Quark Gluon Plasma

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Quark Gluon Plasma : Heavy Ion Collisions

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Why RHIC ?

Bjorken Picture

Elliptic Flow

Jet Quenching

J/ψ Suppression

Summary

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- $\Longrightarrow$ Heavy Ion Collisions at 99.5-99.995 % of velocity of light to produce Quark-Gluon Plasma : $L \sim 2.4A^{1/3} \sim 14$ fm for Gold-Gold collisions.

- It may **indeed** have been, produced in Heavy Ion Collisions in SPS, CERN and BNL, New York and would likely be produced at LHC, CERN.

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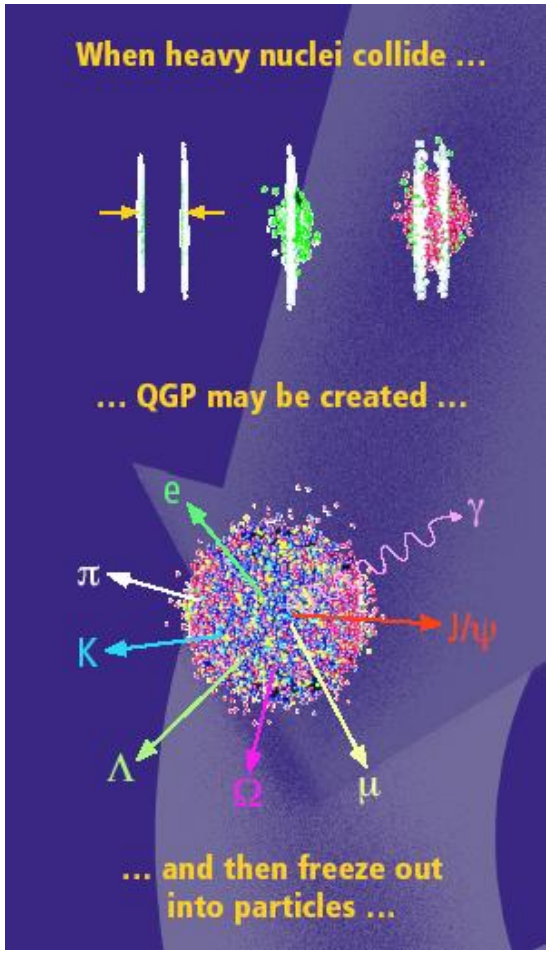

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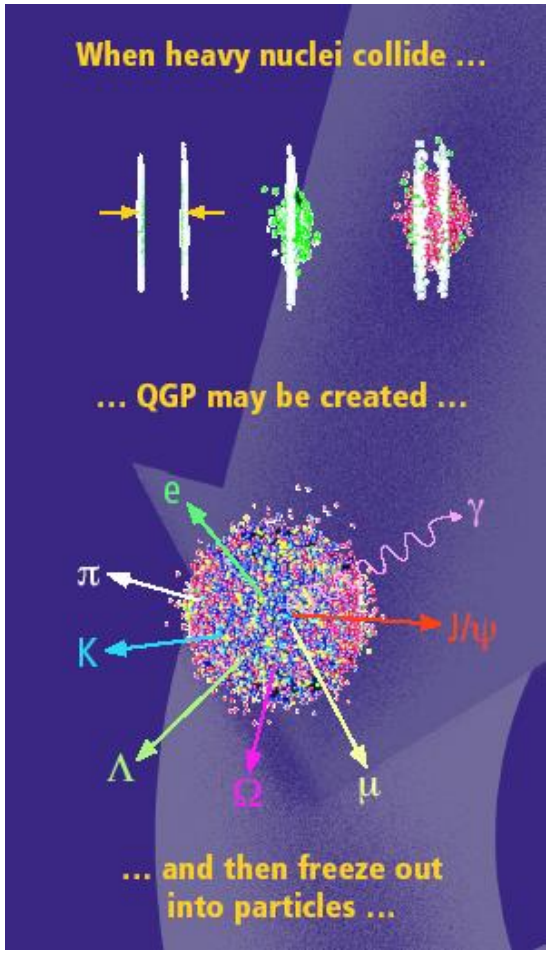

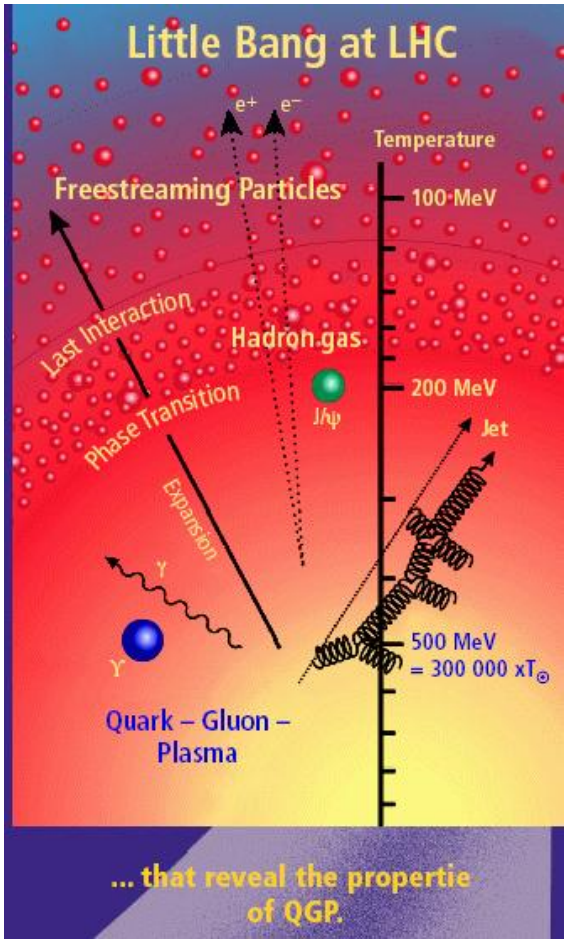

Bjorken Picture

- Inspired by the pp and pd data, Bjorken [PRD 1983] assumed that at sufficiently high $\sqrt{s}$, there exists
  - a "Central Plateau" in rapidity $y = 0.5 \ln[(E + p_z)/(E - p_z)]$ for AA collisions, i.,e., dN/dy is constant near $y = 0$ and
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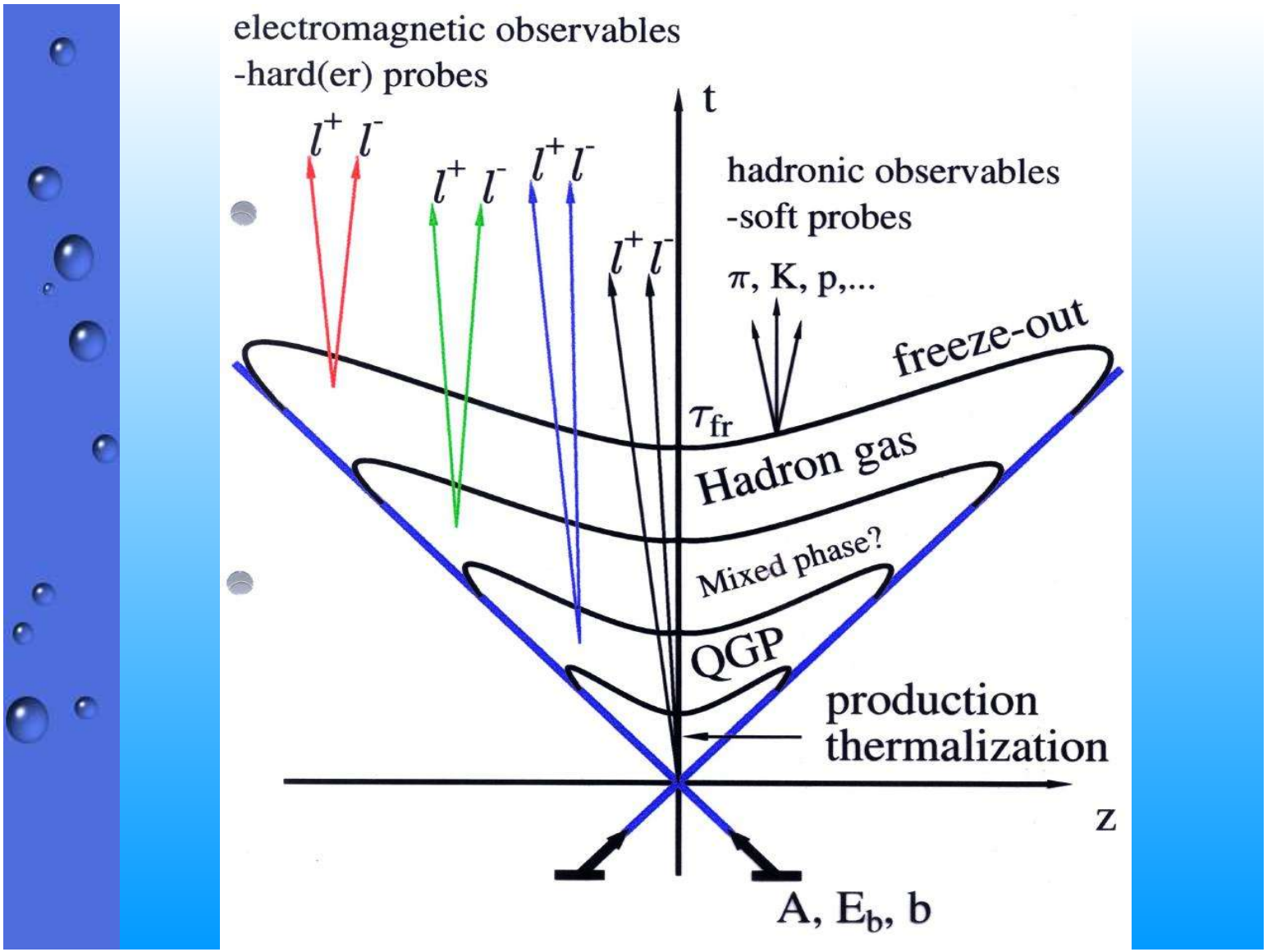
  - Bjorken estimated energy in a slice Δy to be $dN/dy \cdot \Delta y \cdot \langle m_T \rangle$ in a volume $\tau_0 A_T \Delta y$ with τ_0 as the thermalization time, $\rightsquigarrow$ an Energy density $\epsilon = 1/(\tau_0 A_T) \cdot dE_T/dy$.


electromagnetic observables
-hard(er) probes
t
l^+ l^-
l^+ l^-
l^+ l^-
l^+ l^-
hadronic observables
-soft probes
π, K, p,...
freeze-out
τ_{fr}
Hadron gas
Mixed phase?
QGP
production
thermalization
z
A, E_b, b

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  - Mean free path estimates – Model dependent.
  - PQCD (Baier et al, PLB 2001) – Parametrically $(\alpha^{13/5} Q_s)^{-1}$ – too large.
  - Semihard or minijets may have enough re-scatterings.
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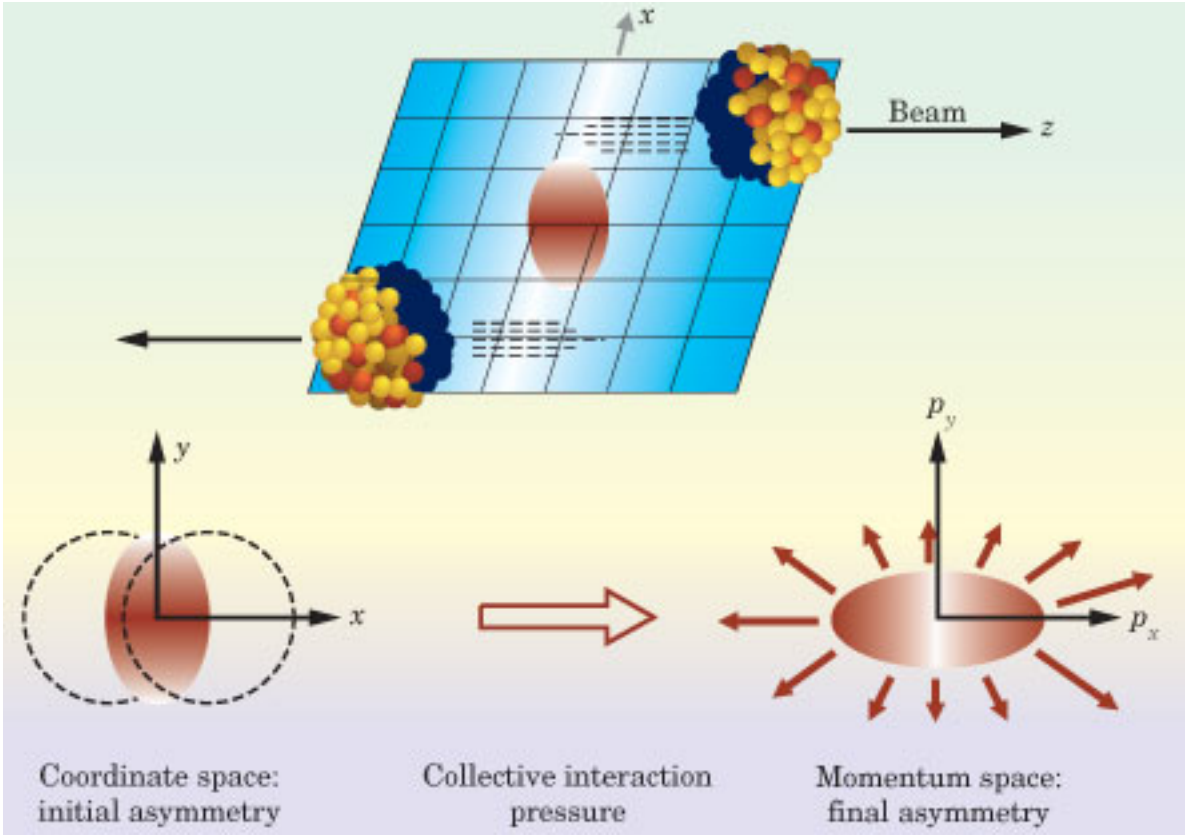
- Life-time of QGP phase $\tau_{QGP} \gg \tau_0$ for imprints to be left as signal.

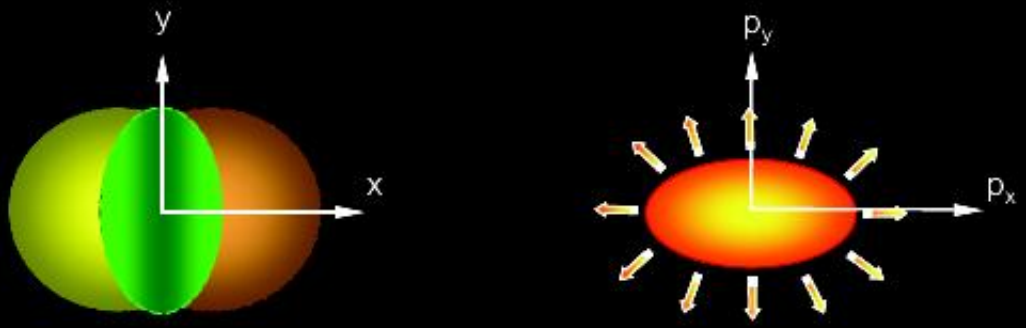
Elliptic Flow

♡ For asymmetric collisions of two nuclei, with their centres not aligned :



Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

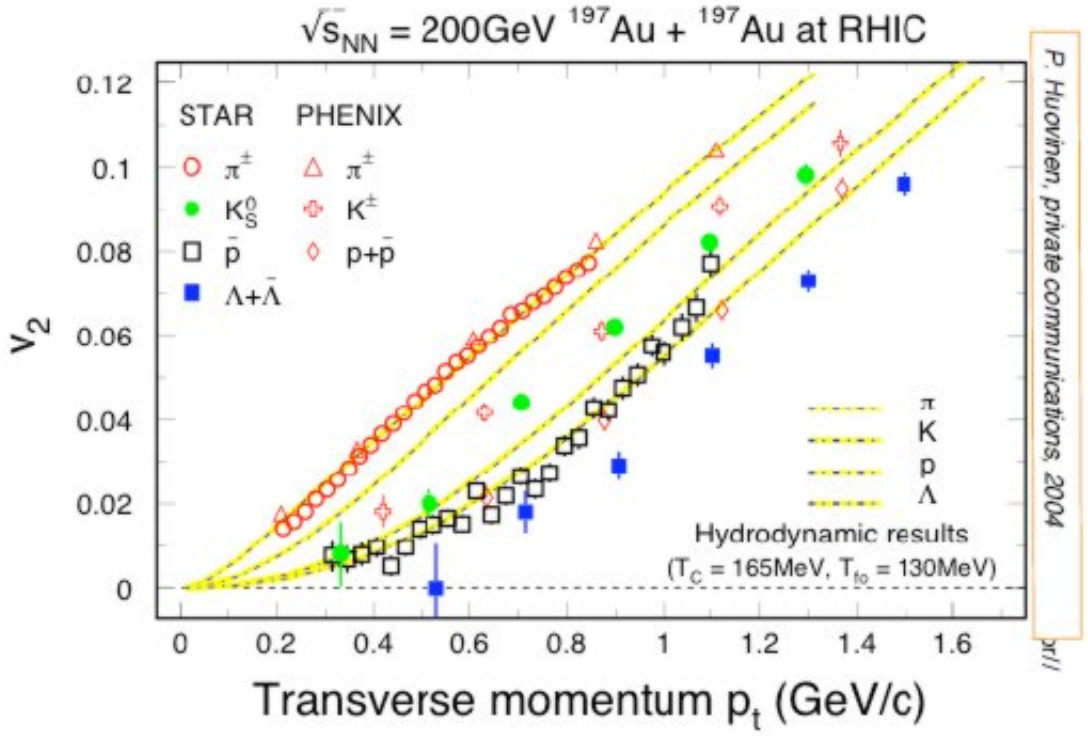


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

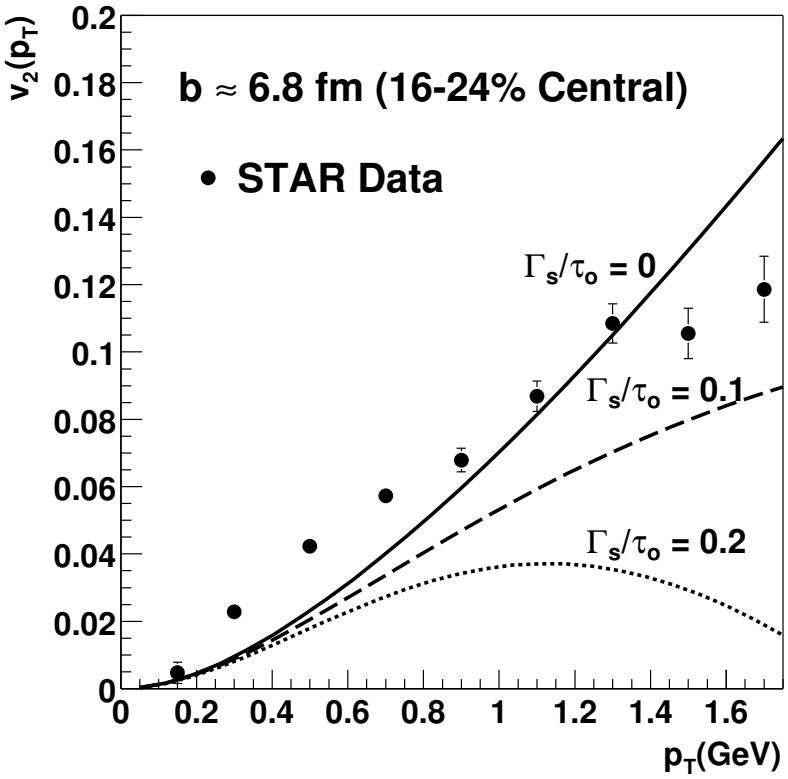
"ICHEP 2006" Moscow, Russia, July 26 - August 2, 2006

v_2 at Low p_T Region



- Minimum bias data! At low p_T, model result fits mass hierarchy well!
- Details do not work, need more flow in the model!

QGP - (Almost) Perfect Liquid



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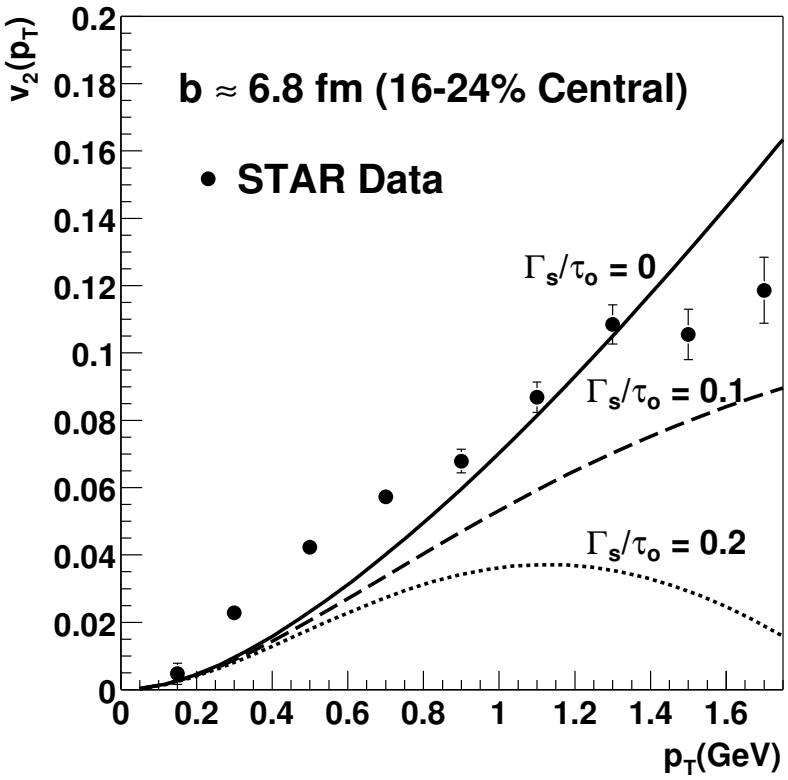

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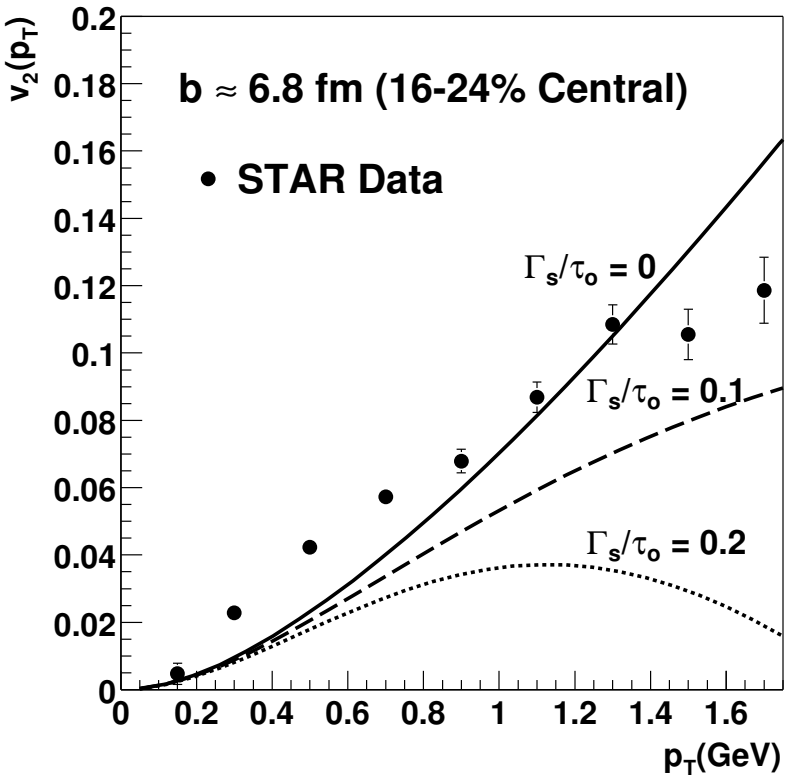

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$$\Gamma_s = \frac{\frac{4}{3}\eta}{sT} \ , \qquad (1)$$

where η is Shear Viscosity and s is entropy density; $\tau = \sqrt{t^2 - z^2}$ is the time scale of expansion.

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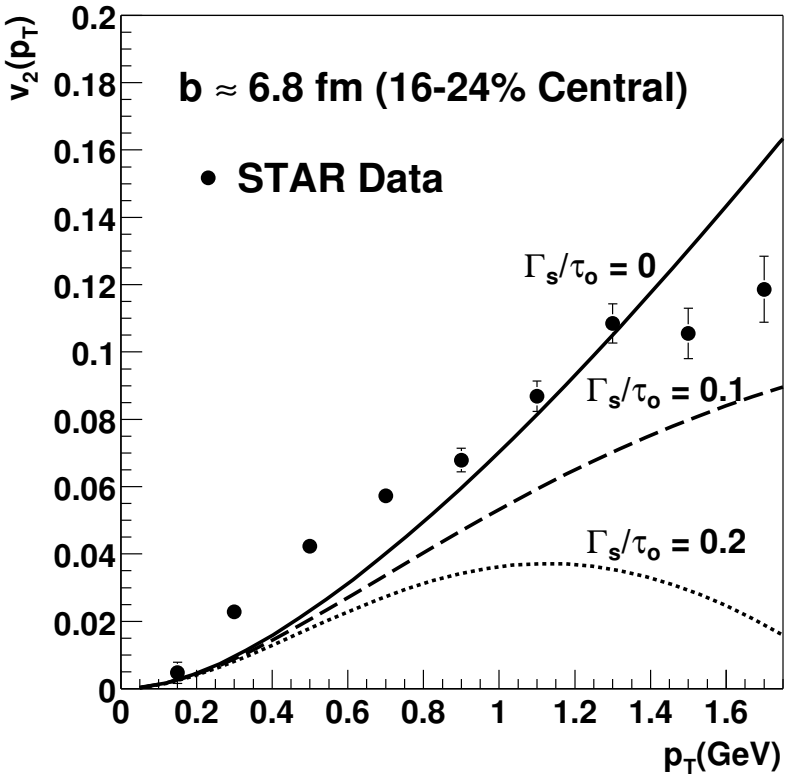

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Perturbation theory $\Rightarrow$ Large η/s
Small $\eta/s \longrightarrow$ Strongly Coupled Liquid.

Anisotropic Flow & QGP as Perfect Liquid

♢ Theoretical Analyses of flow suggest very low viscosity :

Quark-Gluon Plasma is a Perfect Liquid!

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♡ Lattice QCD estimates also hint at such small values, though the computations are a bit crude still.

Hard Probes of Quark-Gluon Plasma

- A Variety of Signals of QGP have been proposed : Excess Strangeness, Event-by-Event Fluctuations, Dileptons, Photons, Jet Quenching, J/ψ-suppression etc.

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- pQCD factorization allows separation between hard and soft scales : $\sigma^{AB\to h} = f_A(x_1, Q^2) \otimes f_B(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{i\to h}(z, Q^2)$.

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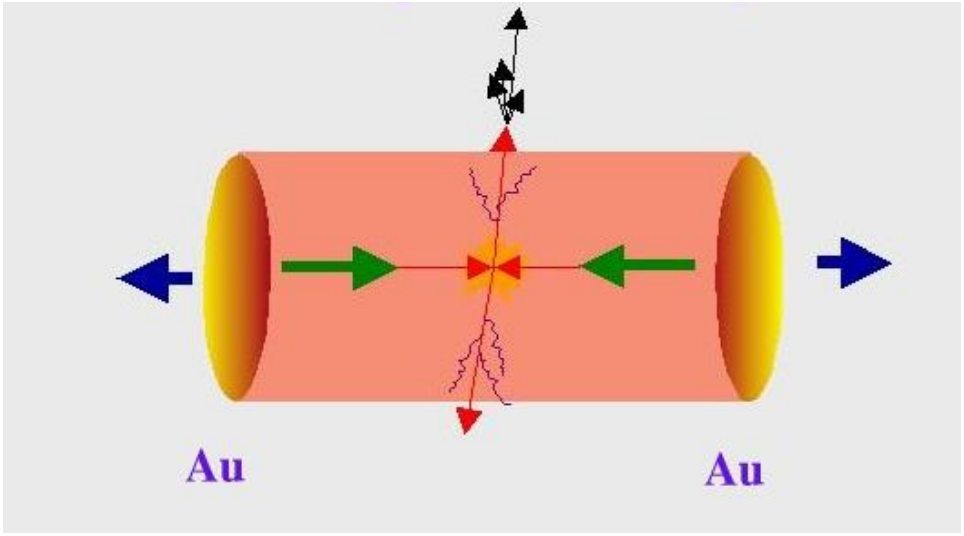
- Medium, i.e, QGP or hot hadron gas, typically modifies the fragmentation function D in case of Jet Quenching, or its analogue matrix element for J/ψ-production,
  E.g. $D^{\rm med}_{i\to h}(x, Q^2) = P_E(\epsilon) \otimes D_{i\to h}(x/(1-\epsilon), Q^2)$.

Jet Quenching



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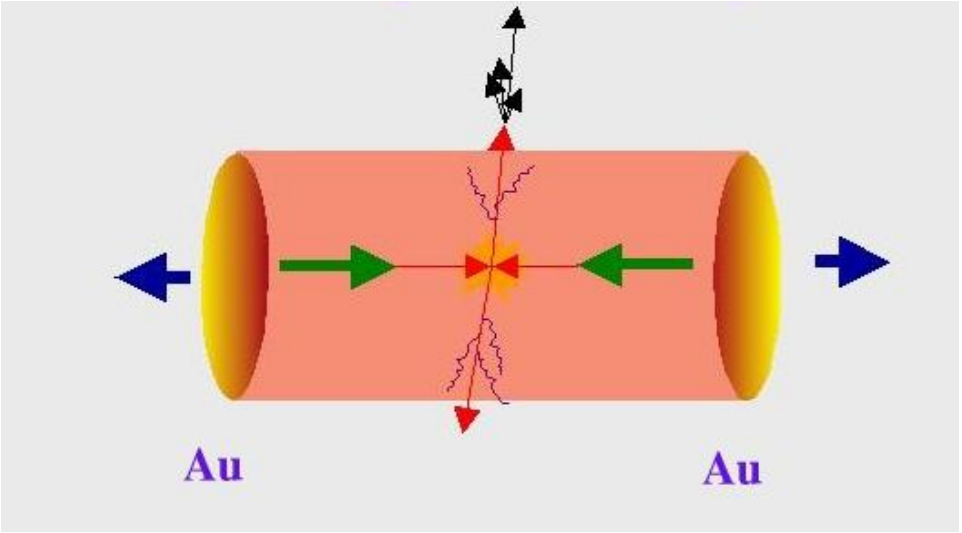

- Jet Quenching :
  - Rare, Highly Energetic Scatterings produce jets of particles : $g + g \rightarrow g + g$.
  - Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.

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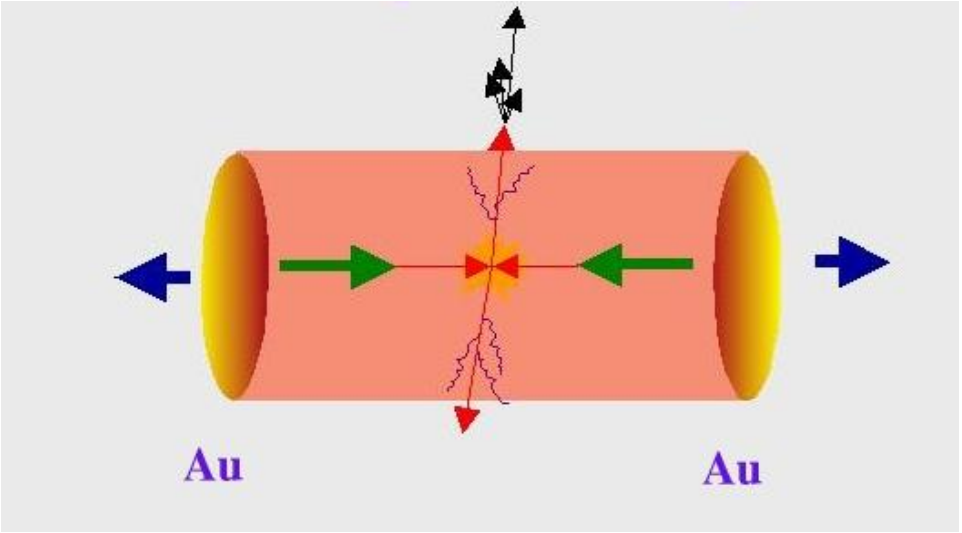

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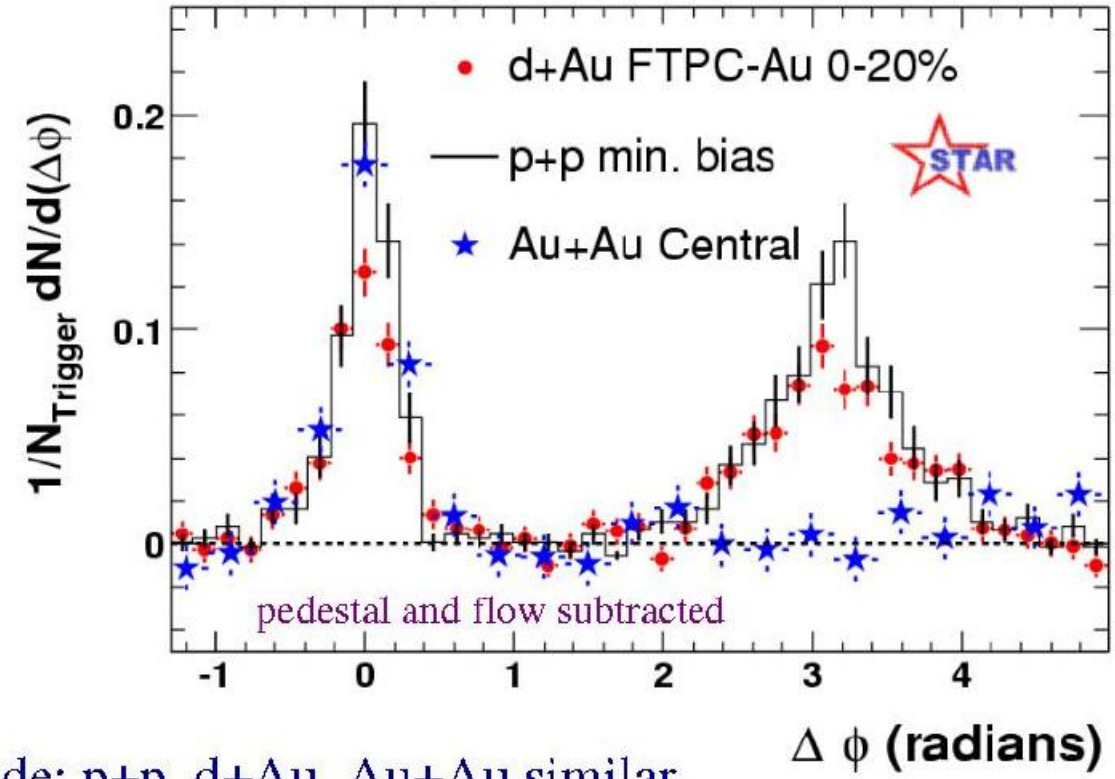
  - On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

Azimuthal distributions



Near- side: p+p, d+Au, Au+Au similar

Back- to- back: Au+Au strongly suppressed relative to p+p and d+Au

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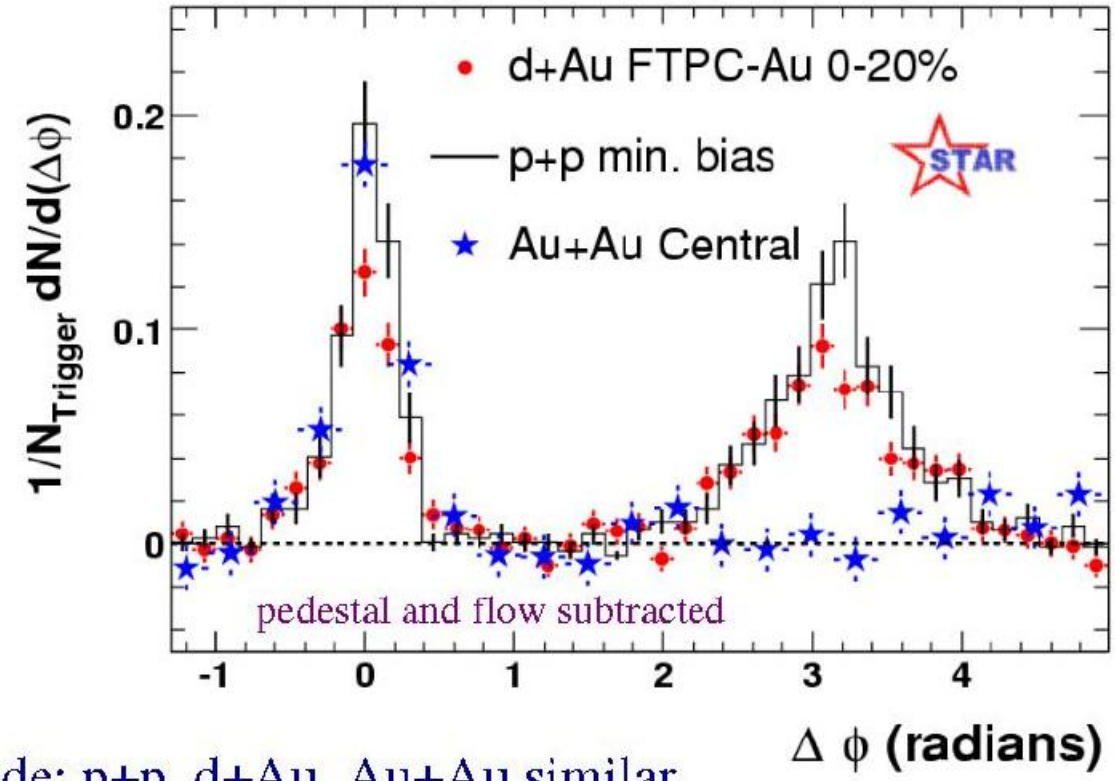

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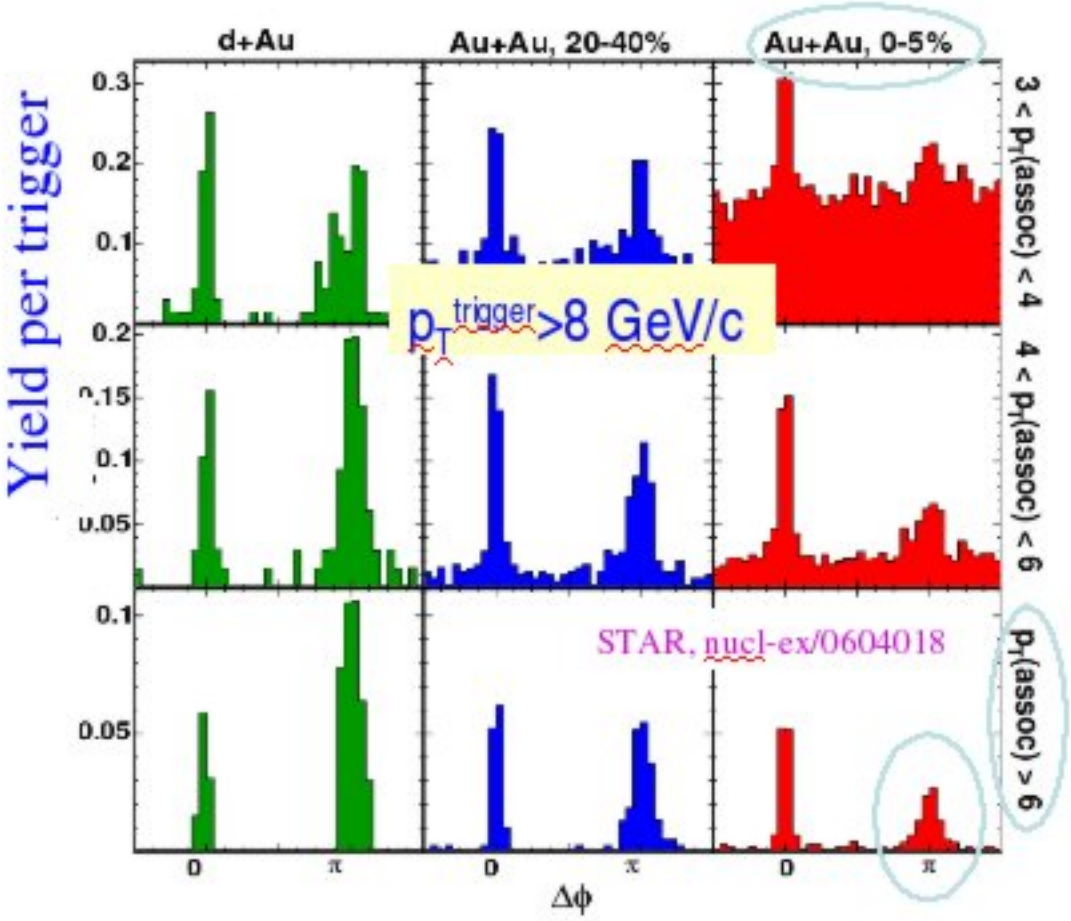
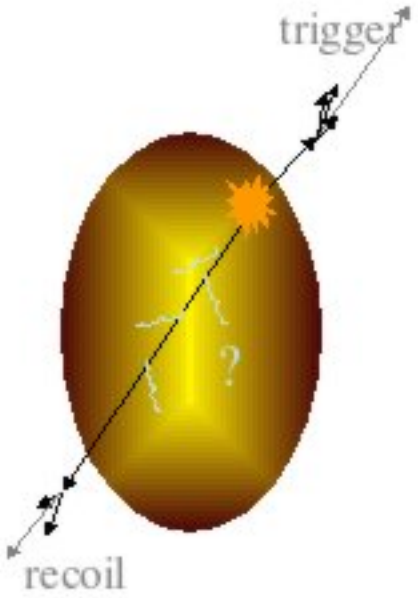
– Appearance of a diminished jet for large enough momenta.

What is new: di-hadron correlations at higher p_T

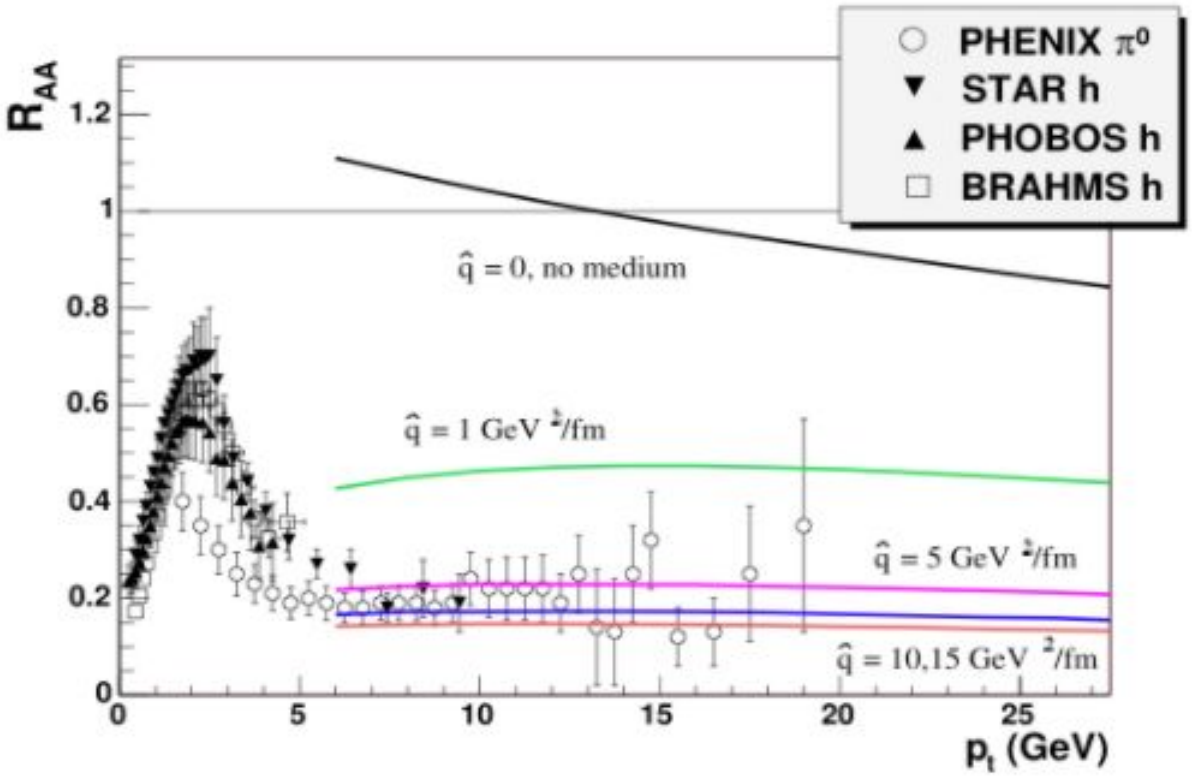
Hallman: ICHEP06





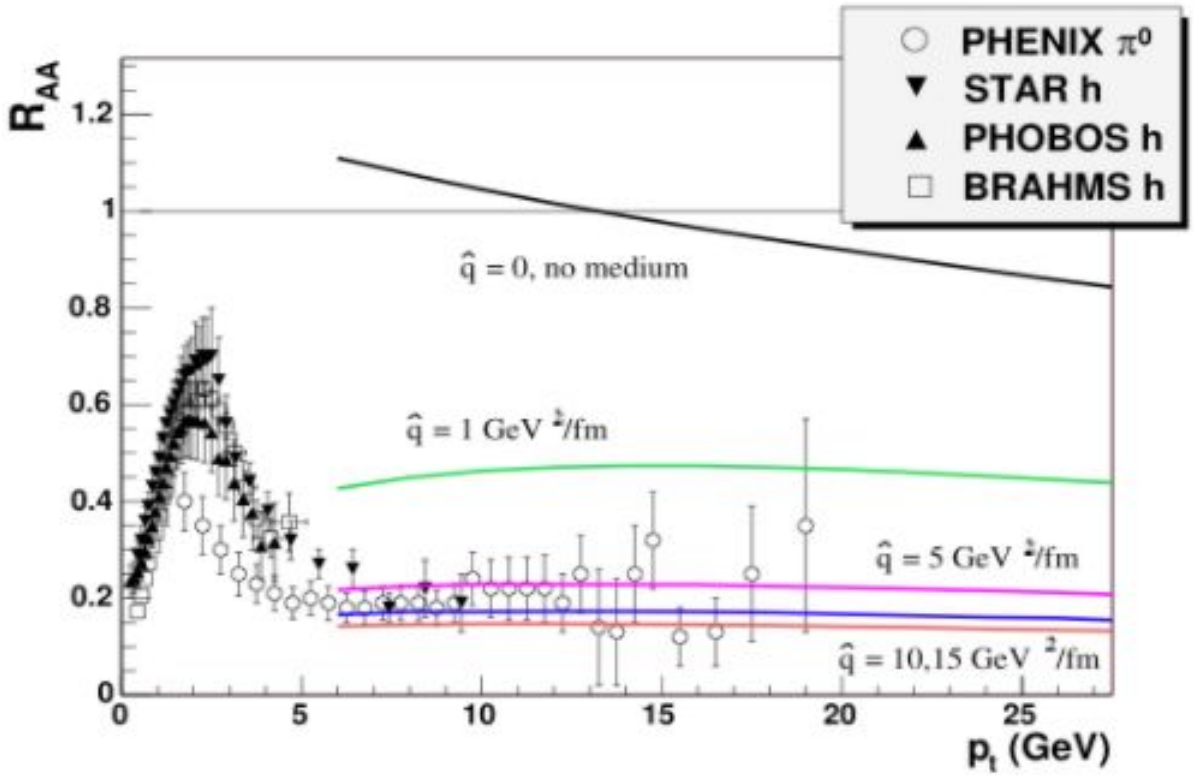
Armesto: ICHEP06

Recoil jet clearly seen above background but at suppressed rate



$\hat{q}$: 5-15 GeV²/fm

From Quark Matter 2006 Plenary Talk of F. Wang.



$\hat{q}$: 5-15 GeV²/fm

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♣ Medium induced transverse momentum squared per unit path length, $\hat{q}$, – typically 5-15 GeV^2/fm – characterizes P_E.

Anomalous J/ψ Suppression : CERN NA50 results

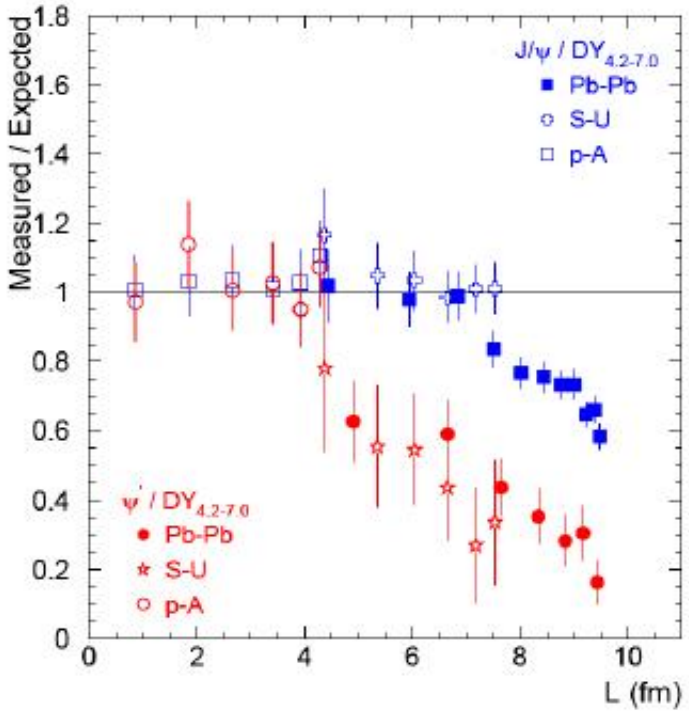
♠ Matsui-Satz idea — J/ψ suppression as a signal of QGP.
♠ Deconfinement $\rightsquigarrow$ Screening of coloured quarks,
which cannot bind.

Anomalous J/ψ Suppression : CERN NA50 results

Expected = Glauber absorption model

$\sigma_{abs}(J/\psi) = 4.18 \pm 0.35$ mb

$\sigma_{abs}(\psi') = 7.60 \pm 1.12$ mb



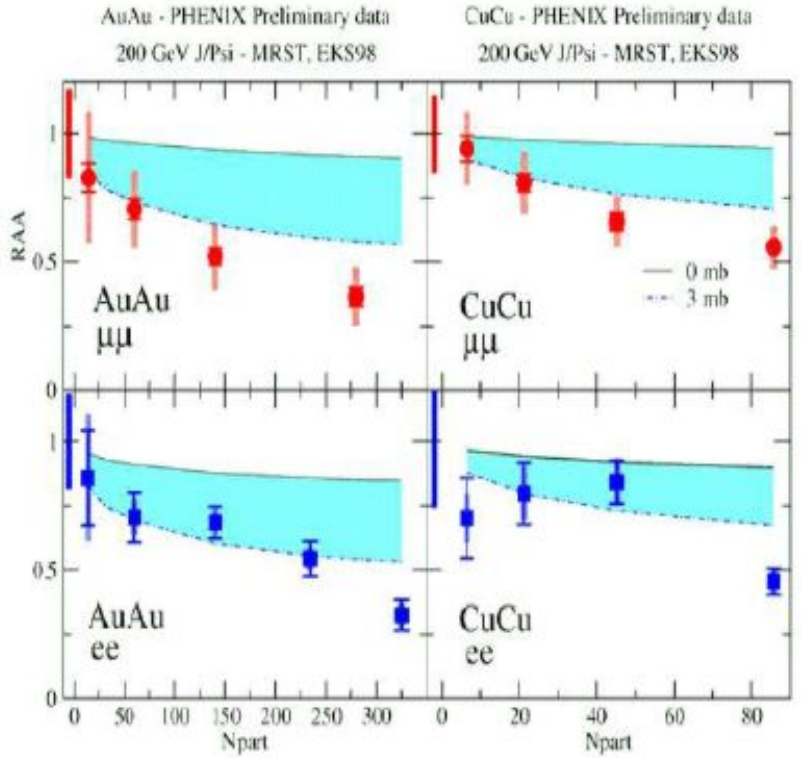
- **S-U** and **peripheral Pb-Pb (J/ψ)/DY** results follow the absorption curve extrapolated from p-A measurements.
- **Pb-Pb central** collisions show an **anomalous (J/ψ)/DY suppression** with respect to p-A behaviour.
- **ψ'/DY** behaviour is the same in **S-U** and **Pb-Pb** interactions and not compatible with the one observed in p-A collisions.
- **ψ' anomalous suppression** sets in earlier than the J/ψ one.

charmonium suppression at RHIC

surprize:
data nearly compatible
with normal nuclear
suppression
(blue shaded area)

suppression models
describing SPS data fail

possible way out:
J/ψ may survive
in plasma until near
$2\ T_c$



Peter Brown-Münziger, Quark Matter 2006.

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- Quarkonia – J/ψ – melts at SPS but not RHIC. Or it does, but charm-anticharm recombines at RHIC ? What will happen at LHC where Υ's will also come on seen ?