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Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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Probing QCD at high parton densities from RHIC to LHC

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V[th] Int. Conf. on Perspectives in Hadronic Physics

Particle-Nucleus & Nucleus-Nucleus Scatt. at Relativistic Energies

ICTP, Trieste, May 24th, 2006

David d'Enterria

CERN, Geneva

(Comprehensive) Overview

- Intro: High-energy AA as a tool to study high-density QCD in the lab
- RHIC: Properties of quark-gluon matter in central AuAu (20-200 GeV):

$\tau < 1$ fm/c:

(1) Total multiplicities consistent w/ saturated nuclear low-x gluon distrib. $\Rightarrow$ **$dN_{ch}/d\eta$**

(2) Very high initial parton densities: $dN^g/dy \sim 1000$
Large transport coefficient $\langle q \rangle = \lambda^2/L \sim O(10)$ GeV^2/fm $\Rightarrow$ **high-p_T hadron dN/dp_T**

(3) Speed of sound $\langle c_s \rangle \sim 0.3$ (?) $\Rightarrow$ **high-p_T hadron $dN_{pair}/d\phi$**

(4) Nearly "perfect-fluid" (hydro. radial & parton elliptic flows) $\Rightarrow$ **hadron v_2, dN_{soft}/dp_T**
"Strongly coupled" $\Rightarrow$ **charm-Q R_{AA}, v_2, ... (?)**

(5) Deconfined (Debye-screened) (?) $\Rightarrow$ **J/ψ yields**

(6) Thermalized (T~350 MeV) (?) $\Rightarrow$ **photon dN/dp_T**

$\tau \sim 1$ fm/c:

(7) Energy densities above ϵ_{crit}: $\epsilon \sim 5$ GeV/fm^3 $\Rightarrow$ **$dE_T/d\eta$**

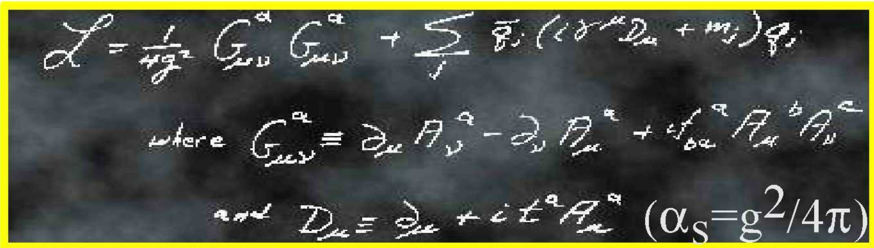
(8) Constituent quark-number scalings at hadronization $\Rightarrow$ **interm. p_T baryon dN/dp_T**

$\tau > 5$ fm/c:

(9) Chemically equilibrated at T~160 MeV $\Rightarrow$ **hadron ratios**

- LHC: Outlook to upcoming experimental opportunities (QGP, CGC).

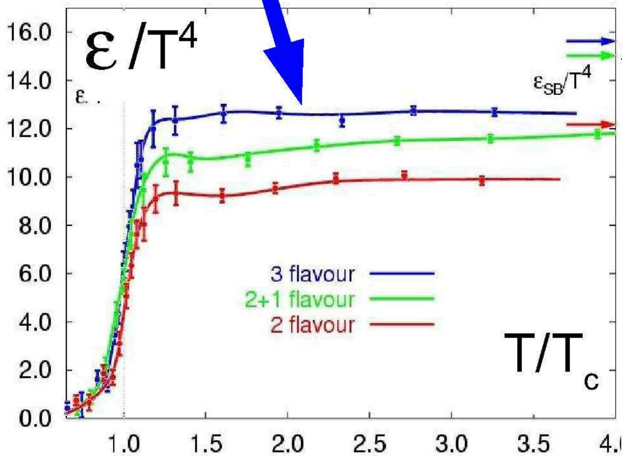
High-energy heavy-ion physics program (in 4 plots)

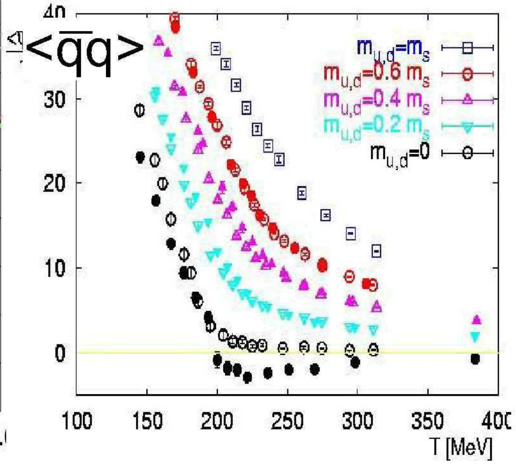


$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

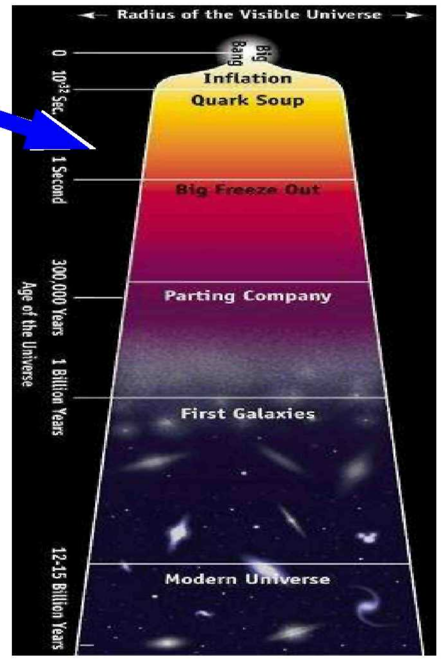
1. Learn about 2 basic properties of strong interaction: (de)confinement, chiral symm. breaking (restoration)

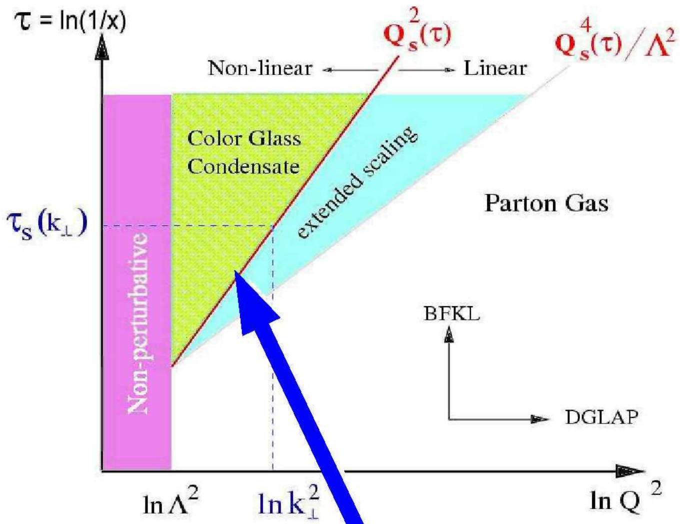
2. Study the phase diagram of QCD matter: esp. produce & study the QGP





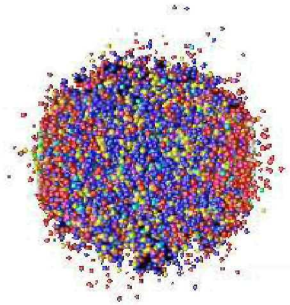
3. Probe quark-hadron phase transition of the primordial Universe (few μsec after the Big Bang)



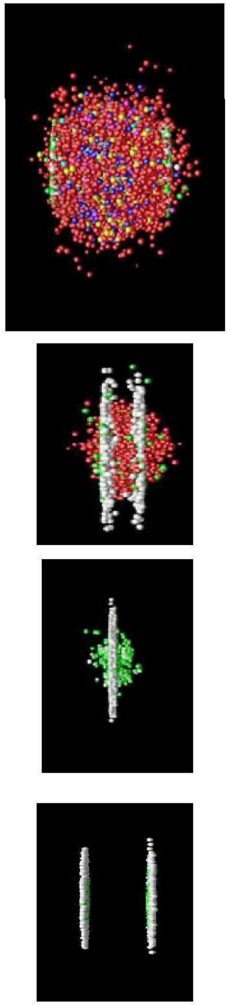


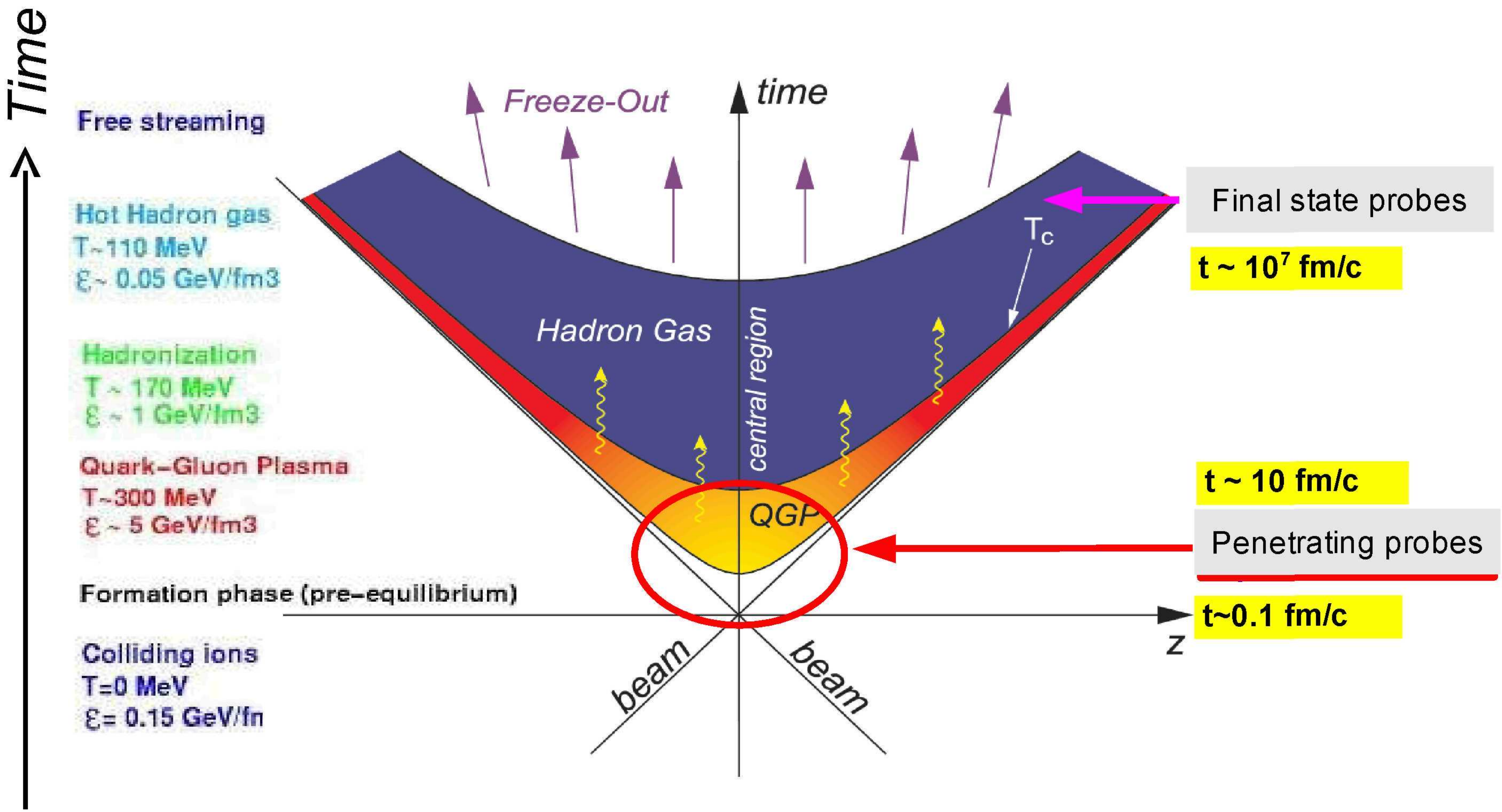
4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

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. reaction 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

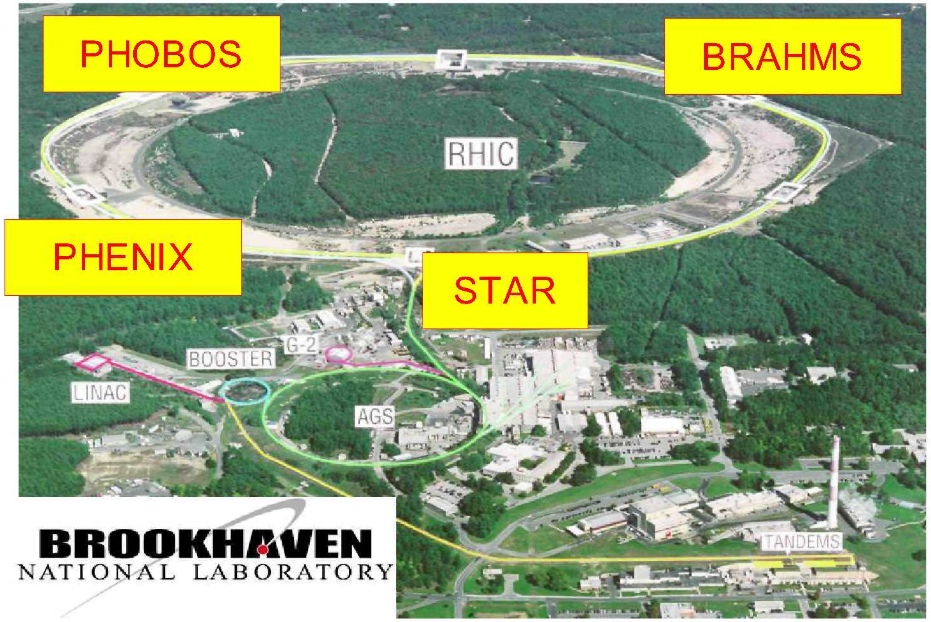
p+A collisions @ $\sqrt{s}_{max}$ = 200 GeV

4 experiments:

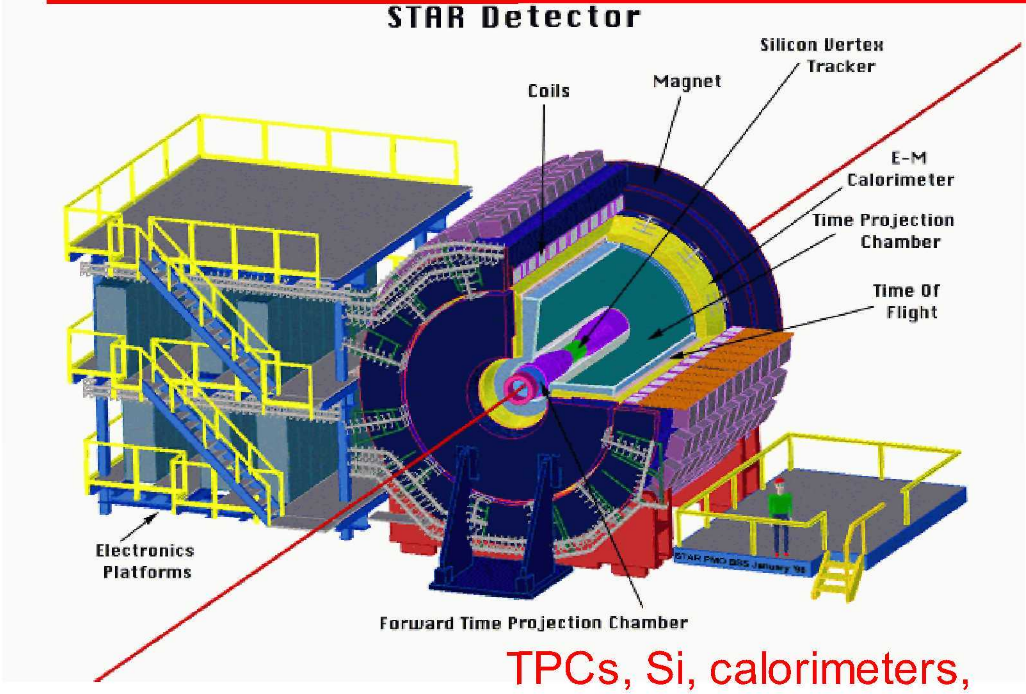
BRAHMS, PHENIX, PHOBOS, STAR

Runs 1 - 6 (2000 – 2006):

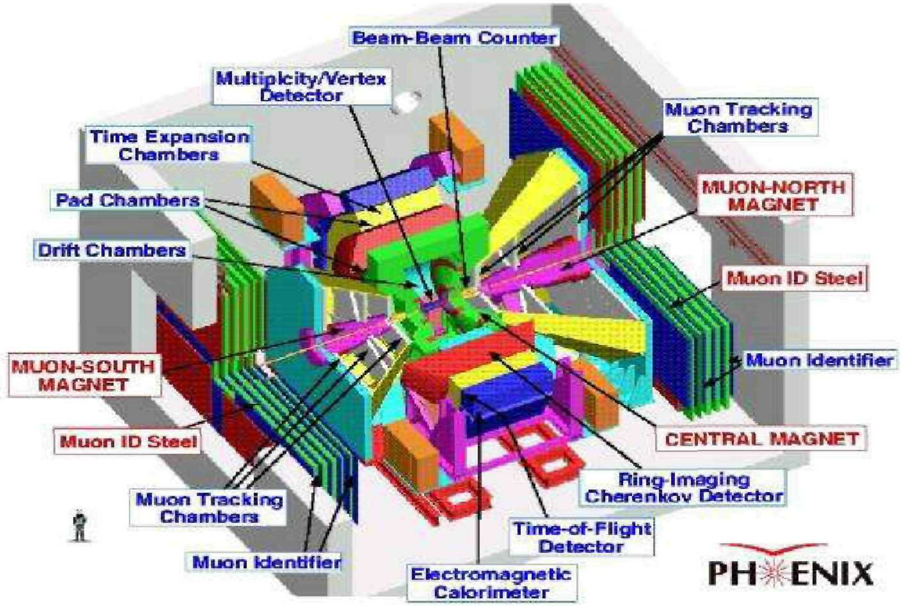
Au+Au @ 200, 130, 62.4, 22 GeV
Cu+Cu @ 200, 62.4 GeV
d+Au @ 200 GeV
p+p (polarized) @ 200, 62, 22 GeV



The 4 RHIC experiments

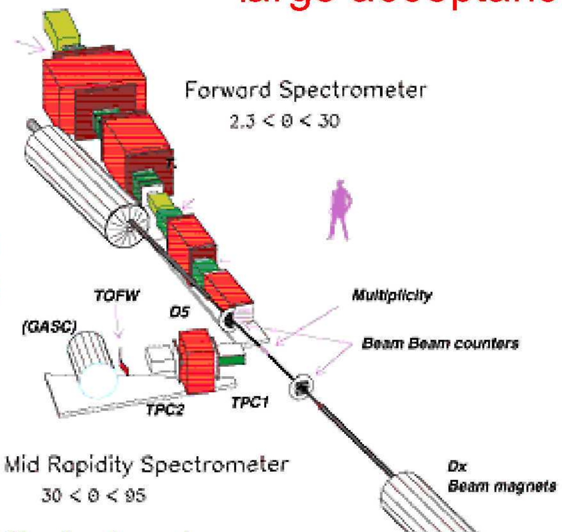


TPCs, Si, calorimeters,
large acceptance



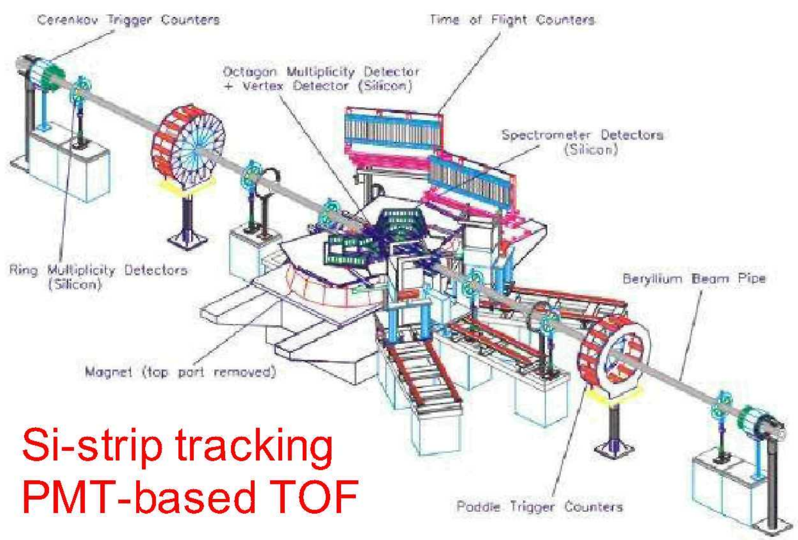
Hadrons, e's, mu, photons. High-rate DAQ.
Rare&penetrating probes

2 magn. dipole
spectrometers
in “fix-target”
config.



BRAHMS detector

PHOBOS Detector



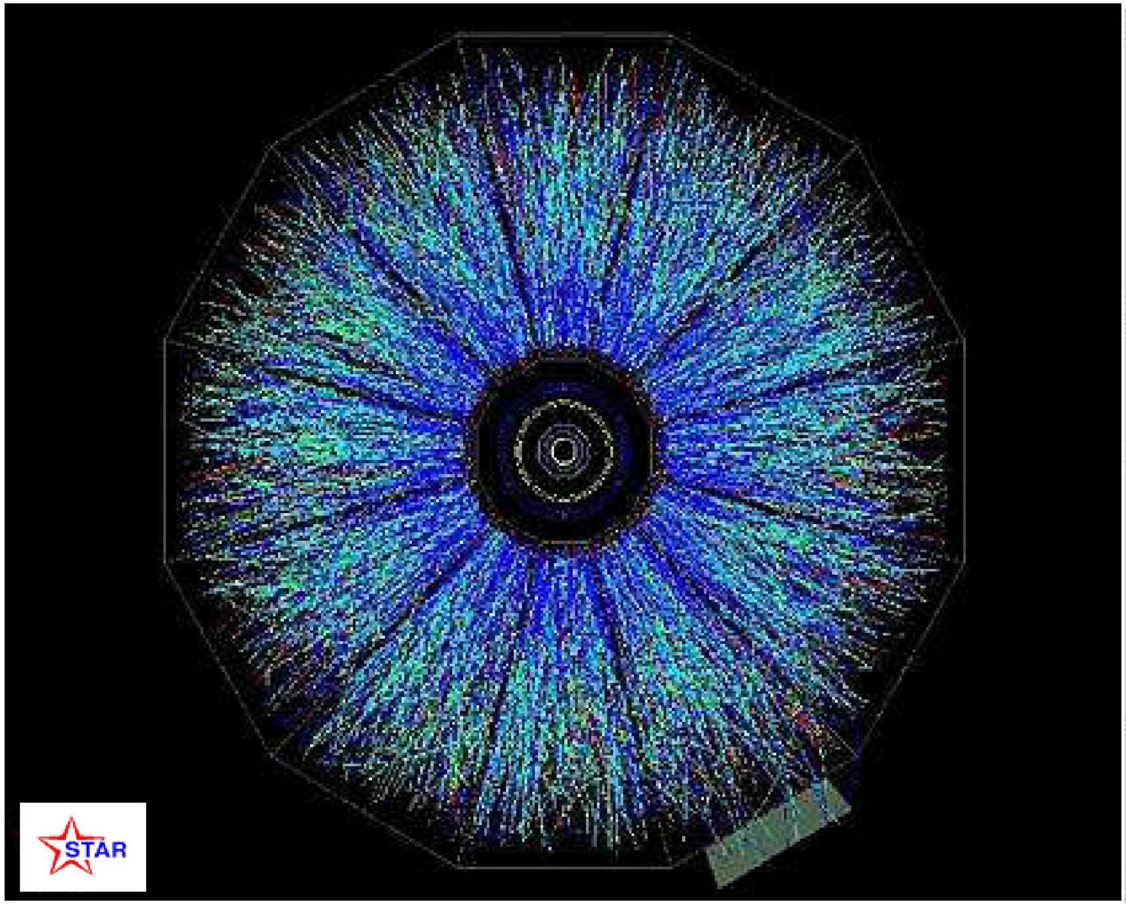
Si-strip tracking
PMT-based TOF

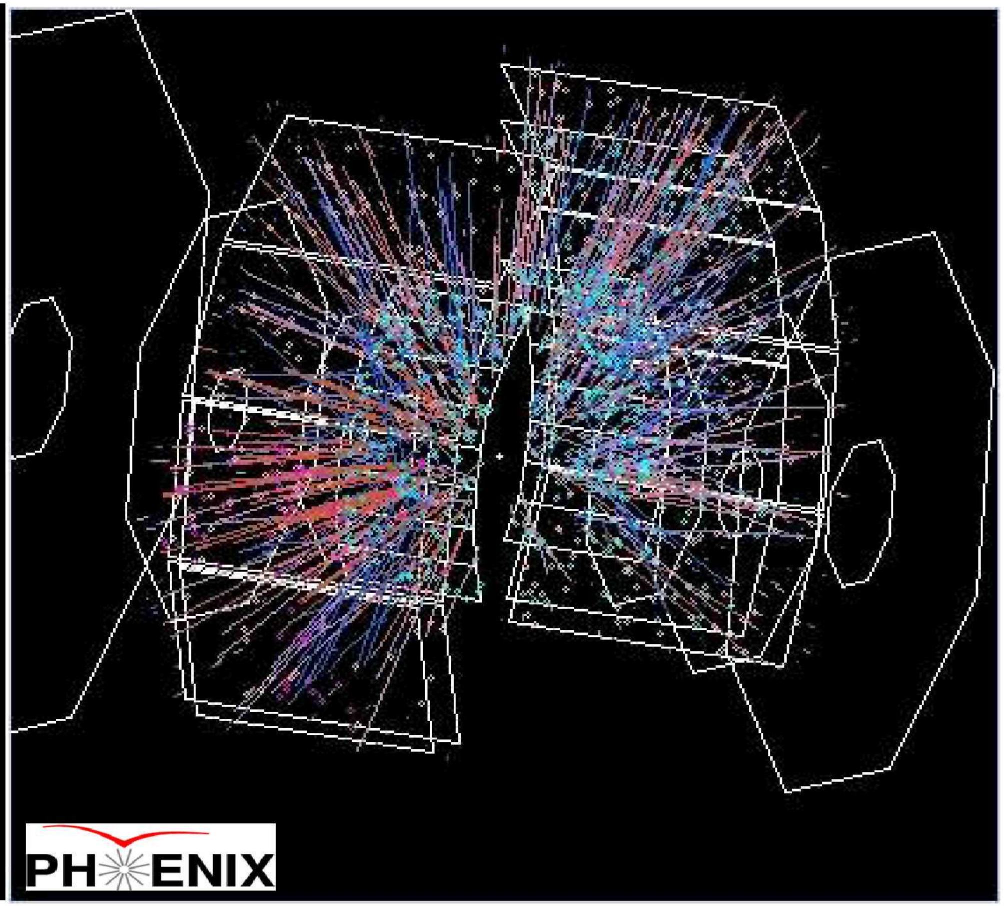
(1) AuAu particle multiplicities ($dN_{ch}/d\eta$)

Hadron multiplicities consistent w/ released # of gluons
from saturated nuclear low-x gluon distribution

See also talks by: E. Iancu / F. Gelis / E. Ferreiro ...

AuAu collisions @ 200 GeV





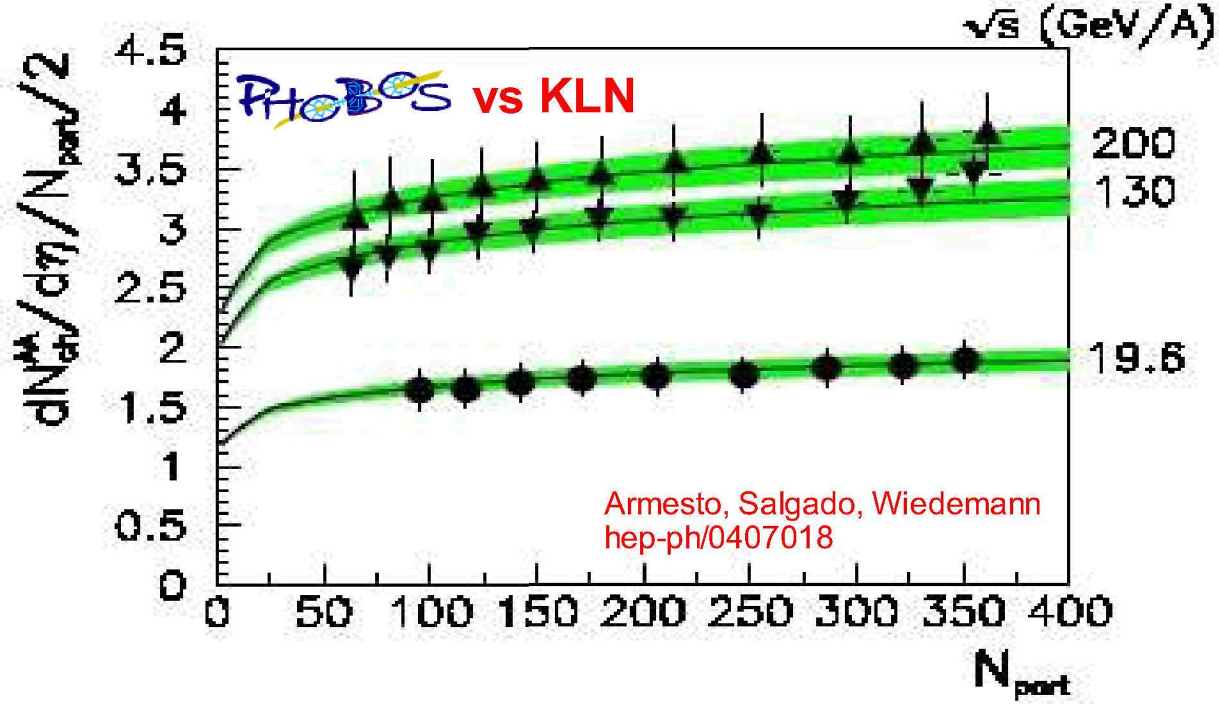
~ 700 charged particles per unit rapidity at midrapidity (top 5% central)

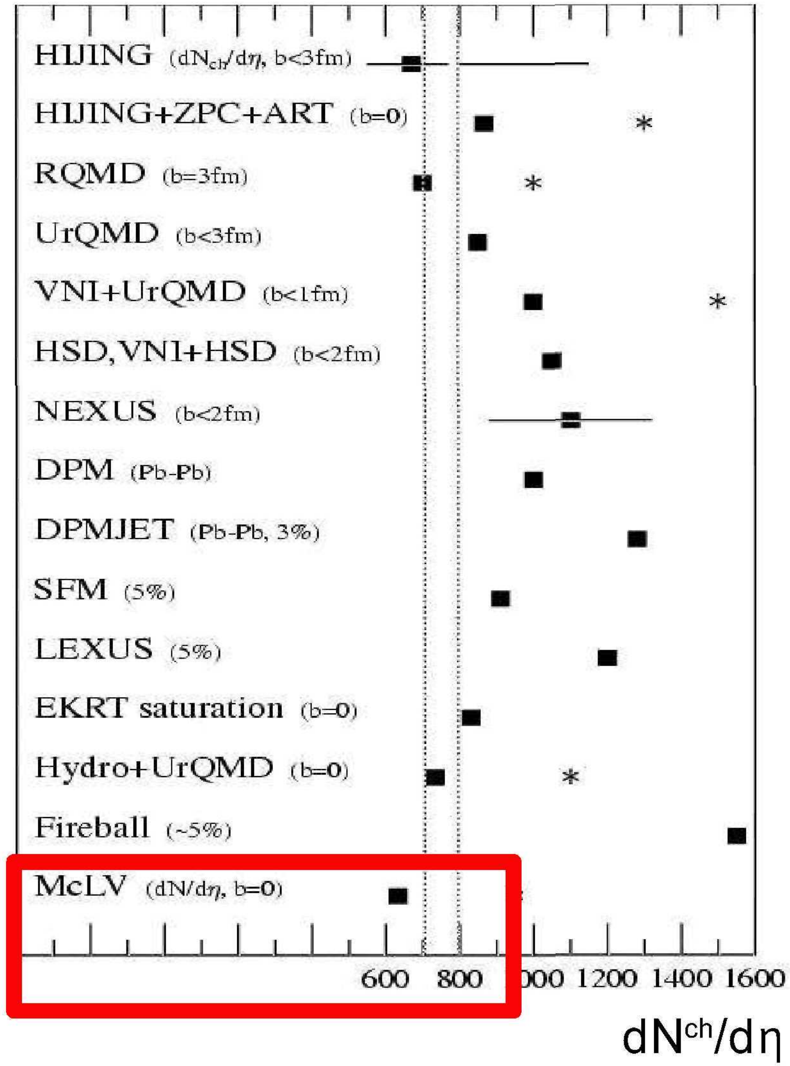
Charged particle multiplicities at RHIC

- Total AuAu particle multiplicity (plus its centrality evolution) related to released number of gluons:

KLN PLB507(01)121 :

$$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)}\,Q_s^2 \propto xG(x,Q_s^2)A^{1/3}$$





Calculations assume "local parton-hadron duality" (1 gluon = 1 final hadron)

- Note: Saturation scale @ RHIC (HERA), Q_s^2~1.5 GeV^2, too close to non-perturb. range

(2) High p_T hadron suppression

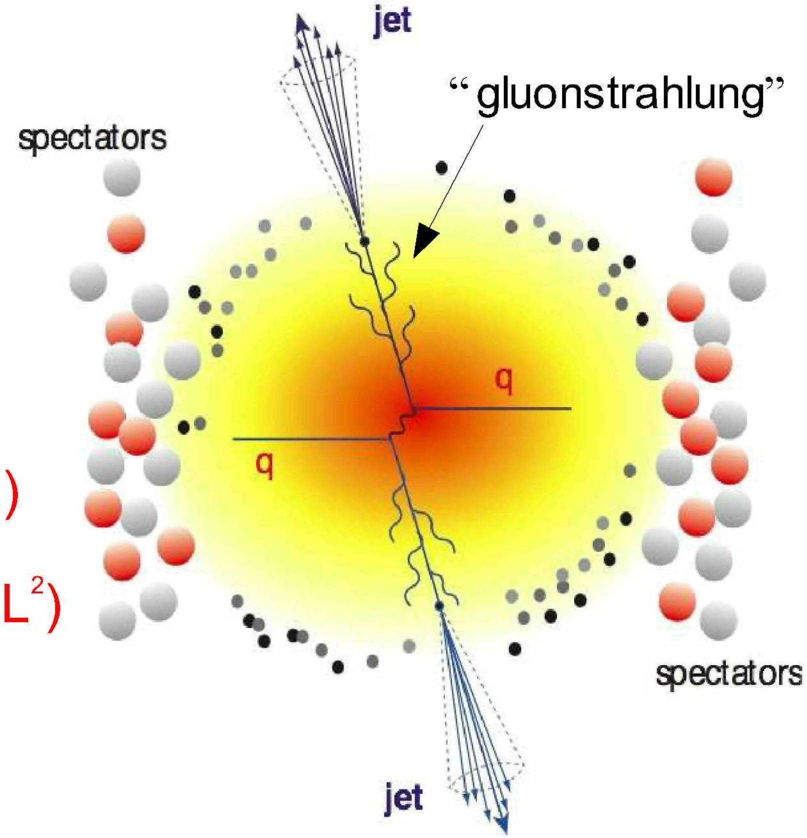
Consistent with "jet quenching" (parton energy loss) calculations:

Initial parton medium densities: $dN^g/dy \sim 1000$

Large transport coefficient: $\langle \hat{q} \rangle \sim O(10)\ \mathrm{GeV}^2/\mathrm{fm}$

See also talks by: N.Armesto, F.Arleo, C.Salgado, U.Wiedemann, ...

"Jet quenching" predictions



- Multiple final-state non-Abelian (gluon) radiation off the produced hard parton induced by the traversed dense medium.

  (Role of elastic energy loss under discussion today)

- Parton energy loss ∝ medium properties:

  GLV: $\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L$ ∝ (gluon density, L)

  BDMPS: $\langle \Delta E \rangle \propto \alpha_S C_R \langle \hat{q} \rangle L^2$ ∝ (transp. coeffic., L^2)

- Flavor dependent energy losses:

  $\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

  (color factor) (mass effect)

- Energy carried away by gluonsstrahlung inside jet cone: $dE/dx \sim \alpha_s \langle k_T^2 \rangle$

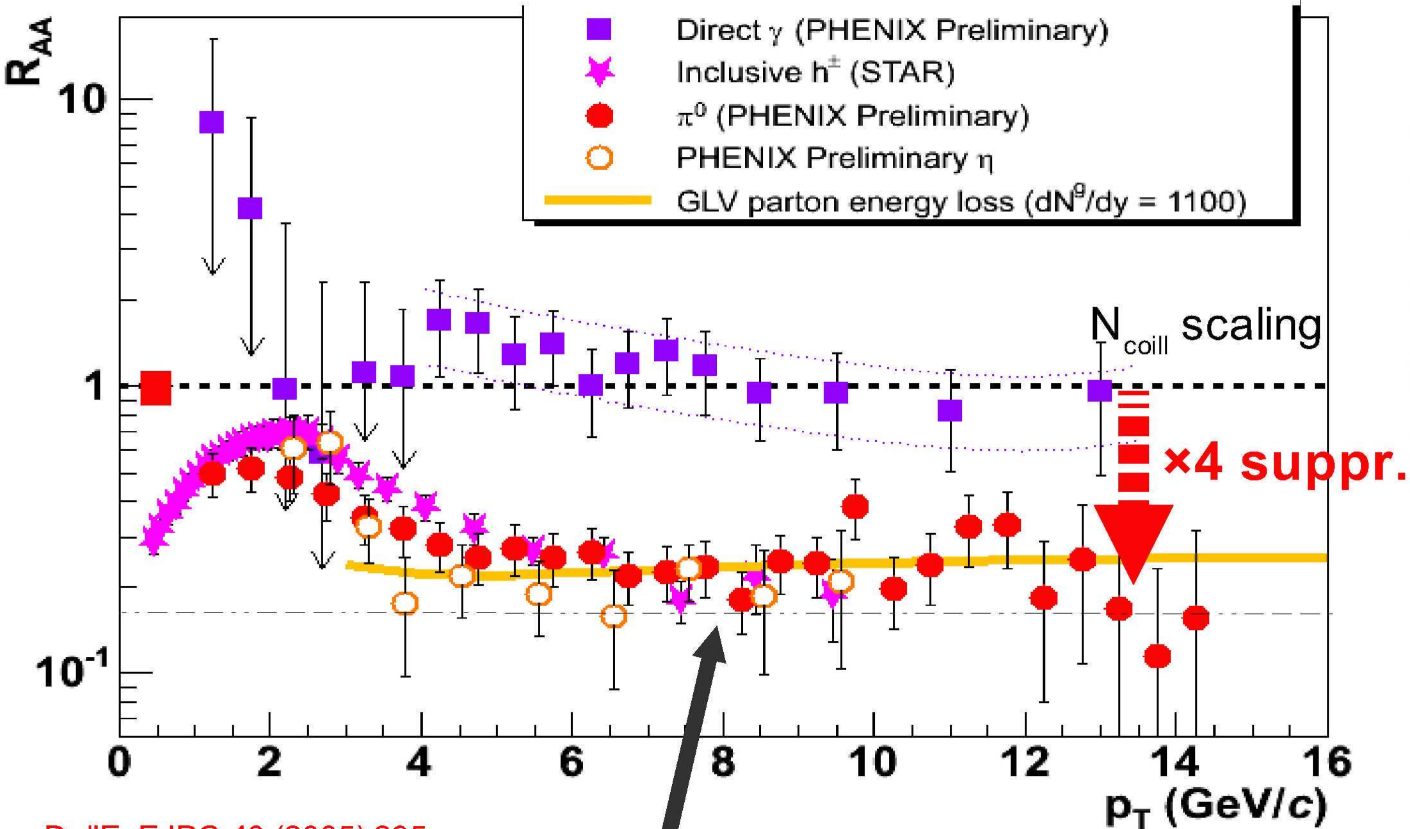
- Comparison to nuclear DIS results needs correction for expanding system:

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

> - Suppression of high p_T leading hadrons
> - Disappeareance of back-to-back (di)jet correlations

Suppressed high p_T hadroproduction in central AuAu

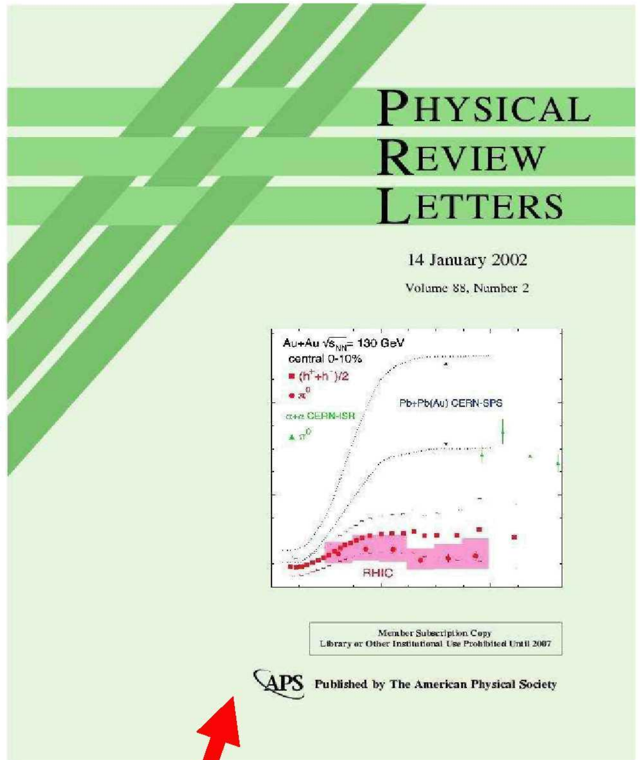
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$ = "QCD medium"/ "QCD vacuum"



D.d'E, EJPC 43 (2005) 295

N_{part} scaling (surface emission)

PHENIX PRL 88, 022301 (2002)



[2002] Discovery of high p_T suppression (one of most significant results @ RHIC so far)

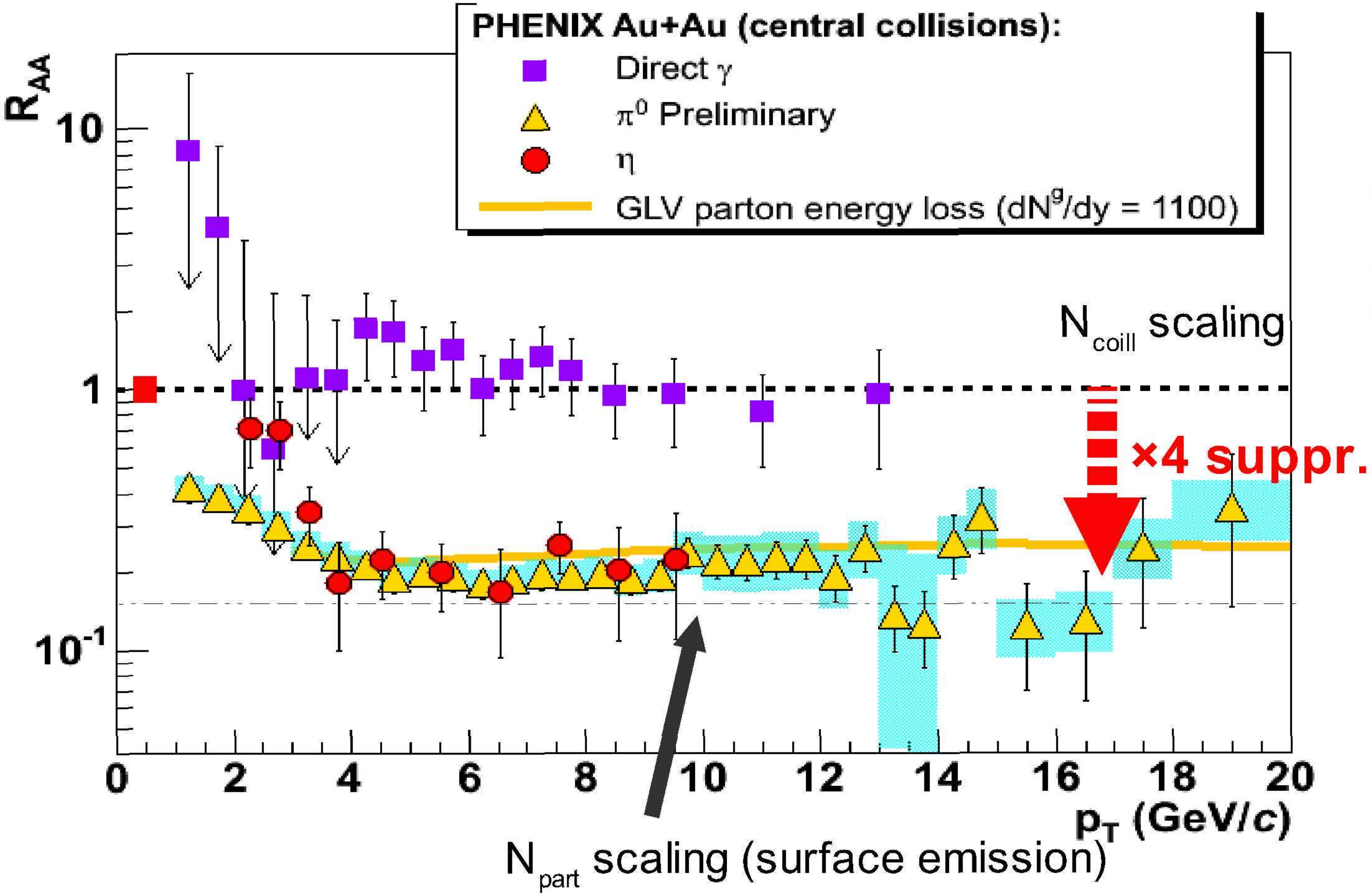
R_{AA}~ 1: Photon spectrum consistent w/ $pQCD \times N_{coll}$ (unaffected by FSI, incoherent sum of pp)

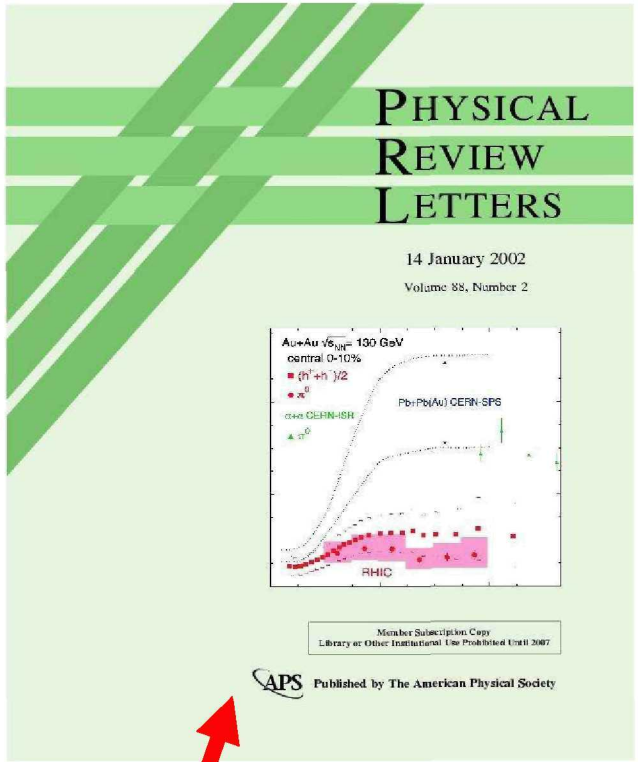
R_{AA} << 1: Hadrons well below pQCD expectations. Parton energy-loss: dN^g/dy ~ 1100, $\langle \hat{q}_0 \rangle$ ~ 14 GeV^2/fm

Suppressed high p_T hadroproduction in central AuAu

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

PHENIX PRL 88, 022301 (2002)





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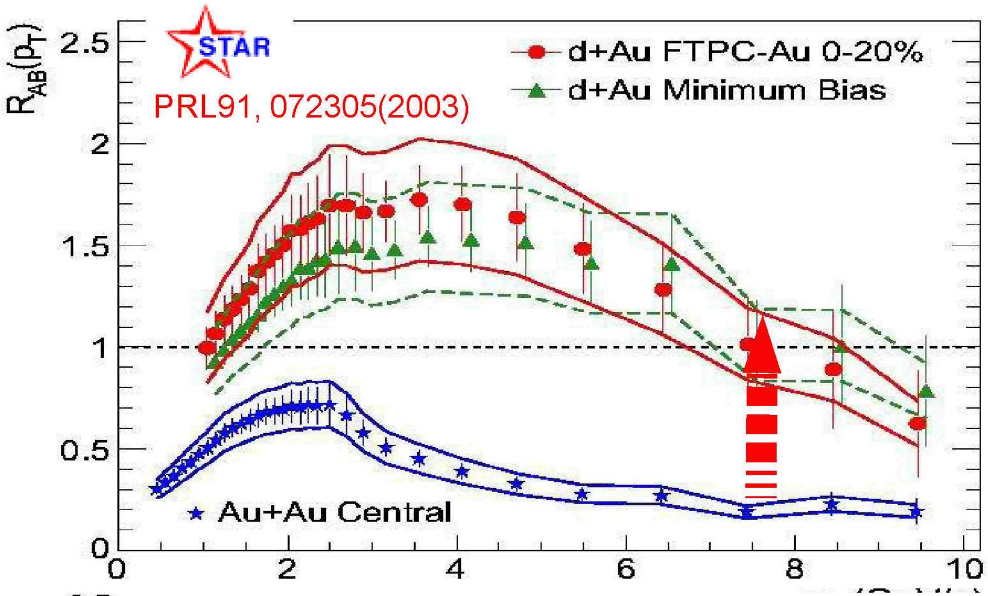
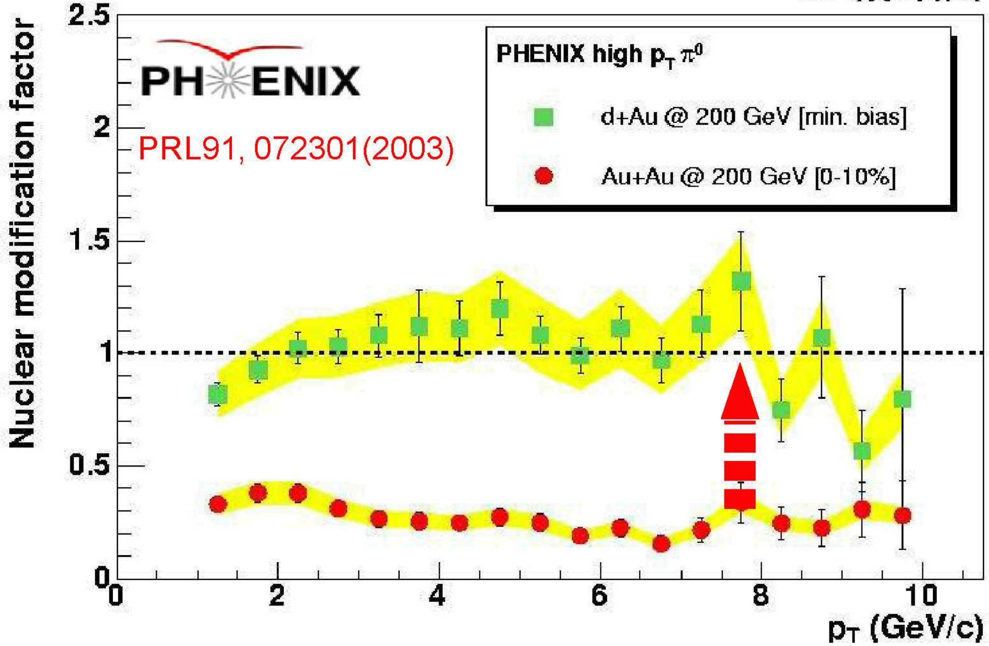
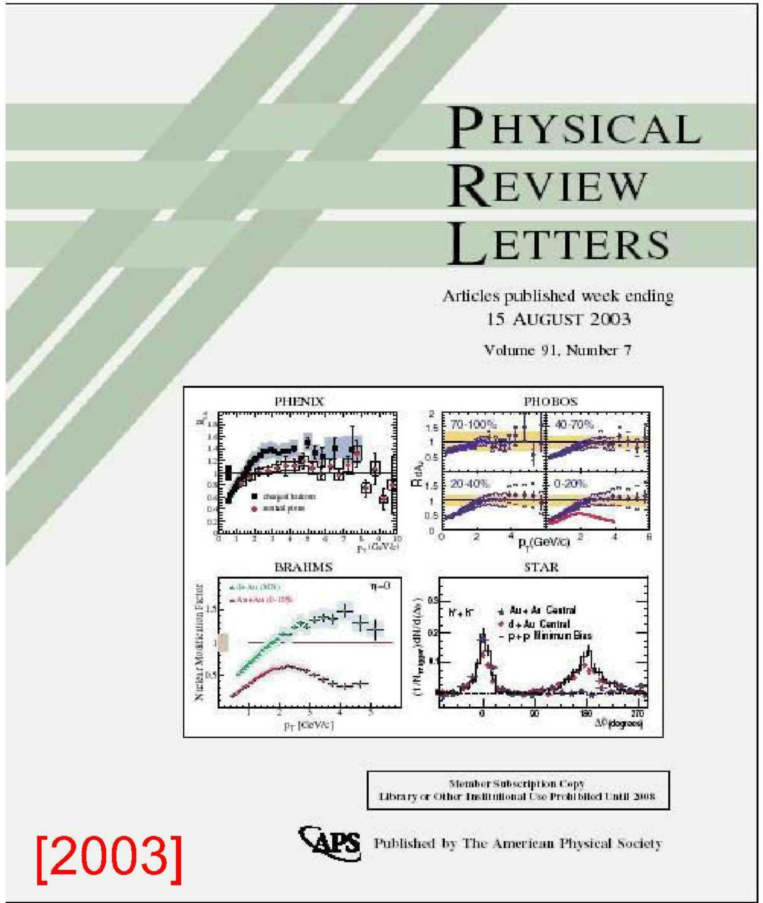
Parton energy-loss: $dN^g/dy \sim 1100$, $\langle q_0\rangle \sim 14$ GeV^2/fm

Unquenched high p_T hadroproduction in dAu







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

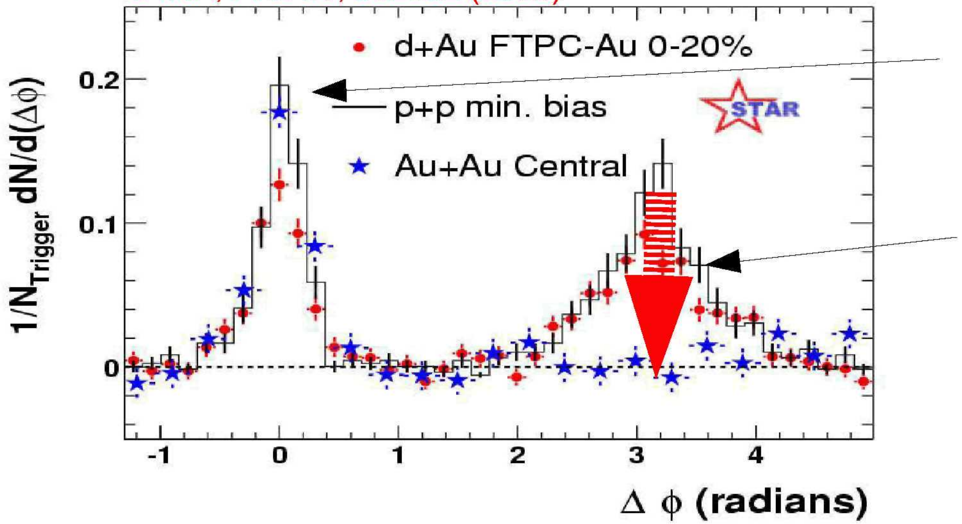
(3) Modified high p_T hadron azimuthal correlations ($dN_{pair}/d\phi$)

Absorbed away-side jet ("mono-jets" configuration)
"Lost" energy redistributed at lower p_T's.

Double-peak structure: Mach cone effect in the plasma ?
Speed of sound c_s~0.3 (?)

High p_T di-hadron Δφ correlations in central AuAu

STAR, PRL 90, 082302 (2003)

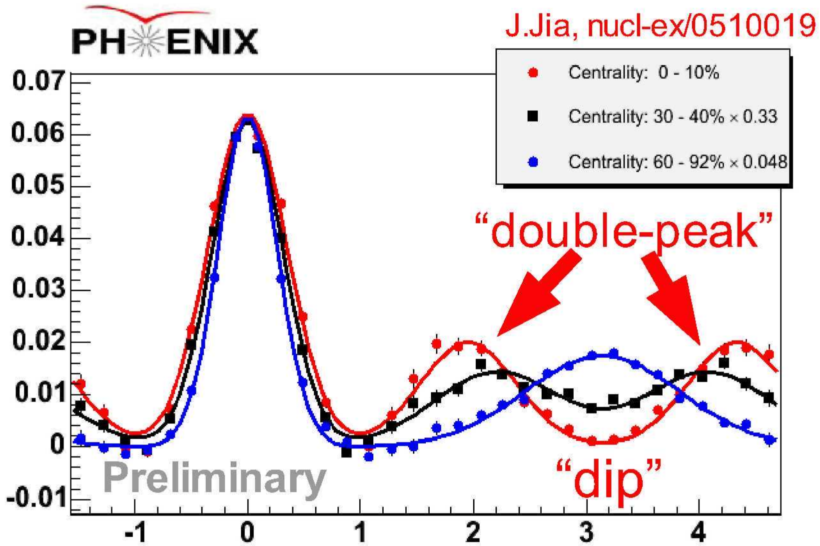


- Near-side jet-like Gaussian peak unmodified (AuAu ~ dAu ~ pp)
- Away-side peak disappearance: "monojet"-like topology

$p_{T\ trigg}$ = 4 – 6 GeV/c
$p_{T\ assoc}$ > 2 GeV/c

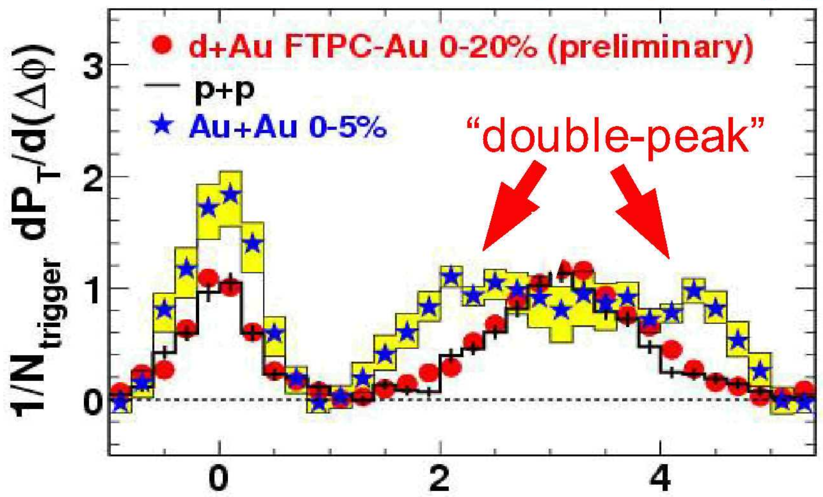
- "Lost" away-side energy dissipated at lower p_T values.
- Away-side Δφ peak splits in two with increasing centrality:

J.Jia, nucl-ex/0510019



$p_{T\ trigg}$ = 2.5 – 4 GeV/c
$p_{T\ assoc}$ = 2 – 3 GeV/c

STAR, PRL95,152301(05)



$p_{T\ trigg}$ = 4 – 6 GeV/c
$p_{T\ assoc}$ = 0.15 – 4 GeV/c

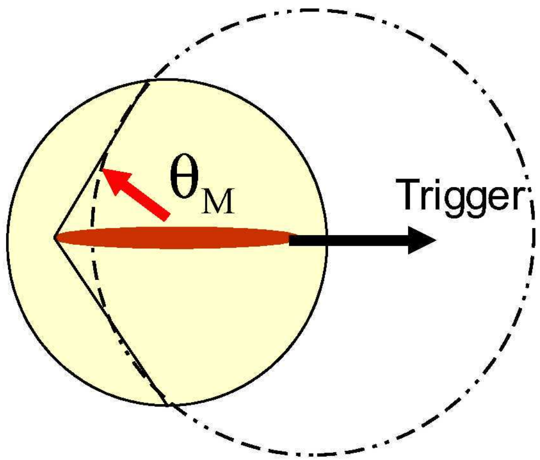
"Double peak" = Mach wave cone ?

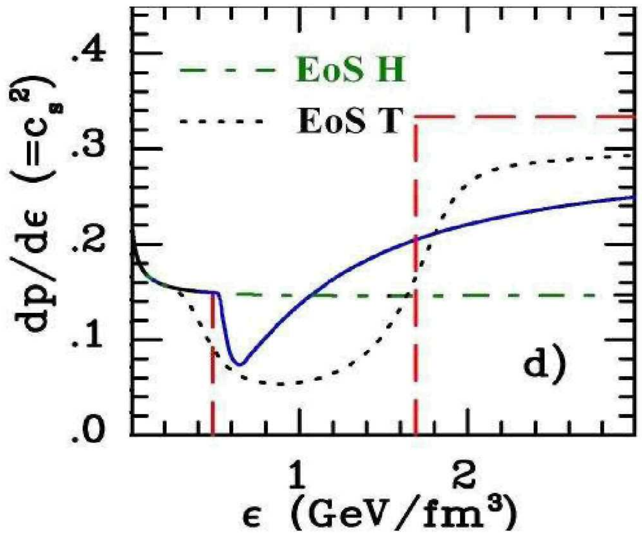
- Double peak structure at at $\pi \pm 1.2$ rad reminiscent of Mach wave conical shock ("sonic boom") $\Rightarrow$ speed of sound accessible

Mach cone: $\cos\theta_M = c_s$

$$c_s^{av} = \frac{1}{\tau_f}\int d\tau c_s(\tau) = 0.33$$

(t-averaged: c^2_s ~ 0.1)





→ QGP ($1/\sqrt{3}$)

→ HRG ($\sqrt{0.2}$)

→ phase transition (0.)

Stoecker, Satarov, Mishutin, hep-ph/0505245.
Casalderrey, Shuryak, Teaney, hep-ph/0411315.

θ = arccos(c^{av}_s) ~ 1.2 rad = 71° ~ θ_{exp}

Note: gluon Cerenkov-like emission also proposed
[medium index refraction: $n=1/\cos(\theta_c)$ accessible ...]

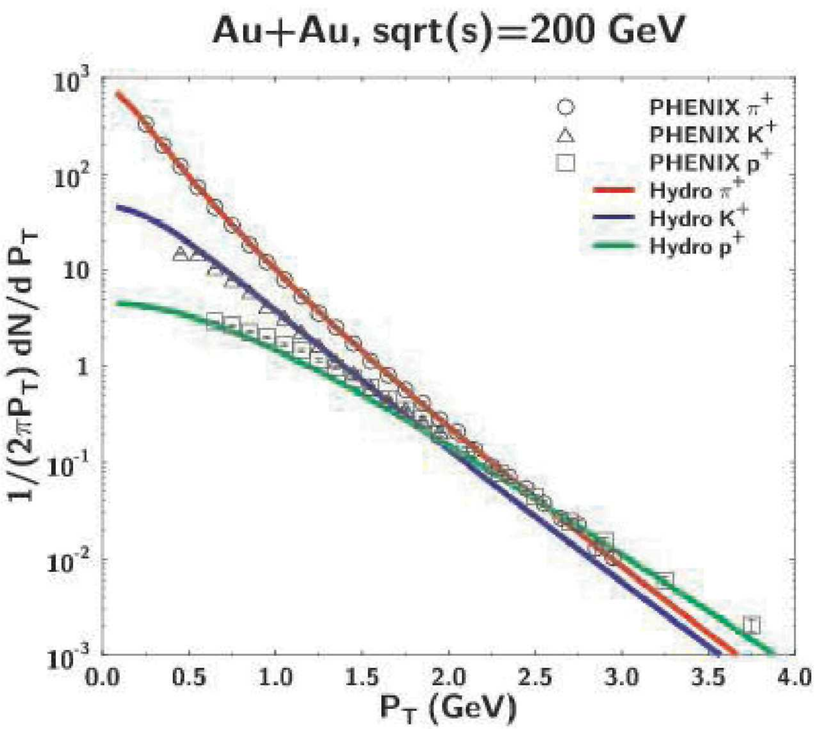
(4) Radial (dN_{soft}/dp_T) and elliptic (v_2) flows

“Perfect fluid” (zero viscosity) hydrodynamics description (with very short thermalization times) of radial (dN_{soft}/dp_T) & parton elliptic flows (v_2).

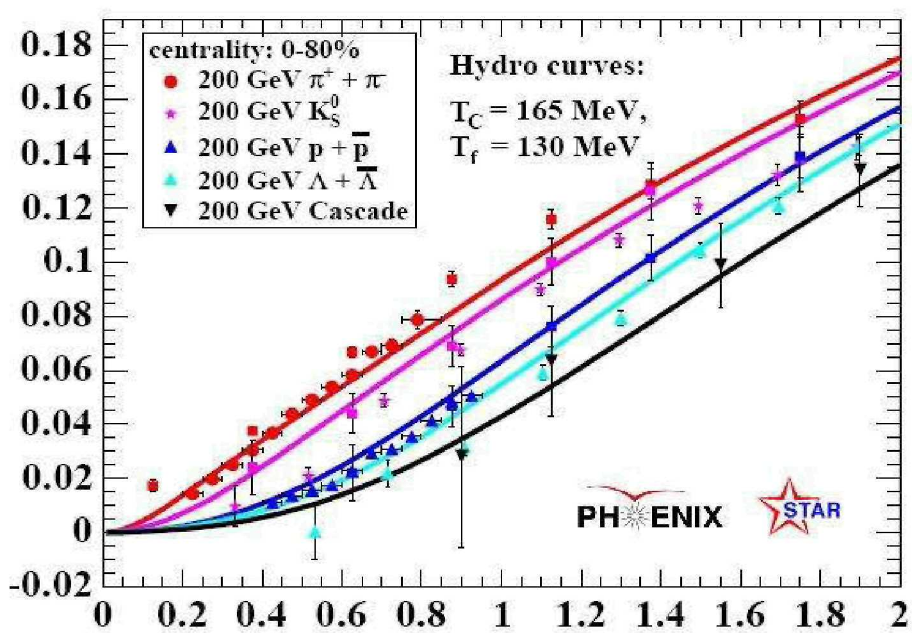
“Strongly coupled” (liquid-like) plasma: small charm-Q diffusion coeffic.

Success of hydro models at RHIC

- "Perfect fluid" hydrodynamics (zero viscosity) with QGP EOS and fast thermalization times (τ_0= 0.6 fm/c) reproduces bulk of particle production:
  - Single hadron ($\pi^{\pm}$, $K^{\pm}$, p, pbar) spectra up to ~2 GeV/c (mass-dependent collective radial flow).
  - Strong elliptic flow for all hadrons ($\pi^{\pm}$, $K^{\pm}$, p, pbar) up to ~2 GeV/c



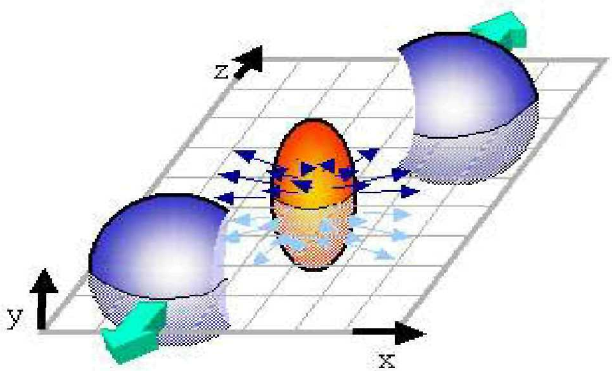
Huovinen, Kolb, Heinz, Hirano, Teaney, Shuryak, Hama, Morita, Nonaka, …….



Huovinen et.al, PLB503

Elliptic flow

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

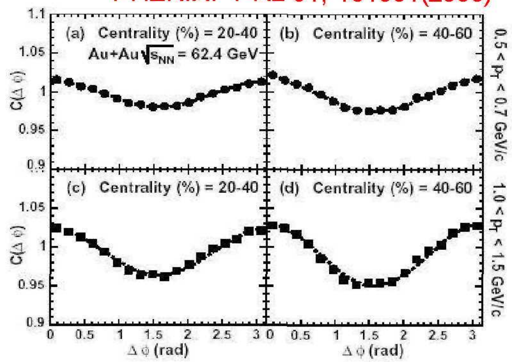


$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2(\phi - \Phi_{RP})$$

Elliptic flow = v_2

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

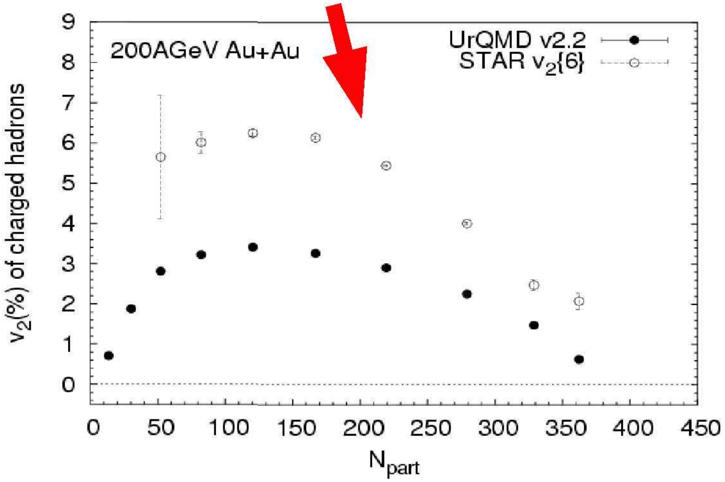
PHENIX: PRL 91, 181301(2003)



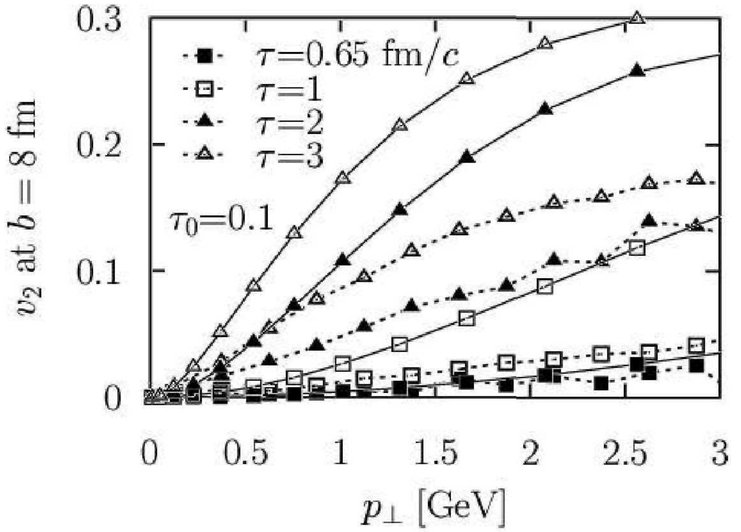
1) Truly collective effect (absent in p+p collisions).

2) Early-state phenomenon: develops in 1st (partonic) instants of reaction.

3) Pure hadronic models predict small v_2



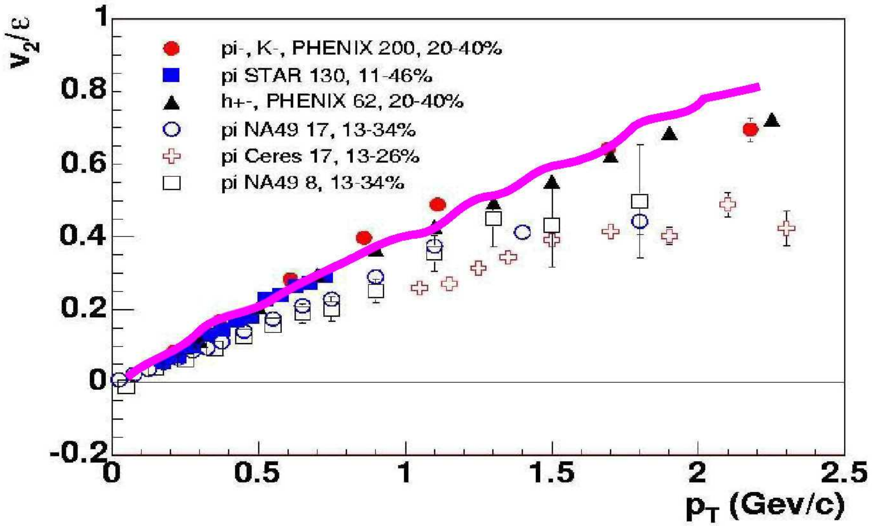
UrQMD X. Zhu et al
PRC72:064911,2005



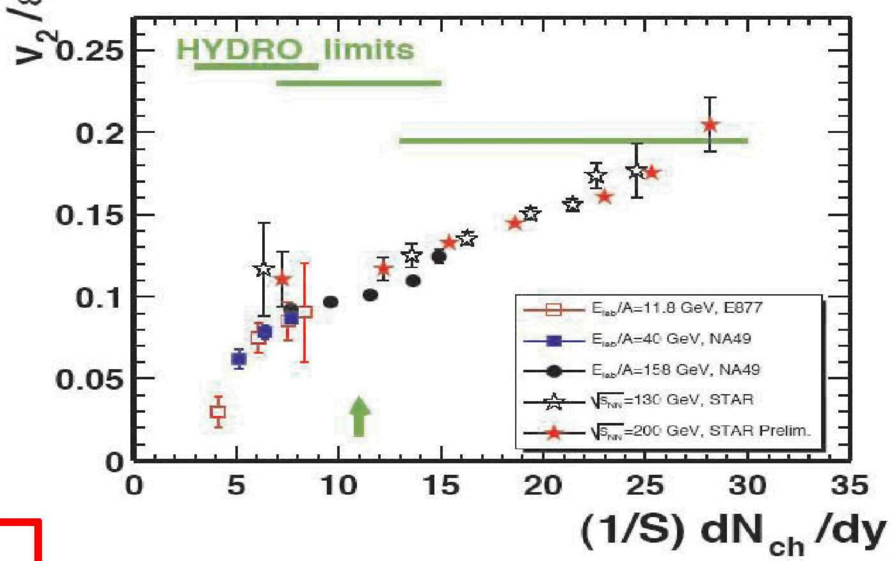
Molnar, Huovinen
PRL 94, 012302 (2005)

Elliptic flow at RHIC

- Large v_2 signal at RHIC ! Exhausts hydro limit for p_T<2 GeV/c



~50% increase from CERN-SPS

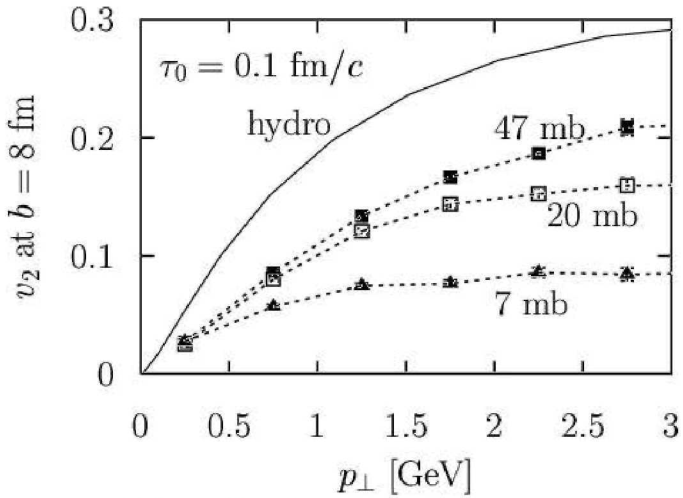


⇒ Strong (collective) pressure grads.

⇒ Large & fast parton rescattering: early thermalization.

- Parton cascade with perturbative parton-parton σ ~3 mb predicts much smaller v_2

⇒ Non ideal-gas (perturb.) behaviour



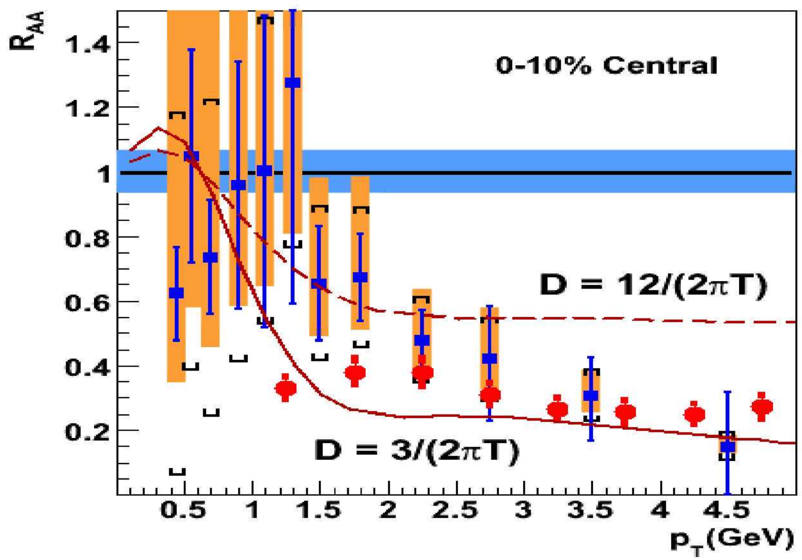
Molnar, Huovinen
PRL 94, 012302 (2005)

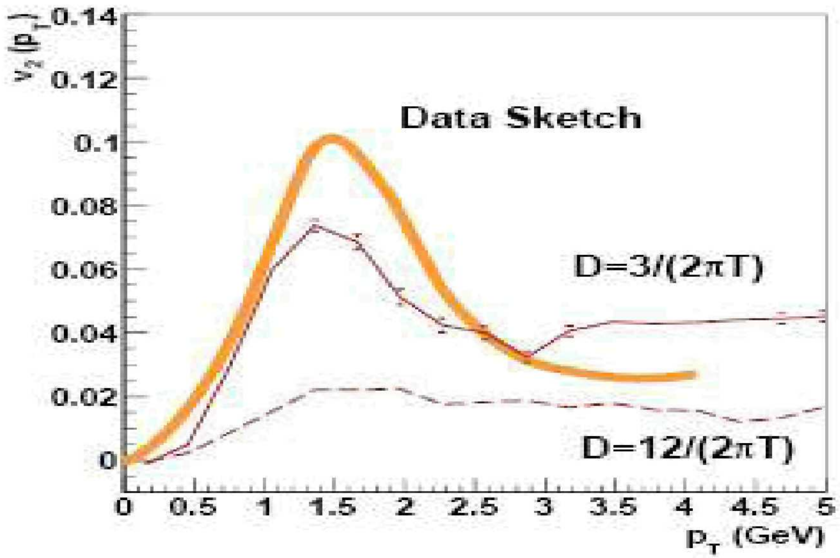
Charm quark suppression, v_2

Moore & Teaney
PRC71, 064904, '05

- Estimates of medium transport coefficients with heavy-Q.
- Small diffusion coefficient ($D = 2T^2/k$, k = mean Q^2 per time): strongly interacting medium:

$D \sim 3/(2\pi T)$





- Many recent applications of "AdS/CFT" to compute medium properties (η/s, D, qhat ...) in strongly-coupled SUSY Yang-Mills (QCD-like) from weakly coupled dual gravity.

- Estimate of plasma Coulomb coupling parameter at RHIC: M.Thoma

$\Gamma = \langle E_{pot} \rangle / \langle E_{kin} \rangle \sim g^2 (4^{1/3}T) / 3T$ **~ 3**

Using: $\langle PE \rangle = g^2/d$ $d \sim 1/(4^{1/3}T)$, $\langle KE \rangle \sim 3T$, $g^2 \sim 4\text{-}6$ and T=200 MeV

$\Gamma > 1$: strongly coupled plasma (liquid-like)

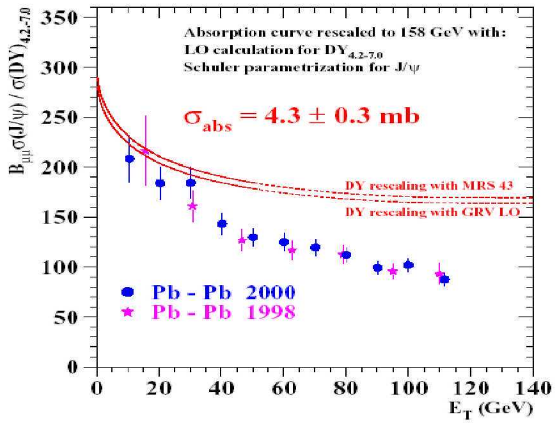
(5) Suppressed J/ψ production

Suppressed J/ψ yields observed at RHIC. Consistent with:
Debye-screened (deconfined) medium (?)
Recombination from ccbar pairs (?)

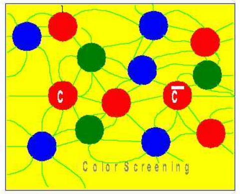
See also talks by: M. Leitch, G.Lykasov

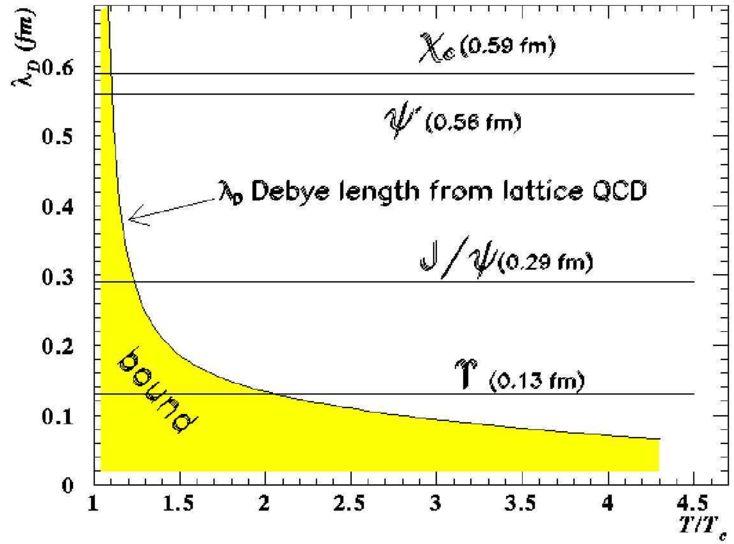
J/ψ suppression (*slide borrowed from Mike Leitch*)

Debye screening predicted to destroy QQbar in a QGP with different states “melting” at different temperatures due to different binding energies.

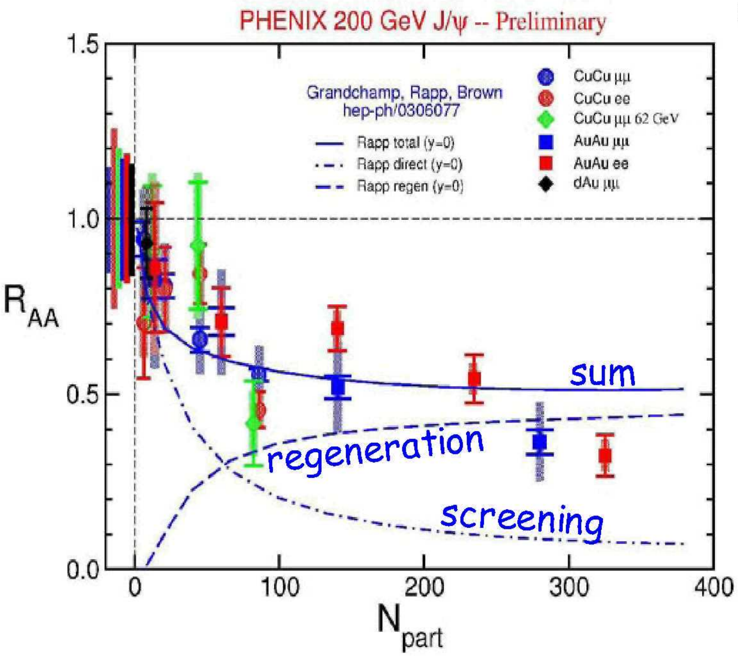


SPS NA50 anomalous suppression



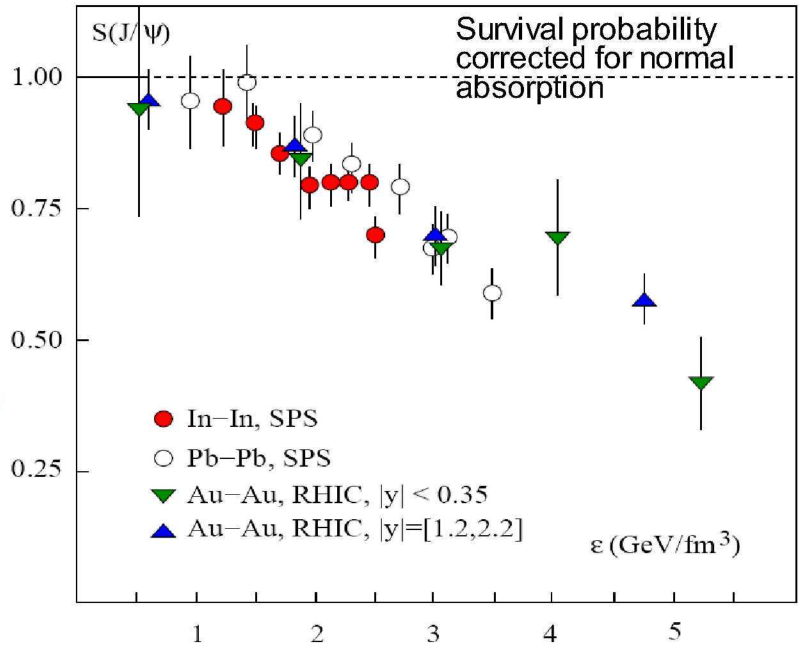


Same suppression observed at RHIC and SPS



ccbar regeneration compensates for screening ?

Rapp et al., Thews



Recent latt. calculations
J/ψ not screened until $2T_c$?
Suppression only via feed-down from screened χ_c & ψ′

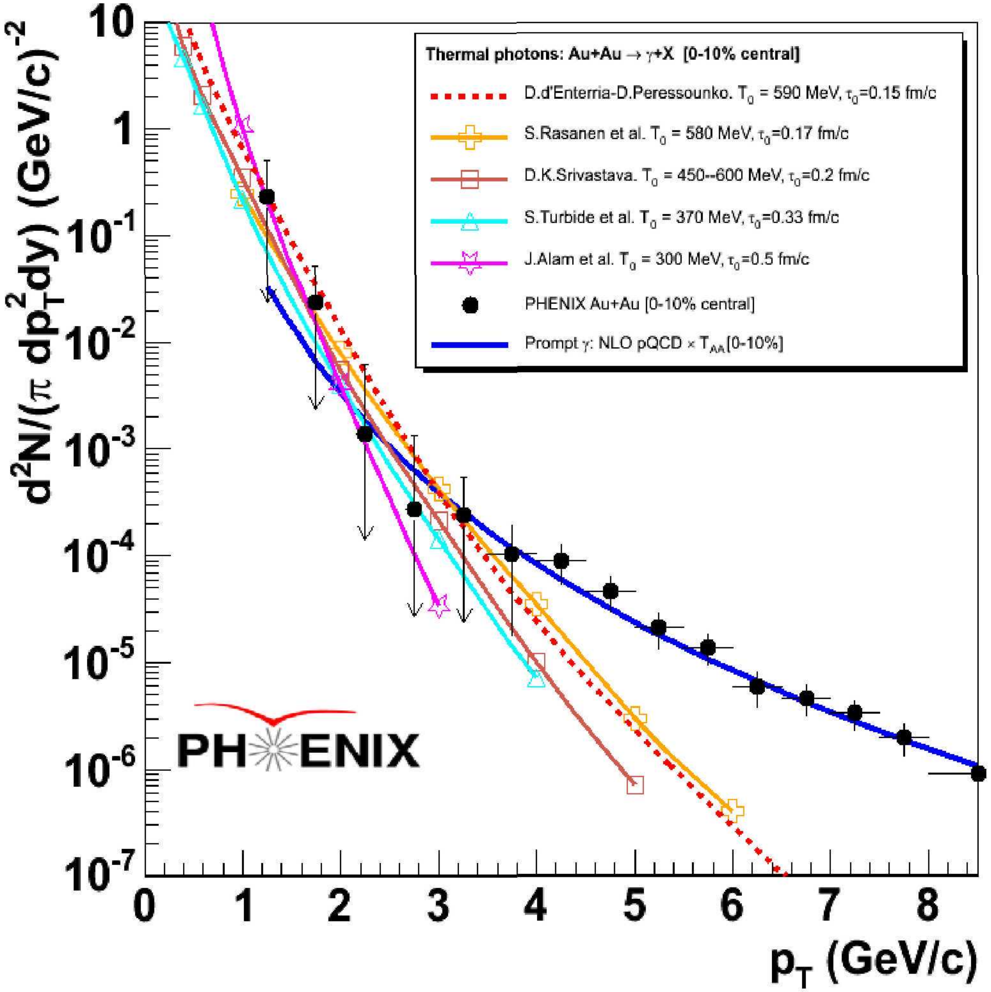
Karsch, Kharzeev, Satz

(6) Thermal (?) photon dN/dp_T spectrum

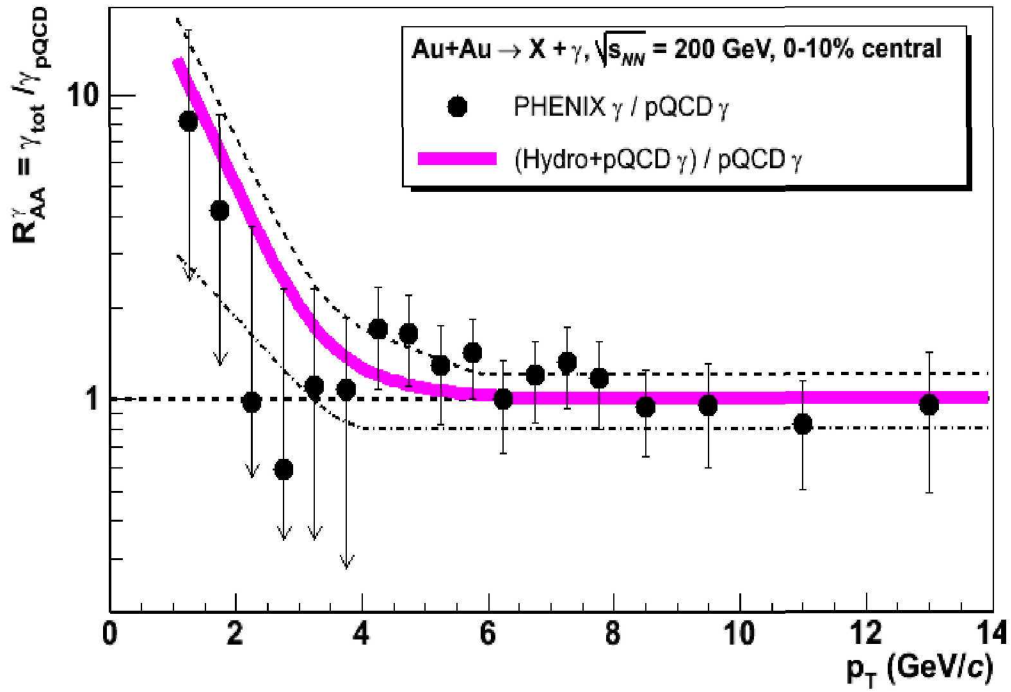
Excess of direct photons at p_T~1-4 GeV/c over primary (pQCD) contribution is consistent with hydro predictions for a hot radiating source (T_0~590 MeV, $\langle T_0 \rangle$~350 MeV).

“Thermal” (?) photon “excess” at p_T~1-4 GeV/c ?

- Central AuAu direct photons excess over pQCD observed at p_T~1-4 GeV/c:



D.d'E. & D.Peressounko
EPJ-C 46, 451 (2006)



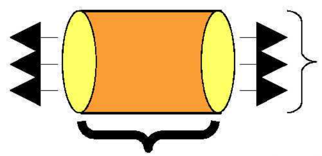
- pQCD+hydro (2D+1, T_0~590 MeV, <T_0>~350 MeV) reproduces data …
- But proton-proton “baseline” could be higher than pQCD expectations

(7) Energy densities ($dE_T/d\eta$)

Energy densities above ϵ_{crit} , ϵ ~5 GeV/fm^3, from transverse energy and “Bjorken estimate” at τ ~1 fm/c:

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

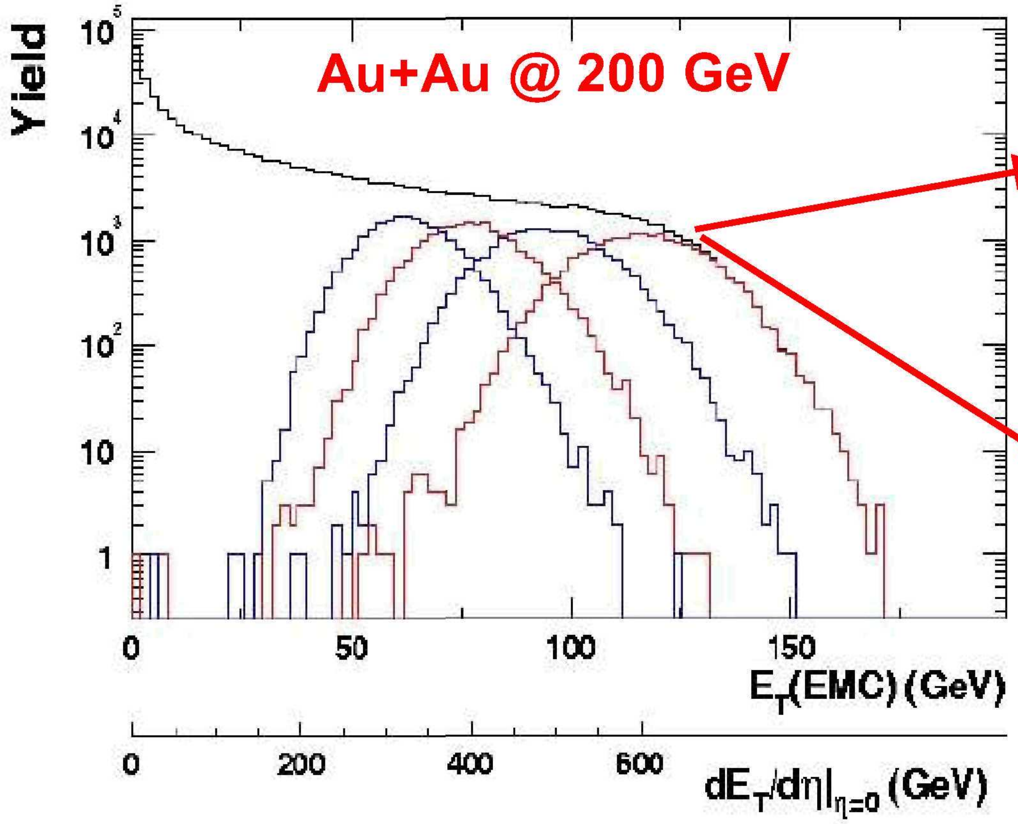
- Bjorken estimate: $\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$



(longitudinally expanding plasma)

τ_0 ~ 1 fm/c > τ_{cross} = 2R/γ ~ 0.15 fm/c

- $dE_T/d\eta$ at mid-rapidity measured by calorimetry (using PHENIX EMCal as *hadronic* calorimeter: E_T^{had} = (1.17±0.05) E_T^{EMCal})



<$dE_T/d\eta$> ~ 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)

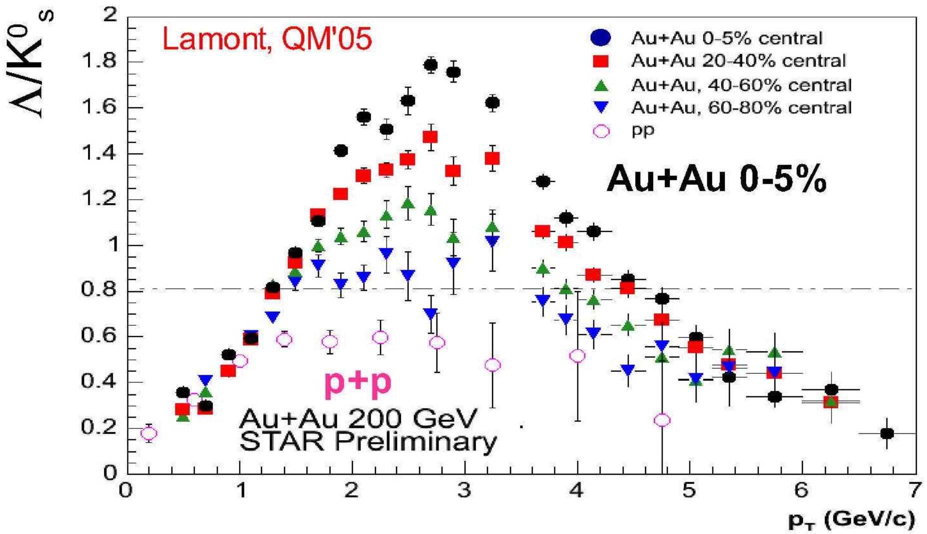
PHENIX, PRL 87, 052301 (2001)

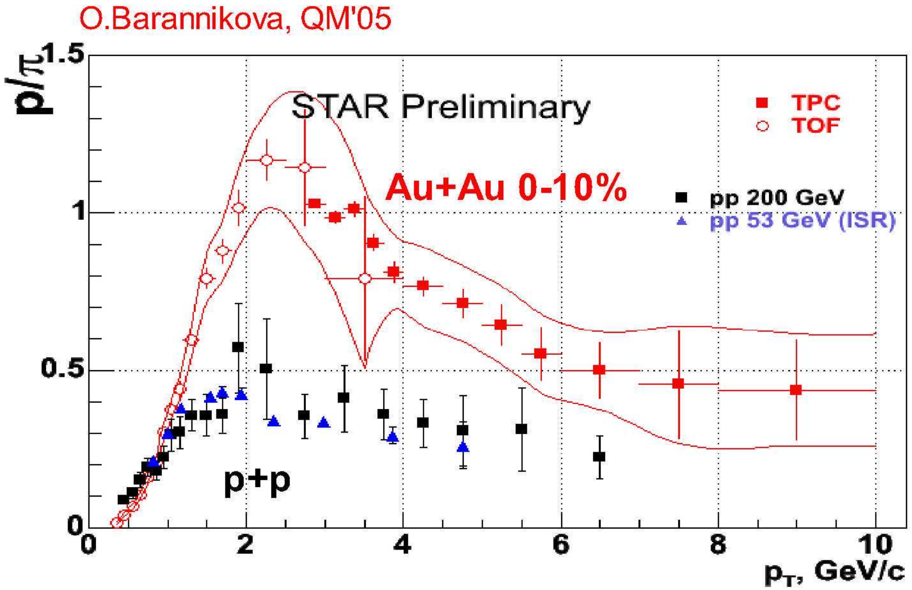
(8) Baryon spectra (dN/dp_T) and v_2 at intermediate p_T

Consistent with constituent quark-number scaling at hadronization

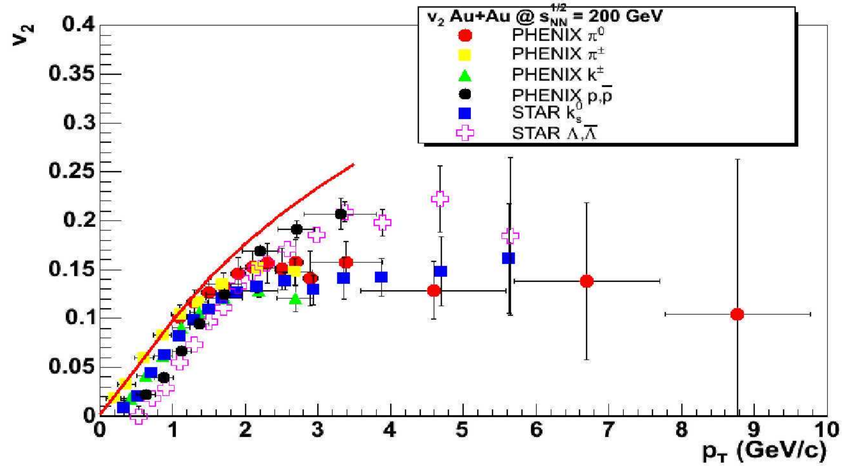
Enhanced baryon spectra and v_2 at intermediate p_T

- Strongly enhanced baryon (p, Λ) production within $p_T \sim 2 – 4$ GeV/c

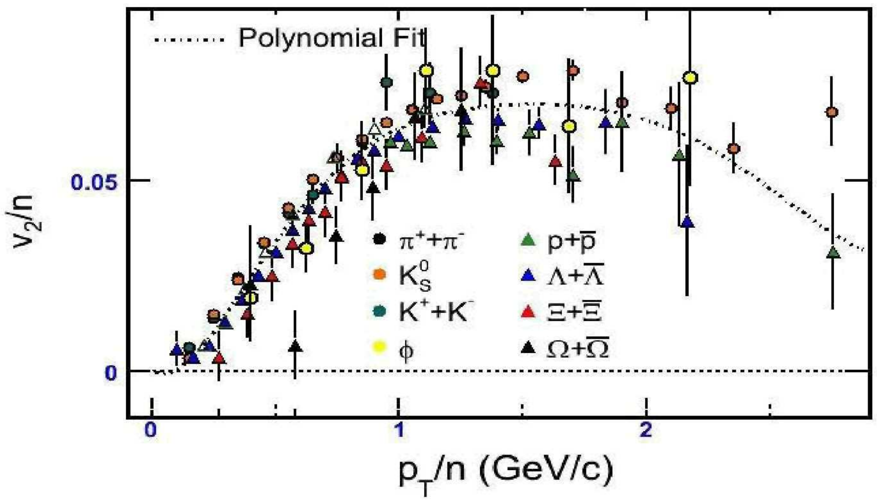




- Diff. v_2 baryon-meson p_T dependence:

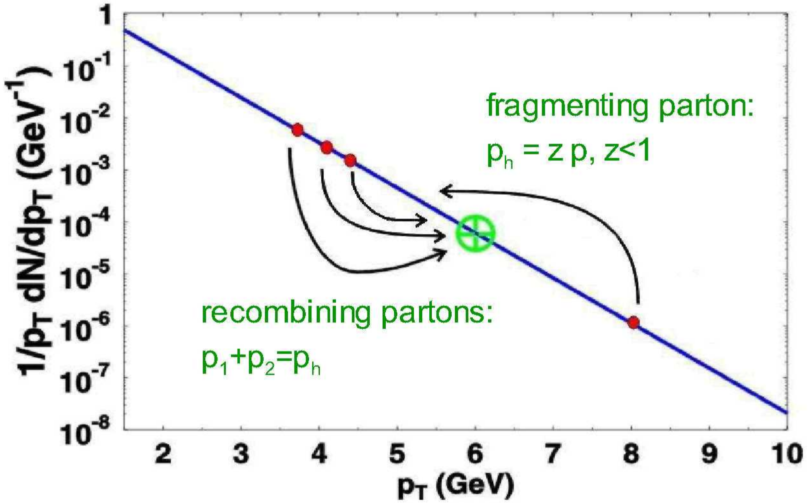


- Simpler v_2 scaling behaviour normalizing v_2 and p_T by number of constituent quarks:

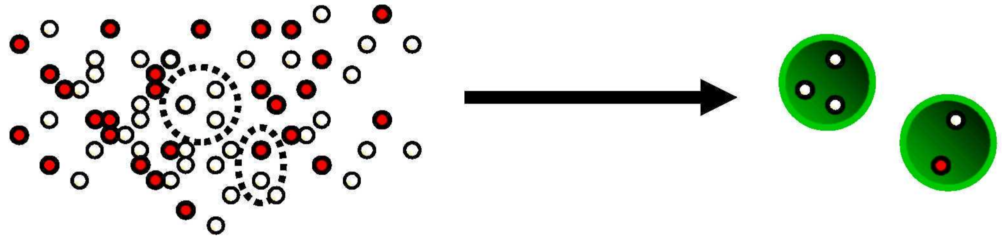


"Quark recombination" models vs. data

- Hadronization at intermediate p_T at RHIC via "quark recombination" (coalescence) in dense (thermal) medium :

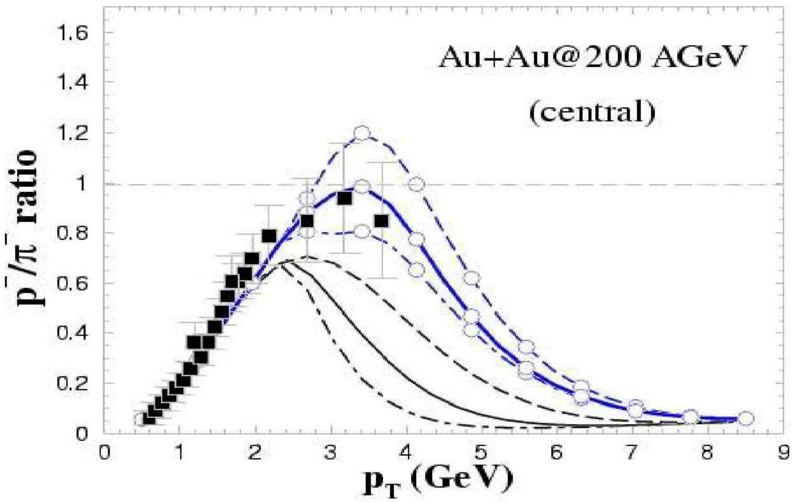


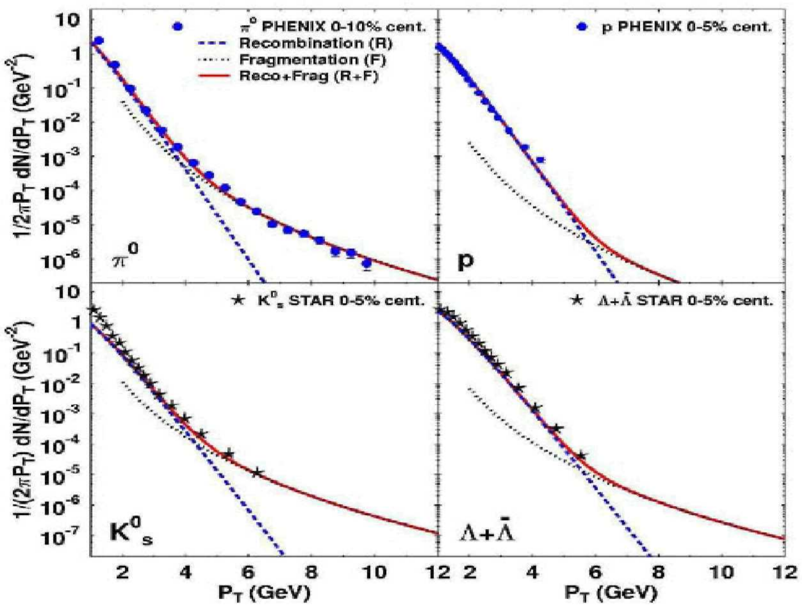
Hwa-Yang
Fries-Mueller-Nonaka-Bass
Greco-Ko-Levai



- Constituent-quark scaling of v_2 due to "universal" parent quark flow

- Anomalous baryon/meson ratio explained:





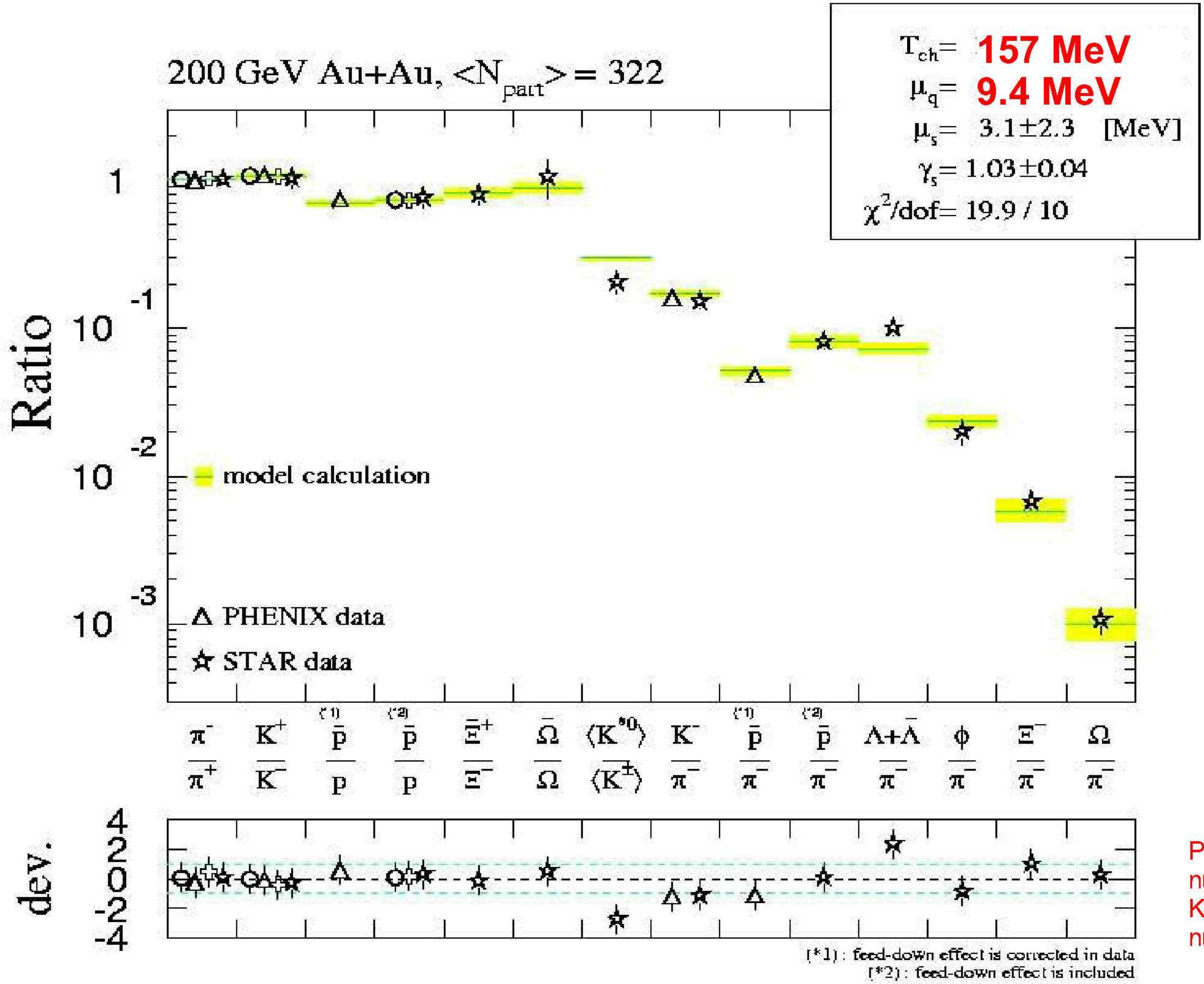
(9) Final AuAu hadron ratios

Chemically equilibrated system:
hadron abundances freezed-out at T~160 MeV

See also talk by F. Becattini

Ratios of particle yields

- Ratios of hadron yields consistent w/ system at chemical equilibrium at hadronization ($T_{chem.freeze-out} \sim T_{crit}$) :



- Assume grand canonical distrib. described by T and μ:

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

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

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

- 2^{nd} ratio (e.g. K/pi) provides T,μ

- All other hadronic yields and ratios predicted

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

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

New Heavy-Ion opportunities at LHC

See also talks by: Y.Kharlov, M.Monteno, A. Panagiotou

Large Hadron Collider (LHC) @ CERN

Specifications:

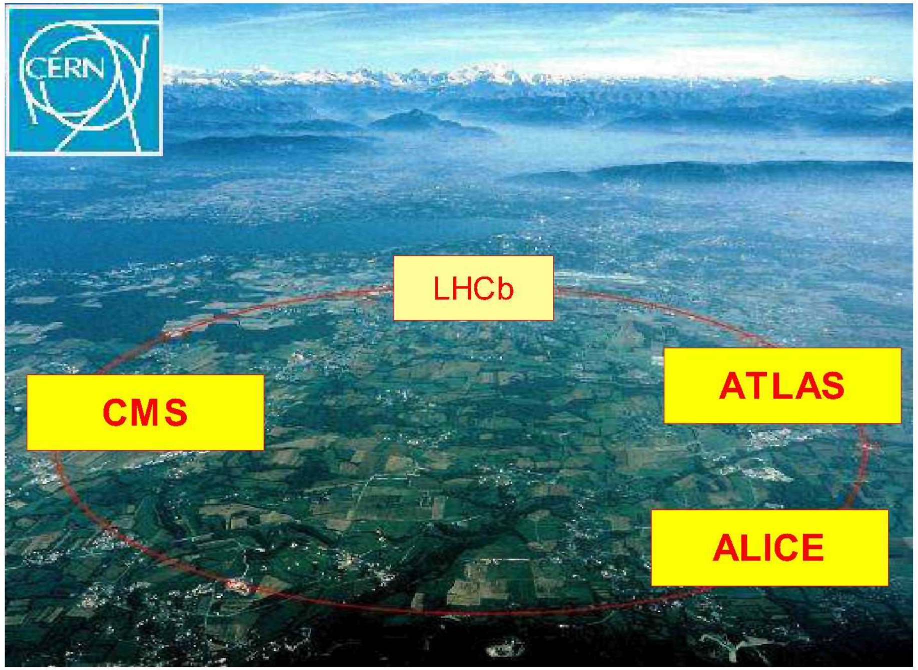
26.66 km circumference

1 ring:

- 8.33 T superconducting coils
- 25 ns crossing time (40 MHz)

pp luminosity: 10^{34} cm^{-2} s^{-1} (10^{7} s/year)

AA luminosity: 10^{27} cm^{-2} s^{-1} (10^{6} s/year)



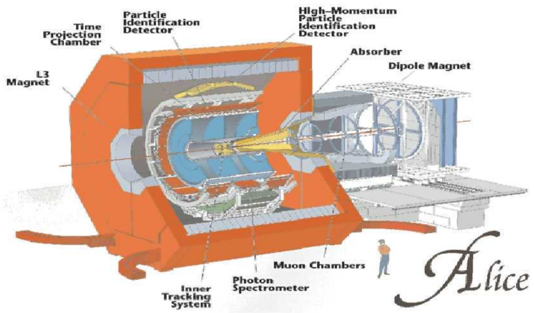
3 experiments:

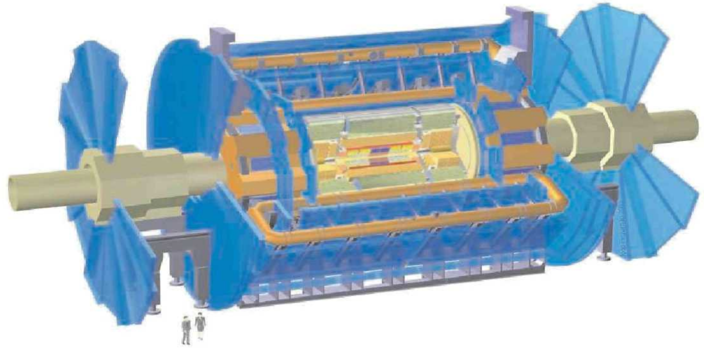
ALICE, ATLAS, CMS

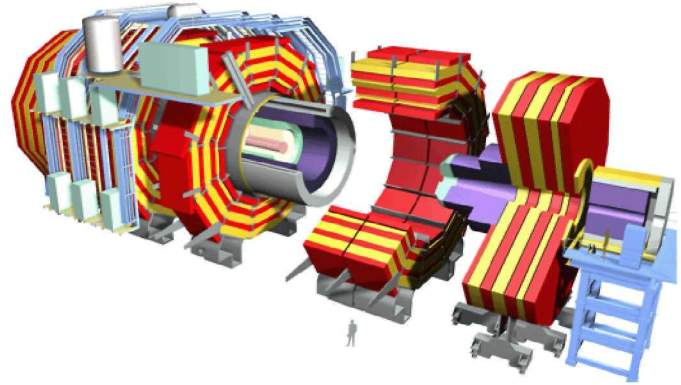
First runs:

pp @ 14 TeV (2007 pilot, 2008)
PbPb @ 5.5 TeV (2008: early cfg.,
2009 std. cfg.)
pPb @ 8.8 TeV (2010?)

The 3 LHC heavy-ion experiments







- ALICE: dedicated HI experiment
- Largest HI community (~1000)
- Tracking ($|\eta|<1$-2): TPC + ITS + TRD
- 0.5 T solenoid magnet
- EMCal under discussion
- Forward muon spectrometer

- Strongest capabilities: low-p_T, light-quark PID, ...

- ATLAS & CMS: multipurpose (pp) + HI program
- People: ~50/2000 (ATLAS), ~70/2300 (CMS)
- $|\eta|<2.5$: Full tracking, muons
- $|\eta|<5$: Calorimetry
- 4 T (CMS), 2 T (ATLAS) mag. field

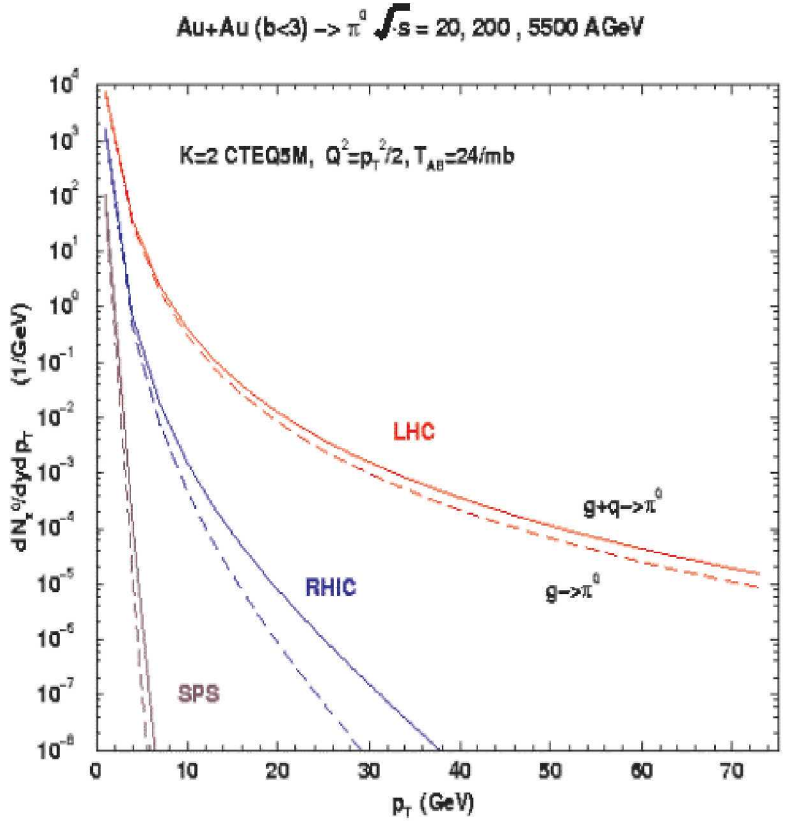
- Forward detectors (CMS)
- Strongest capabilities: hard-probes, full jet reco, heavy-Q jet PID

LHC: new regime for QGP studies

- Produced quark-gluon matter: hotter, denser, bigger, longer lifetime

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	X 28
dN_{ch}/dy	500	850	1500-3000	x 2-3
τ^0_{QGP} (fm/c)	1	0.2	0.1	faster
T/T_c	1.1	1.9	3.0-4.2	hotter
ε (GeV/fm^3)	3	5	15-60	denser
τ_{QGP} (fm/c)	≤2	2-4	≥10	longer
τ_f (fm/c)	~10	20-30	30-40	
V_f (fm^3)	few 10^3	few 10^4	few 10^5	bigger

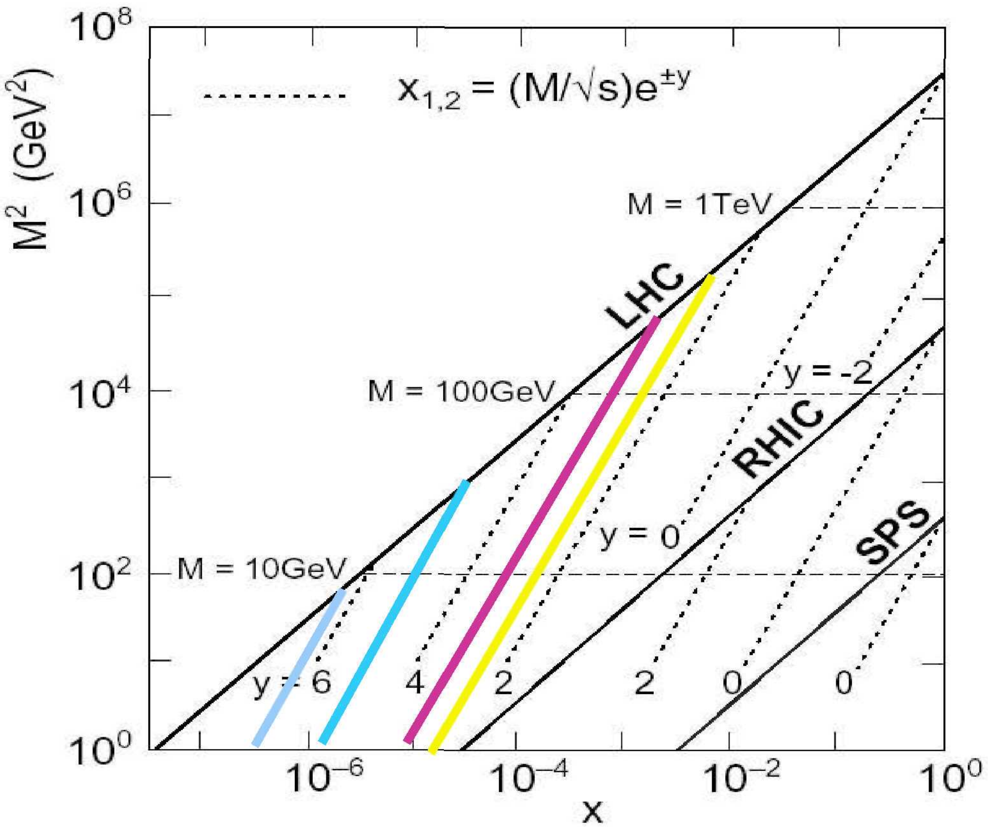
Very large pQCD cross-sections: well calibrated probes of QCD medium.



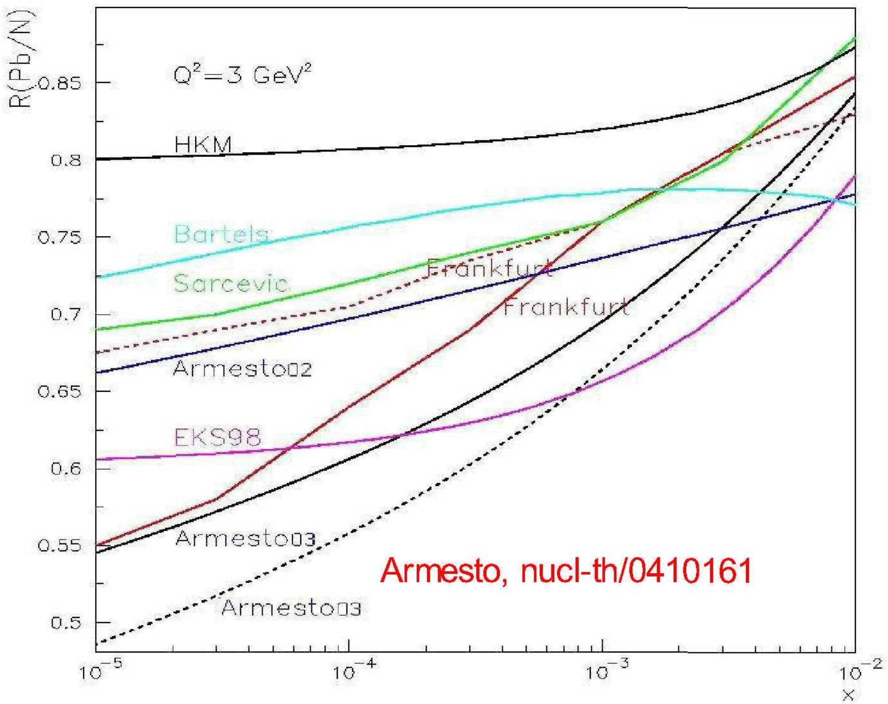
- Coulomb plasma parameter: Liquid- (RHIC, Γ >1) to gas-like (LHC, Γ ~1) transition ?

LHC: New low-x QCD regime

- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:
  (i) Bjorken $x=2p_T/\sqrt{s}$, ~30-45 times smaller x than AuAu,dAu @ RHIC
  (ii) Very large perturbative (jets, QQbar, DY, high-p_T) cross-sections.
  (iii) Forward detectors allows for measurements down to $x \sim 10^{-6}$!



Nuclear $xG(x,Q^2)$ currently unknown for $x<10^{-3}$



- Unique low-x physics possible: full studies of CGC, non-linear QCD ...

(Comprehensive) Summary

- High-energy AA unique tool to study high-density QCD in the lab
- RHIC: Properties of quark-gluon matter in central AuAu (20-200 GeV):

τ < 1 fm/c:

(1) Total multiplicities consistent w/ saturated nuclear low-*x* gluon distrib. $\Rightarrow$ **$dN_{ch}/d\eta$**

(2) Very high initial parton densities: $dN^g/dy \sim 1000$
Large transport coefficient $\langle q \rangle = \lambda^2/L \sim O(10)$ GeV^2/fm $\Rightarrow$ **high-p_T hadron dN/dp_T**

(3) Speed of sound $\langle c_s \rangle \sim 0.3$ (?) $\Rightarrow$ **high-p_T hadron $dN_{pair}/d\phi$**

(4) Nearly "perfect-fluid" (hydro. radial & parton elliptic flows) $\Rightarrow$ **hadron v_2, dN_{soft}/dp_T**
"Strongly coupled" $\Rightarrow$ **charm-Q R_{AA}, v_2, ... (?)**

(5) Deconfined (Debye-screened) (?) $\Rightarrow$ **J/ψ yields**

(6) Thermalized (T~350 MeV) (?) $\Rightarrow$ **photon dN/dp_T**

τ ~1 fm/c:

(7) Energy densities above ϵ_{crit}: $\epsilon \sim 5$ GeV/fm^3 $\Rightarrow$ **$dE_T/d\eta$**

(8) Constituent quark-number scalings at hadronization $\Rightarrow$ **interm. p_T baryon dN/dp_T**

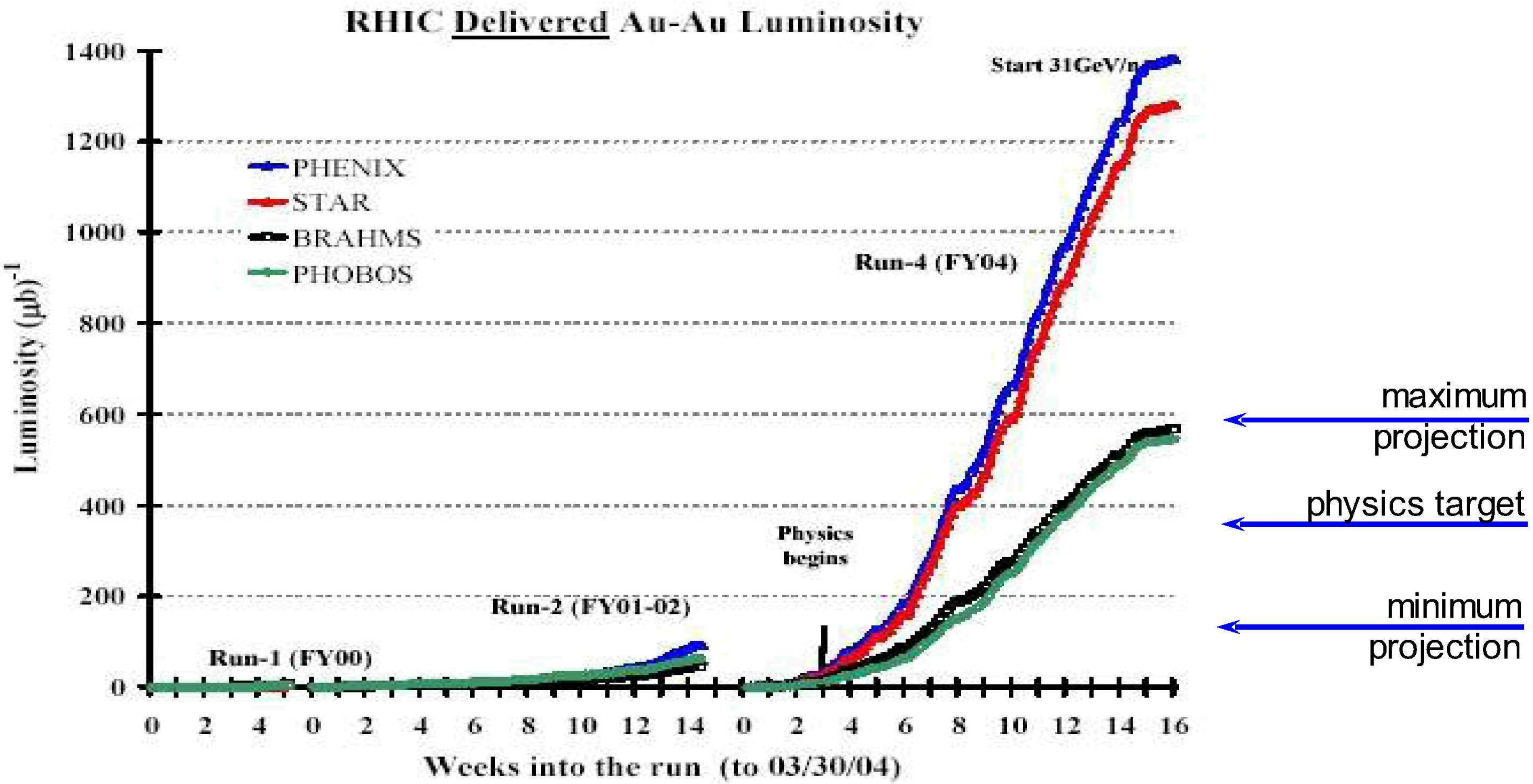
τ > 5 fm/c:

(9) Chemically equilibrated at T~160 MeV $\Rightarrow$ **hadron ratios**

- LHC: Unparalleled exp. opportunities for QGP,CGC studies in new regimes.

backup slides ...

RHIC A+A luminosities (Runs 1- 4)



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

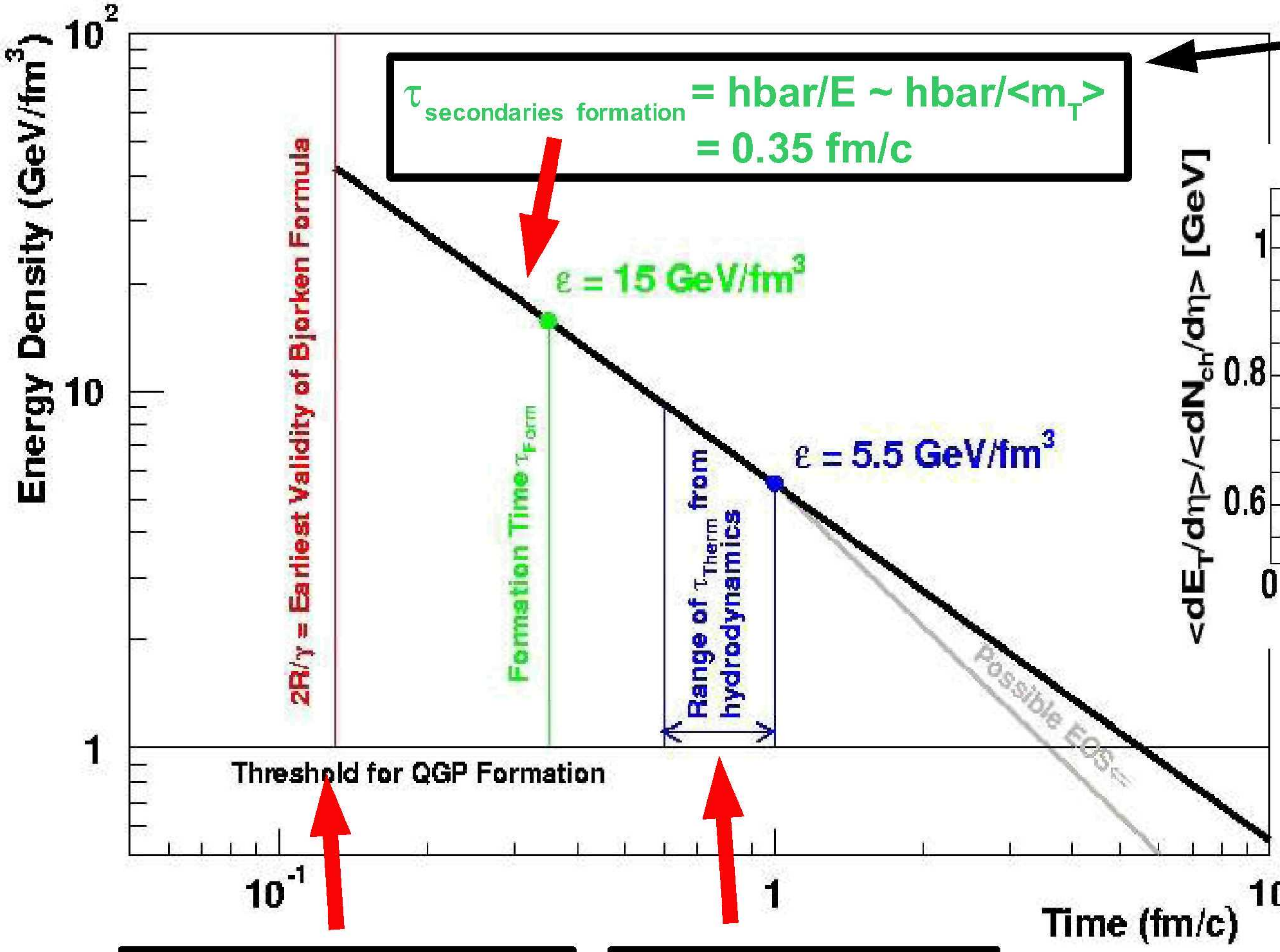
	max energy [GeV/u]	no of bunches	ions/bunch $[10^9]$	β^* [m]	emittance [mm mrad]	$\mathcal{L}_{peak}$	$\mathcal{L}_{store,ave}$ $[10^{26}cm^{-2}s^{-1}]$	L_{week} $[\mu b^{-1}]$
Run-1 (FY2000)	65	55	0.3	3	15-40	0.3	0.2	4
Run-2 (FY2001/2002)	100	55	0.5	1	15-40	3.7	1.5	24
Run-4 (FY2004)	100	45	1.1	1	15-40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

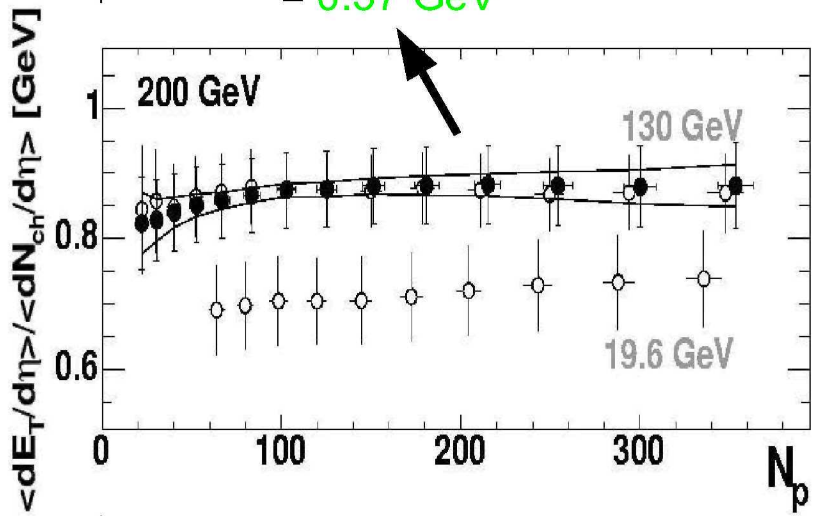
1 fm/c thermalization time ?

- 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: $\varepsilon \sim 1/\tau$

$\langle m_T \rangle = (dE_T/d\eta)/(dN/d\eta) \sim (dE_T/d\eta)/(3/2 \cdot dN_{ch}/d\eta) = 0.57$ GeV

$\tau_{secondaries\ formation}$ = hbar/E ~ hbar/$\langle m_T \rangle$ = 0.35 fm/c





PHENIX Collab.
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)

RHIC (dA,AA): (indirect) evidences for gluon saturation

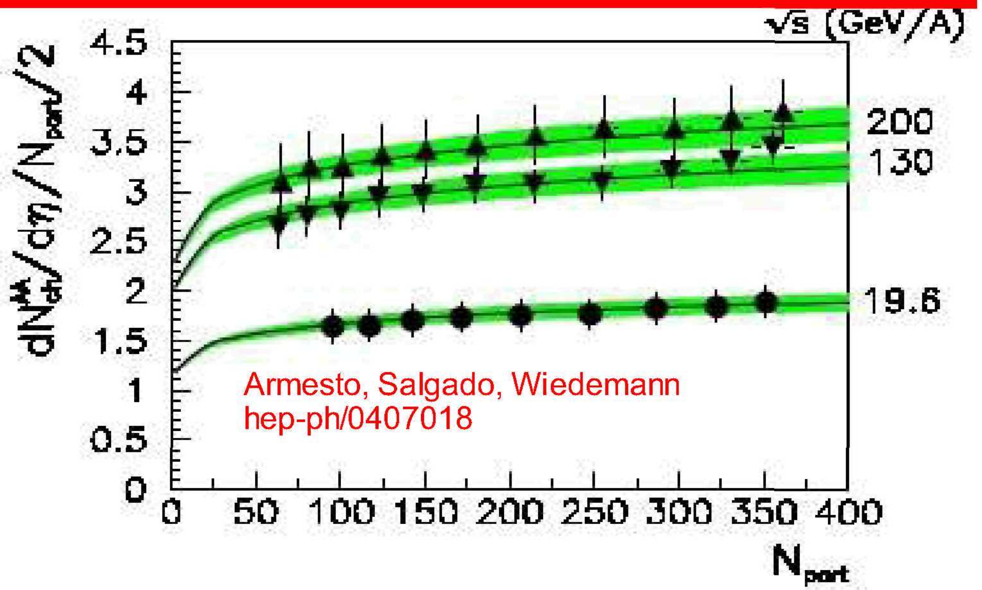
- Total AuAu particle multiplicity (plus its centrality evolution):

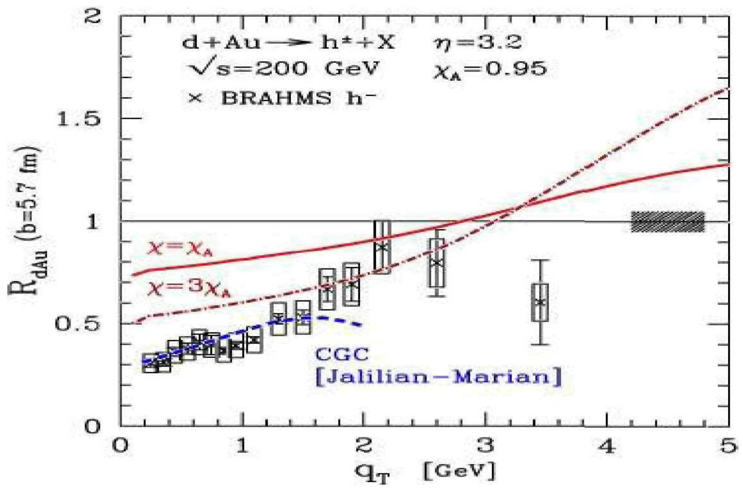
Nardi, PLB507(01)121 :

$$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x,Q_s^2)A^{1/3}$$

+ assumes "local parton-hadron duality"

1 gluon = 1 final hadron





- d+Au moderate-p_T spectra (& y-evolution) at forward rapidities (suppression):
- CGC "plus": A theory that describes:
  - (leading-twist) "shadowing" (ext. scaling)
  - Cronin-effect (BK quantum evolution)
- However: evidences at ~low p_T. Q_s @ RHIC (HERA) close to non-perturb. range

"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:

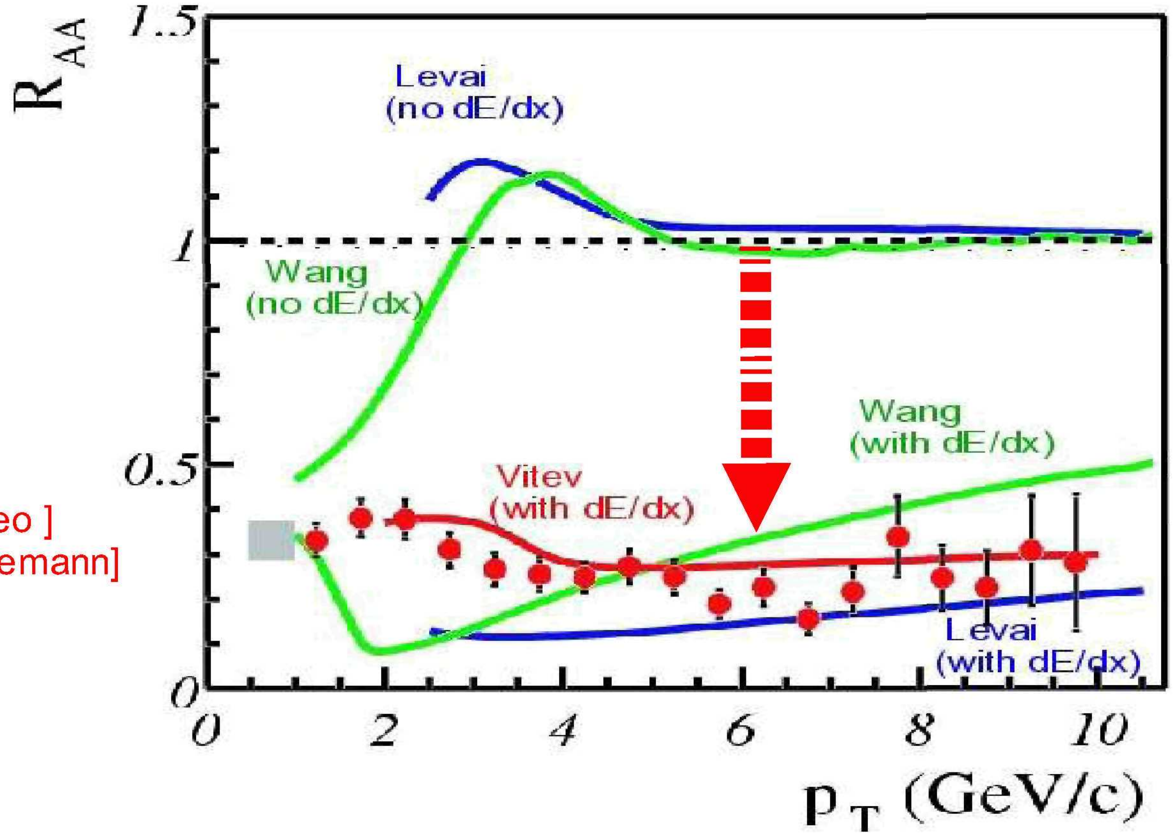
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]

  - Transport coefficients:

    $\langle q_0 \rangle \sim 14\ GeV^2/fm$ [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]

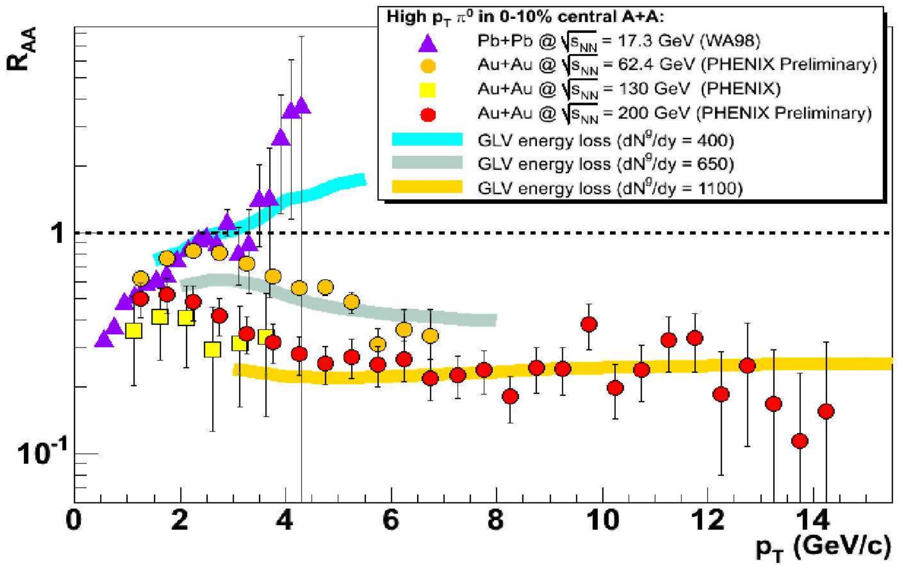


- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\varepsilon_{crit\ QCD}$ (in thermalized syst.)

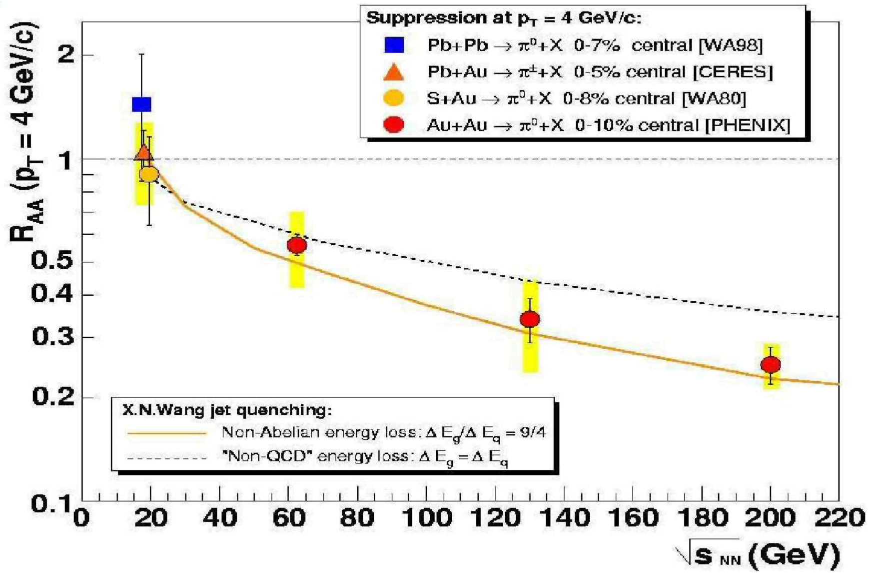
"Jet quenching" model vs. data (II)

- sqrt(s)-dependence:

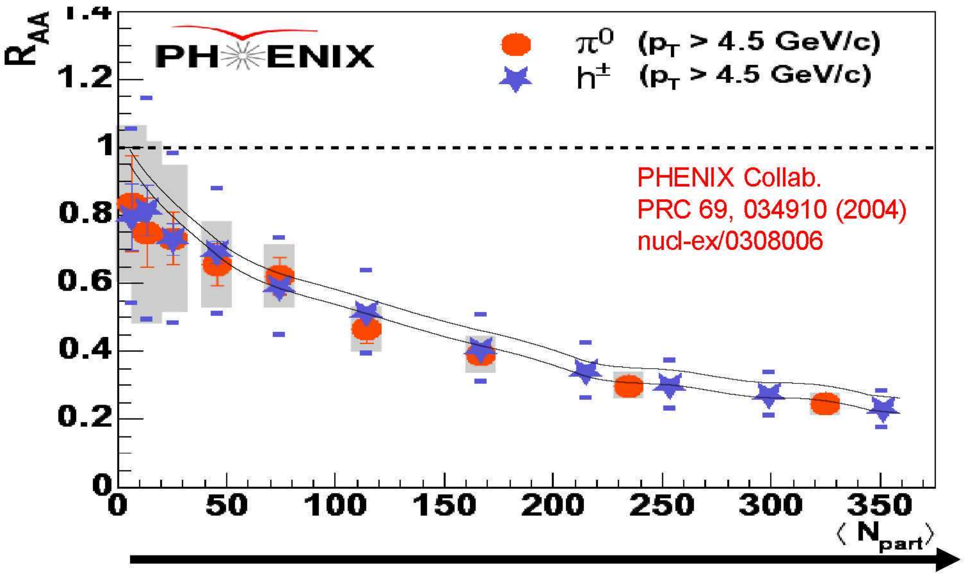
D.d'E., HP'04
EJPC 43 (2005) 295



- Non-Abelian energy loss:

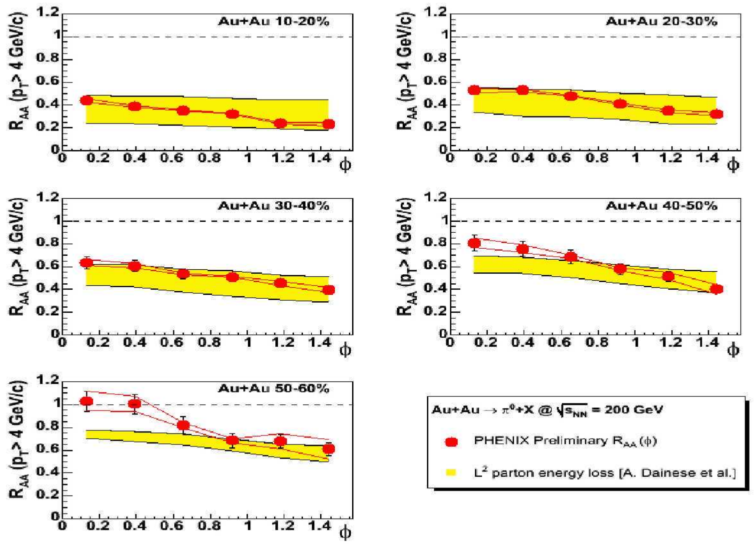


- Centrality dependence:



peripheral → central

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

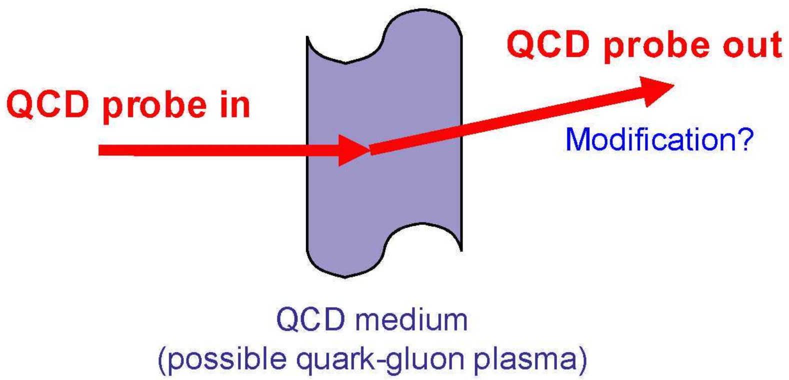


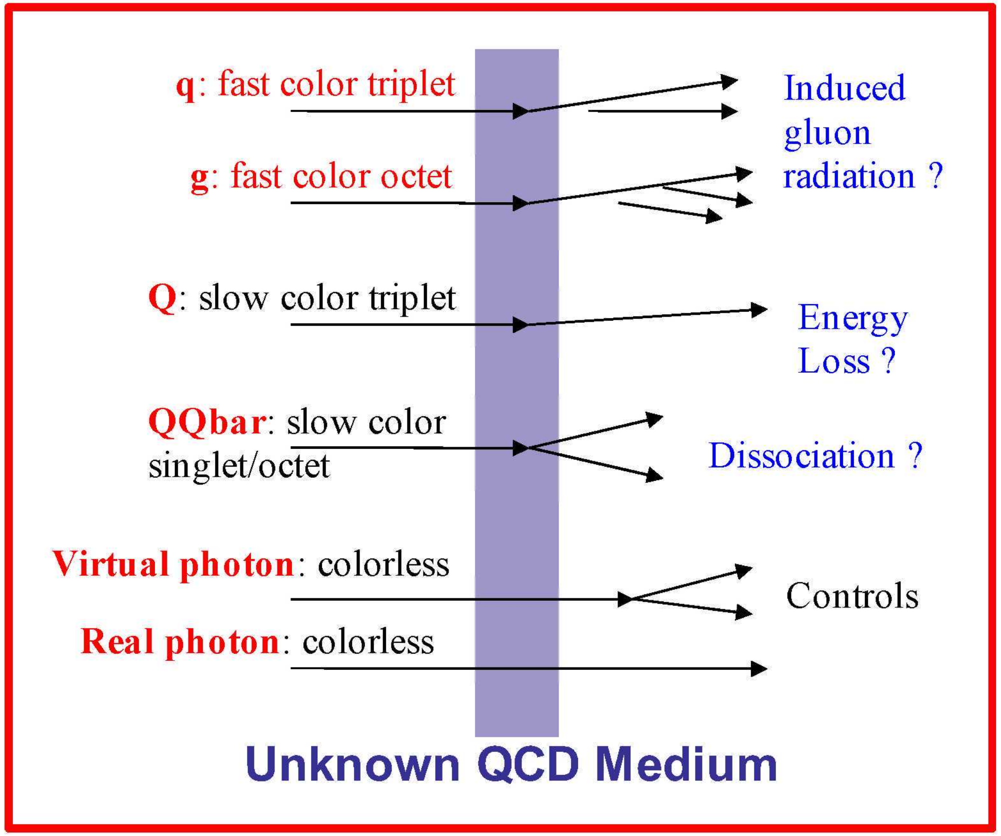
Hard QCD probes (I)

- 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:



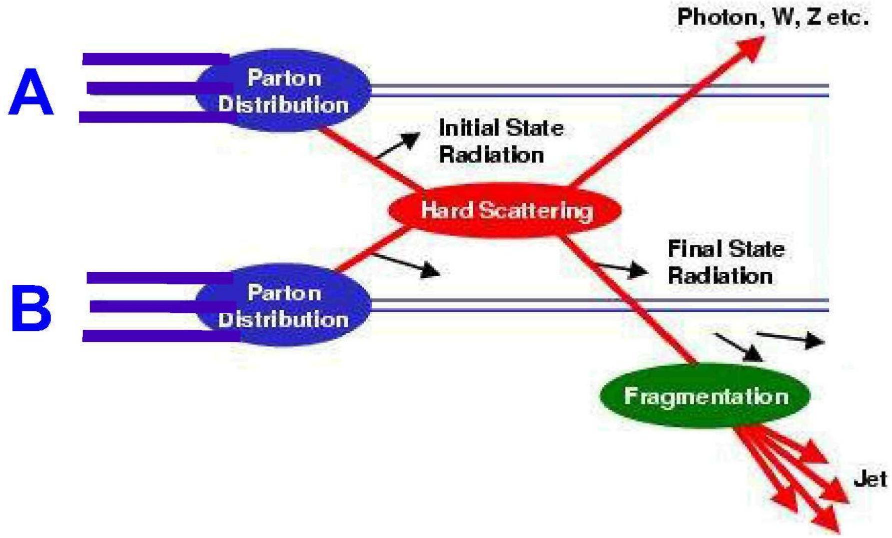


Hard QCD probes (II)

3. Production yields theoretically calculable via perturbative-QCD:

"Factorization theorem":

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



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"

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

At impact parameter b:

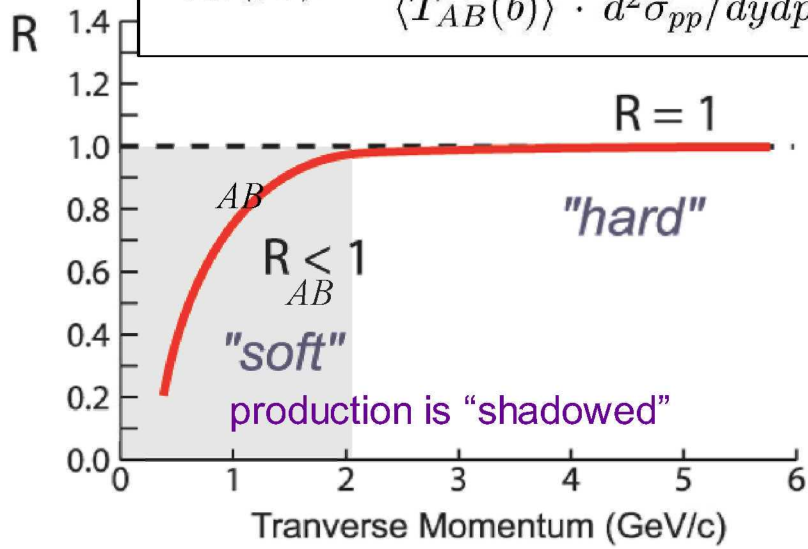
$$dN_{AB\to\text{hard}}(b) = T_{AB}(b)\cdot d\sigma_{pp\to\text{hard}}$$

geom. nuclear overlap at b

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

Nuclear Modification Factor:

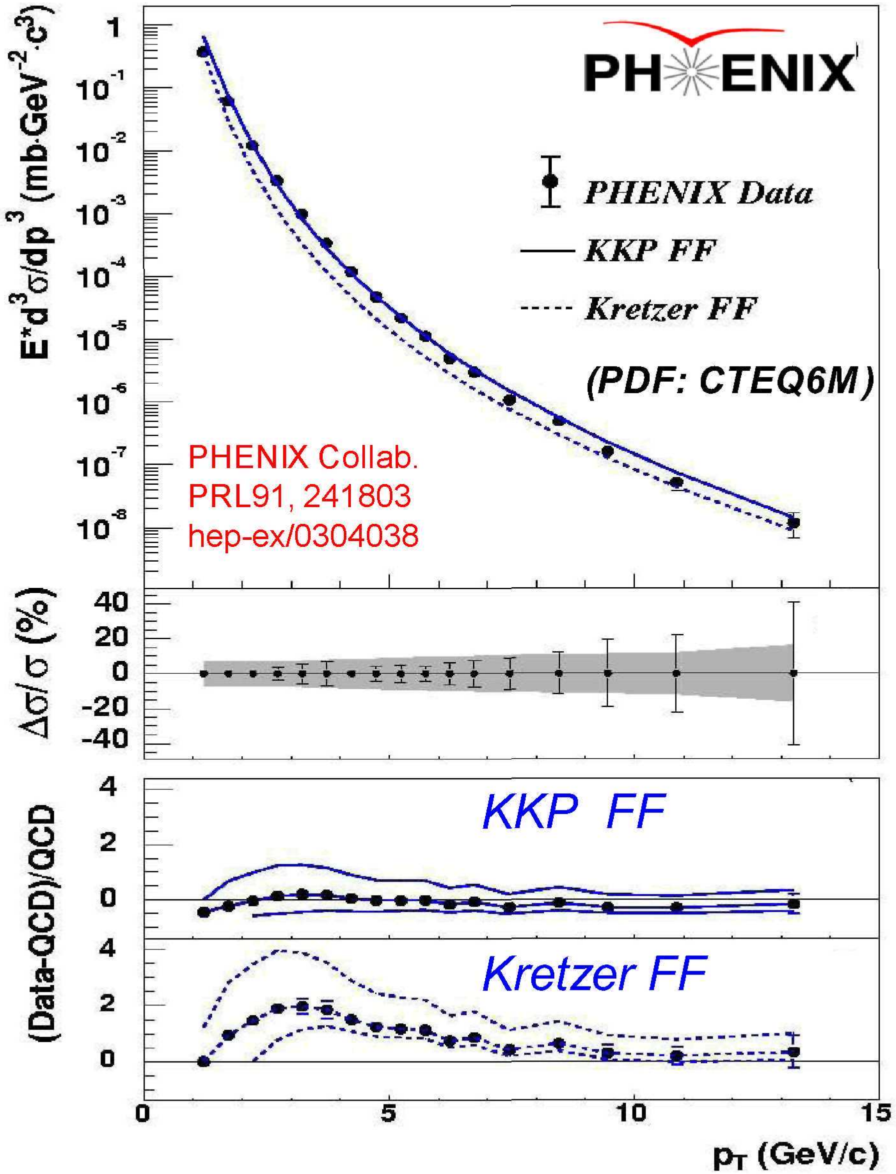
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dy dp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dy dp_T}$$



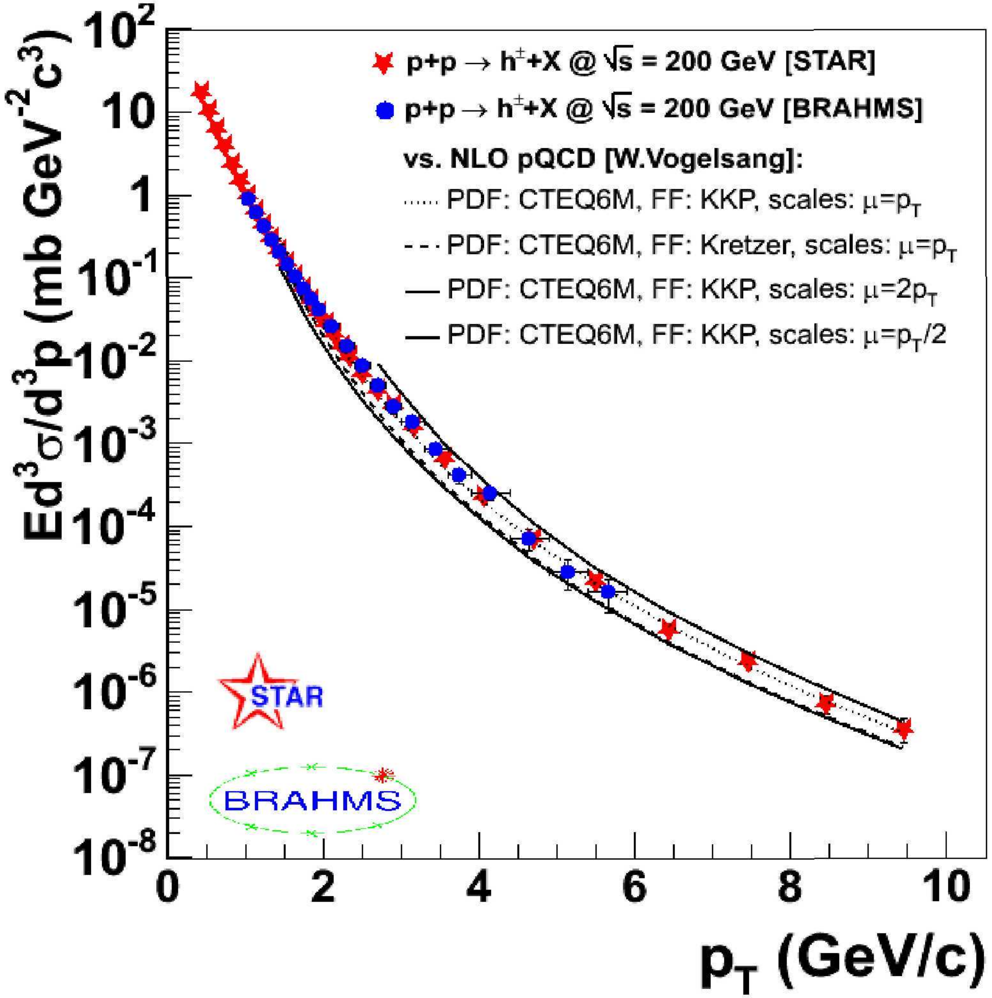
High p_T p+p baseline data well described by pQCD

- Good theoretical (NLO pQCD) description:

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



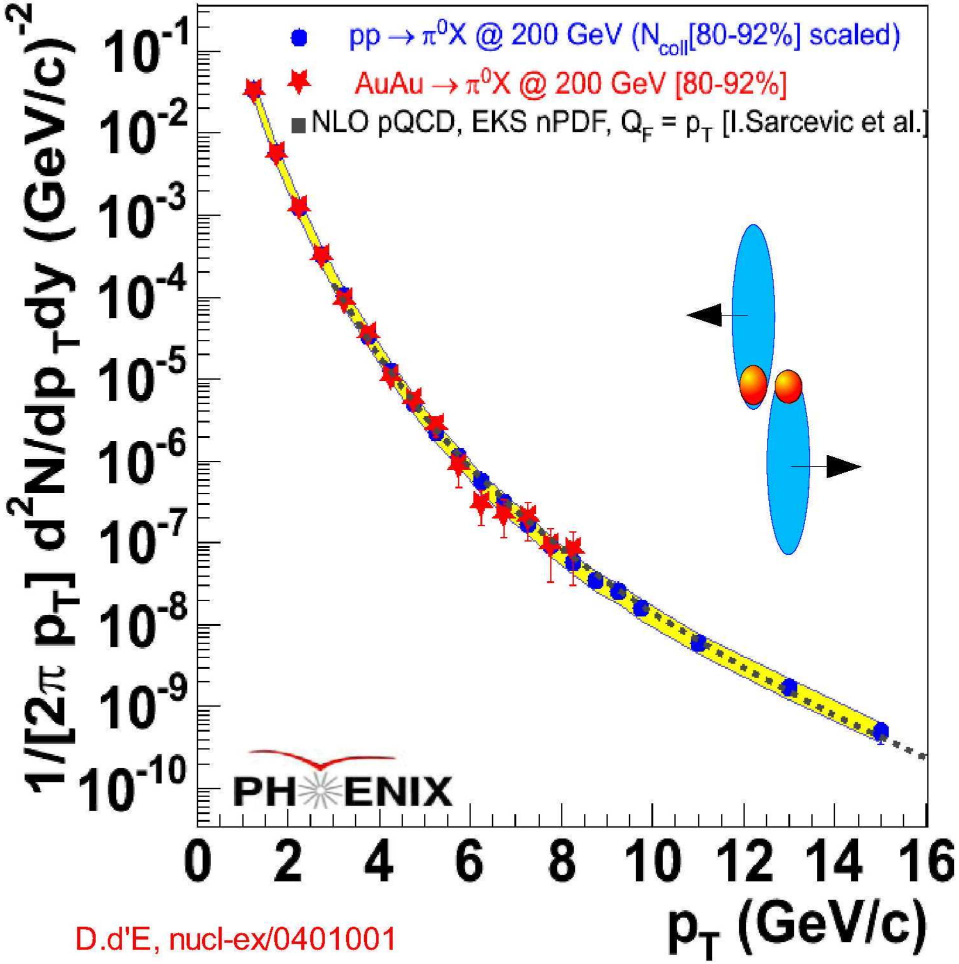
$p+p \rightarrow h^{\pm} X$ (non singly diffractive)



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

Suppressed high p_T hadroproduction in Au+Au @ RHIC !

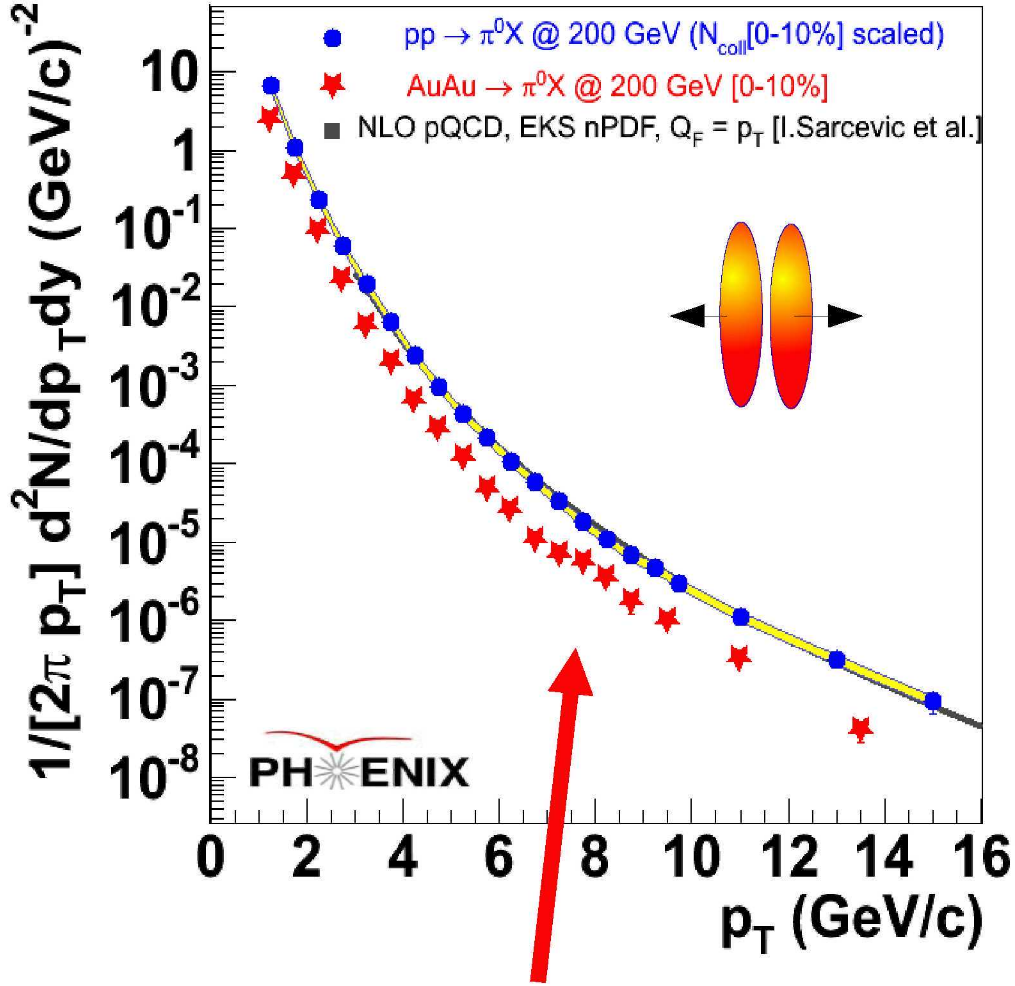
Au+Au→ π^0 *X* (peripheral)



D.d'E, nucl-ex/0401001

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

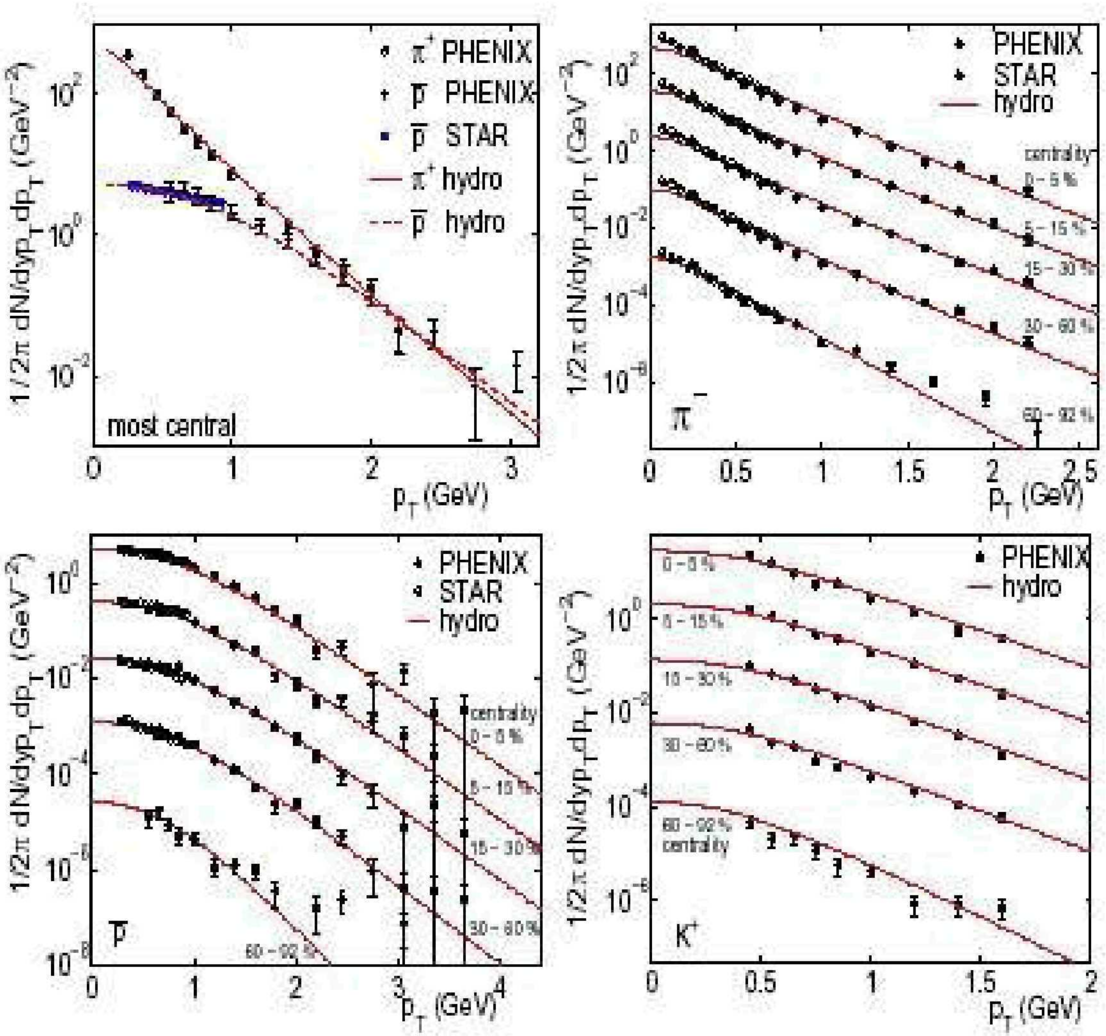
Au+Au→ π^0 *X* (central)



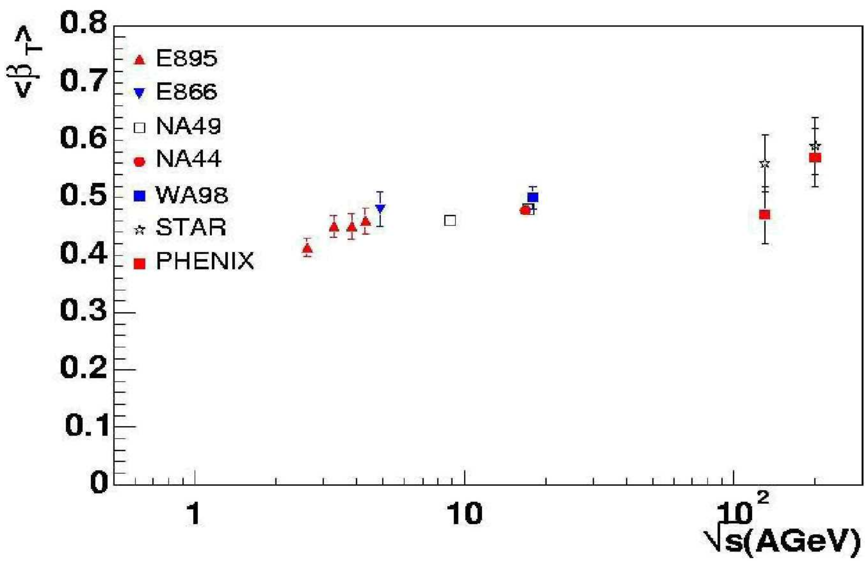
Strong suppression in
central Au+Au collisions

Soft particle spectra

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

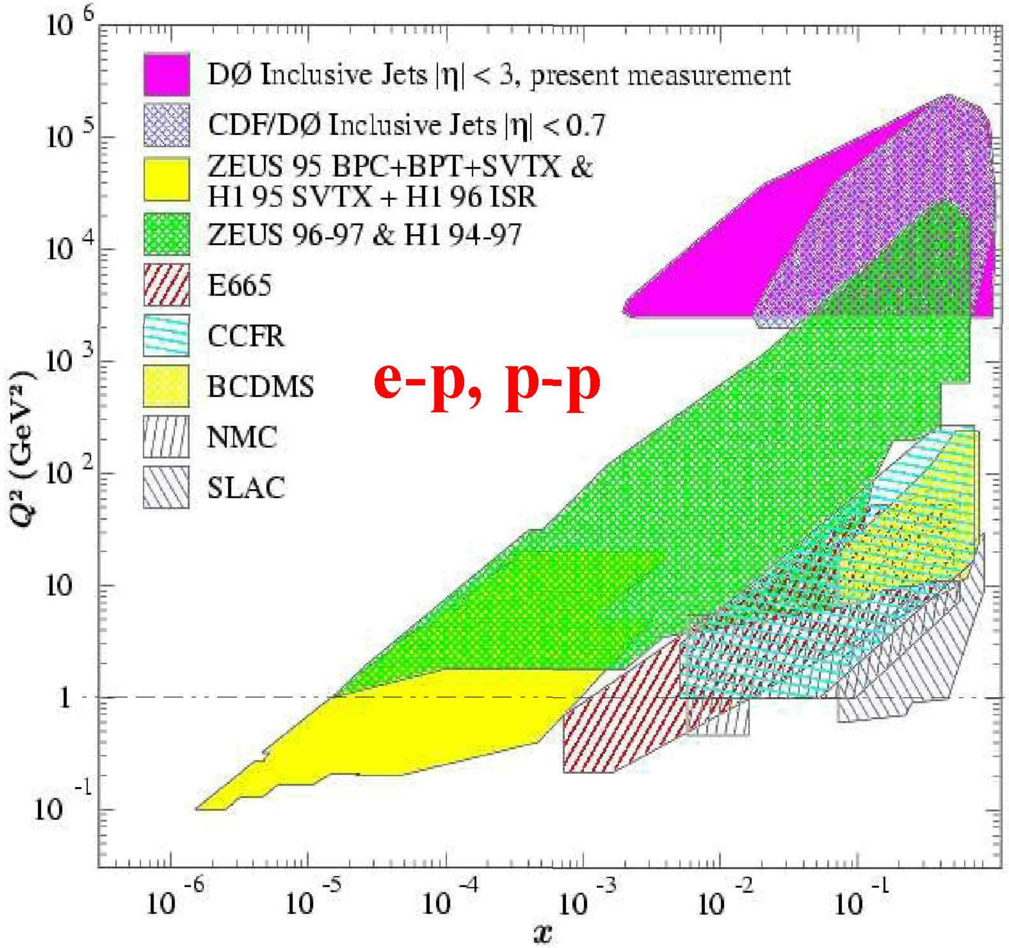


Strong radial collective flow built-up at freeze-out: $<\beta_T> \approx 0.6$



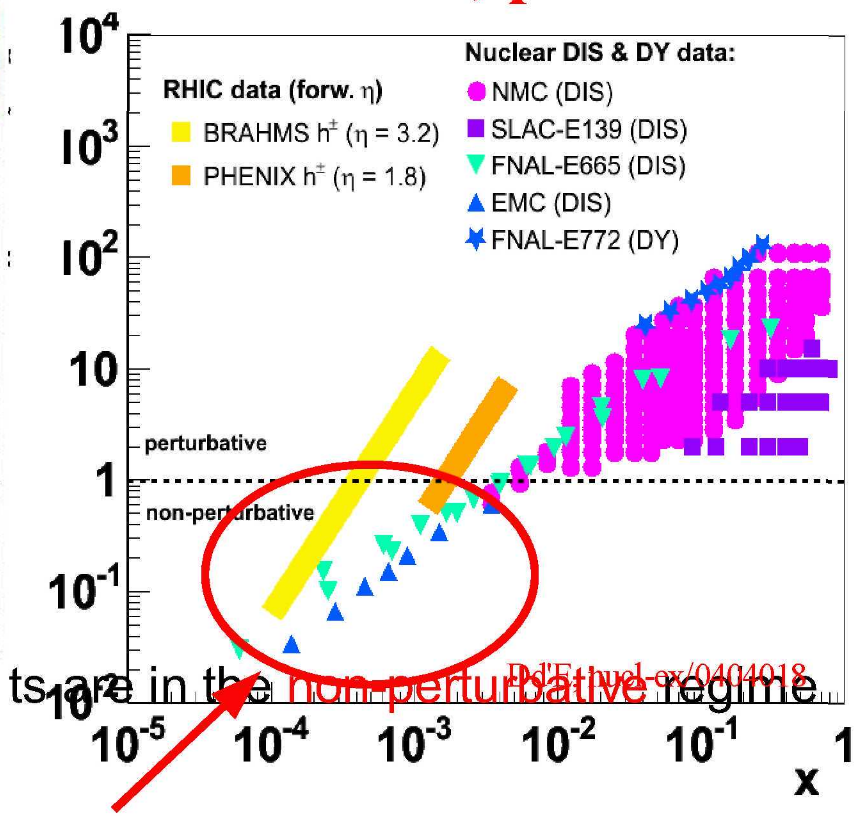
Experimental access to low-*x* parton distrib. (II)

- Kinematical (x,Q^2) domains covered experimentally:

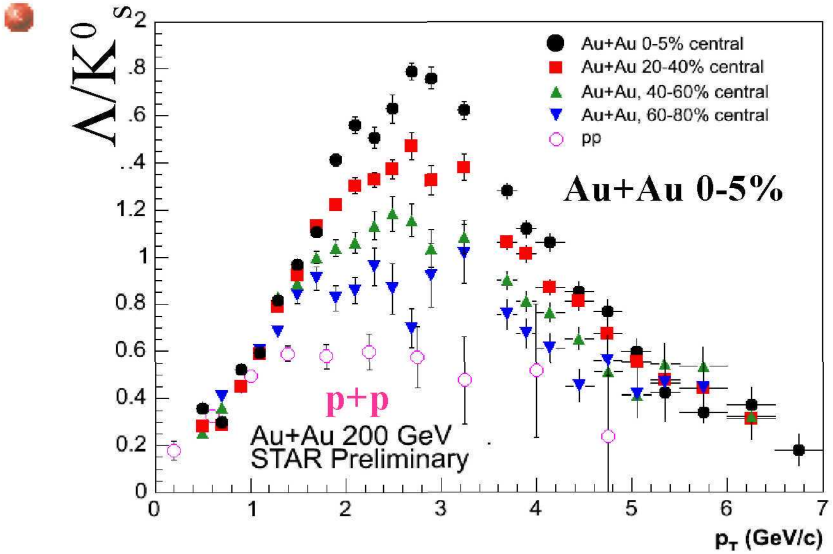


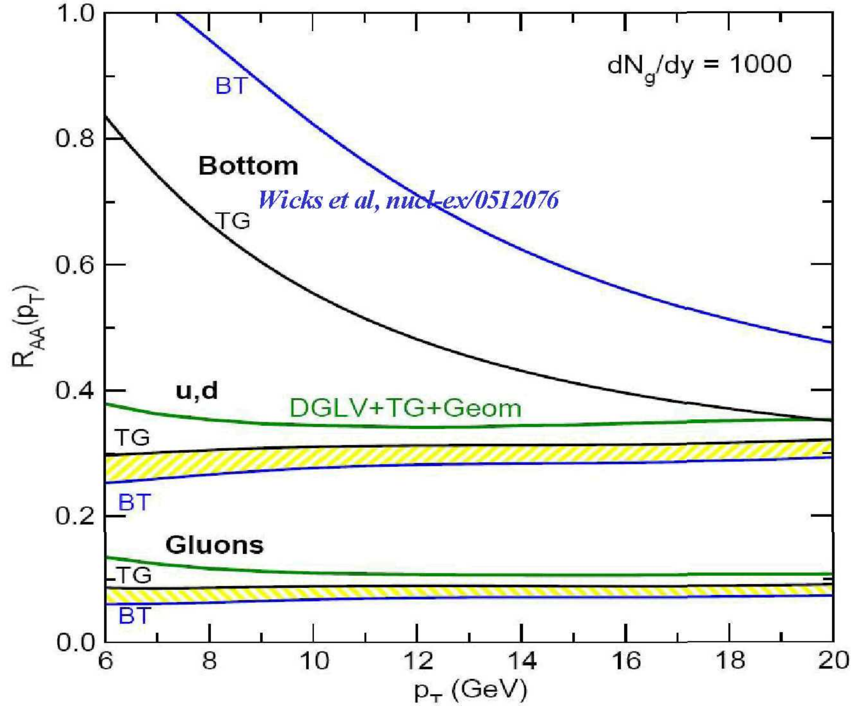
much less nuclear PDF data available:

e-A, p-A



STAR QM05 and nucl-ex/0601042





STAR WW06, Ruan