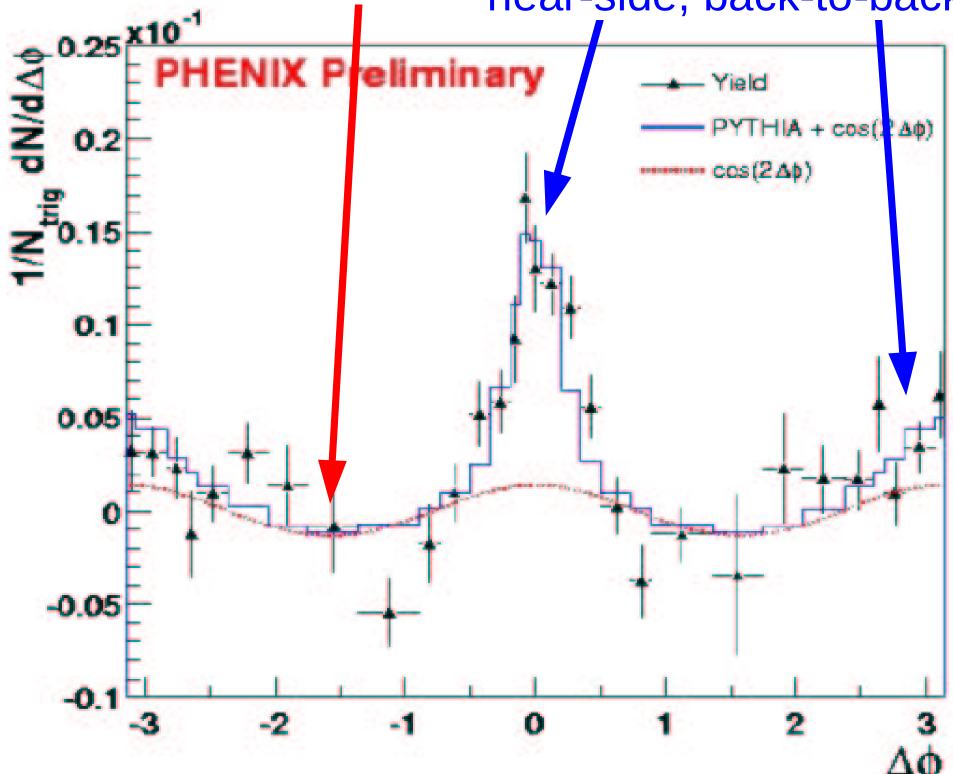
High p_T azimuthal correlations: jet signals in AA

- High-p_T γ (π^0) triggered (p_T > 4GeV/c) events: $dN/d\Delta\phi$ for $h^\pm$ (p_T = 2- 4 GeV/c)

$$\frac{1}{N_{trig}}\frac{dN_{ch}}{d\Delta\phi} \sim \left(a_{bkg} + a_{flow}\cos(2\Delta\phi) + a_{pythia}\frac{1}{N_{pythia}}\frac{dN_{ch}}{d\Delta\phi}\right)$$

Flow harmonic contribution

Jet-like signal: near-side, back-to-back



- Near-side correlation unmodified: trigger particles (p_T > 4GeV/c) from jets

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

✔ *Goal: explain central colls. (magnitude of quench, p_T dependence)*

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

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

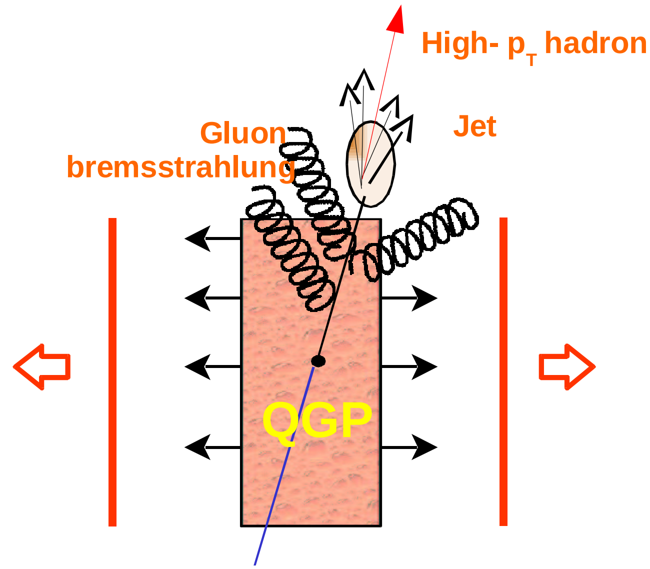
APPROACH "B" ("classical" QCD):

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)

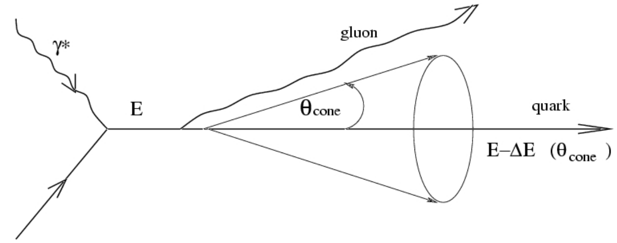
- Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium:



  - 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: $dE/dx \sim \alpha_s \langle k^2_T \rangle$
  - Formalisms: BDMPS (thick plasma), GLV (thin plasma), Wiedemann (both).
  - Correction for expanding plasma:
    $\Delta E_{1\text{-}D} = (2\tau_0/R_A) \cdot \Delta E_{stat} \sim 15 \cdot \Delta E_{stat}$ (τ_0=0.2 fm/c, R_A=6 fm)

Final-state QGP effects (II)

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

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

  - Large initial gluon densities:

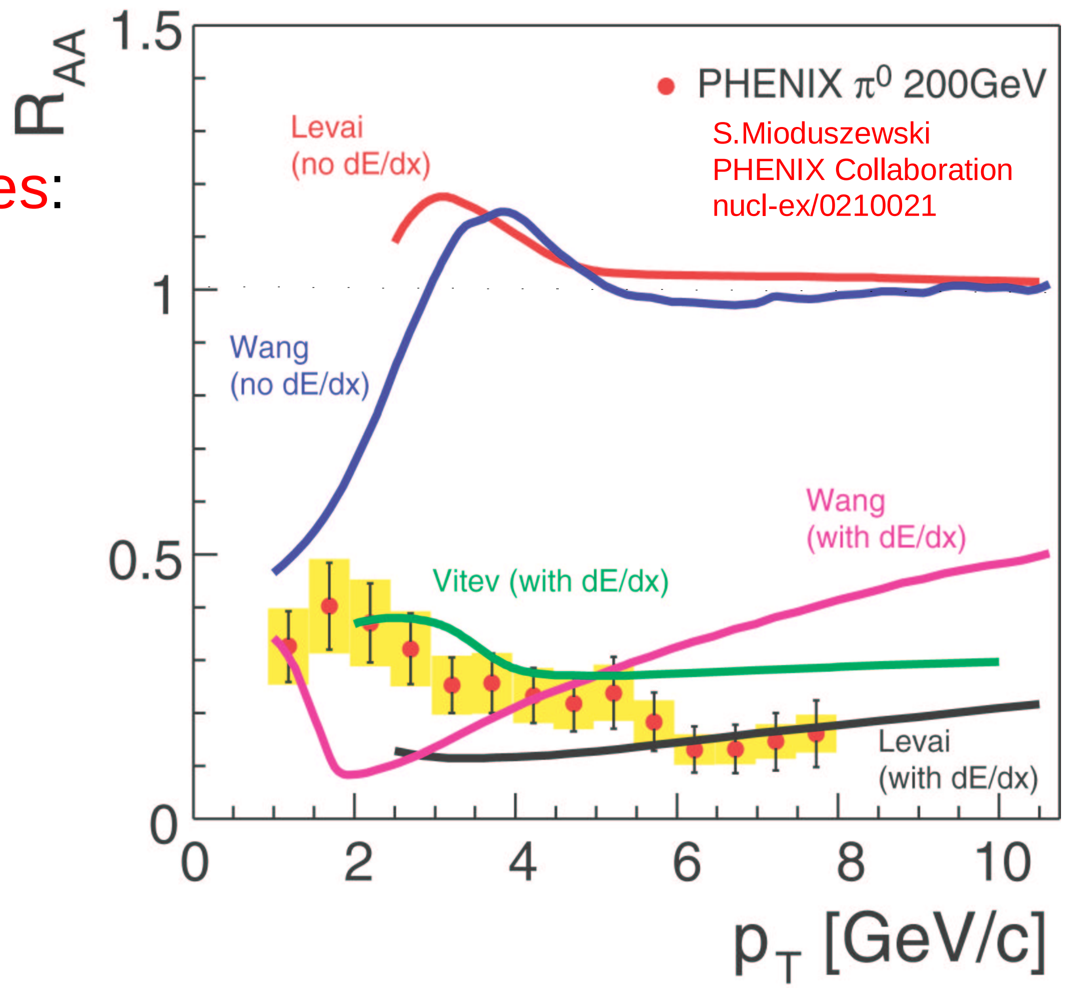
    $dN^g/dy \sim 800\text{-}1200$

  - Transport coefficients:

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

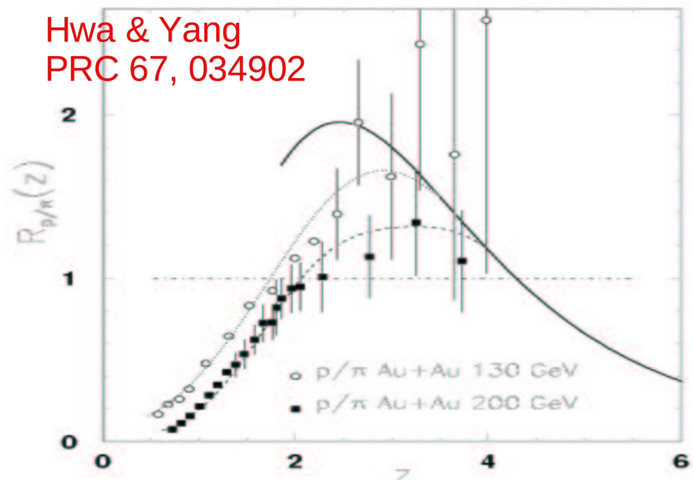
  - Medium-induced gluon radiative energy losses:

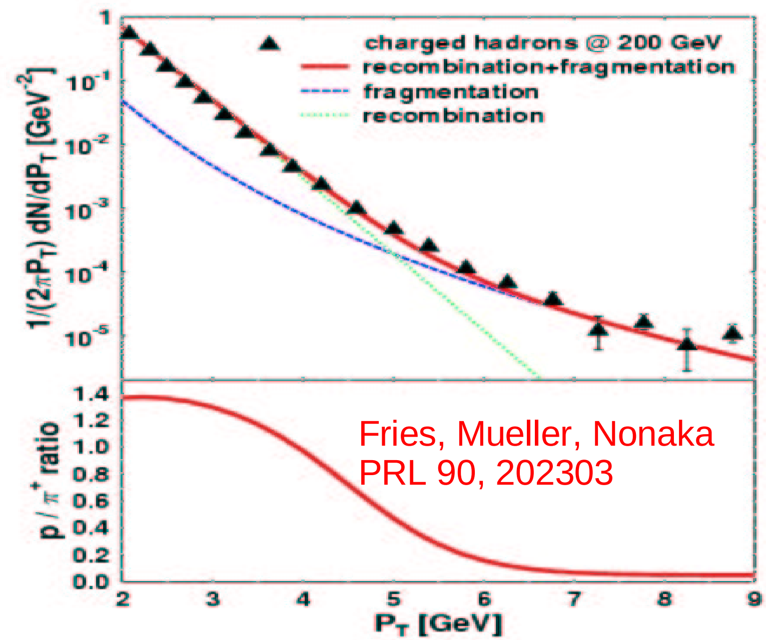
    $dE/dx \approx 0.25$ GeV/fm (expanding)
    $dE/dx|_{eff} \approx 14$ GeV/fm (static source)

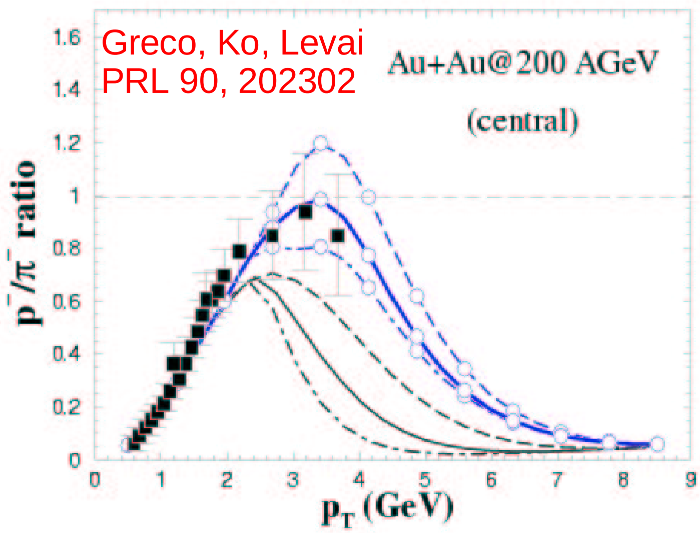


Final-state QGP effects (III)

- Quark recombination/coalescence tries to explain the anomalous high p_T "chemistry"







- High parton densities in a thermal medium favor 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 $z<1$

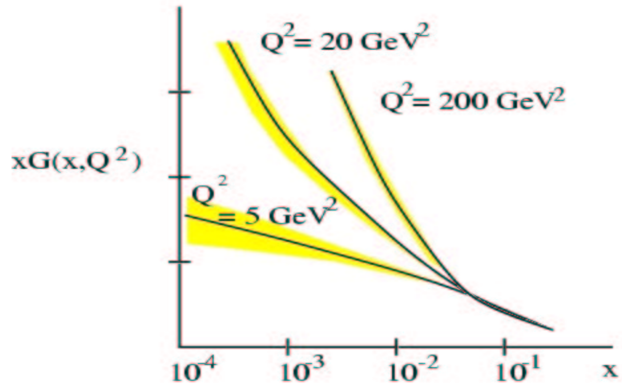
Initial-state effects in a Color Glass Condensate

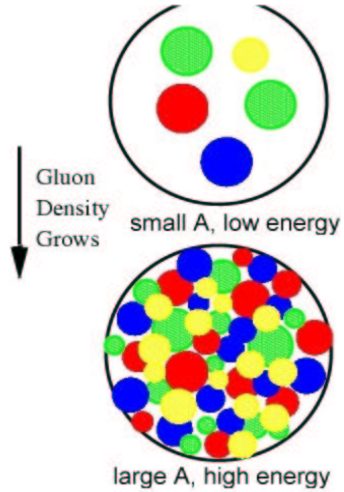
- Initial conditions at RHIC: high-energies + large nuclei
  - Values of small-x: $x_{Bj} = 2p_T/\sqrt{s} \ll 1$

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:

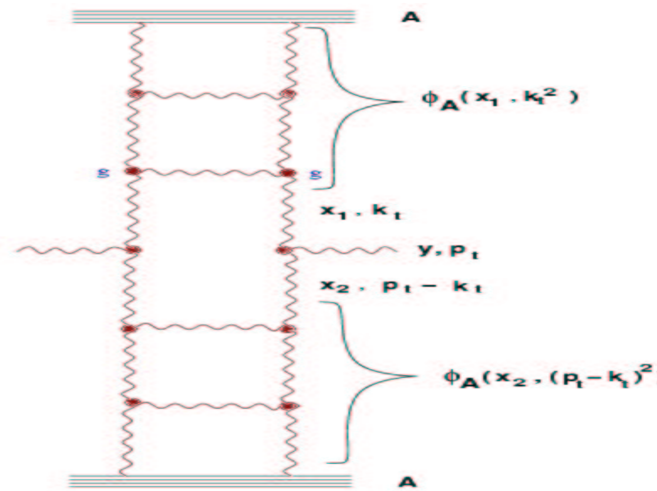
$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2} \sim 1.5\ \text{GeV}^2/c^2 \text{ @ RHIC}$$

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

"Classical" (Chromo-Dynamics) methods applicable

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

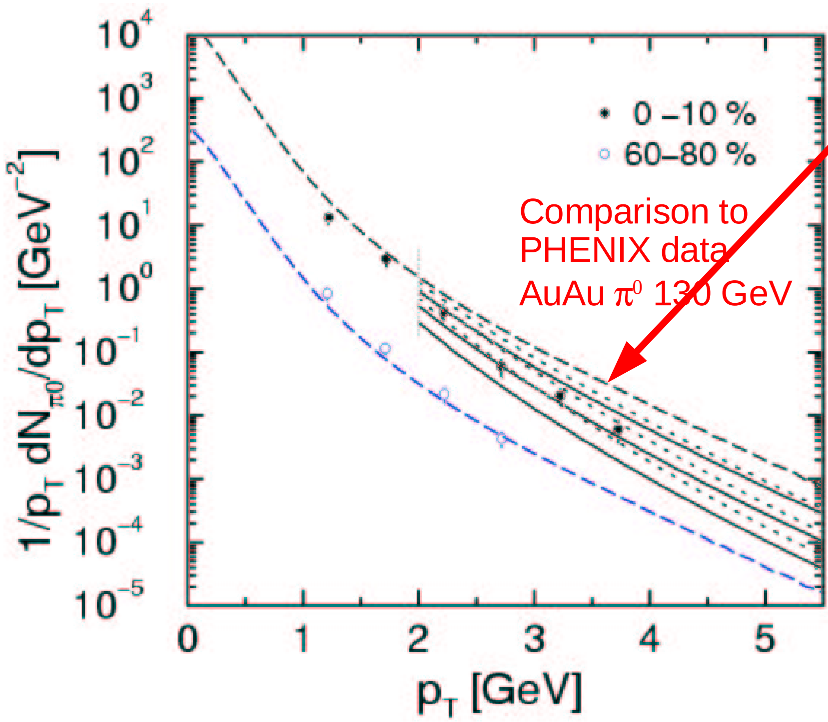
- Particle production via glue-glue collisions:

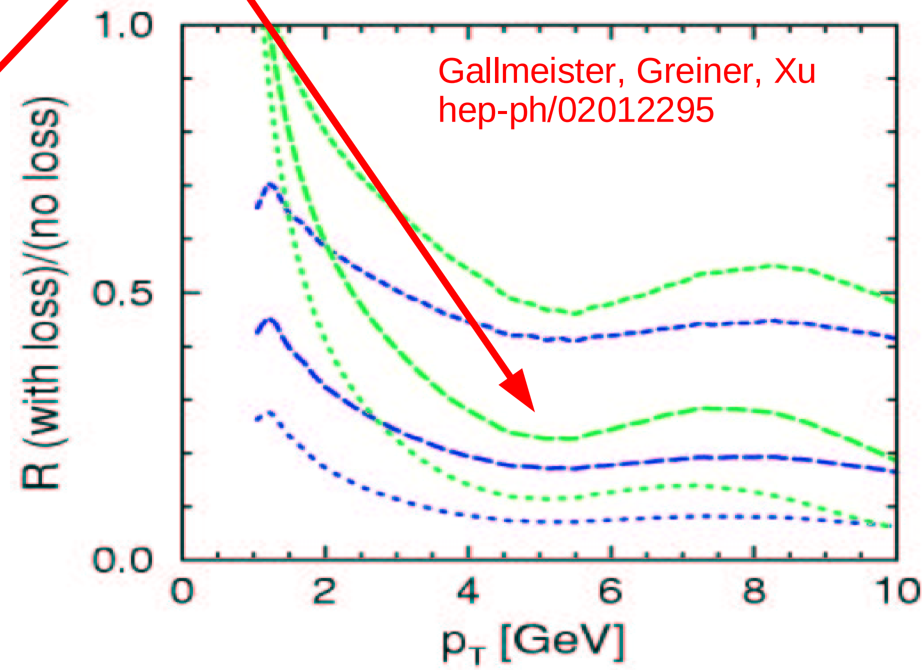


- Suppression due to reduced partonic scattering centers in the initial-state

Final-state effects in a dense hadronic medium ?

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

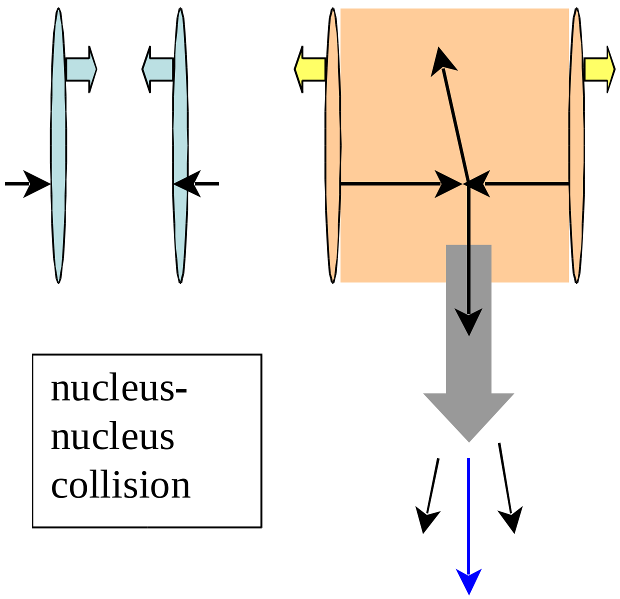


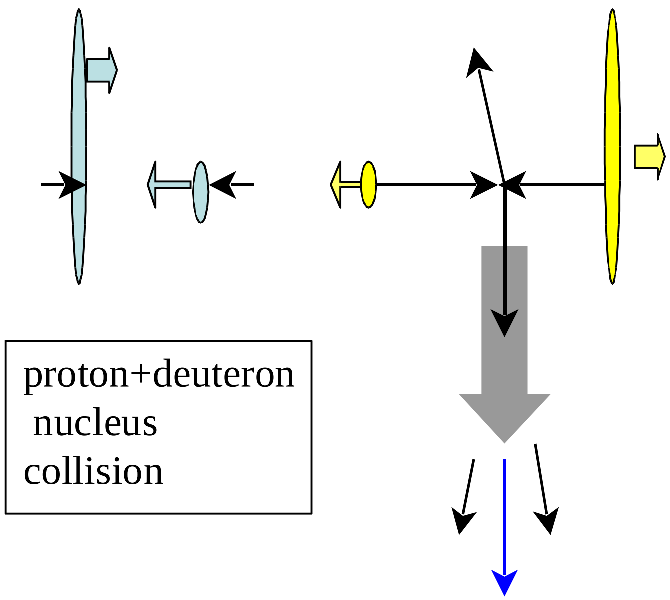


- Main argument: fast parton hadronization time + rescatering of hadronic jet fragments inside expanding fireball.
- Description of scattering in the hadronic phase realistic enough ?
(“... *our calculations are at best semiquantitative* ...”).

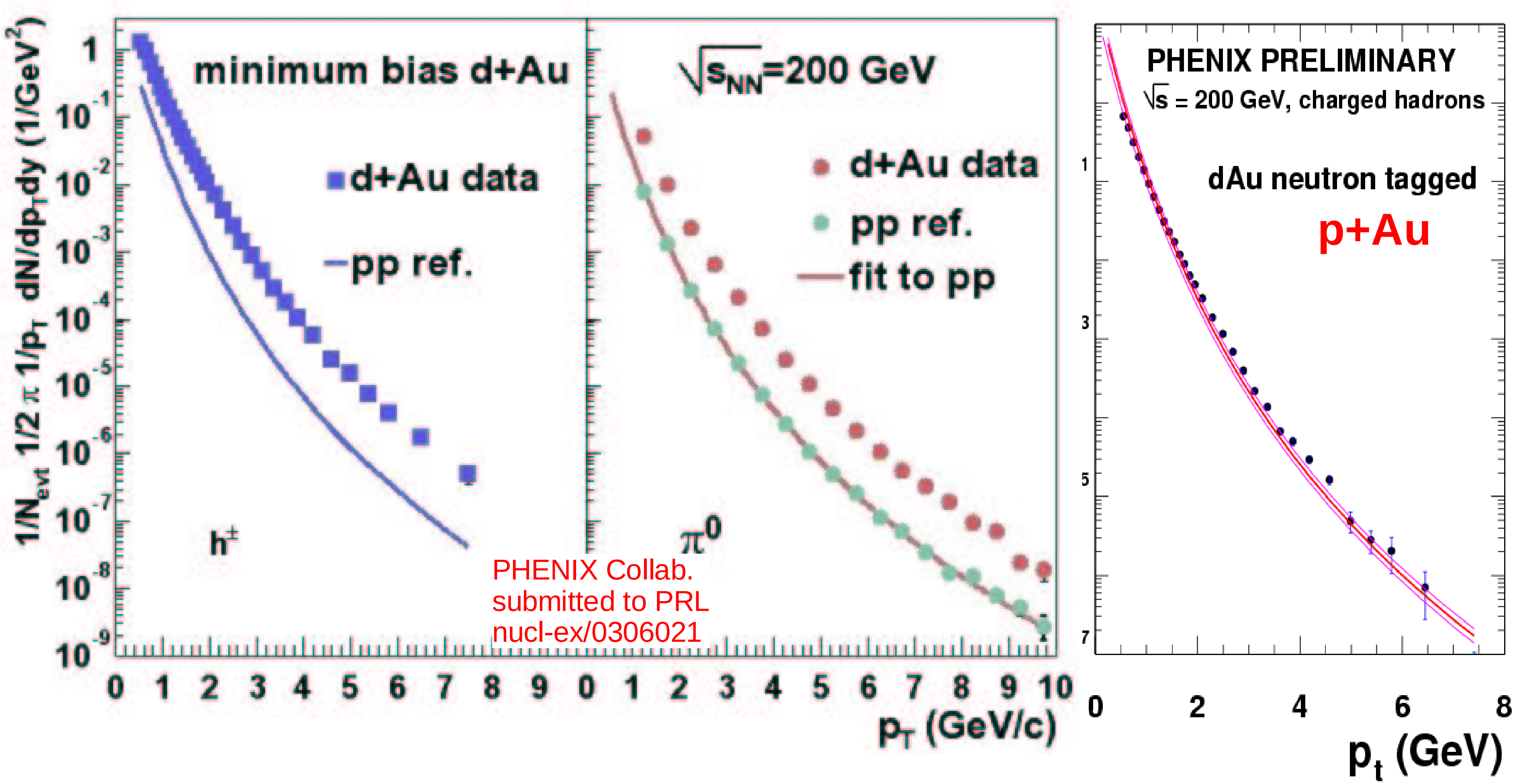
d+Au (“control” experiment)
high p_T results

“hot & dense” vis-à-vis “cold” QCD medium.
(final- versus initial- state effects)



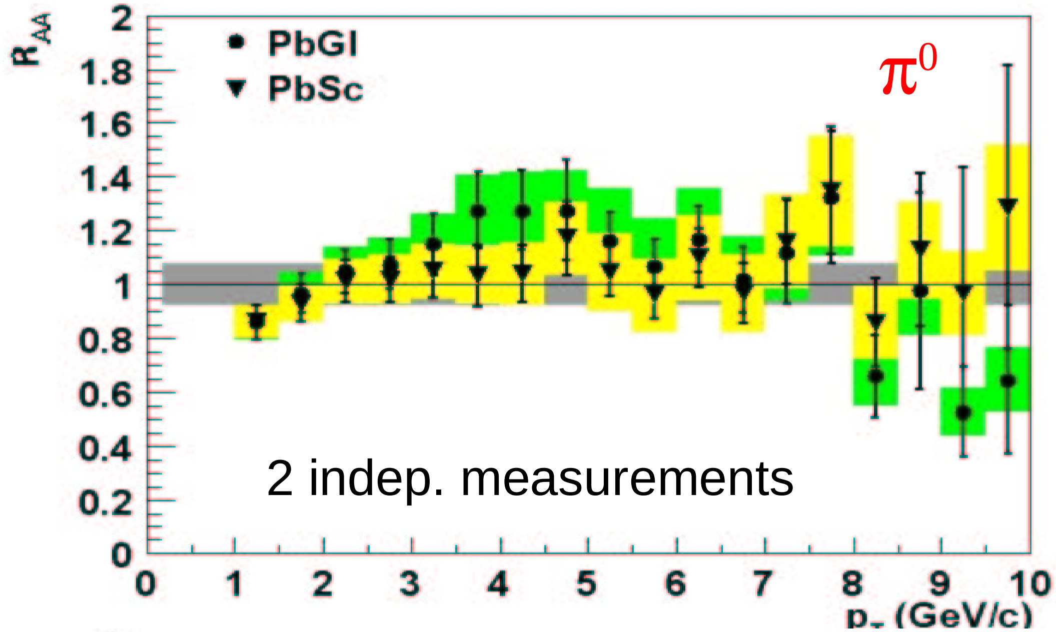


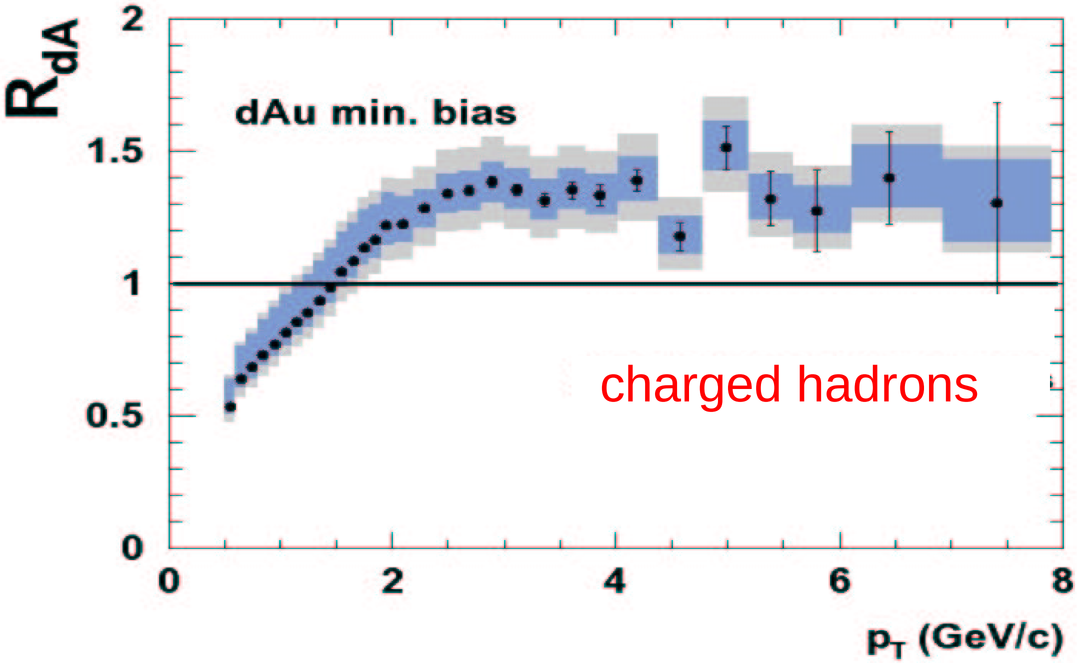
High p_T in d+Au, p+Au @ 200 GeV



- Neutral pions up to ~10 GeV/c. Charged hadrons up to ~8 GeV/c.
- p+Au collisions selected in neutron-tagged d+Au events

d+Au (min. bias) nuclear modification factor (I)





No suppression observed in min. bias d+Au reactions (N_{coll}= 8.4±0.4)

- Neutral pions: R_{dAu} ~ 1.1
  (Slight enhancement with respect to collision scaling)

  Apparent decreasing trend above 8 GeV/c

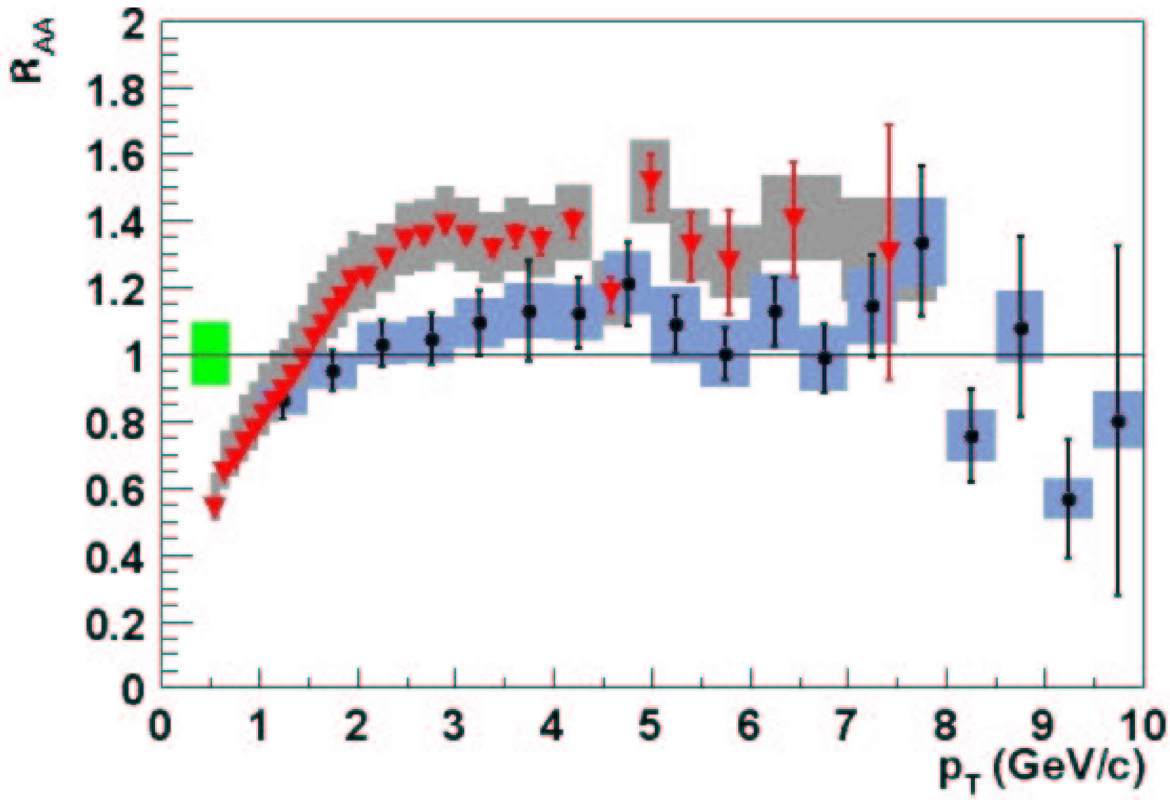
- Charged hadrons: R_{dAu} ~ 1.4
  (Larger enhancement)

  ~ flat between 3 – 8 GeV/c

PHENIX collab.
submitted to PRL
nucl-ex/0306021

d+Au (min.bias) nuclear modification factor (II)

- Combined R_{dAu} for charged hadrons and π^0 :

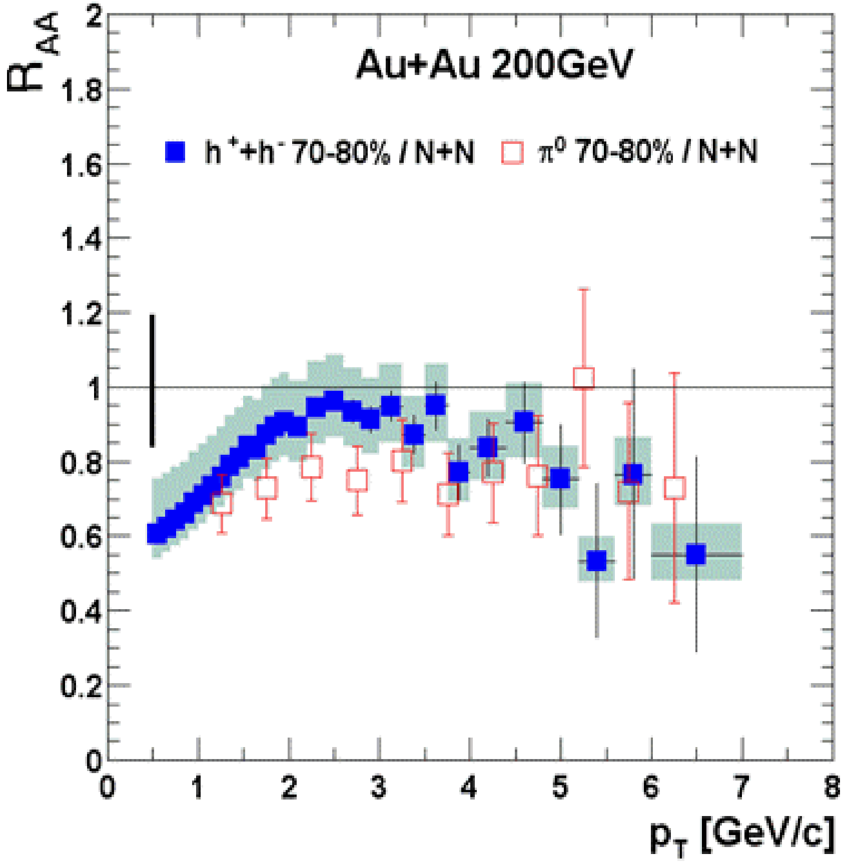


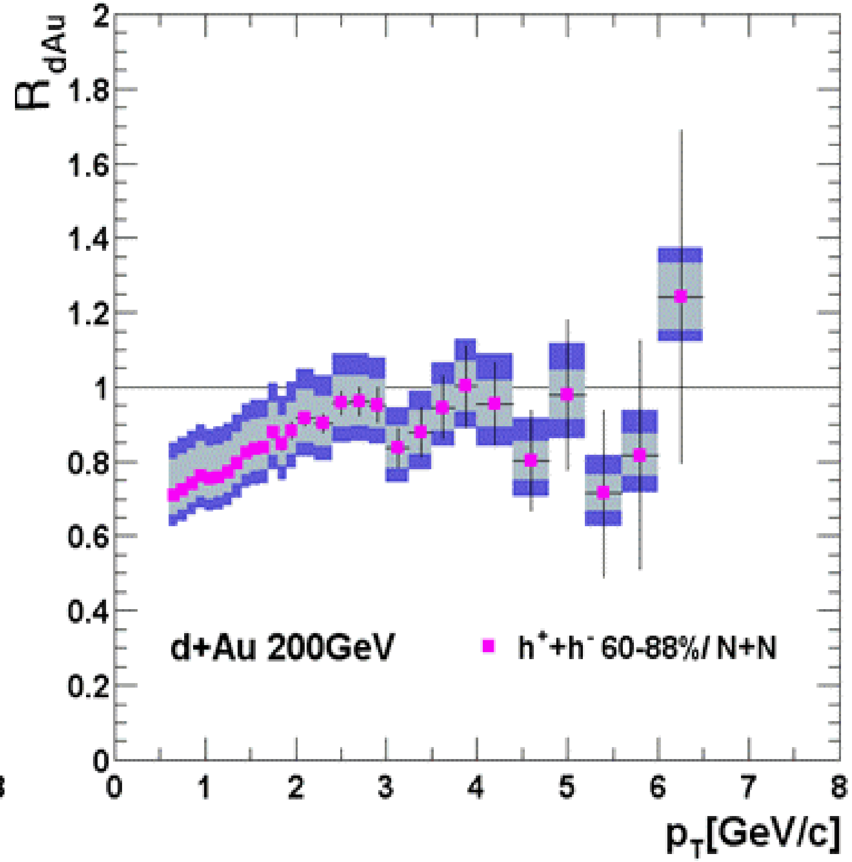
PHENIX collab.
submitted to PRL
nucl-ex/0306021

- d+Au results at RHIC clearly reminiscent of p+A "Cronin effect" (initial-state soft and semihard scatterings).
- No shadowing or strong saturation of Au PDF.
- Same results in p+Au (neutron-tagged) collisions

Nuclear modification: d+Au vs Au+Au

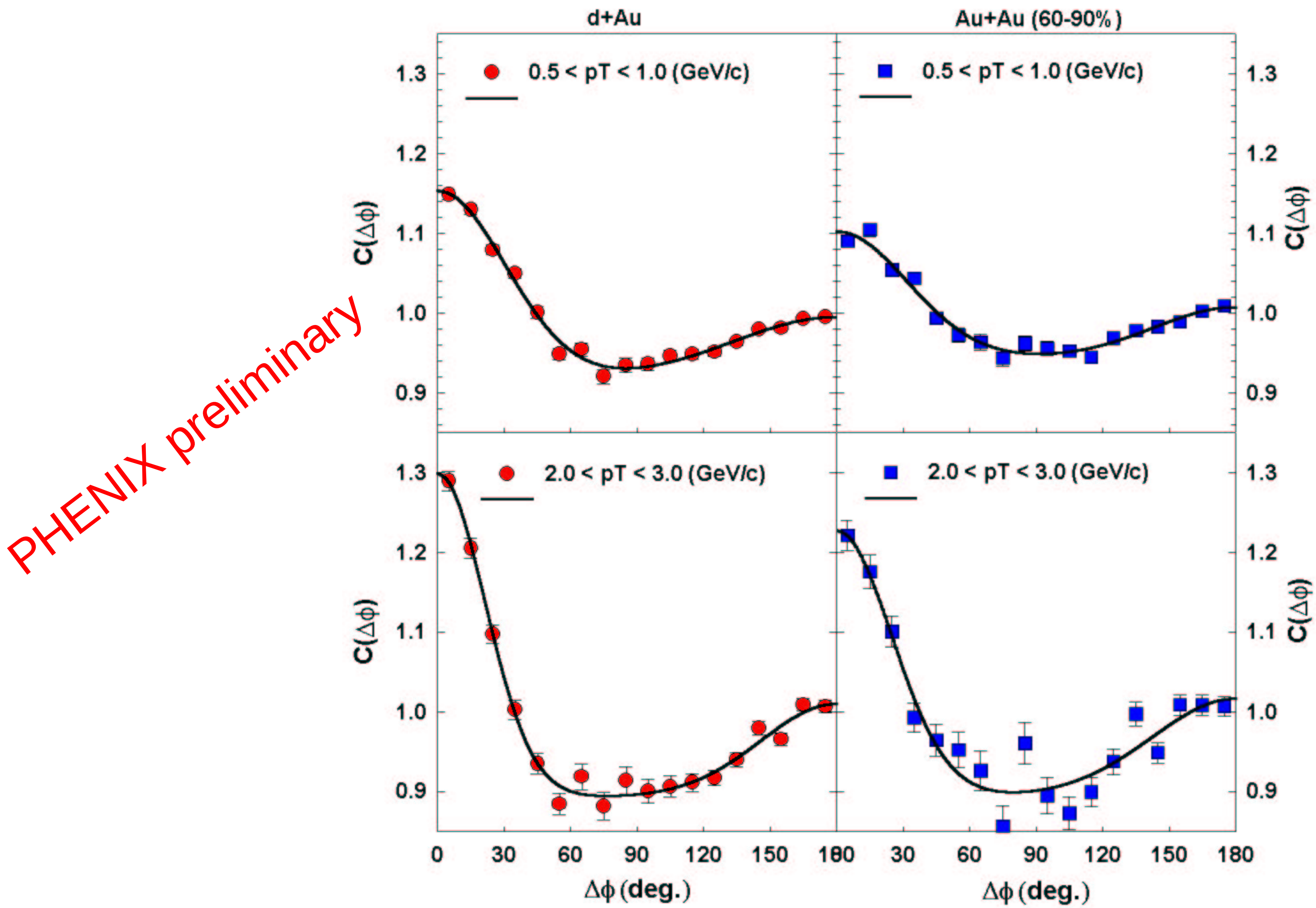
PHENIX preliminary





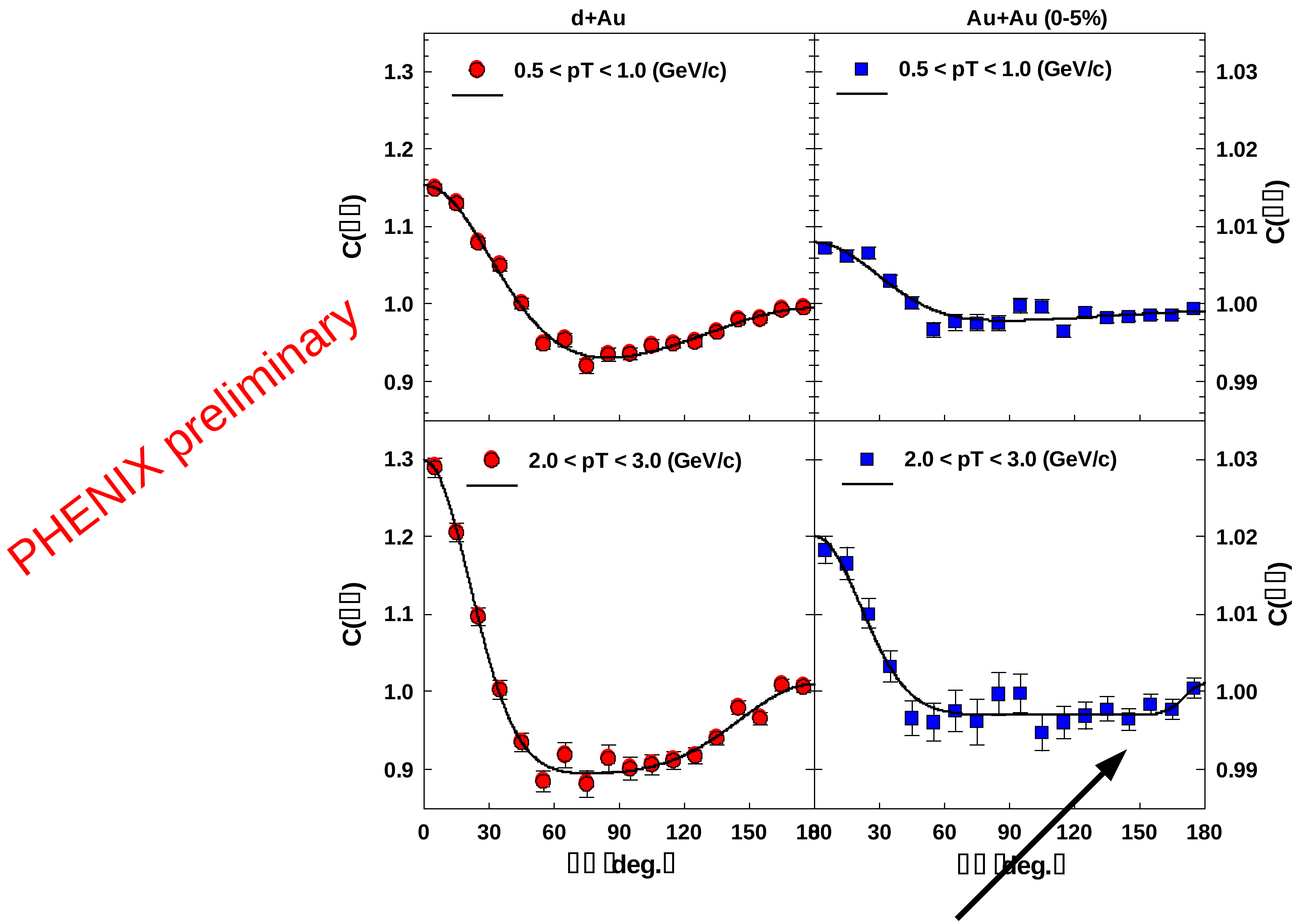
- Opposite centrality dependence of nuclear enhancement (in p+Au) compared to nuclear suppression (in Au+Au) !
- Conclusion: Au+Au suppression not due to a "cold" nuclear matter (initial-state) effect.

High p_T azimuthal correlations (d+Au and Au+Au periph)



- Jet-like near- and away- side azimuthal correlations.

High p_T azimuthal correlations (d+Au and Au+Au central)



- Diminished away-side correlation consistent with lost jet “far side”

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.

(*) by confronting data to theory

“QGP” models vs. data (I)

arguments in favour ...

✔ Foreword: Jet quenching is a true prediction of QGP models.

✔ Magnitude of Au+Au suppression → properties of dense 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 (detailed comparison of quenching vs N_{part} needed).

✔ x_T dependence of Au+Au yields → indication of perturbative (hard) mechanisms (modulo baryons in central reactions).

✔ No suppression in d+Au collisions.

"QGP" models vs. data (II)

somehow "weaker" points ...

- p_T dependence of Au+Au suppression → not described in 1st instance:
  - Additional nuclear effects needed to "flatten" LPM R_{AA} (though they are probably justified given the d+Au results)
- √s dependence of Au+Au suppression clear ?
  - Why there is no jet quenching observed in Pb+Pb @ SPS if $dN^g/dy \sim 500$?
  (*usual explanations: small plasma life-time, quark-dominated plasma, very small hard scattering cross-section, ...*)
- Particle species dependence of Au+Au suppression ("baryon enhancement") → not described in 1st instance:
  - Additional non-perturbative final state effects (quark recomb., baryon junctions, others ?) needed.

"CGC" models vs. data

- ✗ Caveat: High p_T at midrapidity at RHIC is above $Q_s \sim$ 1-2 GeV/c (straight application of CGC questionable in first instance).
- ✔ Magnitude of Au+Au suppression → saturated Au wave function (Kharzeev *et al.*). But: no suppression expected in Baier, Wiedemann *et al.* calculations
- ✔ Centrality dependence of Au+Au suppression → N_{part} scaling -like observed (modulo quantitative details).
- ✗ Some deficit expected in d+Au collisions (Kharzeev *et al.*).
- ✔ d+Au Cronin enhancement built in the initial wave function (Baier, Wiedemann *et al.*). Similar conclusions by J.Jalilian too (though no calculations at y = 0), but missing in KLM.

Somewhat confusing interpretation of Au+Au, d+Au results.
More converging agreement needed between diff. calculations ...
(in any case, they seem to describe either Au+Au or d+Au observations, but not both at once)

Hadronic model vs. data

✗ Caveat: 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 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 !

Summary (I)

- Scientific goals of high-energy heavy-ion physics:
  - Investigate the QCD phase diagram.
  - Produce/study the QGP in the laboratory: color deconfinement & chiral symmetry restoration
  - Probe the quark-hadron phase transition of the early Universe.
  - Study high gluon density & small-x physics.

- Means:
  - Producing the densest and hottest matter ever formed on Earth in high-energy ($\sqrt{s}$ ~ 200 GeV) Au-Au collisions.
  - Analyzing the experimental probes (global, hard, ...) that are sensitive to this new state of matter.

- PHENIX high p_T data:
  - *Au+Au @ $\sqrt{s_{NN}}$ = 130 GeV: inclusive charged hadrons, π^0, p,pbar, $e^{\pm}$*
  - Au+Au, p+p @ $\sqrt{s_{NN}}$ = 200 GeV: inclusive spectra, π^0, p,pbar, azimuth. corr.
  - d+Au @ $\sqrt{s_{NN}}$ = 200 GeV: inclusive charged hadrons, π^0, azimuth. corr.

Summary (II)

- Central Au+Au collisions:
  - Strong suppression (factor ~ 4-5) of π^0 and $h^\pm$ (with respect to N_{coll} scaling) above p_T~ 4 GeV/c.
  - Flat p_T dependence of suppression above ~4 GeV/c.
  - Very different behaviour than at lower $\sqrt{s}$ (high p_T enhancement).
  - Suppression pattern seemingly gradual with centrality (no apparent step-wise pattern tough this is not yet 100% settled).
  - Very approx. N_{part} scaling.
  - No apparent suppression of (anti)protons up to ~4 GeV/c: "anomalous" p/π ~ 0.8 ratio >> than in p+p and e+e- jet fragmentation.
  - Hadron/meson ~ 1.6 above p_T~ 5 GeV/c as in p+p (baryon enhancement limited to p_T<5 GeV/c).
  - Strong elliptic flow signal (early collective rescattering).
  - Jet-like signal in azimuthal near-side correlations.
  - Suppression of jet away-side azimuthal correlations.

Summary (III)

- 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 in min. bias d+Au (and p+Au) reactions.
  - 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 "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) reproduce more aspects of the data (Au+Au, d+Au) than other approaches.
  - Non negligible "leftovers" lacking fully consistent explanation.

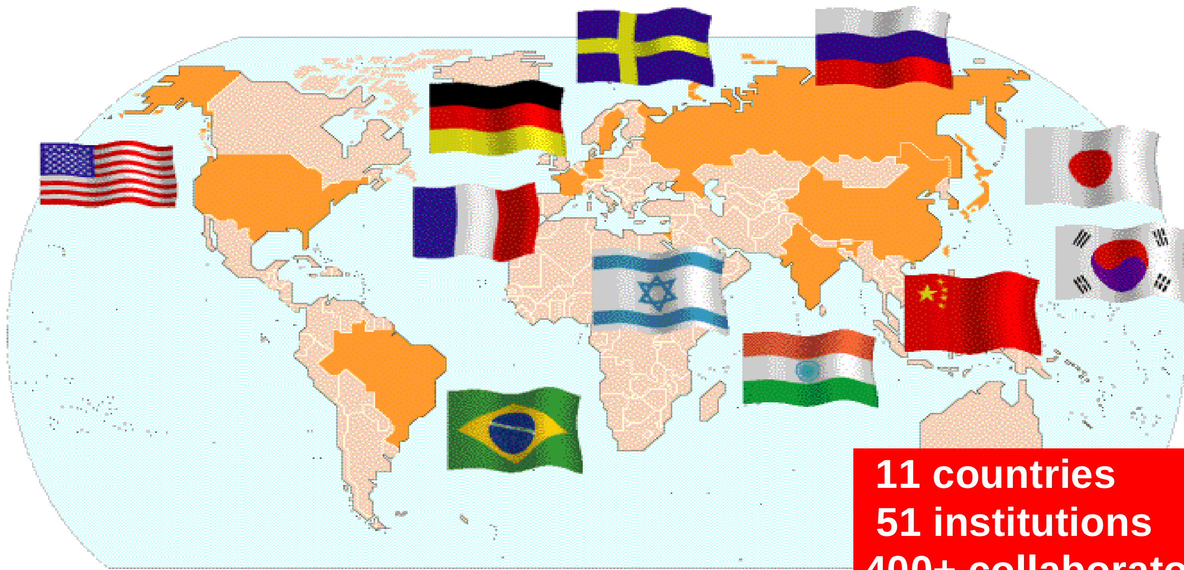
- (Personal) Corollary: "*We've got ~1/3 of QGP evidence at RHIC. Let's wait (not very long !) for the J/ψ and the photons ...*"

backup slides ...

The PHENIX collaboration

Pioneering High-Energy Ion eXperiment

PHENIX



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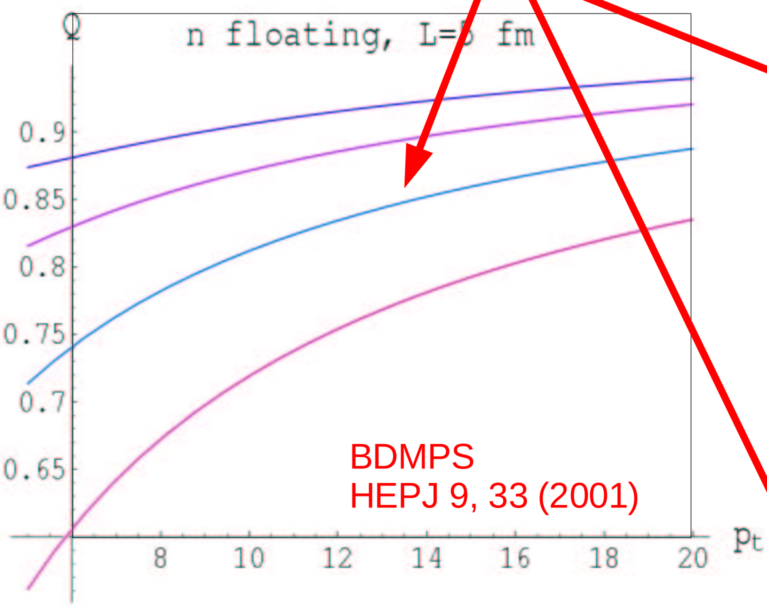
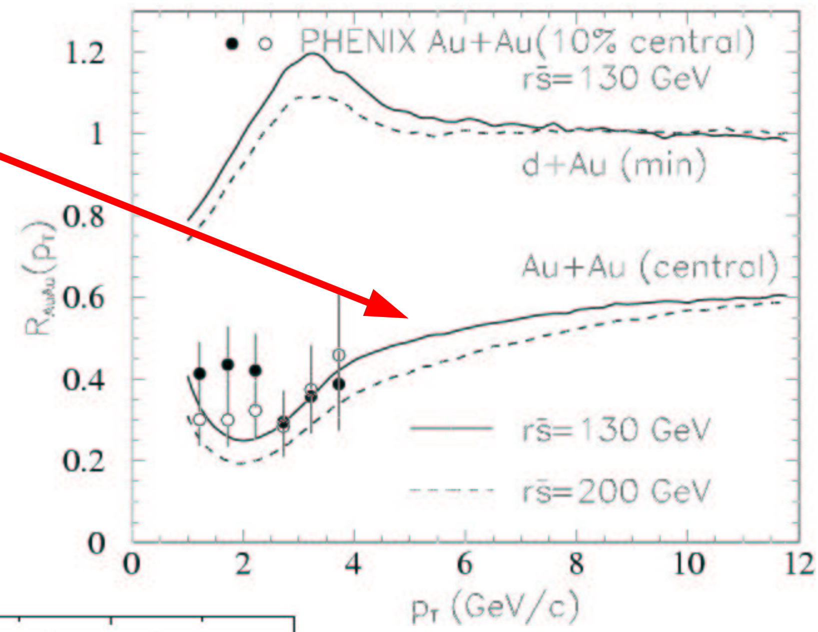
Vanderbilt University, Nashville, TN 37235, USA

"Jet quenching" models: p_T depend. of suppression (I)

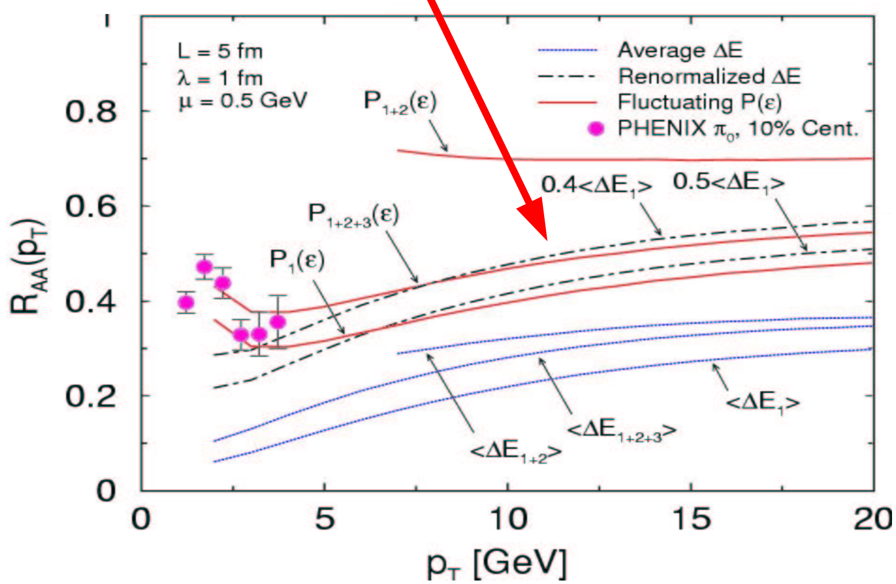
- All medium-induced (LPM) energy-loss models predict a smooth decrease of suppression ($\propto \sqrt{p_T}$) not seen in the data ...



BDMPS
HEPJ 9, 33 (2001)



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



GLV
PLB538, 282(2002)

“Jet quenching” models: p_T depend. of suppression (II)

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

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

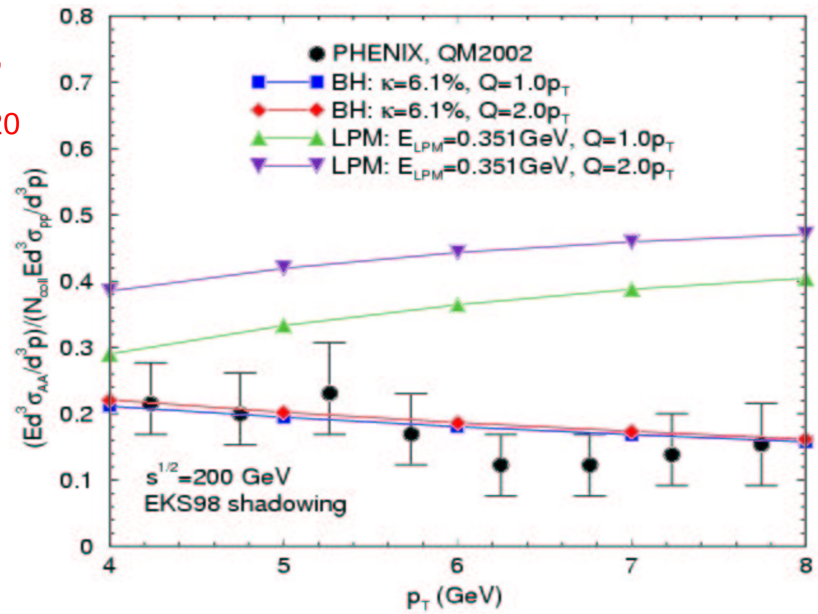
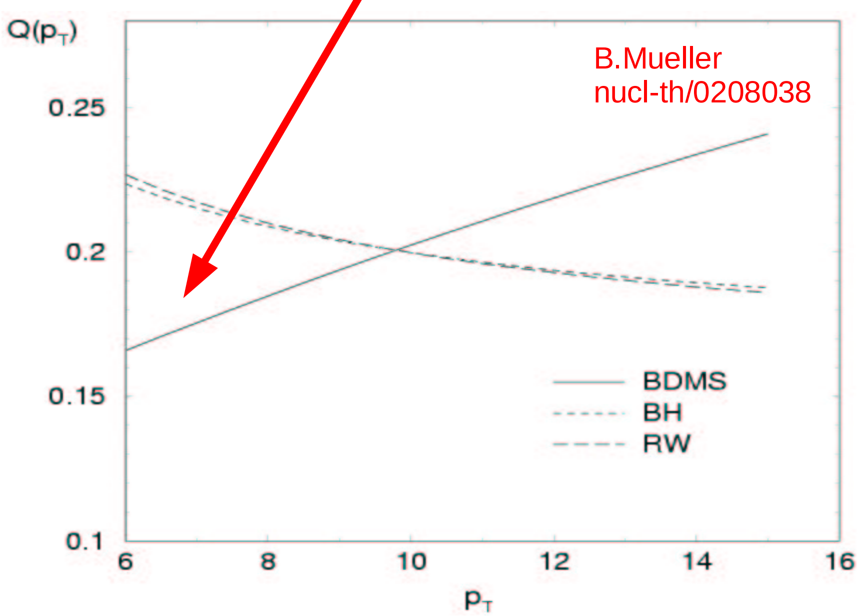


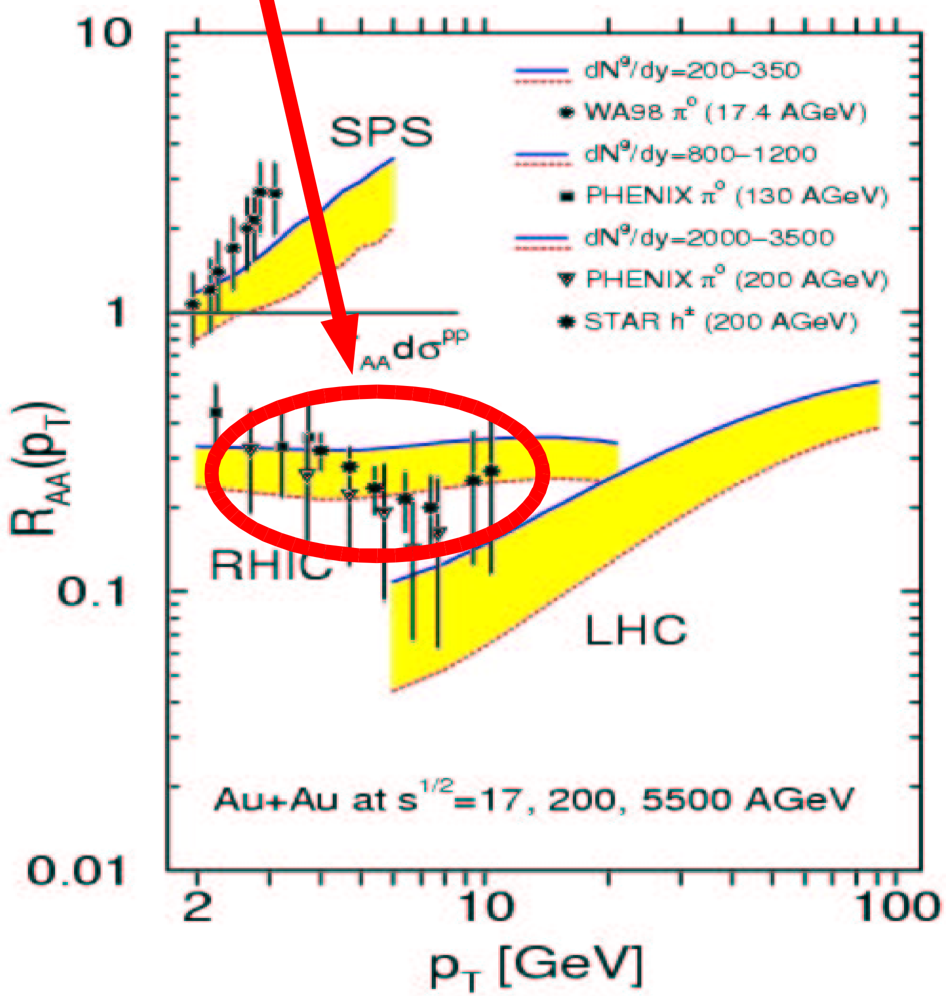
FIG. 8. Ratio of inclusive π^0 cross sections in heavy ion and p-p collisions at $\sqrt{s} = 200$ GeV, compared with PHENIX



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

"Jet quenching" models: parton en. loss + shadowing + Cronin = flat R_{AA}

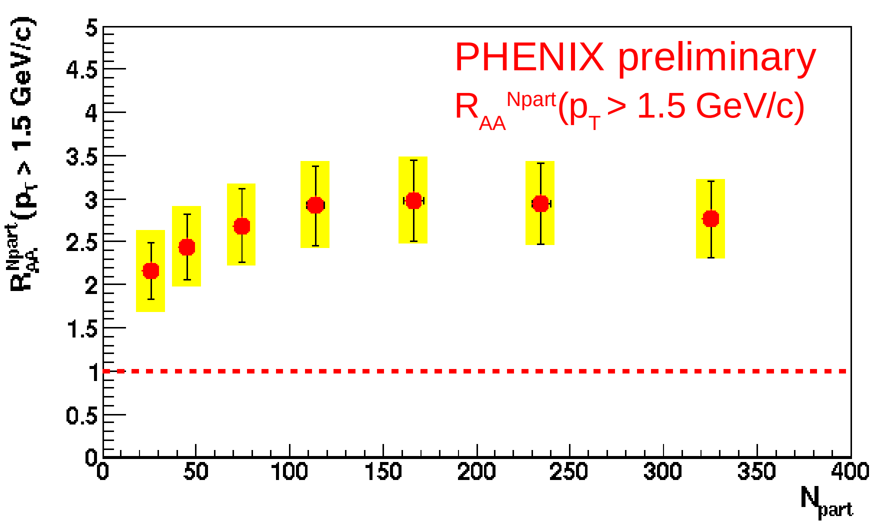
- Initial state p_T broadening provides: (1) the needed enhancement at intermediate p_T , (2) the small decrease at higher p_T so as to compensate for the p_T dependence of energy loss and give the observed ~flat R_{AA} (p_T)

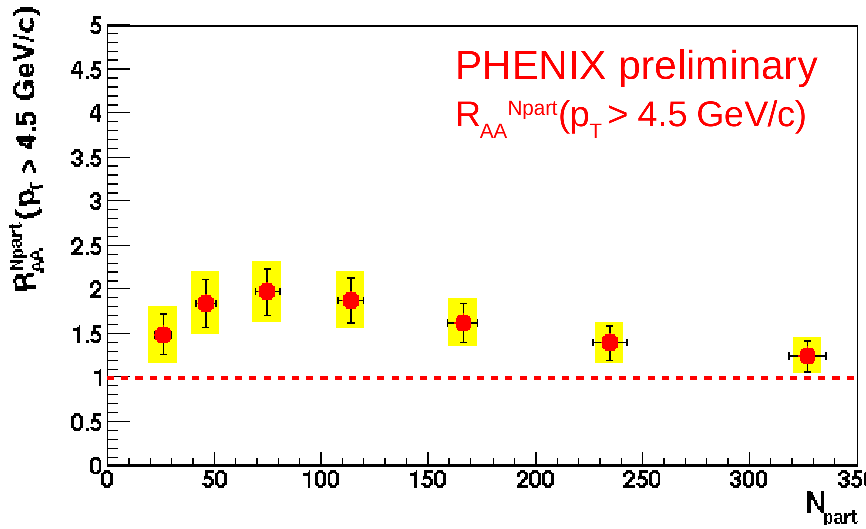


I.Vitev,
M.Gyulassy
PRL 89 252301 (2002)

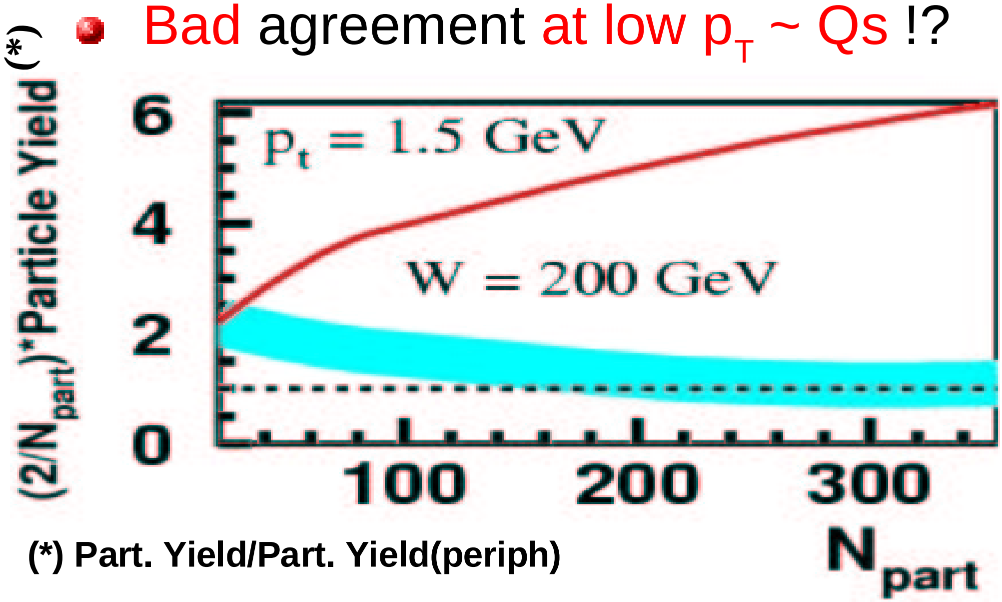
Gluon saturation models:
Centrality-dependence of π^0 suppression

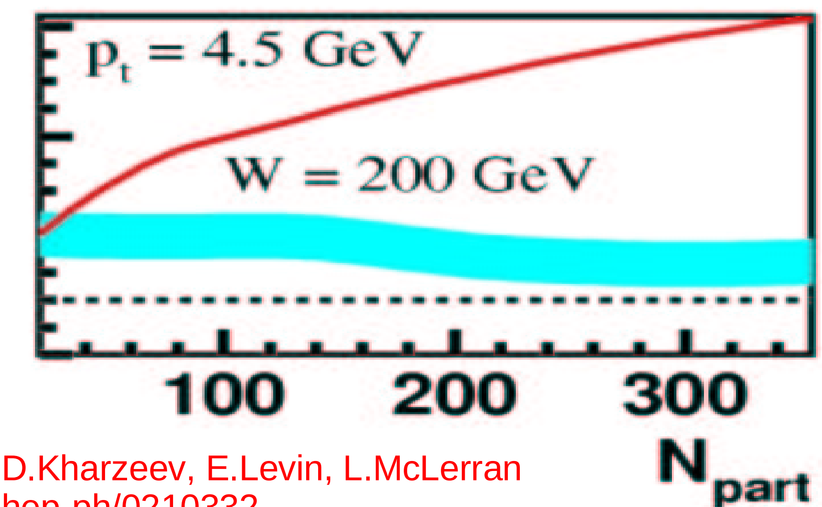
- Integrated R_{AA}^{Npart} above a given p_T (1.5 GeV/c, 4.5 GeV/c) vs. N_{part} compared to gluon saturation predictions:





- Bad agreement at low $p_T \sim Qs$!?   Reasonable agreement at high p_T





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

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