Probing QCD at extreme energy densities in nucleus-nucleus collisions: Latest results from PHENIX @ RHIC

International School for Subnuclear Physics

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Overview

1. Introduction: QGP physics, high-energy heavy-ion colls., PHENIX
2. High p_T results (Au+Au vs. p+p vs. d+Au): yield suppression, "anomalous" hadron composition, away-side jets disappeareance, ...
3. Summary.

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

$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

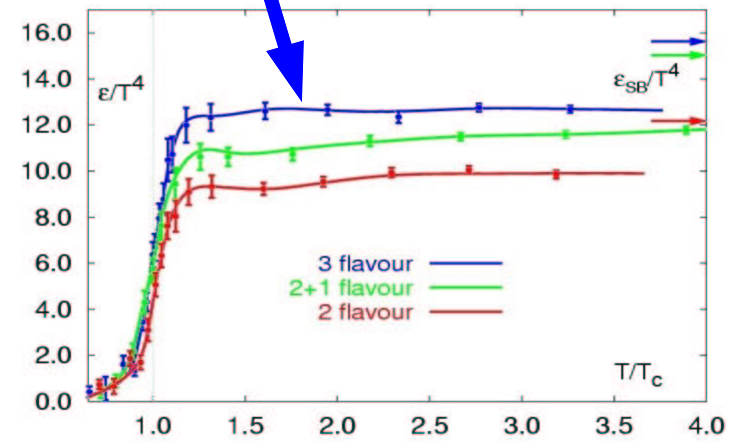
where $G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^a_{bc} A^b_\mu A^c_\nu$

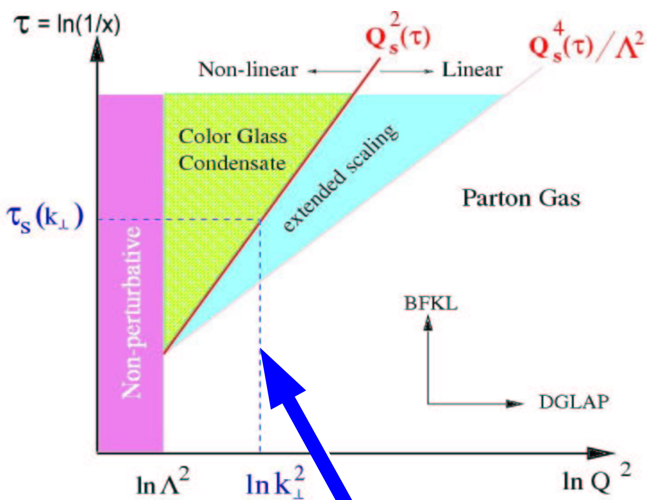
and $D_\mu = \partial_\mu + i t^a A^a_\mu$ $\quad (\alpha_S = g^2/4\pi)$

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

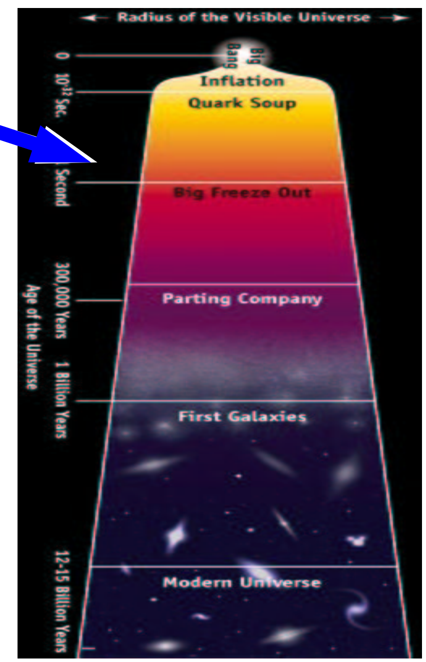
1. Learn about 2 (so far unexplained) properties of the strong interaction: confinement, chiral symmetry breaking

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



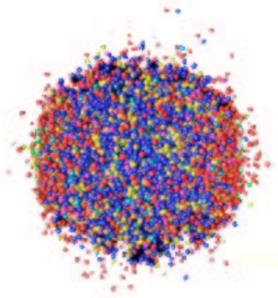


3. Probe the properties of the primordial Universe (few µsec after the Big Bang).

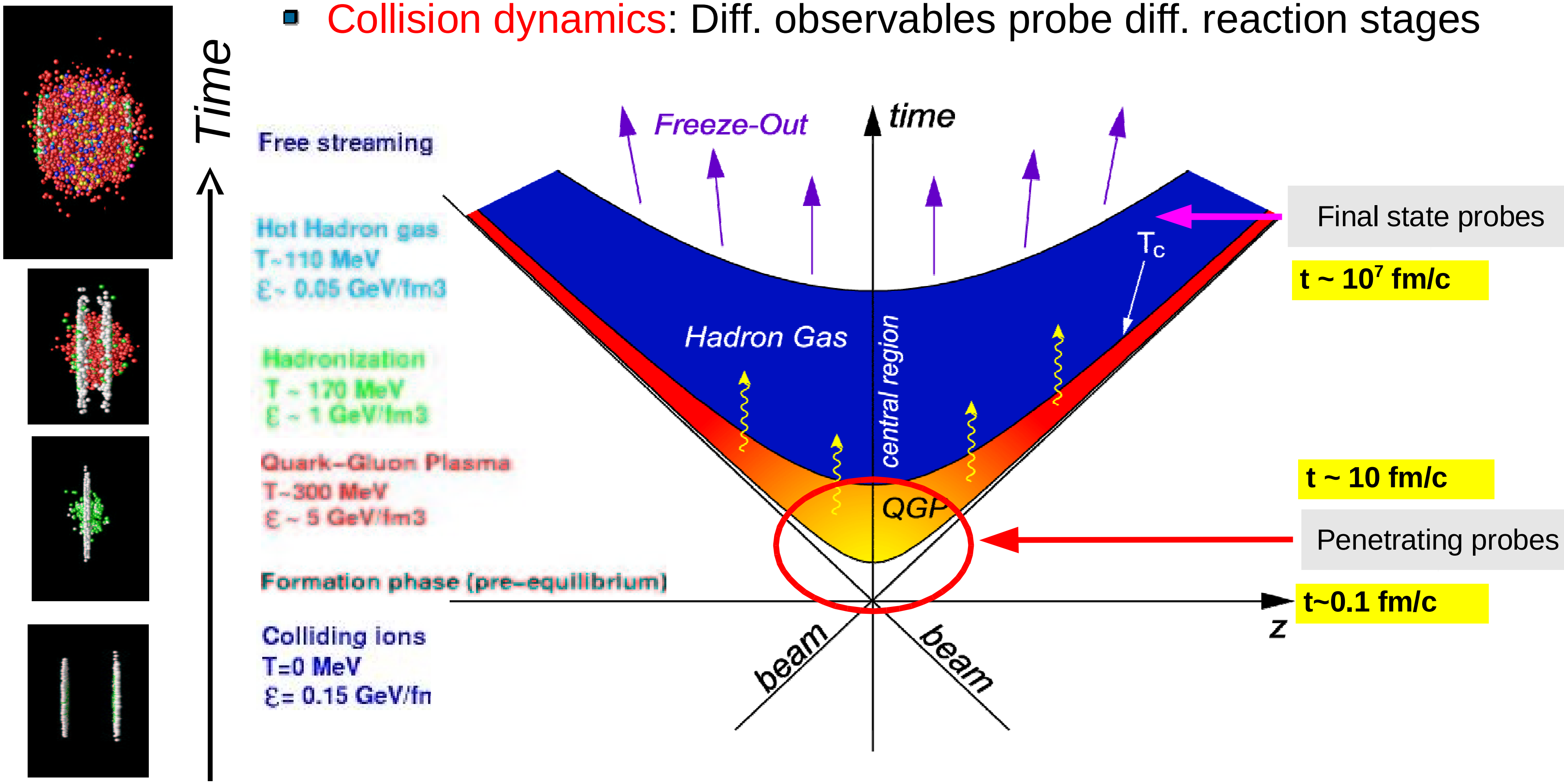


4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC).

The "Little Bang" in the lab



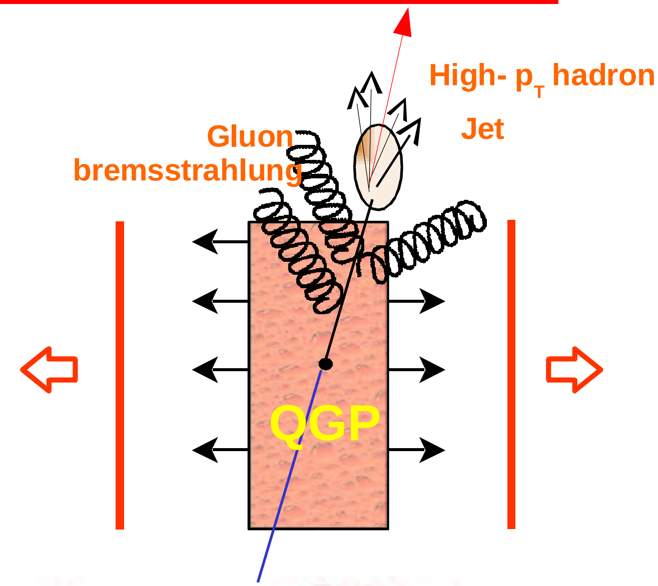
- High-energy nucleus-nucleus collisions: in fixed-target reactions (√s~17 GeV, SPS) or in colliders (√s~200 GeV, RHIC)
- QGP expected to be formed in a tiny region (~10^{-14} m) and to last very short times (~10^{-23} s).
- Collision dynamics: Diff. observables probe diff. reaction stages



"Canonical" QGP signals

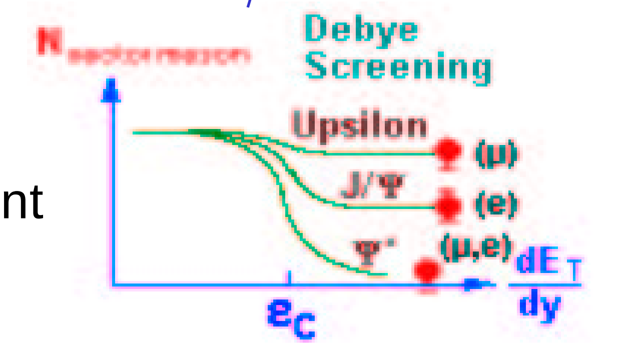
1. "Jet quenching":

- Multiple final-state gluon radiation off the produced hard parton induced by the traversed medium ($\Delta E_{loss} \sim \rho_{gluon}$)
- Probe: Jet absorption, suppression leading particle (high p_T) spectra



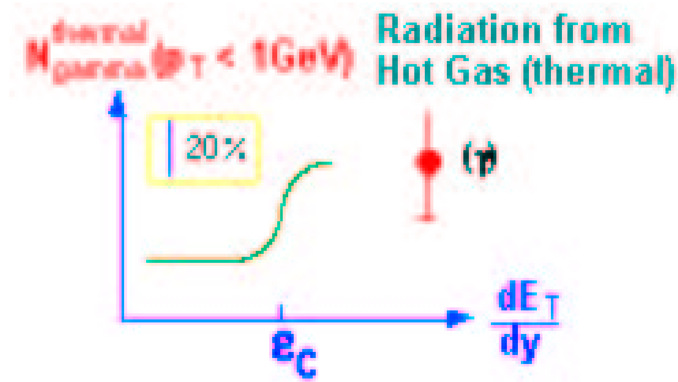
2. Quarkonia suppression:

- Debye screening of $Q\bar{Q}$ potential at deconfinement
- Probe: J/Ψ, Υ



3. Enhanced direct photon production:

- Thermal radiation from the hot medium
- Probe: Prompt γ, Prompt γ^* (e^+e^-, $\mu^+\mu^-$)



Relativistic Heavy-Ion Collider (RHIC) @ BNL

Specifications:

3.83 km circumference

2 independent rings:

- 120 bunches/ring
- 106 ns crossing time

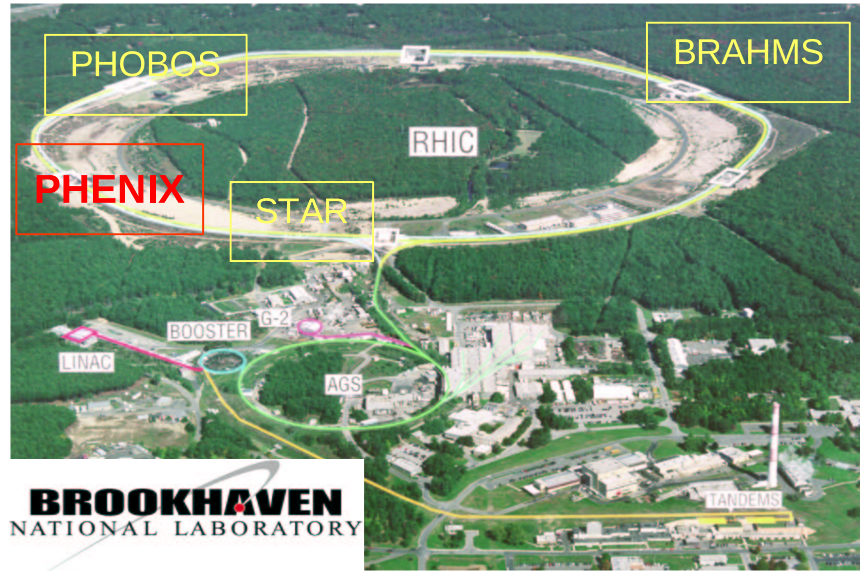
Au + Au collisions @ √s = 200 GeV

(~10 times CERN-SPS energy)

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

p+p collisions @ 500 GeV

p+A collisions @ 200 GeV



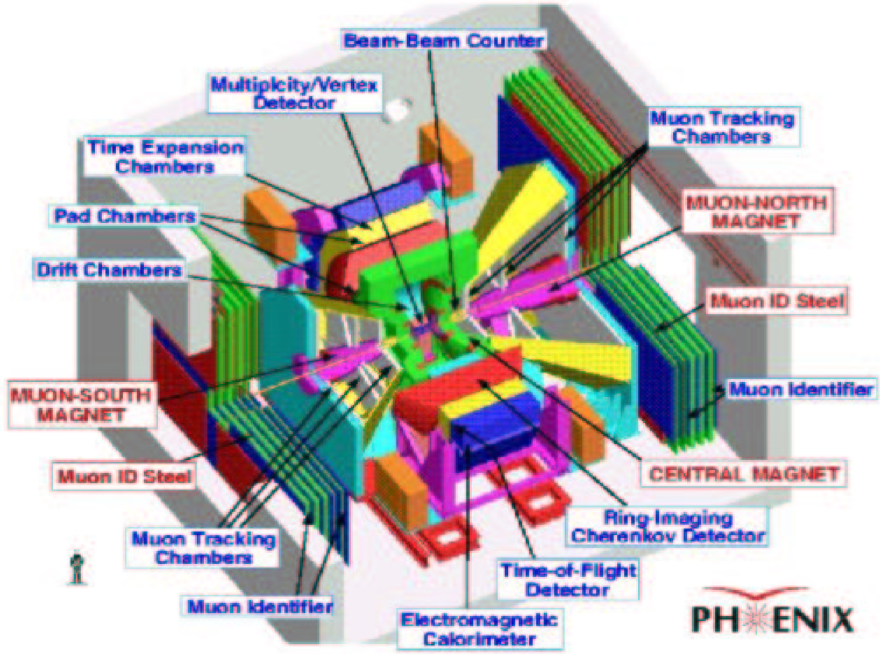
4 experiments:

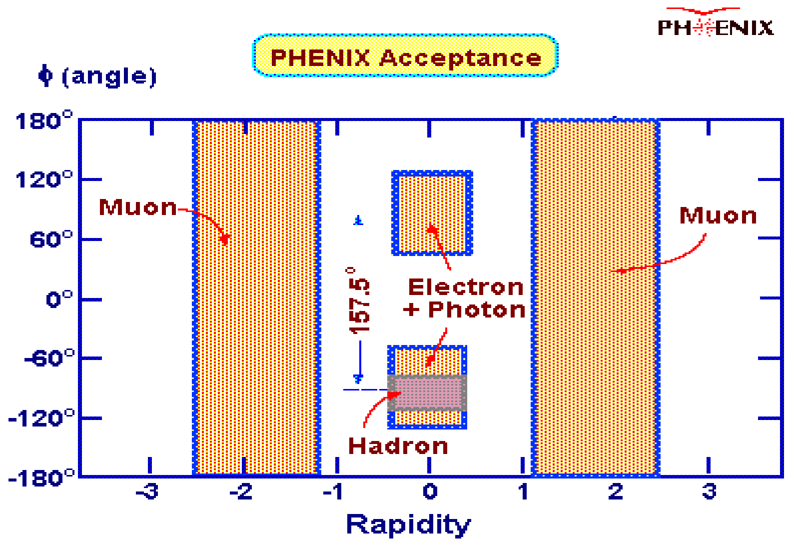
PHENIX, STAR, PHOBOS, BRAHMS

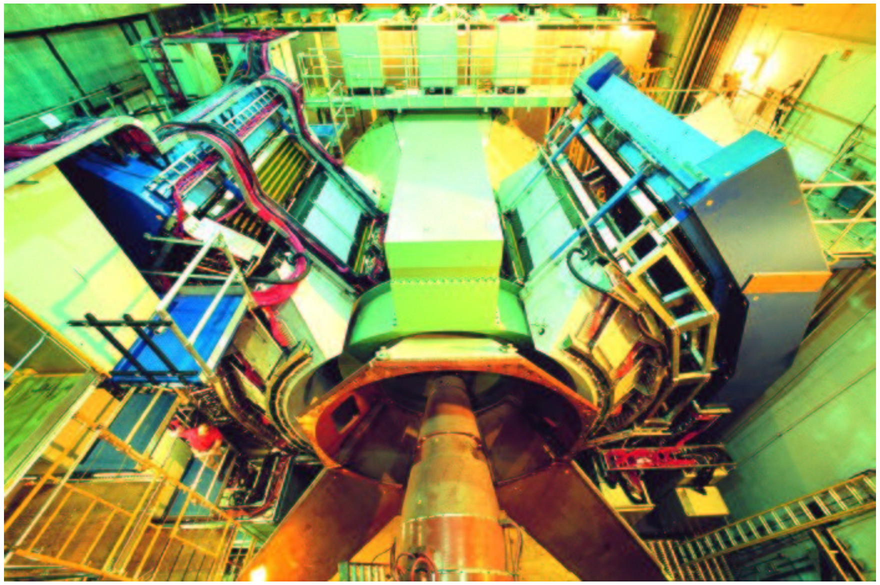
Run-1 (2000): Au+Au @ 130 GeV
Run-2 (2001-2): Au+Au, p+p @ 200 GeV
Run-3 (2002-3): d+Au, p+p @ 200 GeV

PHENIX @ RHIC

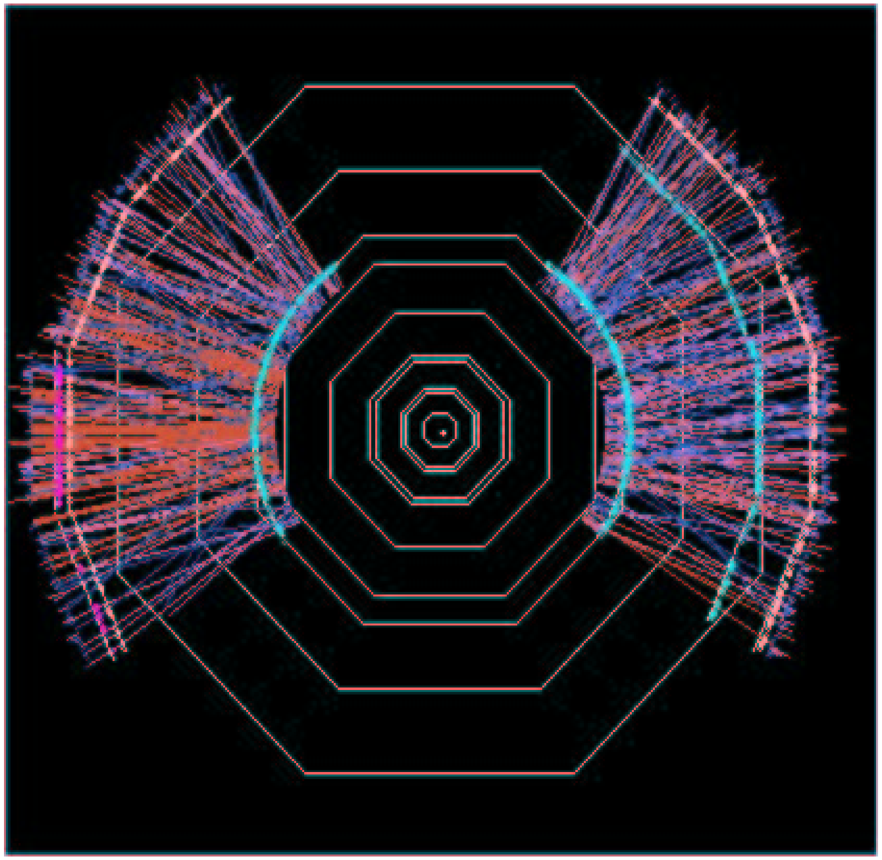
- International collaboration:
  ~400 people
  50 institutions
  14 countries
- 11 detector subsystems:
  2 central arms, 2 forward arms
  Global dets.
- Designed to measure rare probes:
  + high rate capability & granularity
  + good mass resolution and PID
  - limited acceptance

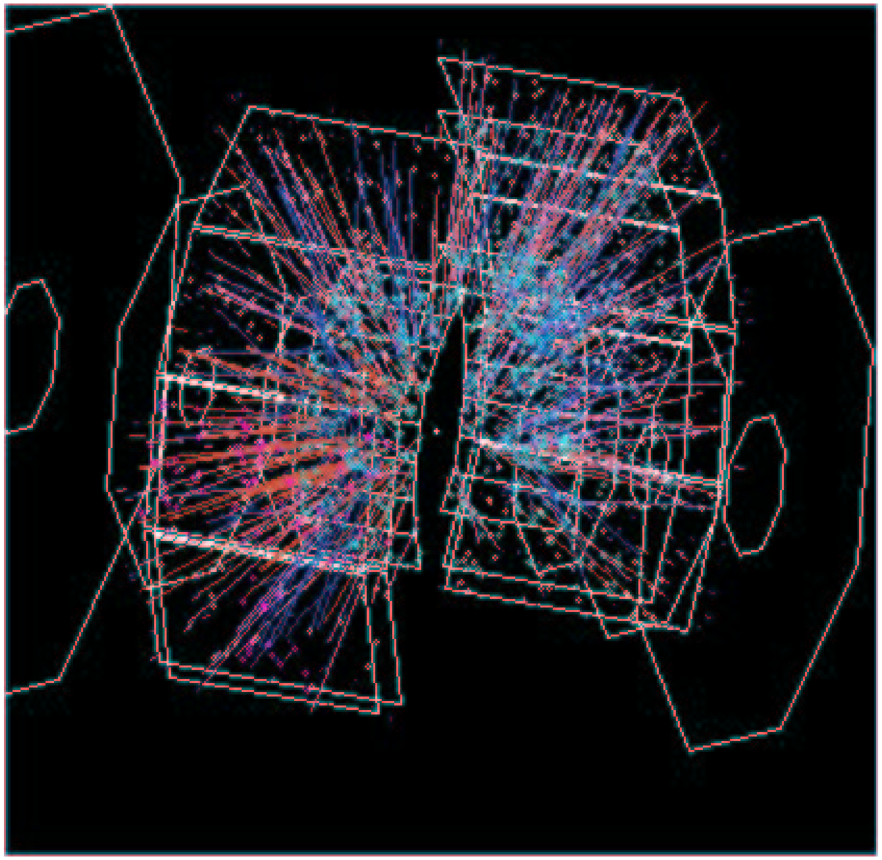






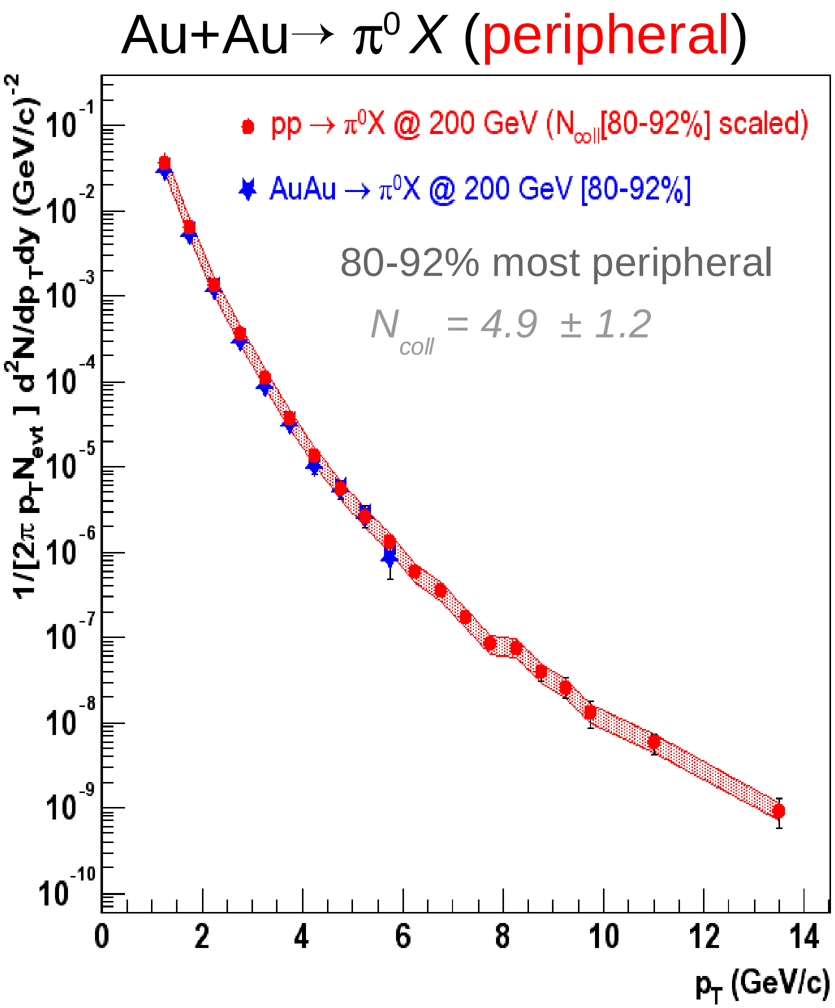
Au+Au in PHENIX

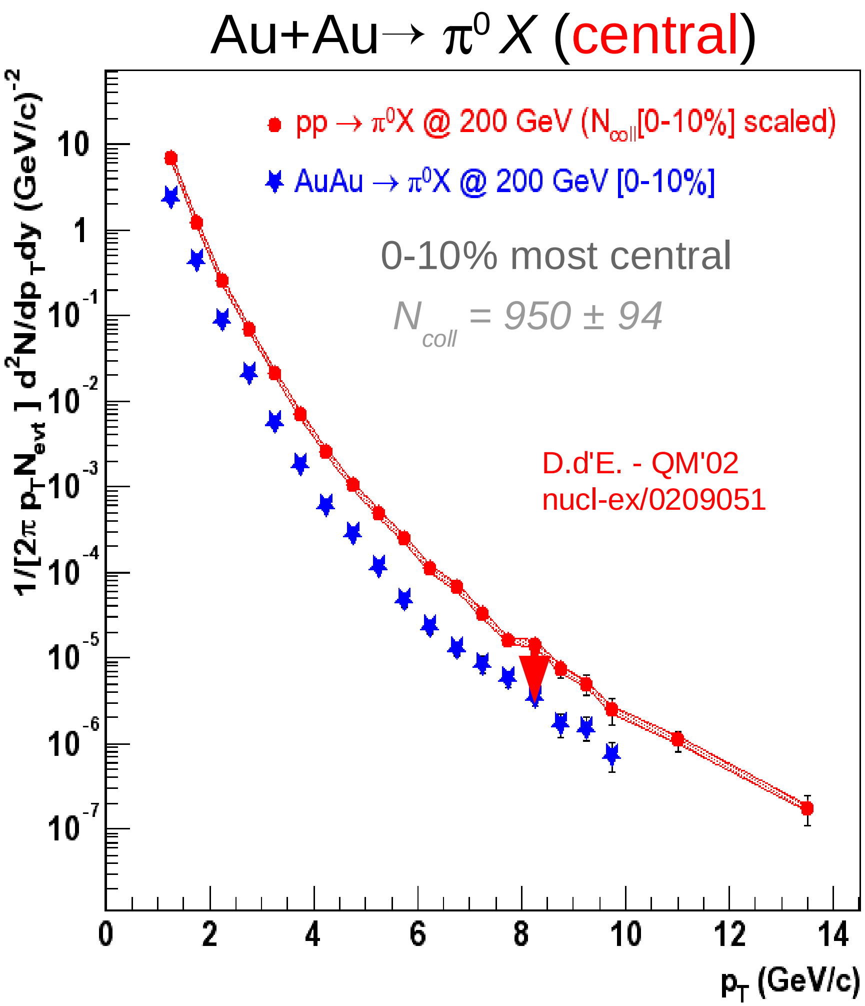




~600 charged particles per unit rapidity at mid-rapidity (5% most central)

High p_T suppression (AuAu *vs* pp)



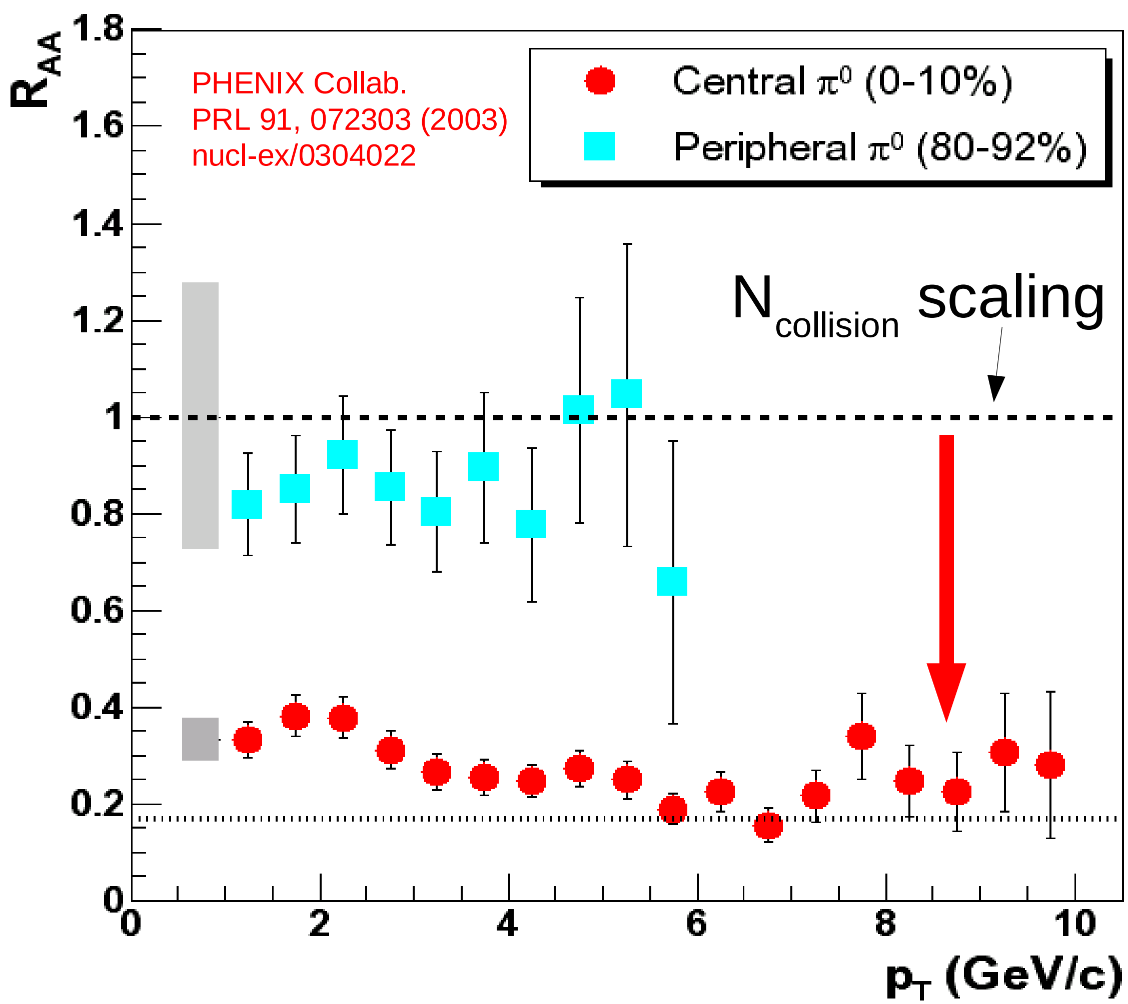


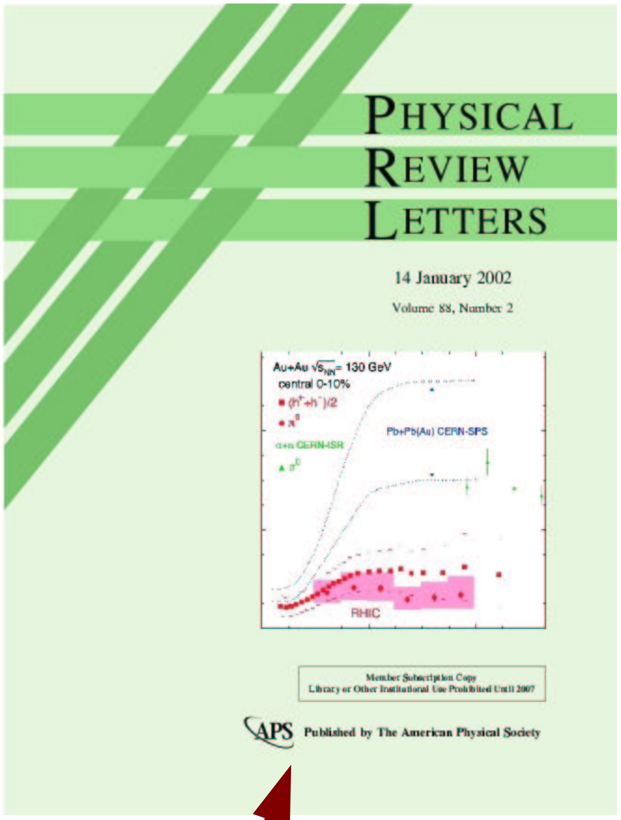
Peripheral data agree with p+p data scaled by # of *NN* collisions (pQCD expectation)

Strong suppression (x4-5) in central AuAu collisions

Nuclear modification factor

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





Discovery of high p_T suppression

(most significant result @ RHIC so far)

Data vs models

- Dense medium properties according to “jet quenching” models (pQCD NLO, nuclear PDFs, gluon radiative energy loss):

  - High opacities:

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

  - Large initial gluon densitie

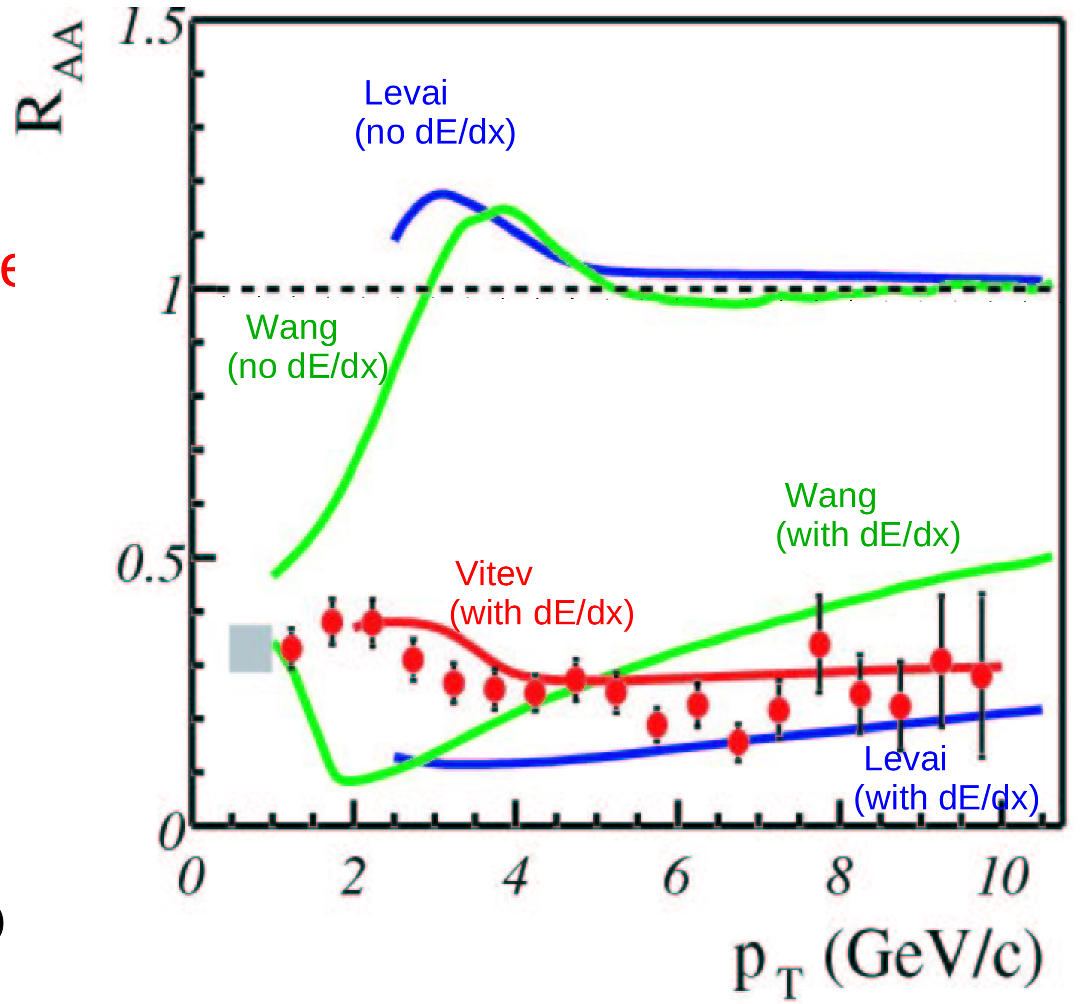
    $dN^g/dy \sim 800\text{-}1200$

  - Transport coefficients:

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

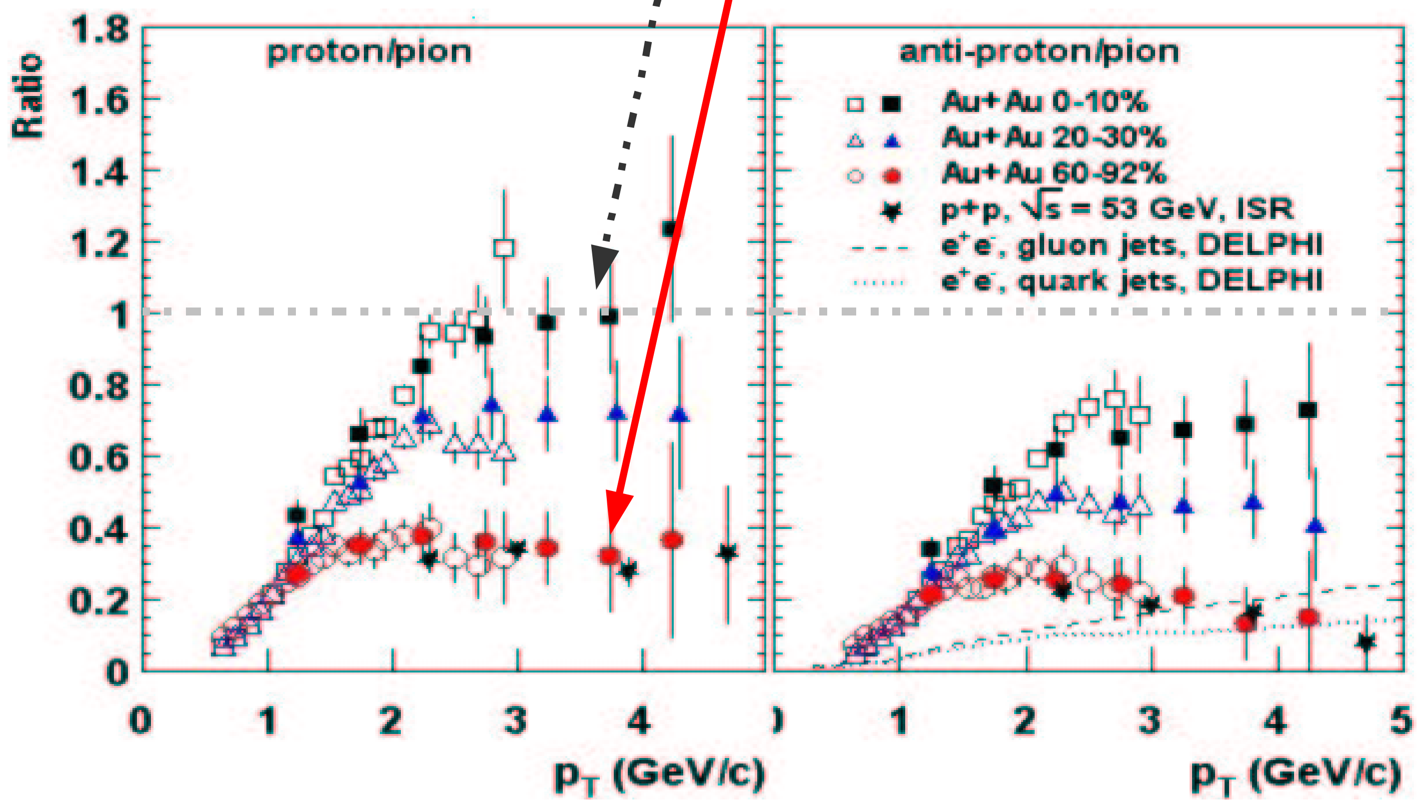
  - Medium-induced gluon radiative energy losses:

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



“Anomalous” hadron composition at high-p_T : p/π ratio

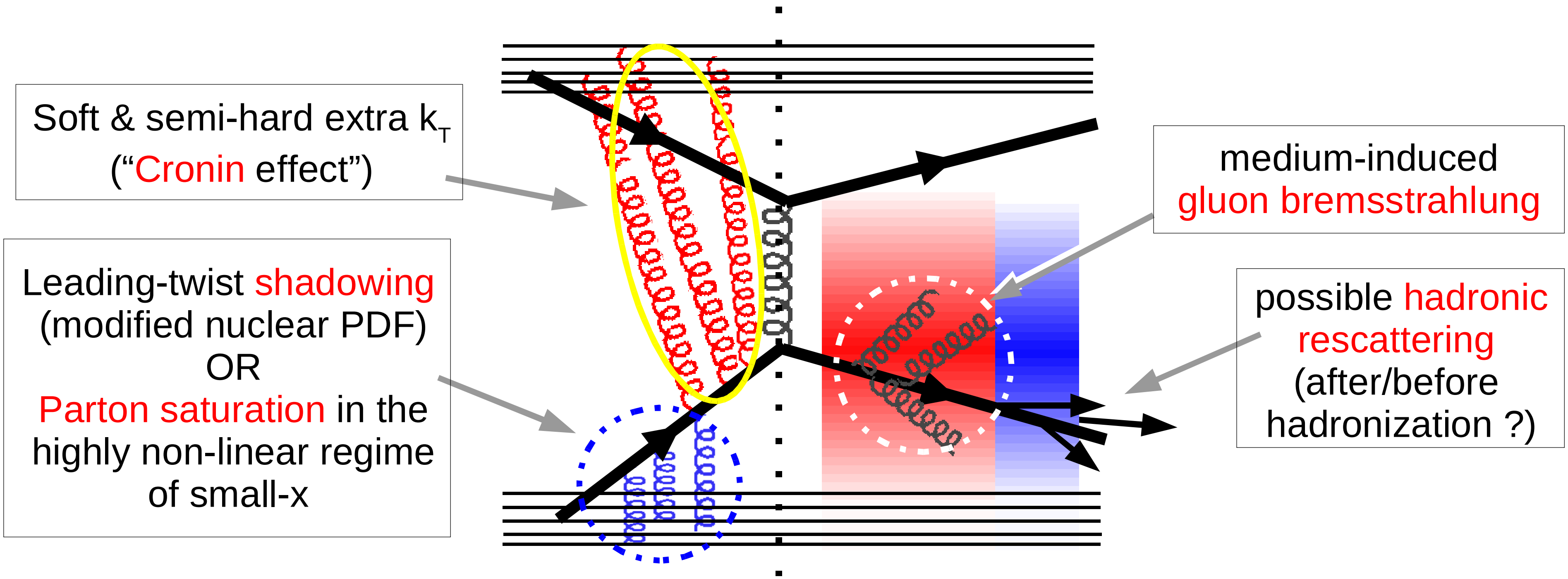
- Central colls.: baryon/meson ~ 1.0 for p_T > 2 GeV/c at variance with perturbative production mechanisms (favour lightest meson).
- Peripheral colls. baryon/meson ~ 0.3 as in p+p,pbar (ISR, FNAL) and in e+e- jet fragmentation



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

High p_T suppression: Initial- or final- state effect ?

- Two theoretical explanations for the high p_T suppression:
  1. "QGP models": Due to non-abelian energy loss of scattered partons in a very dense medium.
  2. "CGC models": Due to (strongly) depleted parton distribution functions in the nuclei at the relevant (x,Q^2).

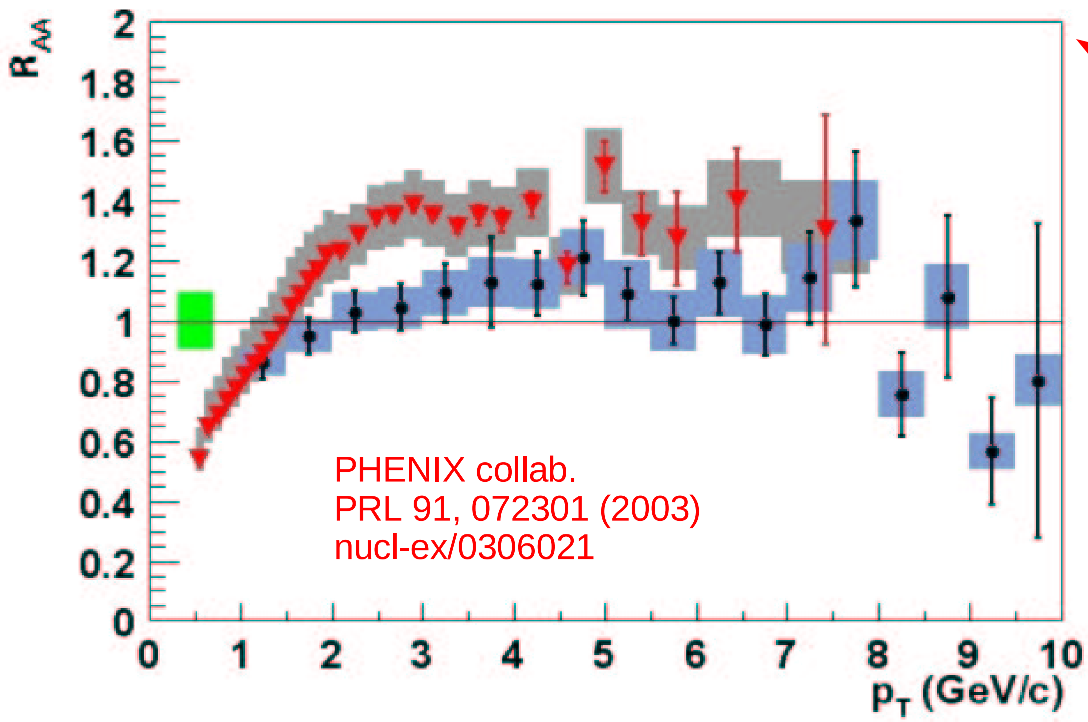


- Experimental disentanglement: p,d+A "control" experiment

  Au+Au ("hot & dense" QCD medium) vis-à-vis d+Au ("cold" QCD medium).

Nuclear modification factor in d+Au (min. bias)

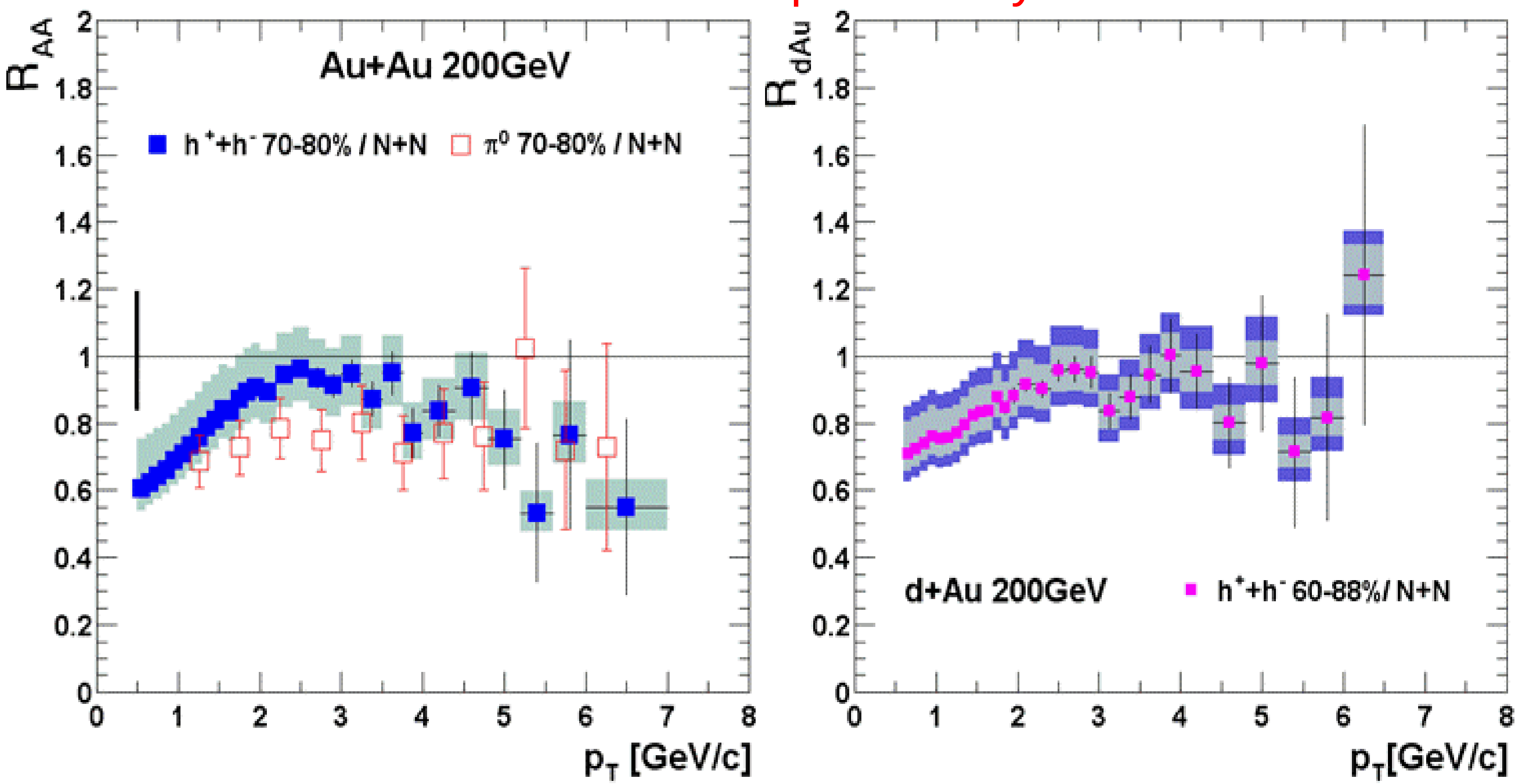
- R_{dAu} for charged hadrons and π^0 :



- No high p_T suppression but enhancement !
- d+Au results at RHIC clearly reminiscent of p+A "Cronin enhancement" (initial-state soft and semihard scatterings).
- No shadowing or strong saturation of Au PDF.

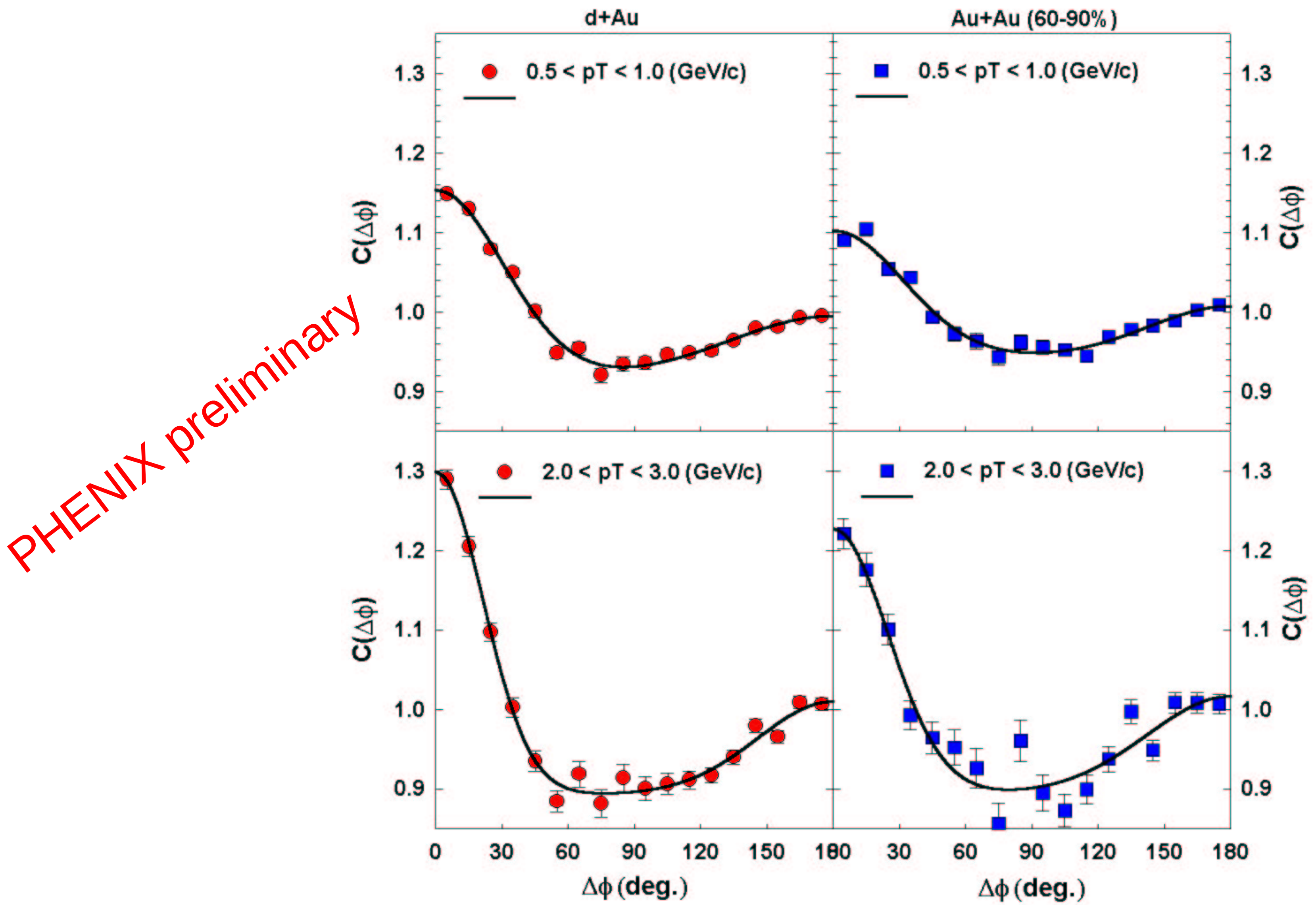
Nuclear modification factor: d+Au vs Au+Au

PHENIX preliminary



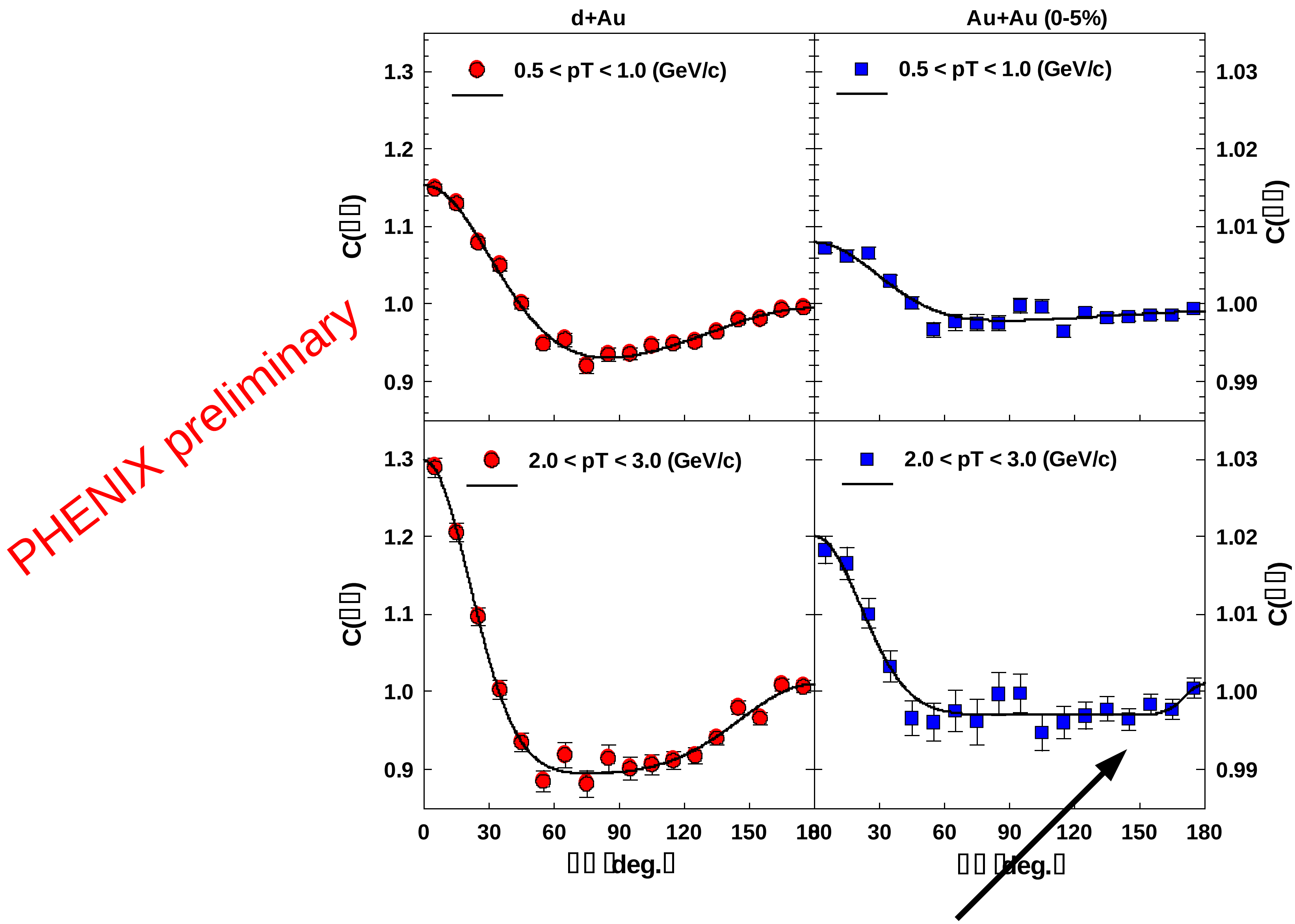
- Opposite centrality dependence of nuclear enhancement (in p+Au) compared to nuclear suppression (in Au+Au) !
- Conclusion: Au+Au suppression not due to a "cold" nuclear matter (initial-state) effect.

High p_T azimuthal correlations (d+Au, Au+Au periph.)



- Jet-like near- and away- side azimuthal correlations (as in p+p).

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



- Diminished away-side correlation consistent with absorbed back-to-back jet

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 sensitive to this new state of matter.
  - Comparing to "vacuum" (p+p) and "cold medium"(d+Au) data.

Summary (II)

- High p_T data in central Au+Au collisions:
  - Strong suppression (factor ~ 4-5) of π^0 and $h^\pm$ above p_T~ 4 GeV/c (compared to p+p collisions).
  - No apparent suppression of (anti)protons in ~1-4 GeV/c: “anomalous” p/π ~ 0.8 ratio >> than in p+p and e+e- jet fragmentation.
  - Disappeareance of jet-like away-side azimuthal correlations.
  - Peripheral Au+Au collisions behave effectively as p+p collisions (i.e. as pQCD) for all species and for all observables.

- High p_T data in d+Au collisions:
  - No suppression observed in min. bias d+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.

- (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 ...*”