Status of QGP search at RHIC
- A PHENIX perspective(*) -

IKF Seminar

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(*) Based upon "PHENIX White Paper": `http://www.phenix.bnl.gov/phenix/WWW/info/comment/`

Overview/Summary

1. Introduction:

- Goal: Study Quantum Chromo (many-body) Dynamics (QGP, CGC) in high-energy A+A collisions [by comparing to p+A (“cold” QCD medium), p+p (“no medium”)].

2. Energy densities:

- Maximum $dE_T/d\eta$ ~ 600 GeV at midrapidity consistent w/ initial $\varepsilon > 5$ GeV/fm^3

3. Elliptic flow:

- Strong elliptic flow v_2 consistent w/ short thermalization times τ_0 ~ 1 fm/c

4. Soft particle spectra:

- Shapes & yields consistent w/ hydrodynam. (thermal+coll. velocity) source emission
- Particles ratios consistent w/ chemical equilibrium before hadronization

5. Hard particle spectra:

- Strong high p_T suppression in central A+A (compared to p+p, p+A & pQCD) consistent w/ final-state partonic energy loss in dense system: dN^g/dy~1100

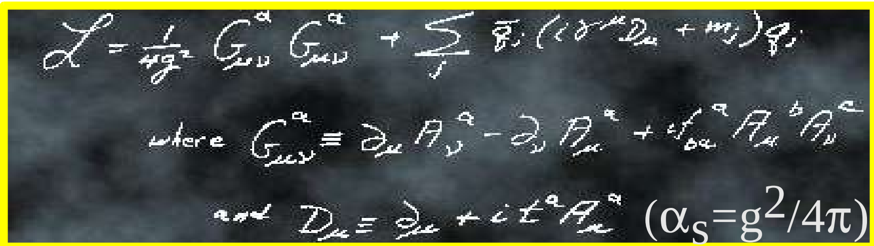
6. Intermediate p_T spectra:

- Enhanced baryon yields & v_2 (compared to meson) consistent w/ quark recombination mechanisms in dense thermal system

7. Summary & open questions: “QGP” ? Observations @ lower $\sqrt{s}$?

Future measurements.

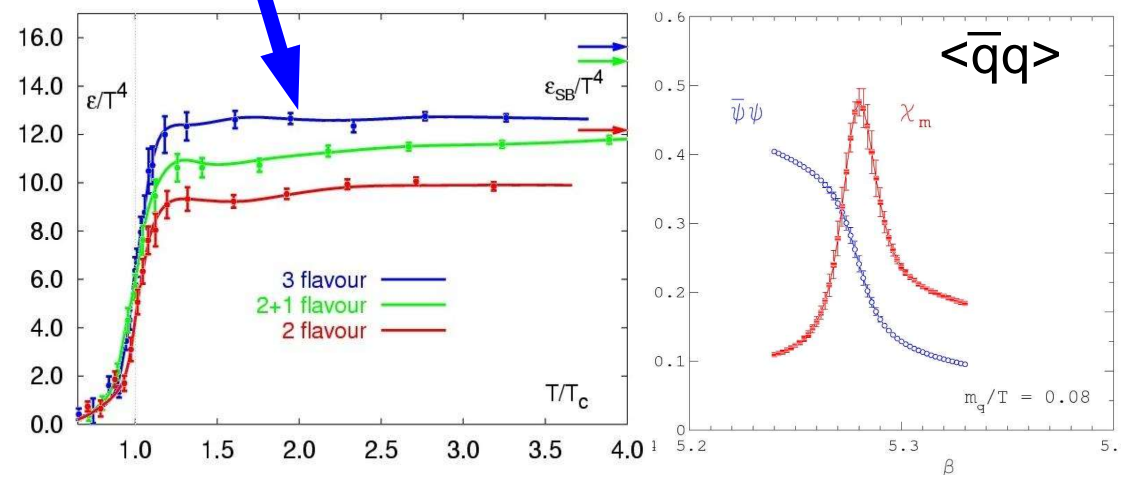
High-energy heavy-ion physics program (in 4 plots)



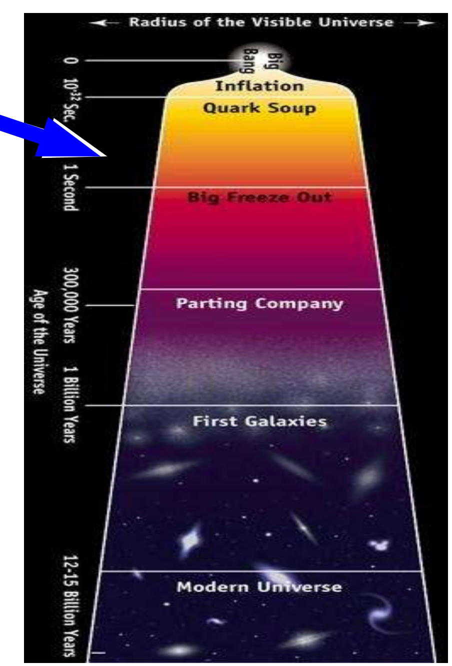
$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

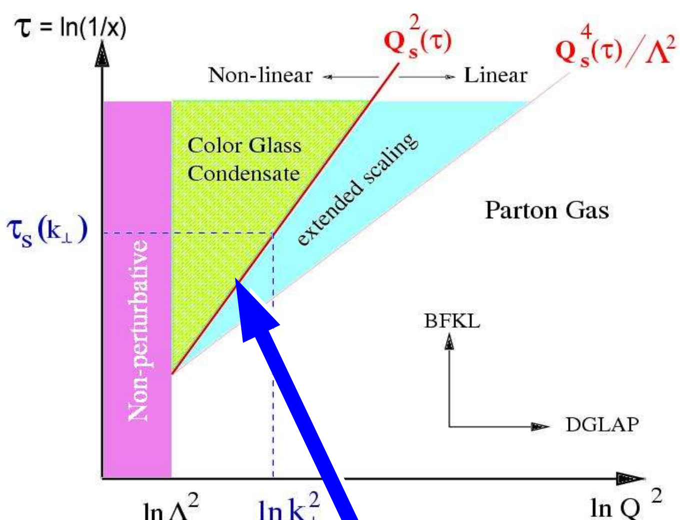
1. Learn about 2 basic properties of strong interaction: (de)confinement, chiral symm. breaking (restoration)

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



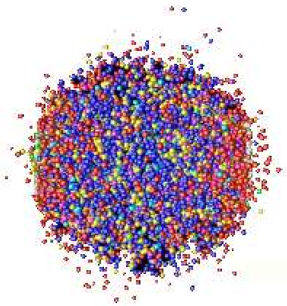
3. Probe quark-hadron phase transition of the primordial Universe (few μsec after the Big Bang)



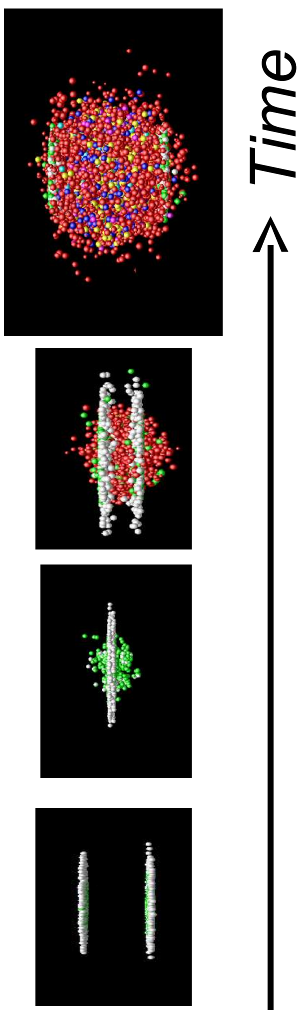


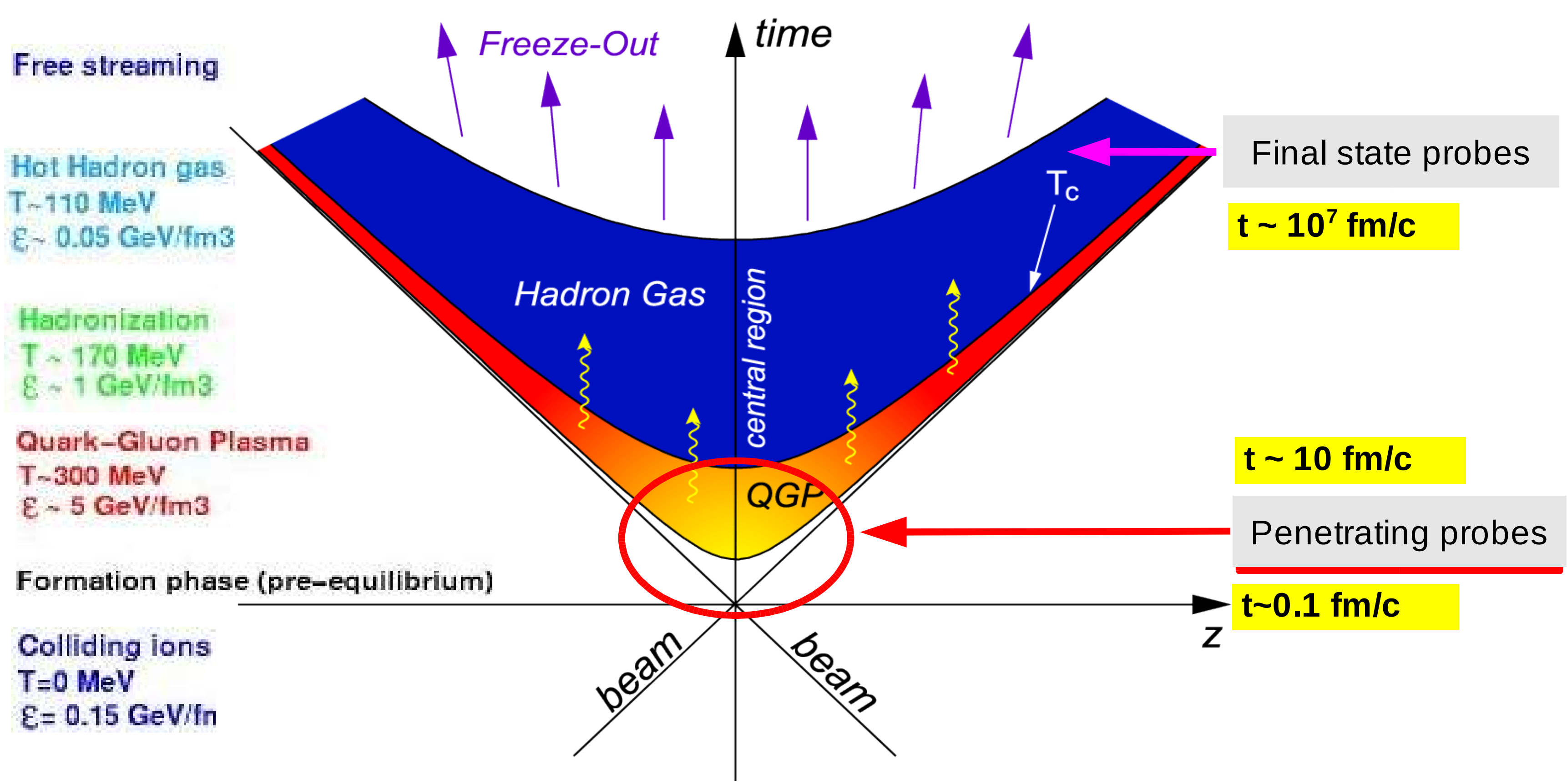
4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

The "Little Bang" in the lab.



- High-energy nucleus-nucleus collisions: fixed-target reactions (√s~17 GeV, SPS) or colliders (√s~200 GeV, RHIC. √s~5.5 TeV, LHC)
  - 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 sensitive to diff. react. stages





Relativistic Heavy-Ion Collider (RHIC) @ BNL

Specifications:

3.83 km circumference

2 independent rings:

- 120 bunches/ring
- 106 ns crossing time

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

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

p+p collisions @ $\sqrt{s}_{max}$ = 500 GeV

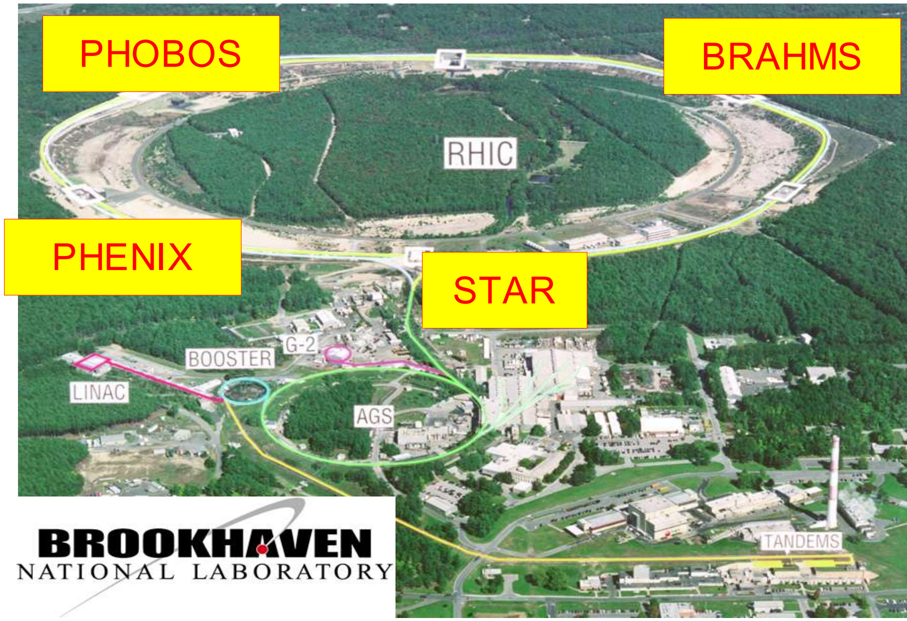
p+A collisions @ $\sqrt{s}_{max}$ = 200 GeV

4 experiments:

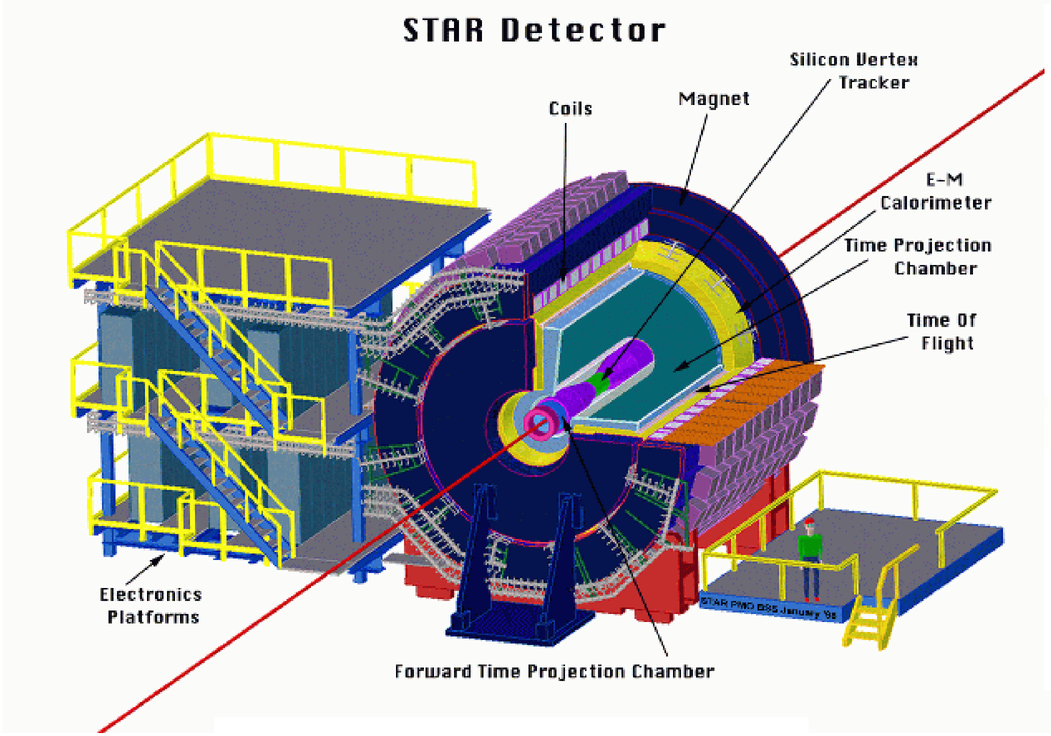
BRAHMS, PHENIX, PHOBOS, STAR

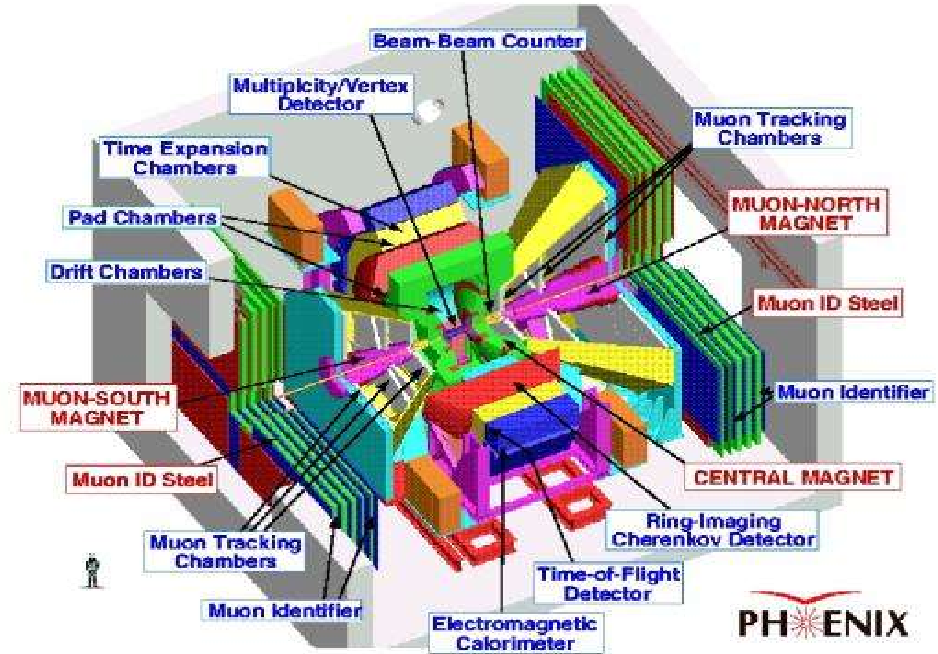
Runs 1 - 4 (2000 – 2004):

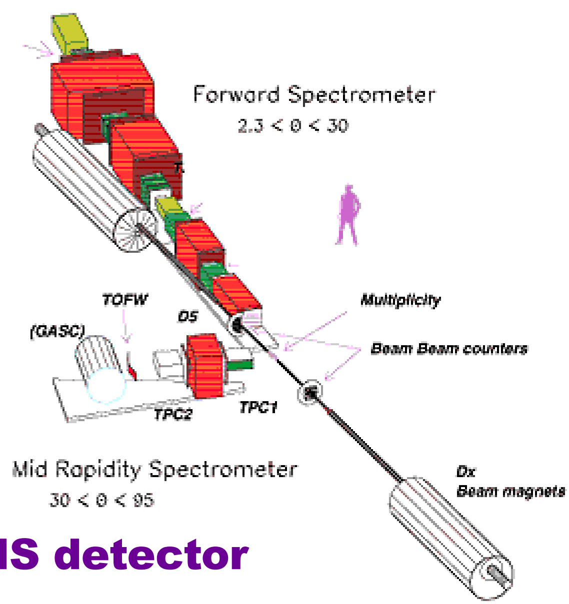
Au+Au @ 200, 130, 62.4 GeV
p+p @ 200 GeV
d+Au @ 200 GeV



The 4 RHIC experiments

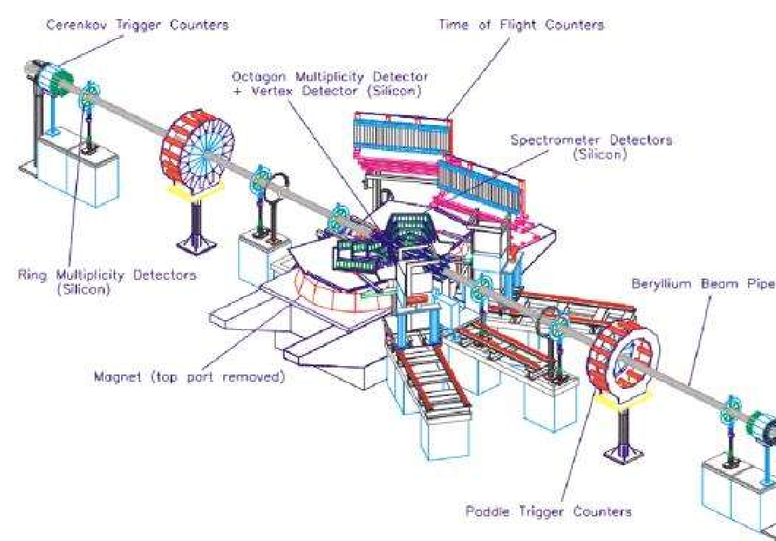




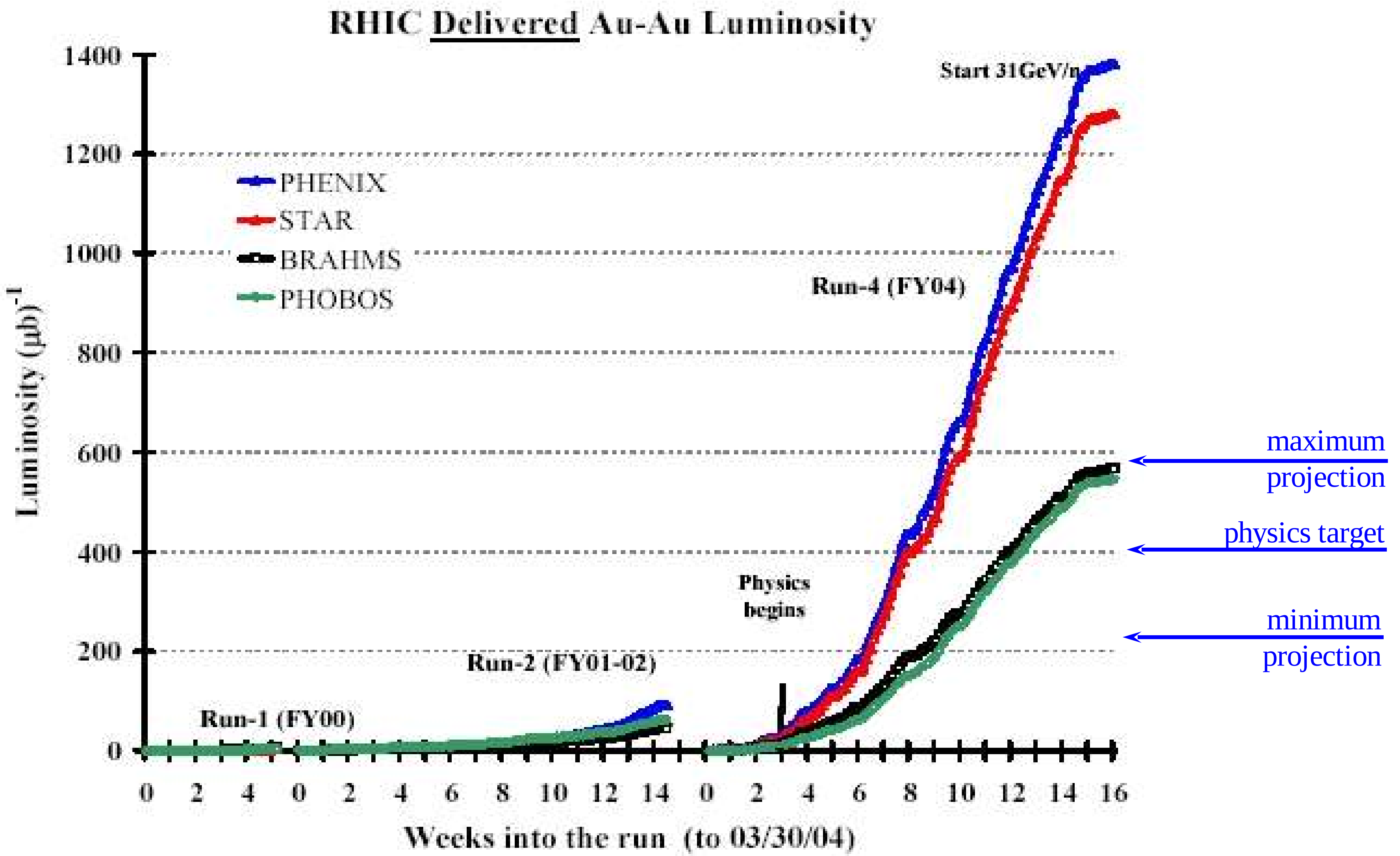


BRAHMS detector

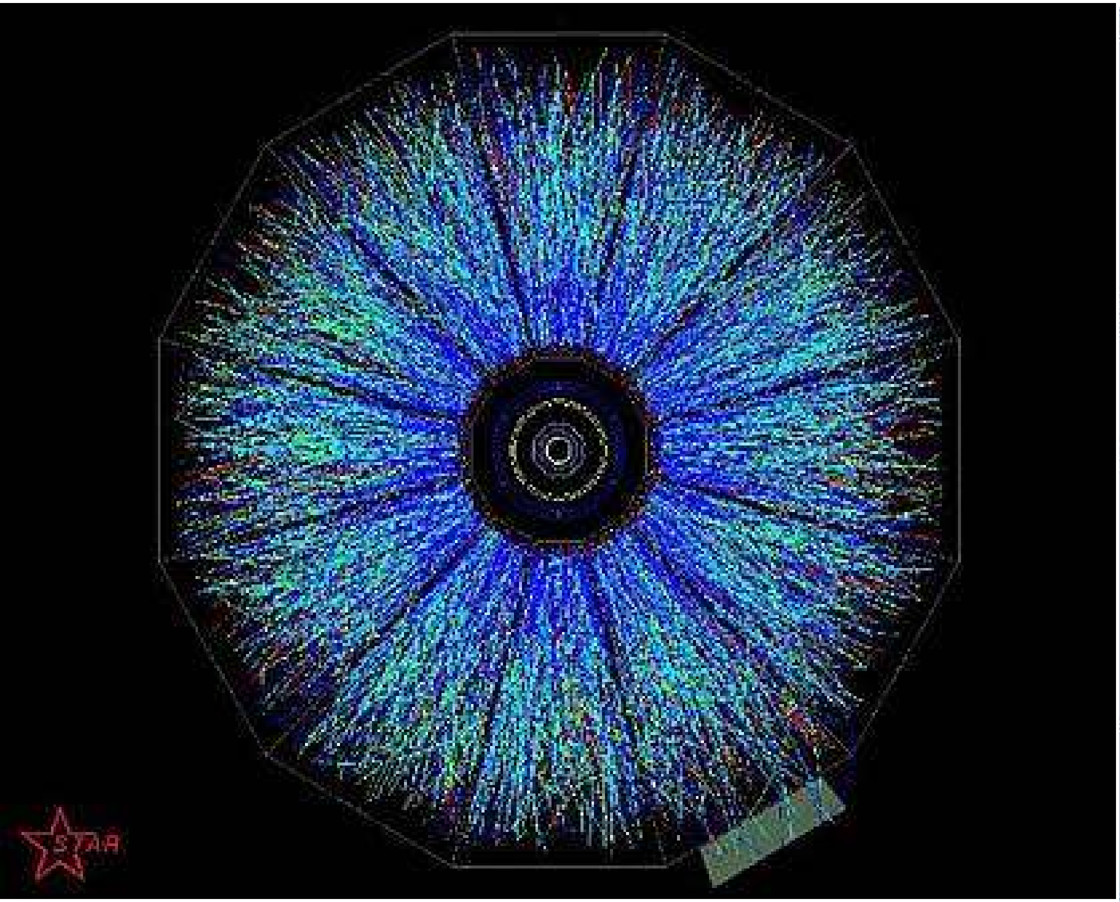
PHOBOS Detector

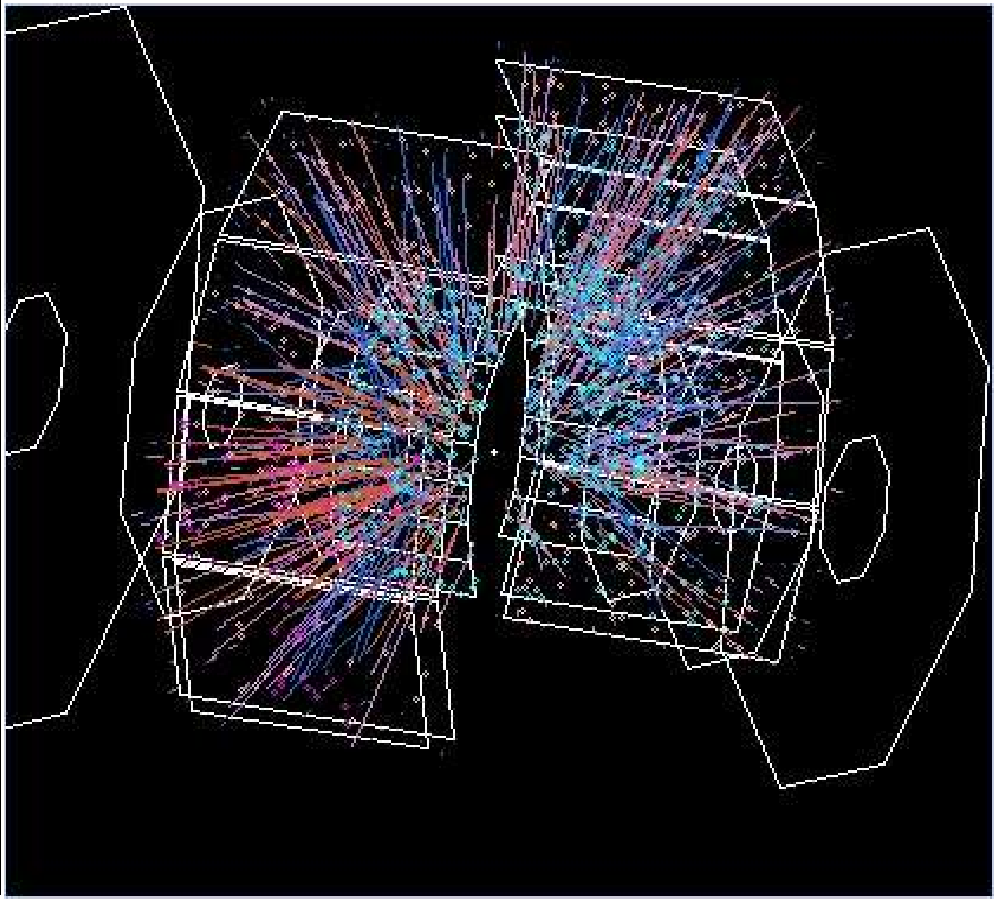


RHIC Au+Au luminosities



Au+Au collisions @ 200 GeV





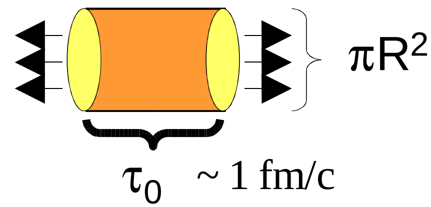
~ 700 charged particles per unit rapidity at midrapidity (top 10% central)

Energy densities at RHIC

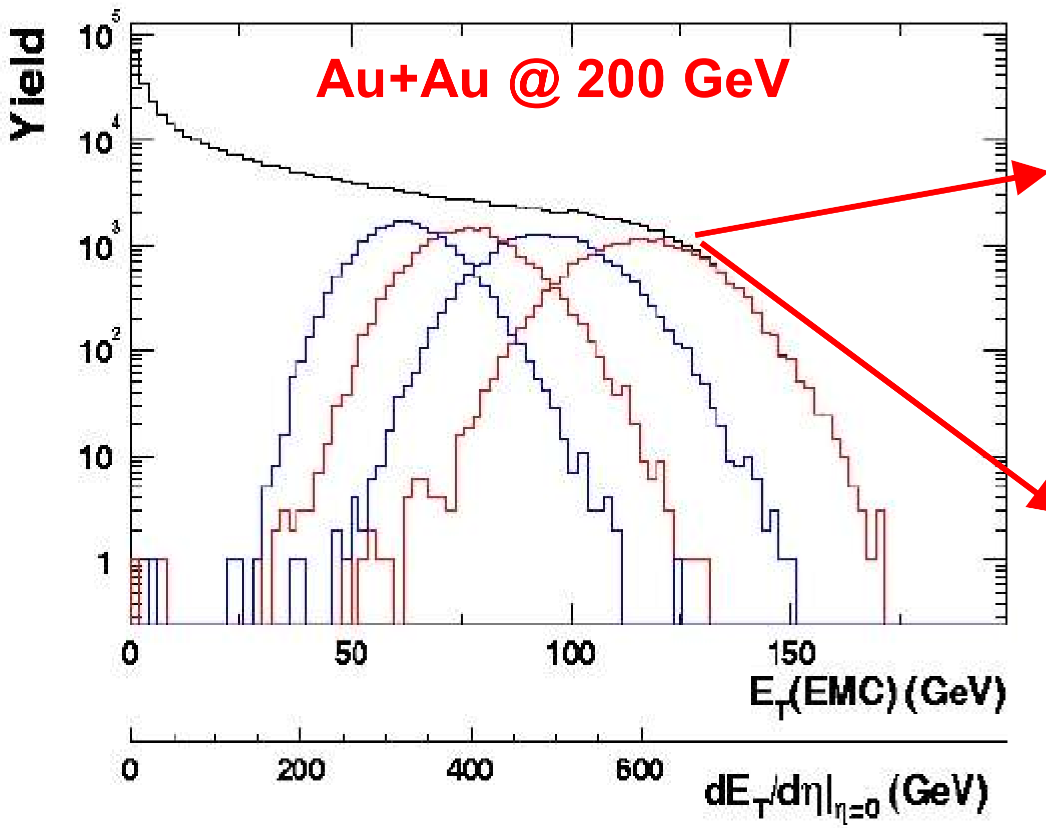
Energy density (Au+Au @ 200 GeV, y=0)

- Bjorken estimate: $\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$

  (longitudinally expanding plasma)



- $dE_T/d\eta$ at mid-rapidity measured by calorimetry (using PHENIX EMCal as *hadronic* calorimeter: $E_T^{had} = (1.17\pm0.05)\ E_T^{EMCal}$)



$\langle dE_T/d\eta \rangle$ ~ 600 GeV (top 5% central)

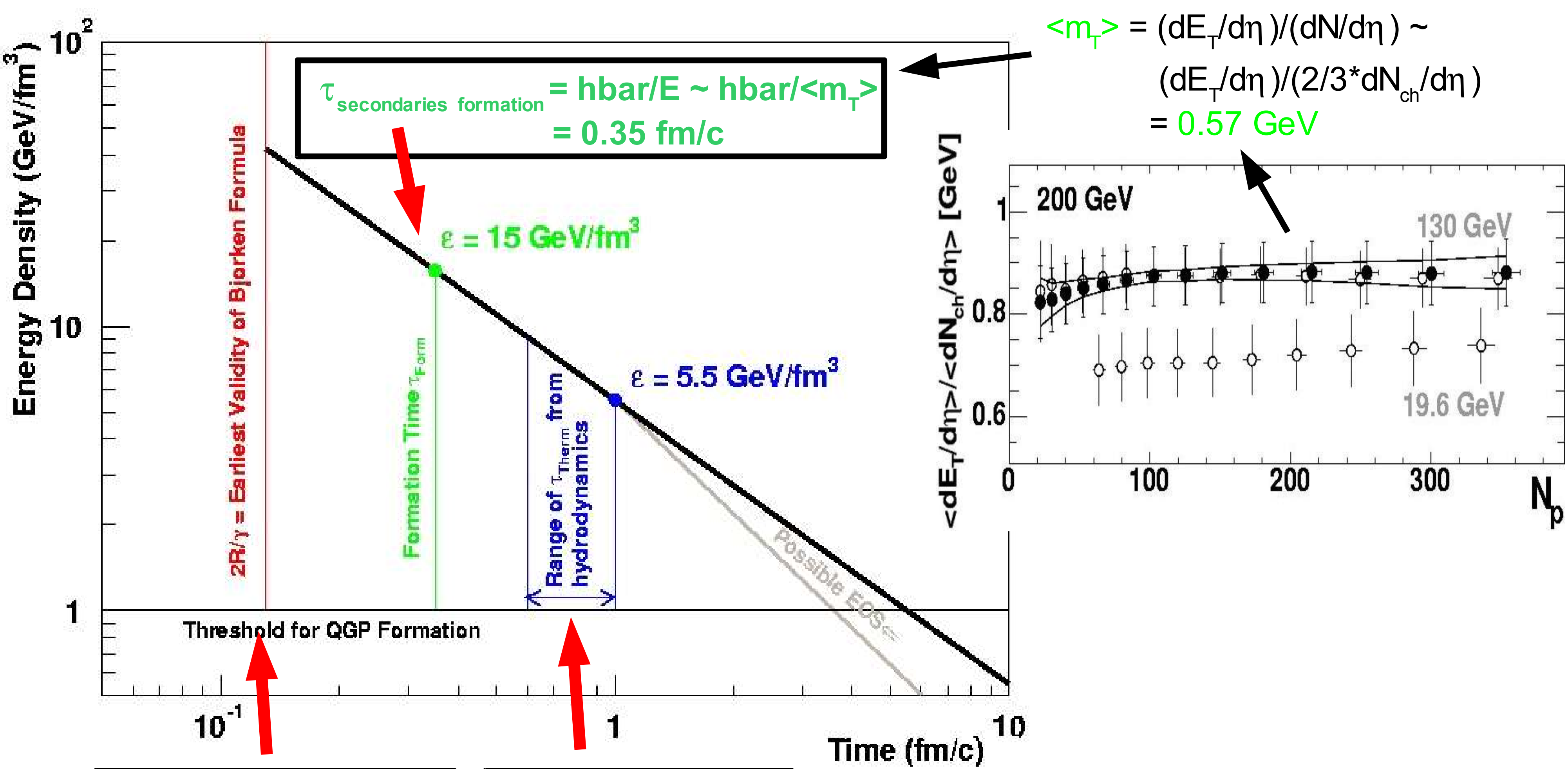
(~70% larger than at SPS)

$\varepsilon_{Bjorken}$ ~5.0 GeV/fm³

> QCD critical density (~1 GeV/fm³)

1 fm/c thermalization time ?

- Not unrealistic at RHIC... (for the 1st time: $\tau_{therm} > \tau_{cross} = 2R/\gamma = 0.13$ fm/c)
- Energy density time evolution in long. expanding system: $\varepsilon \sim 1/\tau$



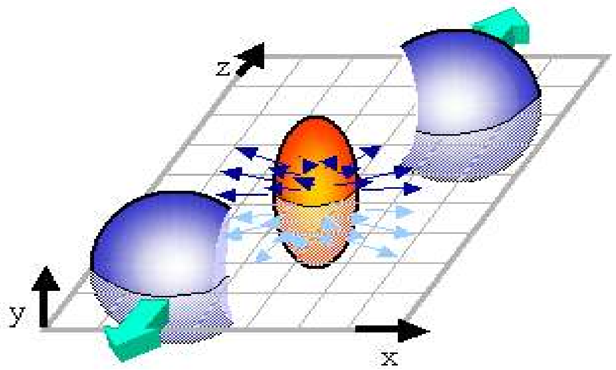
$\tau_{cross} = 2R/\gamma = 0.13$ fm/c

$\tau_{therm} \sim 0.6 - 1$ fm/c (from hydrodynamics, see next)

Elliptic flow at RHIC

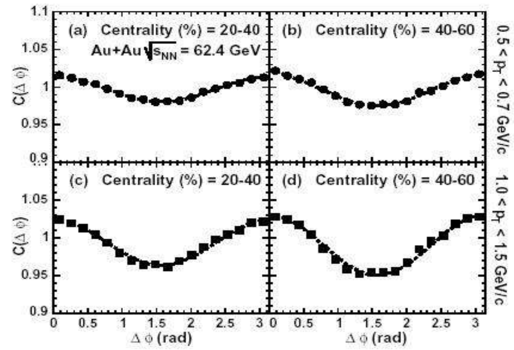
Elliptic flow

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



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

Elliptic flow = v_2
(2^{nd} Fourier coefficient)

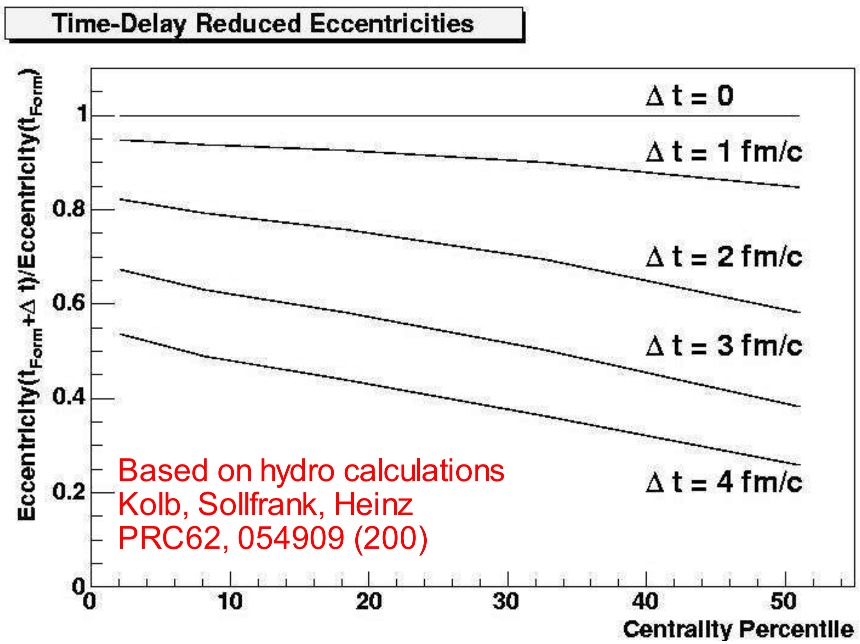


1. Truly collective effect (absent in p+p collisions).

2. Early-state phenomenon:
develops only in 1^{st} instants of reaction,
strongly self-quenches after t~2 fm/c

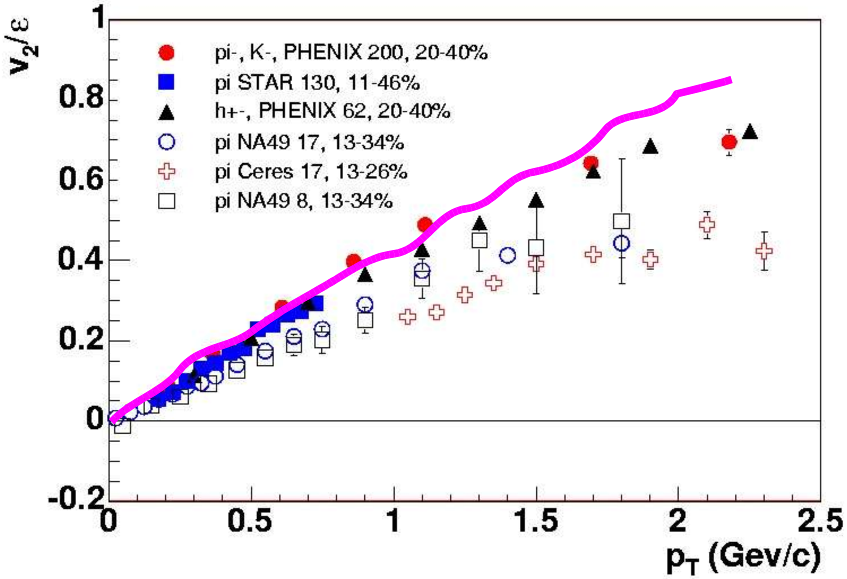
Time evolution of ellipsoid eccentricity:

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



Elliptic flow at RHIC

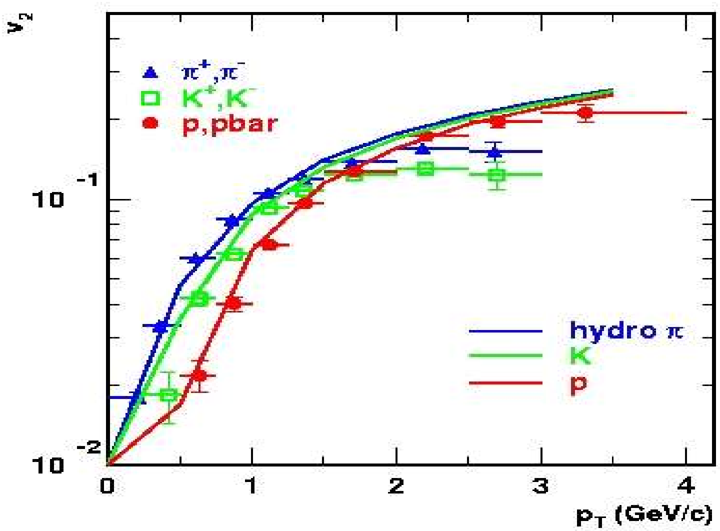
- Large v_2 signal at RHIC:
  Exhausts hydro limit for p_T<1.5 GeV/c



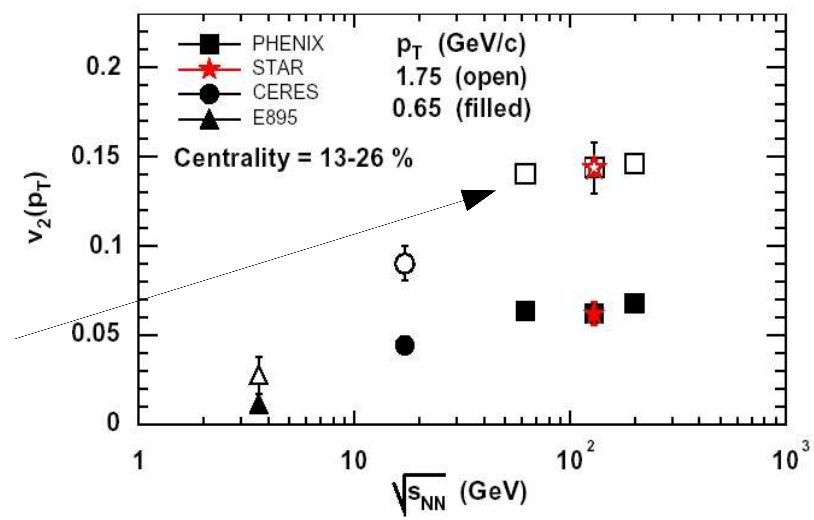
⇒ Strong (collective) pressure grads.

⇒ Large & fast parton rescattering: early thermalization.

- Mass dependence of v_2
  consistent w/ hydrodynamics too:



- $\sqrt{s}$-dependence of v_2:
  ~50% increase from SPS
  Apparent saturation within 62-200 GeV

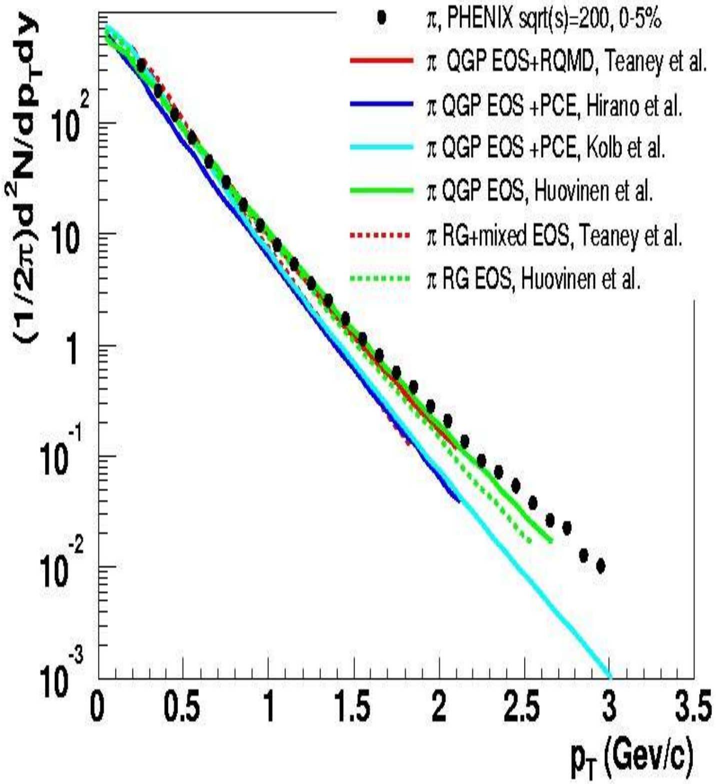


Soft particle production at RHIC

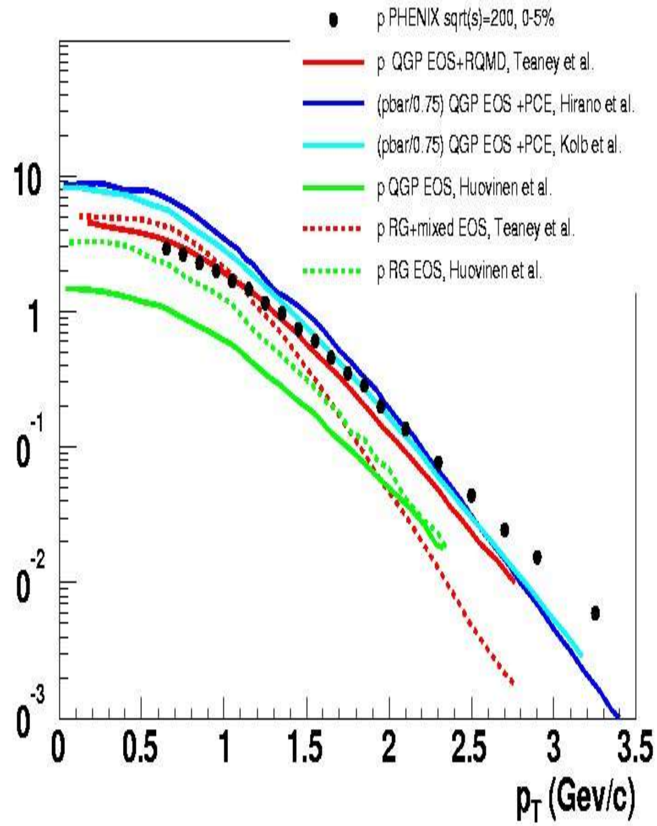
Soft particle spectra

- Bulk $\pi^{\pm}$, p(pbar) spectra ~reproduced by hydro w/ QGP EOS at τ_0=0.6 fm/c

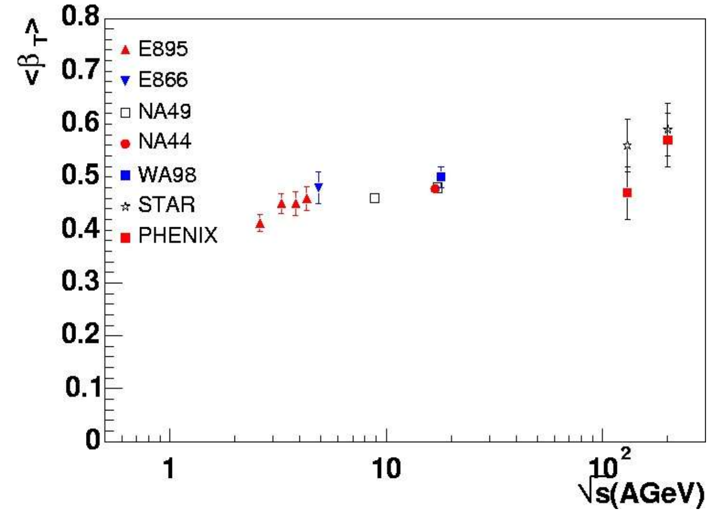
pions:



protons:



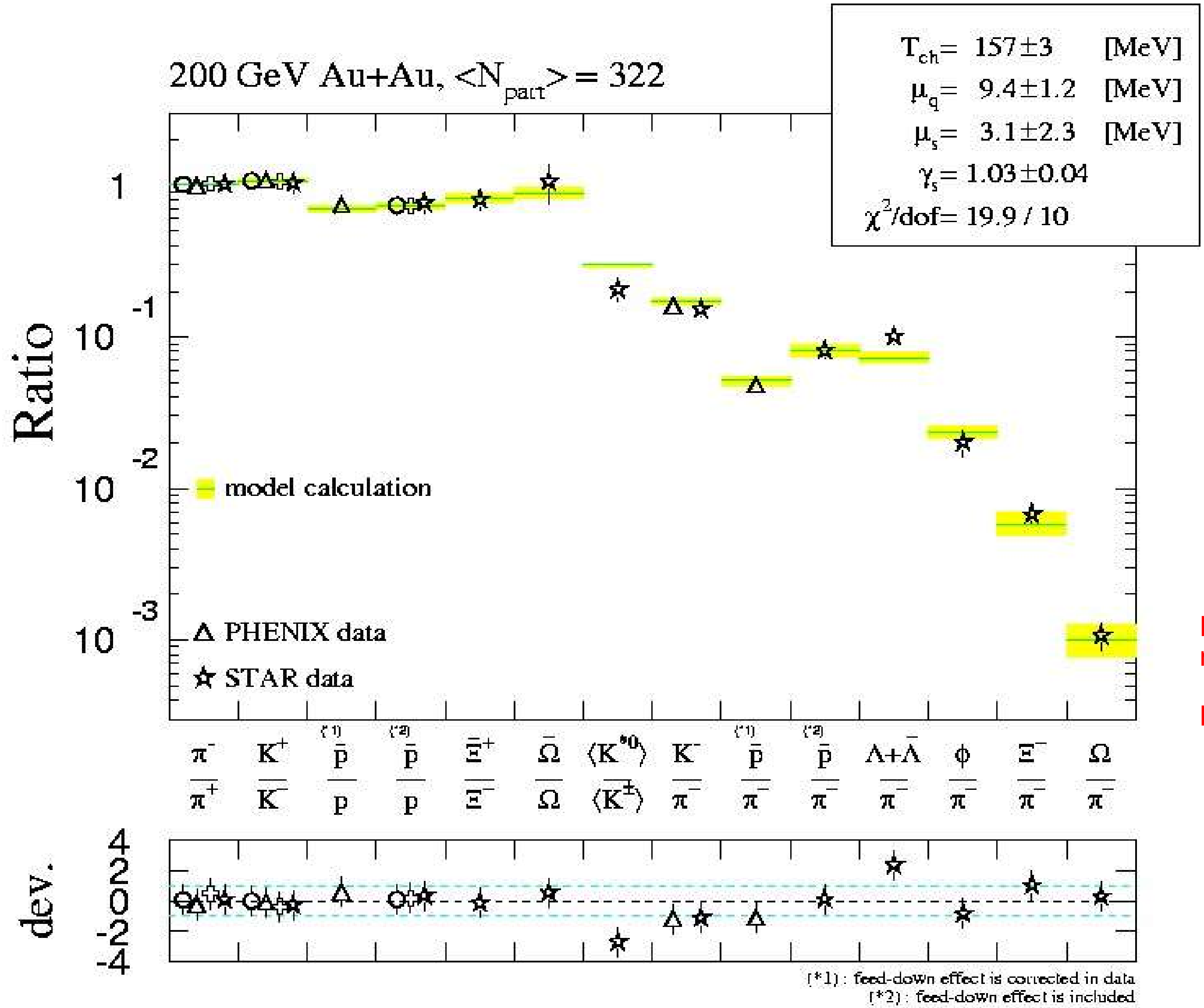
Radial collective flow built-up at freeze-out: $\langle\beta_T\rangle \approx 0.55$



Solid lines: QGP+HG
Dashed lines: HG

Ratios of particle yields

- Ratios of hadron yields consistent w/ system at chemical equilibrium (strangeness saturation factor γ_s=1) before hadronization ($T_{chem.freeze-out} \sim T_{crit}$) :



PBM, Redlich, Stachel nucl-th/0304013

Kaneta, Xu nucl-th/0405068

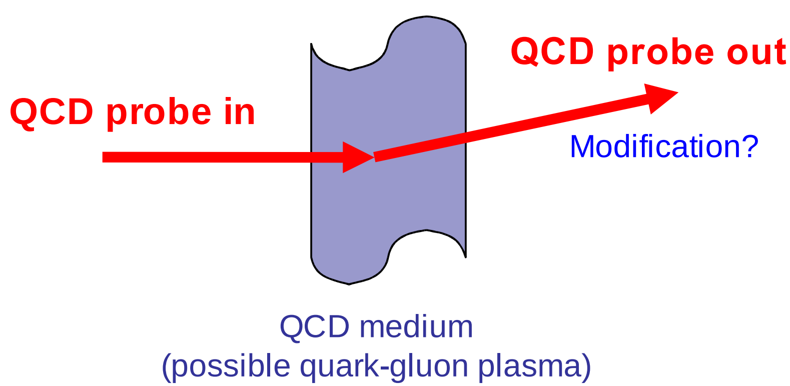
Hard QCD production at RHIC

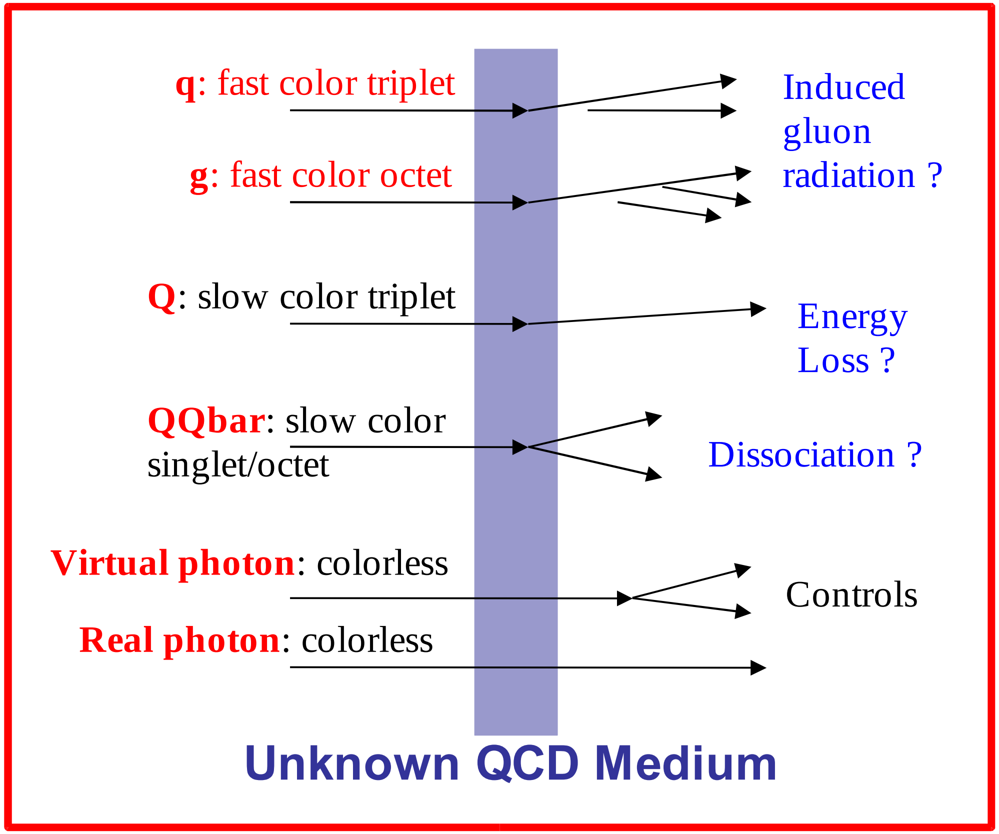
Hard QCD probes (I)

- 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) $\Rightarrow$ Sensitive to QCD medium properties:



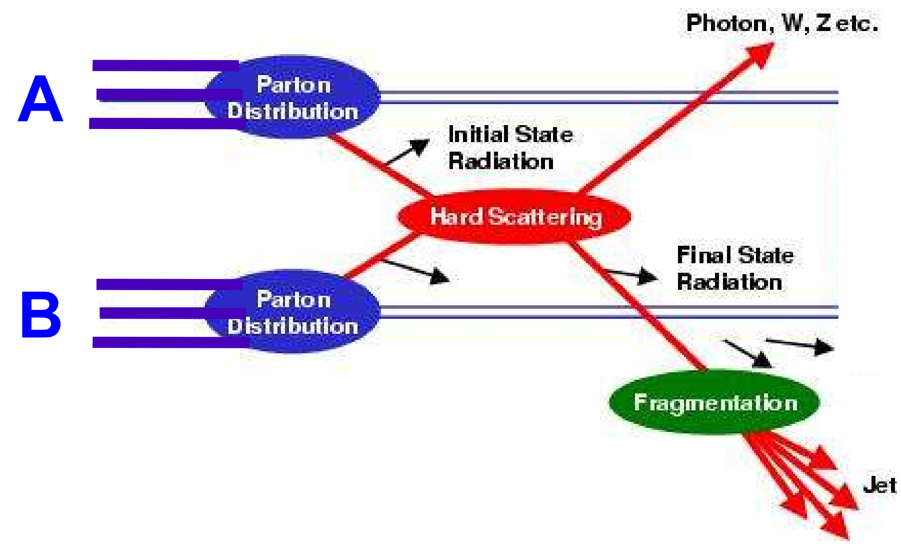


Hard QCD probes (II)

3. Production yields theoretically calculable via perturbative-QCD:

"Factorization theorem":

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



Independent scattering of "free" partons:

$$f_{a/A}(x,Q^2) = A\, f_{a/p}(x,Q^2)$$

A+B = "simple superposition of p+p collisions"

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

At impact parameter b:

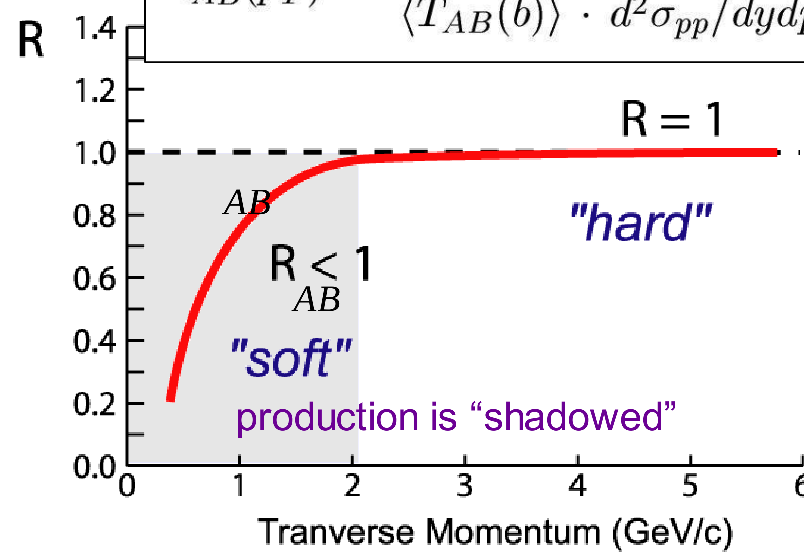
$$dN_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

geom. nuclear overlap at b

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

Nuclear Modification Factor:

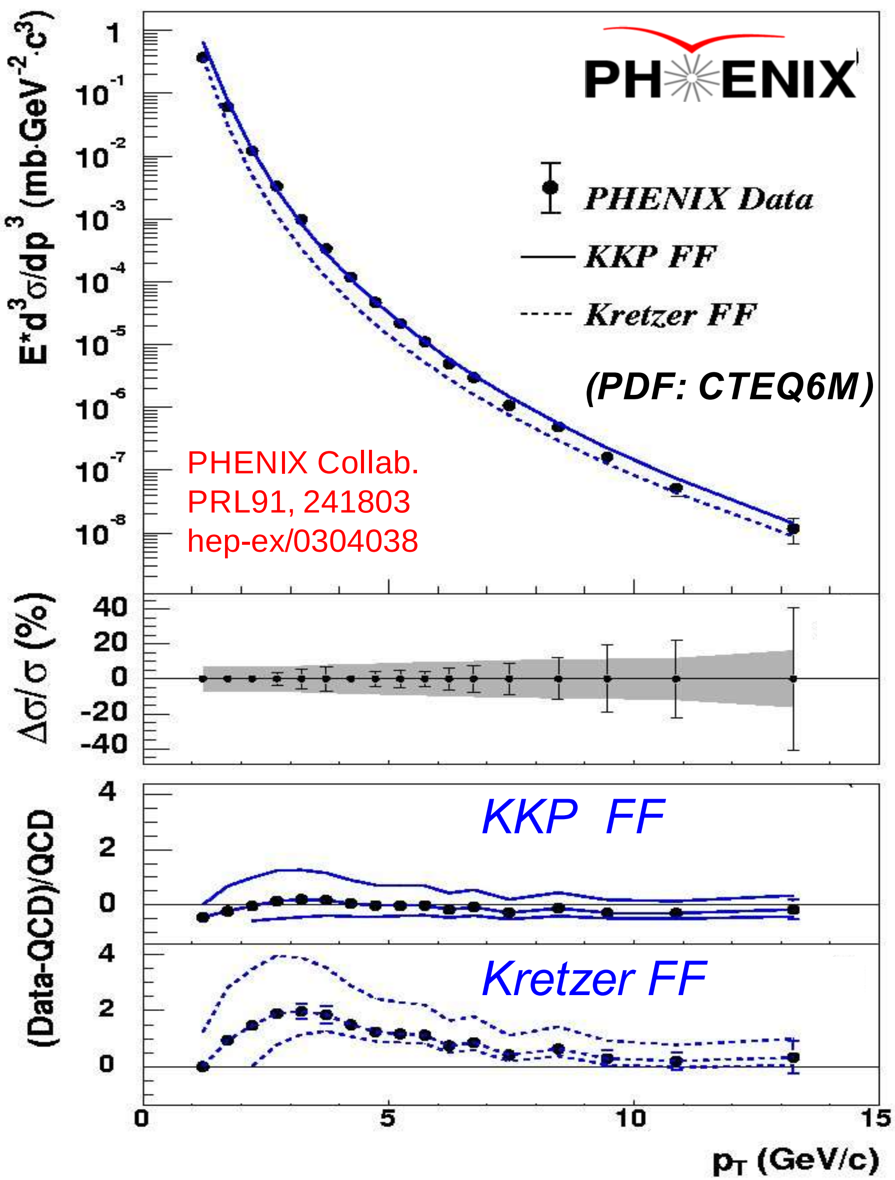
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle\cdot d^2\sigma_{pp}/dydp_T}$$

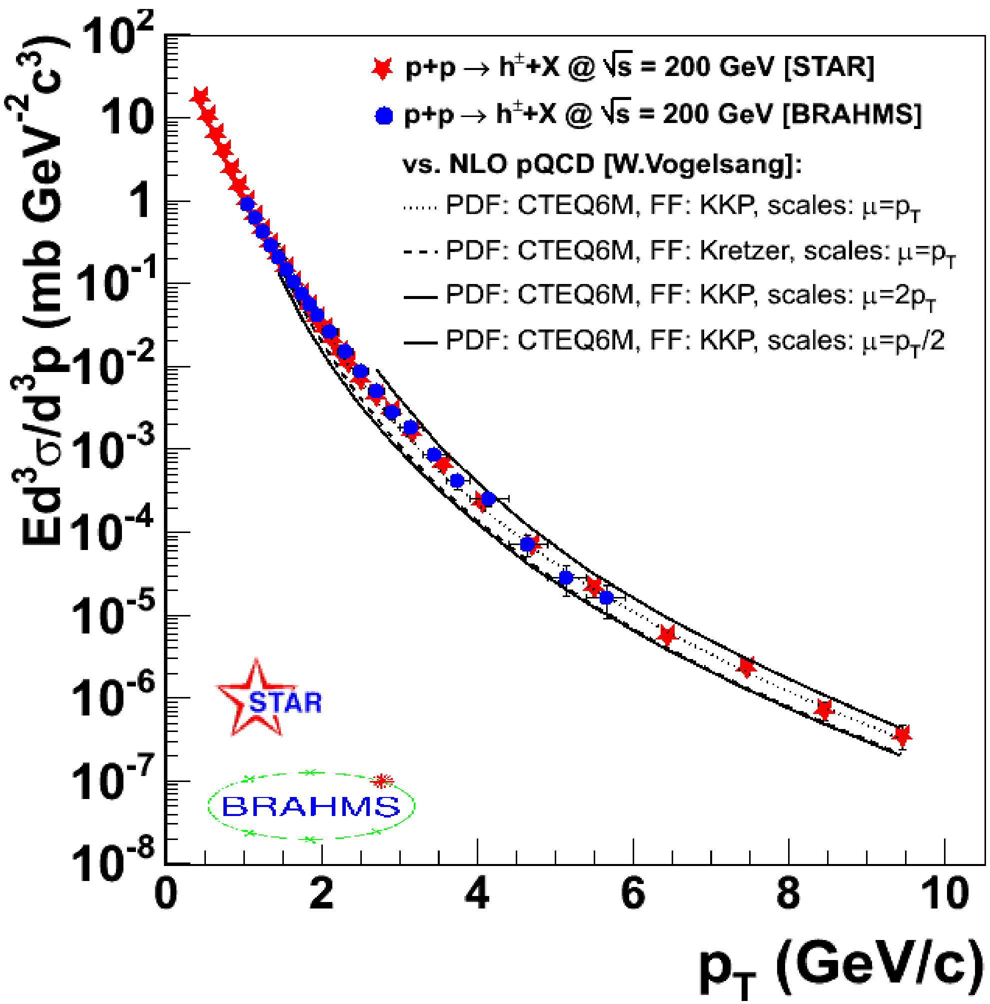


High p_T p+p baseline data well described by pQCD

- Good theoretical (NLO pQCD) description:

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

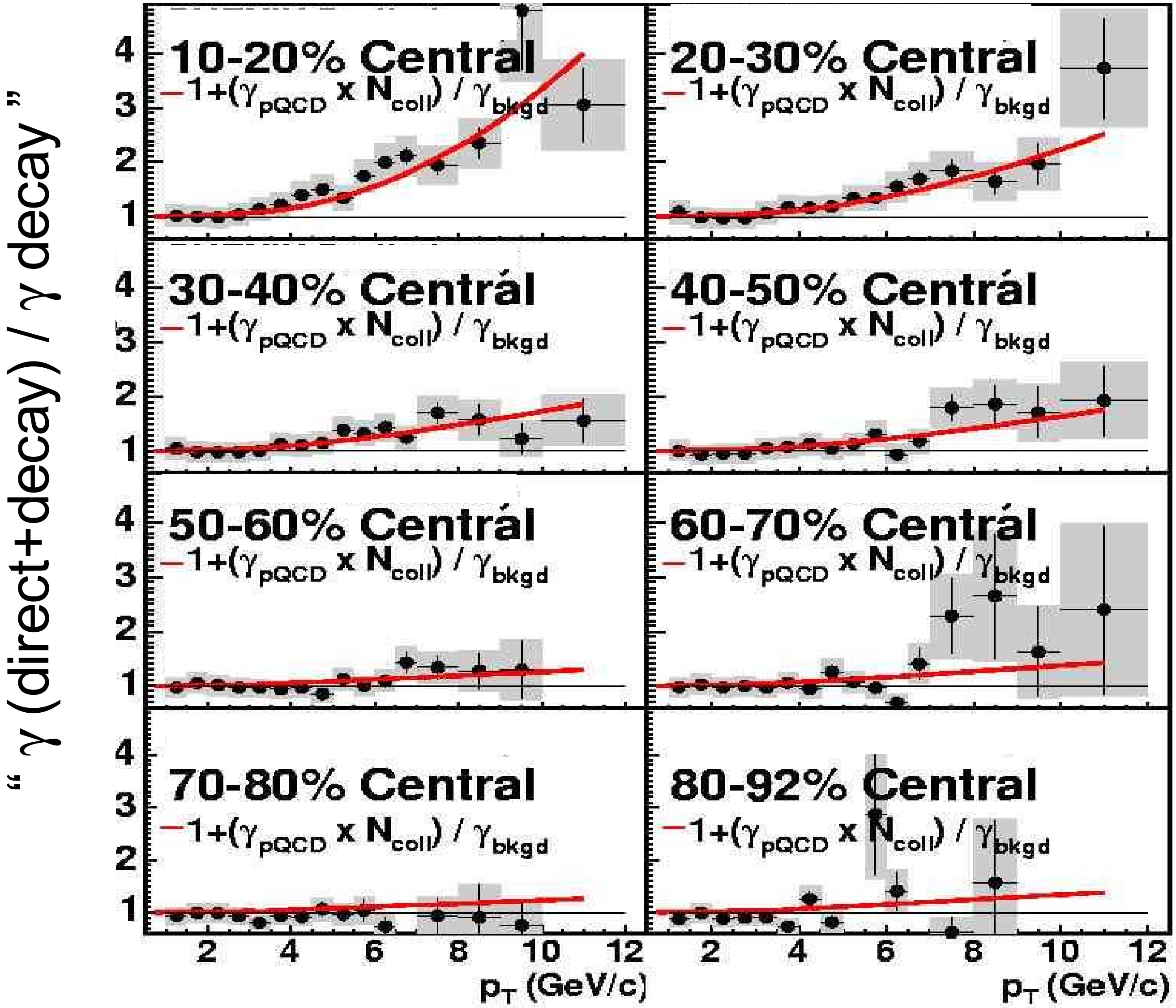




- Well calibrated (experimentally & theoretically) p+p references at hand

"N_{coll} scaling" in Au+Au @ 200 GeV: Direct Photons

- Direct photon production in Au+Au (all centralities) consistent w/ N_{coll}-scaled p+p pQCD predictions:

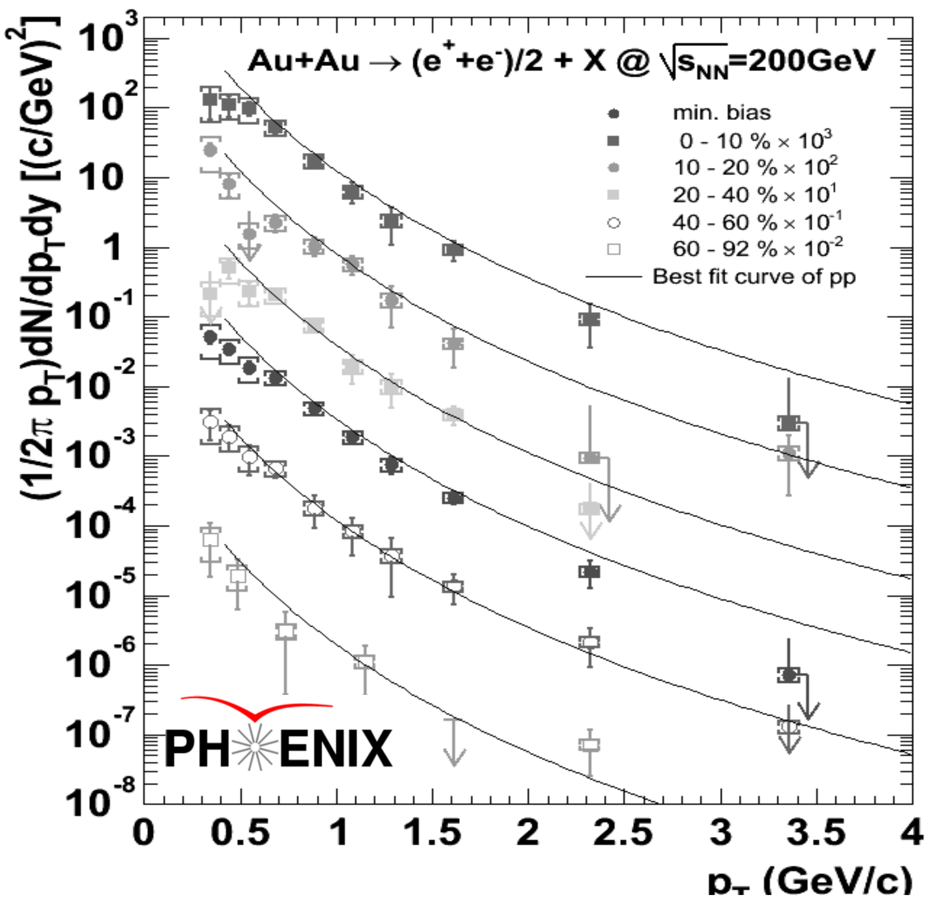


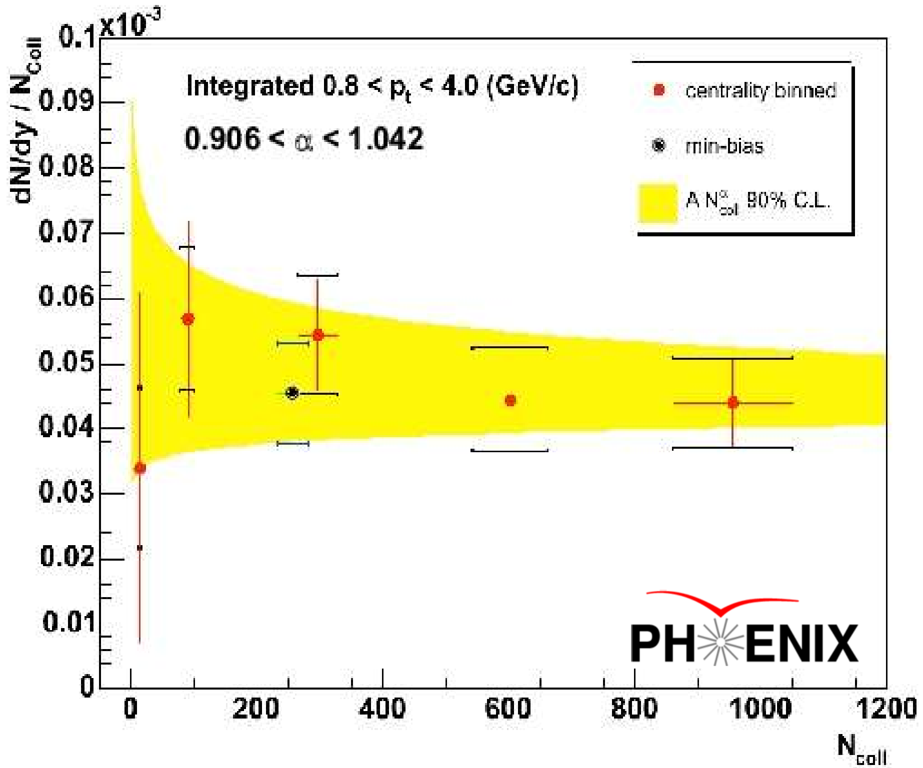
PHENIX Preliminary

[J.Frantz QM'04]

"N_{coll} scaling" in Au+Au @ 200 GeV: Total charm

- Open-charm indirect measurement via semi-leptonic channel: $D \rightarrow e^{\pm} + X$
- Single $e^{\pm}$ Au+Au spectra & total cross-section consistent w/ N_{coll} -scaled p+p charm production:

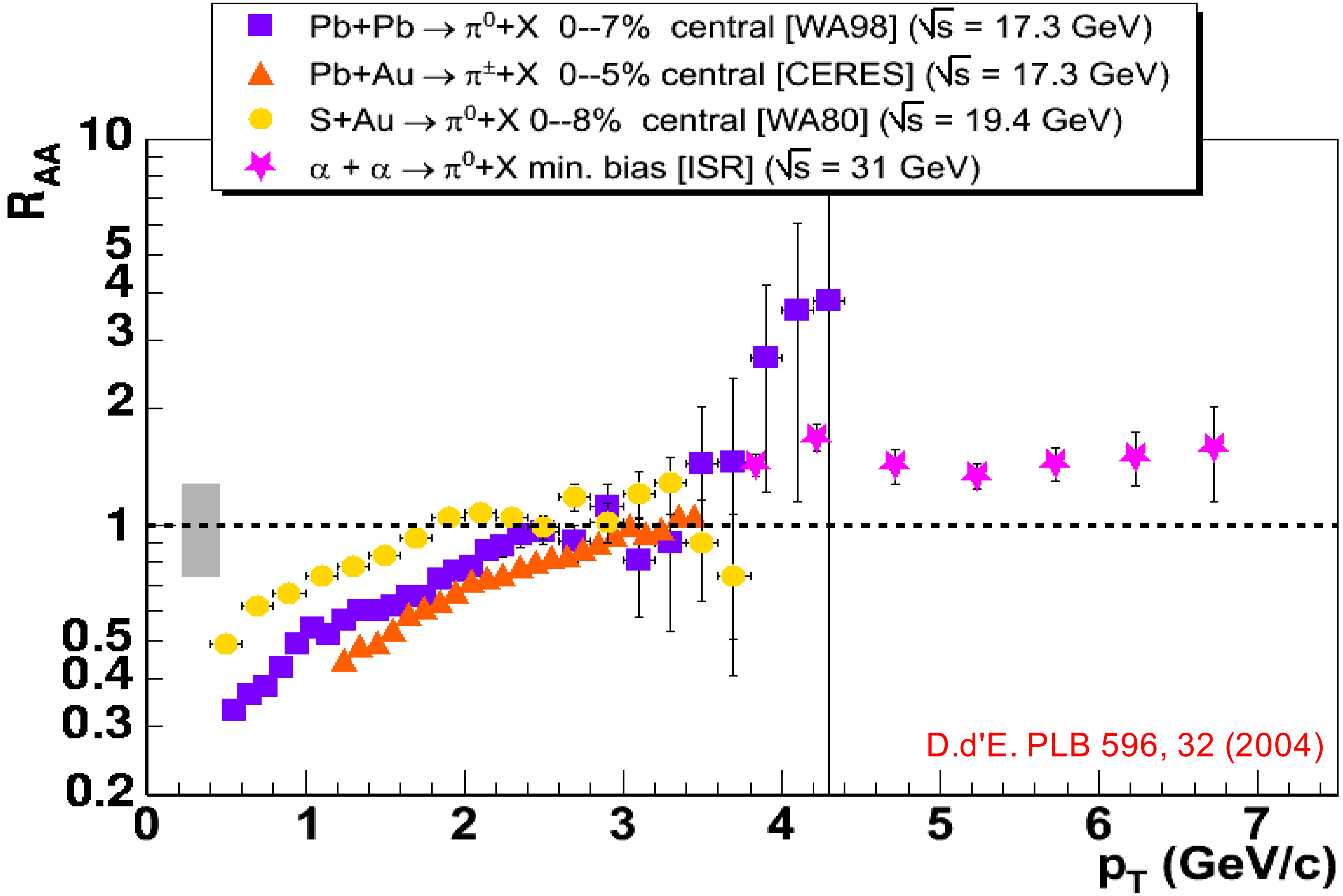




- pQCD parton scattering holds for hard processes in Au+Au (all centralities).

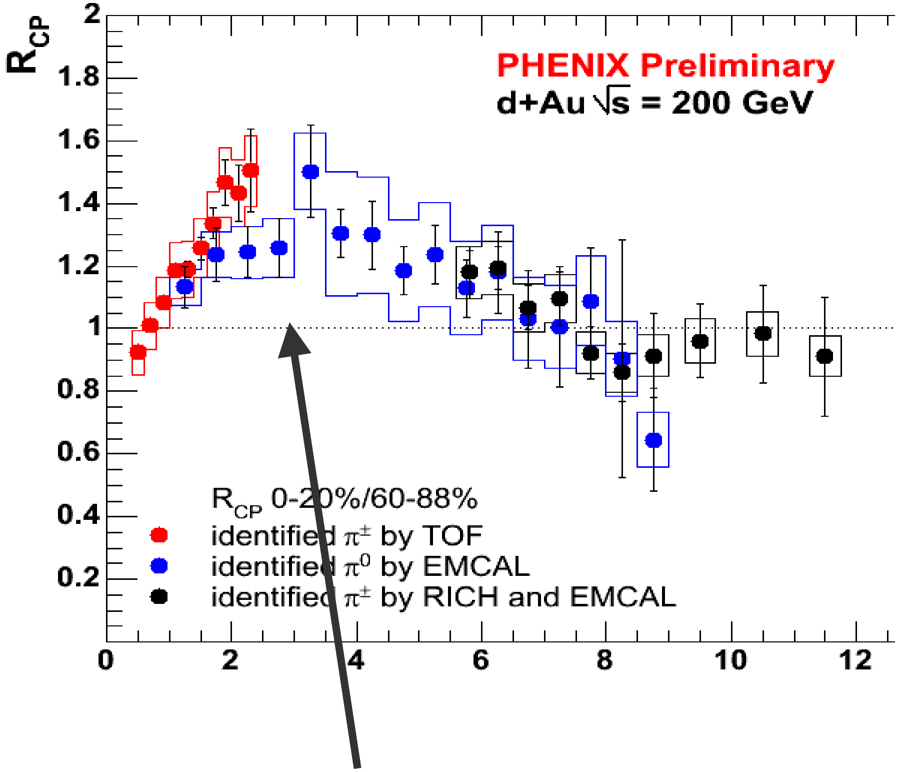
"N_{coll} scaling" in A+A @ 17, 31 GeV: High p_T hadrons

- High p_T π^0 production in (0-10%) central A+A at SPS (and $\alpha+\alpha$ @ ISR) energies: consistent w/ "N_{coll}-scaling" (or Cronin enhancement):

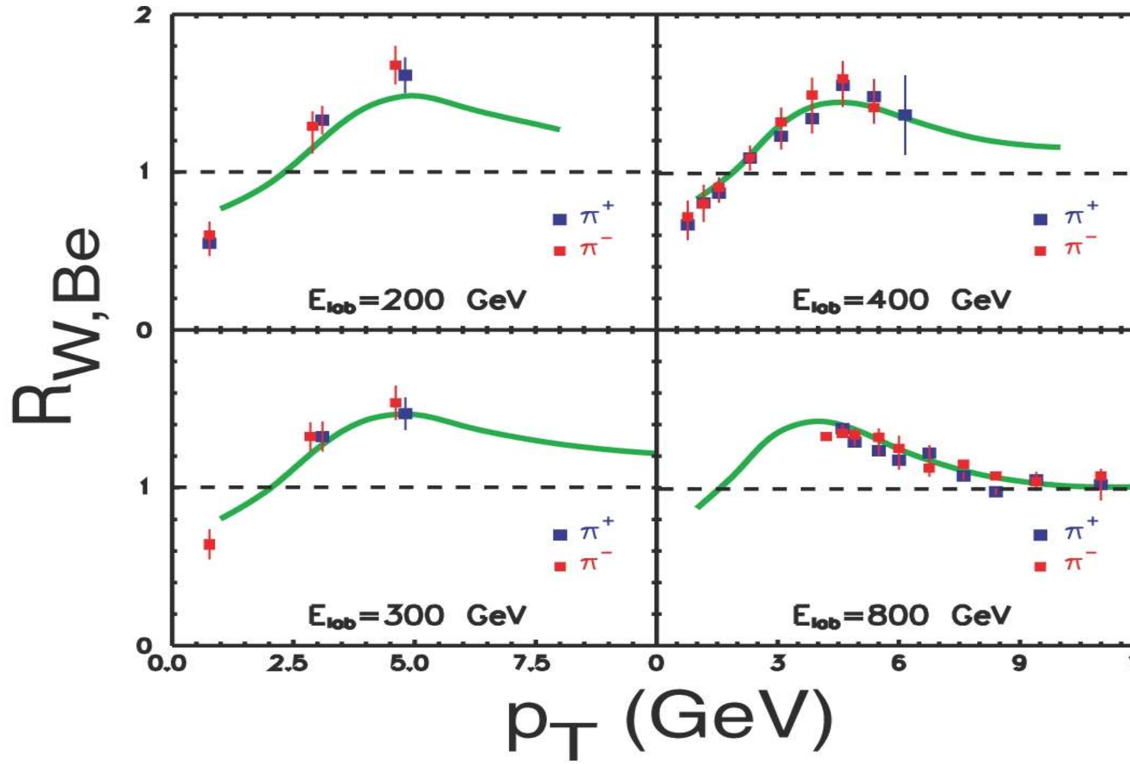


"N_{coll} scaling" in d+Au @ 200 GeV: High p_T hadrons

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



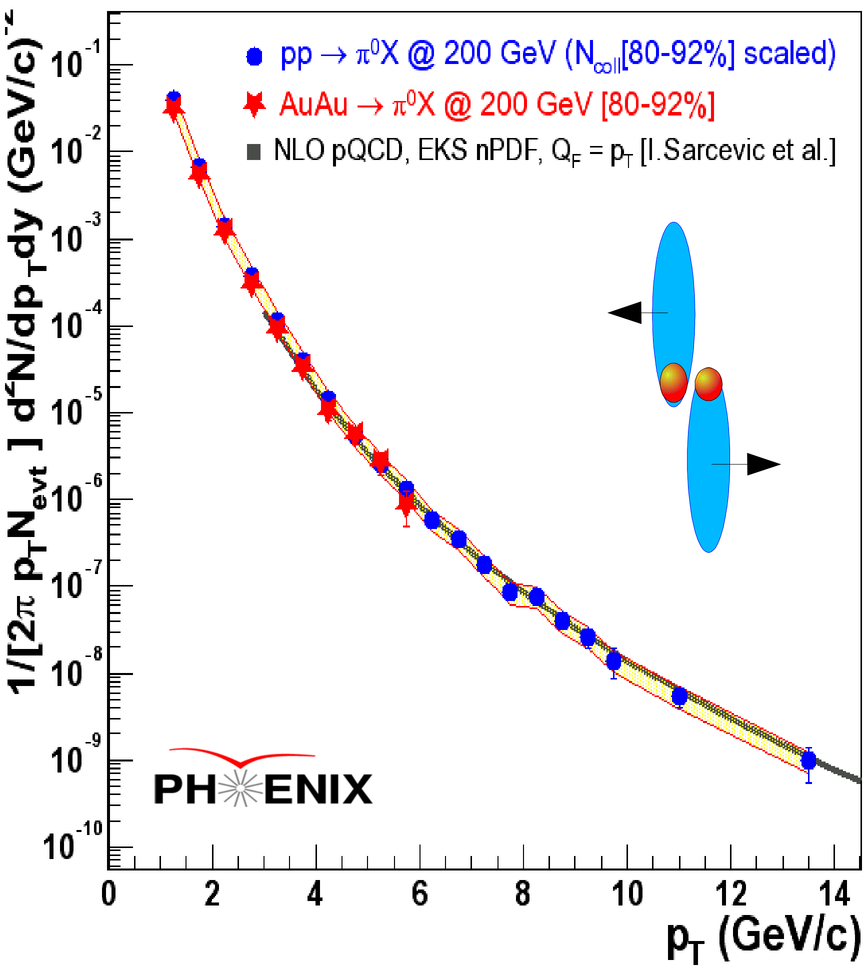
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



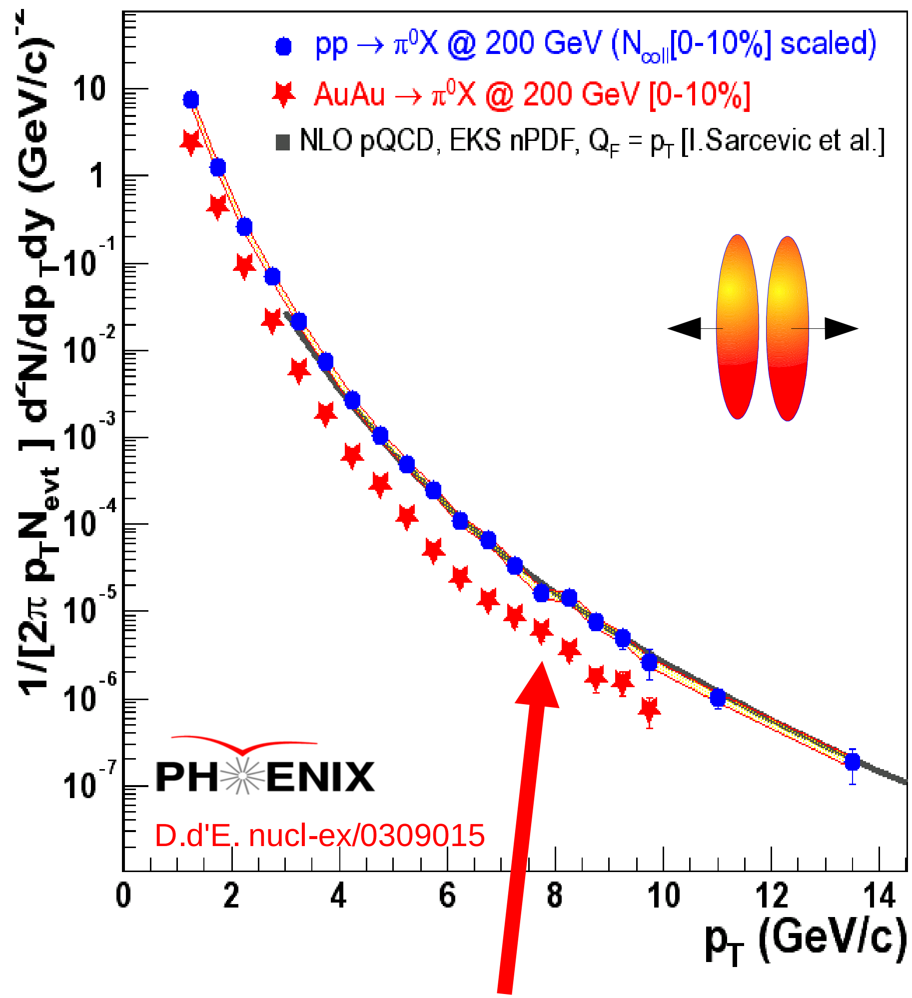
- Enhanced high p_T production in d+Au (R_{dAu} > 1) also found in p+A at lower √s ("Cronin enhancement"): p_T broadening due to initial-state soft & semihard scattering.
- Expected pQCD behaviour ($R_{pA,dA}$~1) recovered for p_T > 8 GeV/c

Suppressed high p_T hadroproduction in Au+Au @ RHIC !

Au+Au→ π^0 *X* (peripheral)



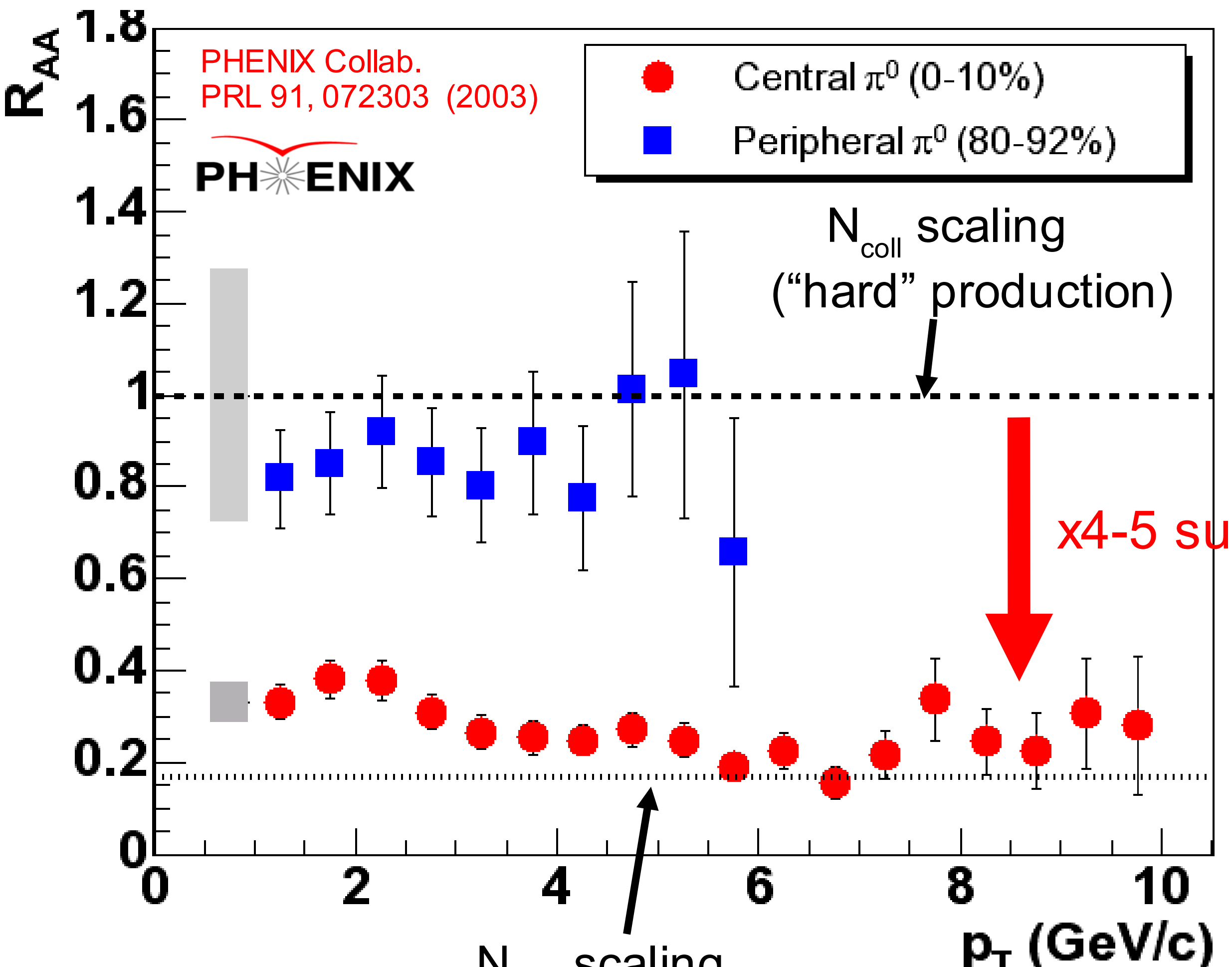
Au+Au→ π^0 *X* (central)

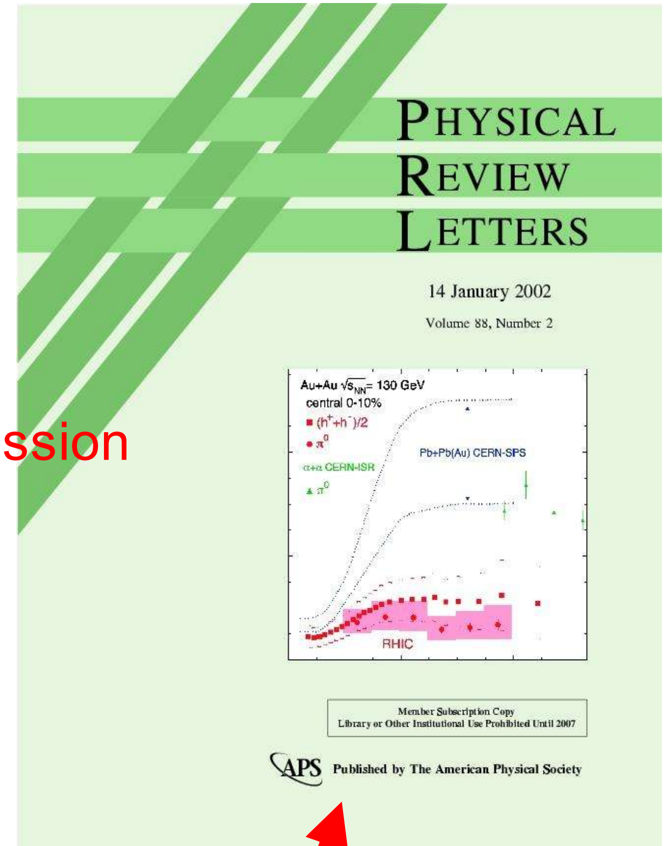


Peripheral data agree well with p+p (data&pQCD) plus N_{coll} scaling

Strong suppression in central Au+Au collisions

Suppressed high p_T hadroproduction @ RHIC : R_{AA} (π^o)



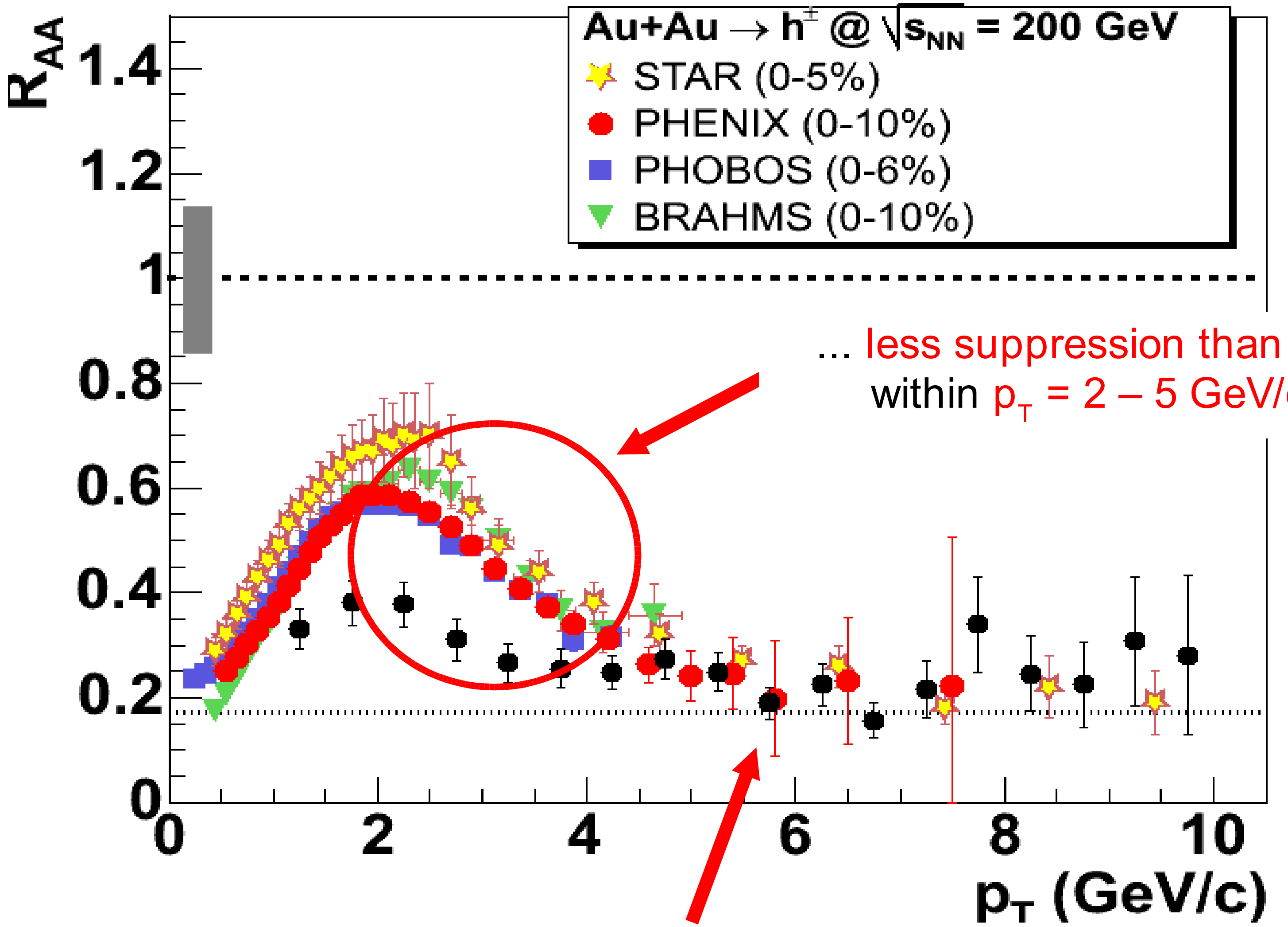


Discovery of
high p_T suppression
(one of most significant results @ RHIC so far)

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

Suppressed high p_T hadroproduction @ RHIC: R_{AA} ($h^{\pm}$ vs π^o)

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

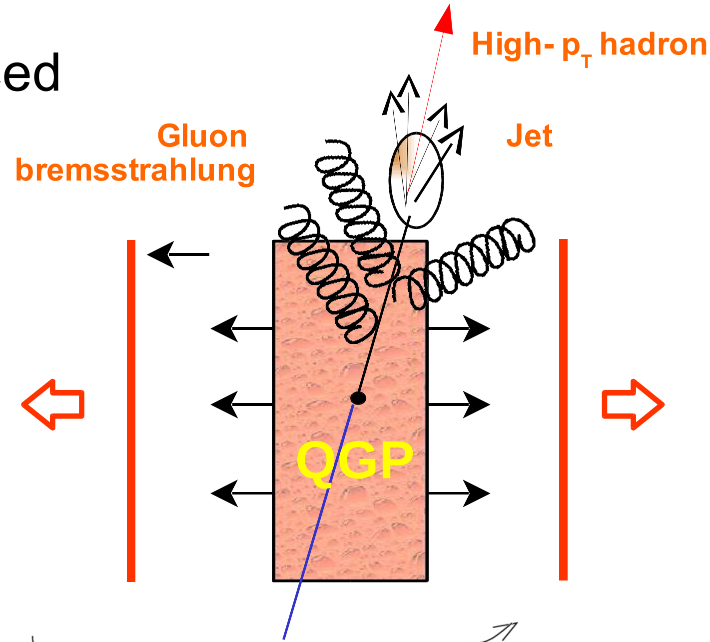


... less suppression than π^0 within p_T = 2 – 5 GeV/c (see later)

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

"Jet quenching" predictions

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

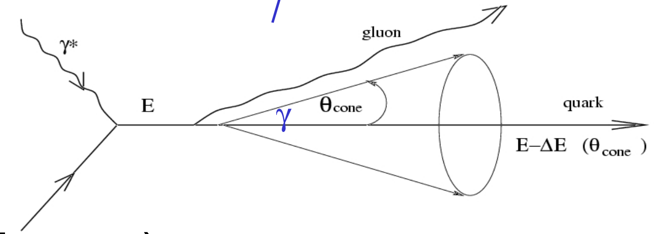


- Mean parton energy loss $\propto$ medium properties:

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

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

"Jet quenching" model vs. data (I)

- Dense medium properties according to final-state parton energy loss 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:

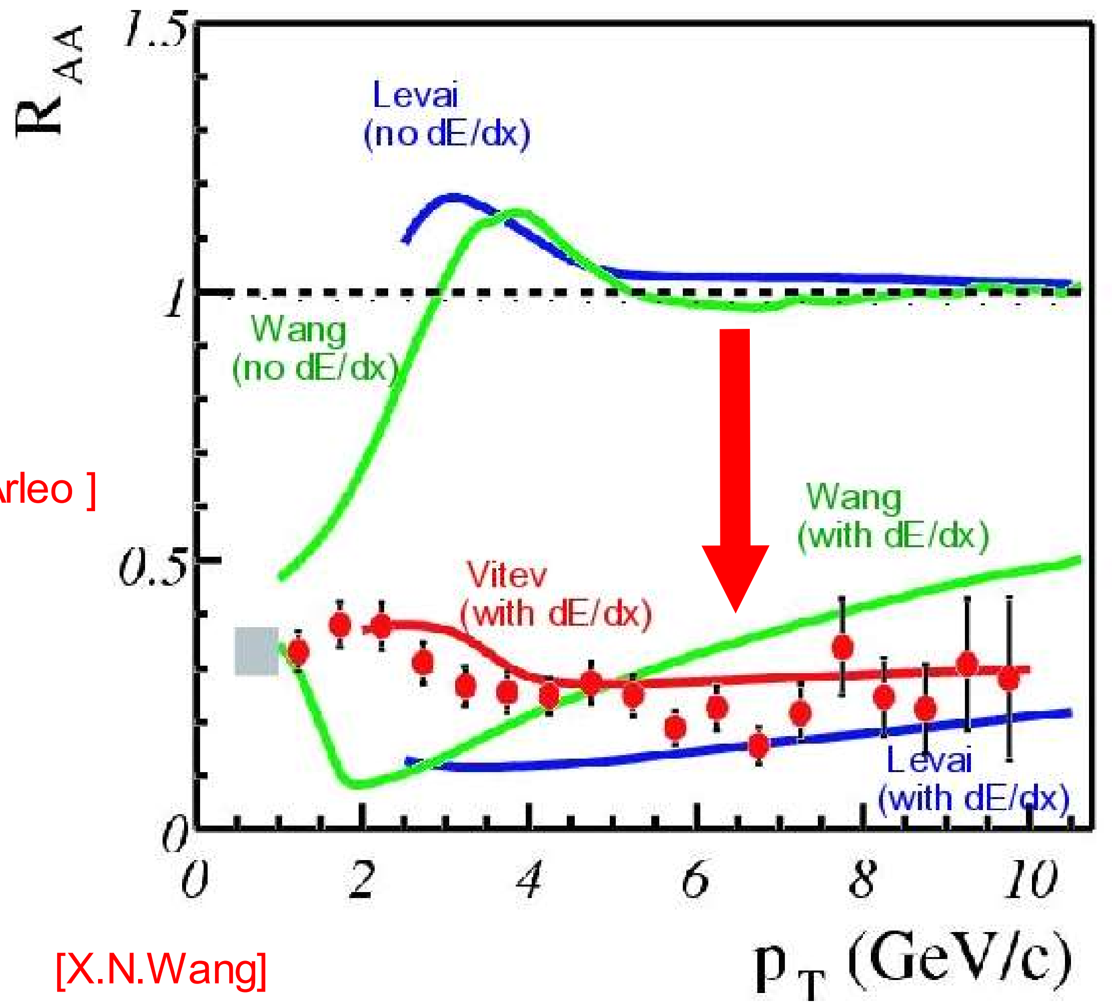
    $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 [BDMPS, F.Arleo]

  - Plasma temperatures:

    T ~ 0.4 GeV [G. Moore]

  - Medium-induced radiative energy losses:

    dE/dx ≈ 0.25 GeV/fm (expanding)
    $dE/dx|_{eff}$ ≈ 14 GeV/fm (static source) [X.N.Wang]



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

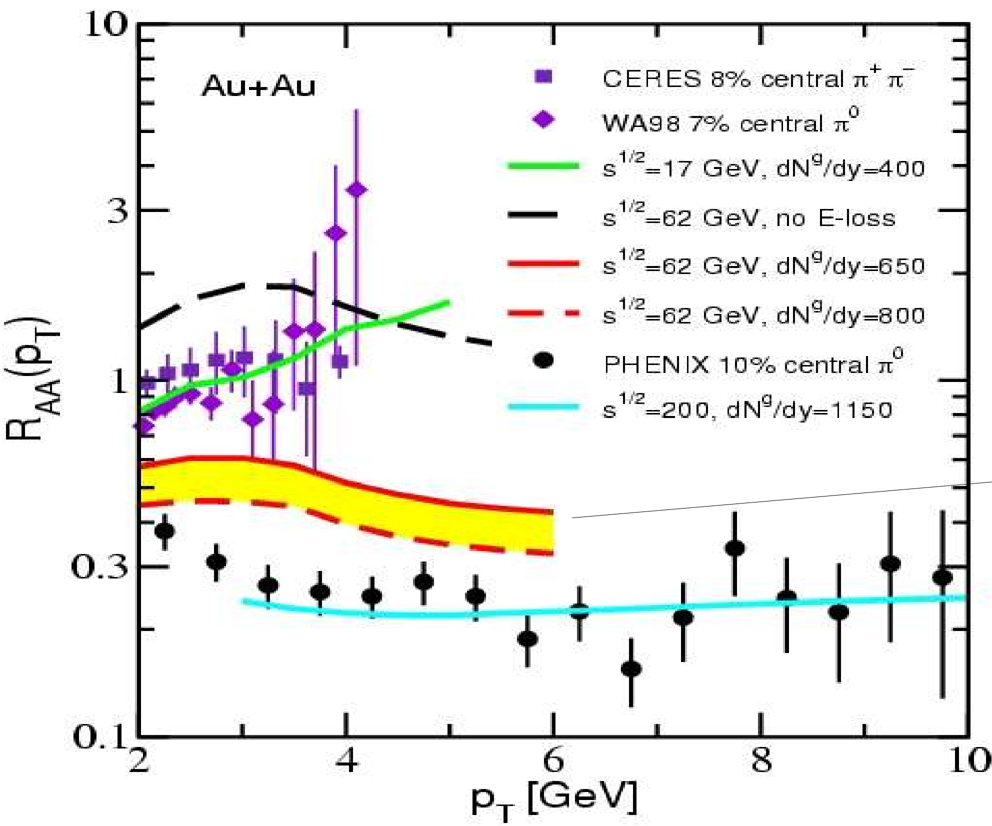
“Jet quenching” model vs. data (II)

- sqrt(s) dependence of high p_T suppression:

  R_{AA} ~ 1 for √s~20 GeV (dN^g/dy~400)

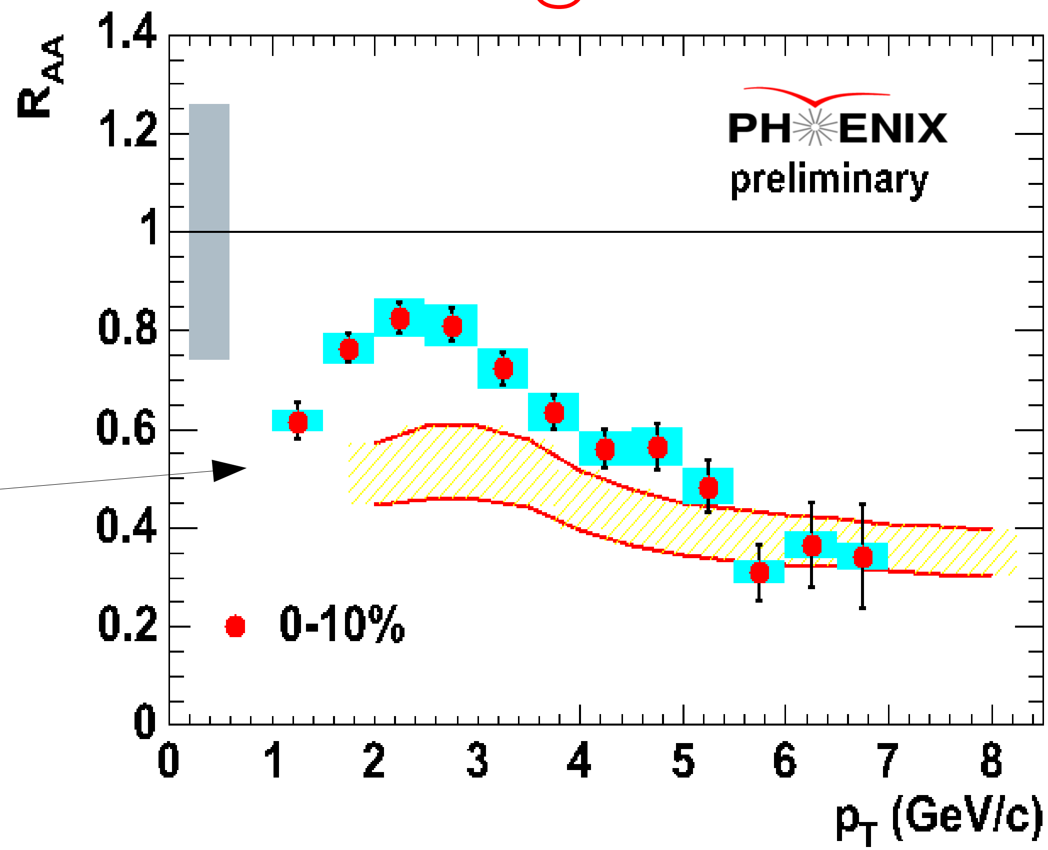
  R_{AA} ~ 0.3 for √s~62 GeV (dN^g/dy~650)

  R_{AA} ~ 0.2 for √s~200 GeV (dN^g/dy~1100)



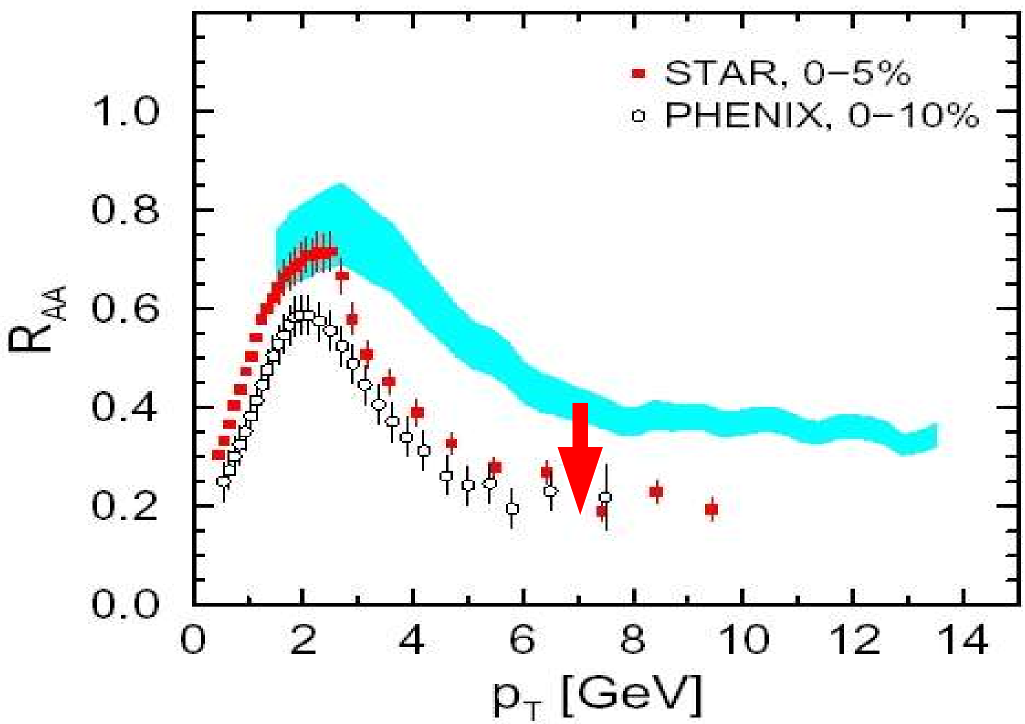
I. Vitev nucl-th/0404052

Au+Au @ 62.4 GeV

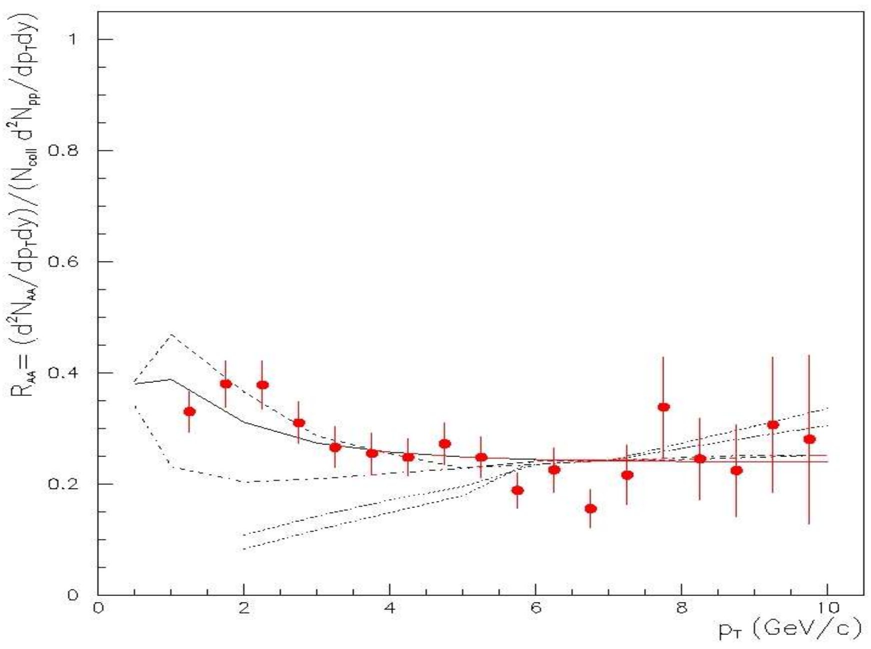


Energy loss in a dense hadronic medium ?

- Hadronic transport models (HSD, UrQMD) or DPM-based models do not produce enough suppression. $_A$dditional pre-hadronic energy loss needed.



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



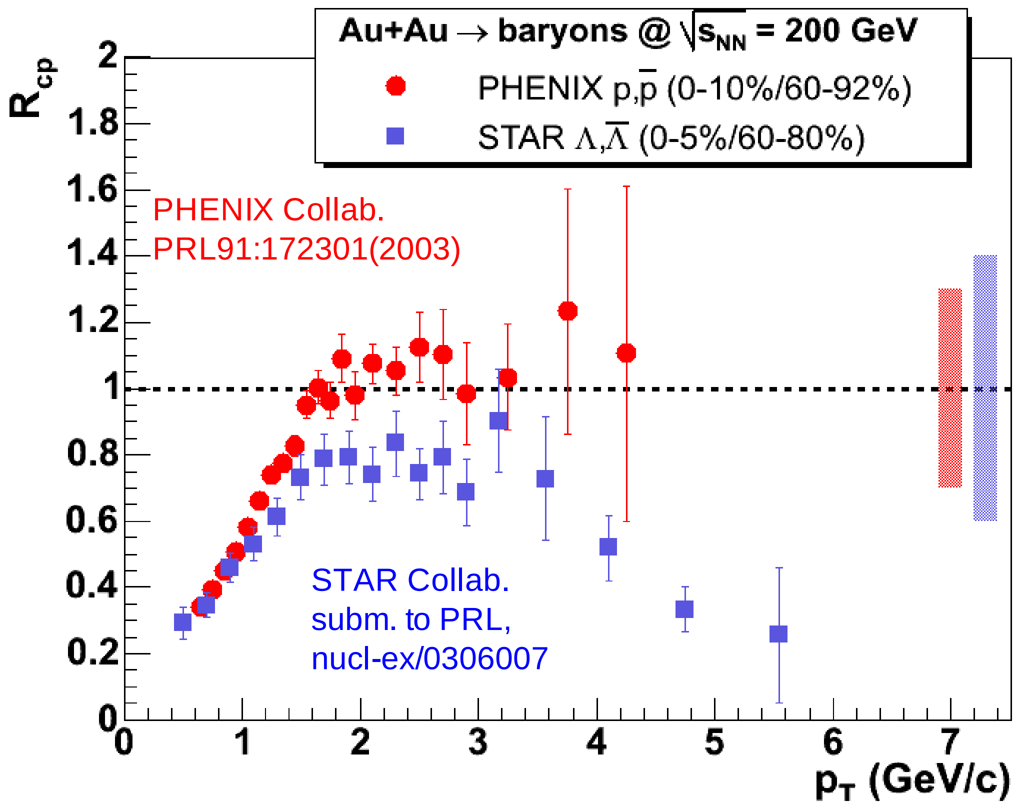
Capella, Ferreiro, Kaidalov, Sousa hep-ph/0403081

Hadron production at intermediate p_T

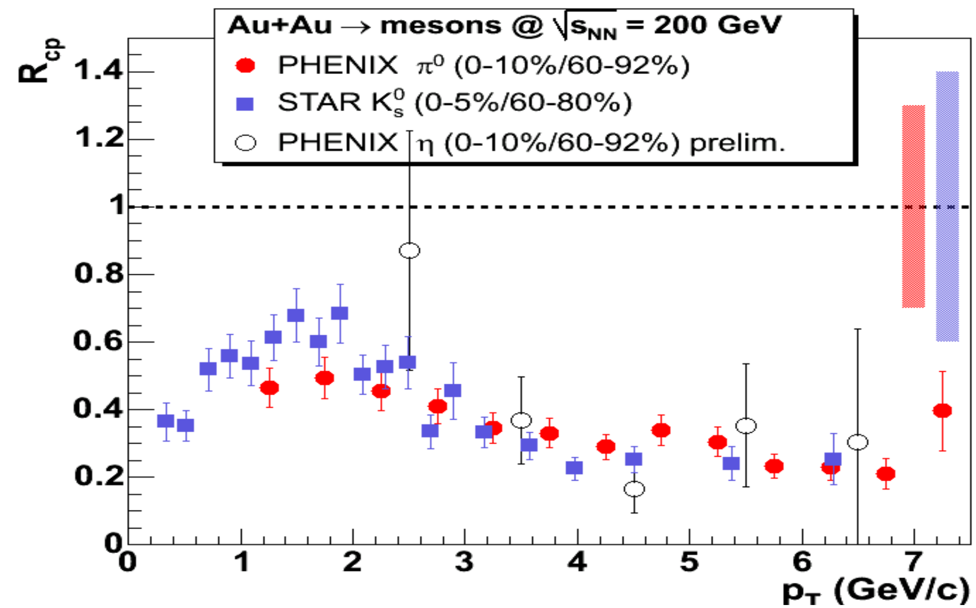
Unsuppressed baryon production

- R_{cp} (ratio central/peripheral) at intermediate p_T = 2 – 4 GeV/c:

  Baryons: p, $\bar{p}$, Λ, $\bar{\Lambda}$ **NOT** (or much less) suppressed in central Au+Au.



Mesons: π^0, k^0_s, η, equally suppressed.

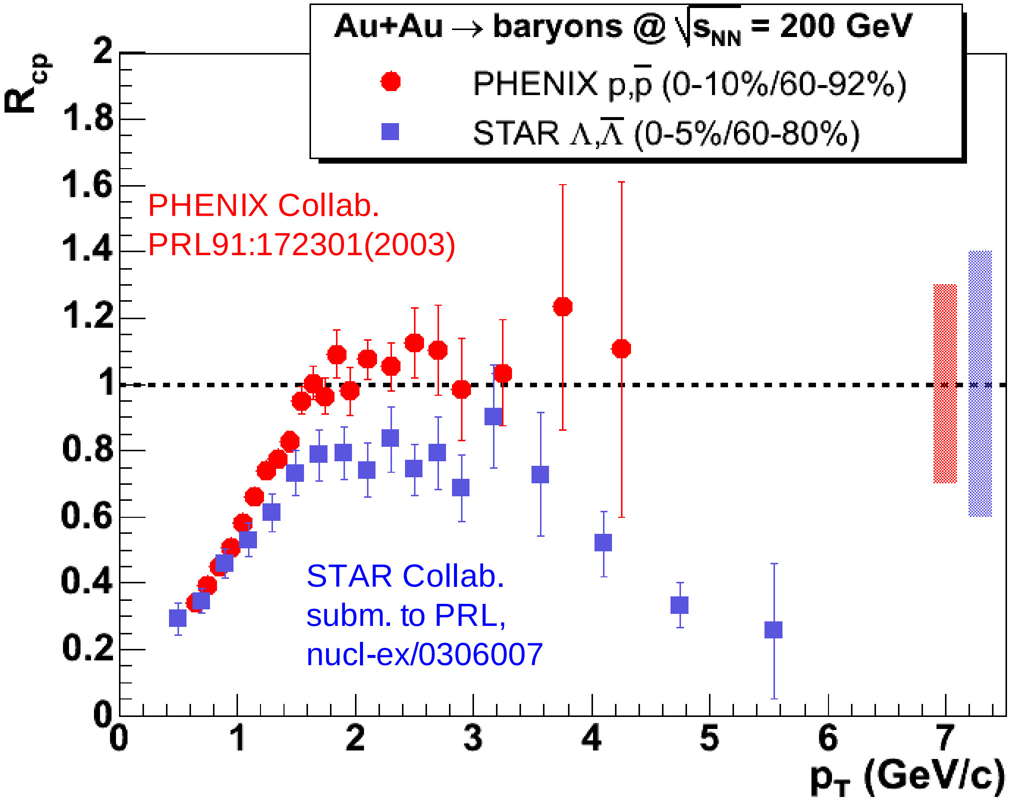


- Particle composition inconsistent with known (universal) fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range

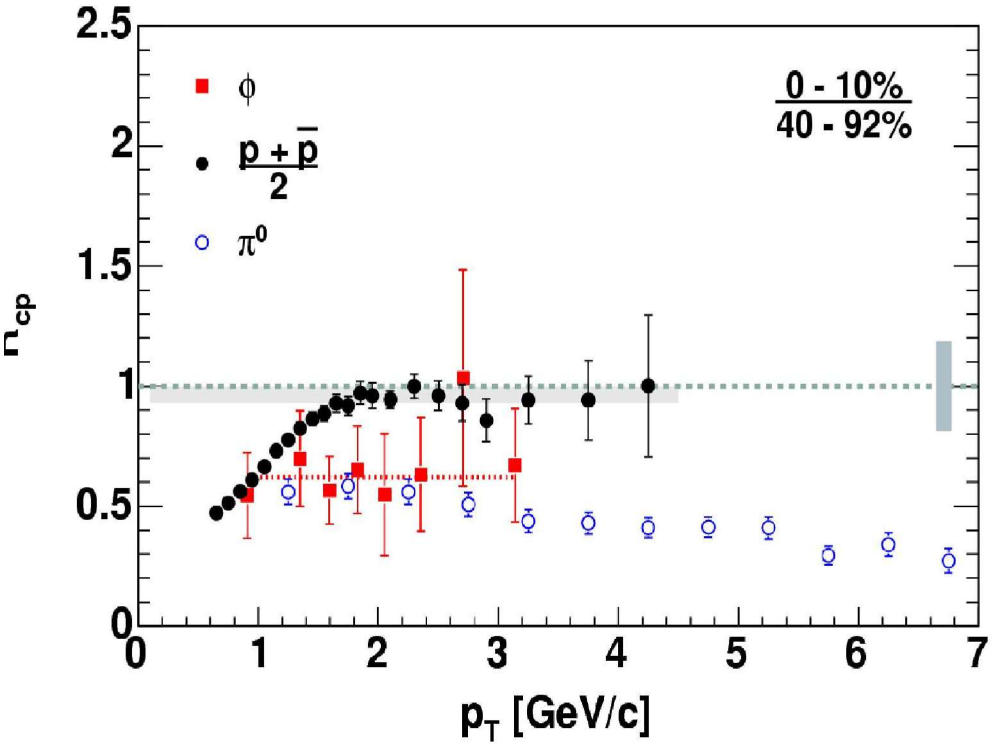
Unsuppressed baryon production: not a mass effect !

- R_{cp} (ratio central/peripheral) at intermediate p_T = 2 – 4 GeV/c:

Baryons: p, $\bar{p}$, Λ, $\bar{\Lambda}$ **NOT** (or much less) suppressed in central Au+Au.



Heavy φ as suppressed as other mesons (π^0, k^0_s, η)

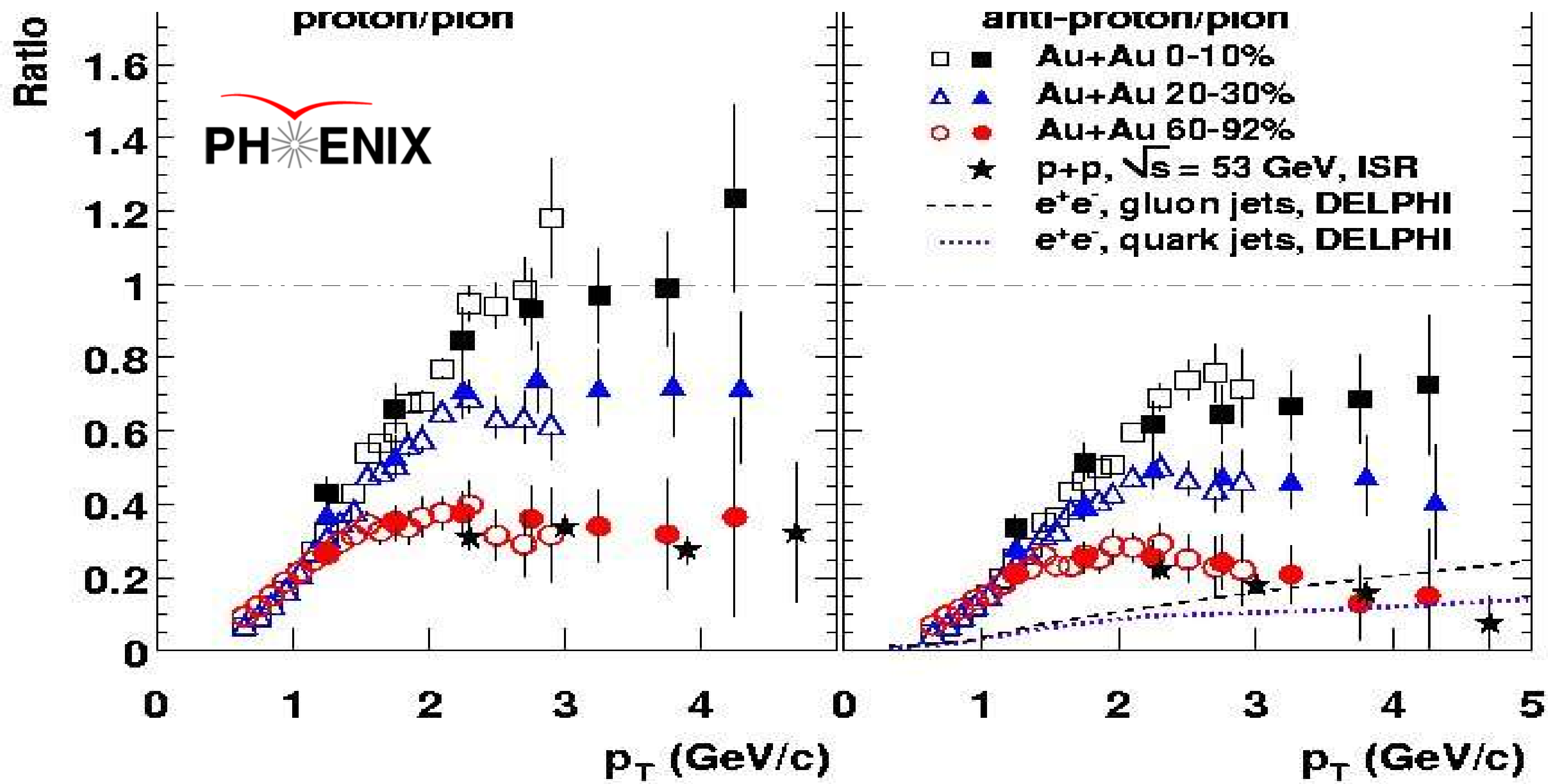


- Particle composition inconsistent with known (universal) fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range

Enhanced baryon/meson ratio

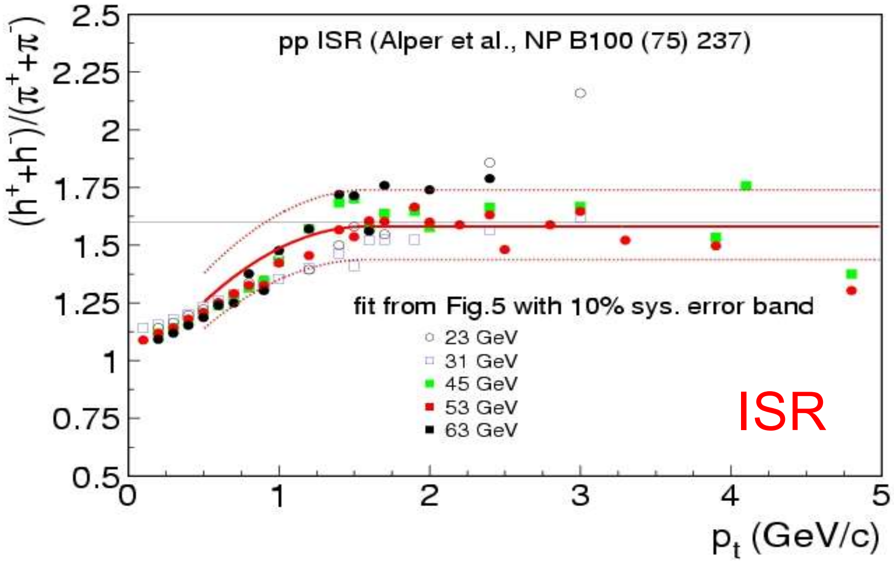
- Central Au+Au: $p/\pi \sim 0.8$ (at p_T = 2 - 4 GeV/c) at variance with perturbative production mechanisms (favour lightest mesons).

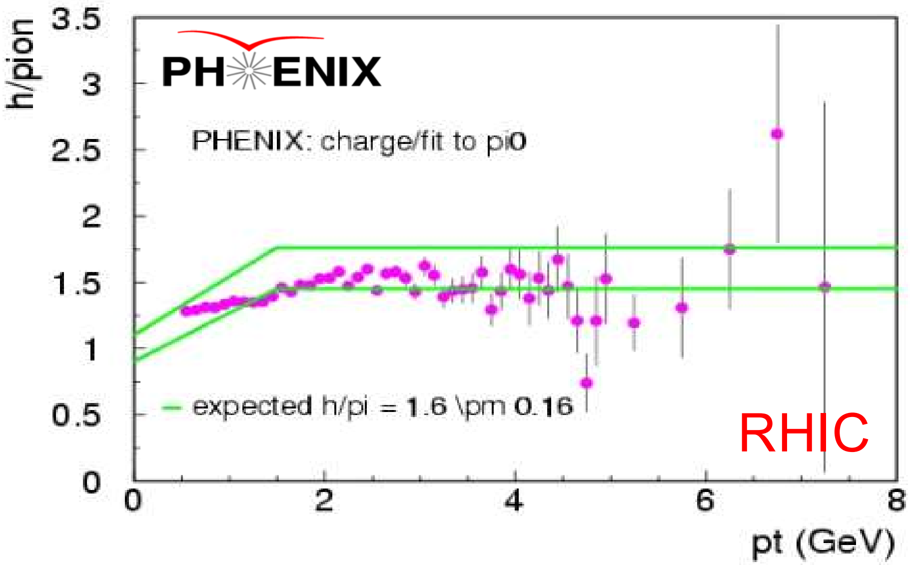
- Periph. Au+Au: $p/\pi \sim 0.2$ as found in p+p (ISR,FNAL) & e+e- jet fragmentation



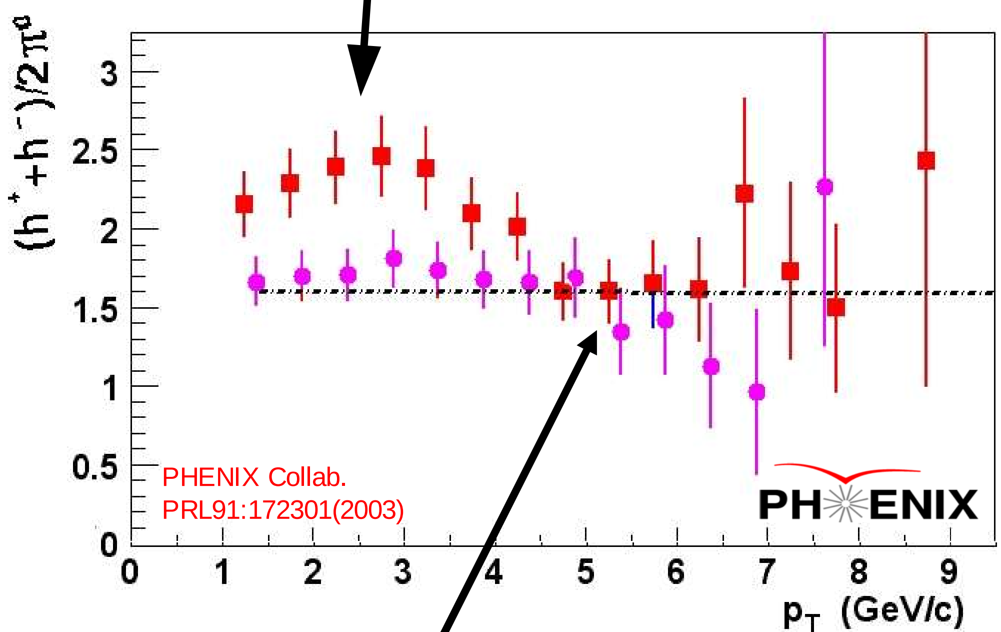
"Anomalous" particle composition: hadron/meson ratio

- p+p collisions: hadron/meson ~ 1.6





- Au+Au (central): hadron/meson ~ 2.5 at p_T = 1 - 4 GeV/c (inconsistent w/ known fragmentation functions).

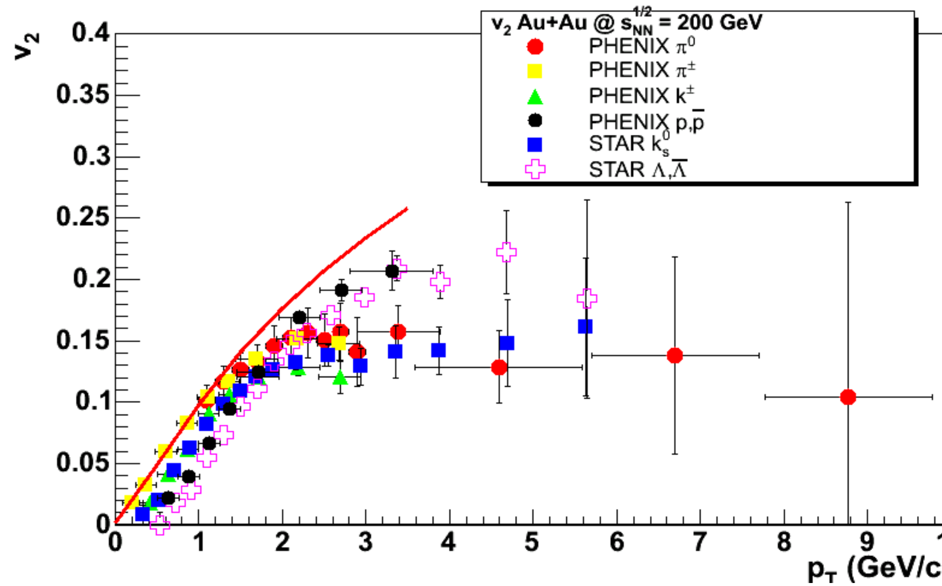


- Baryon enhancement limited to p_T < 5 GeV/c ($h^{\pm}/\pi$ ~ 1.6, perturb. ratio): $h^{\pm}$, π^0 equally suppressed

Enhanced baryonic elliptic flow

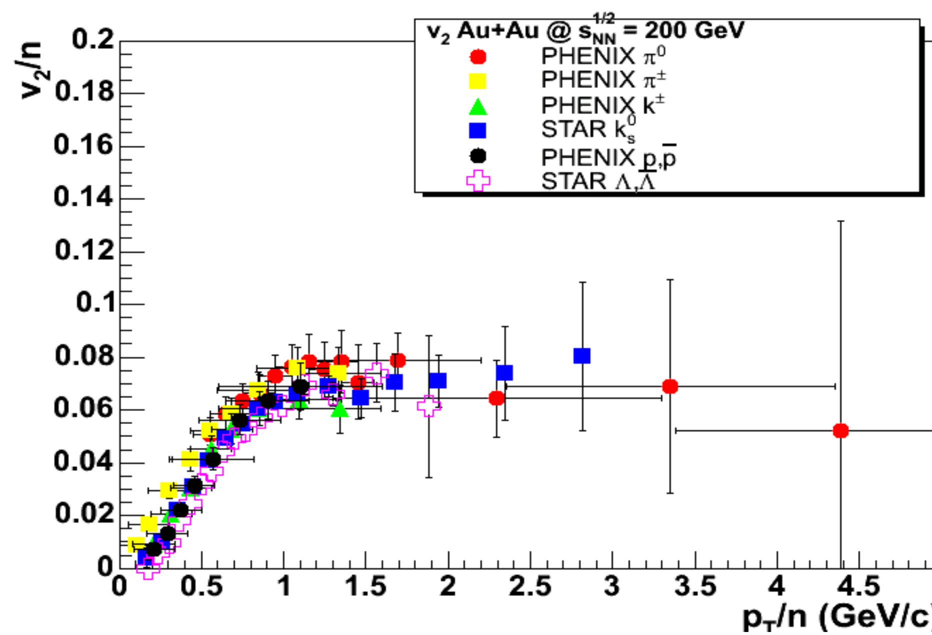
- Particle species hierarchy of flow values:

  $v_2^{meson} > v_2^{baryon}$ 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



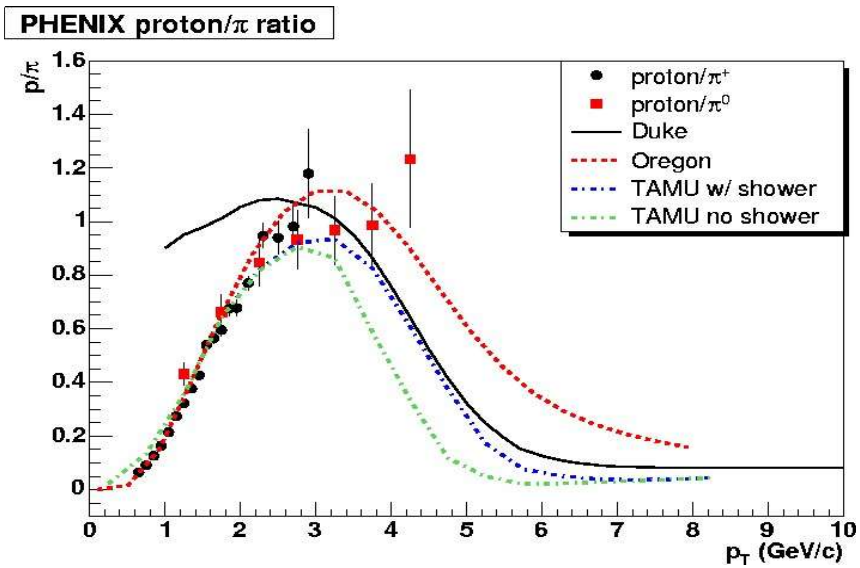
- Simple v_2 scaling behaviour when v_2 and p_T normalized by number of constituent quarks:

  n = 2 mesons
  n = 3 baryons



"Quark recombination" models vs. data

- Quark recombination (coalescence) mechanisms provide a simple explanation of anomalous baryon enhancement & v_2 at p_T= 2-5 GeV/c:



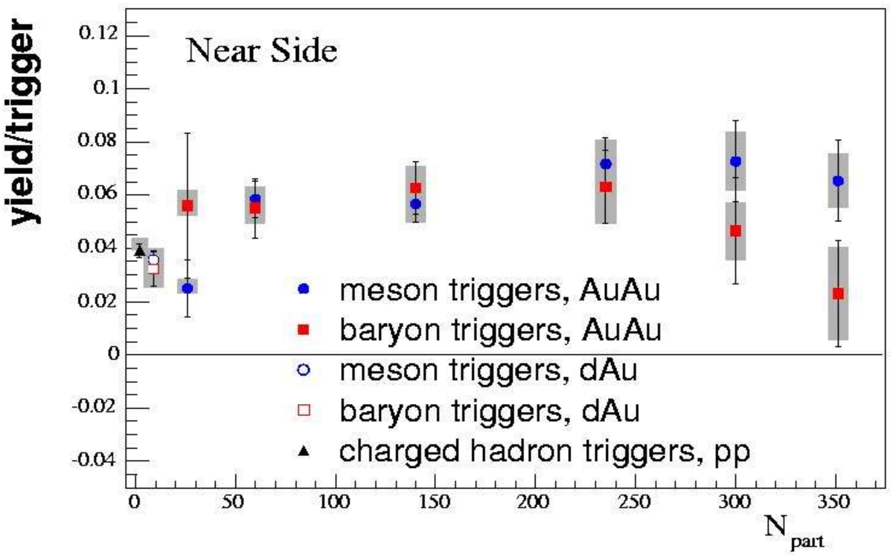
- Via quark momenta addition, recombination dominates for p_T ~ 1- 4 GeV/c:

  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

- Constituent-quark scaling of v_2 naturally explained



- However ... pure thermal + thermal parton recombination inconsistent w/ jet-like (baryon and meson) near-side azimuthal correlations. Simple recomb. does not work.

Summary

1. Energy densities:

- Maximum $dE_T/d\eta$ ~ 600 GeV at midrapidity consistent w/ initial $\varepsilon > 5$ GeV/fm$^3 > \varepsilon_{crit}$

2. Elliptic flow:

- Strong elliptic flow v_2 consistent w/ short thermalization times τ_0 ~ 1 fm/c

3. Soft particle spectra:

- Shapes & yields consistent w/ hydrodyn. (thermal+coll. velocity) source emission
- Particles ratios consistent w/ chemically equilibrated system before hadronization

4. Hard particle spectra:

- Strong high p_T suppression in central A+A (compared to p+p, p+A & pQCD) consistent w/ final-state partonic energy loss in dense system: dN^g/dy~1100

5. Intermediate p_T spectra:

- Enhanced baryon yields & v_2 (compared to meson) consistent w/ quark recombination mechanisms in a thermal and dense system

All observations consistent with formation of thermalized dense partonic matter in central Au+Au collisions

OK ... but didn't we hear the same at SPS in 2000 ?

CERN50 - The historical milestones in 50 year ...

50 years of | Science | Events | Memories

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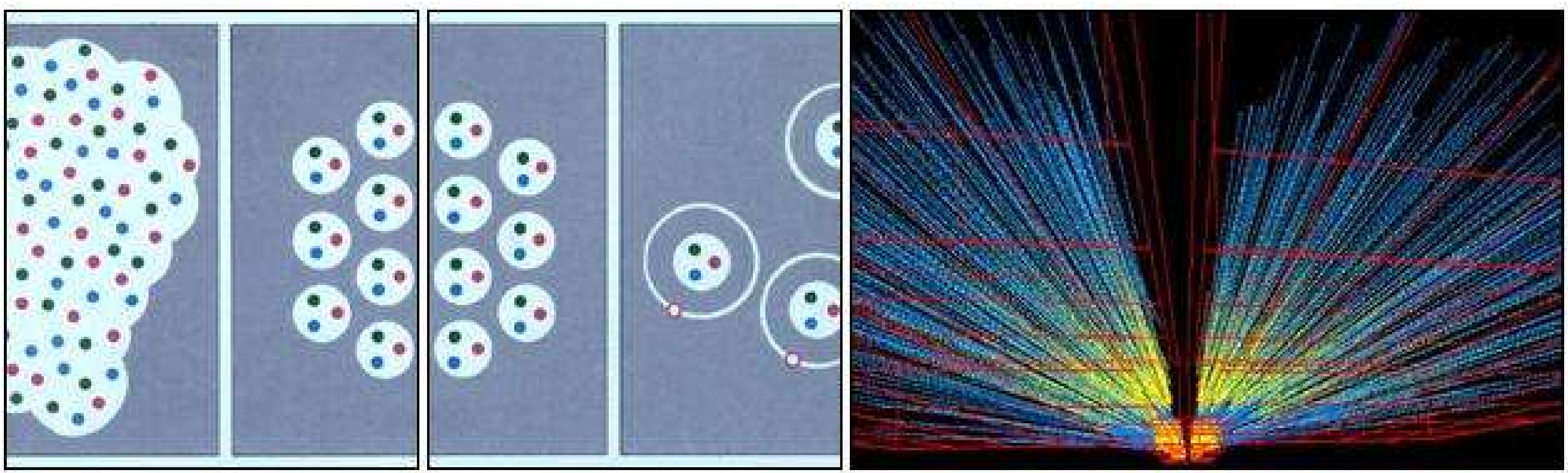
2000

Quark gluon plasma



Creation of a new state of matter, quark-gluon plasma, which probably existed just after the Big Bang.

Summary (2)

1. Energy densities:

- Maximum $dE_T/d\eta \sim 600$ GeV at midrapidity consistent w/ initial $\varepsilon > 5$ GeV/fm^3 $> \varepsilon_{crit}$
- **Seen at SPS ? Yes.** $\varepsilon > 3.9$ GeV/fm^3 $> \varepsilon_{crit}$ (Note, however τ_{cross}=1.6 fm/c $>\tau_0$ = 1 fm/c)

2. Elliptic flow:

- Strong elliptic flow v_2 consistent w/ short thermalization times $\tau_0 \sim 1$ fm/c
- **Seen at SPS ? No.** Not as large v_2. Described by hydro only with too short freezeout.

3. Soft particle spectra:

- Shapes & yields consistent w/ hydrodynam. (thermal+coll. velocity) source emission
- Particles ratios consistent w/ chemically equilibrated system before hadronization
- **Seen at SPS ? Yes.**

4. Hard particle spectra:

- Strong high p_T suppression in central A+A (compared to p+p, p+A & pQCD) consistent w/ final-state partonic energy loss in dense system: $dN^g/dy \sim 1100$
- **Seen at SPS ? Probably.** Suppression (not that strong) w.r.t. peripheral.

5. Intermediate p_T spectra:

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We need a few additional observables to claim “QGP” at RHIC ...
thermal photons (temperature of system), J/Ψ (deconfined system)

Summary (2)

1. Energy densities:
   - Maximum $dE_T/d\eta$ ~ 600 GeV at midrapidity consistent w/ initial ε > 5 GeV/fm^3 > ε_{crit}
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We need a few additional o... es to claim “QGP” at RHIC ...
thermal photons (ter... of system), J/Ψ (deconfined system)

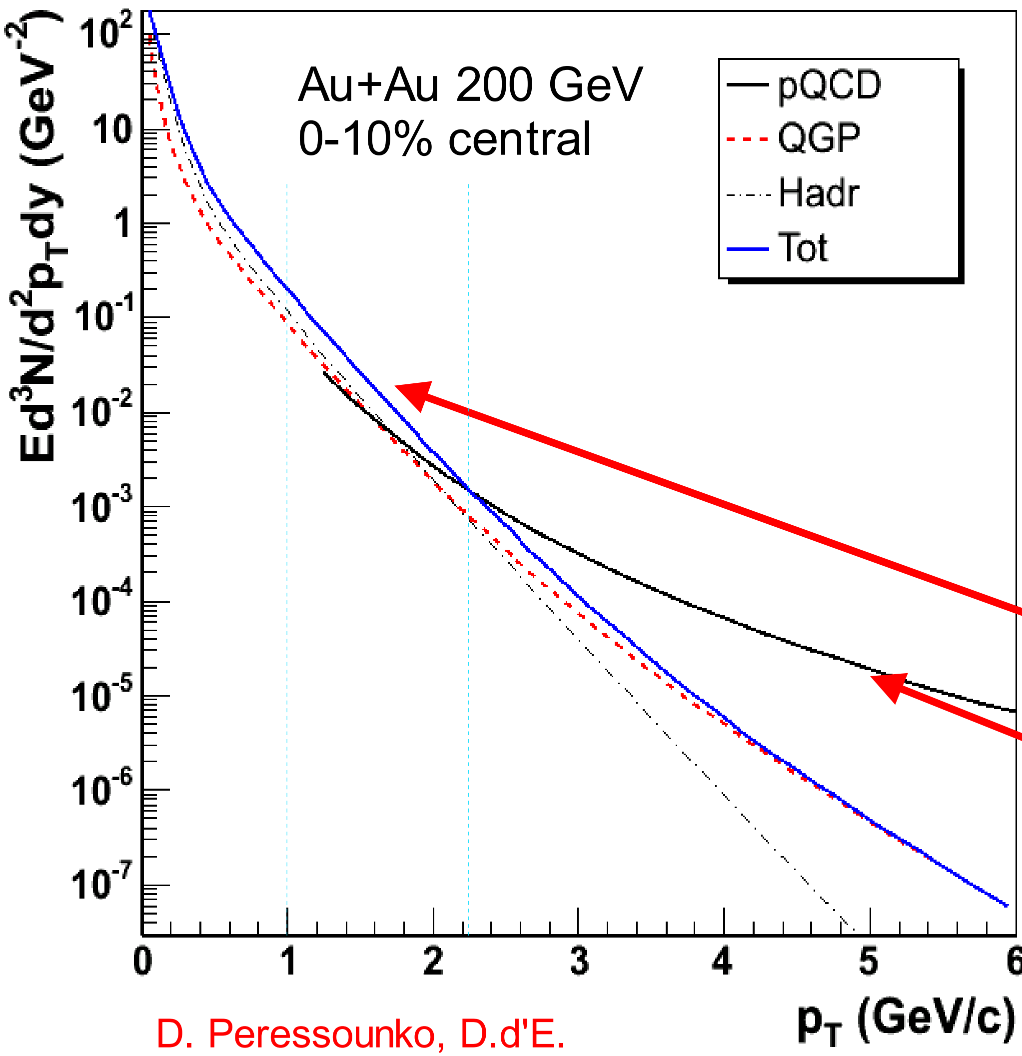
Stay tuned !

backup slides ...

Thermal photons at RHIC

Thermal photon production in Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV

- Thermal (real&virtual) γ are the most direct (the only ?) probe sensitive to the thermodynamical state (EOS) of underlying matter.



D. Peressounko, D.d'E.
(in preparation)

2+1 hydro predictions:

Initial conditions:

τ_0 = 0.15 fm/c

T_0 = 580 MeV

(reproduces bulk π, K, p dN/dp_T)

EOS:

QGP (2.5 flavors) + hadron res. gas + 1^{st} order phase transition (ΔE=0.8 GeV)

Thermal (QGP+HG) component

NLO pQCD x T_{AB} scaling

Thermal production (only) apparent within $p_T \approx 1 – 2.5$ GeV/c

Medium effects in Au+Au→ γ + X @ √s = 200 GeV

- However, (part of the) prompt photons can be distorted by the dense QCD medium (esp. in the region p_T< 4 GeV/c).
- Photon production in p+p @ 200 GeV:

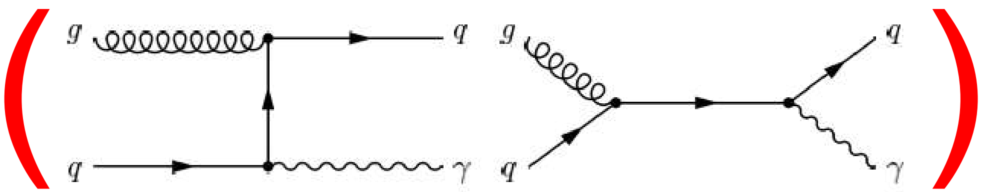


Figure 2.1: Compton diagrams.

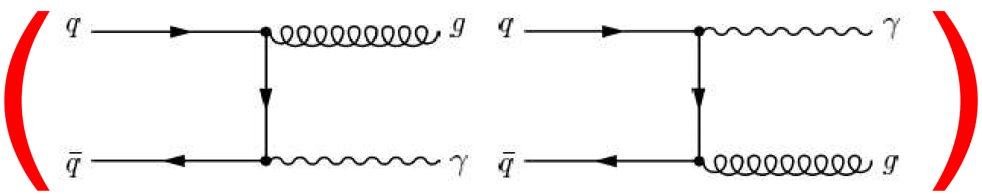


Figure 2.2: Annihilation diagrams.

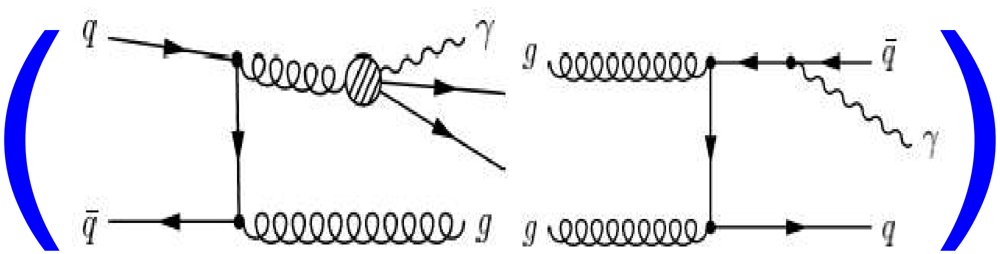
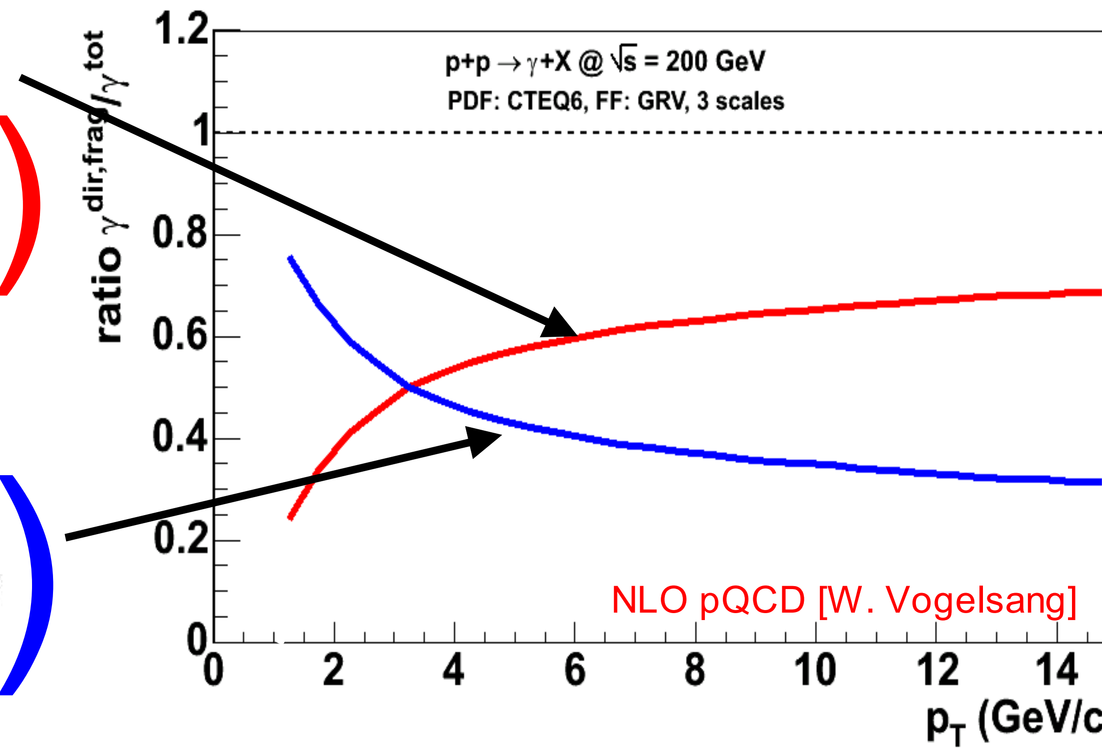


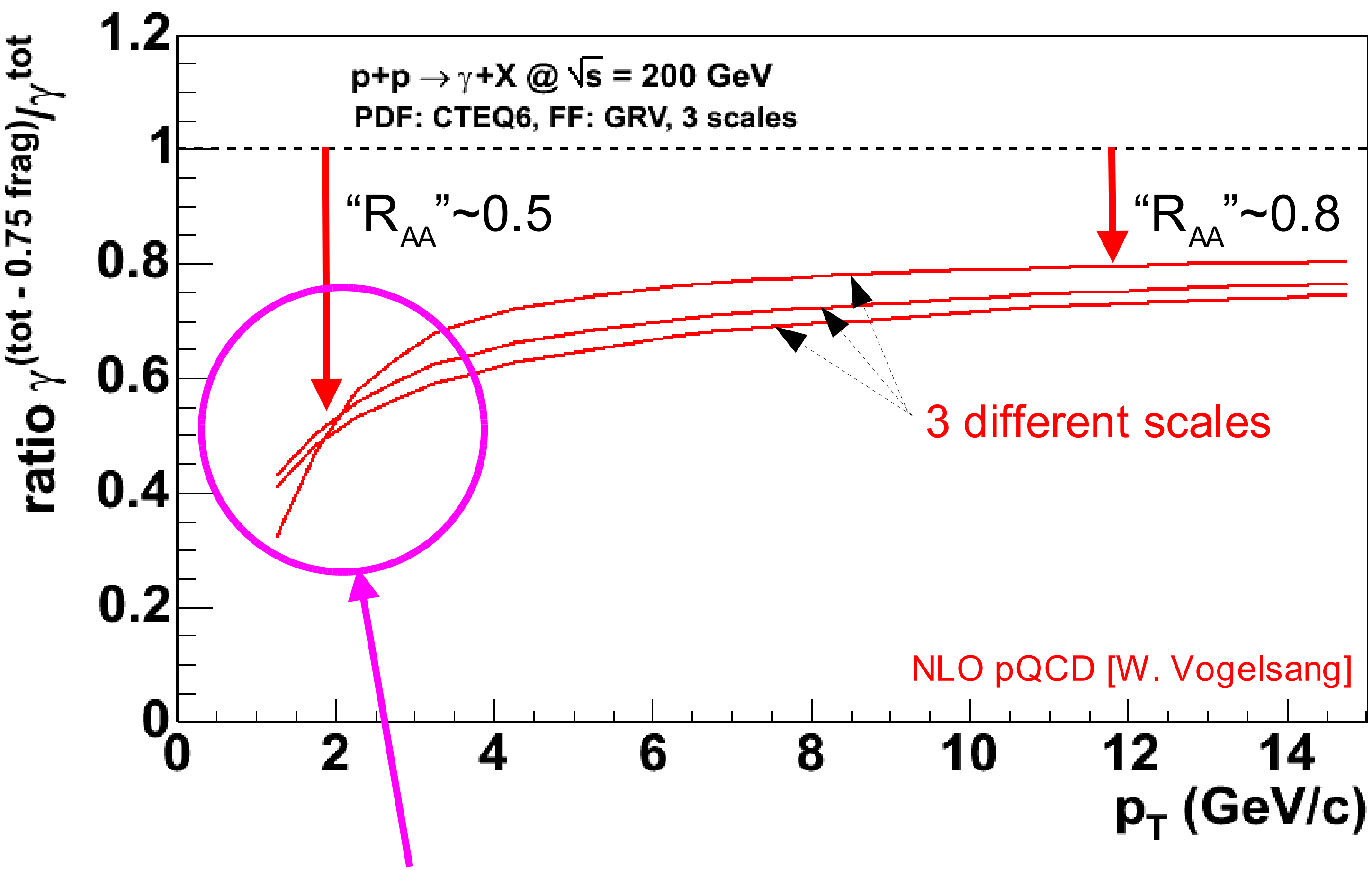
Figure 2.3: Bremsstrahlung diagrams.

Below p_T ≈ 4. GeV/c dominated by γ from collinear q,g fragmentation



"Nuclear modif. factor" Au+Au→ γ + X @ $\sqrt{s}$ = 200 GeV

- Back-of-the-envelope ansatz for γ suppression: R_{AA}(γ frag.) = R_{AA}(q,g) ≈ 0.25
- R_{AA} ≈ Ratio of γ(tot – 0.75*frag)/γ(tot):



(No shadowing corrs. included)

Results confirmed by more involved calculations: F.Arleo: hep-ph/0406291

- ~50% depleted prompt photon yield could mask the expected (enhanced) thermal emission around p_T = 2 GeV/c

Disentangling "thermal" γ from quenched prompt γ

- **Step 1:** Measure p+p → γ(isolated) + *X*
  down to p_T = 1 GeV/c
  with uncertainties ~10%

Handle on γ from qg-Compton, qqbar annihilation

- **Step 2:** Measure p+p → γ(total) + *X*
  down to p_T = 1 GeV/c
  with uncertainties ~10%

Handle on fragmentation γ production

- **Step 3:** Measure Au+Au → γ(total) + *X*
  down to p_T = 1 GeV/c
  with uncertainties ~10%

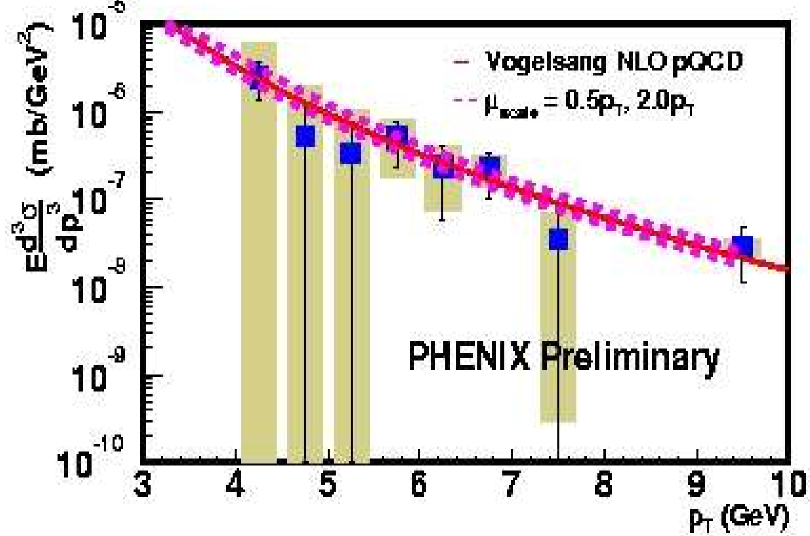
- **Step 4:** (AuAu γ_{total}) – T_{AB}•(pp $\gamma_{isolated}$)

Upper limit on thermal spectrum.

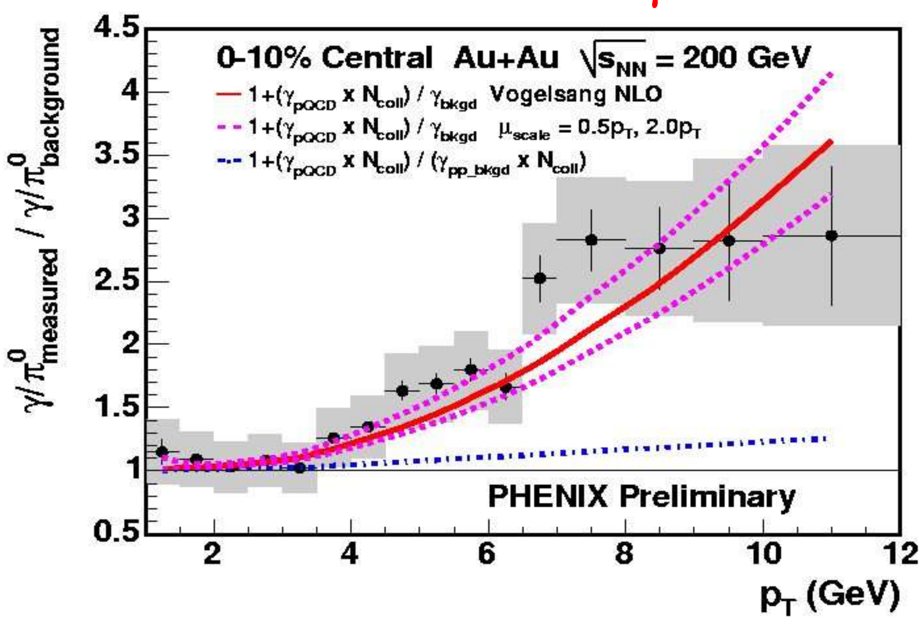
- **Step 5:** (AuAu γ_{total}) – T_{AB}•(pp γ_{total})

Lower limit on thermal spectrum.

Daunting tasks ! ...
Current best p+p γ data:



Current best Au+Au γ data:



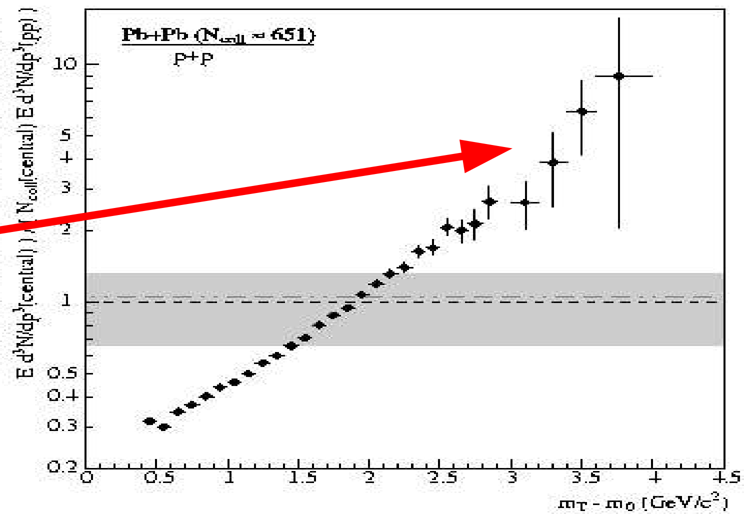
High p_T suppression at SPS ?

Enhanced high p_T production in Pb+Pb @ CERN-SPS ?

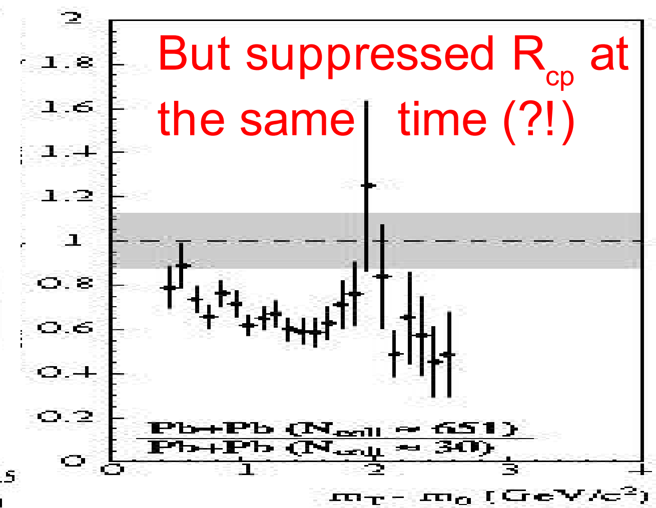
- NO $p+p \rightarrow \pi^0 X$ baseline measurement at SPS Pb+Pb energy ($\sqrt{s}$ = 17.3 GeV)
- R_{AA} for central Pb+Pb constructed with 2 different parametrizations:

WA98 Collab.
EPJ C23 (93)225

Huge Cronin enhancement

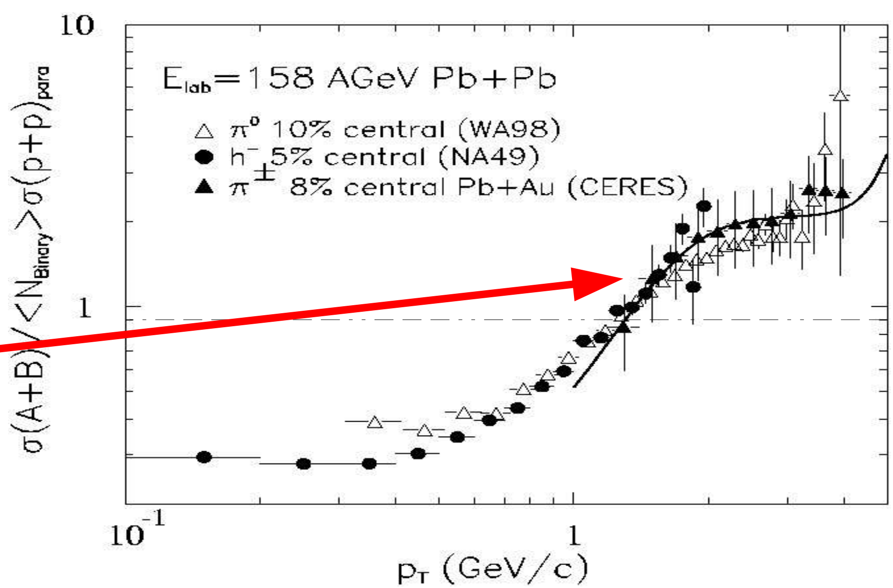


But suppressed R_{cp} at the same time (?!)



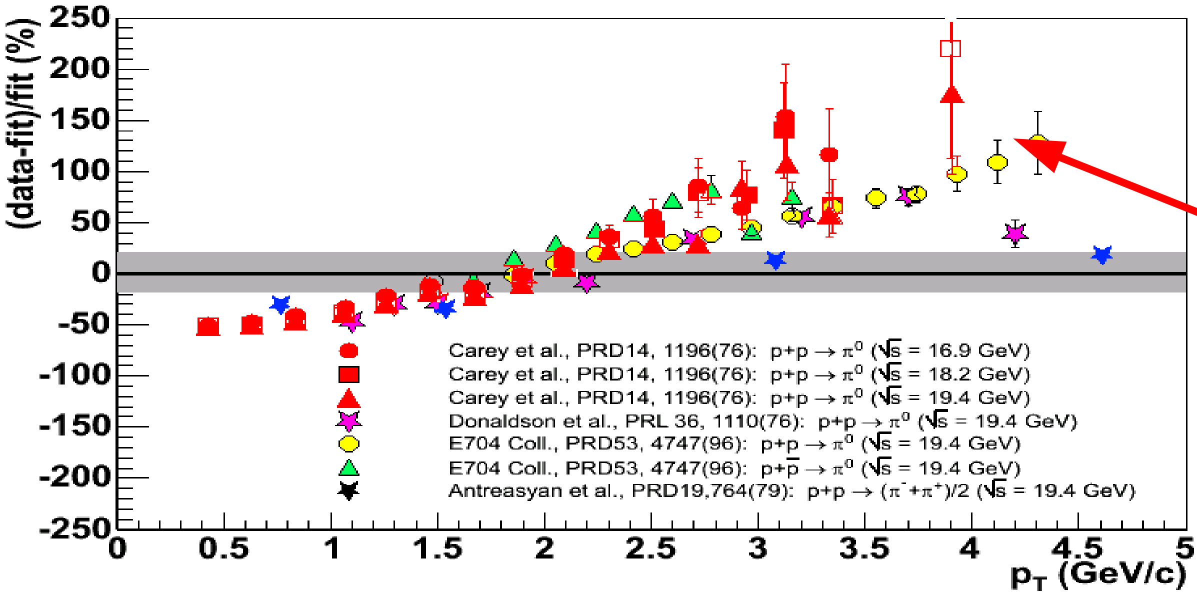
Wang&Wang
PRC 64 (01) 034901

Cronin enhancement



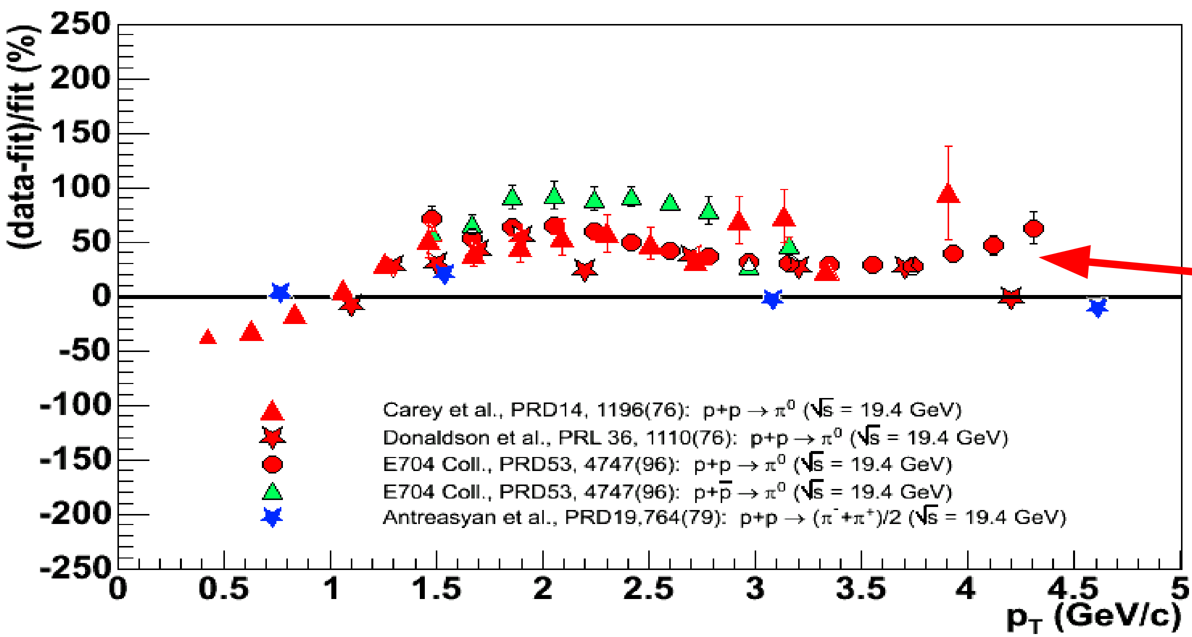
p+p → π +X references @ √s ≈ 20 GeV

- p+p → $\pi^0 X$ parametrizations confronted to data @ √s = 16 – 20 GeV:



WA98 parametrization undershoots the data by up to a factor of ~3

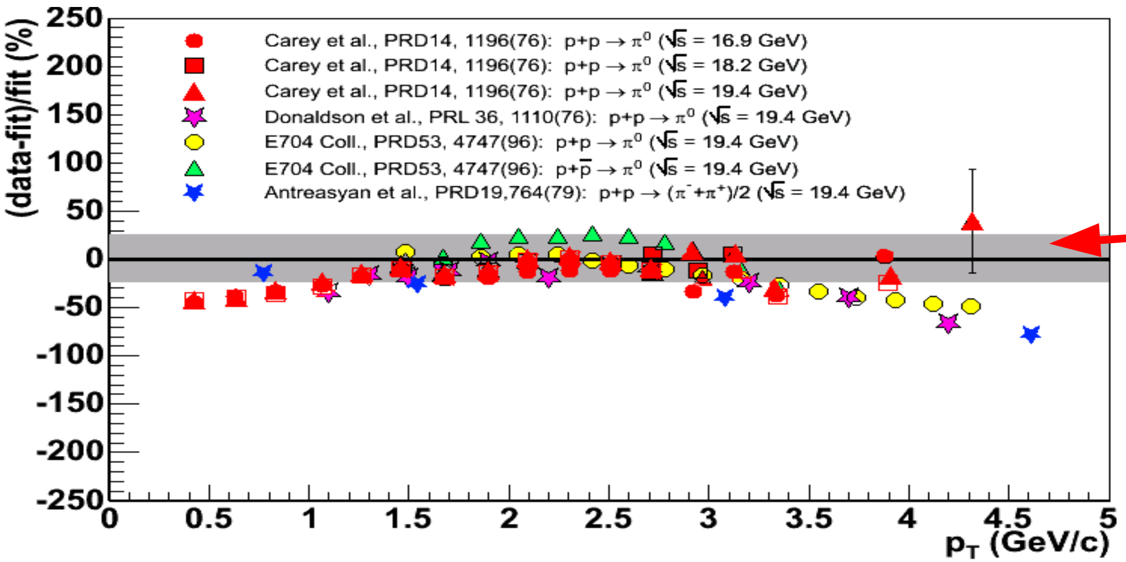
D.d'E. nucl-ex/0403055
PLB 596 (2004) 32



X.N.Wang parametriz. undershoots the data by up to a factor of ~2

New p+p → π +X reference @ √s ≈ 20 GeV

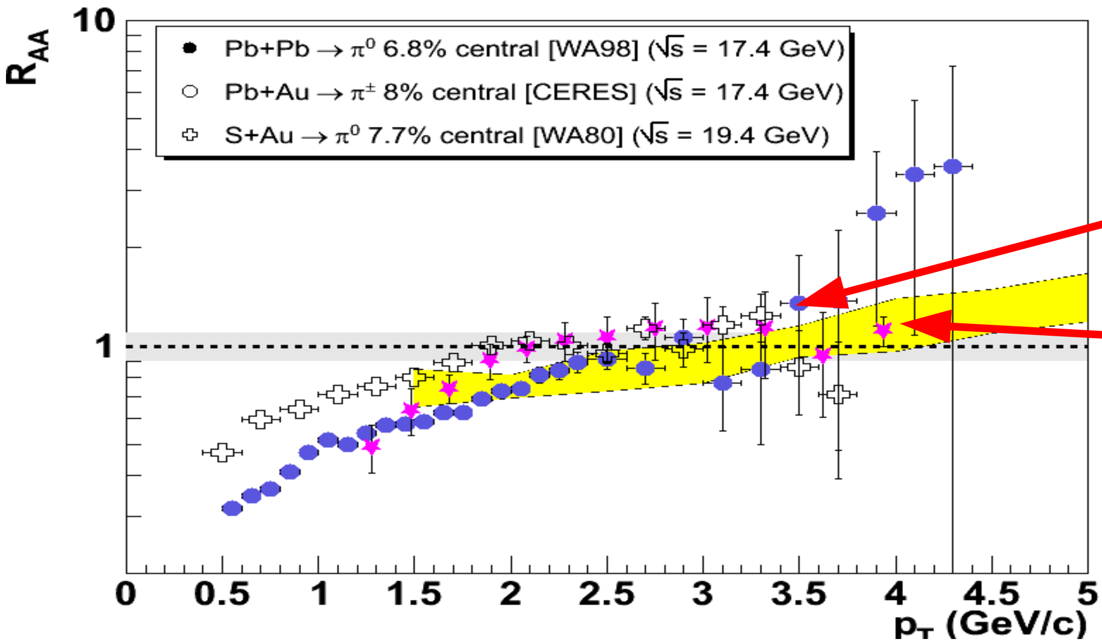
- New parametrization [Blattnig00] versus p+p data √s = 16 – 20 GeV:



Much better agreement in shape and magnitude (within exp. uncertainties)

D.d'E. nucl-ex/0403055
PLB 596 (2004) 32

- New WA98, WA80 & CERES nuclear modification factors:

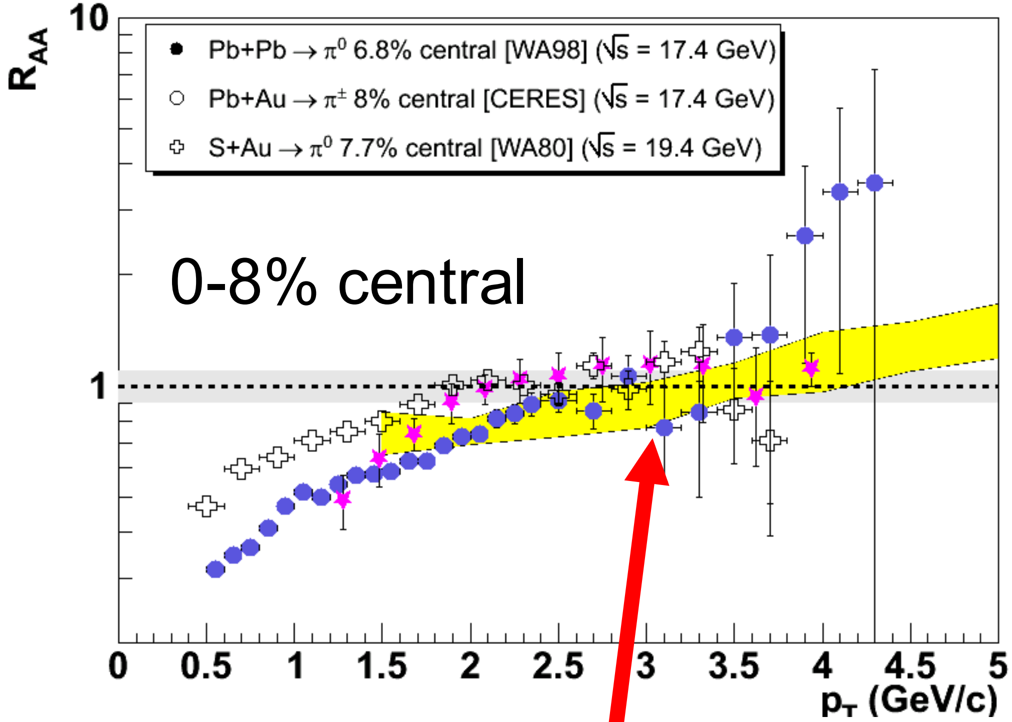


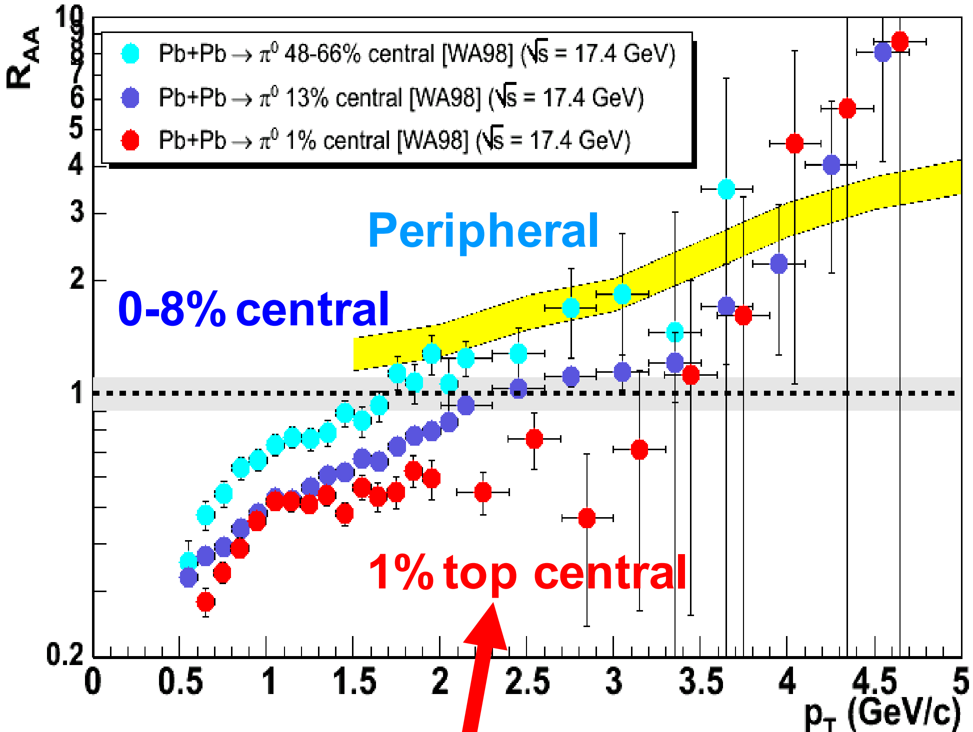
R_{AA} at SPS are not enhanced but consistent with “collision scaling”.

Agreement with parton energy loss calculations [I.Vitev nucl-th/0404052] in moderately dense system (dN^g/dy ~ 400-600)

Indications of high p_T suppression @ SPS

- Centrality evolution of high p_T π^0 production at SPS:



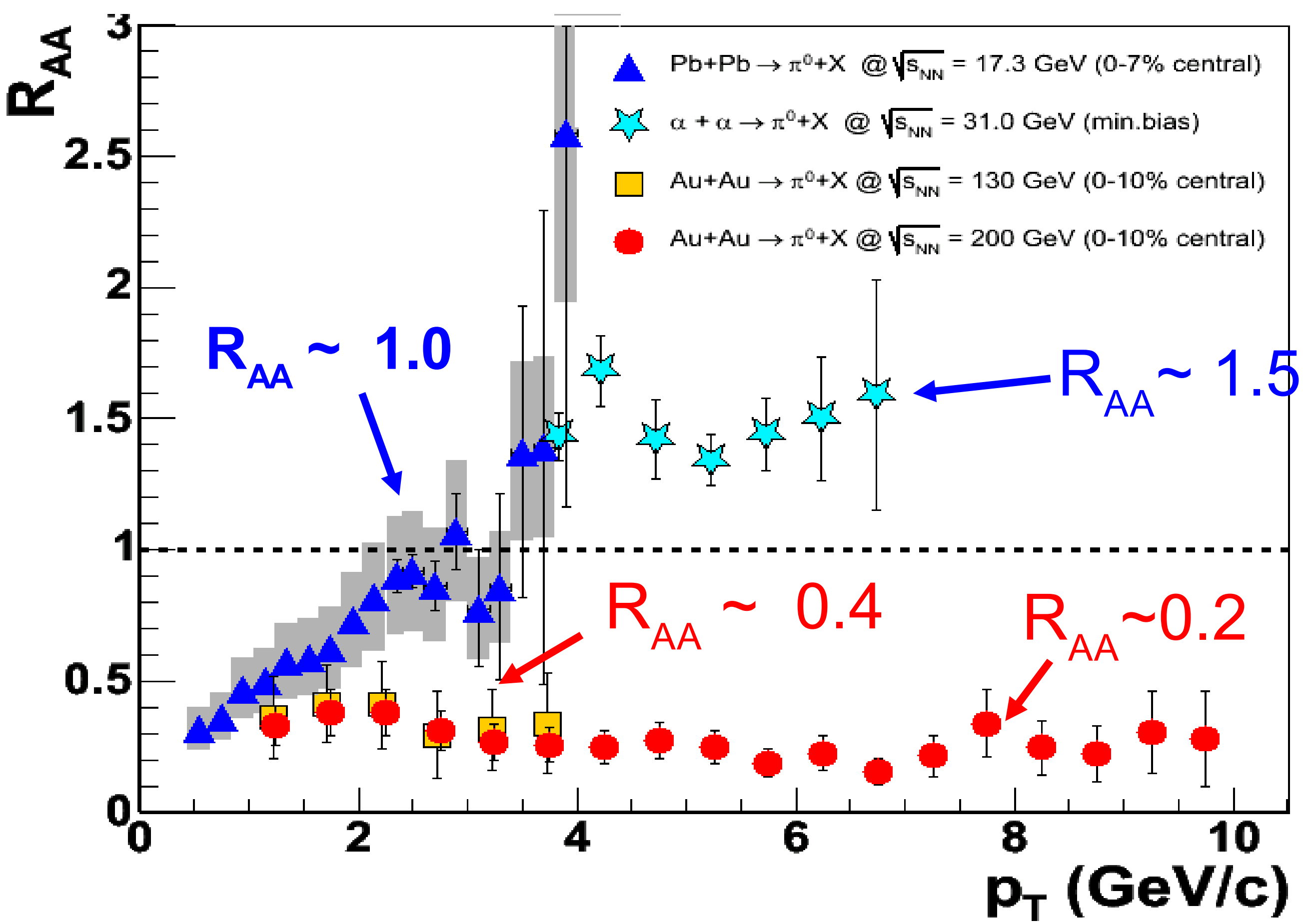


- "Collision scaling" in 0-8% central collisions (R_{AA} ~ 1).
- "Cronin" enhancement in peripheral ... and suppression in 1% most central
- Look for onset of suppression at RHIC Au+Au, p+p @ $\sqrt{s_{NN}} \approx$ 20 GeV ?

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: $\alpha+\alpha$ ($\sqrt{s_{NN}}$= 31 GeV): Cronin enhancement.
- RHIC: Au+Au ($\sqrt{s_{NN}}$ = 62, 130, 200 GeV): x3 - x5 suppression.



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

WA98, EPJ C 23, 225 (2002)

(*) Reanalysis: D.d'E. PLB 596, 32 (2004)

PHENIX, PRL 88 022301 (2002)

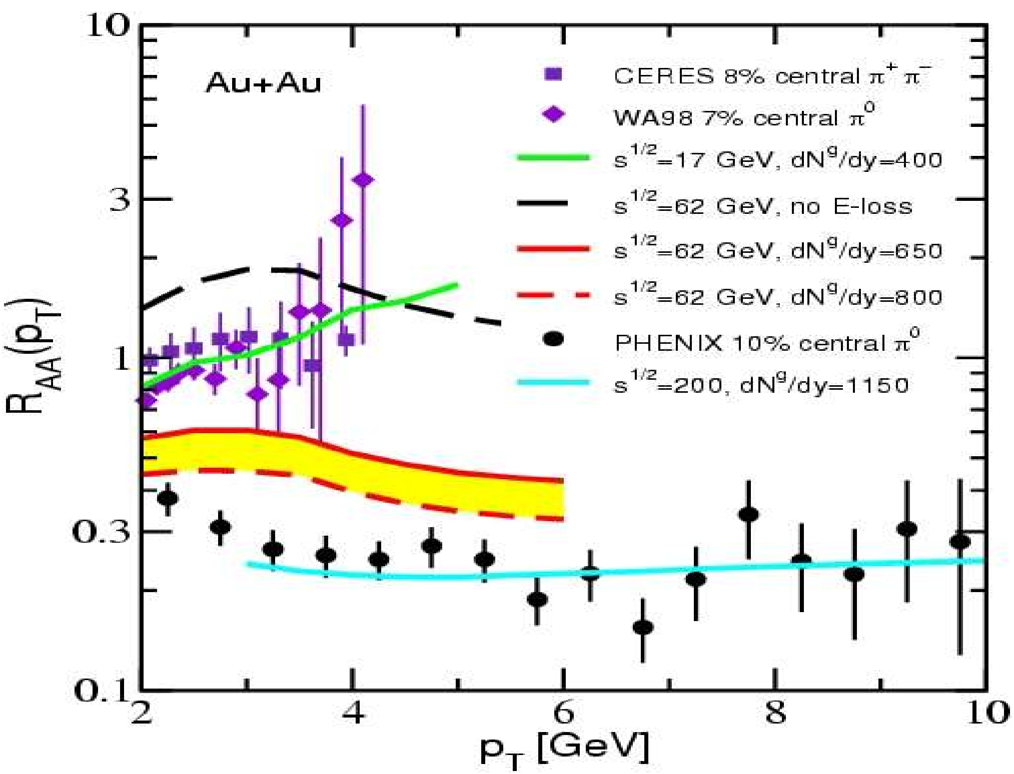
PHENIX, PRL 91, 072303 (2003)

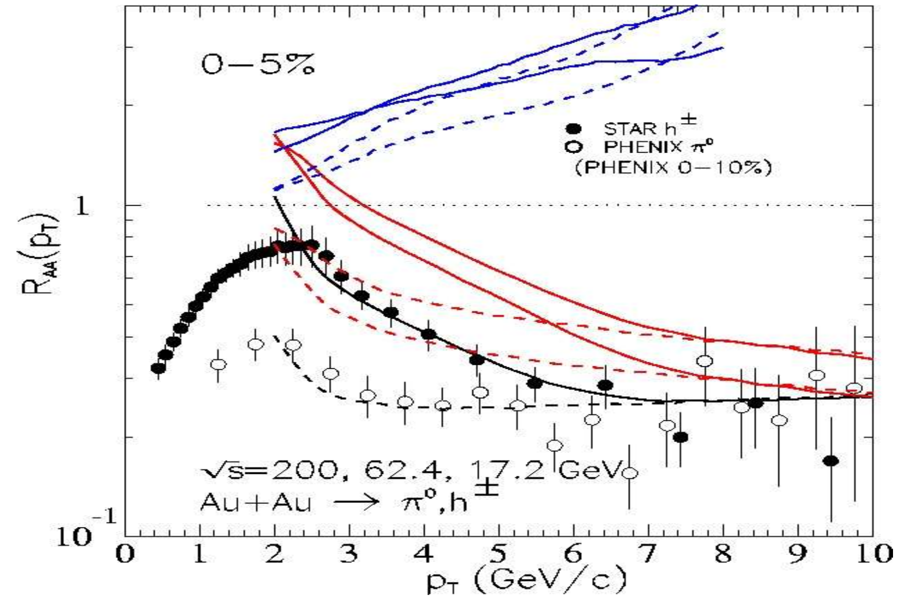
High p_T suppression at 62.4 GeV

Au+Au @ 62.4 GeV (central): suppression predictions

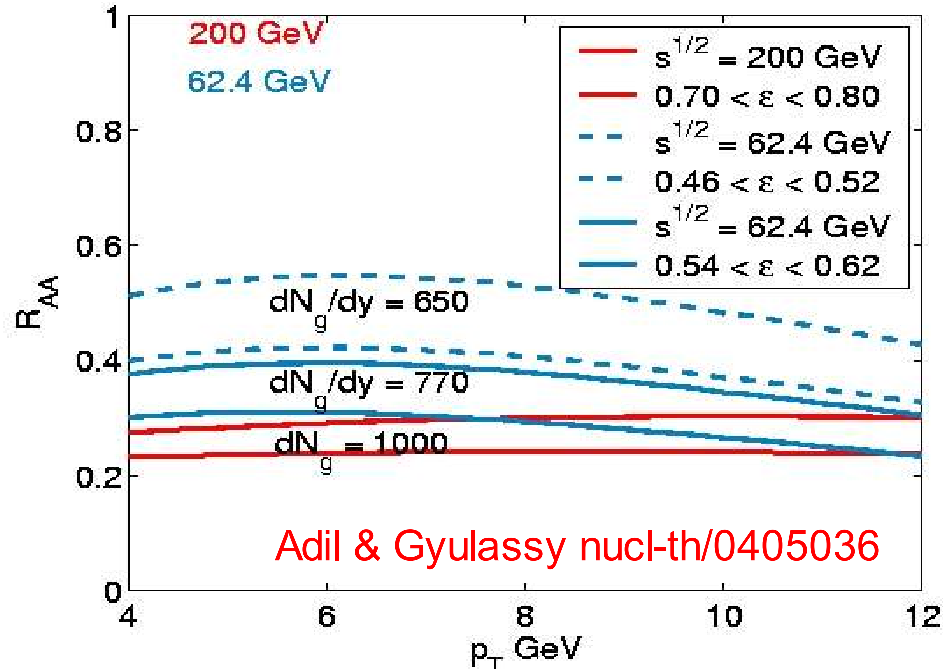
R_{AA} (π^0) ~ 0.5 - 0.3

I. Vitev nucl-th/0404052





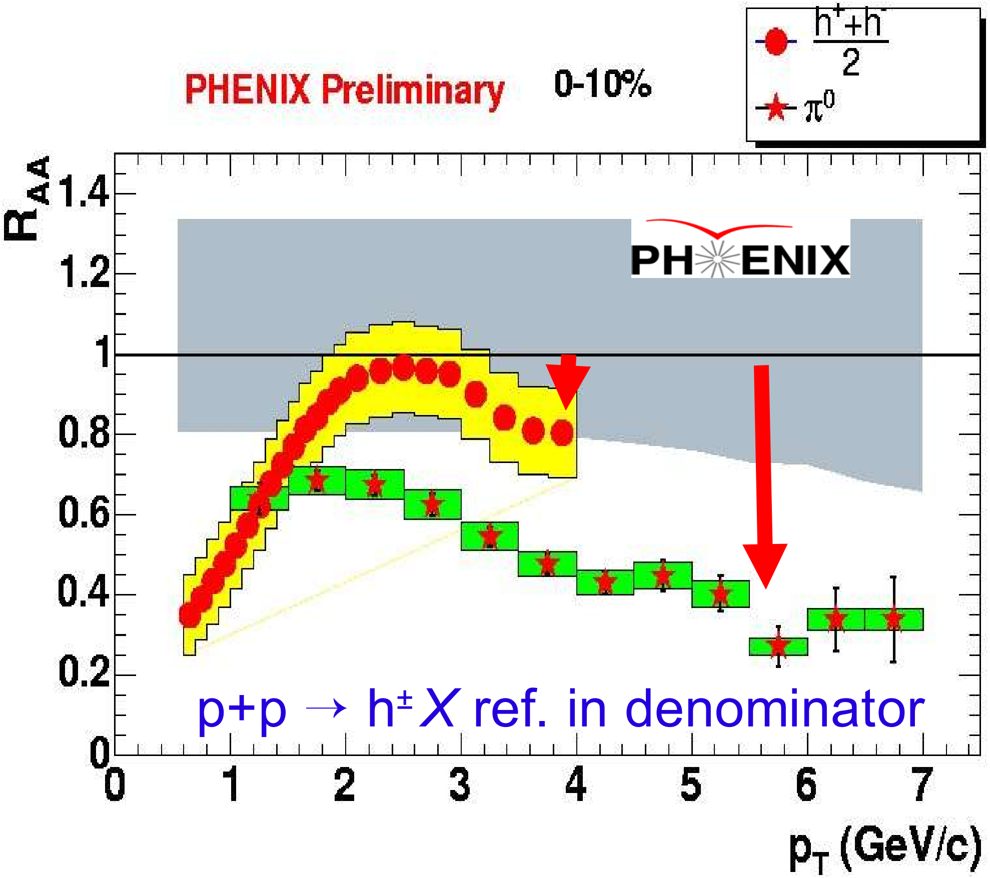
X.N. Wang nucl-th/0405029



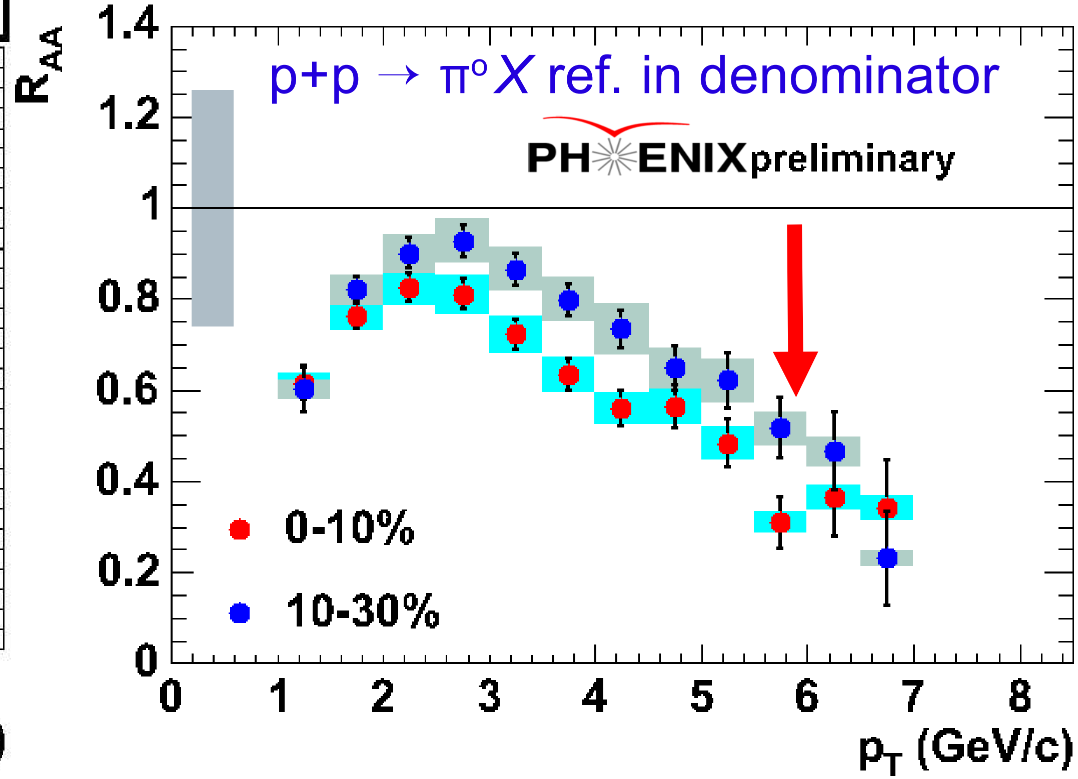
Adil & Gyulassy nucl-th/0405036

Au+Au @ 62.4 GeV (R_{AA} central): π^0 suppression !

Charged hadrons vs. pions



Neutral pions



- Pions more suppressed than $h^{+/-}$ at intermediate p_T (also found at 200 GeV): R_{AA} ~ 0.6 at p_T~2 GeV/c
- "Universal" (PID) and constant suppr. at high p_T: R_{AA} ~ 0.3 for p_T > 6 GeV/c

Gluon saturation at RHIC ?

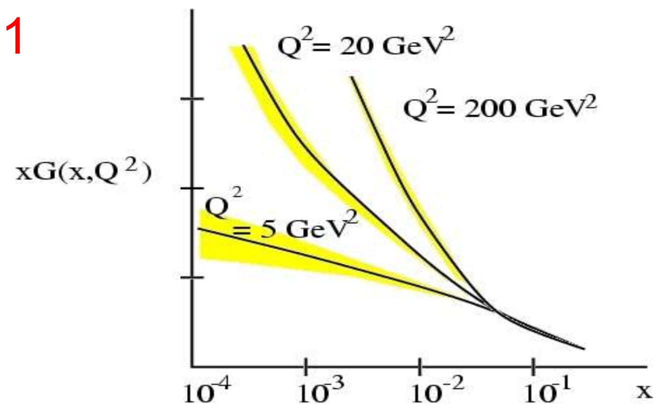
Initial-state CGC effects

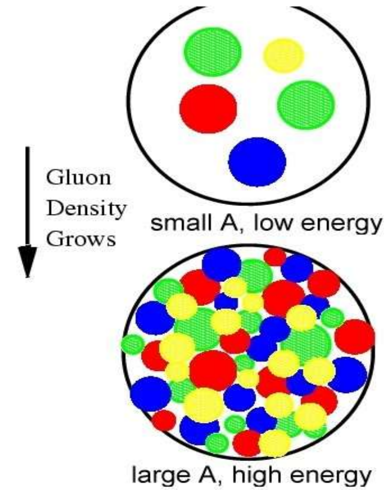
- Initial conditions at RHIC: high-energies + large nuclei
  - Values of small-x: $x_{Bj} = 2p_T/\sqrt{s} <<1$

    Large gluon densities

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

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



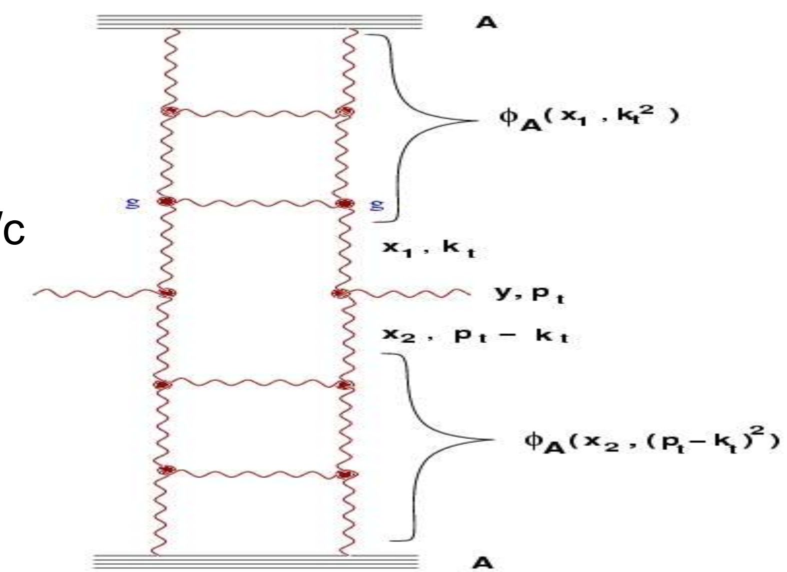


- Colliding nuclei described via a colored highly saturated gluonic wave-function ("Color Glass Condensate").

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

- Particle production via glue-glue collisions:

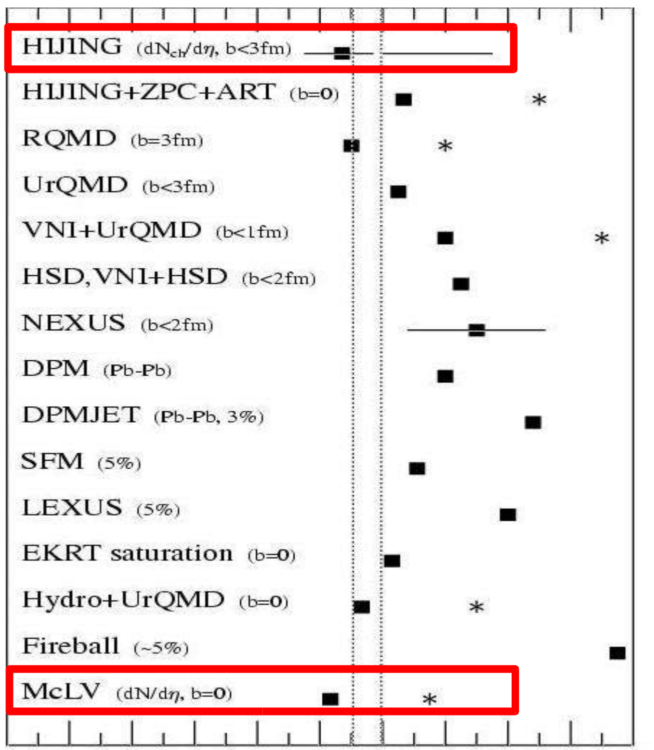
  Extension to $p_T > Q_s$ ("geometric scaling") via quantum evolution.



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

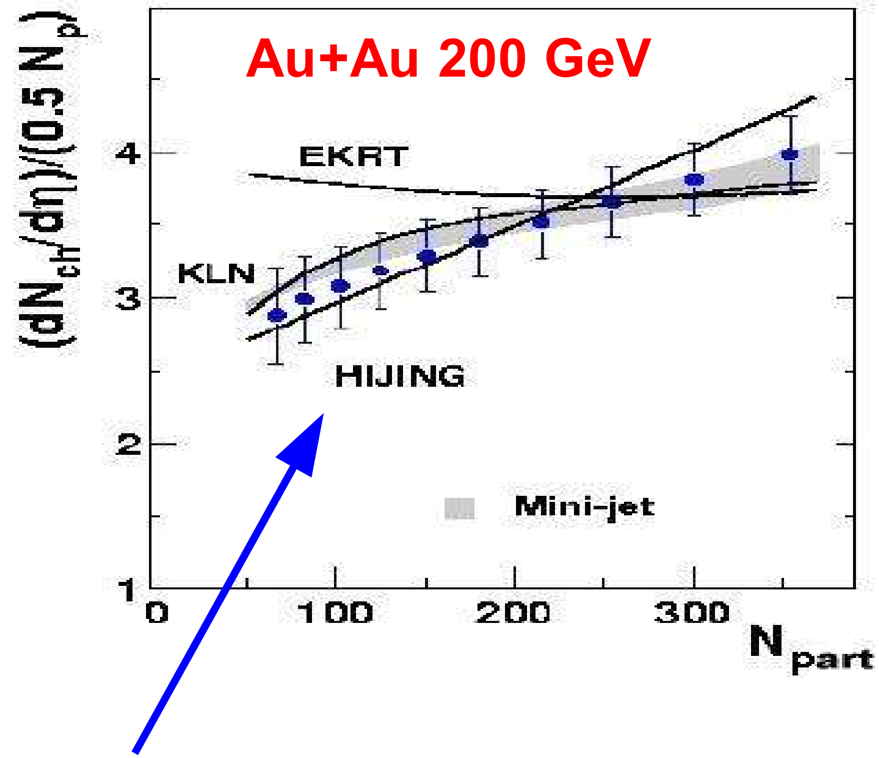
Particles density at central rapidity in Au+Au

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



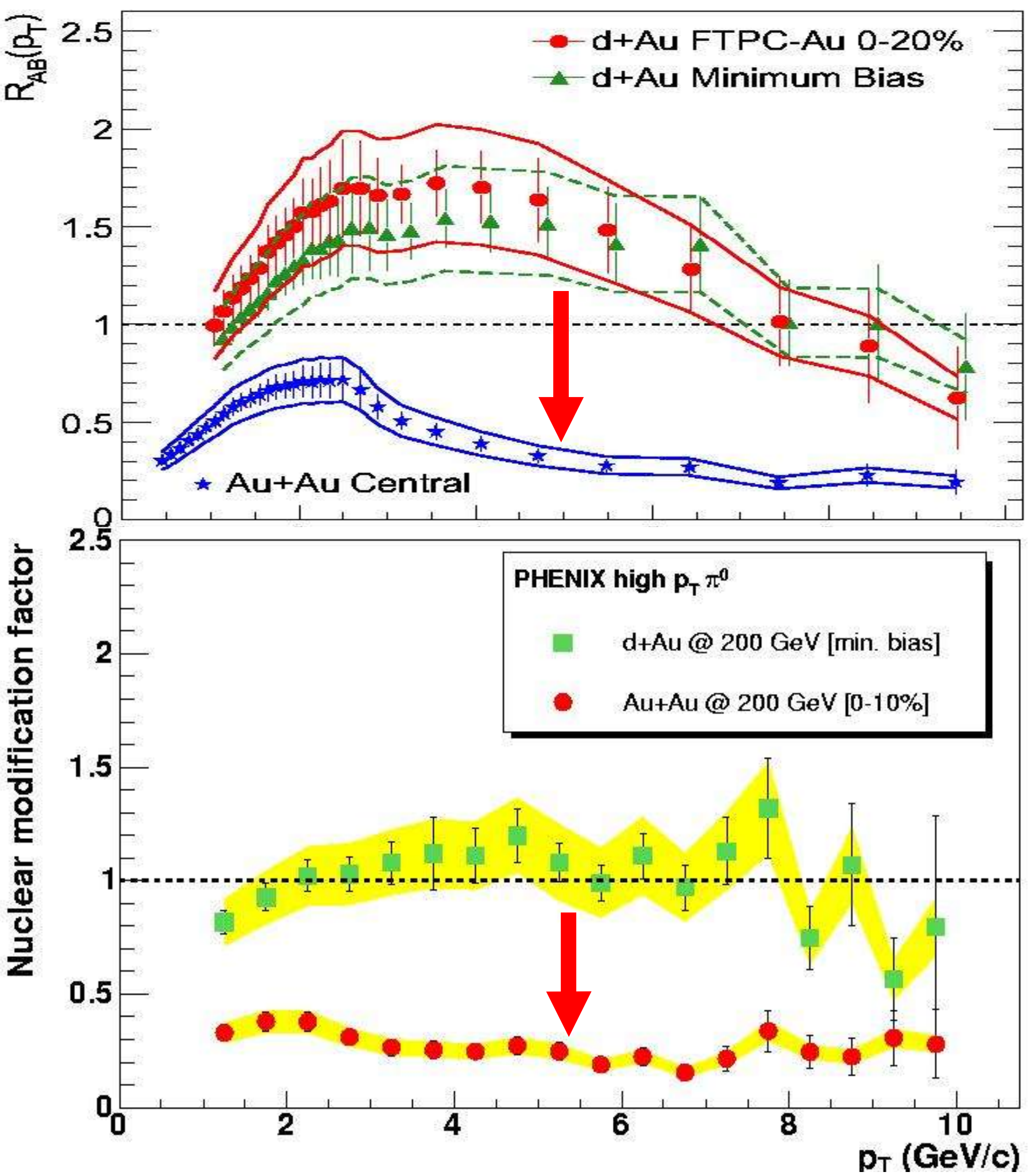
N.Armesto et al.
Int.J.Mod.Phys. A15, 2019

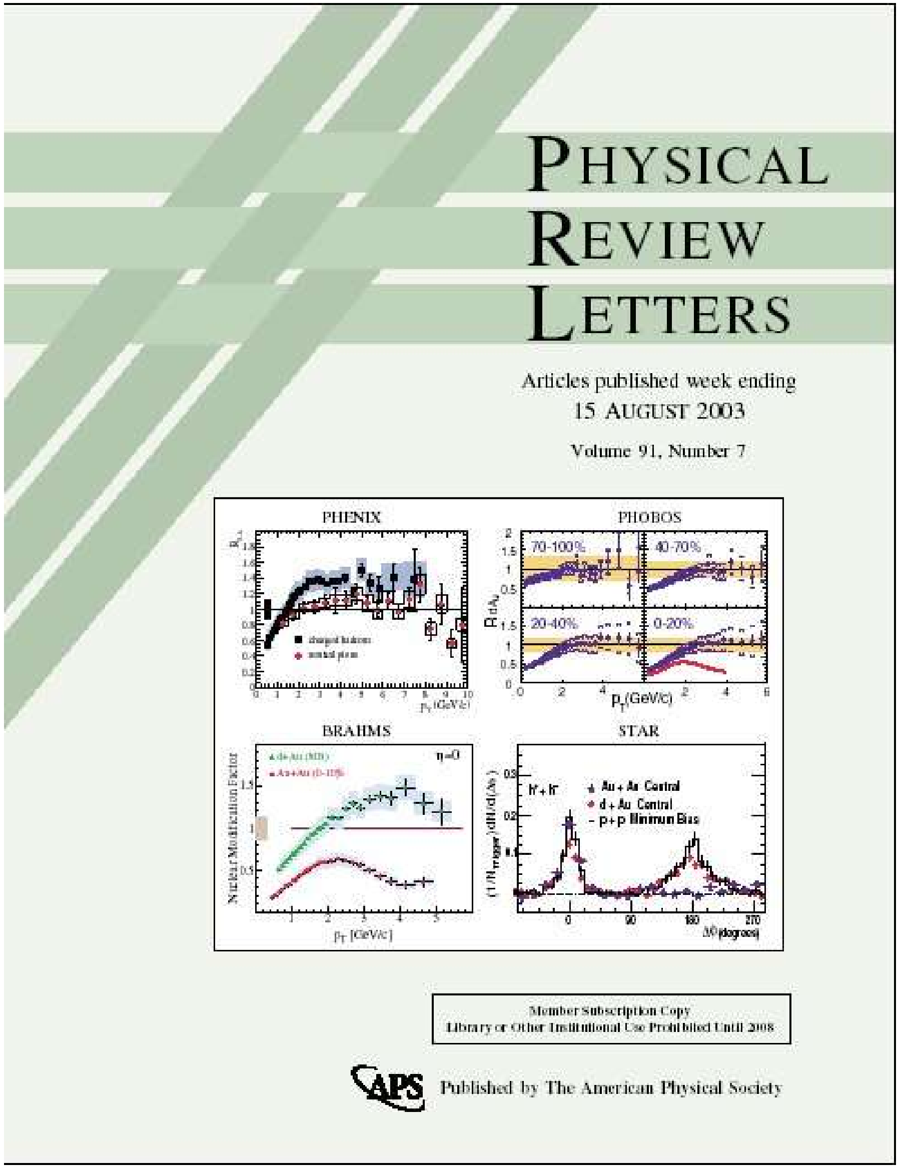
centrality dependence:



- 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): $dN_{ch}/dy \sim dN_{gluon}/dy \sim 1/\alpha_s \sim N_{part} \ln(N_{part})$

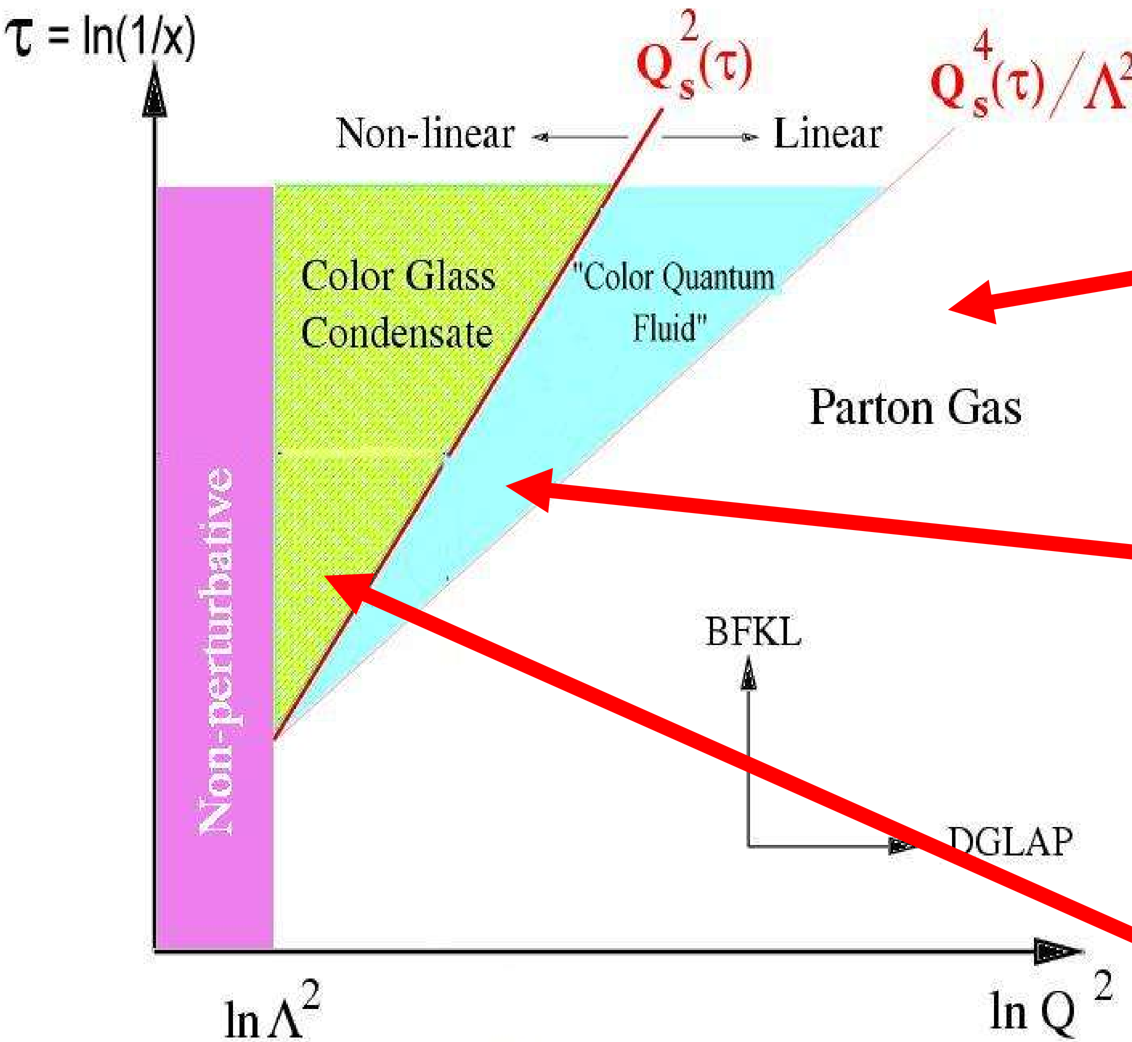
Unquenched d+Au production at high p_T





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

The quest for gluon saturation effects @ RHIC ...



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

x small: Look forward in rapidity !

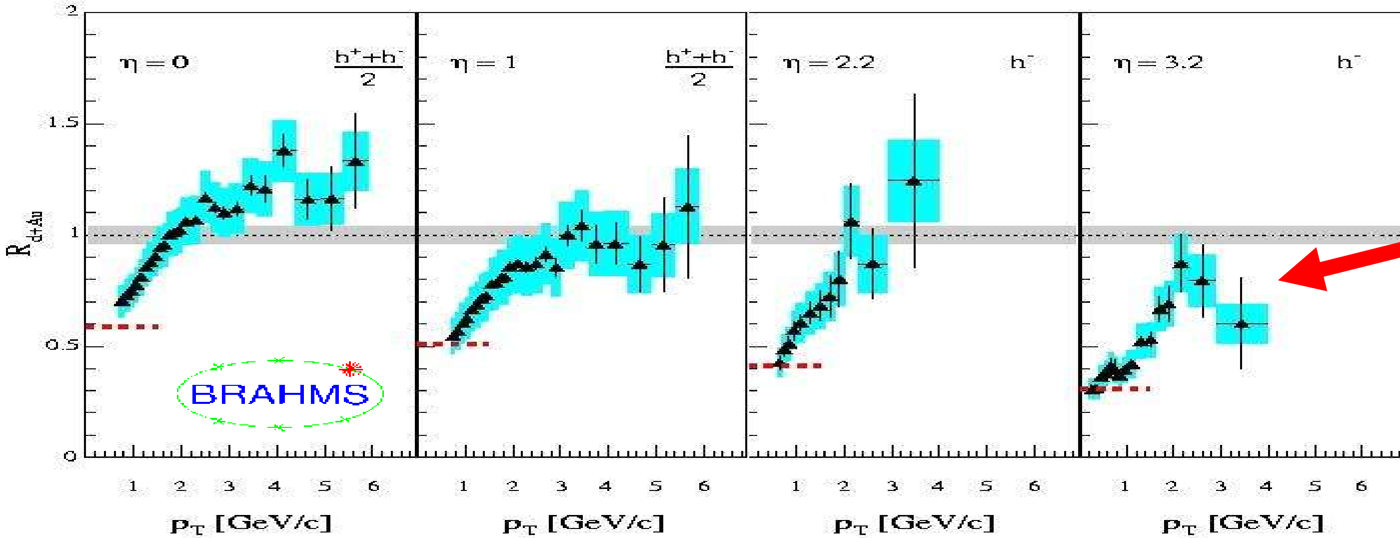
RHIC kinematical regime:

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

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

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

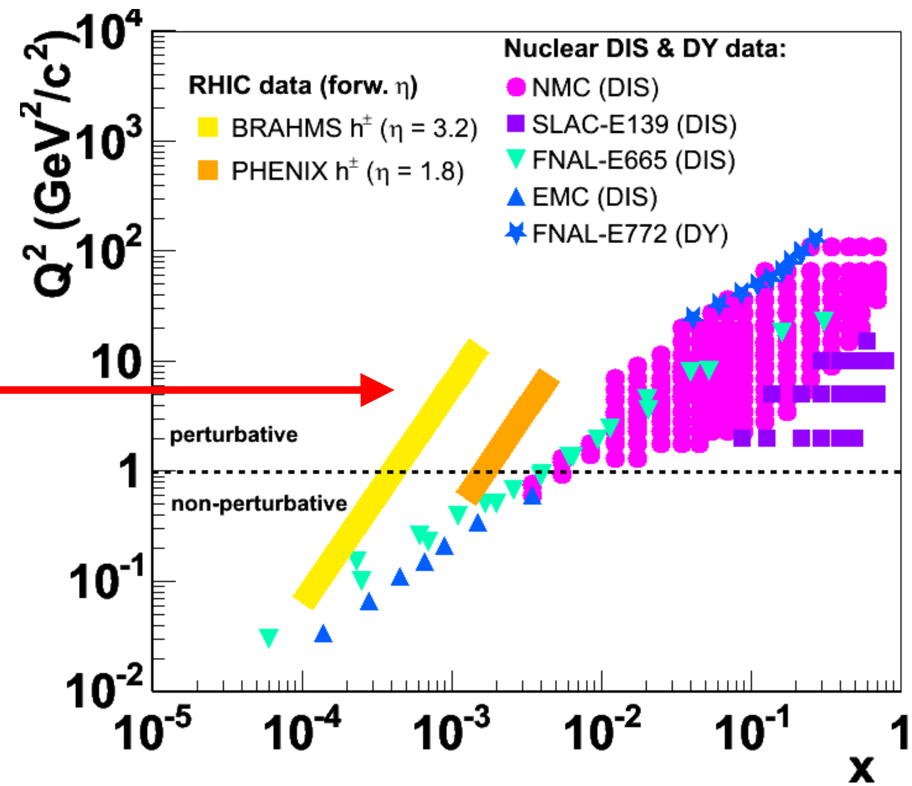
d+Au nuclear modification factor (η = 3.2)



- Factor ~2 suppression in hadron production: p_T = 1-3 GeV/c, 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.

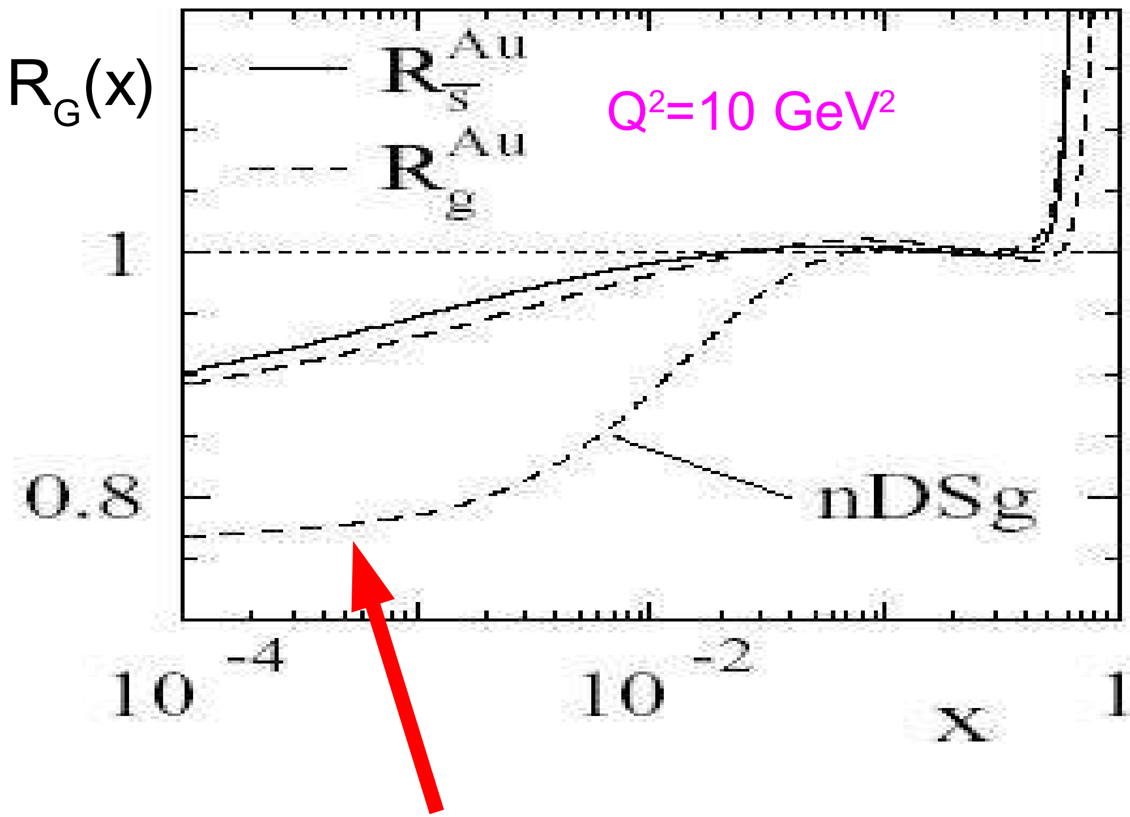
- So far unexplored(*) perturbative region of nuclear (x,Q^2) plane.



(*) Caveat: The "back-of-the-envelope" estimates ($x \sim p_T e^{-y}$) of the small-x values probed at forw. rapidities at RHIC provide usually too low values. Effective $\langle x_2 \rangle$ values are at least ~10 times larger.

Is this “standard” nuclear shadowing ?

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



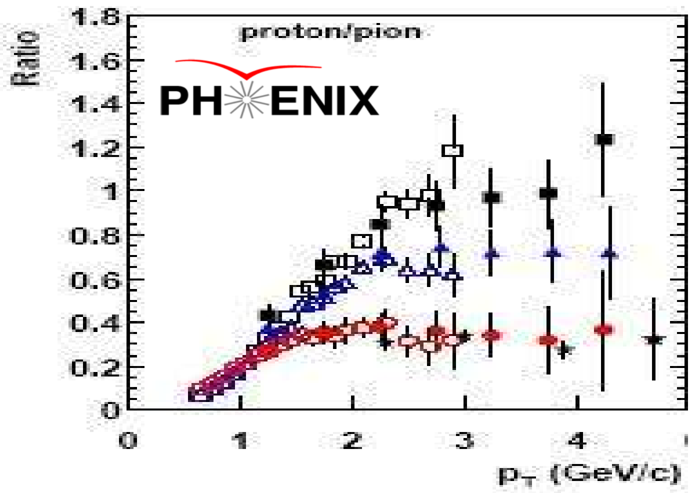
NLO DGLAP global analysis of nuclear PDFs

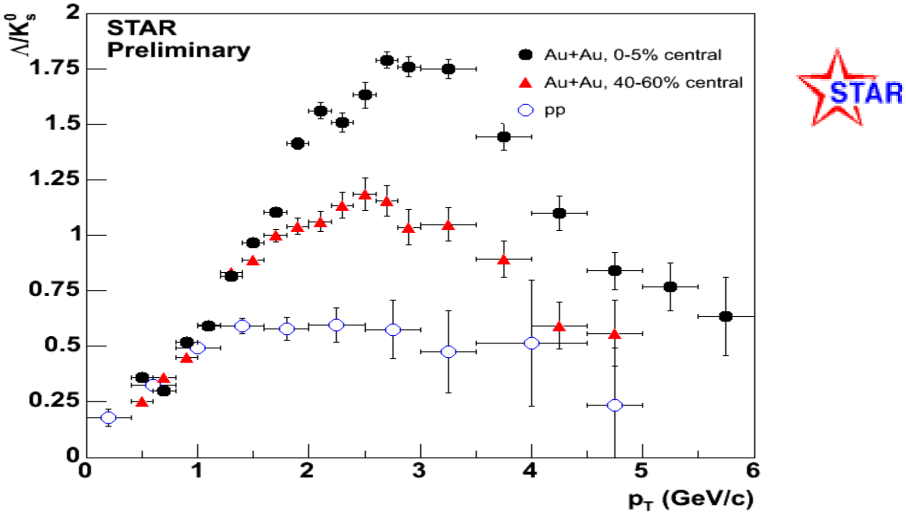
D. de Florian & R.Sassot
hep-ph/0311227

- Maximum gluon shadowing at $x \sim 10^{-4}$ (indirectly) constrained by available DIS data on nuclear targets is ~0.8
- IF indeed $R_{dAu}(p_T \sim 2$ GeV/c$) \approx 0.5 \equiv R_G(x=10^{-4}) \approx 0.5$ 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 ...]

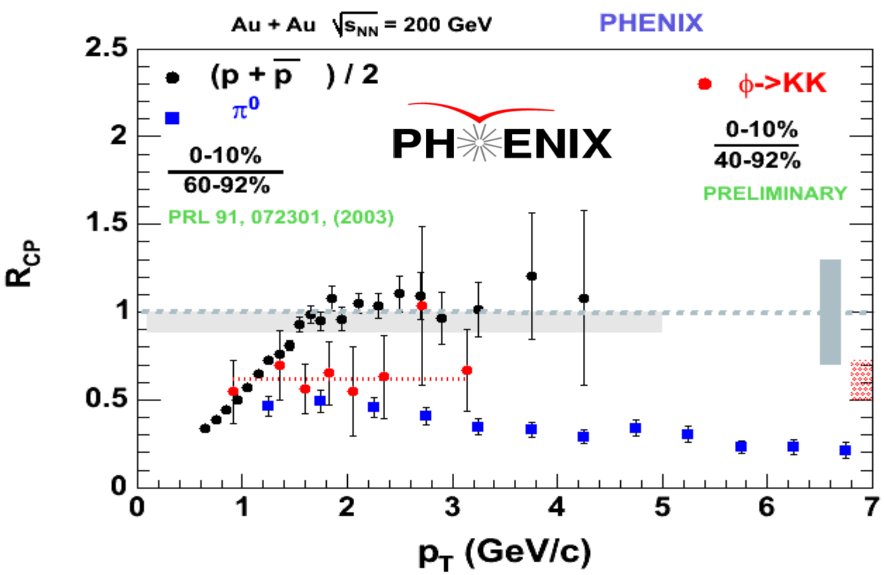
Au+Au @ 200 GeV (central): baryons > mesons !

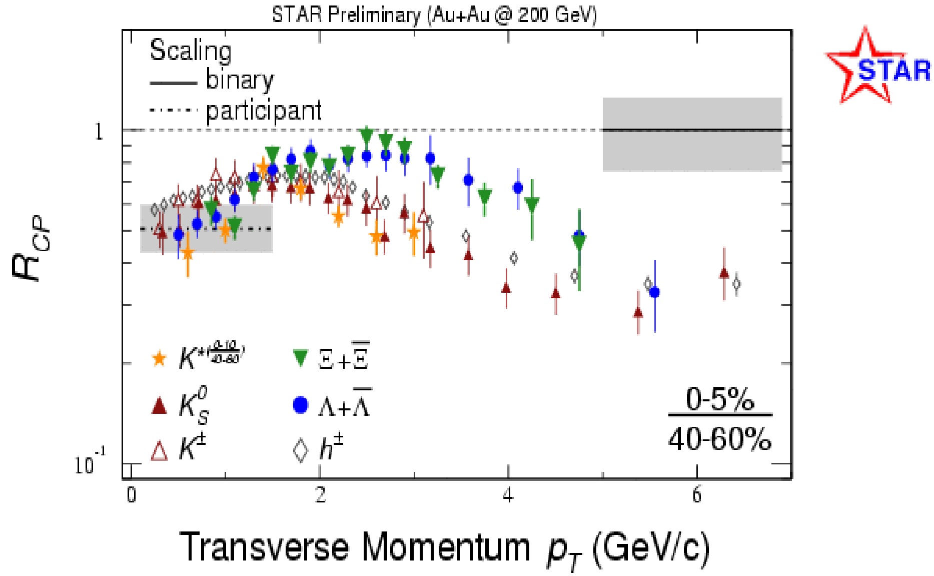
- Baryon/meson ratios: ~1 !





- Rcp baryons vs. mesons: very heavy mesons (ϕ ,k*) =! baryons





- Additional production mechanism for baryons in the intermediate p_T range