Bilan de la recherche du QGP au RHIC
- Une perspective de PHENIX (*) -

Institut de Recherches Subatomiques
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(*) Basé sur "PHENIX White Paper": `http://www.phenix.bnl.gov/phenix/WWW/info/comment/`

Overview/Summary

0. 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 (QCD vacuum).

(1) Energy densities:

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

(2) Elliptic flow:

- Strong elliptic flow v_2 consistent w/ short thermalization times $\tau_0 \sim 1$ fm/c

(3) Soft particle spectra:

- Shapes & yields consistent w/ hydrodynam. (thermal+coll. velocity) source emission
- Particles ratios consistent w/ chemical equilibrium 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: $dN^g/dy \sim 1100$

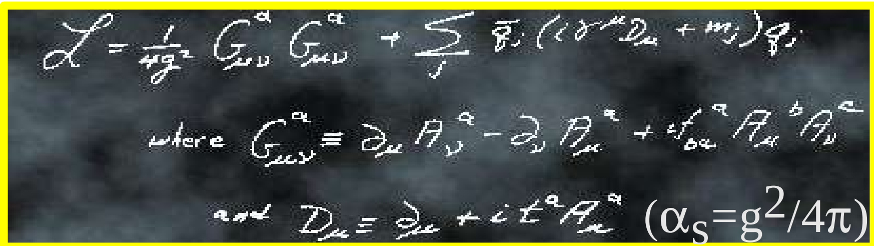
(5) Intermediate p_T spectra:

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

6. Summary & open questions: "QGP" ? Observations @ lower $\sqrt{s}$?

Future measurements.

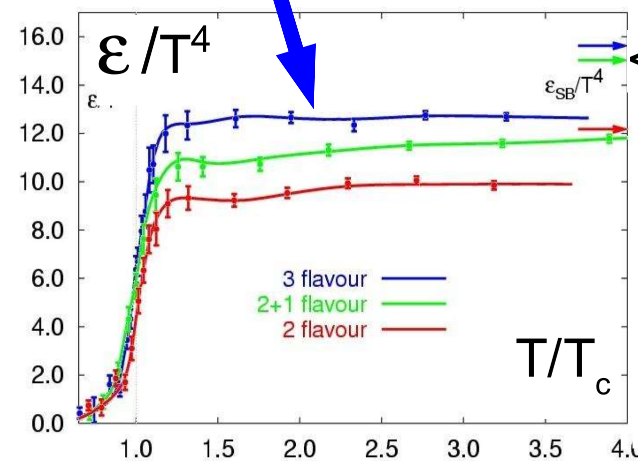
High-energy heavy-ion physics program (in 4 plots)

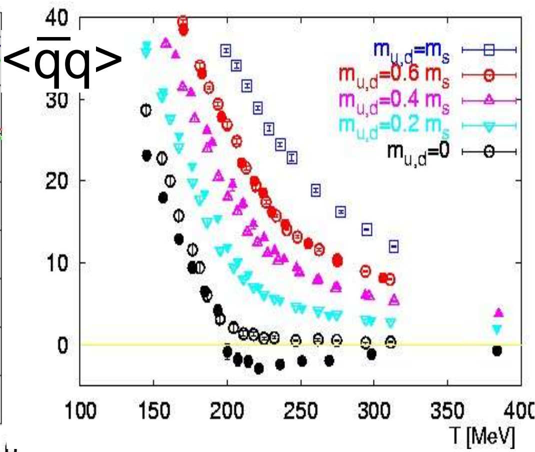


$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

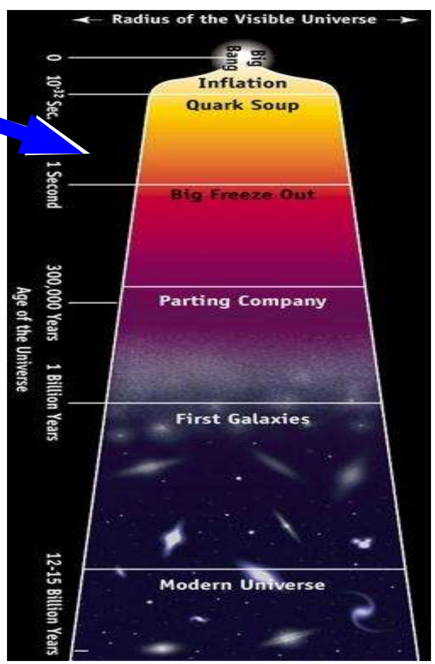
1. Learn about 2 basic properties of strong interaction: (de)confinement, chiral symm. breaking (restoration)

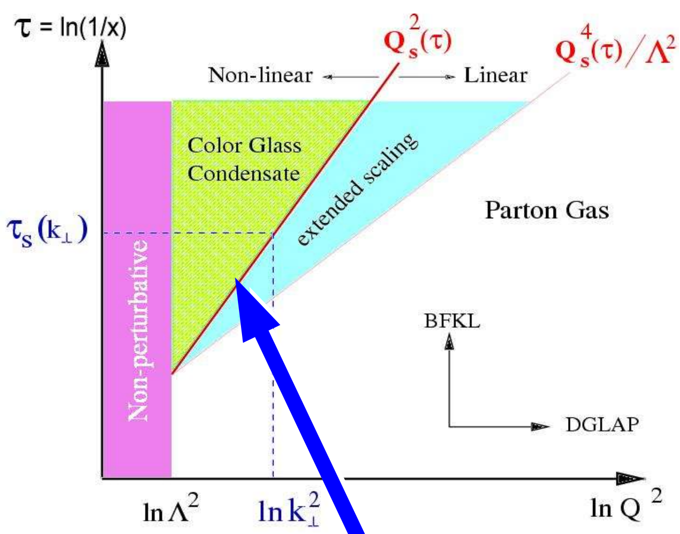
2. Study the phase diagram of QCD matter: esp. produce & study the QGP





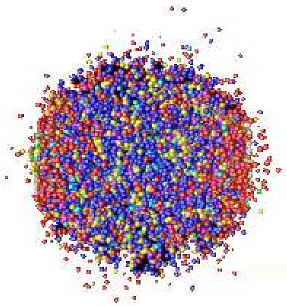
3. Probe quark-hadron phase transition of the primordial Universe (few μsec after the Big Bang)



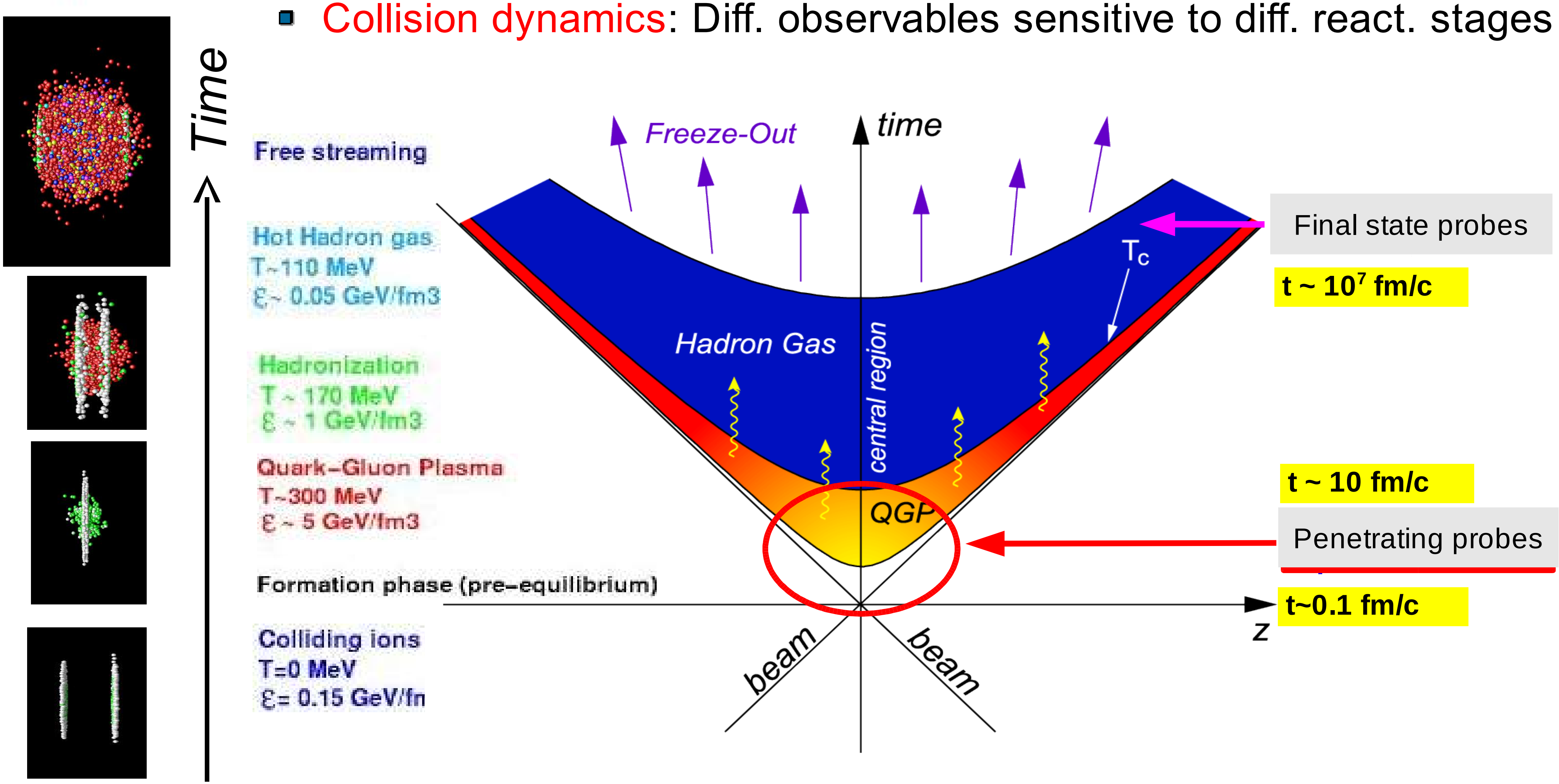


4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

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

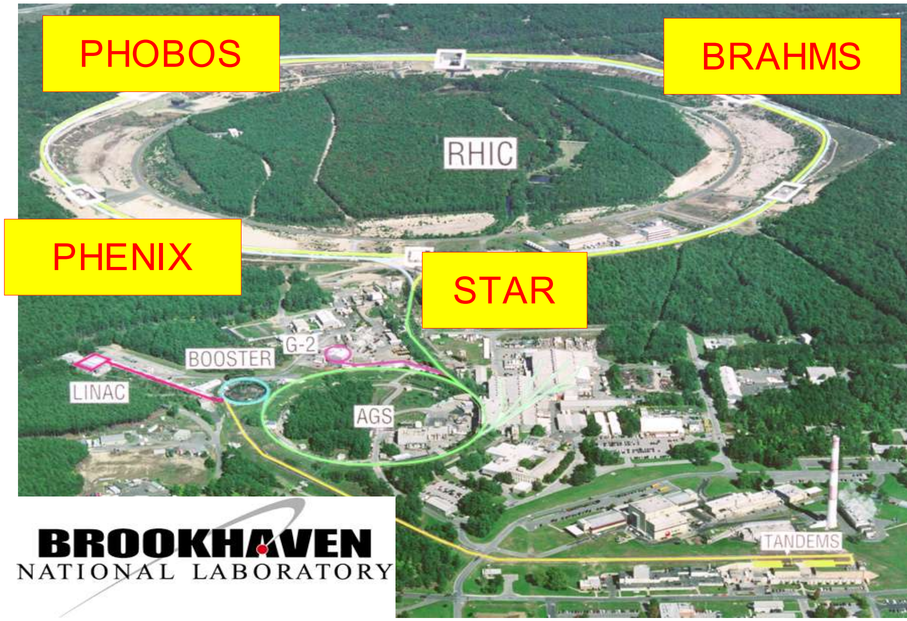
p+A collisions @ $\sqrt{s}_{max}$ = 200 GeV

4 experiments:

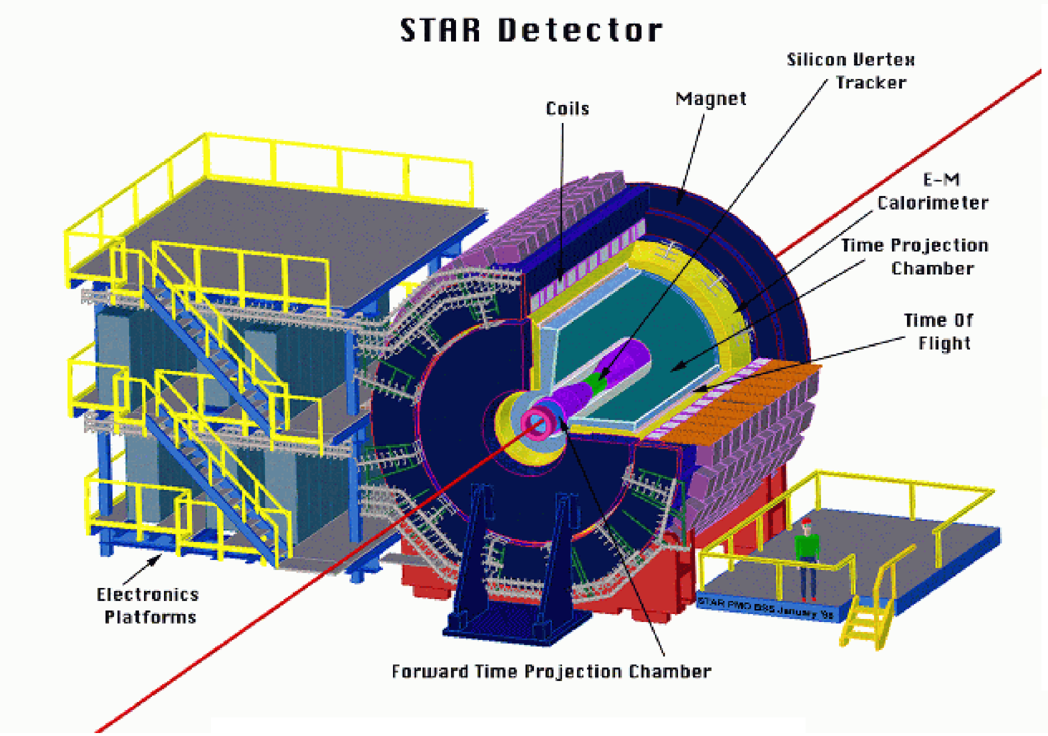
BRAHMS, PHENIX, PHOBOS, STAR

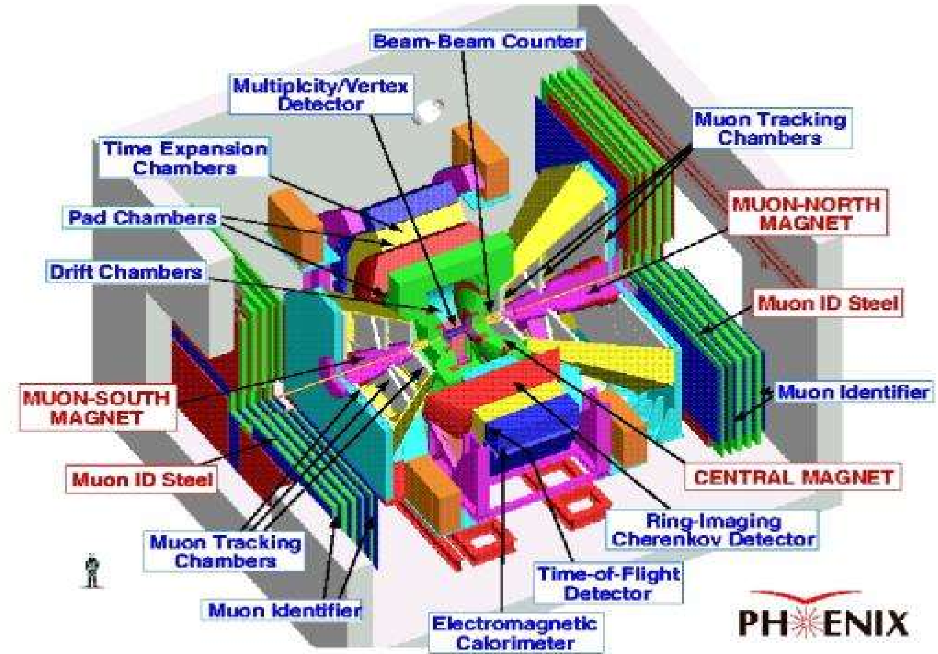
Runs 1 - 5 (2000 – 2005):

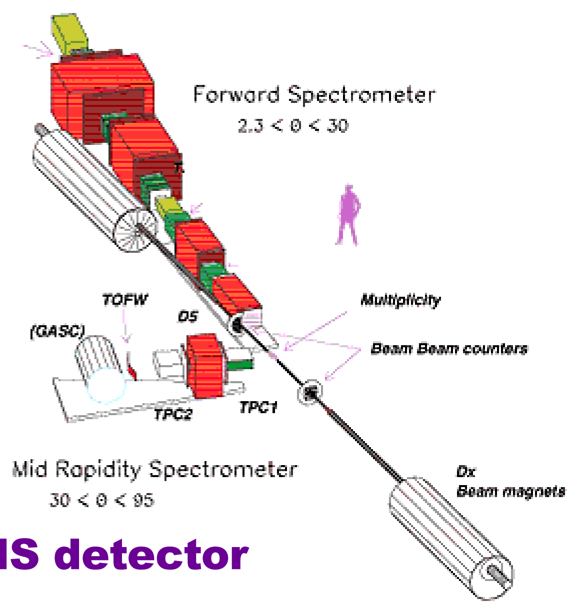
Au+Au @ 200, 130, 62.4 GeV
p+p @ 200 GeV
d+Au @ 200 GeV
Cu+Cu @ 200 GeV



The 4 RHIC experiments

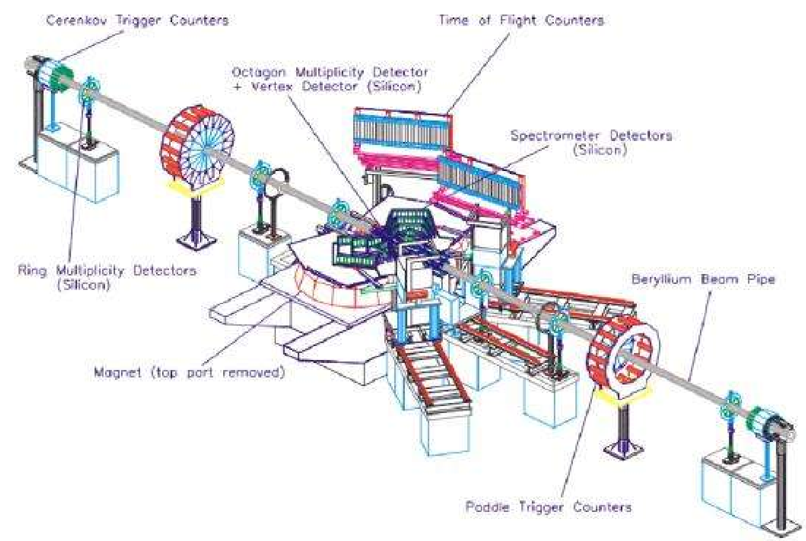




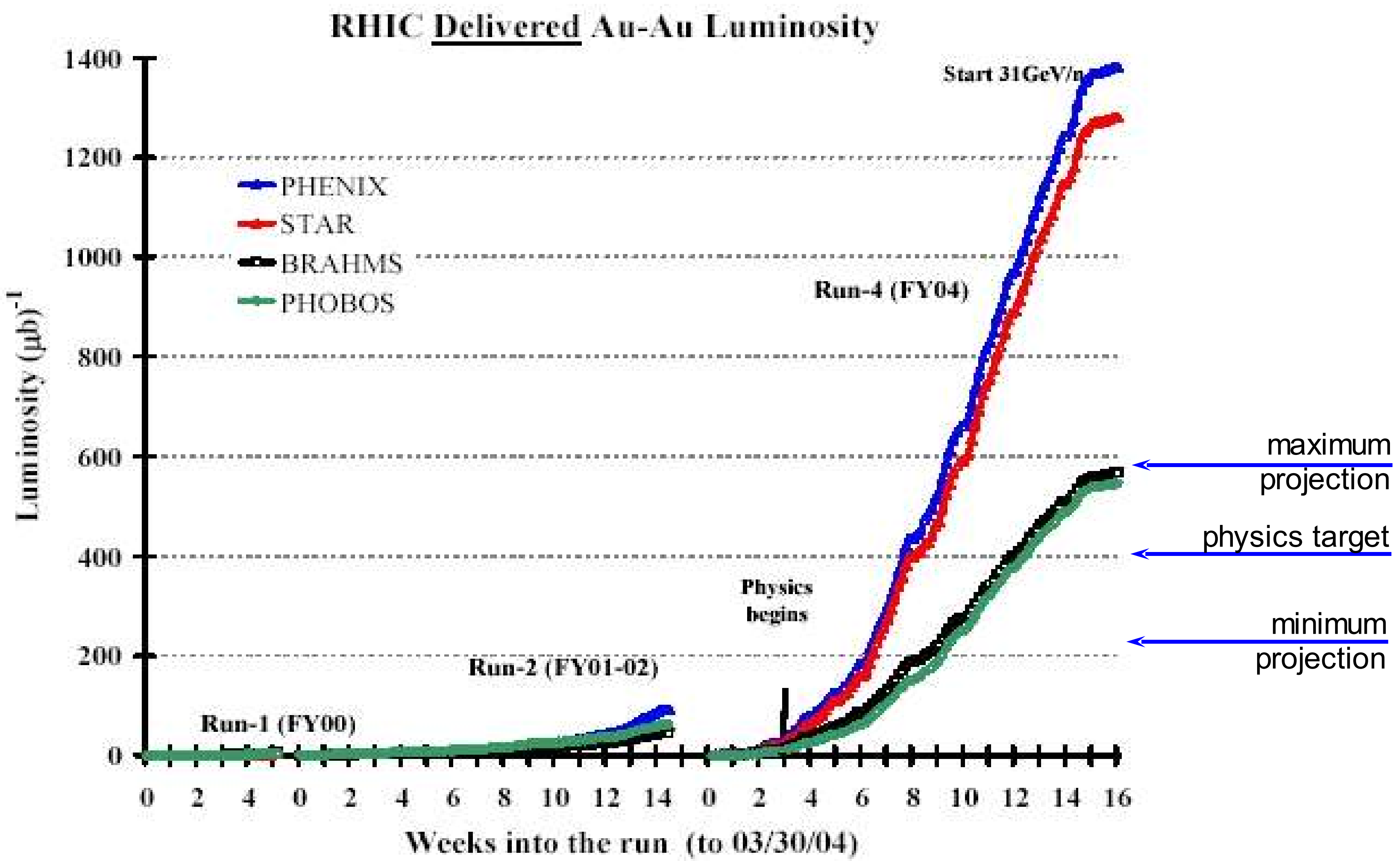


BRAHMS detector

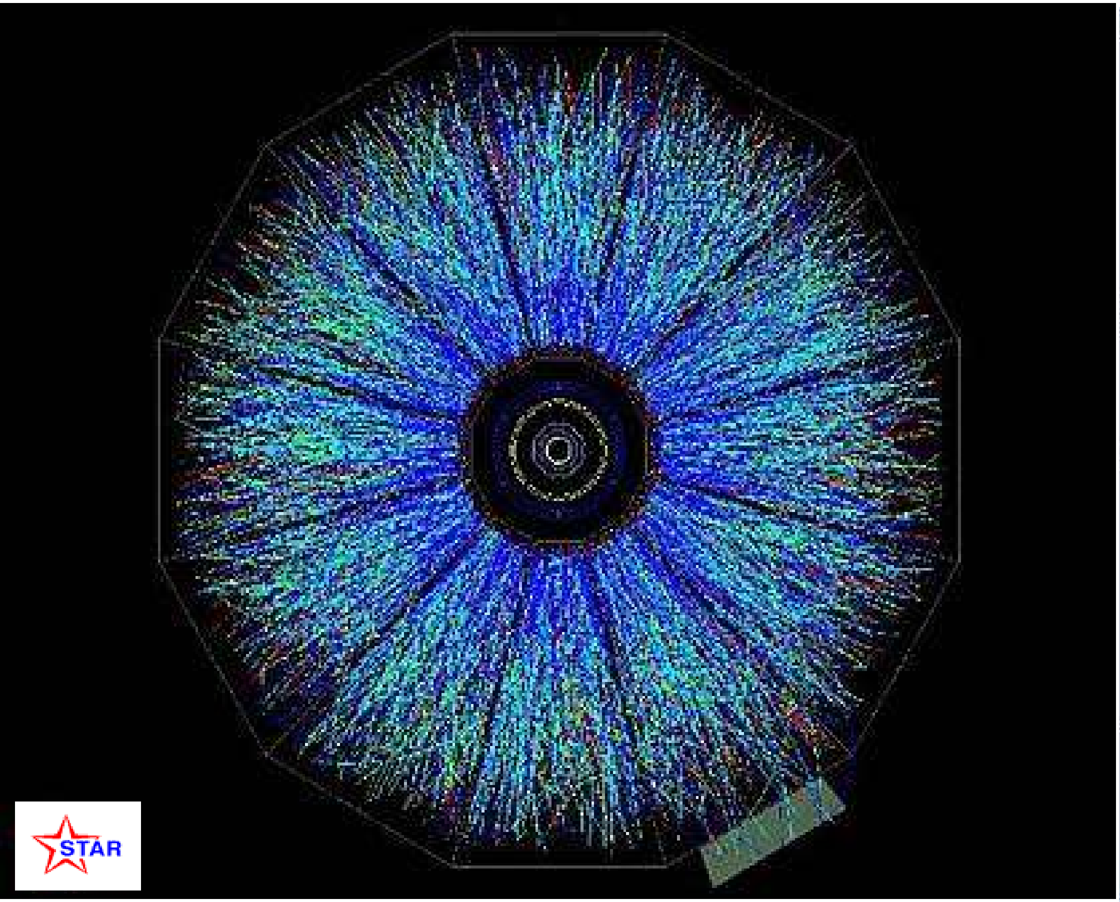
PHOBOS Detector

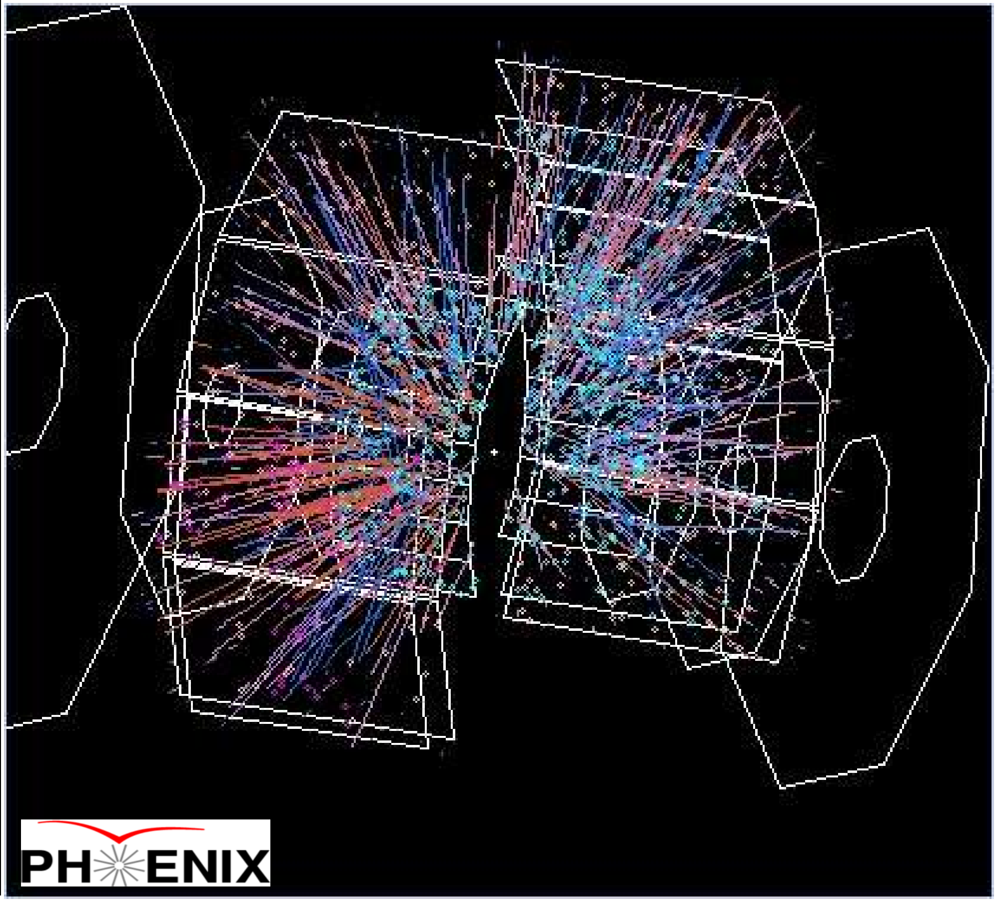


RHIC Au+Au luminosities



Au+Au collisions @ 200 GeV





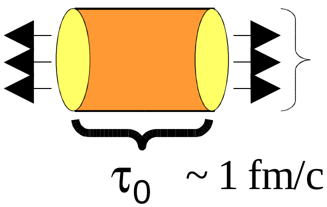
~ 700 charged particles per unit rapidity at midrapidity (top 10% central)

(1) Energy densities at RHIC

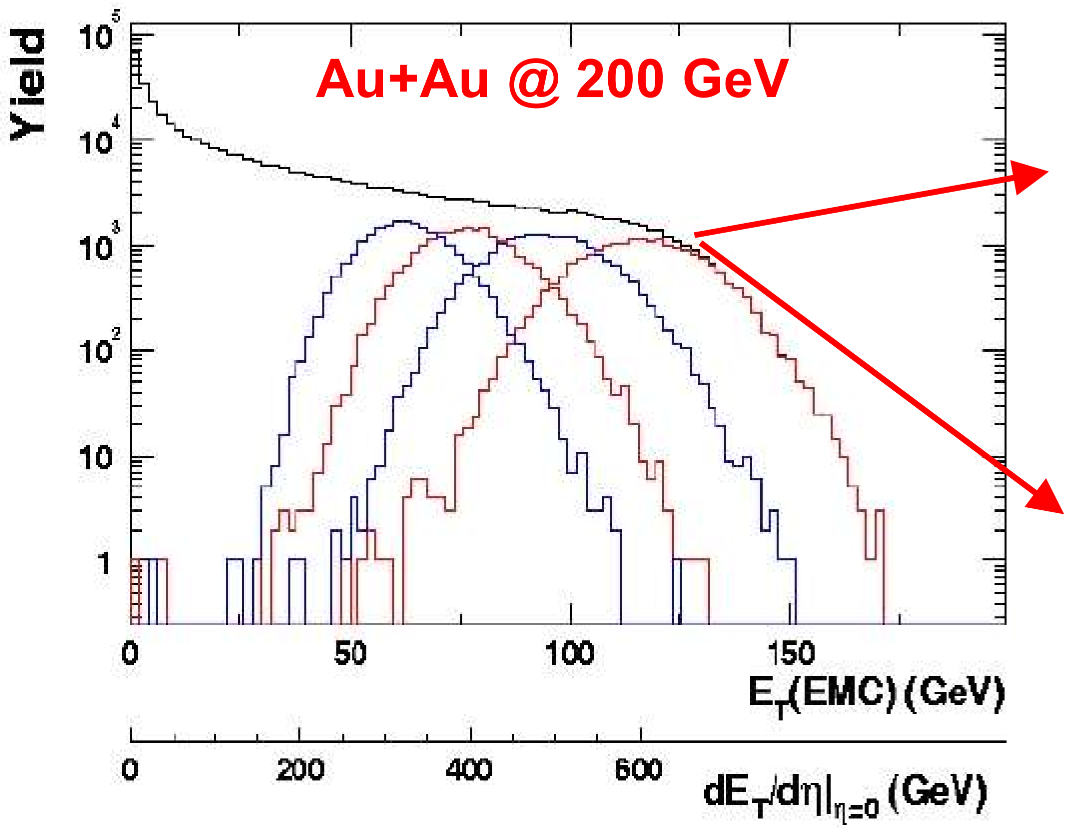
Energy density (Au+Au @ 200 GeV, y=0)

- 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: $E_T^{had} = (1.17 \pm 0.05)\, E_T^{EMCal}$)



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

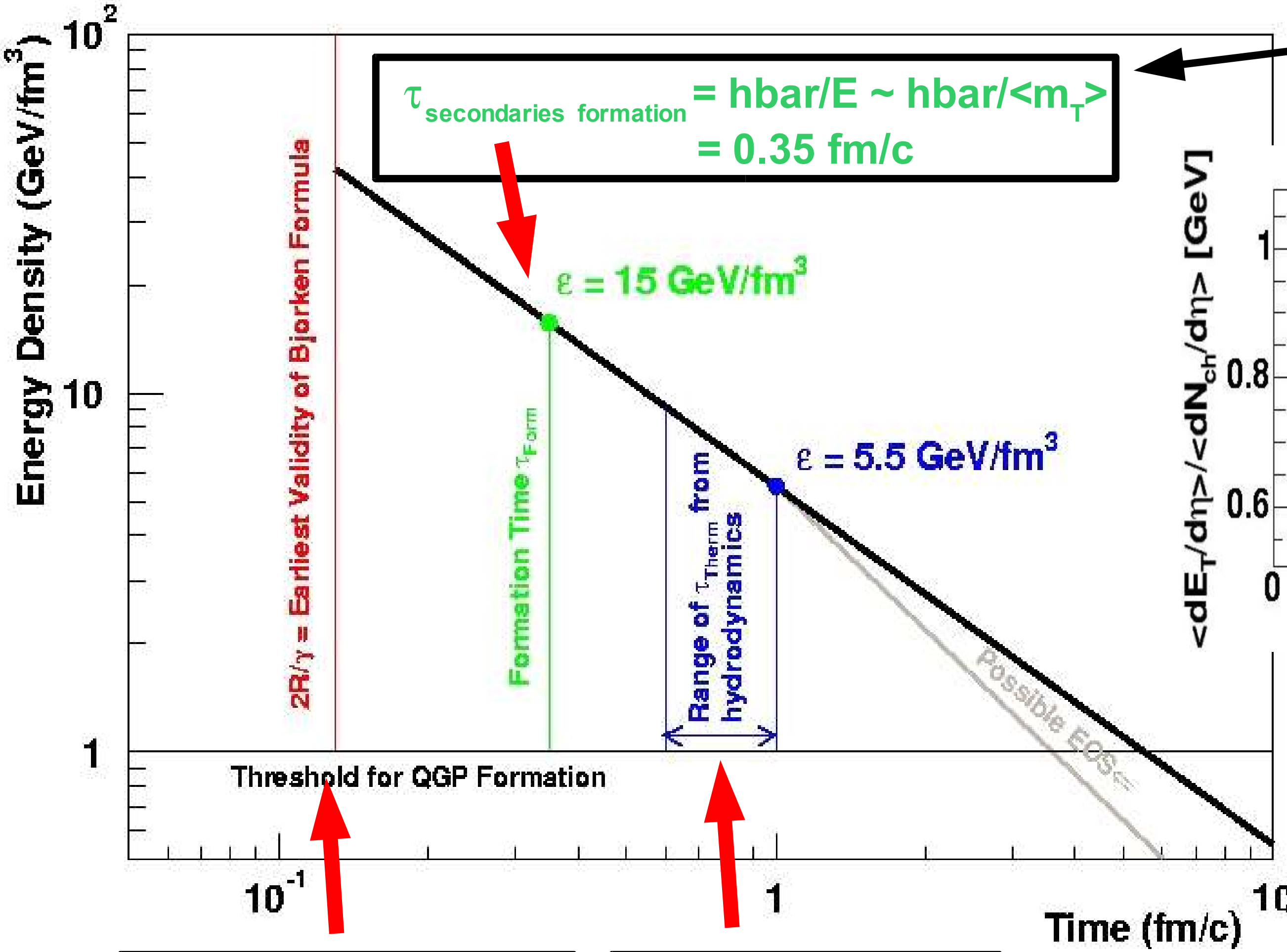
(~70% larger than at SPS)

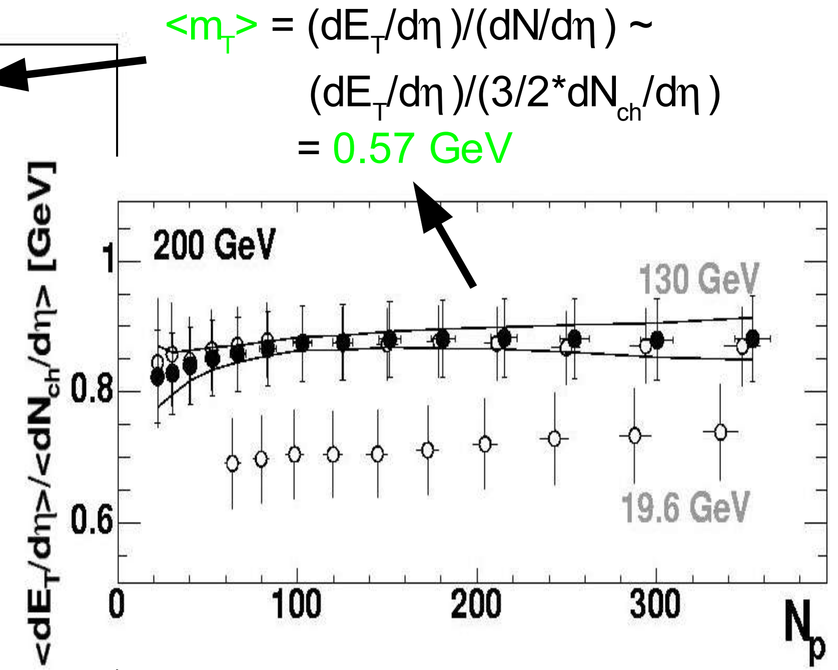
$\varepsilon_{Bjorken}$ ~5.0 GeV/fm^3

> QCD critical density (~1 GeV/fm^3)

1 fm/c thermalization time ?

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





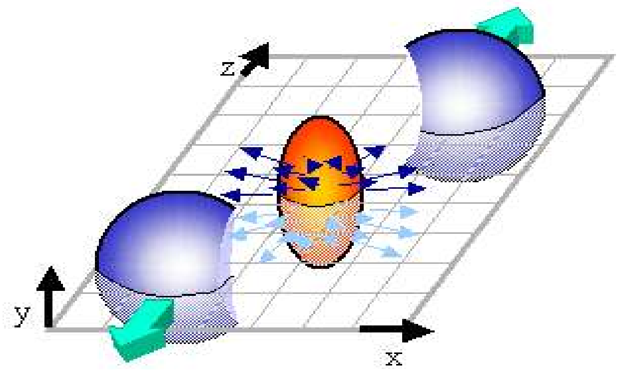
$\tau_{cross} = 2R/\gamma = 0.13$ fm/c

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

(2) Elliptic flow at RHIC

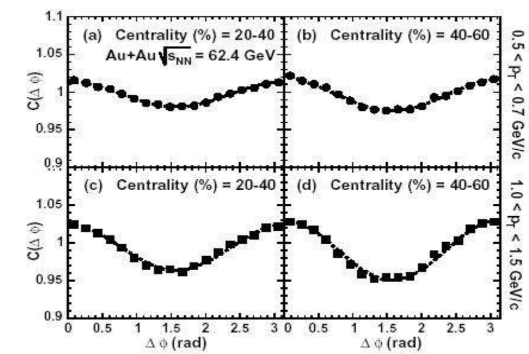
Elliptic flow

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



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

Elliptic flow = v_2
(2nd Fourier coefficient)

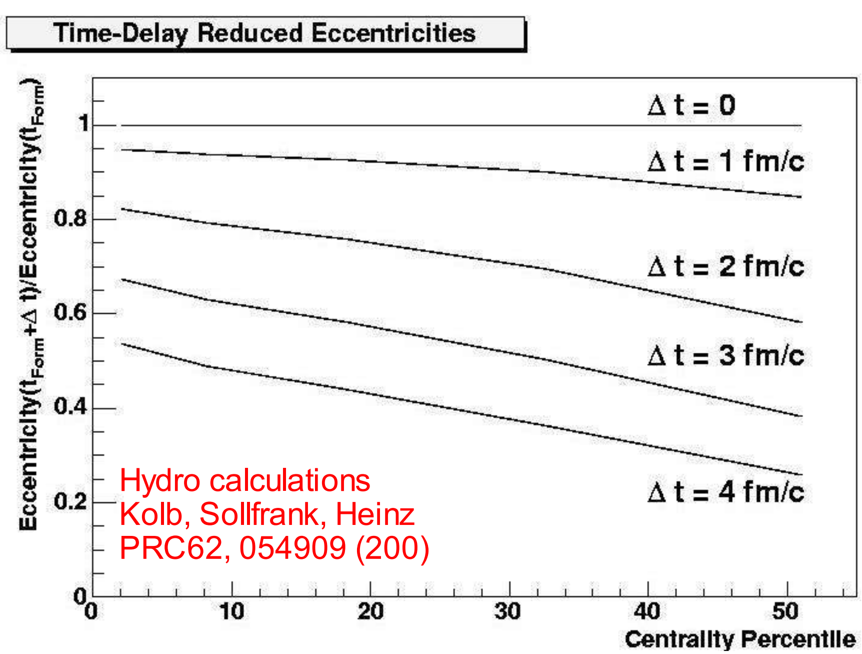


(1) Truly collective effect (absent in p+p collisions).

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

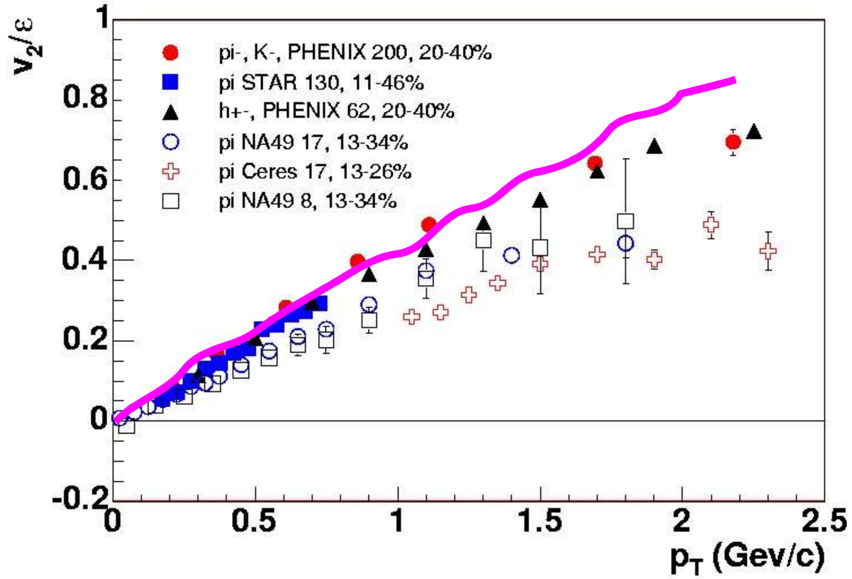
Time evolution of ellipsoid eccentricity:

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

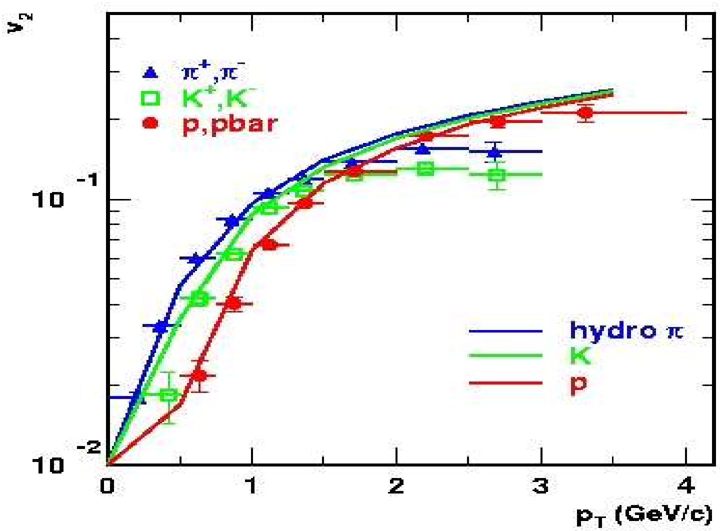


Elliptic flow at RHIC

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

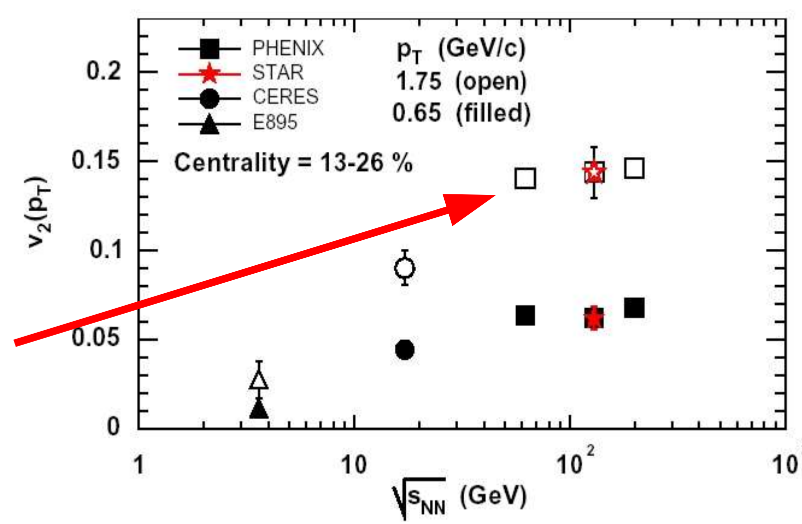


- Mass dependence of v_2
  consistent w/ hydrodynamics too:



⇒ Strong (collective) pressure grads.
⇒ Large & fast parton rescattering:
early thermalization.

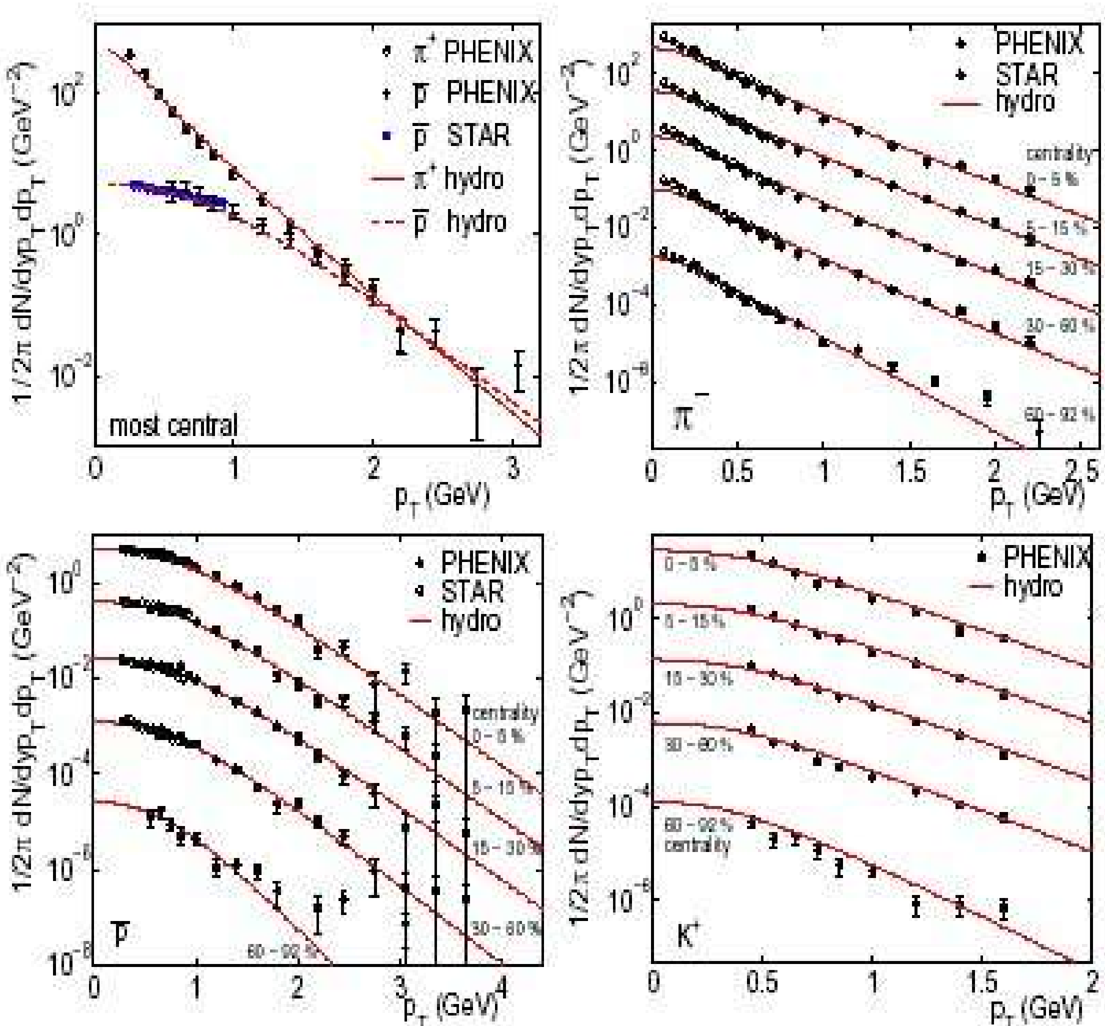
- √s-dependence of v_2:
  ~50% increase from SPS
  Apparent saturation within 62-200 GeV



(3) Soft particle production at RHIC

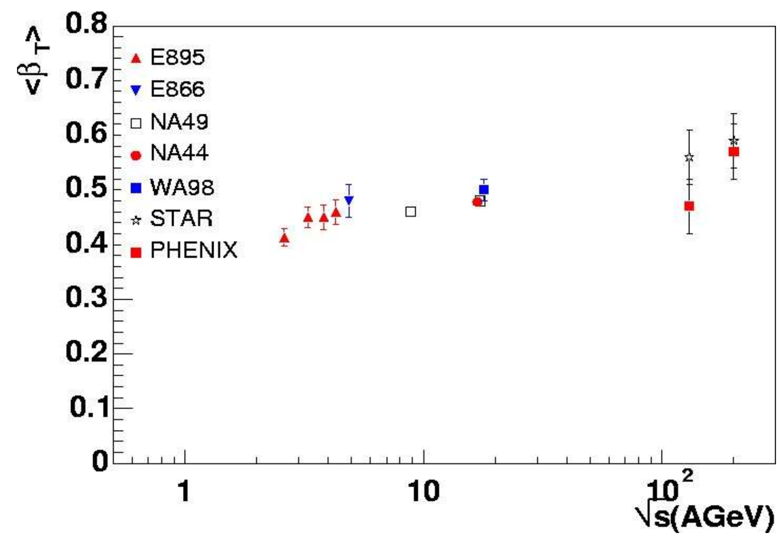
Soft particle spectra

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



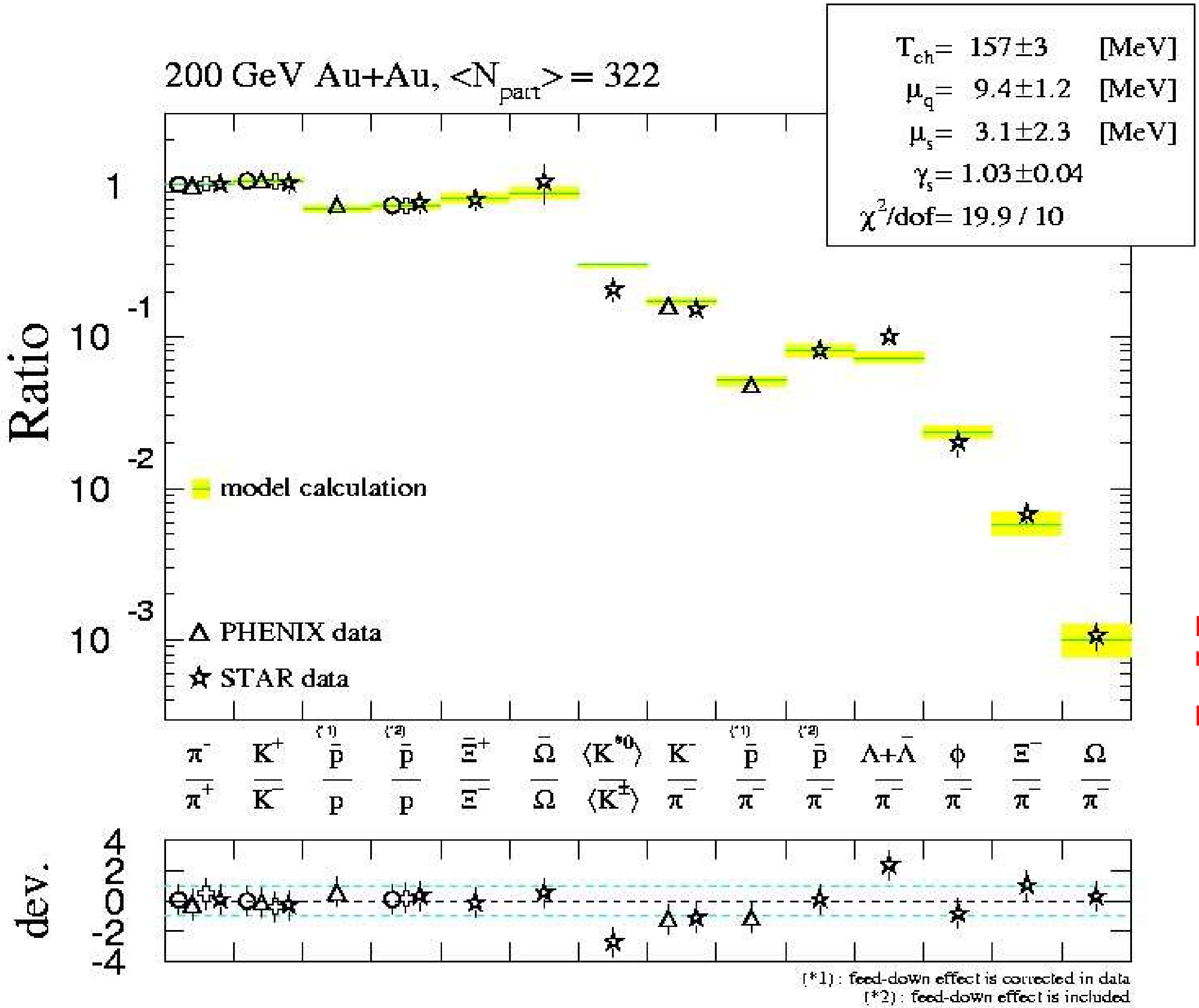
Kolb&Heinz
nucl-th/0305084

Radial collective flow built-up at freeze-out: $\langle\beta_T\rangle \approx 0.6$



Ratios of particle yields

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



PBM, Redlich, Stachel nucl-th/0304013

Kaneta, Xu nucl-th/0405068

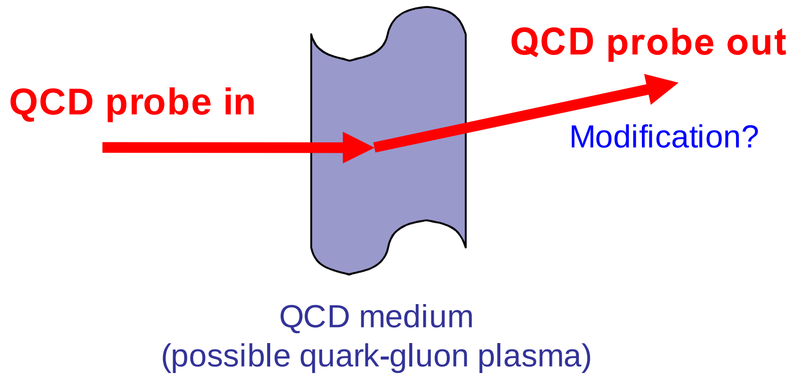
(4) Hard QCD production at RHIC

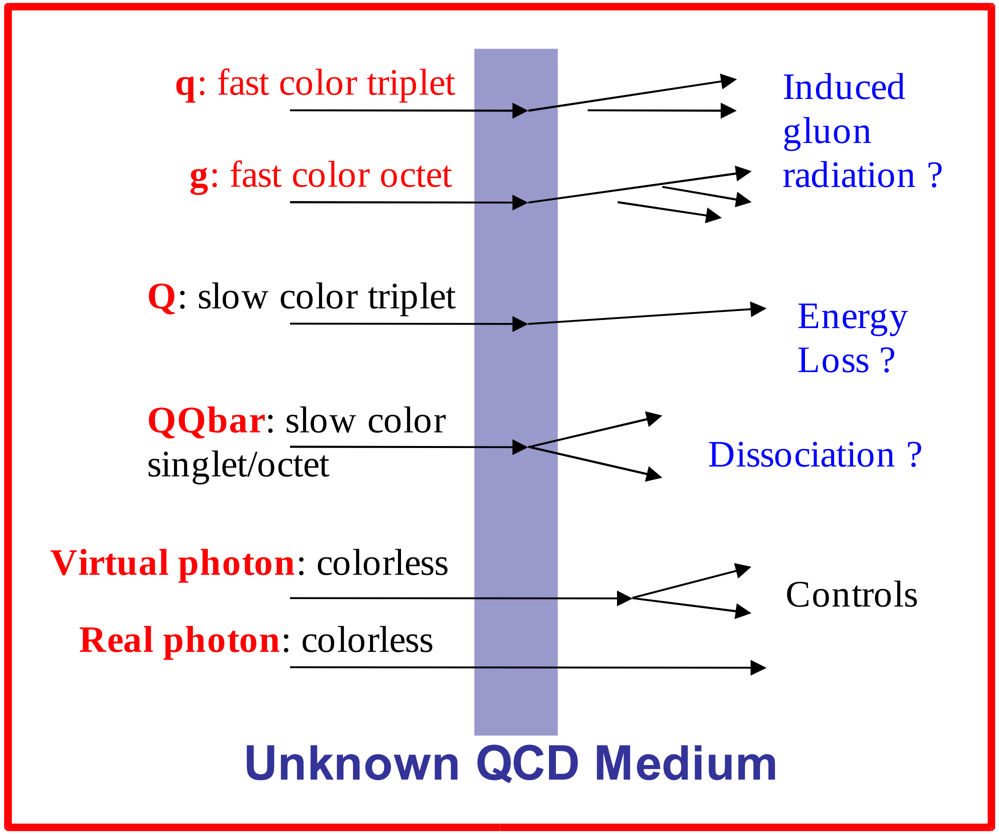
Hard QCD probes (I)

- 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:



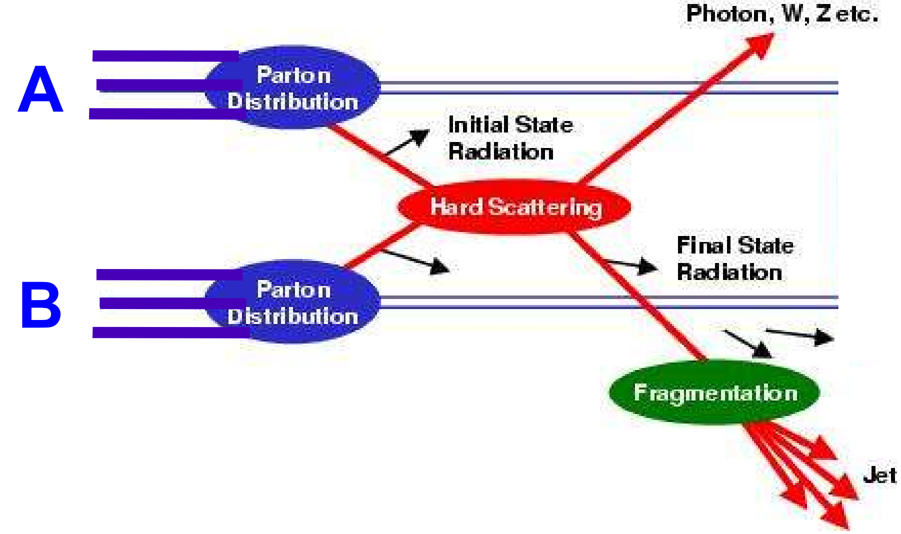


Hard QCD probes (II)

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:

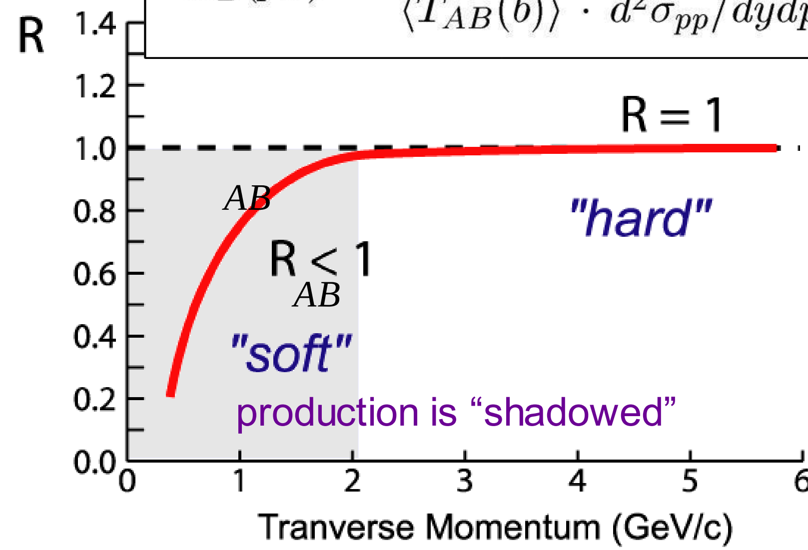
$$dN_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

geom. nuclear overlap at b

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

Nuclear Modification Factor:

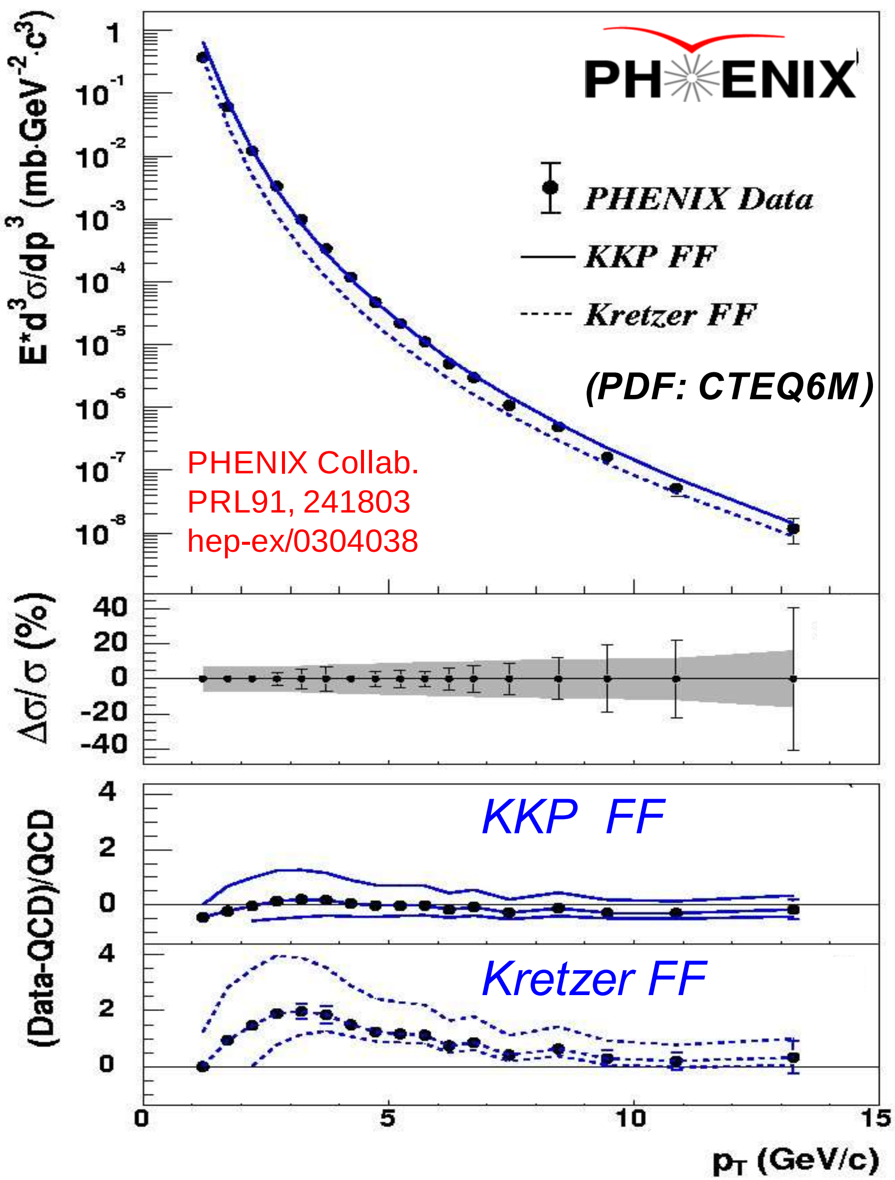
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$



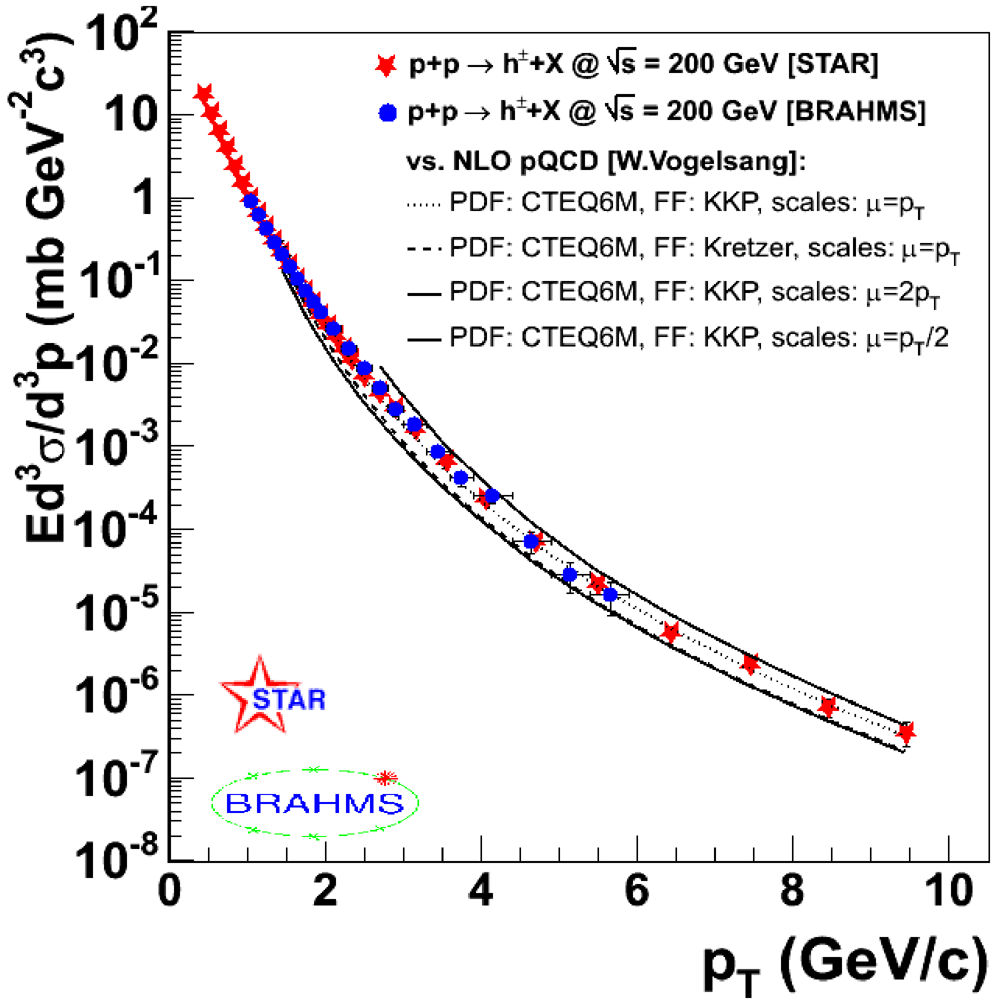
High p_T p+p baseline data well described by pQCD

- Good theoretical (NLO pQCD) description:

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



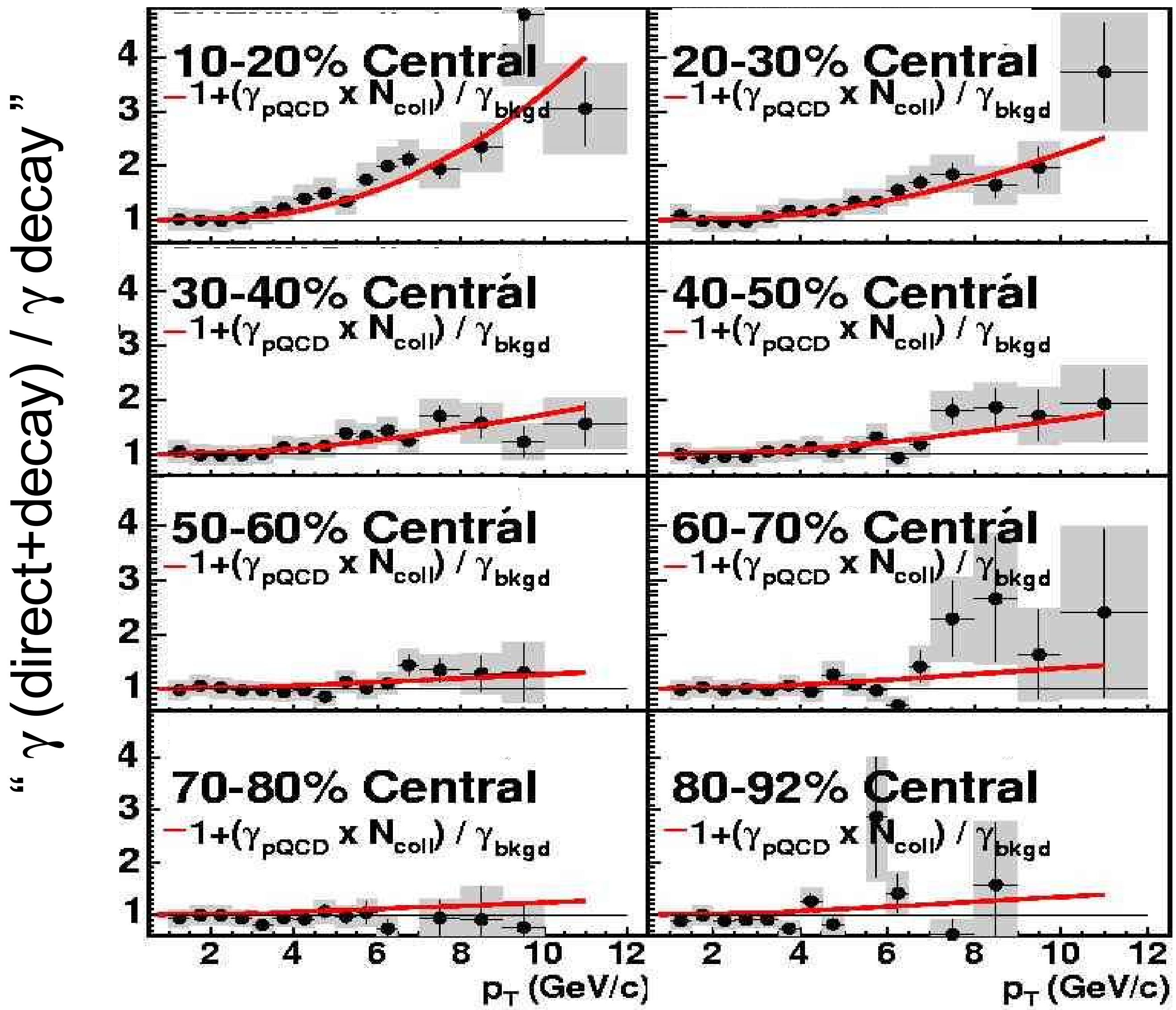
$p+p \rightarrow h^{\pm} X$ (non singly diffractive)



- 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/ p+p incoherent scattering ("N_{coll}-scaled" pQCD) predictions:



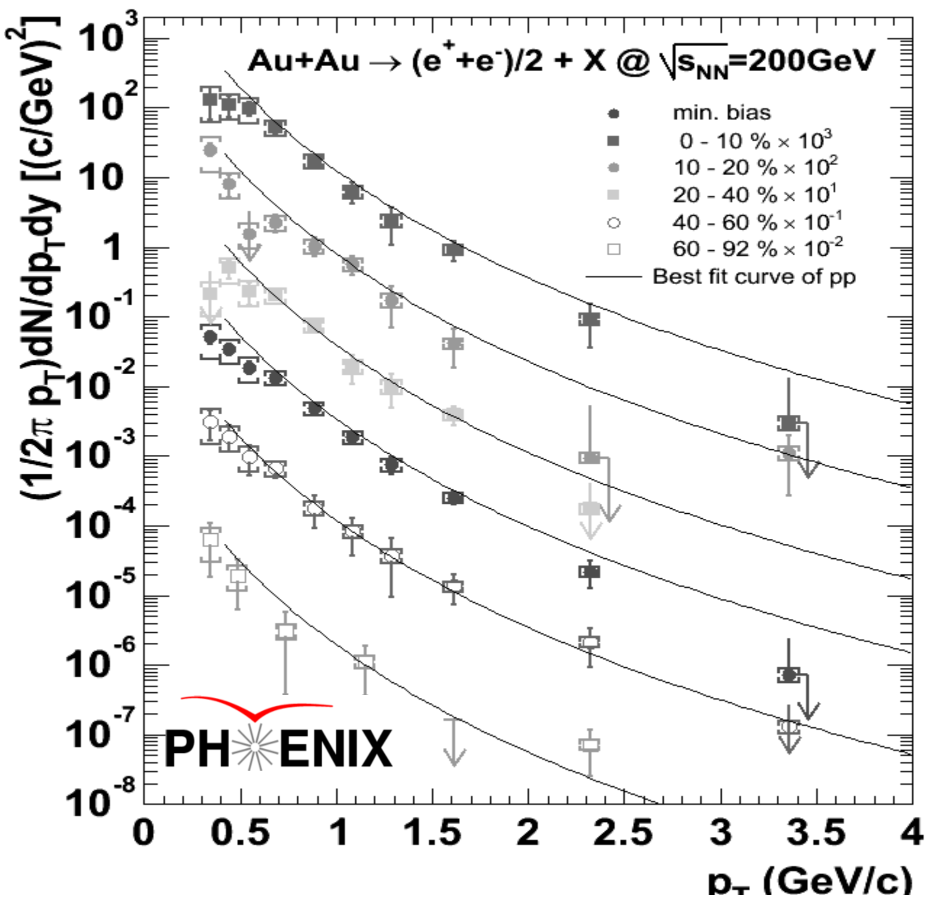
--- "N_{coll}-scaled" p+p pQCD

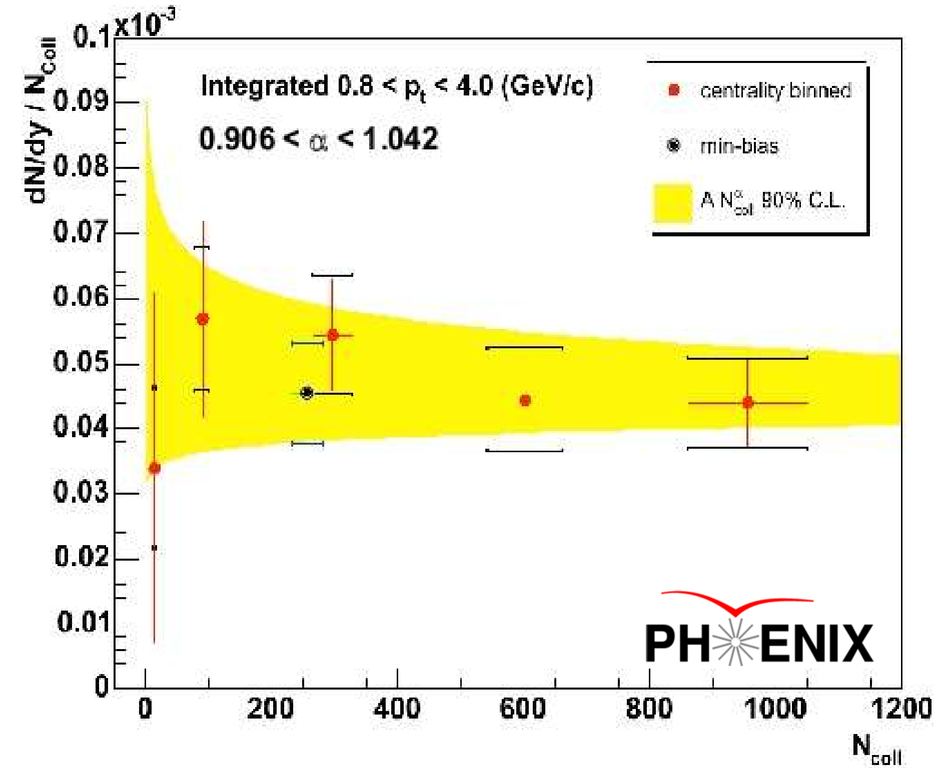
PHENIX Preliminary

[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:

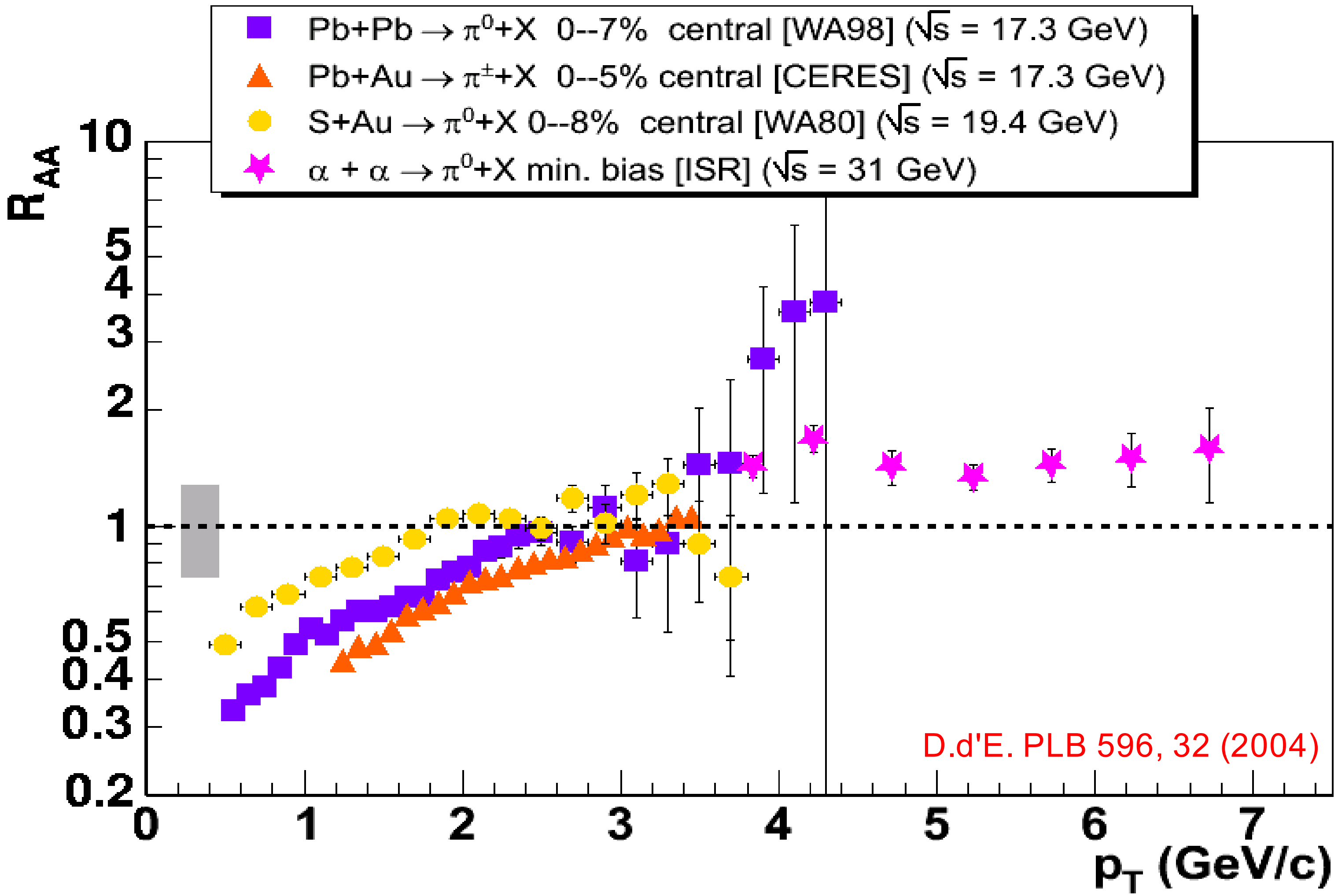




- pQCD parton scattering holds for hard processes in Au+Au (all centralities).

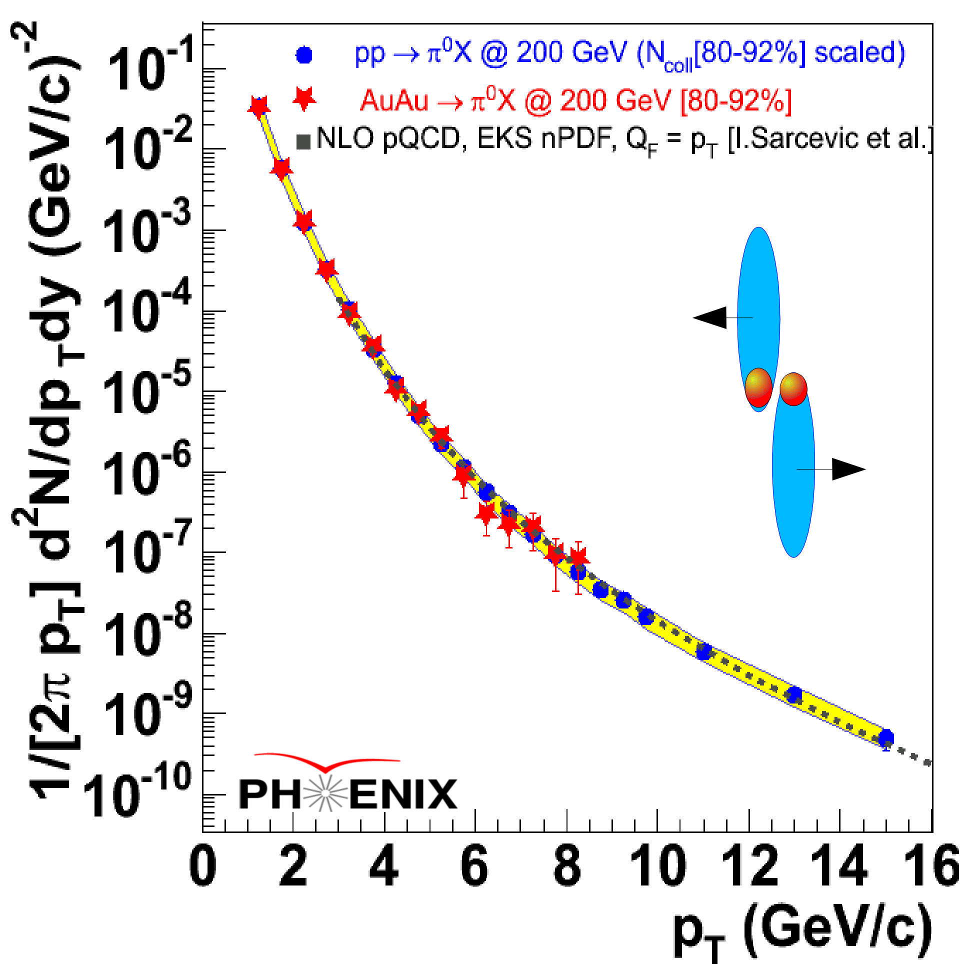
"N_{coll} scaling" in A+A @ 17, 31 GeV: High p_T hadrons

- 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):

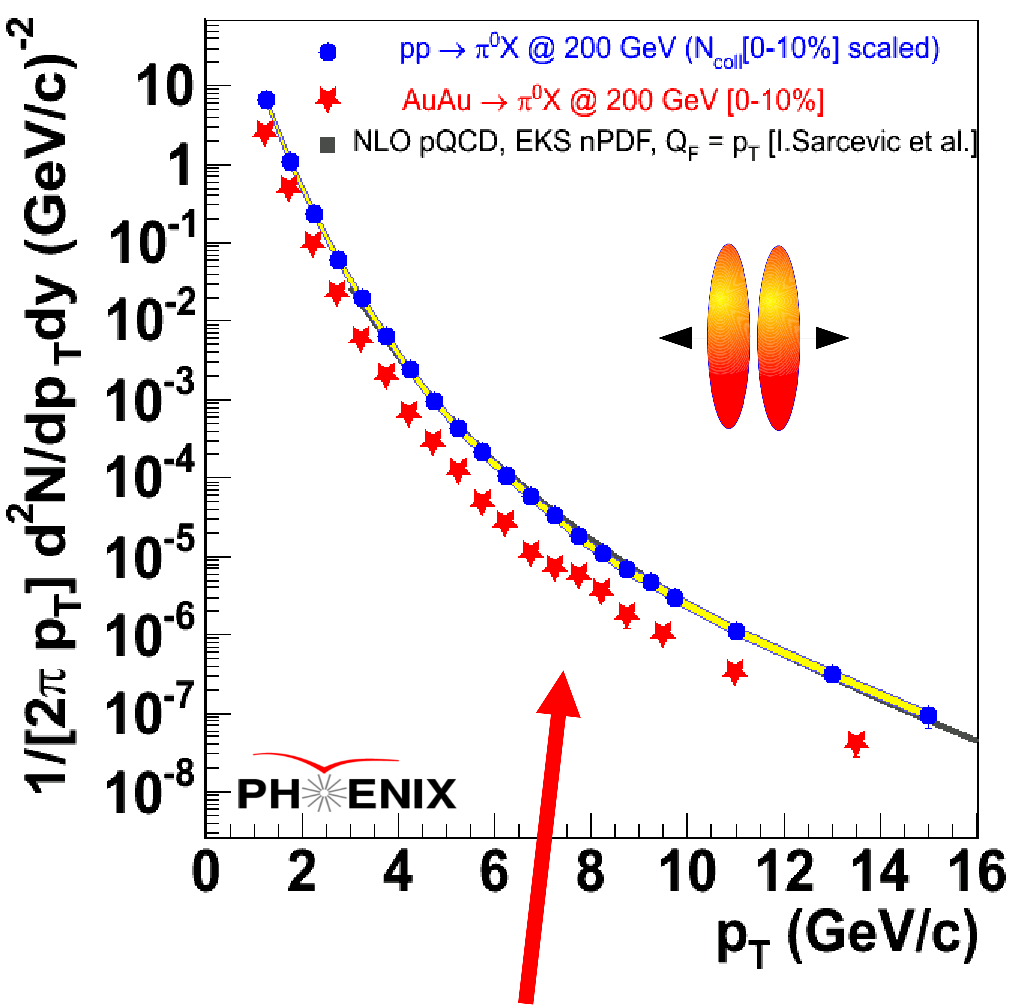


Suppressed high p_T hadroproduction in Au+Au @ RHIC !

Au+Au→ $\pi^0 X$ (peripheral)



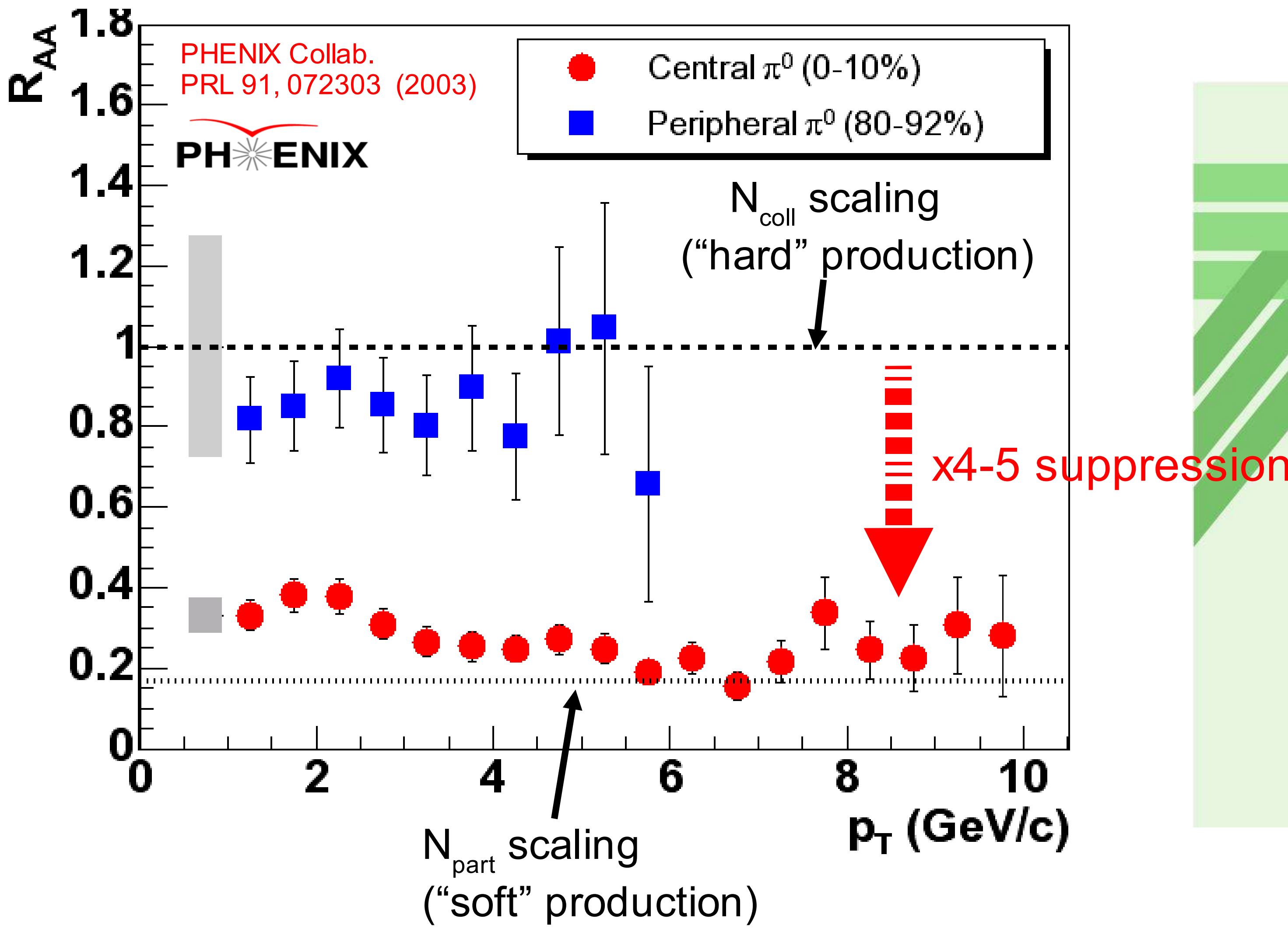
Au+Au→ $\pi^0 X$ (central)

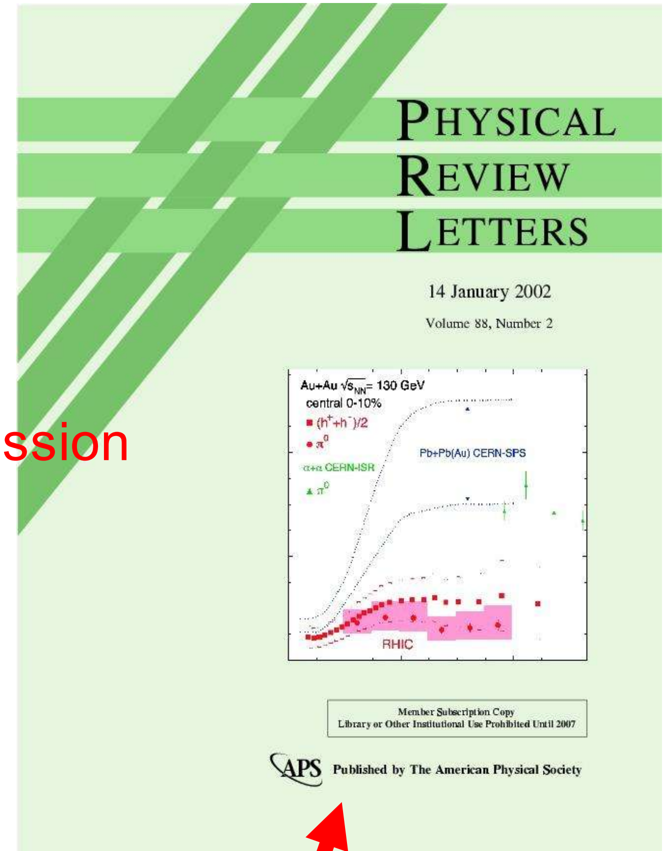


Peripheral data agree well with p+p (data&pQCD) plus N_{coll} scaling

Strong suppression in central Au+Au collisions

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

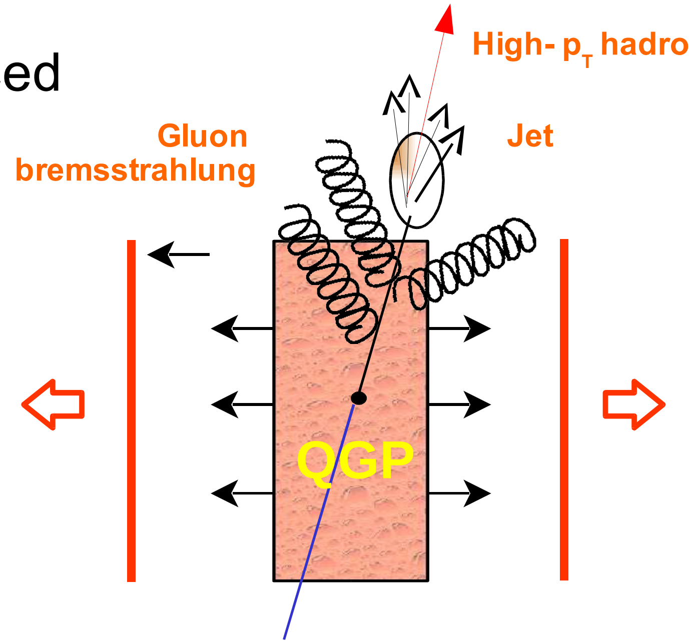




R_{AA} << 1: well below pQCD (collinear factorization) expectations for hard scattering cross-sections

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

"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 inside jet cone: $dE/dx \sim \alpha_s \langle k^2_T \rangle$ [Armesto-Salgado-Wiedemann]

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

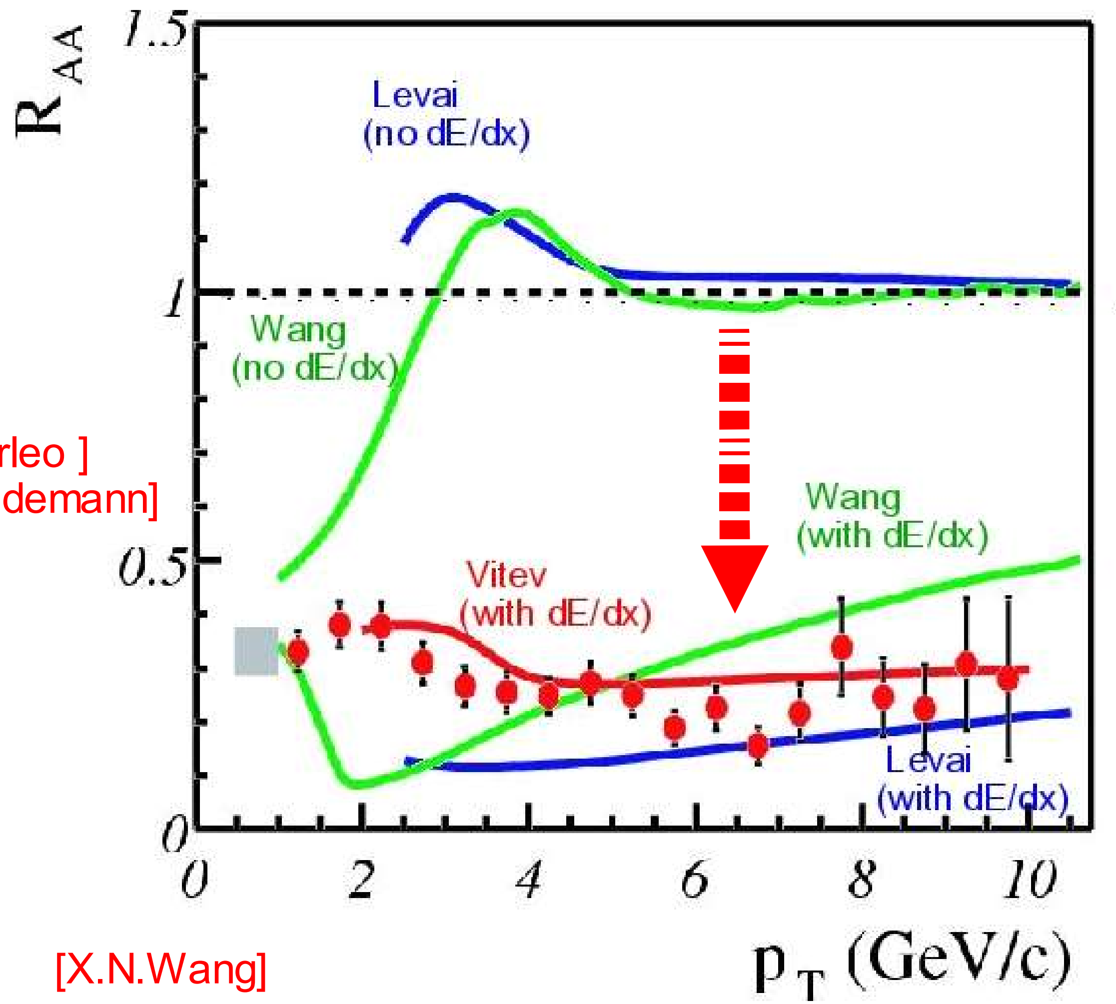
- Correction for expanding plasma (1-D):

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

"Jet quenching" model vs. data (I)

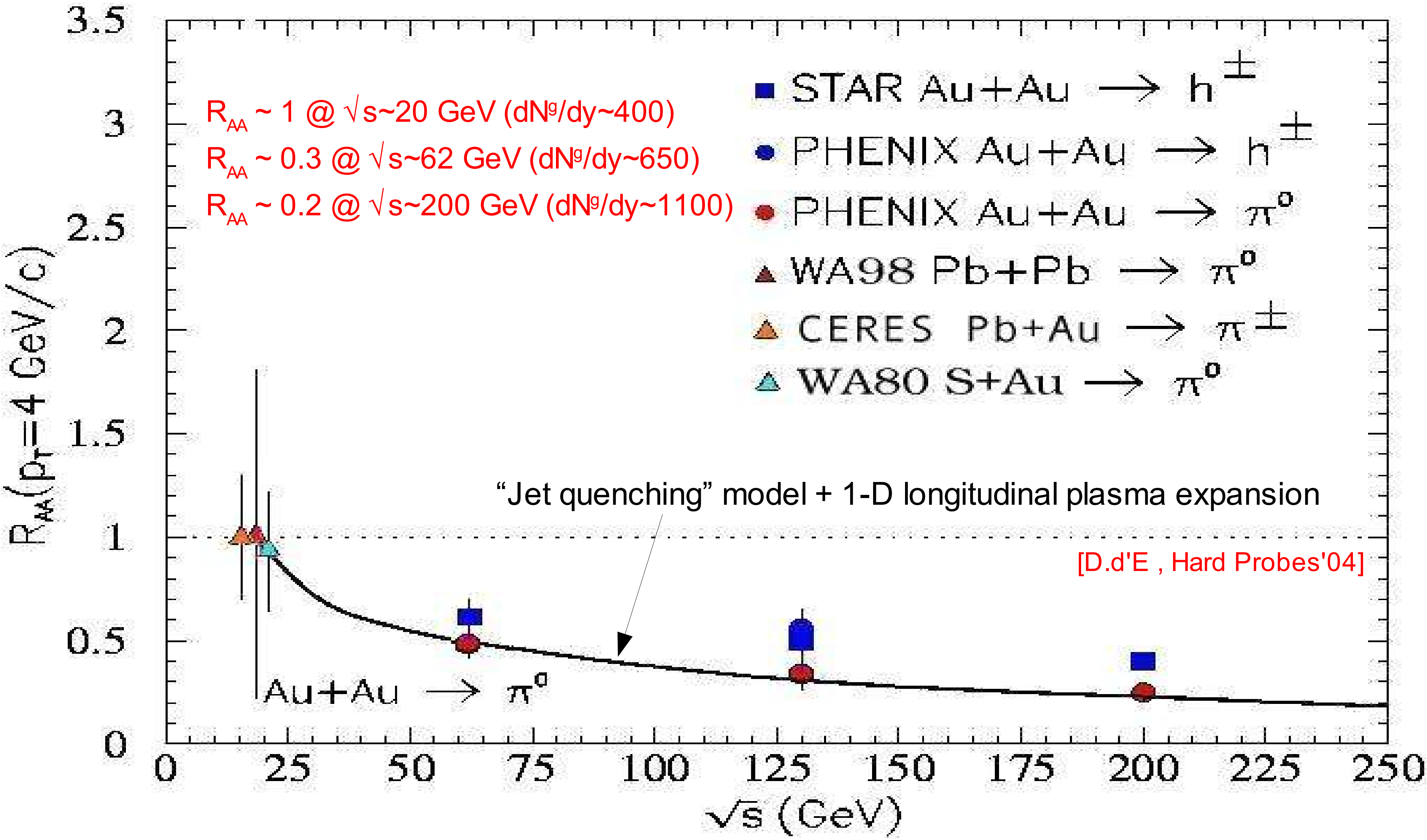
- Dense medium properties according to final-state parton energy loss models:
  - Initial gluon densities:
    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]
  - Opacities:
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]
  - Transport coefficients:
    $\langle q_0 \rangle \sim 3.5$ GeV/fm^2 [BDMPS, F.Arleo] [Salgado-Wiedemann]
  - Plasma temperatures:
    $T \sim 0.4$ 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]



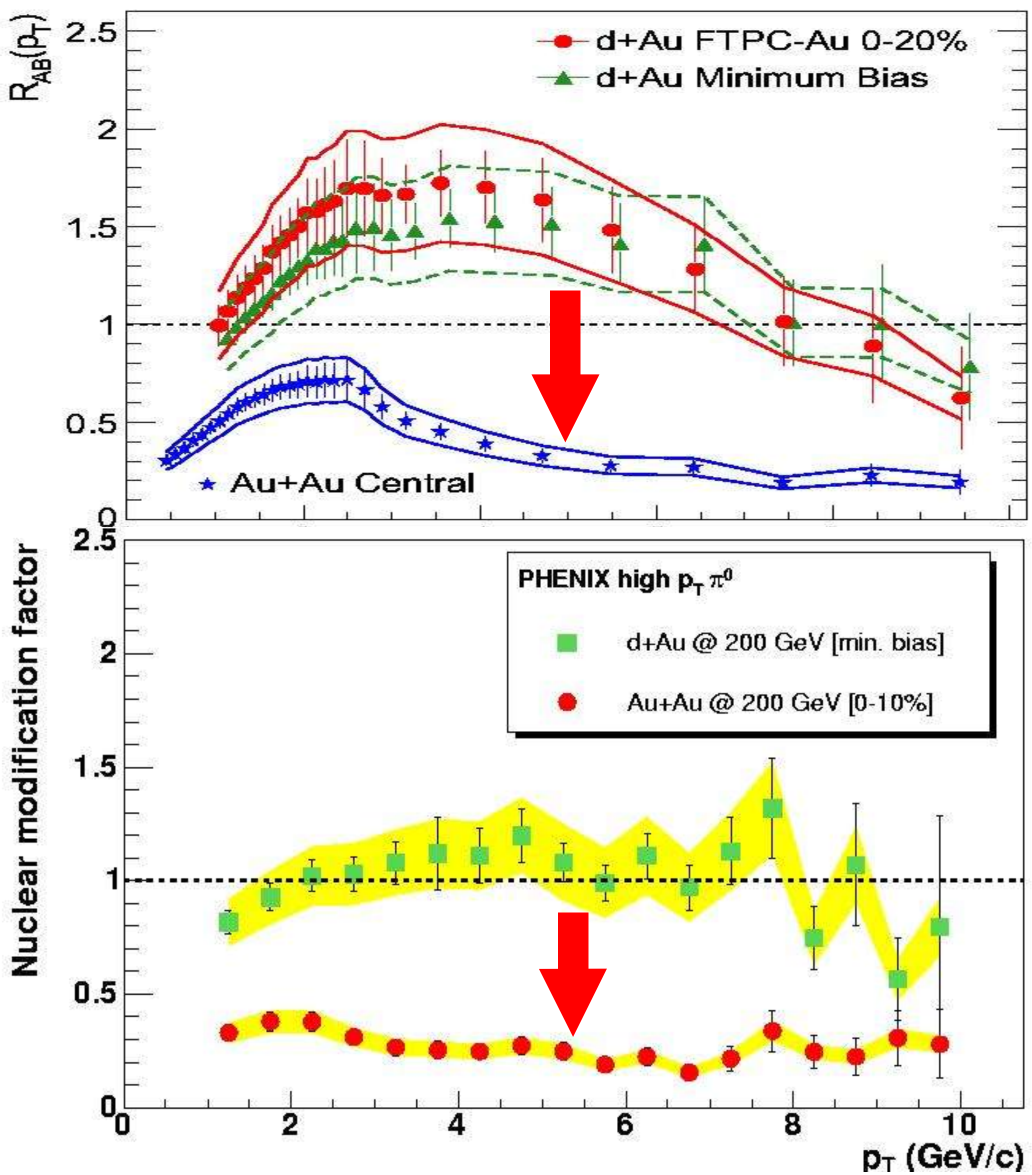
- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\varepsilon_{crit\ QCD}$ in thermalized syst.

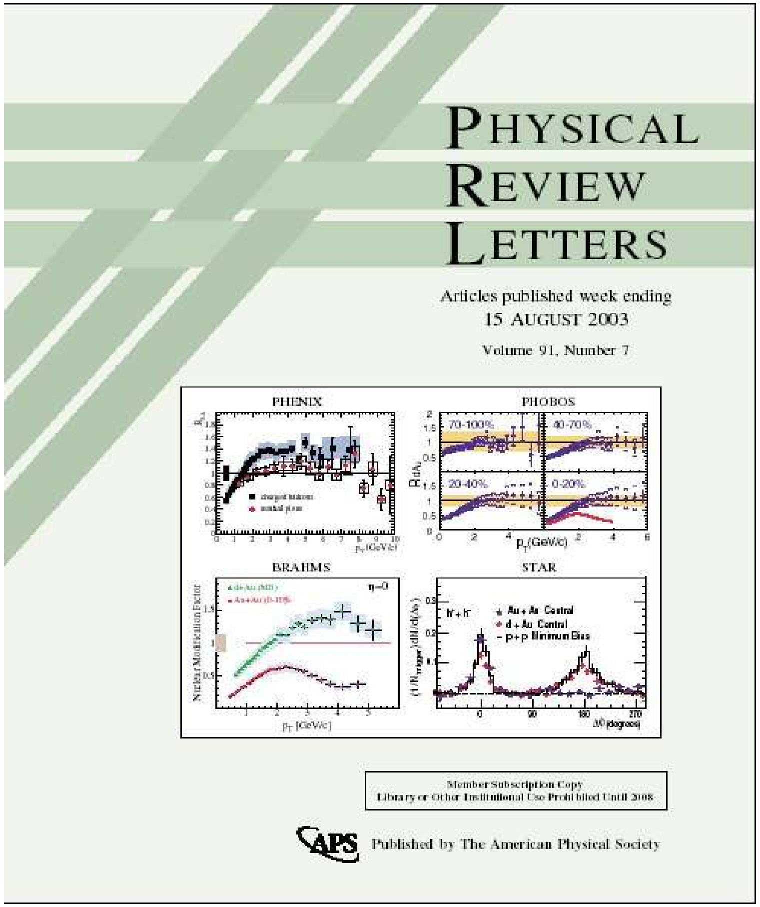
“Jet quenching” model vs. data (II)

- Excitation function of high p_T suppression:



Unquenched d+Au production at high p_T



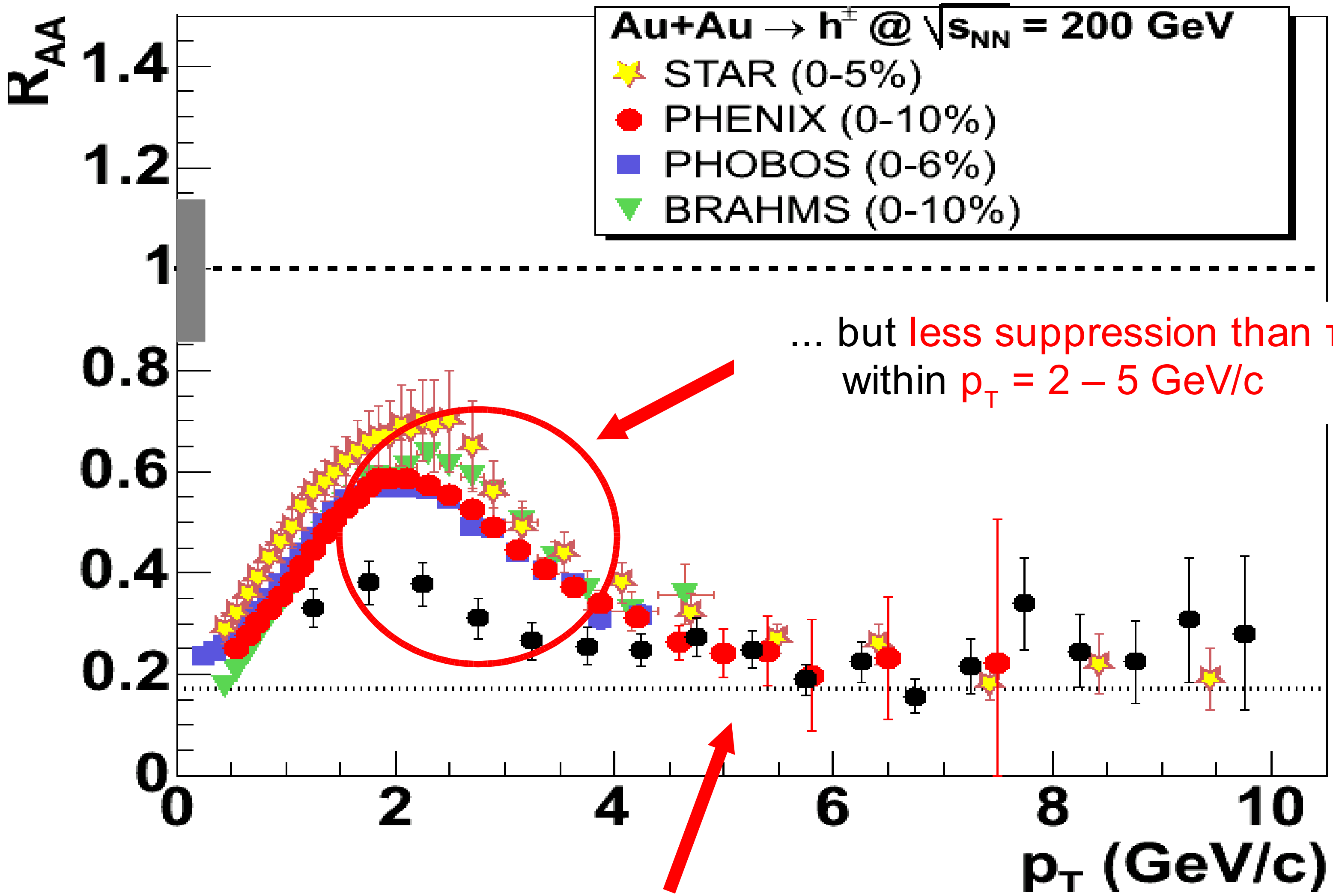


- Conclusion: High p_T suppression in central Au+Au due to final-state effects

(5) Hadron production at intermediate p_T

Suppressed high p_T hadroproduction @ RHIC: $h^\pm$ vs π^o

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



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

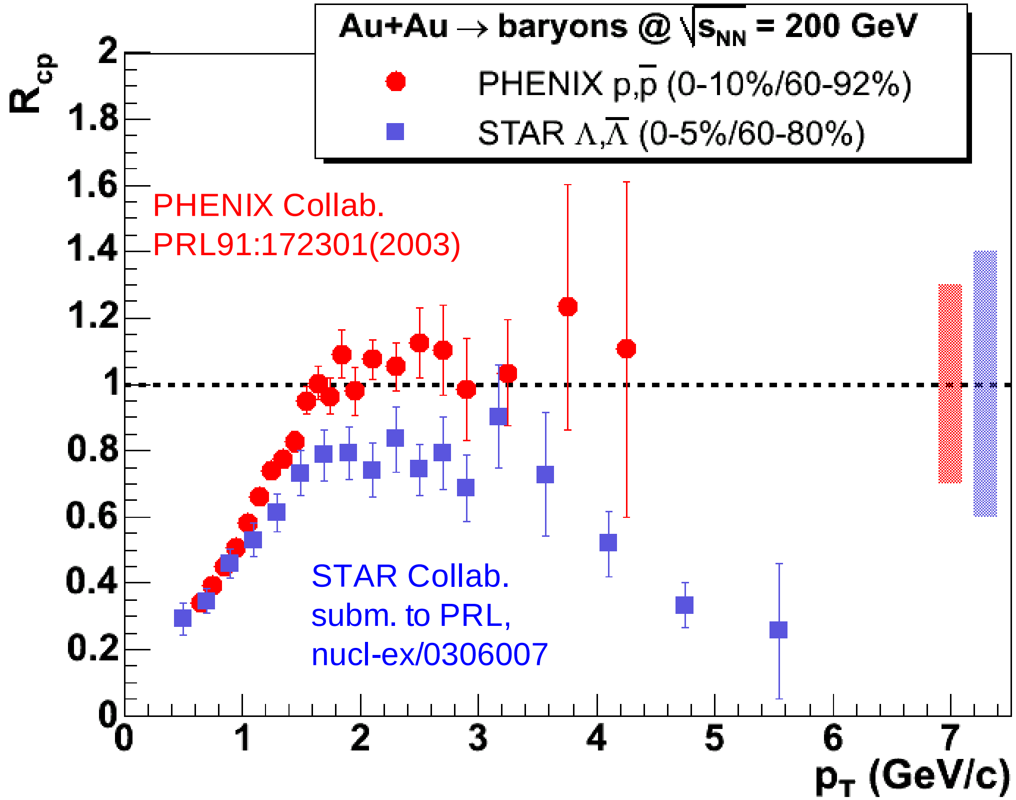
- Universal (PID-wise) suppression above p_T = 5 GeV/c

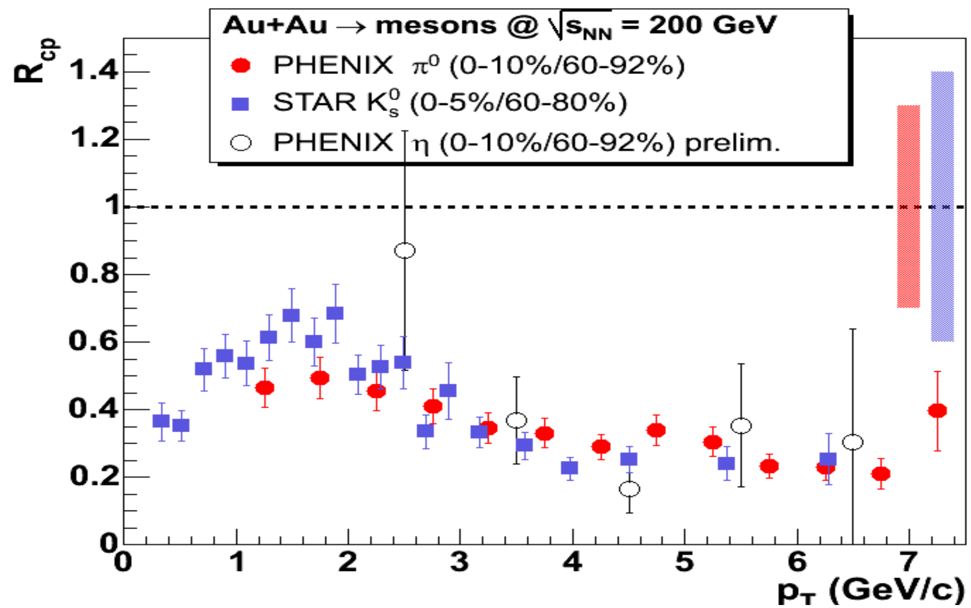
Unsuppressed baryon production

- 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.

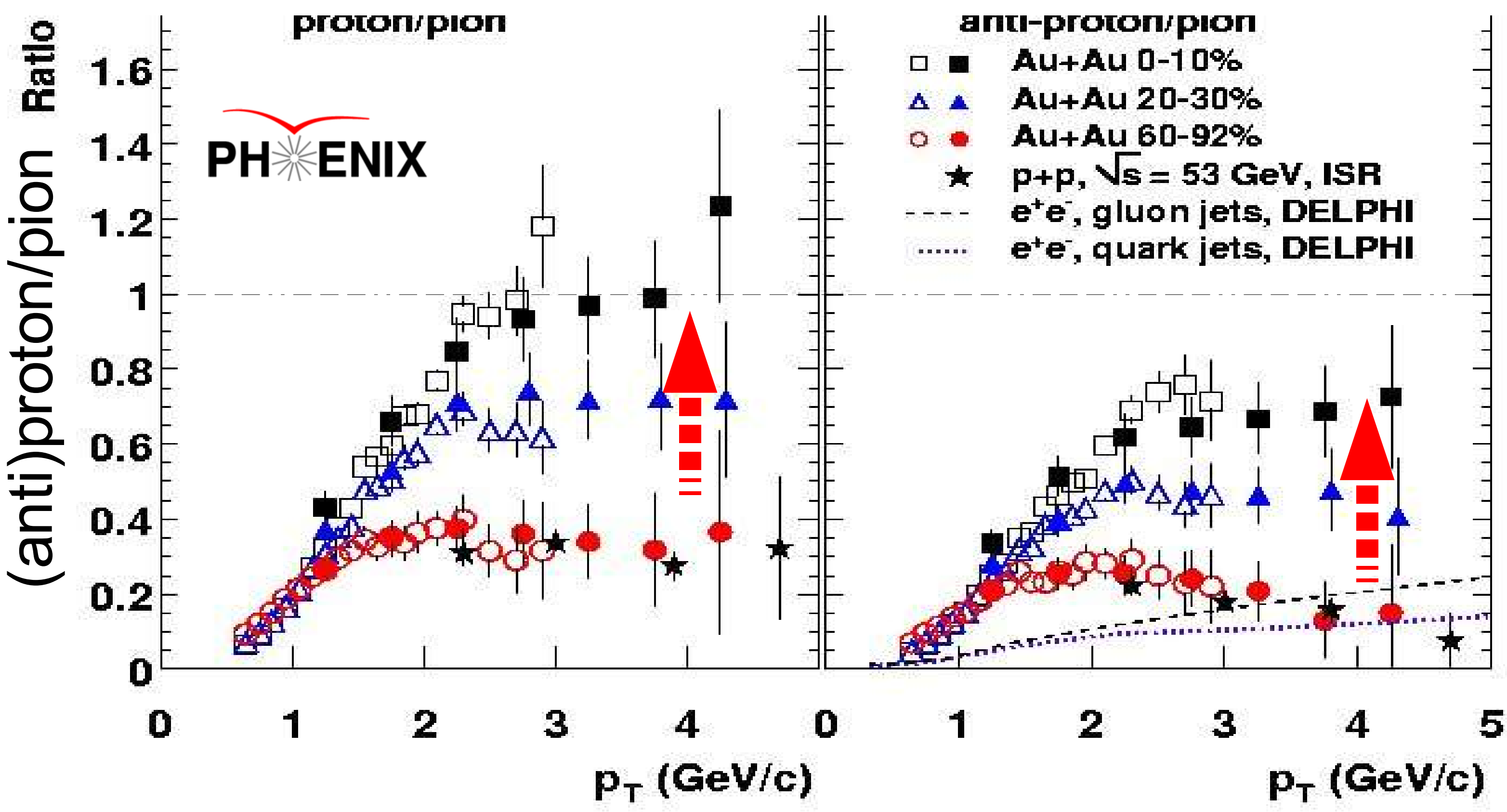




- Particle composition inconsistent with known (universal) fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range

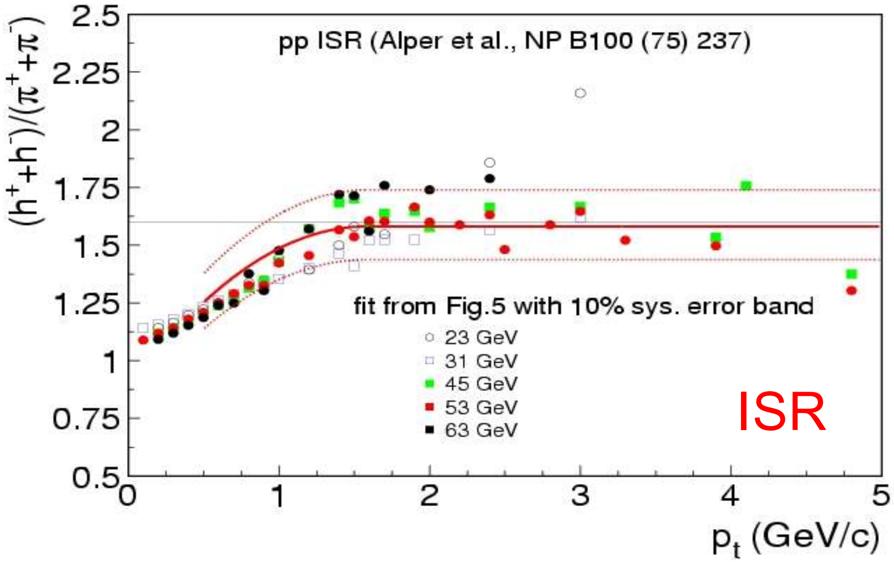
Enhanced (anti)proton/pion ratio

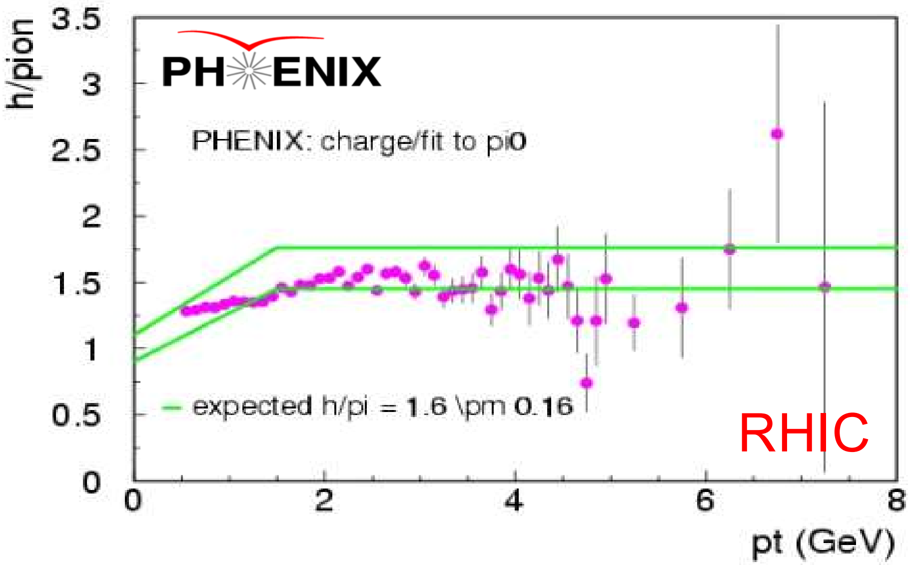
- Central Au+Au: $p/\pi \sim 0.8$ (at p_T = 2 - 4 GeV/c) at variance with perturbative production mechanisms (favour lightest mesons).
- Periph. Au+Au: $p/\pi \sim 0.2$ as found in p+p (ISR,FNAL) & e+e- jet fragmentation



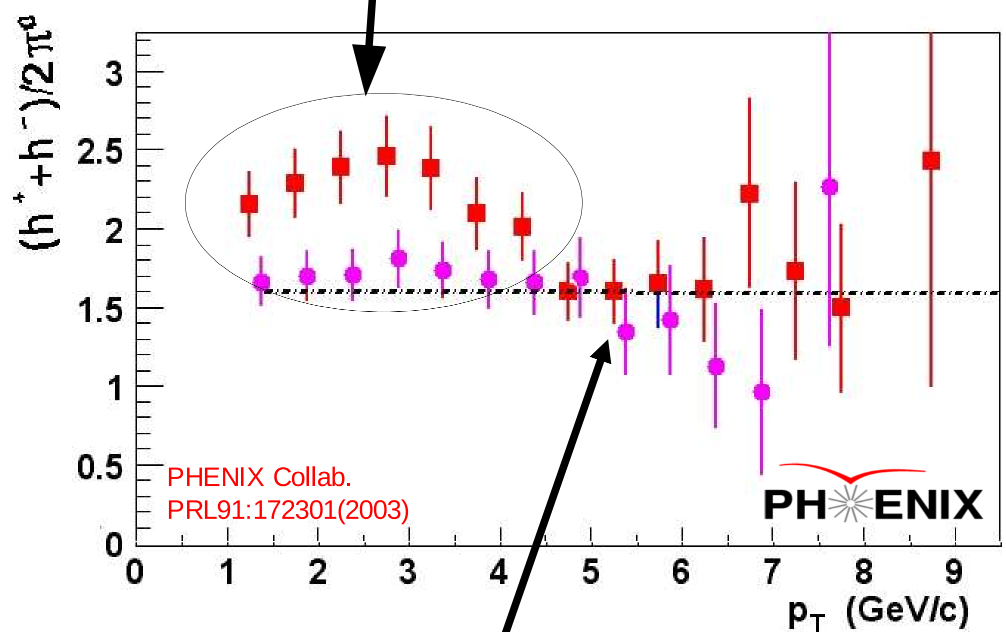
“Anomalous” particle composition: hadron/meson ratio

- 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).

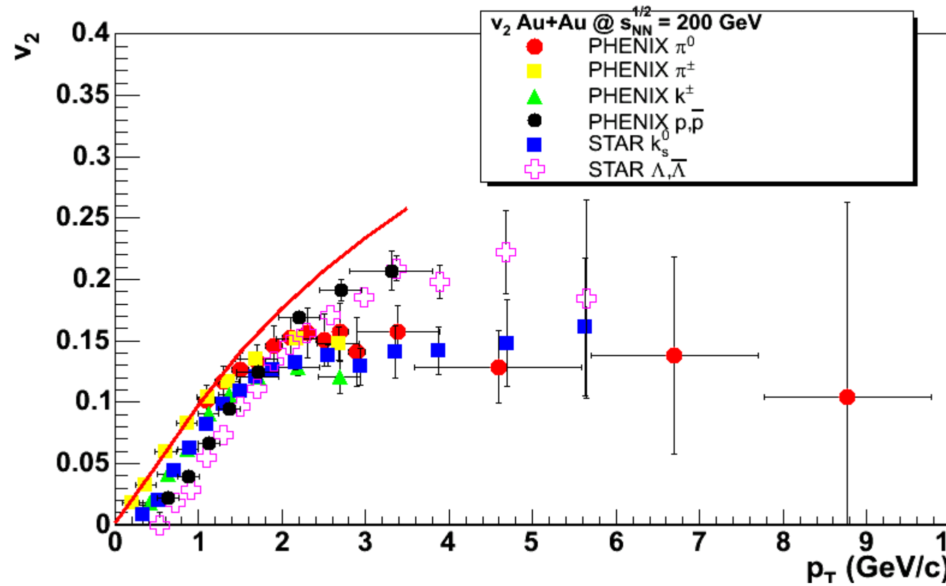


- Baryon enhancement limited to p_T < 5 GeV/c ($h^\pm/\pi$ ~ 1.6, perturb. ratio): $h^\pm$, π^0 equally suppressed

Enhanced baryonic elliptic flow

- Particle species
  hierarchy of flow values:

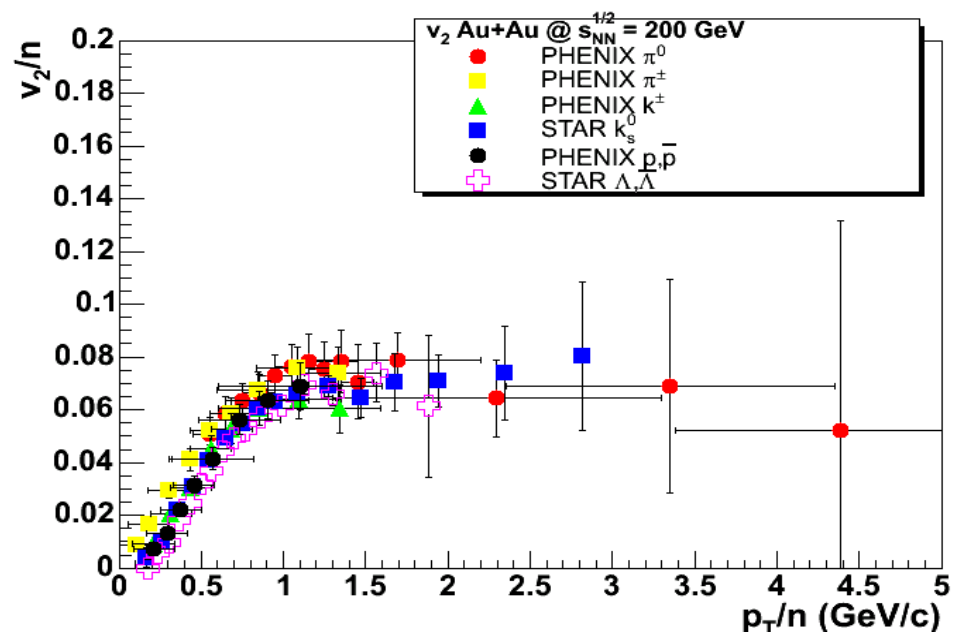
  $v_2^{meson} > v_2^{baryon}$ at low p_T
  $v_2^{meson} \approx v_2^{baryon}$ at $p_T \approx$ 2 GeV/c
  $v_2^{meson} < v_2^{baryon}$ at higher p_T



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

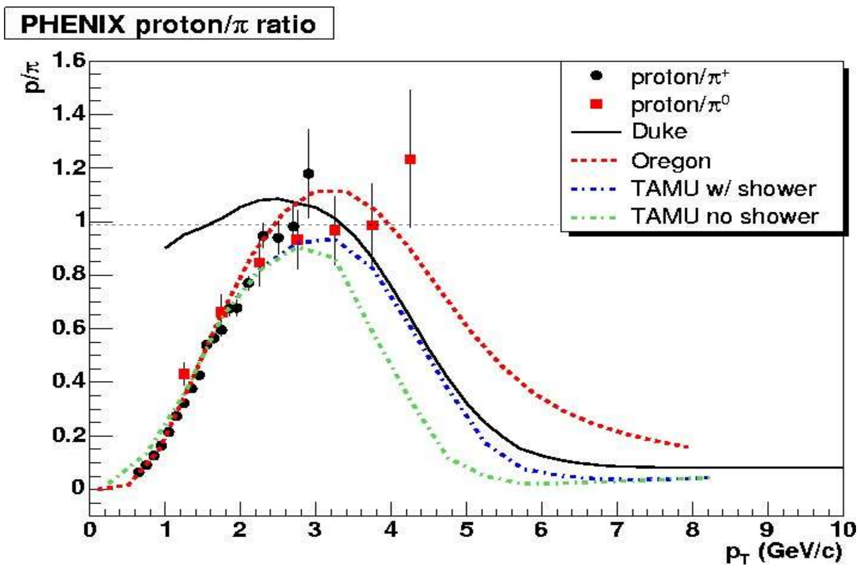
  n = 2 mesons
  n = 3 baryons

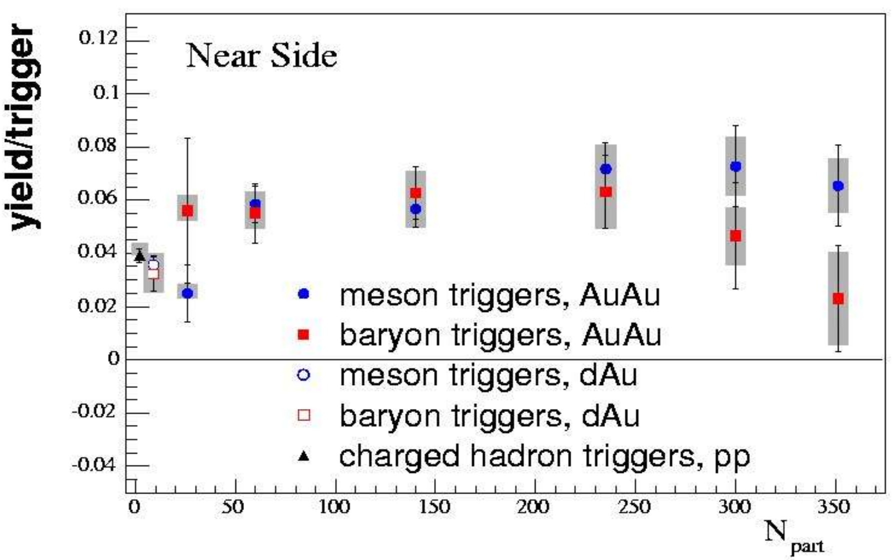
  ("universal" parent quark flow ?)



"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 ... Near-side azimuthal correlations of high p_T trigger (leading) baryons is jet-like:
- No pure thermal + thermal parton recombination produces such jet-like correlations ... (thermal+hard ?)

Summary

1. Energy densities:

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

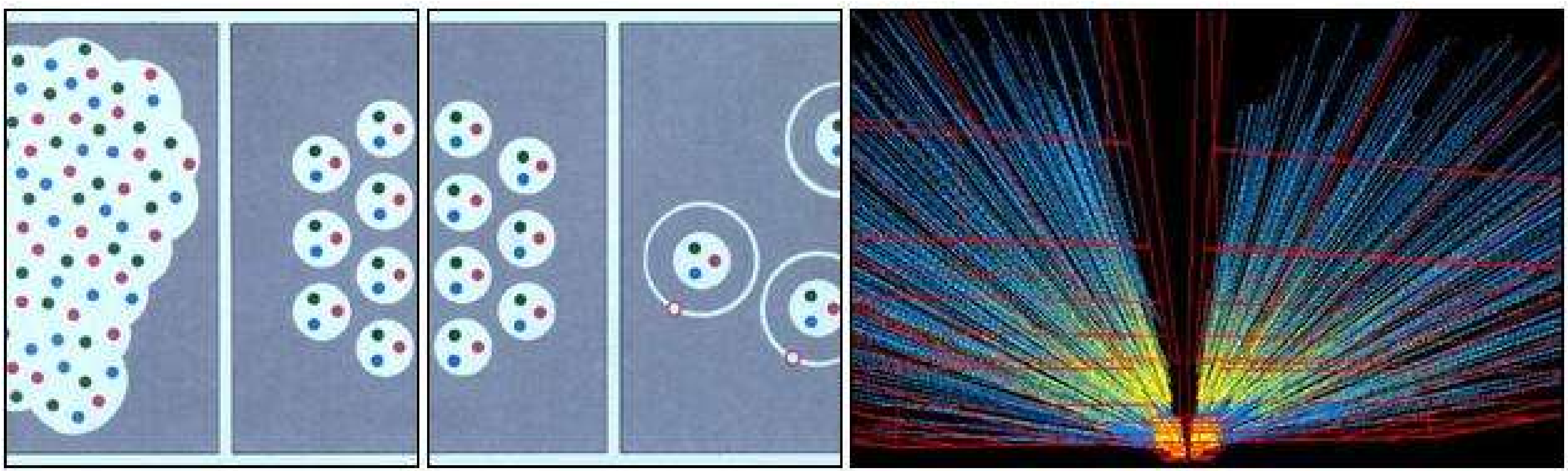
- Enhanced baryon yields & v_2 (compared to meson) consistent w/ quark recombination mechanisms in a thermal and dense system

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

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

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 $dE_T/d\eta$ ~ 600 GeV at midrapidity consistent w/ initial $\varepsilon > 5$ GeV/fm$^3 > \varepsilon_{crit}$
   - **Seen at SPS ? Yes.** $\varepsilon > 2.9$ 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 τ_0 ~ 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
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   - 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
   - **Seen at SPS ? Probably.** Suppression (not that strong) w.r.t. peripheral.
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We need a few additional observables to claim "QGP" at RHIC ...
thermal photons (temperature of system), J/Ψ (deconfined system)

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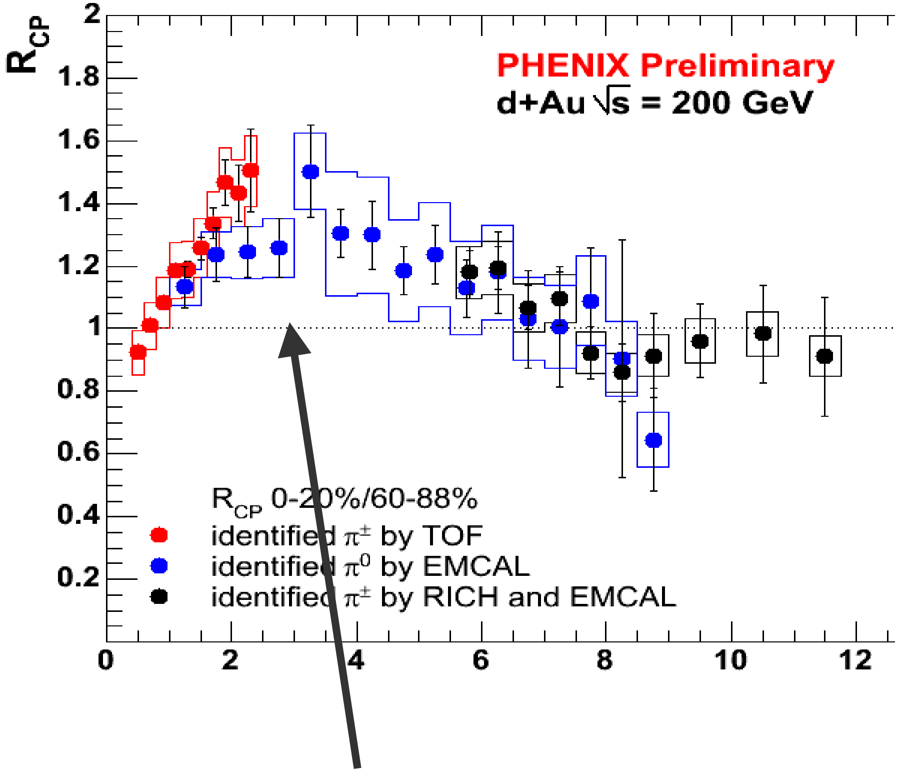
Stay tuned !

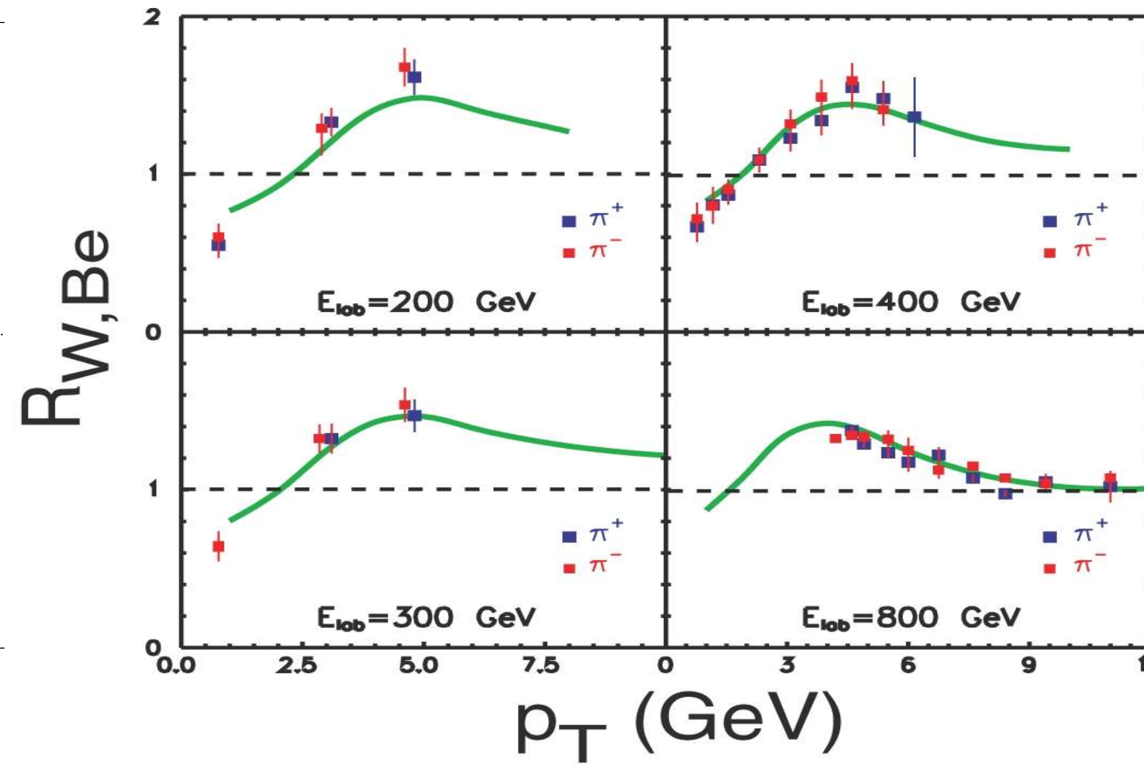
backup slides ...

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

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



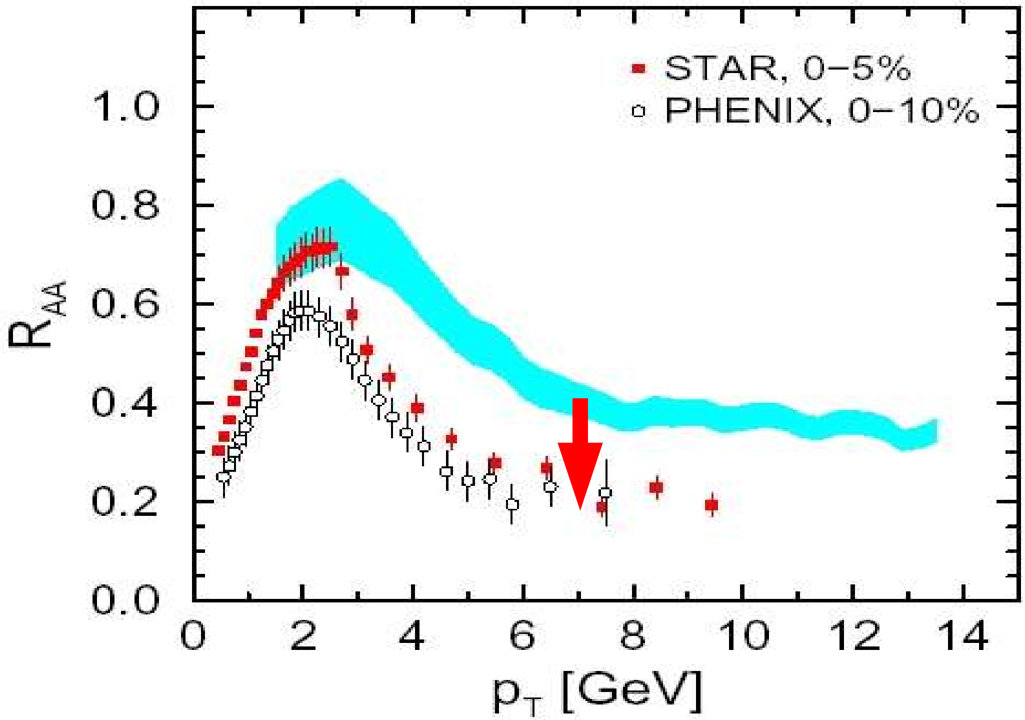
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



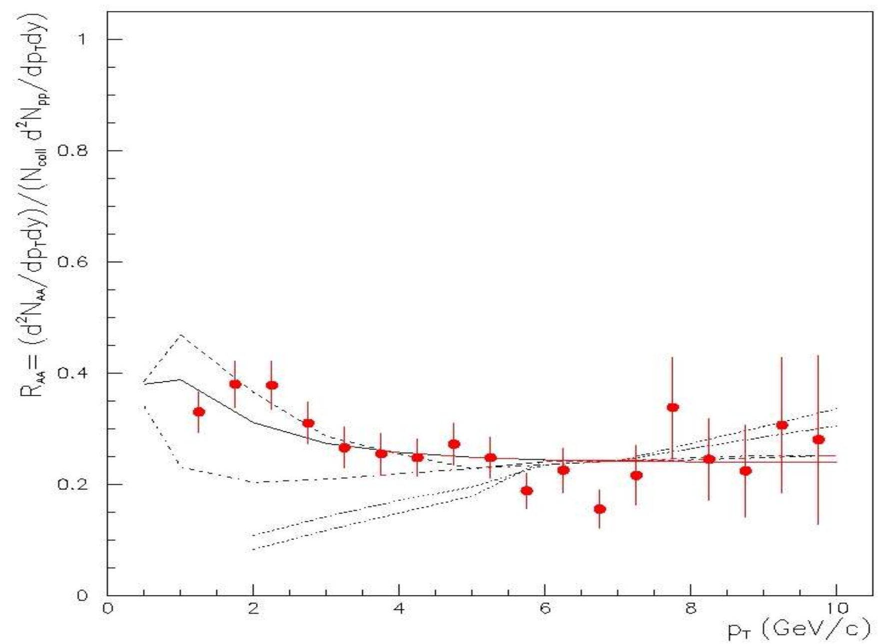
- Enhanced high p_T production in d+Au (R_{dAu} > 1) also found in p+A at lower √s ("Cronin enhancement"): p_T broadening due to initial-state soft & semihard scattering.
- Expected pQCD behaviour ($R_{pA,dA}$~1) recovered for p_T > 8 GeV/c

Energy loss in a dense hadronic medium ?

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



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



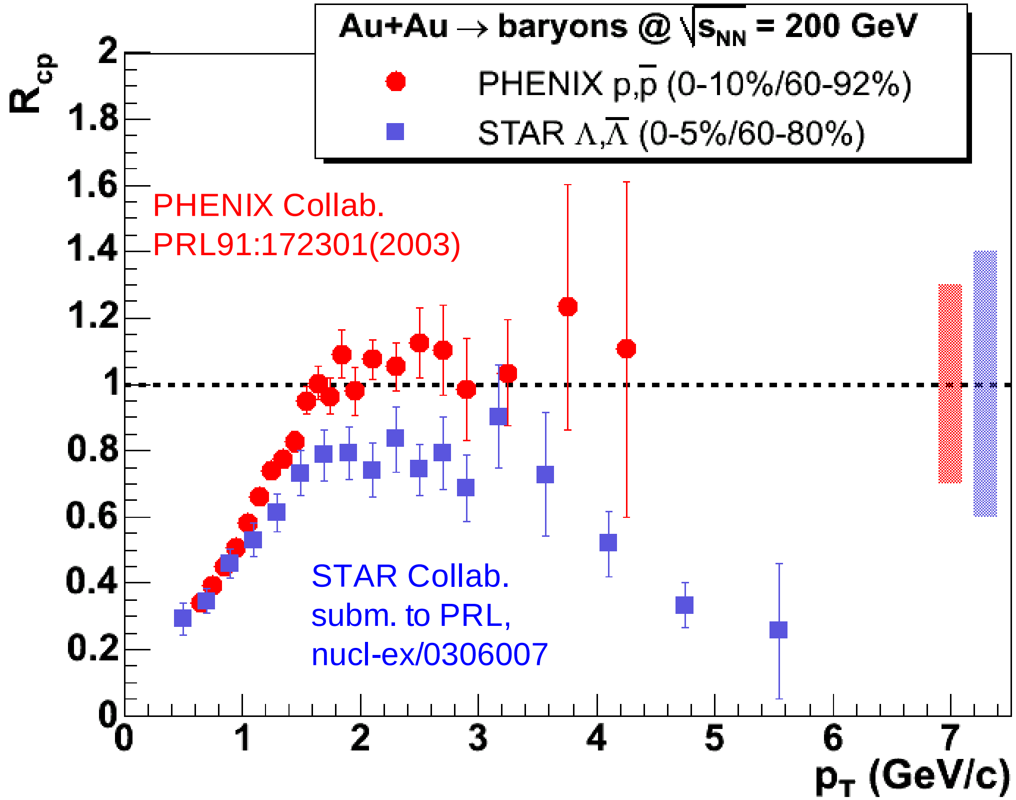
Capella, Ferreiro, Kaidalov, Sousa hep-ph/0403081

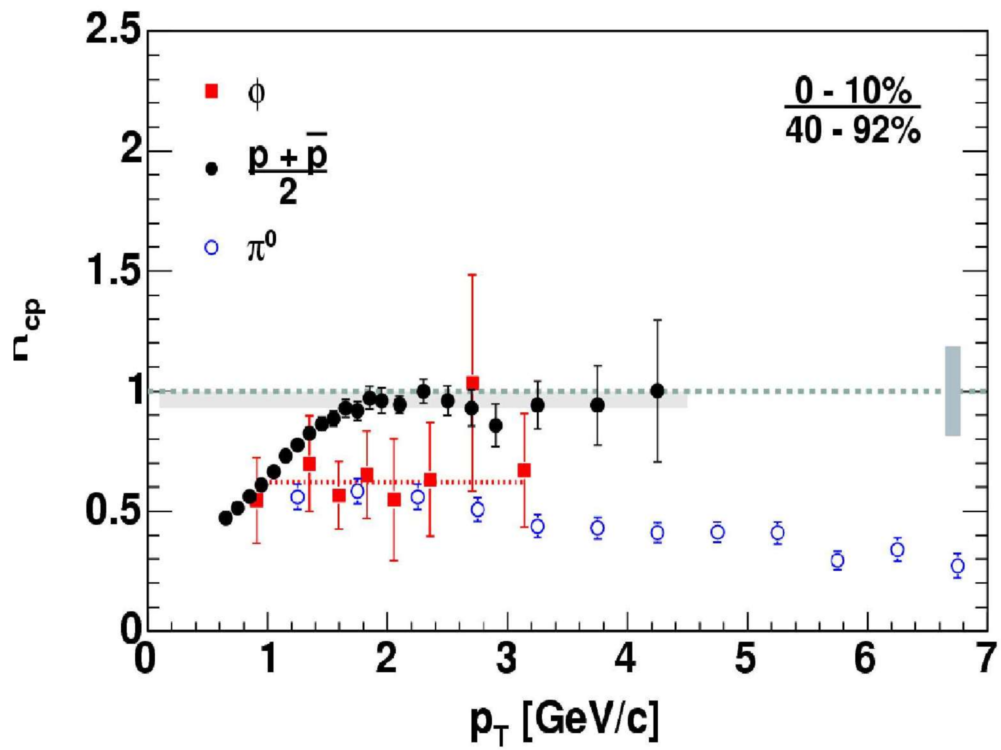
Unsuppressed baryon production: not a mass effect !

- 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)





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