Bulk properties of QCD from the hard sector at RHIC

Institut de Physique – Université de Liège

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Overview

1. Introduction:
   - The goal: study Quantum Chromo many-body Dynamics: QGP, CGC.
   - The means: compare hard scattering production in diff. colliding systems.

2. "QCD vacuum" production – high p_T spectra in p+p:
   - Baseline reference data of hard scattering in free space.

3. "Hot QCD medium" production – high p_T spectra in central A+A:
   - ➡ Suppressed hadron production (compared to free space): $\sqrt{s}$, p_T, y, centrality, and particle species dependence. } **QGP ?**

4. "Cold QCD medium" production – high p_T spectra in d+Au:
   - ➡ Enhanced hadron production at $y \leq 0$ (mid-rapidity & high x_2 in Au): p_T, centrality, and particle species dependence.
   - ➡ Suppressed at $y \geq 1$ (small x_2 in Au). ⟶ **CGC ?**

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

Review of QCD properties

The QCD Lagrangian:

- Degrees of freedom: quarks and gluons
- Non-abelian gauge theory
- Internal symmetry group: $SU(3)_{color}$

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

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

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

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

Properties of the strong interaction:

1. Confinement: Quarks do not occur isolated in nature: only in hadronic (colorless) bound-states as mesons [$q\bar{q}$] & baryons [qqq]. $\alpha_s(Q^2)$ strong at large distances (low Q^2).

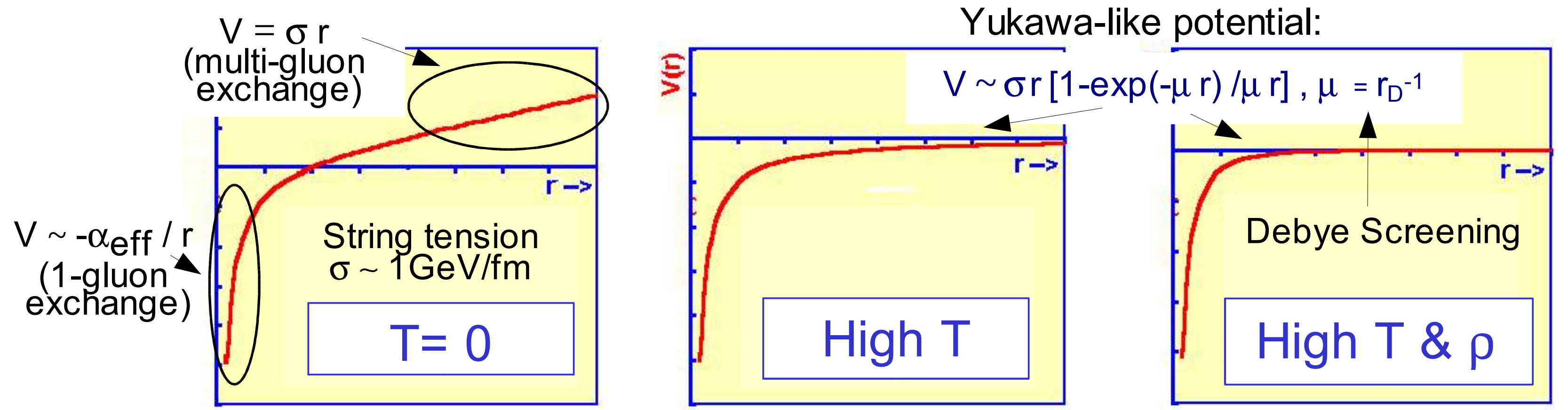
2. Asymptotic freedom: At short distances (high Q^2), $\alpha_s(Q^2)$ decreases logarithmically: quarks & gluons weakly coupled. Perturbative methods applicable (pQCD).

3. Chiral symmetry breaking:

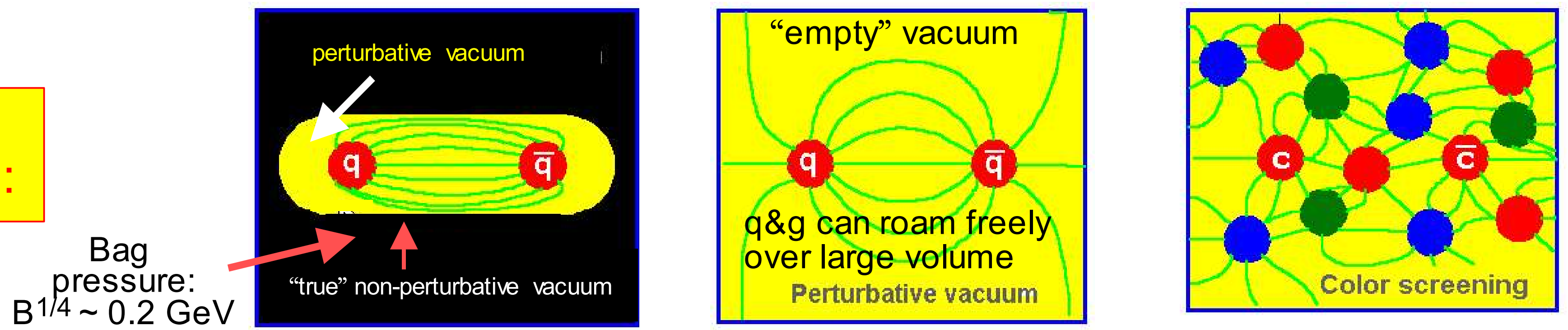
   - Quarks acquire dynamically a mass in a confined medium:
     Current m_q (5-10 MeV) << Constituent m_q (~300 MeV)
   - Non-zero QCD ground-state (non-perturbative vacuum, "sea") filled with quark-antiquark and gluon-gluon virtual pairs :
     quark & gluon condensates: $\langle\Psi\Psi\rangle \approx -(235\text{ MeV})^3$, $\langle\alpha_s G_{\mu\nu} G^{\mu\nu}\rangle \approx -(500\text{ MeV})^4$

QCD at finite T and ρ

QCD color potential:

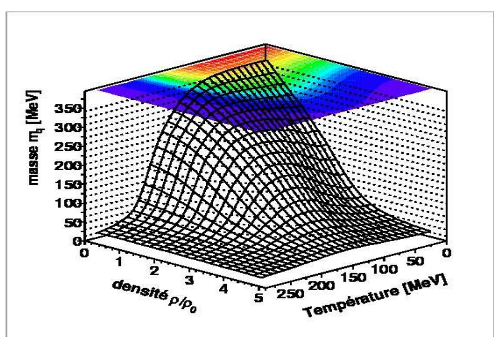


QCD vacuum:

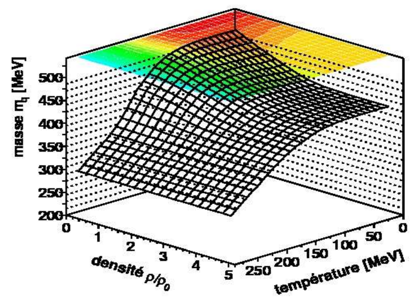


Quark masses:

u/d quarks:



s quark :



$m_q \sim m_0 + C\langle\bar{\Psi}\Psi\rangle$
(NJL model)

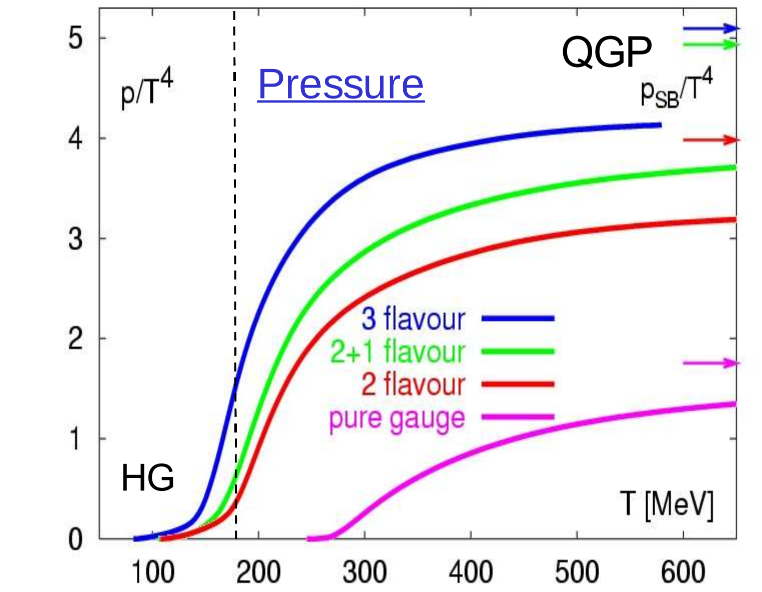
Nuclear matter at high temperatures and densities exhibits:

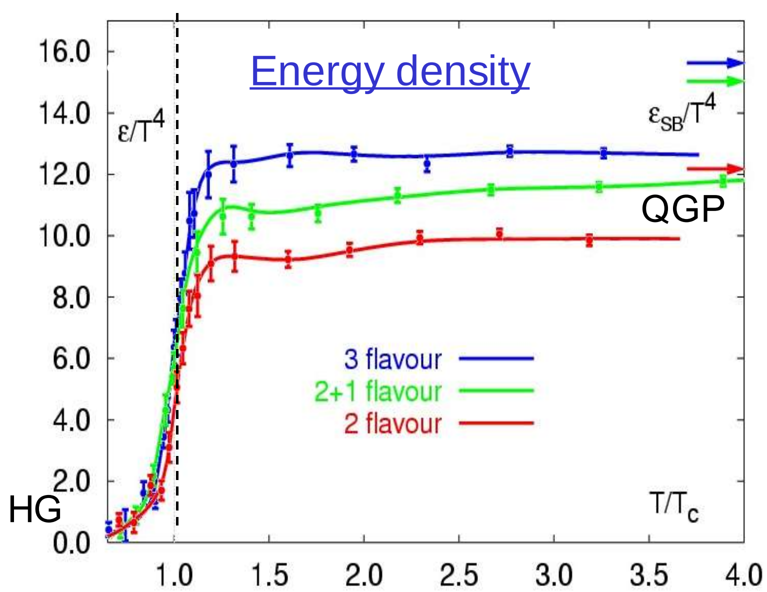
- Color deconfinement: $\alpha_{eff}(T) \sim 1/\ln(T,\rho) \rightarrow 0$
- Chiral symmetry restoration: $m_q(T,\rho) \rightarrow 0$

} New state of matter

QCD thermodynamics on the lattice (*)

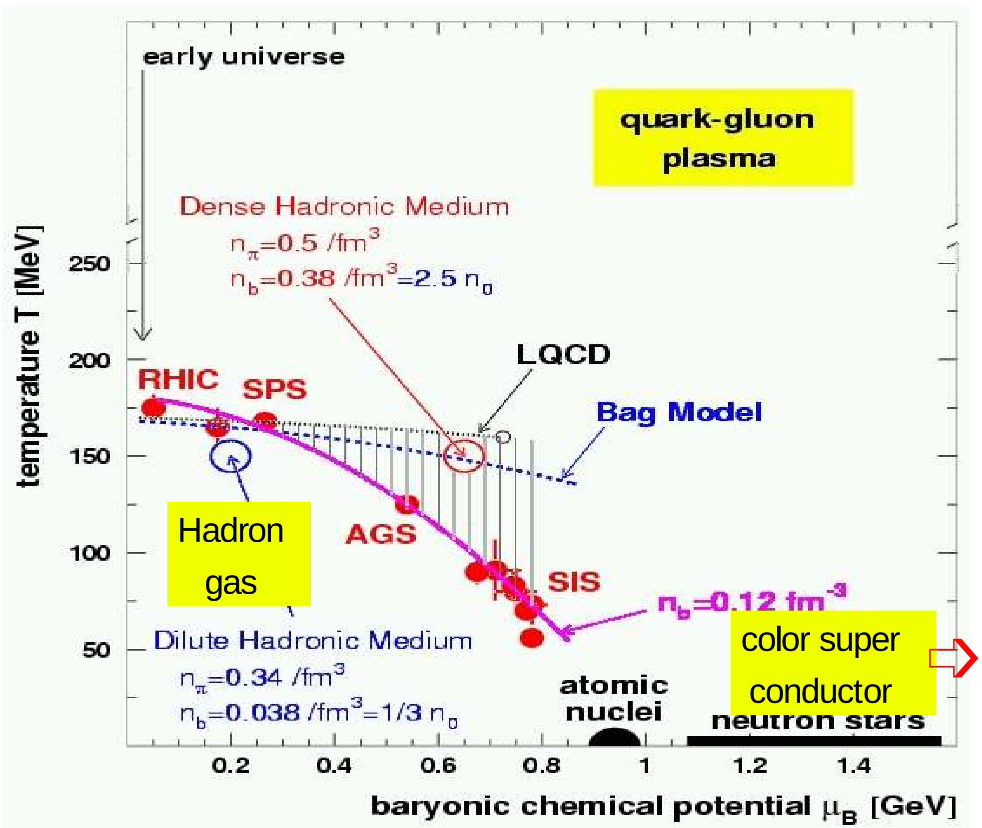
QCD Equation of State





(*) At zero baryon number density (μ_B=0)

Phases of strongly interacting matter



QCD critical temperature:

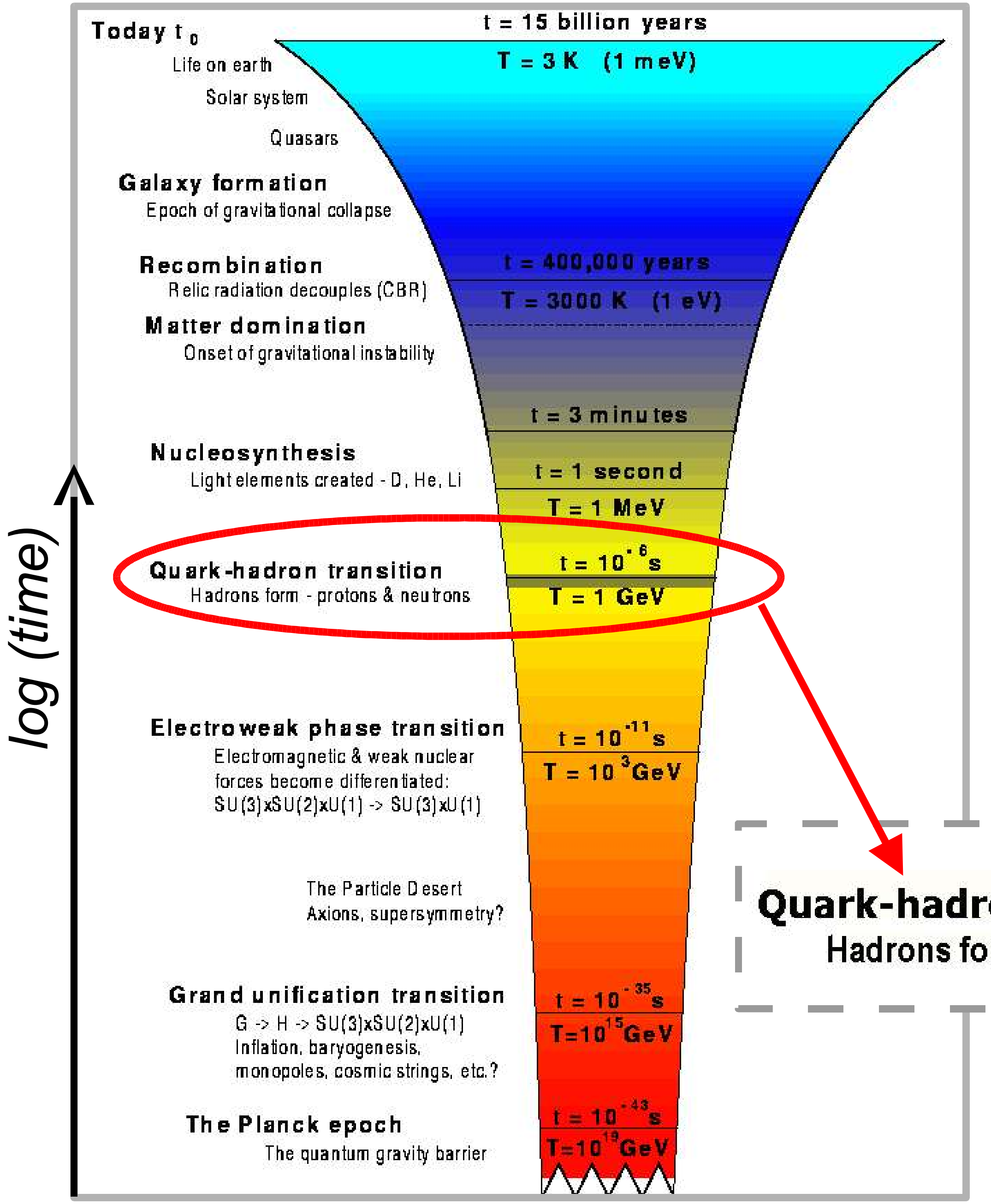
T_C = (173 ±10) MeV [n_f =2]

T_C = (154 ±10) MeV [n_f =3]

Critical energy density:

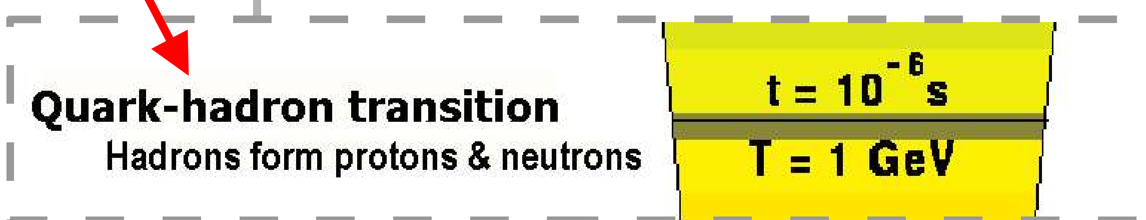
$\varepsilon_C=(6 \pm 2)T_C^4 \Rightarrow \varepsilon_C=(0.7\pm0.3)\ \mathrm{GeV/fm^3}$

Cosmological QCD transition



The universe was in the QGP state ~10 μs after the “Big Bang”

Insights into the cosmology and phase transitions of the early universe



phase transition: *O* (μs)

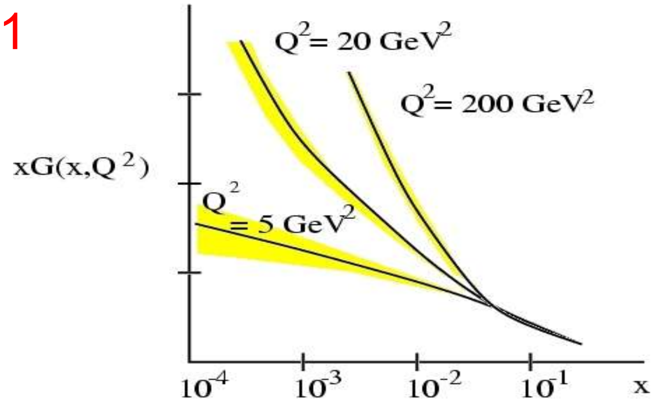
Small-x and saturation physics

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

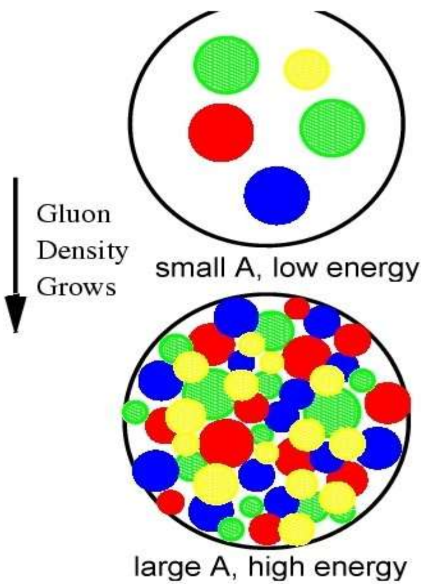
Large gluon densities

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

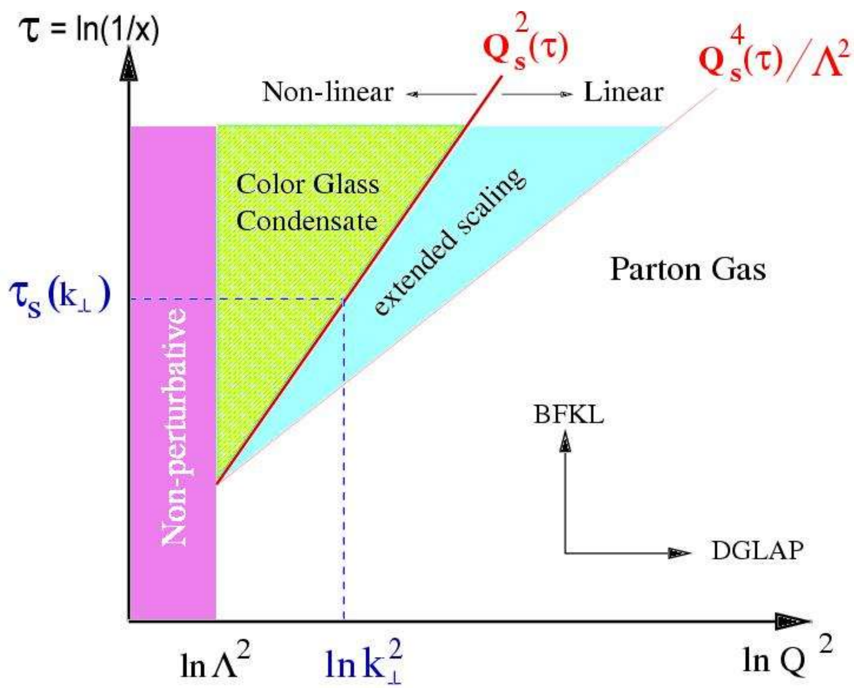
RHIC ~ HERA x $A^{1/3}$



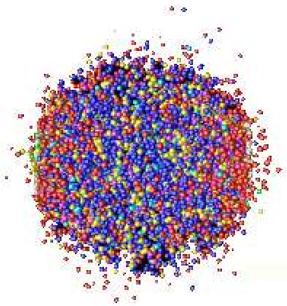
- Colliding nuclei described via a colored highly saturated gluonic wave-function ("Color Glass Condensate"):



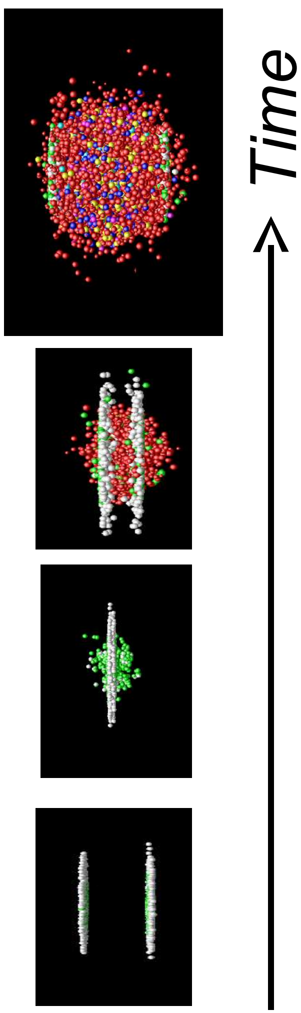
Study regime of non-linear (high density) many-body parton dynamics @ small-x (CGC).

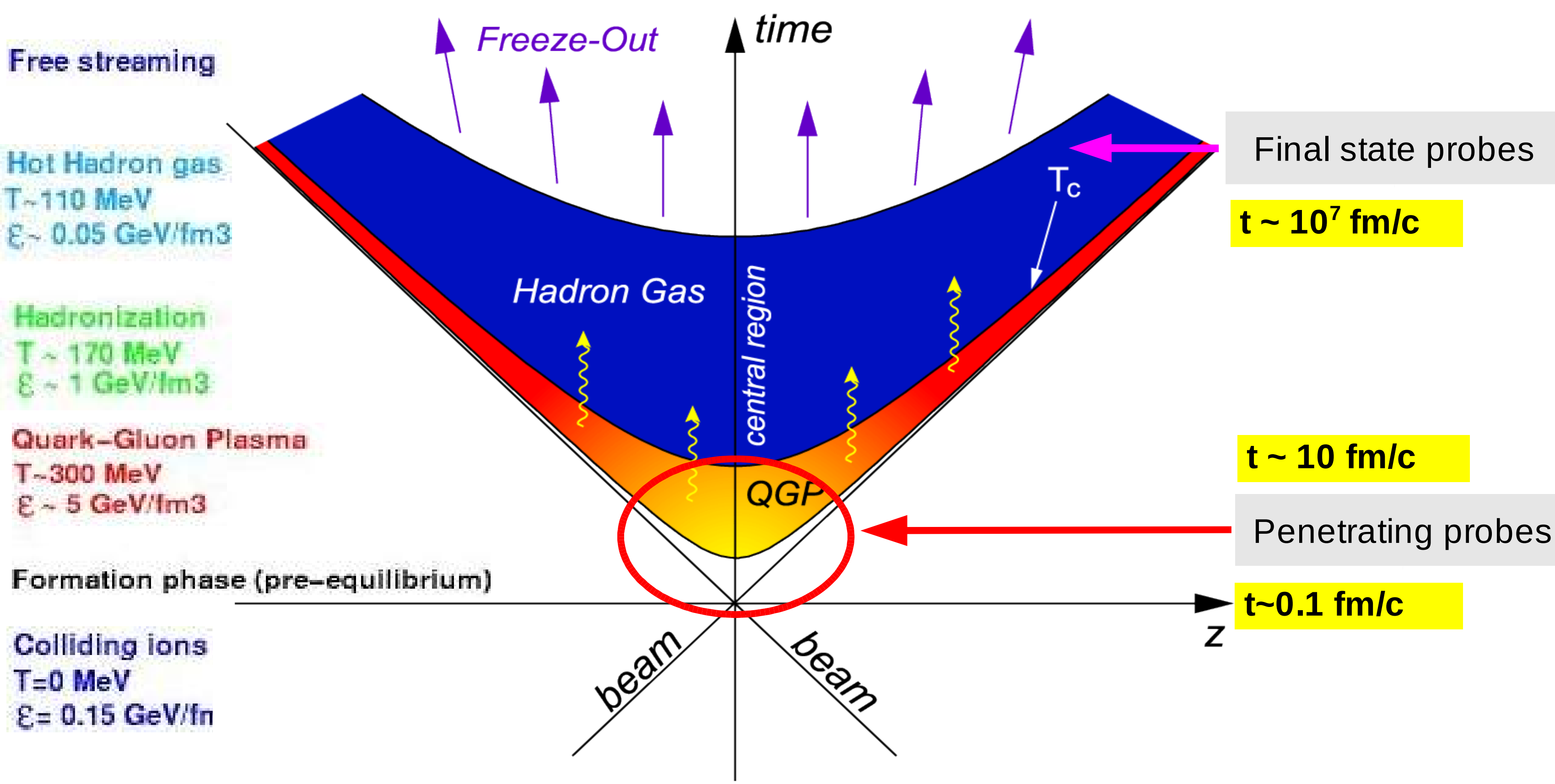


The "Little Bang" in the lab.



- High-energy nucleus-nucleus collisions: in fixed-target reactions ($\sqrt{s}$~17 GeV, SPS) or at colliders ($\sqrt{s}$~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





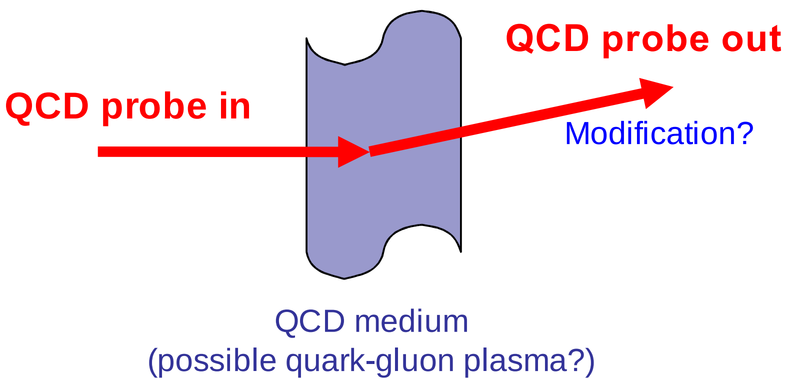
Hard QCD probes. Motivation (I)

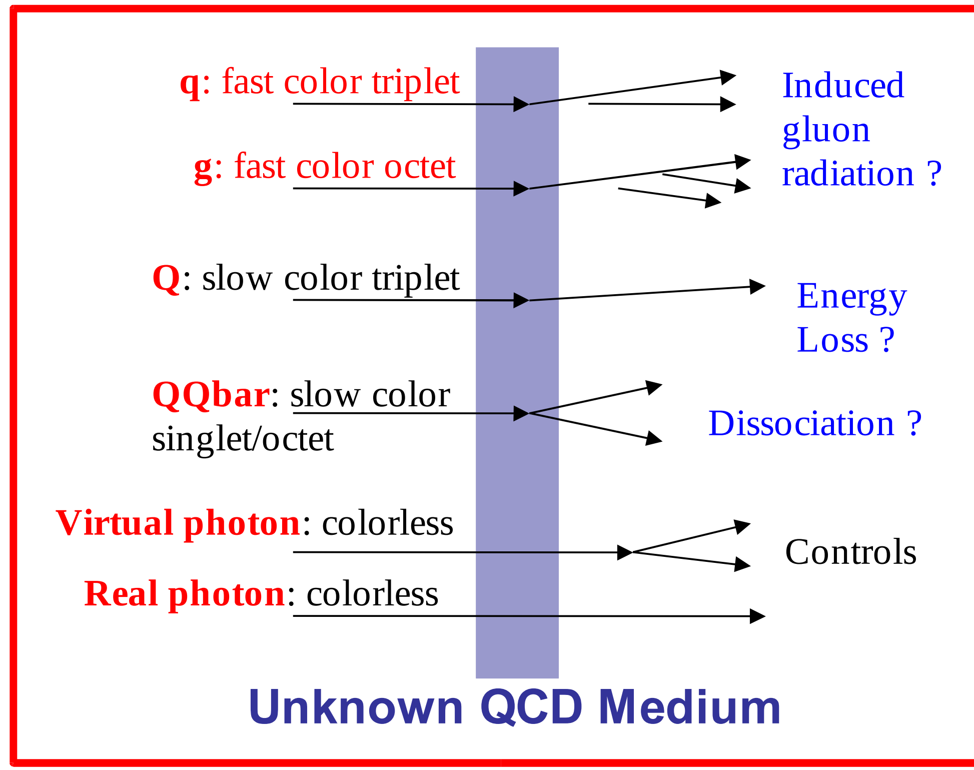
- Hard probes: High-p_T, jets, direct γ, heavy-quarks (D, B), ...

[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:





[3] Incoherent processes: Direct comparison A+A to p+p yields via " N_{coll} scaling" :

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

At impact parameter b: $d\sigma_{AB}(\text{hard}) = T_{AB}(b)\, d\sigma_{pp}(\text{hard})$

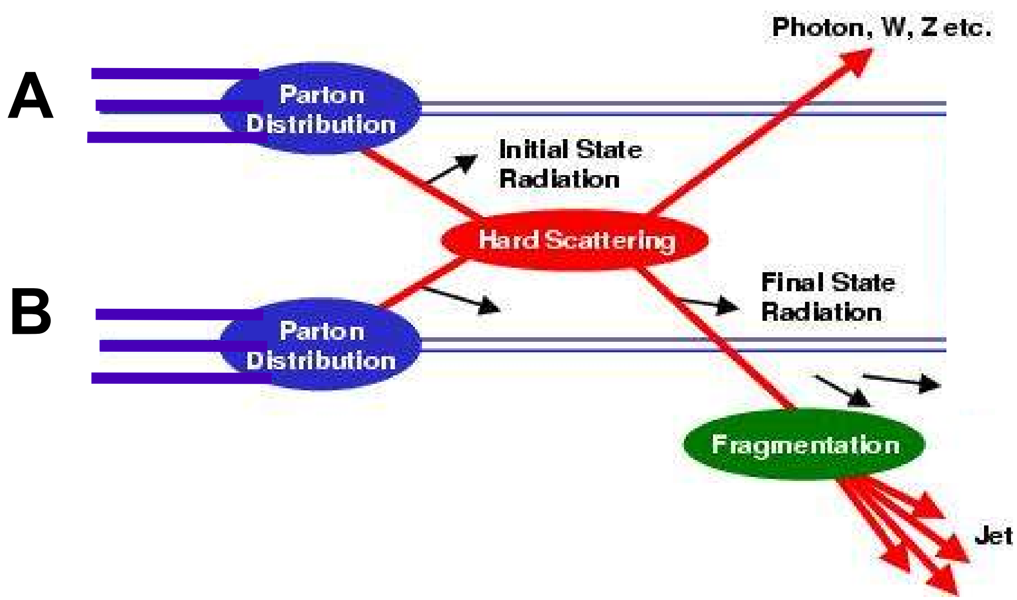
Nuclear overlap: $\mathbf{T_{AB}}(b) \propto N_{coll}(b)$: number of inel. *NN* collisions.

Hard QCD probes. Motivation (I)

[4] Production yields theoretically calculable via:

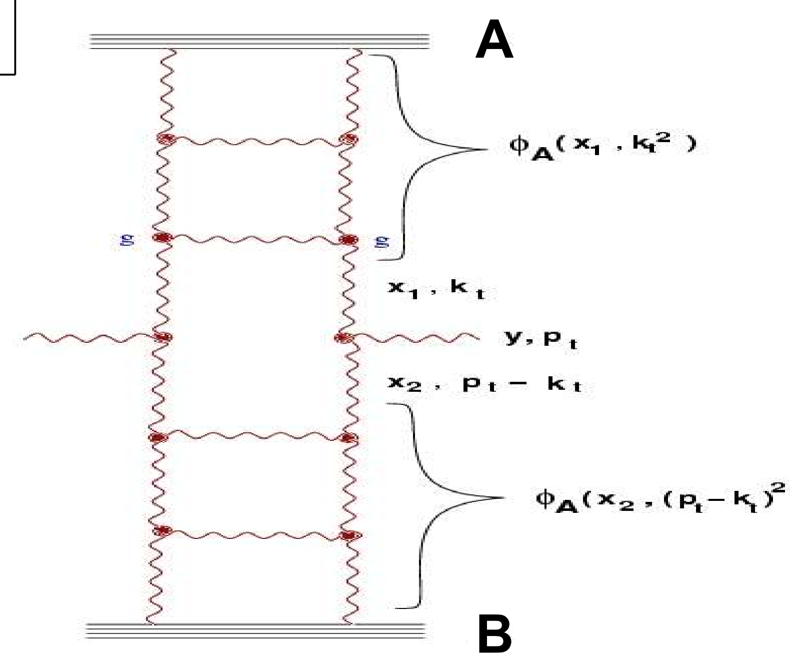
perturbative-QCD or ...

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



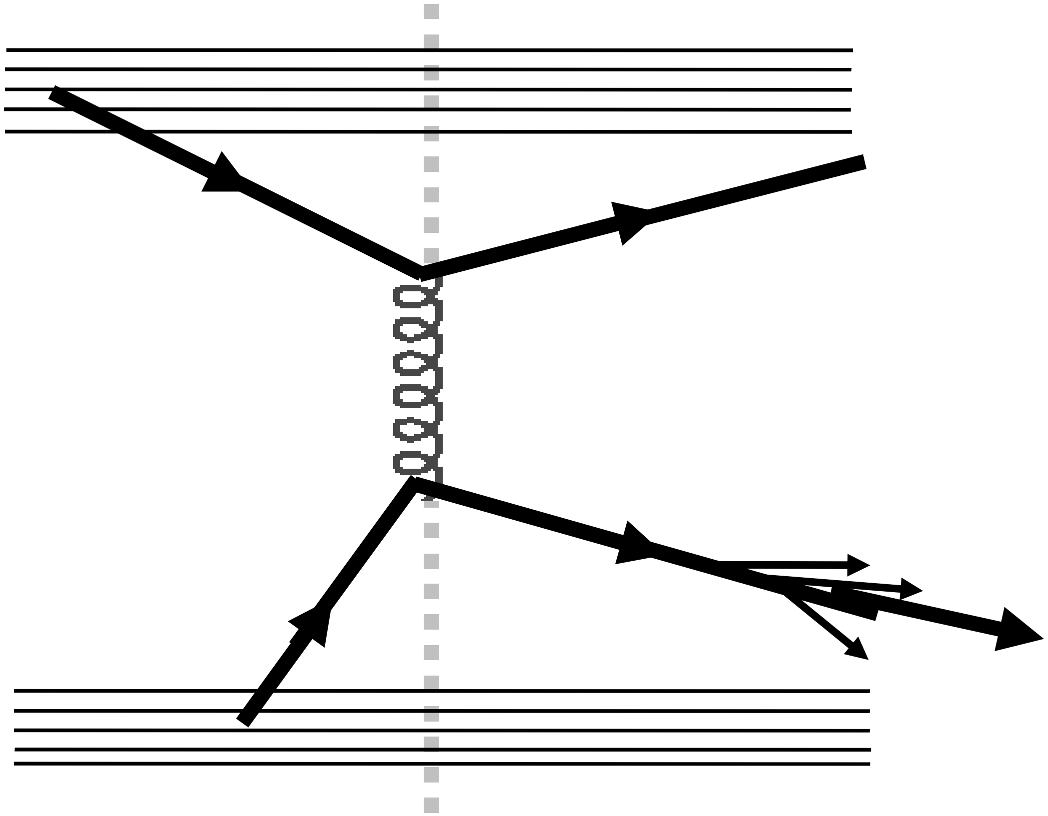
classical-field QCD:

at small-x ...



Mueller diagram for classical glue radiation

Hard scattering in A+A collisions



Hard scattering in A+A collisions

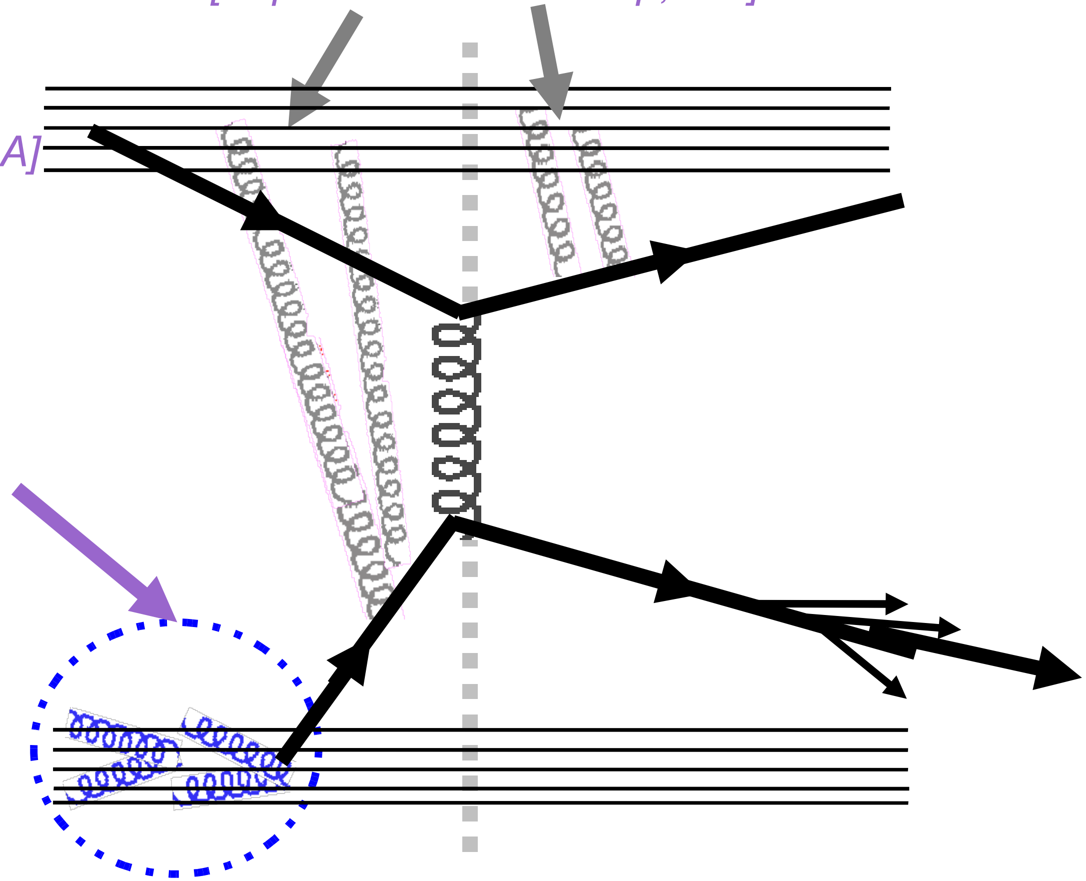
p_T broadening
(Cronin enhancement)

[Experimental handle: p,d+A]

Initial-state effects

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

Leading-twist shadowing
or
Gluon saturation (**CGC**)



Hard scattering in A+A collisions

p_T broadening
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[Experimental handle: p,d+A]

Initial-state effects

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

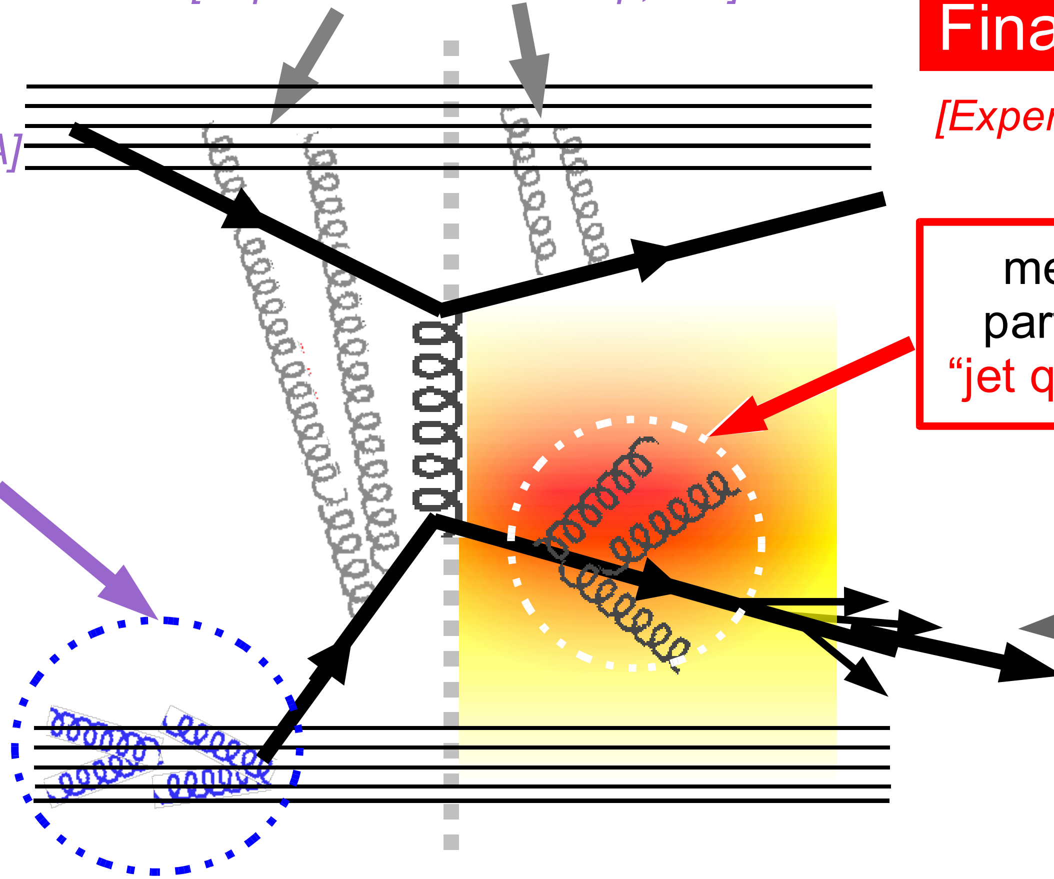
Leading-twist shadowing
or
Gluon saturation (CGC)

Final-state effects

[Experimental handle: A+A]

medium-induced
parton energy loss:
“jet quenching” in **QGP**

possible
hadronic
rescattering



Hard scattering in A+A collisions

p_T broadening (Cronin enhancement)

[Experimental handle: p,d+A]

Initial-state effects

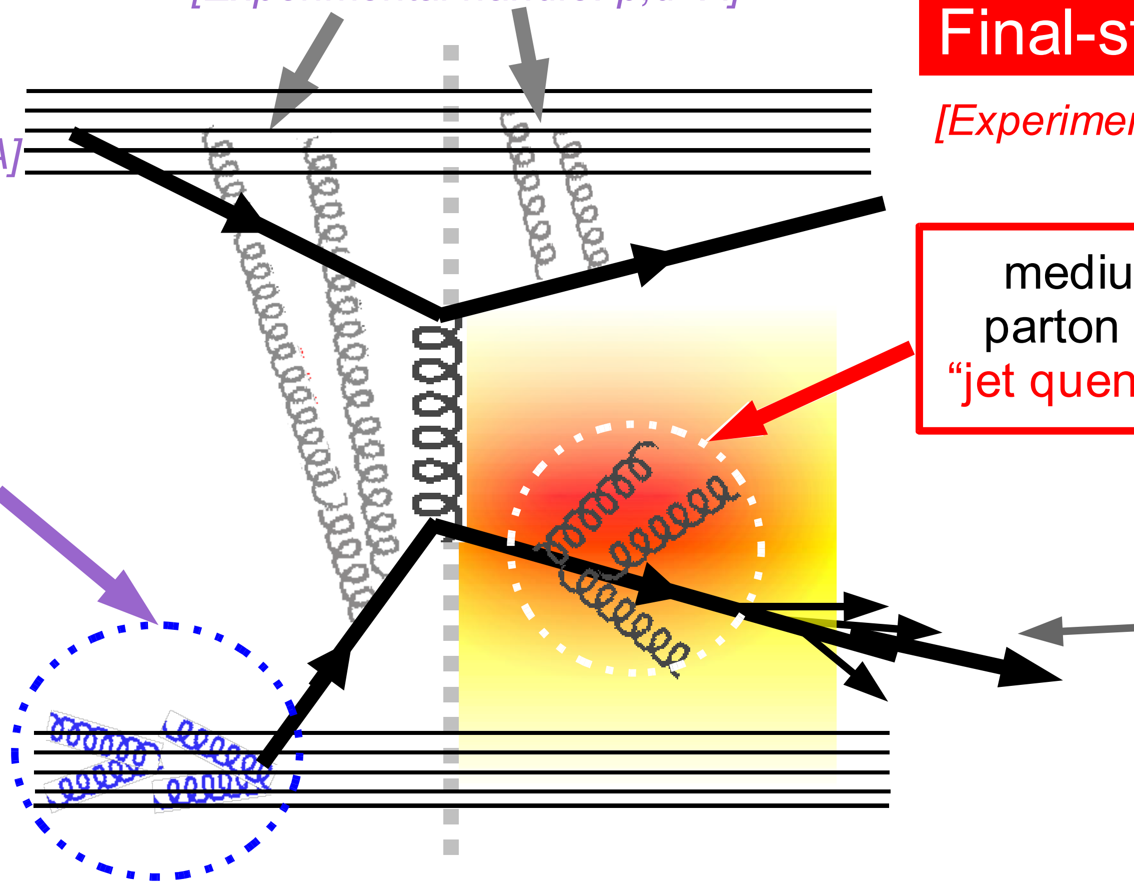
[Experiment. handle: e+A, p,d+A]

Leading-twist shadowing
or
Gluon saturation (CGC)

Final-state effects

[Experimental handle: A+A]

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

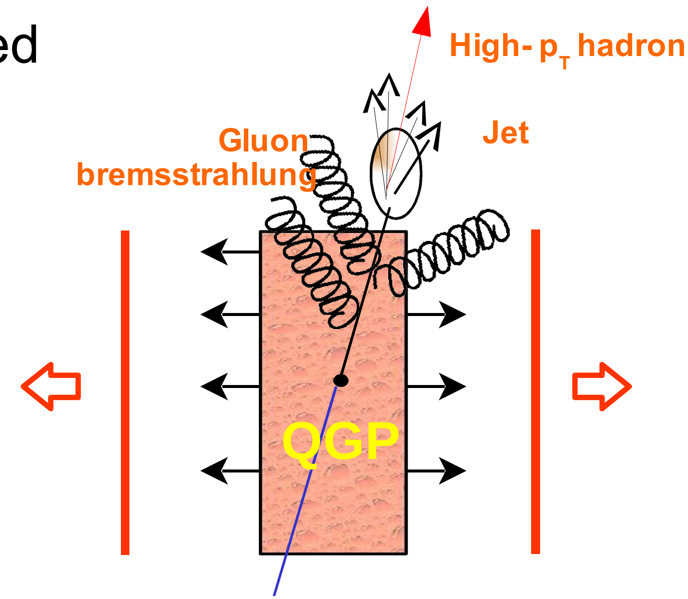


possible hadronic rescattering

- 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

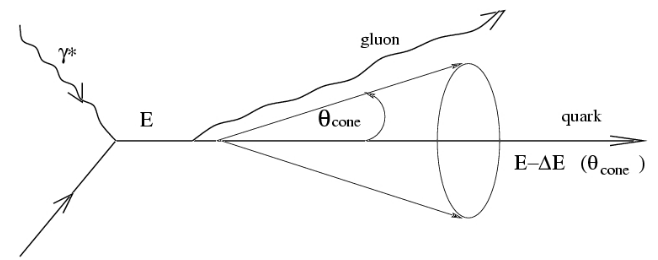
- Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium:



  - Mean parton energy loss probes medium properties:

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

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



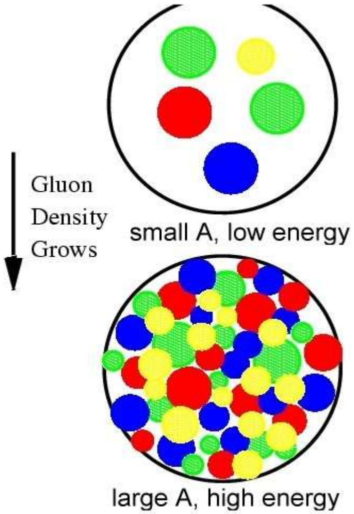
  - Energy is carried away by gluonstrahlung outside jet cone: $dE/dx \sim \alpha_s \langle k^2_T \rangle$
  - Formalisms: BDMPS (thick plasma), GLV (thin plasma),
  - Correction for expanding plasma (1-D):

    $\Delta E_{1\text{-}D} = (2\tau_0/R_A) \cdot \Delta E_{static} \sim 15 \cdot \Delta E_{static}$ (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

- Nucleus-nucleus collisions described as a collision of two "classical" gluonic wave-functions ("Color Glass Condensate").



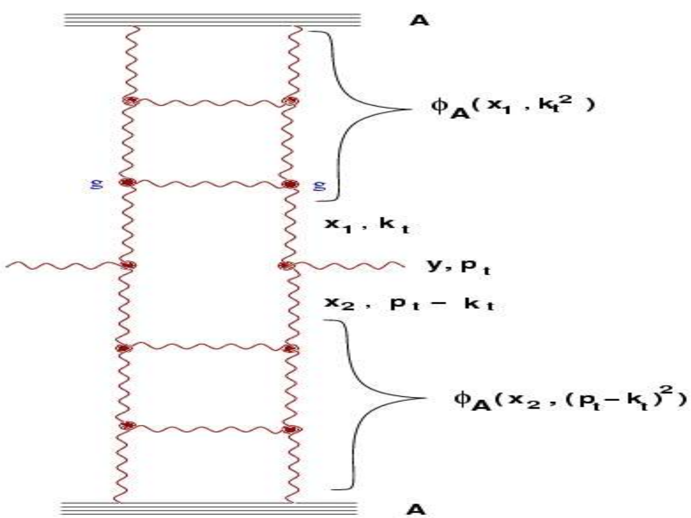
- Approximation valid around "saturation scale":

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

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

"Classical" (Chromo-Dynamics) methods applicable

- 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 @ √s = 200 GeV

Luminosity: $2\cdot10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)

p+p collisions @ 500 GeV

p+A collisions @ 200 GeV

4 experiments:

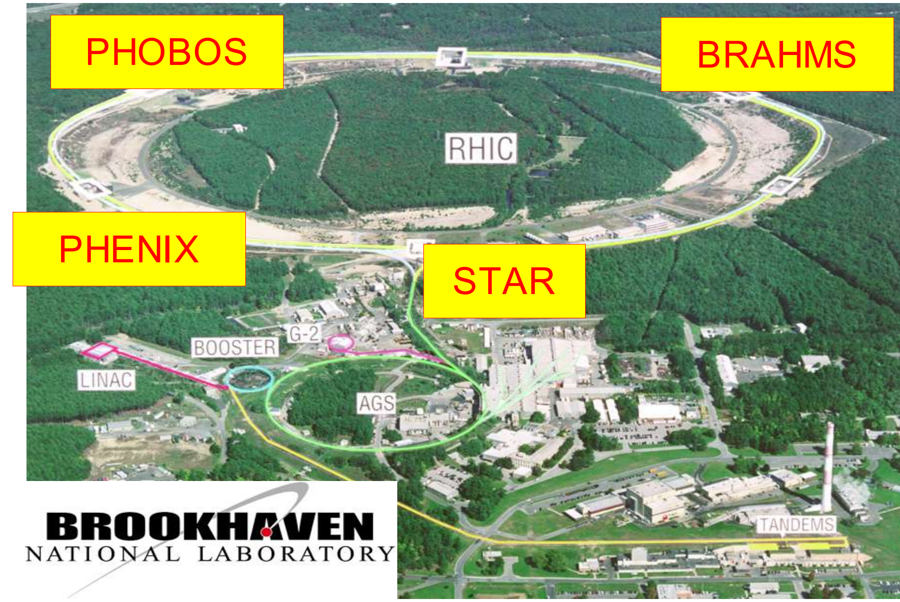
BRAHMS, PHENIX, PHOBOS, STAR

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**

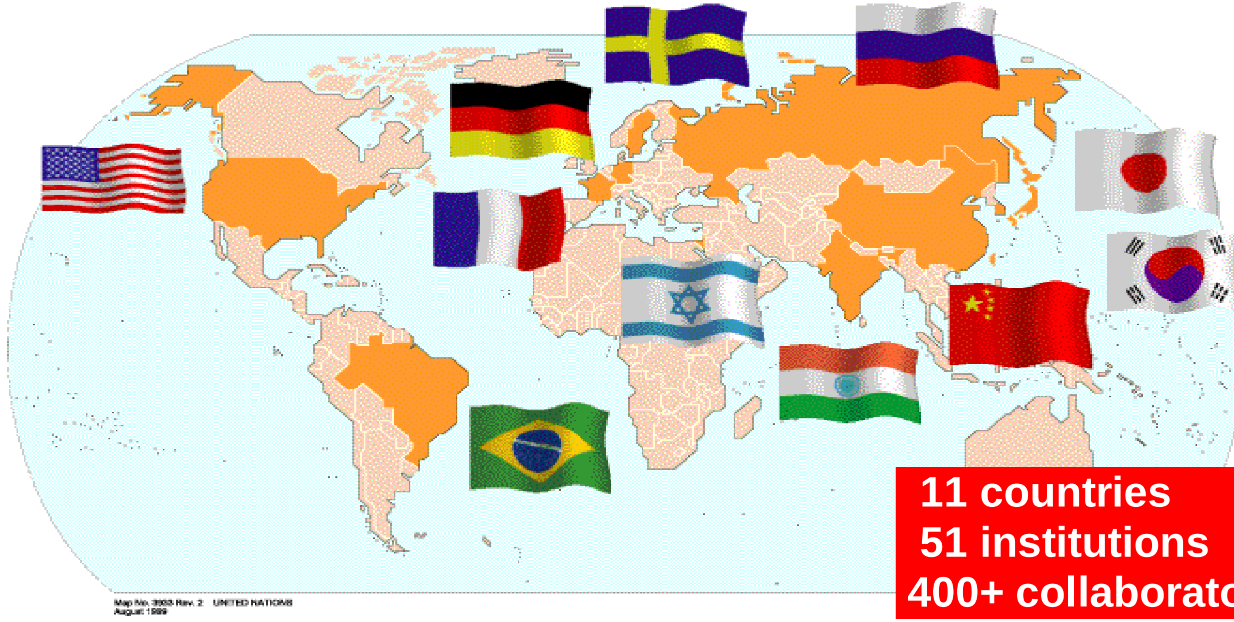


David d'Enterria (Columbia Univ.)

The PHENIX collaboration

Pioneering High-Energy Ion eXperiment

PHENIX



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51 institutions
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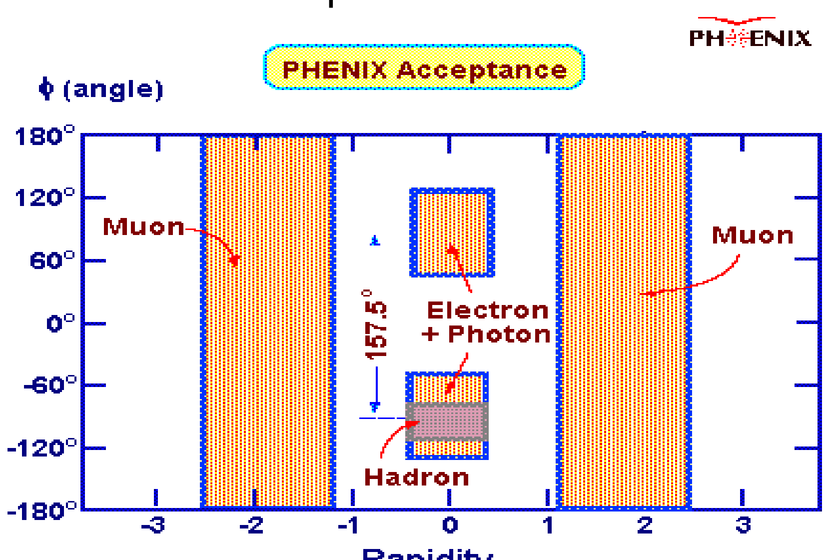
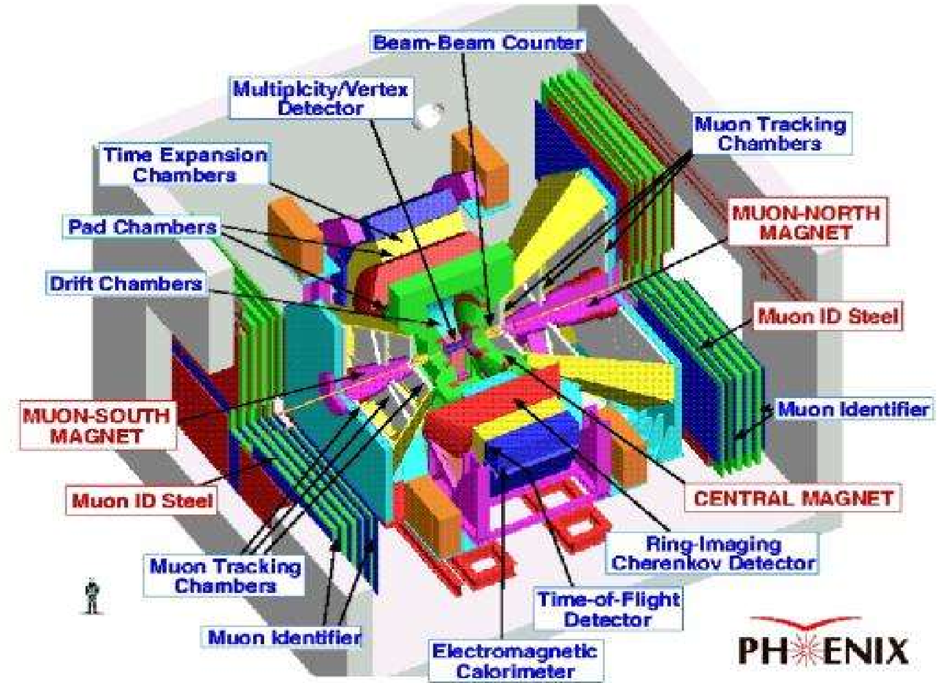
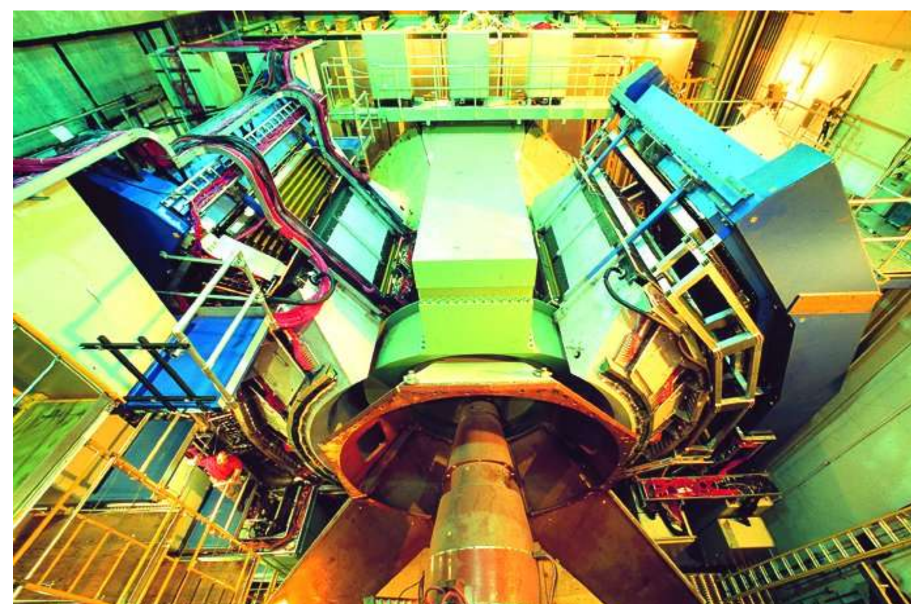
PHENIX @ RHIC

- 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



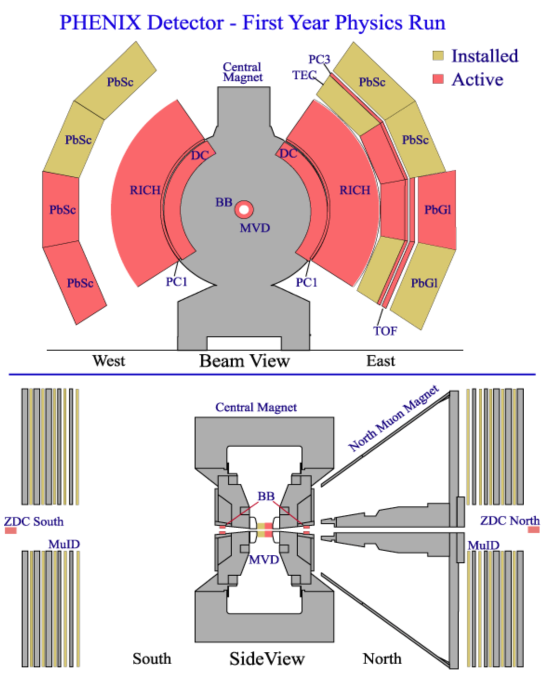




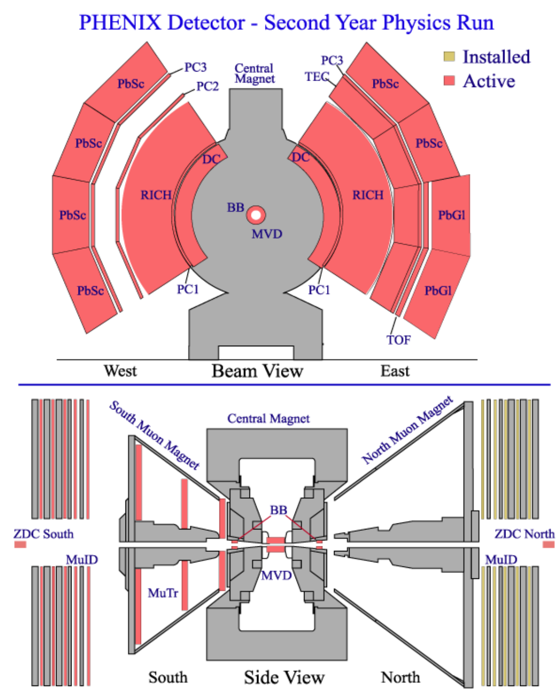
PHENIX run history

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

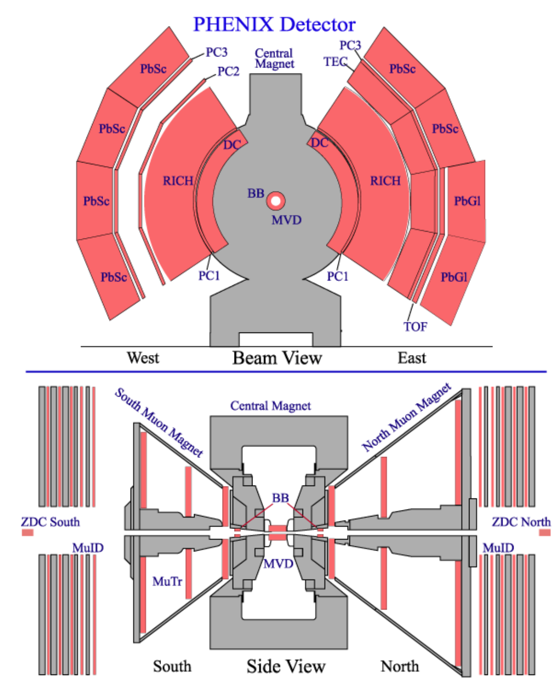
2000



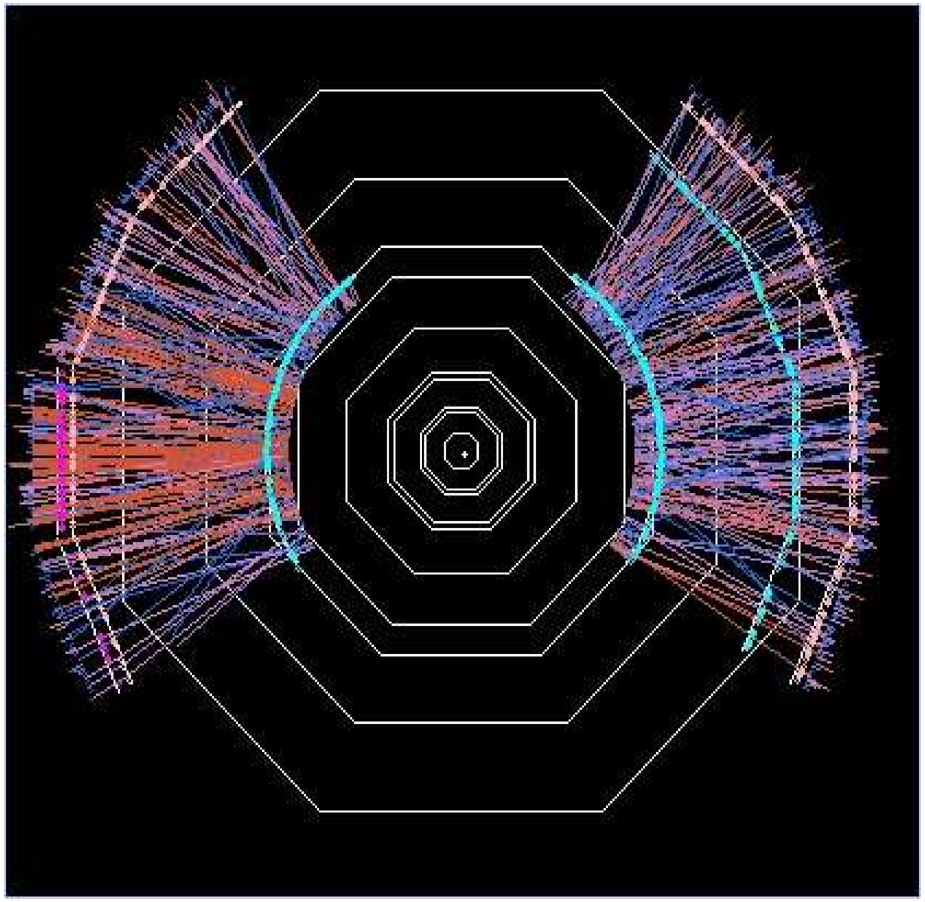
2001/2002

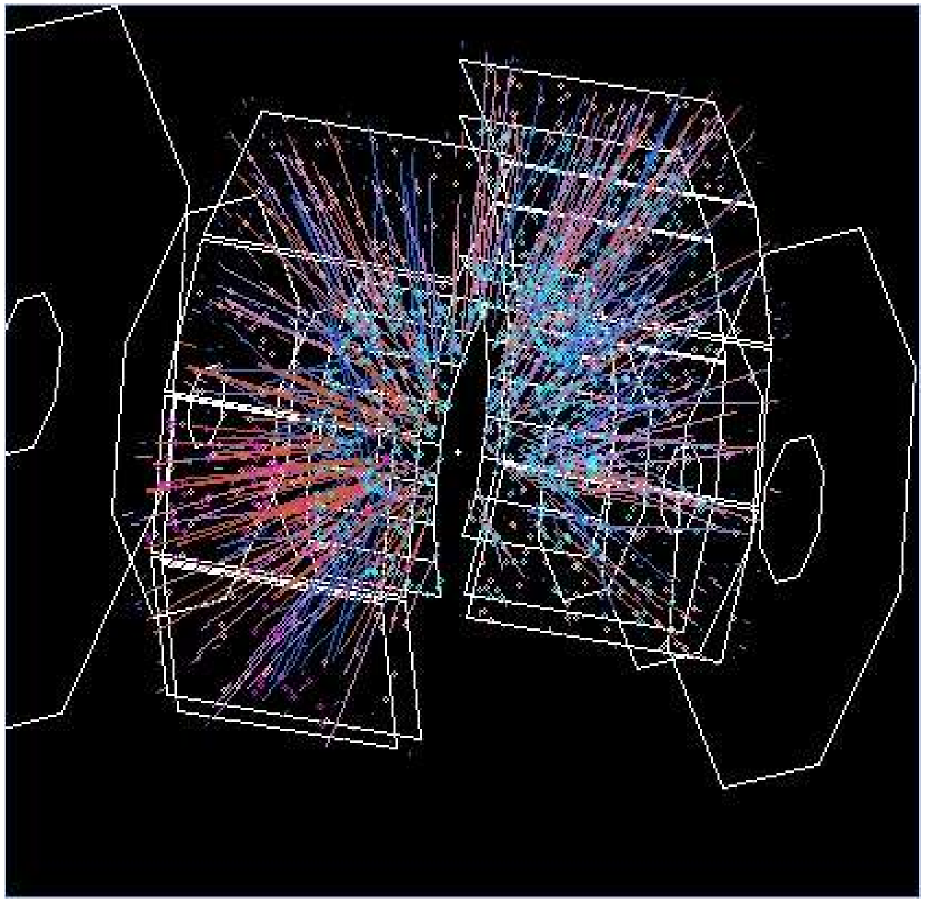


2002/2003



Au+Au @ 200 GeV in PHENIX

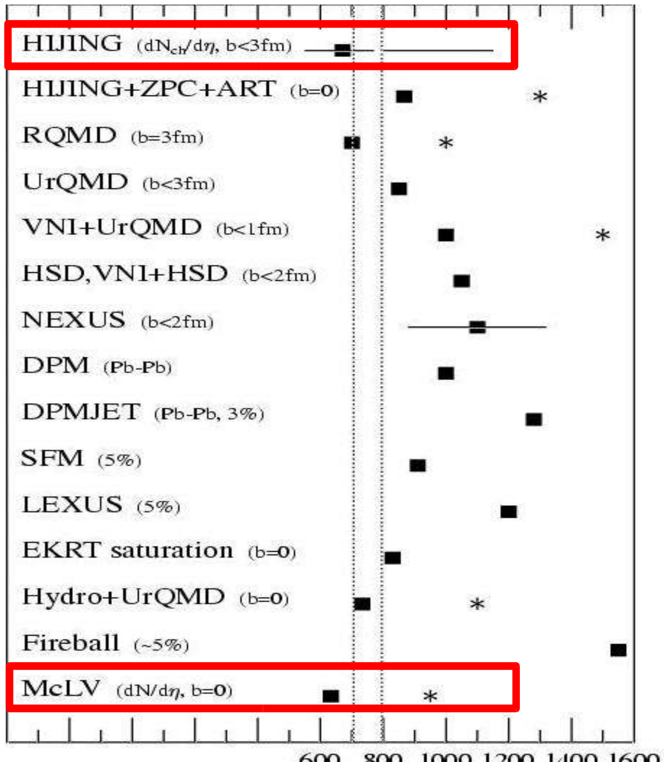




~ 600 charged particles per unit rapidity at midrapidity (top 10% central)

Foreword: central rapidity densities in Au+Au

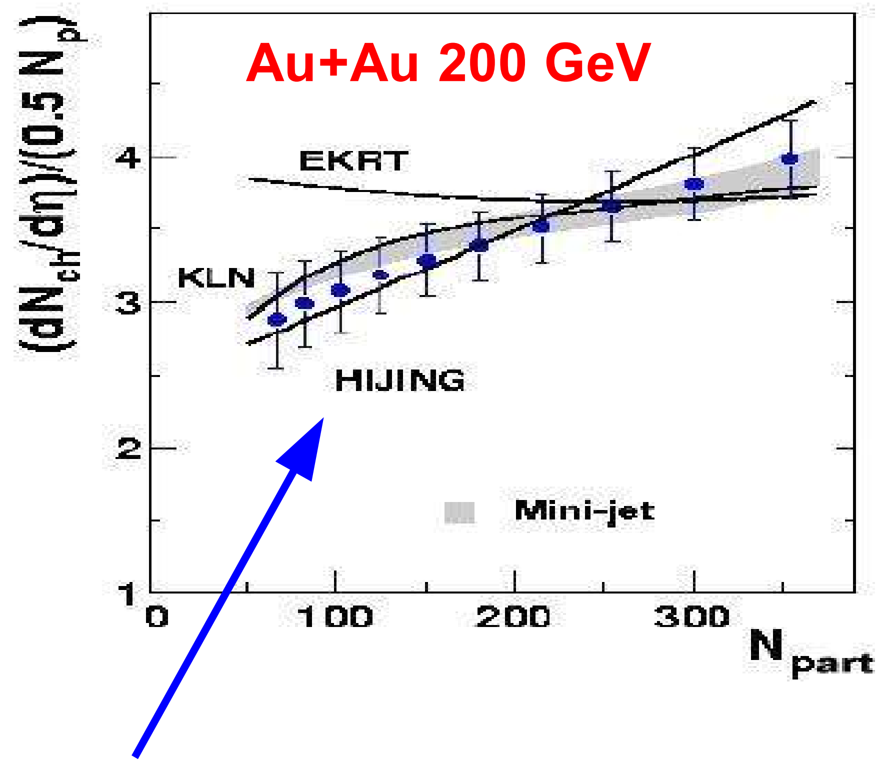
- dN_{ch}/dy constraints mechanisms of initial multi-particle production:



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

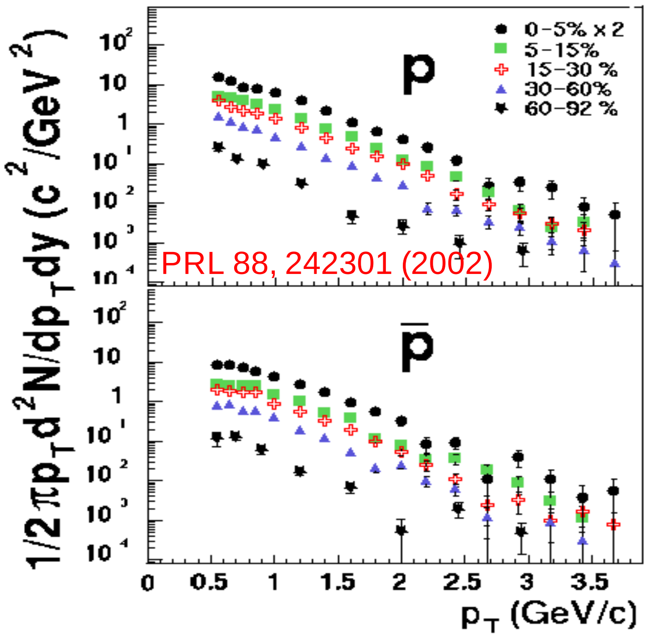
dN_{ch}/dy

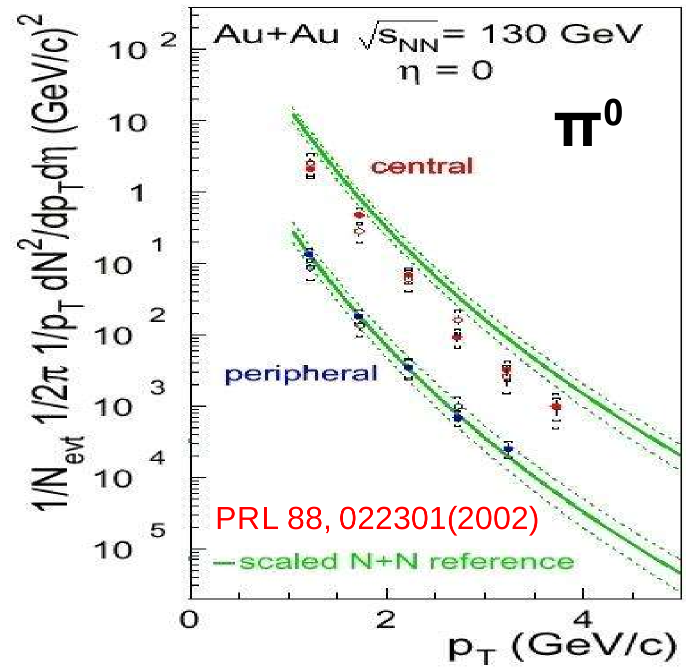
centrality dependence:

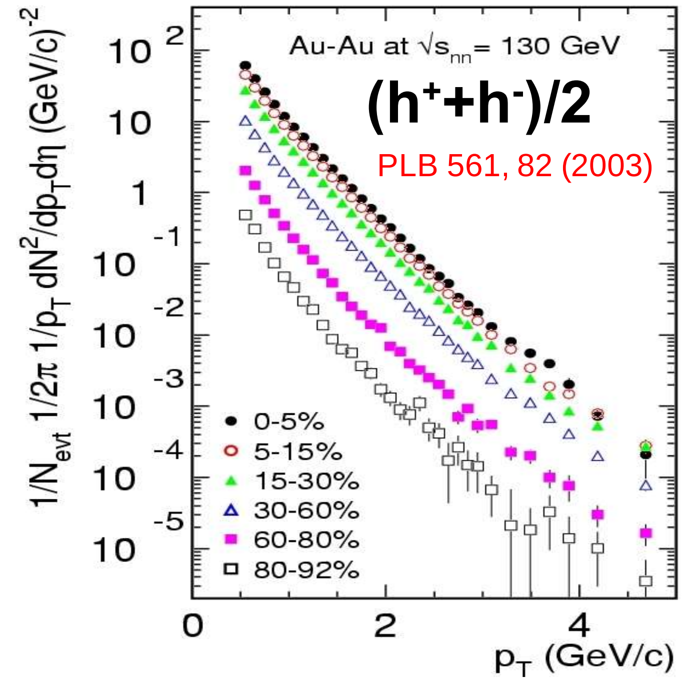


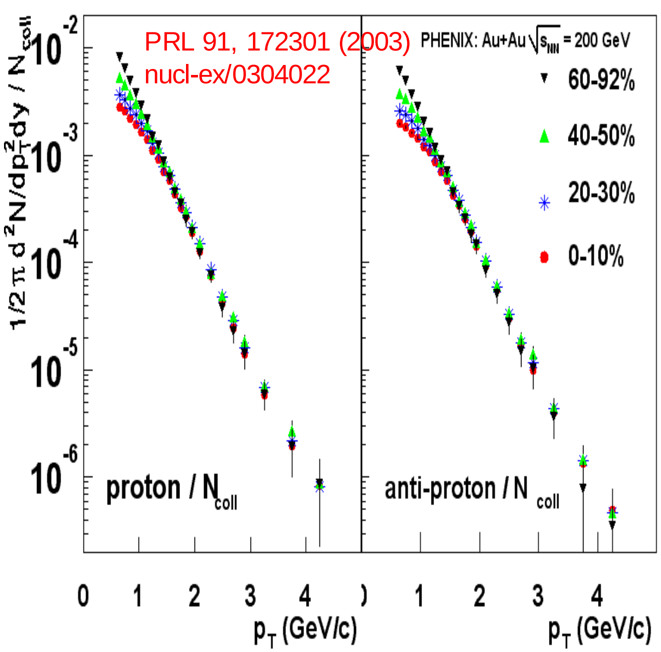
- dN_{ch}/dy (per participant pair) increases faster than linearly with N_{part} :
- Particle density at y=0 well described by pQCD- & CGC- based models alike:
  - ✔ "Soft + hard" (string + pQCD "minijet"): increased hard contribution ($\propto N_{coll}$)
  - ✔ Initial-state gluon saturation (CGC): $dN_{ch}/dy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

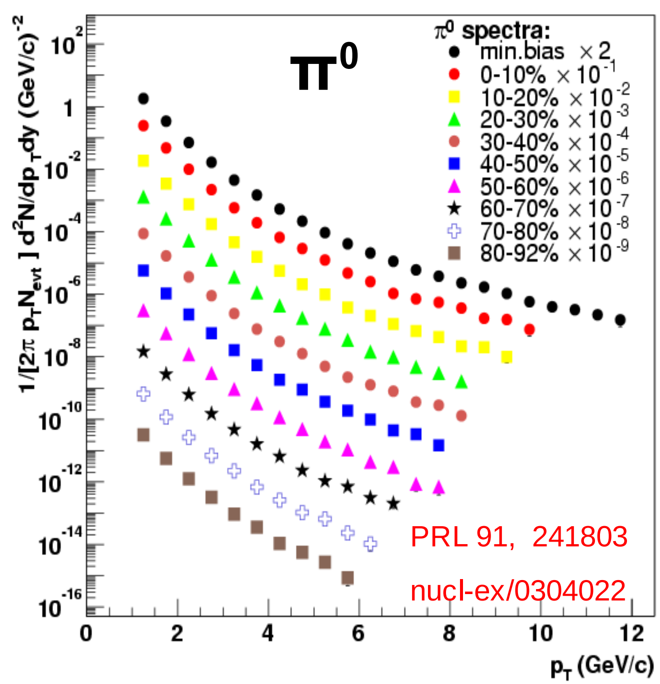
Au+Au: high p_T spectra

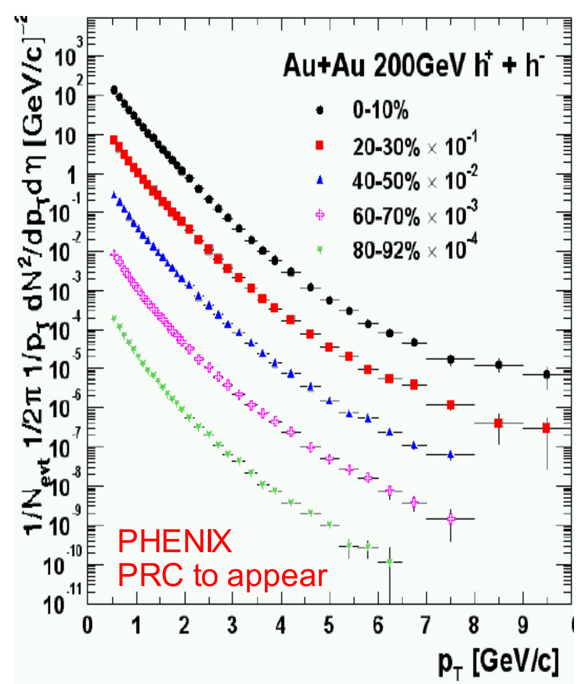




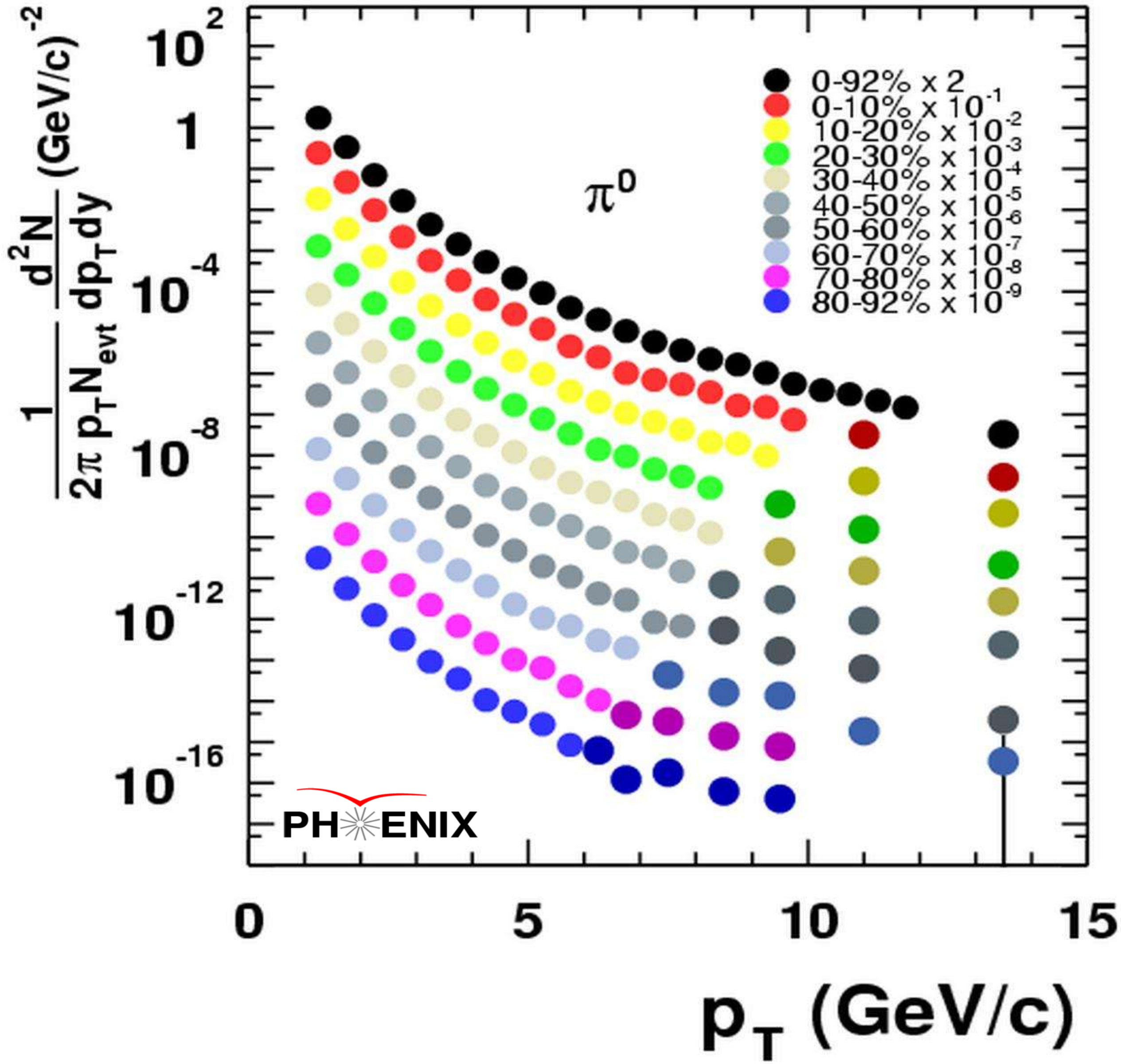








Au+Au: latest π^0 high p_T spectra ...



10 centralities

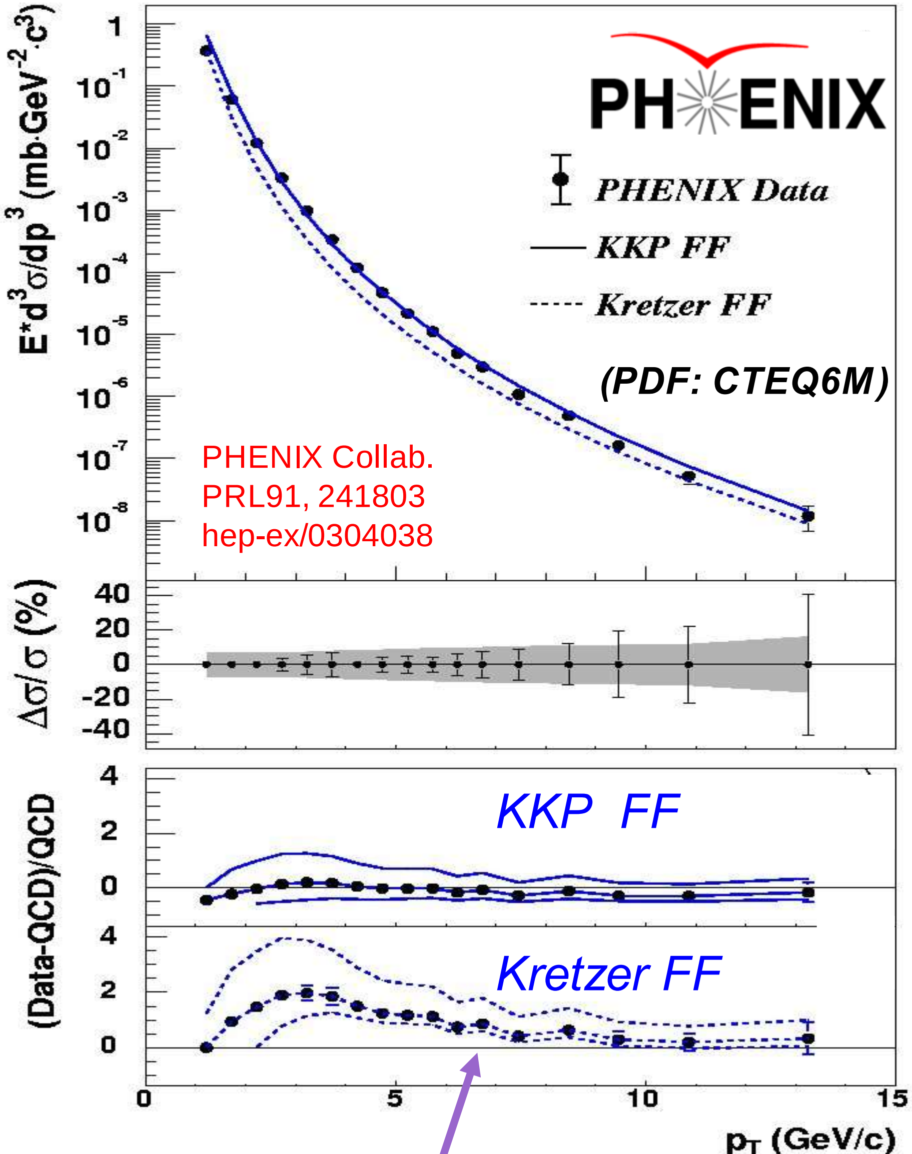
8 orders of magnitude

p_T^{max} = 15 GeV/c

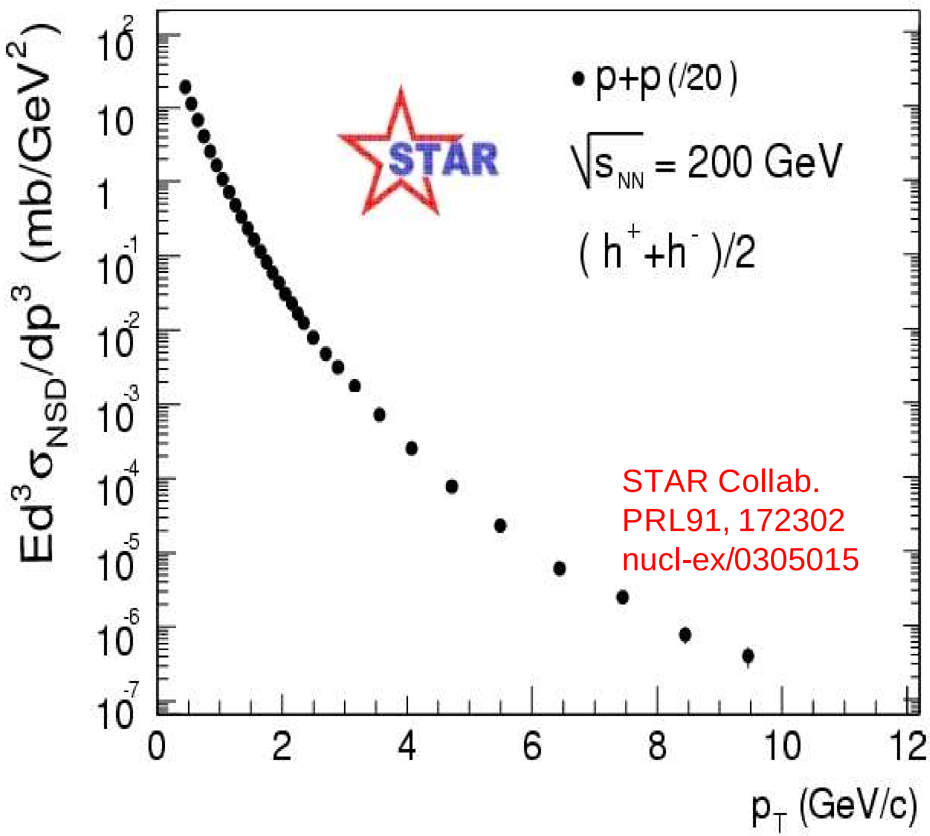
large amount of high quality high p_T data

High p_T p+p @ 200 GeV: “baseline” data

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



$p+p \to h^{\pm} X$ (Non Singly Diffractive)



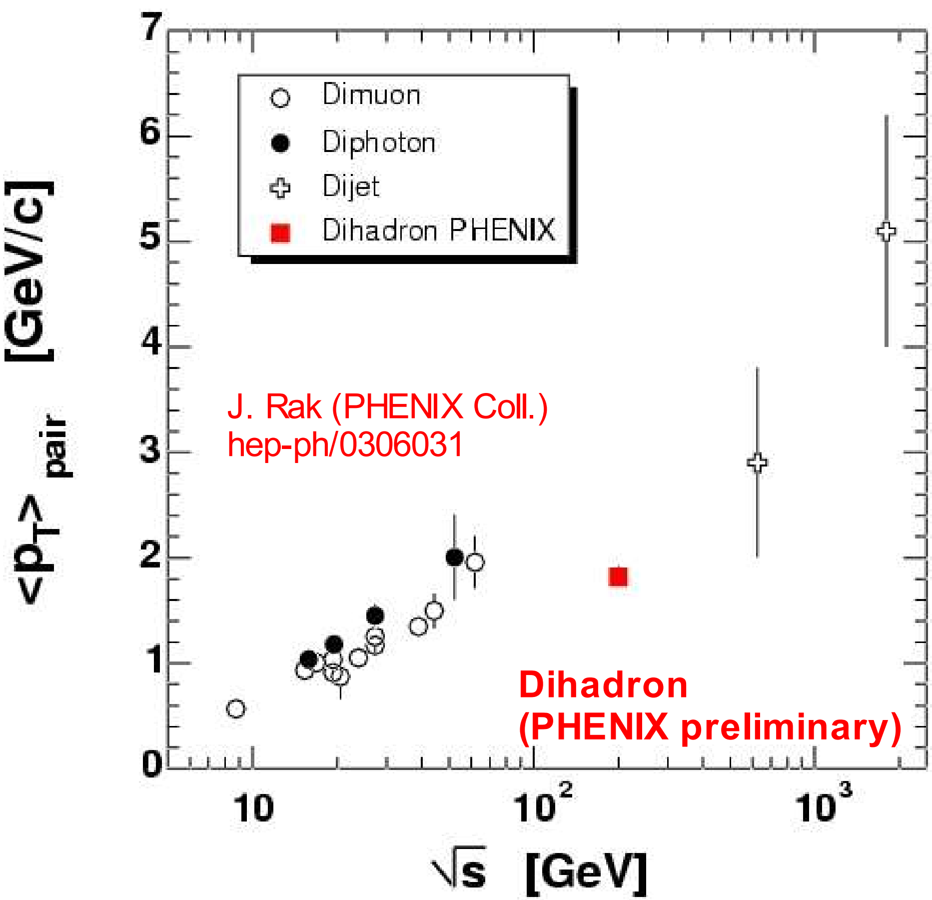
- Well calibrated (experimentally & theoretically) p+p references at hand !

Good theoretical (NLO pQCD) description

Parenthesis (1): p+p physics @ high p_T

p+p→ di-X

Intrinsic $\langle k_T \rangle$ = 725 ± 34 MeV/c



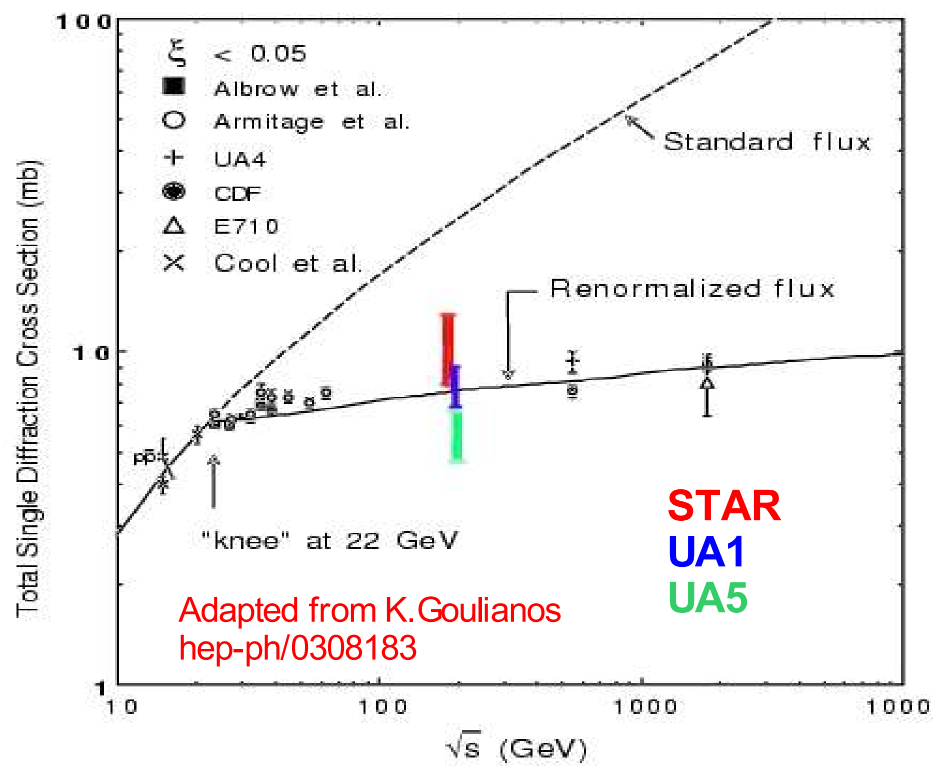
- Jet characterization (k_T, j_T …)

p+p,pbar → $h^{\pm}$ X (Singly Diffractive)

σ_{SD}(STAR) ~ 9 ± 3.5 mb

σ_{SD}(UA1) = 7 ± 1 mb

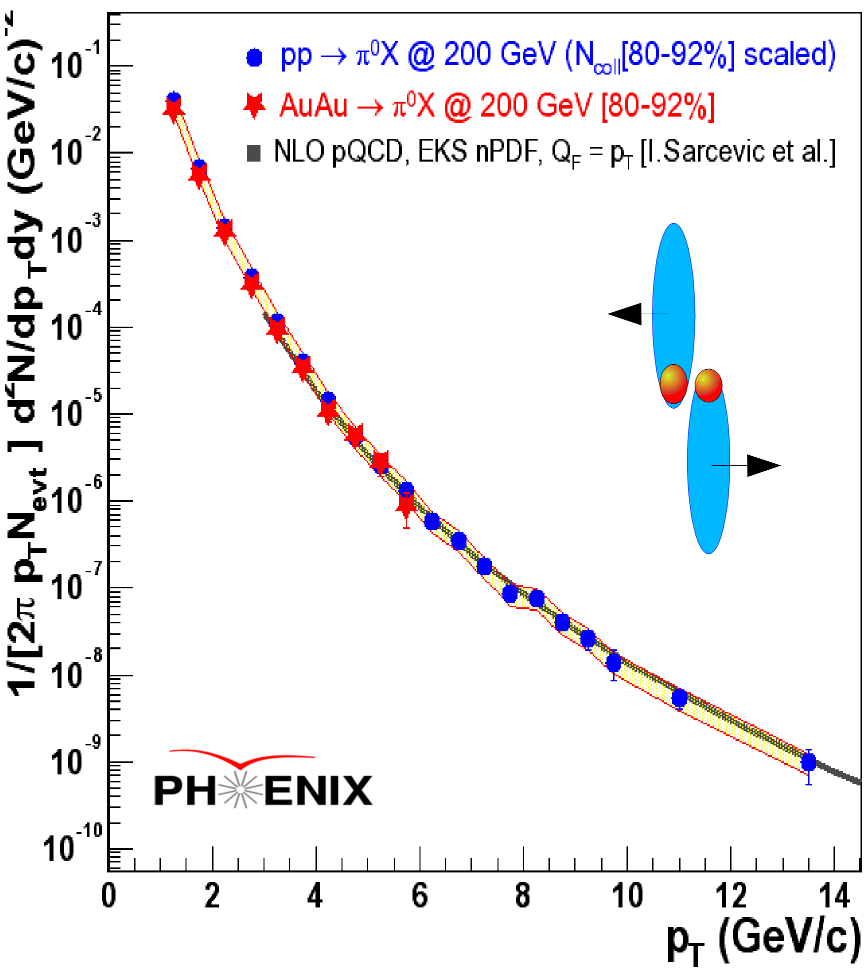
σ_{SD}(UA5) = 4.8 ± 0.9 mb



- Diffractive physics

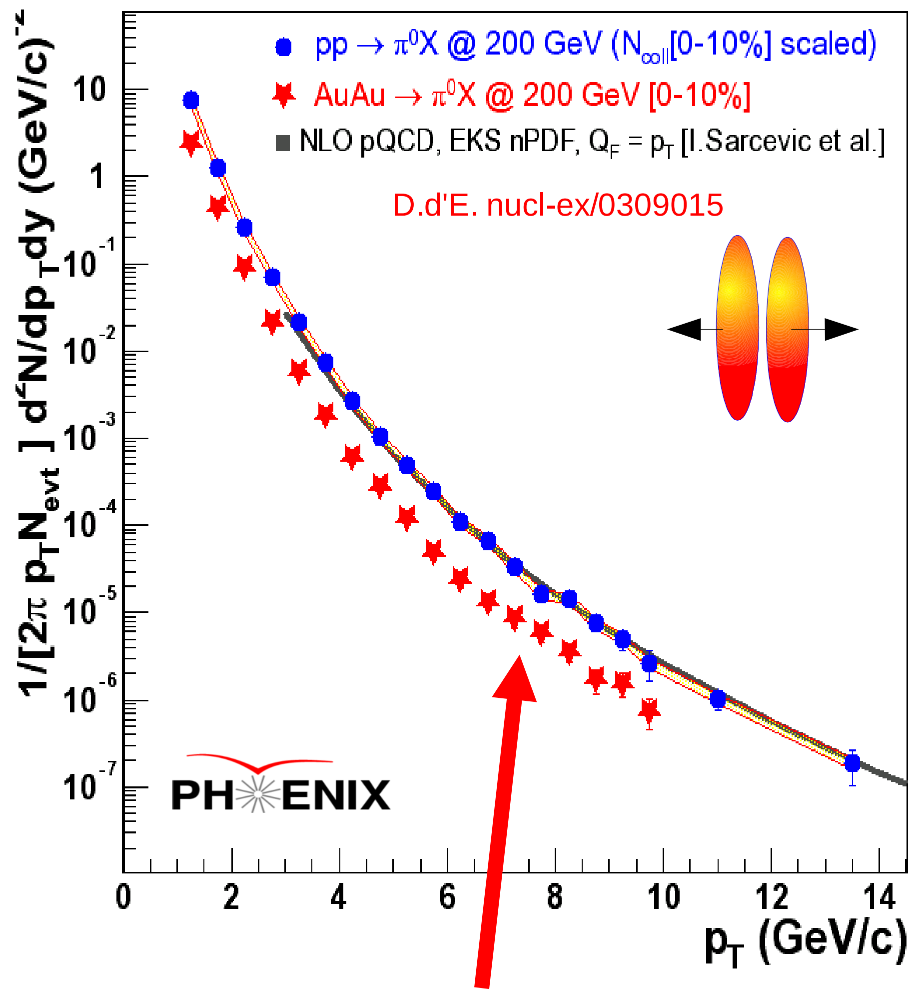
Au+Au *vs.* p+p @ 200 GeV (π^0)

Au+Au→ $\pi^0 X$ (peripheral)



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

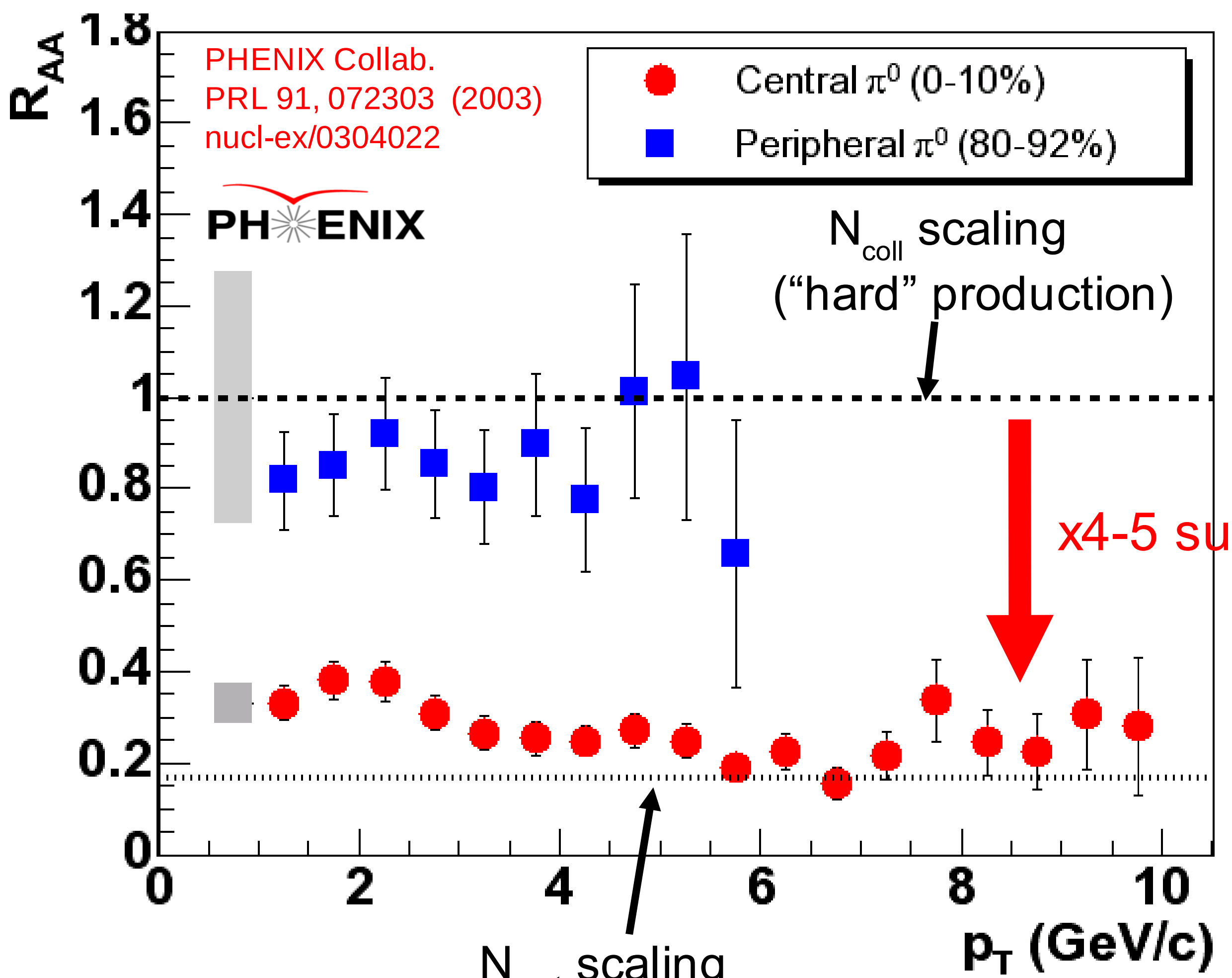
Au+Au→ $\pi^0 X$ (central)



Strong suppression in central Au+Au collisions

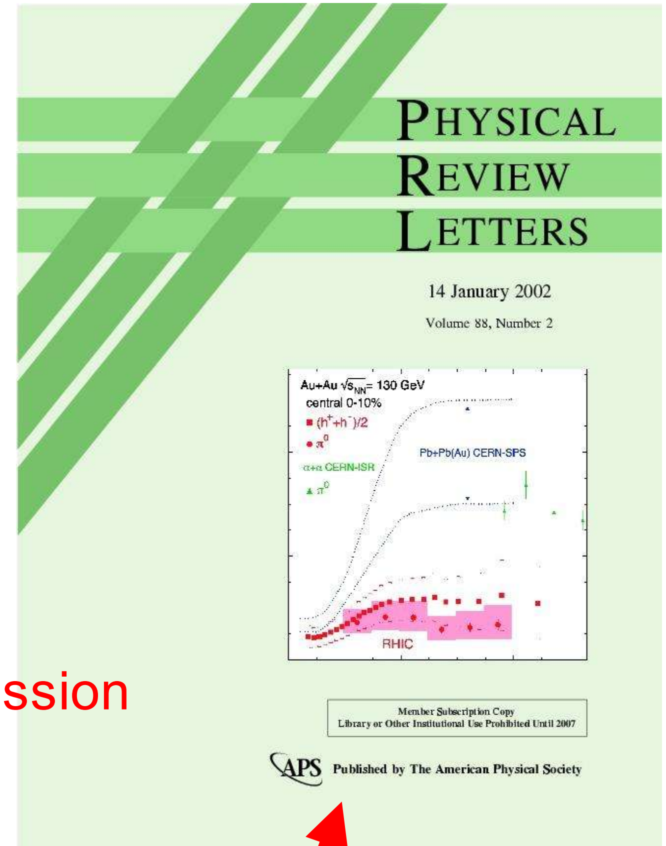
Nuclear modification factor (π^0)

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



x4-5 suppression

N_{part} scaling
("soft" production)

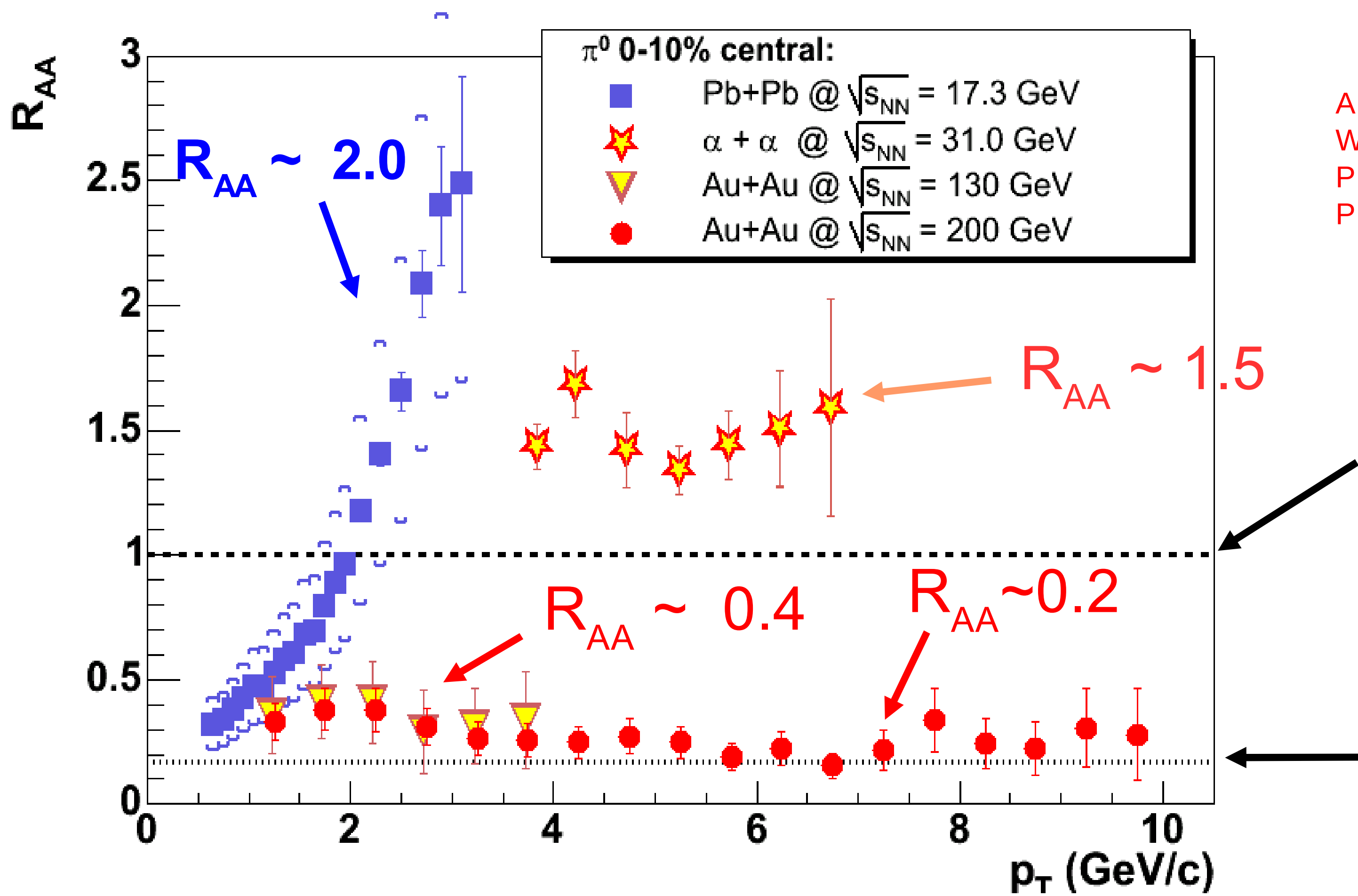


Discovery of
high p_T suppression
(one of most significant results @ RHIC so far)

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

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

- CERN: Pb+Pb ($\sqrt{s_{NN}}$ = 17.3 GeV), $\alpha+\alpha$ ($\sqrt{s_{NN}}$ = 31 GeV): Cronin enhancement.
- RHIC: Au+Au ($\sqrt{s_{NN}}$ = 130, 200 GeV): x 4-5 suppression.

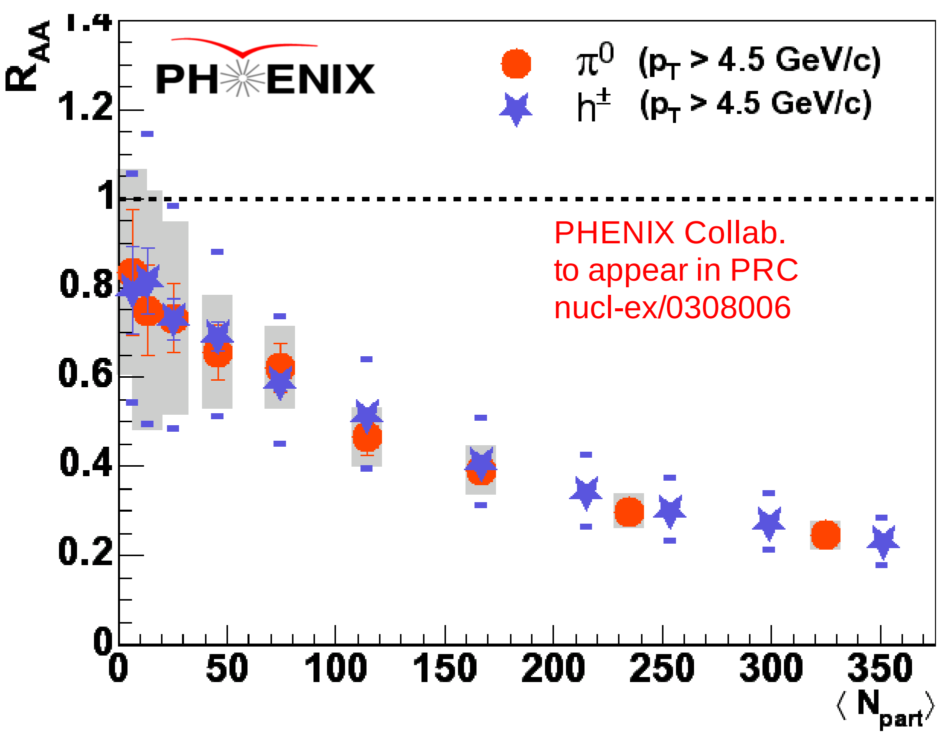


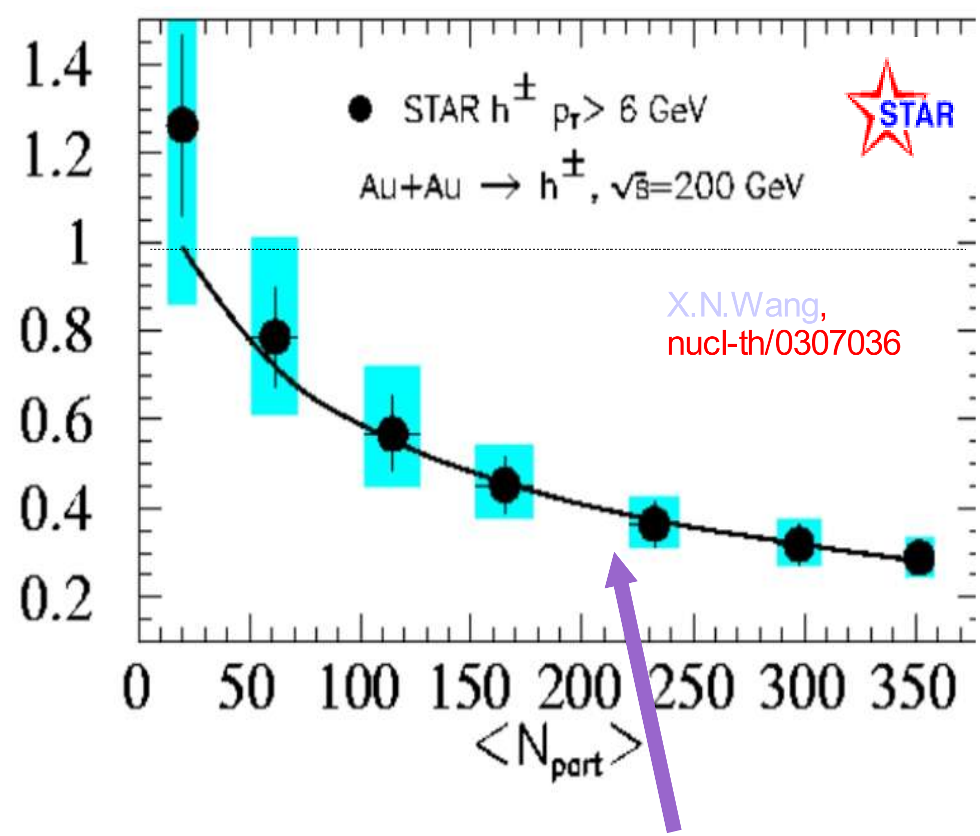
A.L.S.Angelis, PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
PHENIX, PRL 91, 072303 (2003)

High p_T suppression: centrality dependence (I)

back to RHIC energies ....

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



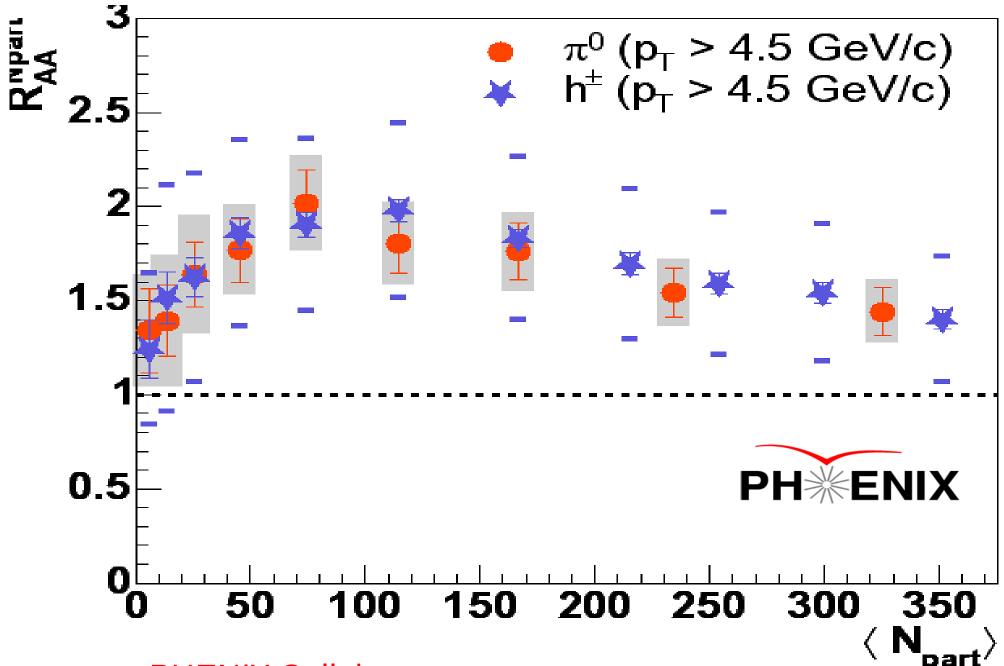


peripheral → central

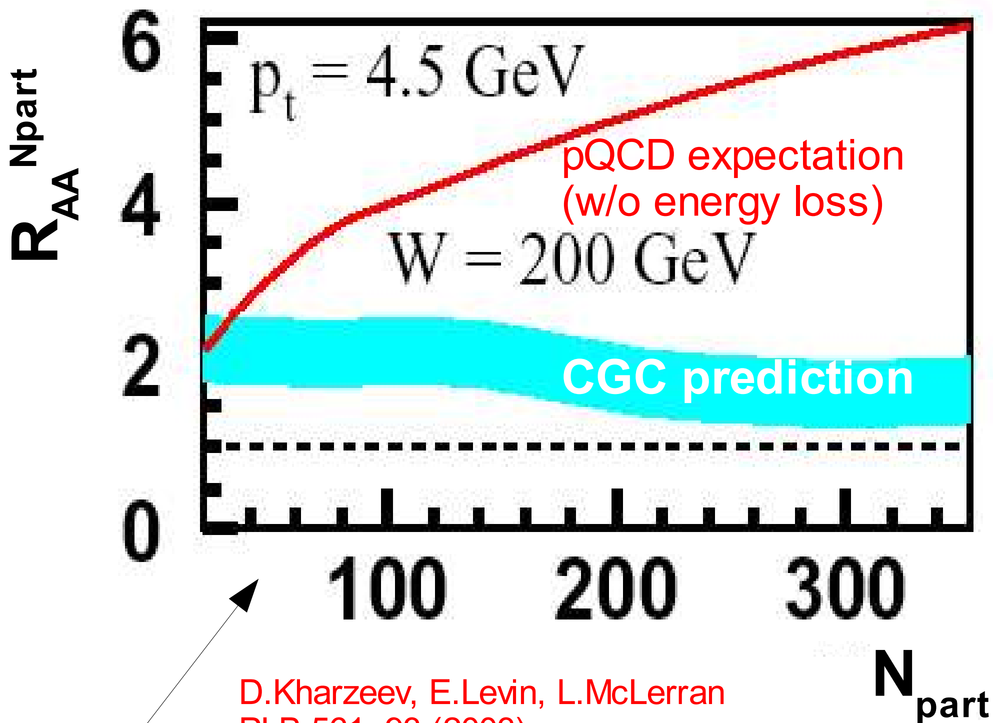
pQCD+partonic ΔE_{loss} (1+1D expansion)

High p_T suppression: centrality dependence (II)

- Let's change the A+A/p+p scaling factor now: N_{coll}(hard) → N_{part}(soft)
- 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

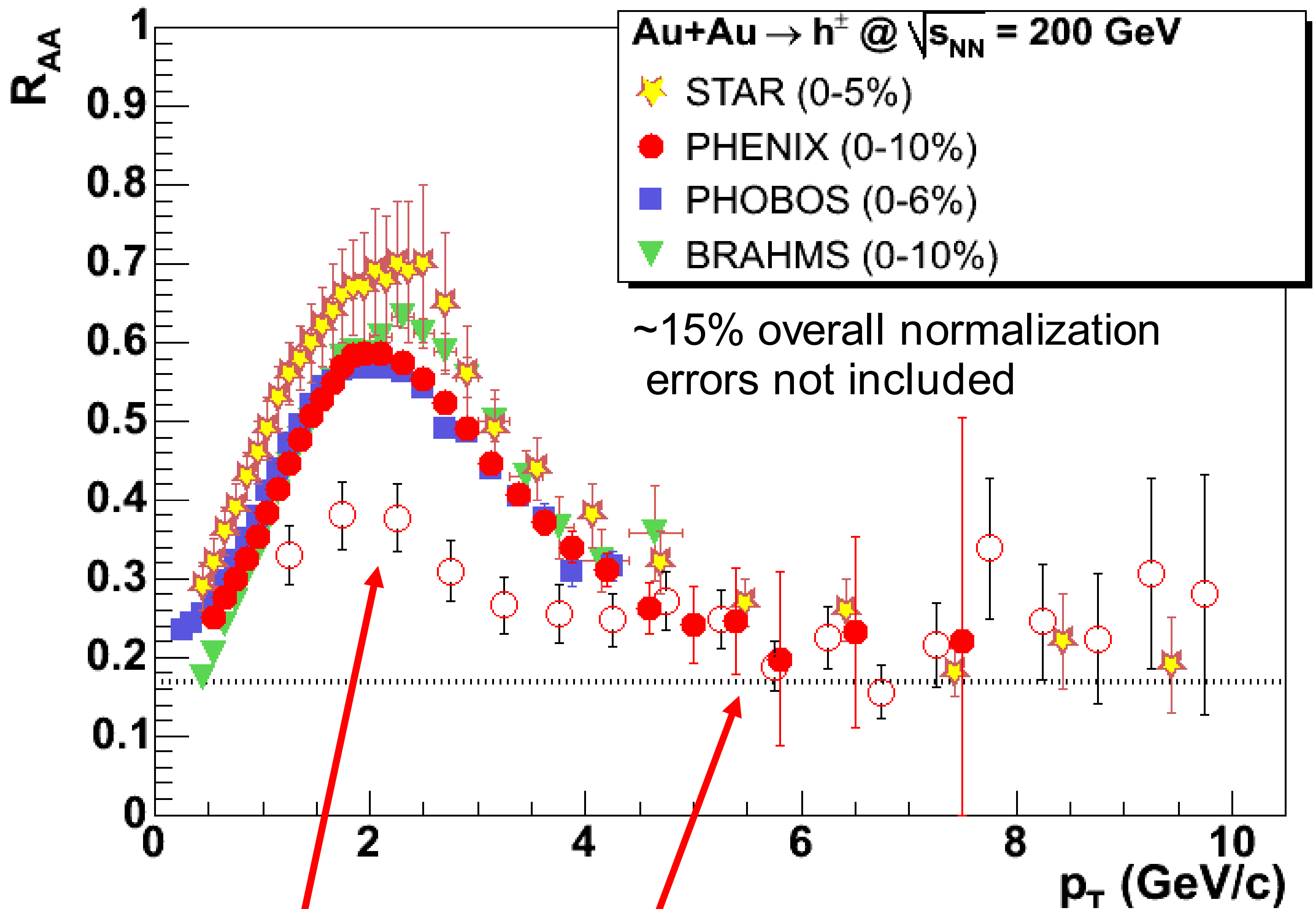


D.Kharzeev, E.Levin, L.McLerran
PLB 561, 93 (2003)

- In accord with Color Glass Condensate predictions too

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

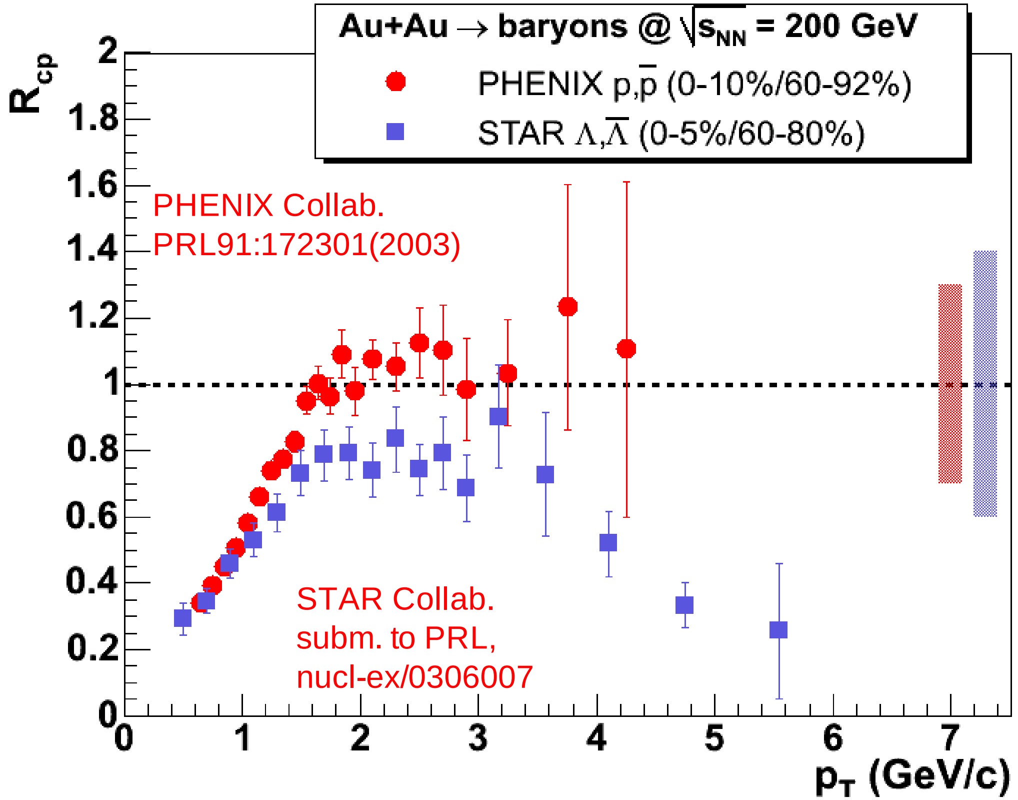
- Inclusive charged hadrons suppressed a factor ~ 4 – 5 at p_T> 5 GeV/c

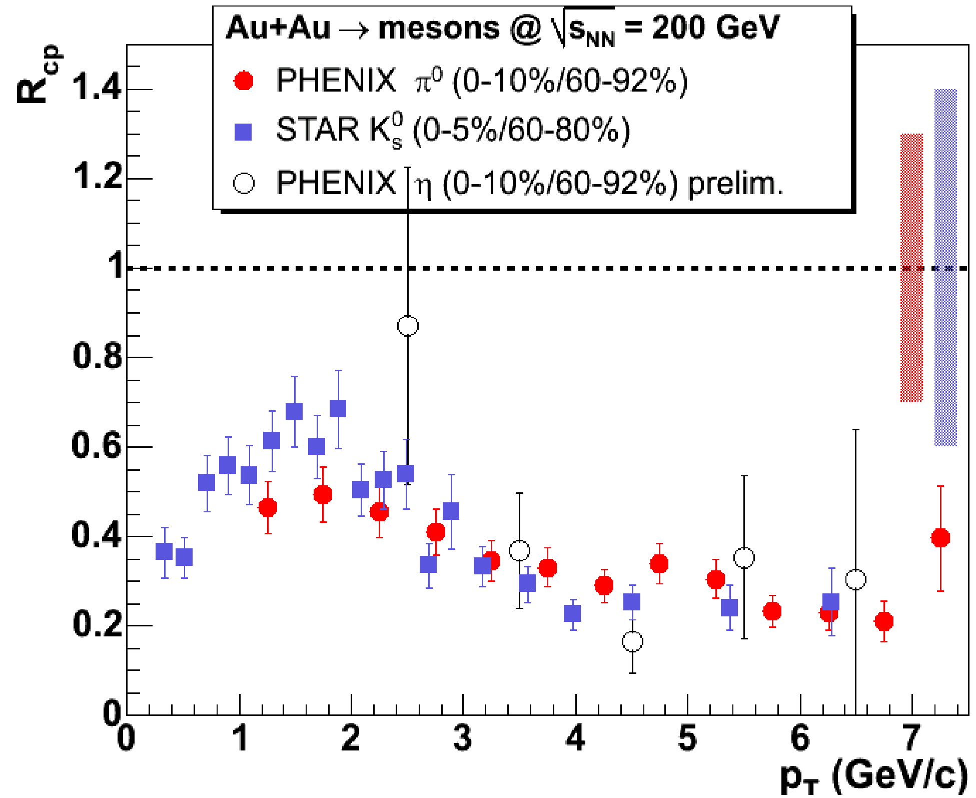


- ... but less suppressed than π^0 within p_T = 2 – 5 GeV/c.
- Universal (PID-wise) suppression above p_T = 5 GeV/c

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** suppressed in central Au+Au.
  2. Mesons: π^0, k^0_s, η equally suppressed.

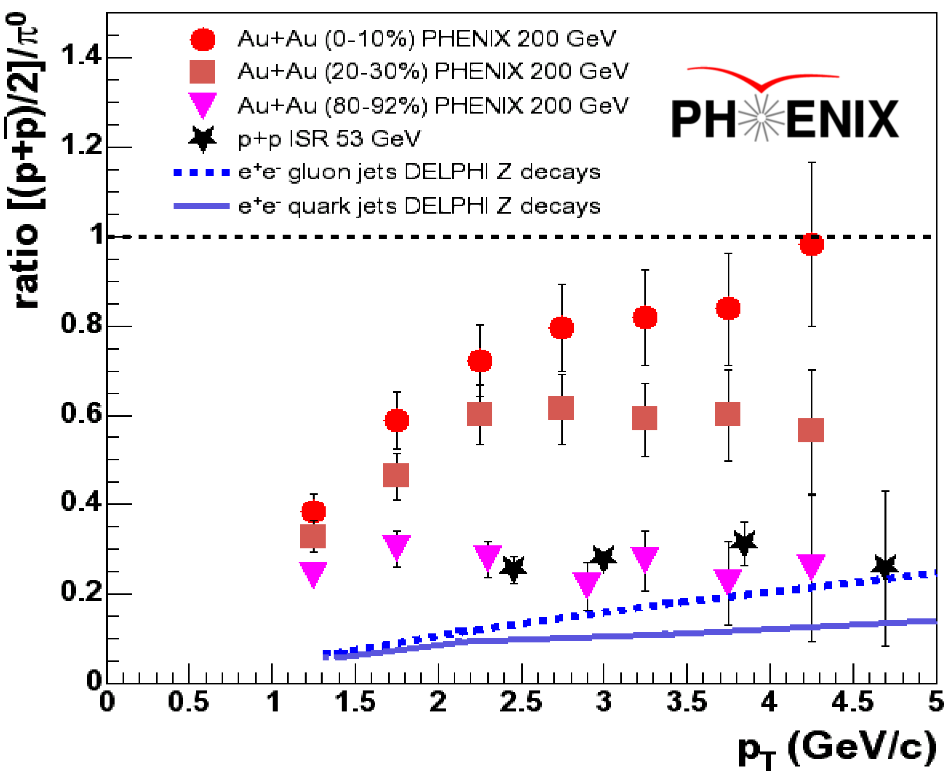


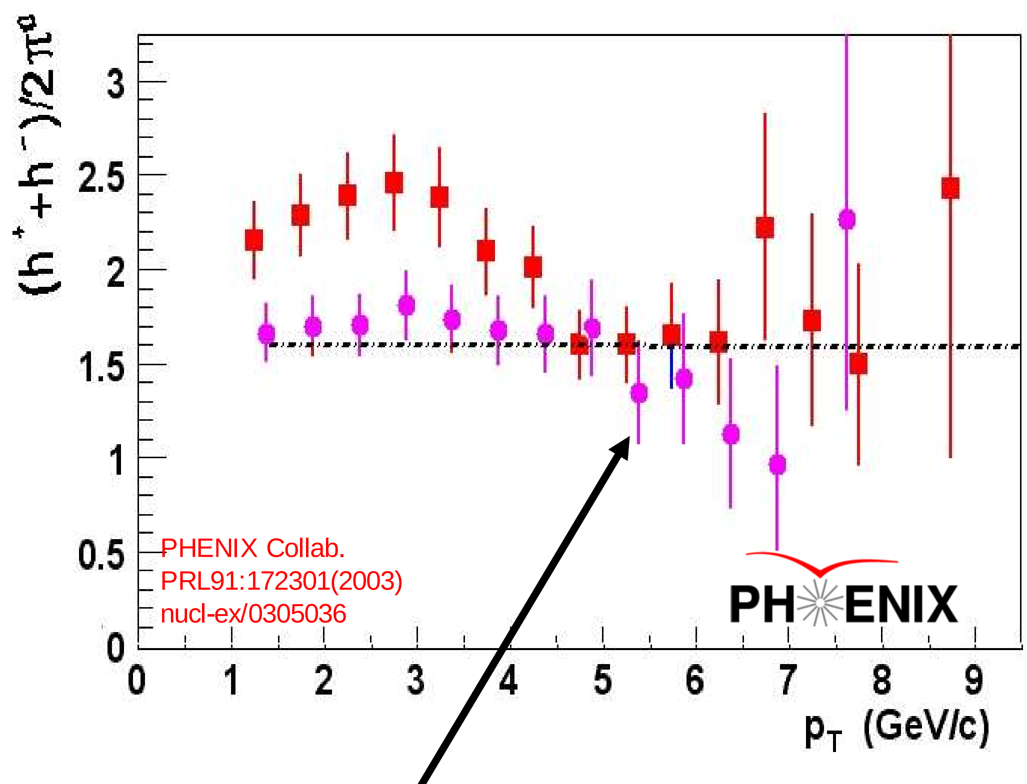


- Particle composition inconsistent with known fragmentation functions.
- Different production mechanism for baryons and mesons in the intermediate p_T range (recombination vs. fragmentation ?).

High p_T suppression - Particle dependence (III): p/π, $h^{\pm}$/π

- Central colls.: p/π ~ 0.8 (at p_T = 2 - 4 GeV/c) at variance with perturbative production mechanisms (favour lightest meson).
- Periph. colls.: p/π ~ 0.2 as in p+p,p (ISR,FNAL) & in e+e- jet fragmentation

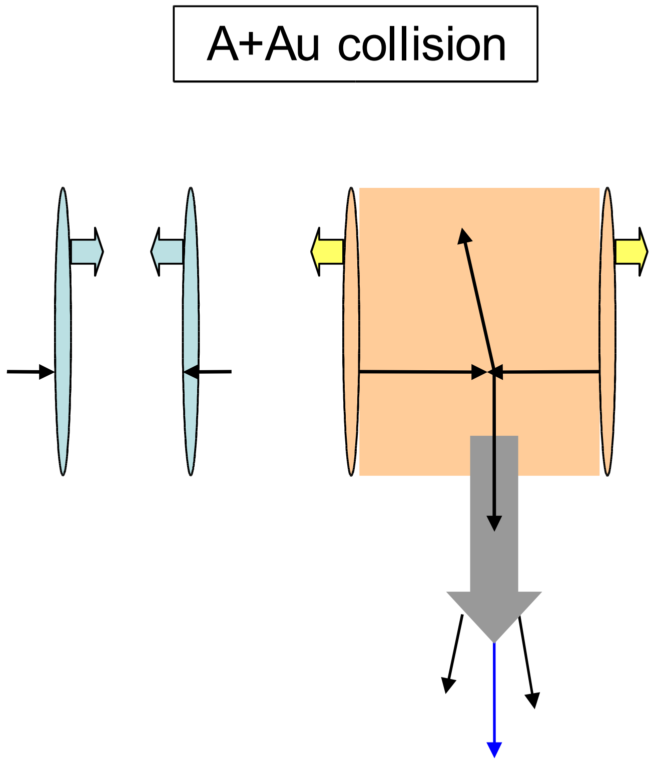


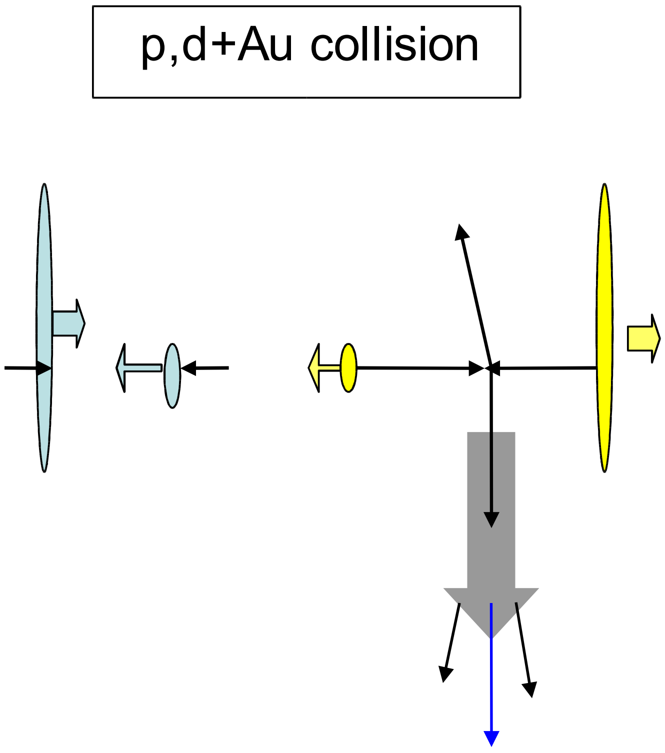


- Baryon enhancement limited to p_T < 4.5 GeV/c: Charged hadron ($h^{\pm} = \pi^{\pm}$ + p (pbar) + $K^{\pm}$) and π^0 equally suppressed above p_T ~ 5 GeV/c:

  h/π ~ 1.6 as in p+p (perturbative ratio)

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





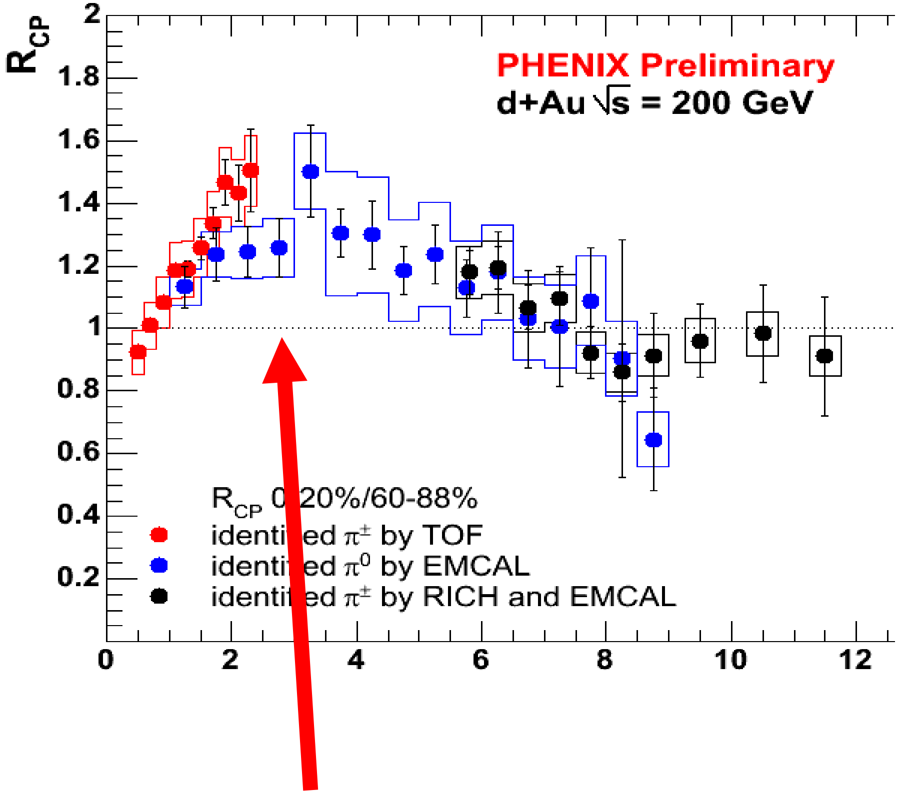
hot & dense medium
(initial+final-state effects)

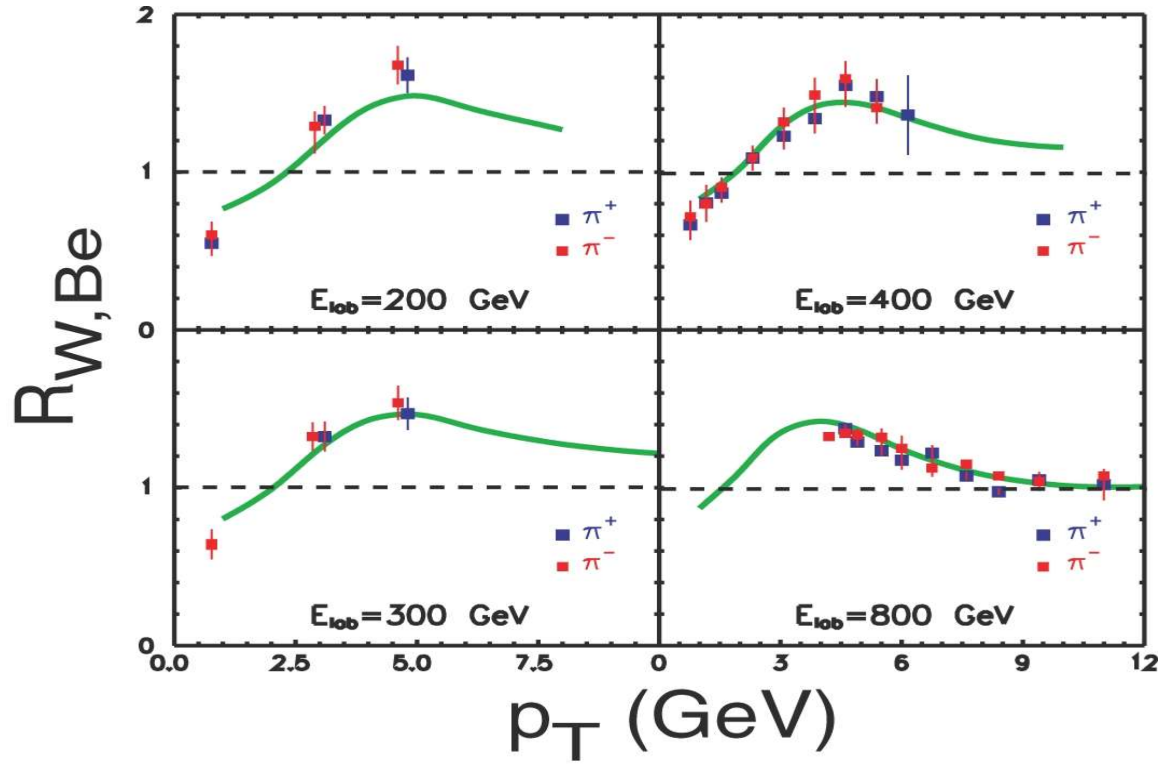
cold medium
(initial- state effects only)

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

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

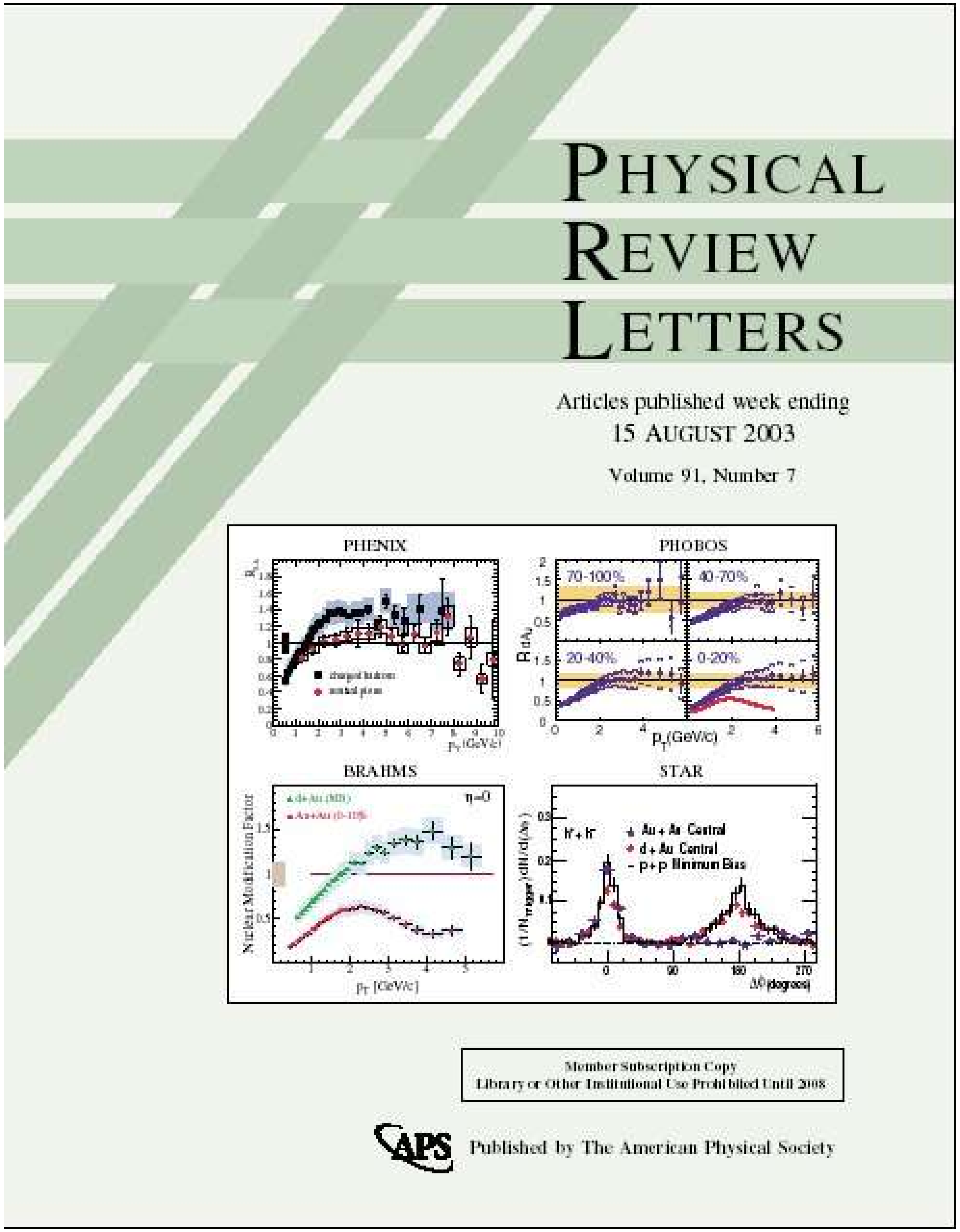
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



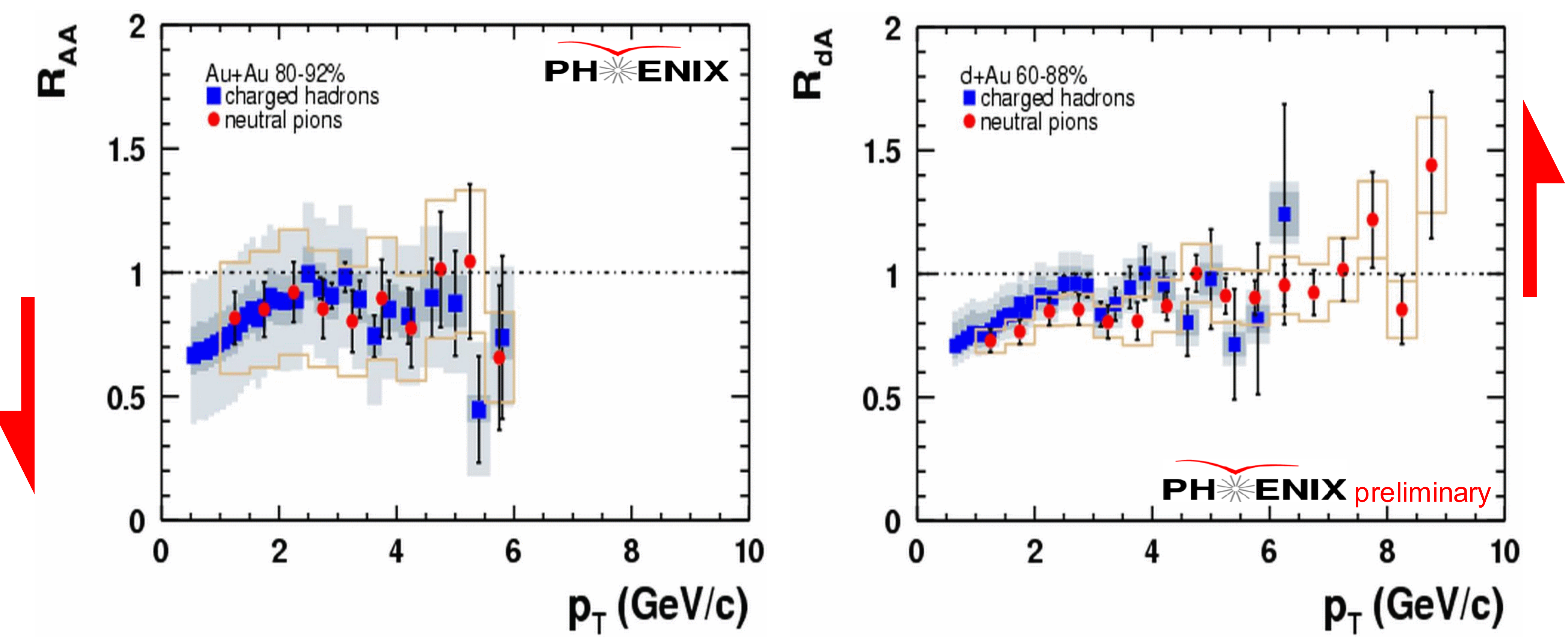


- High p_T d+Au unquenched ! $R_{dAu} > 1$.
- Reminiscent of p+A "Cronin enhancement" (initial-state soft & semihard scattering).
- No Au gluon saturation effects in kinematic region probed (y= 0).

d+Au nuclear modification factor

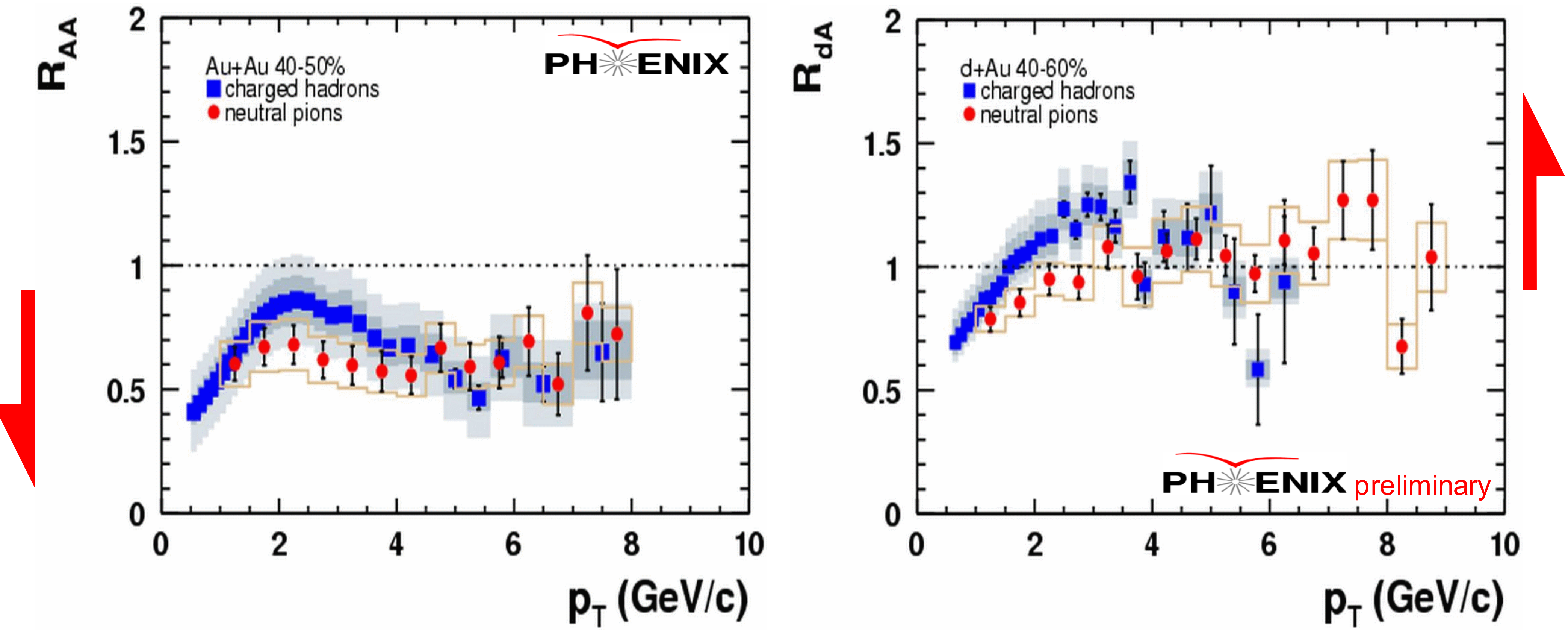


R_{AA} vs. R_{dA} (y = 0) : centrality dependence



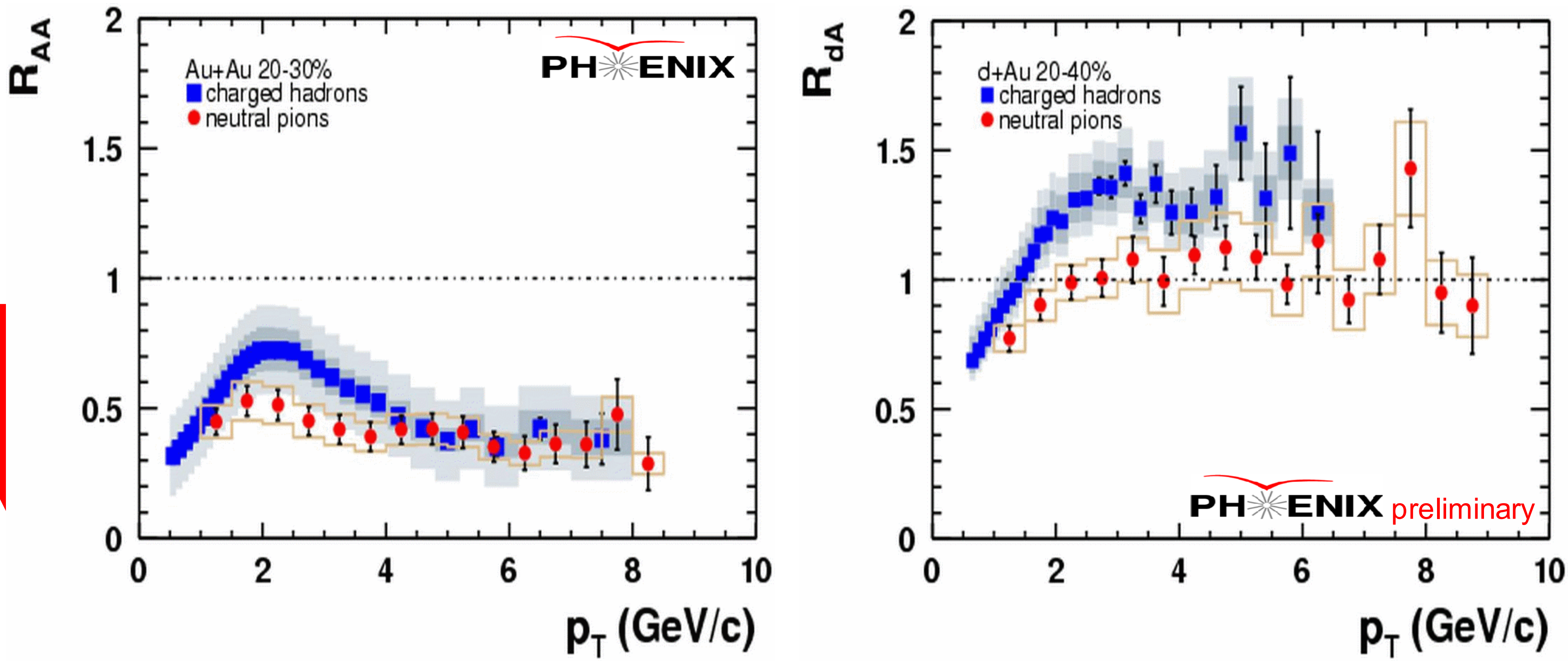
- PERIPHERAL Au+Au & d+Au

R_{AA} vs. R_{dA} (y = 0) : centrality dependence



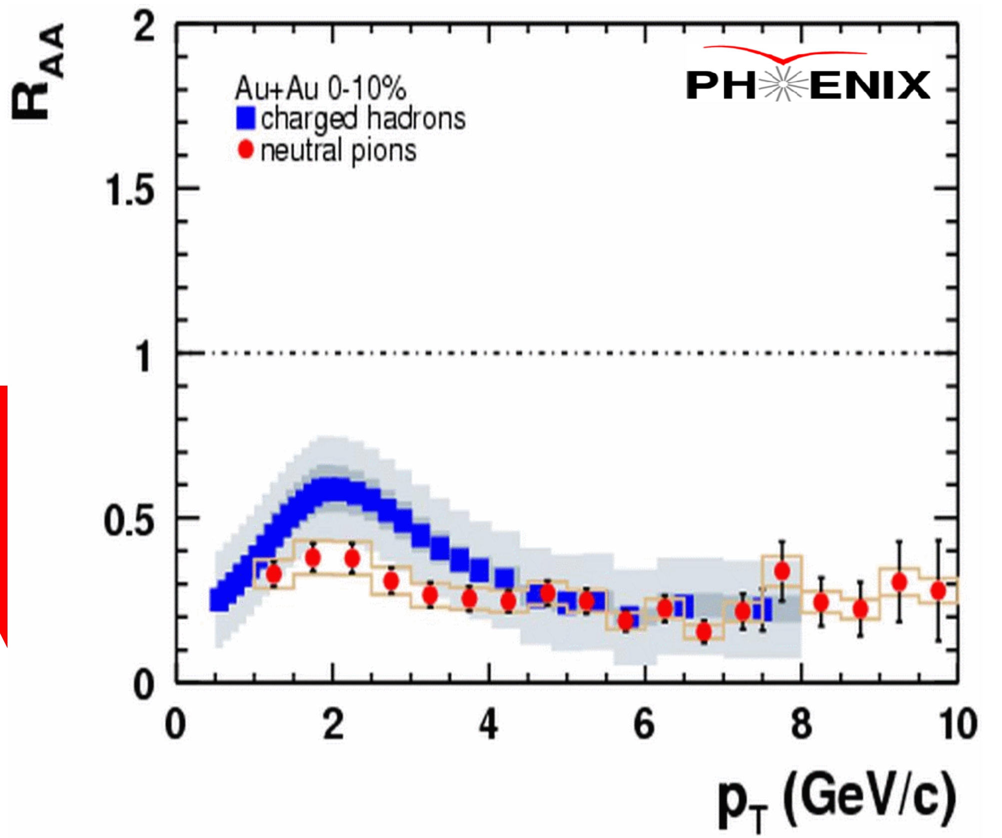
- MID-PERIPHERAL Au+Au & d+Au

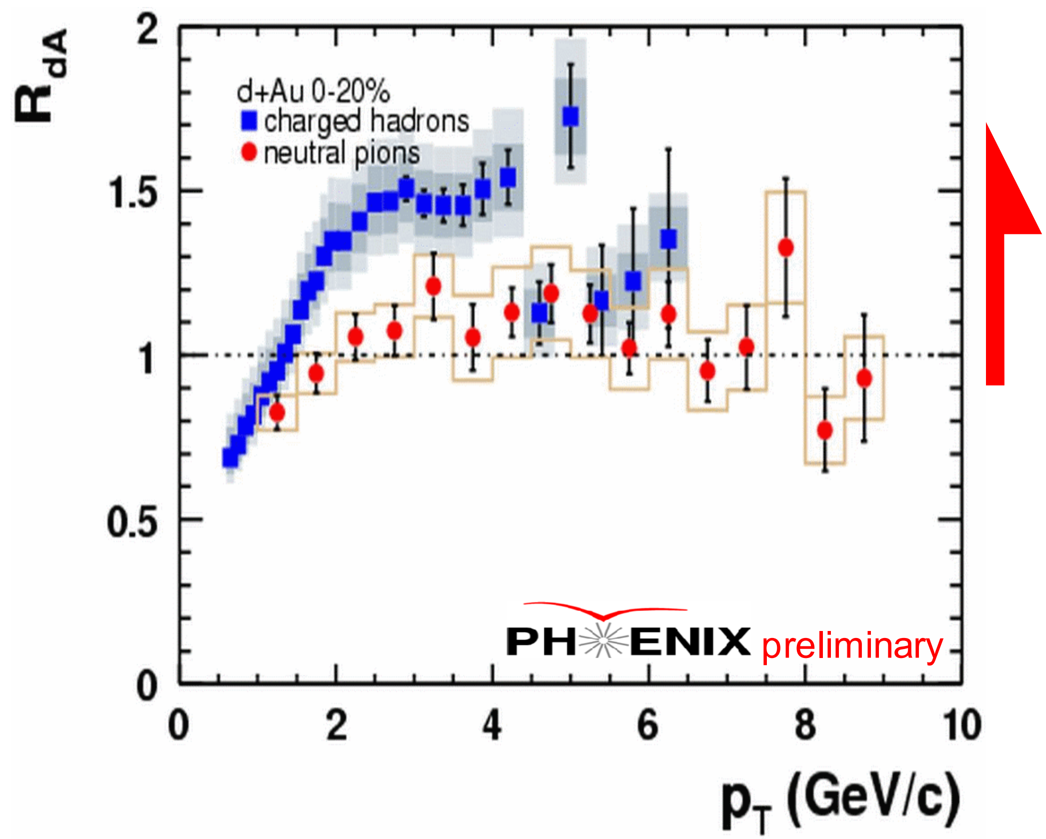
R_{AA} vs. R_{dA} (y = 0) : centrality dependence



- MID-CENTRAL Au+Au & d+Au

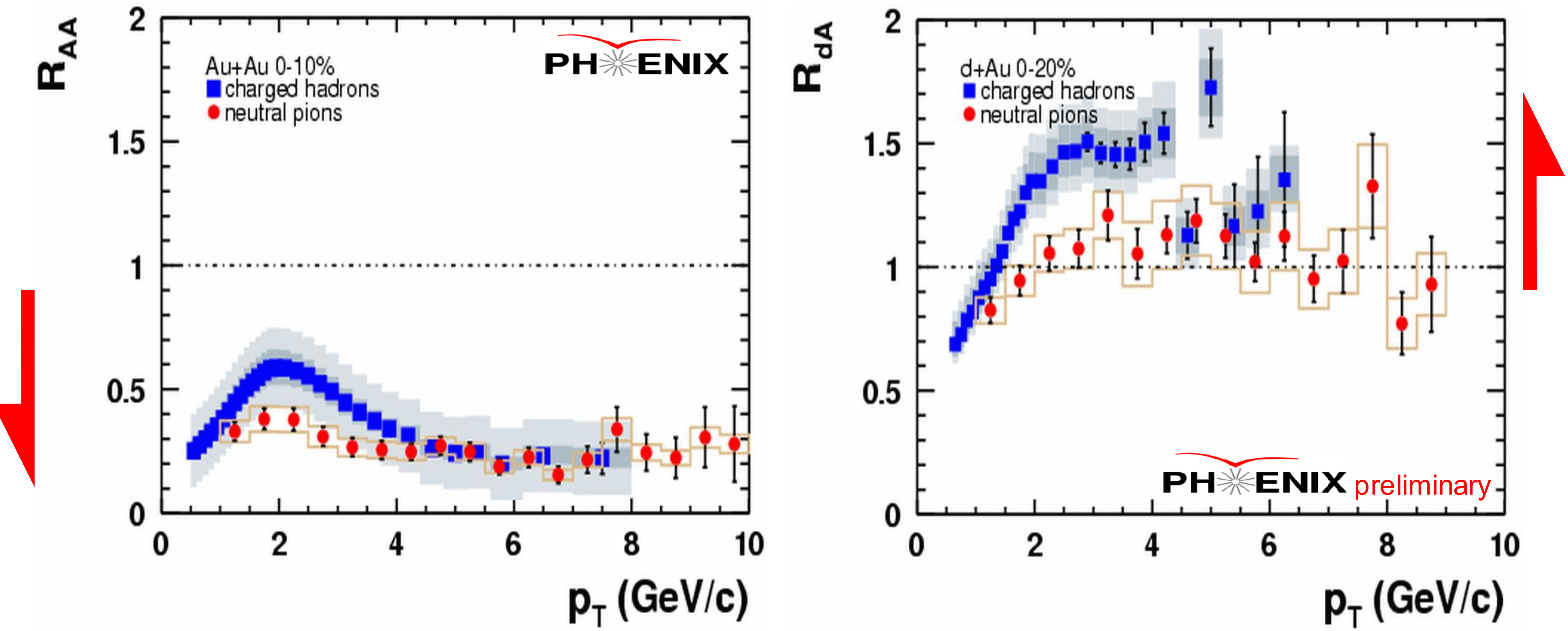
R_{AA} vs. R_{dA} (y = 0) : centrality dependence





- CENTRAL Au+Au & d+Au

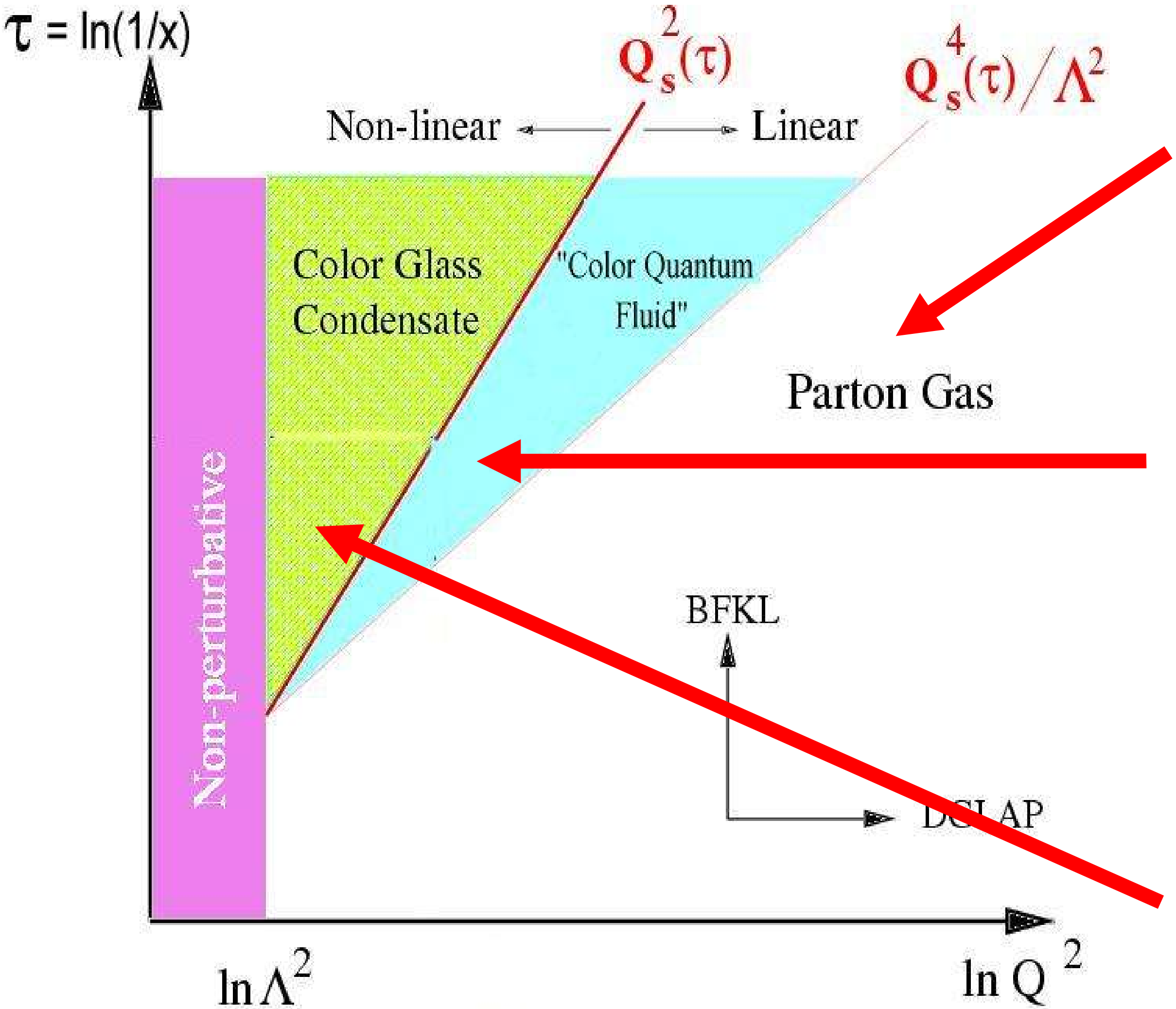
R_{AA} vs. R_{dA} (y = 0) : centrality dependence



- Opposite centrality dependence of d+Au nuclear enhancement compared to Au+Au nuclear suppression.
- (Model-independent) conclusion: Au+Au suppression at y = 0 not due to a "cold" (initial-state) nuclear matter effect: gluon saturation effects not relevant, final-state (QGP) interpretation favoured.

The quest for gluon saturation effects @ RHIC ...

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



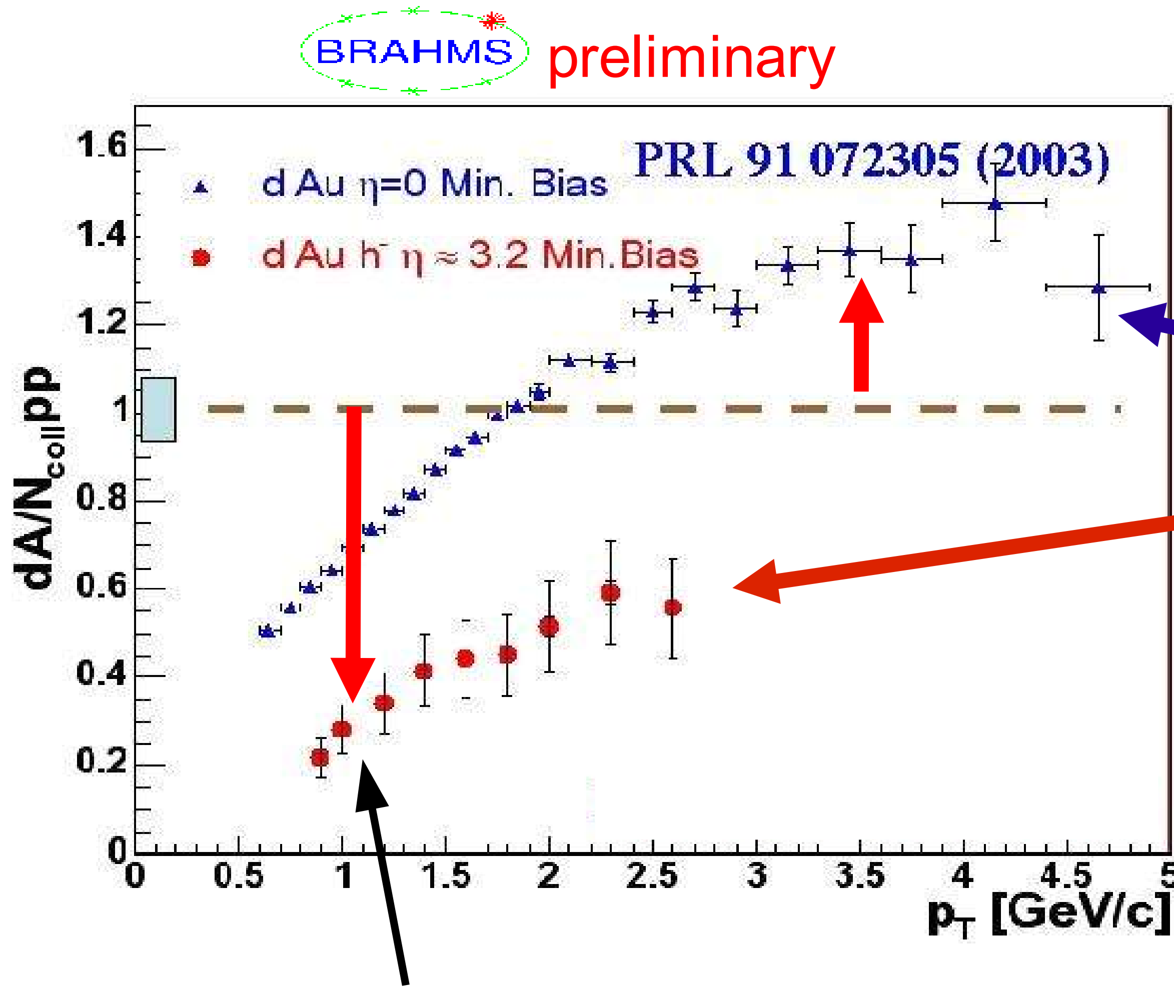
RHIC kinematical regime:

- **High p_T @ midrapidity:**
  $y = 0$, $Q^2 = 1\text{-}100\ \mathrm{GeV^2/c^2}$
  - pQCD collinear factorization
  - DGLAP evolution (g splitting)
  - small (~20%) nuclear effects in PDFs (LT shadowing).

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

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

d+Au nuclear modification factor (η = 3.2)



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

for p_T=2 GeV/c:

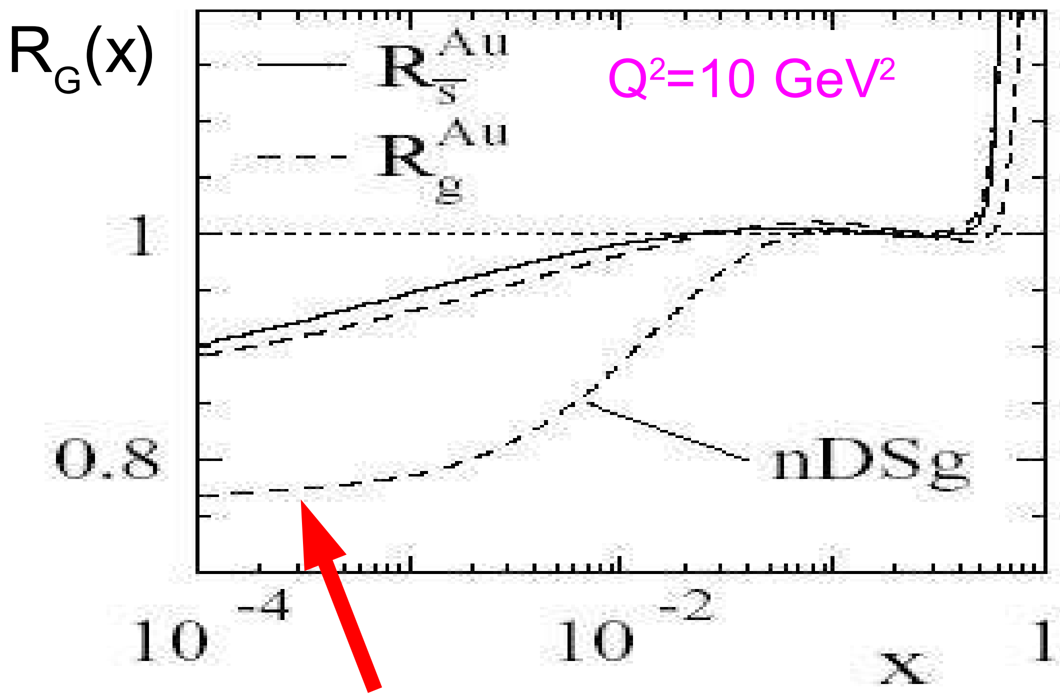
η = 0. (x ≈ 10^{-2})

η = 3.2 (x ≈ $5\cdot10^{-4}$)

- Significant suppression (factor ~2-3) of moderately high p_T hadro-production at η = 3.2 (small x_2 in Au).
- First time a large suppression is seen at small-x and high p_T
- Qualitative agreement with gluon saturation / strong shadowing effects.

why the excitement in some circles...

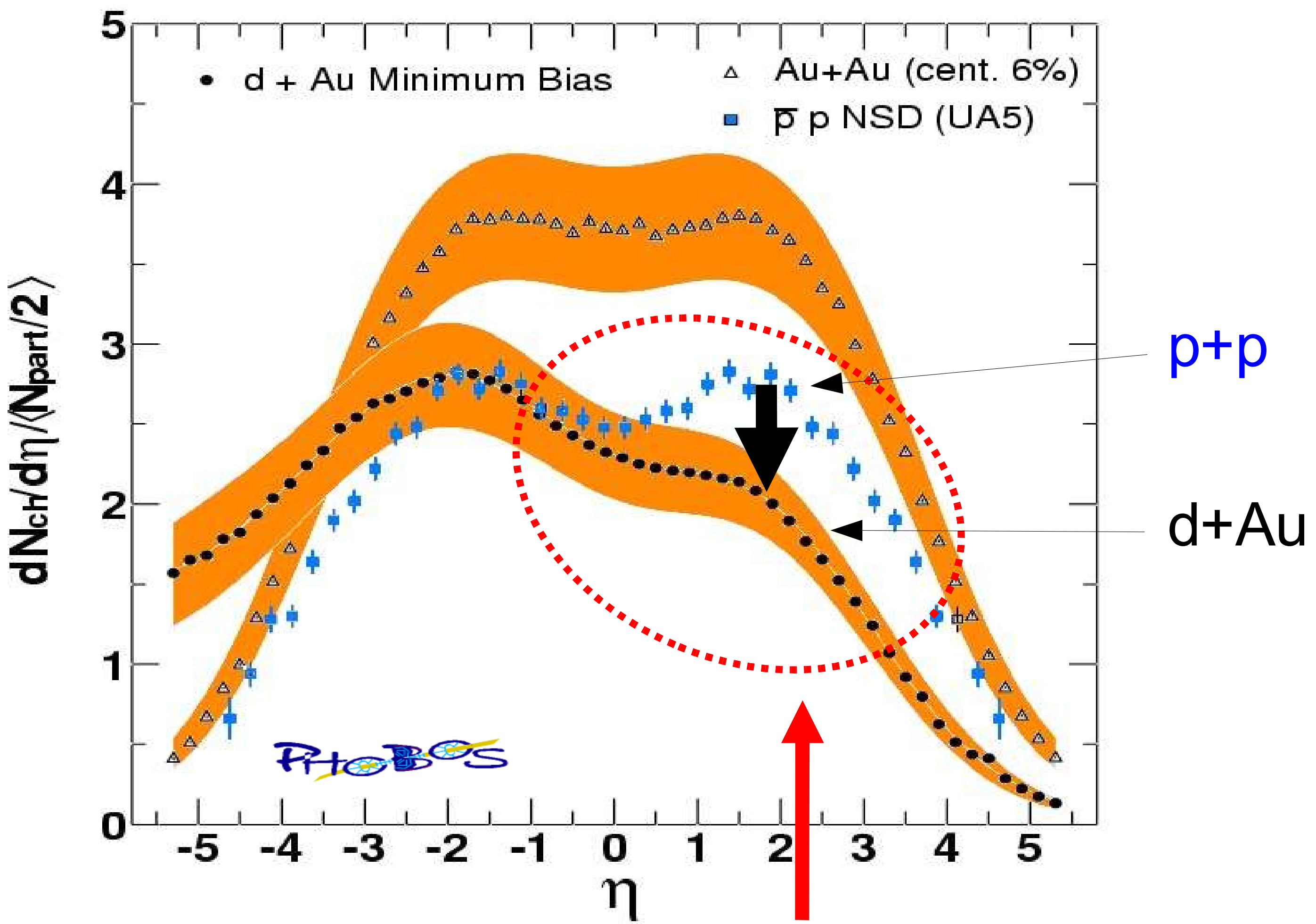
- Take the predictions of a standard "leading twist" approach ...
- NLO DGLAP global analysis of nuclear PDFs (fit to ~450 experimental points from e,μ+A, p+A Drell-Yann data):



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

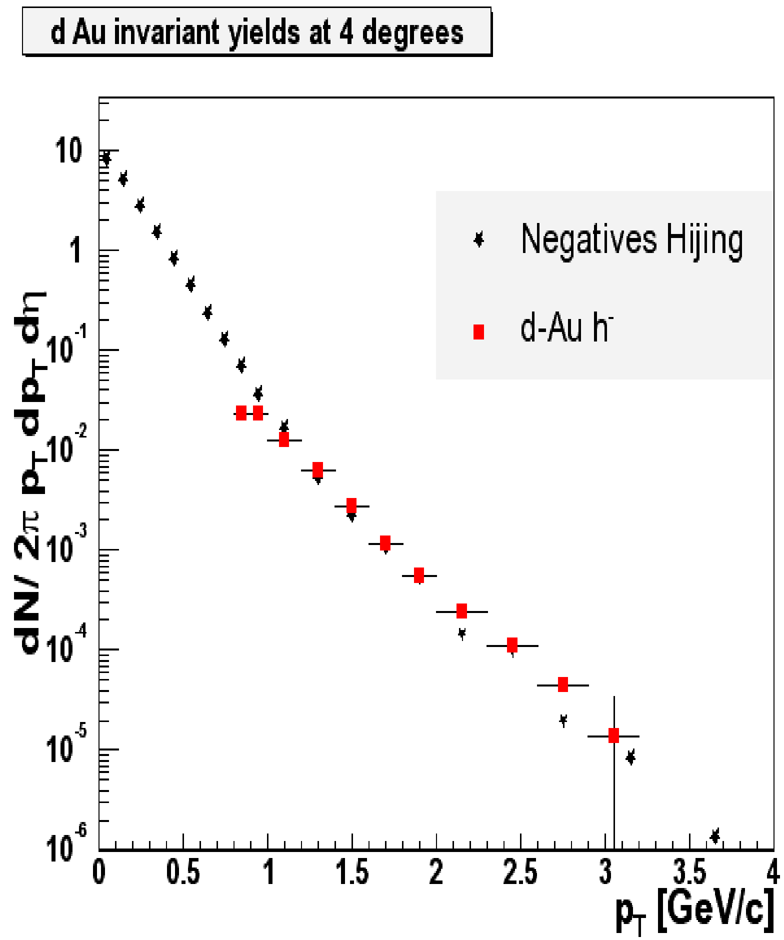
- Maximum gluon shadowing at $x \sim 10^{-4}$ (indirectly) constrained by all available DIS data on nuclear targets is ~0.8
- IF indeed $R_G(x=10^{-4}) \approx 0.4$ (as suggested by BRAHMS), this could be an evidence of breakdown of QCD factorization at high p_T (due to high twist effects at small-x).

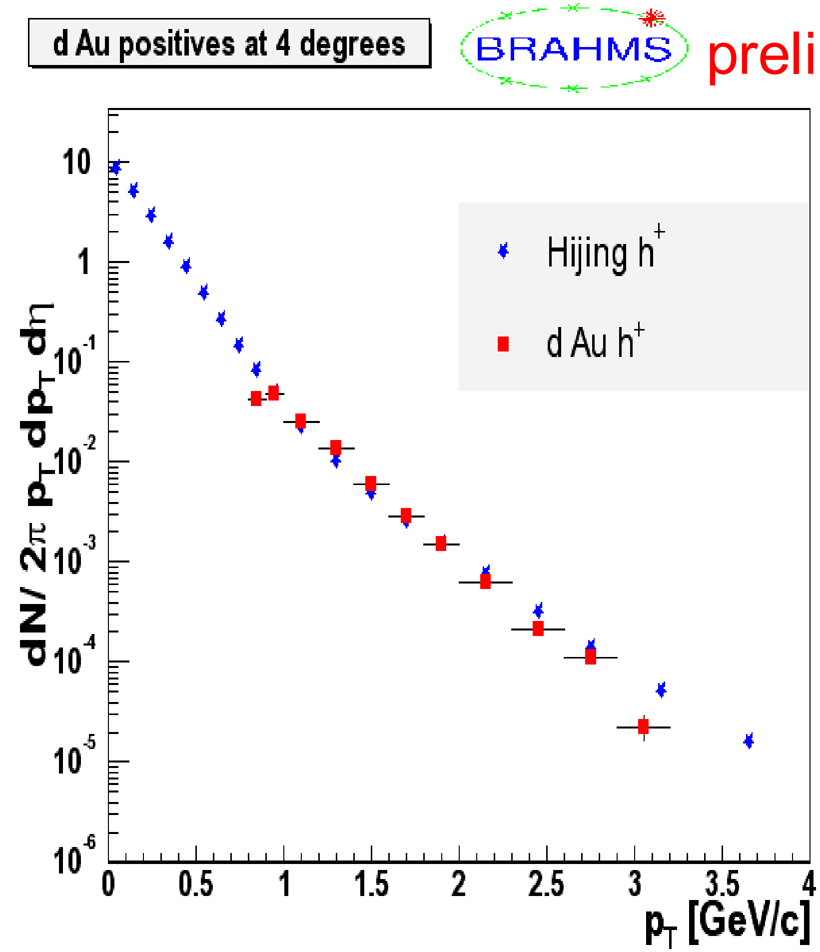
but (1) ... soft production is also suppressed in d+Au



- Particle multiplicities (low p_T) in d+Au well below expectations from $N_{part\ tot}$ scaling compared to p+p at forward rapidities (d fragmentation) ! Well known from p+A at lower sqrt(s). How this affect high p_T production?
- Bottom line: Be careful with blind application of "usual" scaling laws for particle production at forward rapidities in asymmetric systems !

but (2) ... valence q (not g) dominate BRAHMS data





BRAHMS preliminary

- h+ > h- : deuteron valence quarks (high x_1) dominate over “wee” gluons from Au (small x_2).
- (Personal) Conclusion: It's premature to claim $R_{Gluon}(x=10^{-4}) \approx 0.4$
  It's premature to claim CGC effects at RHIC.

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.

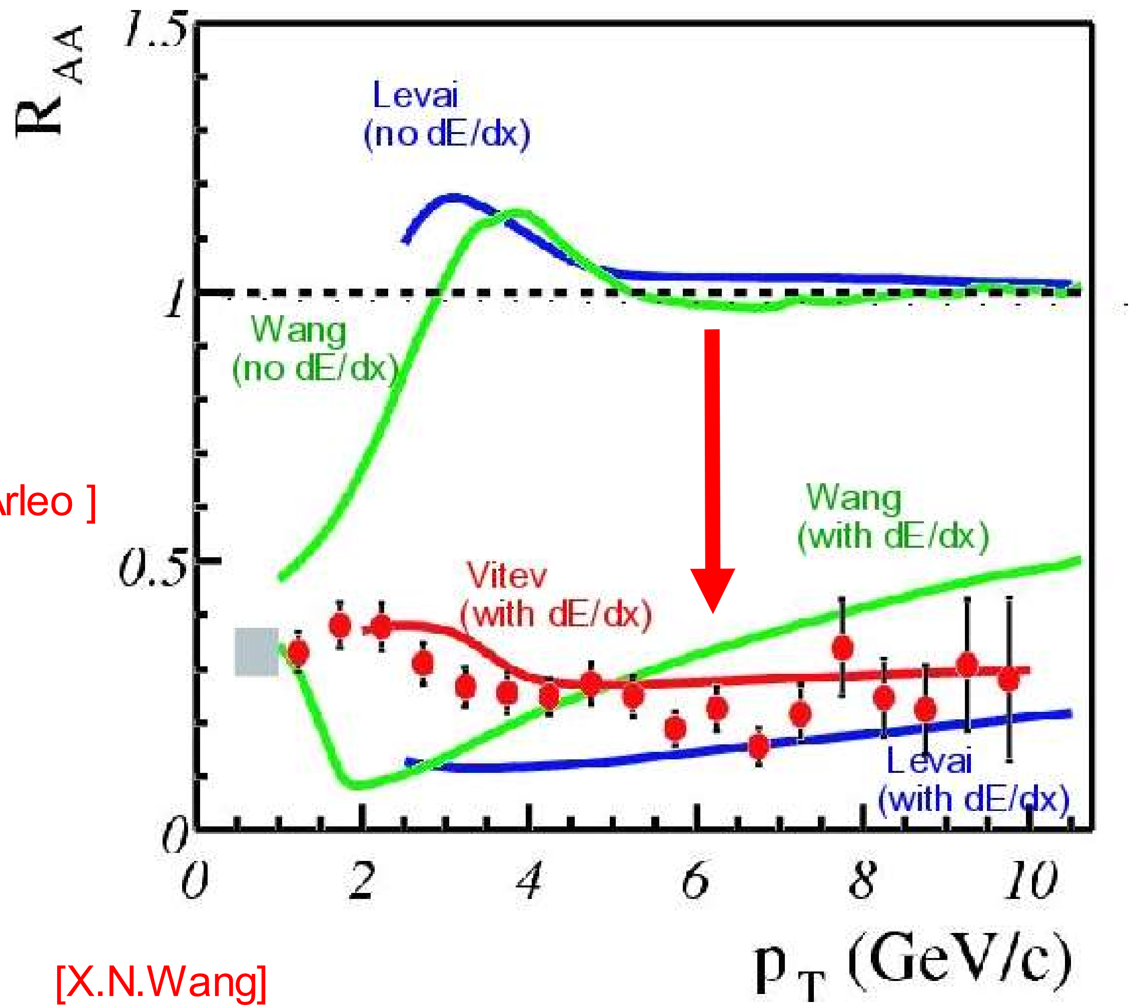
2. Dense initial-state partonic medium: Gluon saturation.

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

(*) via confronting data to theory

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

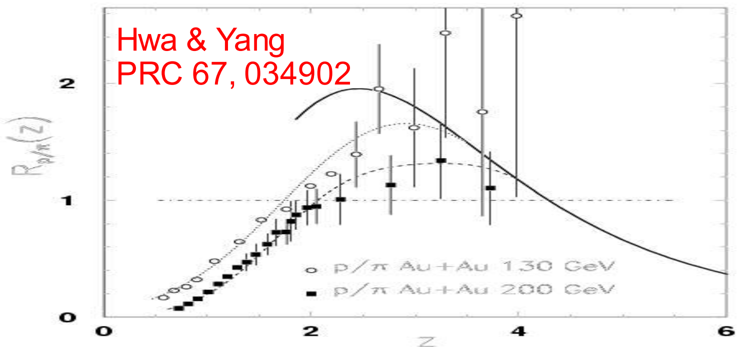
- Dense medium properties according to "jet quenching" models:
  - ✯ Initial gluon densities:
    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]
  - ✯ Opacities:
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]
  - ✯ Transport coefficients:
    $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 [BDMPS,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

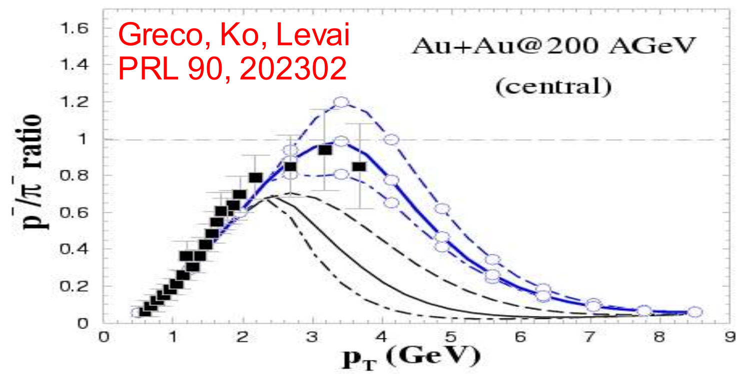


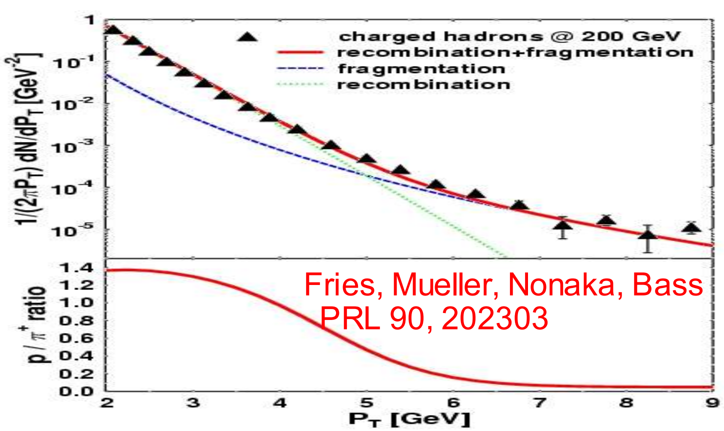
- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\epsilon_{crit\ QCD}$ in thermalized syst.

Final-state “QGP” effects vs. data (II)

- Quark recombination (coalescence) mechanisms provide a simple explanation of anomalous chemistry at intermediate p_T's (2-5 GeV/c):







- By quark momenta addition, 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:

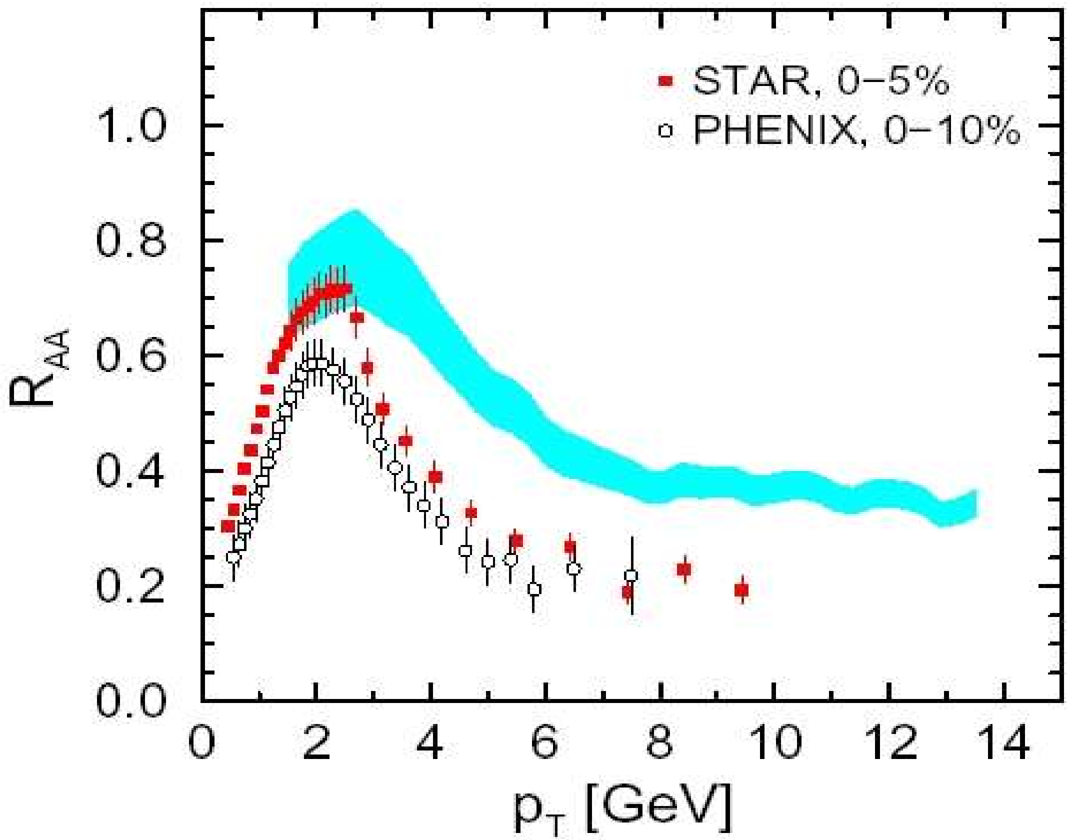
  p_T(hadrons)= z p_T(partons) , with z<1

- High parton 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 ?

- Energy loss of “pre-hadrons” inside a dense expanding hadronic fireball.
- Nuclear modification factor for a expanding system with $\epsilon_{init} \approx 1$ GeV/fm^3



Cassing, Gallmeister, Bratkovskaya, Greiner, Stoecker, nucl-th/0312049

- State-of-the-art hadronic models (HSD, UrQMD) produce suppression but not enough to explain the observed suppression factor at high p_T

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. (possible suppression already at $\sqrt{s} \approx 20$ GeV).

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

☆ 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 ? (Run-4 @ RHIC): thermal γ from plasma ?, J/Ψ suppression ?

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

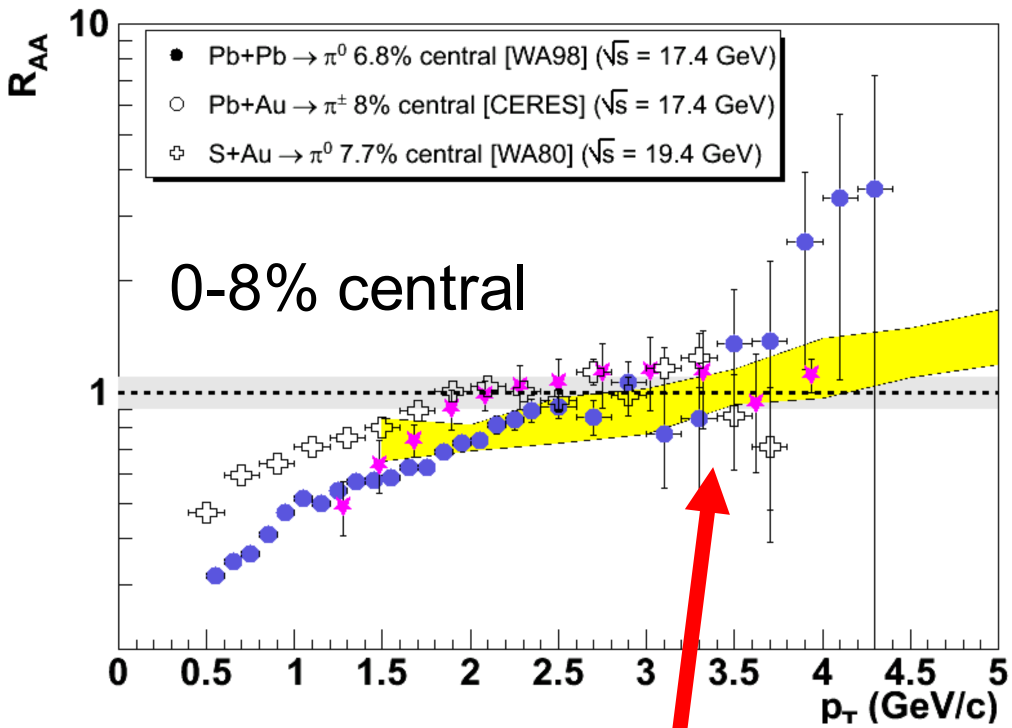
➡ Observation 6: Spectra suppressed by a factor ~2.

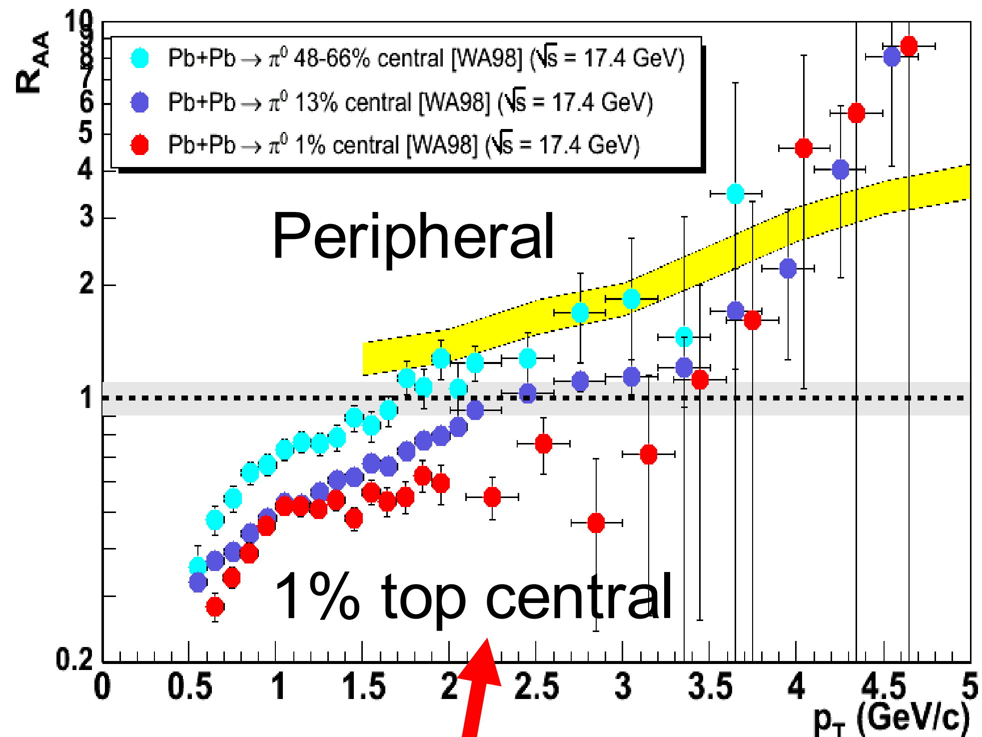
☆ "Explanation" (6): possible evidence of high twist effects at small-x.

backup slides ...

High p_T @ CERN-SPS: "Cronin" or "quenching" ?

- New nuclear modification factor (better p+p → π^0 ref. @ $\sqrt{s_{NN}}$ = 17.3 GeV)



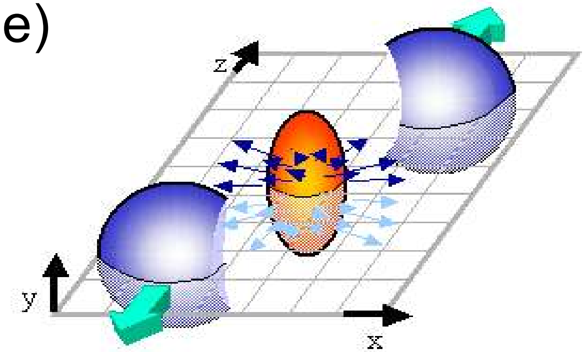


[D.d'E. to be submitted]

- No "Cronin" effect in central collisions (R_{AA} ~ 1).
- "Cronin" enhancement in peripheral ... and suppression in top central ?
- Look for onset of suppression at RHIC Au+Au, p+p @ $\sqrt{s_{NN}} \approx$ 20 GeV ?

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)



Elliptic flow = v_2 second Fourier coefficient

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

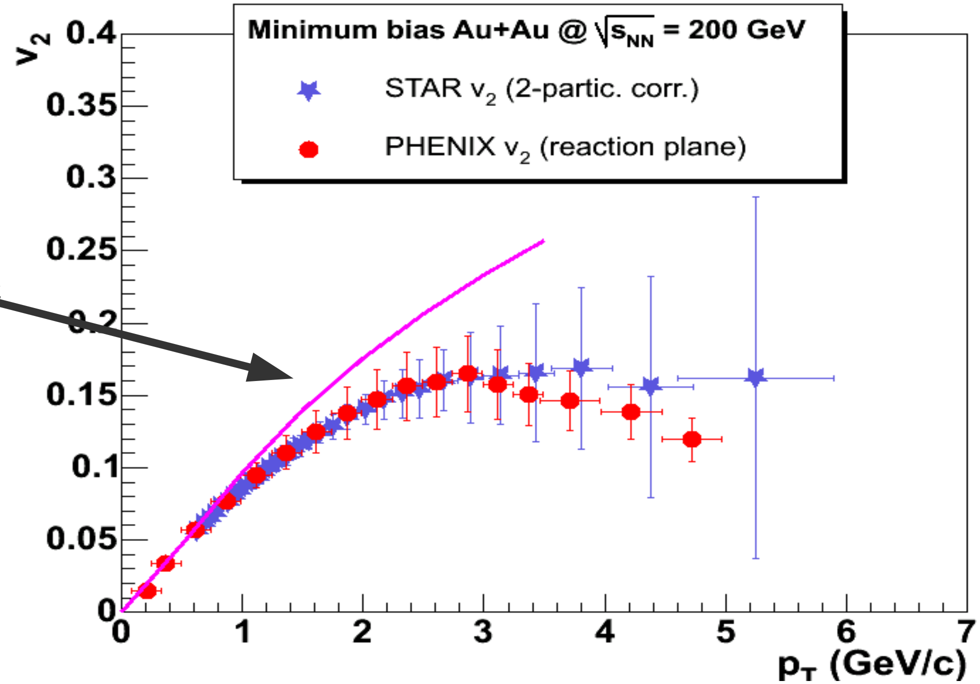
1. Truly collective effect (absent in p+p colls.).
2. “Hard” probe: develops exclusively in first instants of the reaction (t<3 fm/c).

- Large v_2 signal (saturating @ high p_T):

Exhausting hydro limit for p_T<1.5 GeV/c

⇒ Strong (collective) pressure grads.

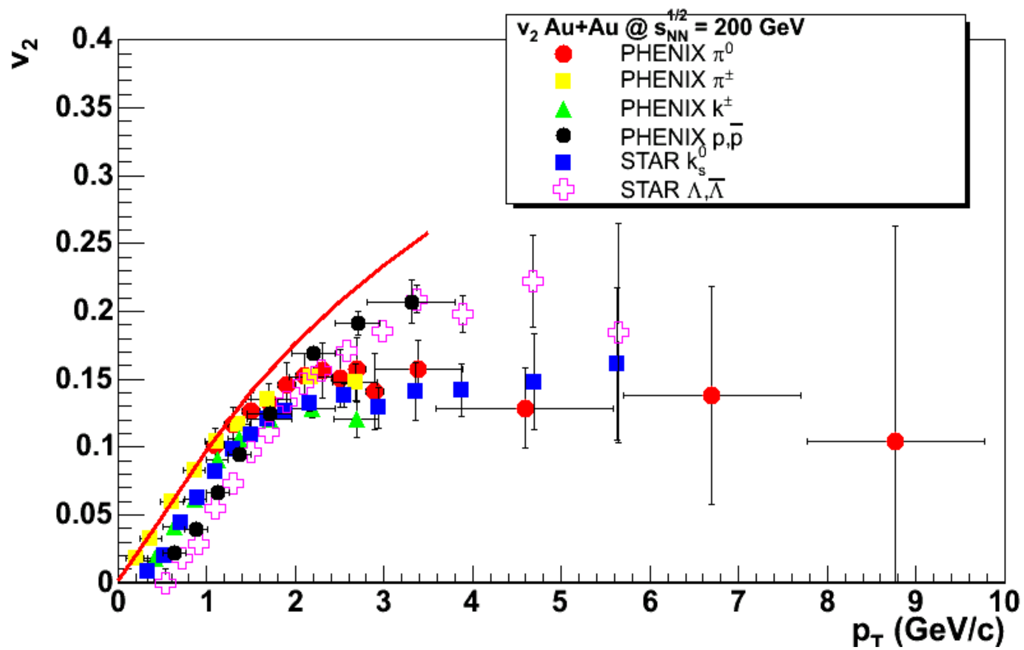
⇒ Large and fast (t<1.0 fm/c) parton rescattering: early thermalization.



High p_T azimuthal correlations: Elliptic flow (II)

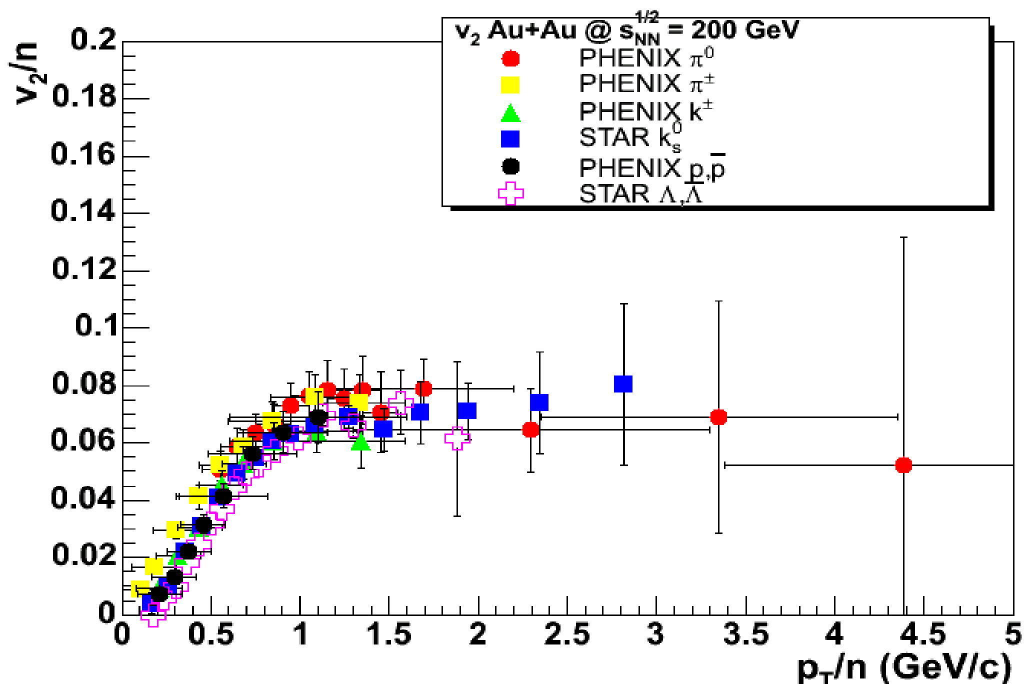
- Particle species hierarchy of flow values:

  $v_2^{meson} > v_2^{baryon}$ at low p_T
  $v_2^{meson} \approx v_2^{baryon}$ at $p_T \approx 2.$ GeV/c
  $v_2^{meson} < v_2^{baryon}$ at higher p_T



- Simple v_2 scaling behaviour predicted by quark recombination models:

  v_2 and p_T normalized by # of constituent quarks:
  n = 2 mesons
  n = 3 baryons

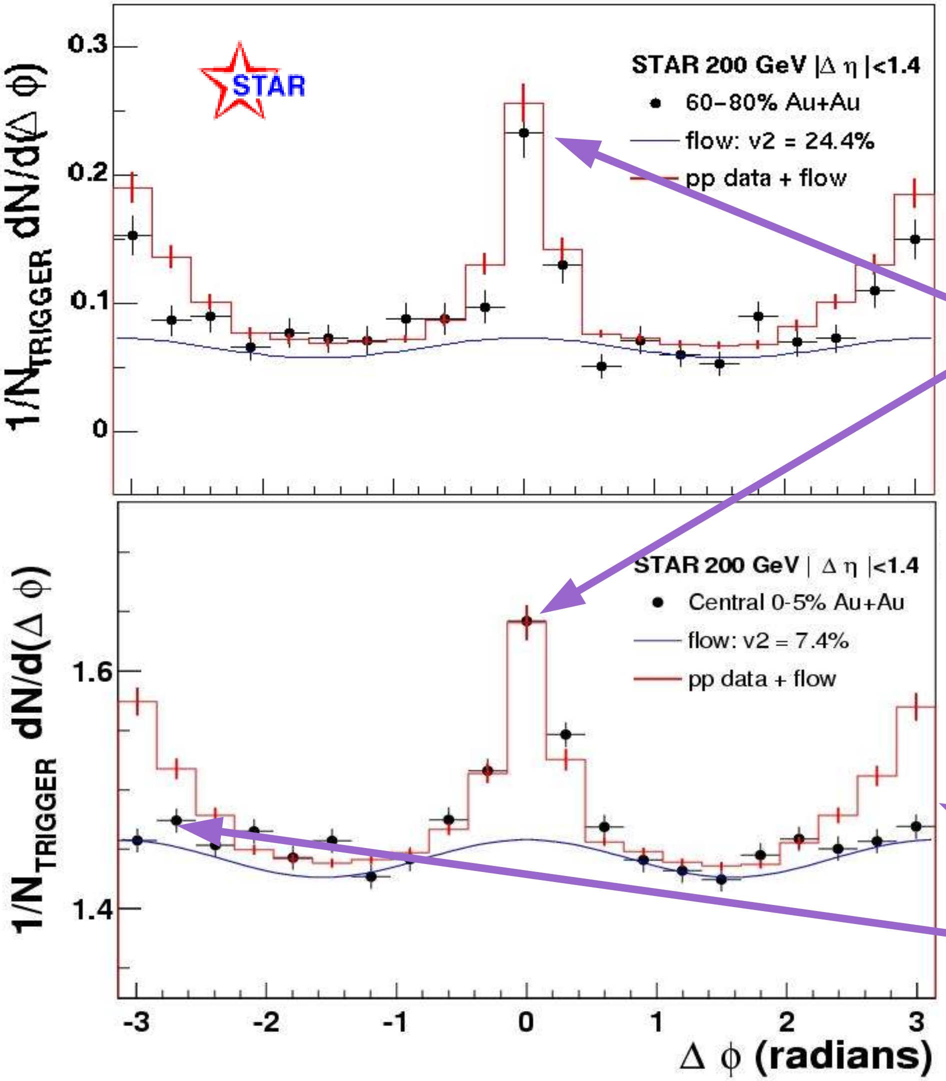


High p_T azimuthal correlations: Jet signals in Au+Au & p+p

- $dN_{pair}/d\Delta\phi$ 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) come from jets.

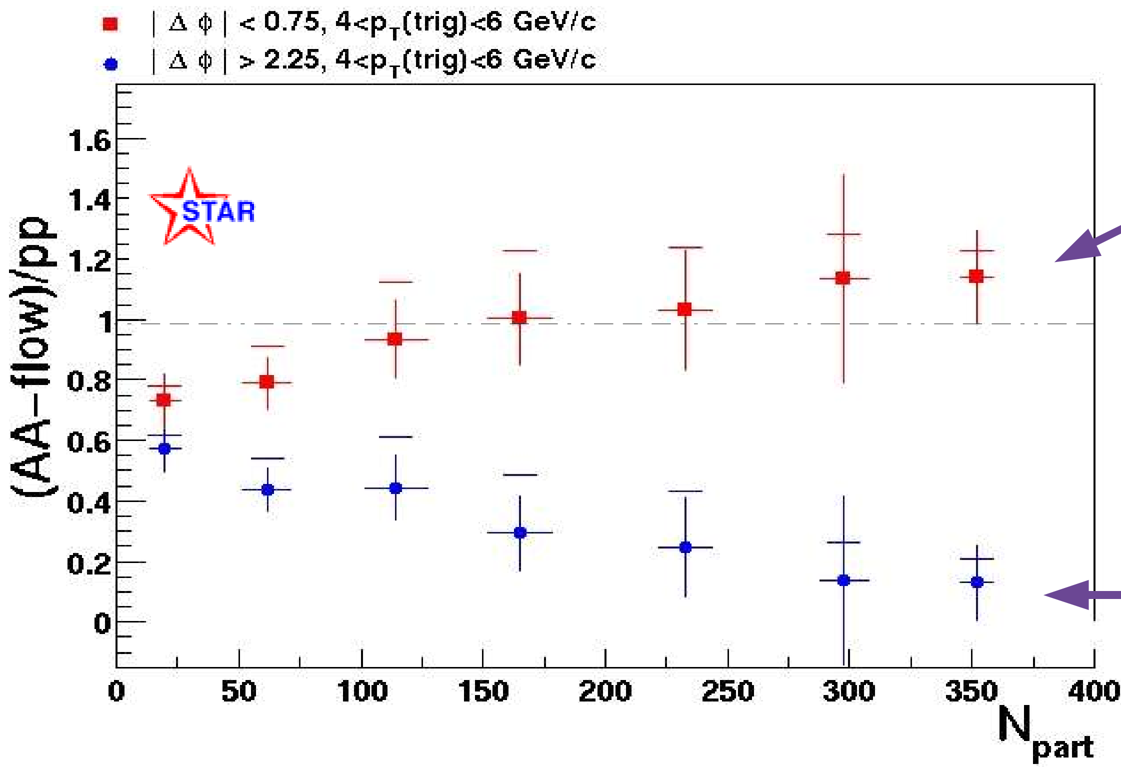
- Away-side peak: Au+Au << p+p

  Back-to-back jets suppressed 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":

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



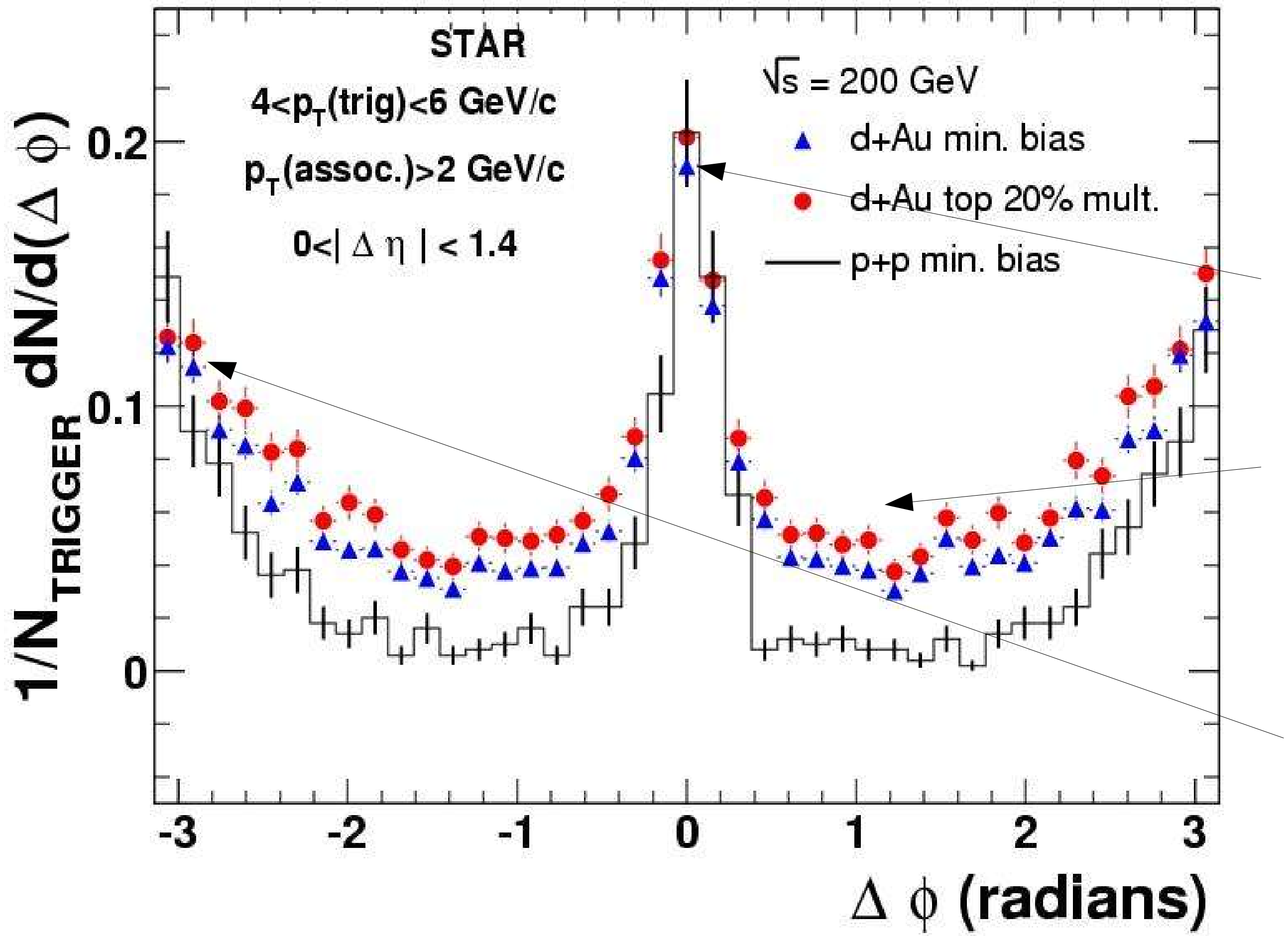
Near-side peak: $I_{AA} \sim 1$

Away-side peak: $I_{AA} \sim 0$

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

Issue (8): I_{AA}(periph)<1 ... is this physics ? an experimental bias ?
(Other independent measurements of correlation functions needed !)

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

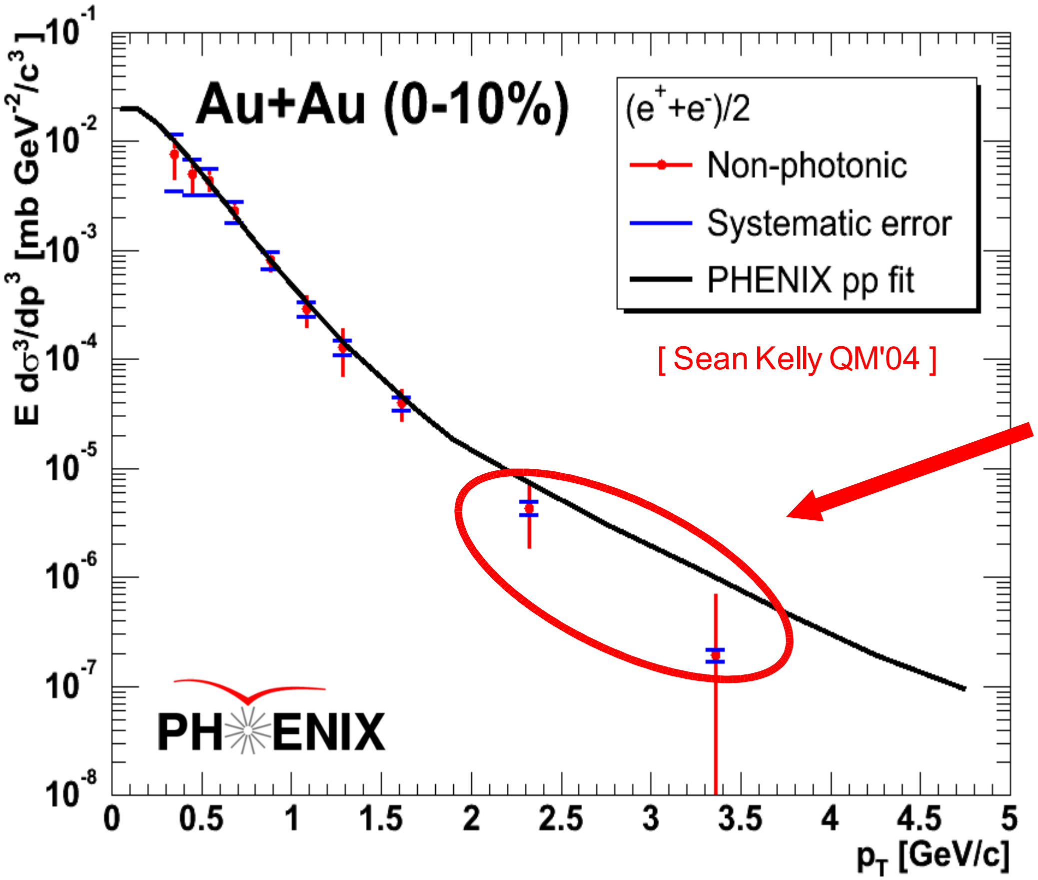


- Near- side: d+Au correlation strength and width similar to p+p (and Au+Au)
- Increasing "underlying event": p+p < d+Au(min.bias) < d+Au(central)
- Away-side: d+Au peak broadens but small centrality dependence

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

Unsuppressed (?) hard heavy-quark production

- Indirect measurement via semileptonic open-charm decays: $D \rightarrow e^{\pm}X$.
- Within uncertainties, single electron Au+Au central spectra and x-section(*) consistent with N_{coll} scaled p+p charm production:



(*) Charm production is intrinsically hard: N_{coll} scaling expected down to low p_T

- Possible reduction (1σ) at high p_T ?

factor ~2 less suppression expected for D than for π (R_{AA}=0.2) in models of medium-induced energy loss

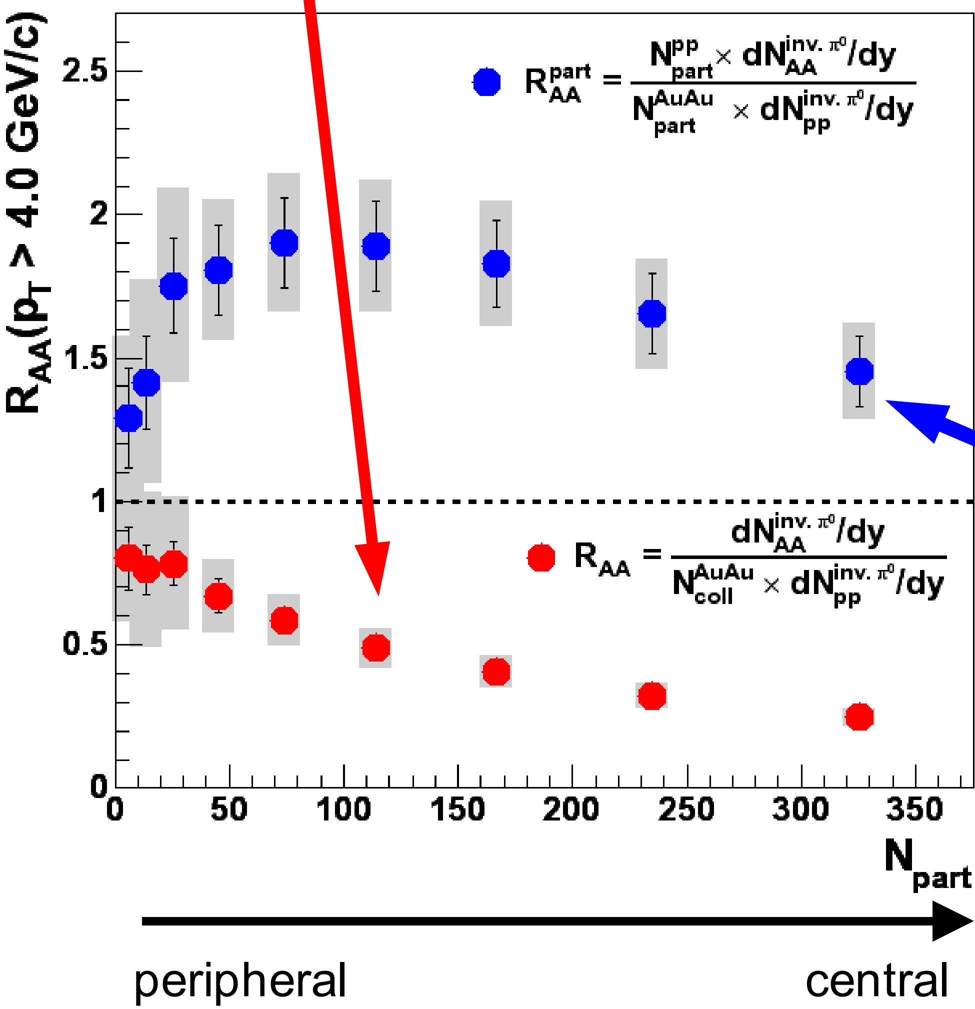
Wait for results from hi-stat. Run-4.

- Strong(*) medium effects on heavy flavor production precluded so far.

(*) at least as strong as for light-quark mesons.

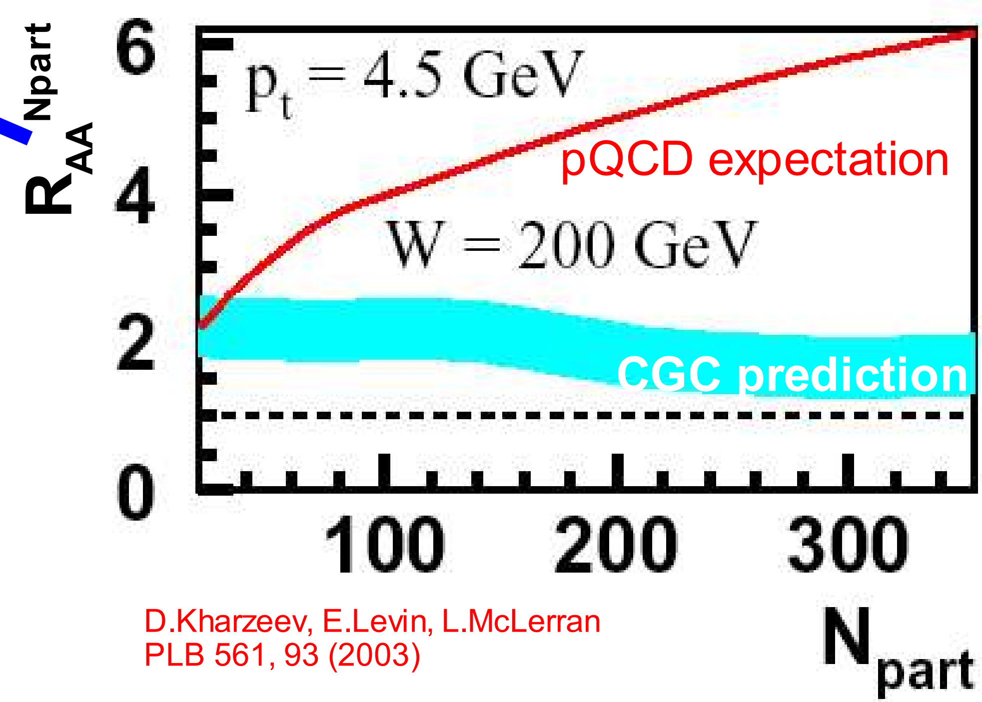
Centrality dependence of suppression (I): N_{part} scaling ?

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



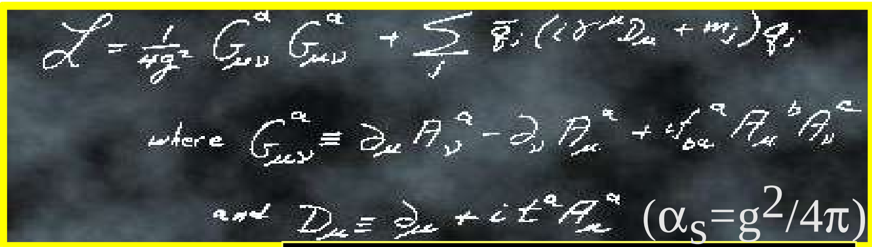
PHENIX
nucl-ex/0304022,
submitted to PRL

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



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

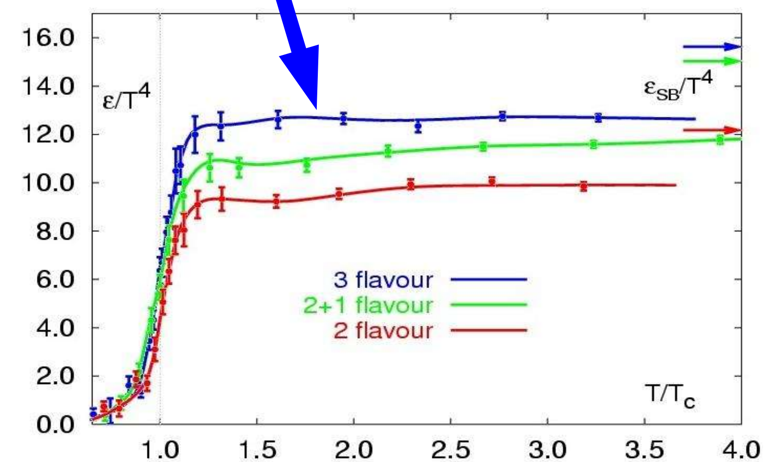
High-energy heavy-ion physics program (in 4 plots)

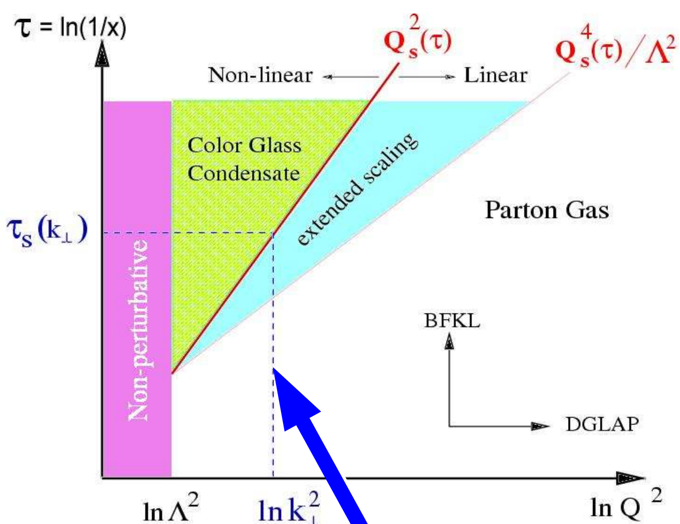


$\alpha_s(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

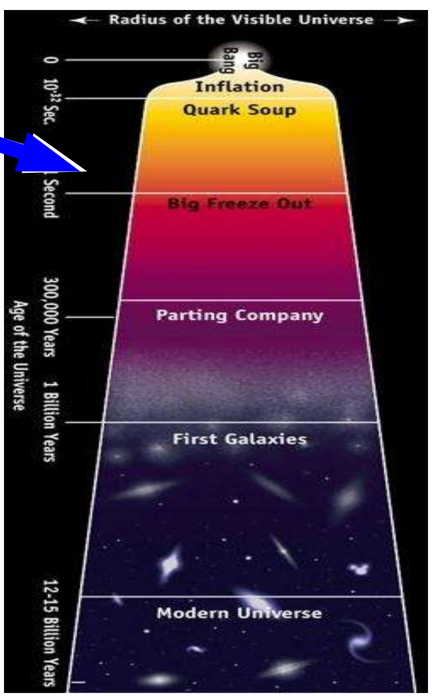
1. Learn about 2 (so far unexplained) properties of the strong interaction: confinement, chiral symmetry breaking

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





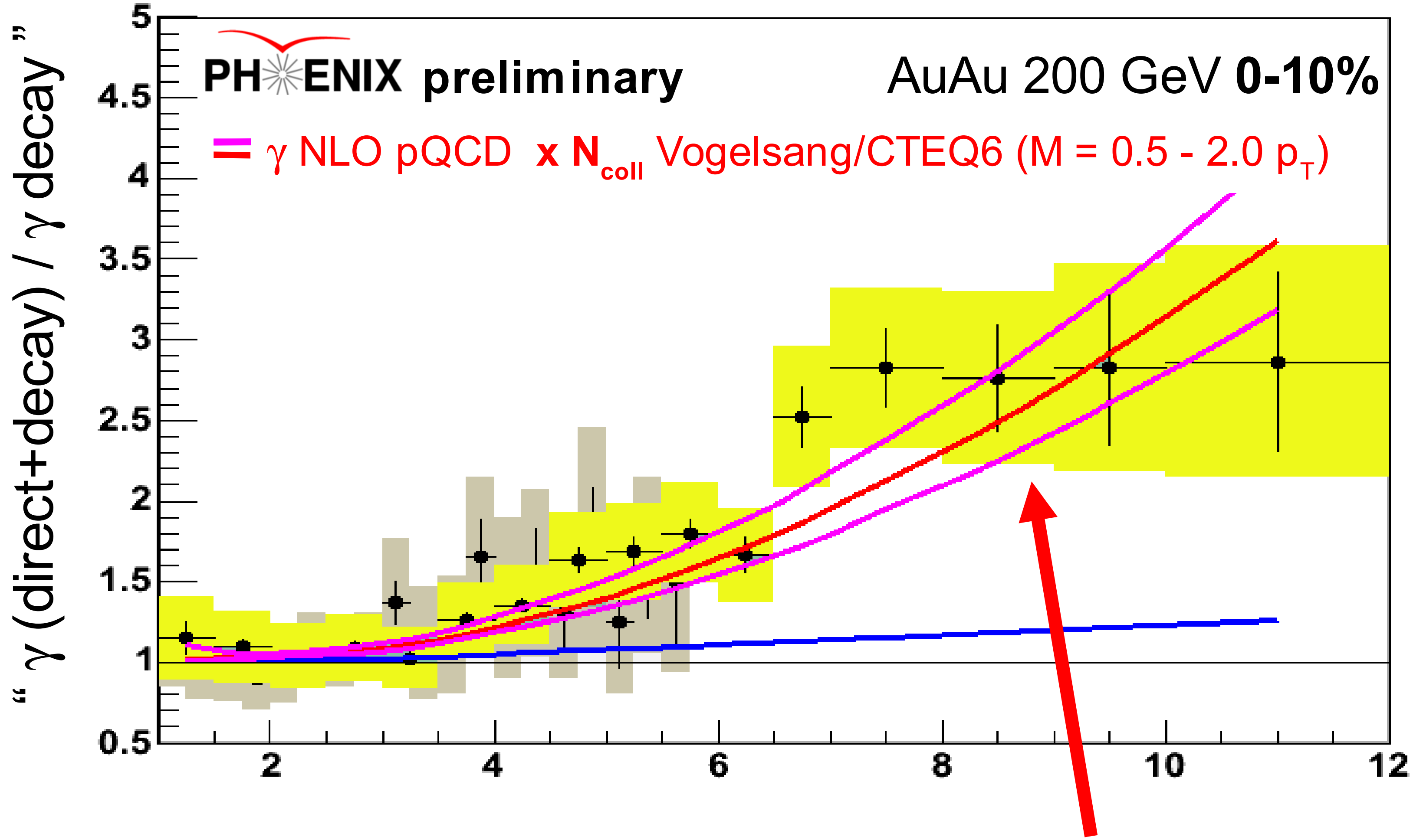
3. Probe the properties of the primordial Universe (few μsec after the Big Bang).



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

Unsuppressed hard colorless production

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



[J.Frantz QM'04]

- Probes insensitive to colored final-state do show collision scaling at high p_T:

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