What have we learned from the RHIC experiments so far ?

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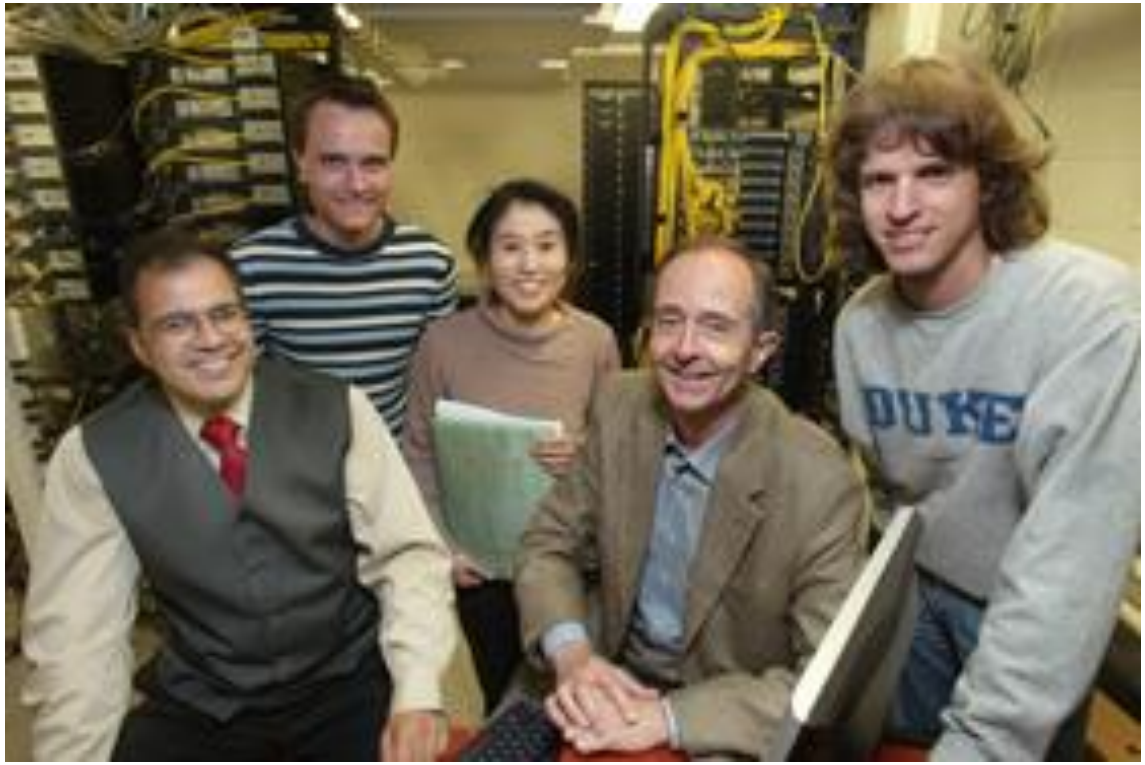
The Duke QCD theory group

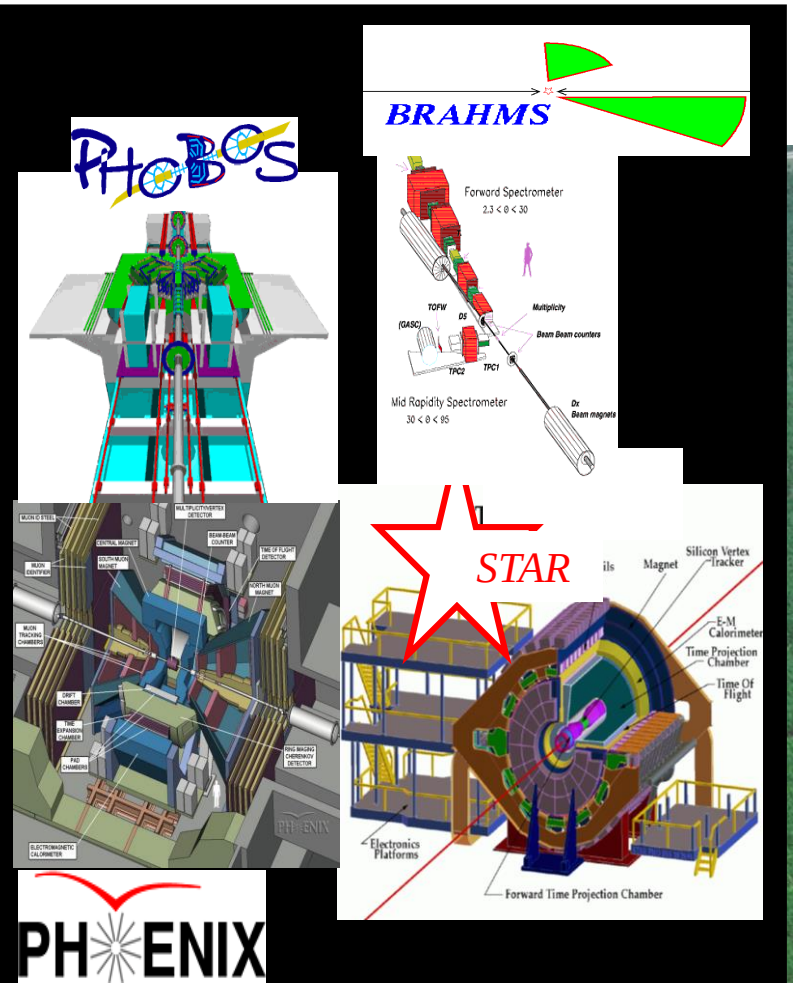


- PRL 90, 202303
- PRC 68, 044902
- PLB 583, 73
- PRC 69, 031902
- PRL 94, 122301

… and the incredible RHIC experimental collaborations!

The road to the Quark-Gluon Plasma…

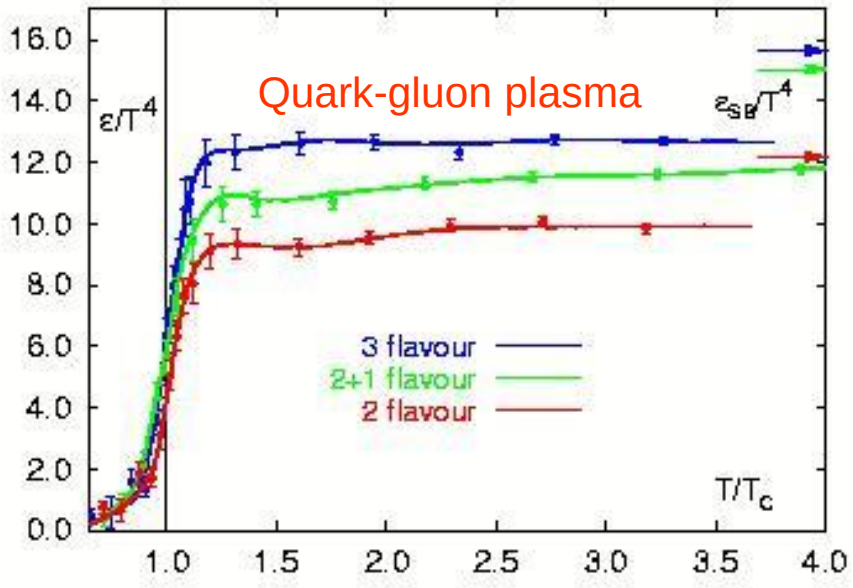
…Is Hexagonal and 2.4 Miles Long



Insights from the RHIC Experiments

The quest for simplicity

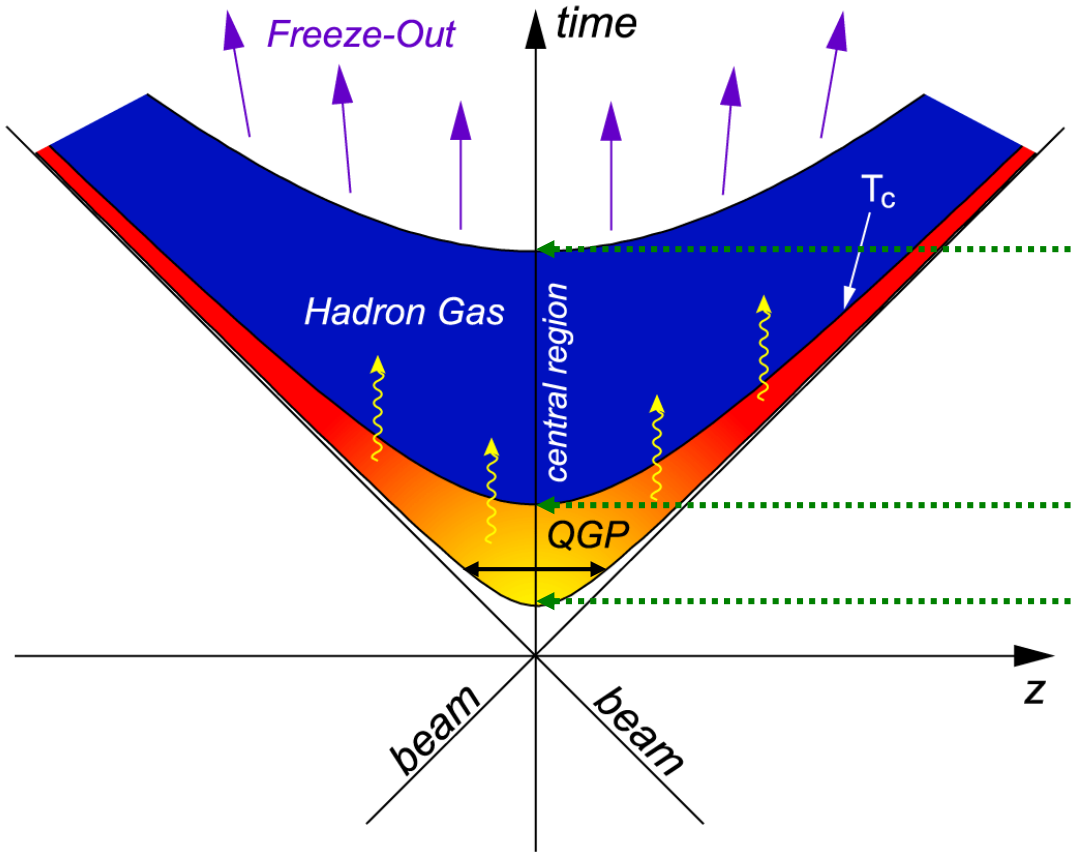
The equation of state of strongly interacting matter according to lattice QCD



$T_c \approx 160$ MeV

- Before the 1975, matter at high energy density was considered a *mess*!
- QCD predicts that hot matter becomes *simple* – the *QGP* (not necessarily weakly interacting!).
- Characteristic features: deconfinement and chiral symmetry restoration.

Space-time picture of a r.h.i.c.



Thermal freeze-out

Hadronization

Equilibration

Frequently Asked Questions

- How do we know that we produced equilibrated *matter*, not just a bunch of particles ?
- What makes this matter *special* ?
- How do we measure its *properties* ?
- Which evidence do we have that quarks are *deconfined* for a brief moment (about 10-23 s) ?
- Which evidence do we have for temporary *chiral symmetry restoration* ?
- What do we still need to learn ?
  - Translation: When can RHIC be shut off ?

FAQ #1

How do we know that we produced equilibrated *matter*,
not just a bunch of particles ?

Answer:

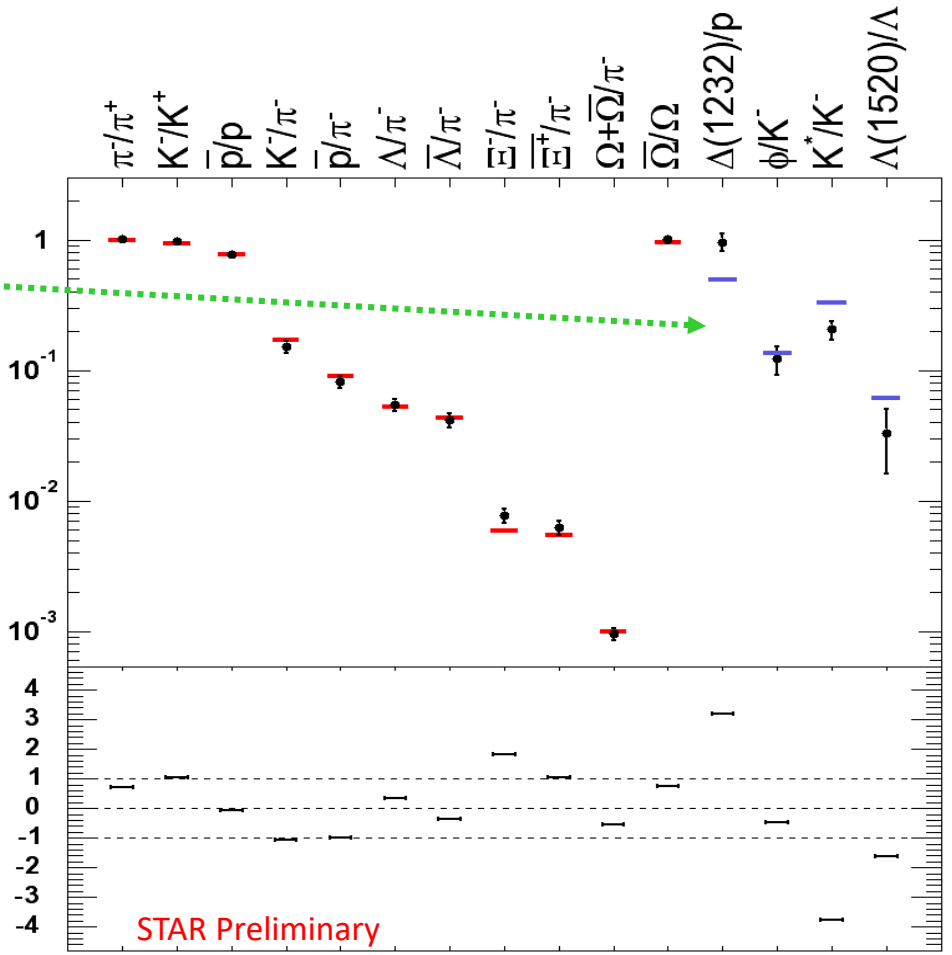
Particles are thermally distributed and it flows !

Chemical equilibrium

- Chemical equilibrium fits work, *except* where they should not (resonances with large rescattering).

RHIC Au+Au @ 200 GeV

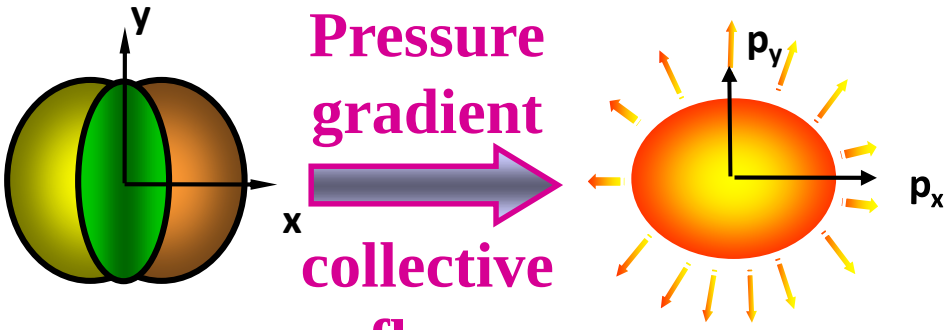
- $T_{ch} = 160 \pm 10$ MeV
- $\mu_B = 24 \pm 5$ MeV

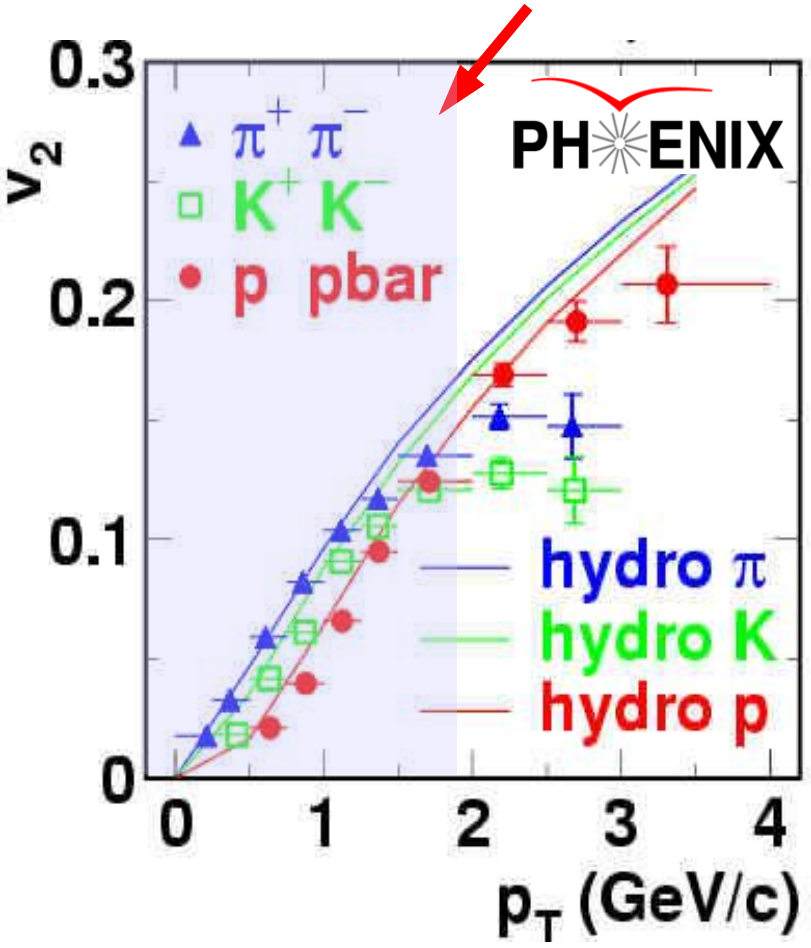


Elliptic flow

Coordinate space: initial asymmetry

Momentum space: final asymmetry





Two-particle correlations

$dN/d(\phi_1 - \phi_2) \propto 1 + 2v_2^2 \cos(2[\phi_1 - \phi_2])$

FAQ #2

What makes this matter *special* ?

Answer:

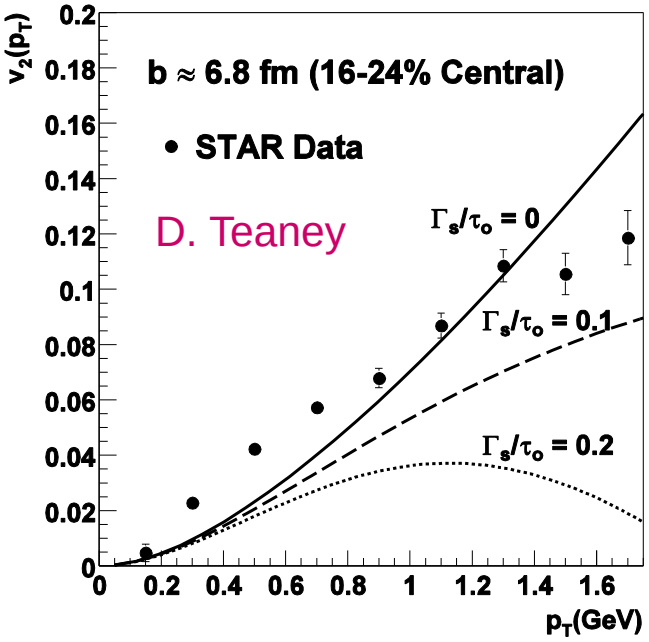
It flows astonishingly smoothly !
“The least viscous non-superfluid ever seen”

V_2 requires ultra-low viscosity

Relativistic viscous fluid dynamics:

$$\nabla_\mu T^{\mu\nu} = 0 \quad \text{with}$$

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \text{trace})$$



QGP($T \approx T_c$) = sQGP

Elliptic flow from hydro with early thermalization requires $\eta/s \lesssim 0.1$

Quantum lower bound on η/s :

$\eta/s = 1/4\pi$ (Kovtun, Son, Starinets)

Realized in strongly coupled ($g \gg 1$)
N = 4 SUSY YM theory, also in QCD ?

$\eta/s = 1/4\pi$ implies $\lambda_f \approx (5\ T)^{-1} \approx 0.3$ d

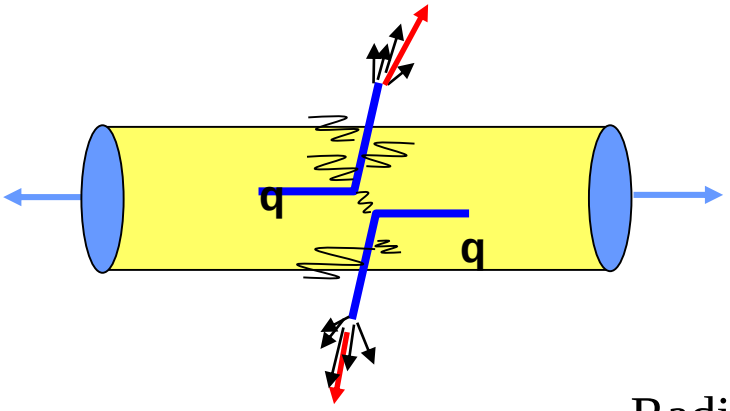
FAQ #3

How do we measure its *properties* ?

Answer:

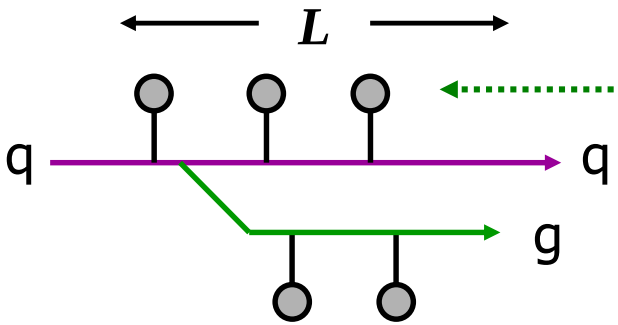
With hard QCD probes,
such as jets, photons, or heavy quarks

“Jet quenching” = Parton energy loss



High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss: $dE/dx \propto \rho L \langle k_T^2 \rangle$



Scattering centers = color charges

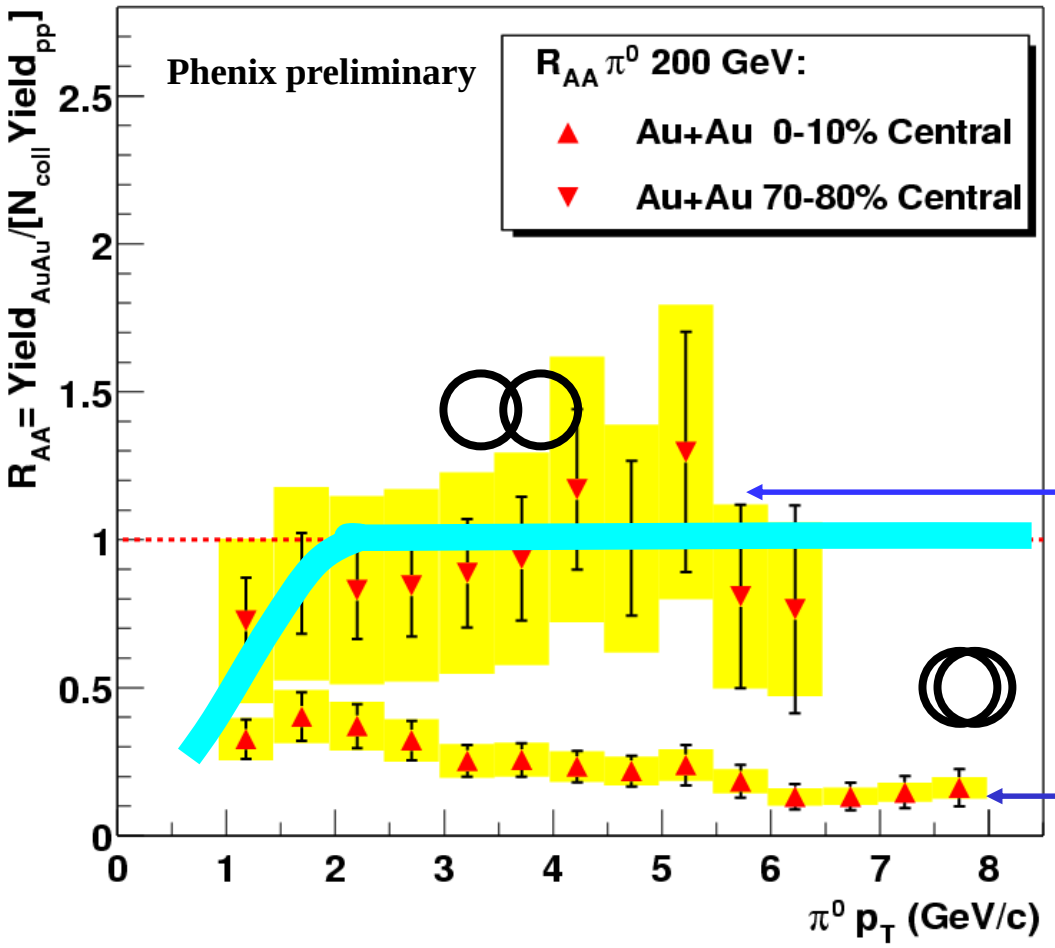
Density of scattering centers

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho \langle k_T^2 \rangle$$

Scattering power of the QCD medium:

Range of color force

Suppression of fast pions (π^0)



$$R_{AA} = \frac{N^{\pi}_{AA}}{N_{coll} N^{\pi}_{pp}}$$

Peripheral collisons

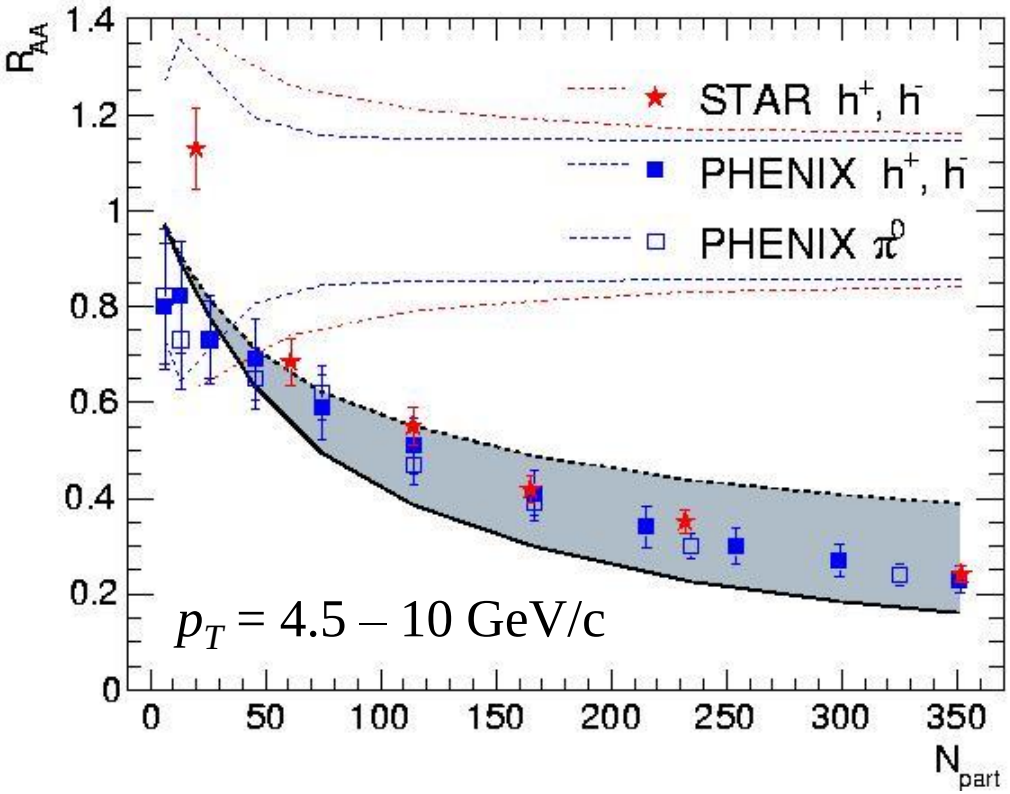
Central collisons

Energy loss at RHIC

- Data are described by a very large loss parameter for central collisions:

$$\langle \hat{q} \rangle \approx 5\text{–}10 \text{ GeV}^2/\text{fm}$$

(Dainese, Loizides, Paic, hep-ph/0406201)



Larger than expected from perturbation theory !

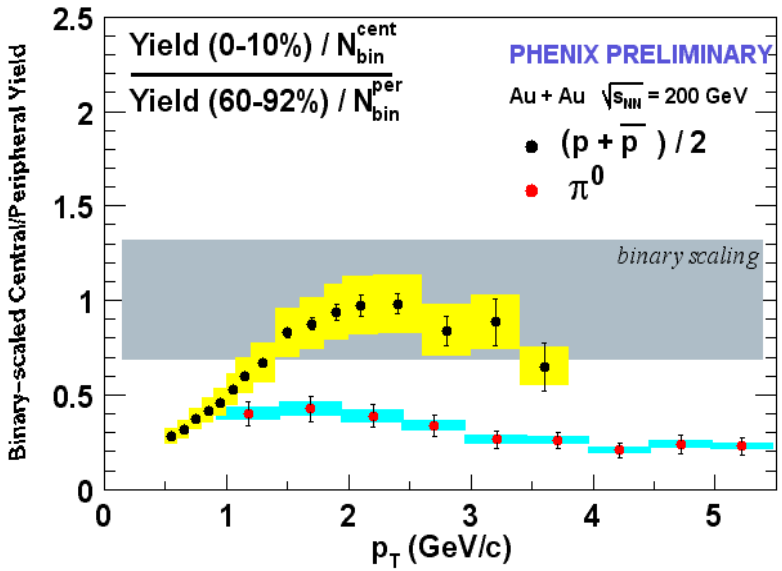
FAQ #4

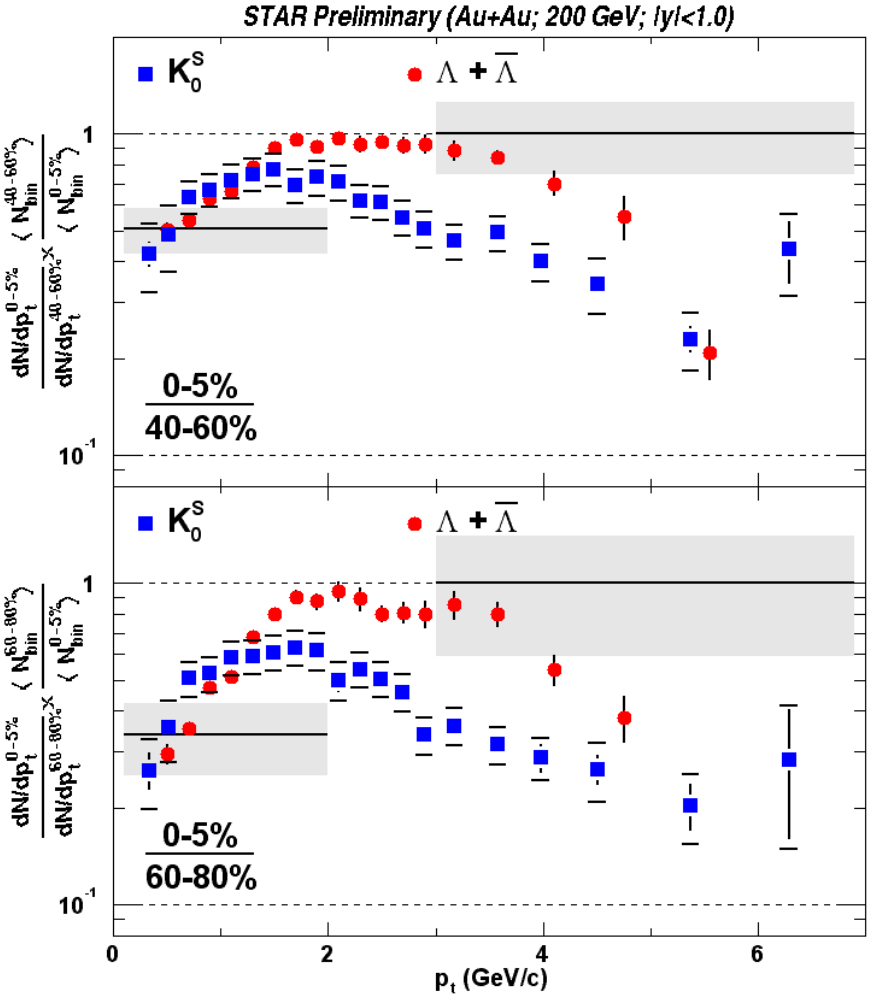
Which evidence do we have that quarks are *deconfined* for a brief moment (about 10-23 s) ?

Answer:

Baryons and mesons are formed
from independently flowing quarks

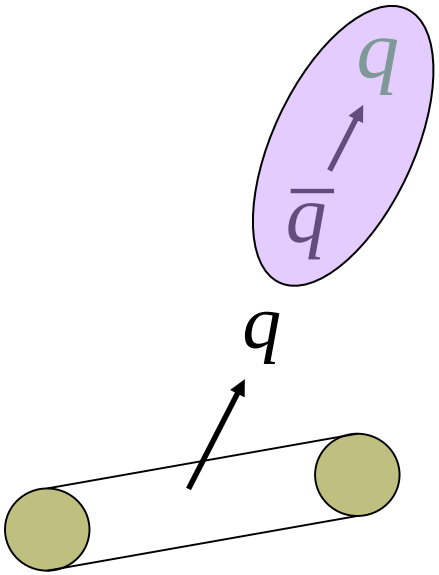
Suppression Patterns: Baryons vs. Mesons





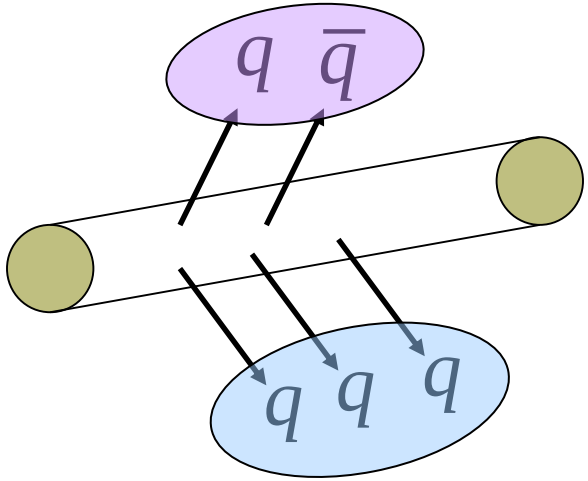
- What makes baryons different from mesons ?

Hadronization Mechanisms



Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} \ll 1$$



Recombination

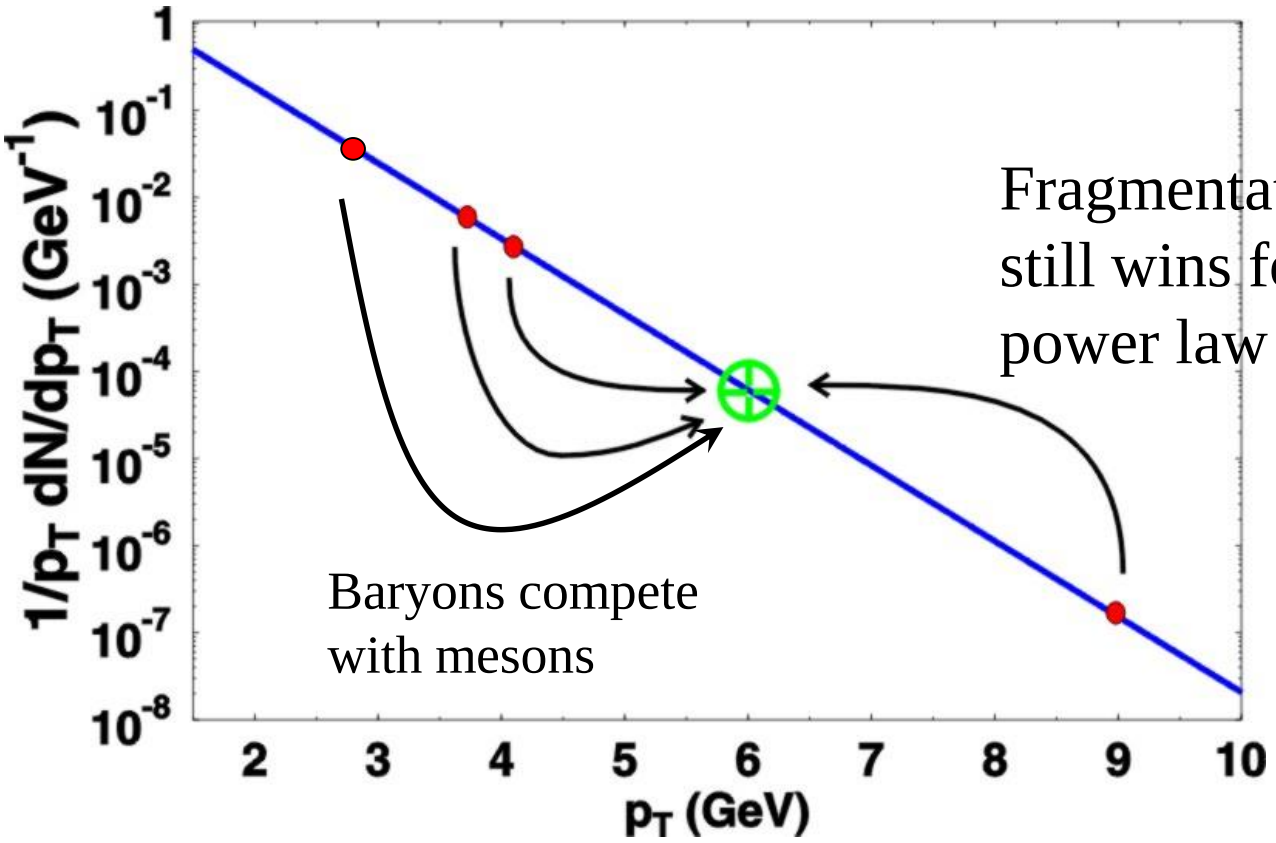
$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

$$p_M \approx 2p_Q \qquad p_B \approx 3p_Q$$

This is not coalescence from a dilute medium !

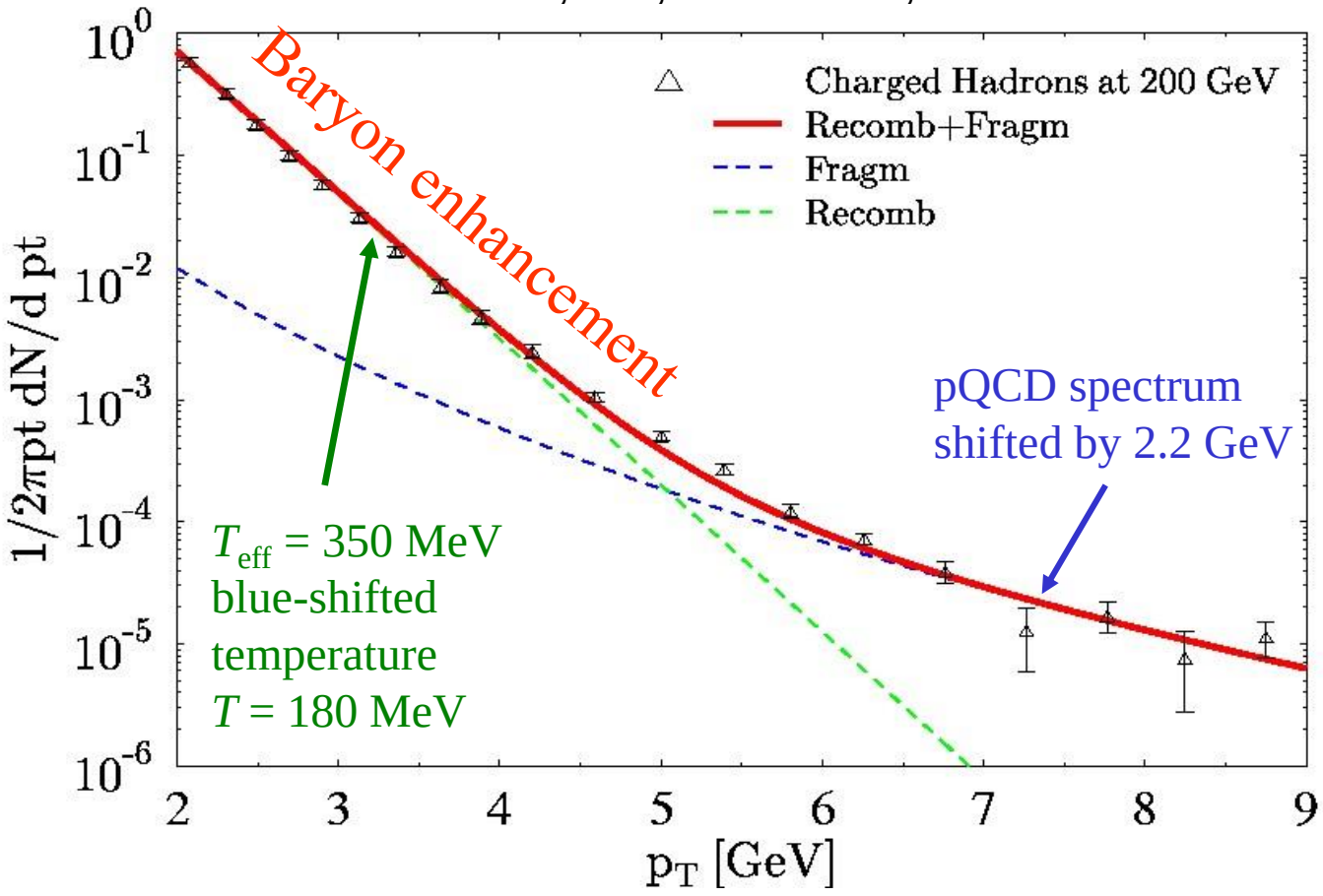
Recombination "wins" …

… always for a thermal source

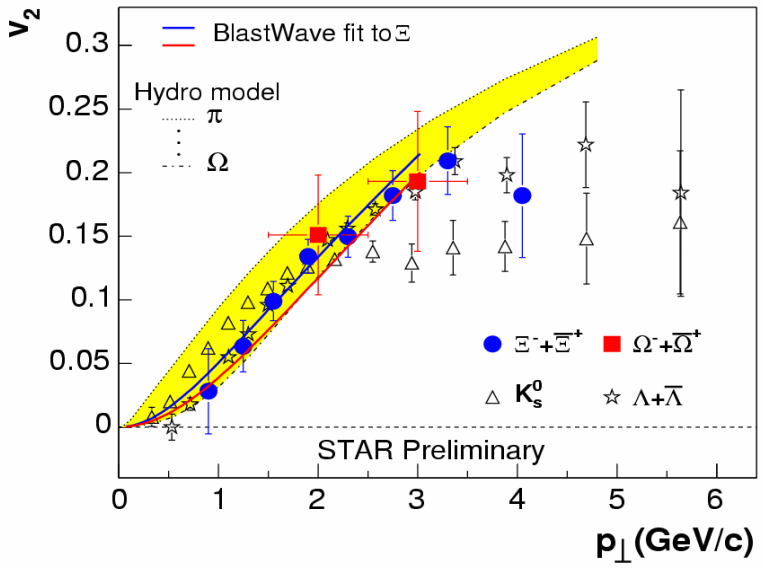


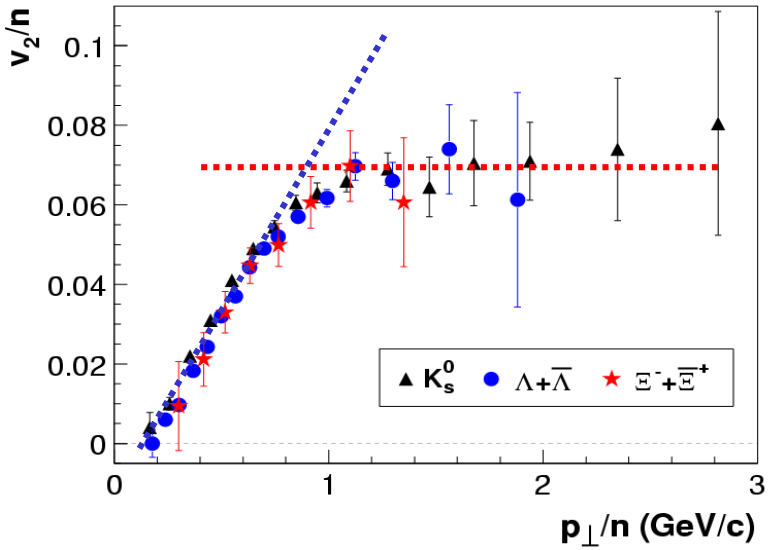
Recombination vs. Fragmentation

R.J. Fries, BM, C. Nonaka, S.A. Bass



Hadron v_2 reflects quark flow !





Recombination model suggests that hadronic flow reflects partonic flow (*n* = number of valence quarks):

$$v_2^{had} \approx n v_2^{part}$$

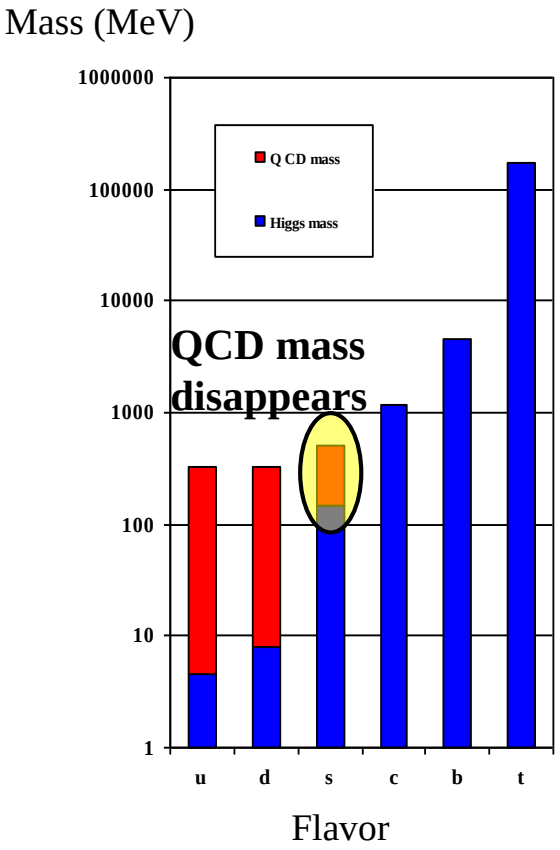
$$p_T^{had} \approx n p_T^{part}$$

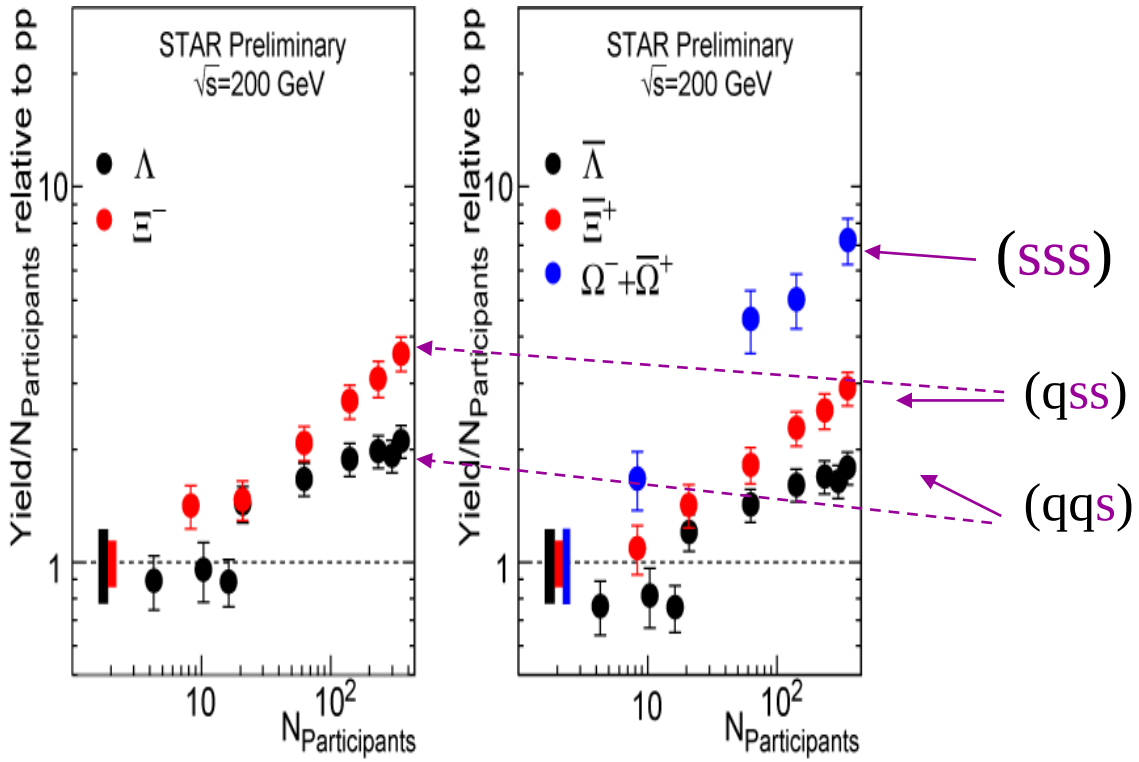
Provides measurement of partonic v_2 !

FAQ #5

Which evidence do we have for temporary *chiral symmetry restoration* ?

Strangeness in Au+Au at RHIC

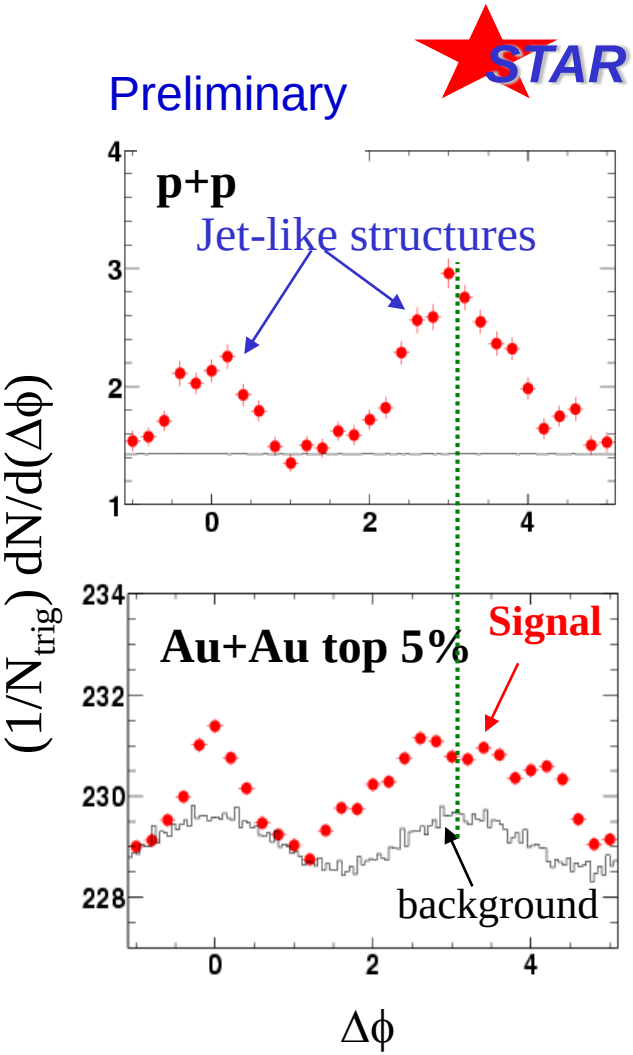




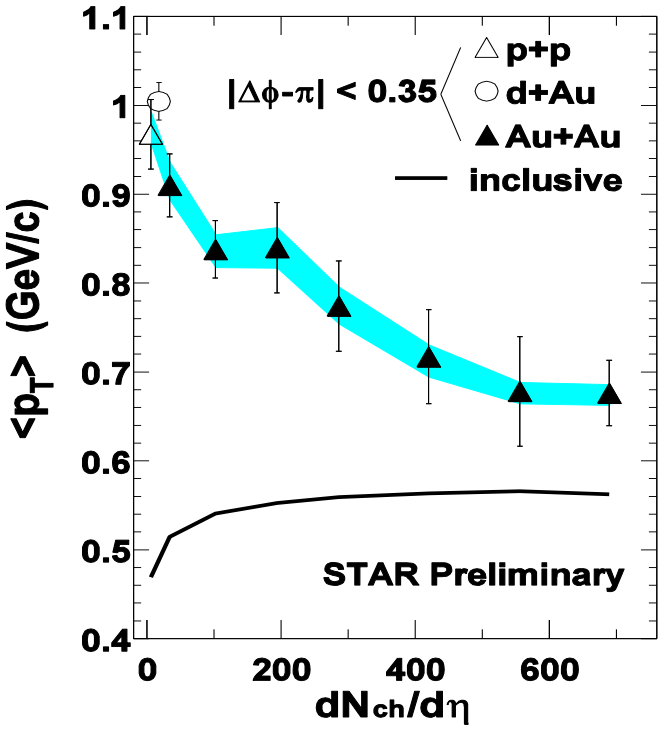
FAQ #6:
What do we still need to (or want to) learn ?

- Number of degrees of freedom:
  - via energy density – entropy relation.
- Color screening:
  - via dissolution of heavy quark bound states (J/Ψ).
- Chiral symmetry restoration:
  - modification of hadron masses via e^+e^- spectroscopy.
- Quantitative determination of transport properties:
  - viscosity, stopping power, sound velocity, etc.
- What exactly is the “s”QGP ?

Associated hadrons



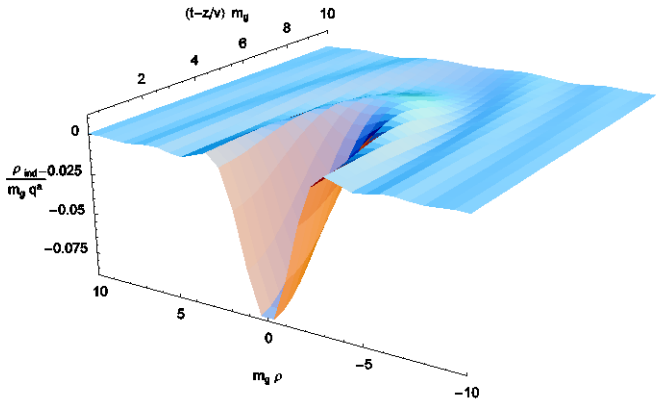
$4 < p_T^{trig} < 6$ GeV/c , $0.15 < p_T^{assoc} < 4$ GeV/c

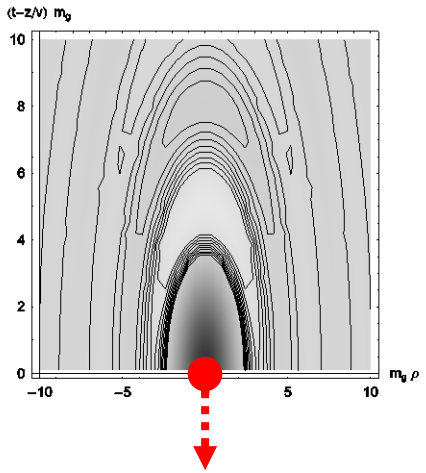


Explore the interaction of an hard parton with the dense medium

"Waking" the sQGP

v=0.55c





v=0.99c