Status of the Quark Gluon Plasma (QGP) search at RHIC

- A PHENIX perspective (*) -

7th Workshop on Percolation,
Heavy-Ion Collisions & Cosmic Rays
IST, Lisbon, April 15th, 2005

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(*) Based upon "PHENIX White Paper": to appear in Nucl. Phys. A, nucl-ex/041003

Overview/Summary

Introduction:

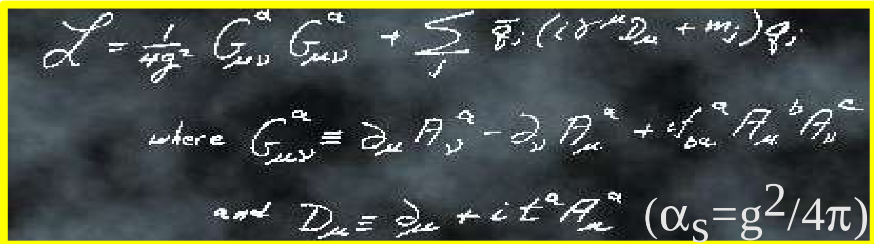
- Goal of high-energy A+A collisions ?
  Study/characterize Quantum Chromo (many-body) Dynamics
  (By comparing A+A to: p+A = "cold QCD medium", p+p = "QCD vacuum" colls.)

Head-on Au+Au collisions @ RHIC energies ($\sqrt{s}$=200 GeV) produce a strongly interacting system:

- with the highest energy densities ever achieved at the lab: $\varepsilon > 5$ GeV/fm^3
- with a strong degree of collectivity at very short time-scales: $\tau_0 < 1$ fm/c
- that behaves like an nearly ideal (hydrodynamical) fluid: dN/dp_T (p_T<2 GeV/c)
- that reaches chemical equilibrium at (or before) hadronization: $T_{chem} \sim T_{crit}$
- with the largest initial gluon densities ever measured: $dN^g/dy \sim 1000$
- with degrees of freedom consistent with constituent quarks

Summary & open questions

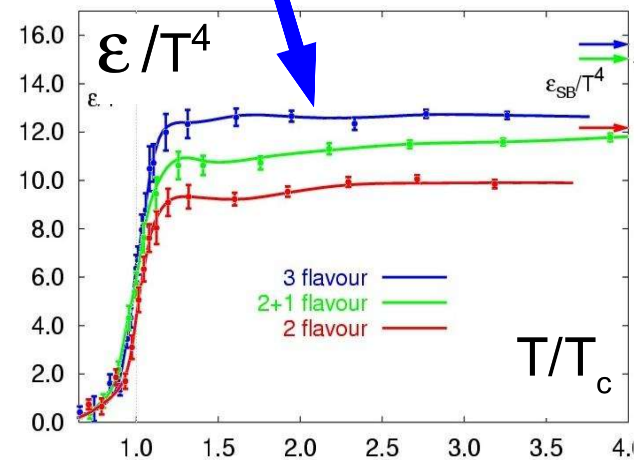
High-energy heavy-ion physics program (in 4 plots)

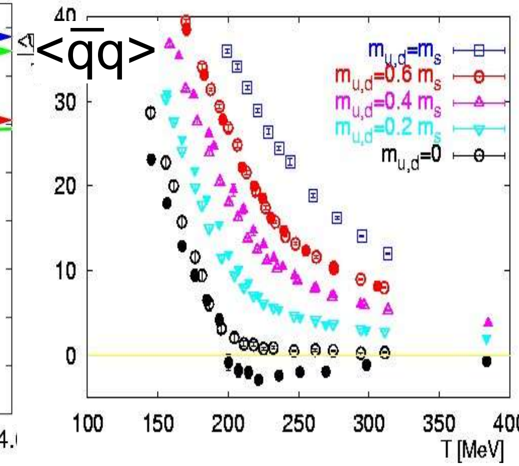


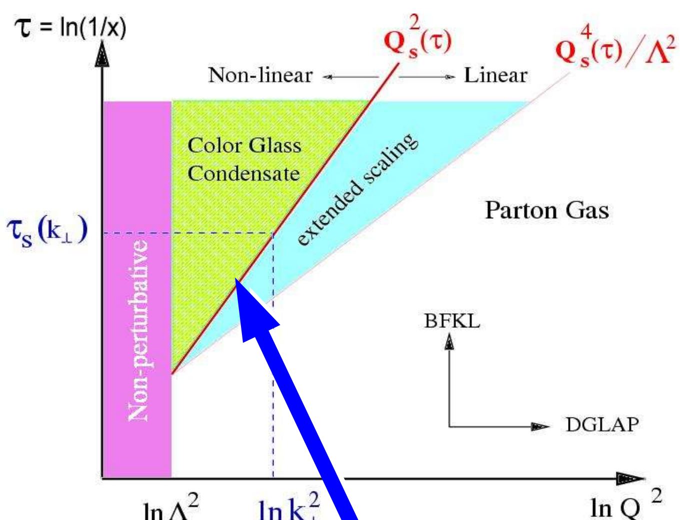
$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

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

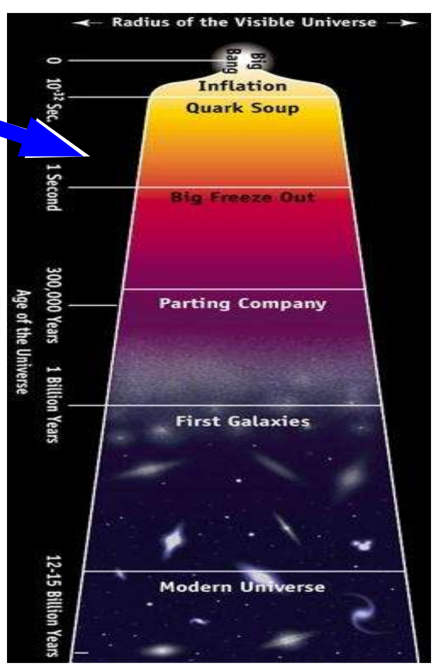
2. Study the phase diagram of QCD matter: esp. produce & study the QGP





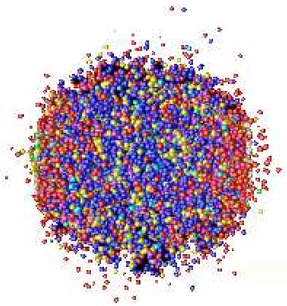


3. Probe quark-hadron phase transition of the primordial Universe (few μsec after the Big Bang)

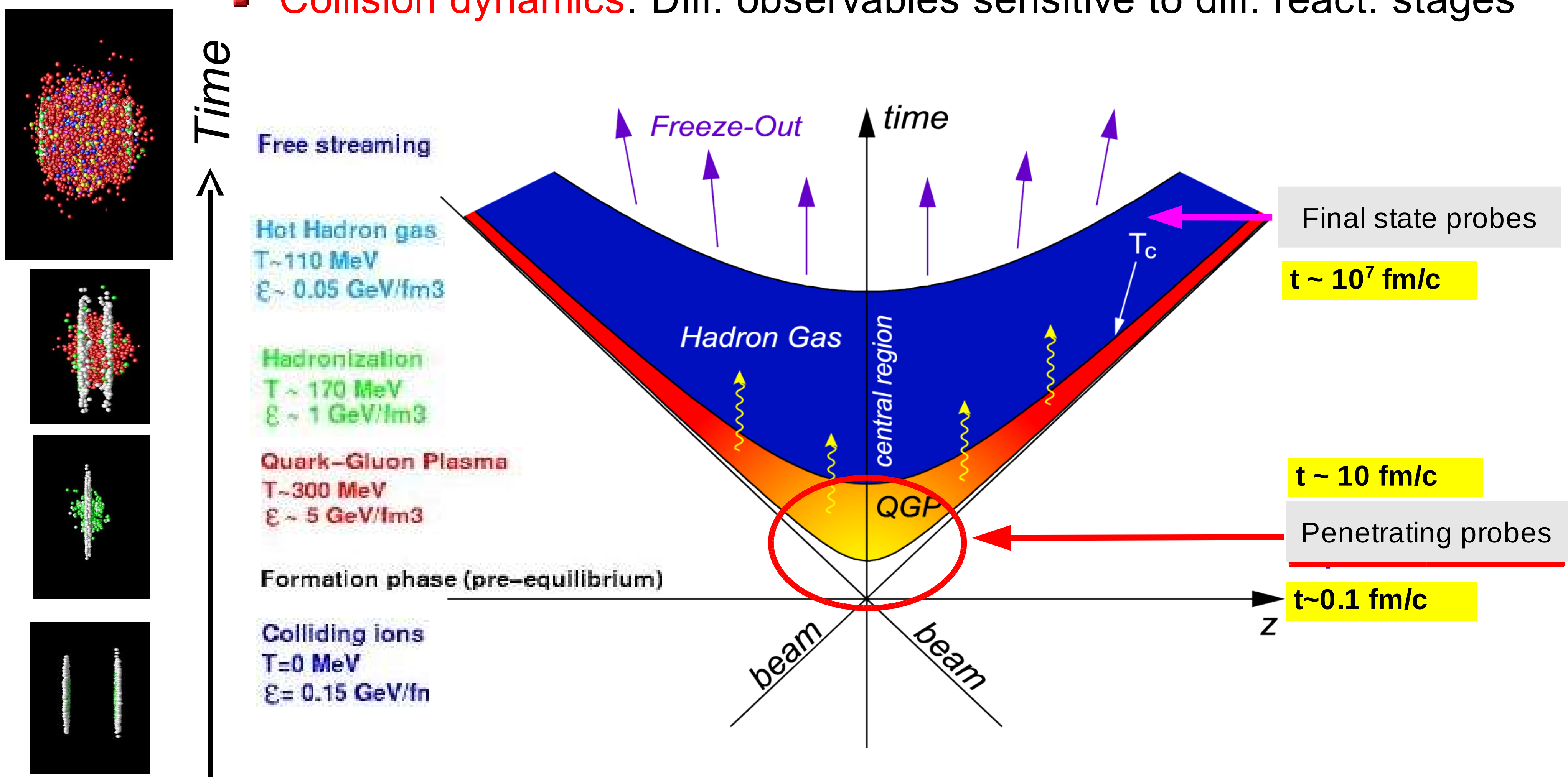


4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

The "Little Bang" in the lab.



- High-energy nucleus-nucleus collisions: fixed-target reactions ($\sqrt{s}$=20 GeV, SPS) or colliders ($\sqrt{s}$=200 GeV, RHIC. $\sqrt{s}$=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

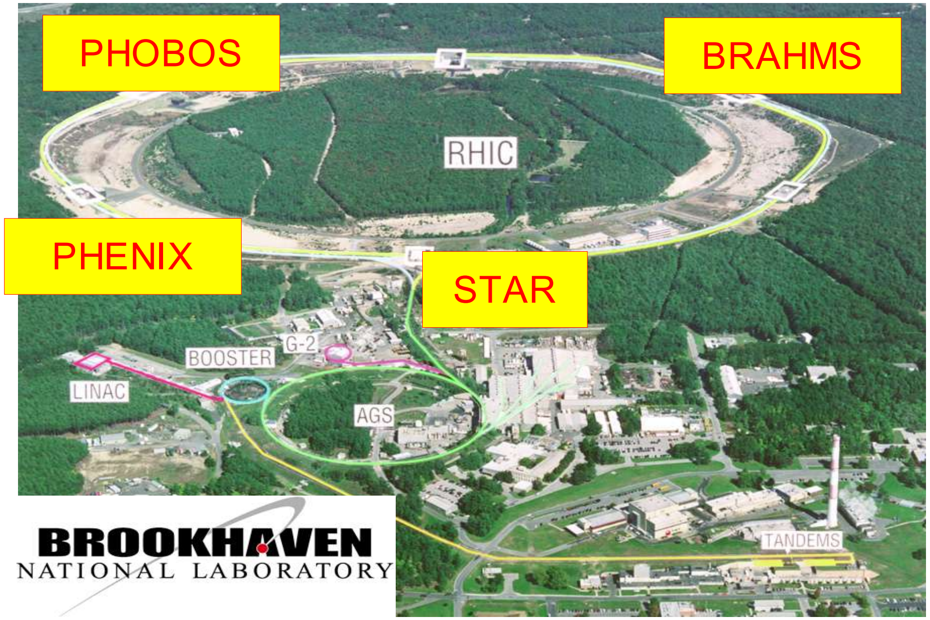
p+A collisions @ $\sqrt{s}_{max}$ = 200 GeV

4 experiments:

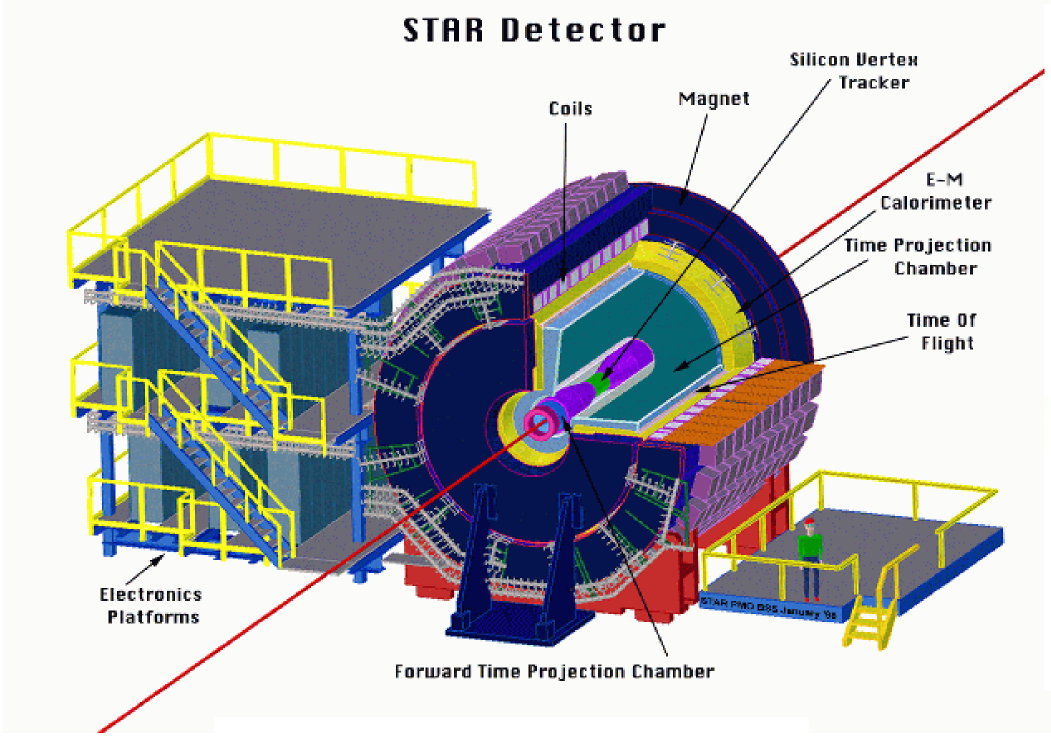
BRAHMS, PHENIX, PHOBOS, STAR

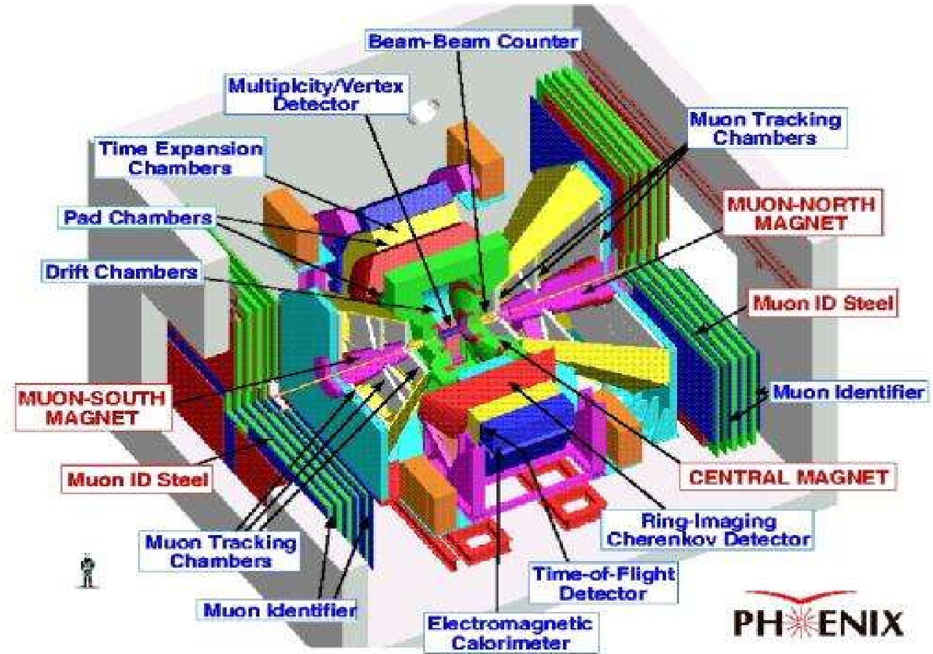
Runs 1 - 5 (2000 – 2005):

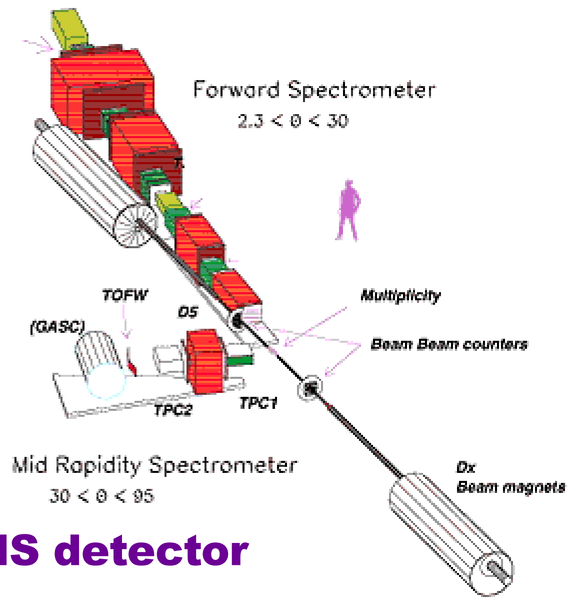
Au+Au @ 200, 130, 62.4 GeV
p+p @ 200 GeV
d+Au @ 200 GeV
Cu+Cu @ 200, 62.4 GeV



The 4 RHIC experiments

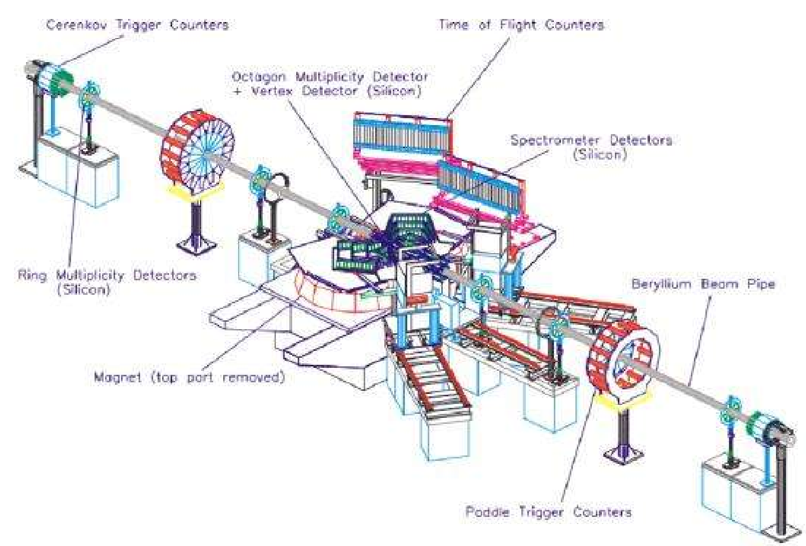




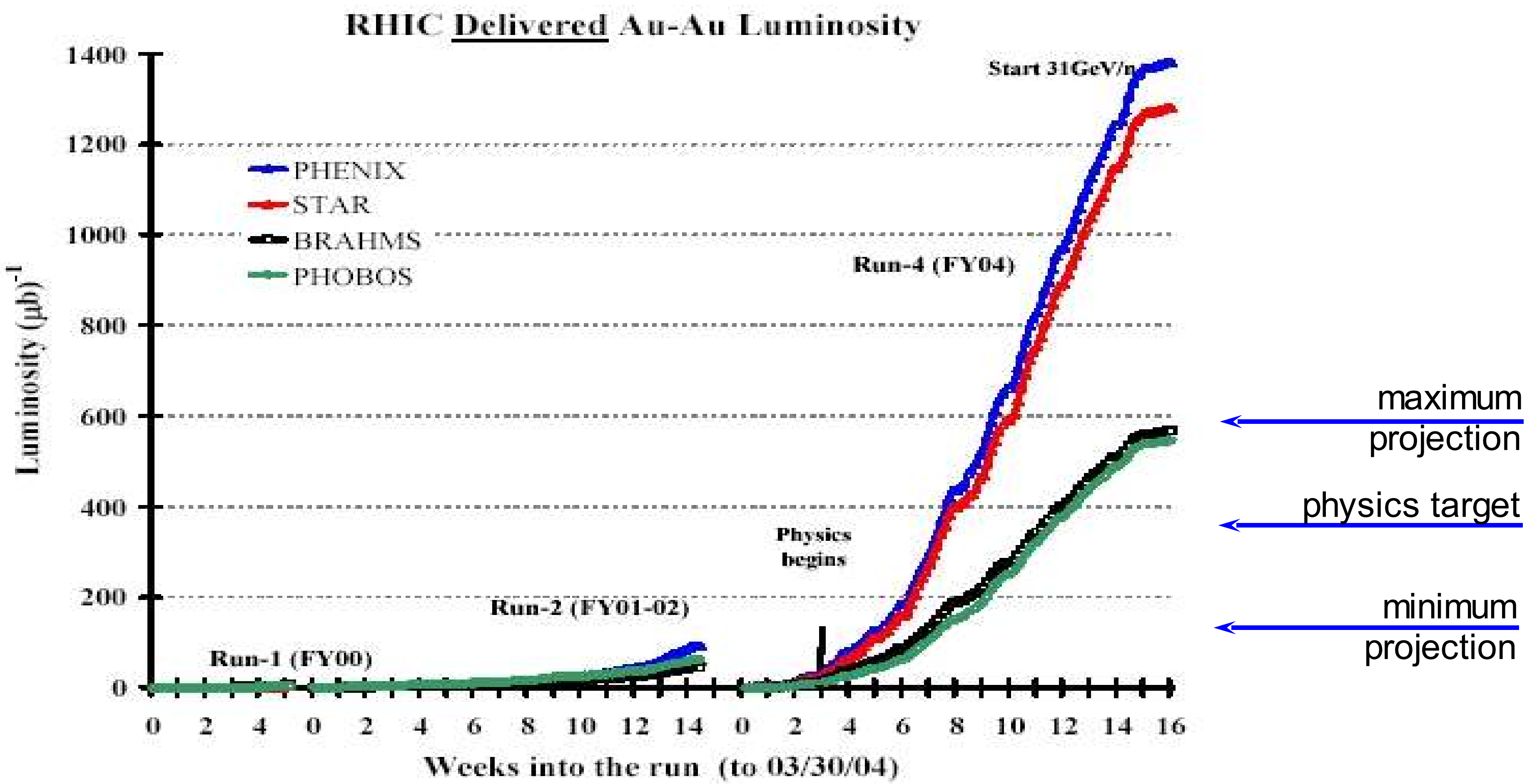


BRAHMS detector

PHOBOS Detector



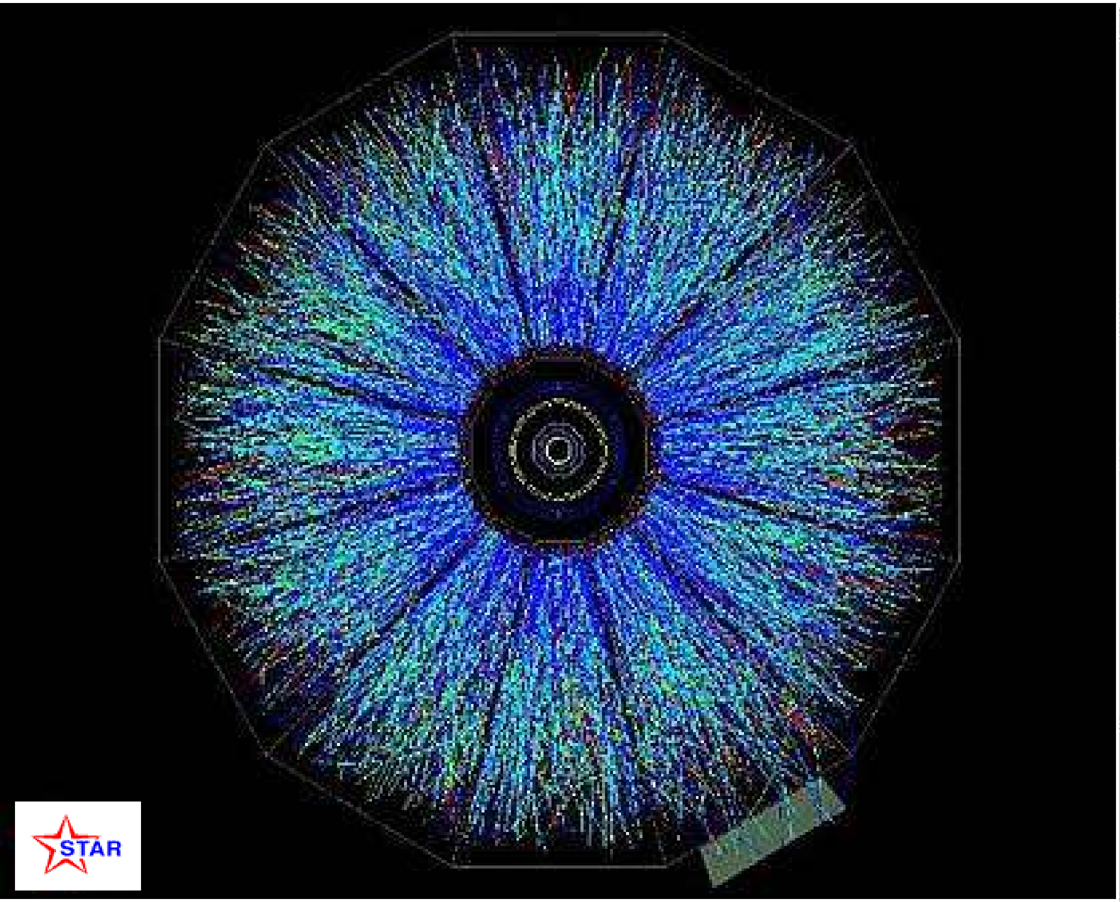
RHIC Au+Au luminosities

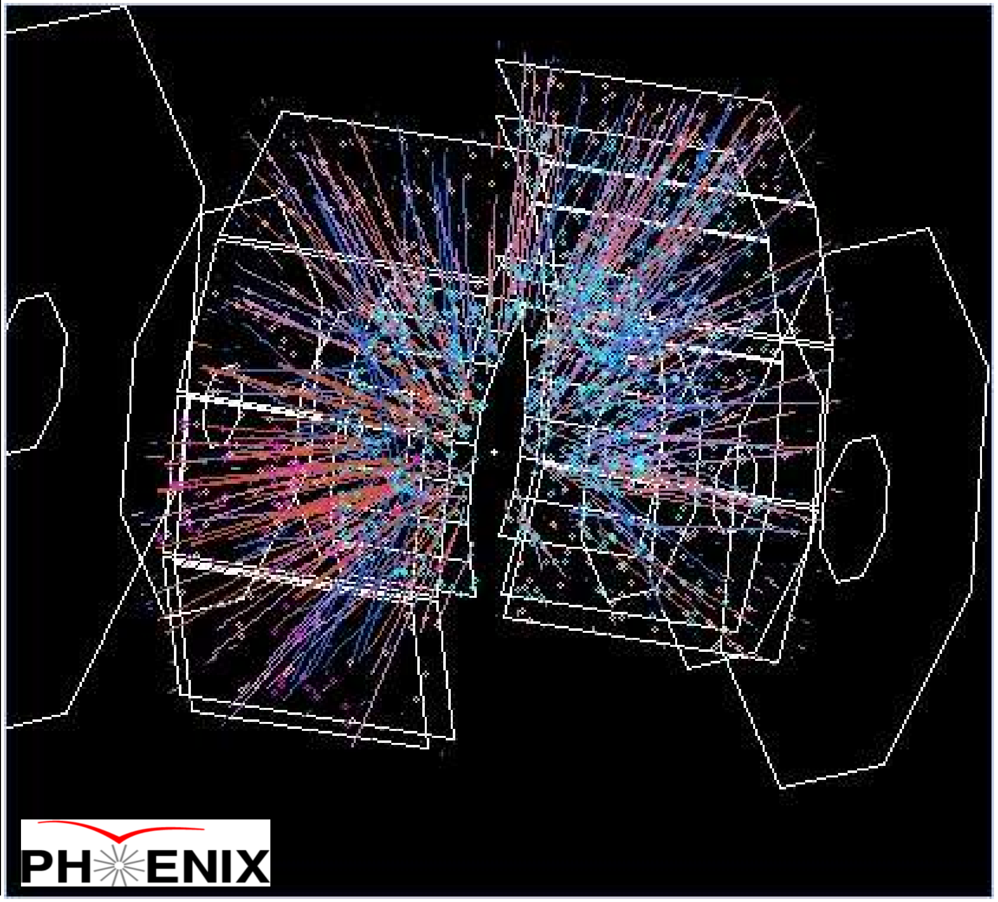


- RHIC (Au+Au) is currently running at ~2x design luminosity

	max energy [GeV/u]	no of bunches	ions/bunch [10^9]	β^* [m]	emittance [mm mrad]	$\mathcal{L}_{peak}$	$\mathcal{L}_{store,ave}$ [10^{26}cm^{-2}s^{-1}]	L_{week} [μb^{-1}]
Run-1 (FY2000)	65	55	0.3	3	15-40	0.3	0.2	4
Run-2 (FY2001/2002)	100	55	0.5	1	15-40	3.7	1.5	24
Run-4 (FY2004)	100	45	1.1	1	15-40	15	4	160
Design	100	55	1.0	2	15-40	9	2	50
Enhanced design	100	112	1.0	1	15-40	30	8	300

Au+Au collisions @ 200 GeV





~ 700 charged particles per unit rapidity at midrapidity (top 5% central)

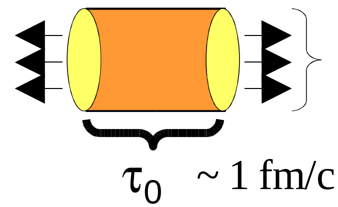
(1) Energy densities at RHIC

- The highest energy densities ever achieved at the lab: $\varepsilon > 5$ GeV/fm^3

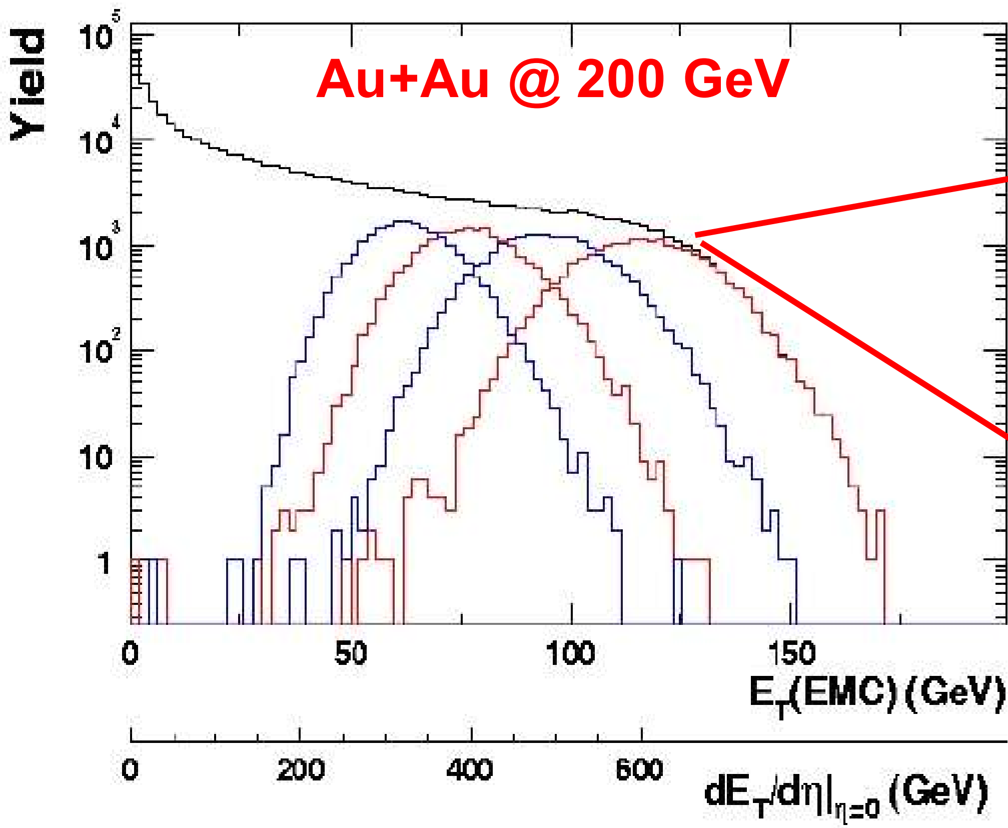
Energy density (Au+Au @ 200 GeV, y=0)

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



$\langle dE_T/d\eta \rangle$ ~ 650 GeV (top 5% central)

(~70% larger than at CERN-SPS)

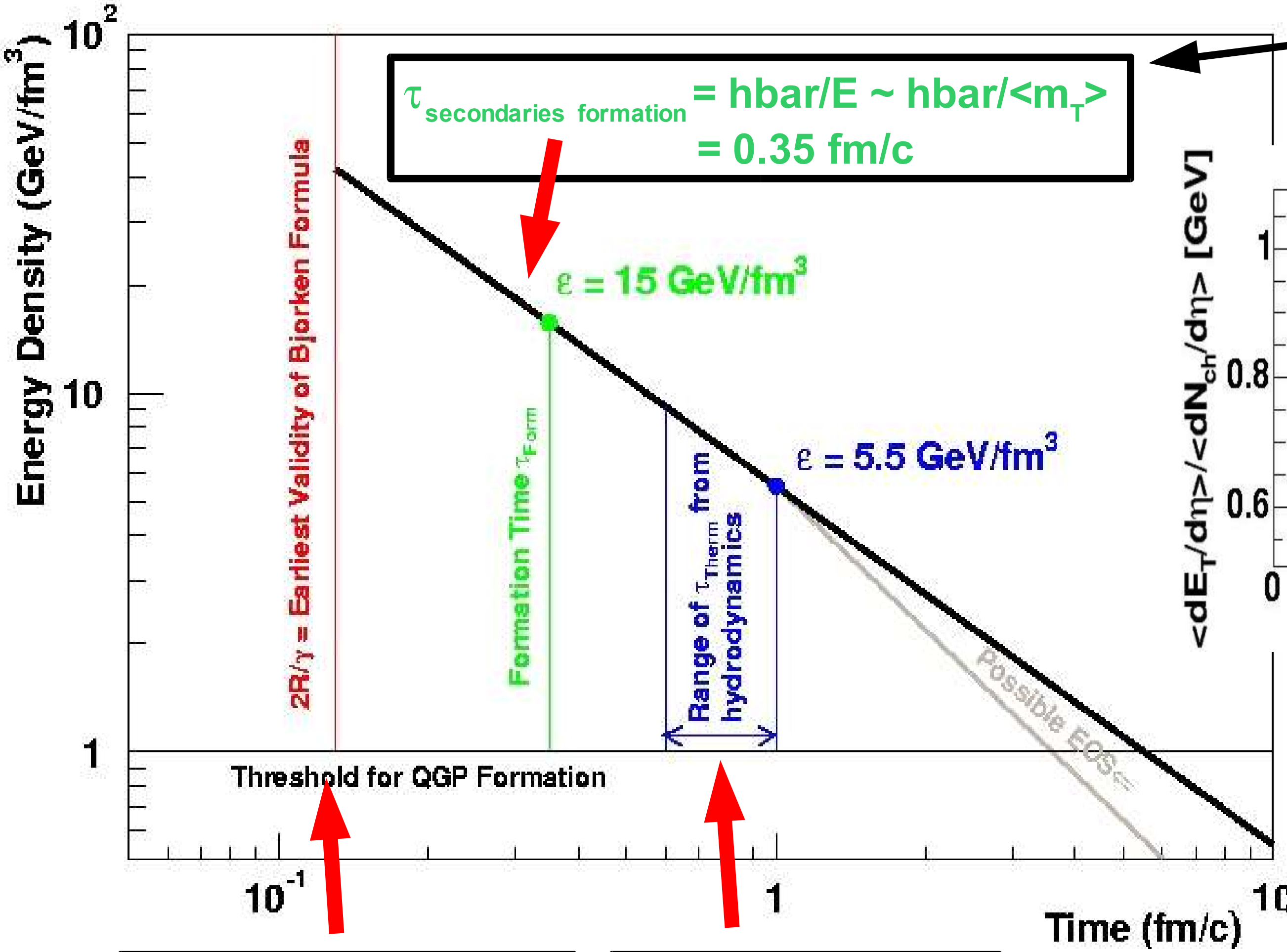
$\varepsilon_{Bjorken}$ ~5.0 GeV/fm^3

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

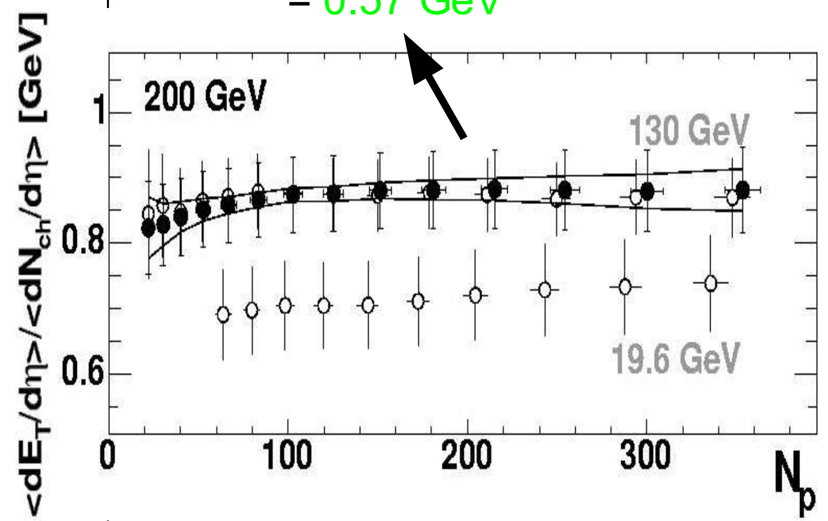
PHENIX Collab.
PRL 87, 052301 (2001)
nucl-ex/0104015

1 fm/c thermalization time ?

- Not unrealistic at RHIC... (for the 1st time: $\tau_{therm} > \tau_{cross} = 2R/\gamma \sim 0.15$ fm/c)
- Time evolution of energy density in longitud. expanding system: $\varepsilon \sim 1/\tau$



$<m_T> = (dE_T/d\eta)/(dN/d\eta) \sim$
$(dE_T/d\eta)/(3/2^*dN_{ch}/d\eta)$
$= 0.57$ GeV



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To appear in NPA
nucl-ex/041003

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

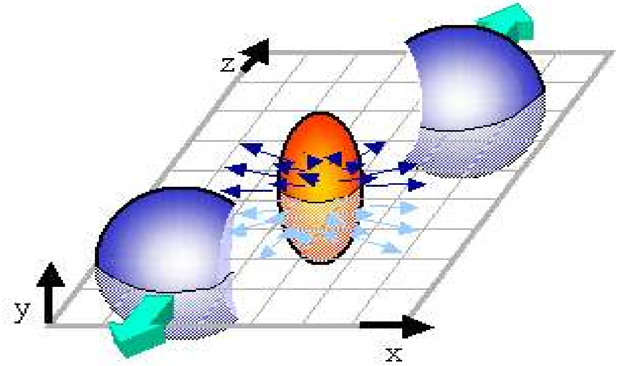
$\tau_{therm} \sim 0.6 - 1$ fm/c (from elliptic flow & hydrodynamics, see next)

(2) Elliptic flow at RHIC

- Strong degree of collectivity at very short time-scales: $\tau_0 < 1$ fm/c

Elliptic flow

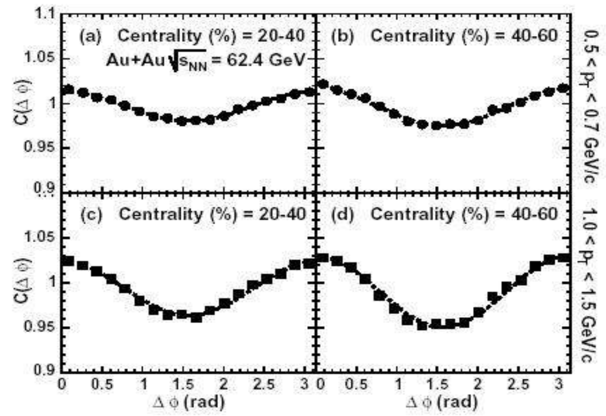
- Initial anisotropy in x-space in non-central collisions (overlap) translates into final azimuthal asymmetry in p-space (transverse to react. plane)



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

Elliptic flow = v_2

2^{nd} Fourier coefficient of dN/dϕ



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PRL 89, 212301 (02)
nucl-ex/0204005

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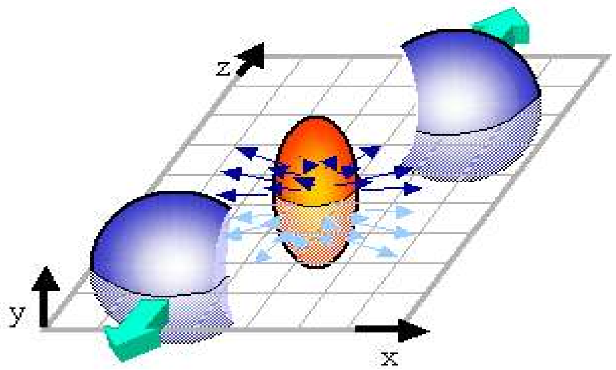

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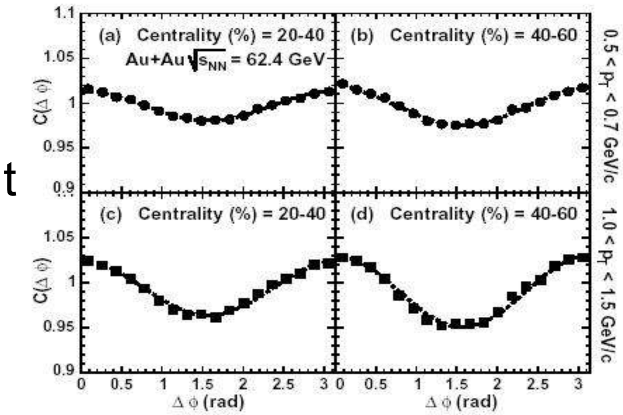

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PRL 89, 212301 (02)
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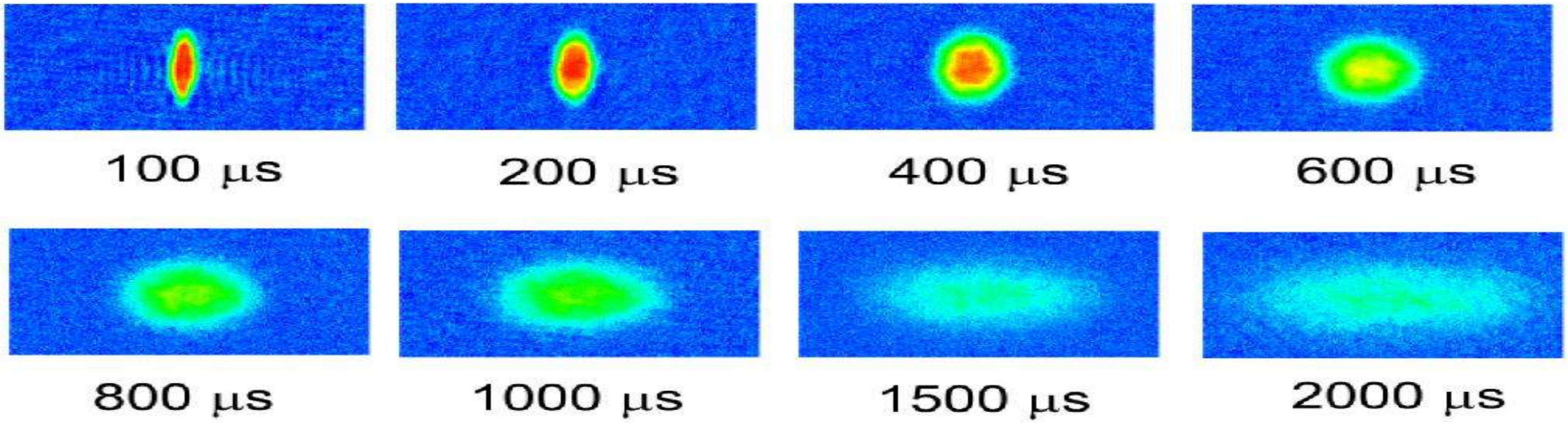
"Elliptic flow" in low -T (strongly coupled) Li atoms:



K.M.O'Hara, Sci. 289, 2179 (2002)
T. Bourdel et al. PRL 91, 020402 (2003)

Elliptic flow

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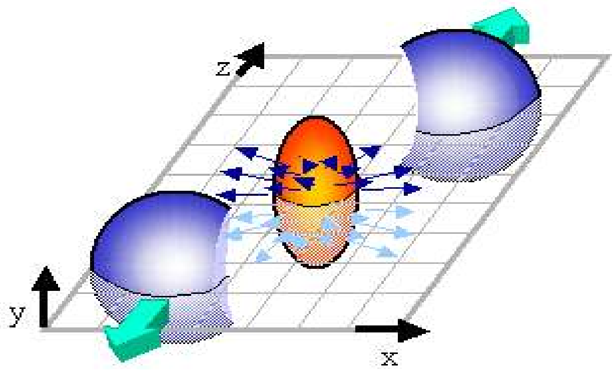

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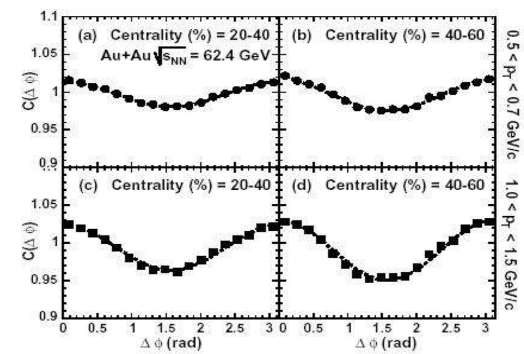
Elliptic flow = v_2

2^{nd} Fourier coefficient of $dN/d\phi$

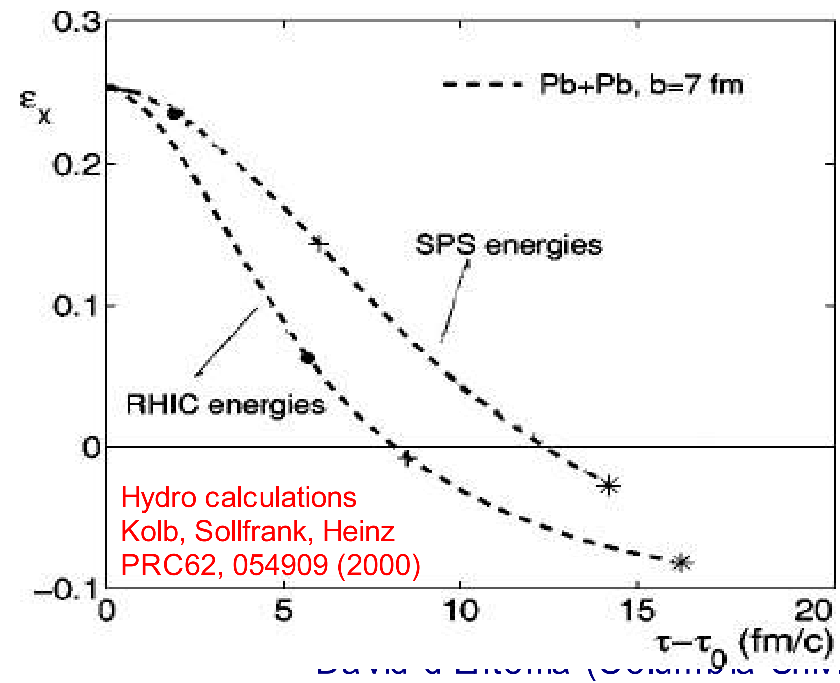


1. Truly collective effect (absent in p+p collisions).

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

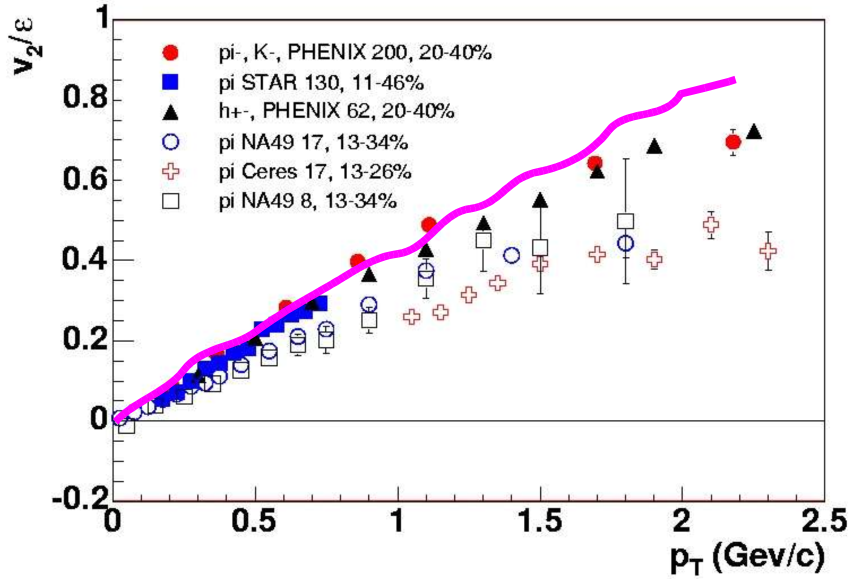
Time evolution of ellipsoid eccentricity:

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

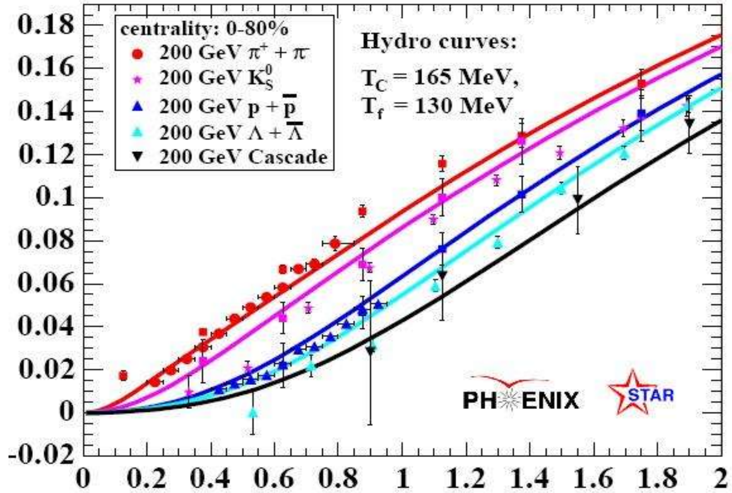


Elliptic flow at RHIC

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



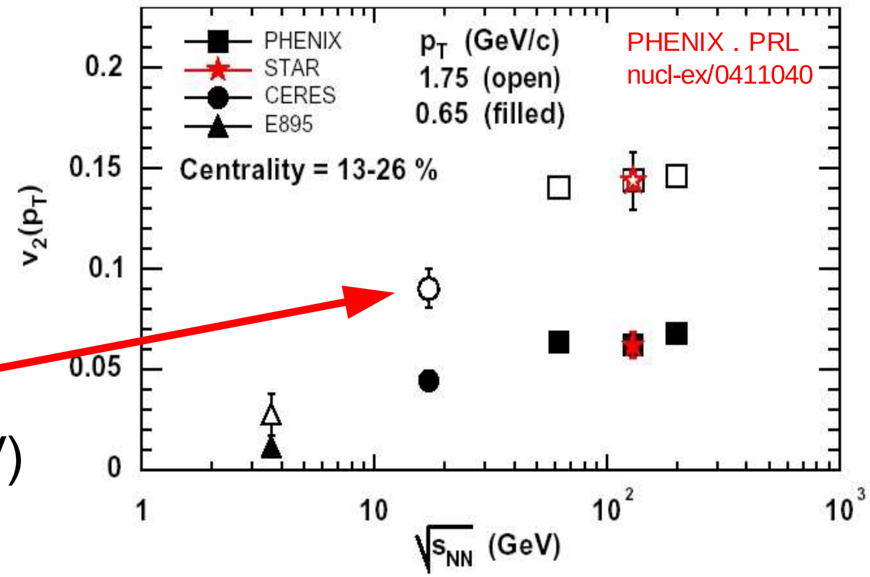
- Mass dependence of v_2 consistent w/ hydrodynamics too:



PHENIX . PRL 91, 181301 (2003) nucl-ex/0305036

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

- √s-dependence of v_2: ~50% increase from CERN-SPS (apparent saturation within 62-200 GeV)

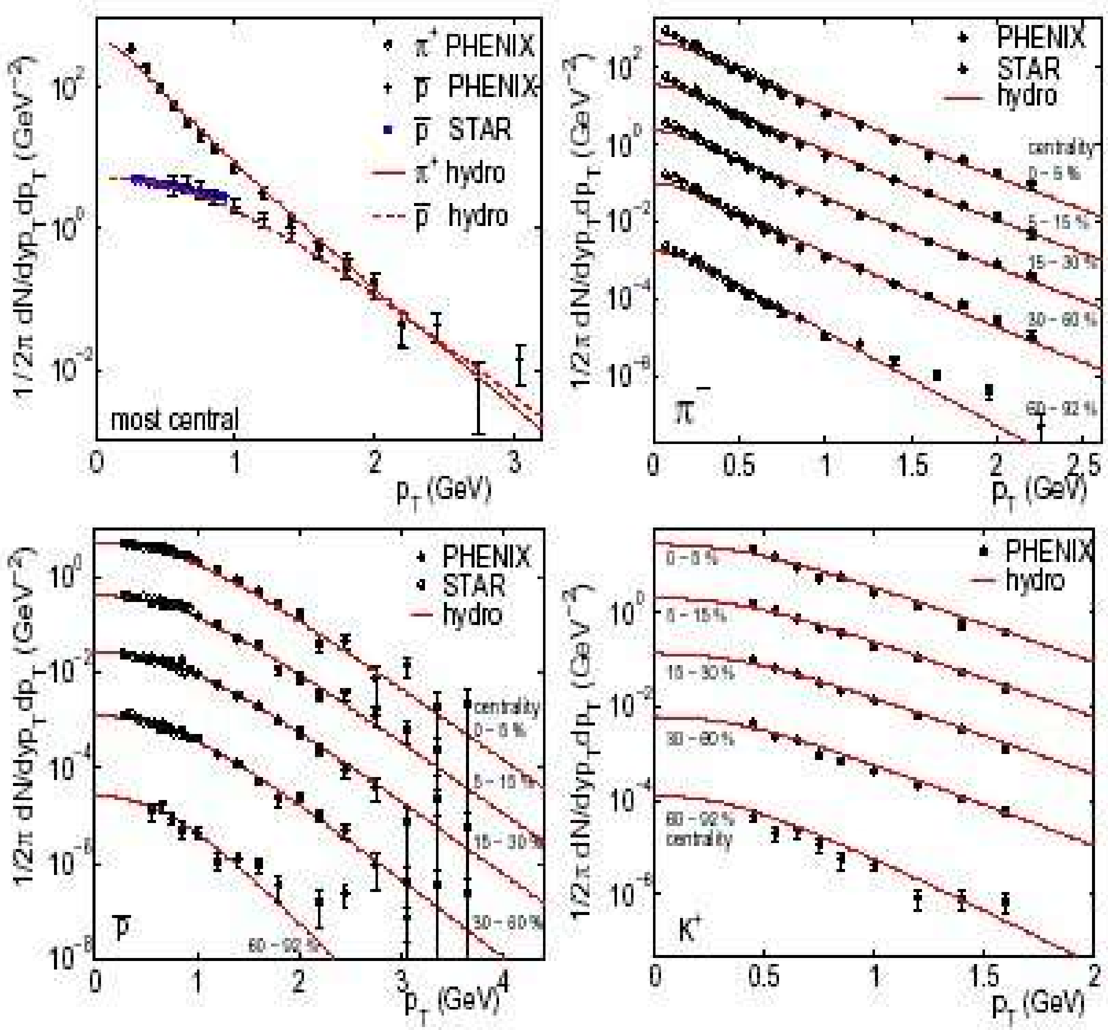


(3) Soft particle production at RHIC

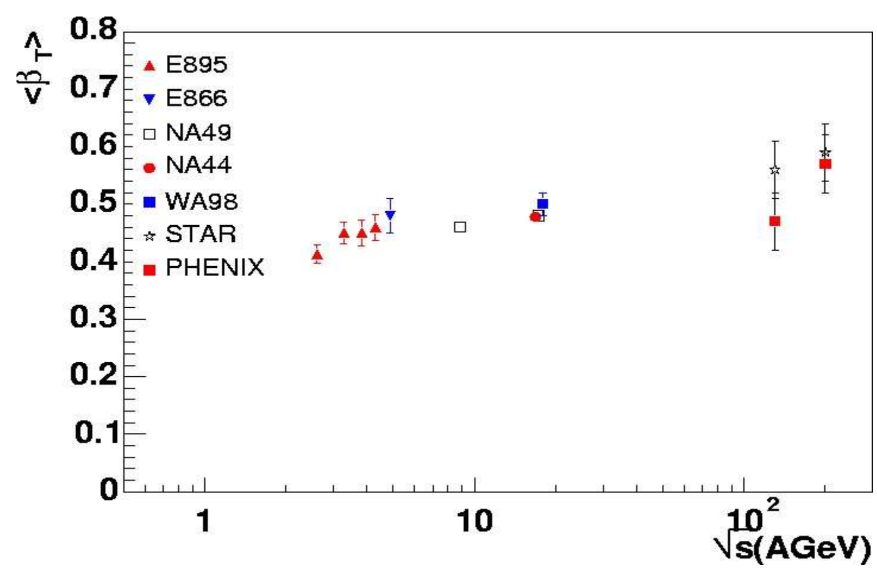
- A system that behaves like an nearly ideal (hydrodynamical) fluid and reaches chemical equilibrium at (or before) hadronization: $T_{chem} \sim T_{crit}$

Soft particle spectra

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



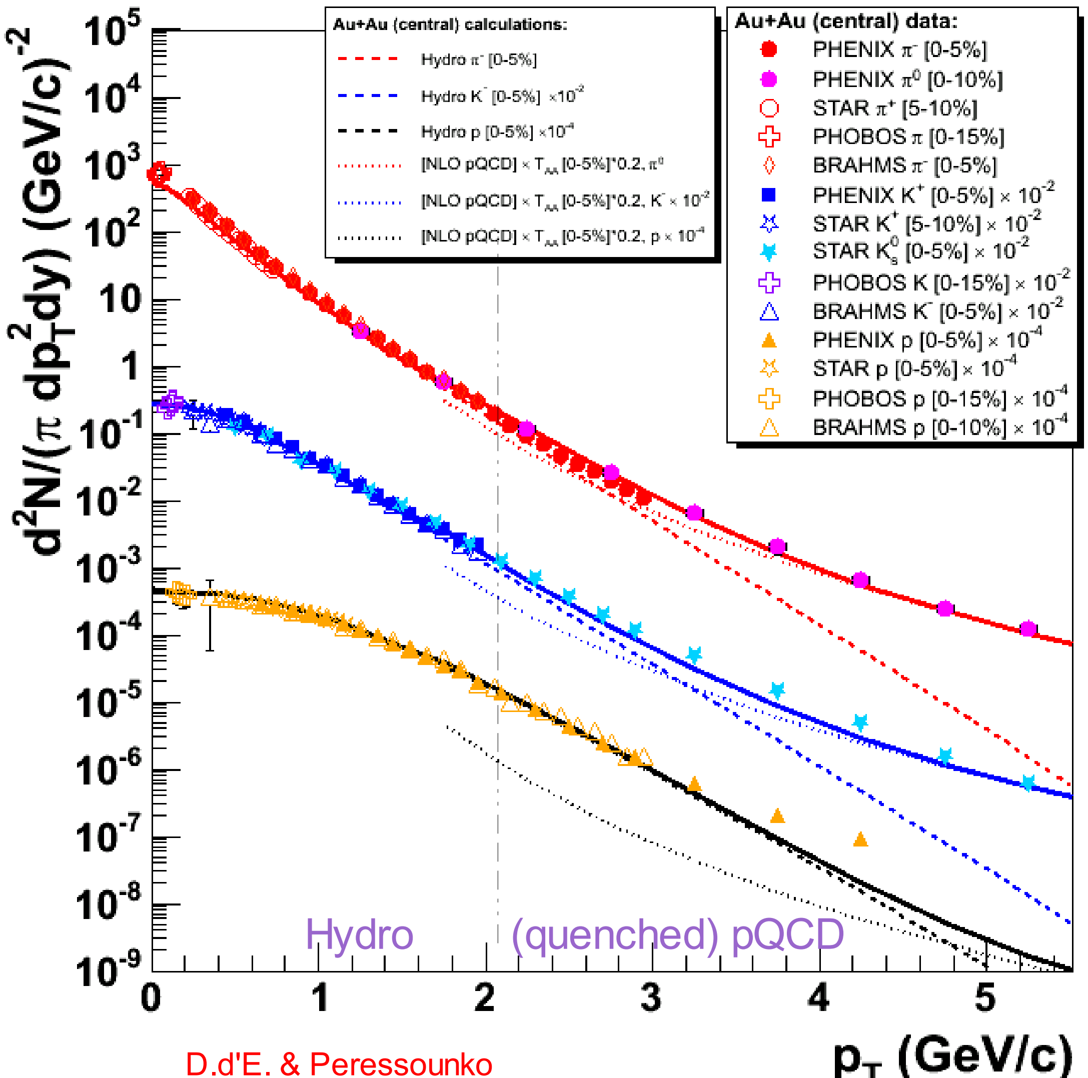
Strong radial collective flow built-up at freeze-out: $\langle\beta_T\rangle \approx 0.6$



Soft particle spectra

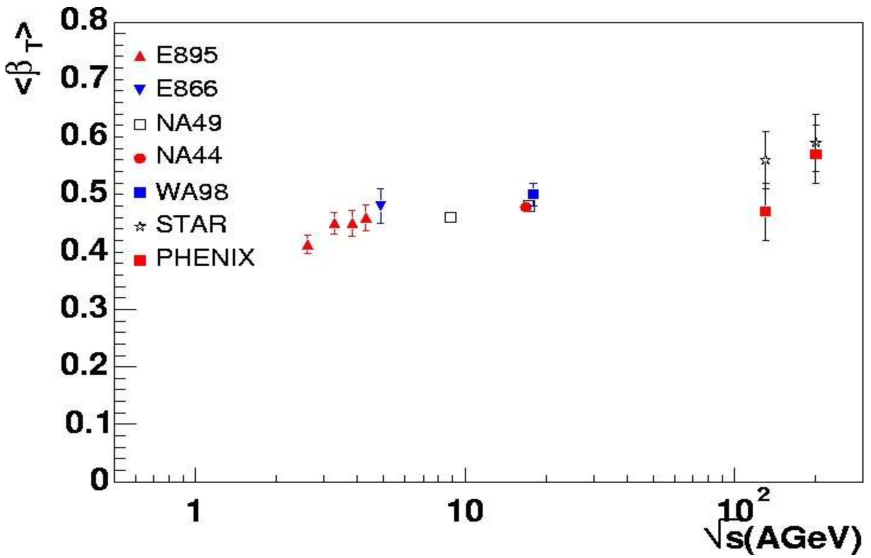
- Bulk $\pi^{\pm}$, $K^{\pm}$, p(pbar) spectra reproduced by hydro w/ QGP EOS at τ_0= 0.6 fm/c

Au+Au central (b = 2.6 fm)



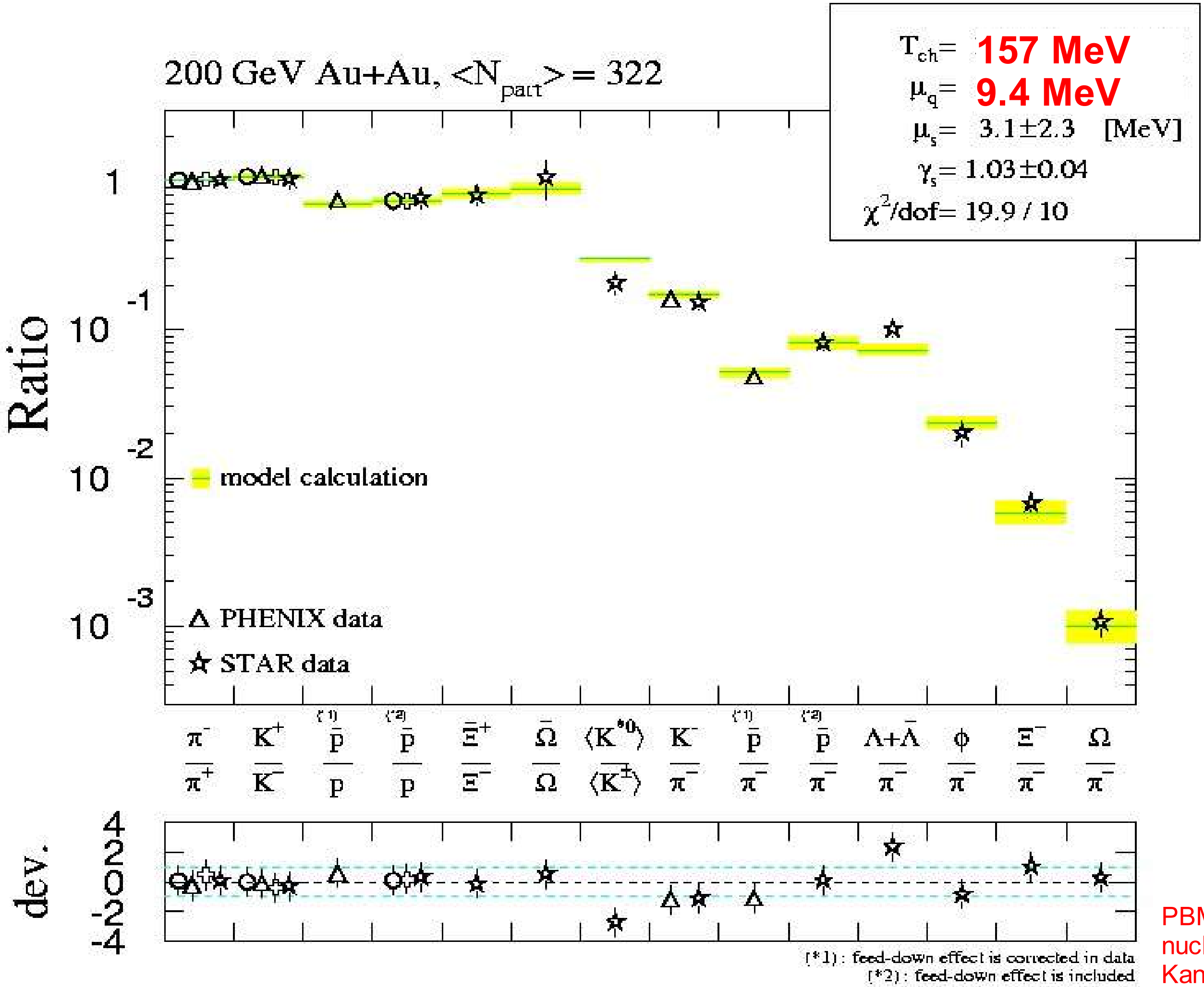
D.d'E. & Peressounko
nucl-th/0503054

Strong 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 at hadronization ($T_{chem.freeze-out} \sim T_{crit}$) :



PBM, Redlich, Stachel
nucl-th/0304013
Kaneta, Xu
nucl-th/0405068

- Assume all distrib. described by one T and one μ:

$$dN \sim e^{-(E-\mu)/T} d^3p$$

- 1 ratio (e.g. $p/\bar{p}$) determines μ/T

$$p/\bar{p} \sim e^{-(E+\mu)/T}/e^{-(E-\mu)/T} = e^{-2\mu/T}$$

- 2nd ratio (e.g. K/pi) provides T,μ.
- Then predict all other hadronic yields and ratios

- Hadron composition (even for strange had., γ_s=1) "fixed" at hadronization

(4) Hard QCD production at RHIC

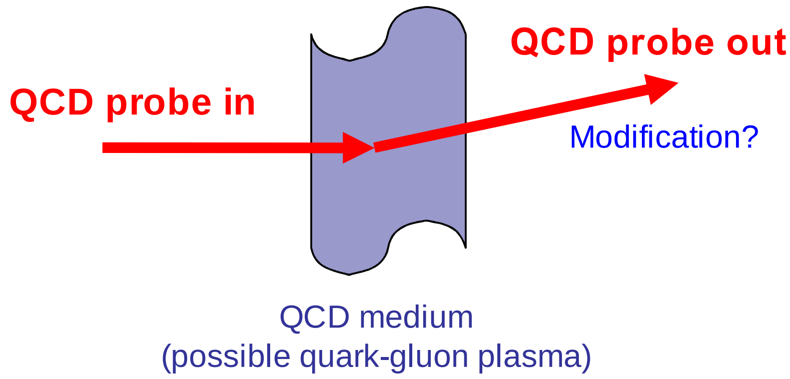
- The largest initial gluon densities ever measured: $dN^g/dy \sim 1000$

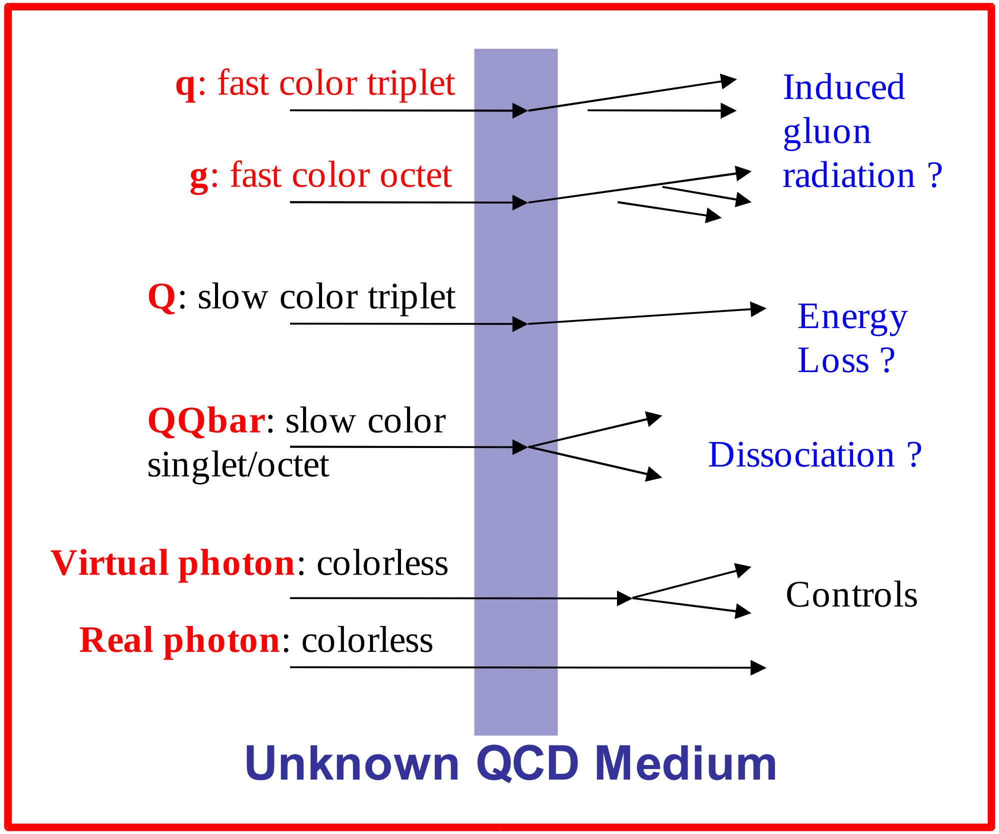
Hard QCD probes (I)

- 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:



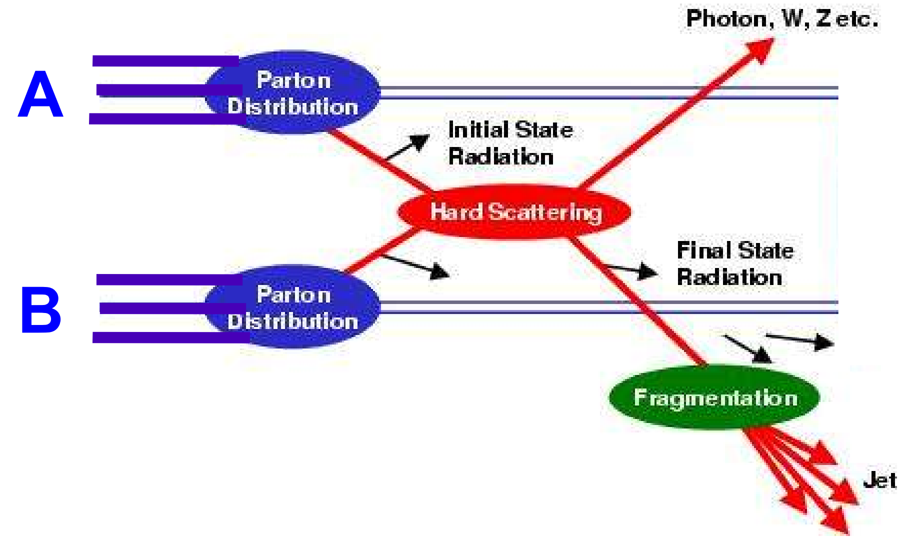


Hard QCD probes (II)

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"

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

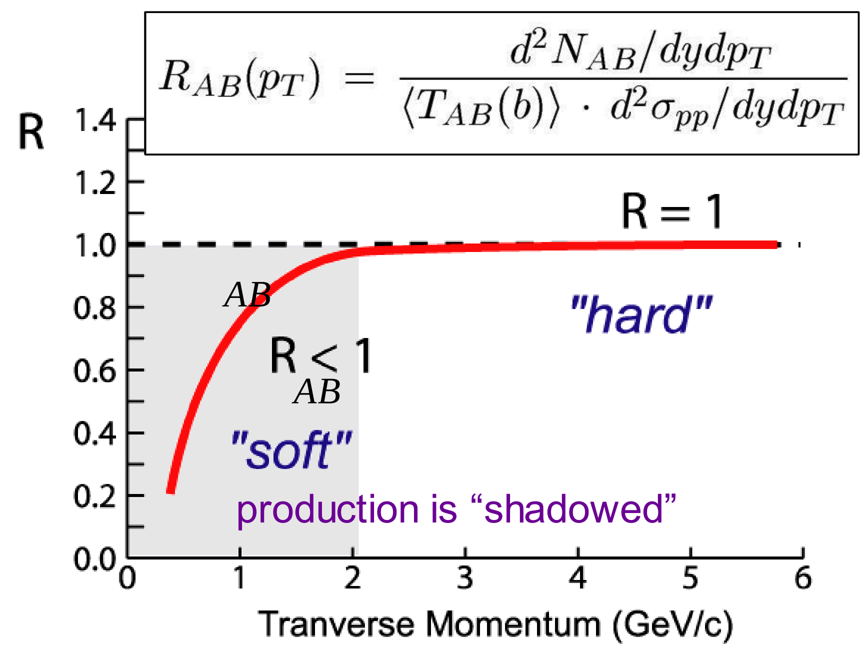
At impact parameter b:

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

geom. nuclear overlap at b

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

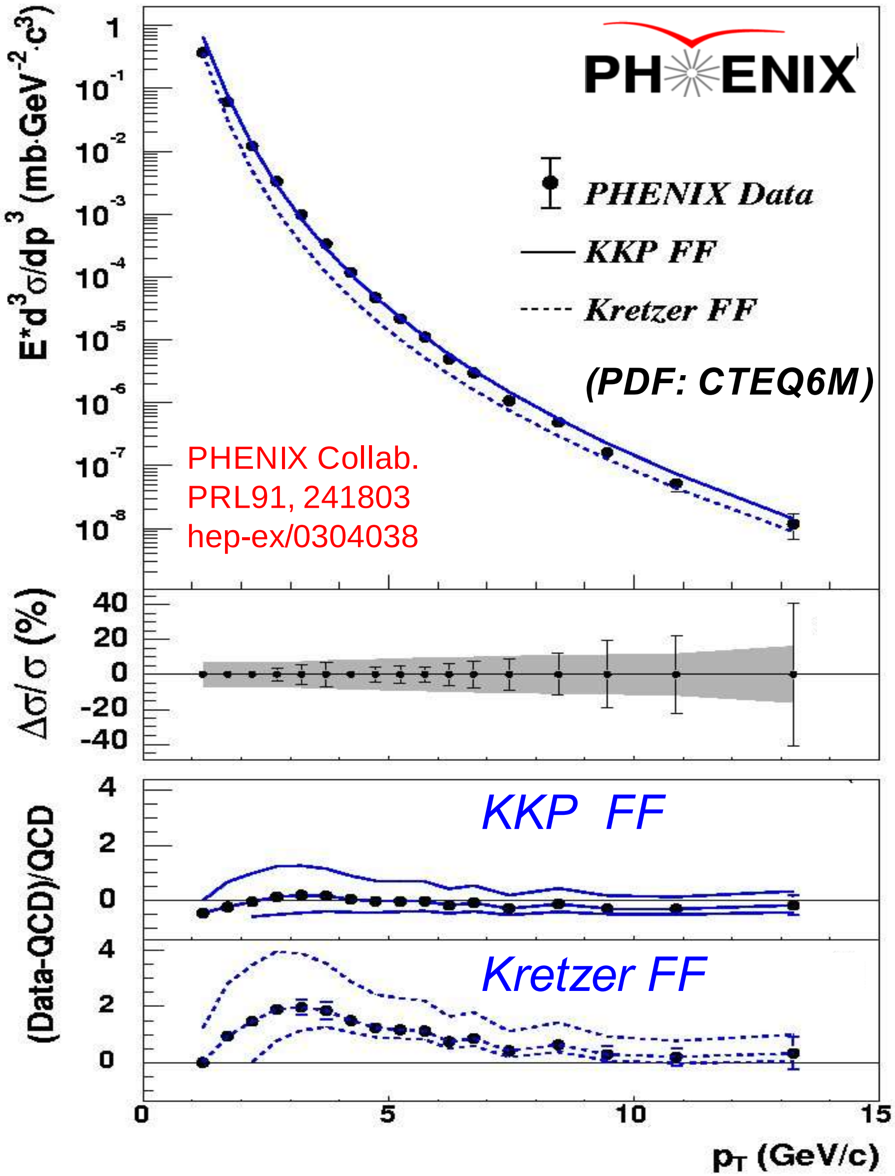
Nuclear Modification Factor:



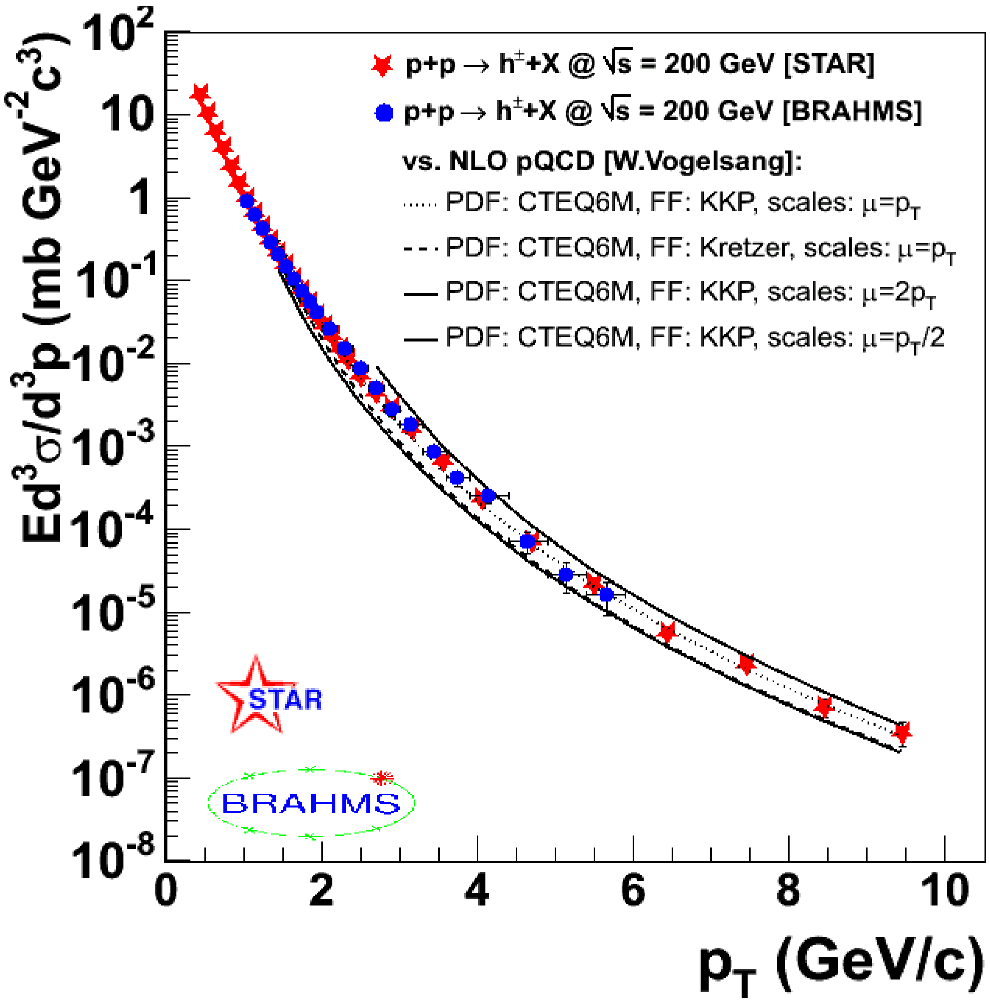
High p_T p+p baseline data well described by pQCD

- Good theoretical (NLO pQCD) description:

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



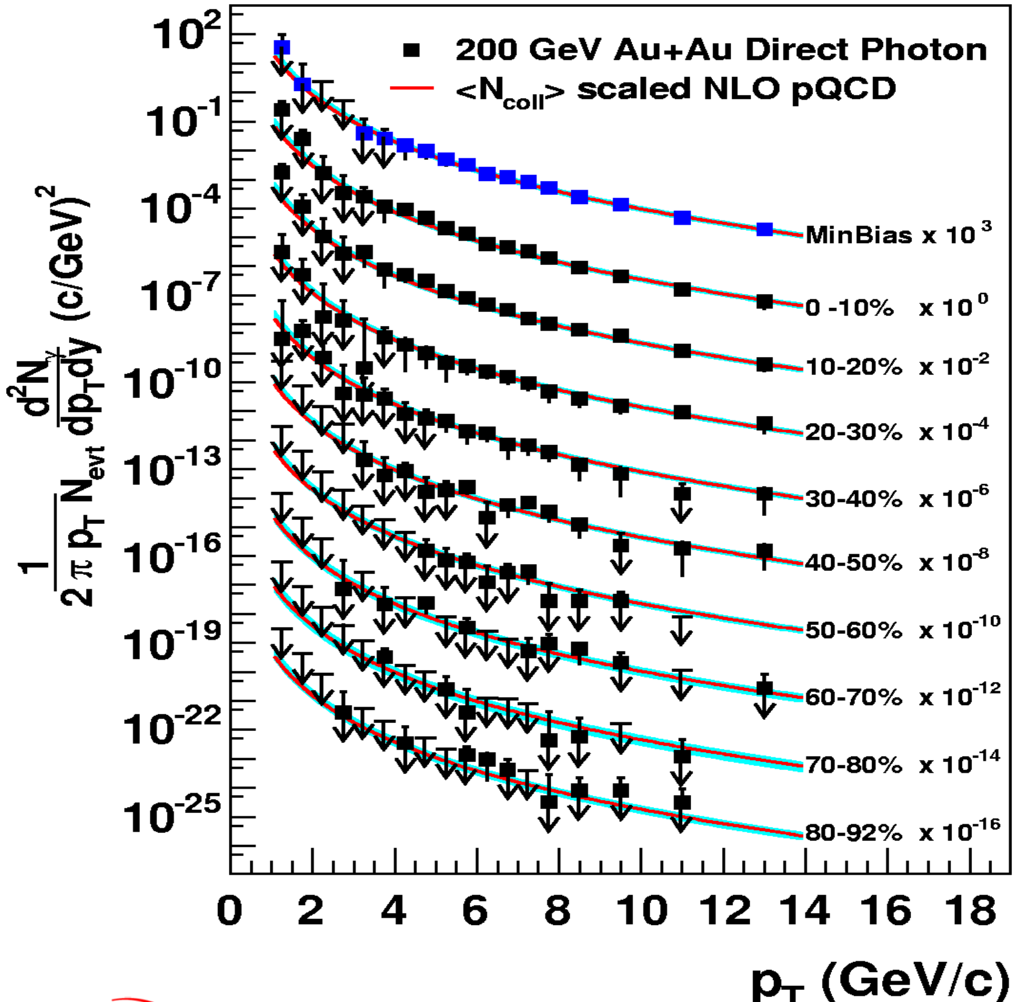
$p+p \rightarrow h^{\pm} X$ (non singly diffractive)



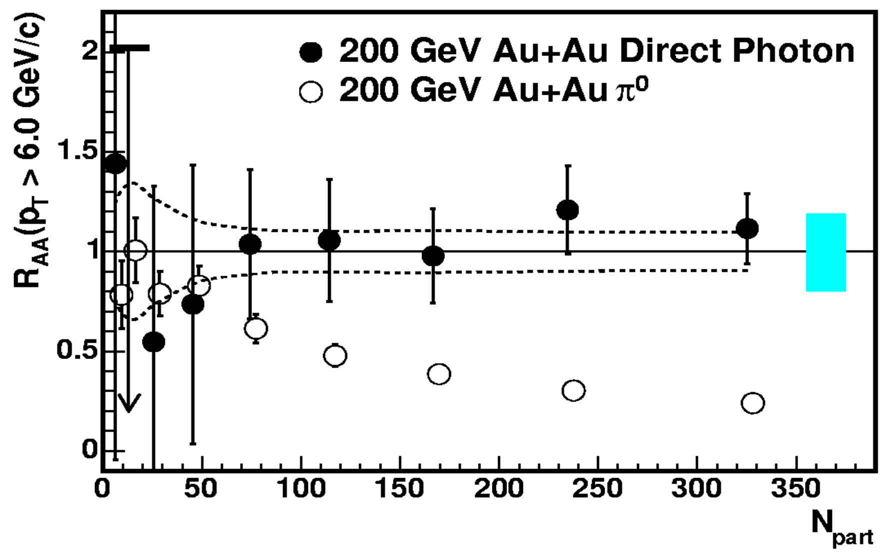
- Well calibrated (experimentally & theoretically) p+p references at hand

“NN scaling” in Au+Au @ 200 GeV: Direct Photons

- Direct photon production in Au+Au (all centralities) consistent w/ p+p incoherent scattering (“NN-scaled” pQCD) predictions:



$$R_{AA}(p_T, y; b) = \frac{\text{“hot/dense QCD medium”}}{\text{“QCD vacuum”}} = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T},$$

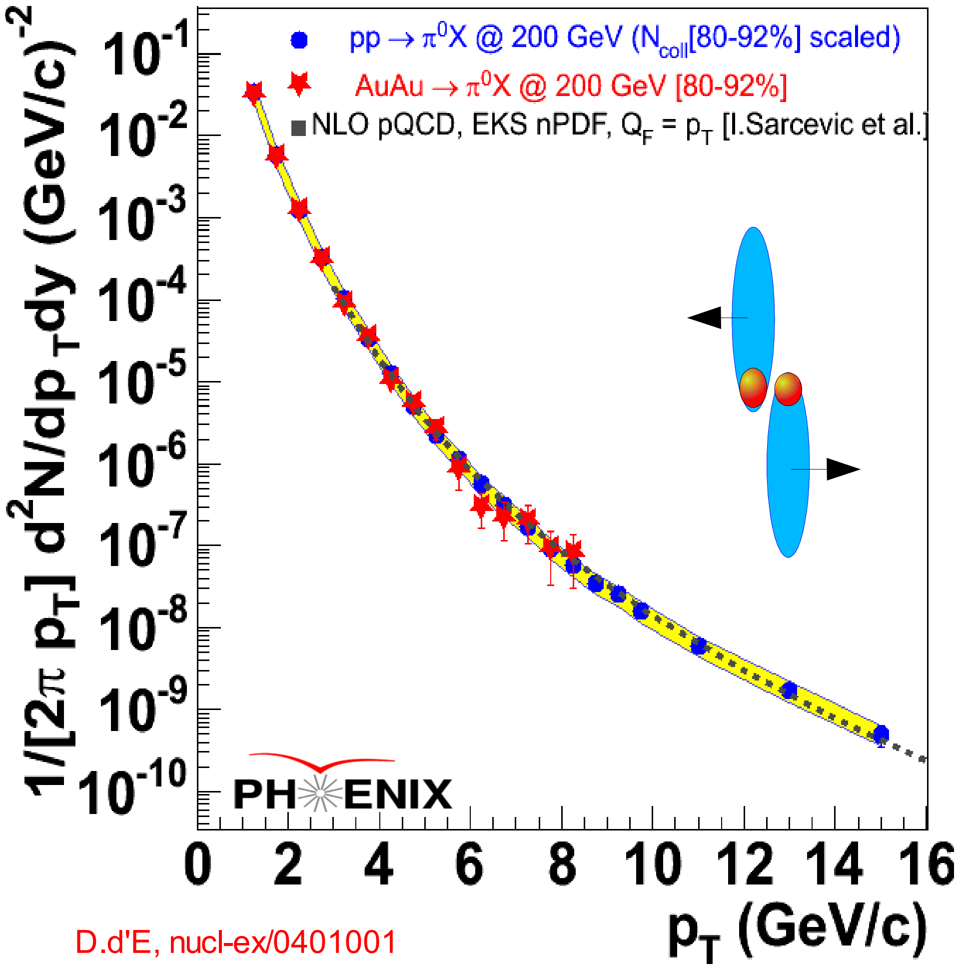


- Direct photon production in Au+Au unmodified by QCD medium.

PHENIX Submitted to PRL nucl-ex/0503003

Suppressed high p_T hadroproduction in Au+Au @ RHIC !

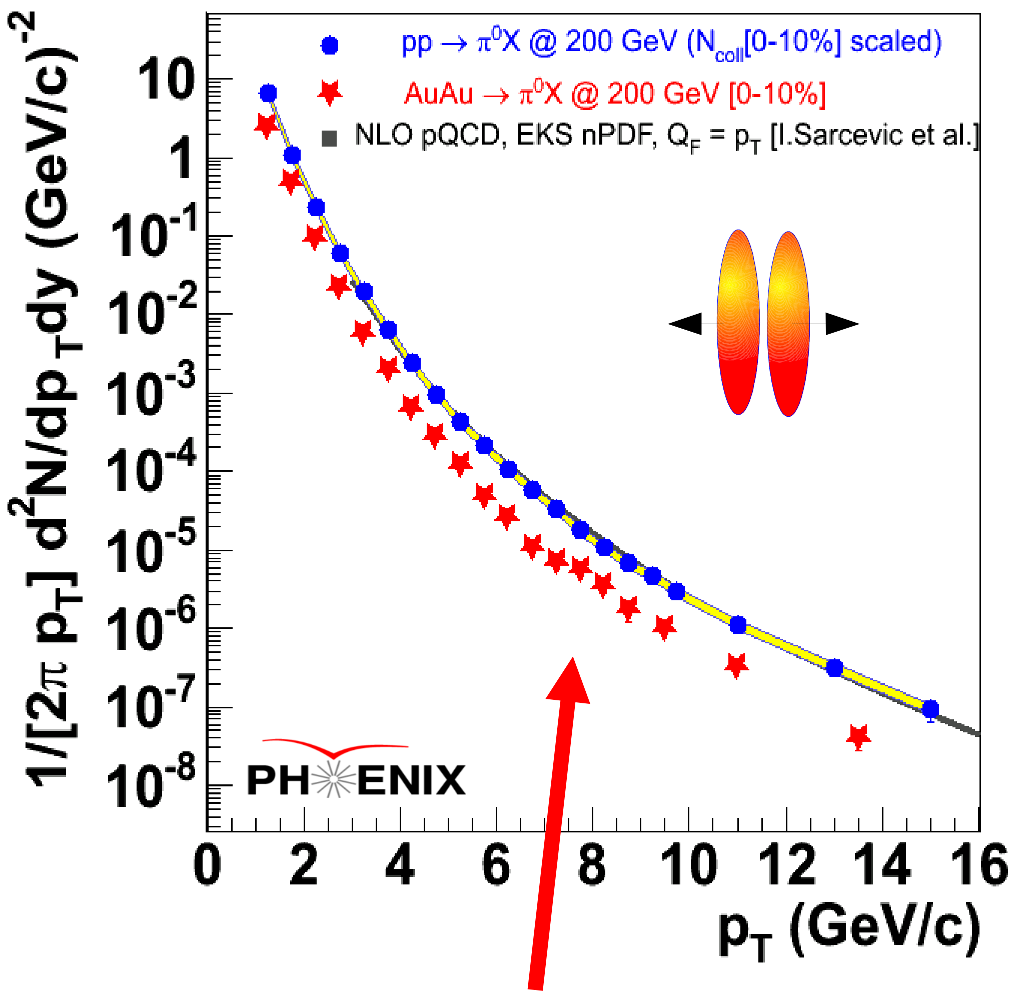
Au+Au→ $\pi^0 X$ (peripheral)



D.d'E, nucl-ex/0401001

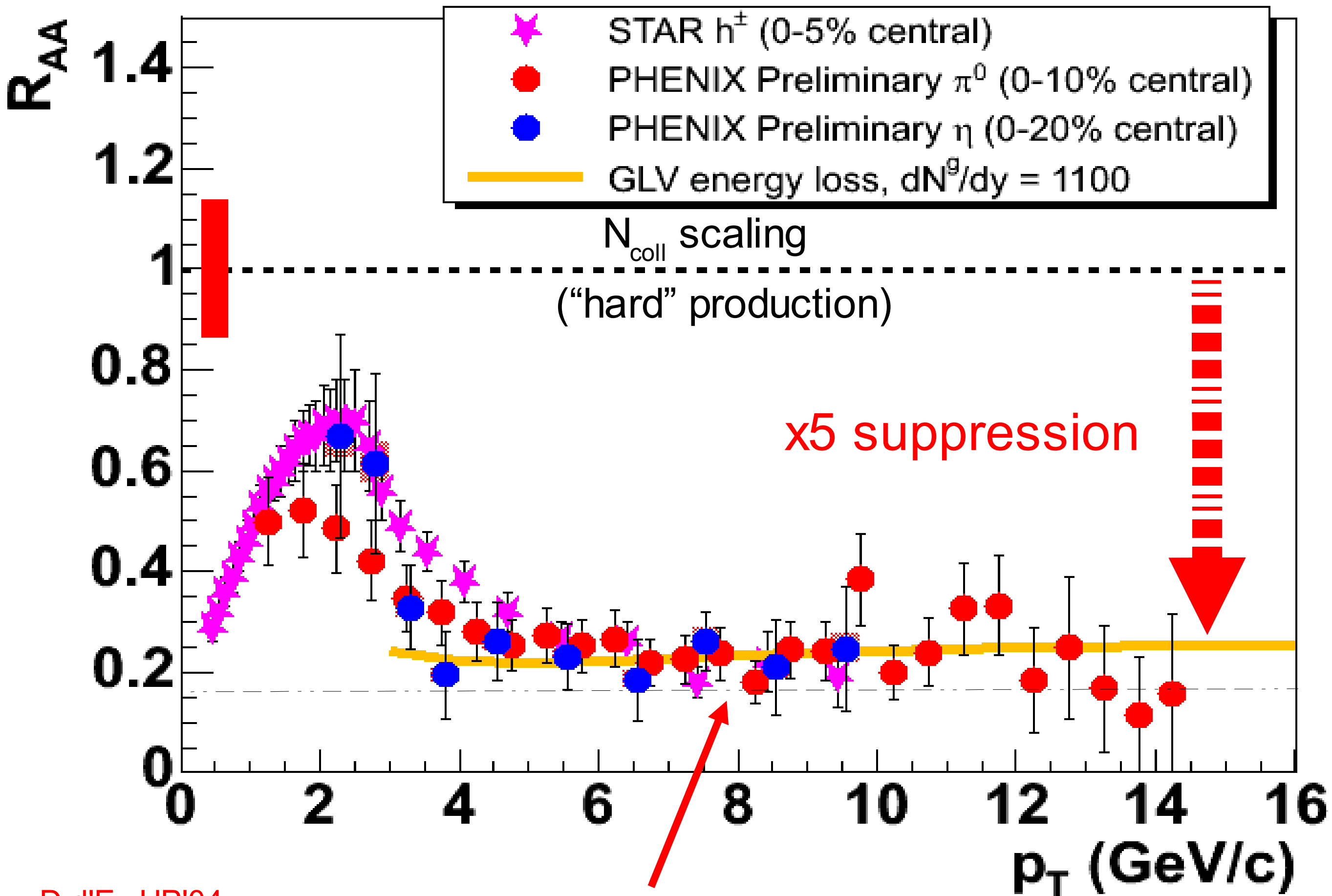
Peripheral data agree well with p+p (data & pQCD) plus N_{coll}-scaling

Au+Au→ $\pi^0 X$ (central)



Strong suppression in central Au+Au collisions

Suppressed high p_T hadroproduction @ RHIC



Npart scaling
(surface emission)

D.d'E., HP'04
nucl-ex/0504001

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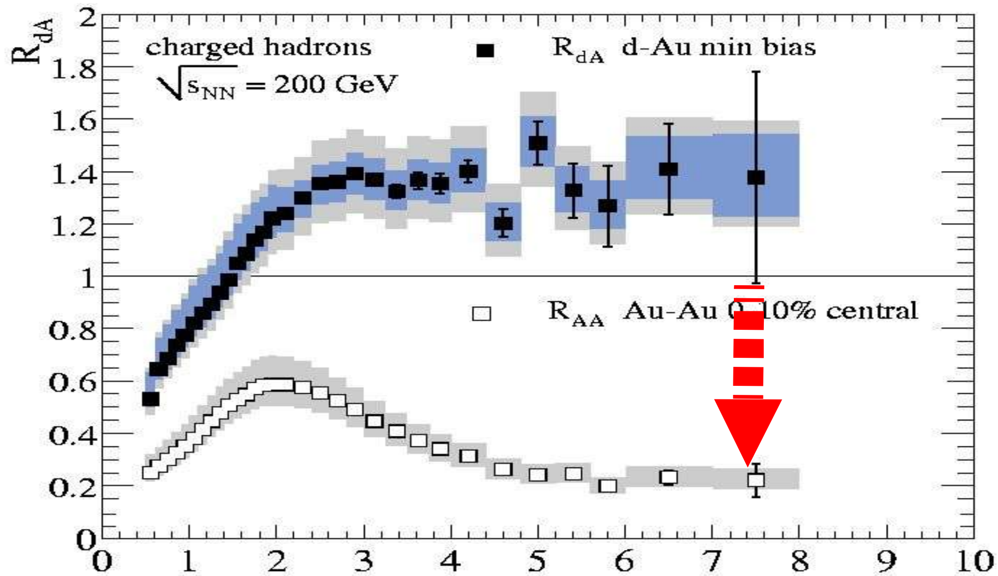
PRL 88, 022301 (2002)
nucl-ex/0109003

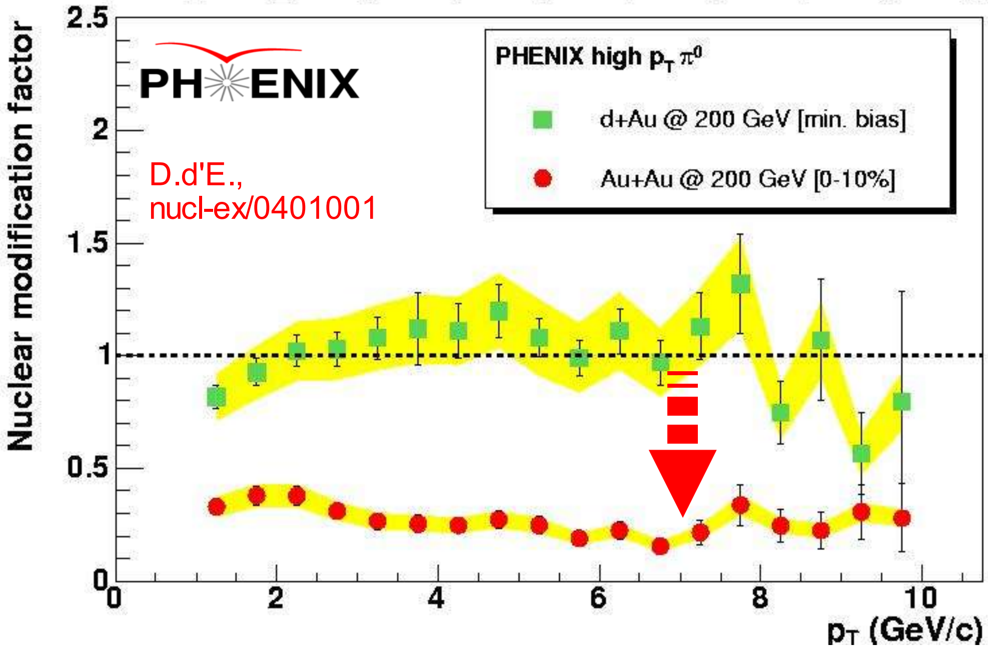
R_{AA} << 1: well below pQCD (collinear factorization) expectations for hard scattering cross-sections

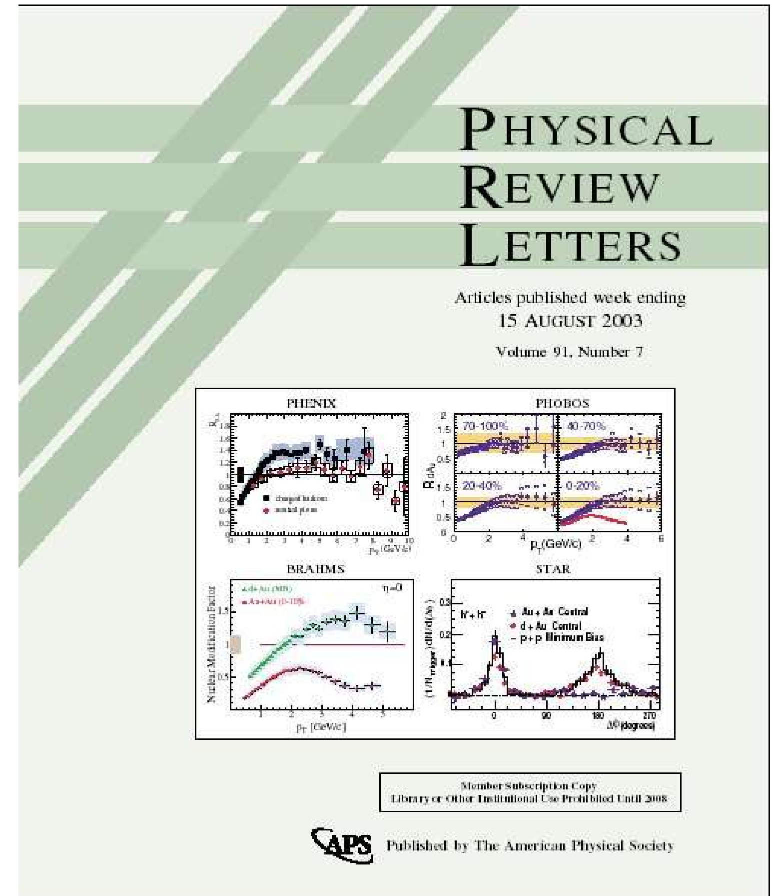
Discovery of high p_T suppression (one of most significant results @ RHIC so far)

Unquenched d+Au production at high p_T



PHENIX. PRL91, 072303(2003)





- Conclusion: High p_T suppression in central Au+Au due to final-state effects (absent in "control" d+Au experiment)

"Jet quenching" predictions

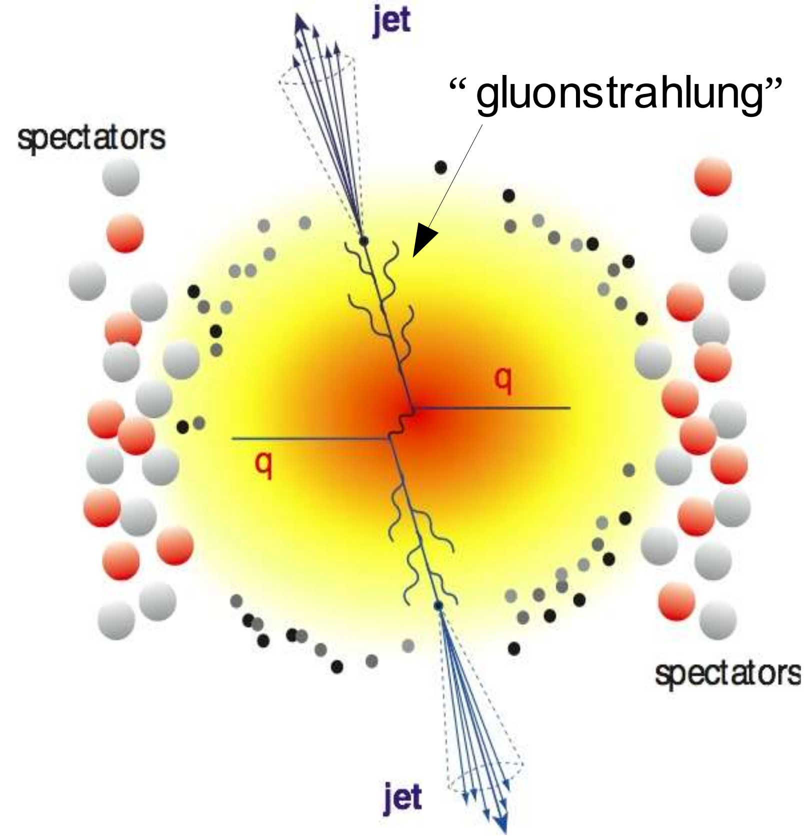
- Multiple final-state non-Abelian (gluon) radiation off the produced hard parton induced by the traversed dense medium.
- Parton energy loss $\propto$ medium properties:

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

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

- Energy is carried away by gluonsstrahlung inside jet cone: $dE/dx \sim \alpha_s \langle k^2_T \rangle$
- Correction for expanding (1-D) plasma :

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



- Prediction I: Suppression of high p_T leading hadrons
- Prediction II: Disappeareance of back-to-back (di)jet correlations

"Jet quenching" model vs. data (I)

- Dense medium properties from pQCD+ final-state parton energy loss models:

  - Initial gluon densities:

    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]

  - Opacities:

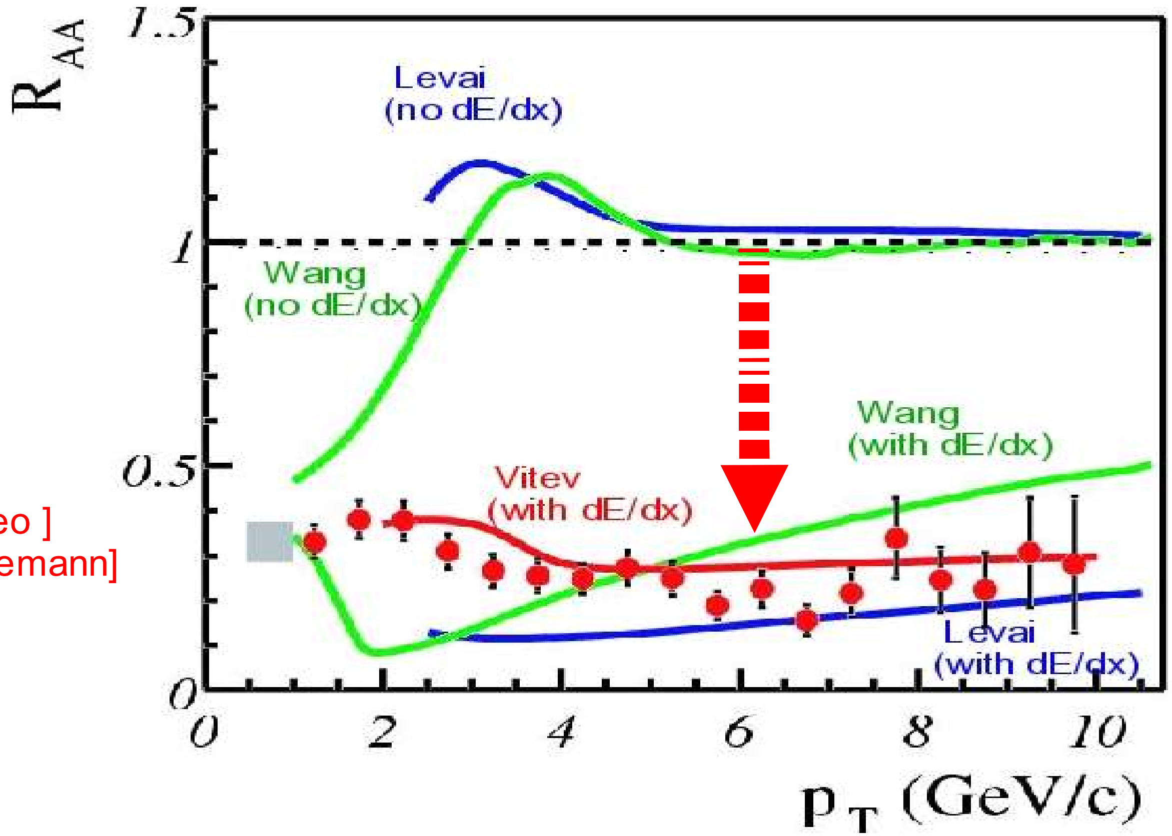
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]

  - Transport coefficients:

    $\langle q_0 \rangle \sim 14$ GeV/fm^2 [BDMPS, F.Arleo] [Salgado-Wiedemann]

  - 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. high p_T suppression (II)

- sqrt(s)-dependence:

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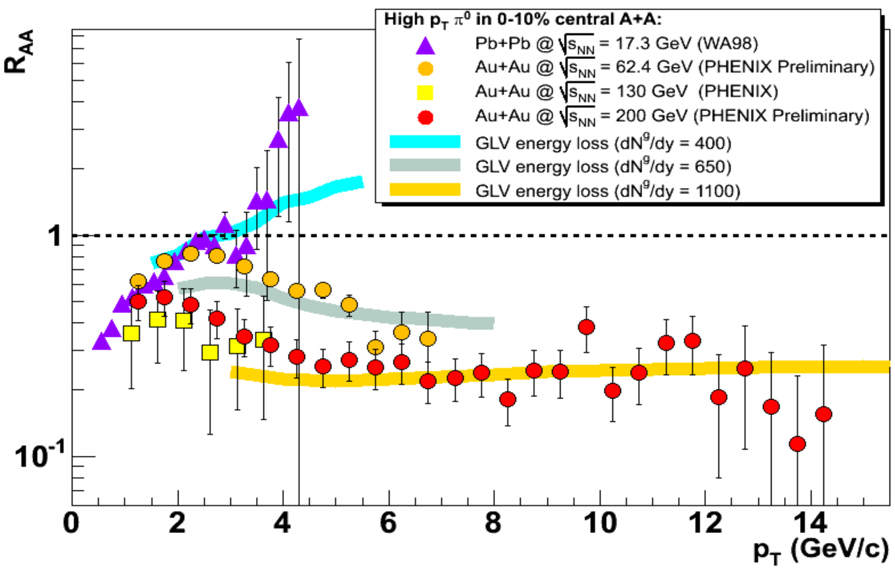
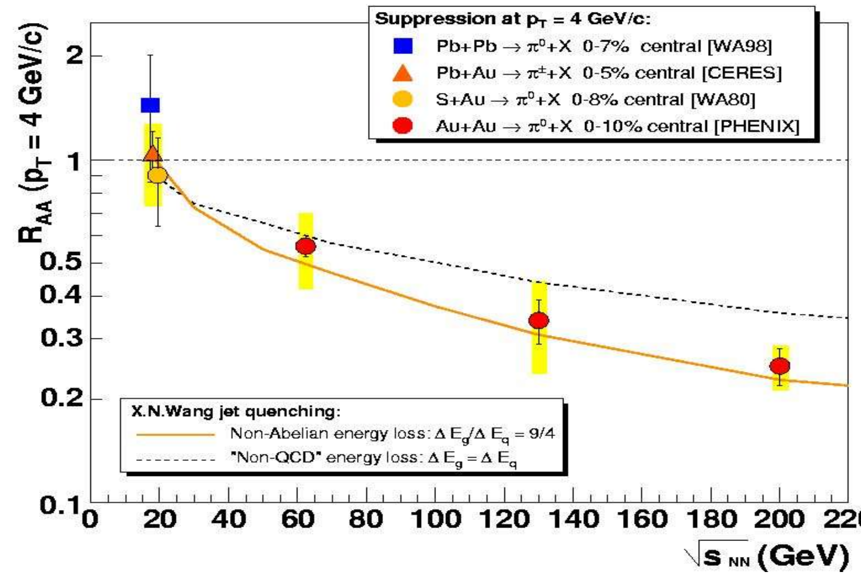
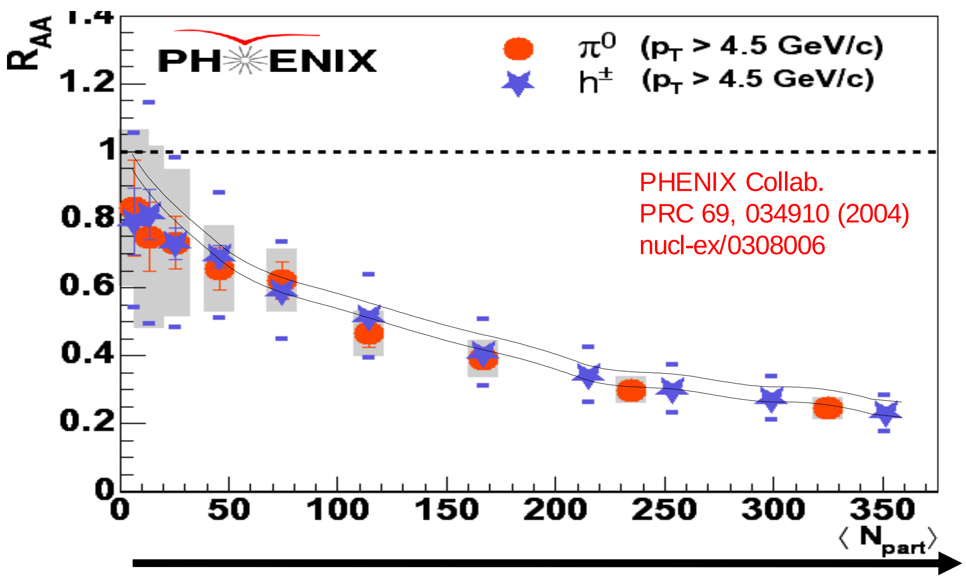
nucl-ex/0504001



- Non-Abelian energy loss:

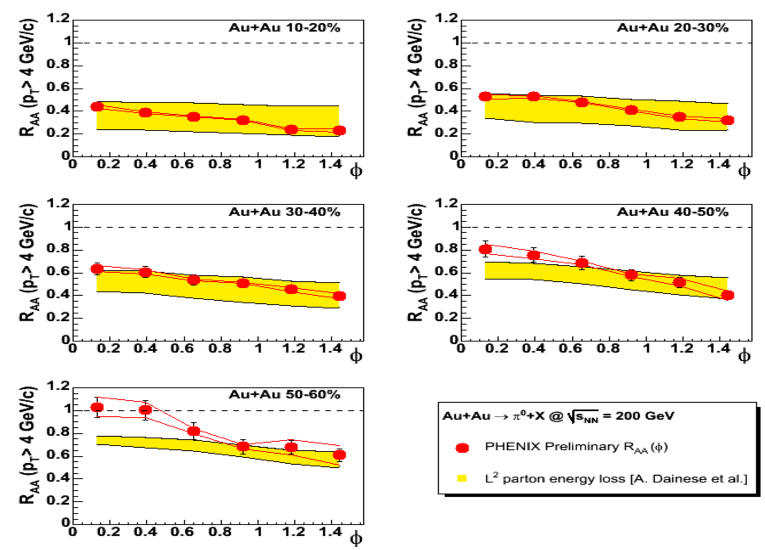


- Centrality dependence:



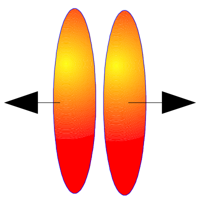
peripheral central

- Reaction-plane (in-medium path length) dependence:

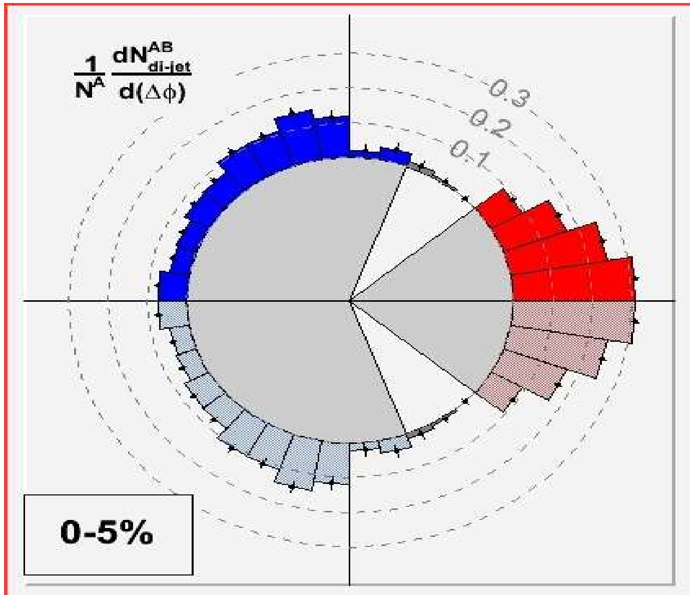


"Jet quenching": modified (di)jet structure

- Strongly modified $dN_{pair}/d\varphi$ high p_T correlations in central Au+Au:



Au+Au central



- Strongly non-Gaussian away-side ("dip") peak.

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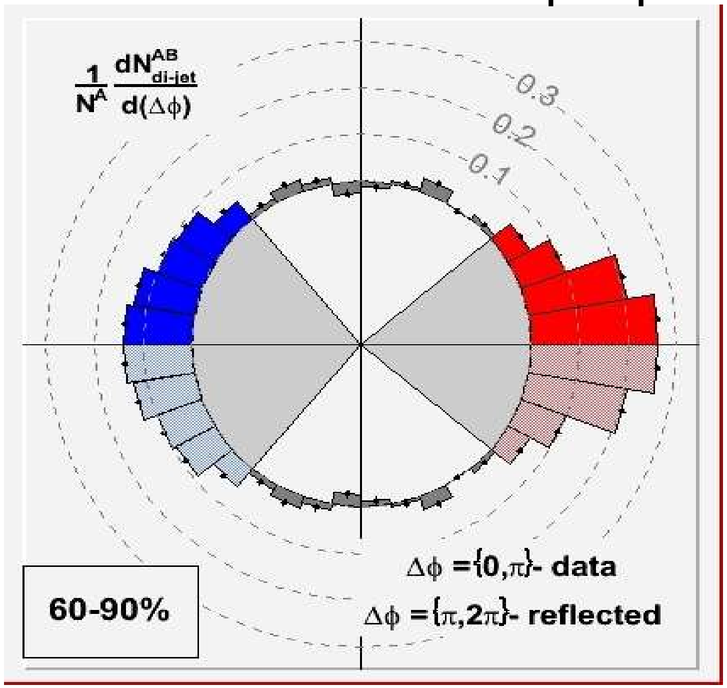
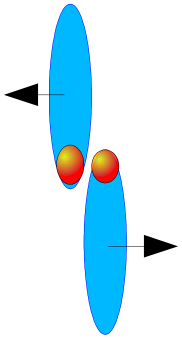
Au+Au periph





- Standard back-to-back di-jet topology:

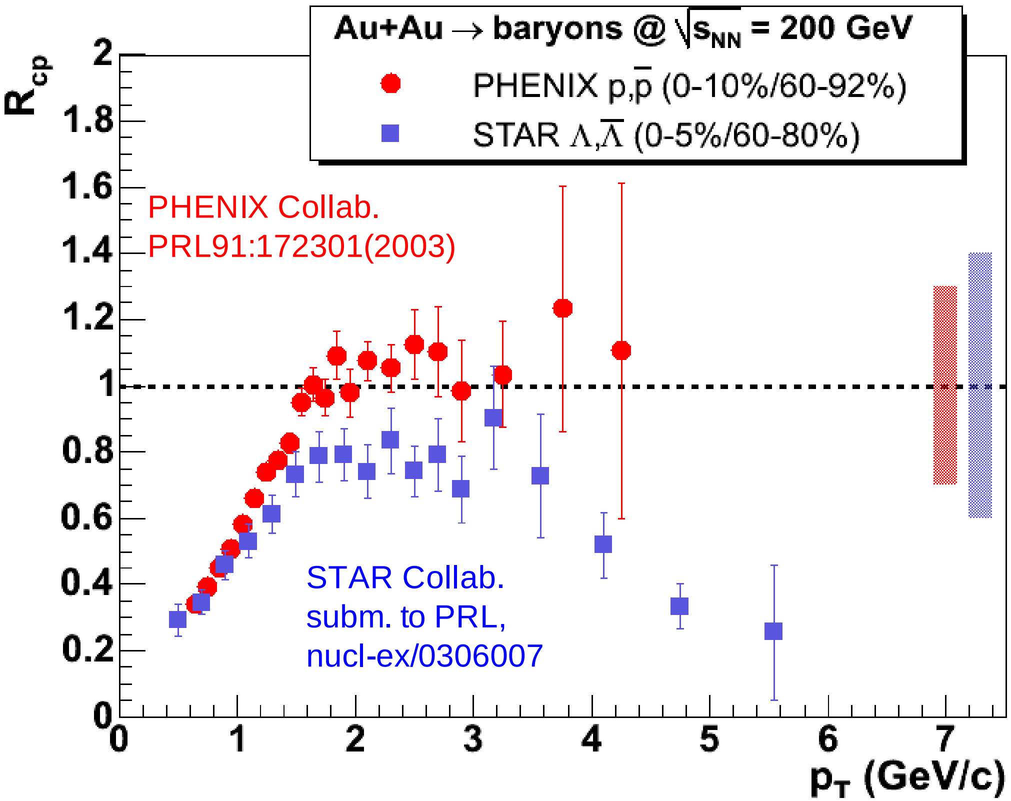
(5) Hadron production at intermediate p_T

- Degrees of freedom consistent with constituent quarks

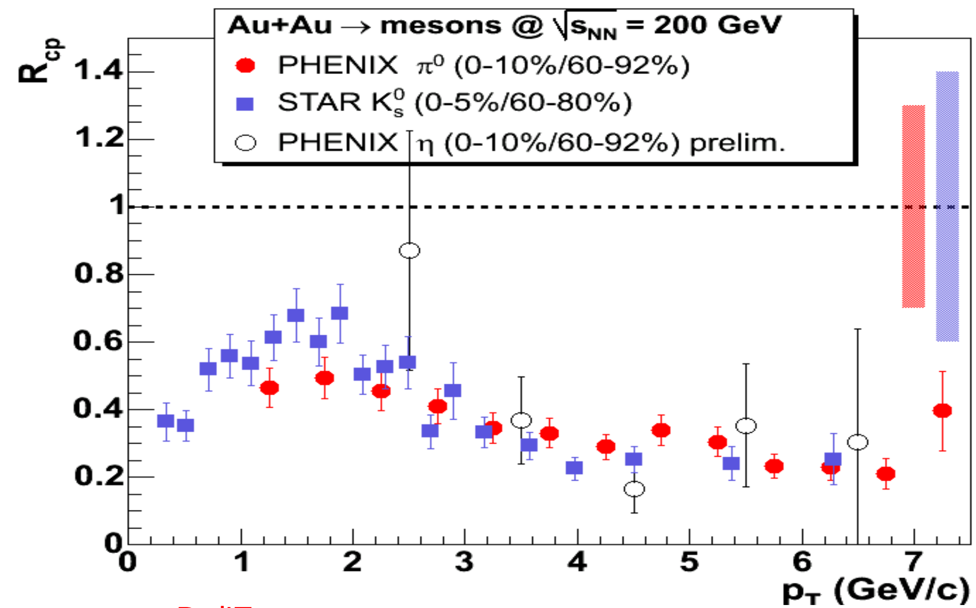
Unsuppressed baryon production

- 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.



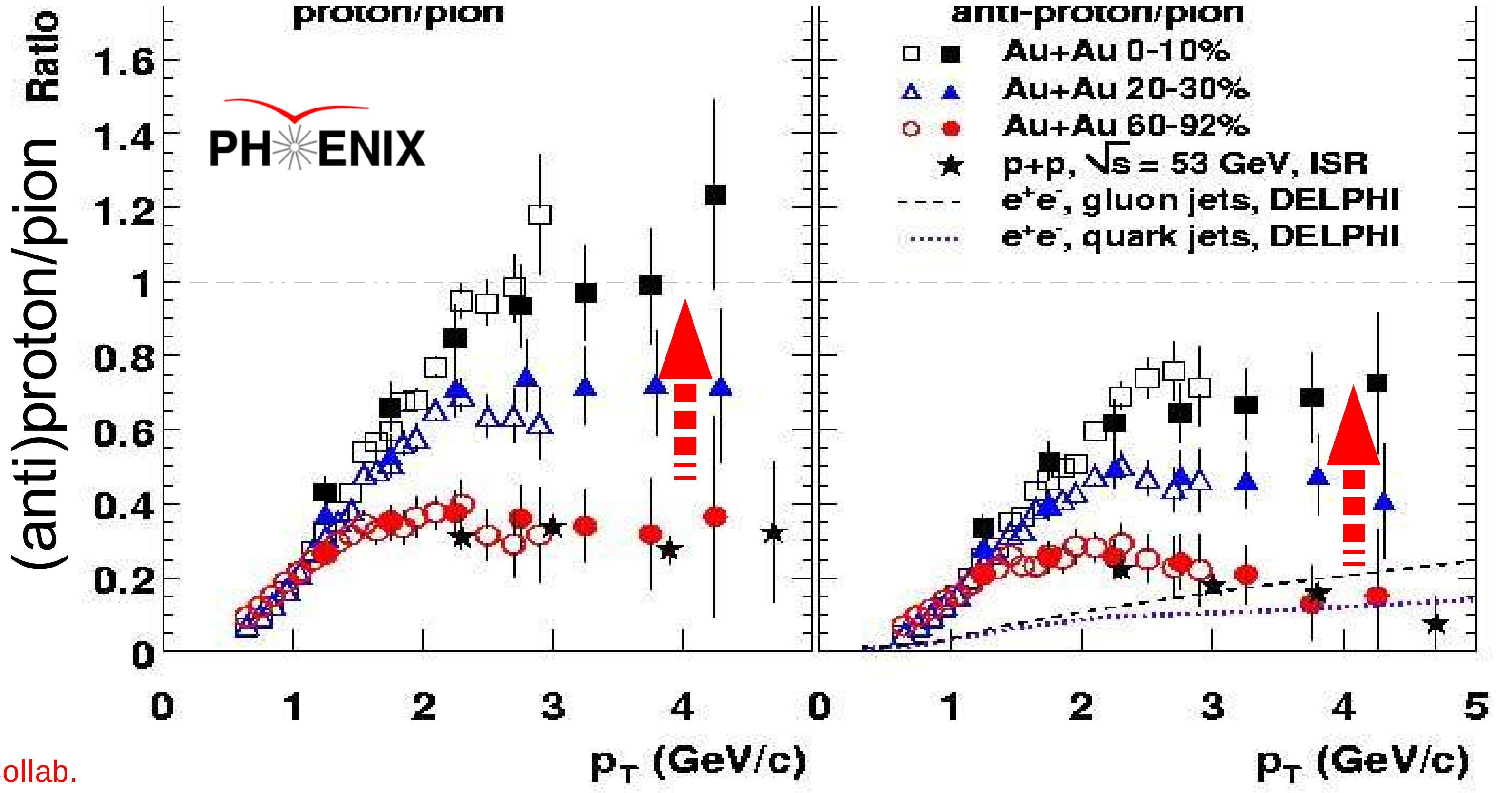
D.d'E.
J.Phys. G30, S677 (2004)

- 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

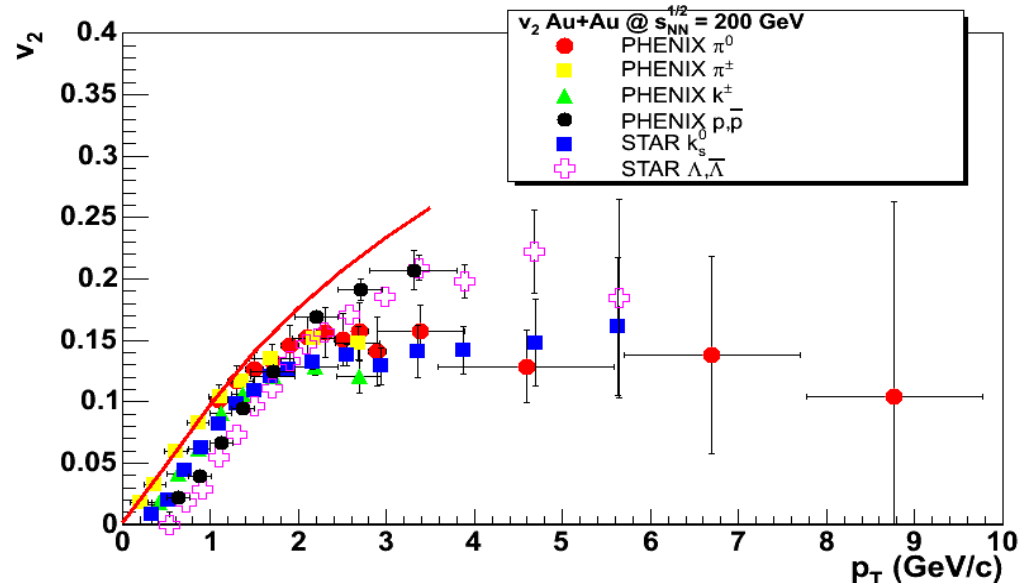


PHENIX Collab.
PRL91:172301(2003)

Enhanced baryonic elliptic flow

- Different v_2 saturation for mesons and baryons:

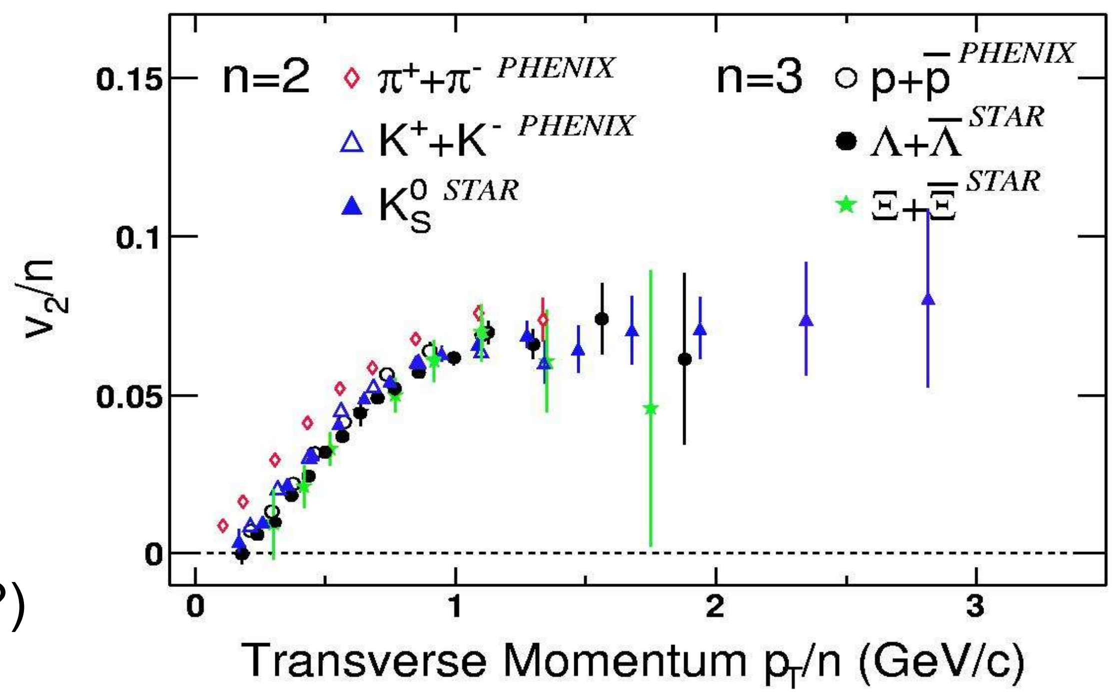
$v_2^{meson} > v_2^{baryon}$ at low p_T
$v_2^{meson} \approx v_2^{baryon}$ at $p_T \approx 2$ GeV/c
$v_2^{meson} < v_2^{baryon}$ at higher p_T



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

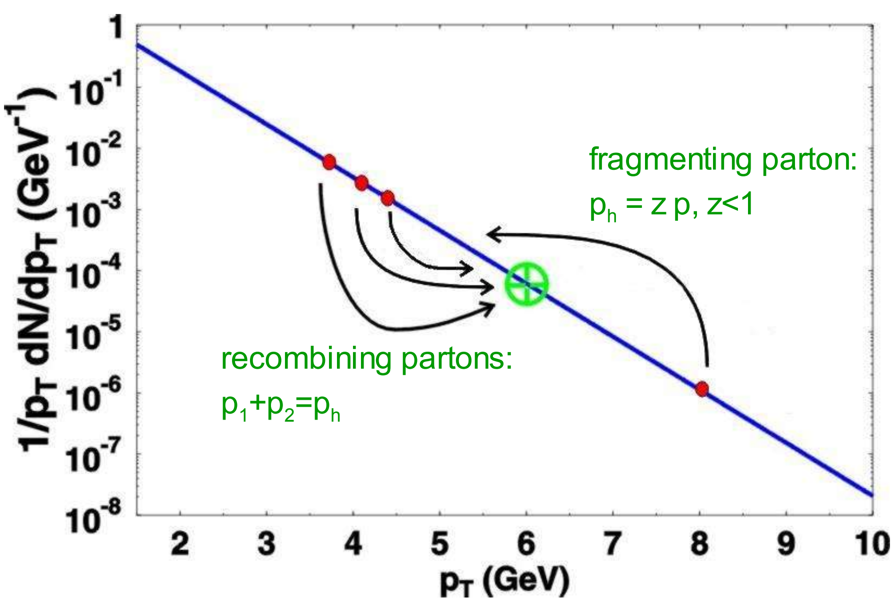
n = 2 mesons
n = 3 baryons

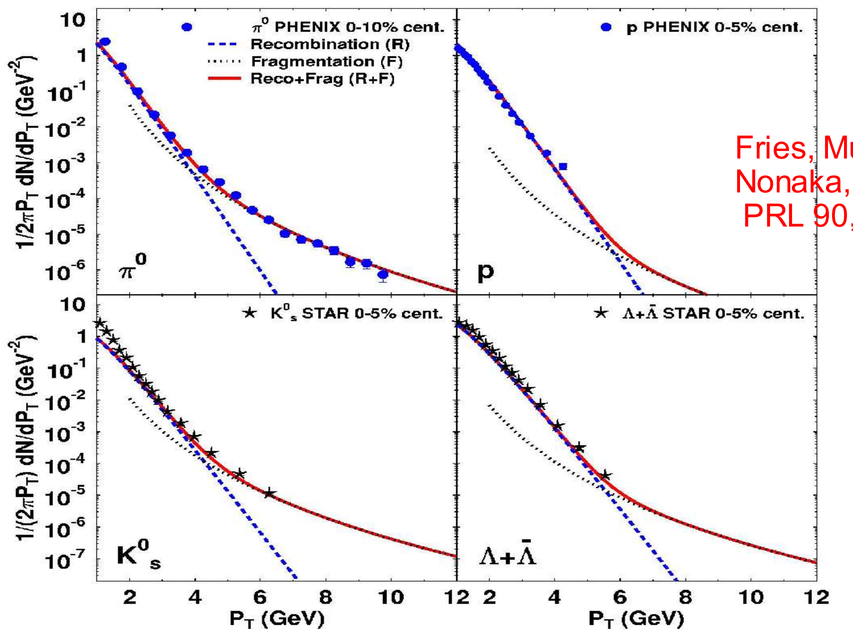
("universal" parent quark flow ?)



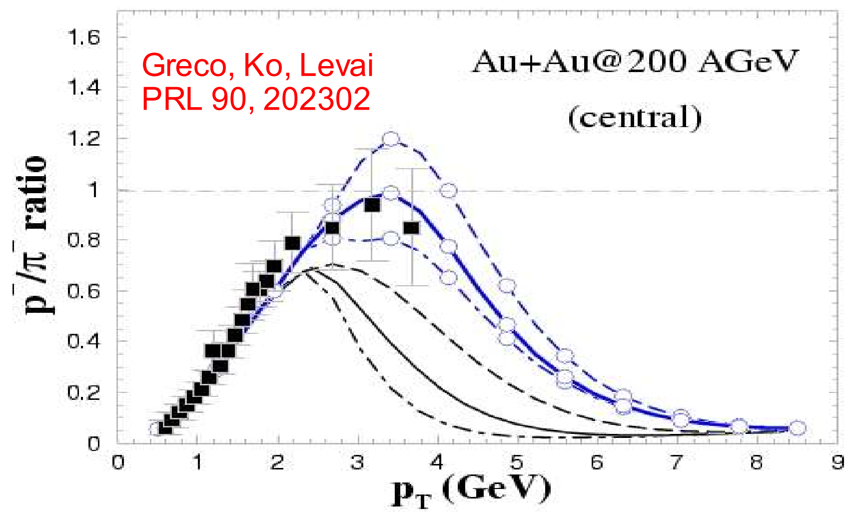
"Quark recombination" models vs. data

- Anomalous baryon enhancement & quark number scaling of v_2 at p_T= 2--5 GeV/c explained by "quark recombination" (coalescence) in dense (thermal) medium:





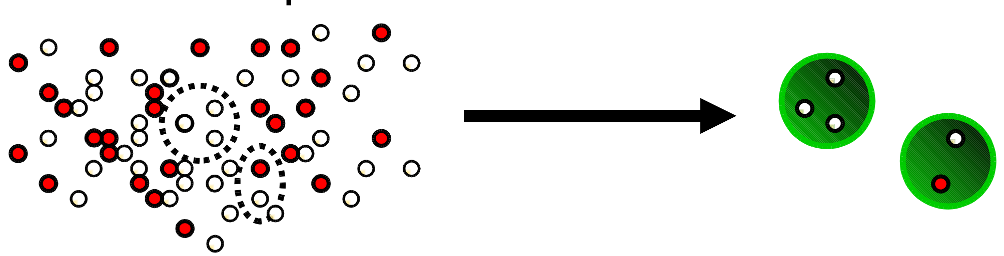
Fries, Mueller Nonaka, Bass PRL 90, 202303



- Rethink hadronization at interm. p_T at RHIC !

  Phase space filled with partons

  Recombine quarks into hadrons



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 $\tau_0 \sim 1$ 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: $dN^g/dy \sim 1100$

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

Outlook: What do we need to claim "QGP !" at RHIC ?

Somebody called us "overly conservative" but we (experimentalist @ RHIC) would like at least to know ...

(1) What is the temperature of the produced system?

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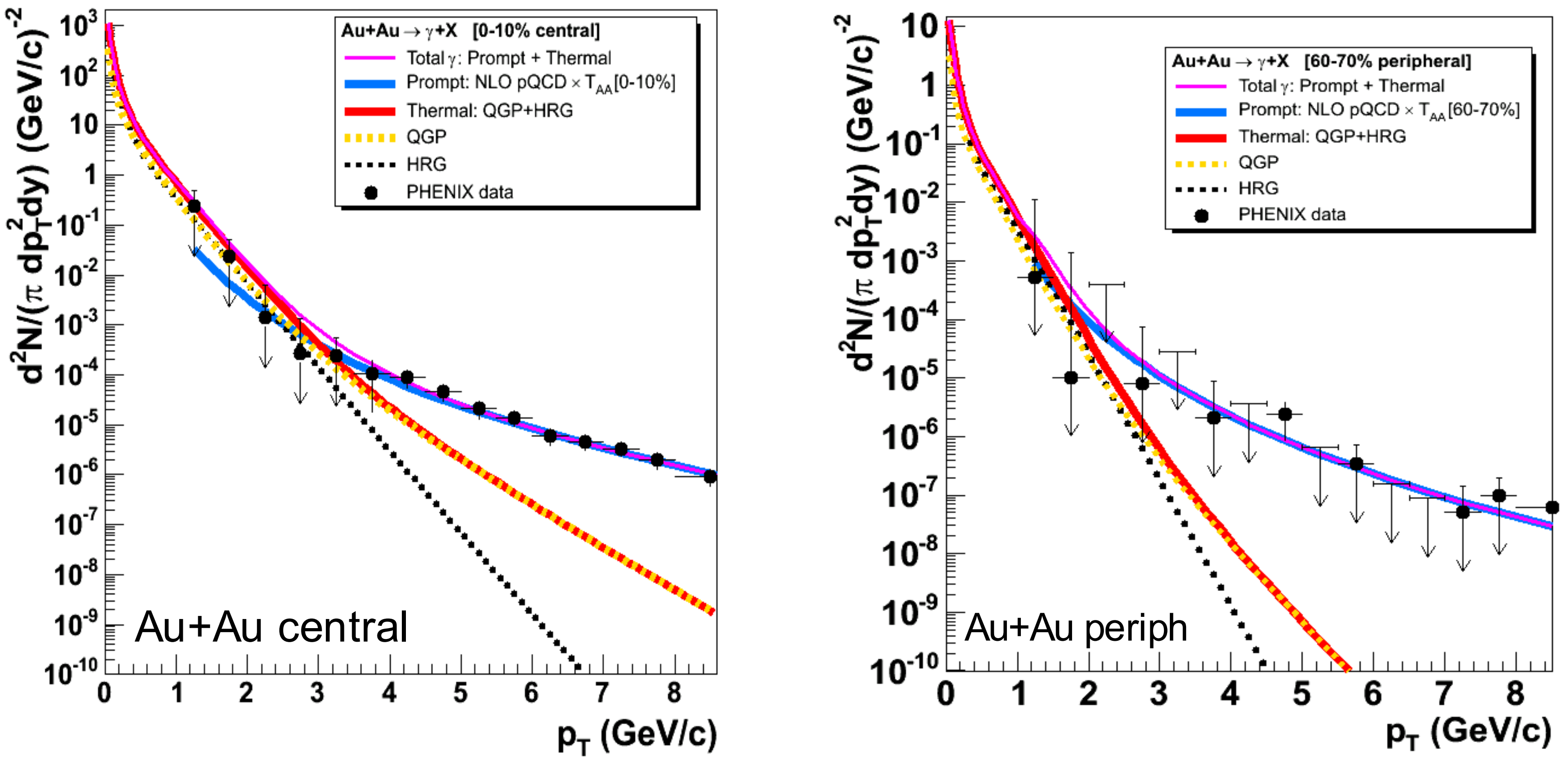

D.d'E. & D.Peressounko
nucl-th/0503054

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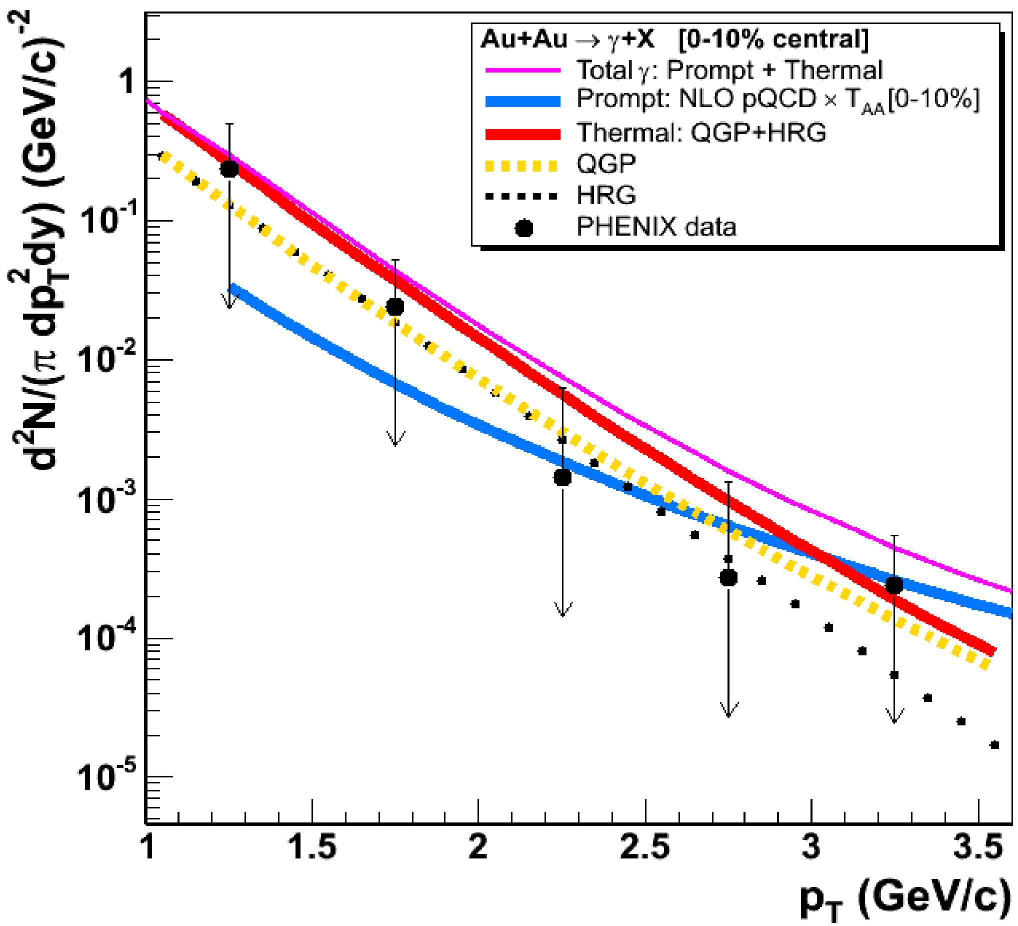

D.d'E. & D.Peressounko nucl-th/0503054

Current experimental upper limits in "interesting" region p_T = 1 – 3 GeV/c preclude a quantitative answer ...

Wait for Run-4 data

Outlook: What do we need to claim “QGP !” at RHIC ?

Somebody called us “overly conservative” but we (experimentalist @ RHIC) would like at least to know ...

(1) What is the temperature of the produced system?

(2) Is the system deconfined ?

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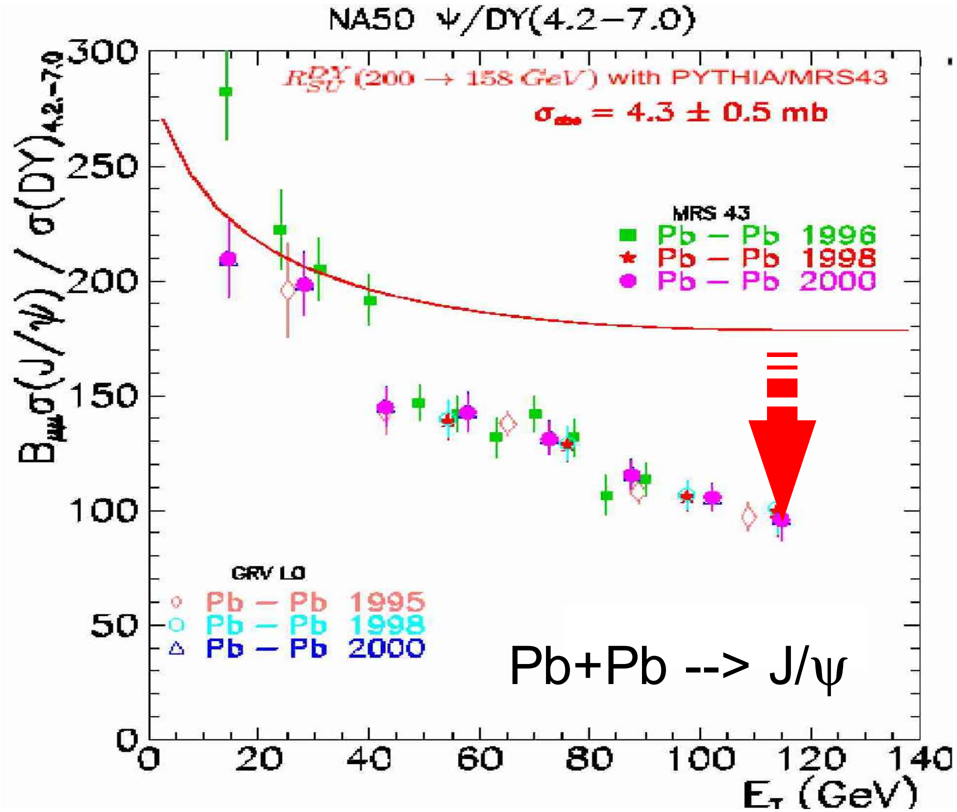

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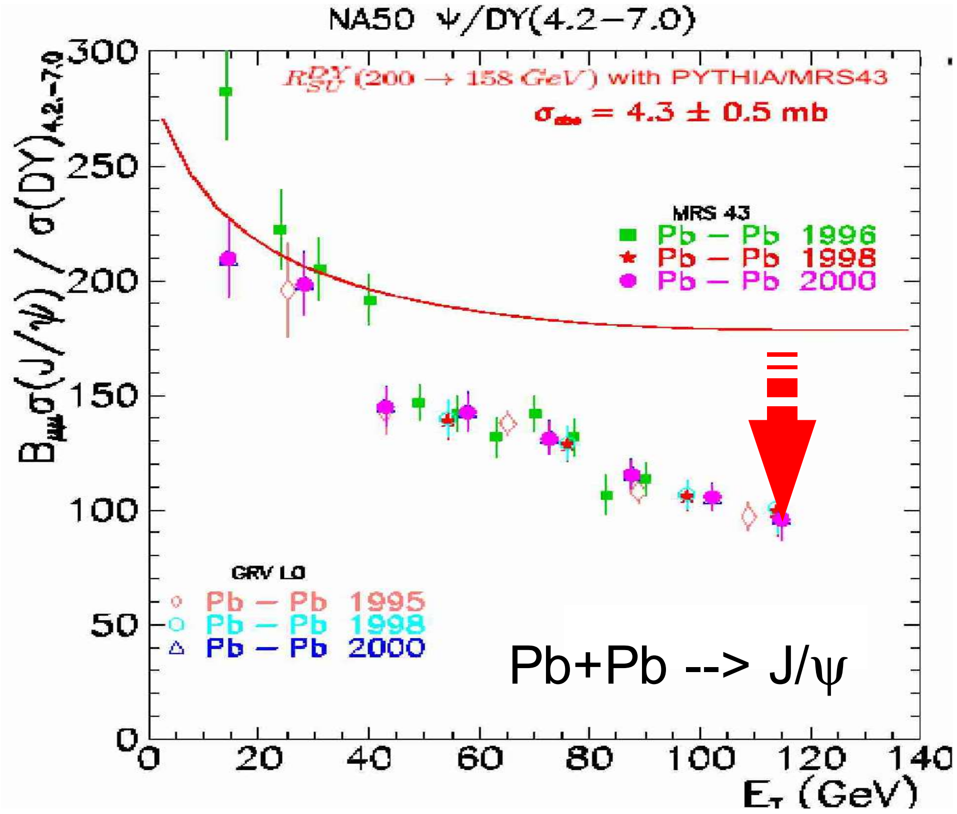

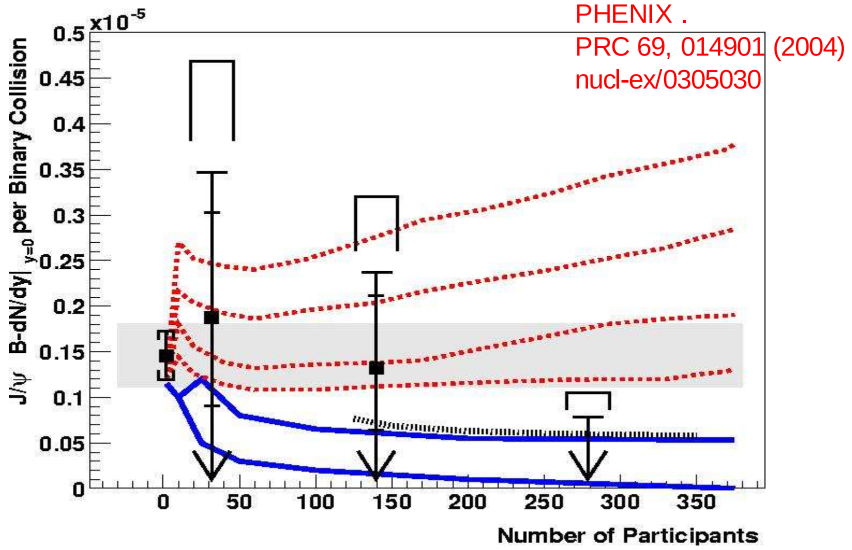

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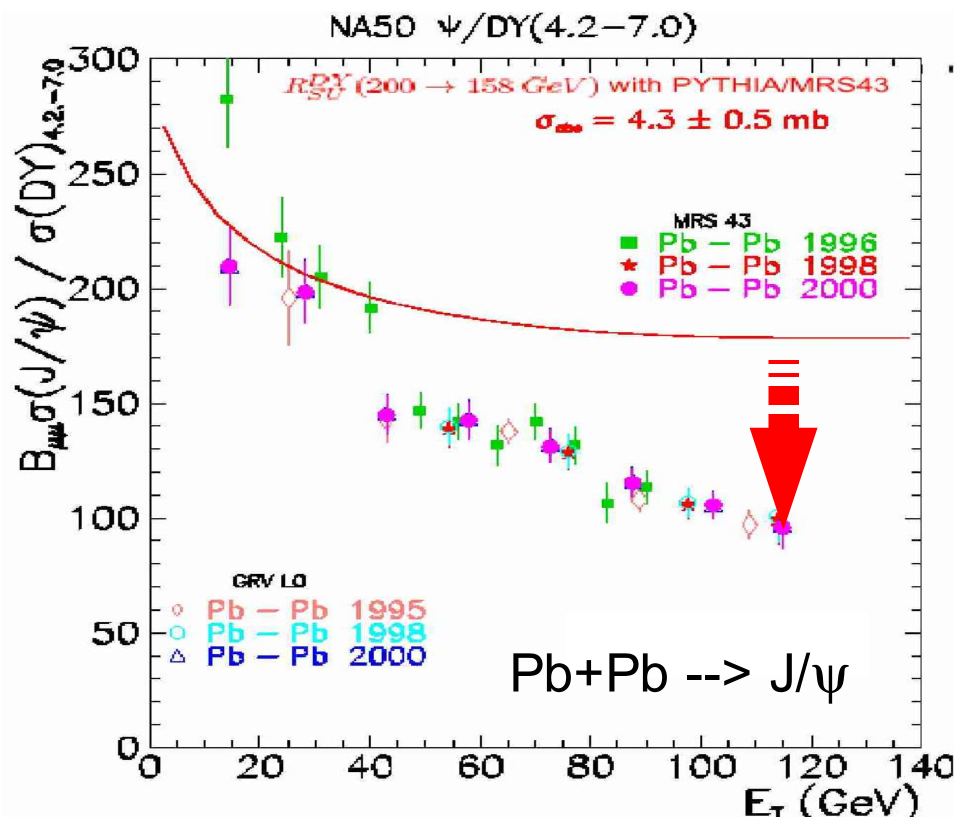
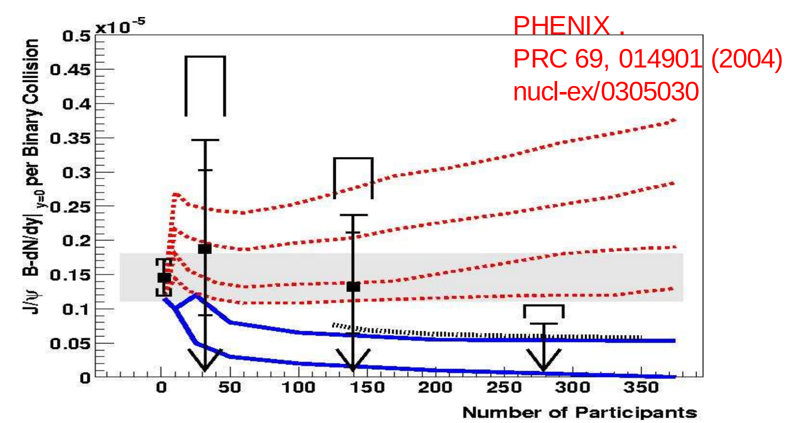




Again the answer is ...

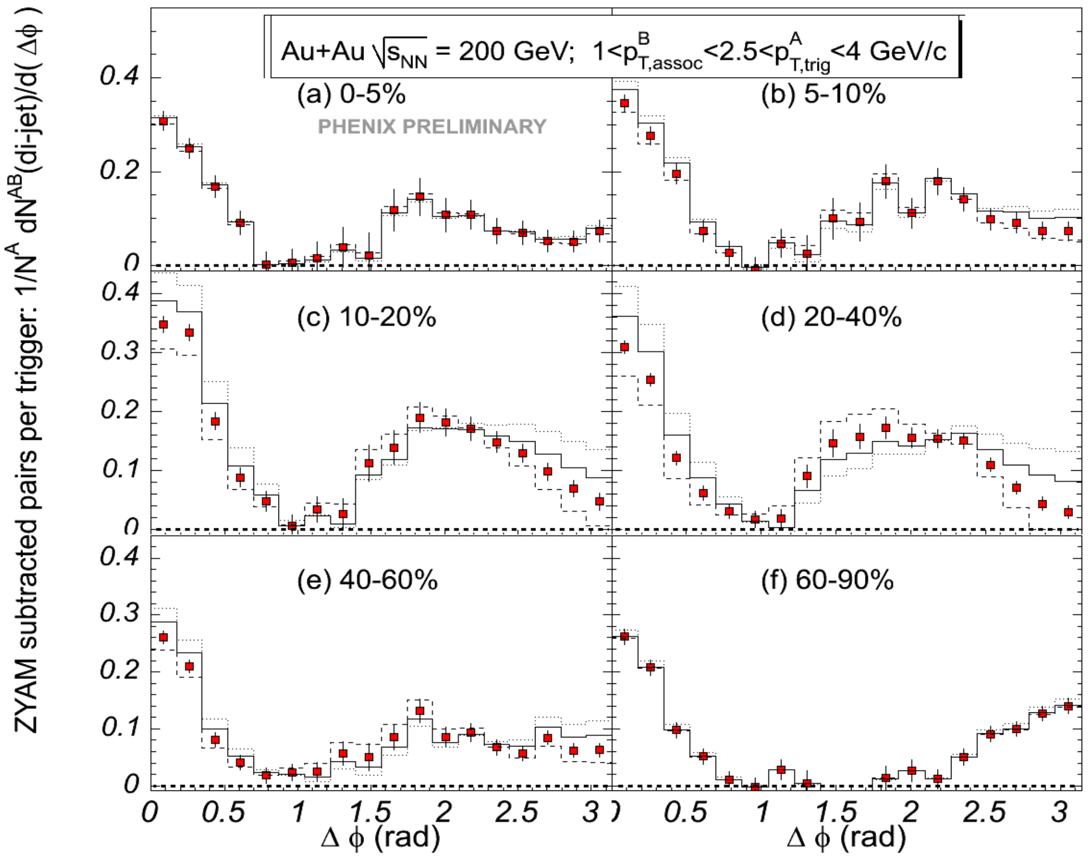
Wait for Run-4 data !

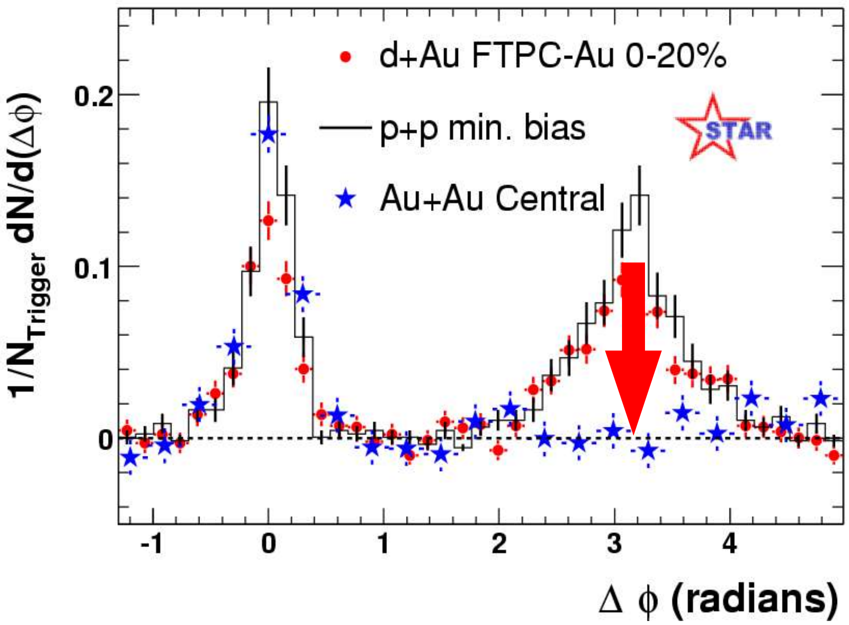
Stay tuned !

backup slides ...

Jet production in hot&dense QCD: modified (di)jet structure (I)

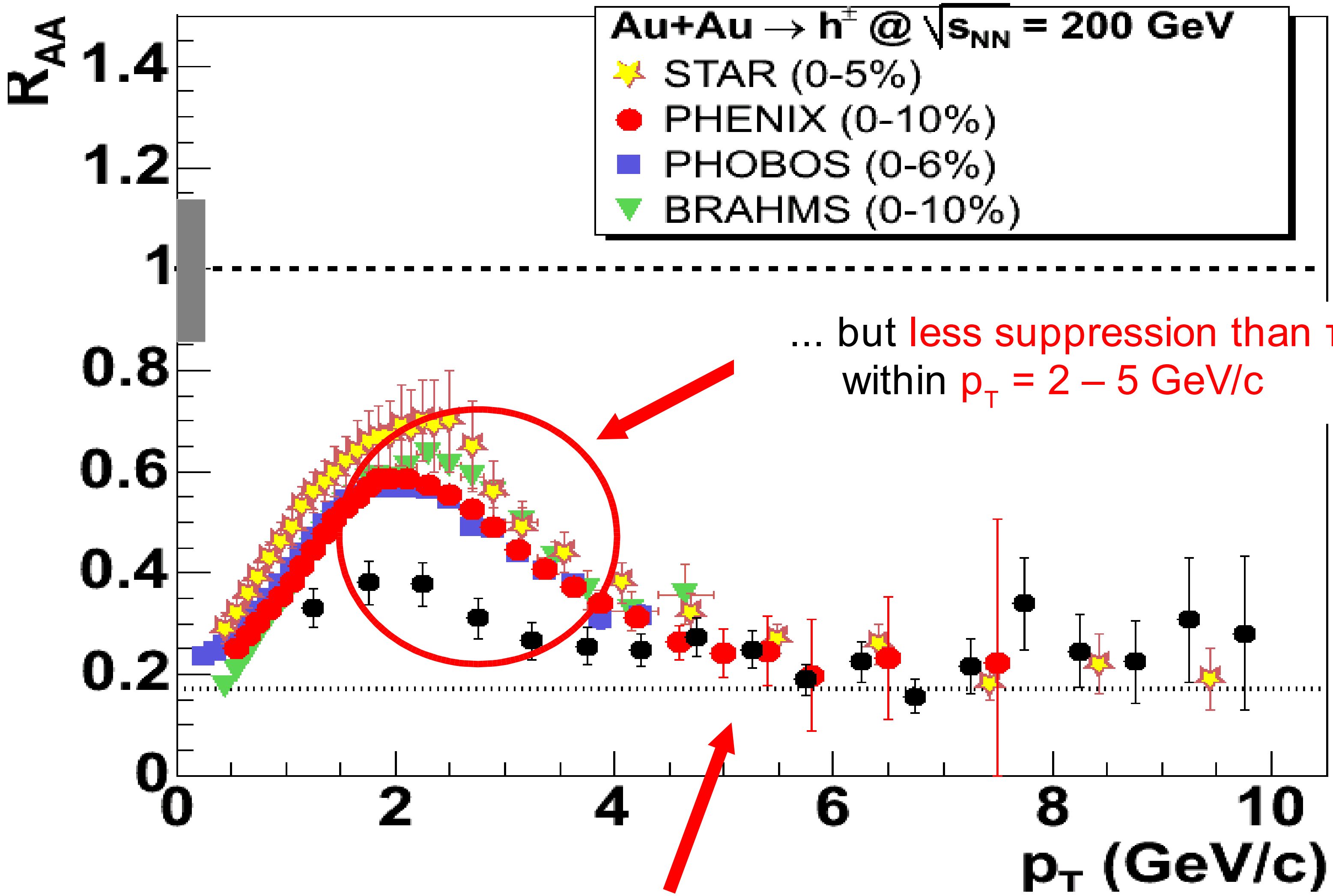
- Discovery of “mono-jet” like topologies (away-side disappearance):





Suppressed high p_T hadroproduction @ RHIC: $h^{\pm}$ vs π^0

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

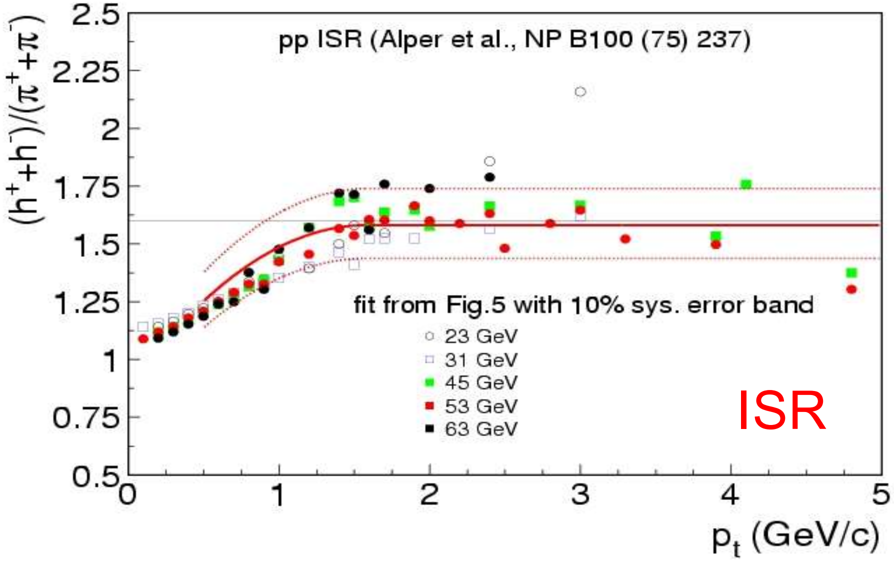


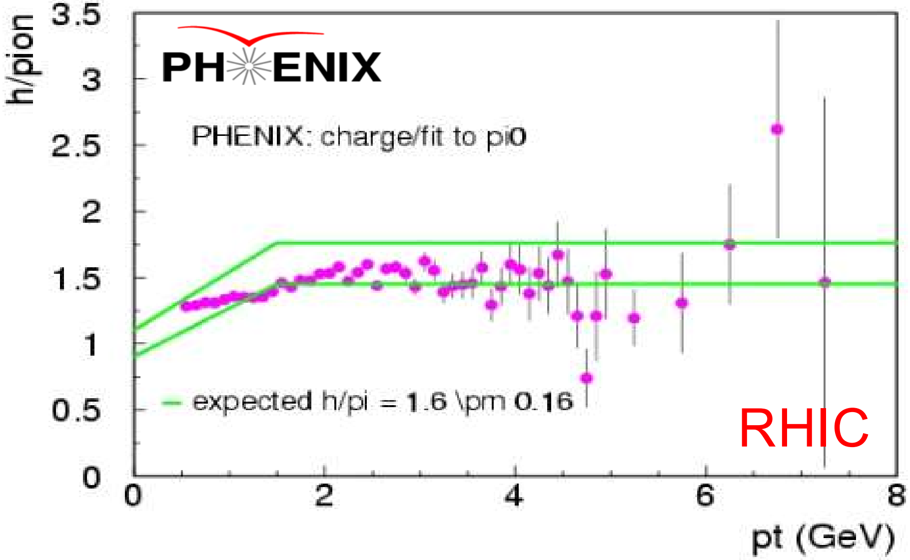
... but less suppression than π^0
within p_T = 2 – 5 GeV/c

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

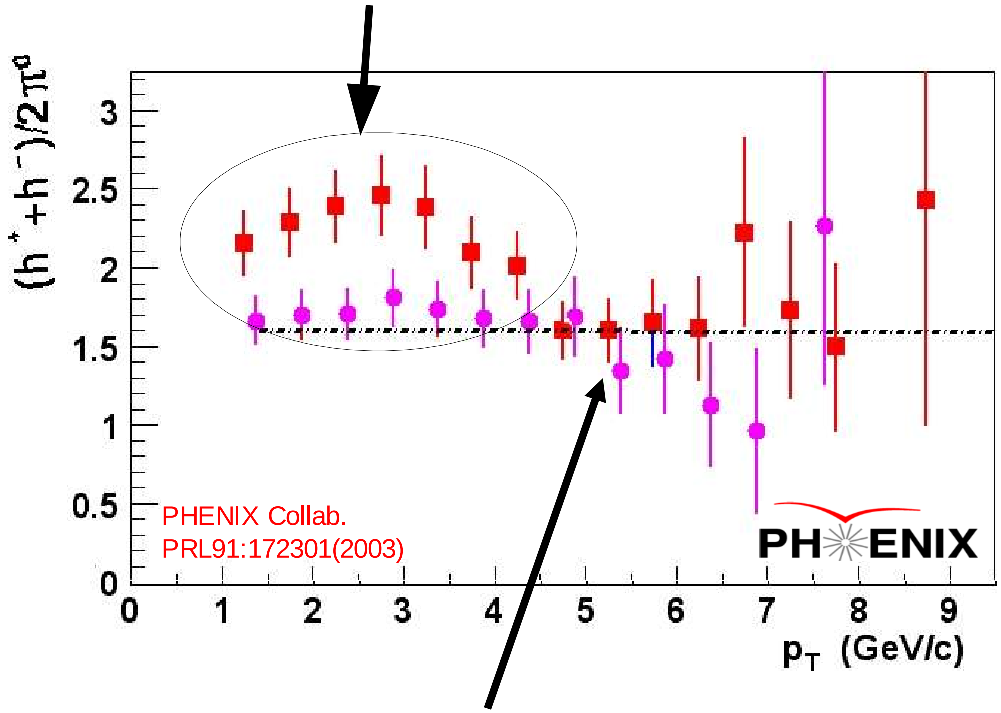
“Anomalous” particle composition: hadron/meson ratio

- 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).



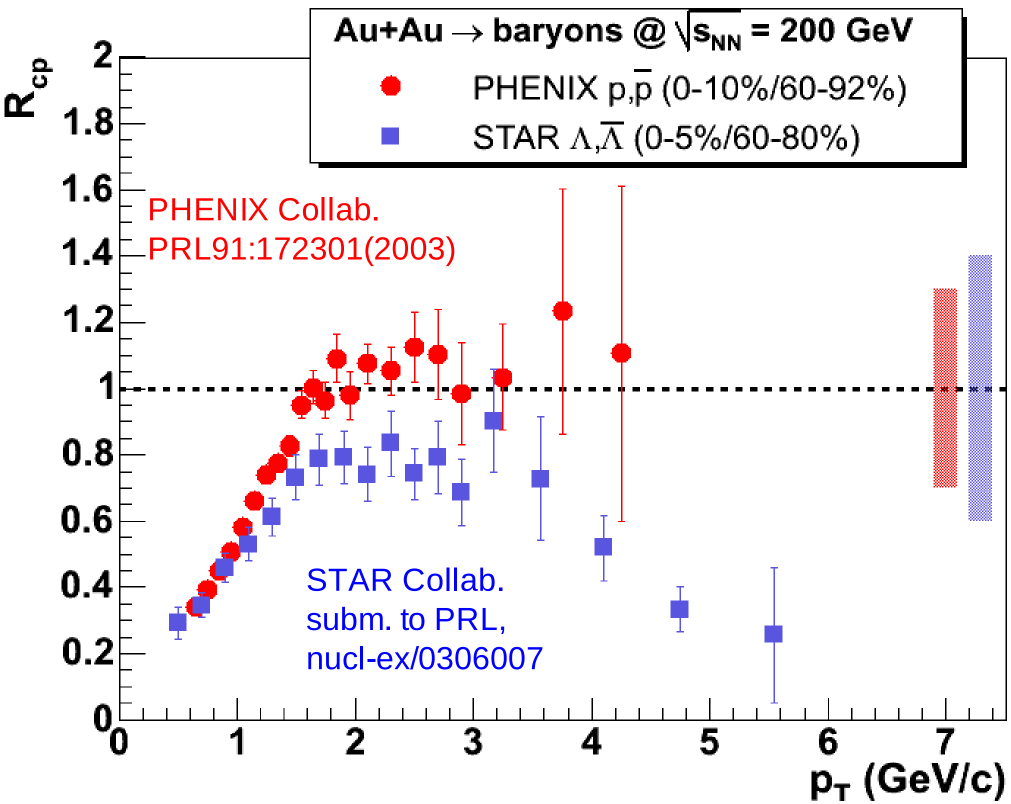
- Baryon enhancement limited to $p_T < 5$ GeV/c ($h^\pm/\pi$ ~ 1.6, perturb. ratio): $h^\pm$, π^0 equally suppressed

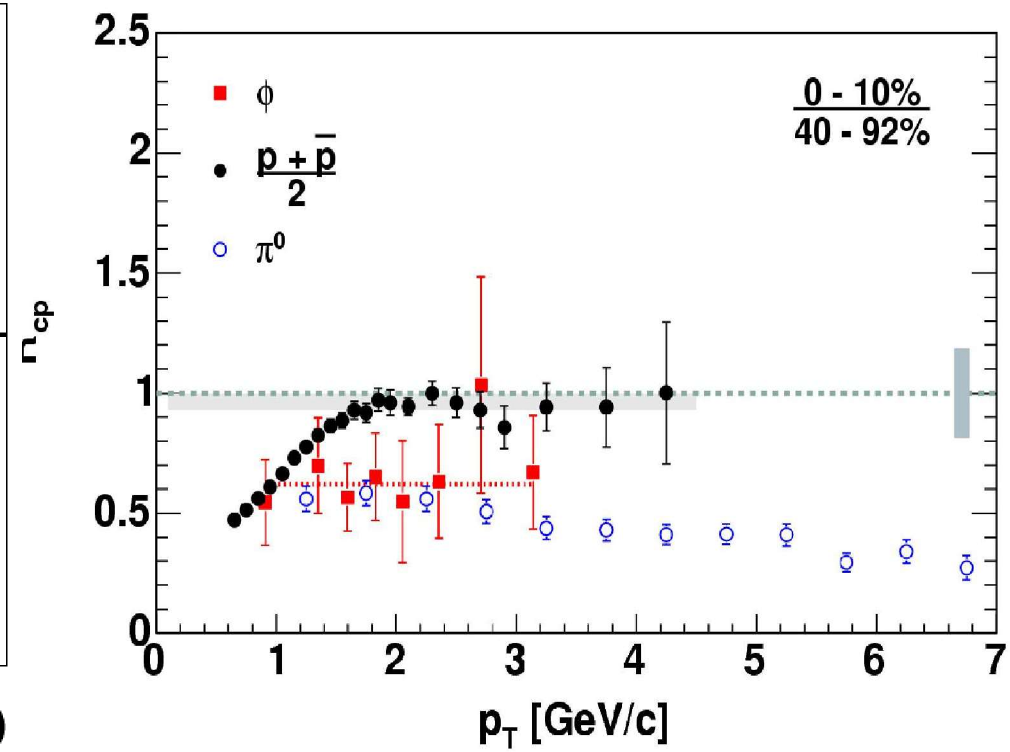
Unsuppressed baryon production: not a mass effect !

- 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)

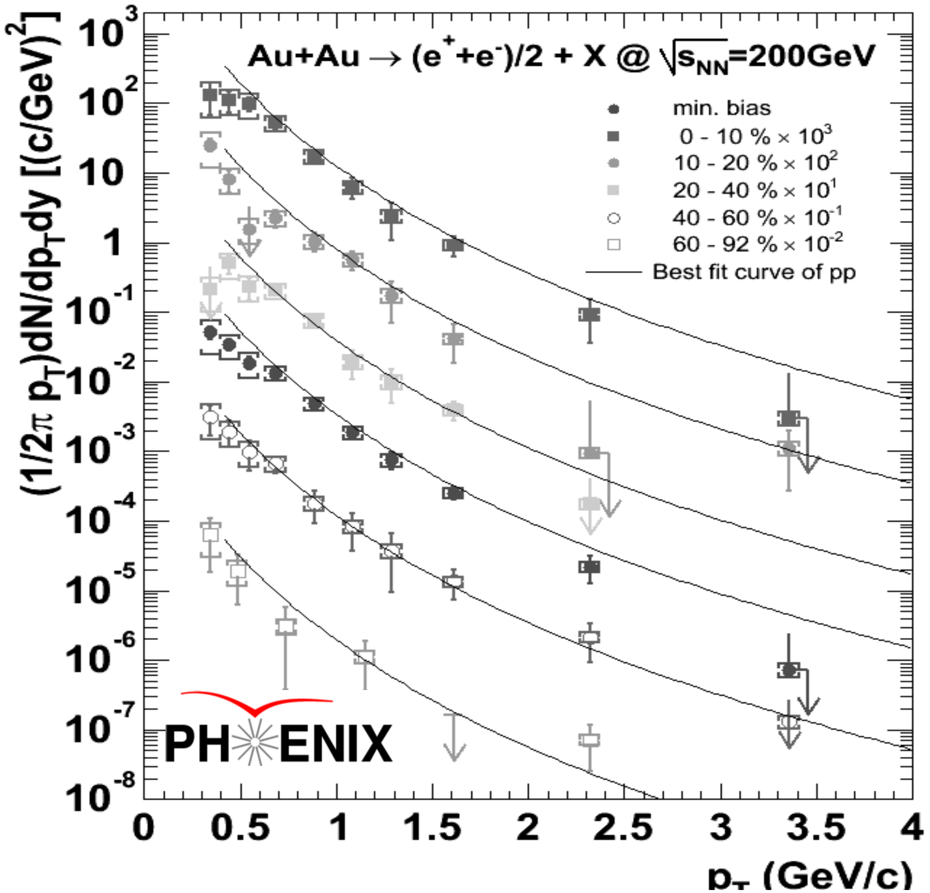


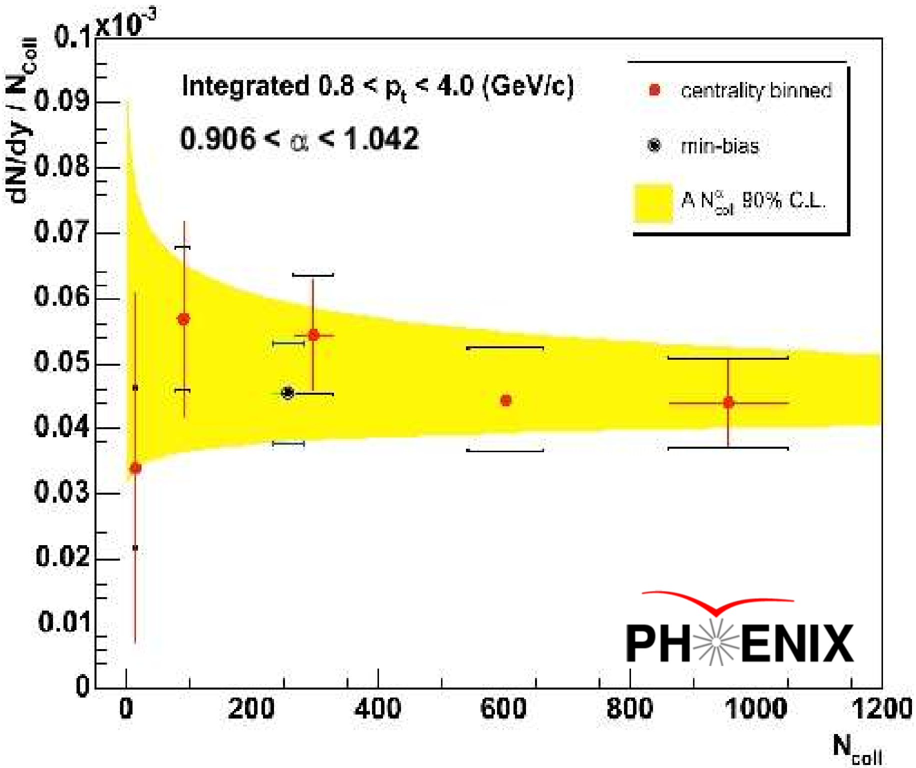


- Particle composition inconsistent with known (universal) fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range

"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:

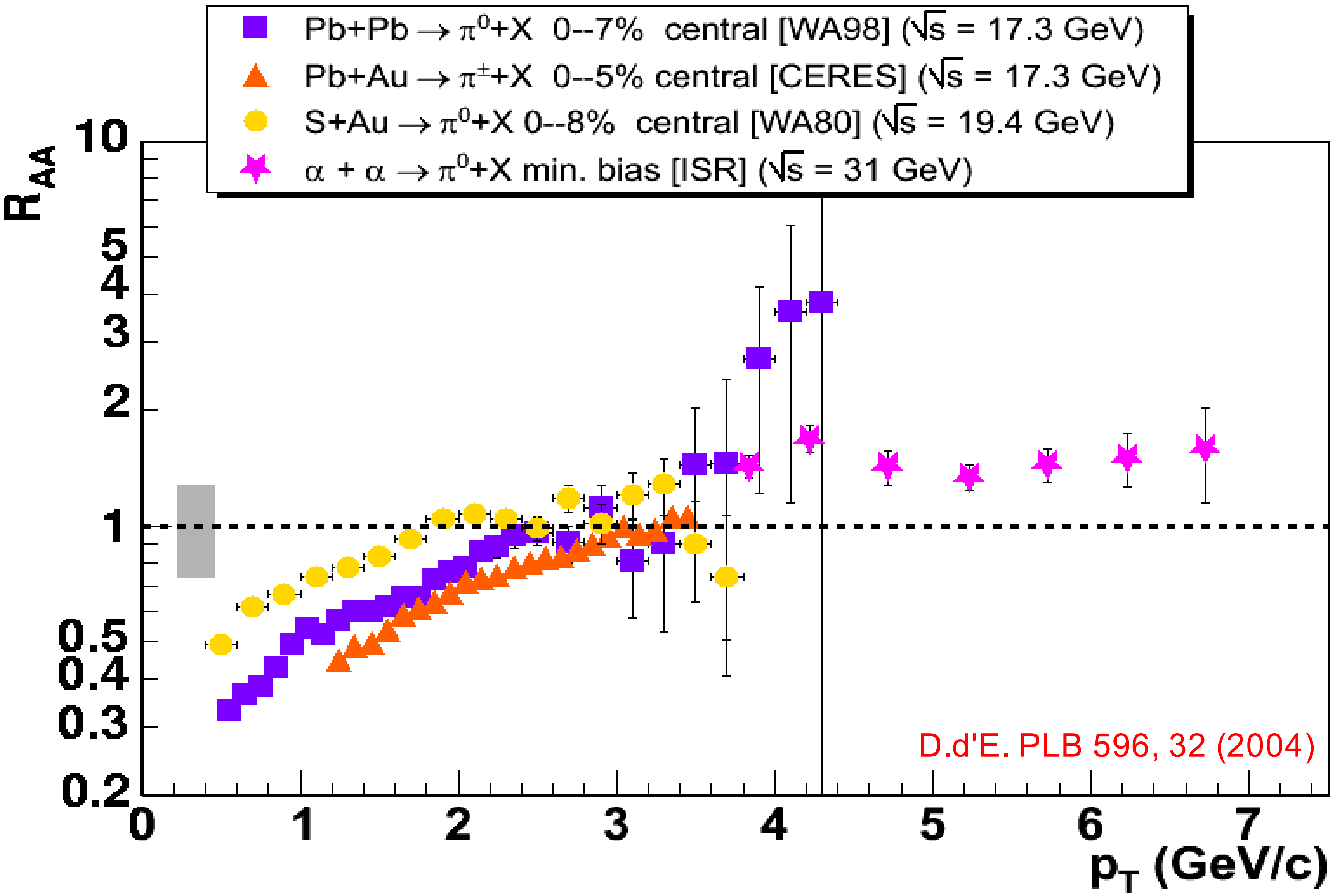




- pQCD parton scattering holds for hard processes in Au+Au (all centralities).

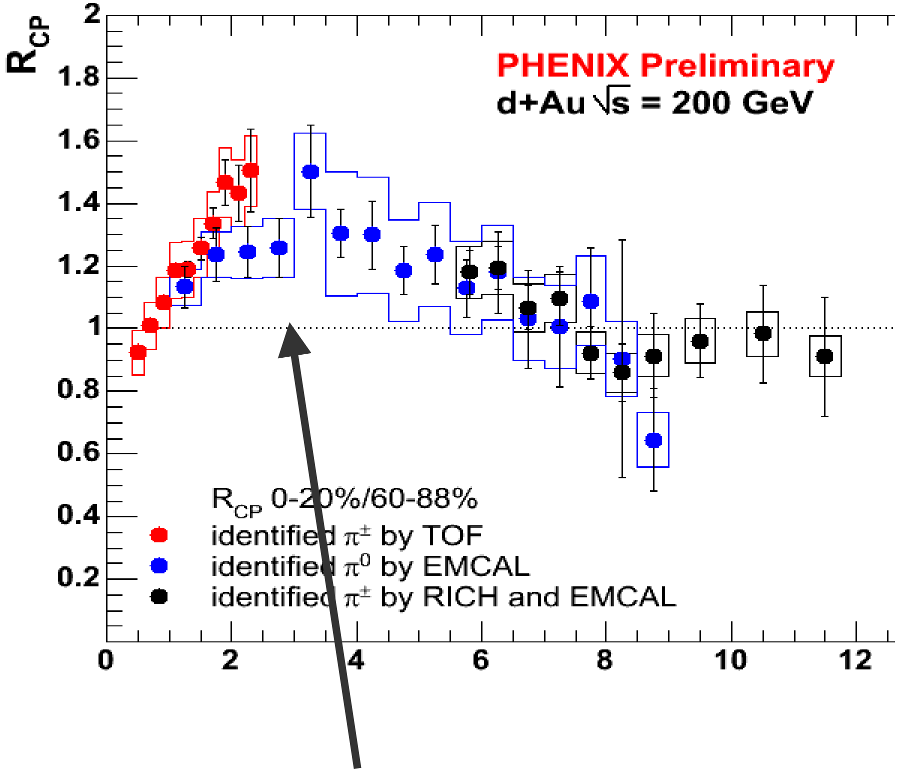
"N_{coll} scaling" in A+A @ 17, 31 GeV: High p_T hadrons

- 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):

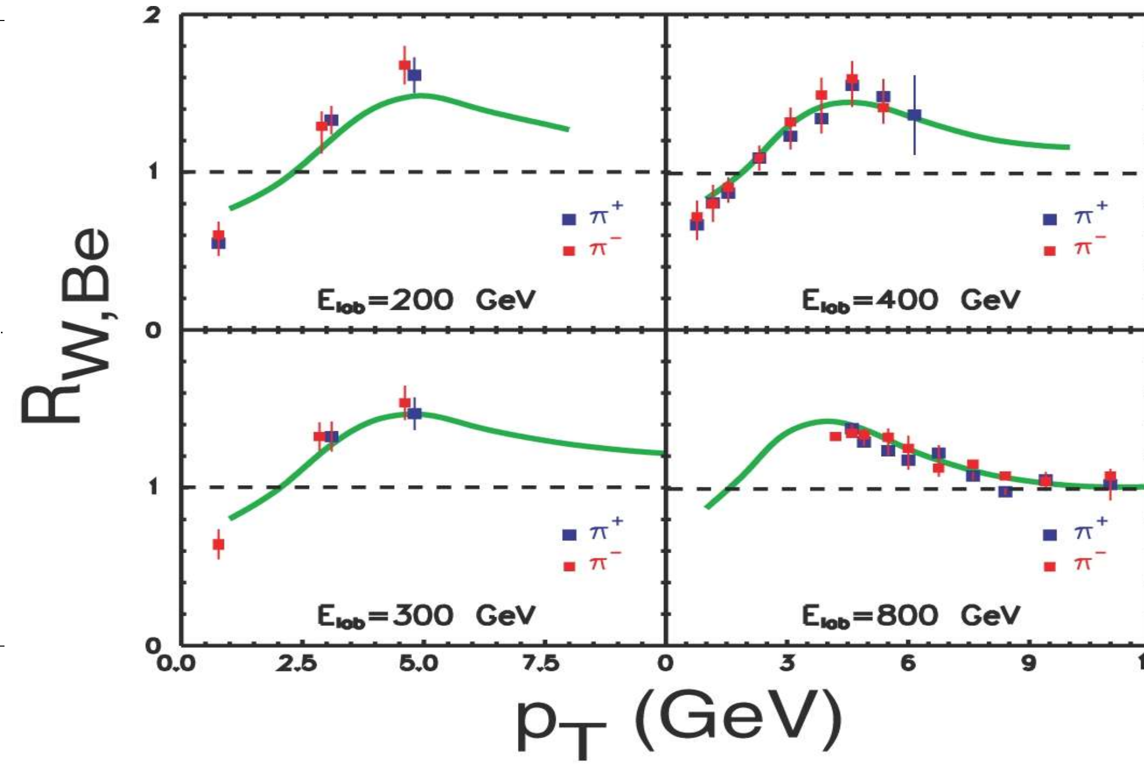


"N_{coll} scaling" in d+Au @ 200 GeV: High p_T hadrons

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



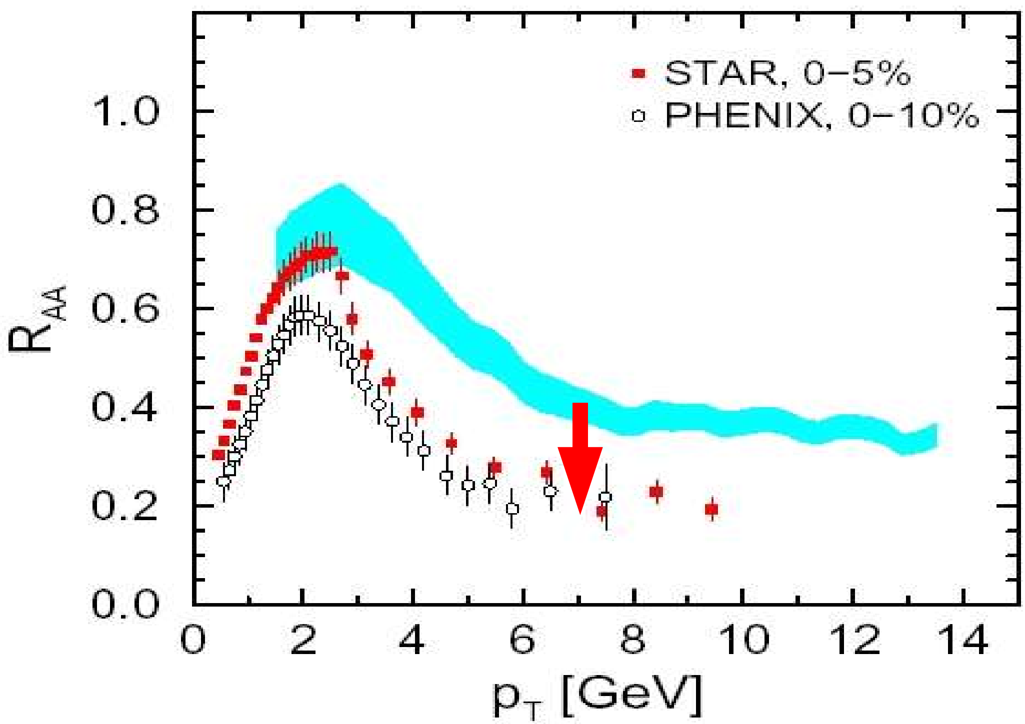
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



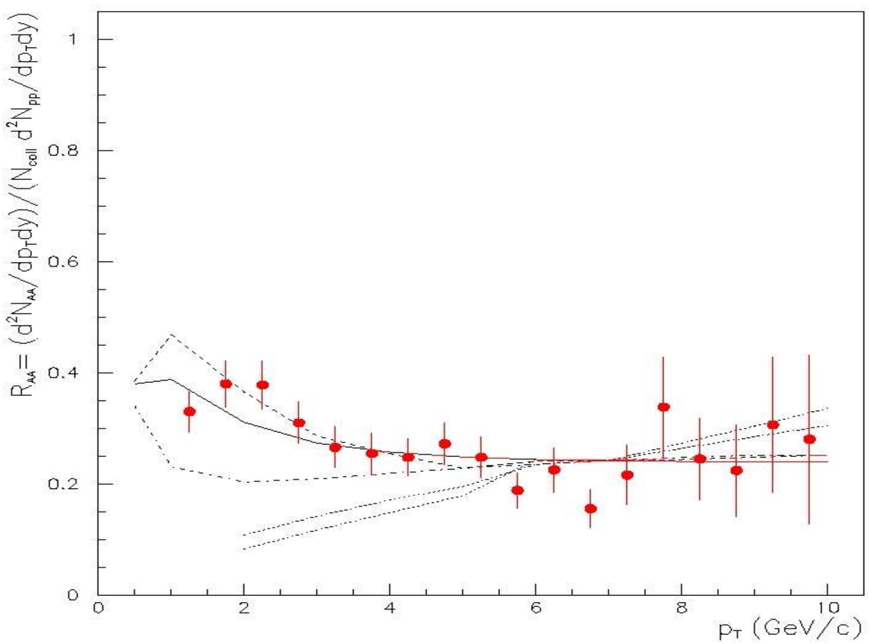
- Enhanced high p_T production in d+Au (R_{dAu} > 1) also found in p+A at lower $\sqrt{s}$ ("Cronin enhancement"): p_T broadening due to initial-state soft & semihard scattering.
- Expected pQCD behaviour ($R_{pA,dA}$~1) recovered for p_T > 8 GeV/c

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