Overview of RHIC results

Jean Gosset

2006 LHC days in Split
October 2, 2006

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Outline

- 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 $\langle q_{hat} \rangle \sim O(10)$ 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) (?) **$\Rightarrow J/\psi$ yields**

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

  $\tau \sim 1$ fm/c:

  (7) Energy densities above ε_{crit}: $\varepsilon \sim 5$ 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**

- Outlook

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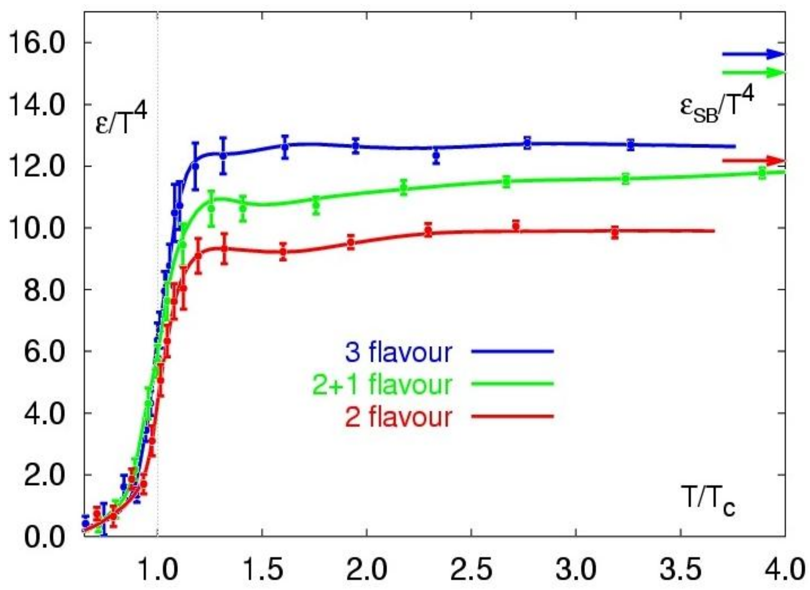
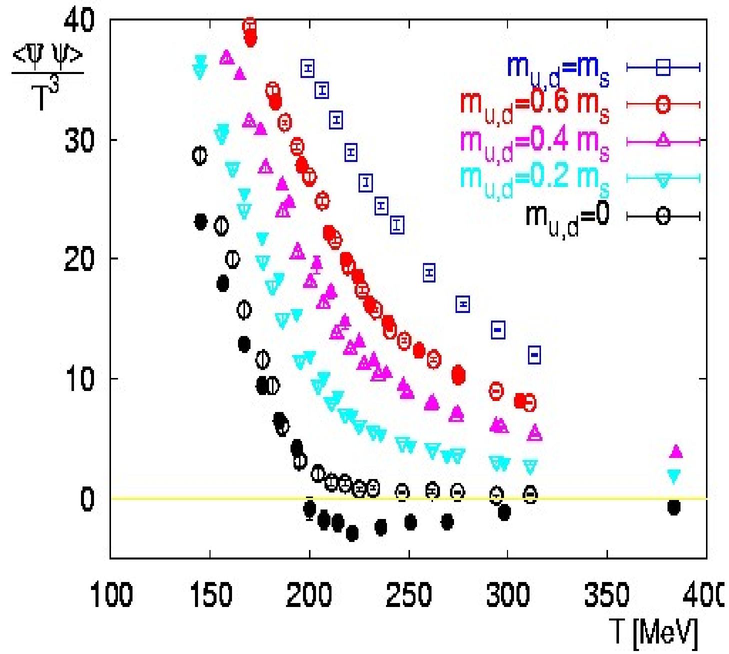
High-energy AA collisions: physics program (1)

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

2. Study the phase diagram of QCD matter:
especially produce and study the QGP

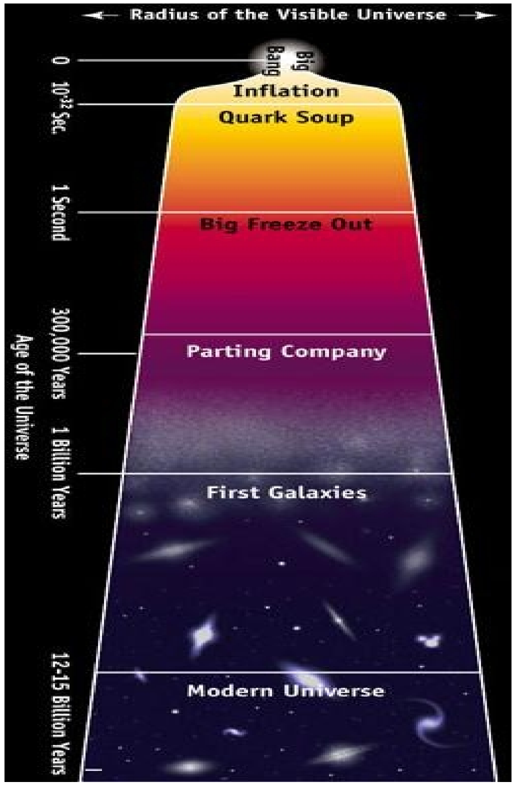


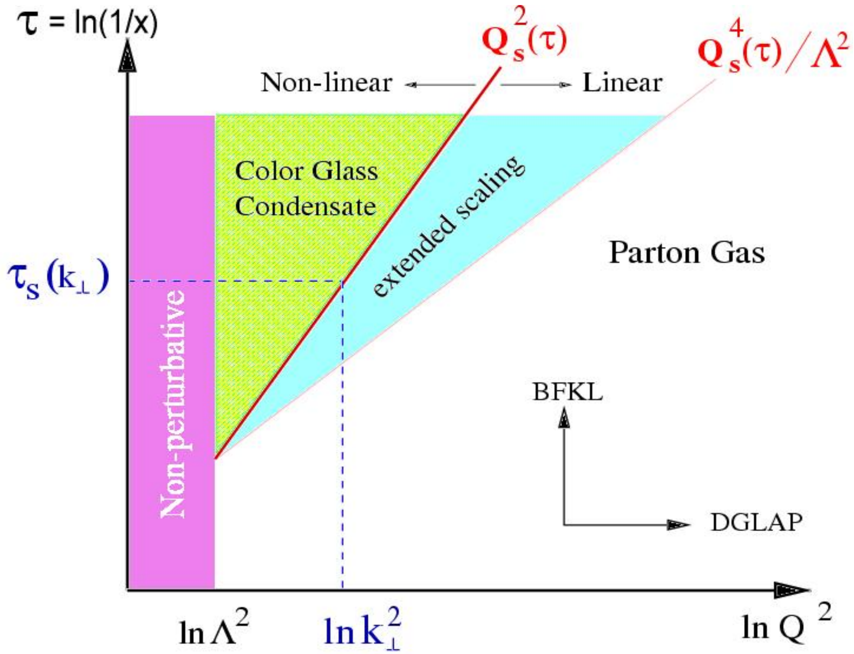


High-energy AA collisions: physics program (2)

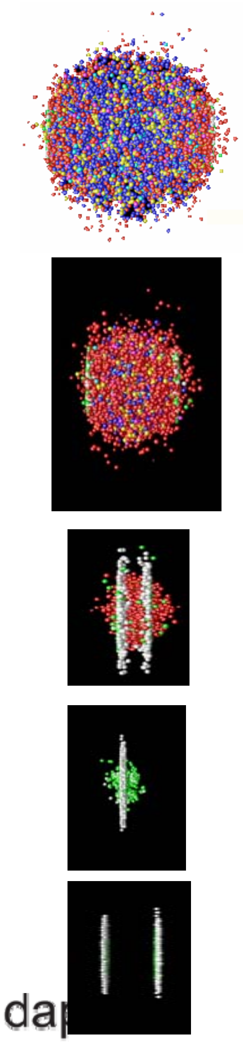
3. Probe quark-hadron phase transition of the primordial Universe (few μs after the Big Bang)

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

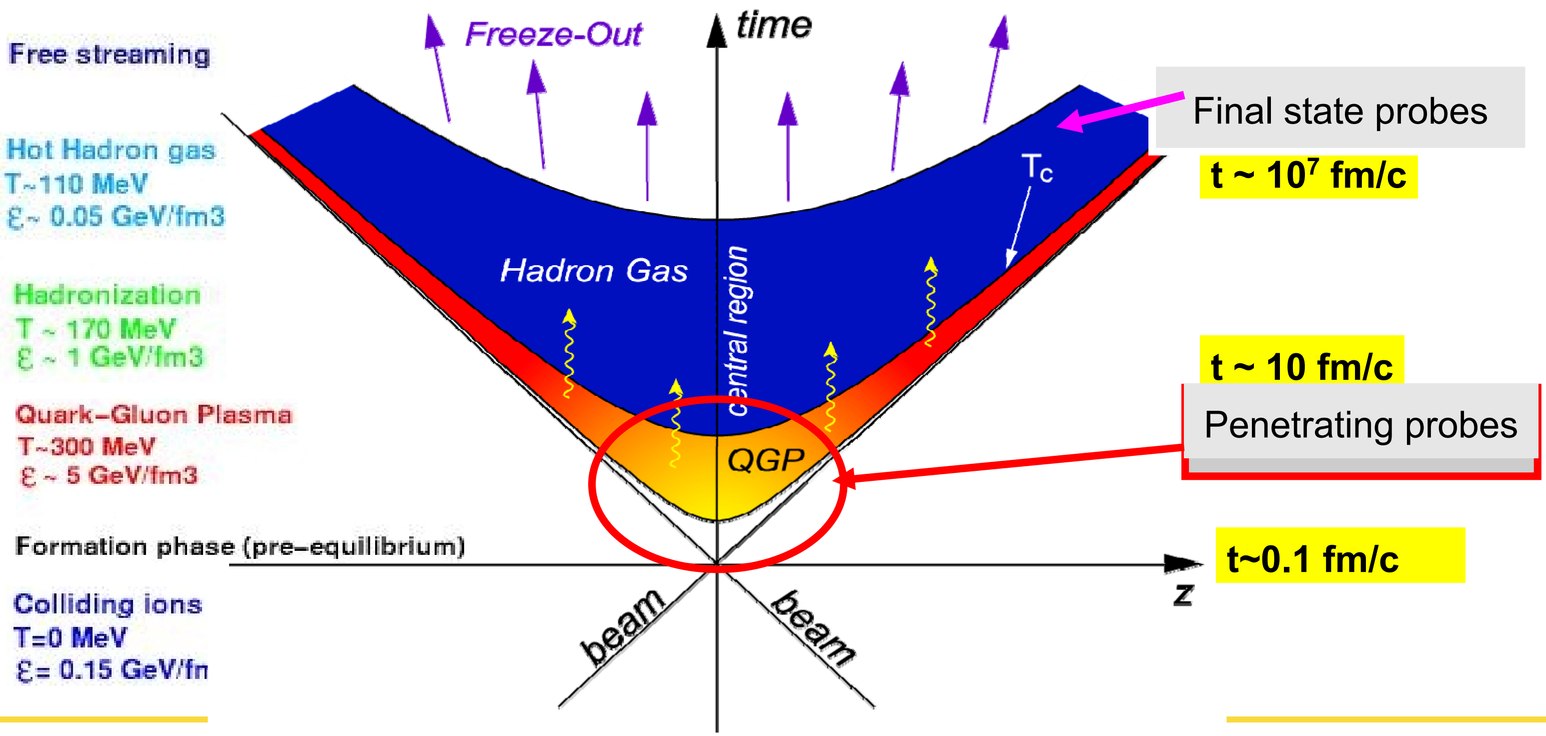




The "Little Bang" in the lab.



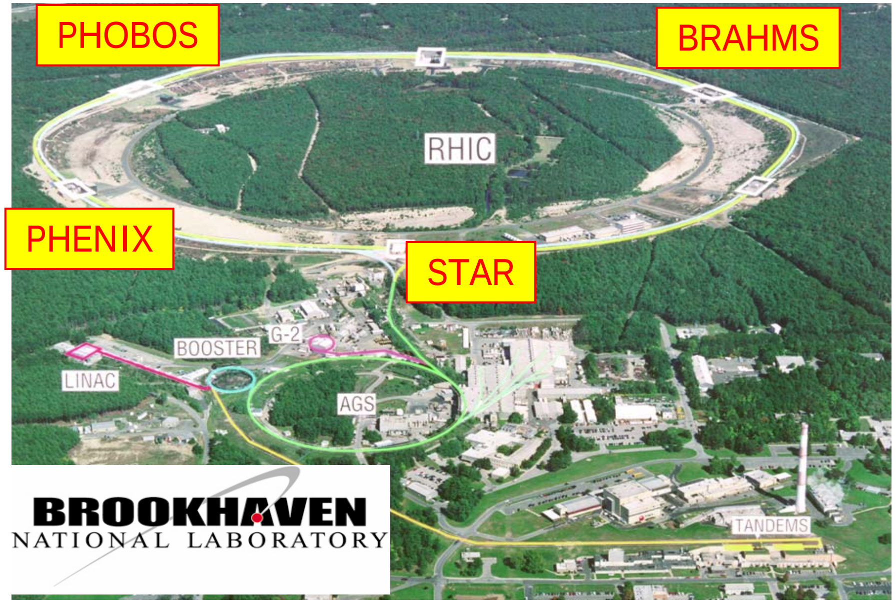
- High-energy nucleus-nucleus collisions:
fixed-target ($\sqrt{s_{NN}}$ = 20 GeV, SPS)
colliders ($\sqrt{s_{NN}}$ = 200 GeV @ RHIC, 5.5 TeV @ LHC)
- QGP expected to be formed in a tiny region (~10^{-14} m) and to last very short times (~10^{-23} s)
- Collision dynamics:
Different observables sensitive to different reaction stages



Relativistic Heavy-Ion Collider (RHIC) @ BNL

- Specifications:
  - 3.83 km circumference
  - 2 independent rings
    - 120 bunches/ring
    - 106 ns crossing time
  - maximum $\sqrt{s_{NN}}$
    - 200 GeV for A + A
    - 500 GeV for p+p
- 4 experiments:

  BRAHMS, PHENIX, PHOBOS, STAR
- Runs 1 - 6 (2000 – 2006):
  - beams and $\sqrt{s_{NN}}$ in GeV
  - Au+Au 200, 130, 62.4, 22
  - Cu+Cu 200, 62.4
  - d+Au 200
  - p+p (polarized) 200, 62, 22



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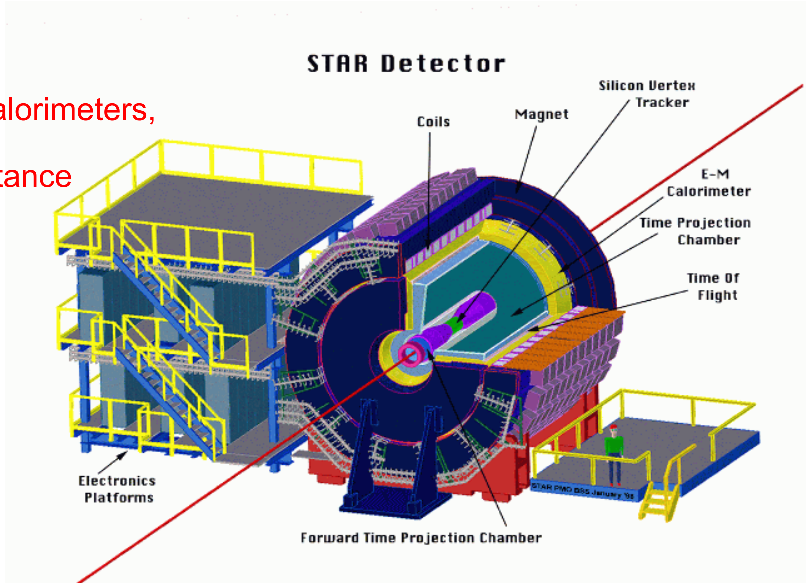
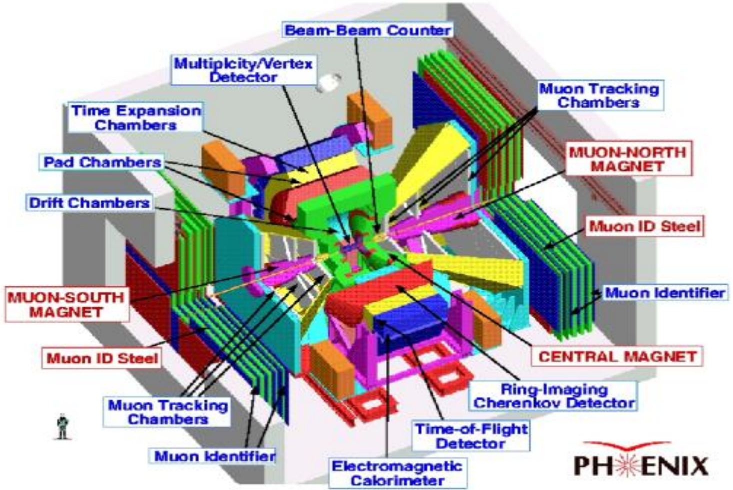
The 4 RHIC experiments

TPCs, Si, calorimeters,

large acceptance

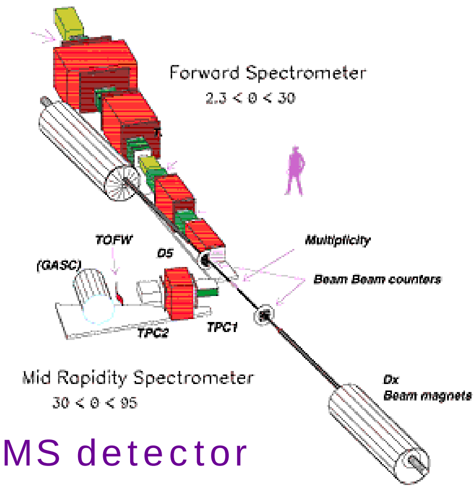




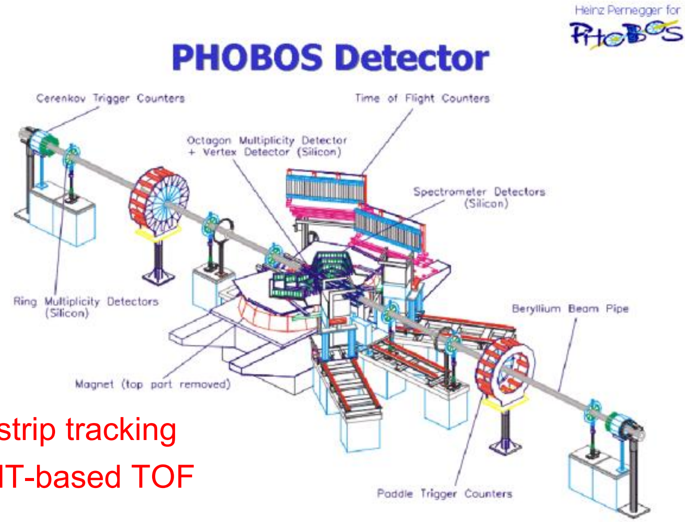
Hadrons, e's, mu, photons. High-rate DAQ.

Rare and penetrating probes

2 magnetic dipole
spectrometers
in "fixed-target"
configuration



BRAHMS detector



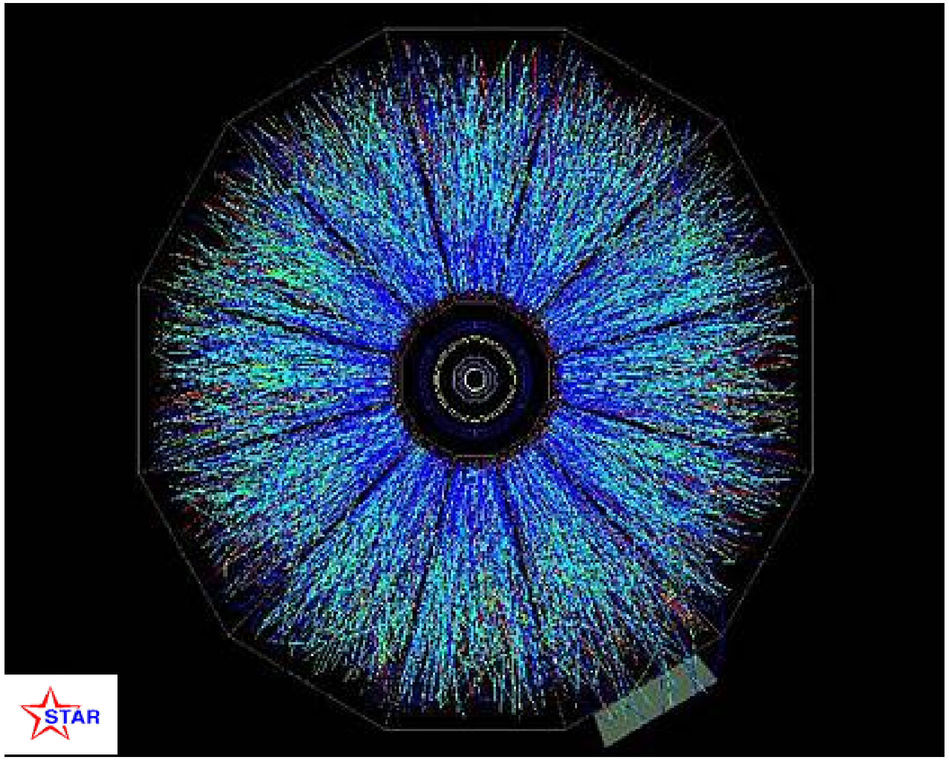
Si-strip tracking

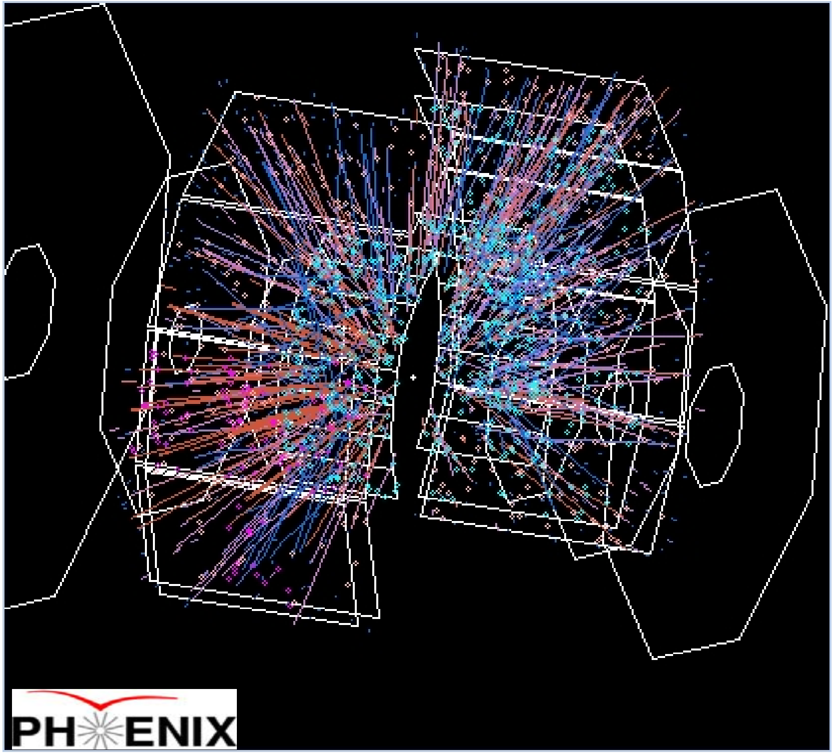
PMT-based TOF

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

Hadron multiplicities consistent
with released number of gluons
from saturated nuclear low-x gluon distribution

AuAu collisions @ 200 GeV





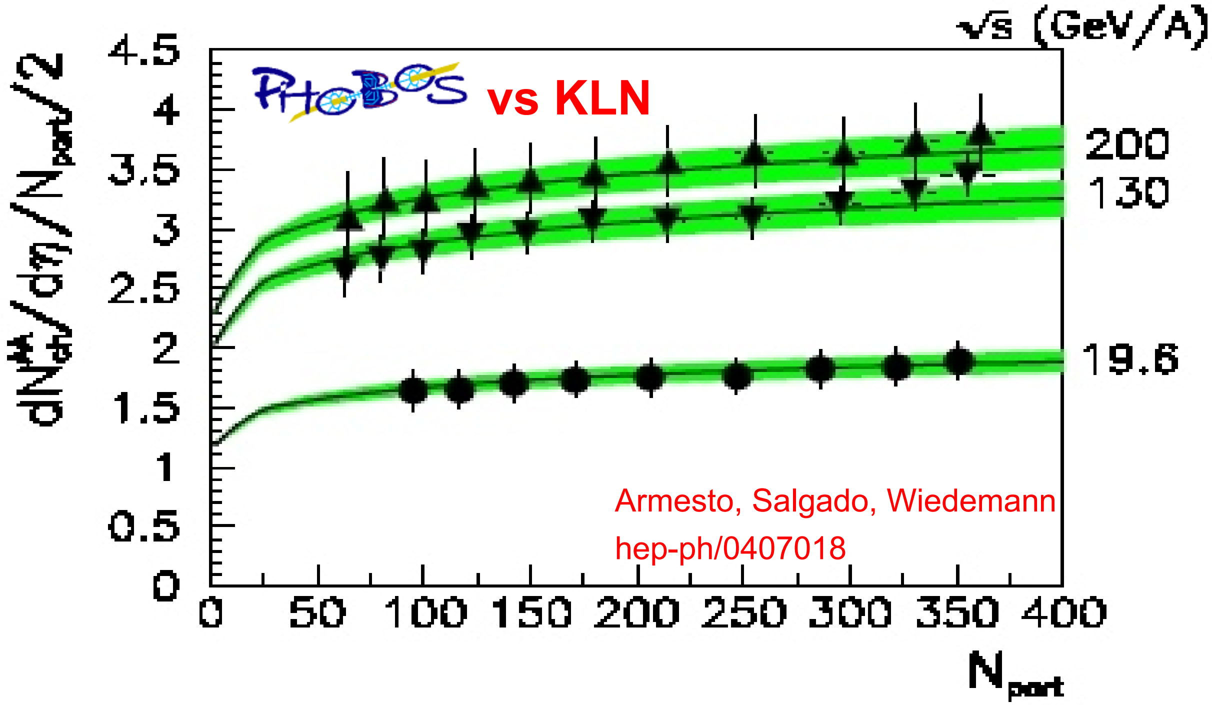
~ 700 charged particles per unit rapidity at midrapidity (top 5% central)

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)

(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: $\langle q_{hat} \rangle \sim O(10)$ GeV^2/fm

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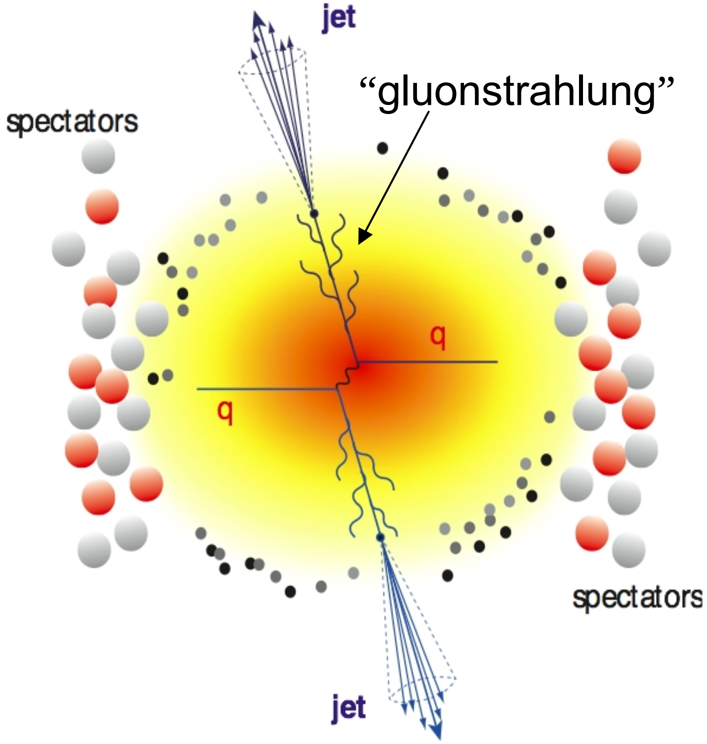
“Jet quenching” predictions

- Multiple final-state non-Abelian (gluon) radiation off the produced hard parton induced by the traversed dense medium
  Role of elastic energy loss (?)
- Parton energy loss ⇒ medium properties:
  GLV: gluon density, L
  BDMPS: transport coefficient, 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:
  $dE/dx \sim \alpha_s \langle k^2_T \rangle$
- Comparison to nuclear DIS results needs correction for expanding system

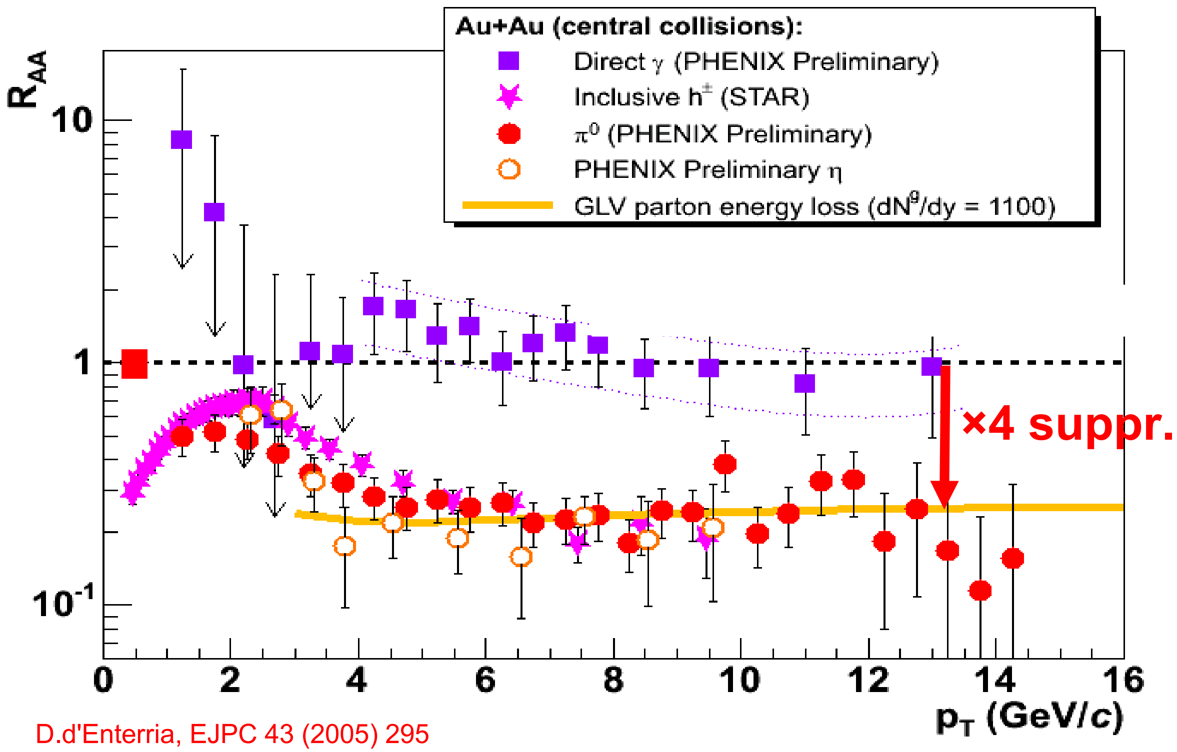


• Suppression of high p_T leading hadrons
• Disappeareance of back-to-back (di)jet correlations

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"

PHENIX PRL 88, 022301 (2002)



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

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

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

R_{AA} << 1: Hadrons well below pQCD expectations.

Parton energy-loss: $dN^g/dy \sim 1100$, $<q_{hat}> \sim 14\ GeV^2/fm$

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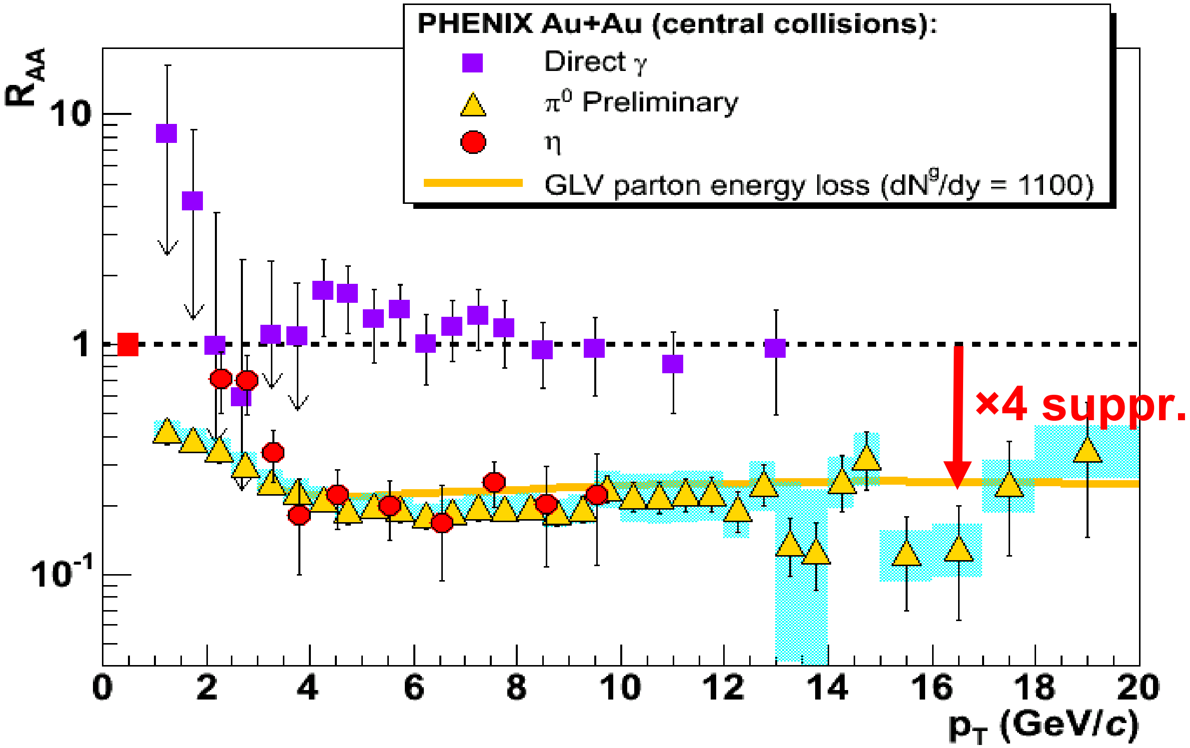

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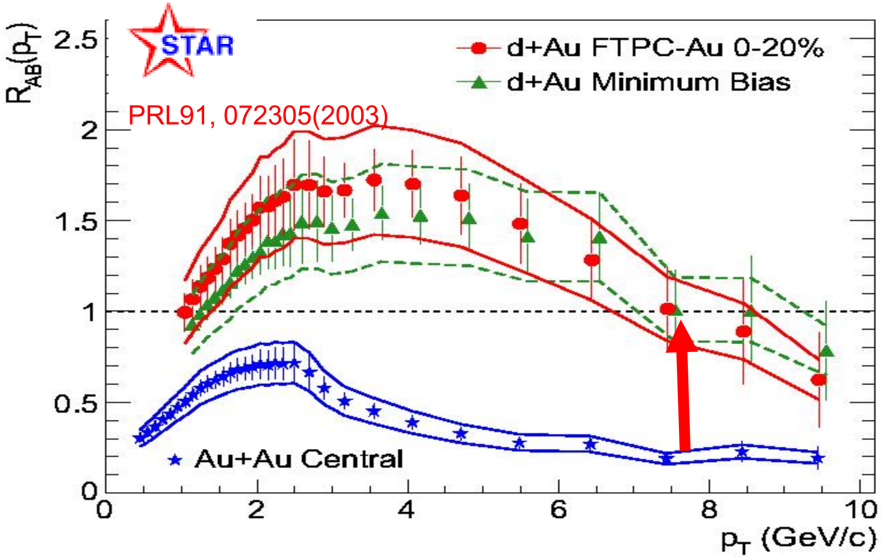
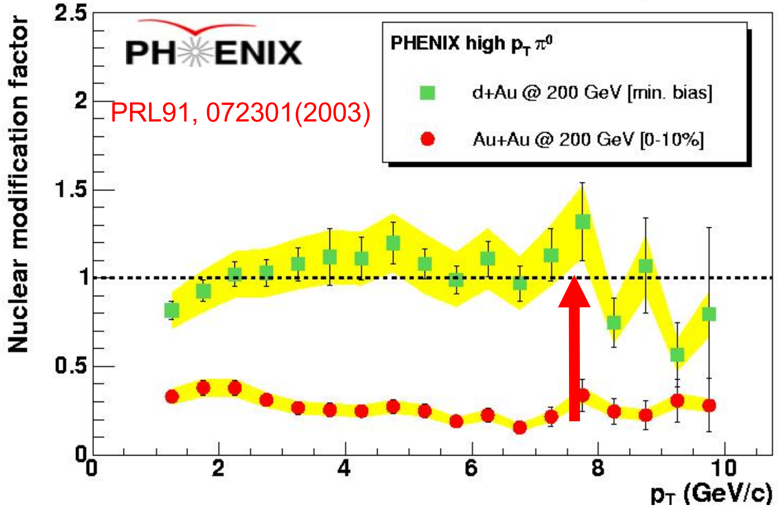
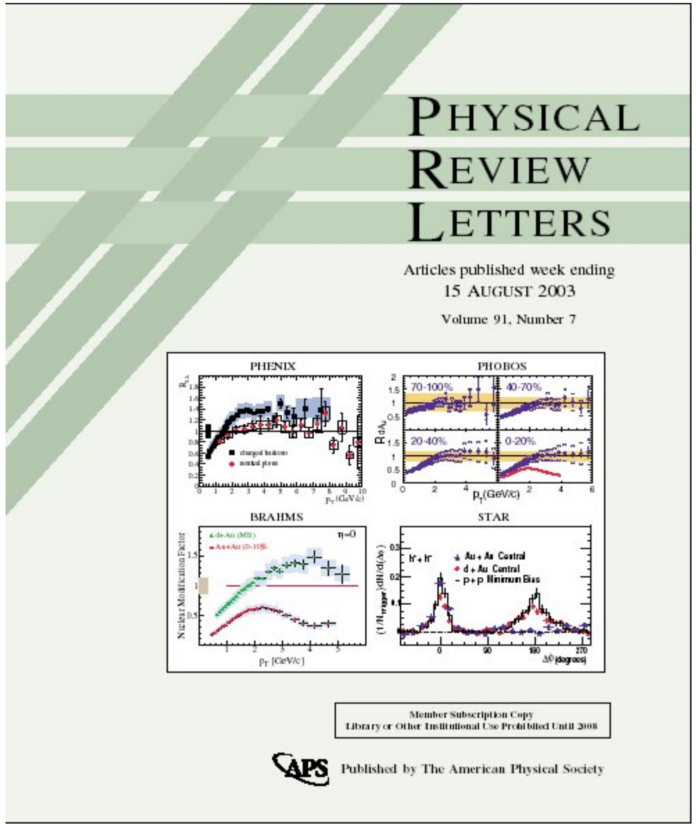
Unquenched high p_T hadroproduction in dAu







[2003]

- 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

Absorbed away-side jet ("mono-jets" configuration)

"Lost" energy redistributed at lower p_T

Double-peak structure:

Mach cone effect in the plasma ?

Speed of sound $c_s \sim 0.3$ (?)

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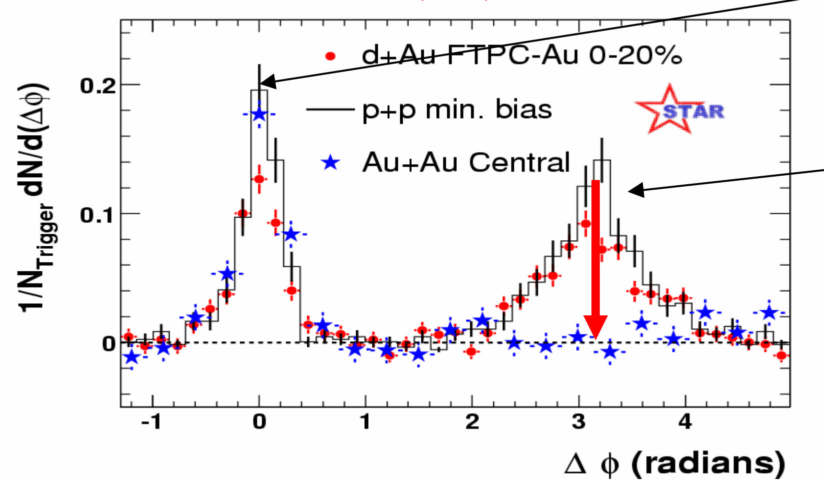
High p_T di-hadron Δφ correlations in central AuAu

STAR, PRL 90, 082302 (2003)



Near-side jet-like Gaussian peak unmodified (AuAu ~ dAu ~ pp)

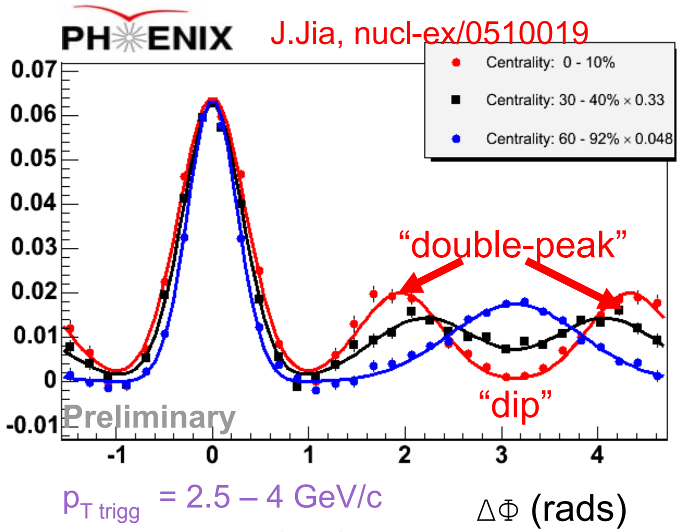
Away-side peak disappearance: "monojet"-like topology

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

"Lost" away-side energy dissipated at lower p_T values

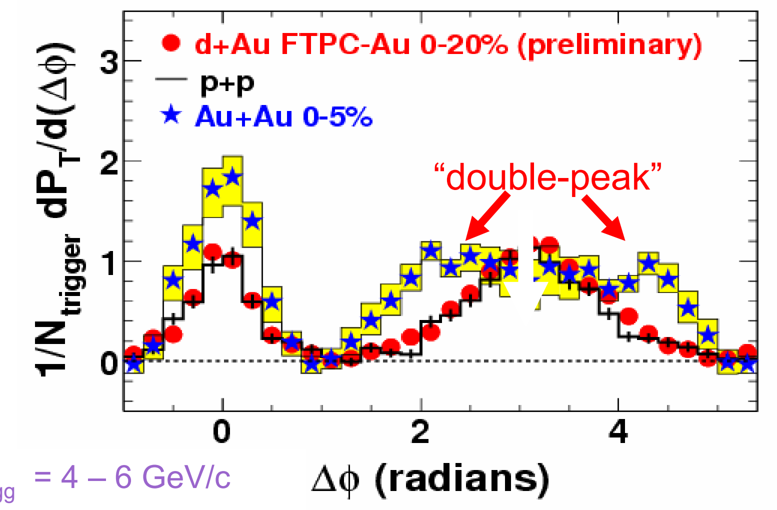
Away-side Δφ peak splits in two with increasing centrality

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 $\pi \pm 1.2$ rad
reminiscent of Mach wave conical shock ("sonic boom")
  - speed of sound accessible through $\cos\theta_M = c_s$
  - Stoecker, Satarov, Mishutin, hep-ph/0505245
    Casalderrey, Shuryak, Teaney, hep-ph/0411315
  - time averaged $c^2_s \sim 0.1$
- gluon Cerenkov-like emission also proposed
  - medium index refraction accessible

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(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) and parton elliptic flows (v_2)

"Strongly coupled" (liquid-like) plasma:

small charm-Q diffusion coefficient

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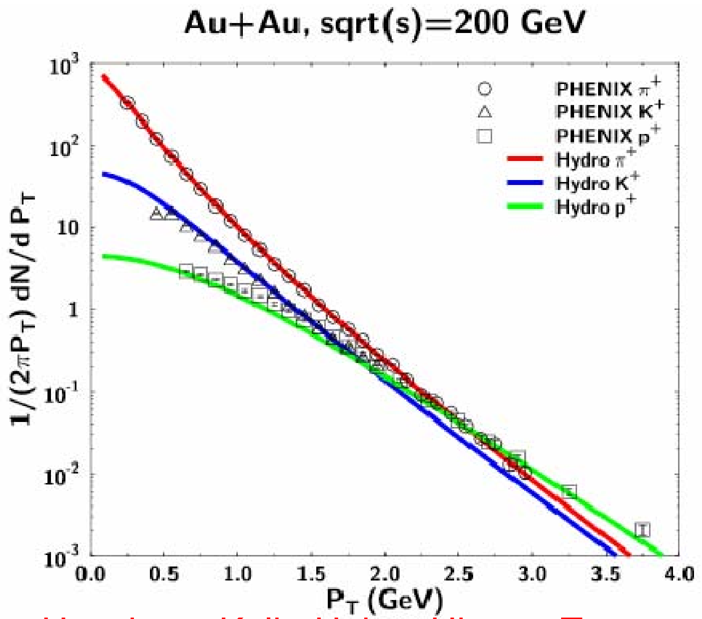
Success of hydrodynamicals models at RHIC

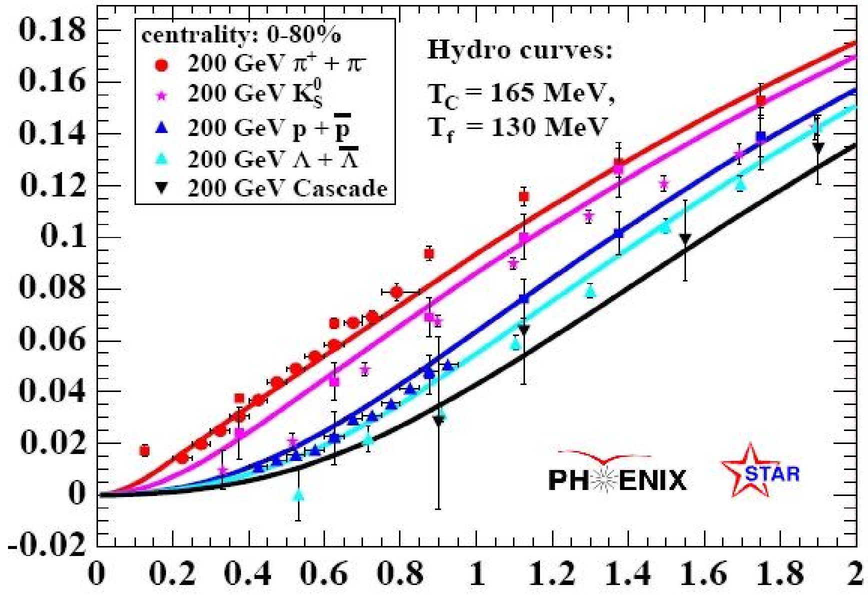
"Perfect fluid" hydrodynamics (zero viscosity) with QGP EOS and fast thermalization times (τ_0= 0.6 fm/c) reproduces bulk of particle production:

Single hadron ($\pi^{\pm}$, $K^{\pm}$, p, pbar) spectra up to ~2 GeV/c (mass dependence from collective radial flow β_T~0.6)



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

Strong elliptic flow for all hadrons ($\pi^{\pm}$, $K^{\pm}$, p, pbar) up to ~2 GeV/c



Huovinen et.al, PLB503

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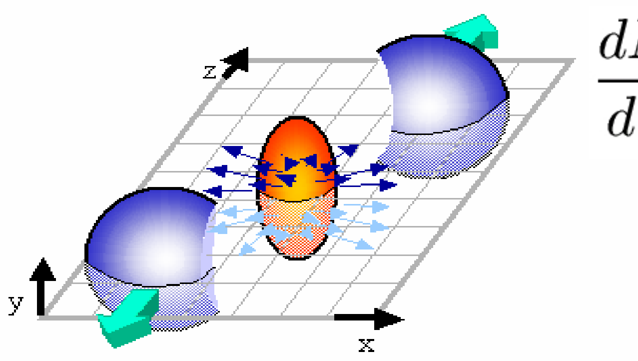
Elliptic flow

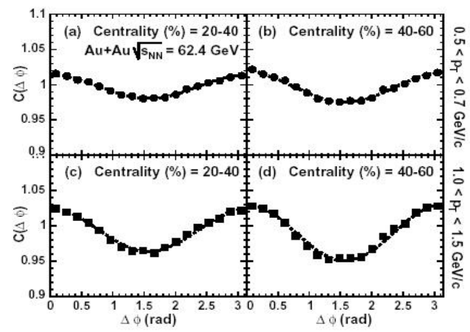
Initial anisotropy in x-space in non-central collisions (overlap) translates into final azimuthal asymmetry in p-space (w.r.t. reaction plane)



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

Elliptic flow = v_2

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

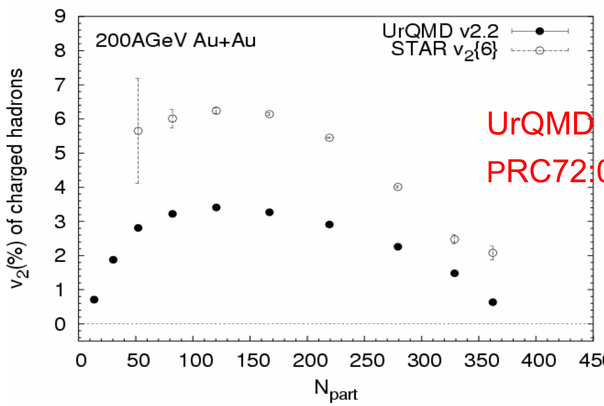


PHENIX: PRL 91, 181301(2003)

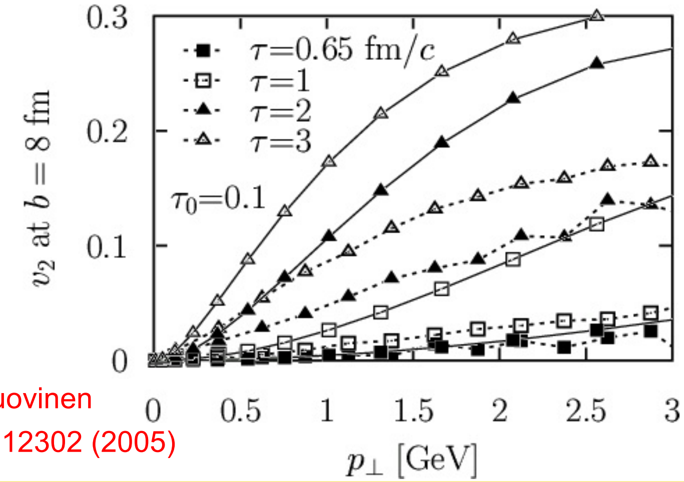
1) Truly collective effect (absent in p+p collisions)

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)

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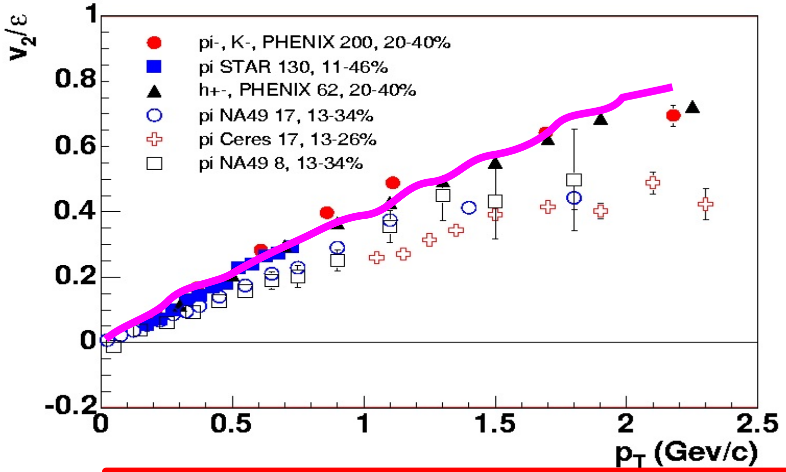
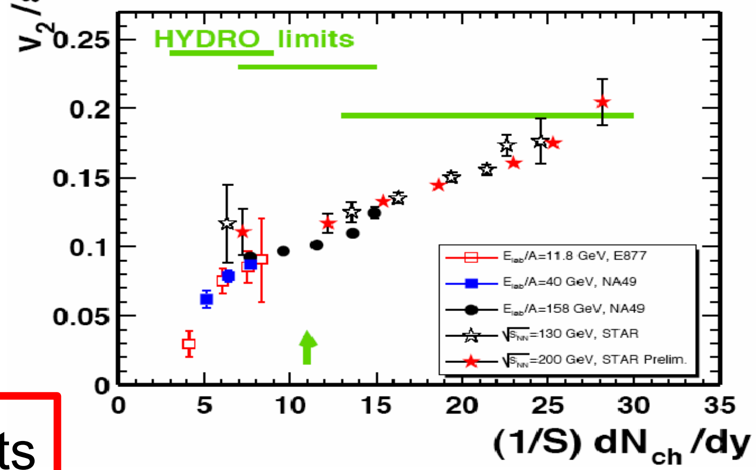
Elliptic flow at RHIC

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



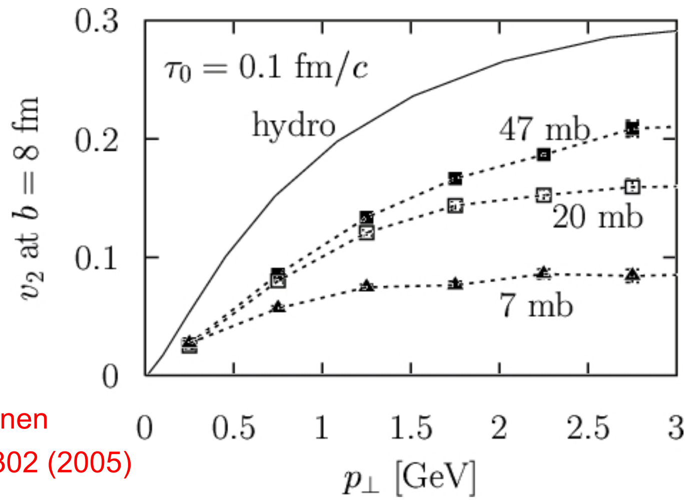
~50% increase from CERN-SPS



⇒ Strong (collective) pressure gradients

⇒ Large and fast parton rescattering:
early thermalization

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



Molnar, Huovinen
PRL 94, 012302 (2005)

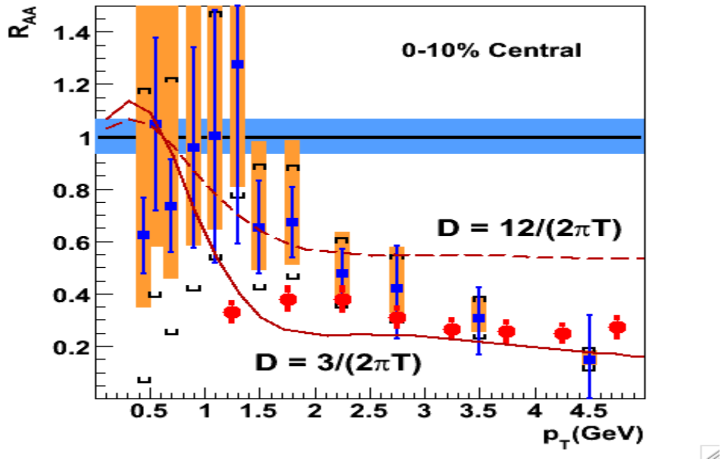
Charm quark: suppression, v_2

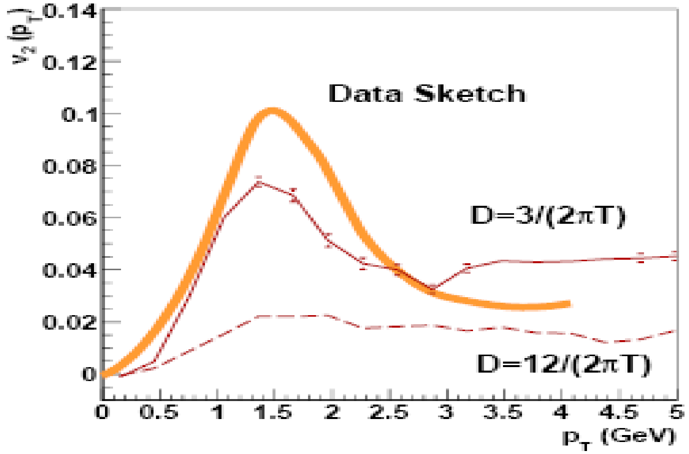
Estimates of medium transport coefficients with heavy-Q

Small diffusion coefficient ($D = 2T^2/k$, k = mean Q^2 per time):

strongly interacting medium: $D \sim 3 / (2\pi T)$

Moore & Teaney
PRC71, 064904, '05





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

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

$\Gamma = \langle E_{pot} \rangle / \langle E_{kin} \rangle$ …

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

(5) Suppressed J/ψ production

Suppressed J/ψ yields observed at RHIC

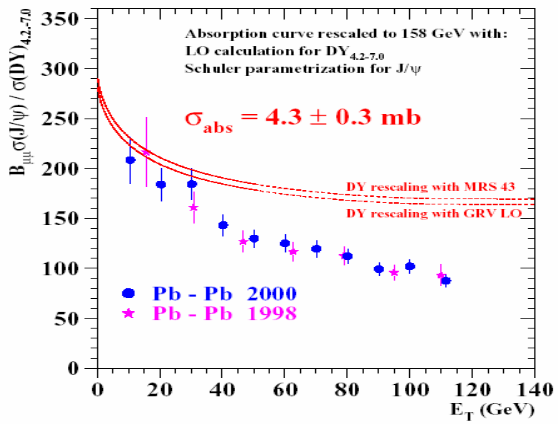
Consistent with:

Debye-screened (deconfined) medium (?)

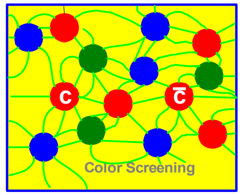
Recombination from ccbar pairs (?)

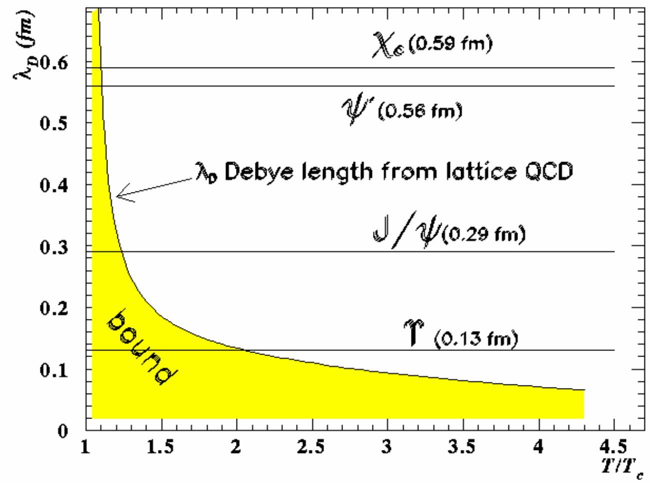
J/ψ suppression

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

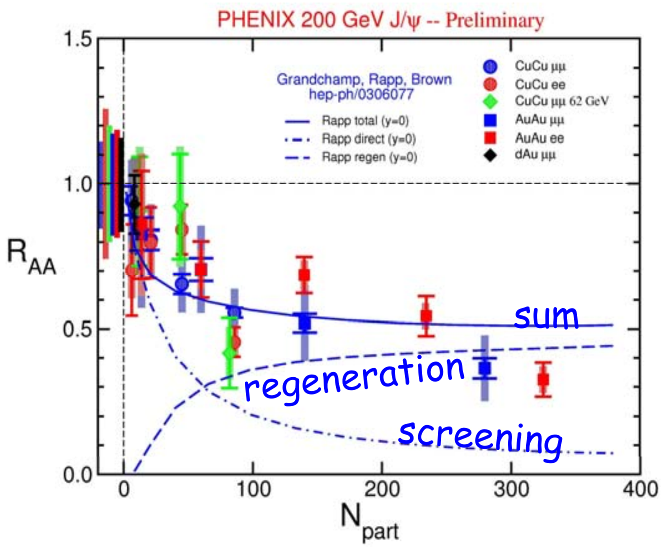


SPS NA50 anomalous suppression





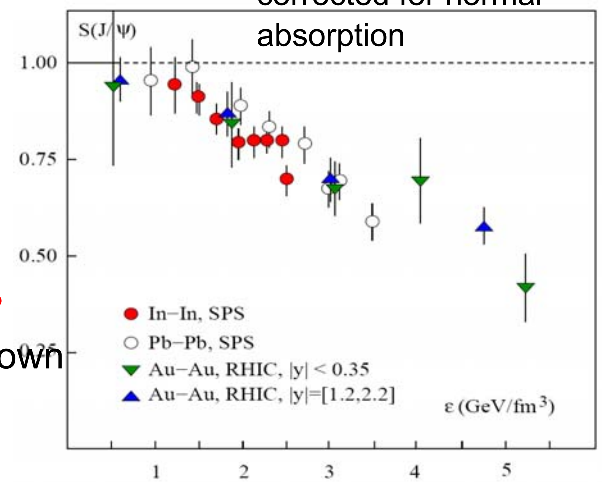
~ Same suppression observed at RHIC and SPS



ccbar regeneration compensates for screening ?

Rapp et al., Thews

Survival probability corrected for normal absorption



Recent lattice calculations

J/ψ not screened until 2 T_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

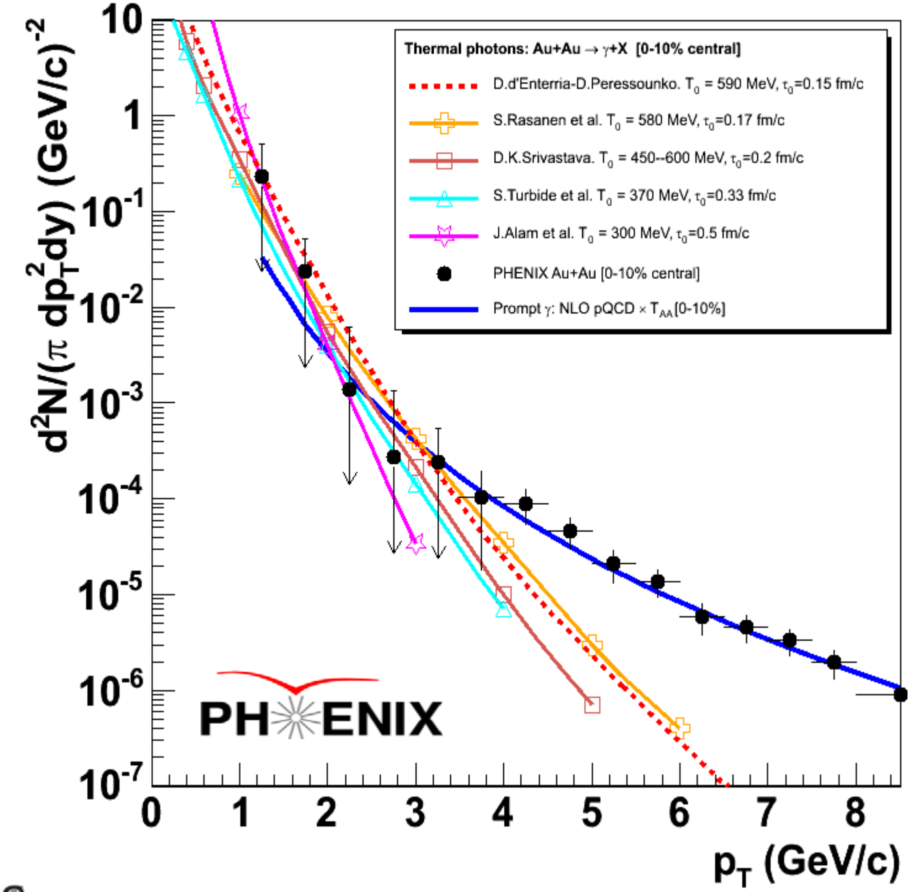
over primary (pQCD) contribution

is consistent with hydro predictions

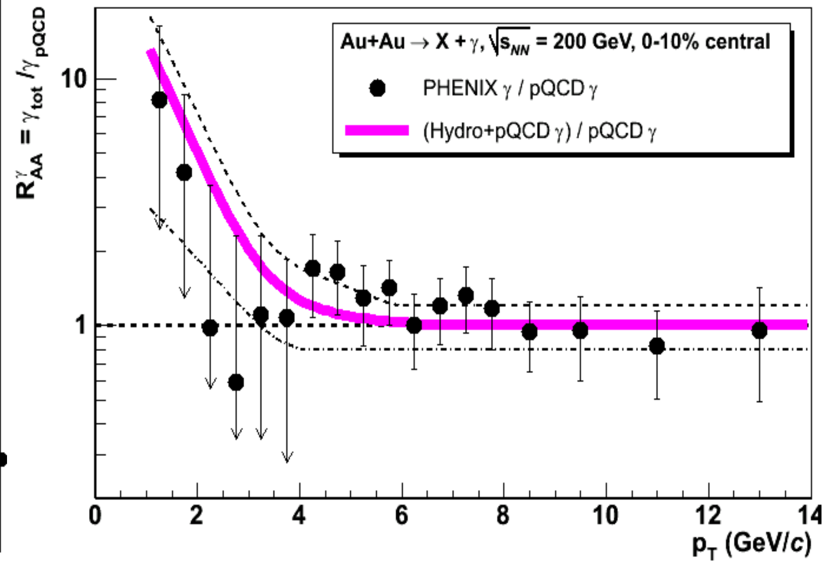
for a hot radiating source (T_0 ~ 590 MeV, <T_0> ~ 350 MeV)

"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'Enterria. & D.Peressounko
EPJ-C 46, 451 (2006)



pQCD+hydro (2D+1, T_0~590 MeV, <T_0>~350 MeV) reproduces data ...

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

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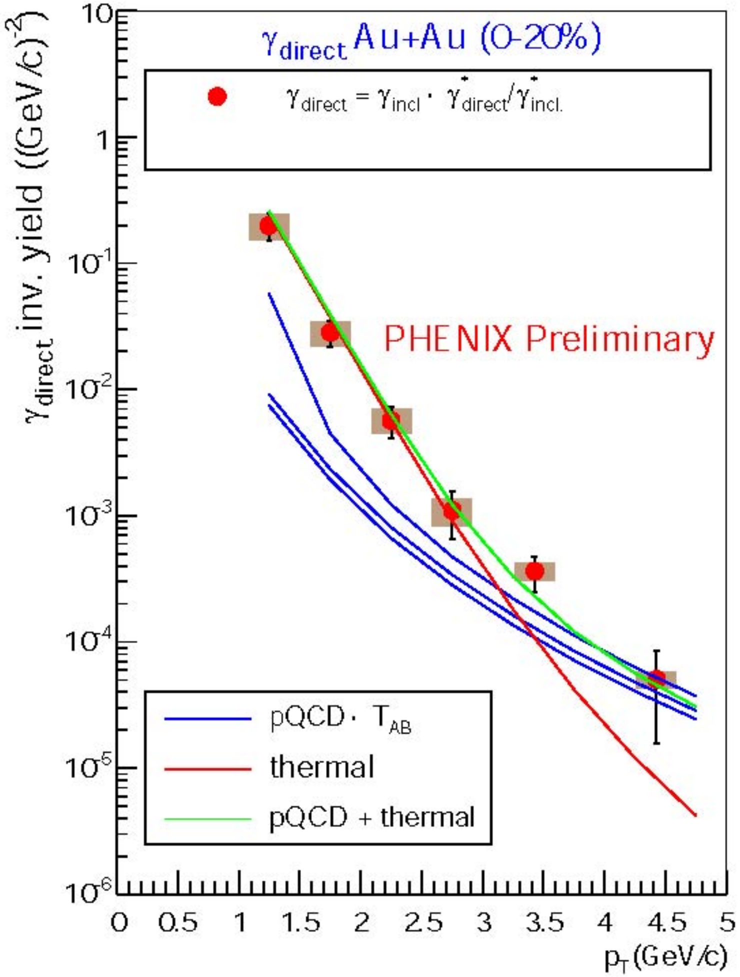


New method:

Very low mass e^+e^- pairs

Subtraction of Dalitz decays

of all sources

pQCD+hydro (2D+1, T_0~590 MeV, <T_0>~350 MeV) reproduces data ...

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

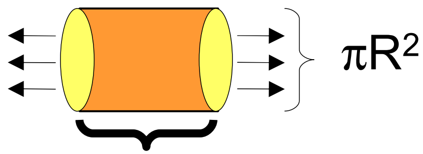
Energy densities $\varepsilon \sim 5$ GeV/fm^3

from transverse energy and “Bjorken estimate” at $\tau \sim 1$ fm/c:

above ε_{crit}

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

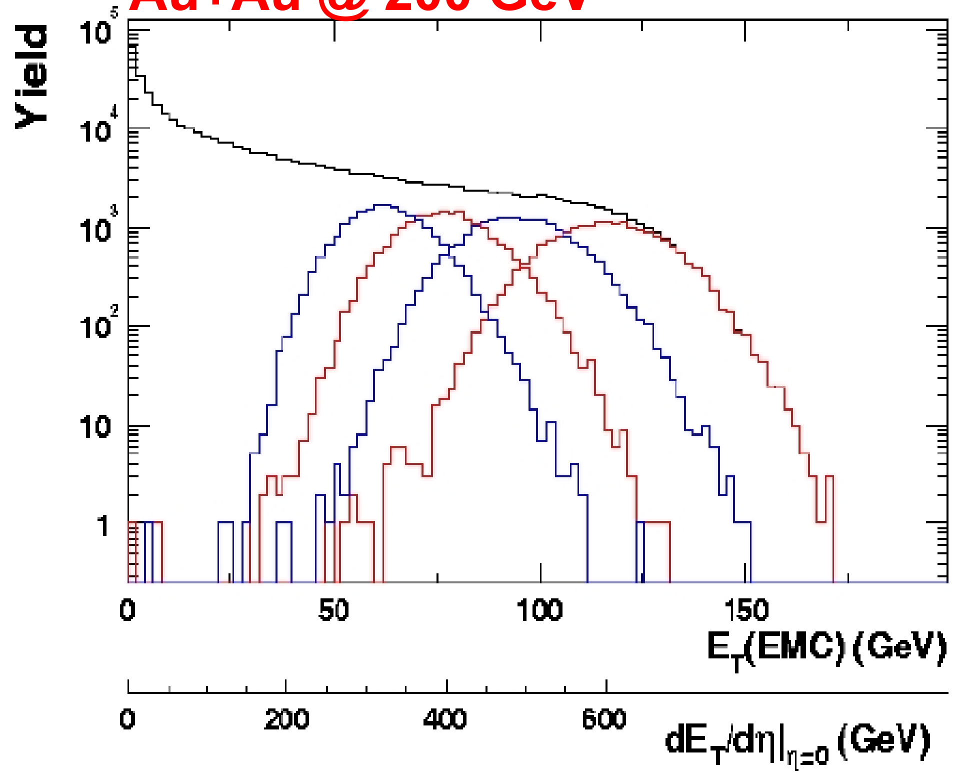
Bjorken estimate: $\epsilon_{Bj} = \frac{dE_T}{dy} \frac{1}{\tau_0 \pi R^2}$



(longitudinally expanding plasma) $\tau_0 \sim 1$ fm/c $> \tau_{cross} = 2R/\gamma \sim 0.15$ fm/c

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

Au+Au @ 200 GeV



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

(~70% larger than at CERN-SPS)

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

> QCD critical density

(~1 GeV/fm^3)

PHENIX, PRL 87, 052301 (2001)

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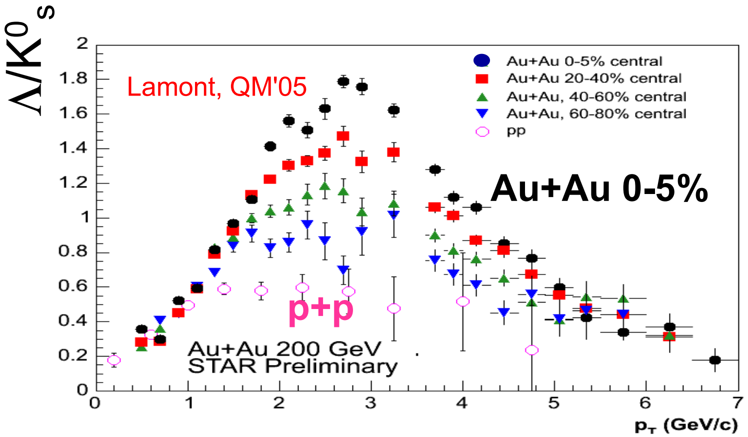
(8) Baryon spectra (dN/dp_T) and v_2 at intermediate p_T

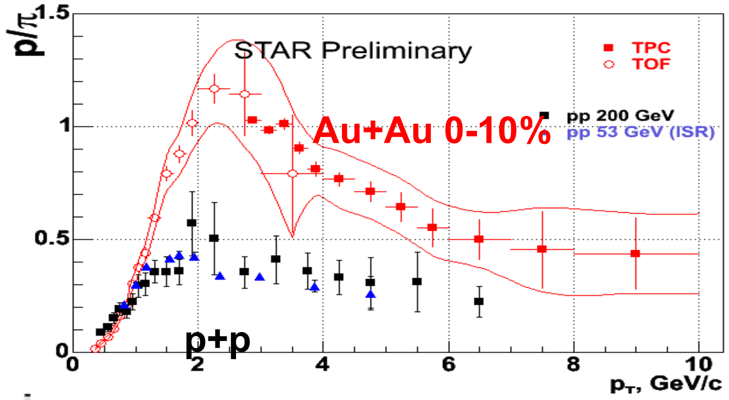
Consistent with

constituent quark-number scaling at hadronization

Enhanced baryon spectra and v_2 at intermediate p_T

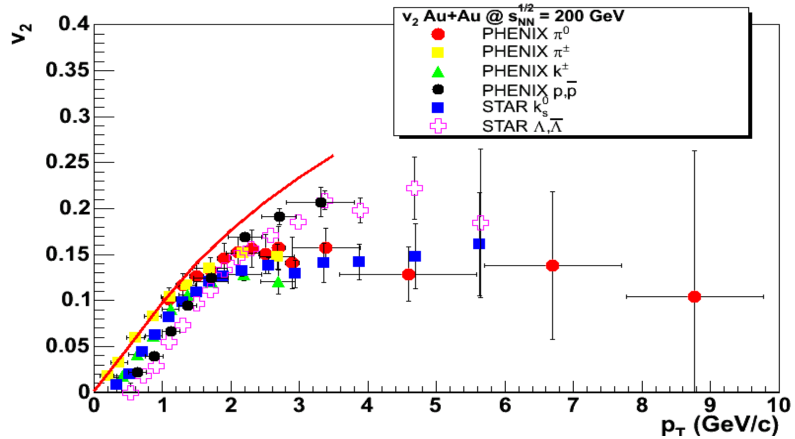
Strongly enhanced baryon (p, Λ) production within $p_T \sim 2 - 4$ GeV/c



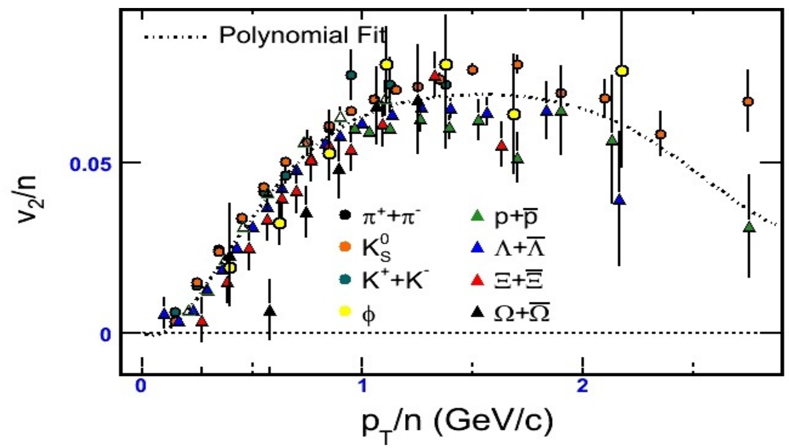


O.Barannikova, QM'05

Diff. v_2 baryon-meson p_T dependence



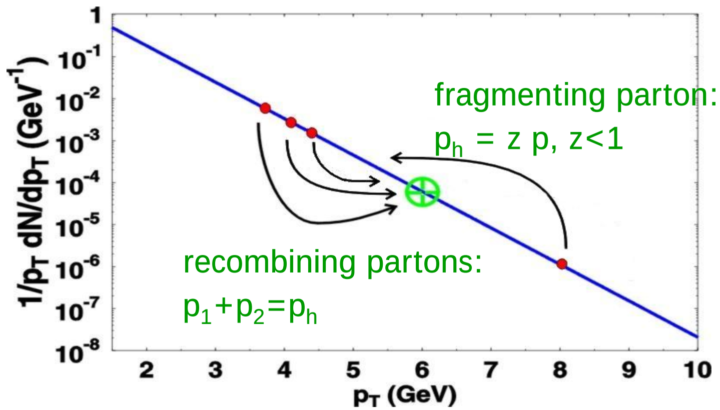
Simpler v_2 scaling behaviour normalizing v_2 and p_T by number of constituent quarks:

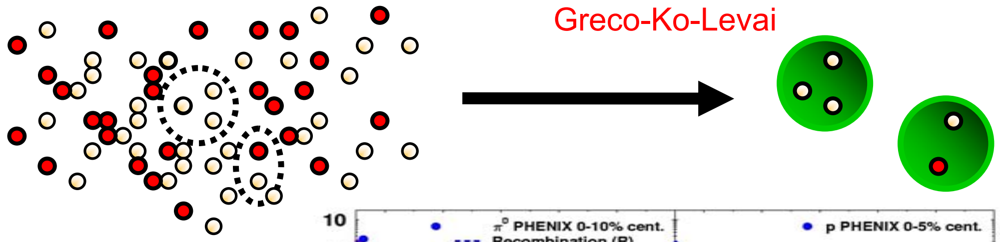


“Quark recombination” models vs. data

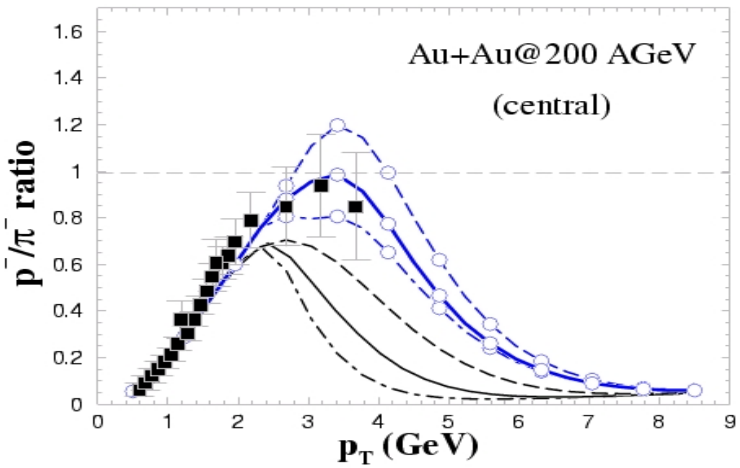
- Hadronization at intermediate p_T at RHIC via “quark recombination” (coalescence) in dense (thermal) medium :

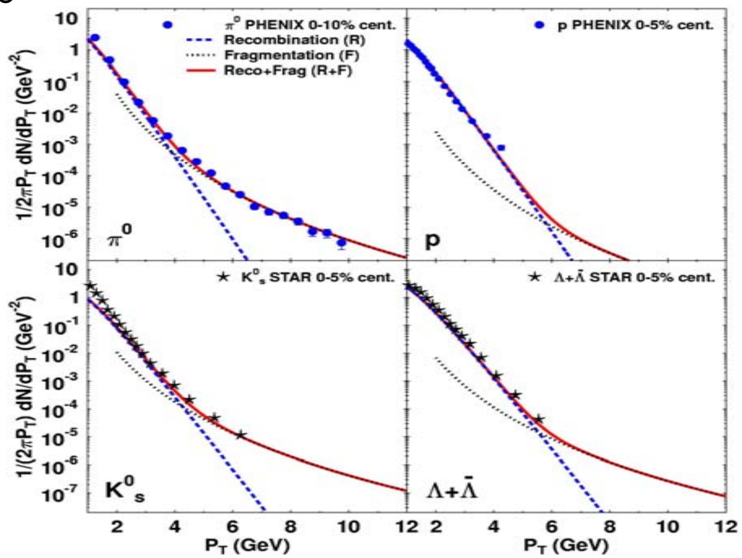
Hwa-Yang
Fries-Mueller-Nonaka-Bass
Greco-Ko-Levai





- Anomalous baryon/meson ratio explained:





Constituent-quark scaling of v_2 due to “universal” parent quark flow

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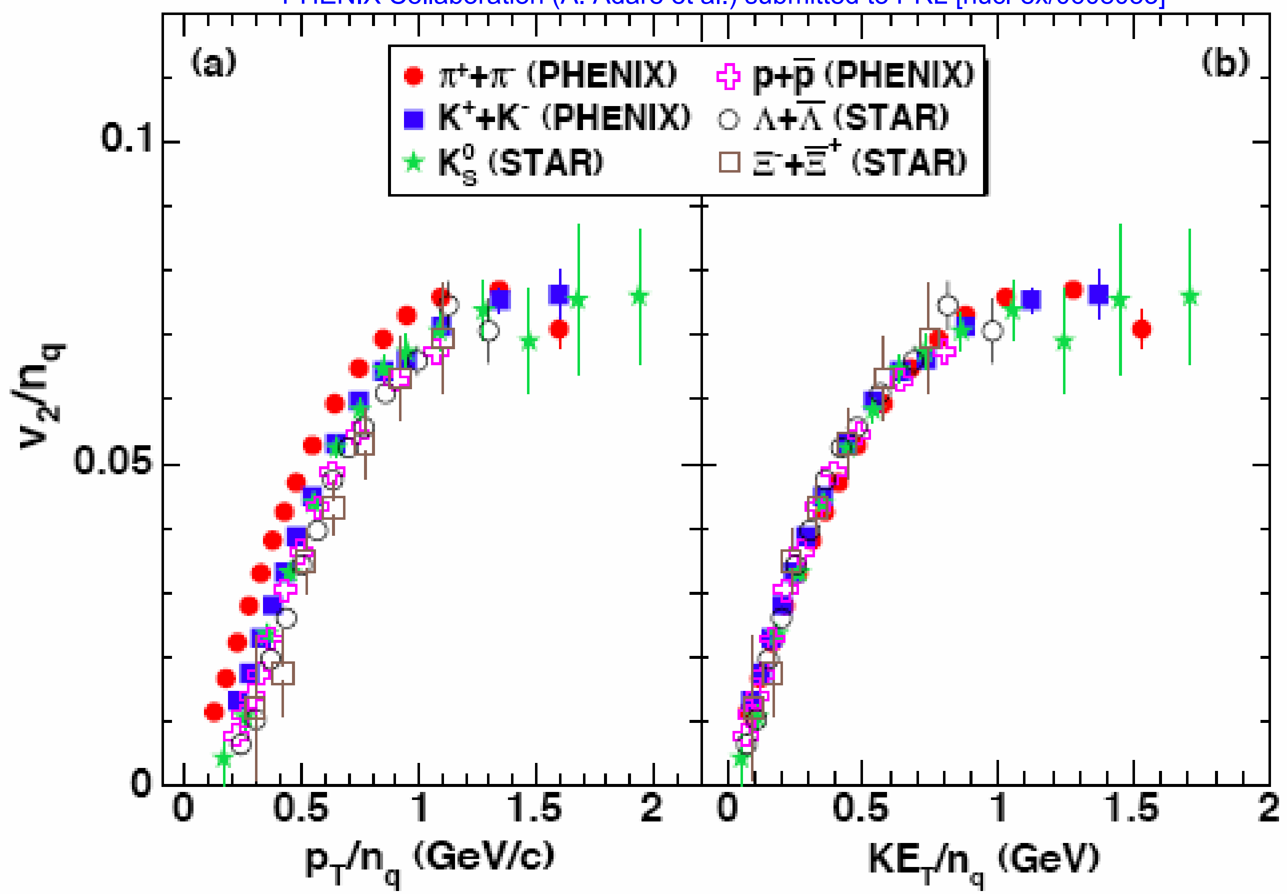
Quark number scaling: v_2 versus KE_T

KE_T = transverse kinetic energy = $m_T - m$

PHENIX Collaboration (A. Adare et al.) submitted to PRL [nucl-ex/0608033]



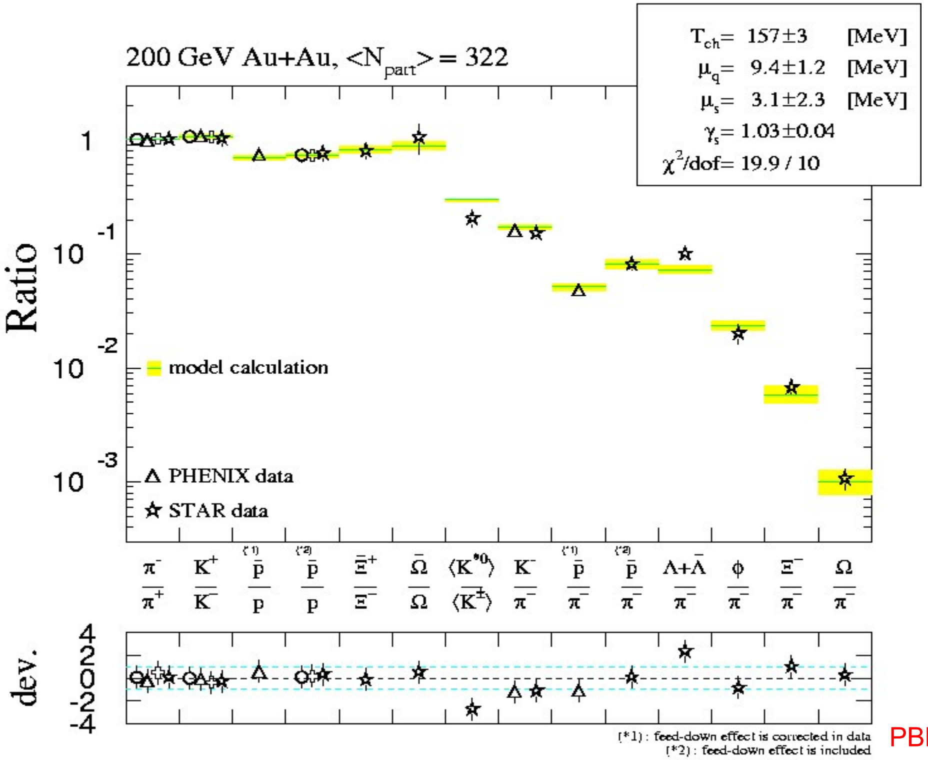
(9) Final AuAu hadron ratios

Chemically equilibrated system:

hadron abundances freezed-out at T~160 MeV

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

T =157 MeV, μ = 9.4 MeV

- 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

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(Comprehensive) overview

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 $\langle q_{hat} \rangle \sim O(10)$ 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}: $\varepsilon \sim 5$ 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**

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Future

- RHIC
  - Use improved luminosities (Au+Au)
  - Detector upgrades
    - PHENIX Hadron Blind Detector
      - e^+e^- pairs in $\rho\omega$ region : chiral symmetry restoration ?
    - Vertex detectors
      - Charm signature
    - etc
- LHC
  - QGP and CGC studies in different regimes
    - more jets, heavier quarks, smaller x

Backup slides