Quantum Chromo many-body Dynamics probed in the hard sector at RHIC

39th Rencontres de Moriond - QCD 2004

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Overview ("Status of QGP & CGC search")

1. Introduction:
   - The goal: Study Quantum Chromo many-body Dynamics: QGP, CGC.
   - The means: Compare hard scattering production in diff. colliding had. systems.
2. "QCD vacuum" reference results – high p_T in p+p
   - Baseline hard scattering data in free space.
3. "Hot QCD medium" highlights – high p_T in central A+A
   - ➡ dN/dp_T light hadrons (u,d,s): suppressed
     $\sqrt{s}$, p_T, centrality, and meson-baryon dependence
   - ➡ $dN_{pair}/d\varphi$ azimuthal anisotropies:
     dissapearence of away-side dijet correlations
   - ➡ dN/dp_T colorless probes (γ): unsuppressed

   } **QGP ?**
4. "Cold QCD medium" highlights – high p_T in d+Au
   - ➡ dN/dp_T light hadrons (u,d,s):
     enhanced at $y \leq 0$ (midrapidity & high x_2 in Au)
     suppressed at $y \geq 1$ (small x_2 in Au)

   } **CGC ?**
5. What have we learnt ? Data vs. theory.
6. Summary

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

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}_f (i\gamma^\mu D_\mu + m_f) q_f$$

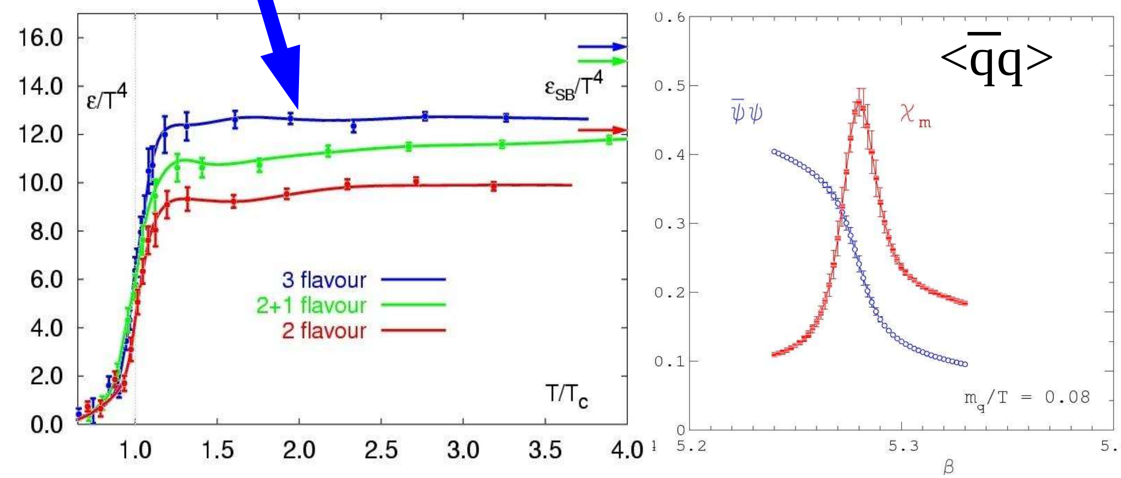
$$\text{where } G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$$

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

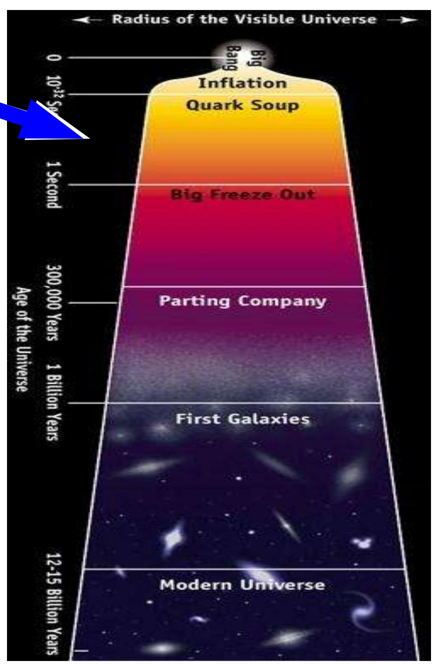
$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

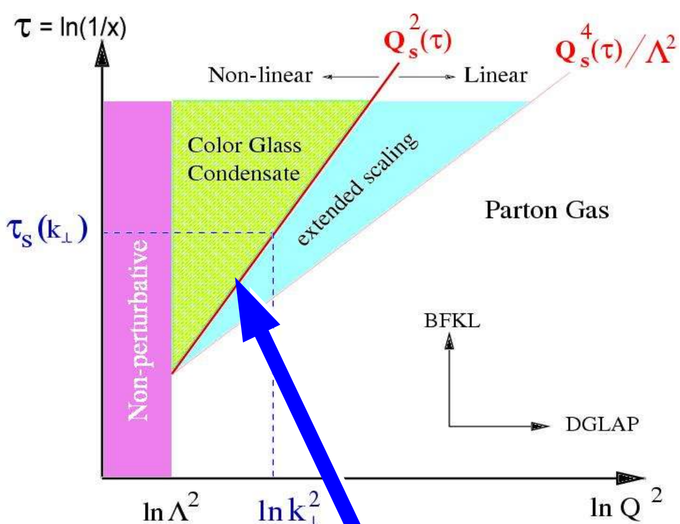
1. Learn about 2 basic properties of strong interaction: confinement, chiral symmetry breaking

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



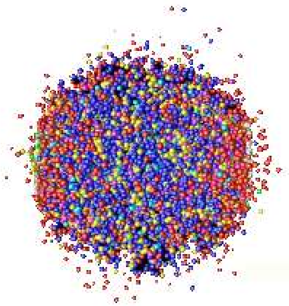
3. Probe quark-hadron phase transition of the primordial Universe (few μsec after the Big Bang)



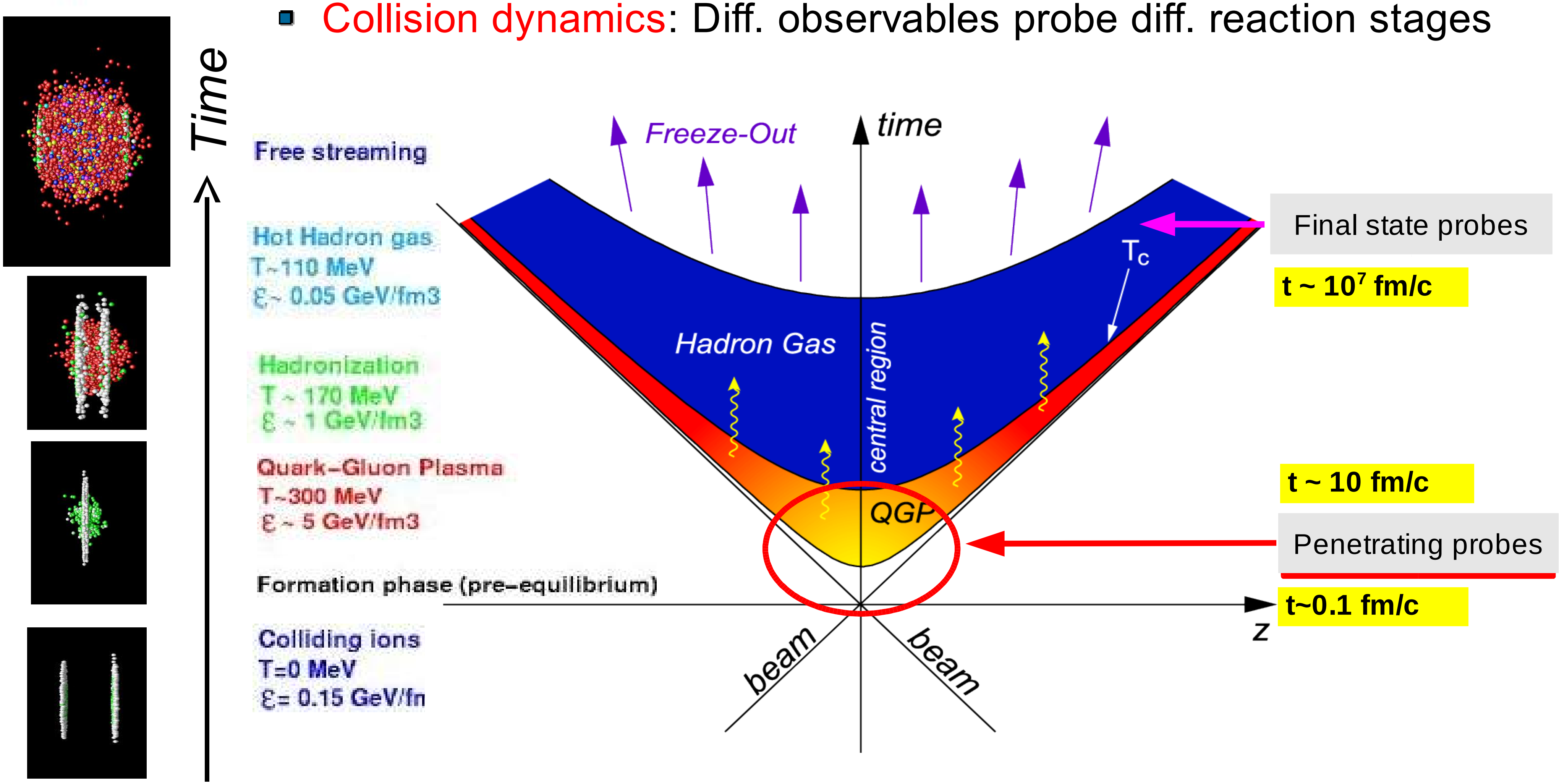


4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

The "Little Bang" in the lab.



- High-energy nucleus-nucleus collisions: fixed-target reactions (√s~17 GeV - SPS) or at colliders (√s~200 GeV - RHIC, √s~5.5 TeV - LHC)
  - QGP expected to be formed in a tiny region ($\sim10^{-14}$ m) and to last very short times ($\sim10^{-23}$ s).
  - Collision dynamics: Diff. observables probe diff. reaction stages

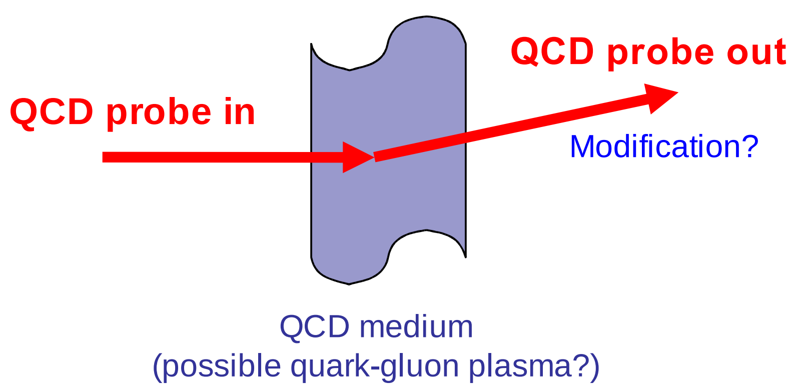


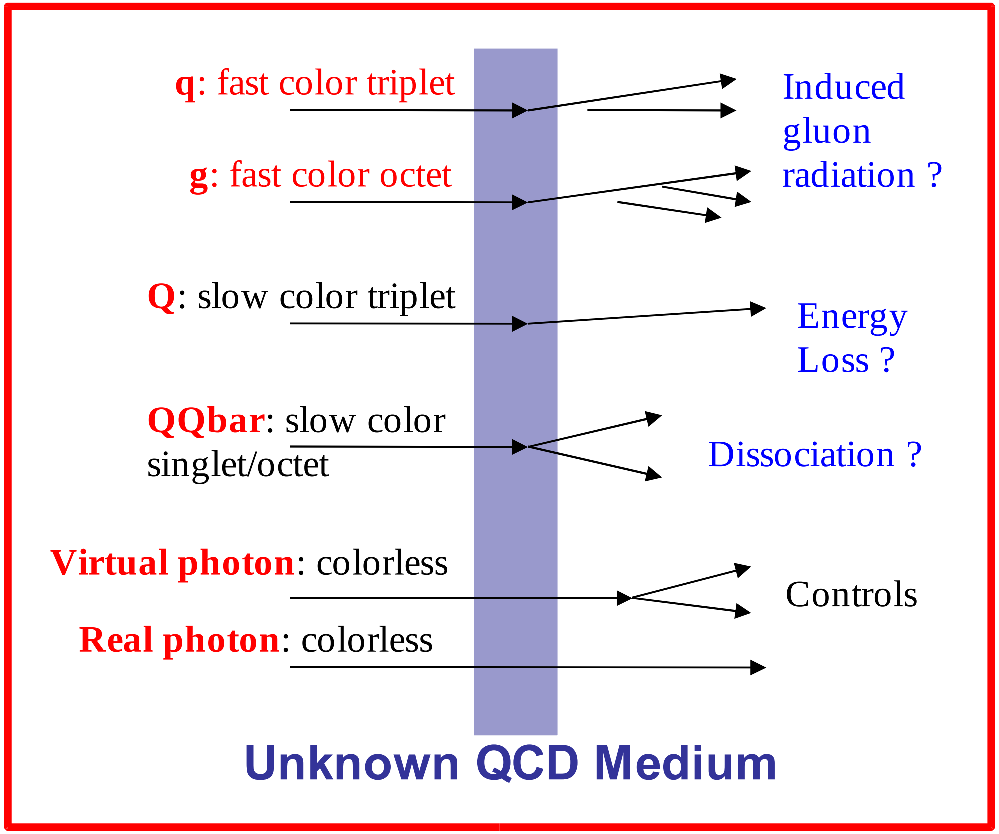
Hard QCD probes. Motivation (I)

- Hard probes: High-p_T, jets, direct γ, heavy-quarks (D, B), ...

[1] Early production ($\tau \sim 1/p_T < 0.1$ fm/c) in parton-parton scatterings with large Q^2:
Closest experimental probes to underlying QCD (q,g) degrees of freedom.

[2] Direct probes of partonic phase(s) $\Longrightarrow$ Sensitive to QCD medium properties:





Hard QCD probes. Motivation (II)

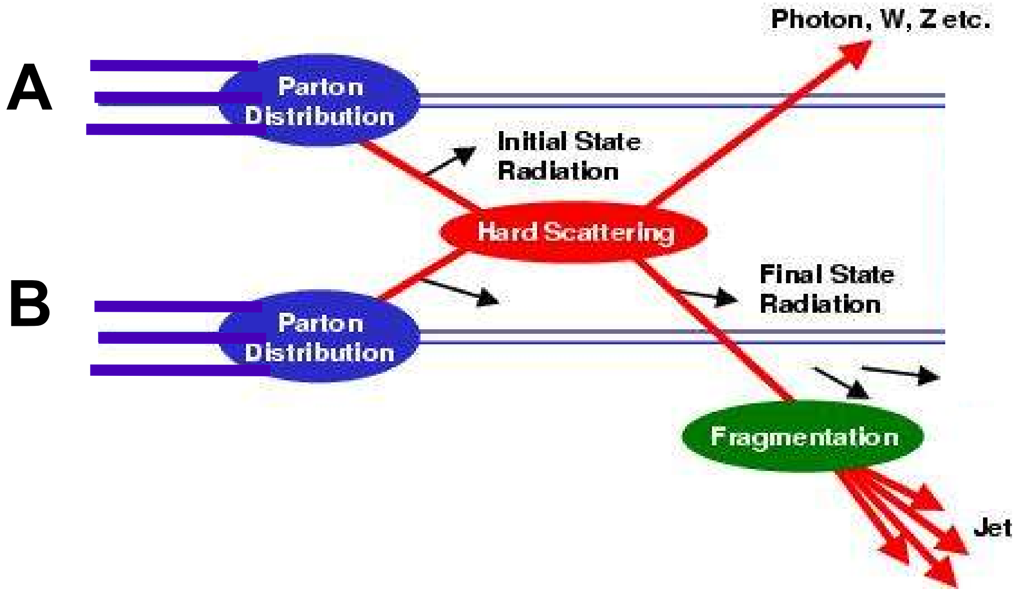
[3] Production yields theoretically calculable via:

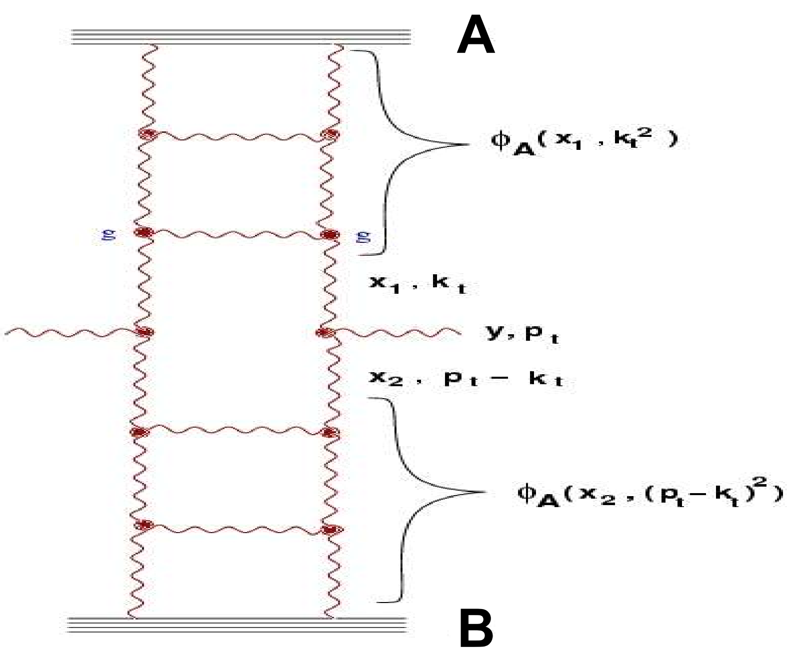
perturbative-QCD or ...

classical-field QCD:

at small-x ...

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





Mueller diagram for
classical glue radiation

Reference pQCD hard cross-sections in A+B

pQCD (factorization theorem) expectation for inclusive A+B hard cross-sections:

Independent scattering of "free" partons: $f_{a/A}(x,Q^2) = A\, f_{a/p}(x,Q^2)$

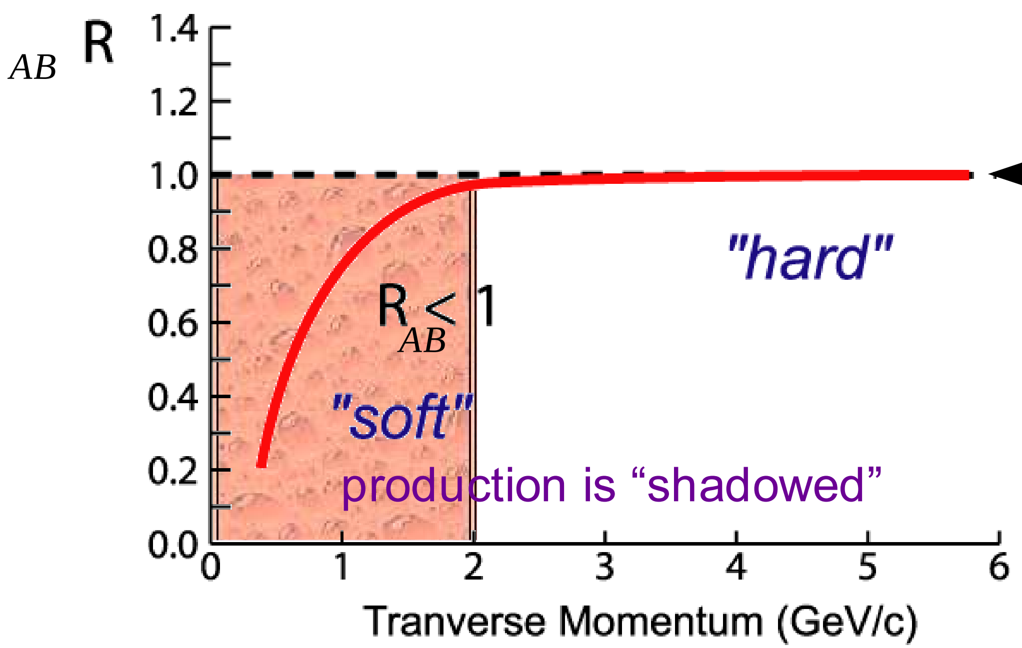
$d\sigma_{AB \to hard} = A \cdot B \cdot d\sigma_{pp \to hard}$

At imp. param. b: $dN_{AB \to hard}(b) = T_{AB}(b) \cdot d\sigma_{pp \to hard}$

geom. nuclear overlap at b

Nuclear Modification Factor:

$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$

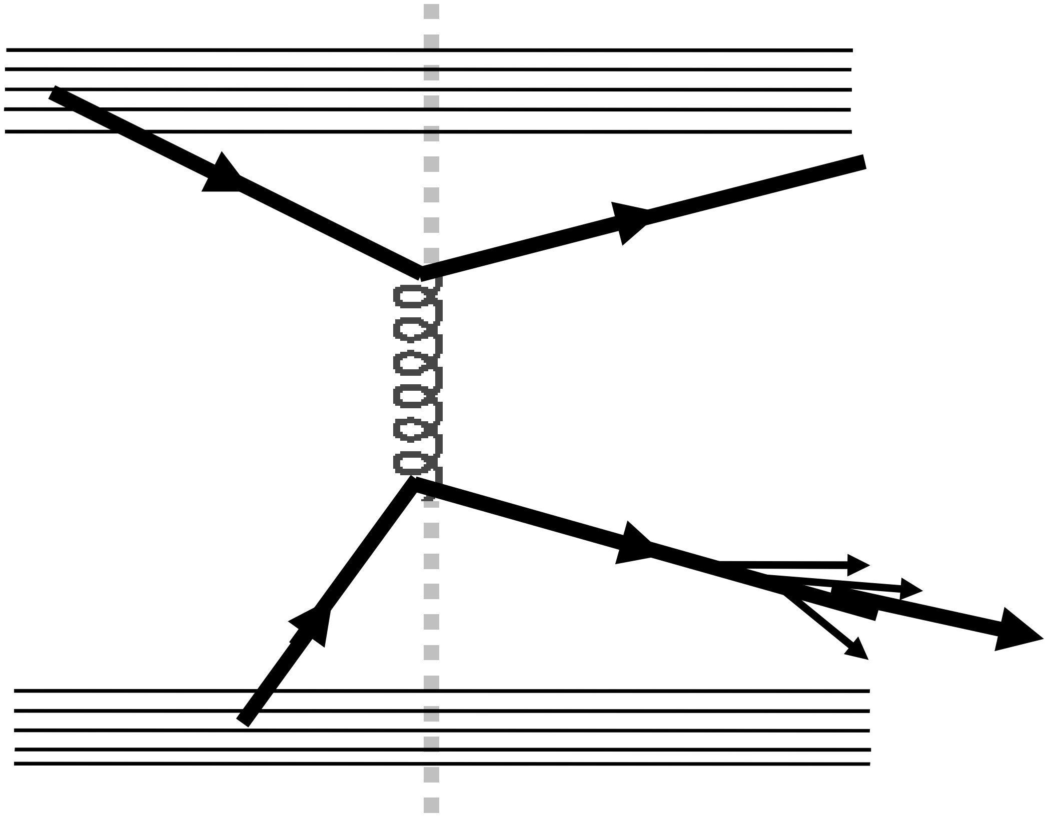


T_{AB} ~ # NN colls. ("N_{coll} scaling")

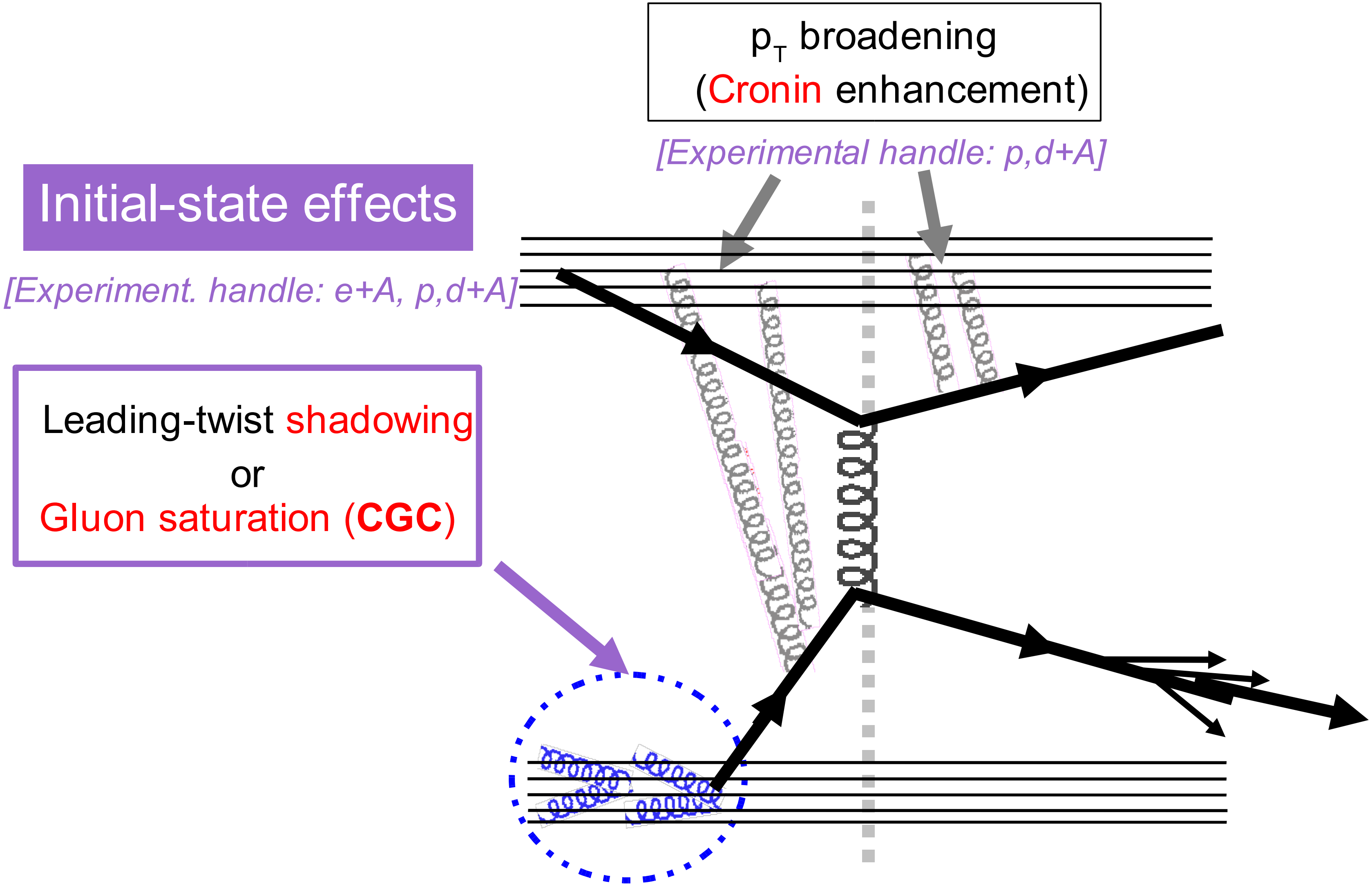
$R_{AA} = 1$

A+A = "simple superposition of p+p collisions" at high-p_T where hard scattering dominates

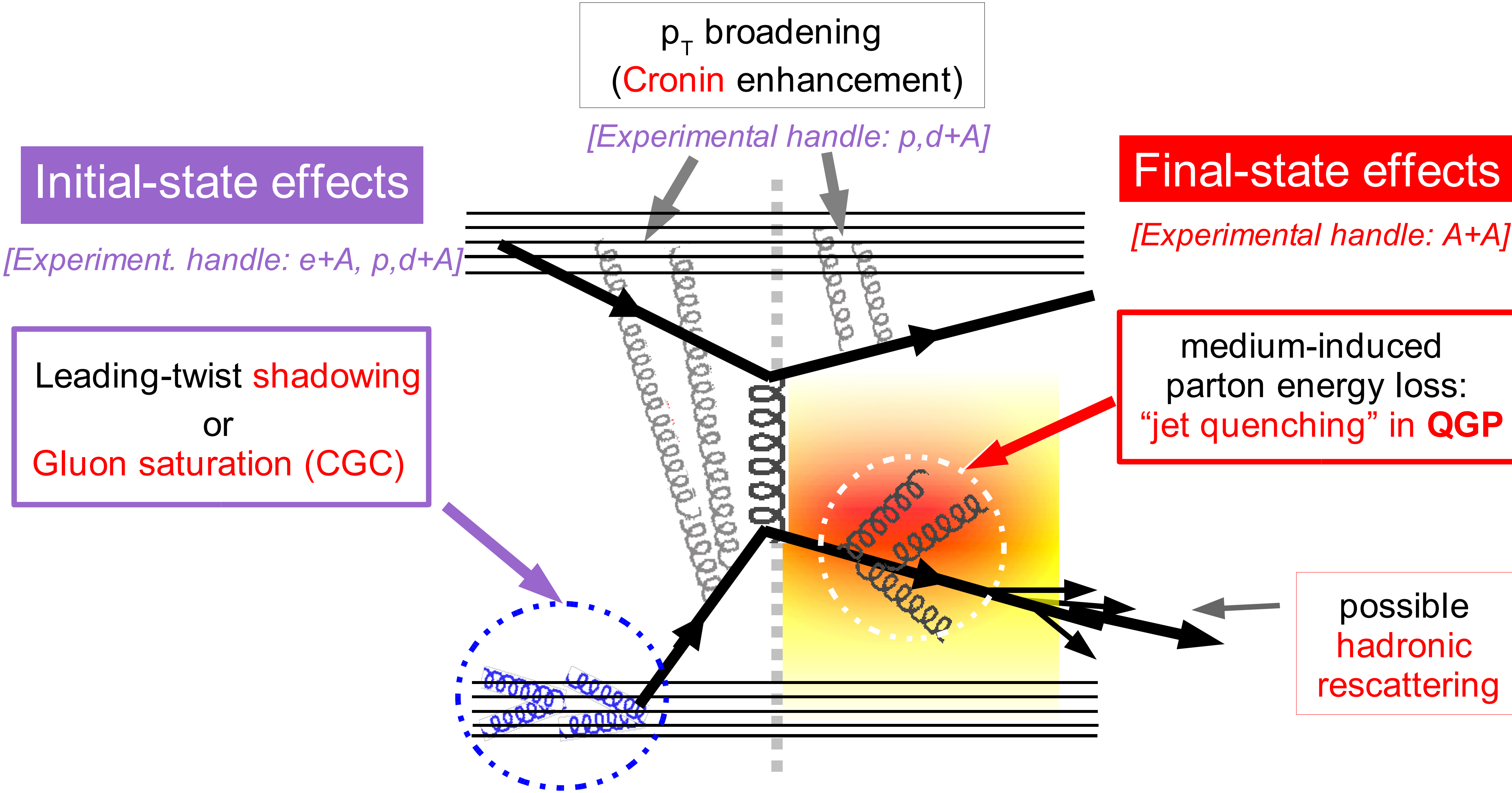
Hard scattering in A+A collisions



Hard scattering in A+A collisions



Hard scattering in A+A collisions



Hard scattering in A+A collisions

p_T broadening
(Cronin enhancement)

[Experimental handle: p,d+A]

Initial-state effects

[Experiment. handle: e+A, p,d+A]

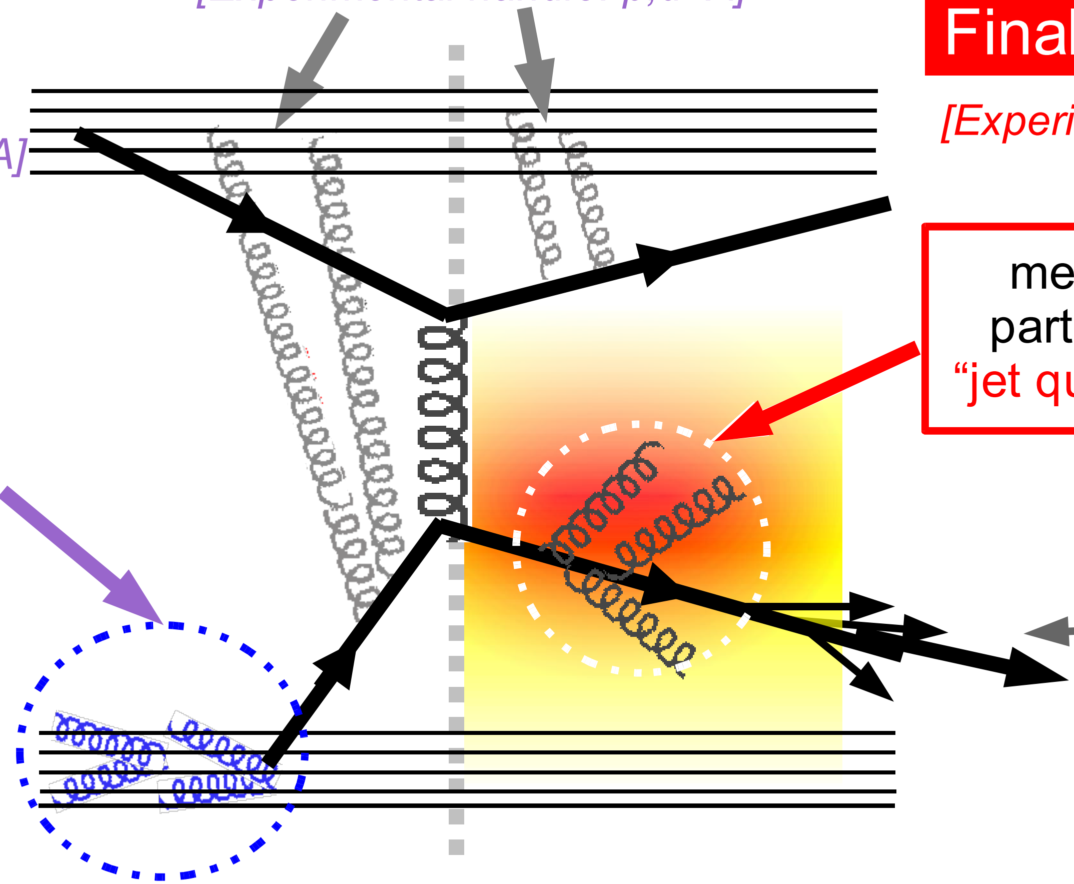
Leading-twist shadowing
or
Gluon saturation (CGC)

Final-state effects

[Experimental handle: A+A]

medium-induced
parton energy loss:
"jet quenching" in QGP

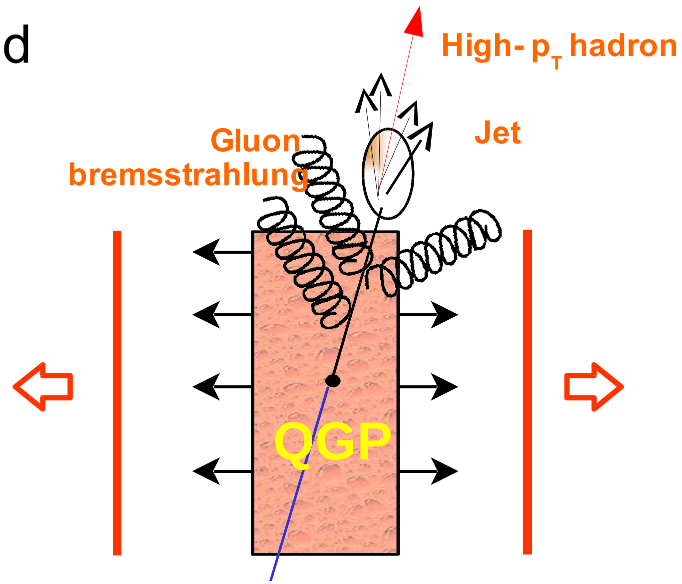
possible
hadronic
rescattering



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

Final-state QGP effects

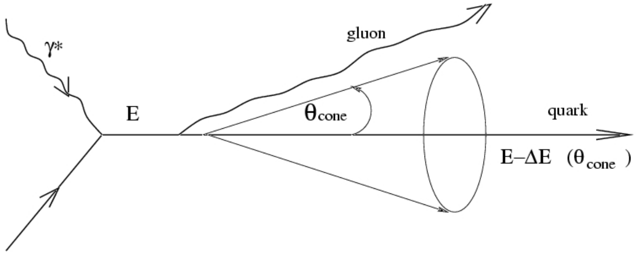
- Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium:



  - Mean parton energy loss probes medium properties:

    $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)

    $\Delta E_{loss} \sim \Delta L^2$ (medium length)



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

  - Formalisms: BDMPS (thick plasma), GLV (thin plasma),

  - Correction for expanding plasma (1-D):
    $\Delta E_{1\text{-}D} = (2\tau_0/R_A) \cdot \Delta E_{static} \sim 15 \cdot \Delta E_{static}$ (τ_0=0.2 fm/c, R_A=6 fm)

- Expected result: Suppression of high p_T leading hadrons due to non-Abelian final-state gluon radiation.

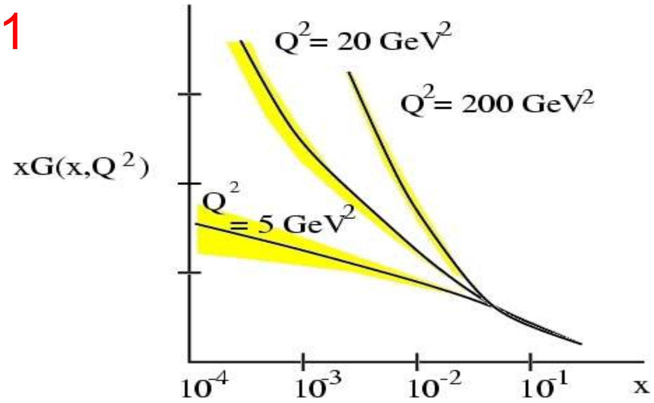
Initial-state CGC effects

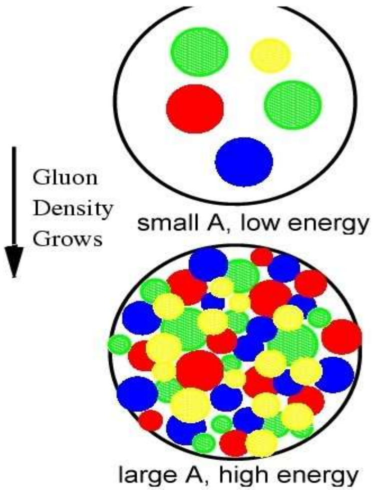
- Initial conditions at RHIC: high-energies + large nuclei
  - Values of small-x: $x_{Bj} = 2p_T/\sqrt{s} \ll 1$

Large gluon densities

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

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



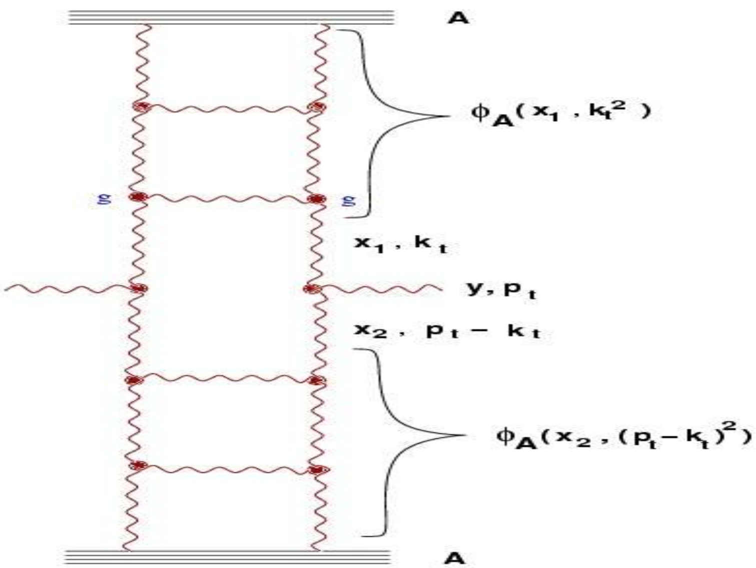


- Colliding nuclei described via a colored highly saturated gluonic wave-function ("Color Glass Condensate").

"Classical" approach valid around "sat. scale": Q_s~1.5 GeV/c

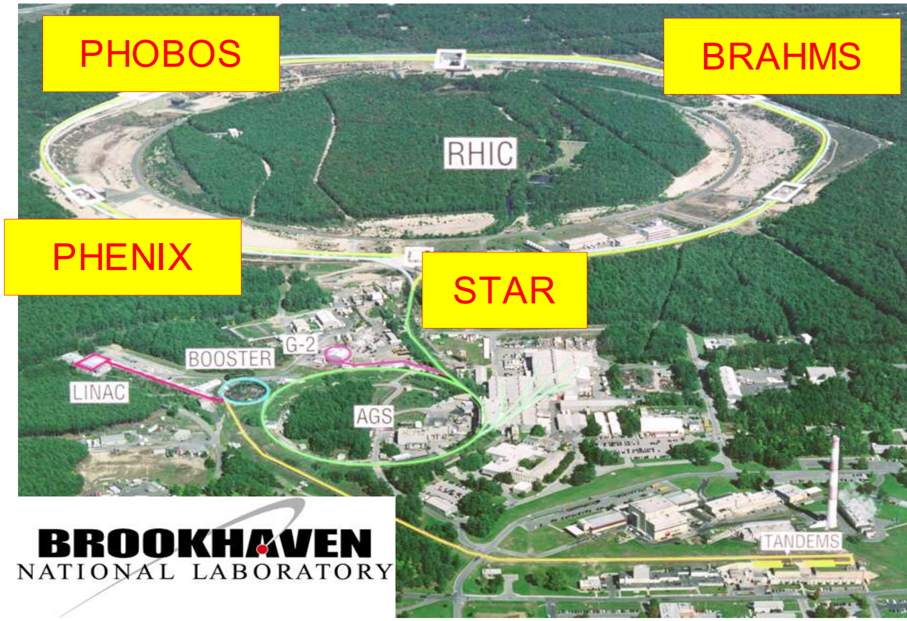
- Particle production via glue-glue collisions:

Extension to $p_T > Q_s$ ("geometric scaling") via quantum evolution.



- Expected result: gluon fusion at low x leads to an effective depletion of the number of partonic scattering centers in the initial state.

Relativistic Heavy-Ion Collider (RHIC) @ BNL



Specifications:

3.83 km circumference

2 independent rings:

- 120 bunches/ring
- 106 ns crossing time

A + A collisions @ $\sqrt{s}$ = 200 GeV

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

p+p collisions @ 500 GeV

p+A collisions @ 200 GeV

4 experiments:

BRAHMS, PHENIX, PHOBOS, STAR

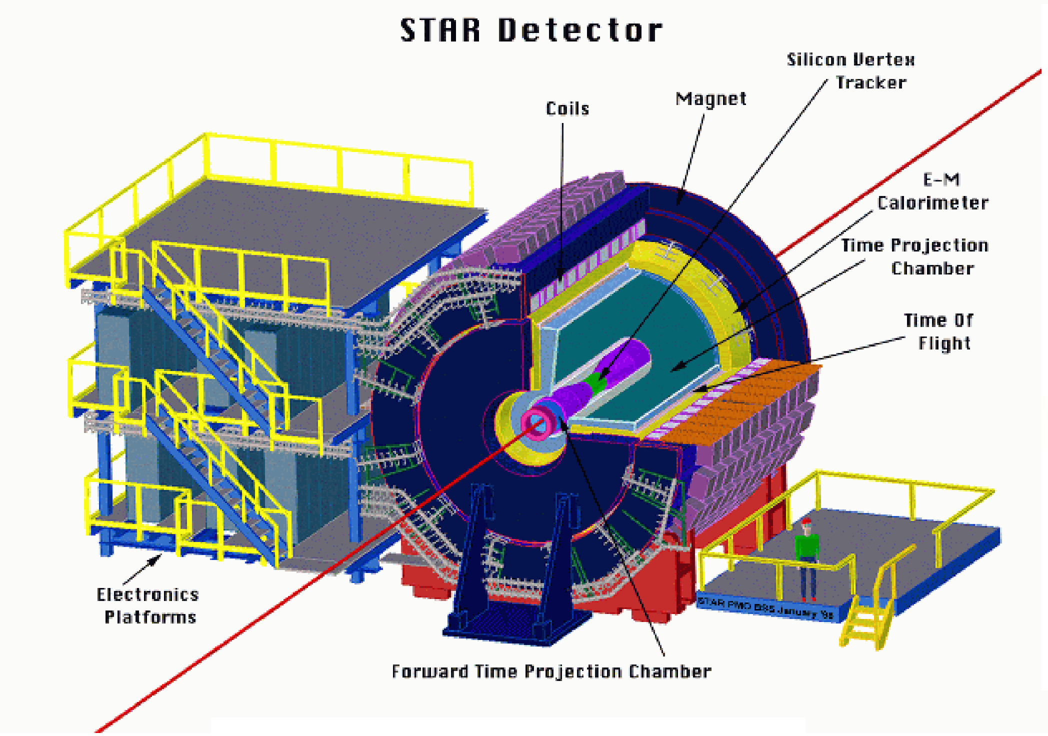
Run-1 (2000): **Au+Au @ 130 GeV**

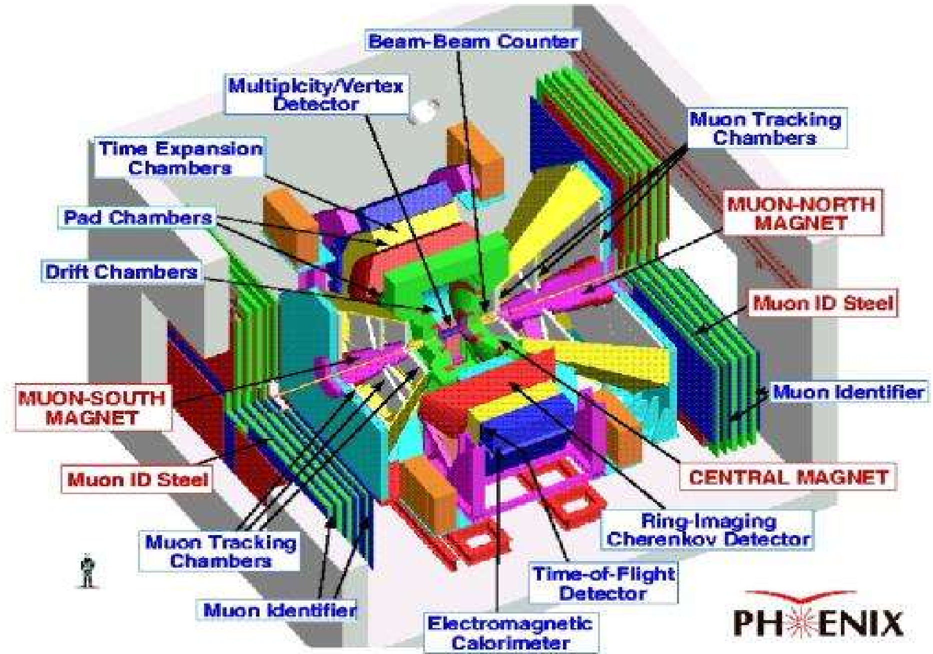
Run-2 (2001-2): **Au+Au, p+p @ 200 GeV**

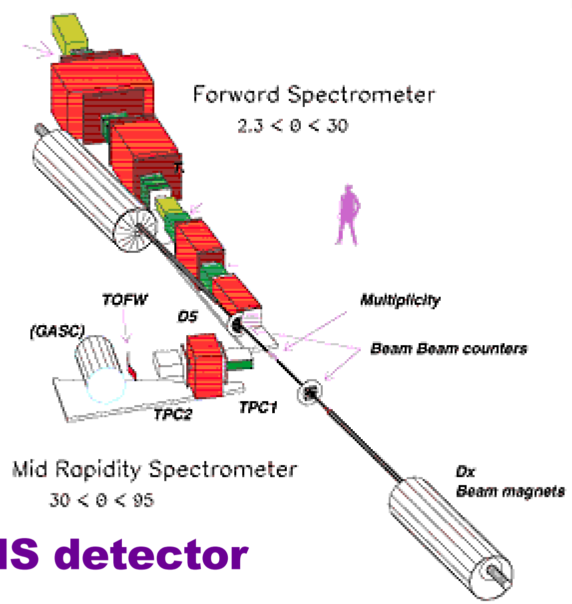
Run-3 (2002-3): **d+Au, p+p @ 200 GeV**

Run-4 (2004): **Au+Au, p+p @ 200 GeV**
Au+Au @ 62 GeV

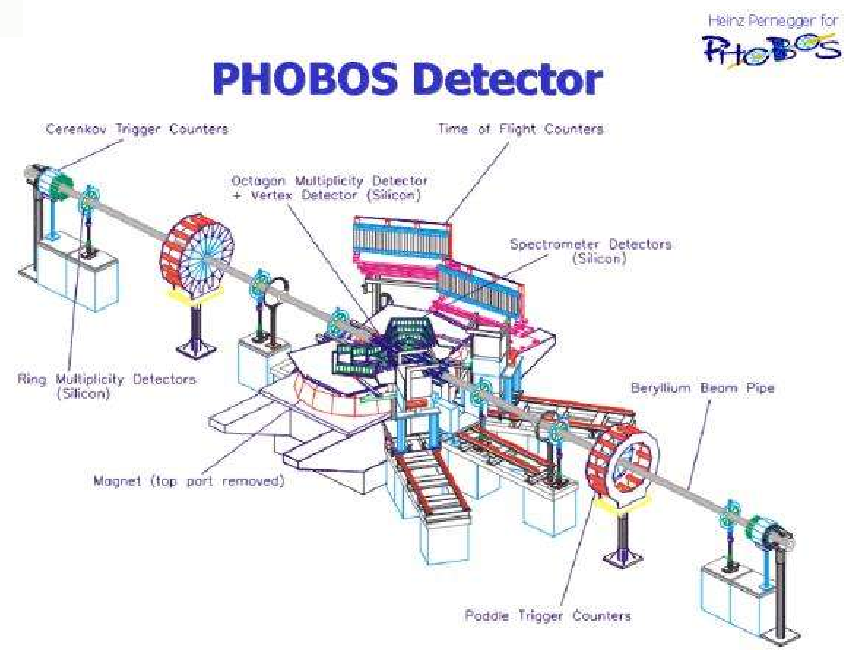
The 4 RHIC experiments



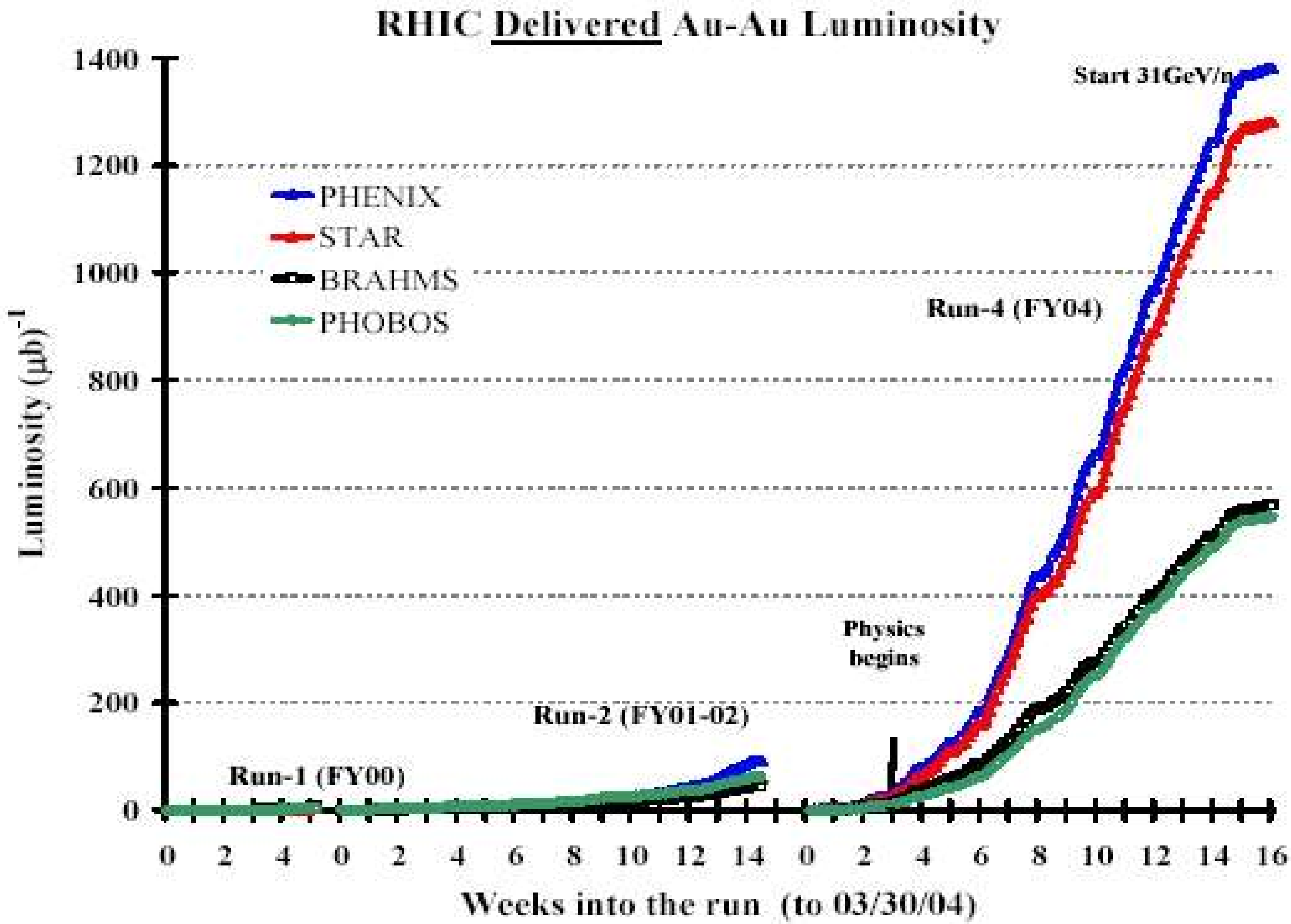




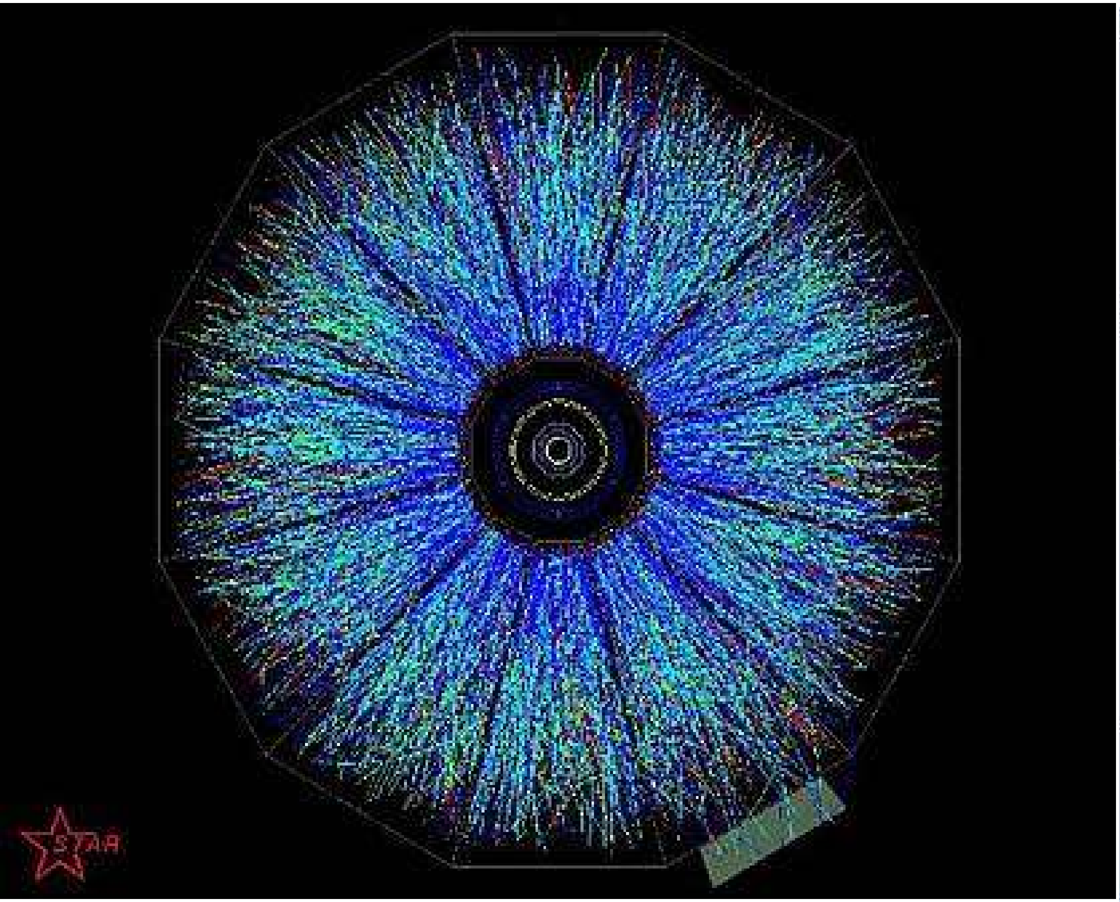
BRAHMS detector

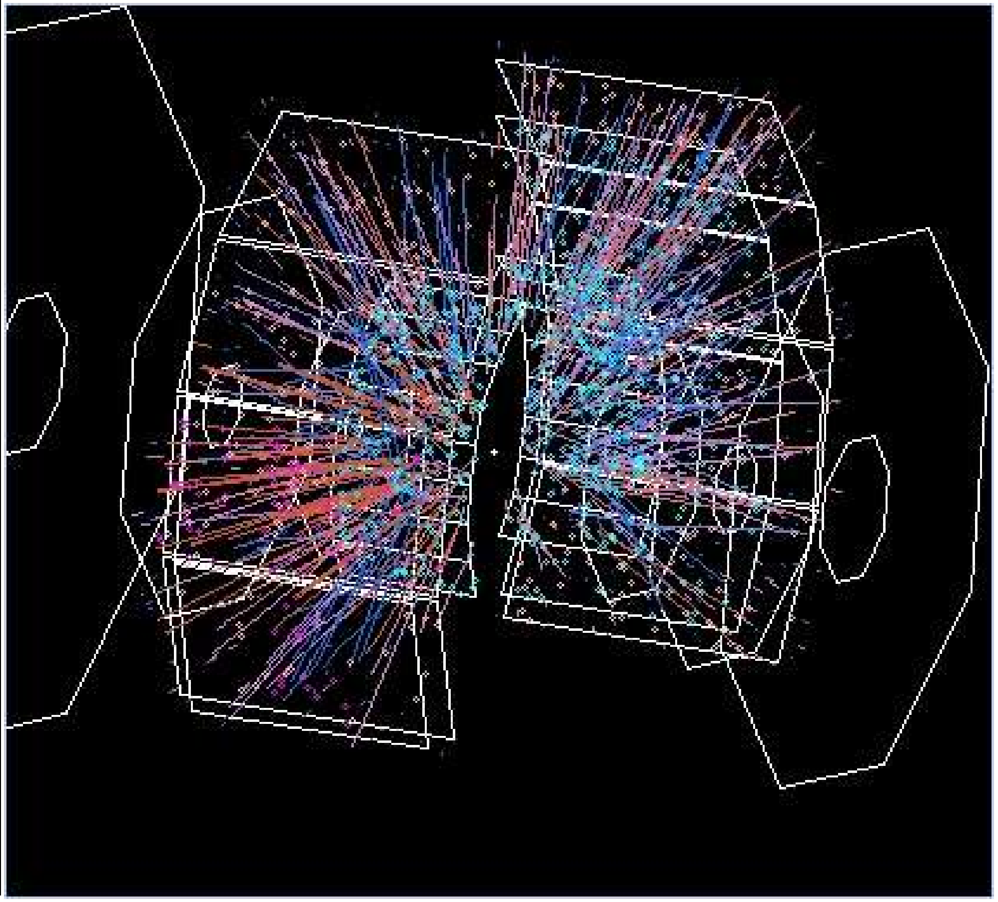


RHIC Au+Au luminosities



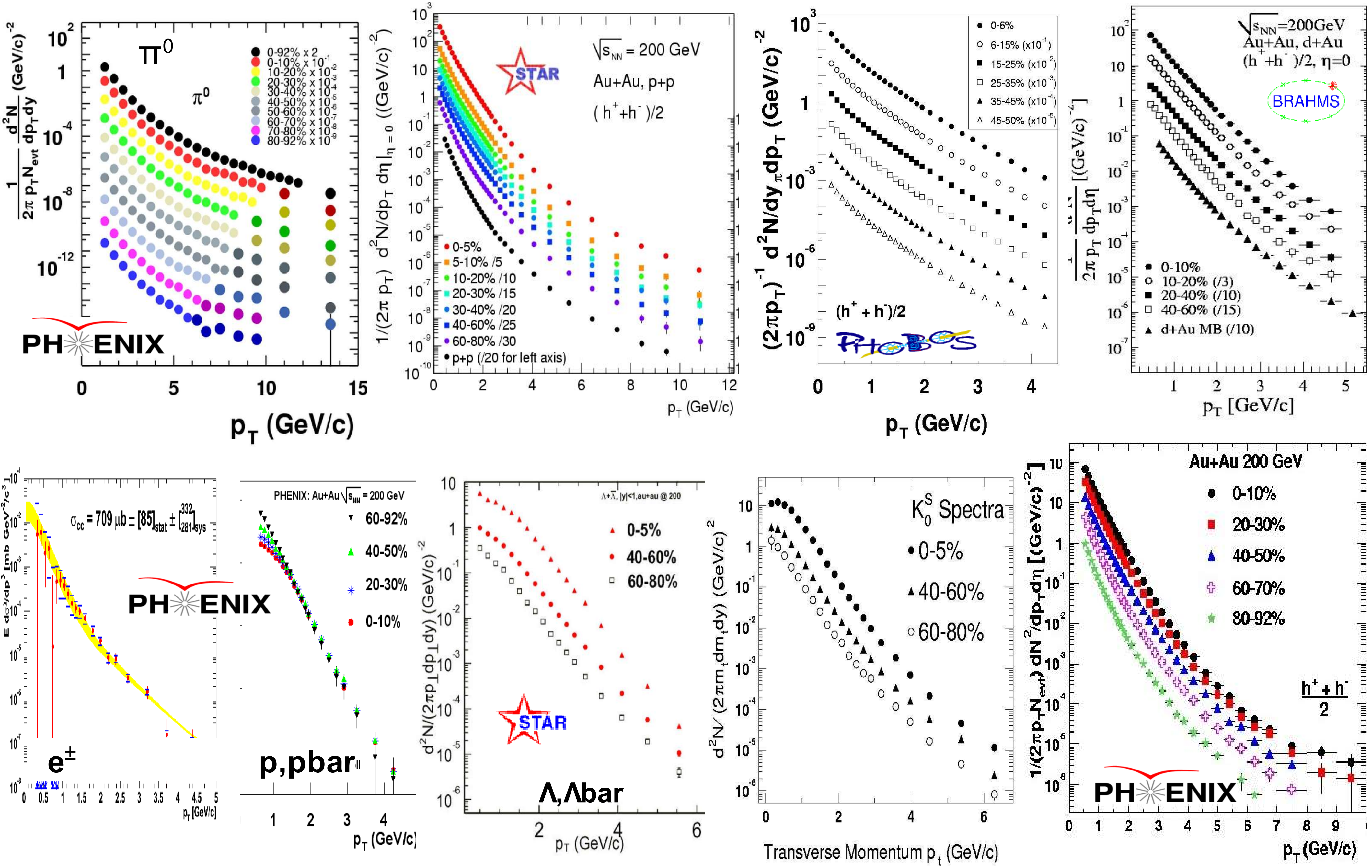
Au+Au collisions @ 200 GeV





~ 600 charged particles per unit rapidity at midrapidity (top 10% central)

High p_T spectra in Au+Au @ 200 GeV

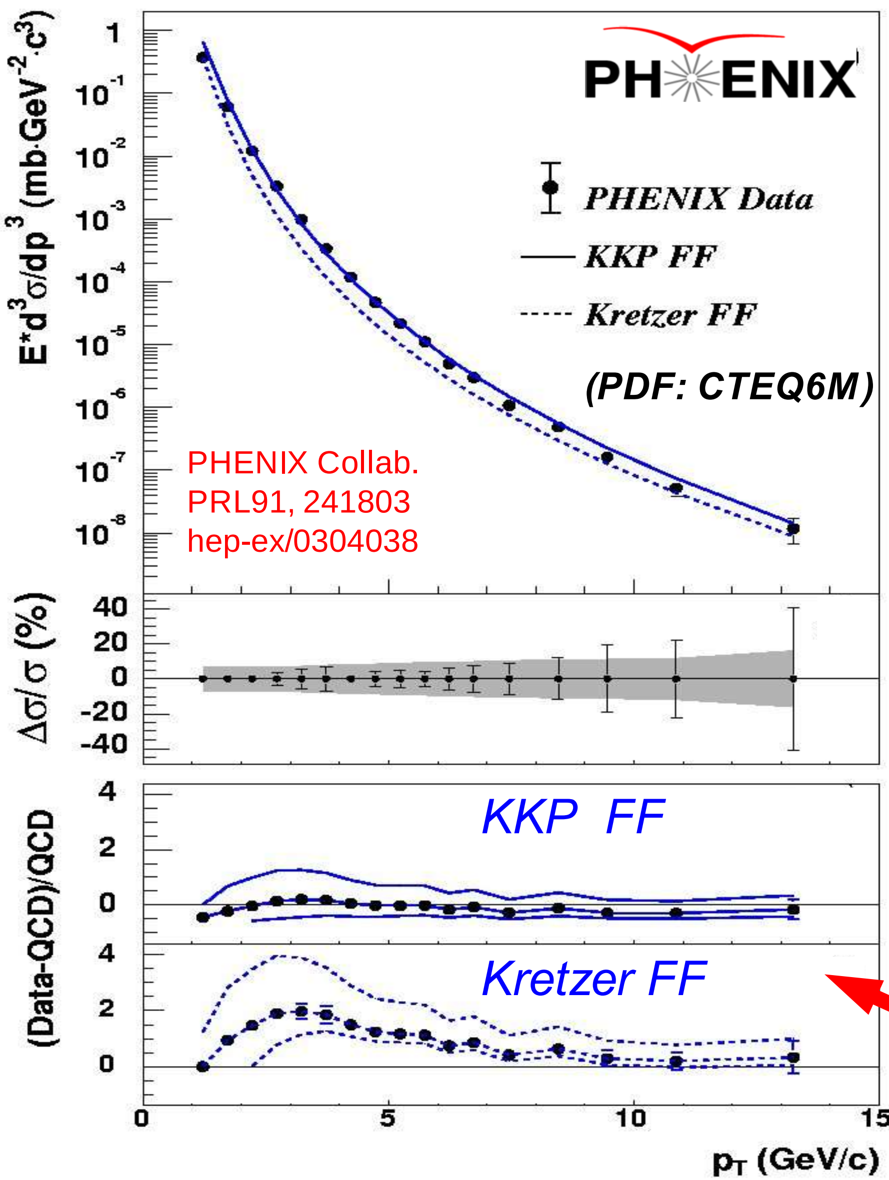


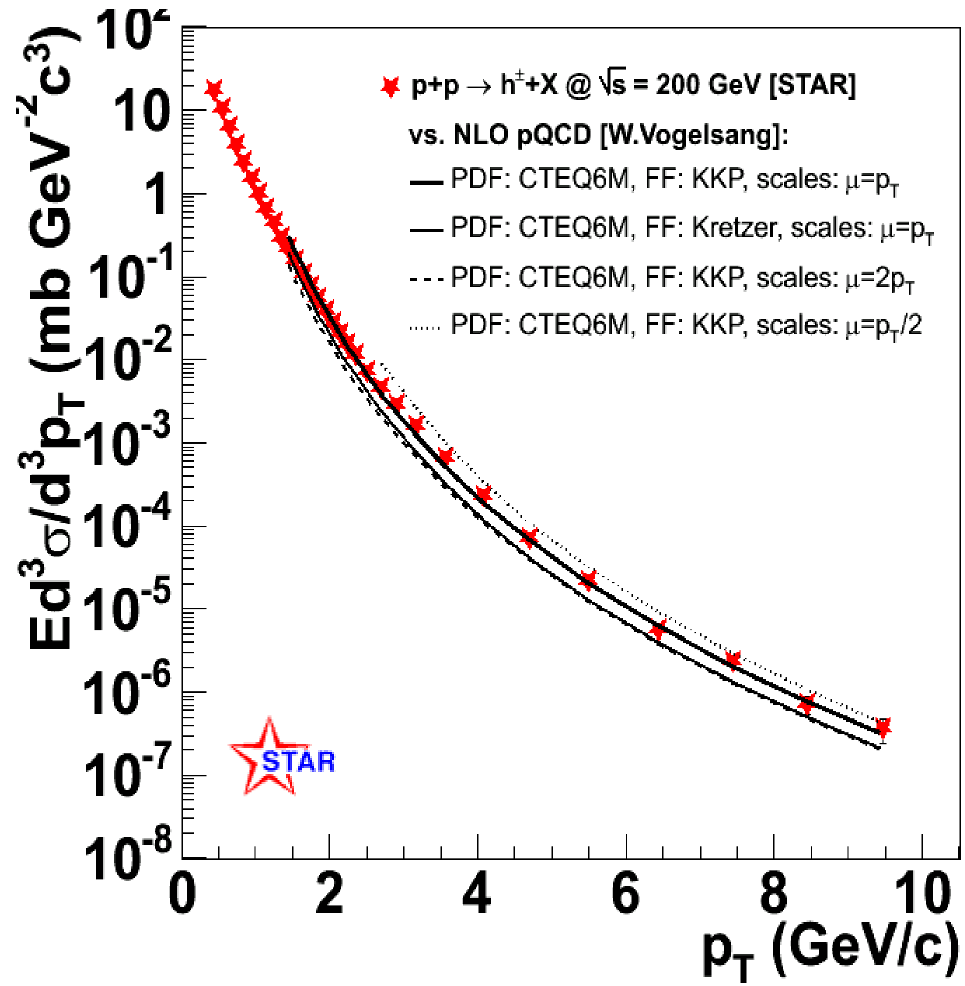
High p_T p+p @ 200 GeV: "baseline" data

- Good theoretical (NLO pQCD) description ...

$p+p \rightarrow \pi^0 X$

$p+p \rightarrow h^{\pm} X$ (non singly diffractive)



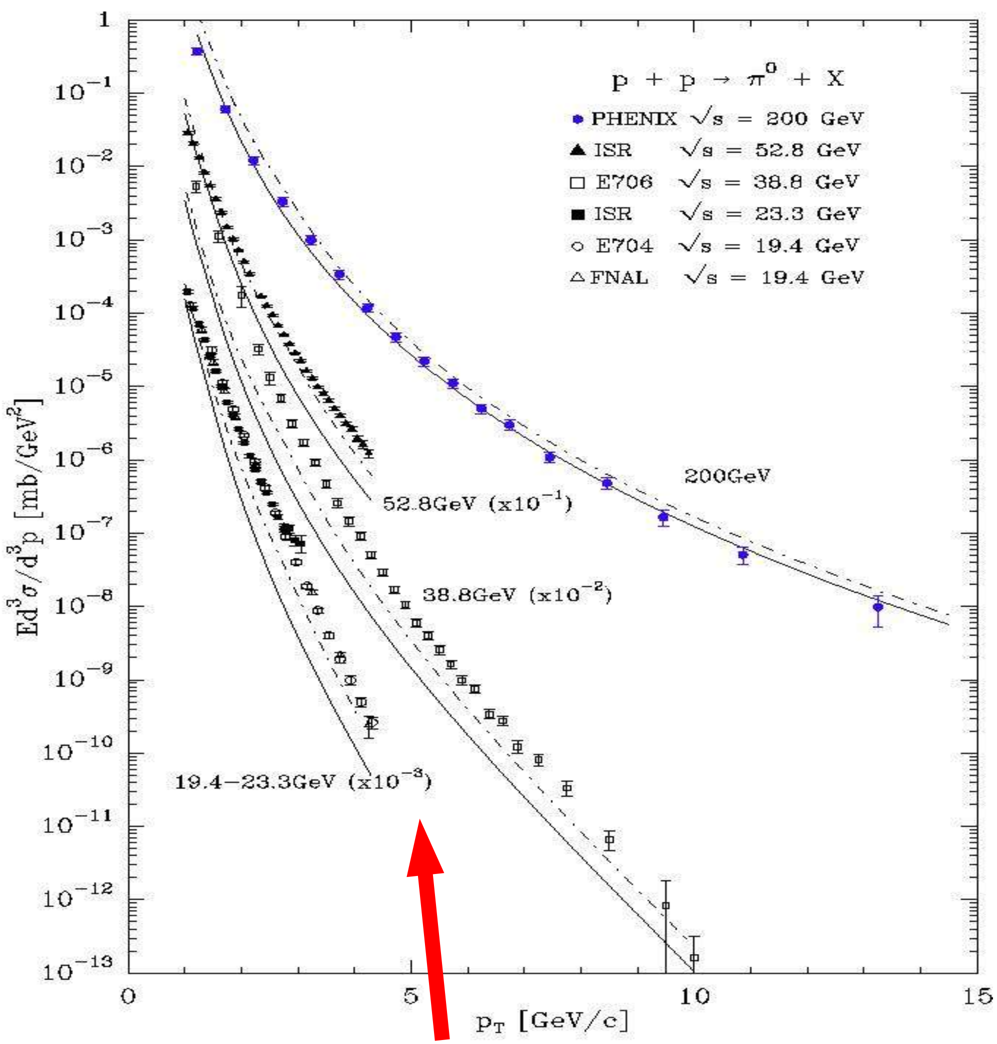


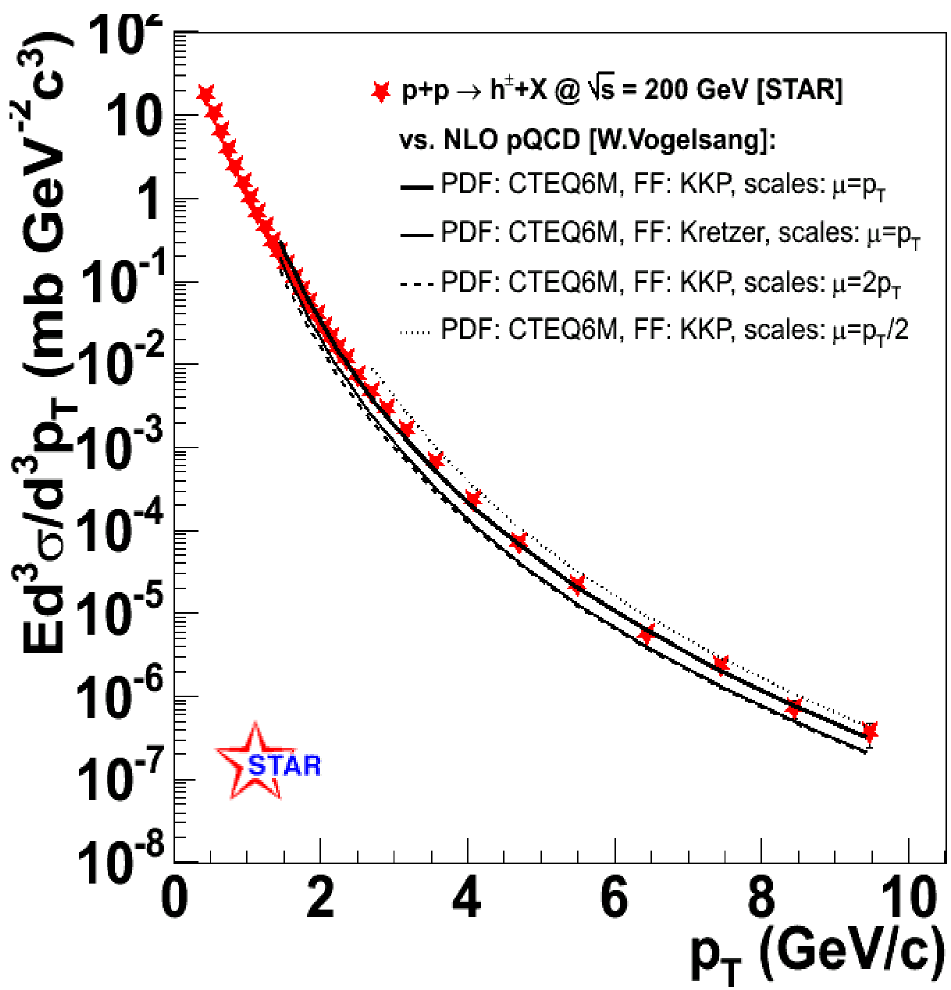
- High quality data: sensitive to different parametrizations of gluon FF

High p_T p+p @ 200 GeV: "baseline" data

- Good theoretical (NLO pQCD) description ...

$p+p \rightarrow \pi^0 X$ | $p+p \rightarrow h^{\pm} X$ (non singly diffractive)



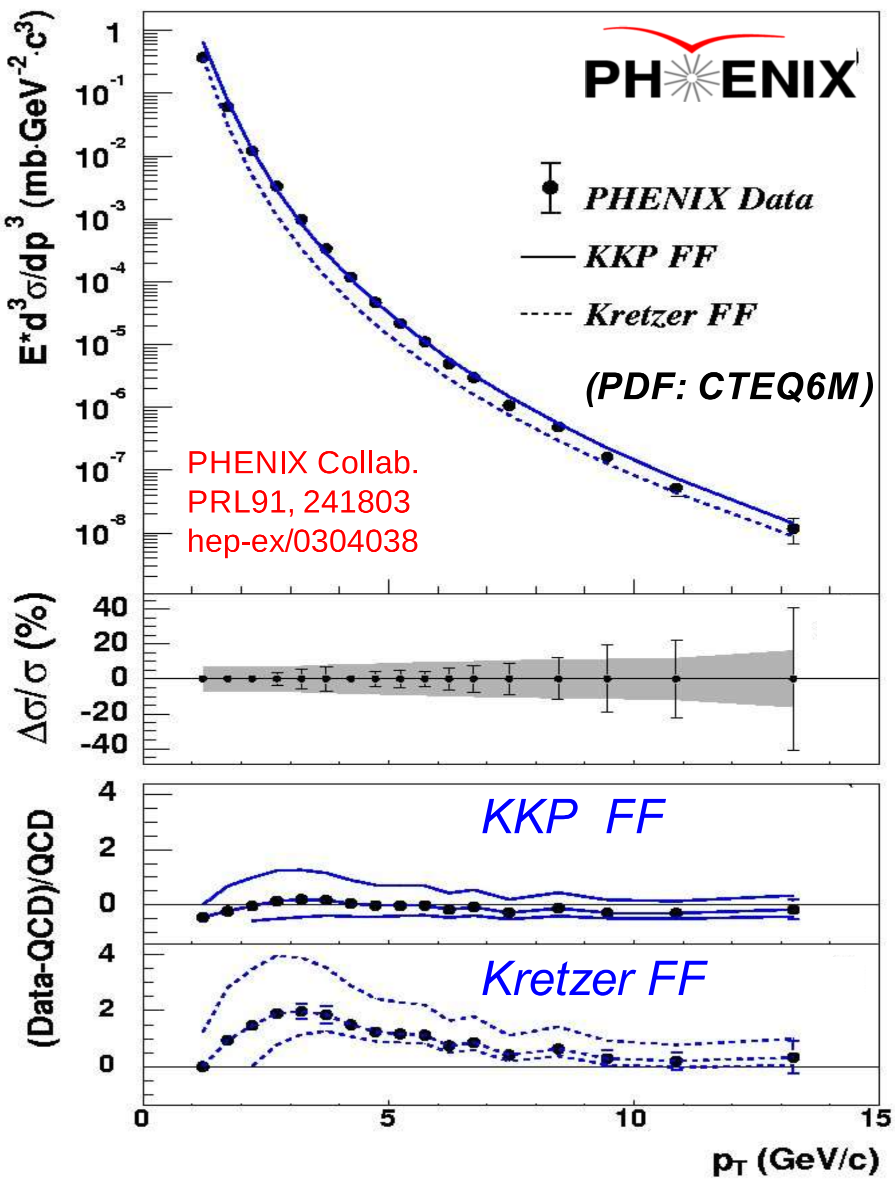


... at variance with lower sqrt(s) results (factors of ~2-4 discrepancy): non-perturbative effects (intrinsic k_T), cured by NLL soft g resummation ?

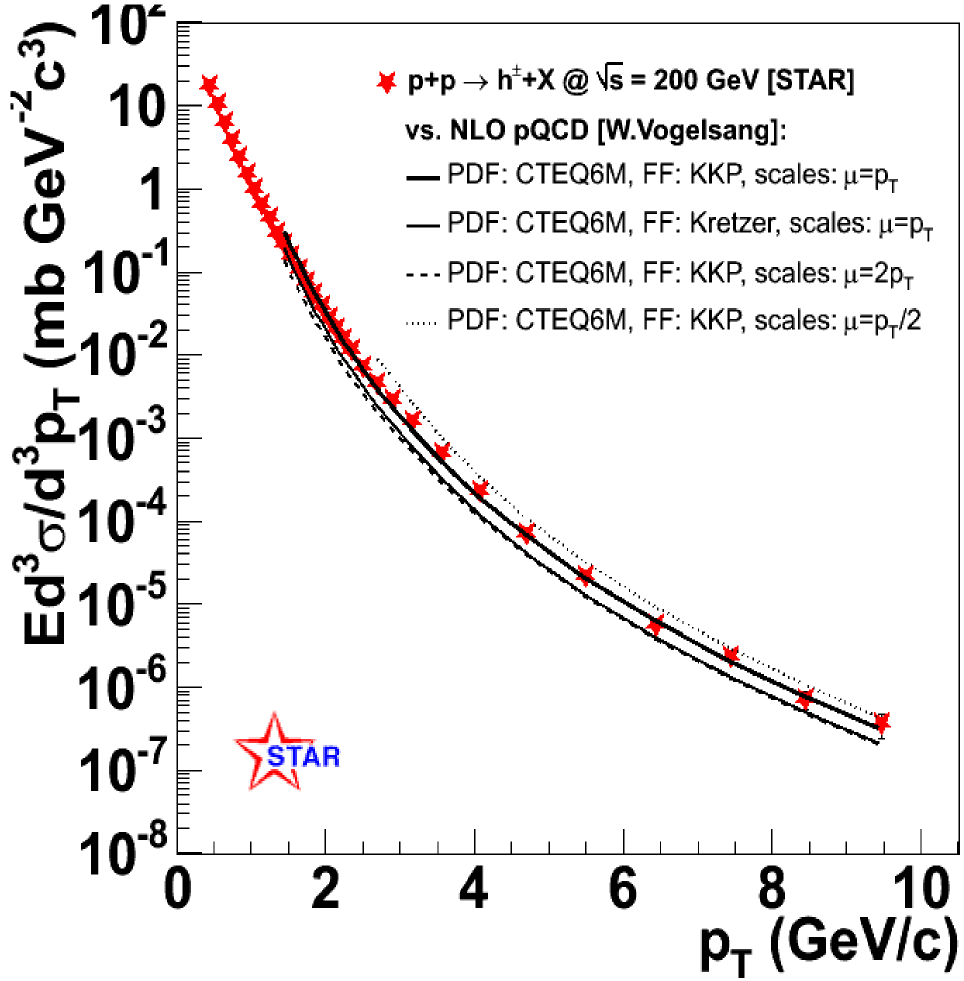
High p_T p+p @ 200 GeV: "baseline" data

- Good theoretical (NLO pQCD) description:

$p+p \rightarrow \pi^0 X$



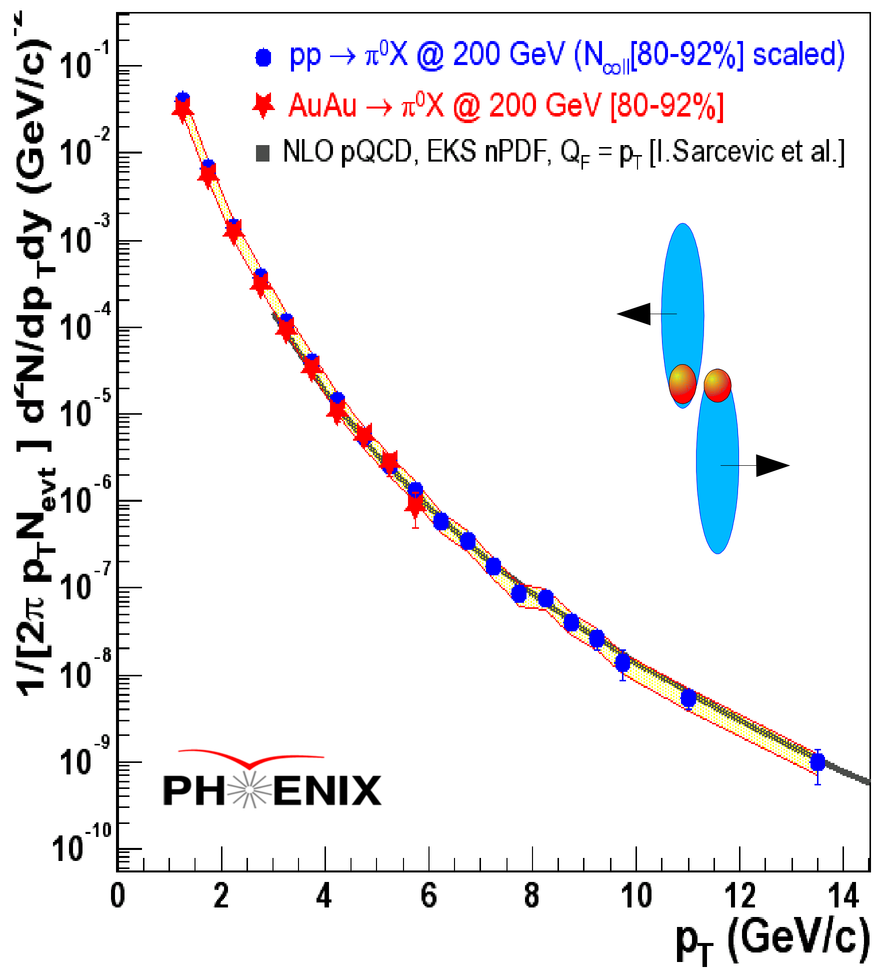
$p+p \rightarrow h^{\pm} X$ (non singly diffractive)



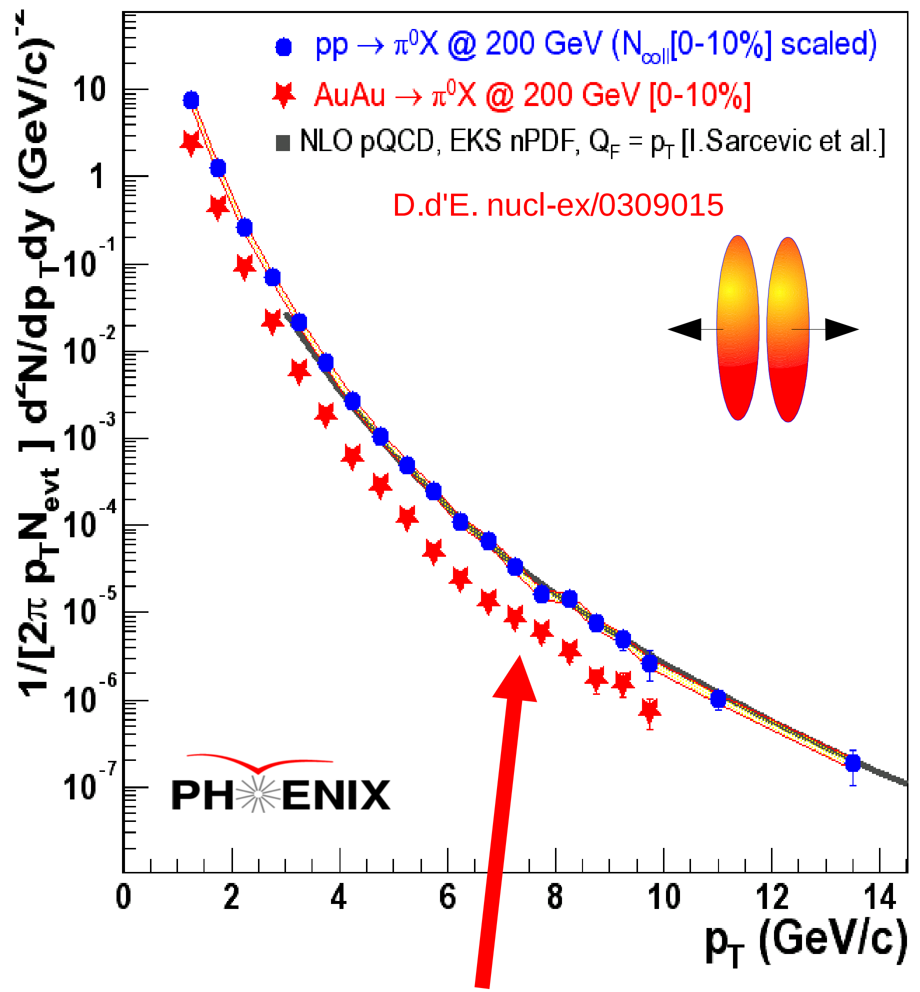
- Well calibrated (experimentally & theoretically) p+p references at hand !

Au+Au *vs.* p+p @ 200 GeV (π^0)

Au+Au→ $\pi^0 X$ (peripheral)



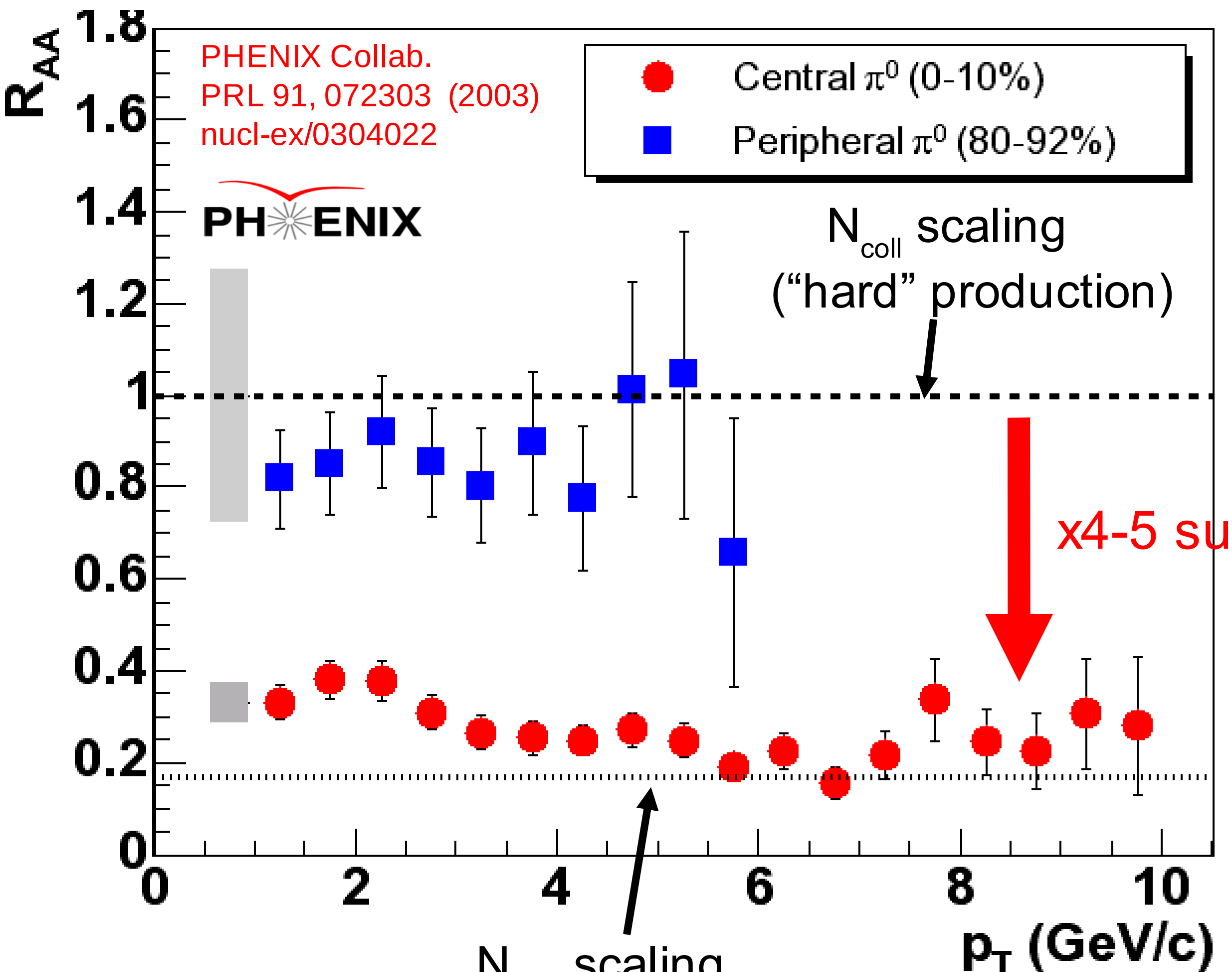
Au+Au→ $\pi^0 X$ (central)

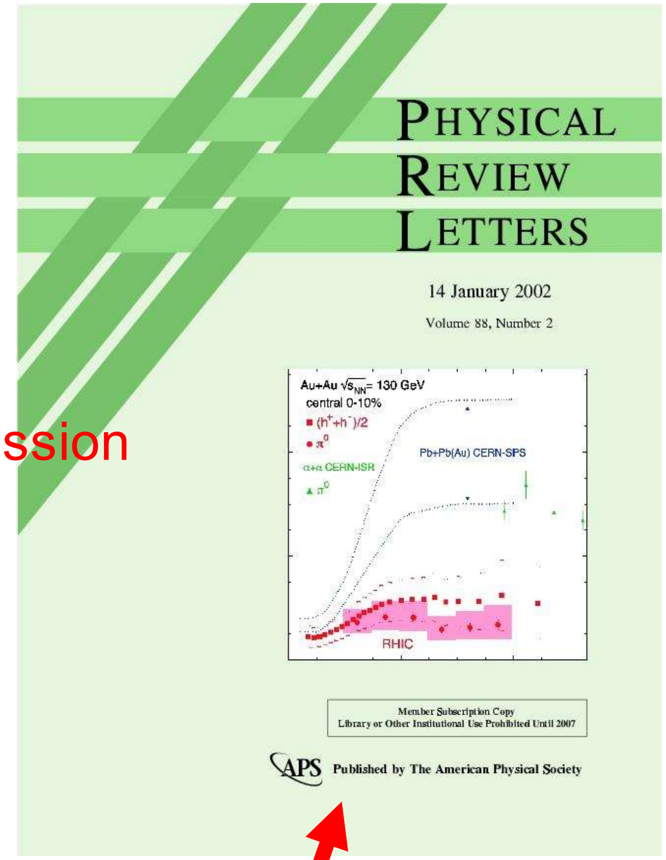


Peripheral data agree well with p+p (data&pQCD) plus N_{coll} scaling

Strong suppression in central Au+Au collisions

Nuclear modification factor (π^0)





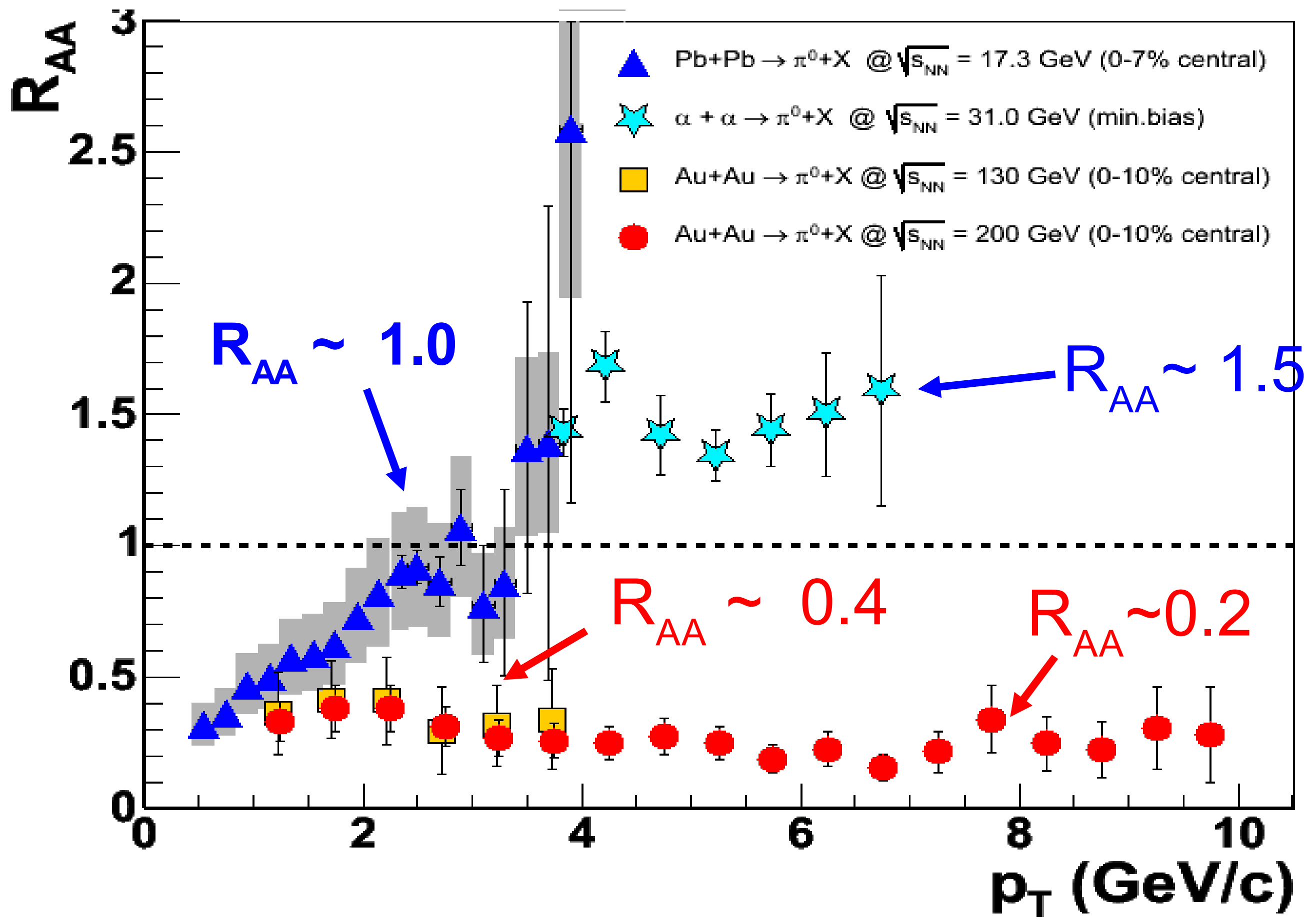
Discovery of high p_T suppression (one of most significant results @ RHIC so far)

R_{AA} << 1: well below pQCD (collinear factorization) expectations for hard scattering cross-section

Nuclear modification factor (π^0): $\sqrt{s_{NN}}$ dependence

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

- CERN-SPS: Pb+Pb central ($\sqrt{s_{NN}}$ = 17.3 GeV): no suppression(*) (within errors)
- CERN-ISR: α+α ($\sqrt{s_{NN}}$= 31 GeV): Cronin enhancement.
- RHIC: Au+Au ($\sqrt{s_{NN}}$ = 130, 200 GeV): x 4-5 suppression.



A.L.S.Angelis, PLB 185, 213 (1987)

WA98, EPJ C 23, 225 (2002)

(*) Reanalysis: D.d'E. nucl-ex/0403055

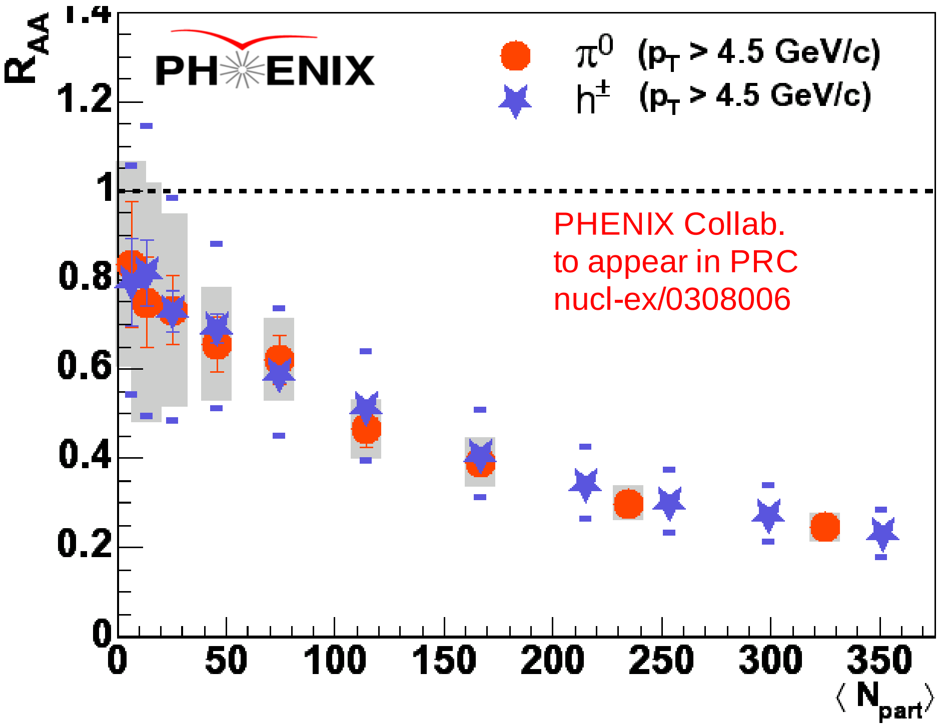
PHENIX, PRL 88 022301 (2002)

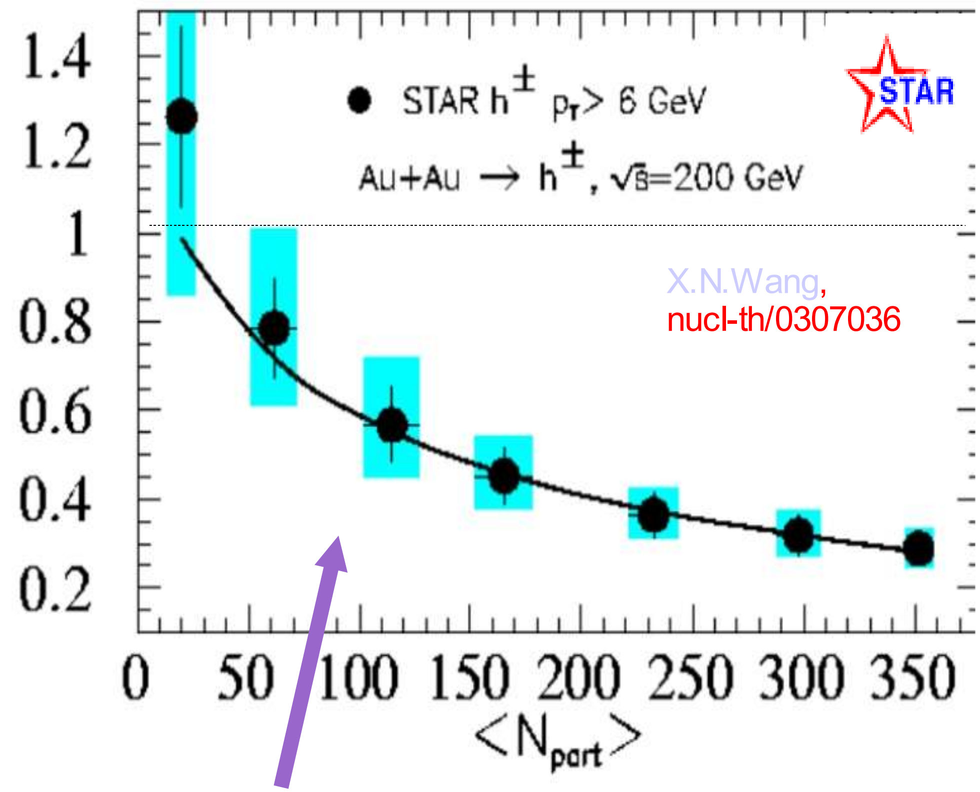
PHENIX, PRL 91, 072303 (2003)

High p_T suppression: centrality dependence (I)

- Smooth evolution of suppression with respect to centrality:

peripheral → central

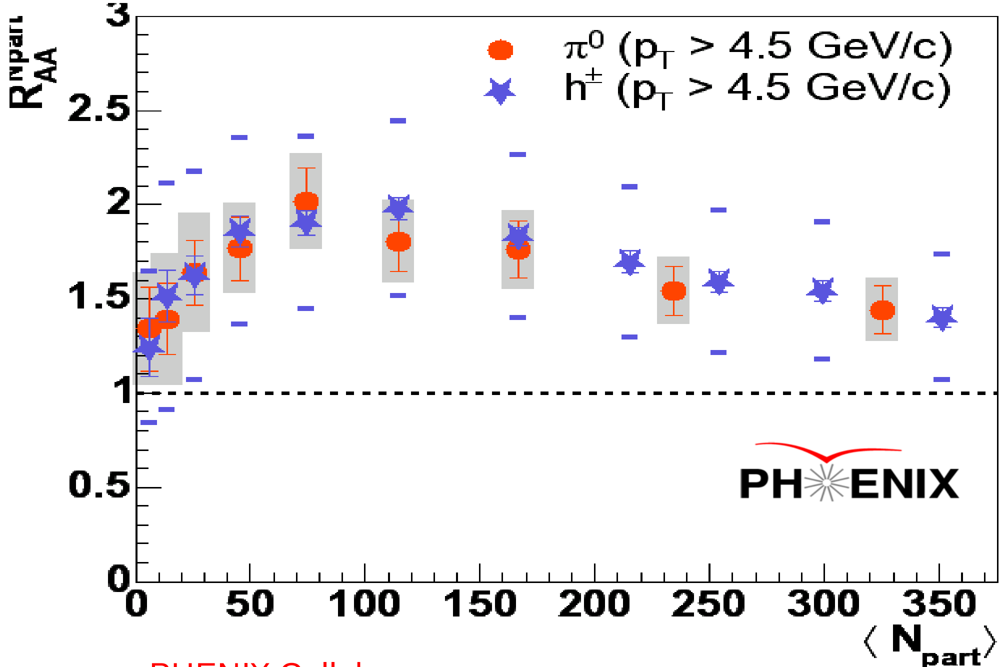




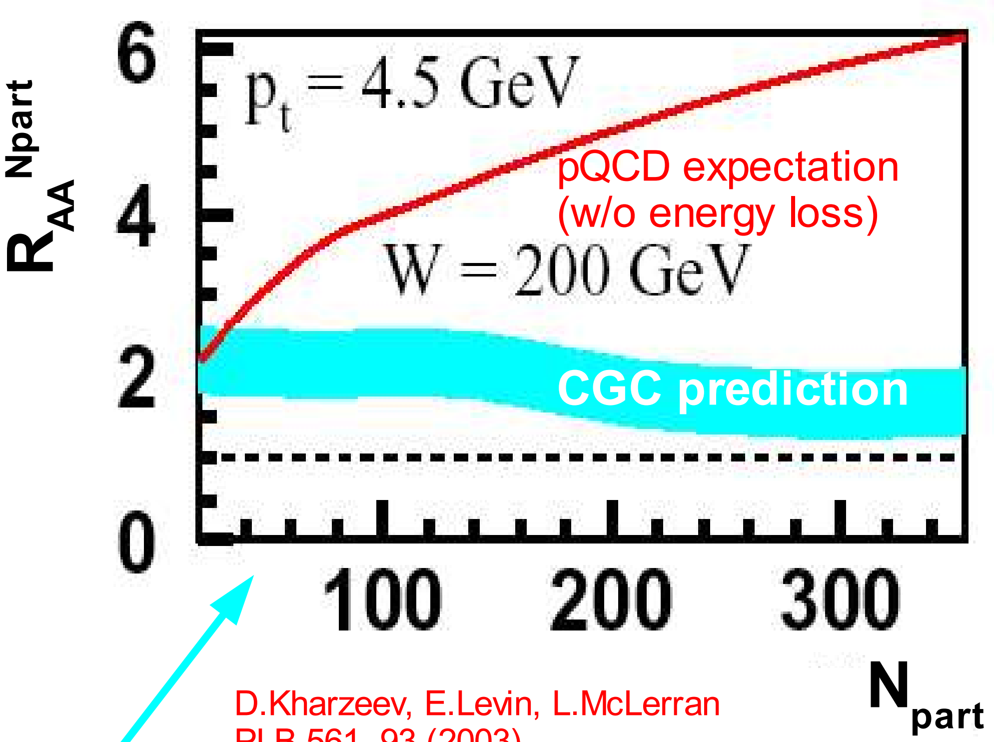
in agreement with pQCD production + parton energy loss in expanding plasma expectations

High p_T suppression: centrality dependence (II)

- R_{AA} using "soft" scaling factor (N_{part}) shows approx. N_{part} scaling: high p_T production per participant pair ~const. in wide range of centralities



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

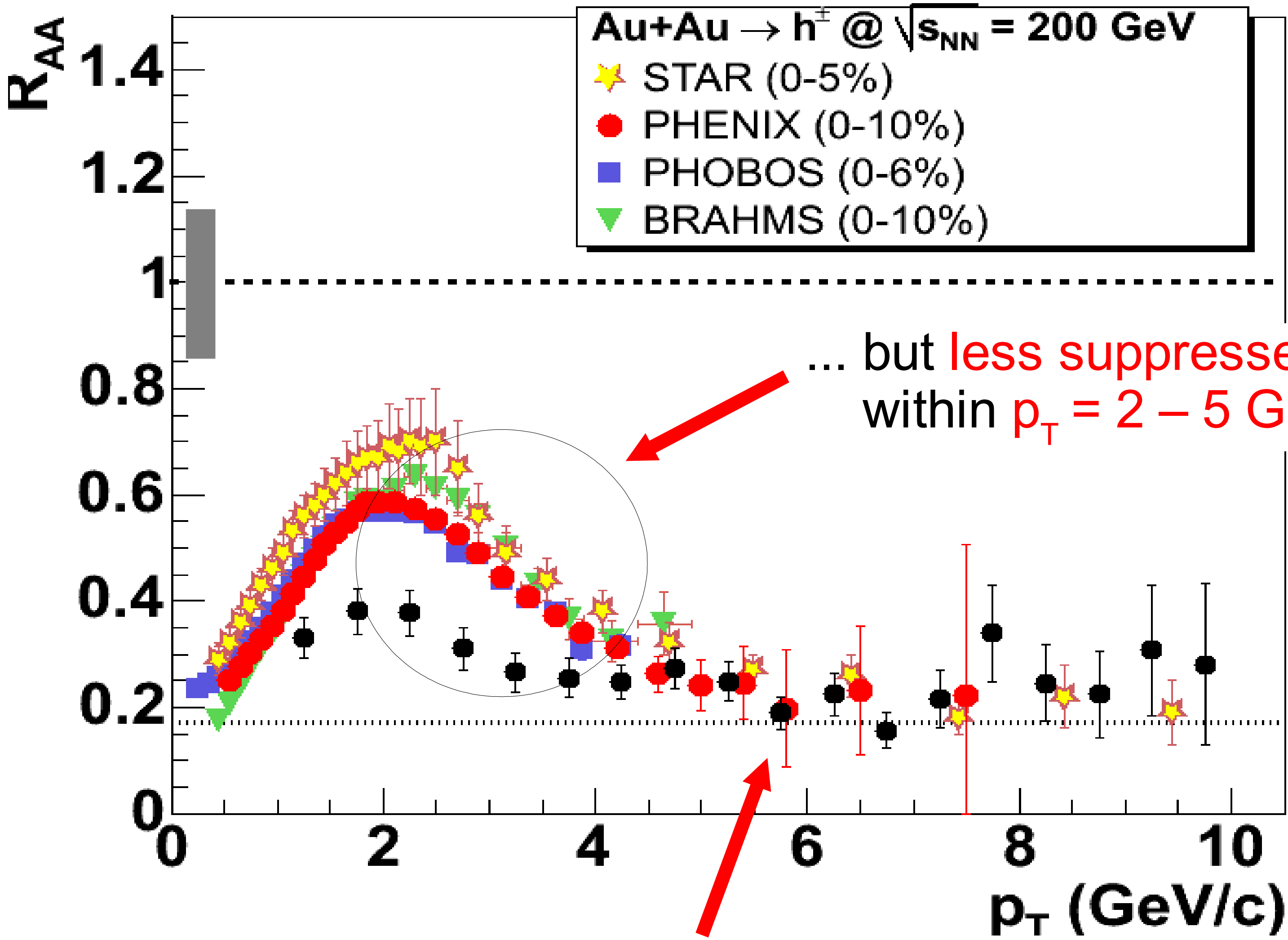


D.Kharzeev, E.Levin, L.McLerran
PLB 561, 93 (2003)

- In accord with Color Glass Condensate predictions too ...

High p_T suppression. Particle dependence (I): $h^{\pm}$ vs. π^0

- Inclusive charged hadrons suppressed a factor ~ 4 – 5 at p_T> 5 GeV/c

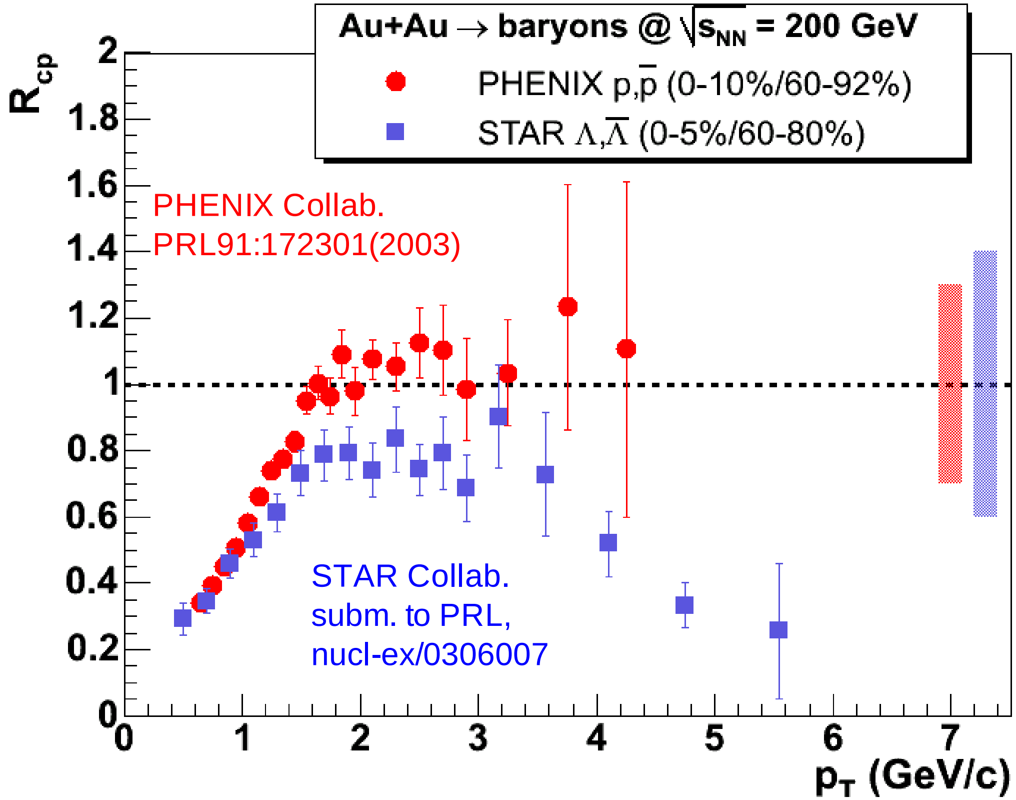


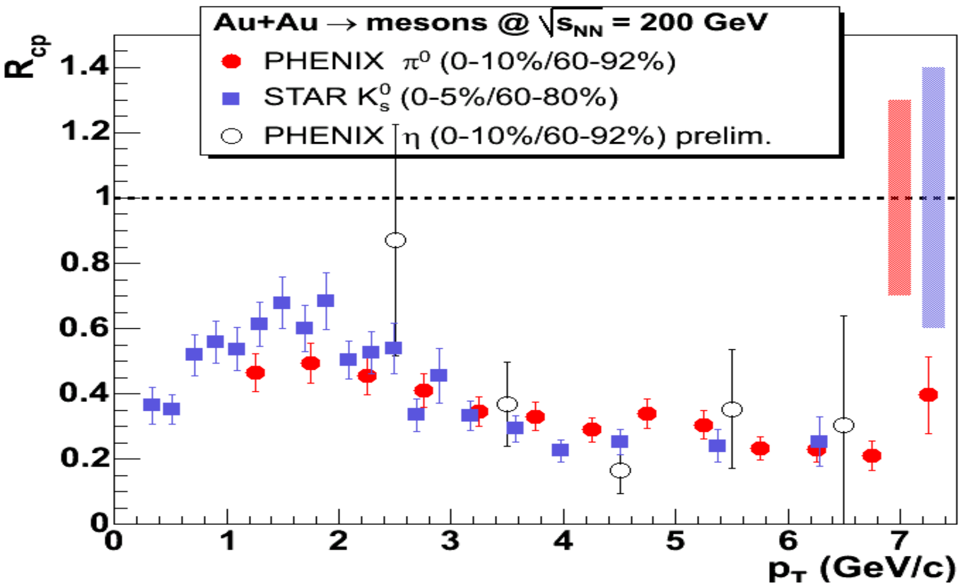
... but less suppressed than π^0 within p_T = 2 – 5 GeV/c

- Universal (PID-wise) suppression above p_T = 5 GeV/c

High p_T suppression - Particle depend. (II): baryons vs. mesons

- R_{cp} (ratio central/peripheral) at intermediate p_T = 2 – 4 GeV/c:
  1. Baryons: p, $\bar{p}$, Λ, $\bar{\Lambda}$ **NOT** (or much less) suppressed in central Au+Au.
  2. Mesons: π^0, k^0_s, η equally suppressed.

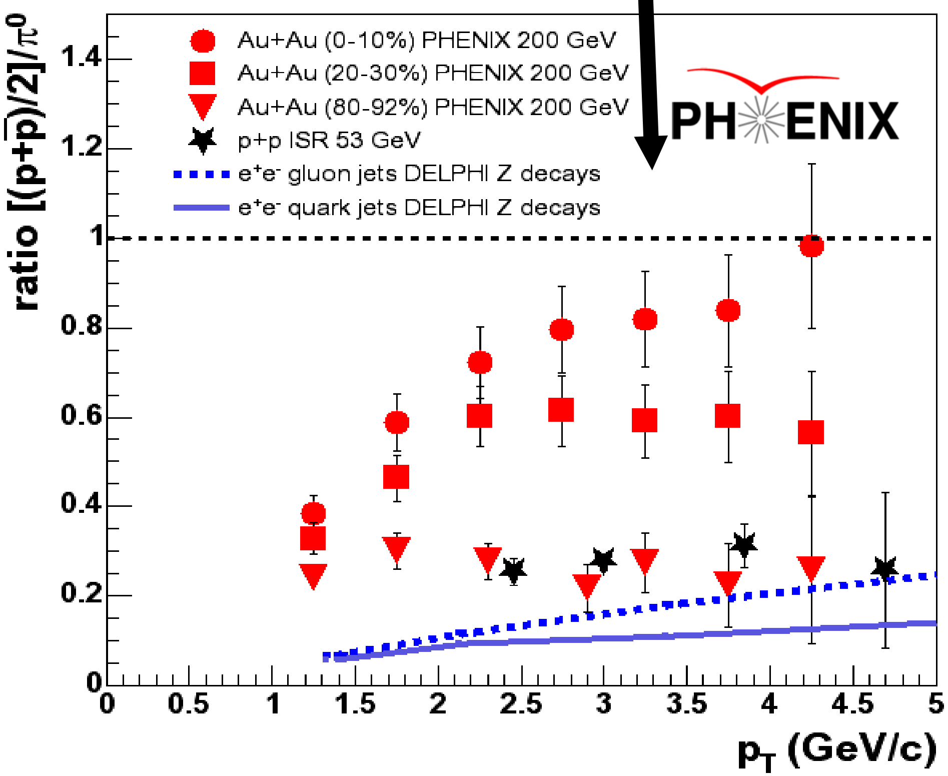


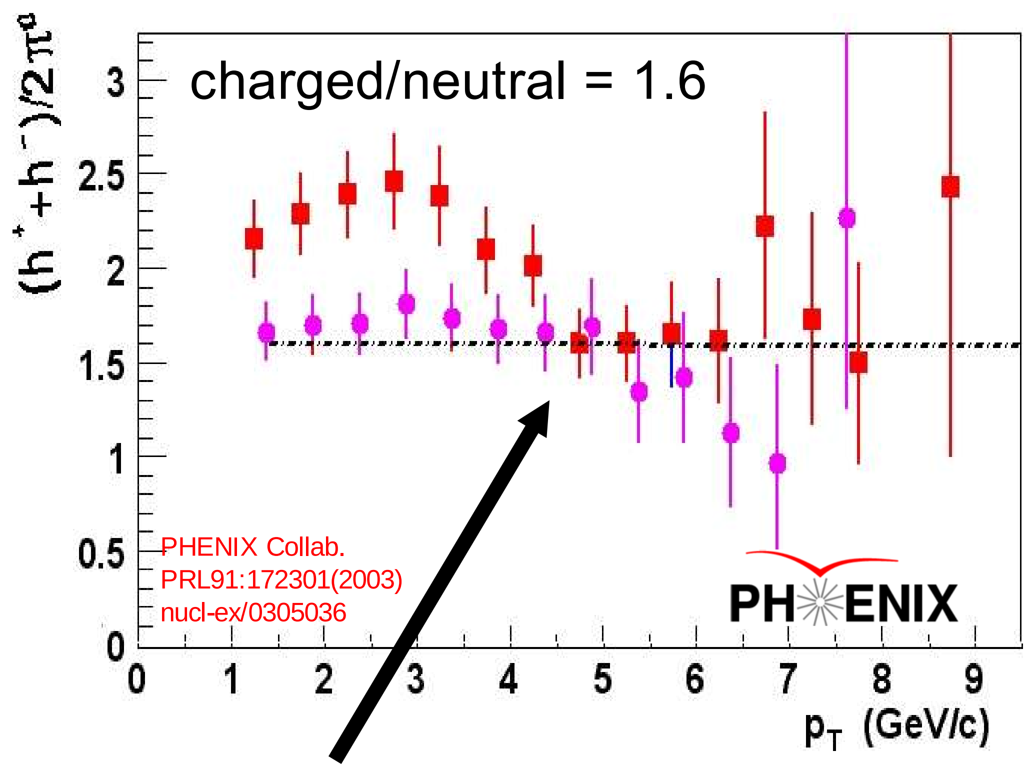


- Particle composition inconsistent with known fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range (quark recombination ?).

High p_T suppression - Particle depend. (III): charged/neutral

- Central Au+Au: $p/\pi \sim 0.8$ (at p_T = 2 - 4 GeV/c) at variance with perturbative production mechanisms (favour lightest meson).
- Periph. Au+Au: $p/\pi \sim 0.2$ = p+p (ISR,FNAL) & e+e- jet fragmentation





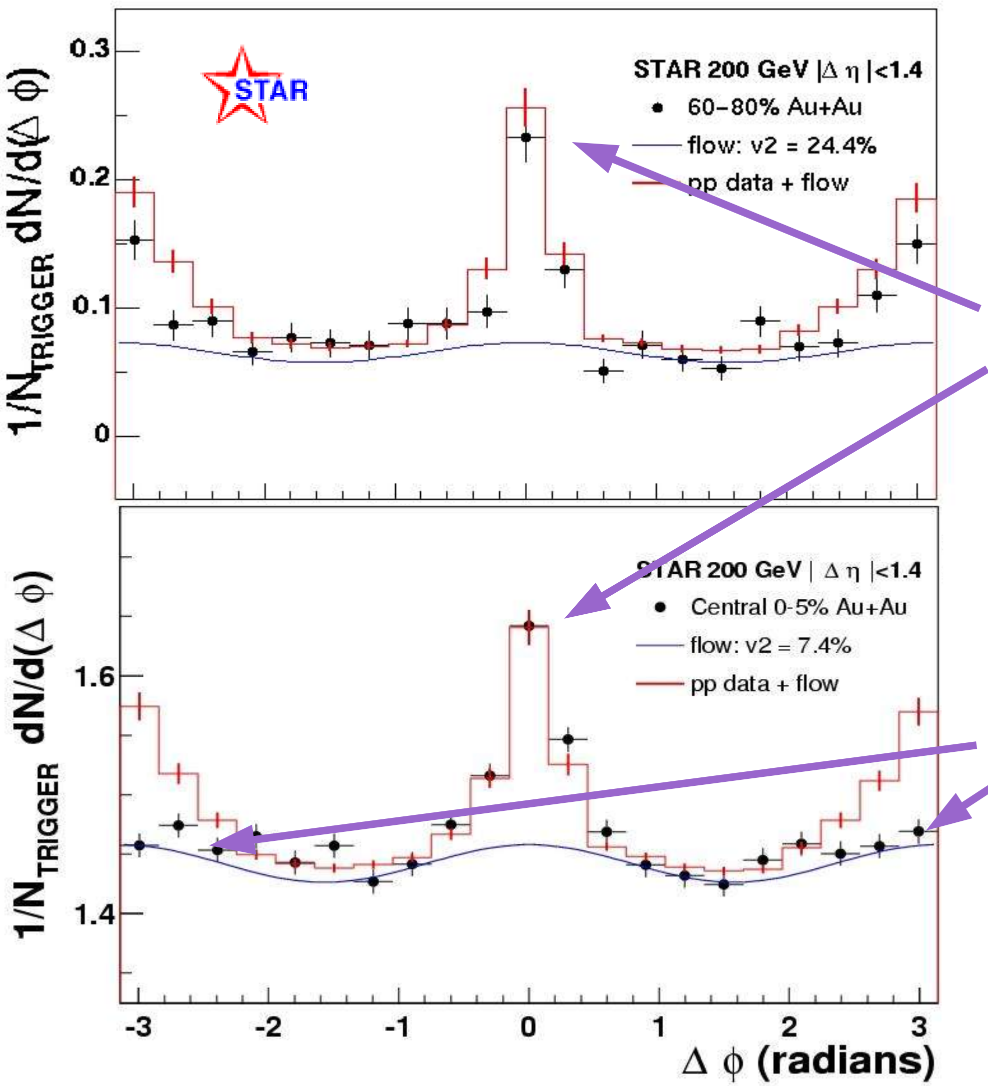
- Baryon enhancement limited to p_T < 4.5 GeV/c ($h^{\pm}/\pi \sim 1.6$, perturbative ratio): charged hadron and π^0 equally suppressed at p_T > 5 GeV/c

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

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

Periph.:

Central:



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

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

  Trigger hadrons (p_T > 4GeV/c) from jet fragmentation.

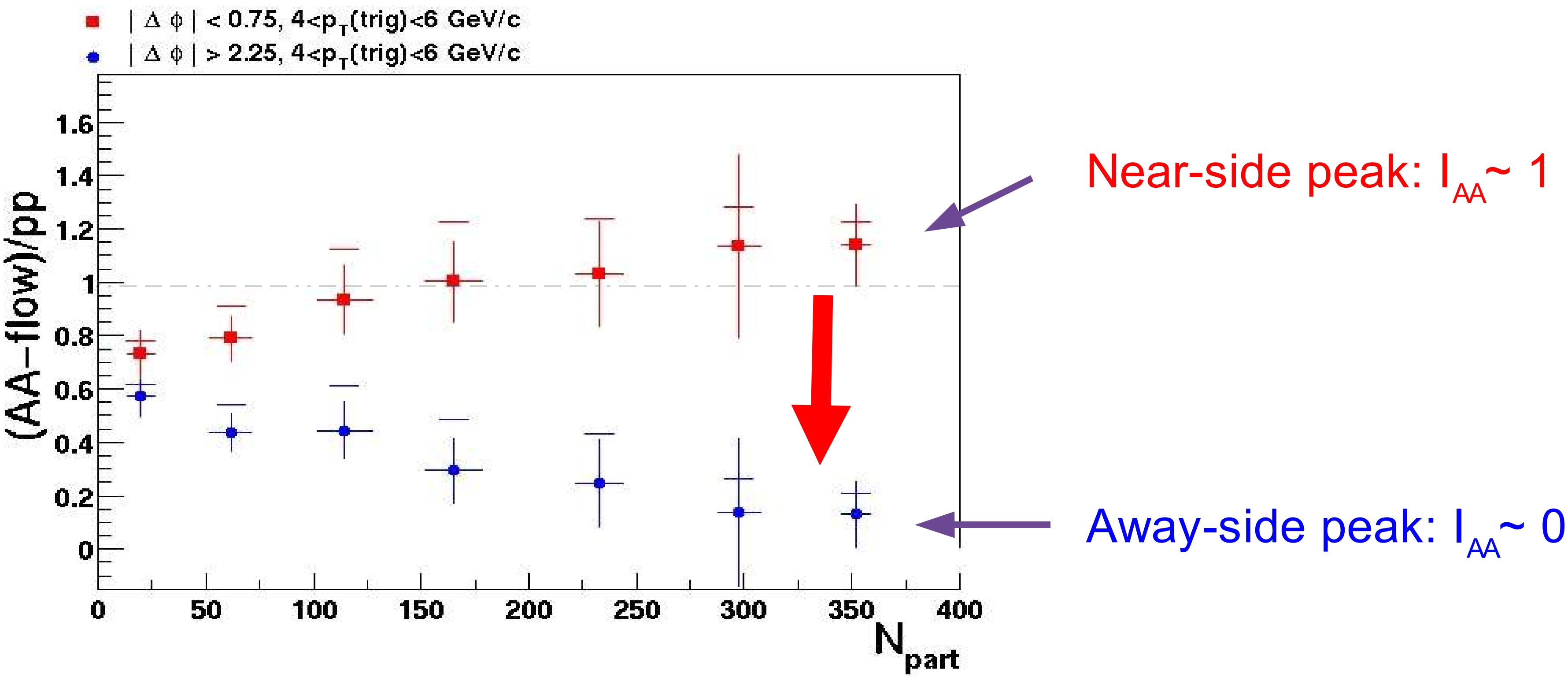
- Away-side peak: Au+Au << p+p

  Back-to-back jets suppressed ("mono-jet") in central Au+Au !

High p_T azimuthal correlations: Au+Au dijet signal disappearance

- Ratio of Au+Au (- flow) over p+p azimuthal correlation "strengths":

$$I_{AA}(\Delta\phi_1, \Delta\phi_2) = \frac{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi)[D^{\rm AuAu} - B(1 + 2v_2^2\cos(2\Delta\phi))]}{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi) D^{\rm pp}}$$



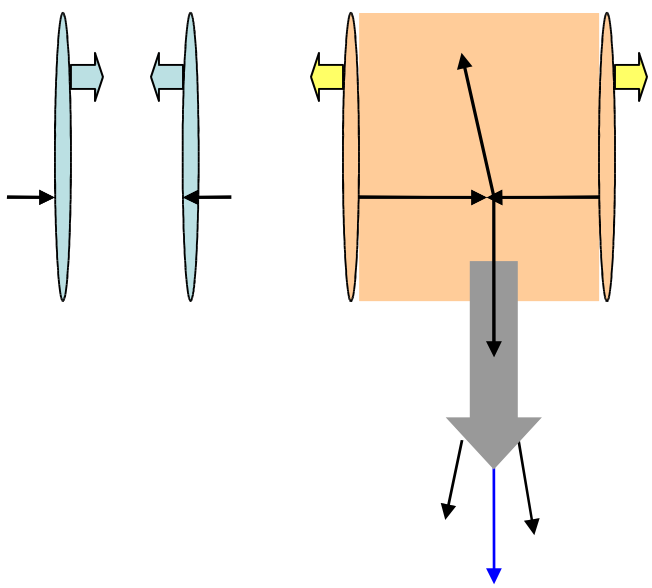
- Increasing dissapearance of back-to-back correlation as a function of centrality.

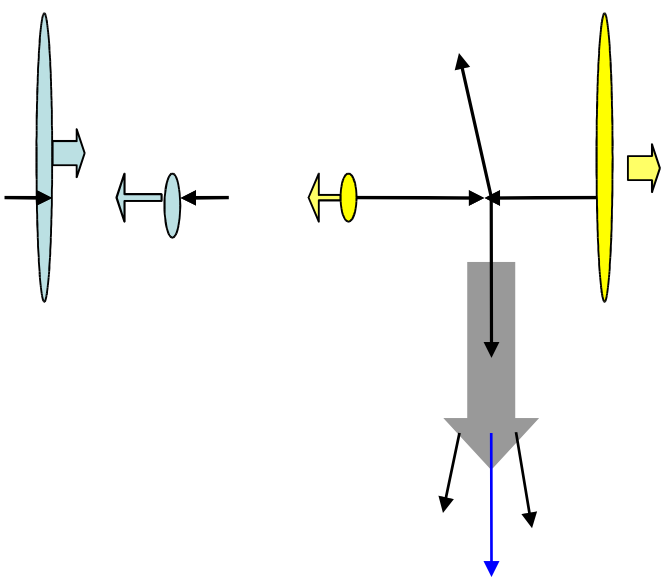
High p_T in d+Au ("control" experiment)

see also talk by B.Cole

Au+Au collision

p,d+Au collision



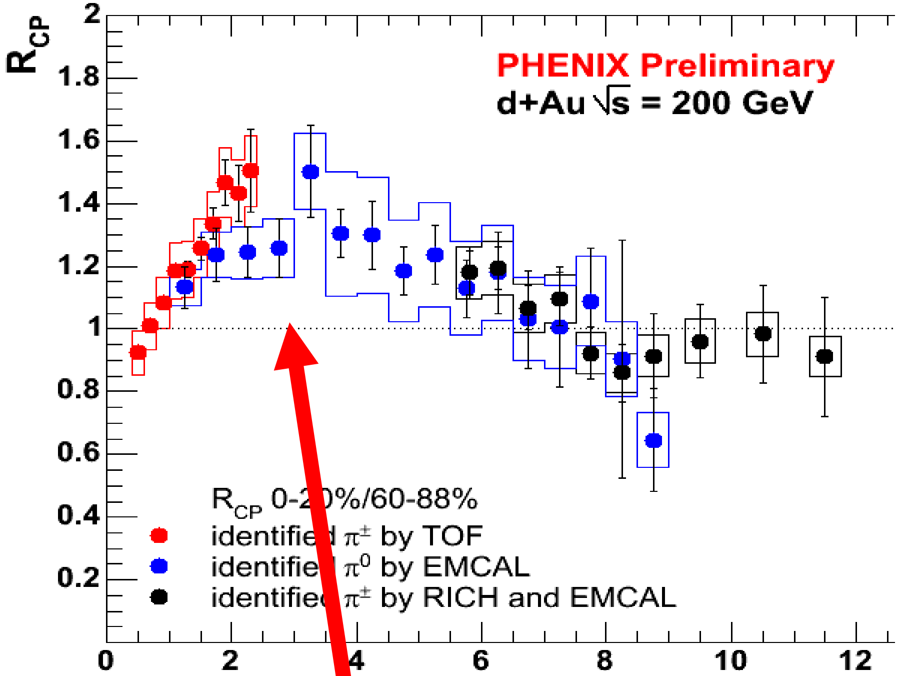


hot & dense medium
(initial+final-state effects)

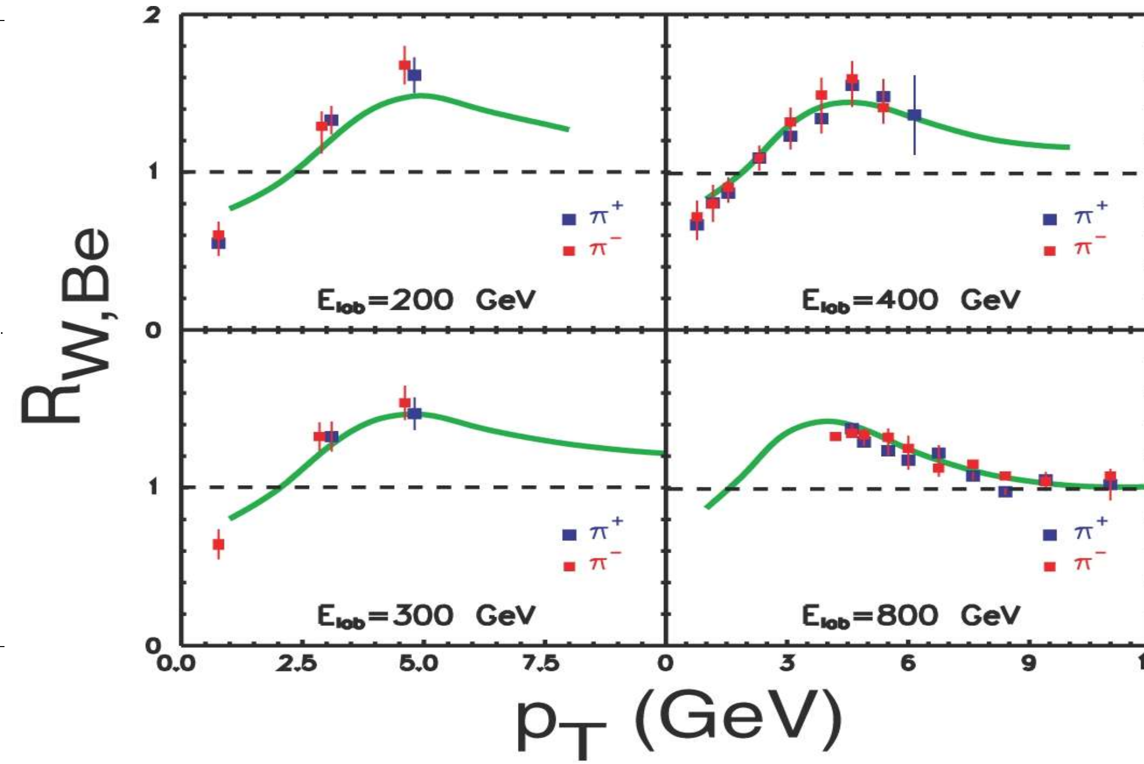
cold medium
(initial- state effects only)

d+Au nuclear modification factor (at y=0)

d+Au @ $\sqrt{s_{NN}}$ = 200 GeV



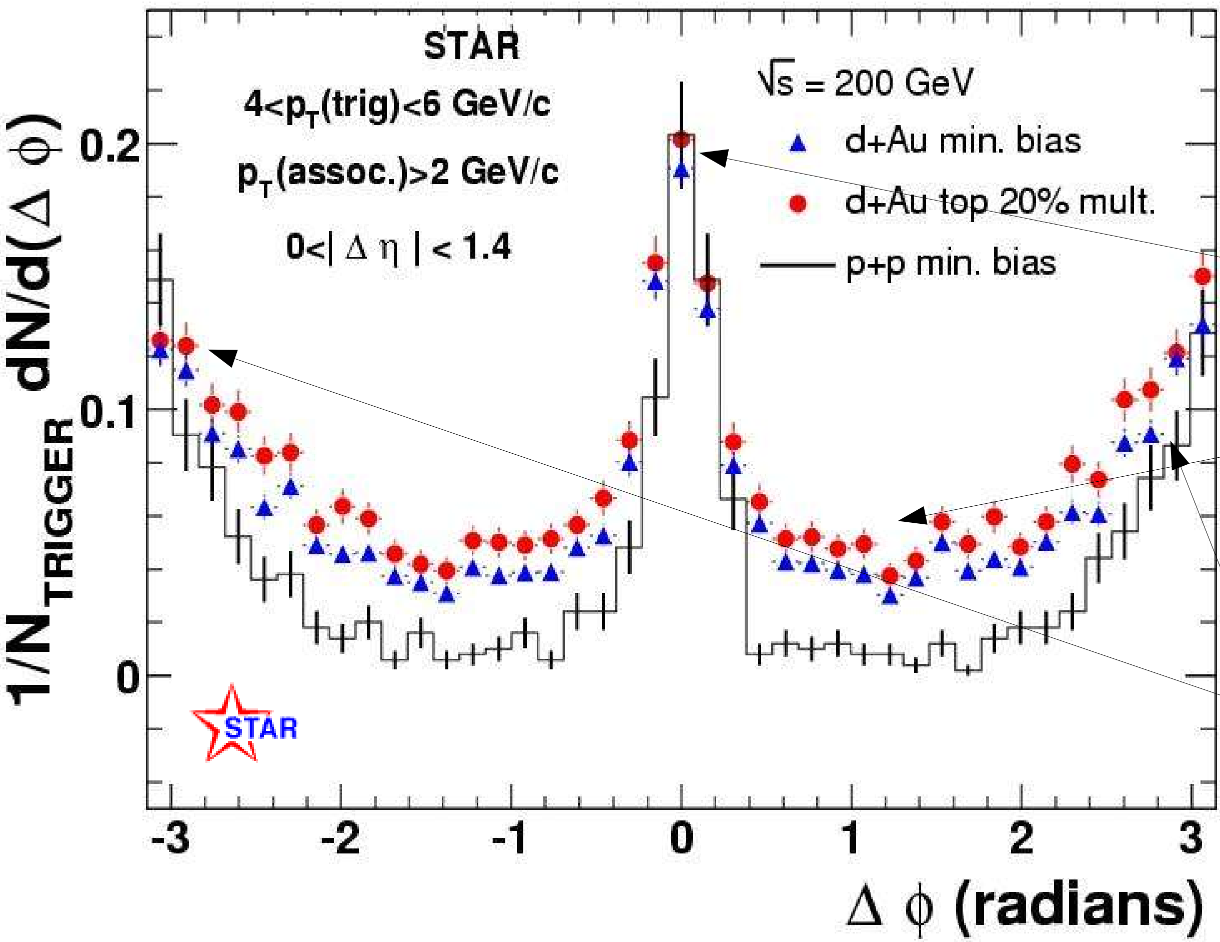
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



- High p_T production in d+Au not suppressed but enhanced ! R_{dAu} > 1
  as in p+A "Cronin enhancement":
  p_T broadening due to initial-state soft & semihard scattering.
- "pQCD" cross-sections (R_{AA}~1) recovered at p_T > 8 GeV/c
- No Au shadowing effects in kinematic region probed (y= 0).

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

see also talk by F.Wang

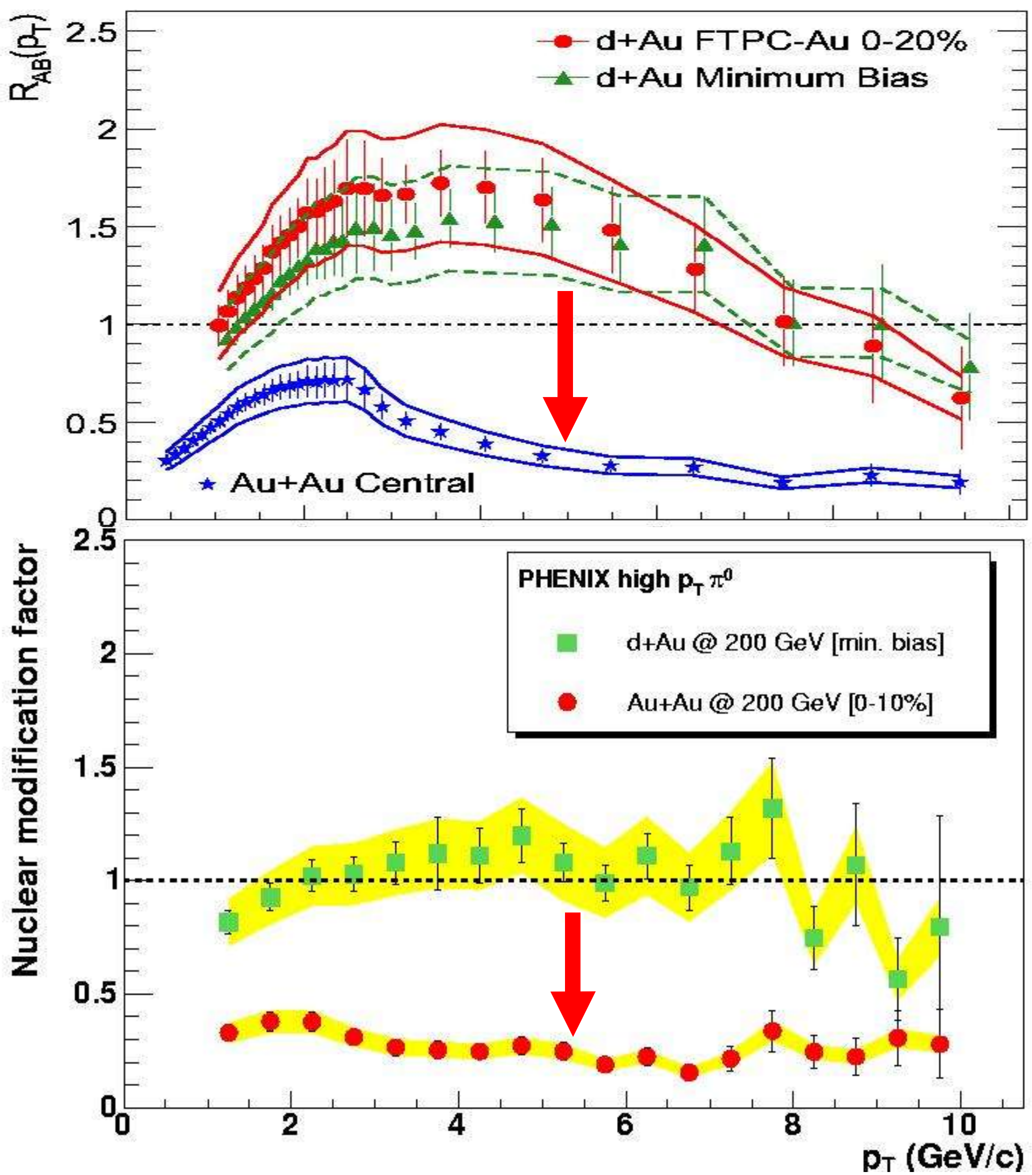


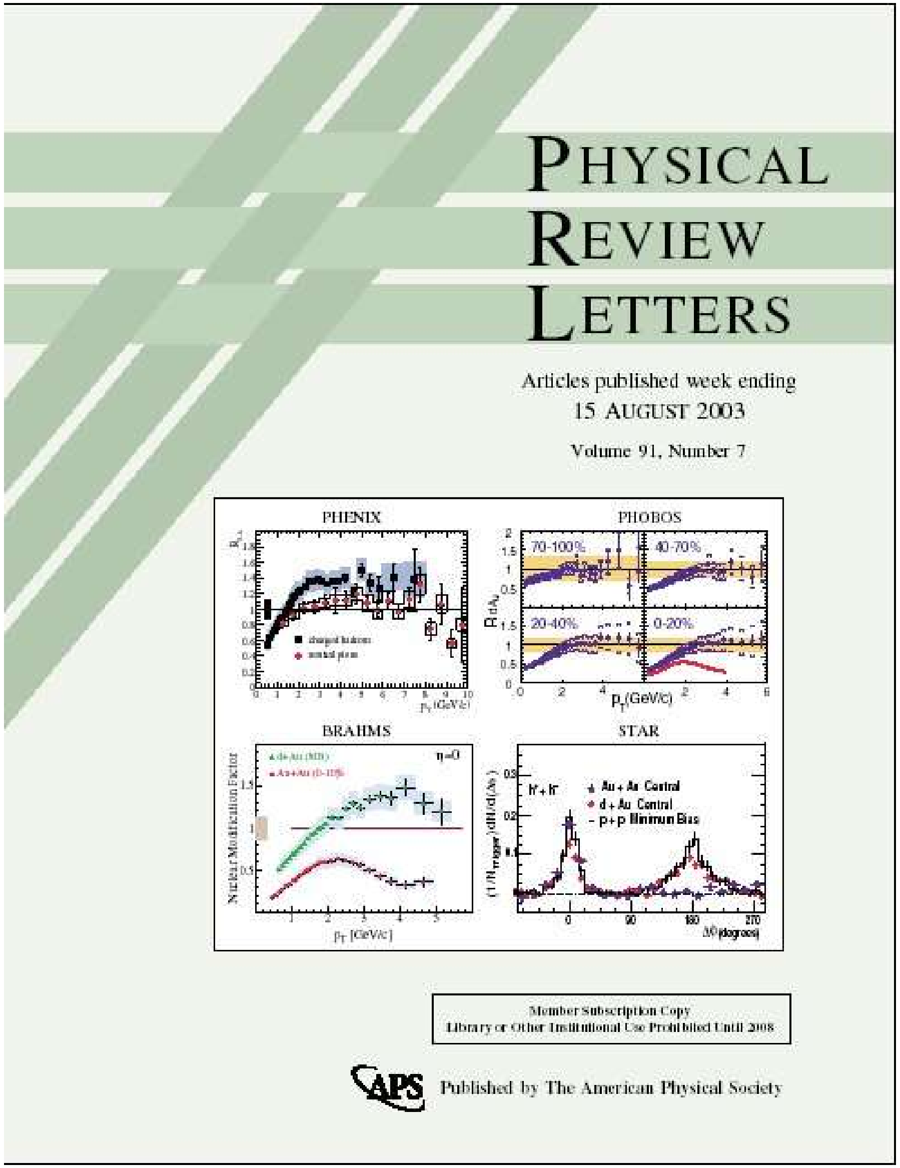
- Near- side: d+Au correlation strength and width similar to p+p (& Au+Au)
- Increasing "underlying event": p+p<d+Au(m.bias)<d+A(central)
- Away-side: d+Au peak broadens but small centrality dependence

- Back-to-back jets do not disappear in central d+Au !

David d'Enterria (Columbia Univ.)

Unquenched d+Au production at high p_T

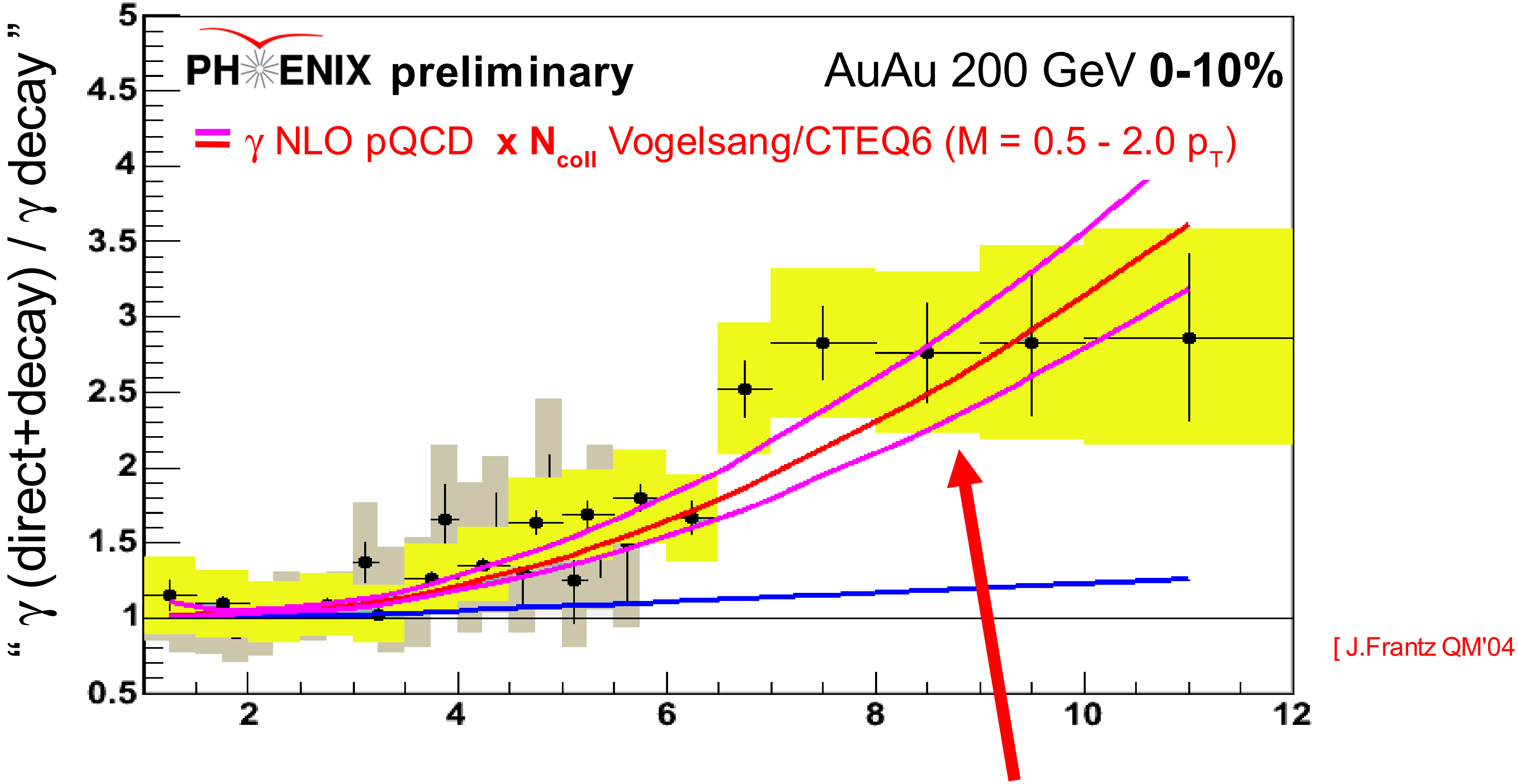




- Suppression in central Au+Au not due to initial-state effects

Confirmation ... unsuppressed hard colorless production in Au+Au central

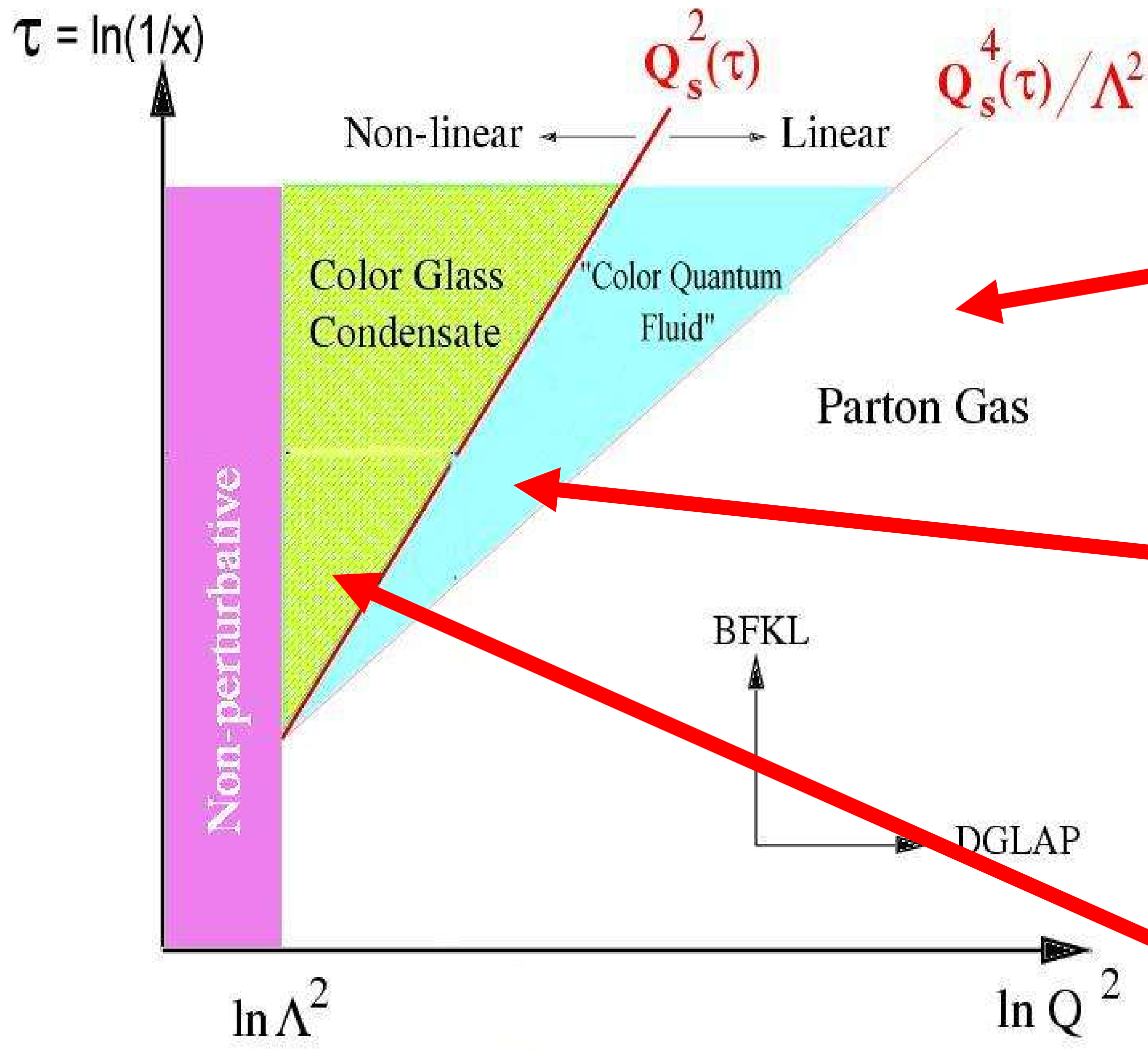
- "Control" observable: direct photons (clean, penetrating = directly coupled to partonic vertex, no fragmentation) non-hadronic hard probes.



Photons (insensitive to final-state effects) show collision scaling at high p_T:

- pQCD parton scattering holds for hard processes in central Au+Au !

The quest for gluon saturation effects @ RHIC ...



RHIC kinematical regime:

- **High p_T @ midrapidity:**
  $y = 0$, $Q^2 = 1\text{-}100\ GeV^2/c^2$
  - pQCD collinear factorization
  - DGLAP evolution (g splitting)
  - small nuclear effects in PDFs (LT shadowing).

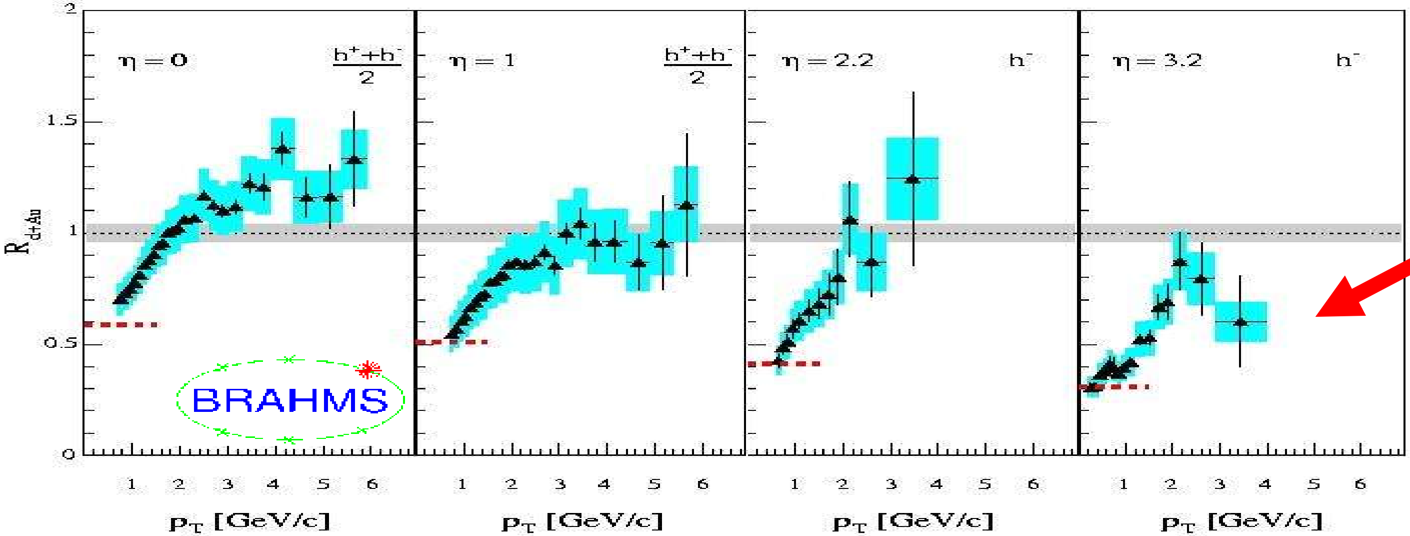
- **Moderate p_T, rapidities:**
  $y \approx 1\text{-}3$, $Q^2 \approx 10\ GeV^2/c^2$
  - k_T factorization
  - linear BFKL evolution (g splitt.)
  - "moderate" nuclear effects (LT shadowing).

- **Low p_T @ large rapidities:**
  $y > 3$, $Q^2 < Q_s^2 \approx 5\ GeV^2/c^2$
  - pQCD factorization breakdown
  - non-linear evolution (g fusion)
  - strong nuclear effects in the initial-state

$(2 \rightarrow 2)$ $x_T = p_T/\sqrt{s}\,(e^{-y}+e^{y})$

x small: Look forward in rapidity !

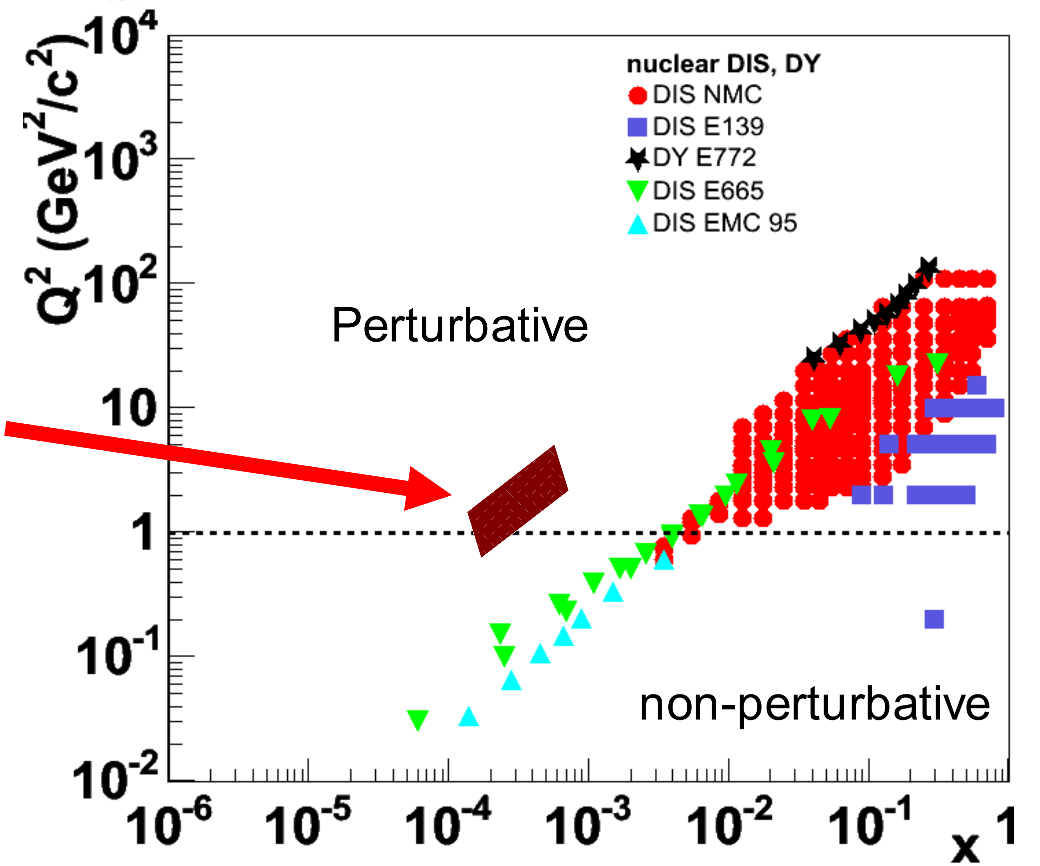
d+Au nuclear modification factor (η = 3.2)



- Factor ~2 suppression p_T = 1-3 GeV/c hadron production at η = 3.2 ($x_2 \sim 10^{-4}$ in Au).

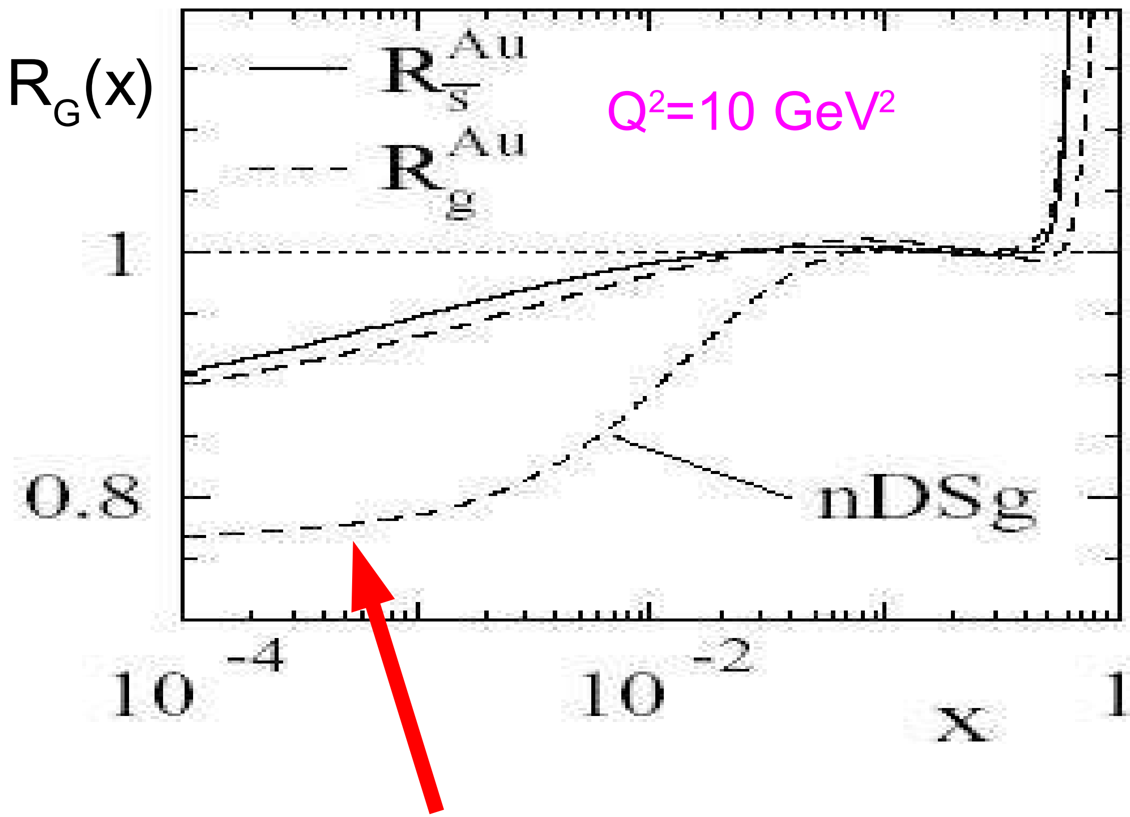
- First time a large "shadowing" is seen at small-x and high p_T in nuclear syst.

- So far unexplored perturbative region of nuclear (x,Q^2) plane.



Is this "standard" nuclear shadowing ?

- Take the predictions of your favourite leading-twist approach ...



NLO DGLAP global analysis of nuclear PDFs

D. de Florian & R.Sassot
hep-ph/0311227

- Maximum gluon shadowing at x~10^{-4} (indirectly) constrained by available DIS data on nuclear targets is ~0.8
- IF indeed $R_{dAu}(p_T$~2 GeV/c) ≈ 0.5 ≡ $R_G(x=10^{-4})$ ≈ 0.5 this could be an evidence of extra higher-twist effects at small-x (breakdown of QCD factorization). BUT, soft physics effects can still be playing a role here ...

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.

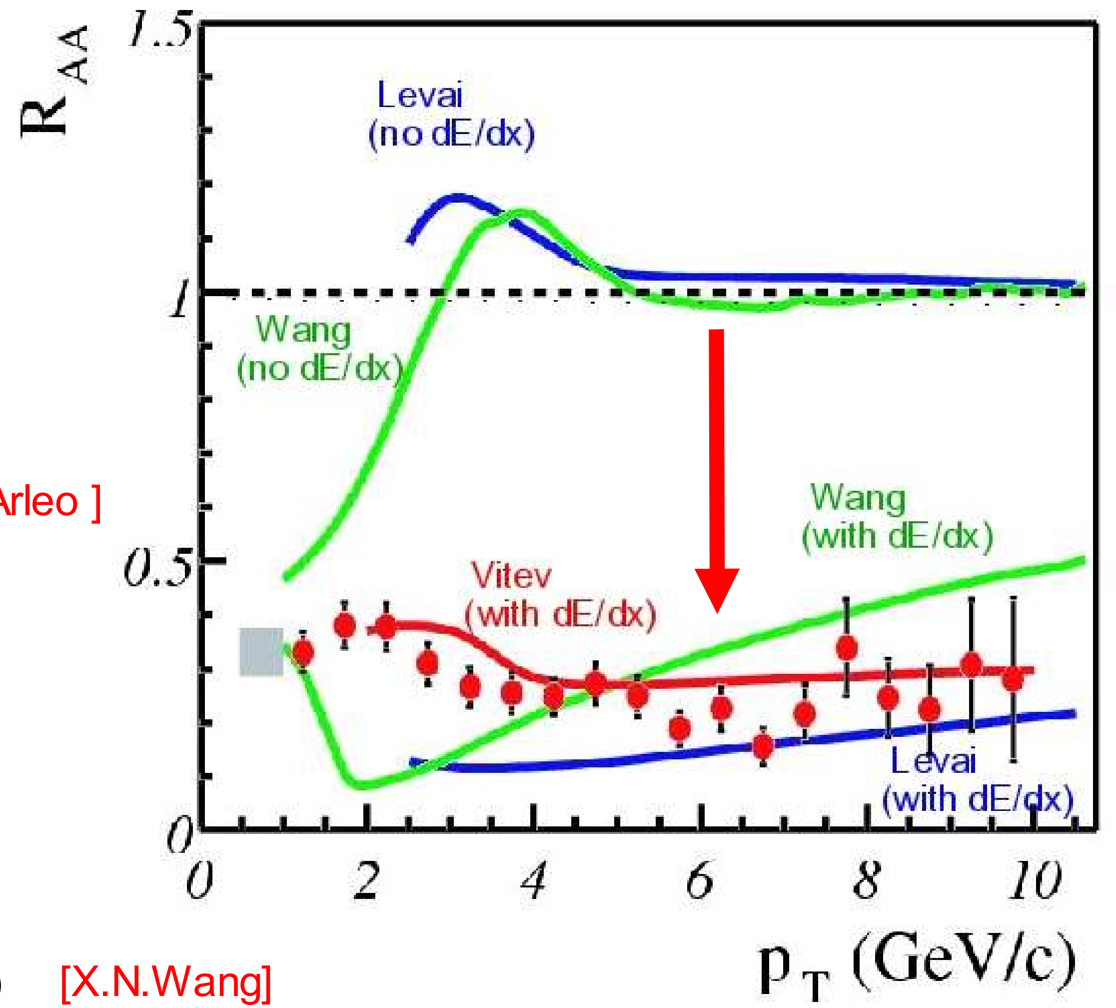
2. Dense initial-state partonic medium: Gluon saturation.

3. Dense final-state hadronic medium: hadronic energy loss.

(*) via confronting data to theory

Final-state "QGP" effects vs. data (I)

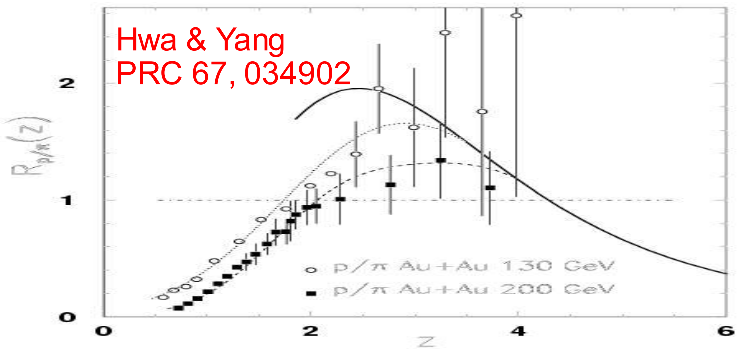
- Dense medium properties according to "jet quenching" models:
  - Initial gluon densities:
    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]
  - Opacities:
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]
  - Transport coefficients:
    $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 [BDMPS, F.Arleo]
  - Plasma temperatures:
    T ~ 0.4 GeV [G. Moore]
  - Medium-induced radiative energy losses:
    $dE/dx \approx 0.25$ GeV/fm (expanding)
    $dE/dx|_{eff} \approx 14$ GeV/fm (static source) [X.N.Wang]

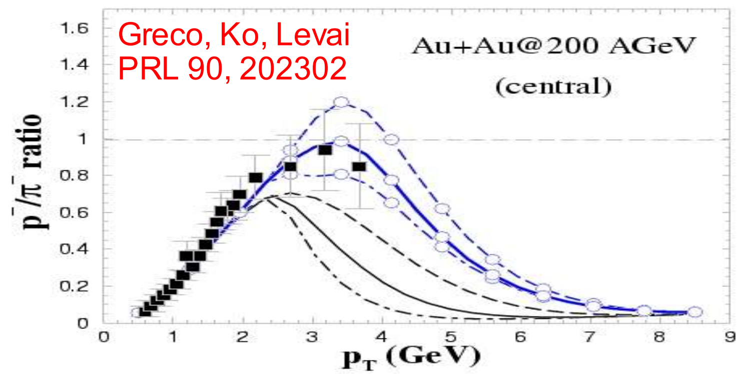


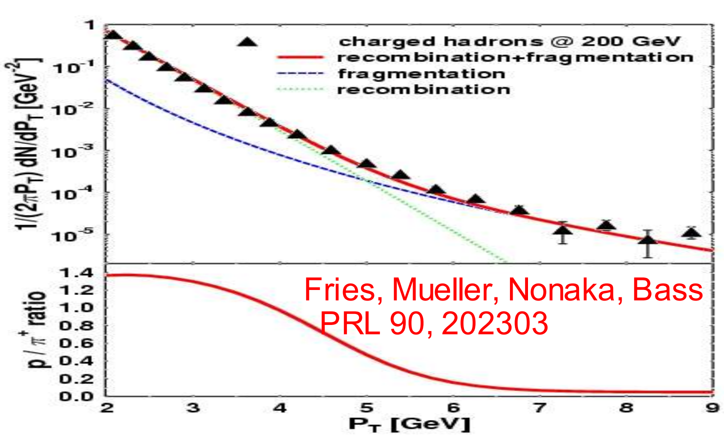
- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\epsilon_{crit\,QCD}$ in thermalized syst.

Final-state "QGP" effects vs. data (II)

- Quark recombination (coalescence) mechanisms provide a simple explanation of anomalous baryon enhancement at interm. p_T's (2-5 GeV/c):







- Via quark momenta addition, recombination dominates for $p_T \sim$ 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

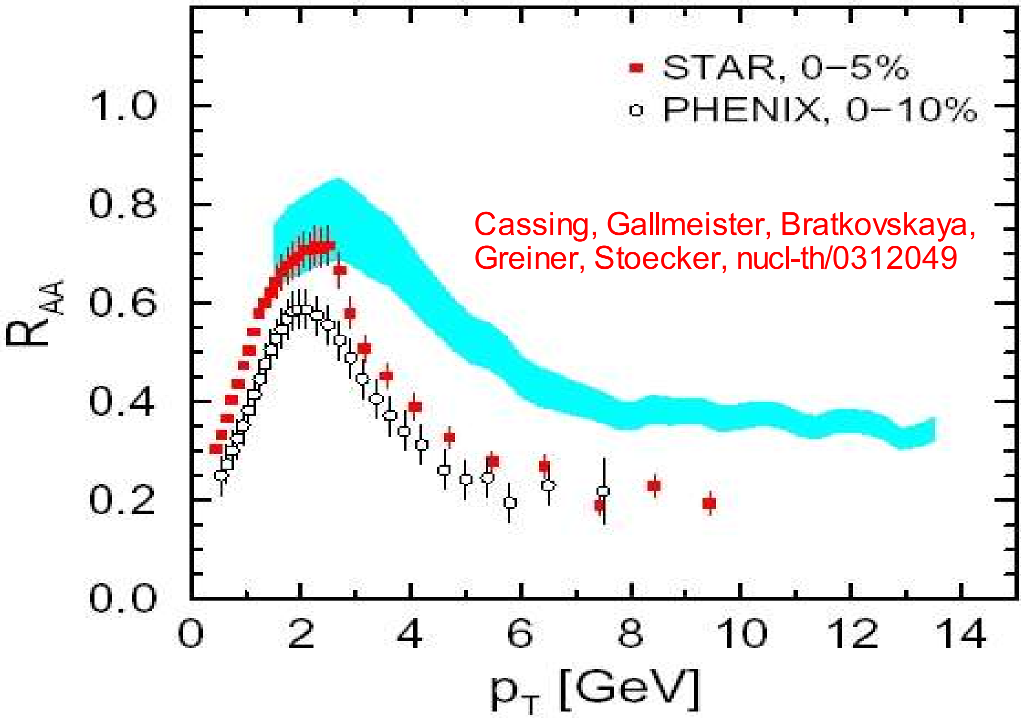
- High quark densities in a thermal medium are required.

- *However... is recomb. consistent with (p+p-like) Au+Au dN/dφ near-side widths ?*

Final-state effects in a dense hadronic medium ?

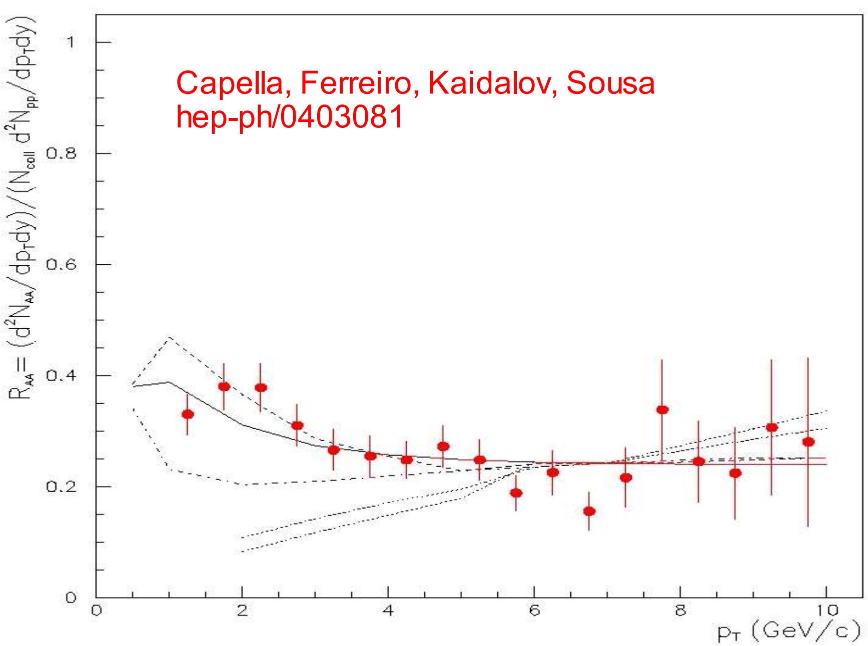
see also talk by E.Ferreiro

- Energy loss of "pre-hadrons" inside a dense expanding hadronic fireball with $\epsilon_{init} \approx 1$ GeV/fm^3



- Hadronic transport models (HSD, UrQMD) produce suppression but not enough to explain the observed suppression factor at high p_T

- Pre-hadronic energy loss in dense medium needed also in Dual-Parton-Model based approaches



Summary

☆ High p_T central Au+Au vs p+p at midrapidity at RHIC:

➡ Observation 1: Light-flavor (u,d,s) spectra suppressed by a factor 4-5.

➡ Observation 2: Intermediate p_T light-flavor composition inconsistent with known fragmentation functions in free space.

➡ Observation 3: Disappearance of away-side jet correlations.

➡ Observation 4: Direct photon spectra unsuppressed.

☆ High p_T d+Au vs p+p at midrapidity at RHIC:

➡ Observation 5: Spectra enhanced by a factor ~1.3

☆ "Explanation" (1,2 via 4,5): pQCD hard scattering + final-state parton energy loss + parton recombination $\Rightarrow$ Dense thermal QCD medium
QGP ? : thermal γ ?, J/Ψ suppression ? (Run-4 @ RHIC)

☆ High p_T in d+Au at forward rapidities at RHIC:

➡ Observation 6: Spectra suppressed by a factor ~2-3.

☆ "Explanation" (6): possible evidence of high twist effects at small-x.