

Quark Gluon Plasma

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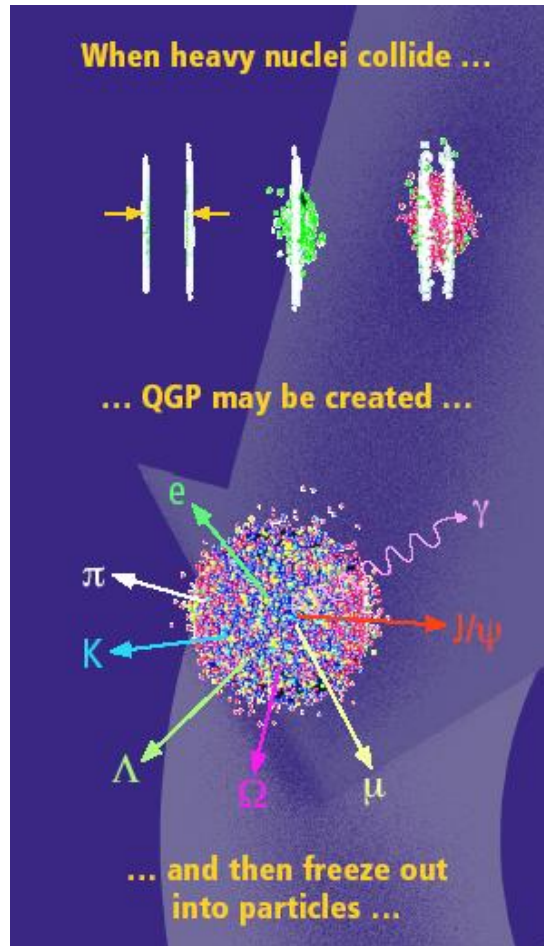
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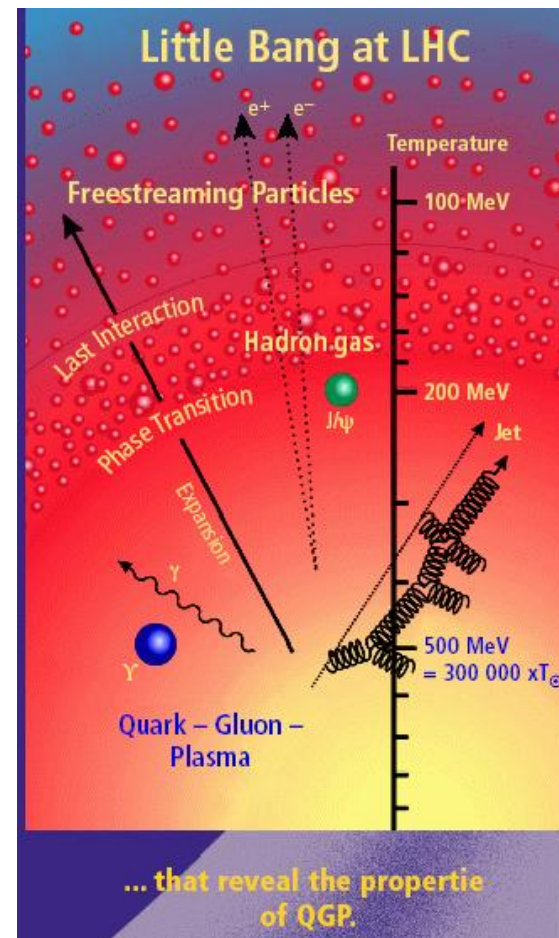
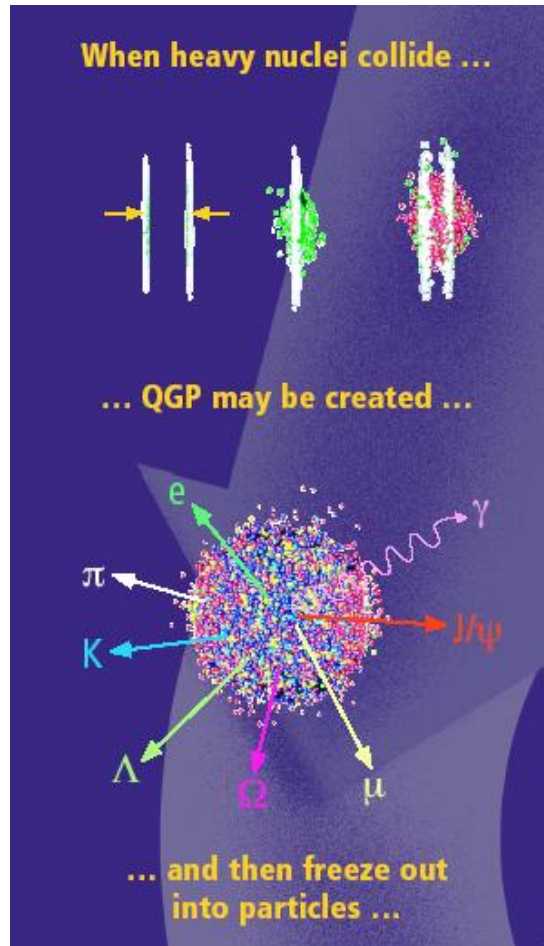
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- \implies Heavy Ion Collisions at 99.5-99.995 % of velocity of light to produce Quark-Gluon Plasma : $L \sim 2.4A^{1/3} \sim 14 \text{ fm}$ for Gold-Gold collisions.

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Bjorken Picture

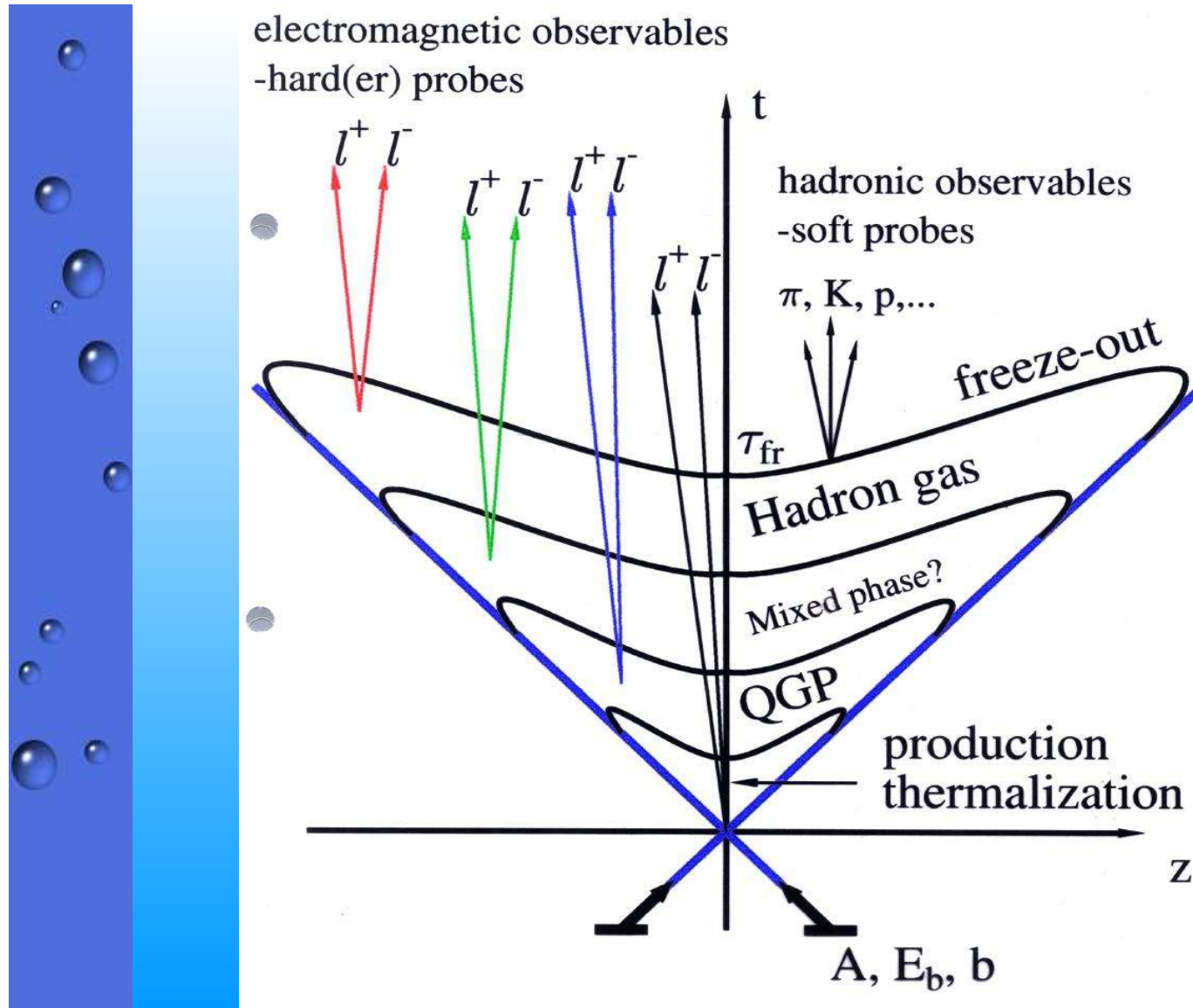
- Inspired by the pp and pd data, Bjorken [PRD 1983] assumed that at sufficiently high \sqrt{s} , there exists
 - a “Central Plateau” in rapidity $y = 0.5 \ln[(E + p_z)/(E - p_z)]$ for AA collisions, i.e., dN/dy is constant near $y = 0$ and
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 - Bjorken 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 $\epsilon = 1/(\tau_0 A_T) \cdot dE_T/dy$.



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 - Semihard or minijets may have enough re-scatterings.
 - Colour Glass Condensate simulations.
 - Chromo-Weibel Instability.

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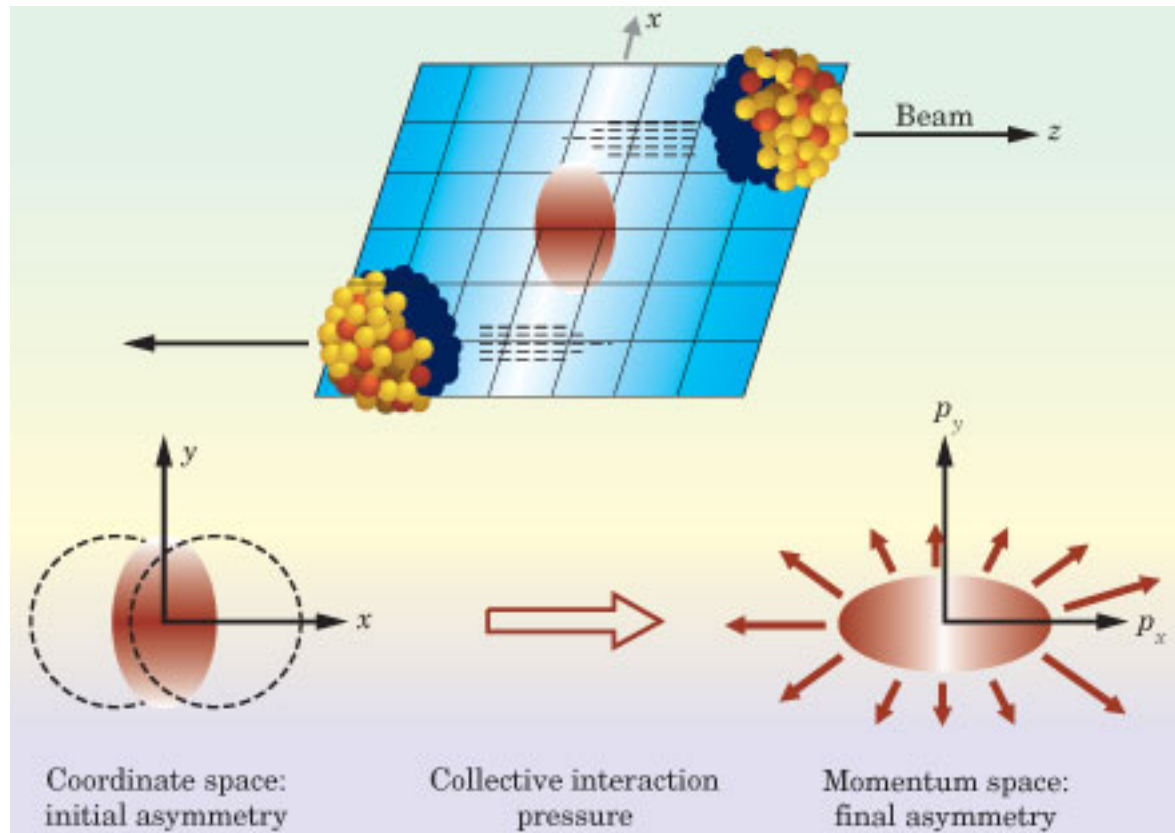
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- Life-time of QGP phase $\tau_{QGP} \gg \tau_0$ for imprints to be left as signal.

Elliptic Flow

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



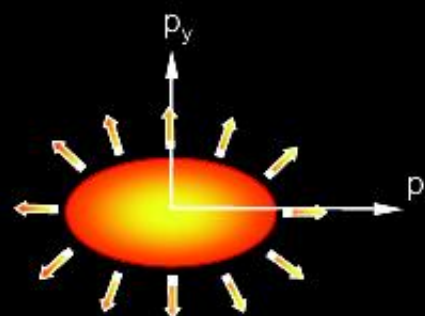
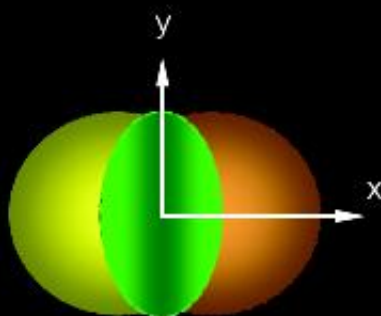


Anisotropy Parameter v_2

coordinate-space-anisotropy



momentum-space-anisotropy



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

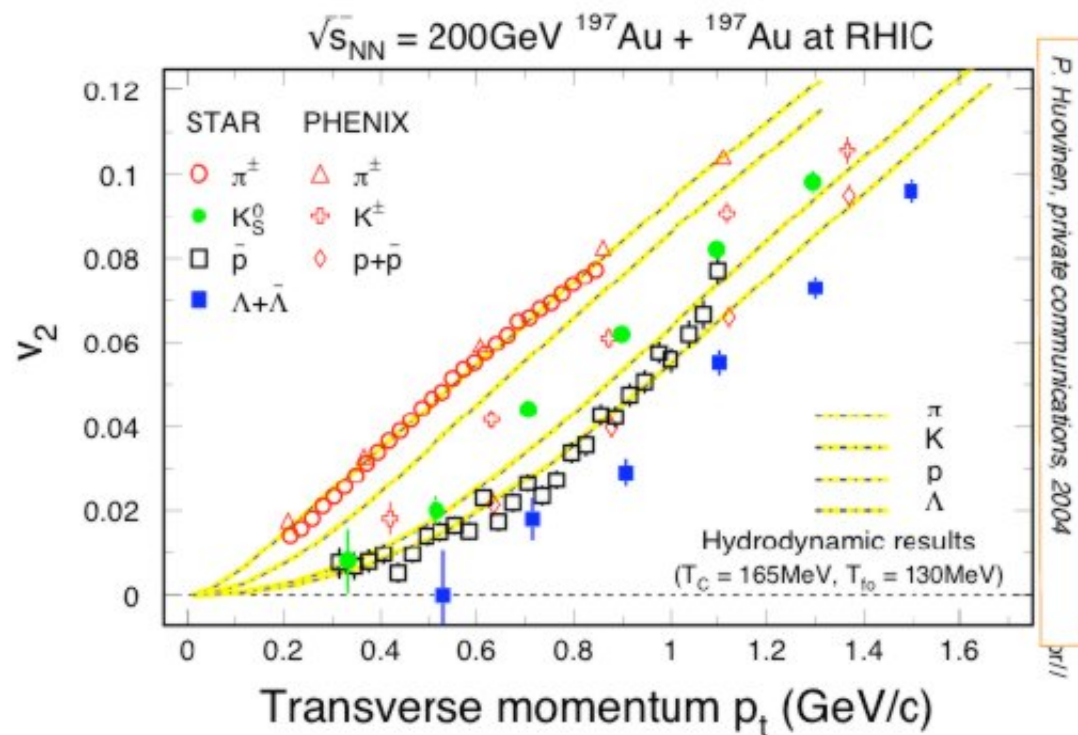
$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

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

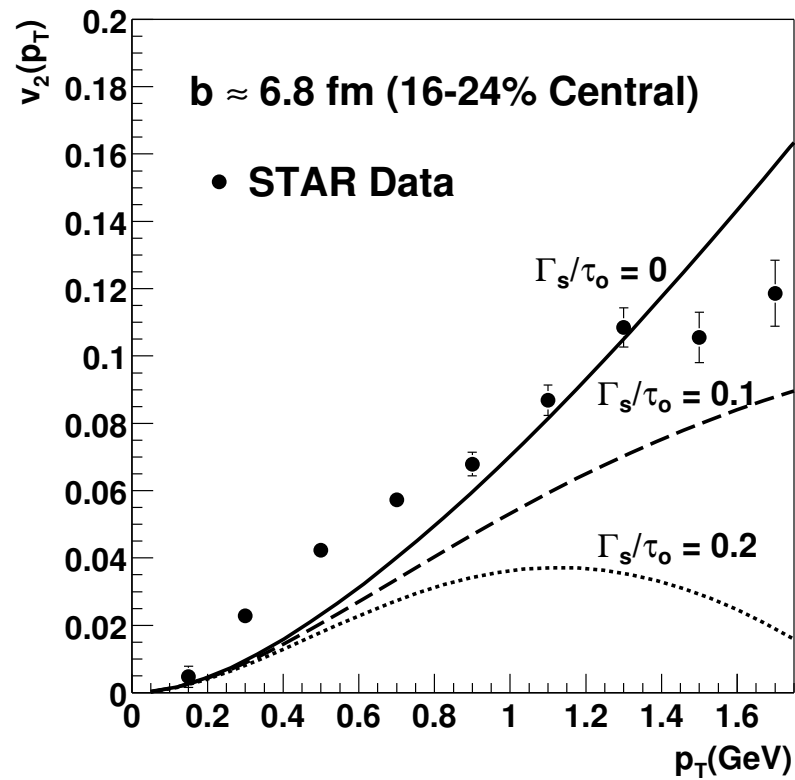


v_2 at Low p_T Region



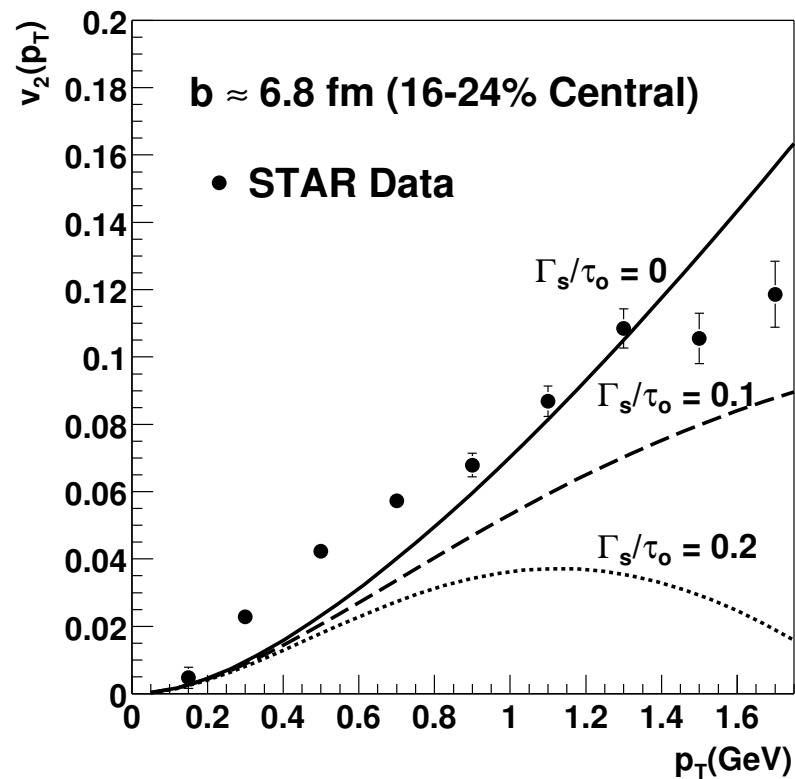
- Minimum bias data! At low p_T , model result fits mass hierarchy well!
- Details do not work, need more flow in the model!

QGP - (Almost) Perfect Liquid



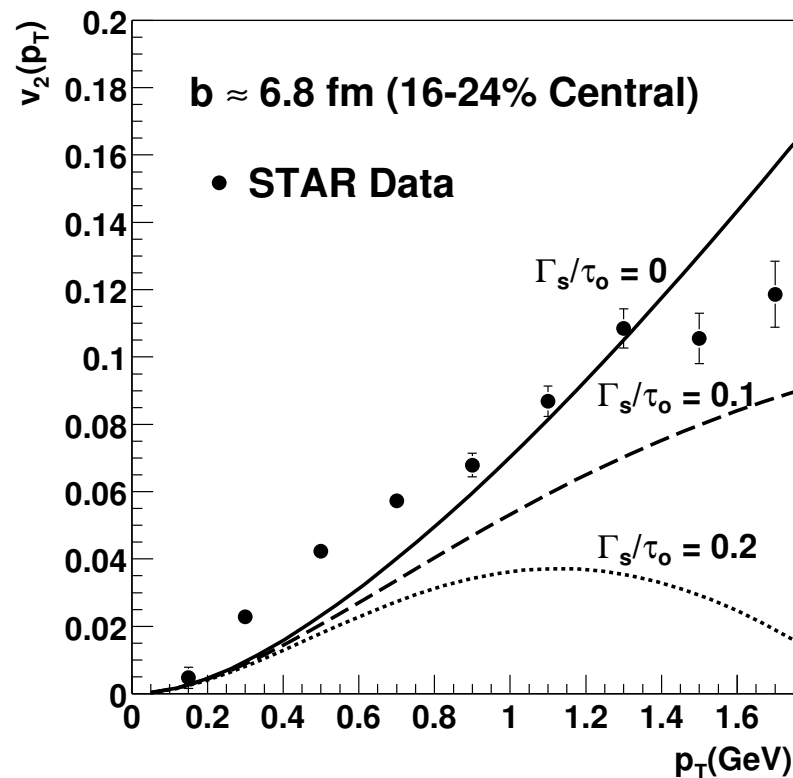
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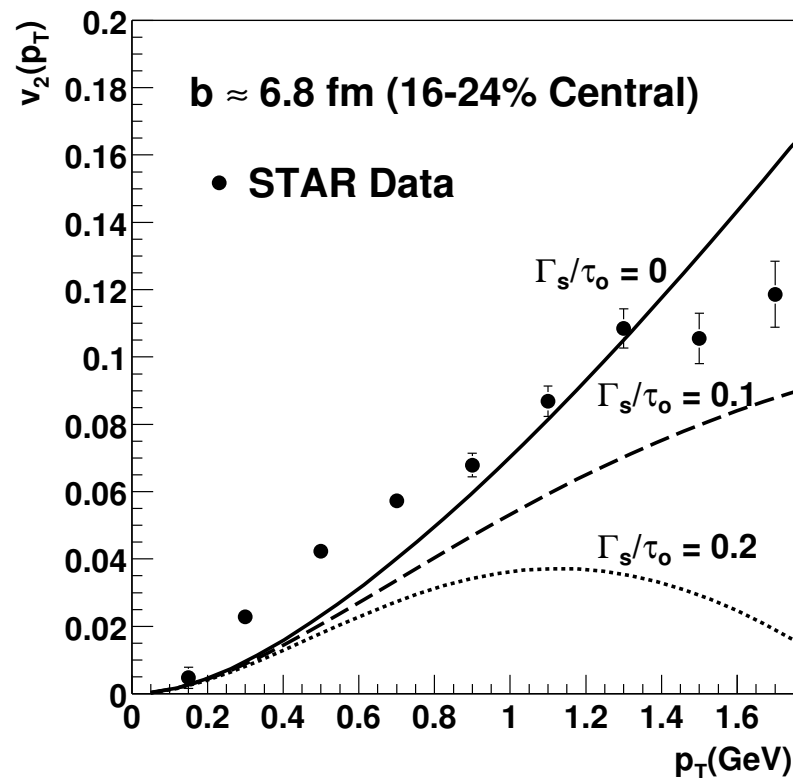


$$\Gamma_s = \frac{\frac{4}{3}\eta}{sT}, \quad (1)$$

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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Perturbation theory \Rightarrow Large η/s
 Small $\eta/s \rightarrow$ 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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Can derive it in certain supersymmetric theory in strong coupling.

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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

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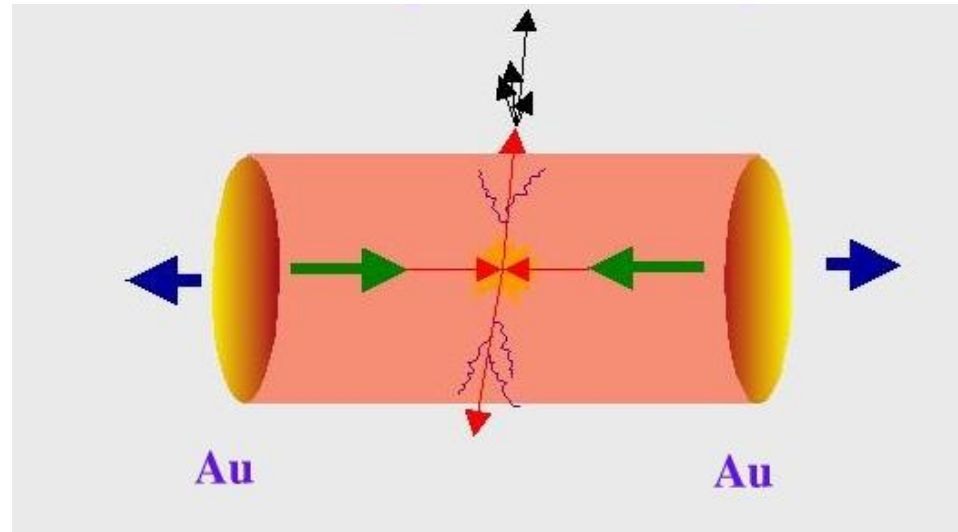
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- pQCD factorization allows separation between hard and soft scales :
$$\sigma^{AB \rightarrow h} = f_A(x_1, Q^2) \otimes f_B(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{i \rightarrow h}(z, Q^2) .$$

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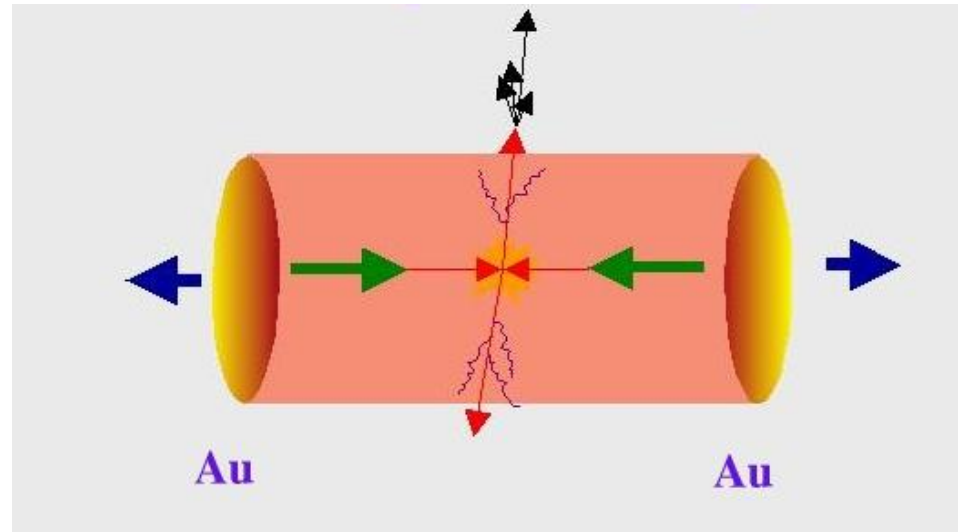
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- Medium, i.e, QGP or hot hadron gas, typically modifies the fragmentation function D in case of Jet Quenching, or its analogue matrix element for J/ψ -production,
E.g. $D_{i \rightarrow h}^{\text{med}}(x, Q^2) = P_E(\epsilon) \otimes D_{i \rightarrow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

Jet Quenching



- Jet Quenching :

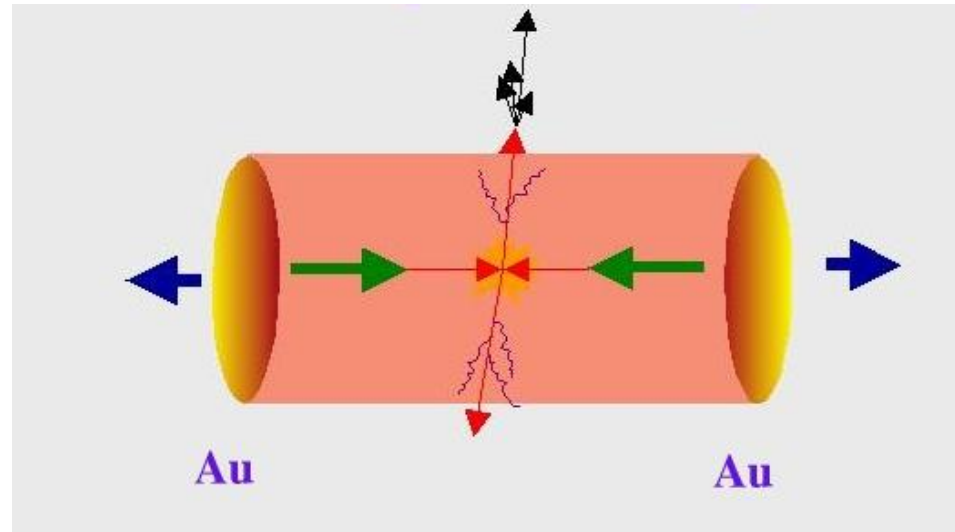
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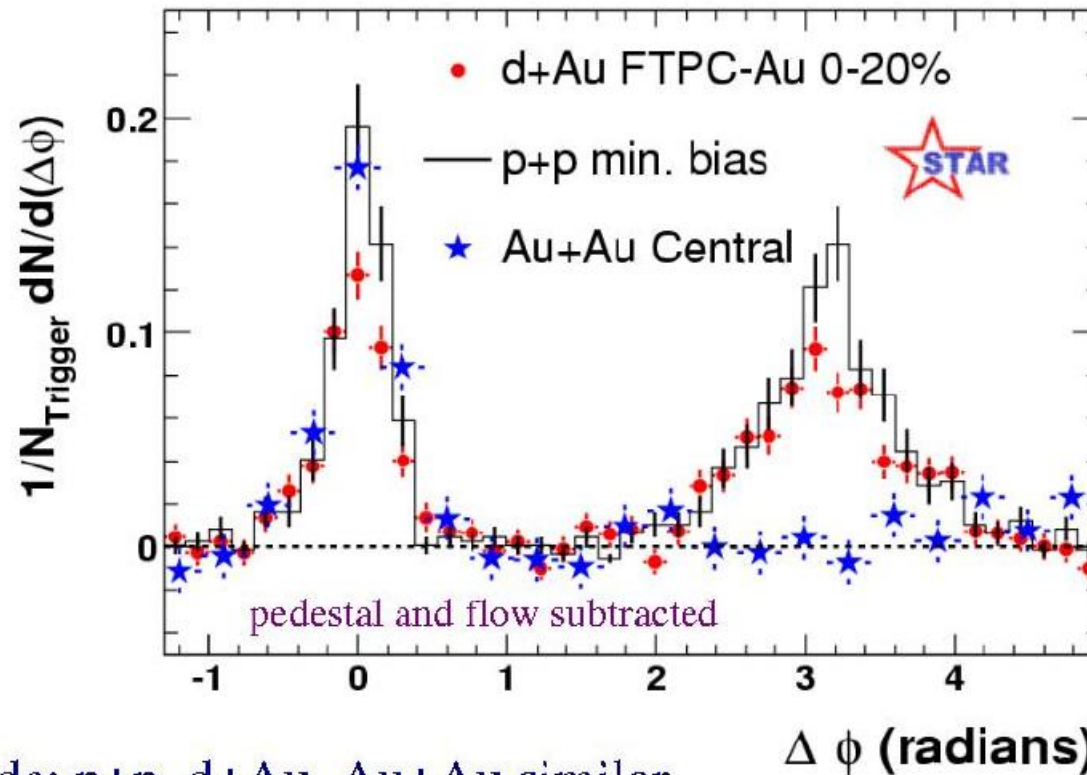
- Rare, Highly Energetic Scatterings produce jets of particles : $g + g \rightarrow g + g$.
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 - Rare, Highly Energetic Scatterings produce jets of particles : $g + g \rightarrow g + g$.
 - Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.
 - On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

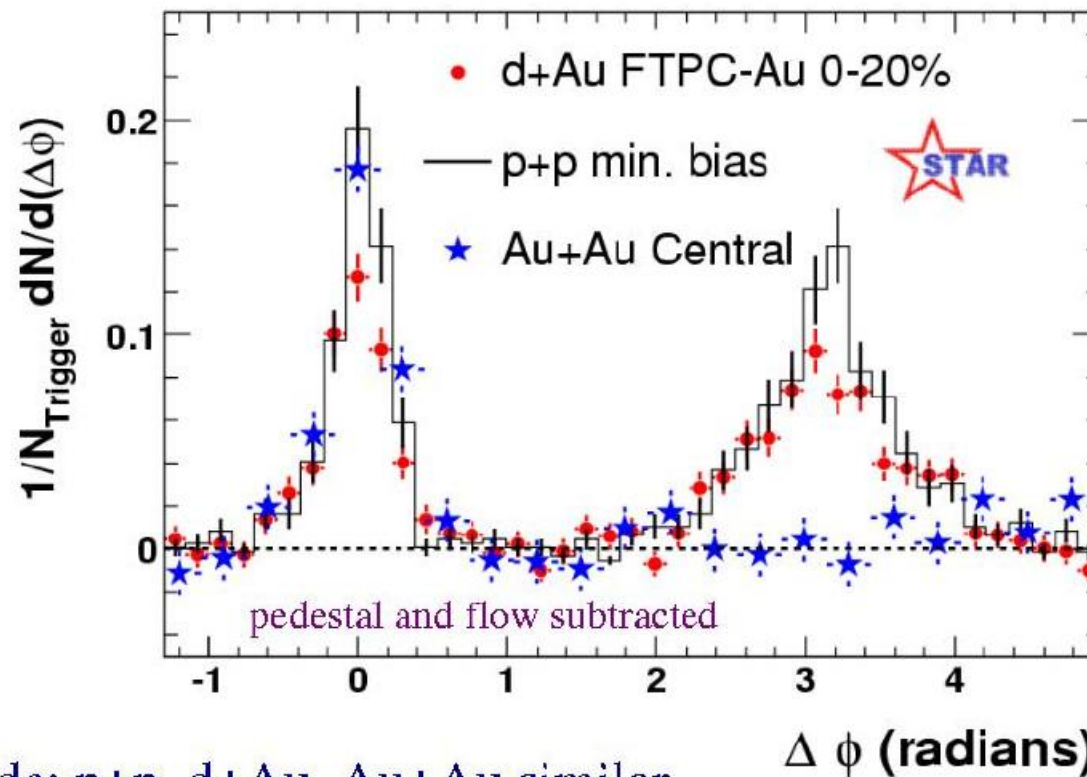
Azimuthal distributions



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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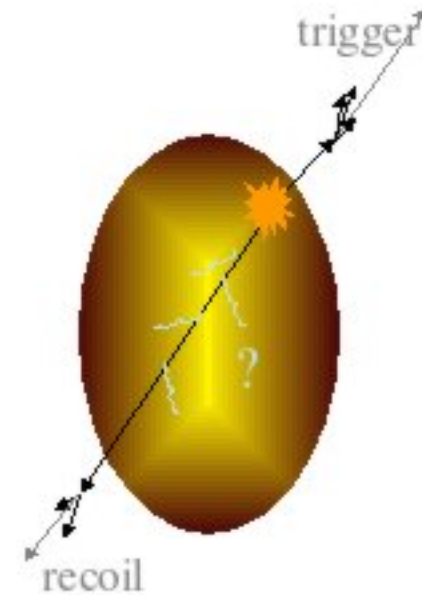
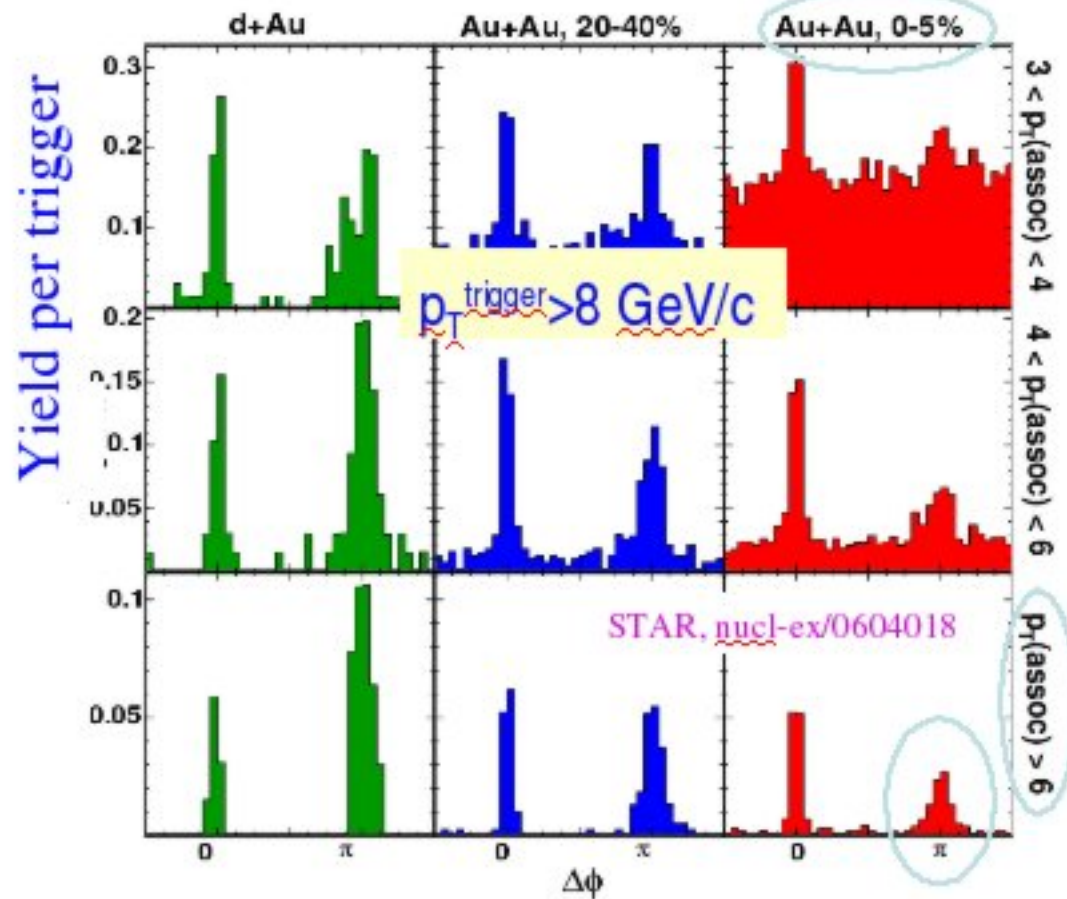
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– Appearance of a diminished jet for large enough momenta.

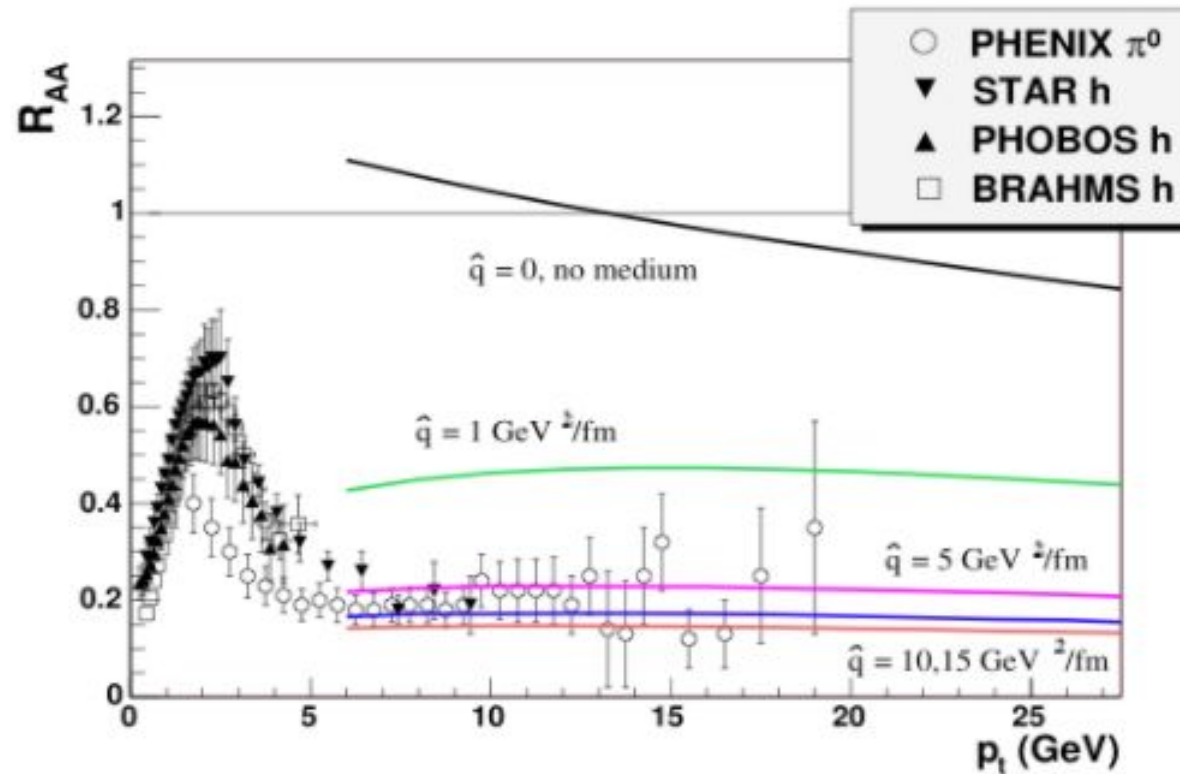
What is new: di-hadron correlations at higher p_T

Hallman: ICHEP06



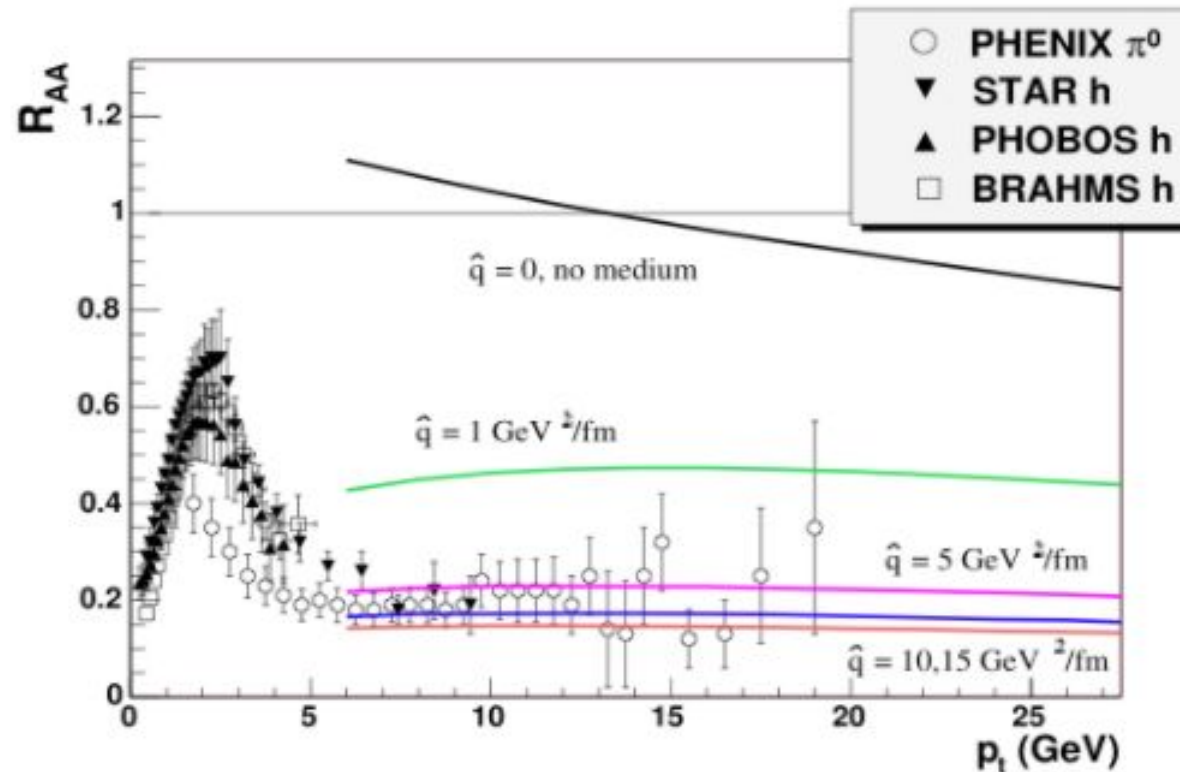
Armesto: ICHEP06

Recoil jet clearly seen above background but at suppressed rate



$\hat{q} : 5\text{-}15 \text{ GeV}^2/\text{fm}$

From Quark Matter 2006 Plenary Talk of F. Wang.



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

Anomalous J/ψ Suppression : CERN NA50 results

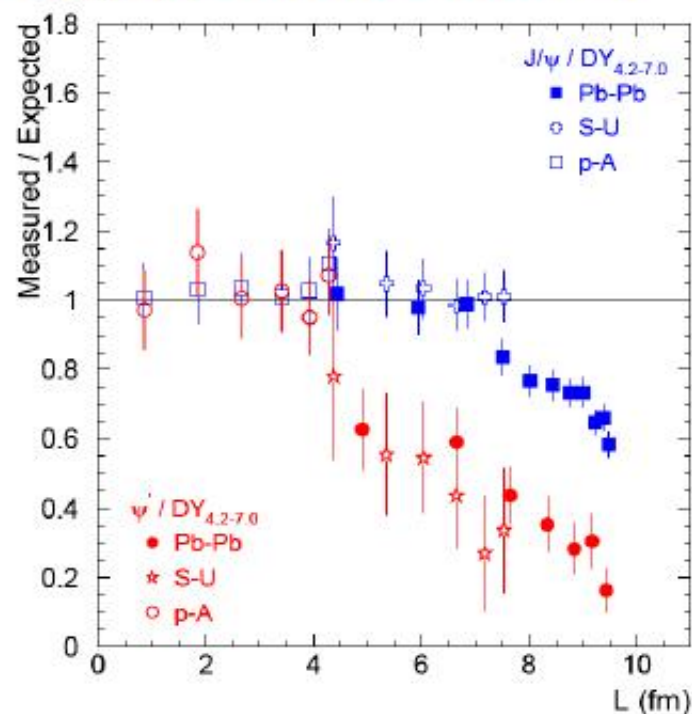
- ♠ Matsui-Satz idea — J/ψ suppression as a signal of QGP.
- ♠ Deconfinement \rightsquigarrow Screening of coloured quarks, which cannot bind.

Anomalous J/ψ Suppression : CERN NA50 results

Expected = Glauber absorption model

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

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



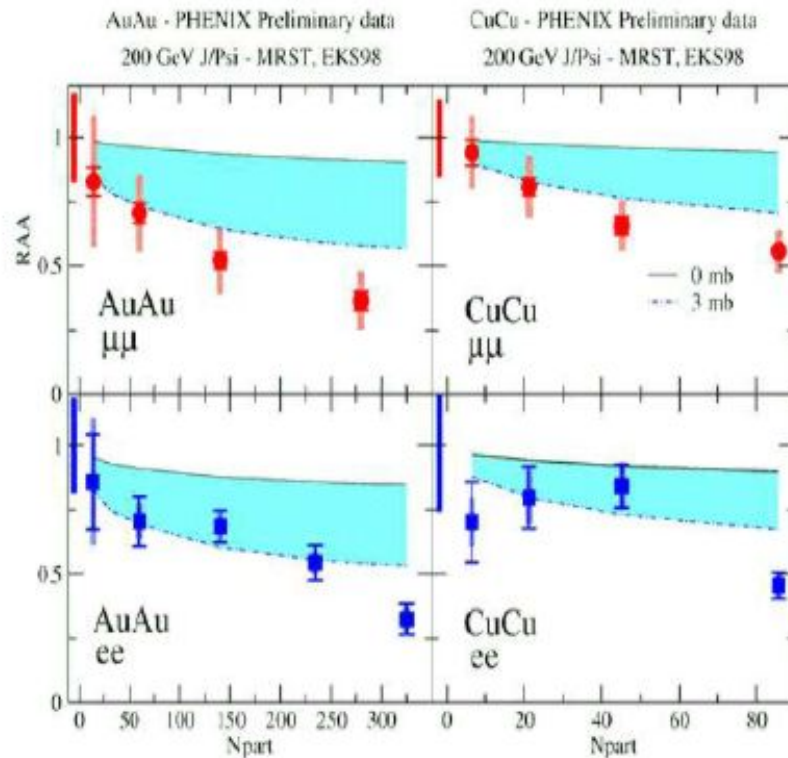
- S-U and **peripheral Pb-Pb $(J/\psi)/DY$** results follow the absorption curve extrapolated from p-A measurements.
- **Pb-Pb central** collisions show an **anomalous $(J/\psi)/DY$ suppression** with respect to p-A behaviour.
- ψ'/DY behaviour is the same in **S-U** and **Pb-Pb** interactions and not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

charmonium suppression at RHIC

surprise:
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-Münzinger, 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 ?