3 ans de physique au RHIC : qu'avons nous appris jusqu'ici ? (une perspective de PHENIX)

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Overview

1. Introduction:

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

2. Results I: Global observables

- Au+Au: Energy density, particle multiplicity, net baryon density.

3. Results II – High p_T probes:

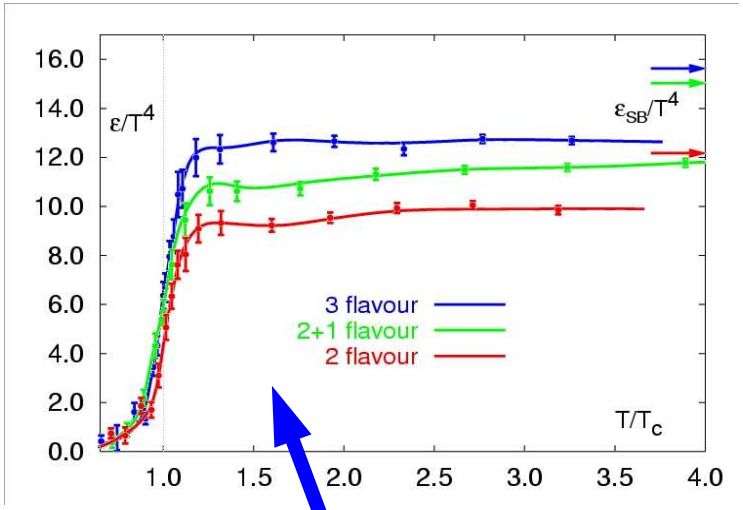
- Au+Au vs p+p: Suppression of high p_T hadron spectra
- Au+Au vs p+p: "Anomalous" hadron composition at high p_T
- Au+Au vs p+p: Collective elliptic flow, away-side jet suppression
- d+Au vs p+p: Cronin-like high p_T enhancement

4. Results III: Au+Au heavy-flavor probes

- Au+Au: Single electrons (open charm)
- Au+Au: First results on J/ψ

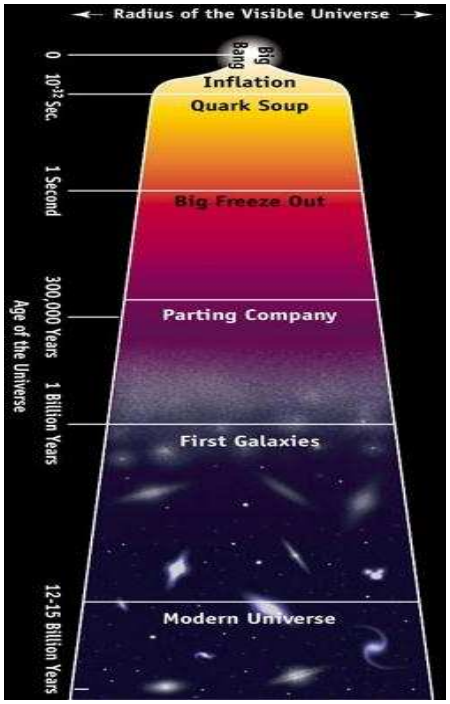
5. Summary

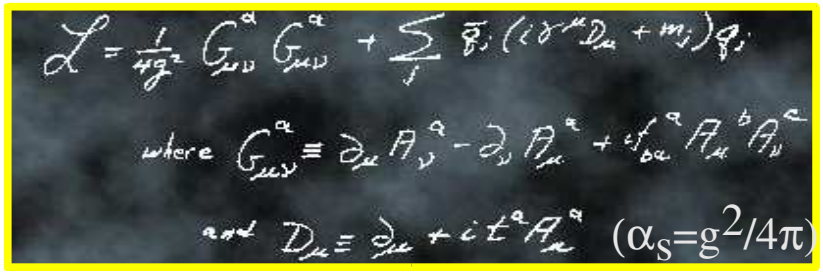
High-energy heavy-ion physics program (in 3 plots)



1. Study the phase diagram (and transport properties) of QCD matter, and especially produce & study the Quark Gluon Plasma.

2. Probe the properties of the primordial Universe (few micro-seconds after the Big Bang).





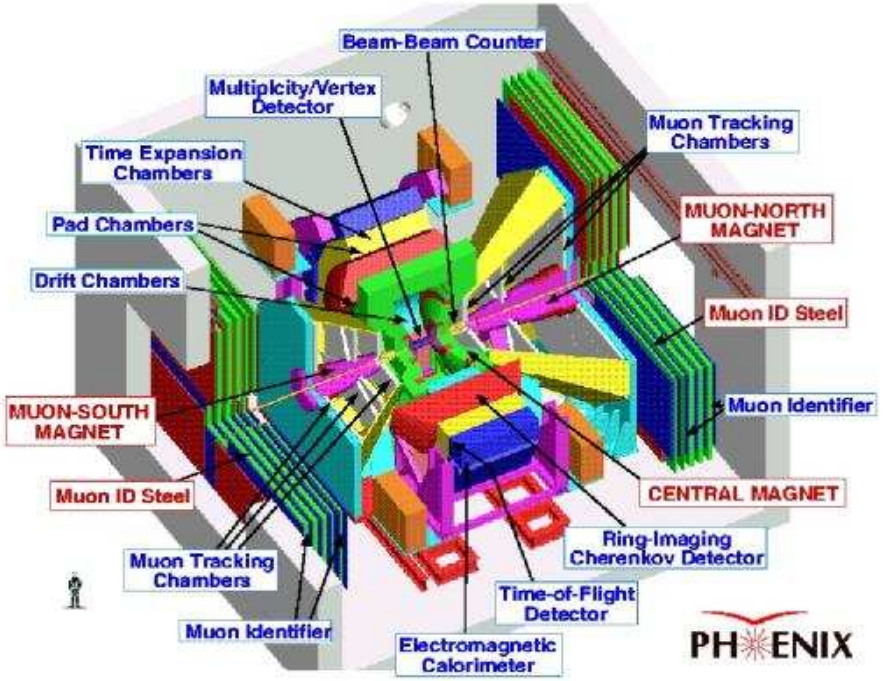
$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

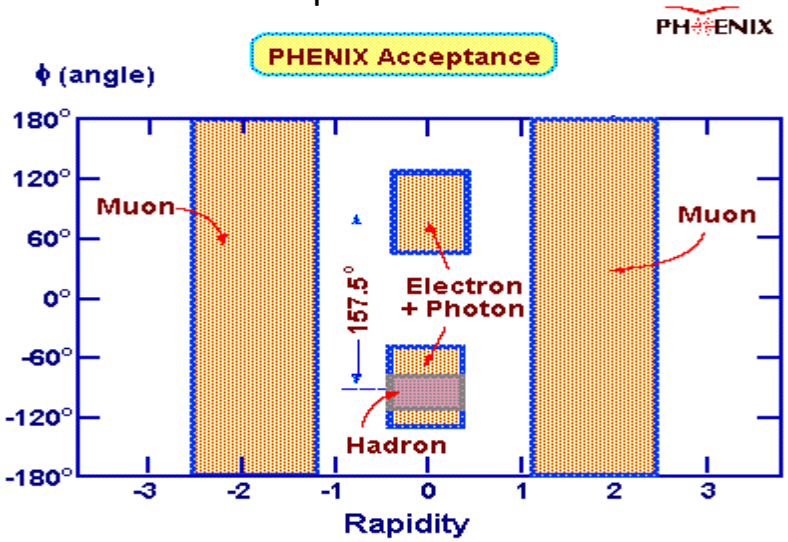
3. Learn about 2 (so far unexplained) properties of the strong interaction: confinement, chiral symmetry breaking

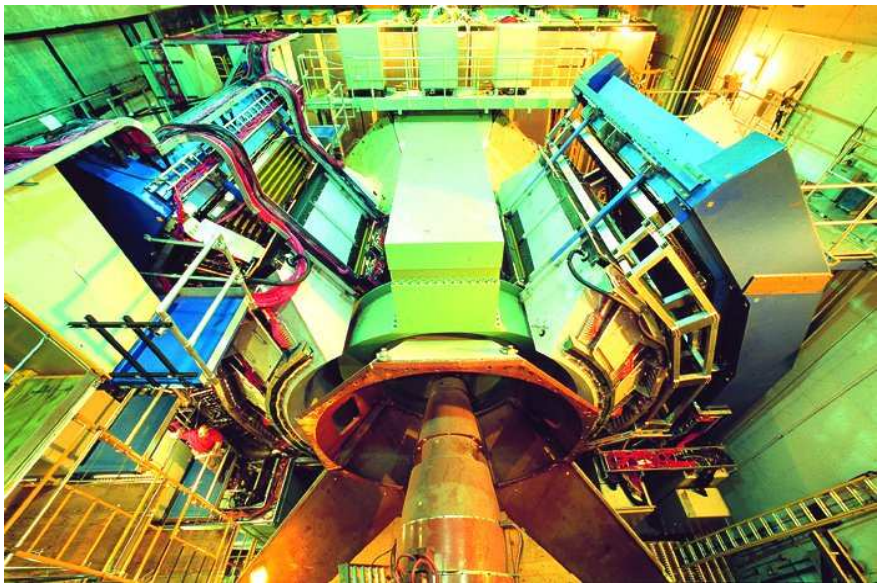
"Produce and study strongly interacting matter at extreme energy densities in high-energy nucleus-nucleus collisions"

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



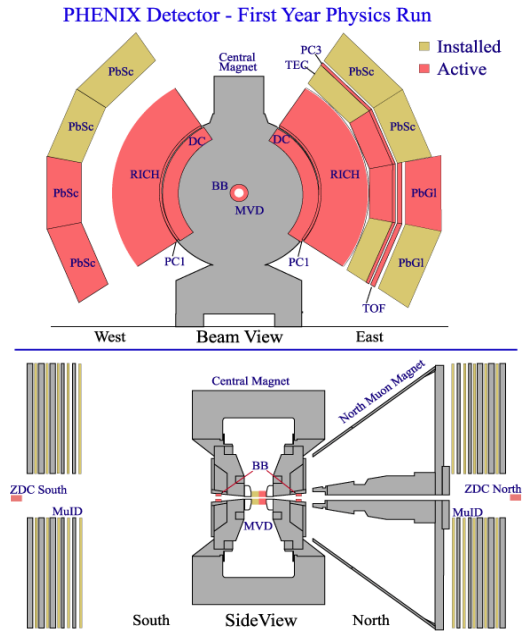




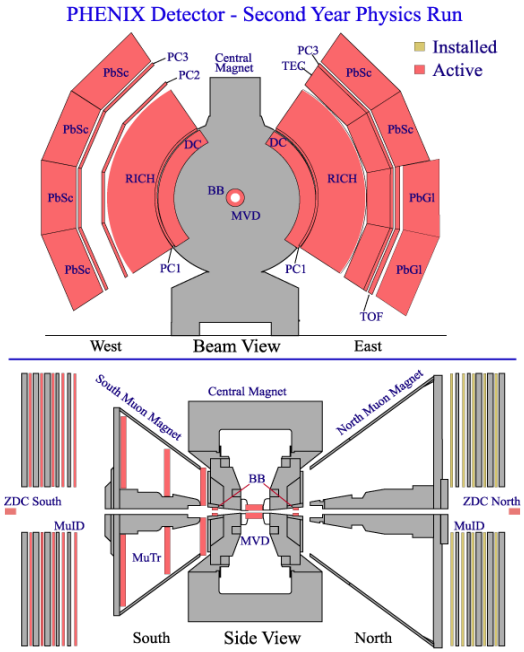
PHENIX run history

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

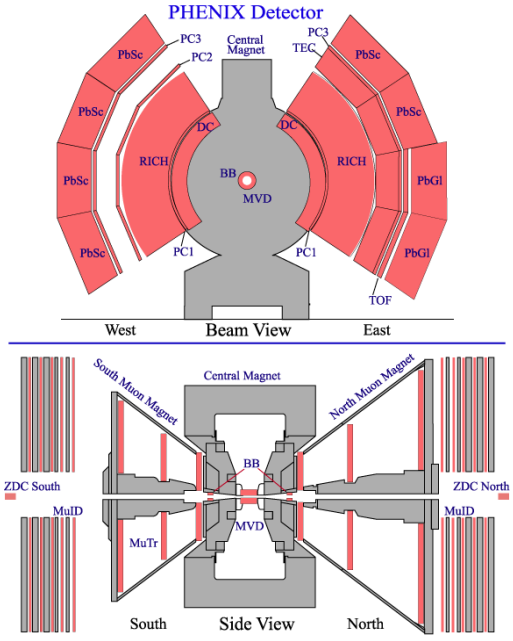
2000



2001/2002

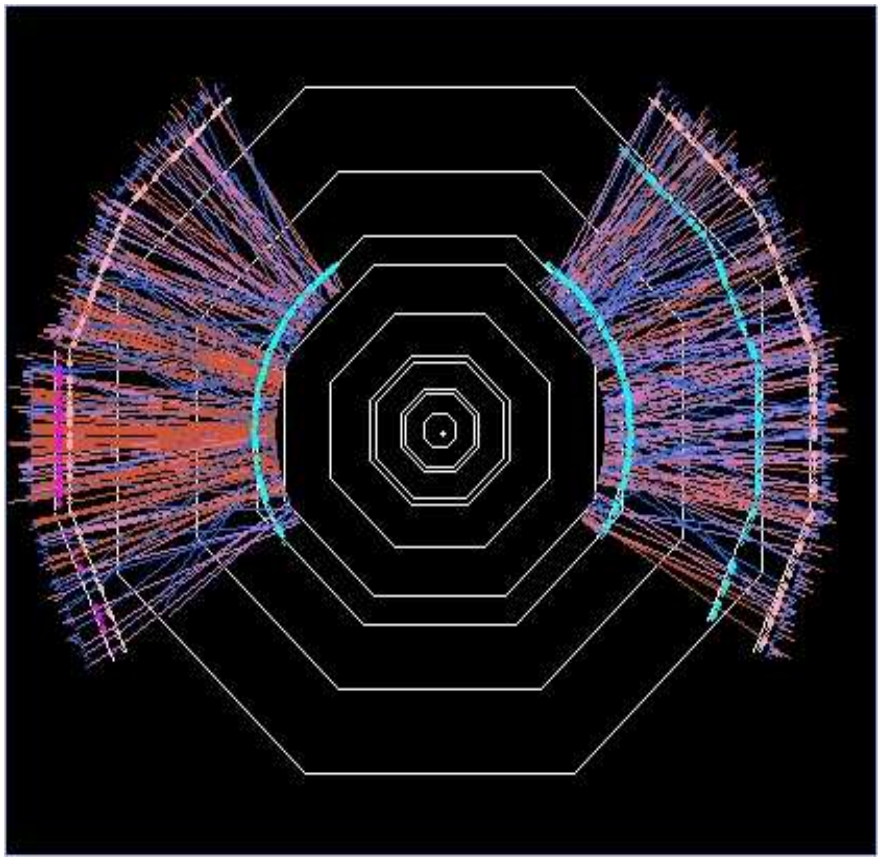


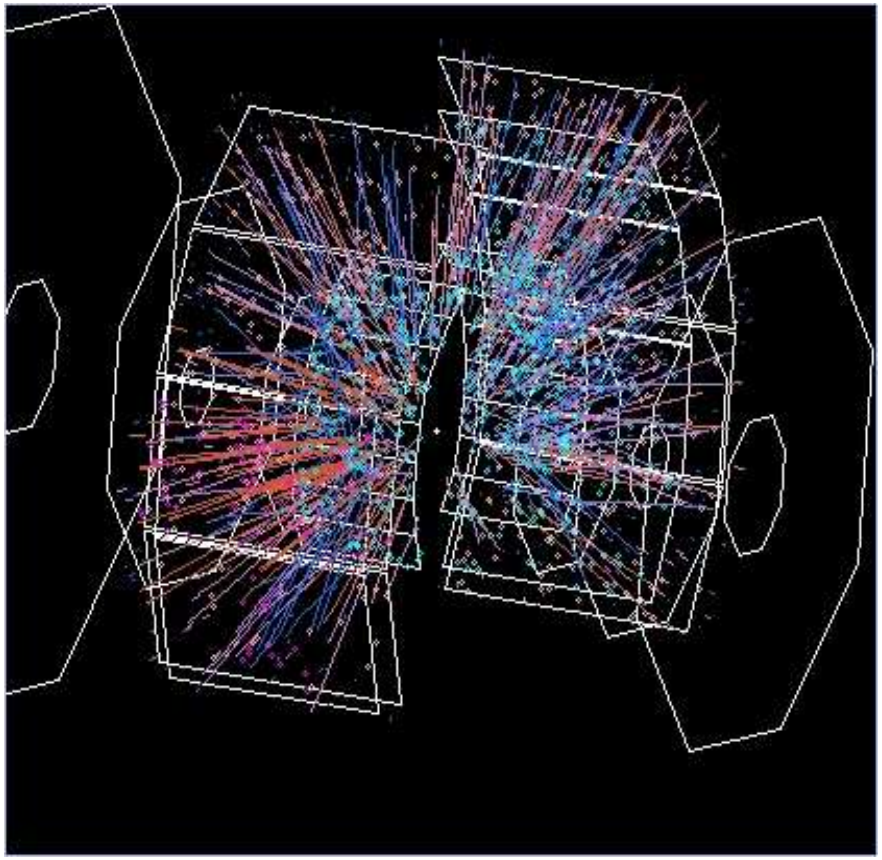
2002/2003



Results I:
Au+Au global observables

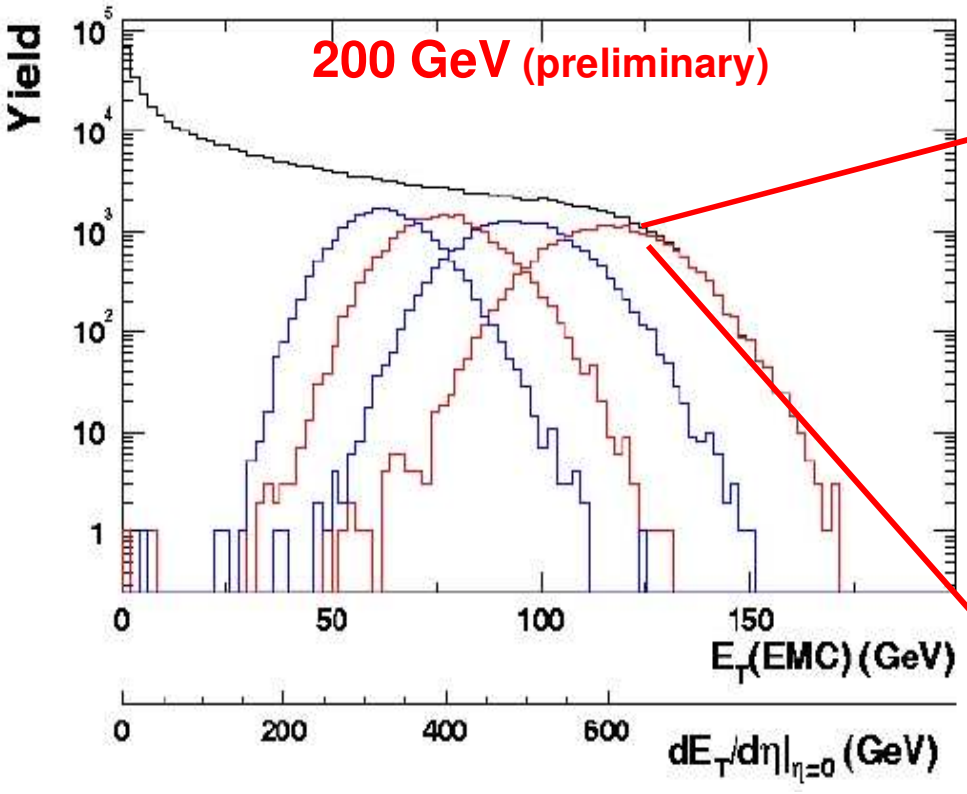
Au+Au in PHENIX





Au+Au Global Results 1: Energy density [PRL 87, 52301 (2001) & QM2002]

- E_T at mid-rapidity measured by calorimetry: PHENIX EMCal is a good *hadronic* calorimeter: $E_T^{had} = (1.17 \pm 0.05)\ E_T^{EMCal}$

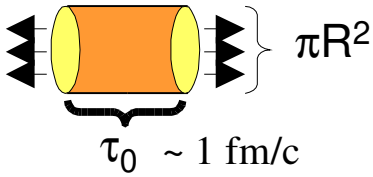


<$dE_T/d\eta$> ~ 600 GeV (top 10% central)

70% larger than at SPS energies

Bjorken's estimate of the energy density (longitudinal expansion):

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



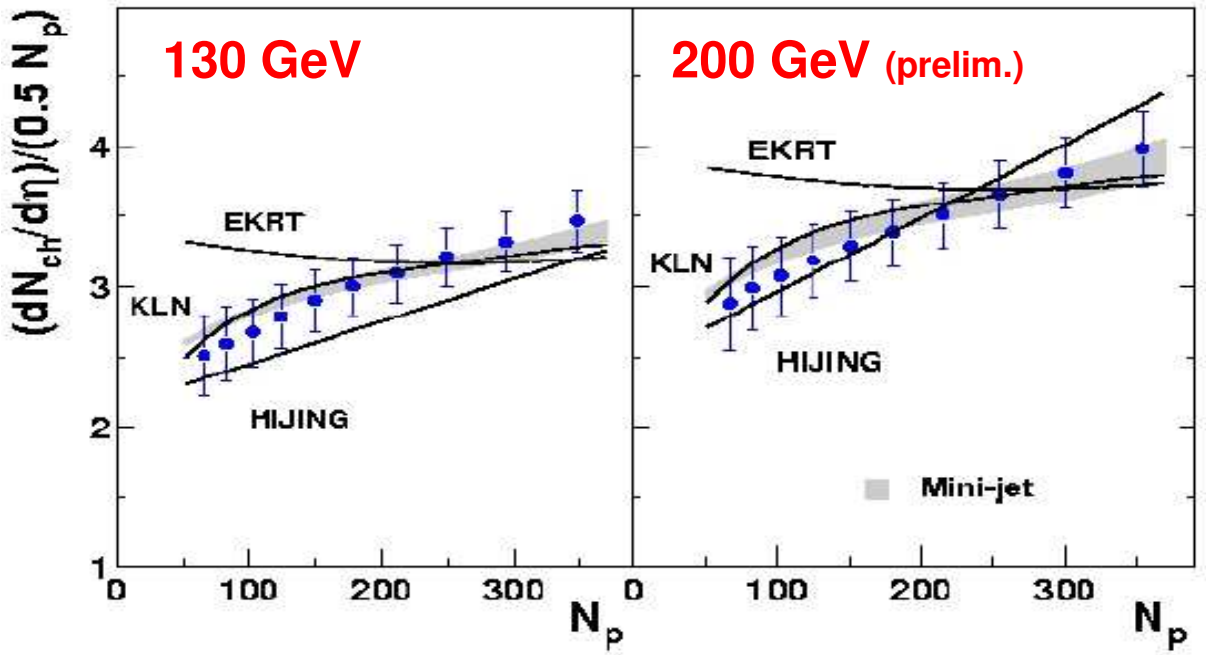
$\varepsilon_{Bjorken}$ ~5.0 GeV/fm^3

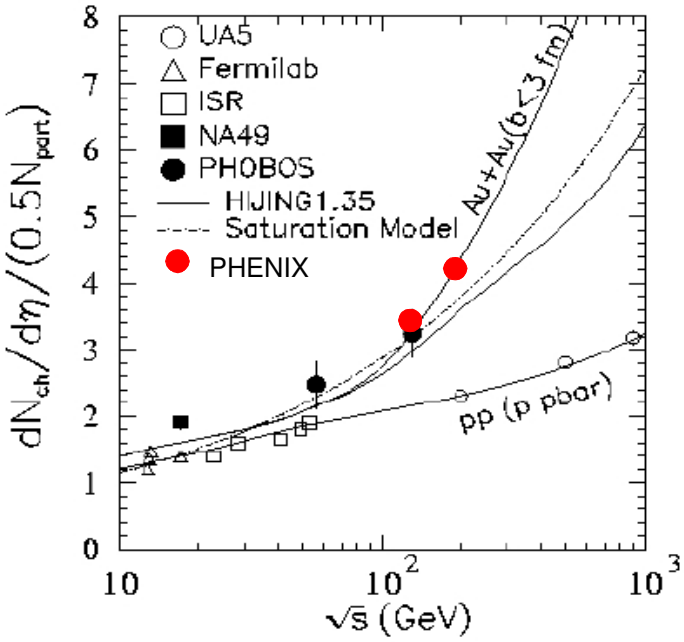
- Energy density (~5 GeV/fm^3) @ RHIC > QCD critical density (~1 GeV/fm^3)

[*modulo: 1D expansion, not fully baryon-free, thermalization time estimate*]

Au+Au Global Results 2: Particle Multiplicity vs. centrality

[PRL 86, 3500 (2001), and QM2002]

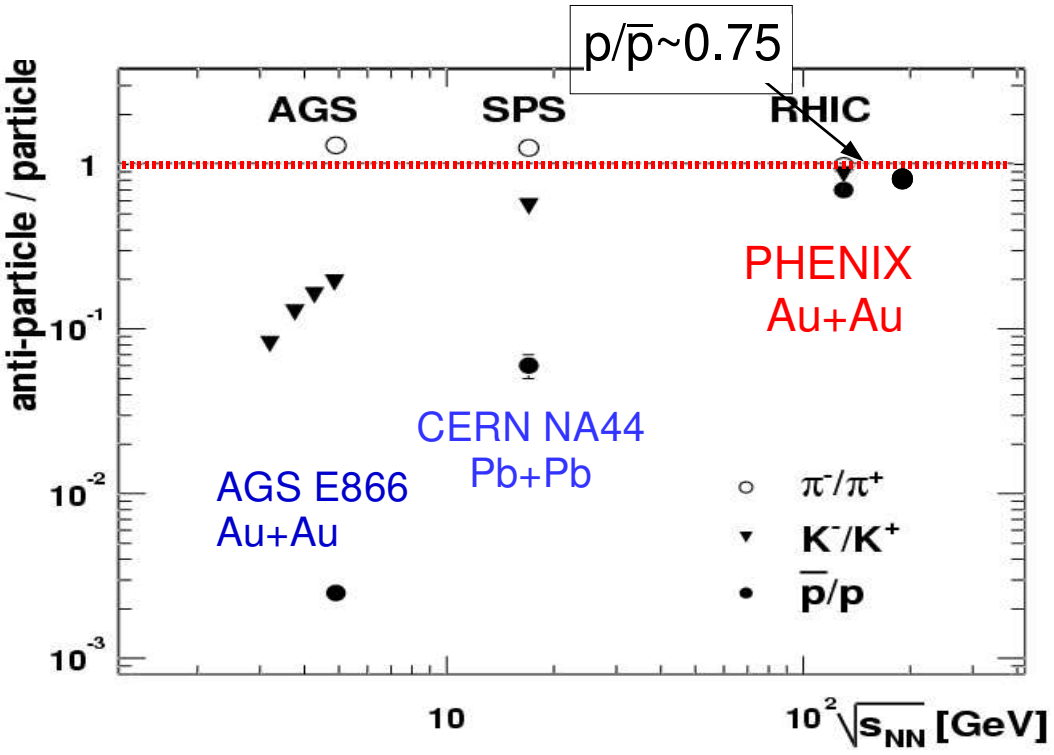




- dN_{ch}/dy (per participant pair) increases faster than linearly with centrality:
- dN_{ch}/dy constraints mechanisms of initial multi-particle production:
  - ✔ "Soft + hard" (HIJING, pQCD “minijet”): increased hard contribution ($\propto N_{coll}$)
  - ✔ Initial-state gluon saturation (CGC): $dN_{ch}/dy \sim dN_{gluon}/dy \sim 1/\alpha_s \sim N_{part} \ln N_{part}$
  - ✖ Final-state gluon saturation (EKRT)

Au+Au Global Results 3: Net baryon density at midrapidity

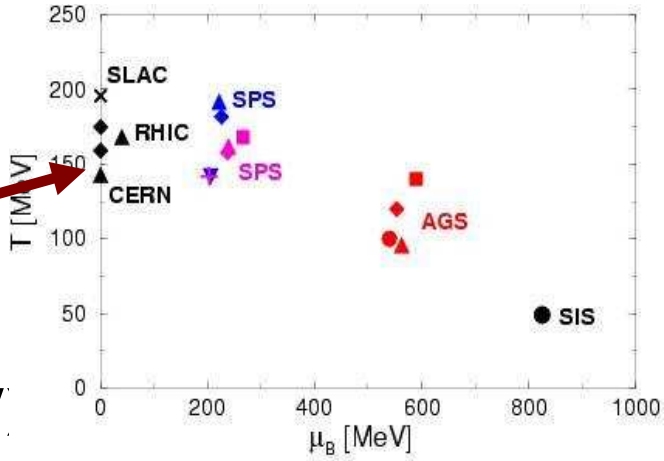
Particle over anti-particle ratios at y=0:



- 3/4 of protons at y = 0 come from pair production
  - Much closer to baryon-free region than SPS
  - Low baryo-chemical potential at freeze-out

  (statistical model Redlich *et al*):

  μ_B ~ 45 MeV (√s=130 GeV), 30 MeV (√s=200 GeV



Results I & II – Hard QCD probes

High p_T & heavy quark observables in Au+Au, p+p, d+Au

Hard QCD probes (I)

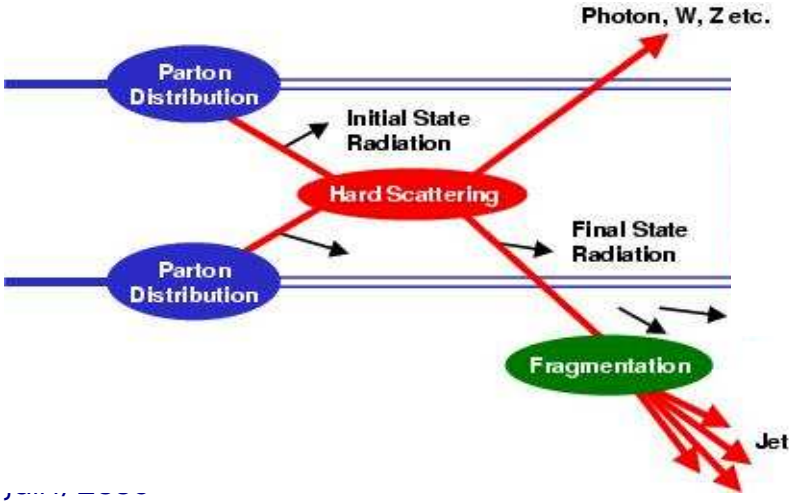
- Early production ($\tau \sim 1/p_T \sim 0.1$ fm/c) in parton-parton scatterings with large Q^2
- Direct probes of partonic phases $\Rightarrow$ Sensitive to dense medium properties: parton energy loss ("jet quenching"), color screening ("onia" suppression).
- Probes: High-p_T (jets, prompt γ), heavy-flavor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

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

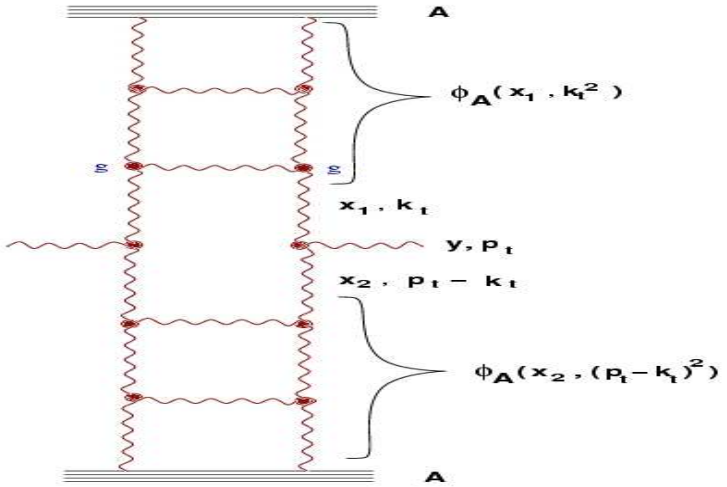
$A{\cdot}B \propto$ # of binary inelastic *NN* colls .

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

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

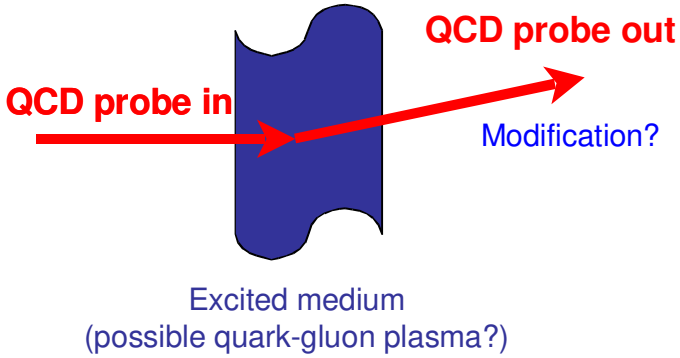


"Mueller diagram for classical glue radiation"



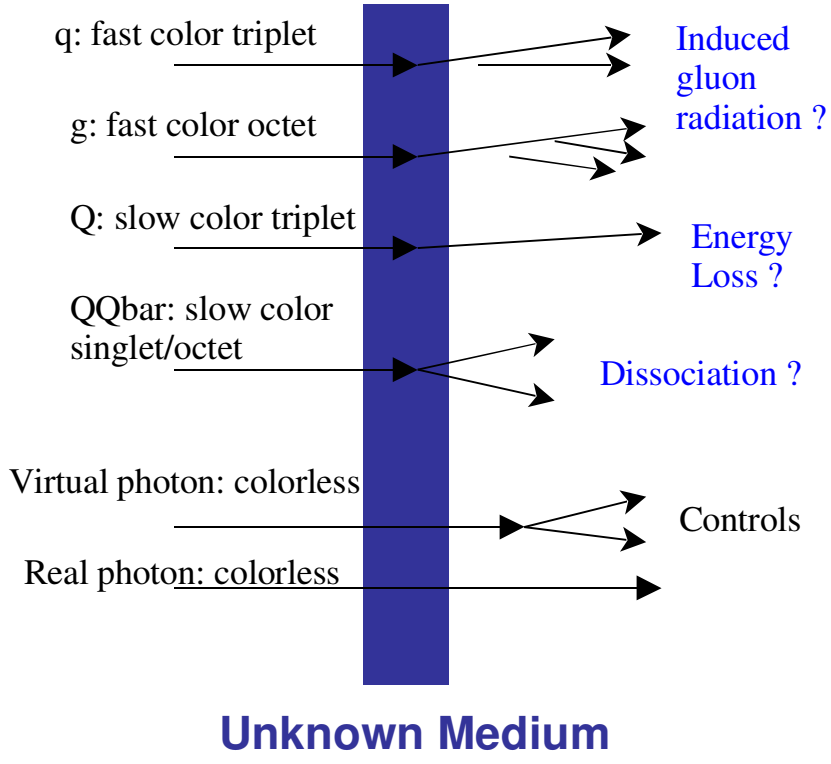
Hard QCD probes (II)

- QCD medium diagnosis via sensitive (well calibrated*) probes:



* experimentally & theoretically

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



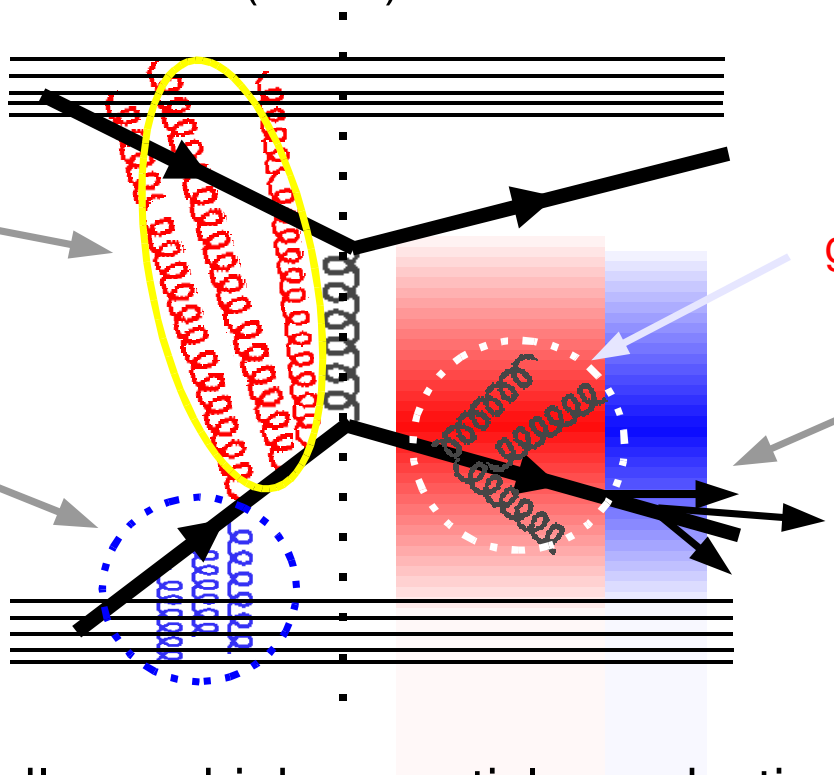
Results II:
High p_T observables

High p_T in a strongly interacting medium

- Initial- (CGC) vs final-state (QGP) medium effects :

Soft & semi-hard extra k_T ("Cronin effect")

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

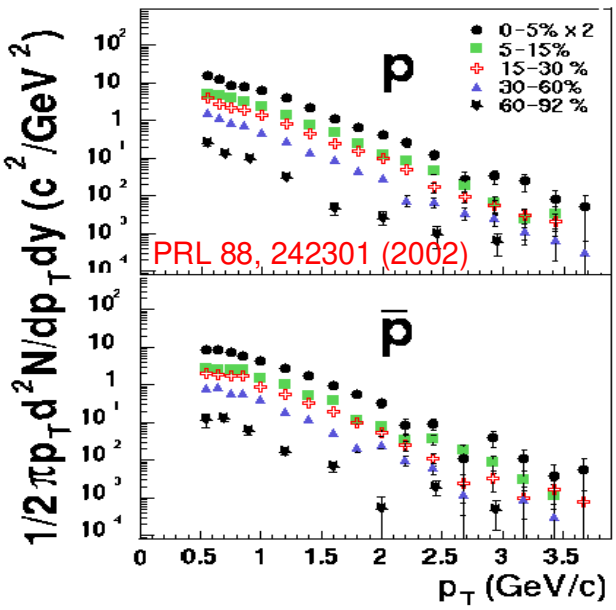


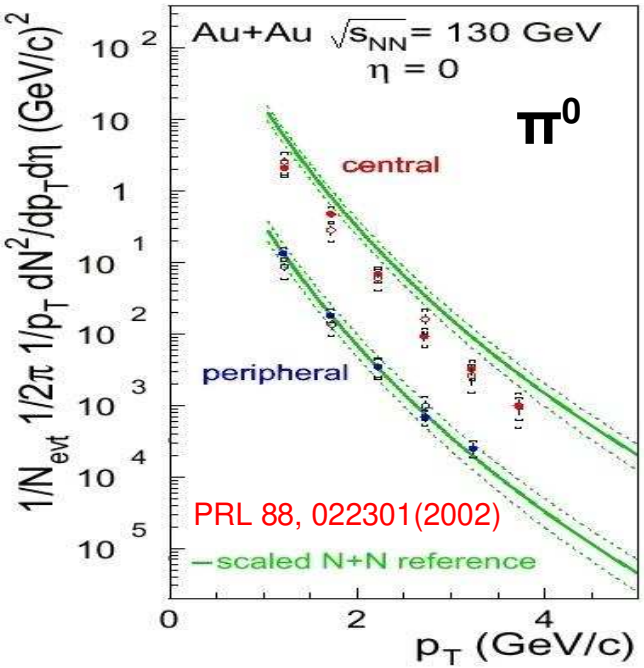
medium-induced gluon bremsstrahlung

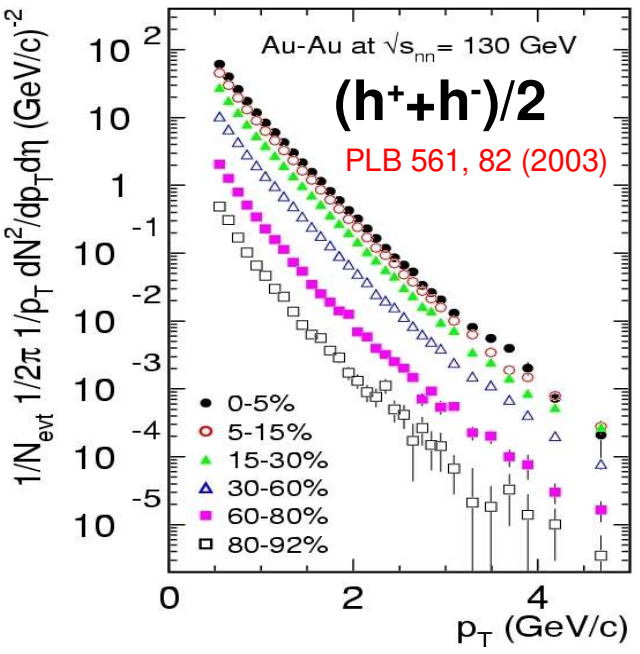
possible hadronic rescattering (after/before hadronization ?)

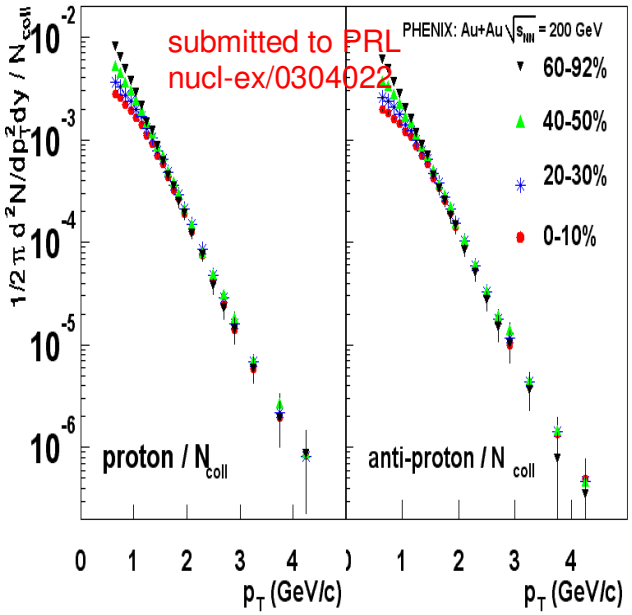
- Experimental handles on high p_T particle production:
  - Depletion of high p_T inclusive hadrons (jet leading particles)
  - Attenuation / absorption of jets ("jet quenching"): photon-tagged jets, direct γ vs fragmentation γ ...
  - Modification of angular correlations between jet products
  - Changes in particle composition

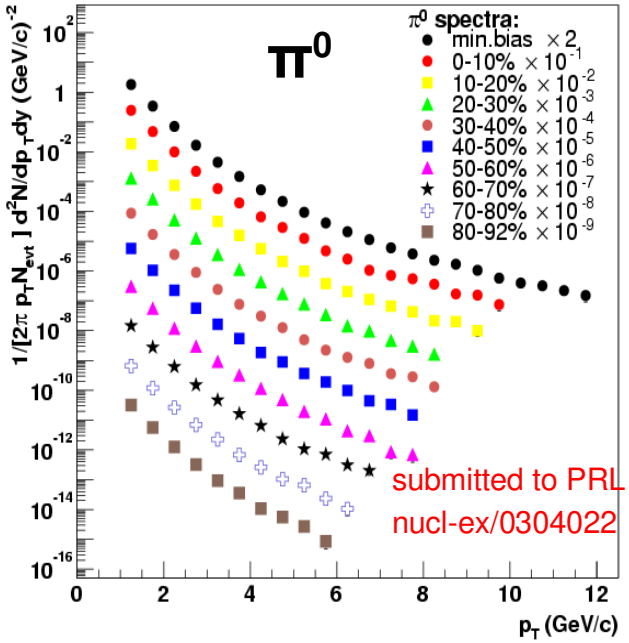
Au+Au: high p_T spectra

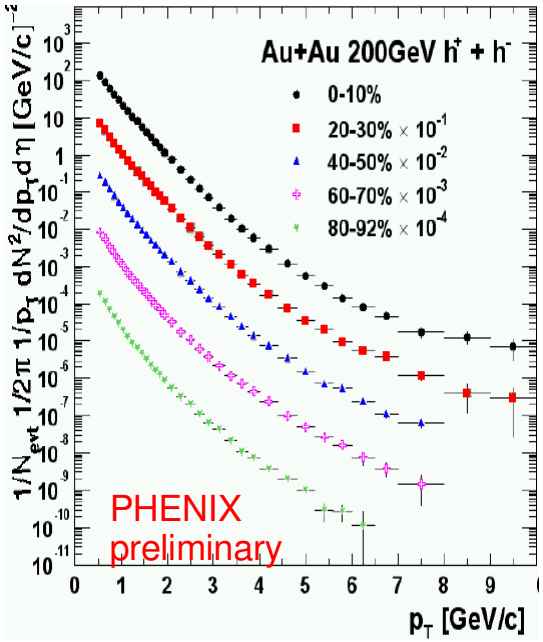




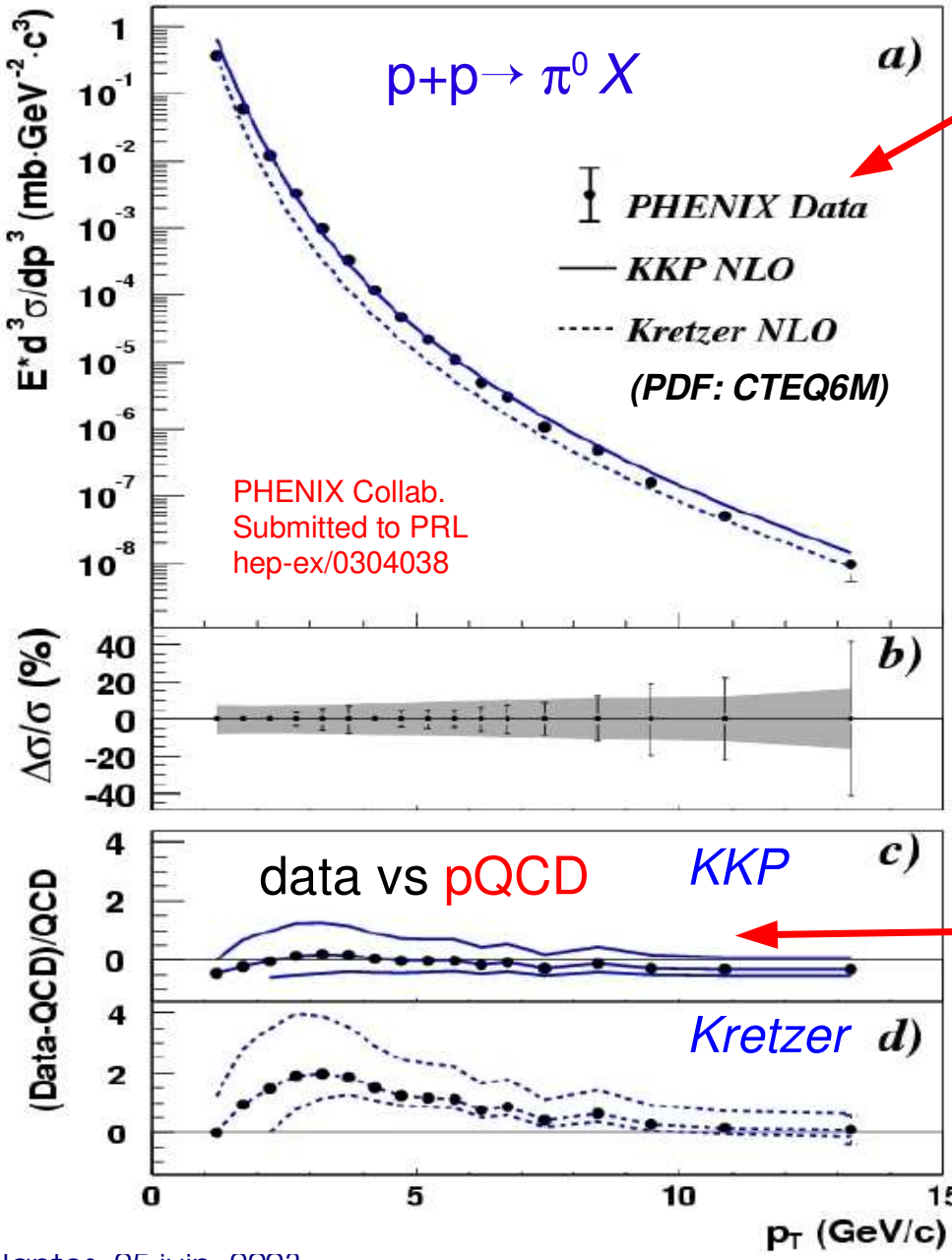




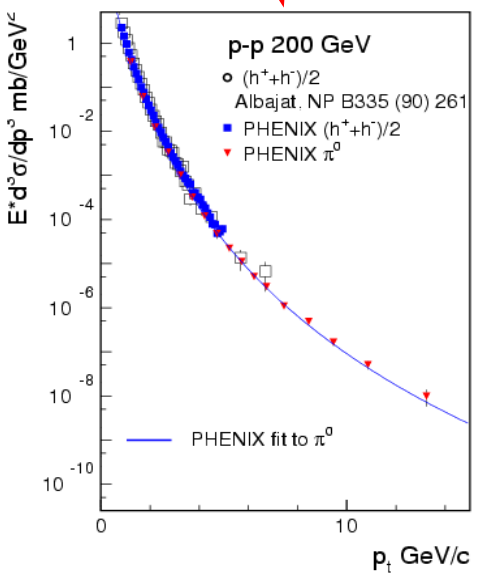


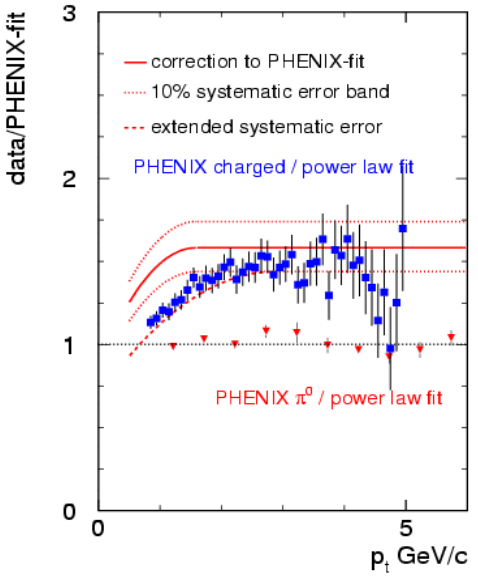


p+p reference @ 200 GeV: high-p_T neutral pions



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



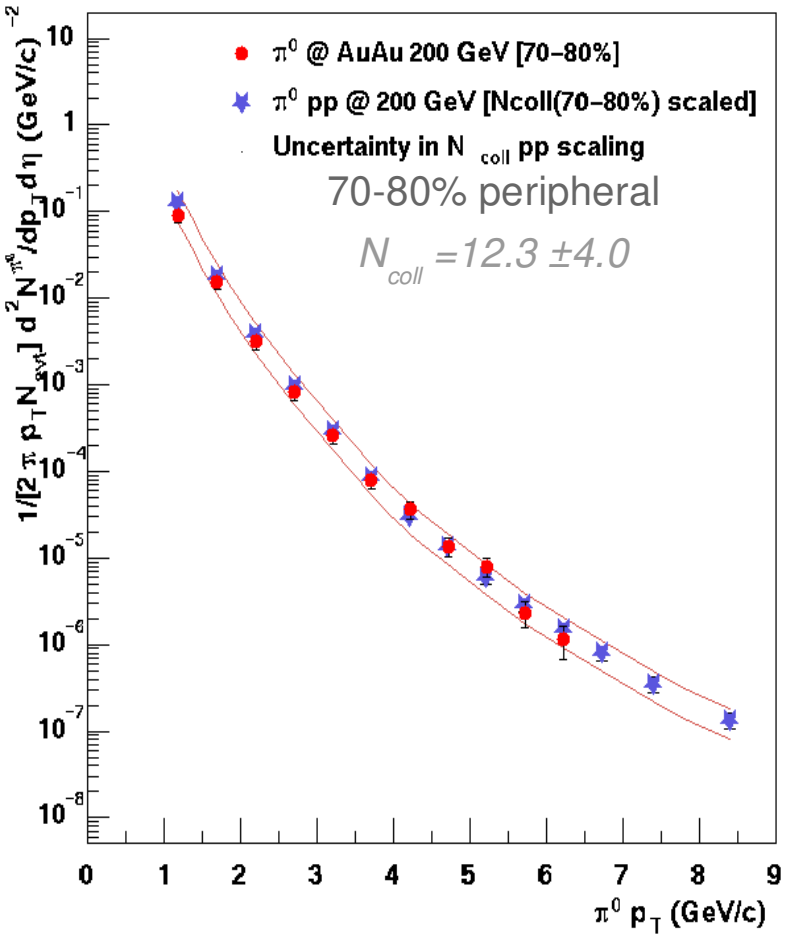


- Good NLO pQCD description

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

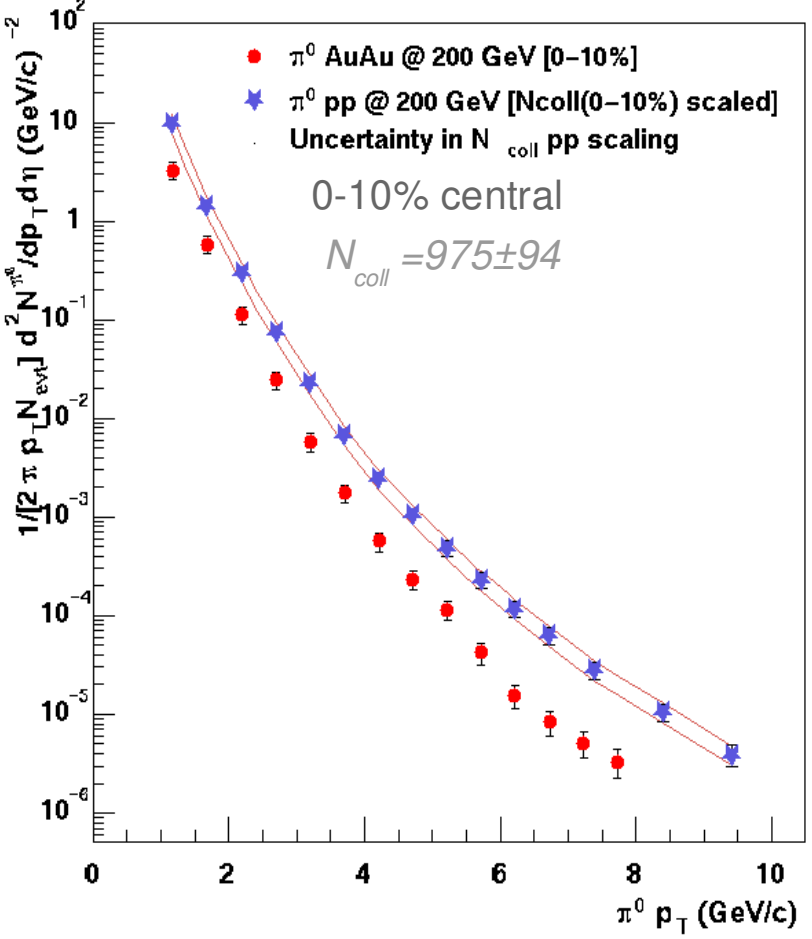
AuAu *vs* pp (neutral pions)

Au+Au→ π^0 *X* (periph)



Peripheral data agree with pp plus collision scaling

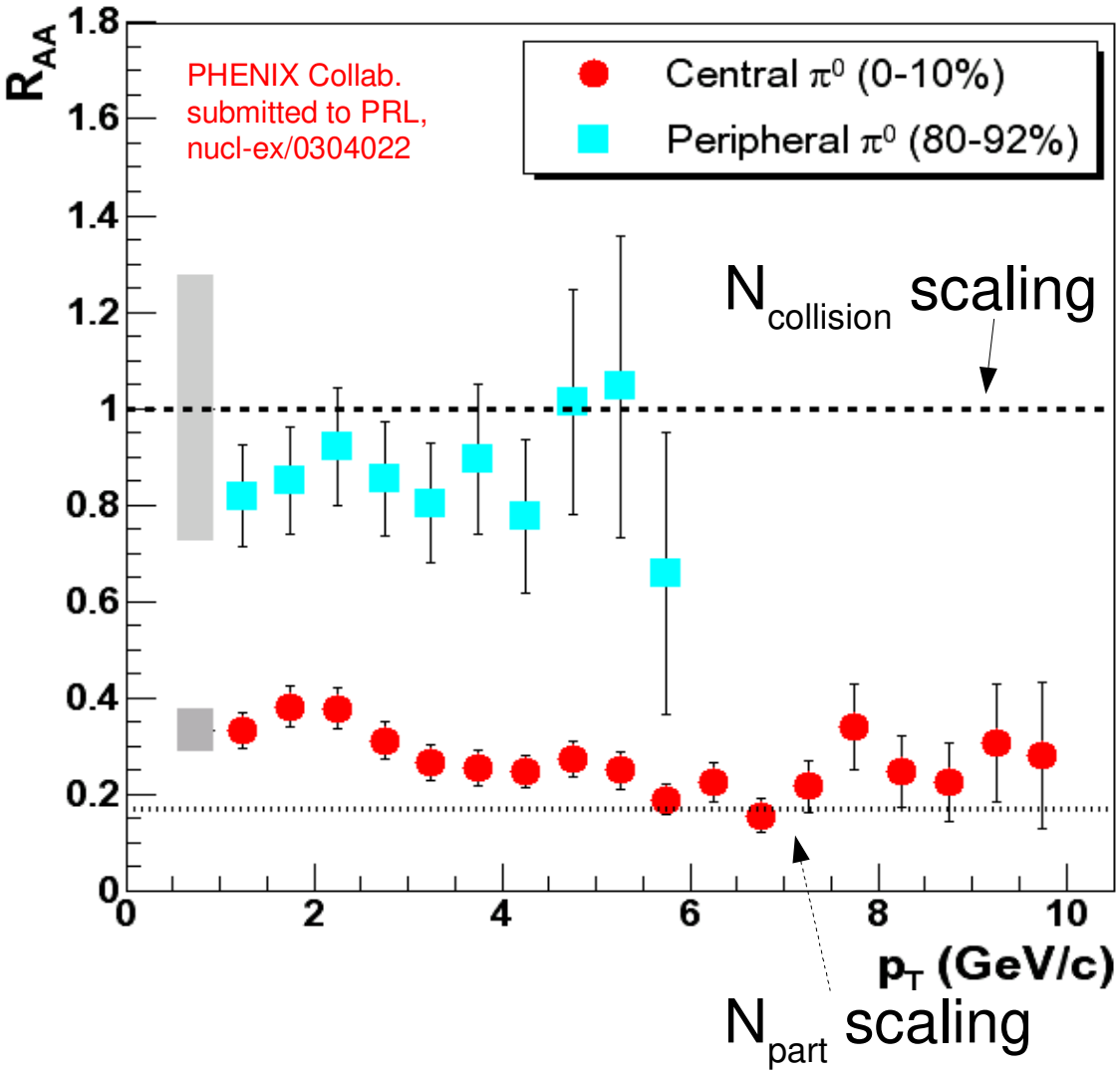
Au+Au→ π^0 *X* (central)

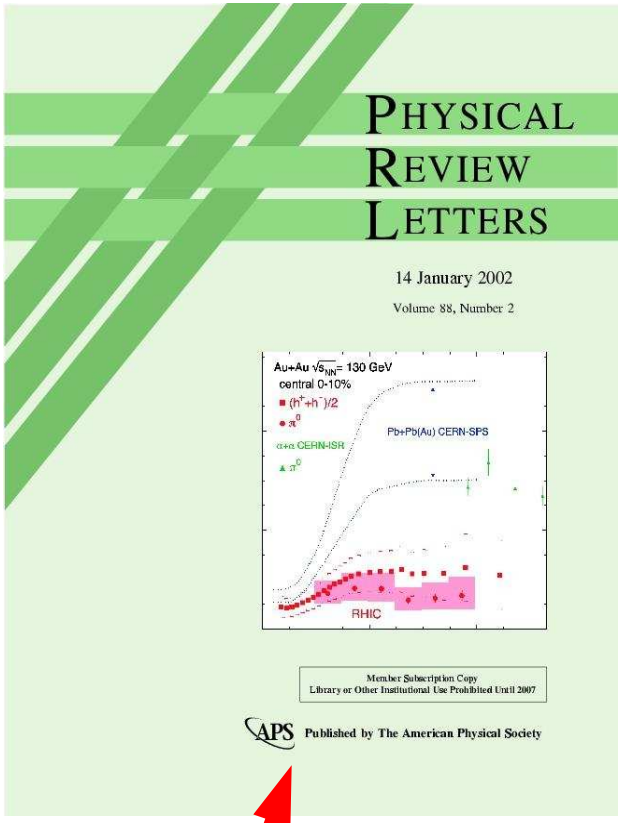


Strong suppression in central AuAu collisions

Nuclear modification factor (π^0)

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





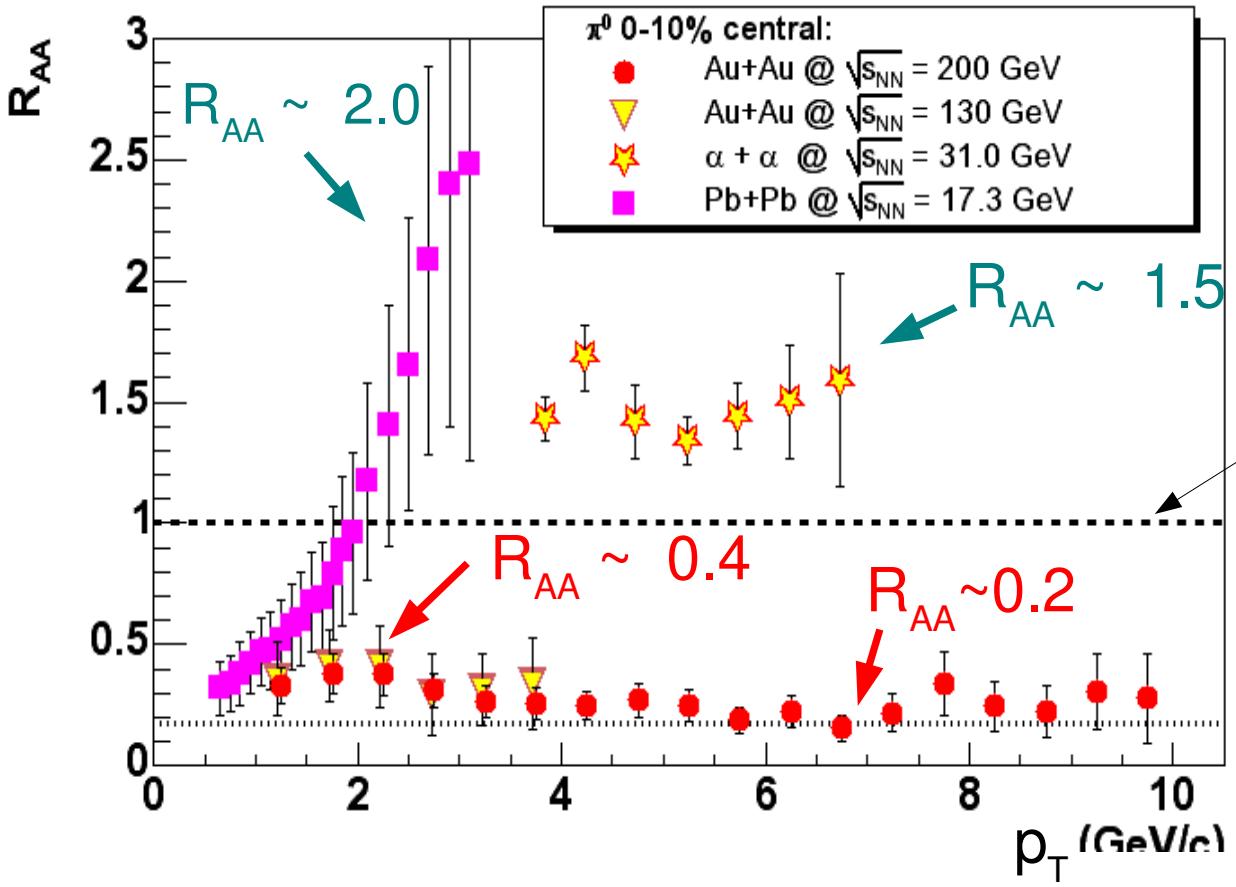
Discovery of high p_T suppression

(most significant result @ RHIC)

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

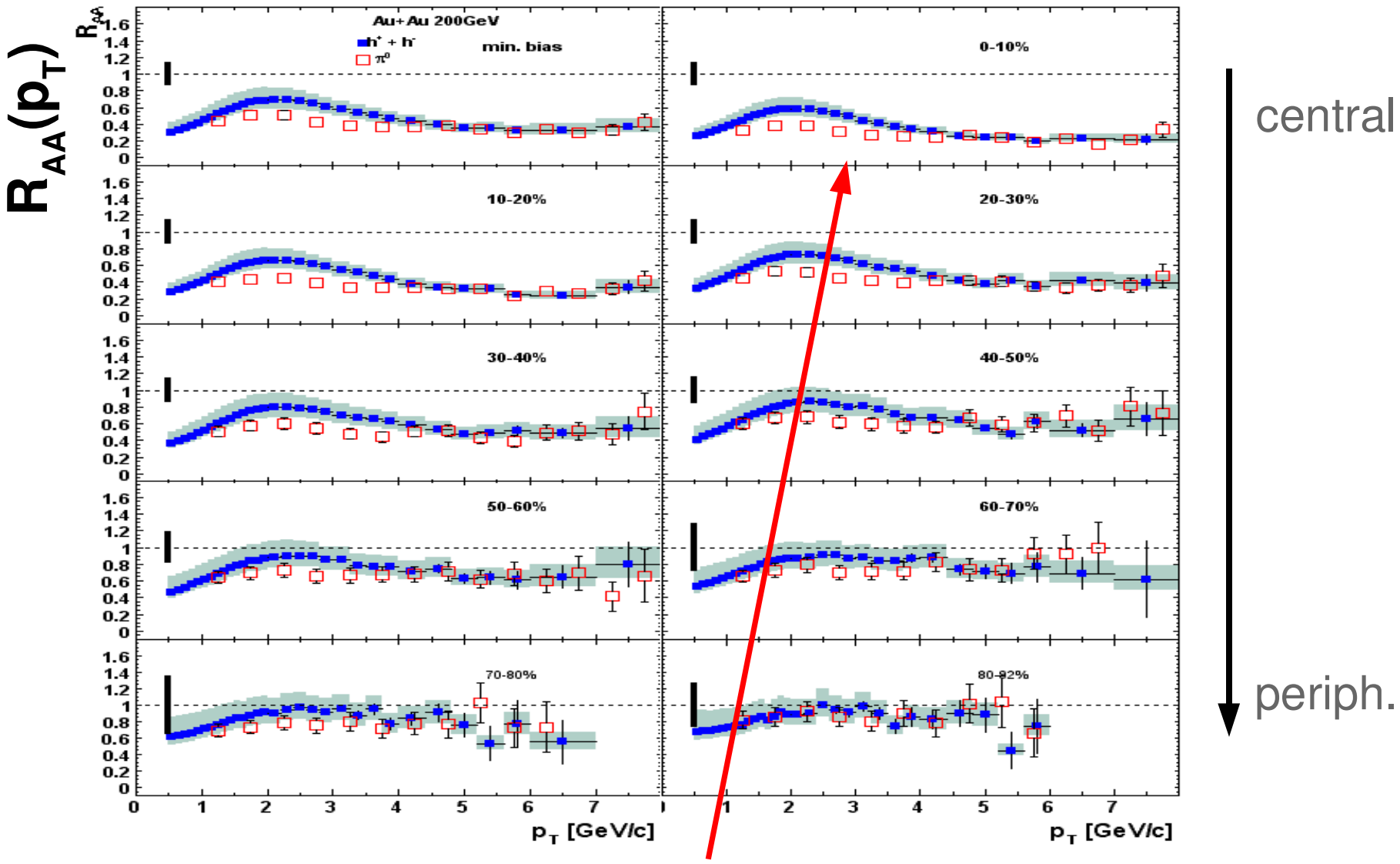
R_{AA} compilation for π^0 in central A+A:

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



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

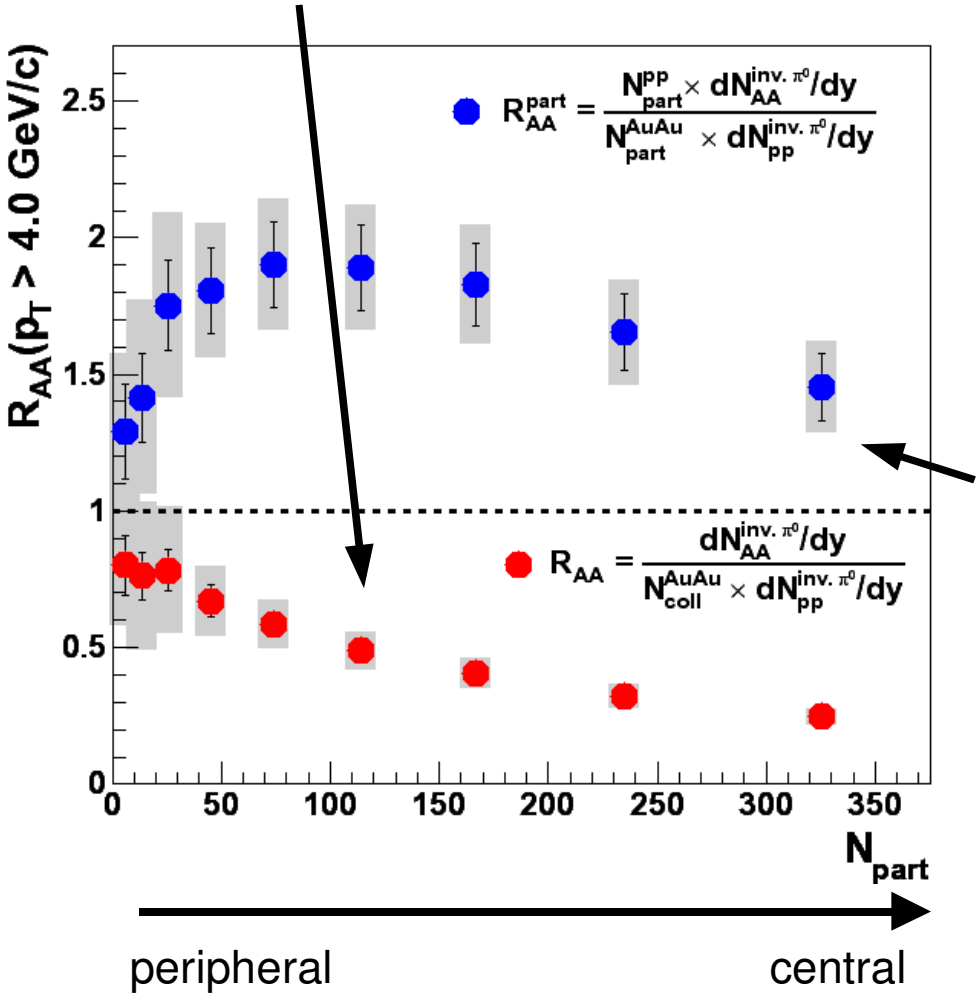
Nuclear modification factor: charged hadrons



- 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

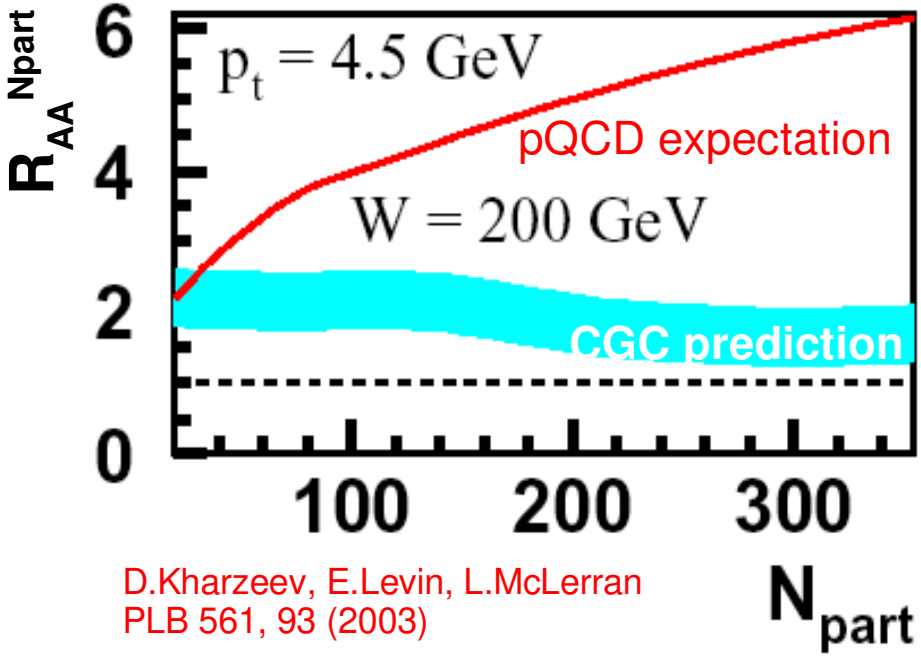
Centrality dependence of suppression: N_{part} scaling ?

- Suppression (N_{coll} scaling) increases smoothly with centrality:



PHENIX
nucl-ex/0304022,
submitted to PRL

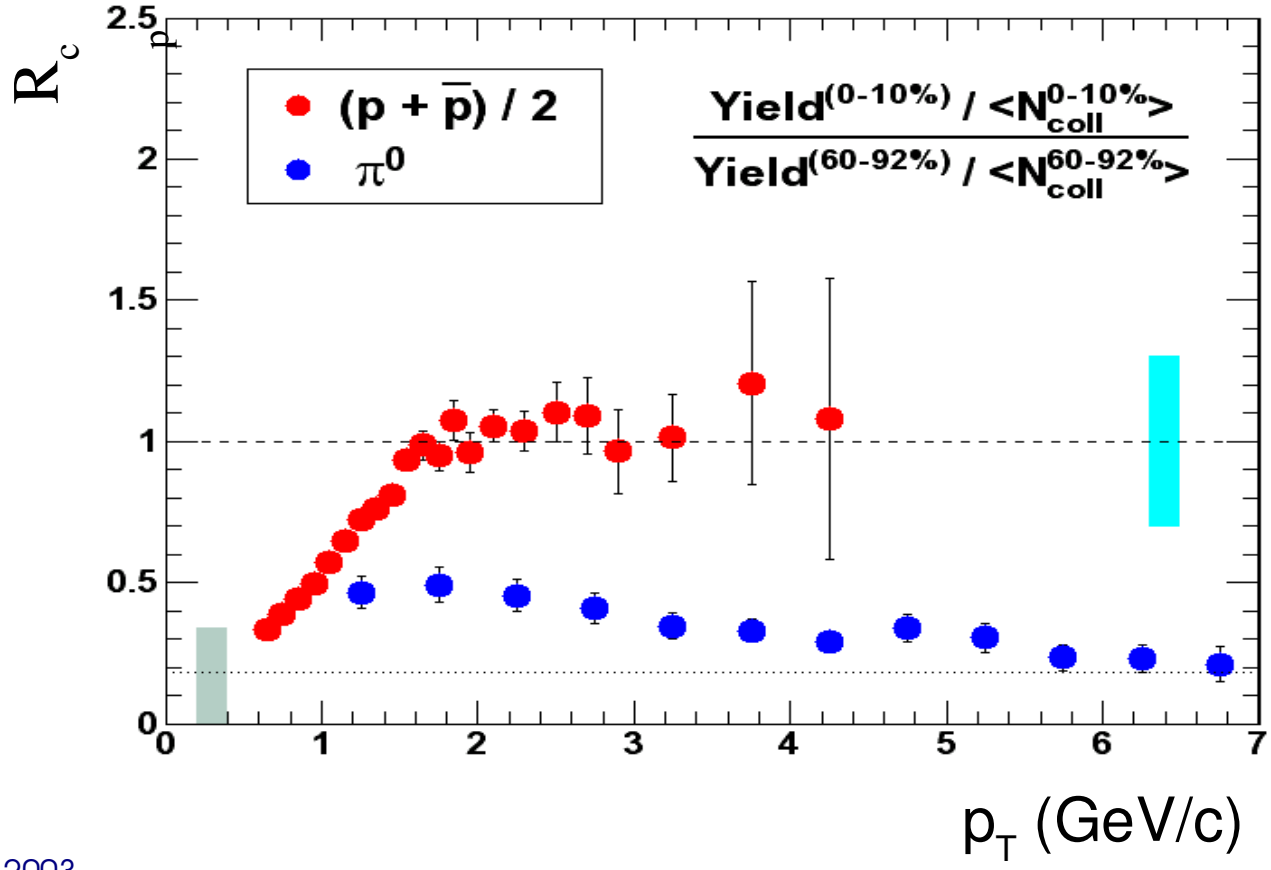
- Approximate N_{part} scaling in semiquantitative agreement with Color Glass Condensate prediction



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

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

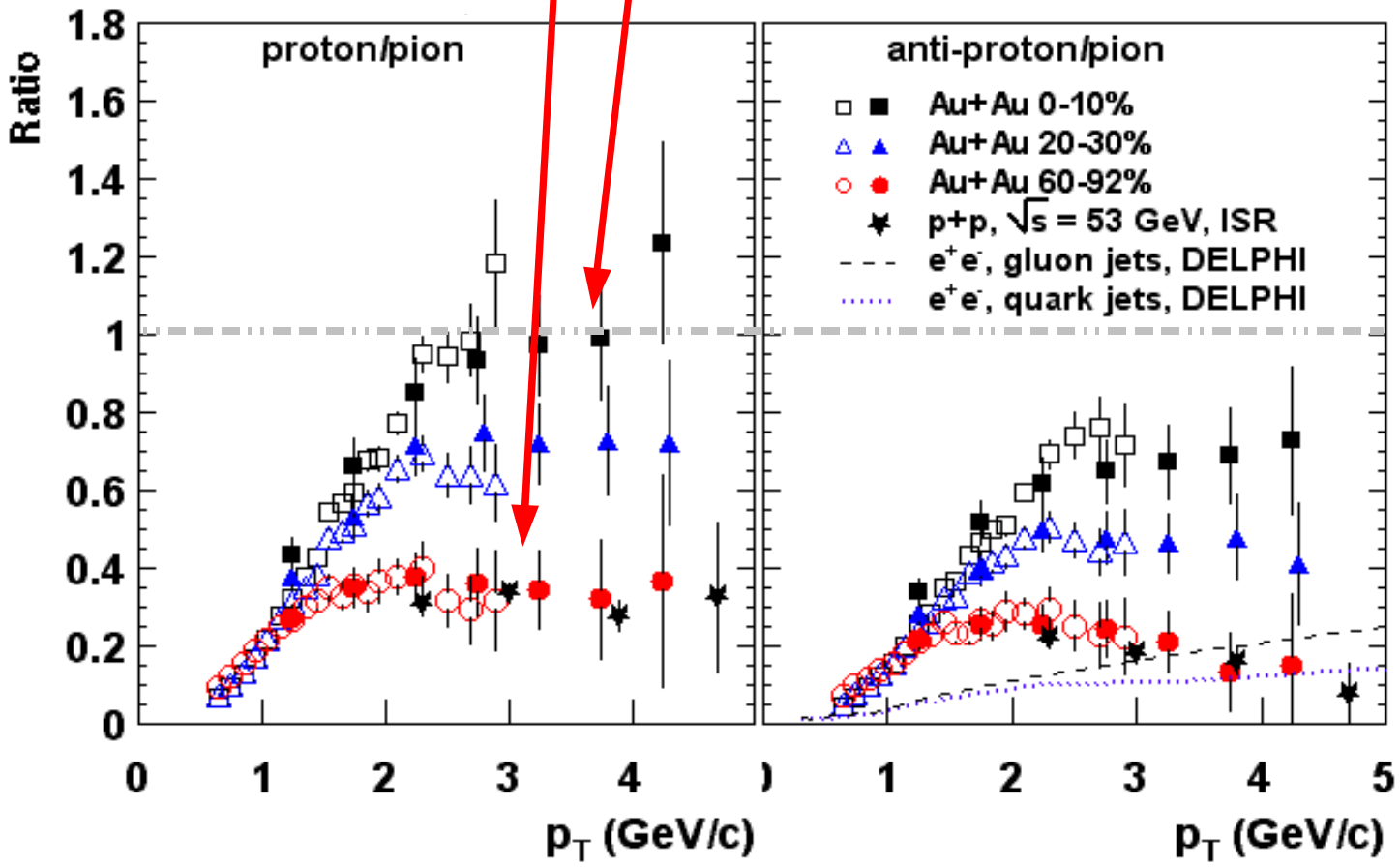
- Protons (antiprotons) **NOT** suppressed in central Au+Au ($p_T < 4.5$ GeV/c)
- Ratio central/periph ~ $R_{AA} \approx 1$. (N_{coll} scaling holds for baryons).
  - *(Consistent with observed $R_{AA}(h^{\pm}) > R_{AA}(\pi^0)$ in the same p_T range).*
  - Points to different production mechanisms for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



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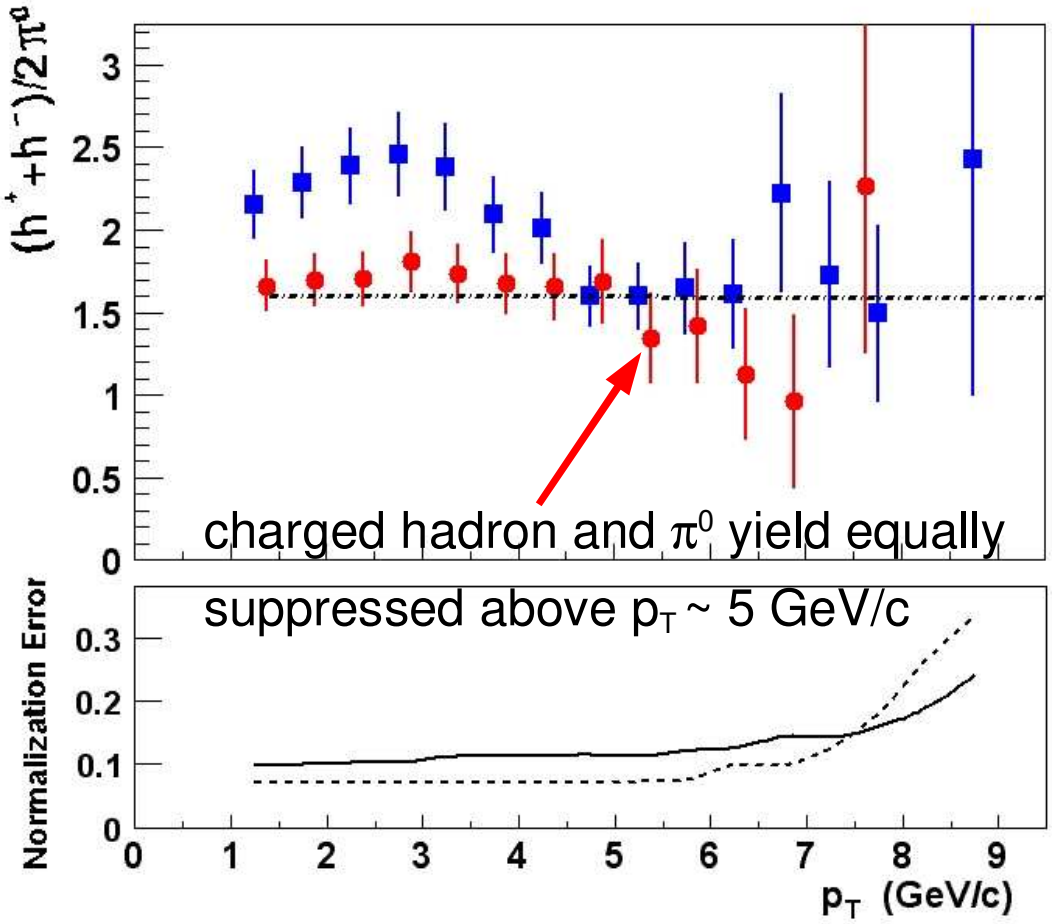
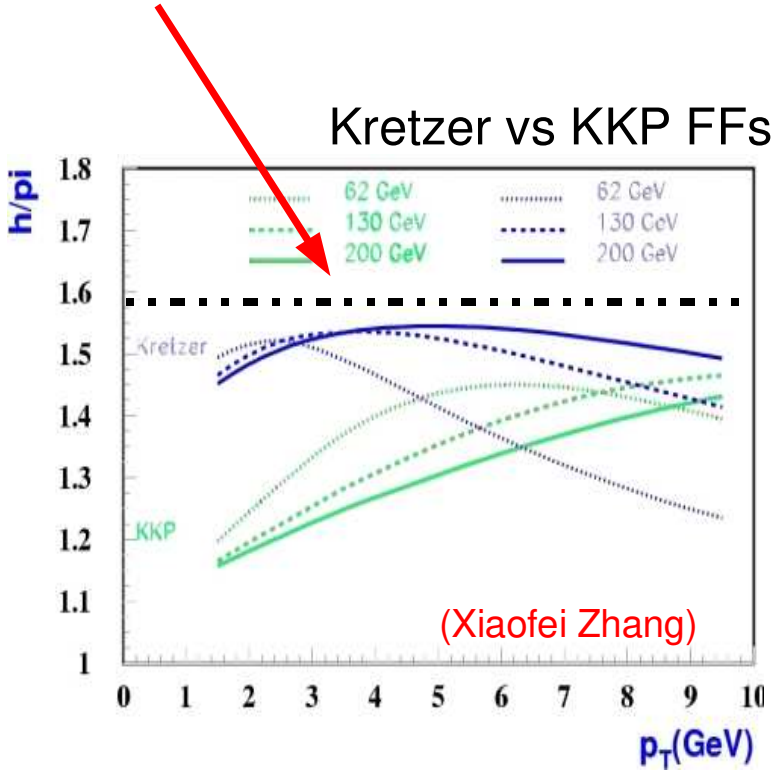
Hadron composition at high-p_T (4): h/π ratio

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



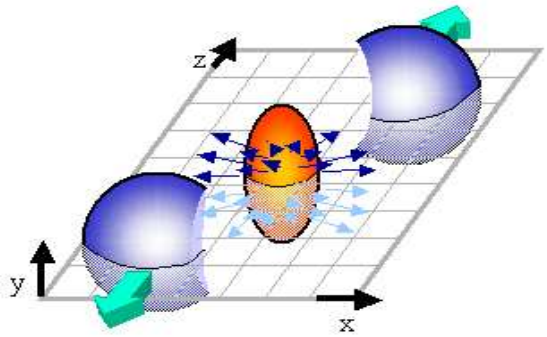


PHENIX Collab.
Submitted to PRL
nucl-ex/0305036

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

High p_T azimuthal correlations: Elliptic flow [PRL 89, 212301 (2002)]

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

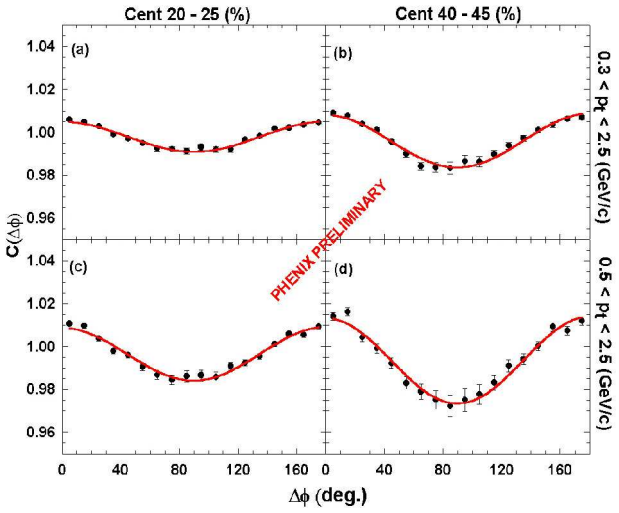


$$\frac{dN}{d^2p_\perp\, d\Phi} = \frac{dN}{d^2p_\perp}\{1 + v_2(p_\perp)\cos(2\Phi)\}\,.$$

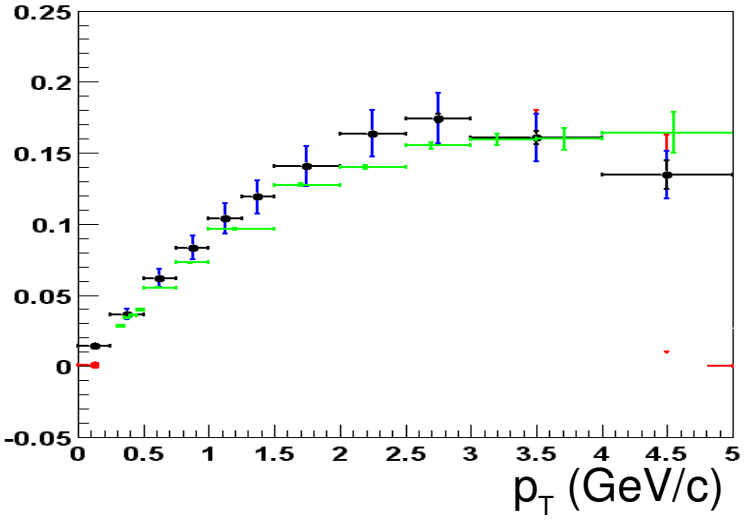
Flow = v_2 Fourier coefficient

Truly collective effect: absent in p+p colls.

- Exp. correlation functions:



- v_2 saturation at high p_T:



- Strong elliptic flow signal ⇒ strong (collective) pressure gradients
  ⇒ large initial state (t<1.0 fm/c) parton rescattering (early thermalization).

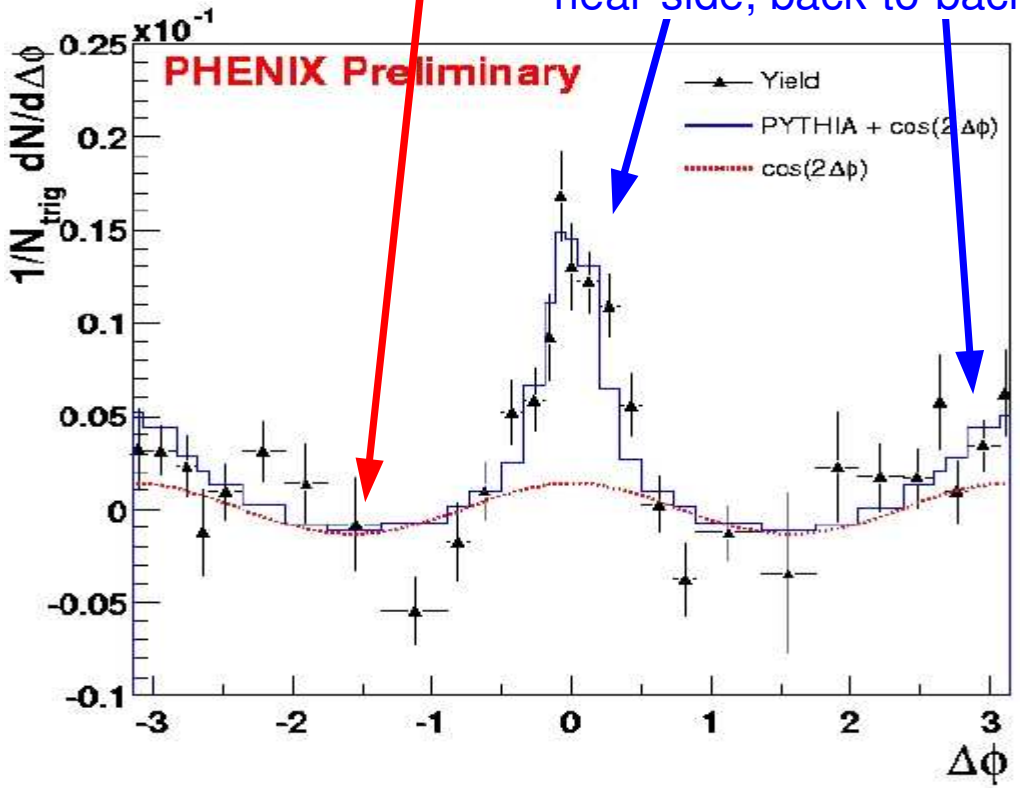
High p_T azimuthal correlations: jet signals in AA

- High-p_T γ (π^0) triggered events: $dN/d\Delta\phi$ for charged-hadrons (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 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, factorization theorem):

  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 (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" CD):

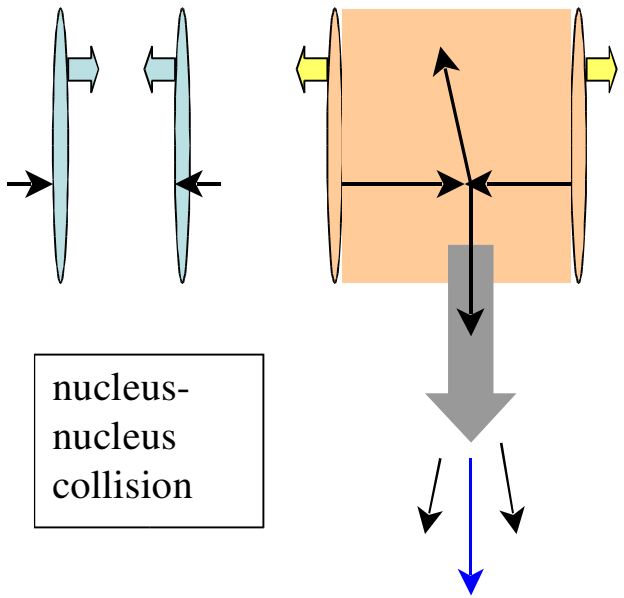
  - Step 1: CGC (gluon saturated nuclear wave function: MLV, KLN)
  - Step 2: glue + glue collisions: gg $\rightarrow$ g
  - Step 3: Gluon fragmentation (FFs)

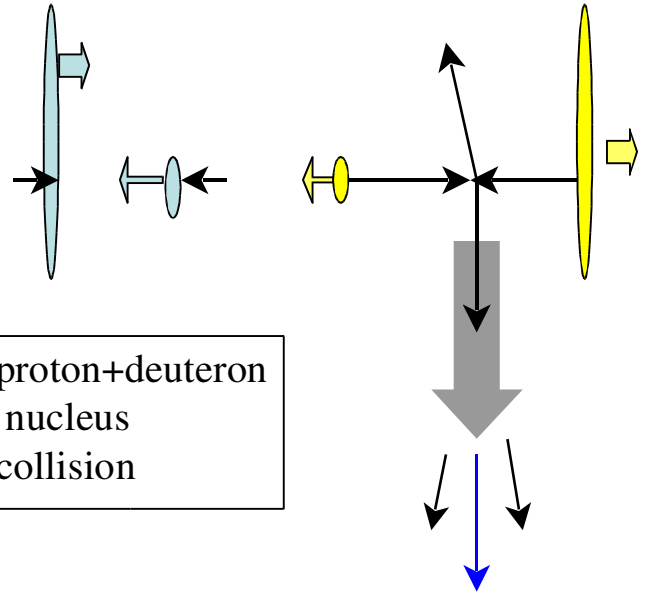
  ✔ *Goal: explain high p_T deficit, N_{part} scaling ...*

- *Data vs. theory — properties of underlying QCD matter:*

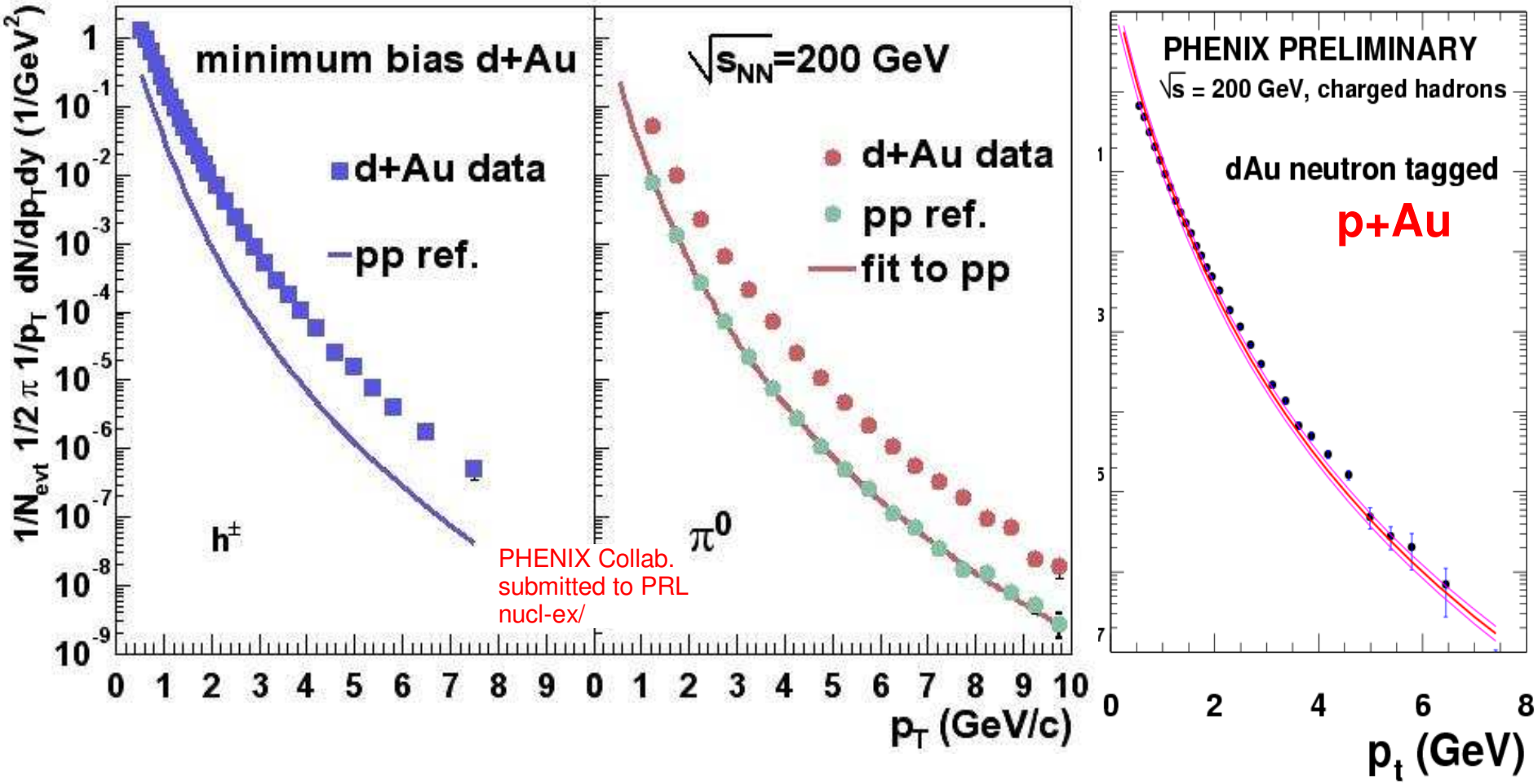
d+Au “control” experiment

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



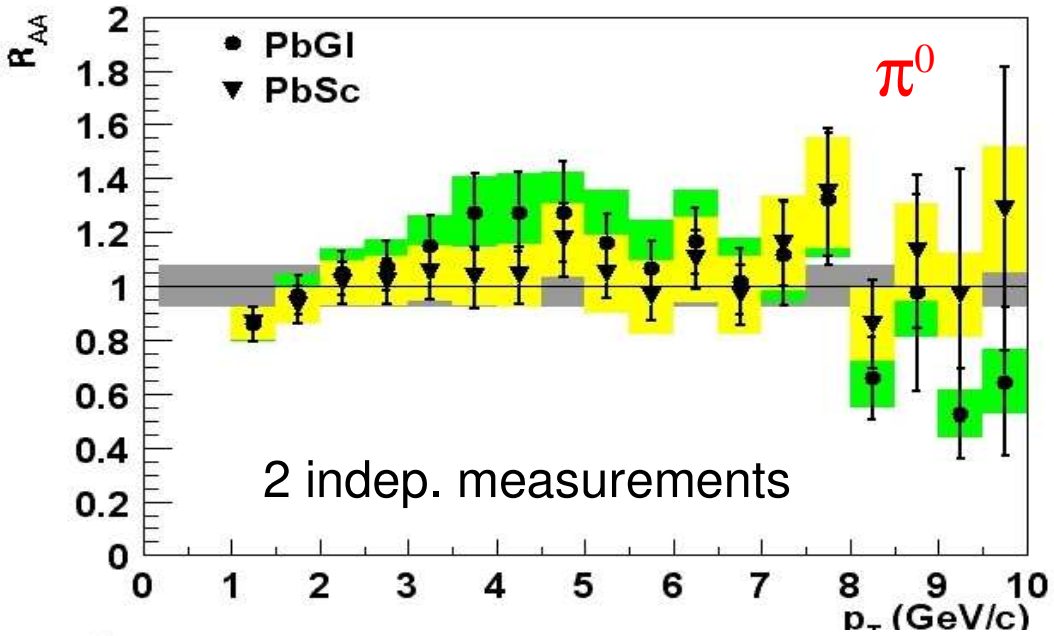


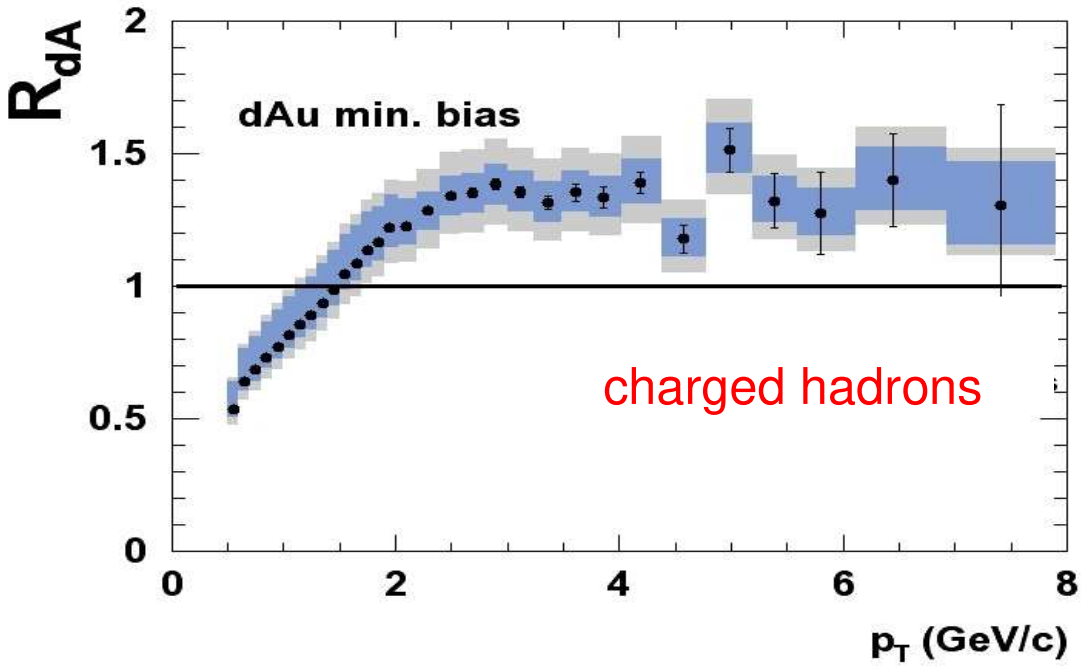
High p_T in d+Au, p+Au @ 200 GeV



- 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

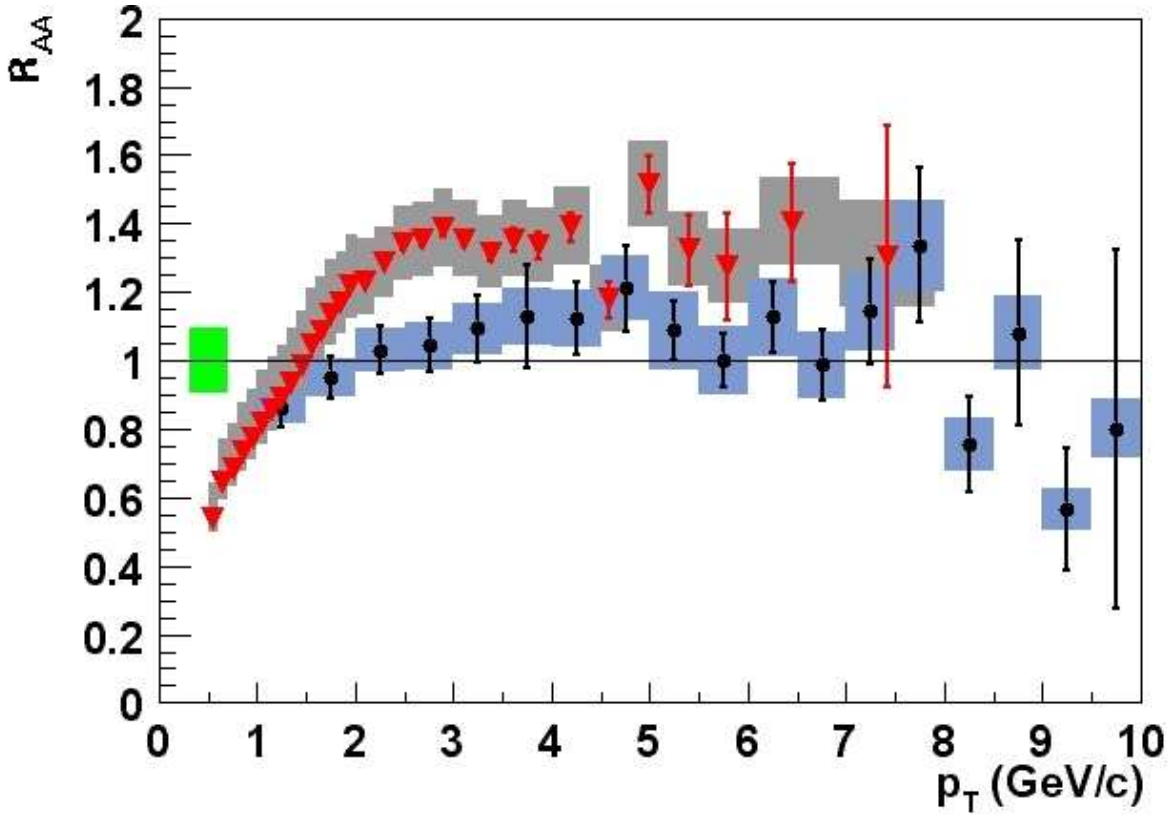
- Charged hadrons: R_{dAu} ~ 1.4
  (Larger enhancement)

  ~ flat between 3 – 8 GeV/c

PHENIX collab.
submitted to PRL
nucl-ex/

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

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



PHENIX collab.
submitted to PRL
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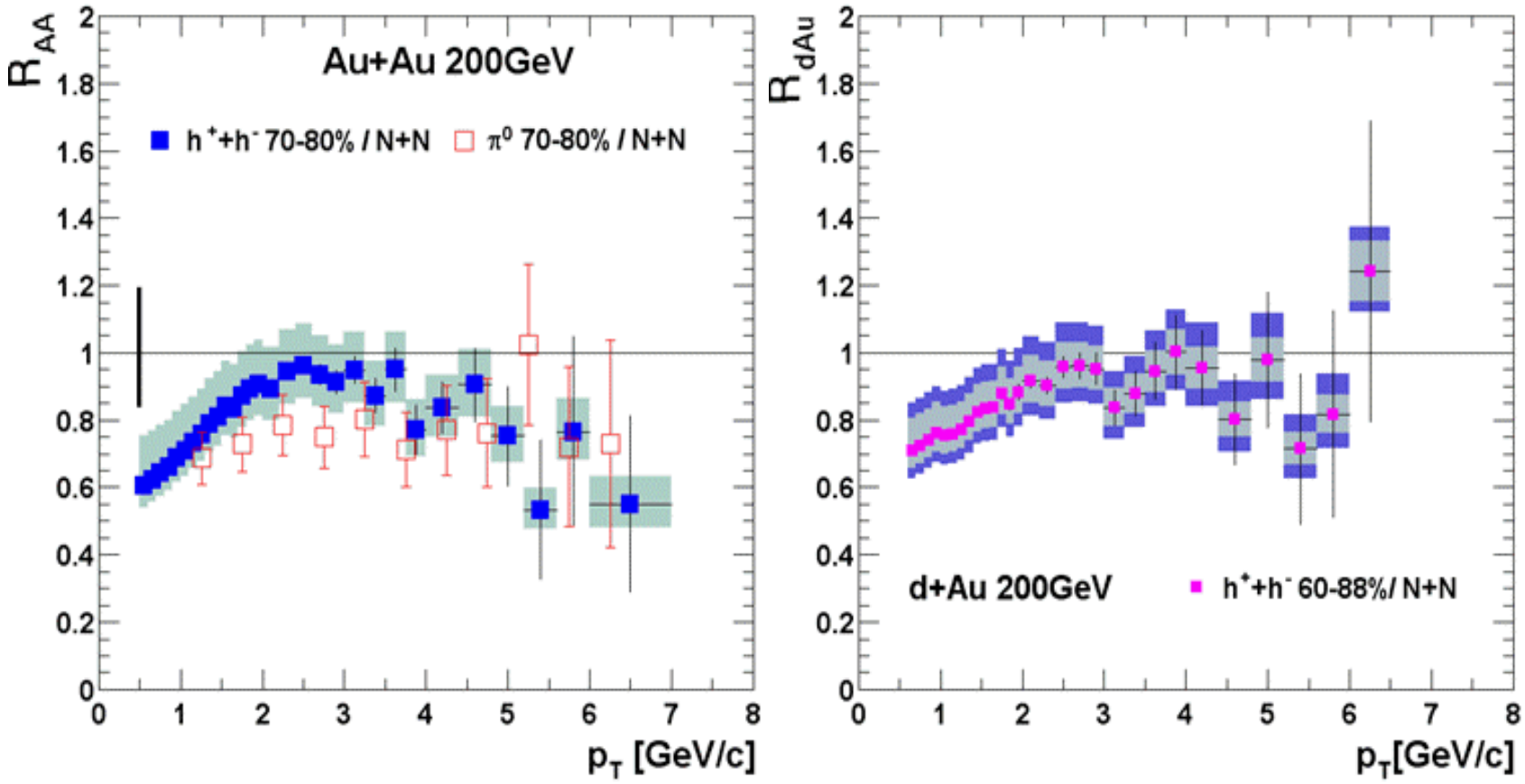
- d+Au results at RHIC clearly reminiscent of p+A "Cronin effect"
- No shadowing or strong saturation of Au PDF.
- Same results in p+Au (neutron-tagged) collisions

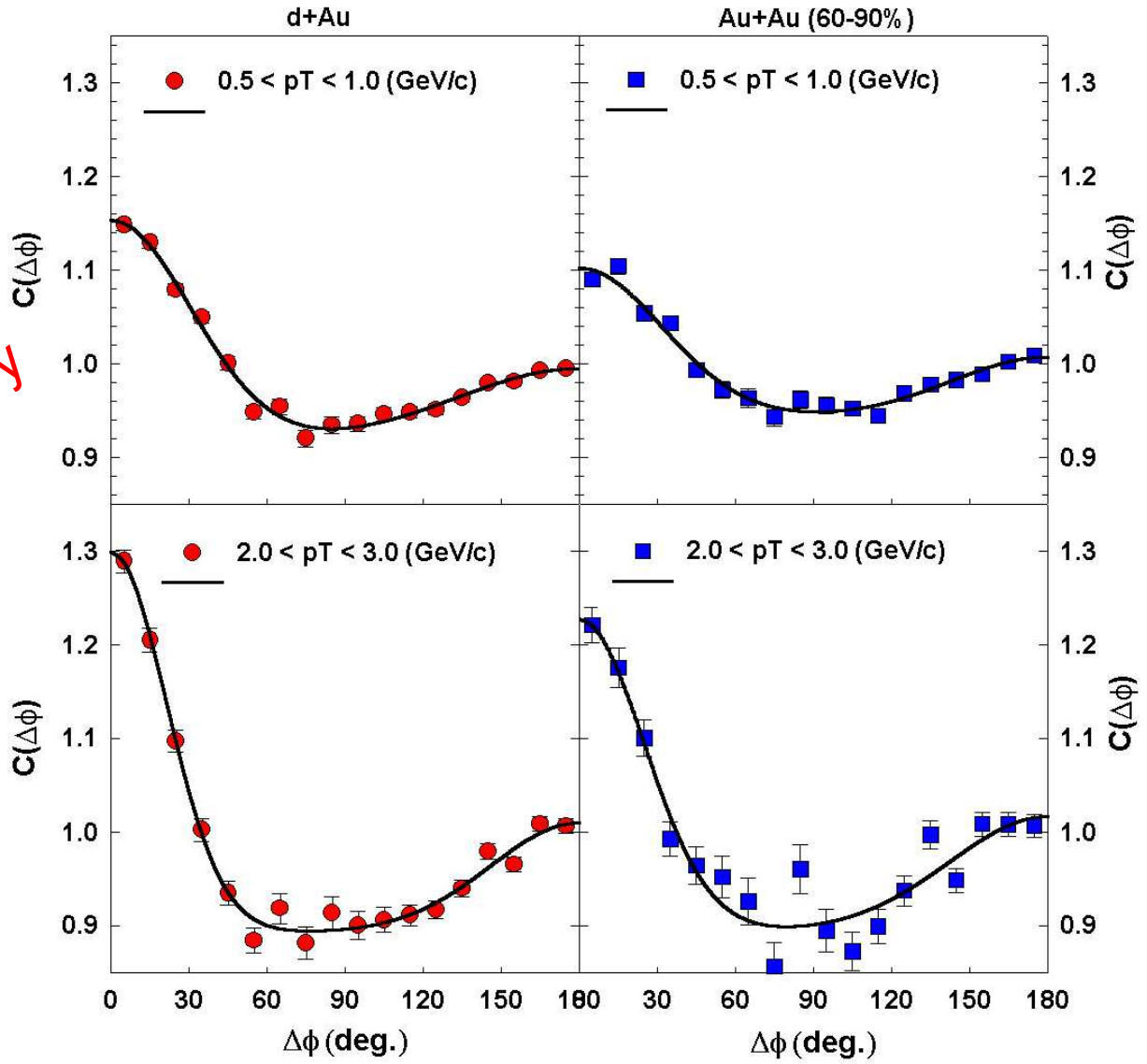
Nuclear modification: d+Au vs Au+Au

PHENIX preliminary



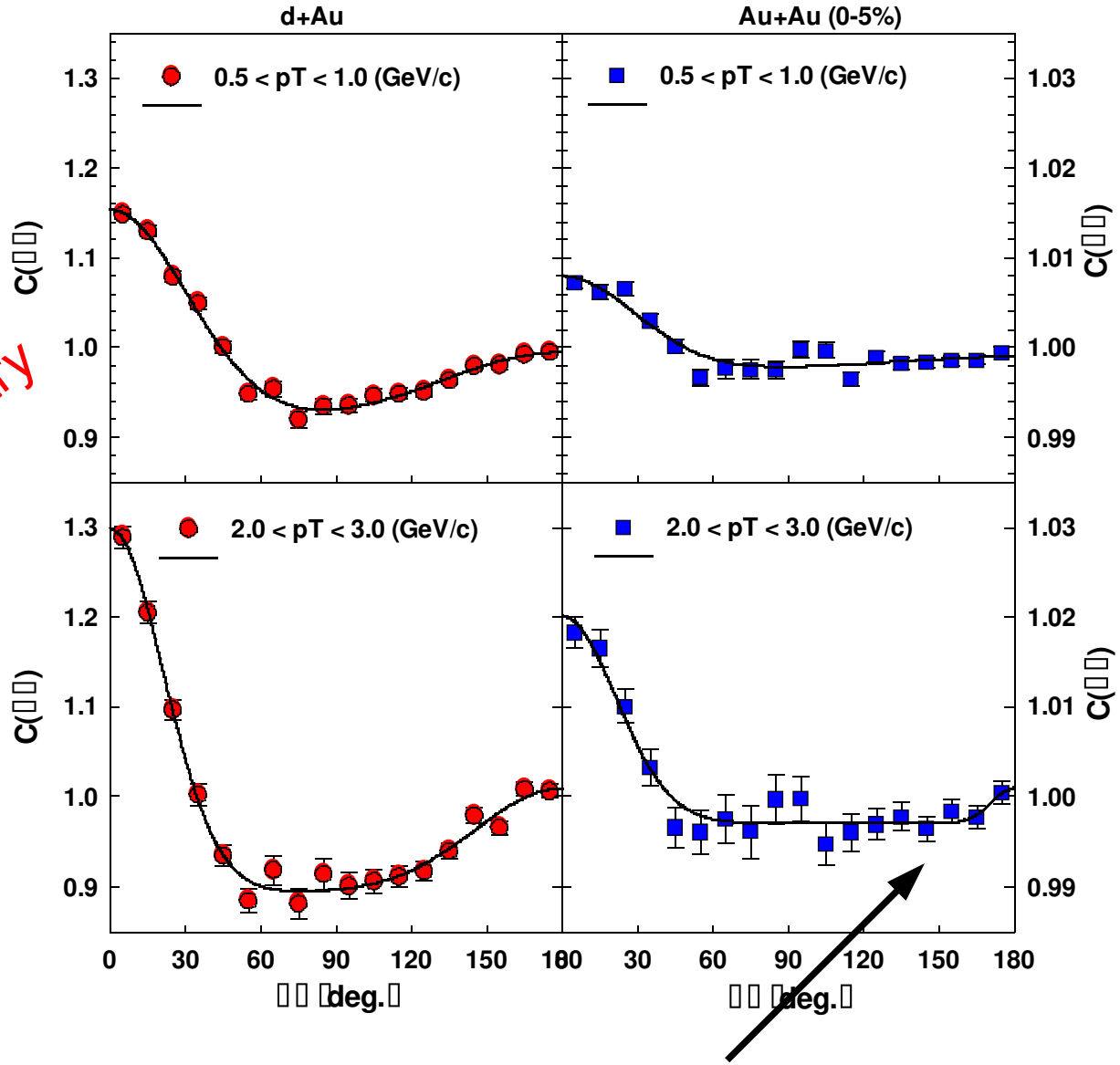
- Opposite centrality dependence of nuclear enhancement (in p+Au) compared to nuclear suppression (in Au+Au) !
- Conclusion: Au+Au suppression not due to a “cold” nuclear matter (initial-state) effect.

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”

"QGP" models (FSI parton energy loss) 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 (FSI parton energy loss) 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)
- $\sqrt{s}$ dependence of Au+Au suppression clear ?
  - Why there is no jet quenching observed in Pb+Pb @ SPS if $dN^g/dy \sim 500$?
- Particle species dependence of Au+Au suppression → not described in 1st instance:
  - Additional non-perturbative final state effects (quark recomb., baryon junctions, others ?) needed.

ISI gluon saturation ("CGC") models vs. data

✗ Caveat: High p_T at midrapidity at RHIC is above Q_s ~ 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 by Baier *et al.*

✔ 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 *et al.*). Similar conclusions by J.Jalilian too (though no calculations at y = 0).

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)

FSI hadronic reinteractions model vs. data

✗ Caveat: Very dense hadronic medium scenarios should result in partonic scenarios by definition.

✔ 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 (due to the assumed formation time ansatz).

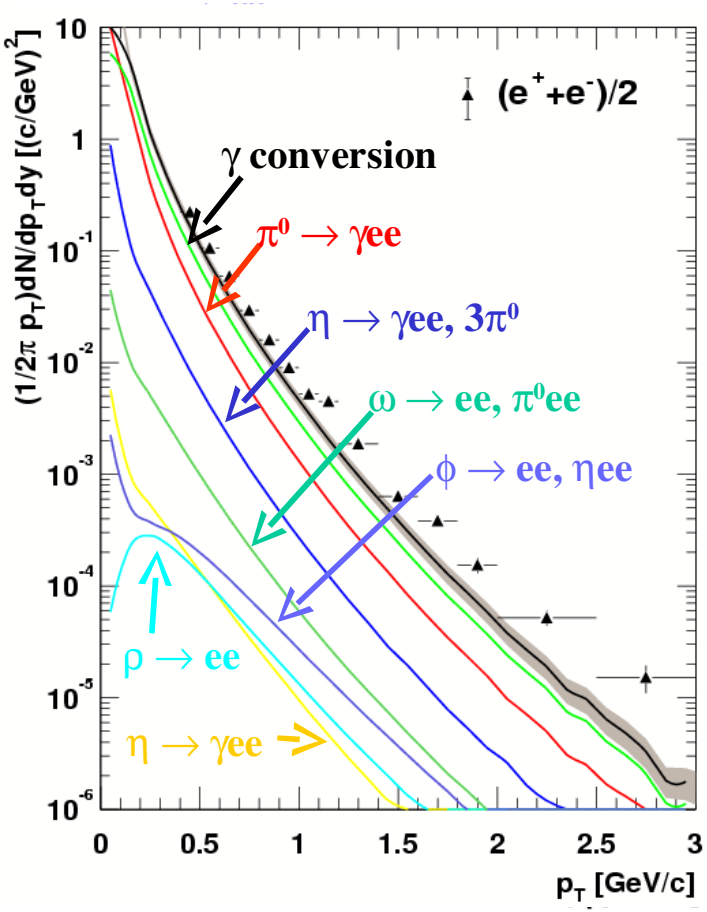
- Possible "control" calculations (not observed in data but expected in hadronic medium description): charm meson energy loss, suppressed near-side jet correlation, ...

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

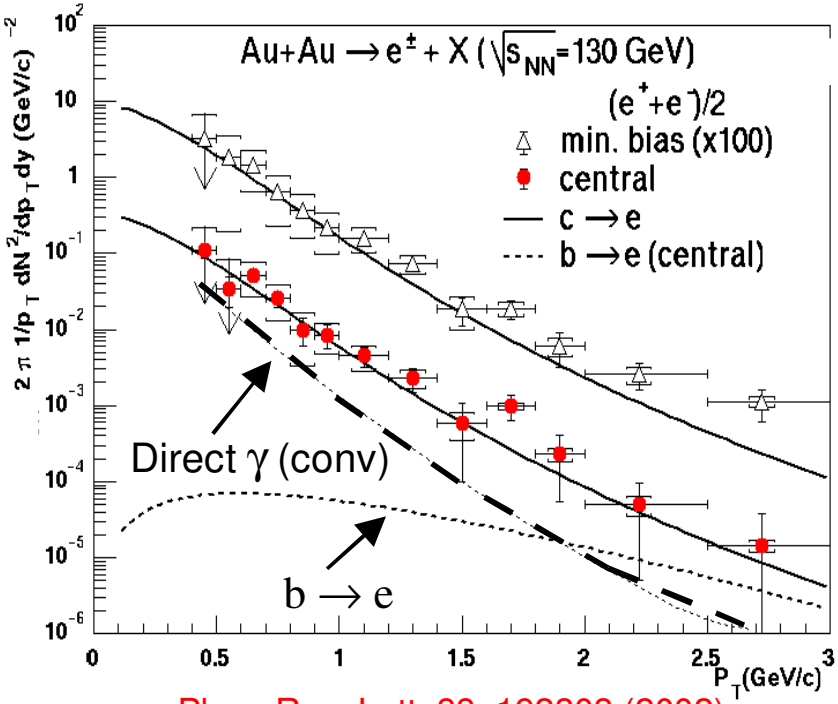
Results III:
Heavy Quark Observables

Hard probes & single electron continuum [PRL 88, 192303 (2002)]

- Hard probes signals contributing to electron spectrum:
  - Heavy quark: open charm & bottom (via semi-leptonic decays c → eX, b → eX): Initial gluon density, energy loss of heavy flavors, baseline for J/Ψ suppression ...
  - Thermal dileptons, direct photons (virtual, conversion), Drell-Yan.
- Background "cocktail":



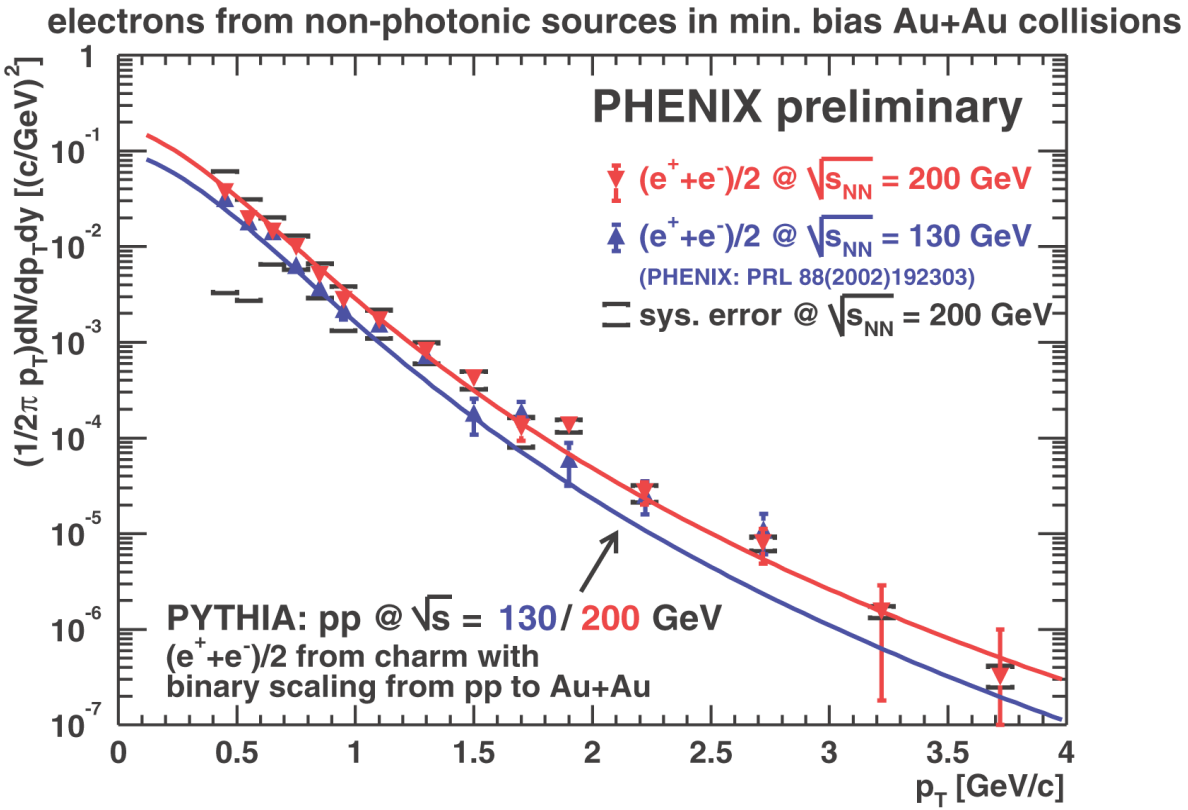
- Inclusive $(e^+ + e^-)/2$ spectrum:



Phys. Rev. Lett. 88, 192303 (2002).

Heavy-Flavor: Open charm from e- data [PRL 88, 192303 (2002), QM 2002]

- Background subtracted single electron spectra (Run-1 & Run-2):

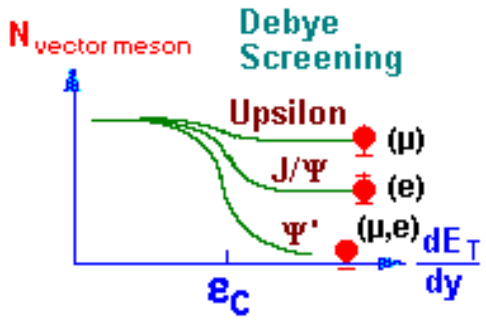


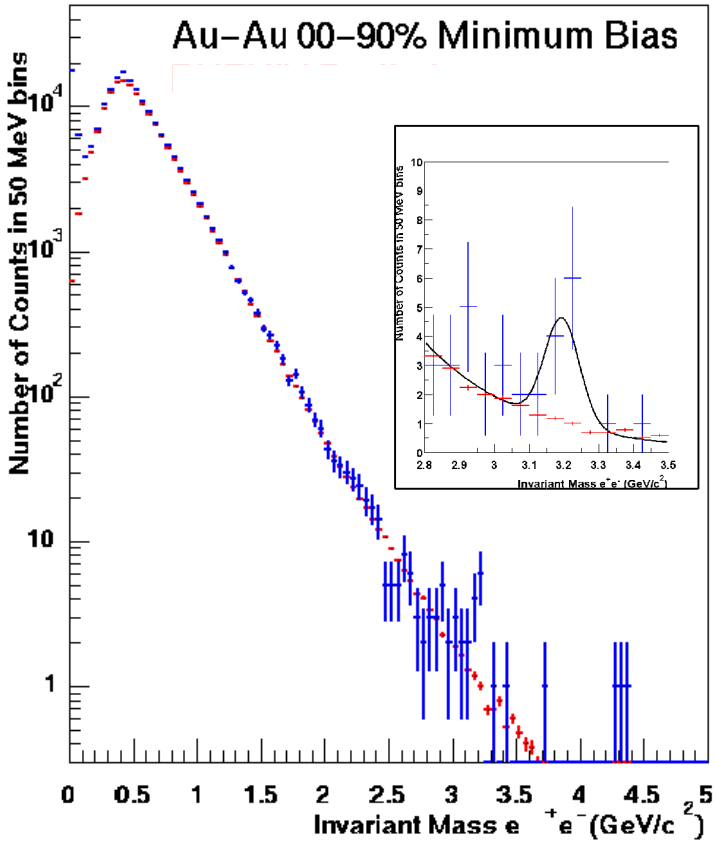
- Electron spectrum/cross-section consistent with *pp* (PYTHIA 6.152) binary-scaled charm production (i.e. no nuclear or medium effects) for all centralities.
- Factor of ~4-5 suppression in high p_T π^0 (relative to binary scaling) not observed. Less energy loss of heavy quarks in medium ("dead-cone" effect) ?

Heavy-Flavor: First J/ψ results

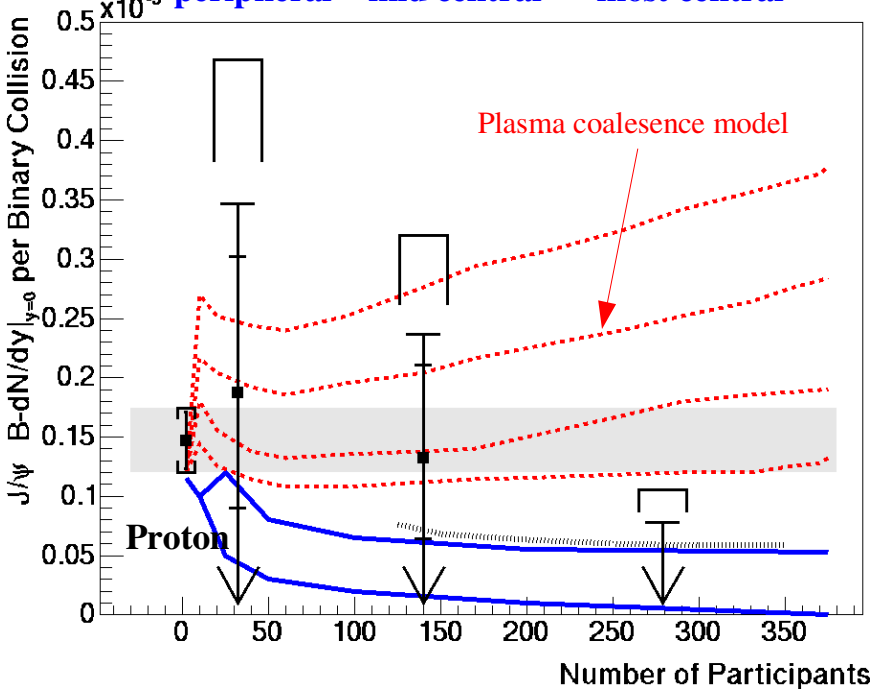
- Motivation: Suppression of heavy quarkonia states due to screening of color potential at deconfinement.
- $J/\psi \rightarrow e^+e^-$ (mid-rapidity) in AuAu:

  N=10.8 ± 3.2 (stat) ± 3.8 (sys)





- Centrality dependence of J/ψ yield:



- Strong J/ψ enhancement ruled out. No definite conclusion on suppression yet.
- Higher luminosity running needed.

Summary

- 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 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, azimuth. corr., J/ψ, ...
  - d+Au @ $\sqrt{s_{NN}}$ = 200 GeV: inclusive charged hadrons, π^0

qu'avons nous appris ?

- PHENIX global results :
  - Very high energy densities (~70% larger than at SPS) >> expected critical value for QGP.
  - Large particle production, rising faster than number of participant nucleons (onset of hard processes and/or saturation physics).
  - Much closer to baryon-free central region than at SPS.
- PHENIX high-p_T results :
  - High-p_T $h^{\pm}$ and π^0 spectra central collisions: factor 4-5 suppression (qualitative agreement with energy loss in opaque medium).
  - Increased baryon over meson yield above $p_T \sim 2$ GeV/c (very different from *pp* data). p,pbar not suppressed up to ~4.5 GeV/c.
  - Strong elliptic flow signal (early collective rescattering).
  - Jet-like signal in azimuthal near-side correlations. Suppression of away-side.
  - Cronin-enhancement in d+Au → Au+Au suppression not due to initial-state
- PHENIX heavy-flavor results :
  - Single electron consistent with *pp* scaled open charm: no medium effect.
  - Strong enhancement of charmonium ruled out. Suppression studies need high luminosity run.

conclusion finale ...

- Les signaux à haut p_T sont très interessants et consistents avec un scénario de formation de plasma.

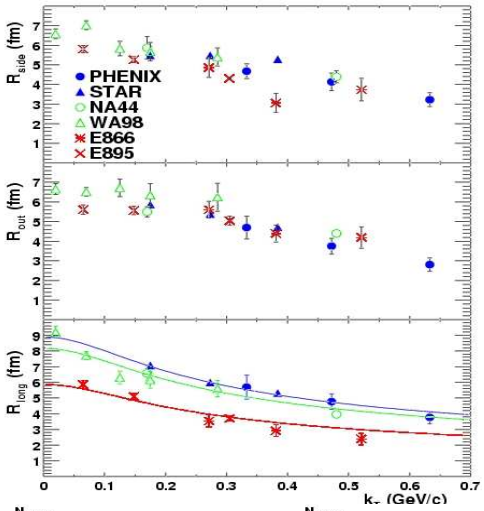
- Des données en train d'etre analysées (photons) plus le Run-4 (haute luminosité) vont apporter des résultats definitifs sur les 2 autres sondes “critiques”: le J/ψ et les photons

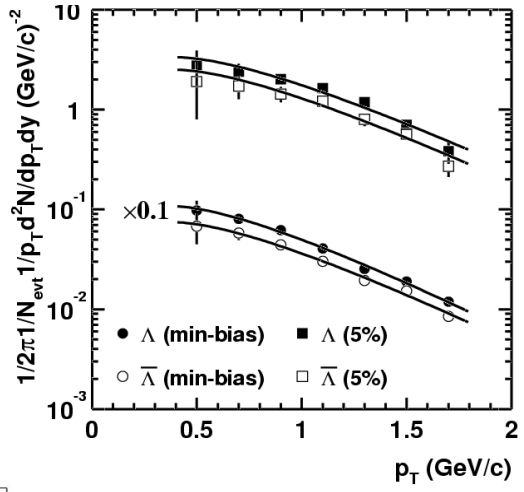
- On ne peut pas encore conclure qu'on a trouvé le QGP mais ... on a parcouru ~1/3 du chemin ...

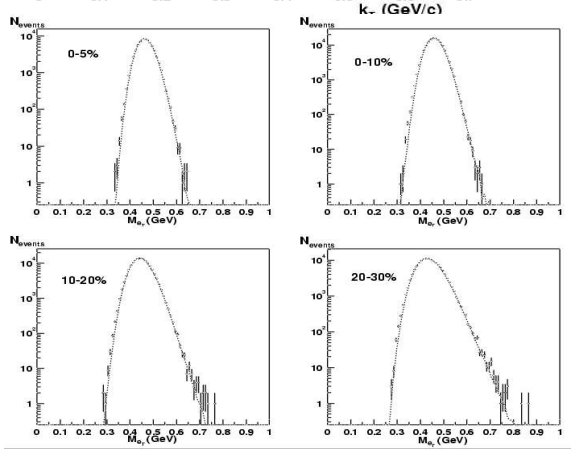
backup slides ...

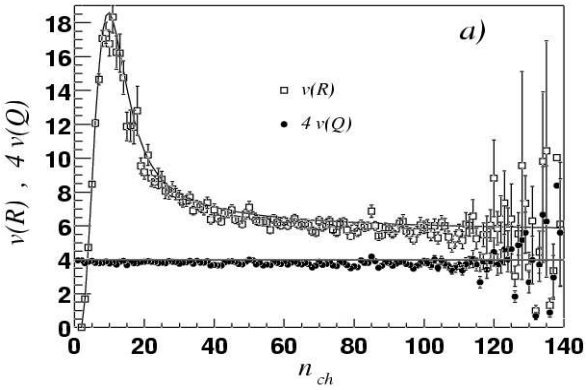
other PHENIX topics *not* covered ...

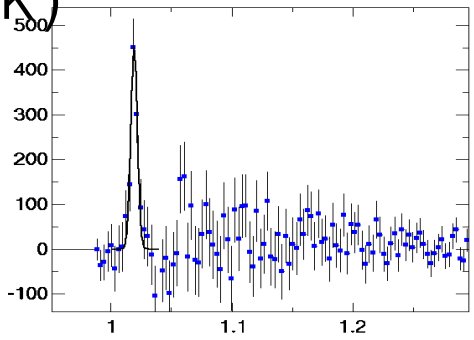
- Two-pion HBT
  PRL 88, 192302 (2002)
- Lambda baryons
  PRL 89, 092302 (2002)
- <p_T>, E_T fluctuations
  PRC 66, 024901 (2002)
- Net charge fluctuations
  PRL 89, 082301 (2002)
- Vector mesons ($\phi \rightarrow e^+e^-$, K^+K^-)
  QuarkMatter 2002, nucl-ex/0209028
- Direct photons
  QuarkMatter 2002, nucl-ex/0209021

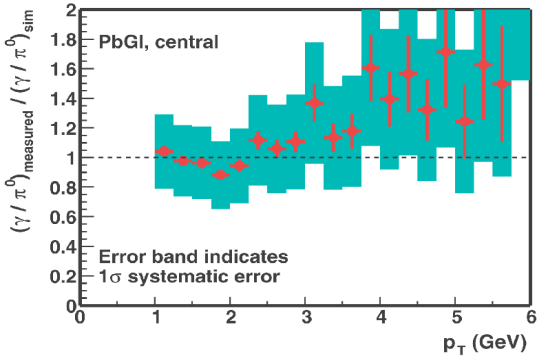












list of latest PHENIX results

Run -2 final results:

- **High pT pi0 (Au+Au @ 200 GeV): submitted to PRL nucl-ex/0304022**
- **High pT pi0 (p+p @ 200 GeV): submitted to PRL hep-ex/0304038**
- **Elliptic flow of identified particles (Au+Au @ 200 GeV): submitted to PRL**
- **J/Psi yields (Au+Au @ 200 GeV) submitted to PRC**
- **J/Psi yields (p+p @ 200 GeV) to be submitted to PRL**
- **p,pbar high pT enhancement (Au+Au @ 200 GeV) submitted to PRL**

- Run-2 preliminary results:
  - **dN/dy and dE_T/dy (Au+Au @ 200 GeV)**
  - **Identified charged particle spectra and yields (Au+Au @ 200 GeV)**
  - **Inclusive charged particle at high pT (Au+Au @ 200 GeV)**
  - **phi -> KK (Au+Au @ 200 GeV)**
  - **Event-by-event fluctuations (Au+Au @ 200 GeV)**
  - **Di-Lepton continuum (Au+Au @ 200 GeV)**
  - **Two-pion correlations (Au+Au @ 200 GeV)**
  - **d and dbars (Au+Au @ 200 GeV)**
- Run-3 final results:
  - **High pT pi0 (d+Au @ 200 GeV)**
  - **High pT inclusive charged particles (d+Au @ 200 GeV)**

High p_T suppression & radiative parton energy loss

- Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium:
  - Mean parton energy loss probes meadium properties:

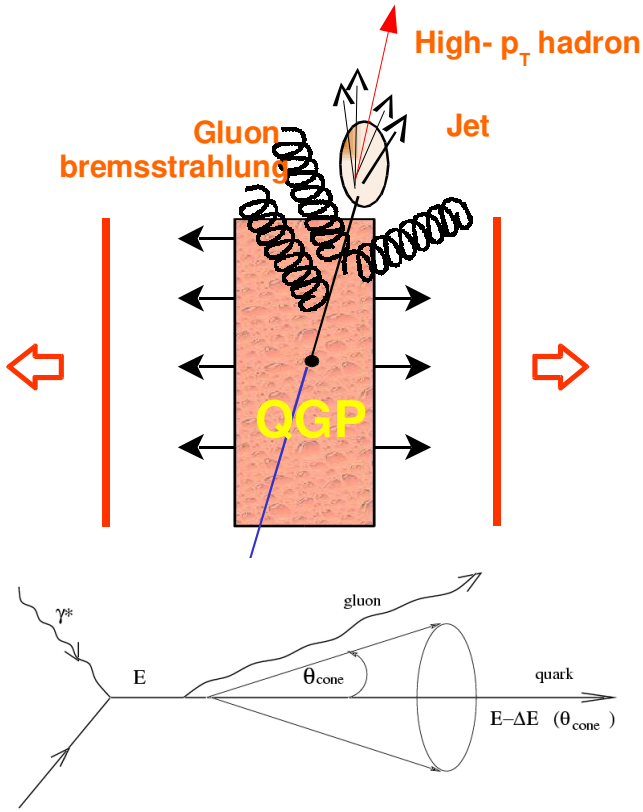
    $\Delta E \sim \rho_{gluon}$ (gluon density)

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

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

  - Expanding vs. static plasma:

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



- Well above energy loss in cold nuclear matter:

BDMPS: $\Delta E(T=250\ \text{MeV}) \sim 15 \cdot \Delta E(T=0)$,
$dE/dx \sim 0.5$ GeV/fm (HERMES *eA* data), FNAL E772: $dE/dx \sim 0.2$ GeV/fm (D.Y. *pA* data)