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

NATO ASI "Structure & Dynamics of Elementary Matter"

Kemer, Turkey, Sept. 29, 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 (central Au+Au vs. p+p):

- Suppression of hadron inclusive spectra
- “Anomalous” hadron composition
- Azimuthal anisotropies: strong collective elliptic flow, disappearance of away-side dijet correlations.

3. Theory vs. data:

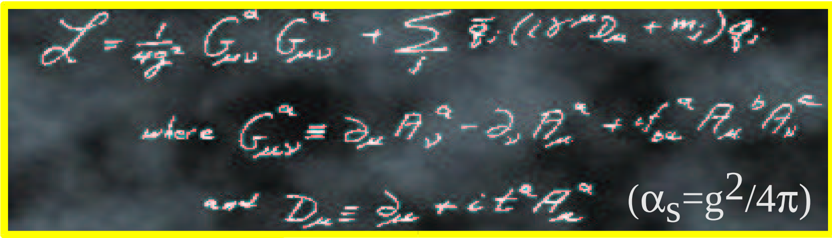
- QGP- and CGC- models vis-à-vis data

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

- Cronin-like enhancement

5. Summary

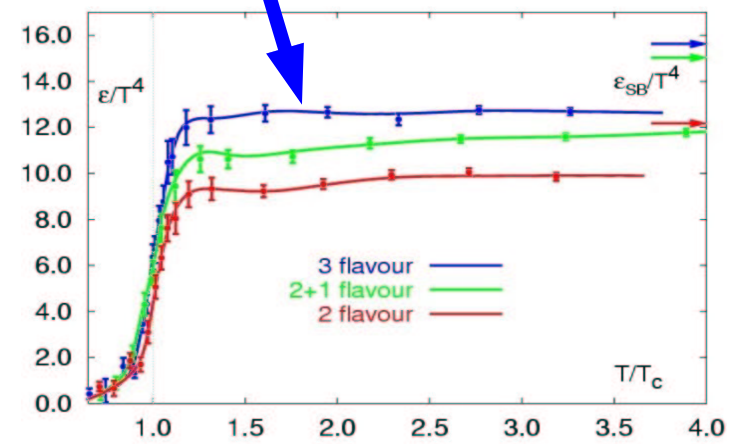
High-energy heavy-ion physics program (in 4 plots)

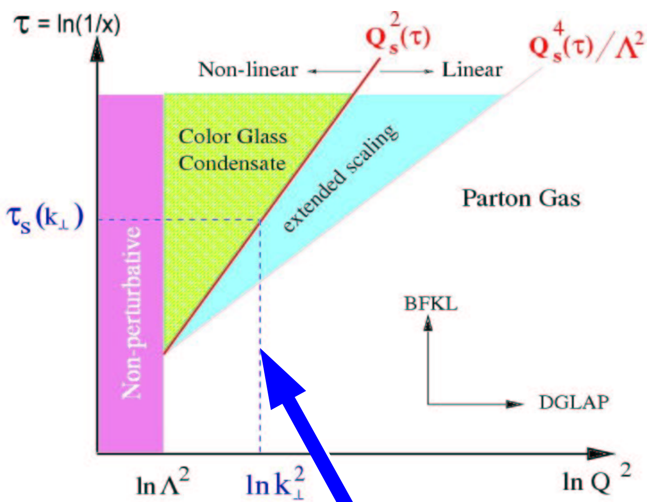


$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

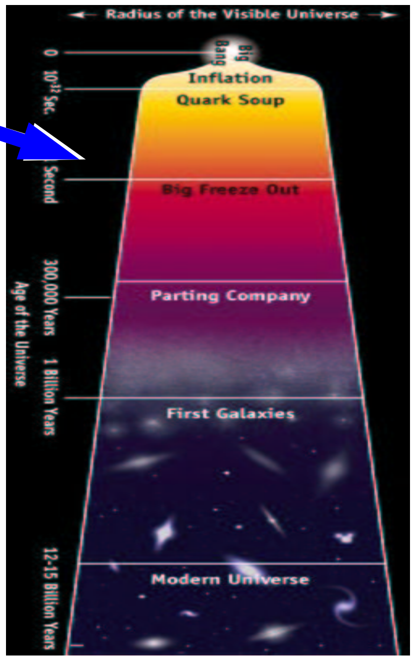
1. Learn about 2 (so far unexplained) properties of the strong interaction: confinement, chiral symmetry breaking

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)

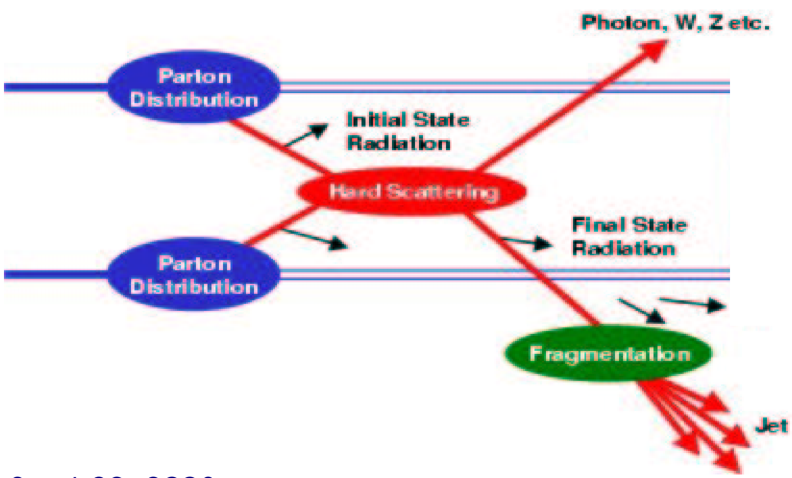
- Hard probes: high-p_T (jets, prompt γ), heavy-flavor (D, B, J/Ψ, ...)
- Early production ($\tau \sim 1/p_T < 0.1$ fm/c) in parton-parton scatterings with large Q^2
- Direct probes of partonic phases ⇒ Sensitive to dense medium properties: parton E_{loss} ("jet quenching"), color screening ("onia" suppression),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

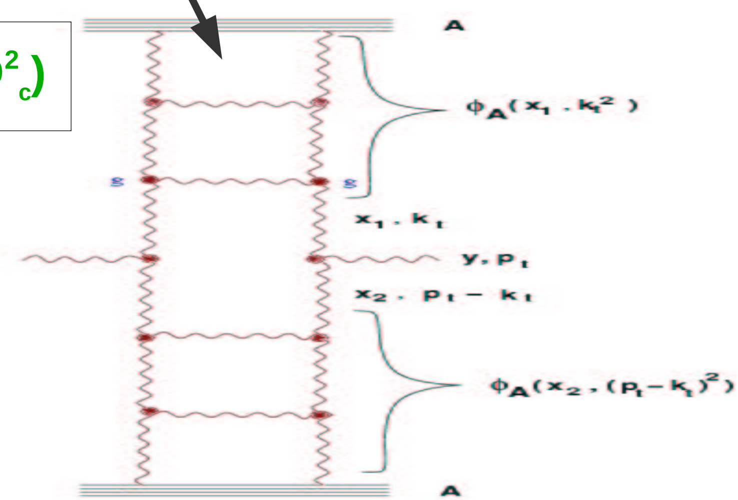
$$\sigma_{AB\,(hard)} = \int d^2b\,[1-e^{-\sigma_{pp}T_{AB}(b)}] \propto T_{AB} \times \sigma_{pp\,(hard)}$$

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

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

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

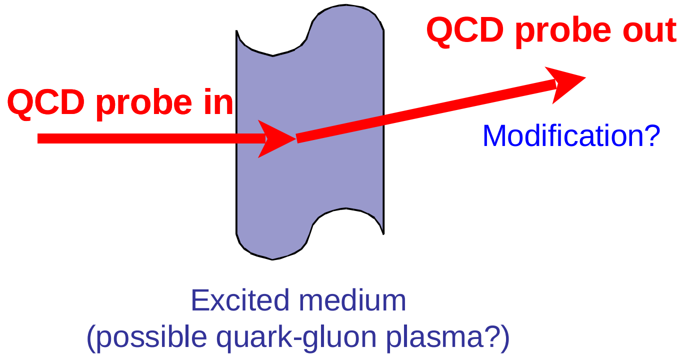


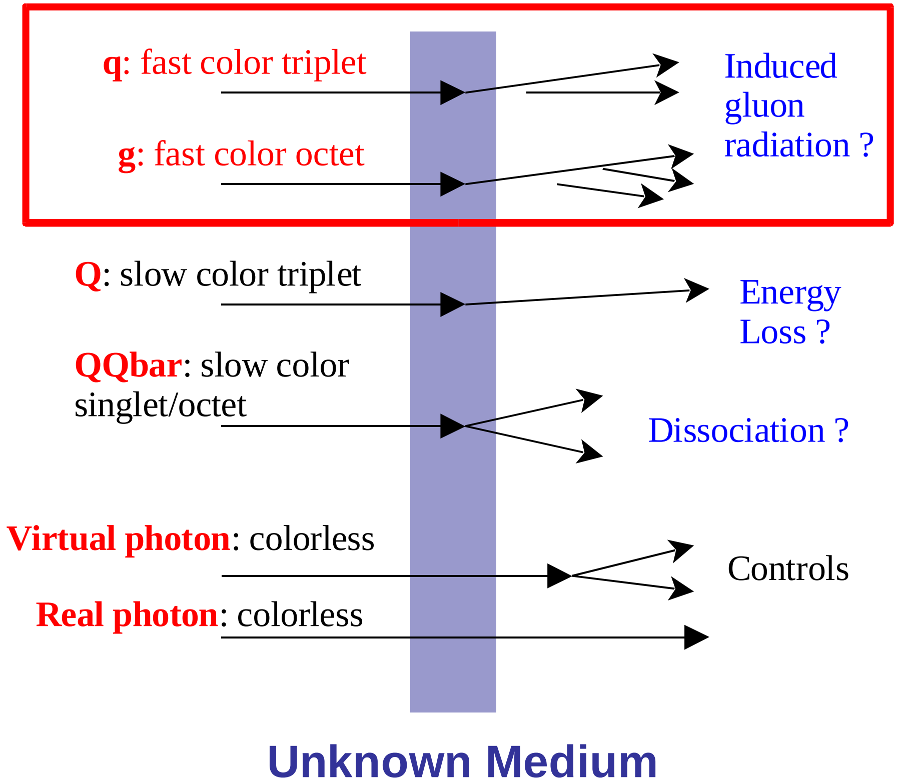


"Mueller diagram for classical glue radiation"

Hard QCD probes (II)

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





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

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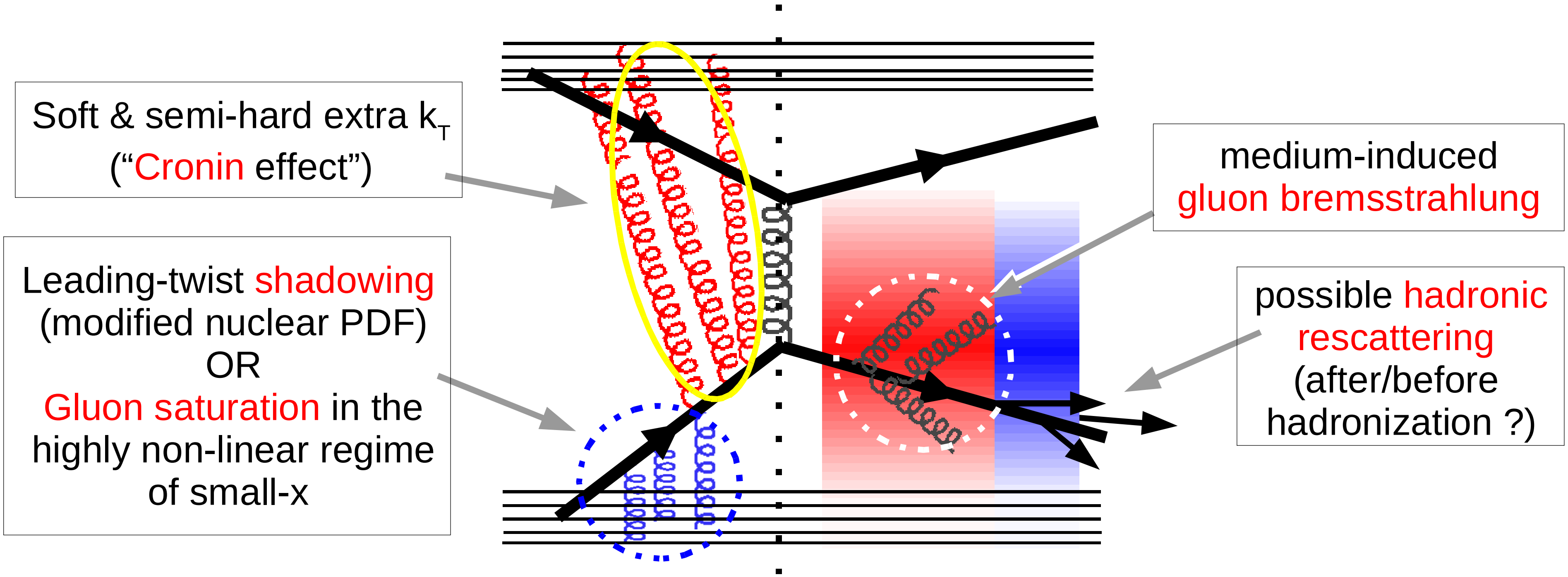
High p_T in a strongly interacting medium

- 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

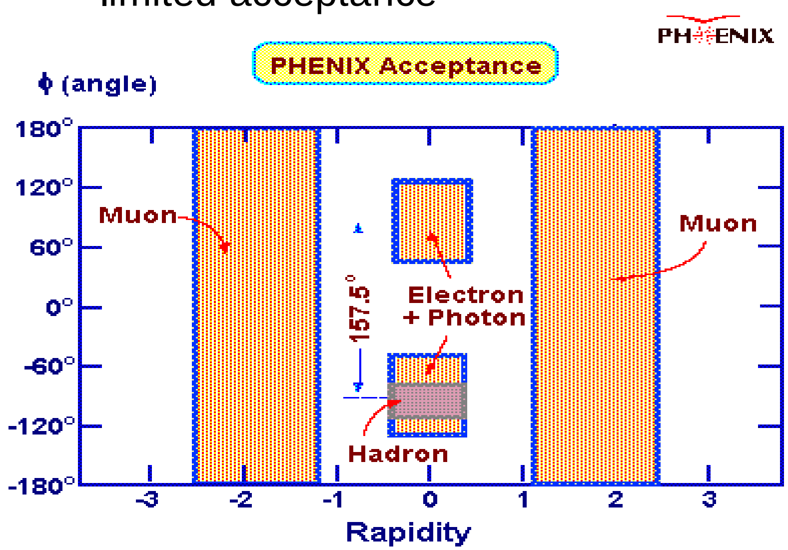
PHENIX @ RHIC

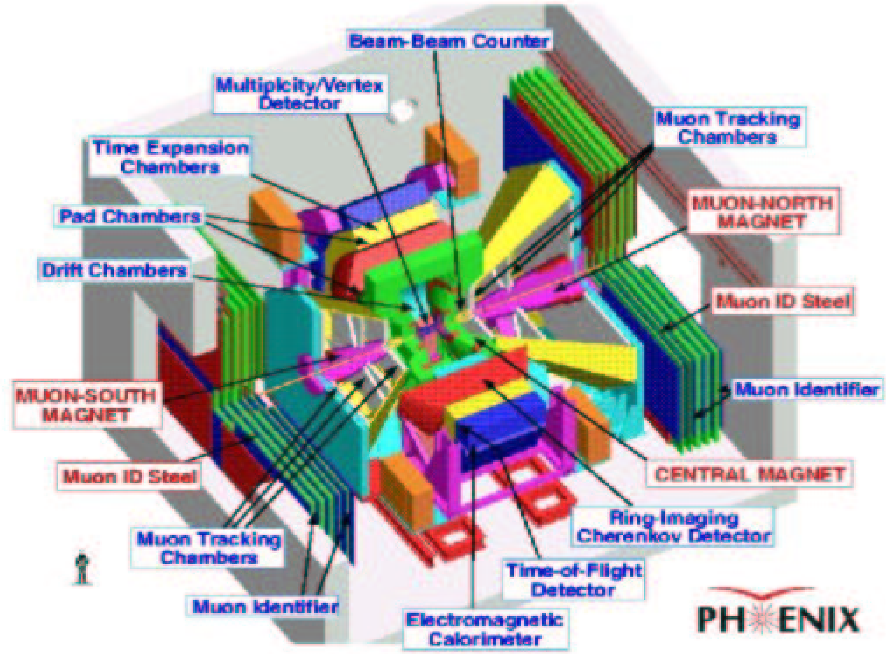
- 11 detector sub-systems
- 2 Arm central spectrometers:
  - $|\eta| < 0.35$, $\Delta\phi = \pi$ (e, γ, hadrons)
  - Open geometry axial field
- 2 forward spectrometers:
  - $1.2 < |\eta| < 2.5$, $\Delta\phi = 2\pi$ (muons)
  - Radial magnetic field
- 3 global (inner) dets.: trigger, centrality
- Designed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

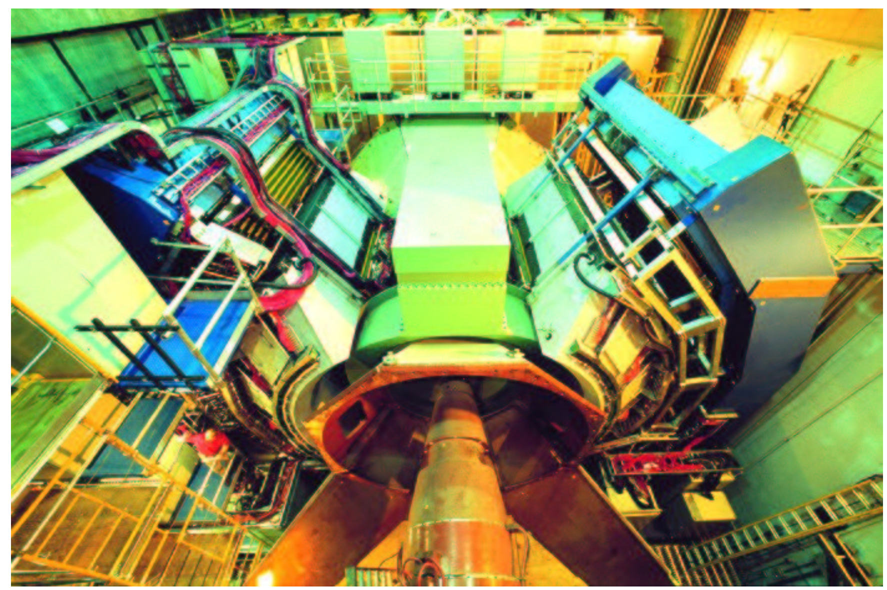
  \+ high rate capability & granularity

  \+ good mass resolution and PID

  \- limited acceptance



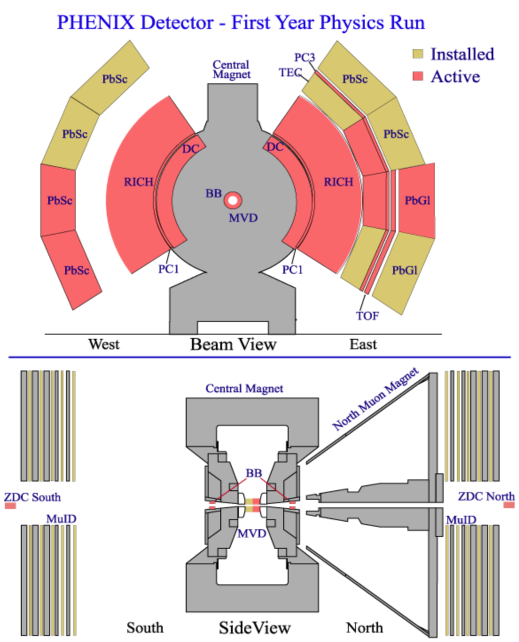




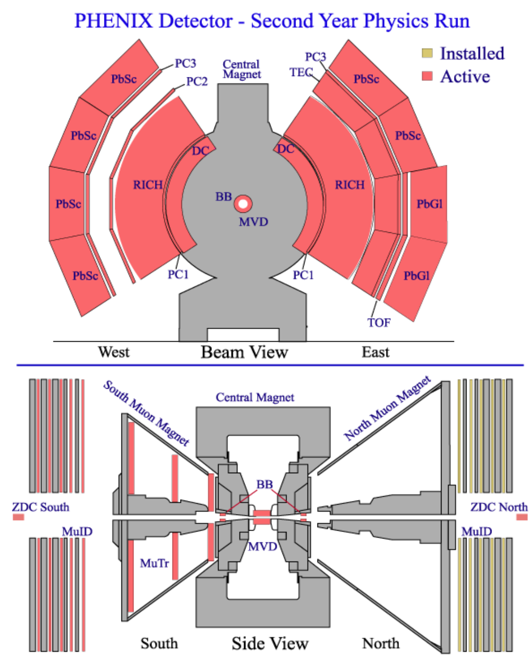
PHENIX run history

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

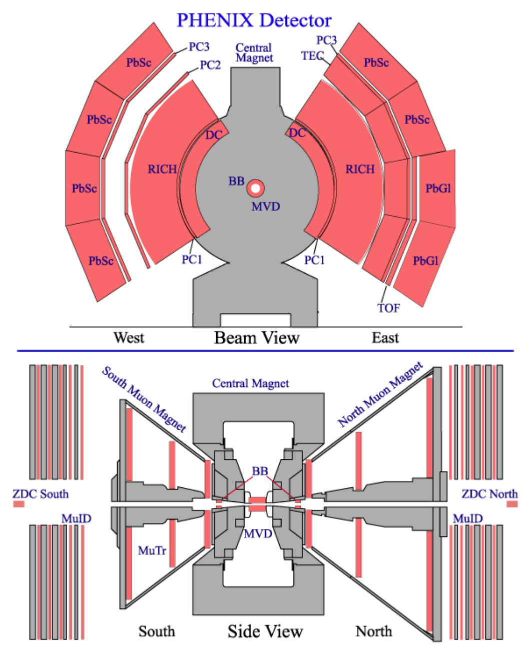
2000



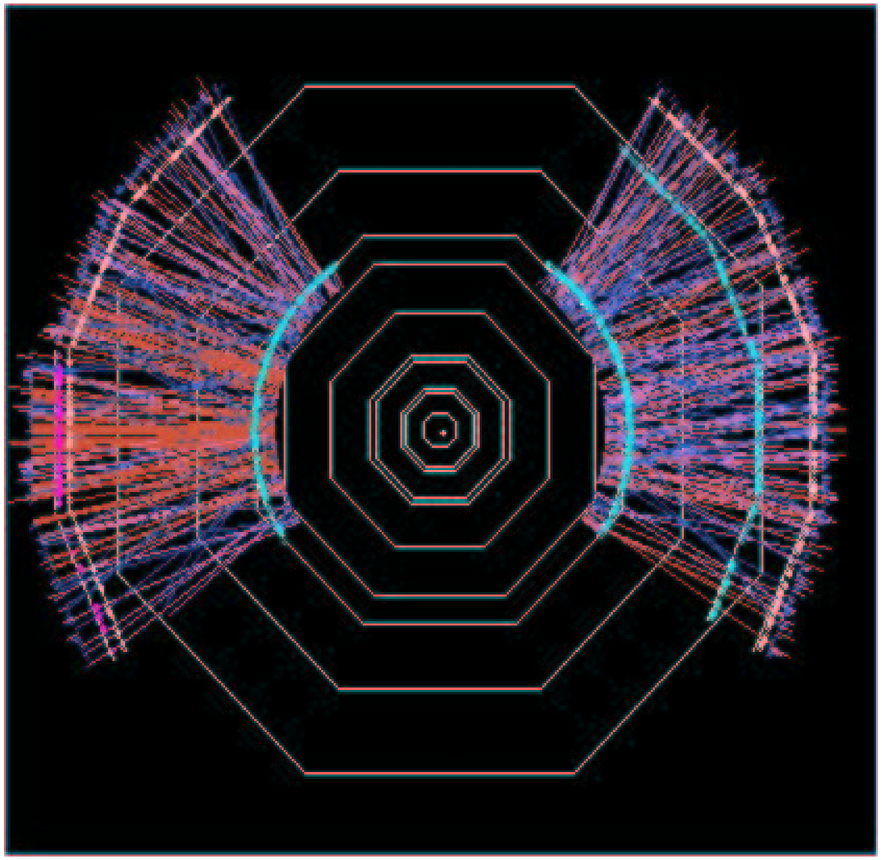
2001/2002

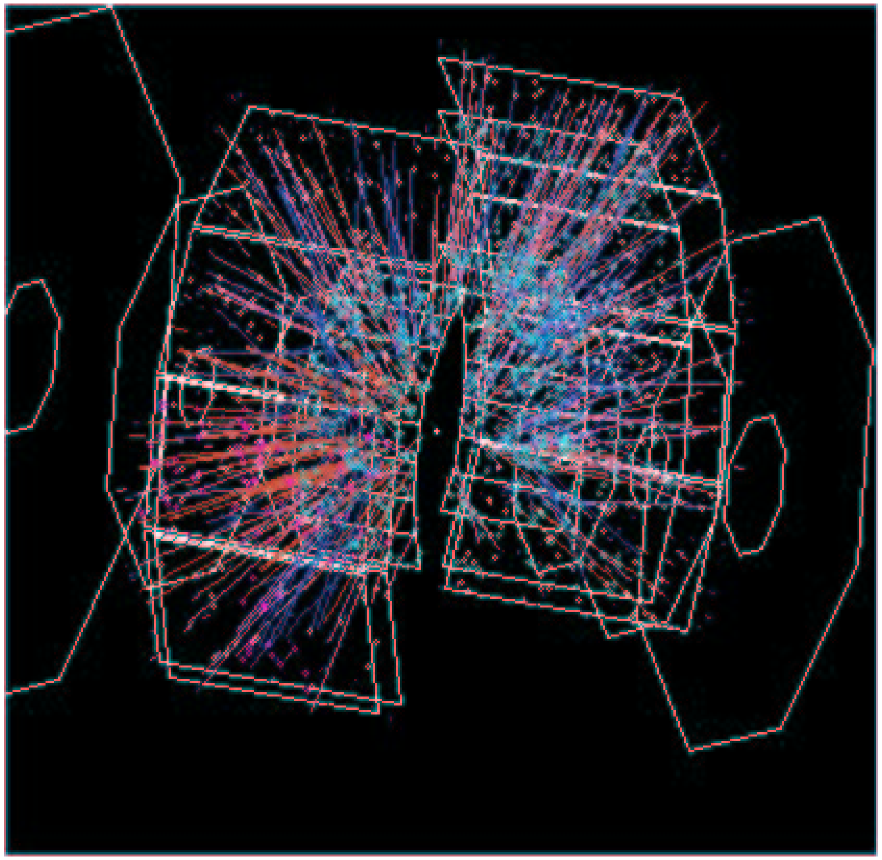


2002/2003



Au+Au in PHENIX

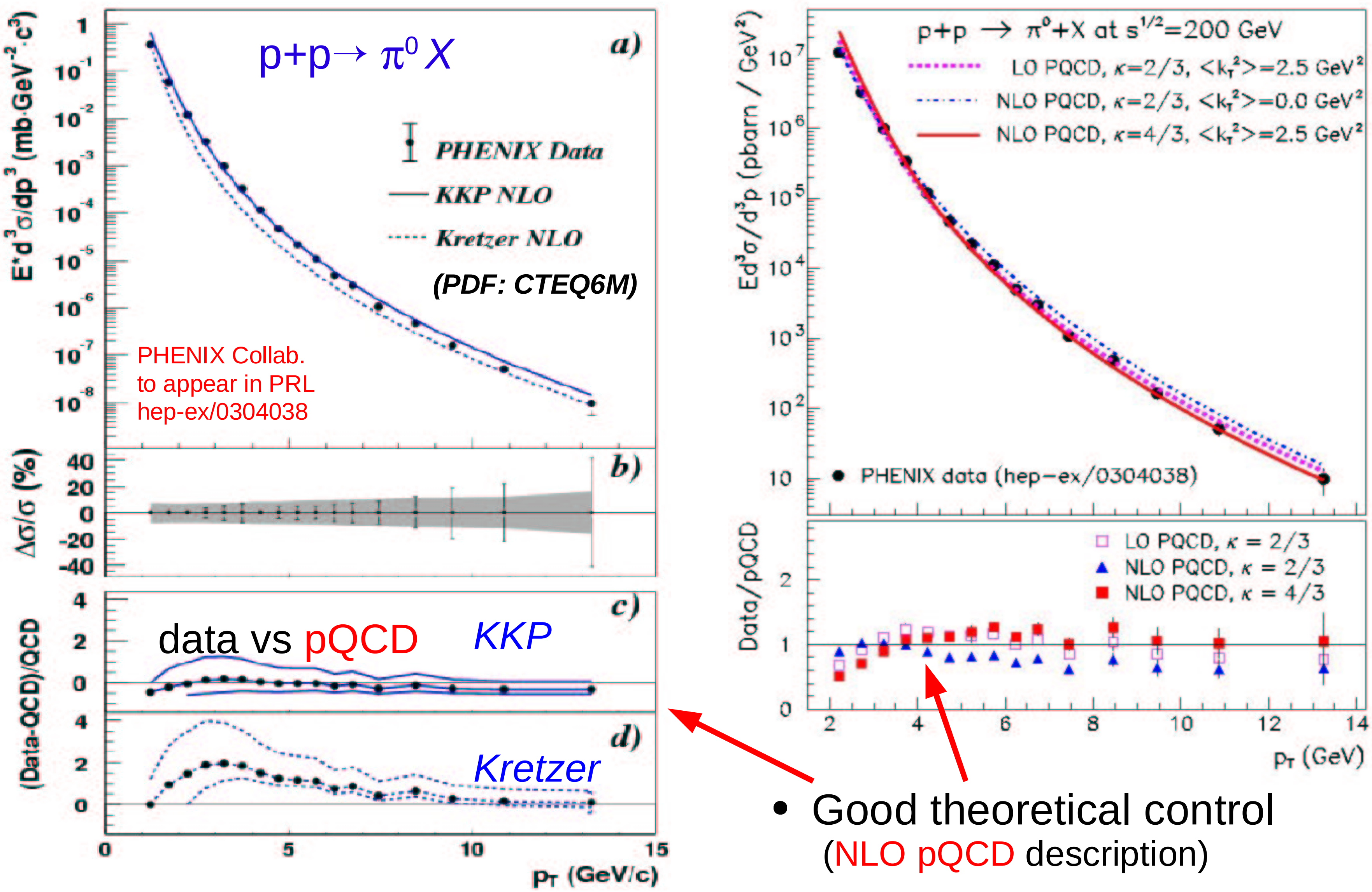




~600 charged particles per unit rapidity at mid-rapidity (5% most central)

p+p reference @ 200 GeV: high-p_T π^0

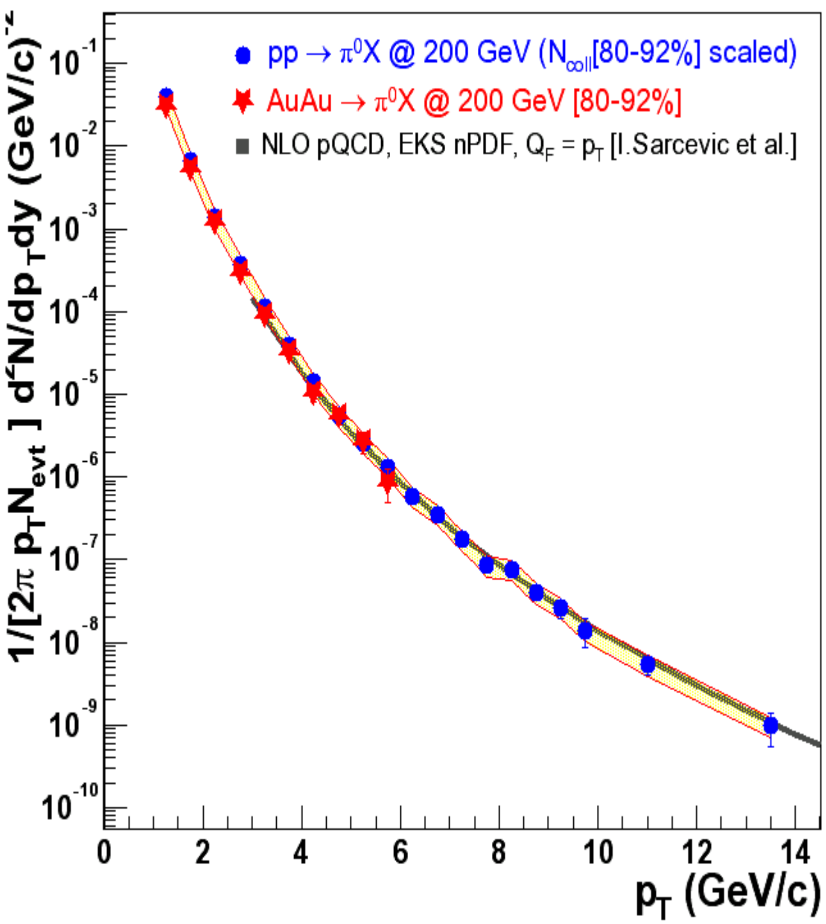
- Experimentally "unbiased" reference for Au+Au → π^0



- Good theoretical control
  (NLO pQCD description)

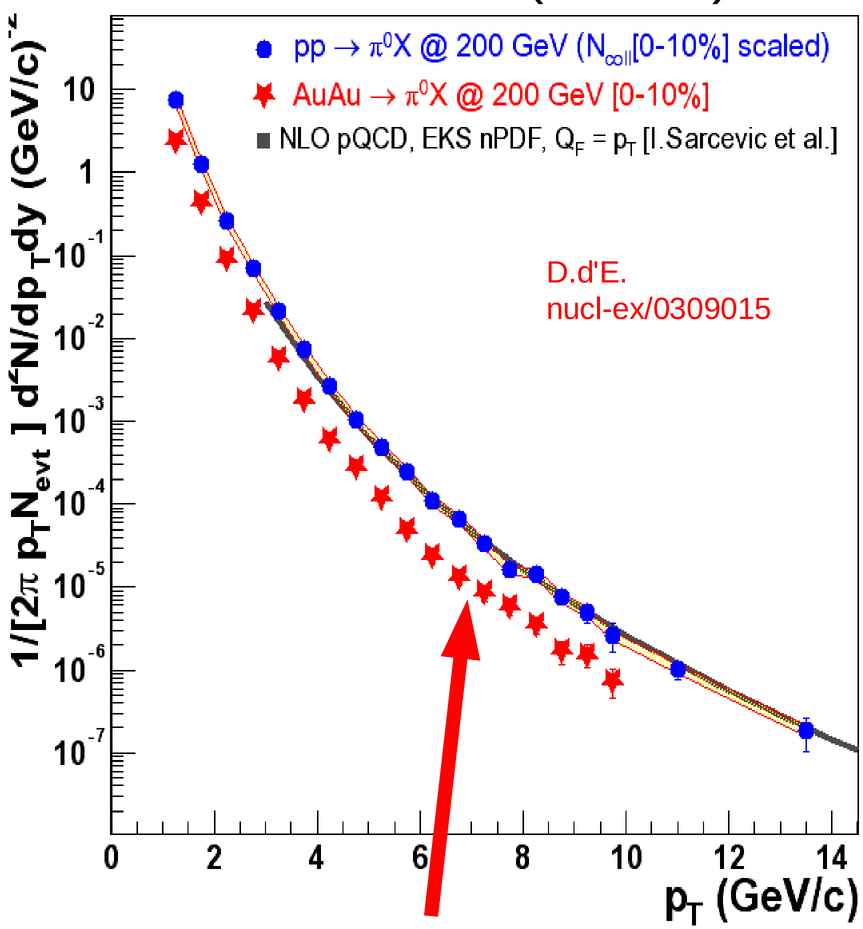
AuAu *vs* pp @ 200 GeV: high p_T π^0

Au+Au→ $\pi^0 X$ (peripheral)



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

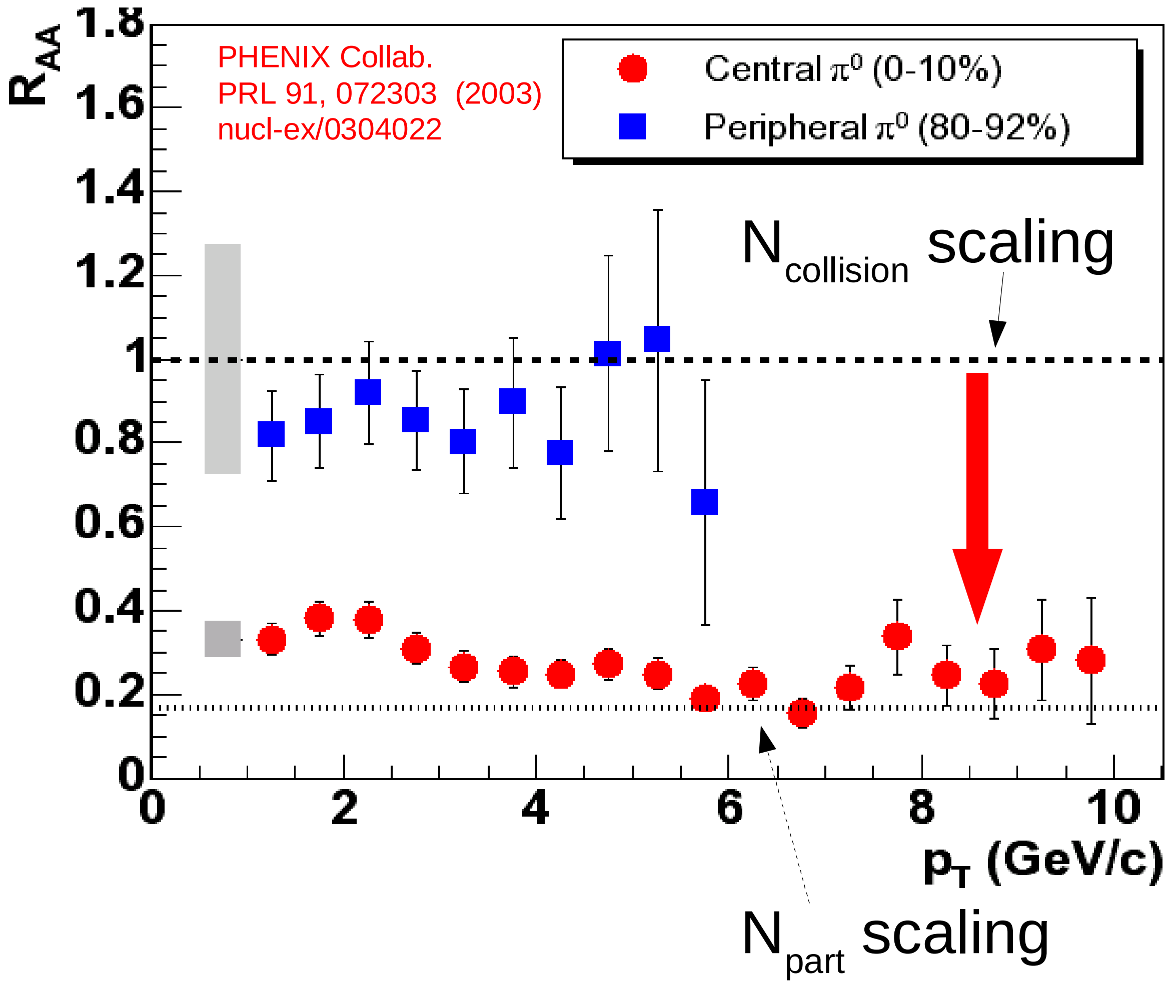
Au+Au→ $\pi^0 X$ (central)

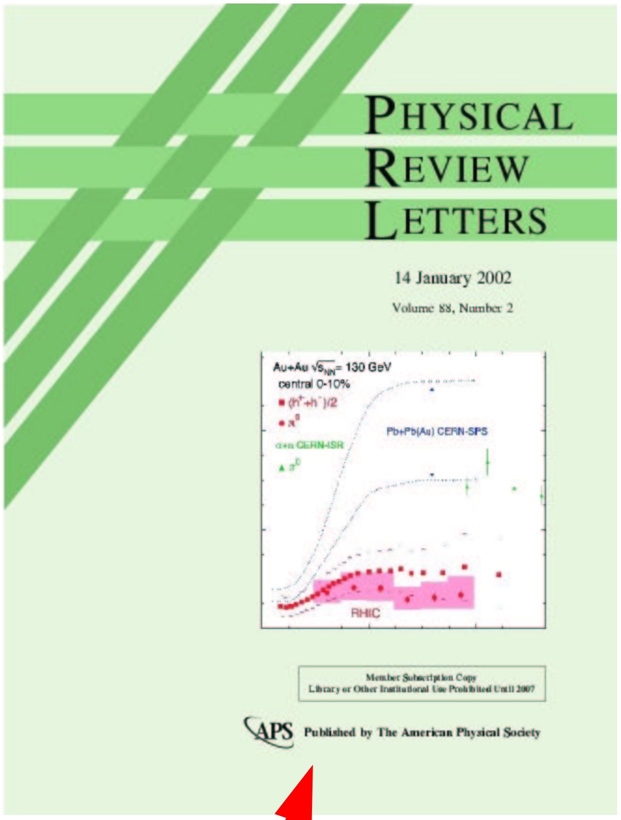


Strong suppression in central AuAu collisions

Nuclear modification factor (π^0)

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





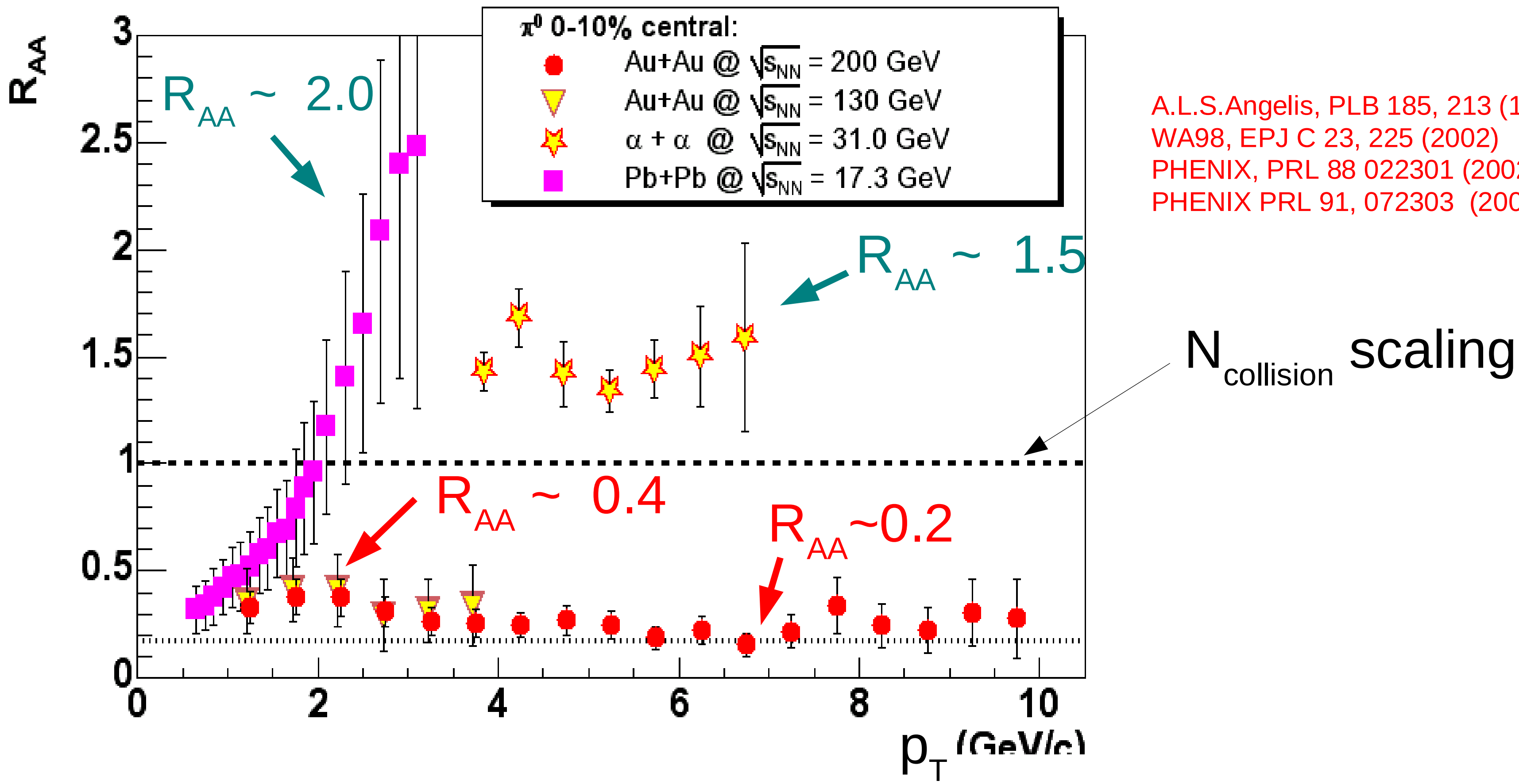
Discovery of high p_T suppression

(most significant result @ RHIC so far)

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

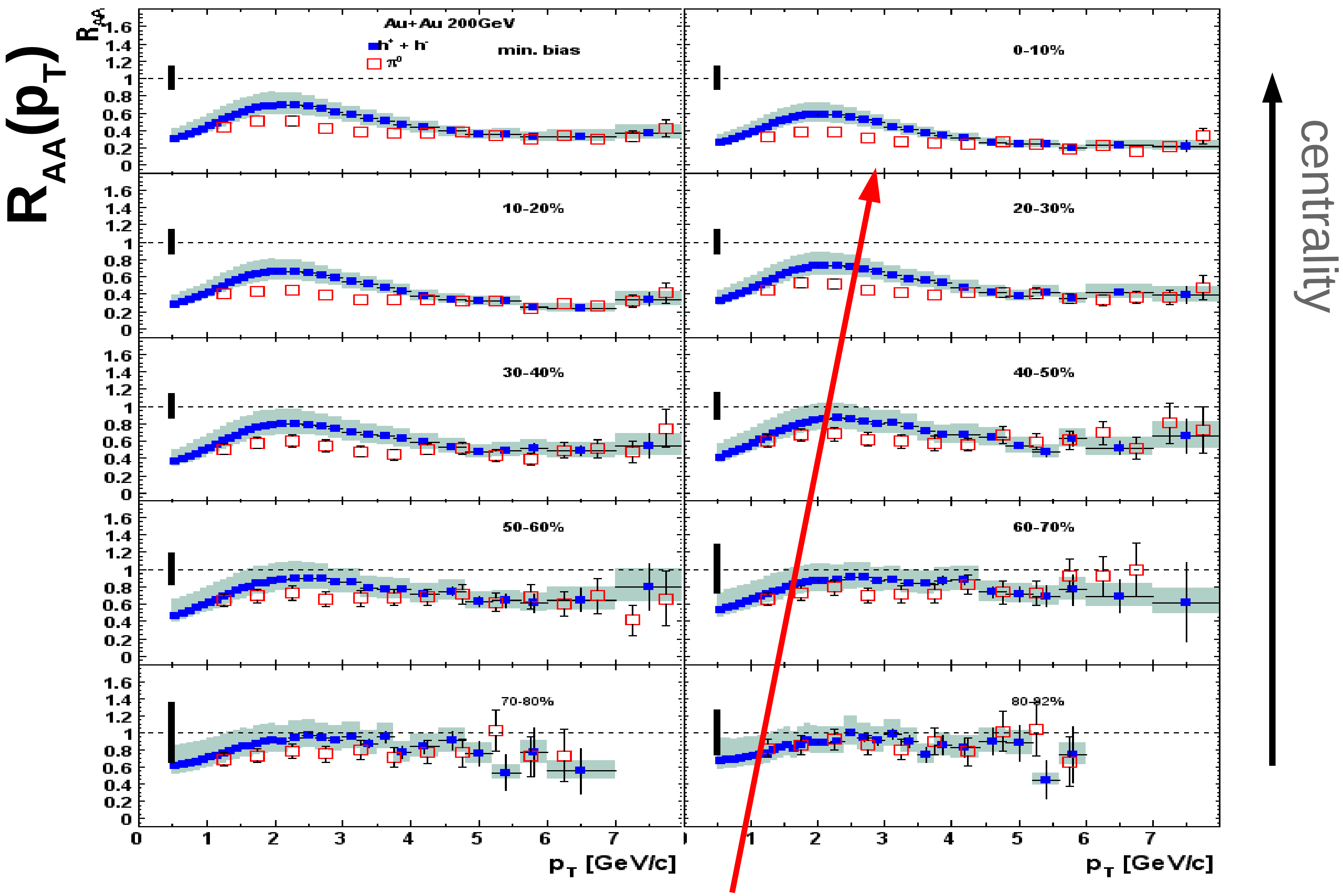
R_{AA} compilation for π^0 in central A+A:

- 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 PRL 91, 072303 (2003)

Nuclear modification factor: π^0 vs. charged hadrons

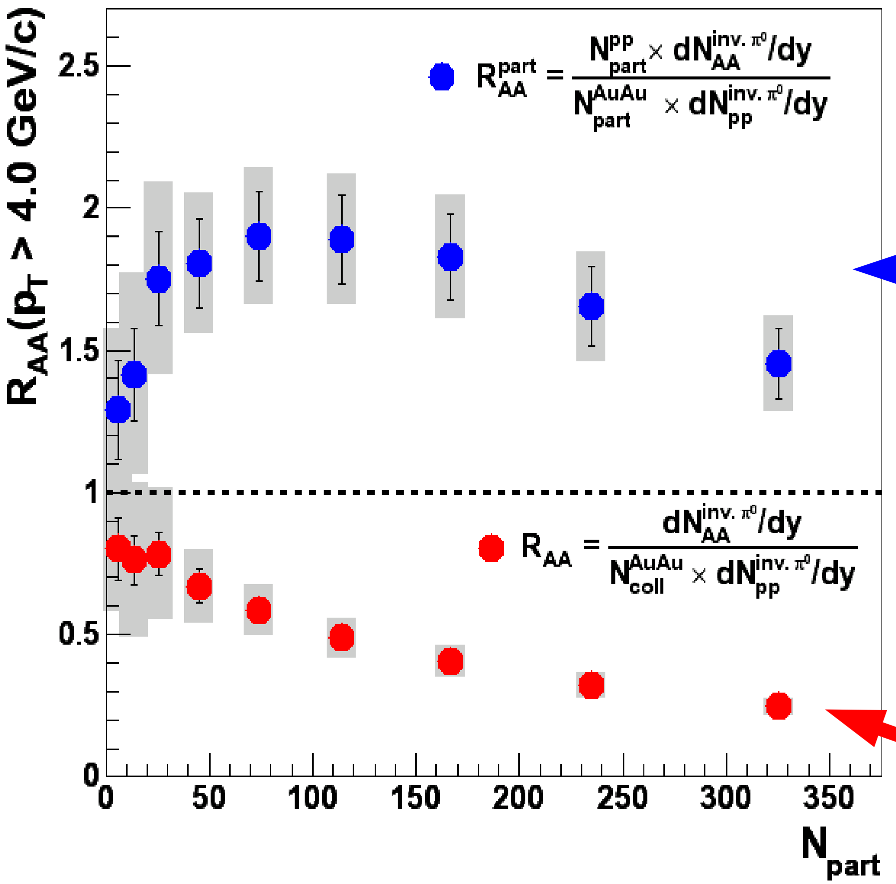


- Less suppression for $h^\pm$ than for π^0 at $p_T \sim 2.$ GeV/c
- "Universal" suppression ($R_{AA} \sim 0.2$) above $p_T \sim 4\text{-}5$ GeV/c

Centrality dependence of suppression

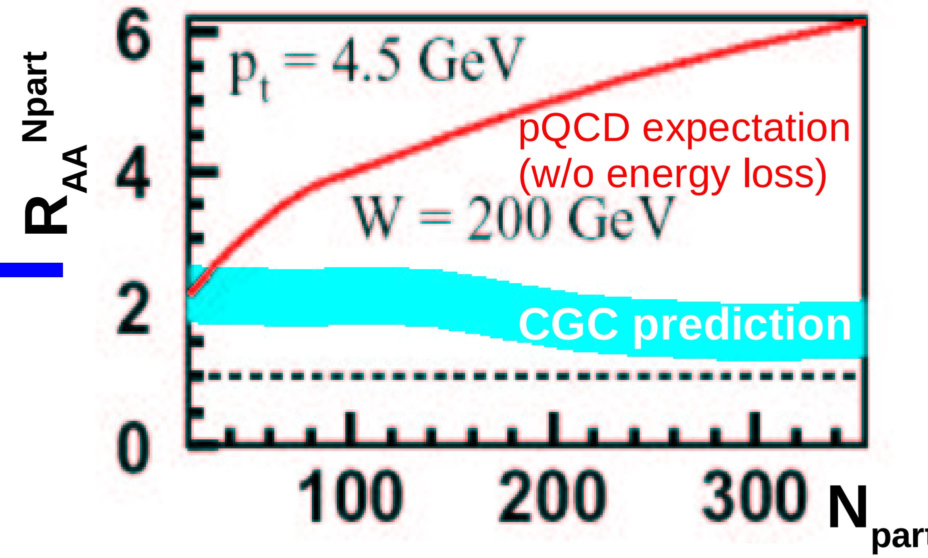
- Approx. N_{part} scaling: ~ agreement with CGC

PHENIX PRL 91, 072303 (2003)

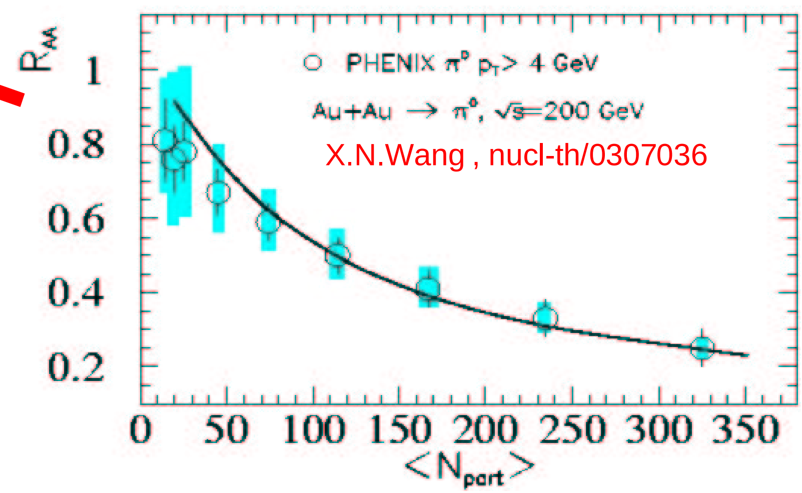


peripheral → central

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

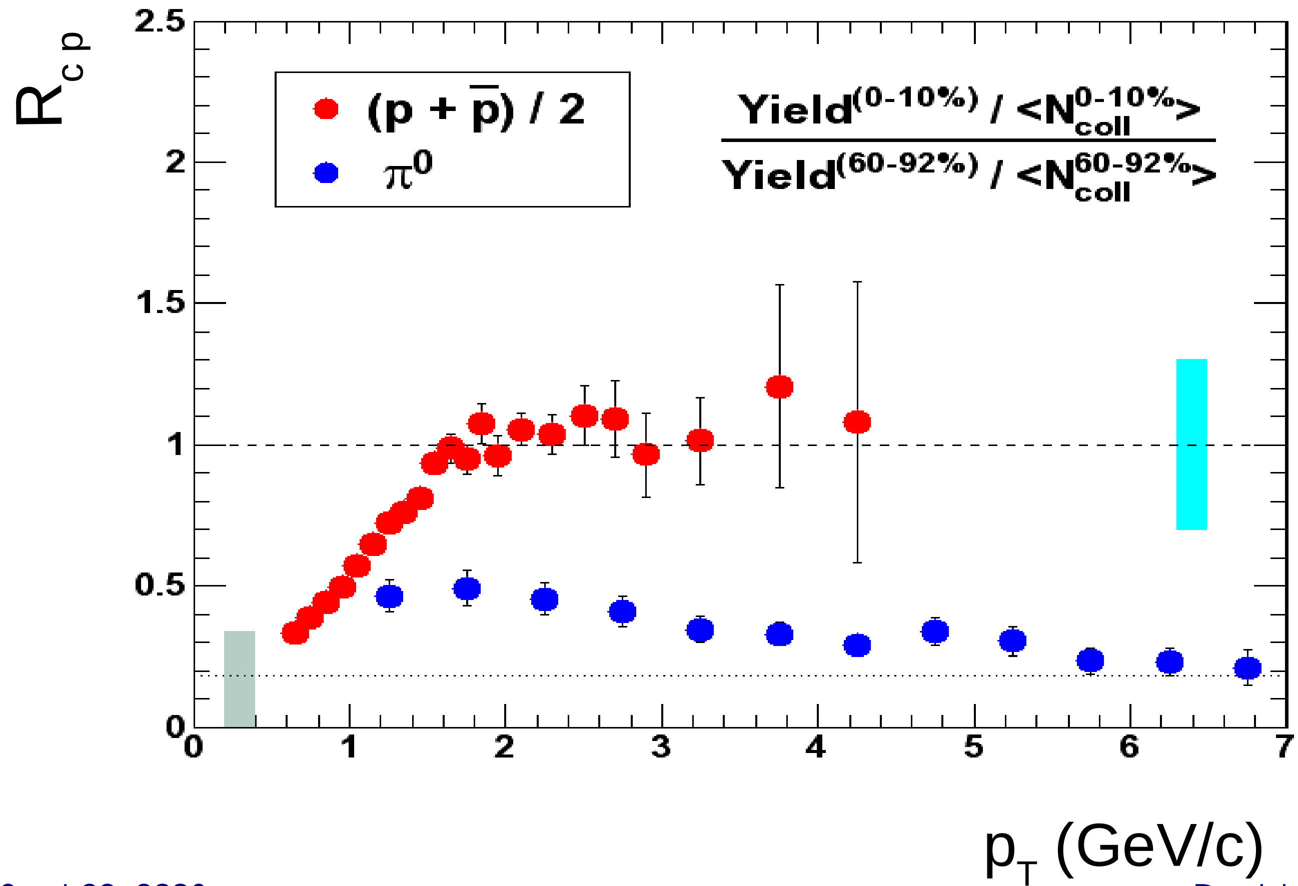


- Smooth evolution of suppression (w.r.t. N_{coll} scaling) expected in pQCD+energy loss:



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

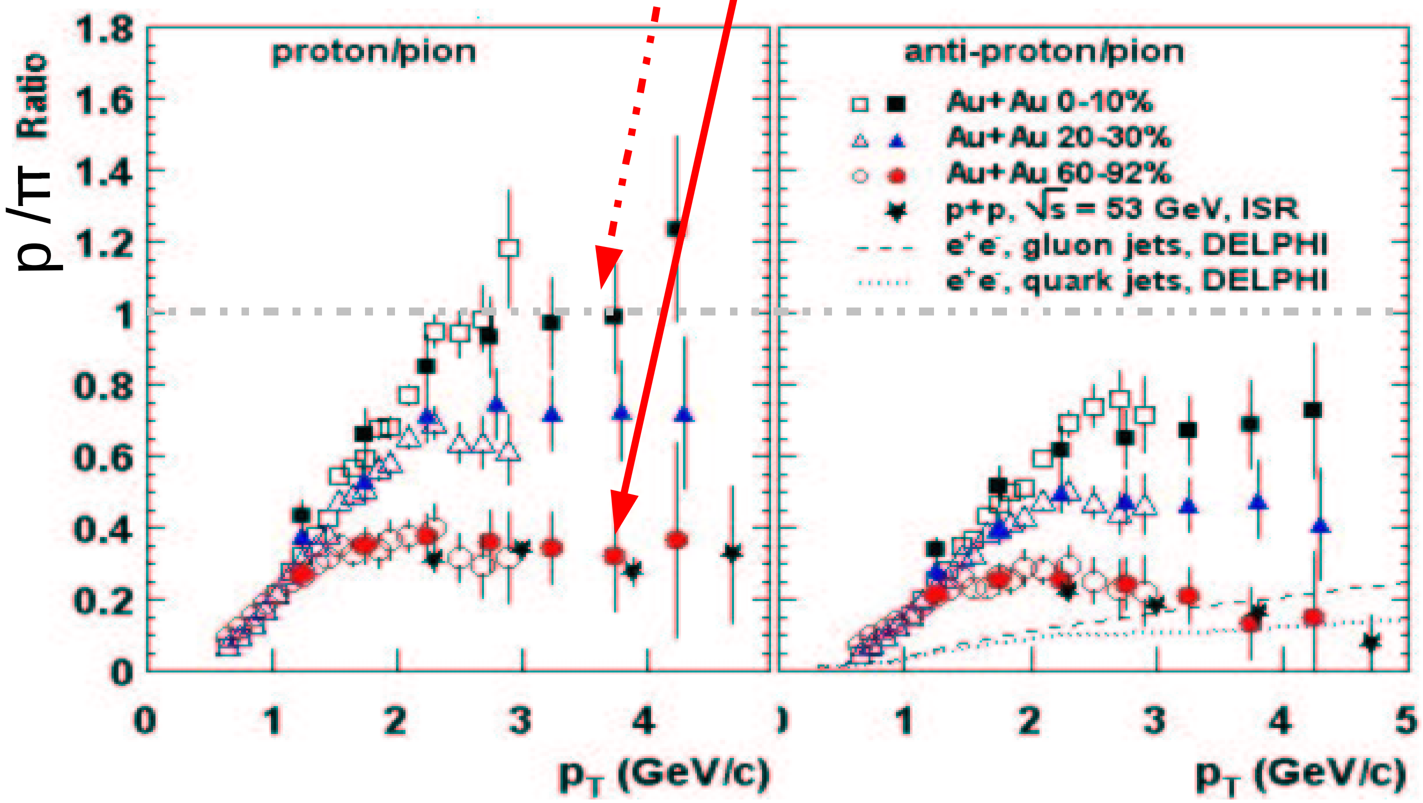
- Protons (antiprotons) **NOT** suppressed in central Au+Au (p_T < 4.5 GeV/c)
- Ratio central/periph ~ $R_{AA} \approx 1 \rightarrow N_{coll}$ scaling holds for baryons.
  - *(Consistent with observed $R_{AA}(h^{\pm}) > R_{AA}(\pi^0)$ in the same p_T range).*
  - Indicates different production mechanisms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



PHENIX Collab.
to appear in PRL
nucl-ex/0305036

Hadron composition at high-p_T (II): 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



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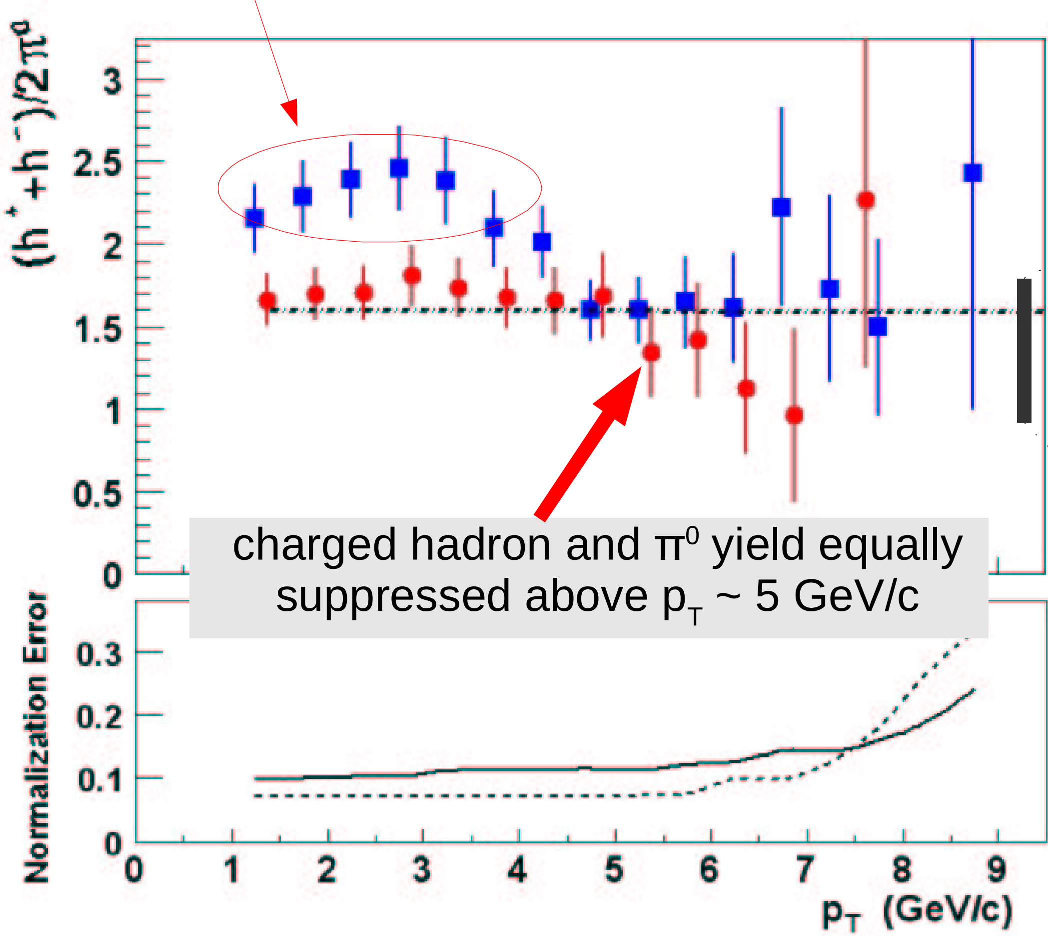
Hadron composition at high-p_T (III): h/π ratio

- 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)



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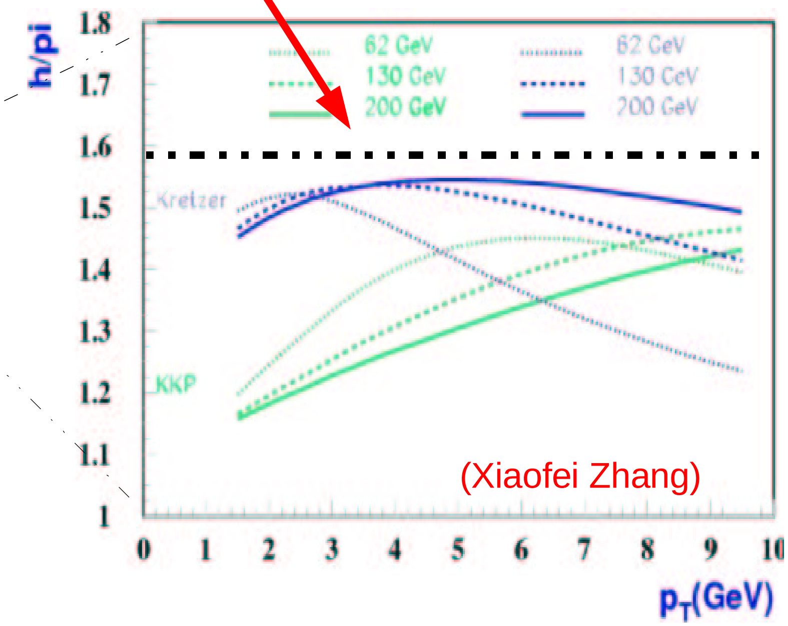
Kretzer vs KKP FFs



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

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.*

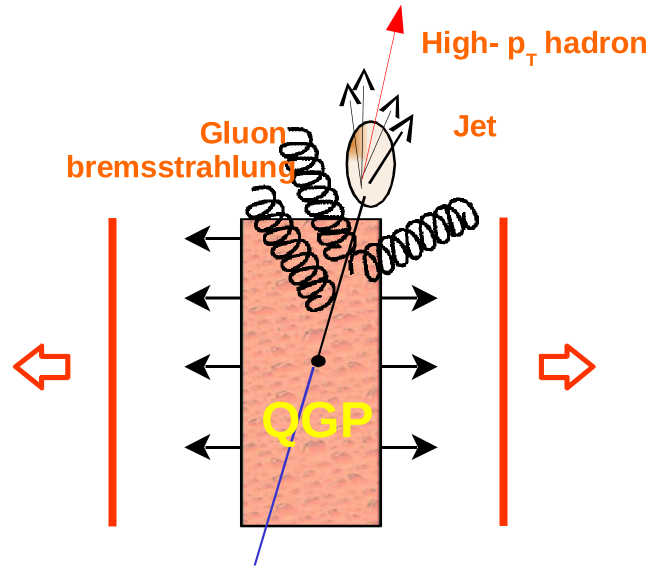
APPROACH "B" ("classical" QCD):

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:

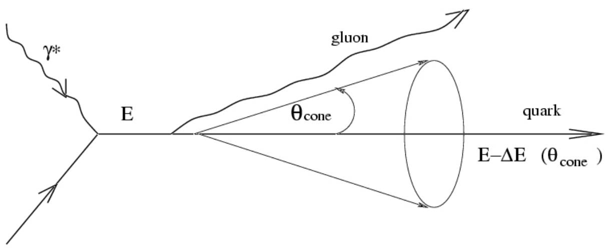


  - Mean parton energy loss probes medium properties:

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

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

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



  - 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)

Final-state QGP effects (II)

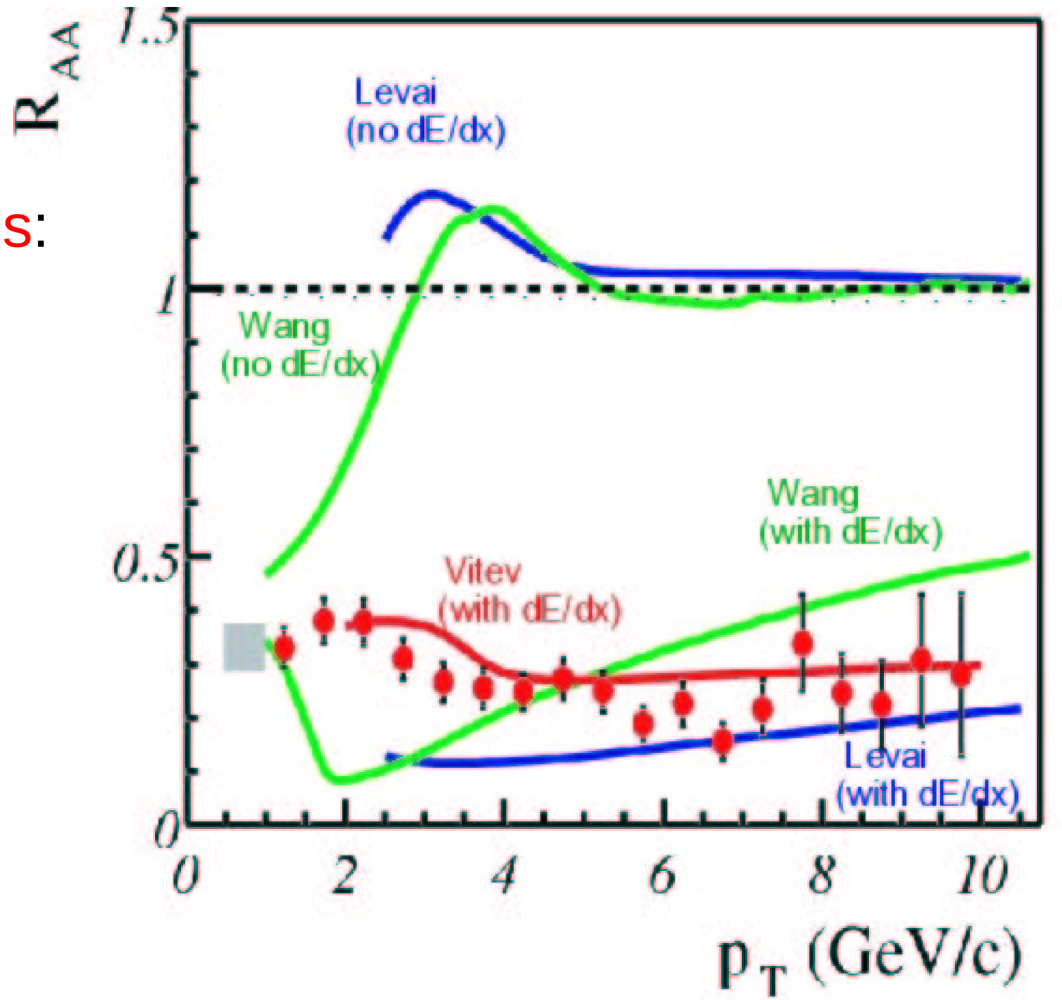
- Dense medium properties according to "jet quenching" models:
  - High opacities:

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



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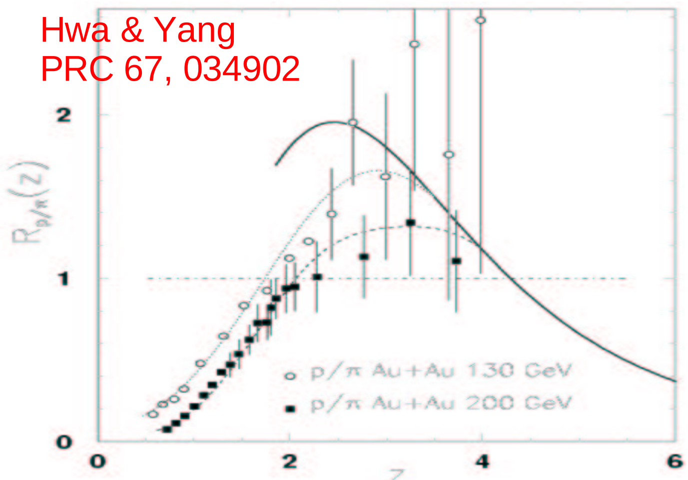
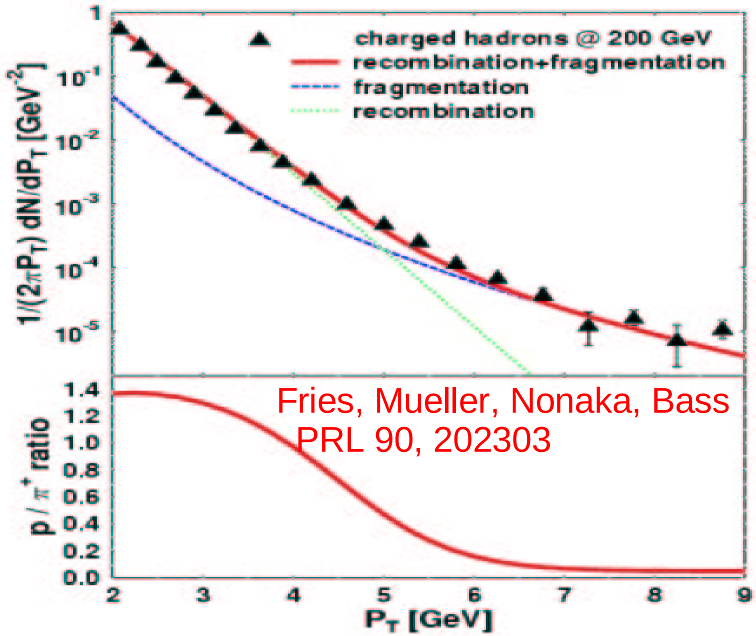
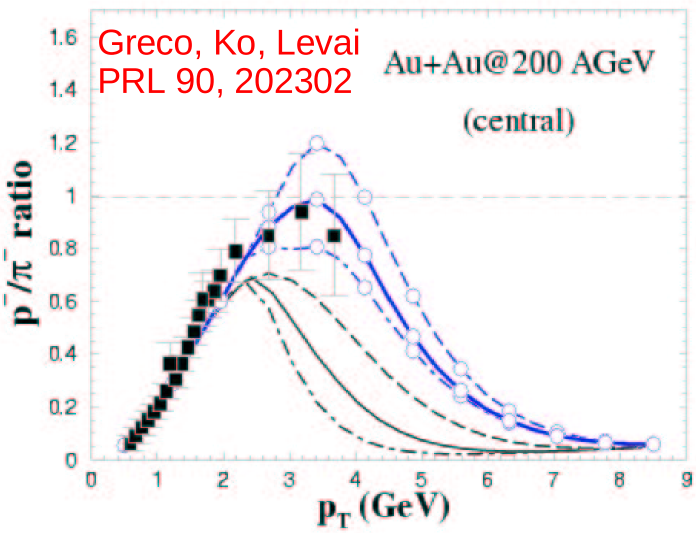
Final-state QGP effects (III)

- 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:

  ⟨p_T(baryons)⟩ > ⟨p_T(mesons)⟩ > ⟨p_T(quarks)⟩

- Fragmentation dominates for p_T > 5 GeV/c:

  p_T(hadrons)= z p_T(partons) , with z<1

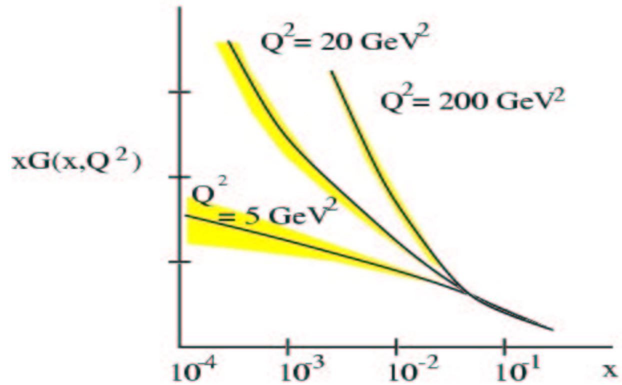
Initial-state effects in a Color Glass Condensate

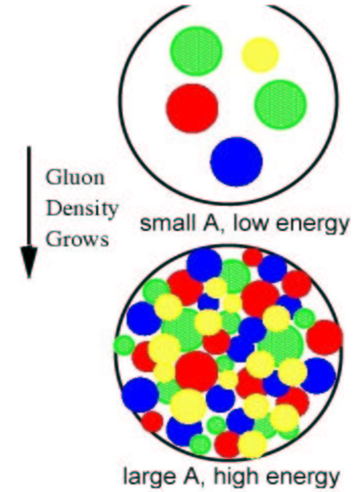
- Initial conditions at RHIC: high-energies + large nuclei
  - Values of small-x: $x_{Bj} = 2p_T/\sqrt{s} << 1$

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:

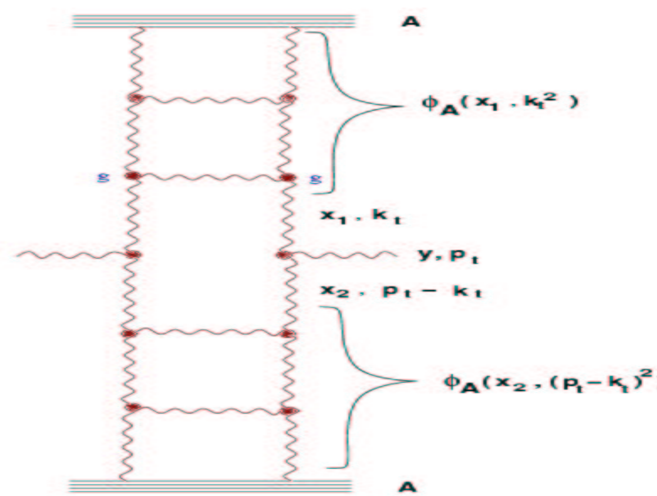
$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2} \sim 1.5 \text{ GeV}^2/c^2 \text{ @ RHIC}$$

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

"Classical" (Chromo-Dynamics) methods applicable

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

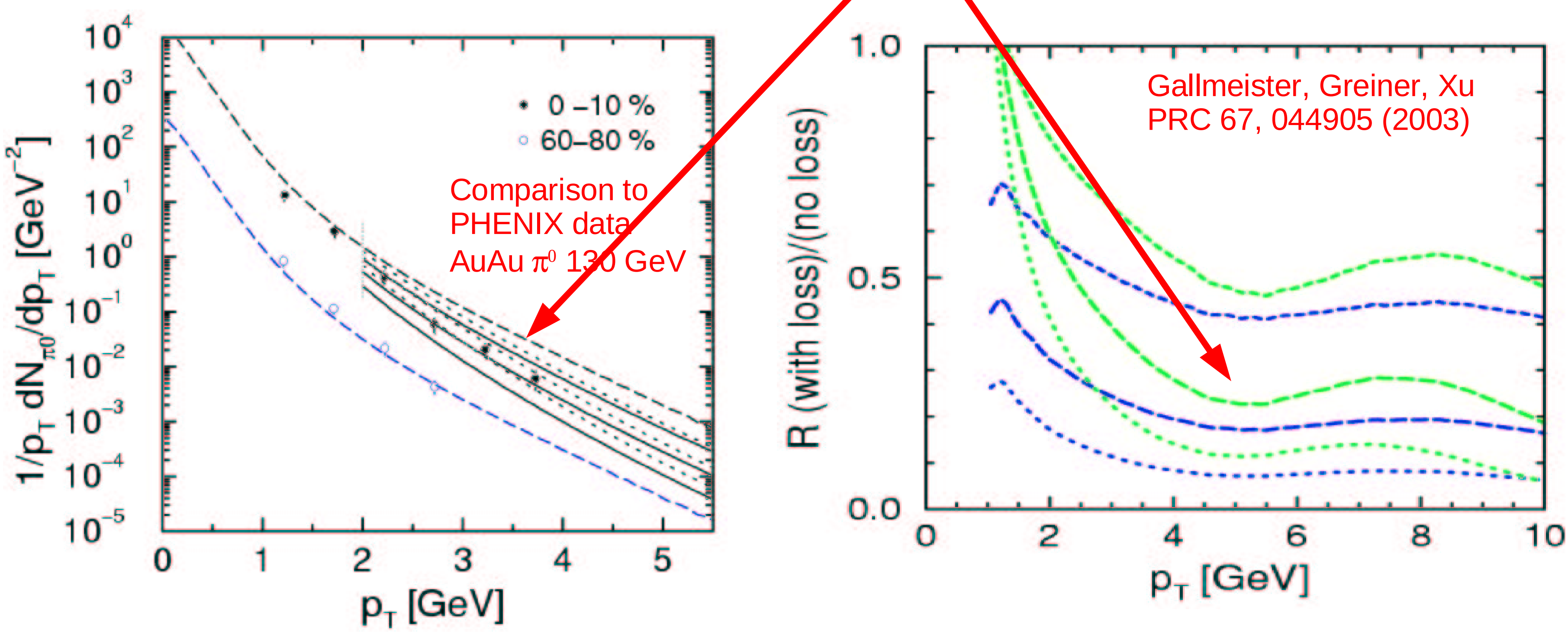
- Particle production via glue-glue collisions:



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

Final-state effects in a dense hadronic medium ?

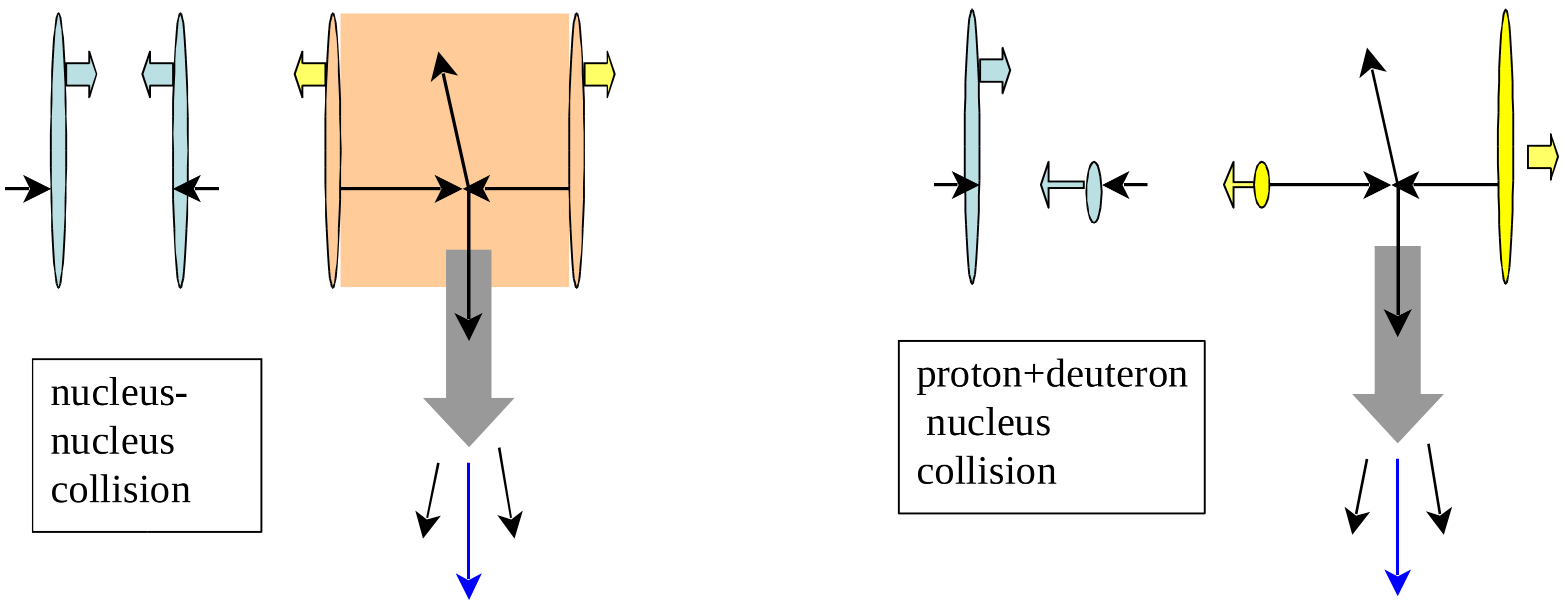
- Energy loss in a dense hadronic medium ($\langle L/\lambda \rangle \sim 2\text{-}3$) seems to provide a (flat ?) suppression too ...



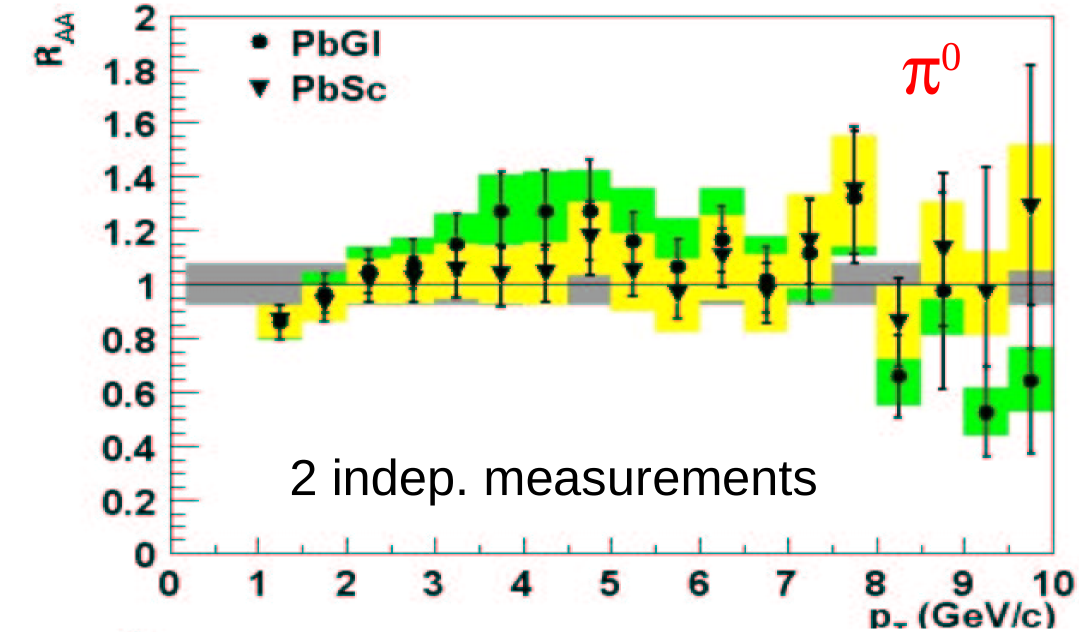
- Main argument: fast parton hadronization time implies rescatering of hadronic jet fragments (“pre-hadrons”) inside expanding fireball.
- Description of scattering in the hadronic phase realistic enough ?
  (“... *our calculations are at best semiquantitative* ...”).
- New results (within HSD transport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

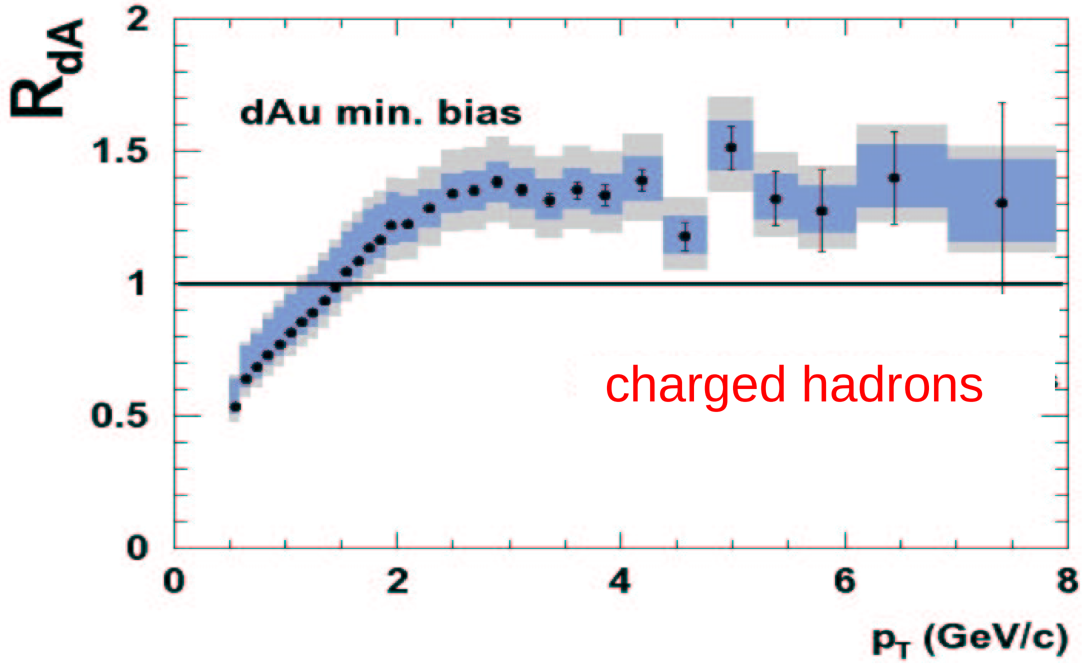
d+Au ("control" experiment) high p_T results

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



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)

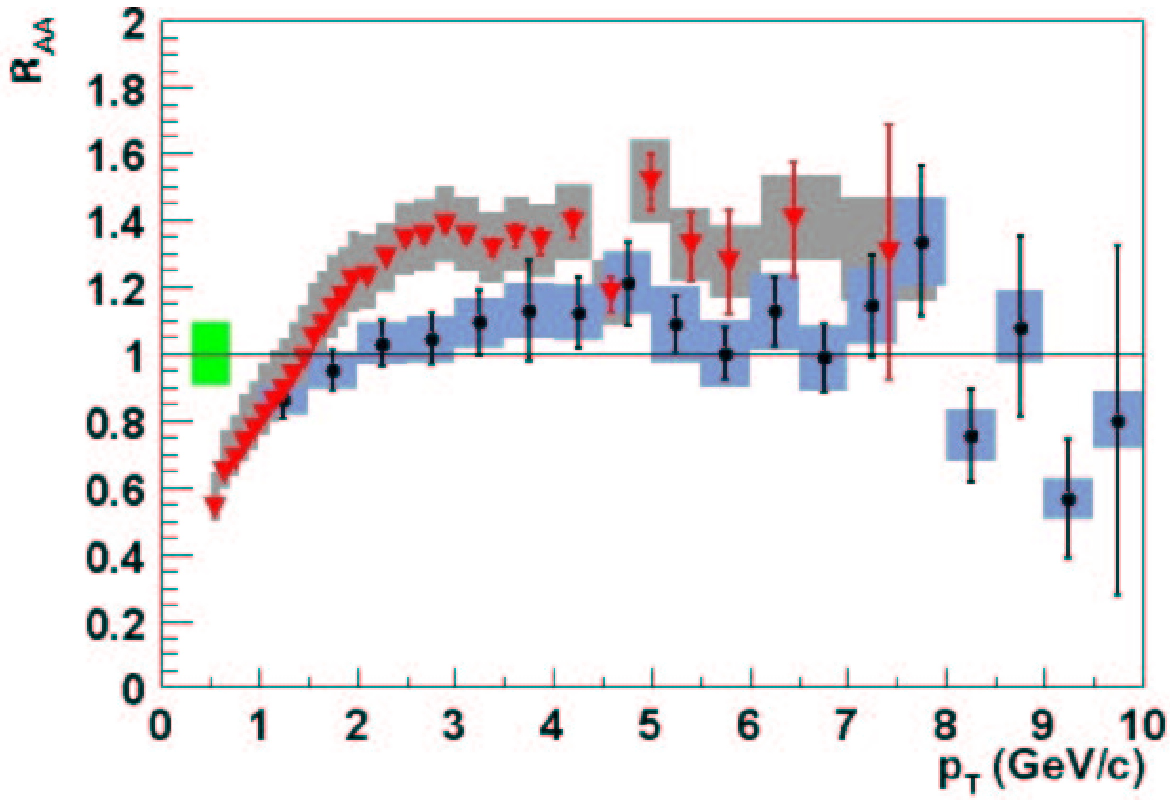
  ~ flat between 3 – 8 GeV/c

PHENIX collab.
PRL 91 072301 (2003)
nucl-ex/0306021

David d'Enterria (Columbia Univ.)

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

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



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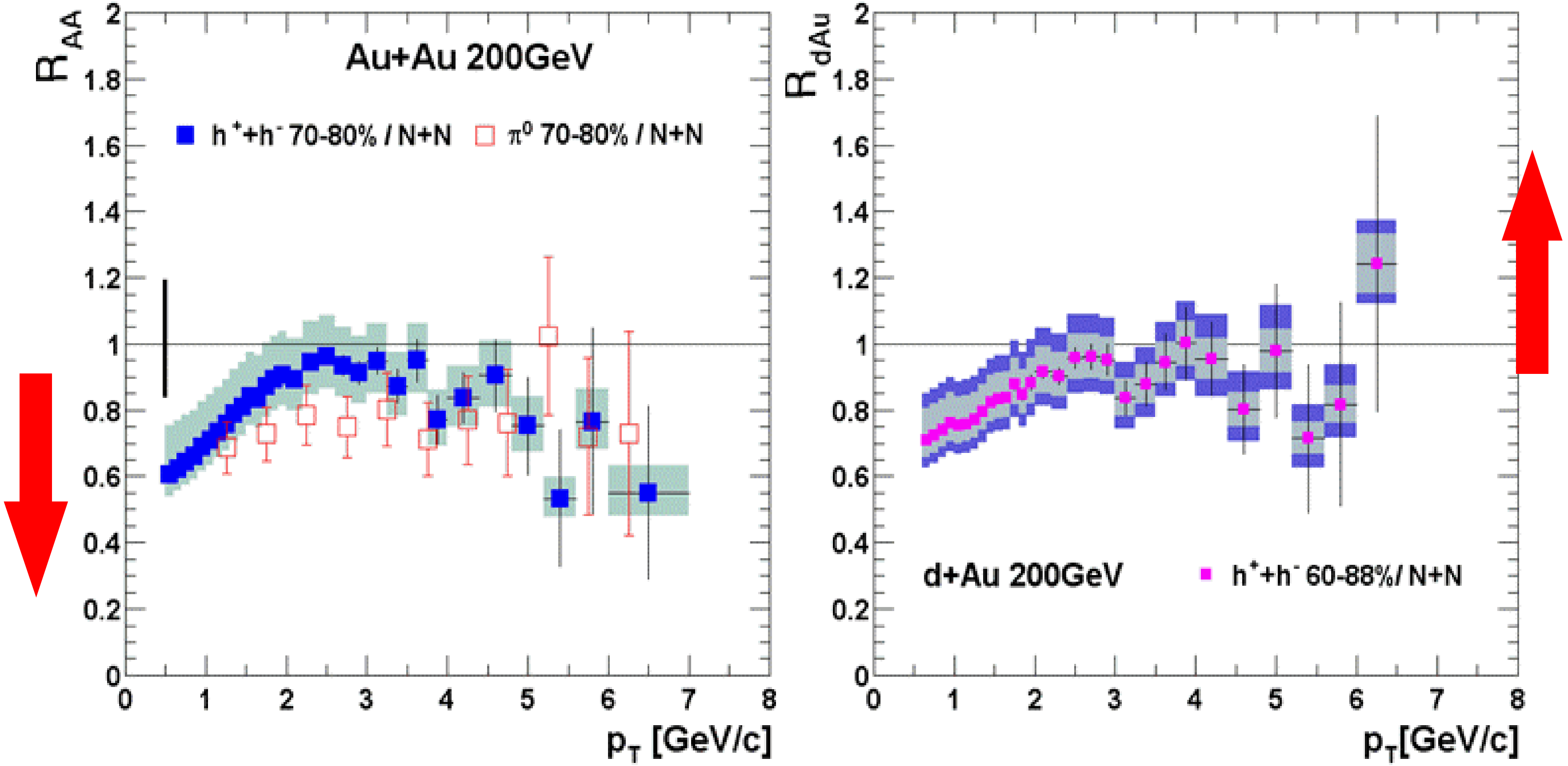
nucl-ex/0306021

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

Nuclear modification: d+Au vs Au+Au

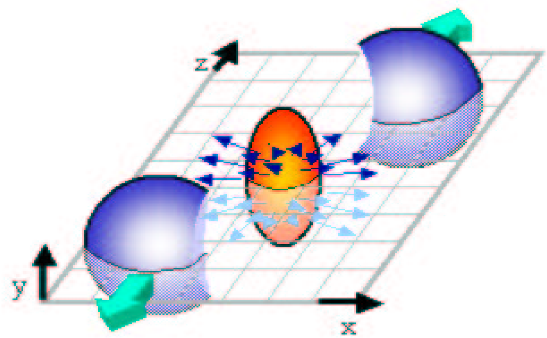
PHENIX preliminary



- 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: 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)



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

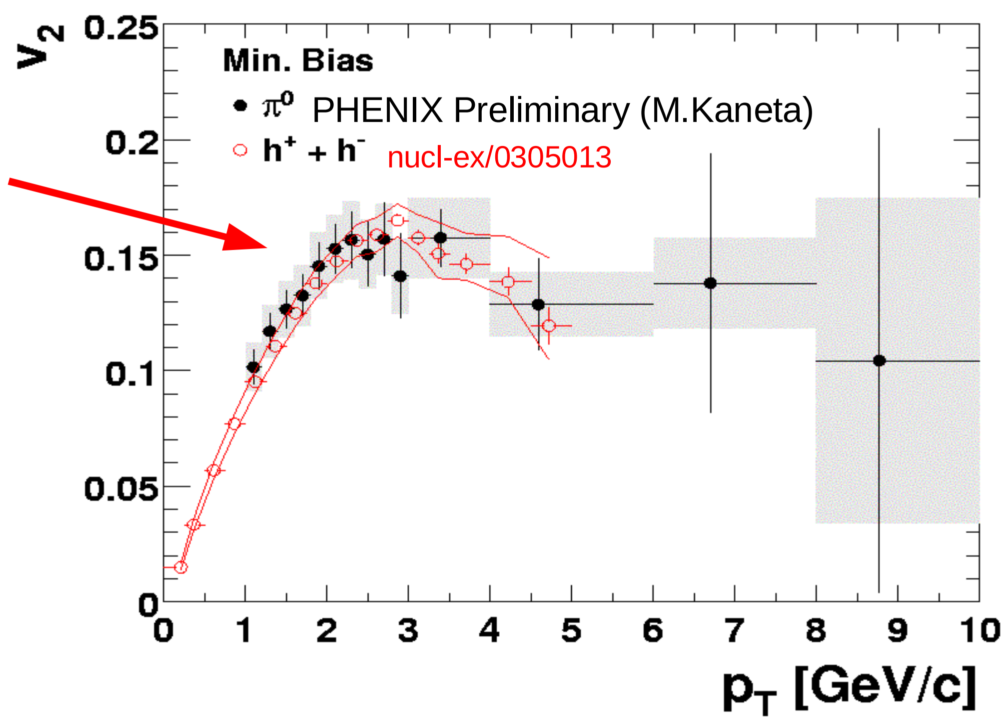
Flow = v_2 second Fourier coefficient

Truly collective effect (absent in p+p colls.)

- Large v_2 signal (saturating @ high p_T)

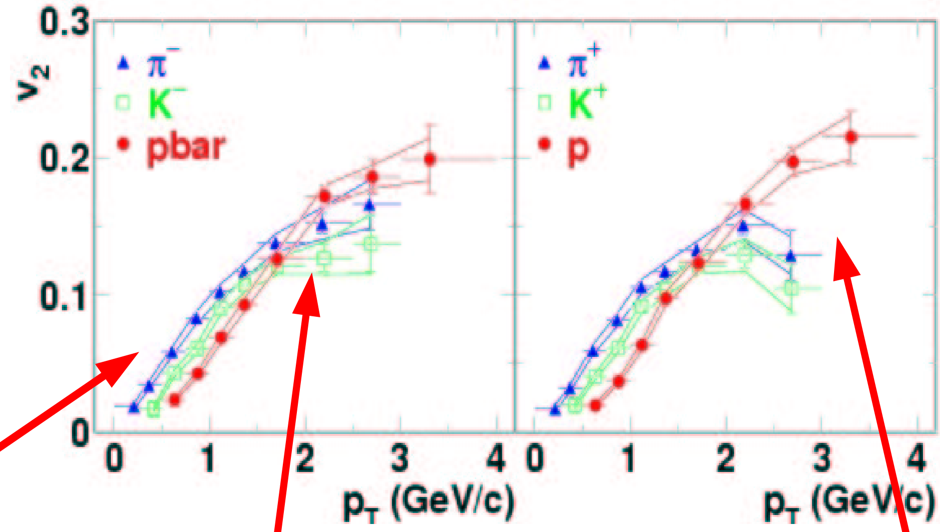
  $\Rightarrow$ strong (collective) pressure grads.

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



High p_T azimuthal correlations: Elliptic flow (II)

- Particle species dependence of flow:



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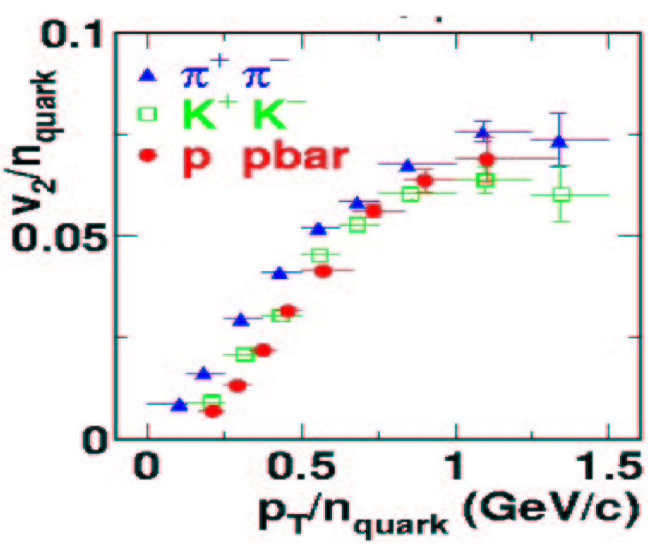
to appear in PRL
nucl-ex/0305013

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

- Reasonably well explained in quark recombination models (v_2 scaled by # of constituent quarks):

(n = 2 for mesons, n = 3 baryons)



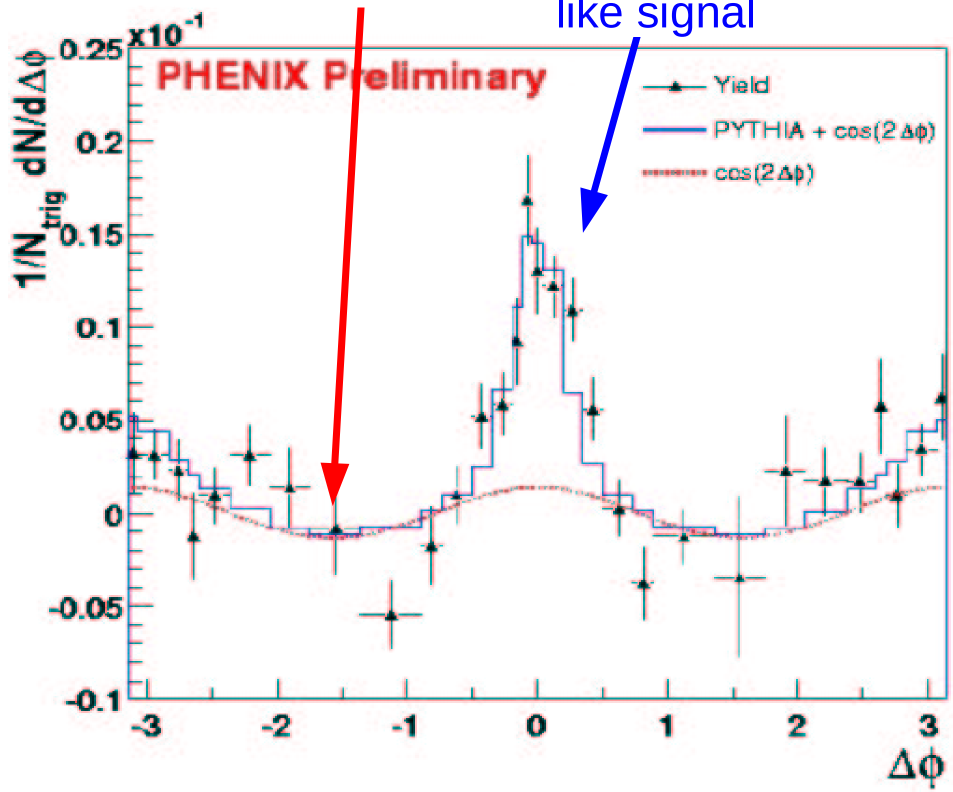
High p_T azimuthal correlations (II): p+p vs Au+Au

- 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)

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

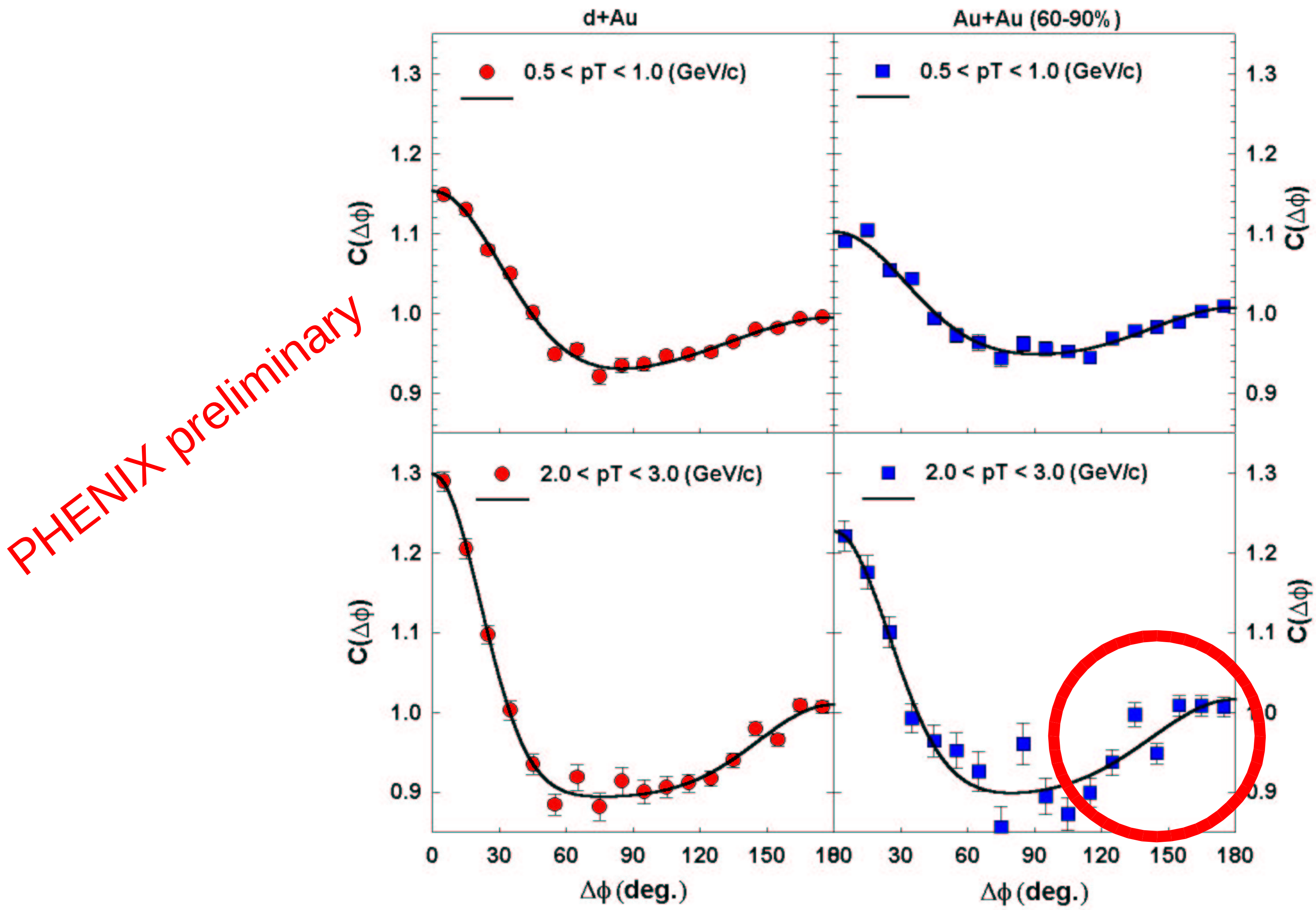
Flow harmonic contribution

Near-side jet-like signal



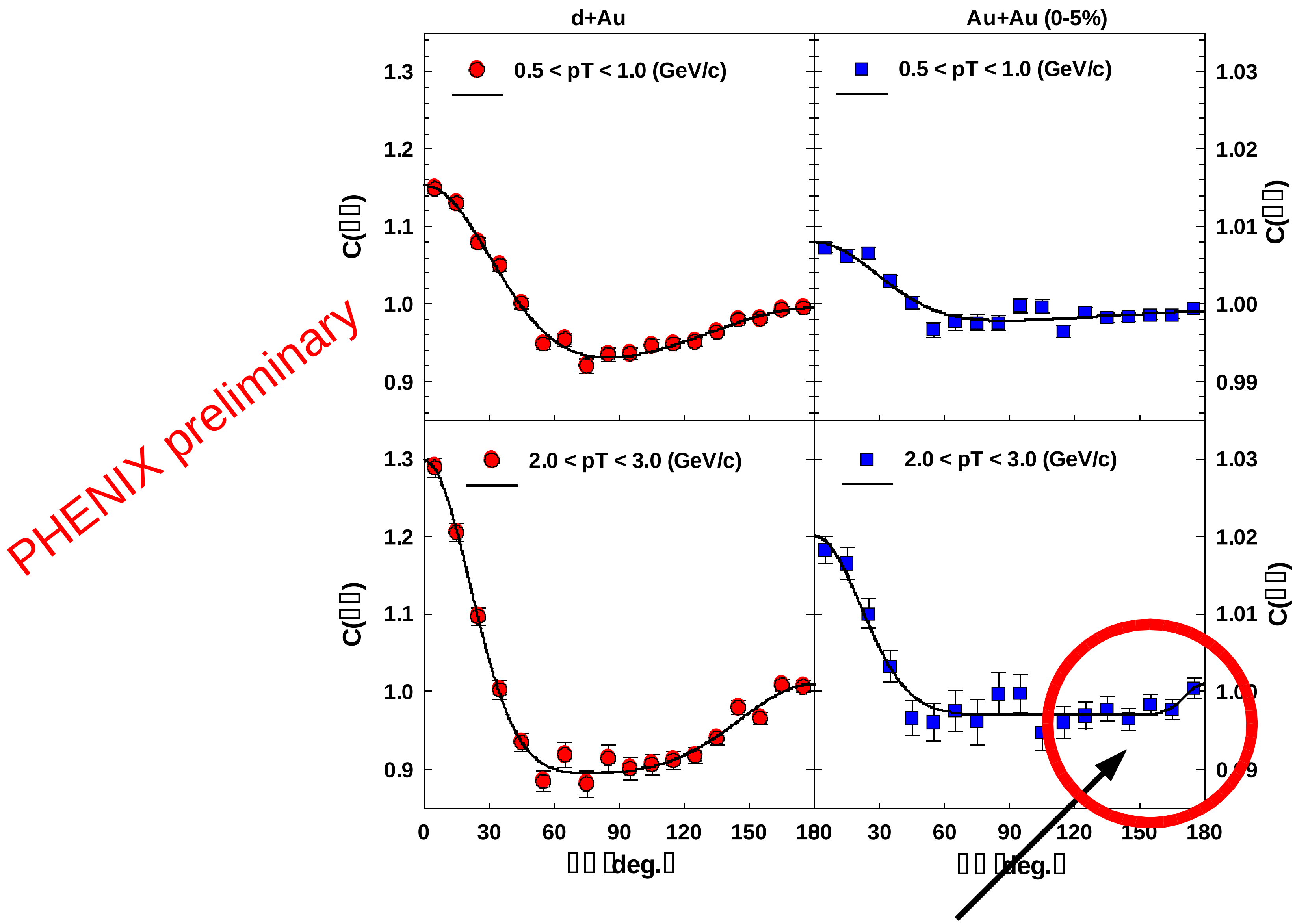
- Near-side correlation as in p+p: trigger particles (p_T > 4GeV/c) come from jets

High p_T azimuthal correlations (III): d+Au vs Au+Au(periph)



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

High p_T azimuthal correlations (IV): d+Au vs Au+Au(central)



- Diminished away-side correlation consistent with lost jet in "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.

(*) via confronting data to theory

“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.

"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 !

Summary (I)

- Vast amount of high p_T data (yields, particle ratios, angular correlations) in p+p, Au+Au, and d+Au collisions @ $\sqrt{s}$ = 200 GeV

- Central Au+Au collisions results:
  - 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).
  - Smooth centrality dependence of suppression (weak N_{part} scaling).
  - No apparent suppression of p,pbar up to ~4 GeV/c: "anomalous" p/π ~ 0.8 ratio >> p/π ~ 0.2 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 (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 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 100% consistent explanation.
- Corollary: $QGP = P_{QCD} + (R_{AA}+I_{AA}) + dAu$ $+ J/\psi + T_\gamma$

"100% evidence of QGP @ RHIC requires the J/ψ & (thermal) photon signals (hopefully soon ...)"