QCD at High Temperature

(Experiment)

Kinematics

CMS: $s = (p_1 + p_2)^2 = 4E_{CM}^2$

Lab: $p_1 = (m, 0)$ $p_2 = (E_L, p_z) = (E_L, \sqrt{E_L^2 - m^2})$

$s = (m + E_L)^2 + (E_L^2 - m^2) = 2m(E_L + m)$ $\qquad E_{CM} = \sqrt{mE_L/2}$

$\mathrm{CERN:}\ \ 200\ \mathrm{GeV}\ (\mathrm{LAB}) \qquad E_{CM} = 10\ \mathrm{GeV} \quad \gamma = 10$

$\mathrm{RHIC:}\ \ 100\ \mathrm{GeV}\ (\mathrm{CMS}) \qquad E_{CM} = 100\ \mathrm{GeV} \quad \gamma = 100$

Rapidity:

$$y = \frac{1}{2}\log\left(\frac{E + p_z}{E - p_z}\right)$$

$\mathrm{CERN:} \qquad \Delta y = 6$

$\mathrm{RHIC:} \qquad \Delta y = 10.6$

Bjorken Expansion

Experimental observation: At high energy ($\Delta y \to \infty$) rapidity distributions of produced particles (in both pp and AA) are "flat"

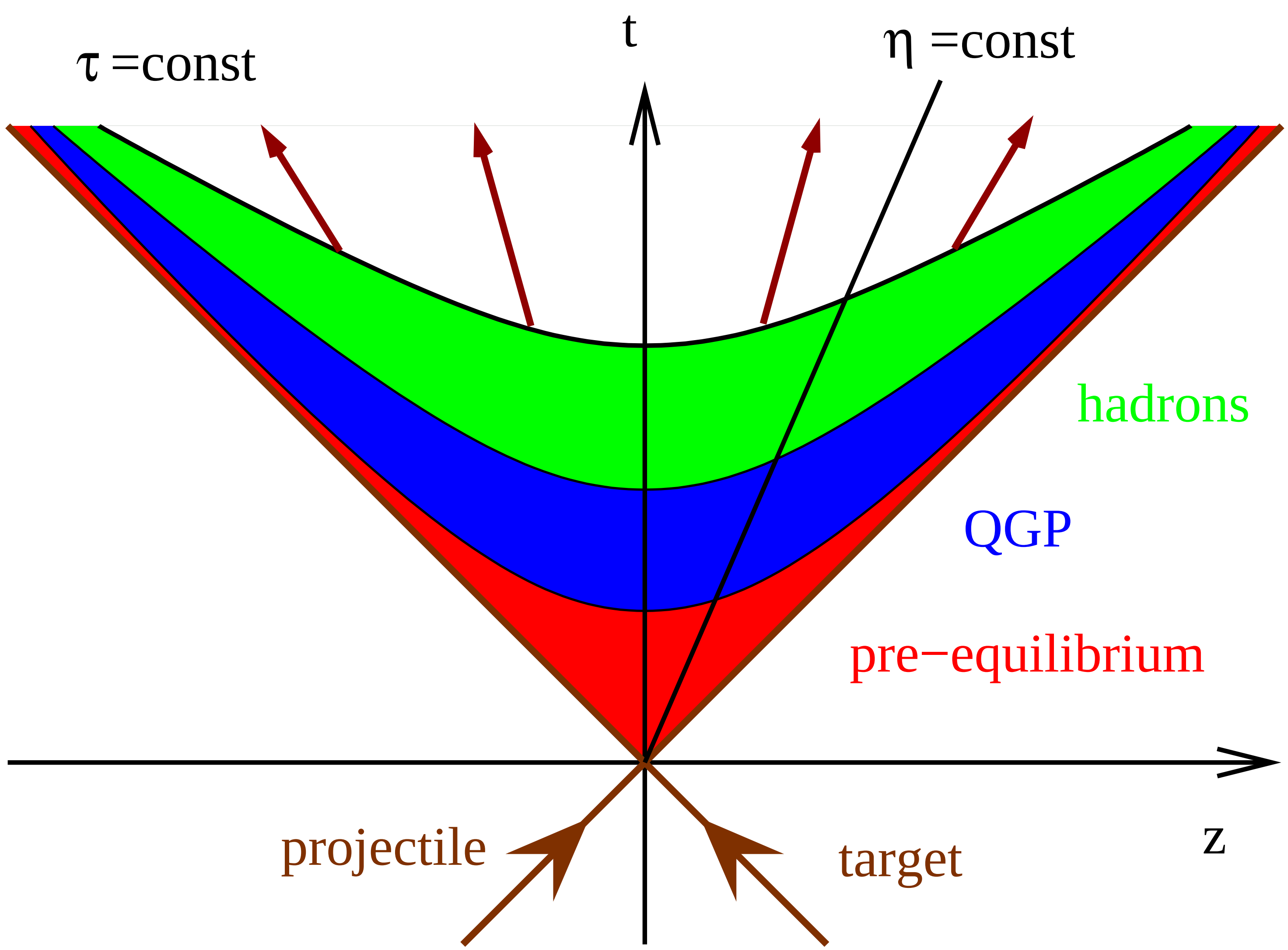
$$\frac{dN}{dy} \simeq const$$

Physics depends on proper time $\tau = \sqrt{t^2 - z^2}$, not on y

All comoving ($v = z/t$) observers are equivalent

Analogous to Hubble expansion

Bjorken Expansion



Bjorken Expansion: Hydrodynamics

Consider perfect fluid ($u_\mu = (1, \vec{v})\gamma$)

$$T_{\mu\nu} = (\epsilon + P) u_\mu u_\nu - P g_{\mu\nu}$$

Hydro = Conservation Laws ($\partial^\mu T_{\mu\nu}$=0) + Equ. of State ($P = P(\epsilon)$)

$$\partial^\mu T_{\mu\nu} = (\partial^\mu \epsilon + \partial^\mu P) u_\mu u_\nu + (\epsilon + P)((\partial^\mu u_\mu) u_\nu + u_\mu \partial^\mu u_\nu) - \partial_\nu P = 0$$

Contract with u_ν, use $u^2 = 1$

$$(\partial^\mu \epsilon + \partial^\mu P) u_\mu + (\epsilon + P) \partial^\mu u_\mu - u^\nu \partial_\nu P = 0$$

$$u_\mu \partial^\mu \epsilon + (\epsilon + P) \partial^\mu u_\mu = 0$$

Thermodynamic relations

$$d\epsilon = T ds \qquad [\text{no } PdV \text{ work}] \qquad \epsilon + P = Ts$$

Hydrodynamic equations

$$u^\mu (T\partial_\mu s) + (Ts)\partial^\mu u_\mu = 0$$

$$\partial_\mu (s u^\mu) = 0 \qquad \text{isentropic expansion}$$

Variables: $t = \tau \cosh\alpha, \ z = \tau \sinh\alpha. \Rightarrow u_\mu = (\cosh\alpha, 0, 0, \sinh\alpha)$

$$\partial^\mu (s u_\mu) = 0 \qquad \Rightarrow \qquad \frac{d}{d\tau}\left[\tau s(\tau)\right] = 0$$

Solution for ideal Bj hydrodynamics

$$s(\tau) = \frac{s_0 \tau_0}{\tau} \qquad T = \frac{const}{\tau^{1/3}}$$

Exact boost invariance, no transverse expansion, no dissipation, ...

Numerical Estimates

Total entropy in rapidity interval $[y, y + \Delta y]$

$$S = s\pi R^2 z = s\pi R^2 \tau \Delta y = (s_0 \tau_0)\pi R^2 \delta y \qquad s_0\tau_0 = \frac{1}{\pi R^2}\frac{S}{\Delta y}$$

Use $S/N \simeq 3.6$

$$s_0 = \frac{3.6}{\pi R^2 \tau_0}\left(\frac{dN}{dy}\right) \qquad \text{Bj estimate}$$

$$\epsilon_0 = \frac{1}{\pi R^2 \tau_0}\left(\frac{dE_T}{dy}\right)$$

Depends on initial time τ_0

CERN: Pb-Pb collisions

$$\frac{dN}{dy} \simeq 600 \qquad \tau_0 = 1 \text{ fm} \qquad s_0 \simeq 20 \text{ fm}^{-3}$$

Use QGP equation of state $s = 2g\pi^2 T^3/45$

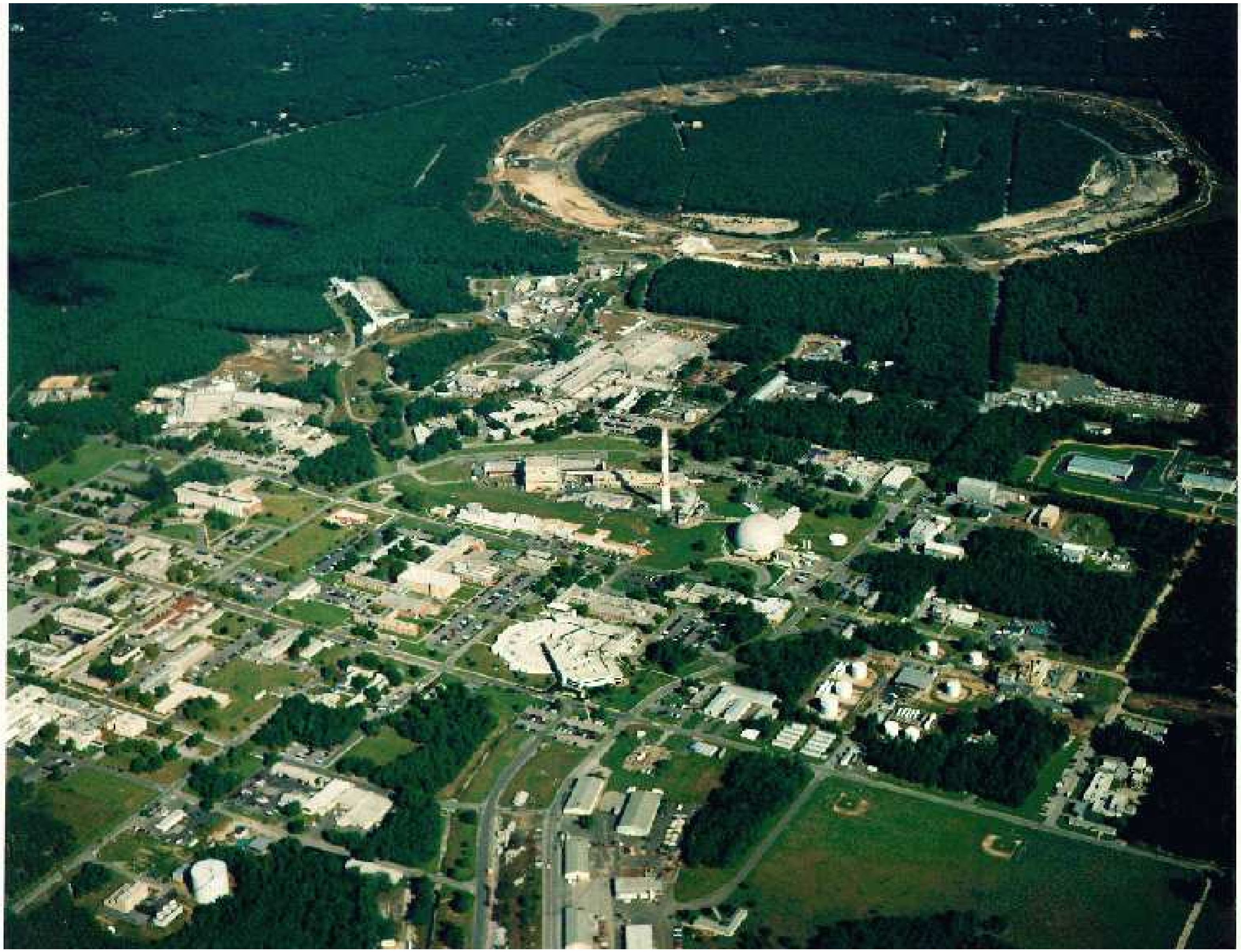
$$T_0 \simeq 200 \text{ MeV} \qquad \epsilon_0 \simeq (2.5 - 3)\text{GeV}/\text{fm}^3$$

RHIC: Au-Au collisions ($\sqrt{s} = 200$ GeV)

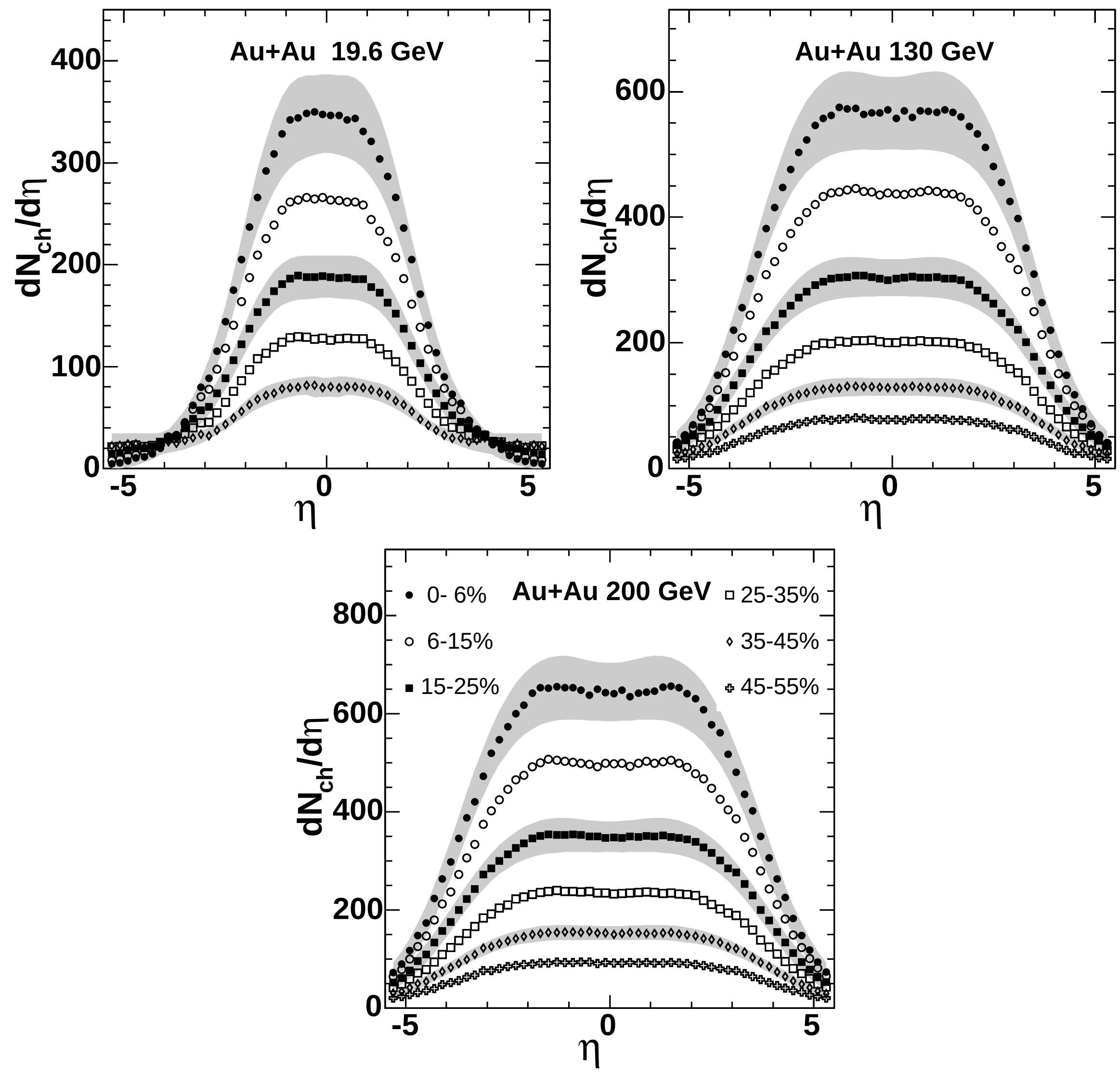
$$\frac{dN}{dy} \simeq 998 \qquad \tau_0 = 1 \text{ fm} \qquad s_0 \simeq 33 \text{ fm}^{-3}$$

$$T_0 \simeq 240 \text{ MeV} \qquad \epsilon_0 \simeq (5 - 6)\text{GeV}/\text{fm}^3$$

BNL and RHIC

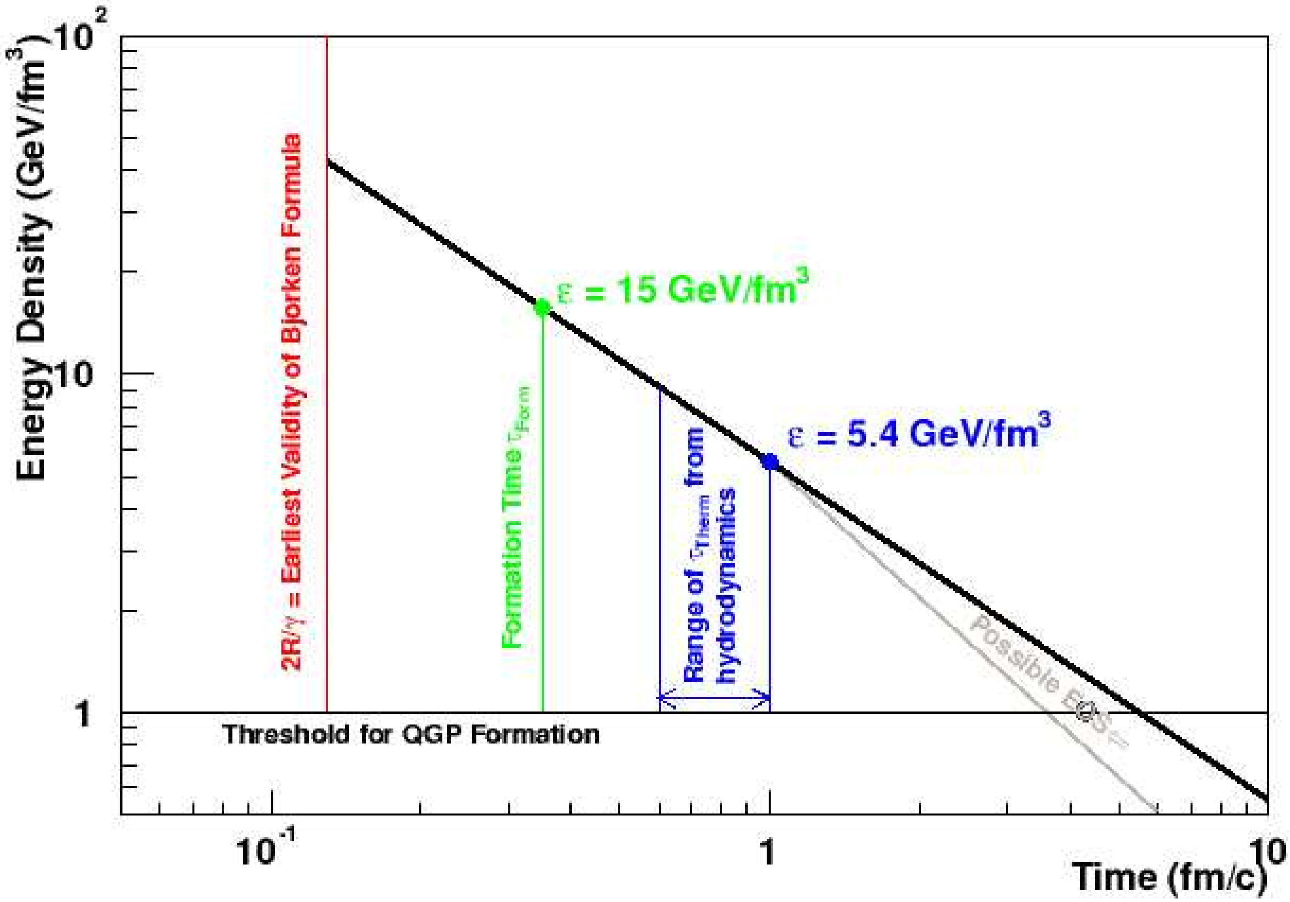


Multiplicities



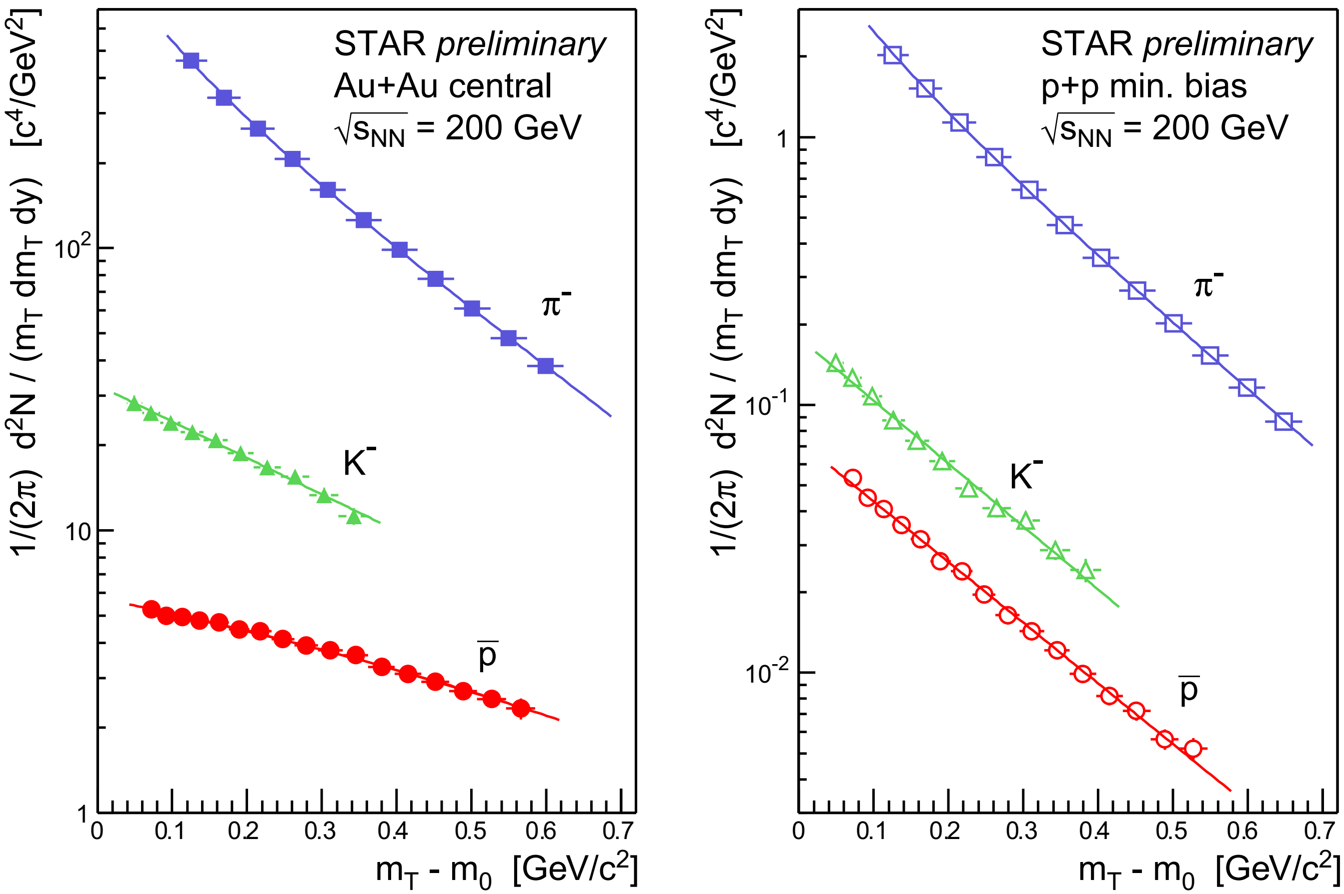
Phobos White Paper (2005)

Bjorken Expansion



Radial Flow

Radial expansion leads to blue-shifted spectra

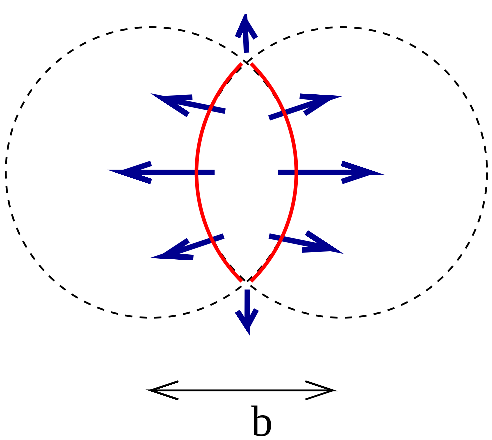


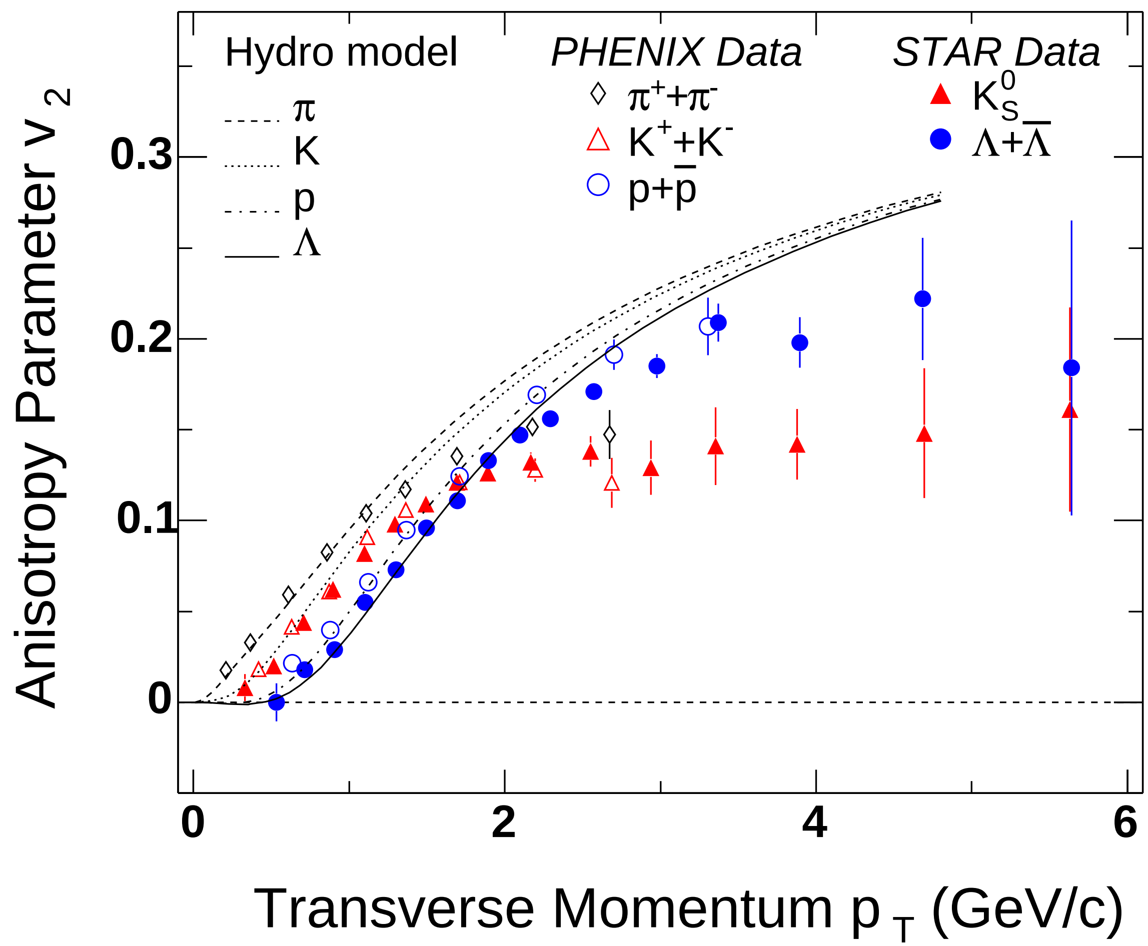
$v_T \sim 0.6c!$

$m_T = \sqrt{p_T^2 + m^2}$

Elliptic Flow

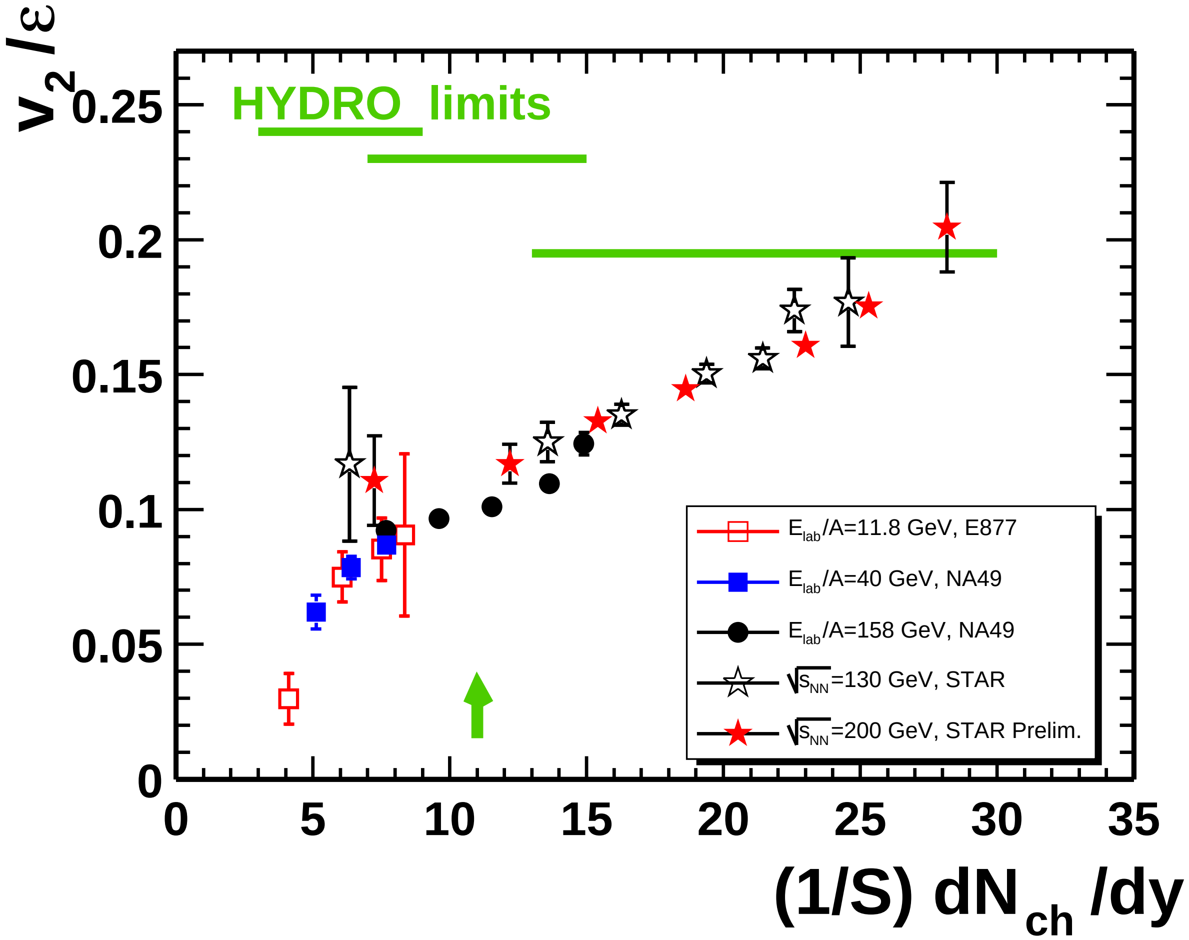
Hydrodynamic expansion converts coordinate space anisotropy to momentum space anisotropy





source: U. Heinz (2005)

Elliptic Flow II



source: U. Heinz (2005)

Viscosity

$$T_{\mu\nu} \to T_{\mu\nu} + \eta(\nabla_\mu u_\nu + \nabla_\nu u_\mu - trace)$$

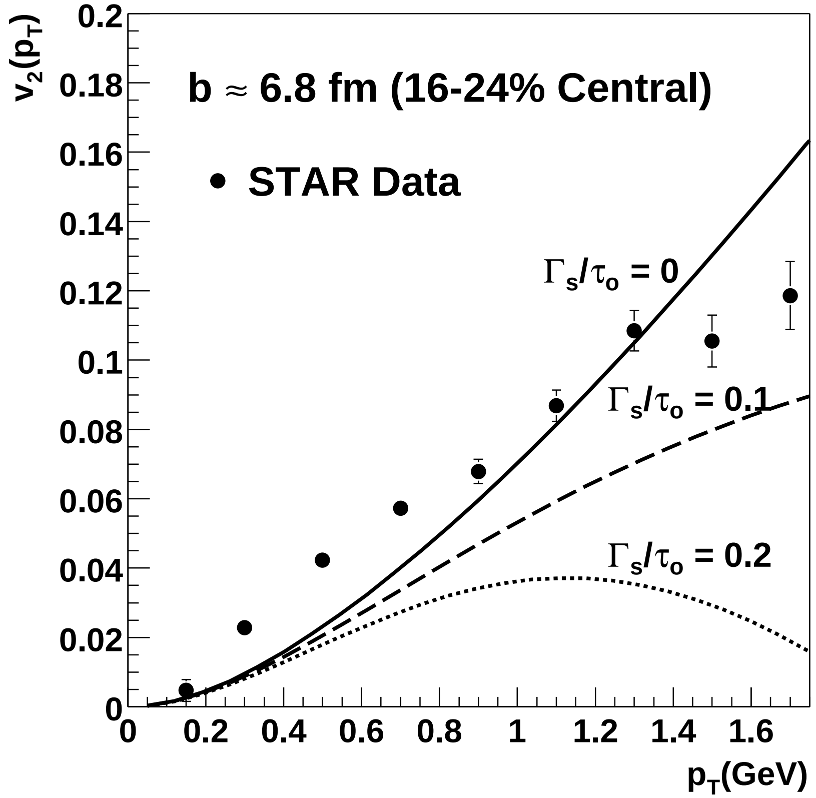
perturbative QCD

$$\eta = 107T^3/(g^4 \log(g^{-1}))$$

universal bound (D. Son)?

$$\eta/s \geq 1/(4\pi)$$

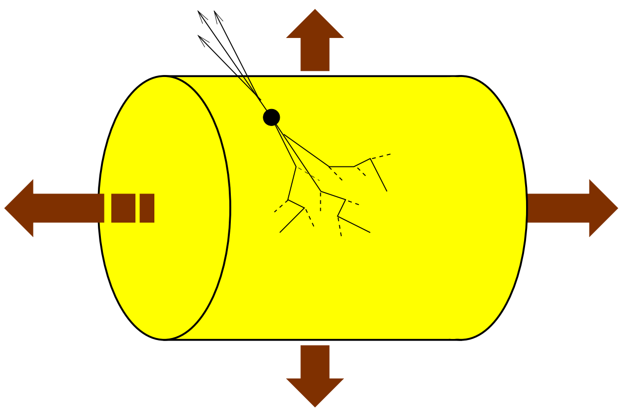
bound saturated in strong coupling SUSY theories with gravitational dual

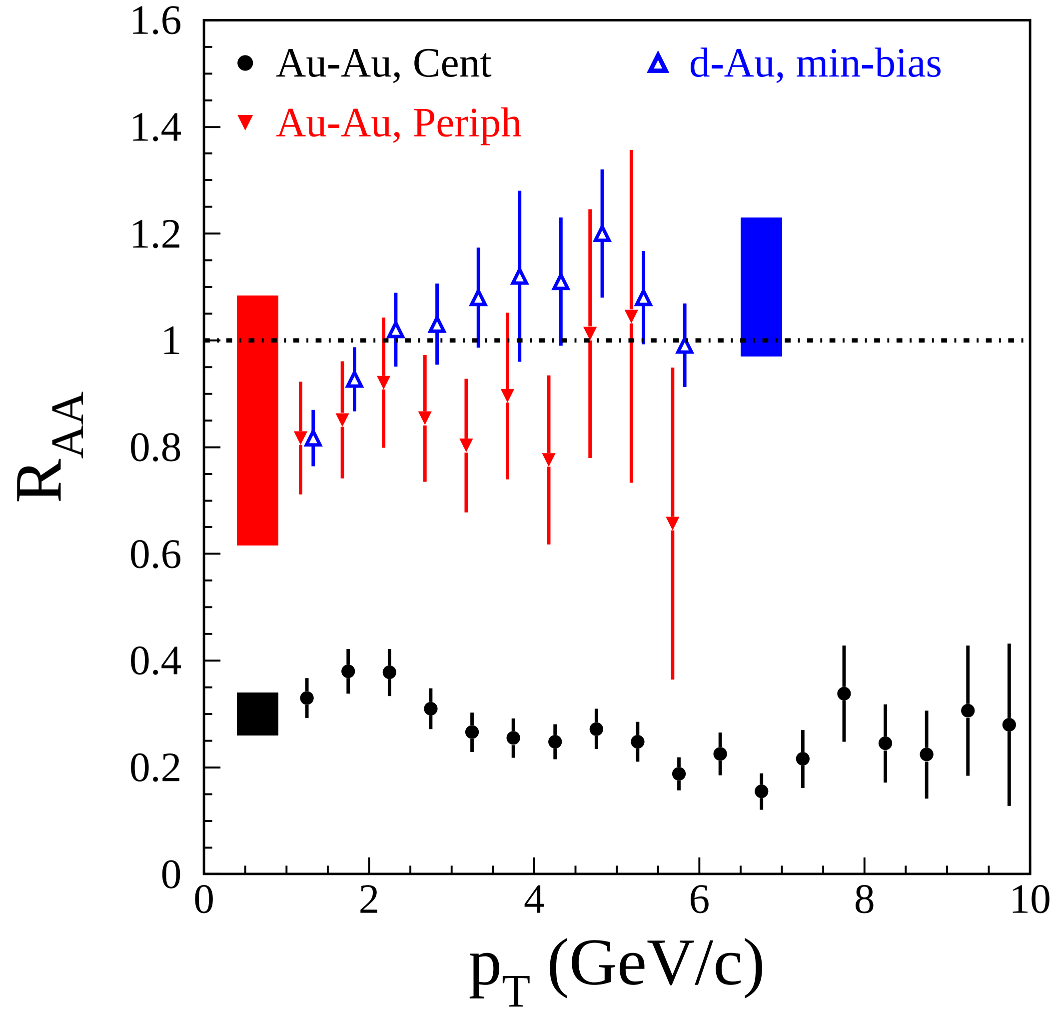


source: D. Teaney (2003)

Jet Quenching

$$R_{AA} = \frac{n_{AA}}{N_{coll} n_{pp}}$$

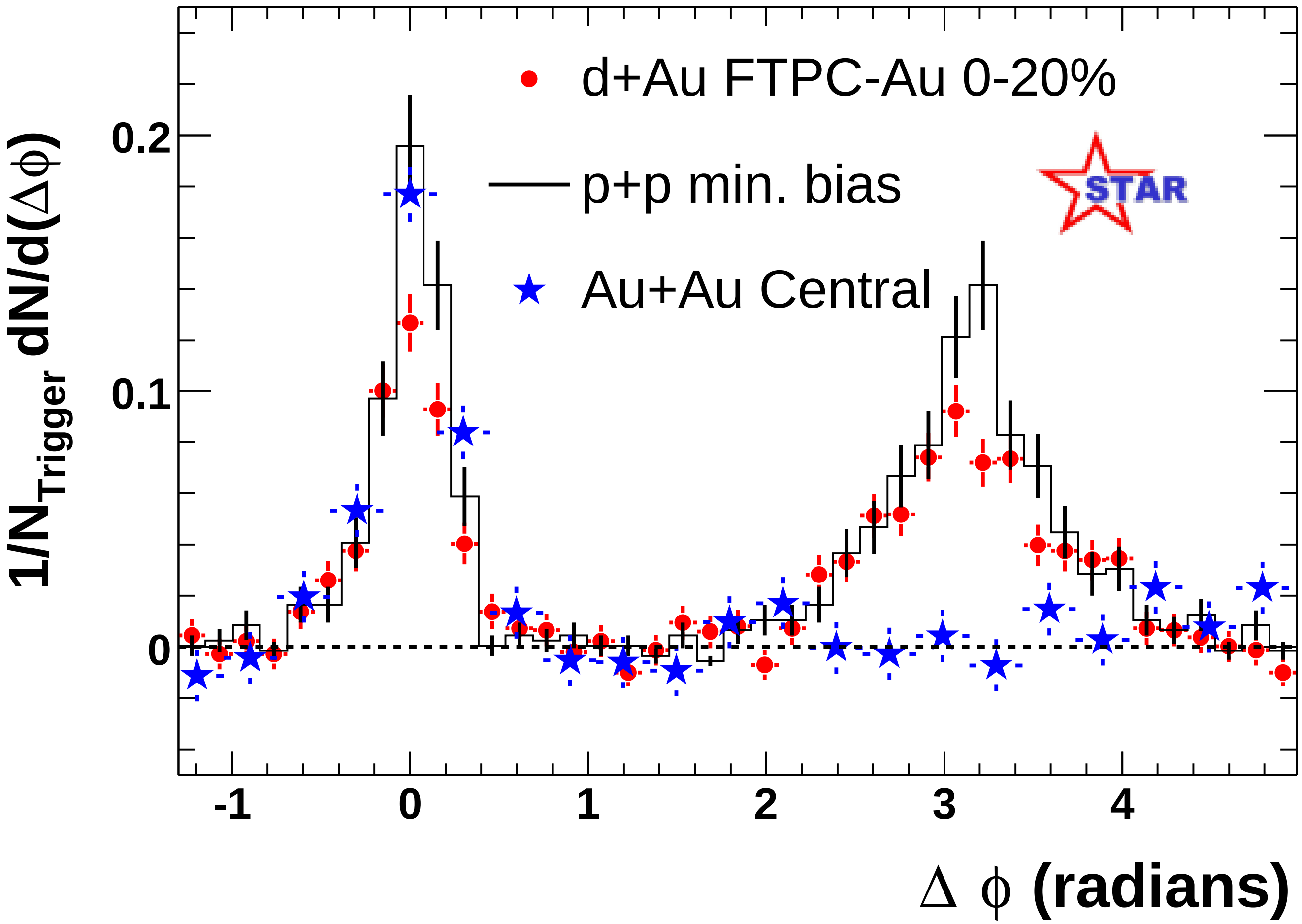




source: Phenix White Paper (2005)

Jet Quenching II

Disappearance of away-side jet

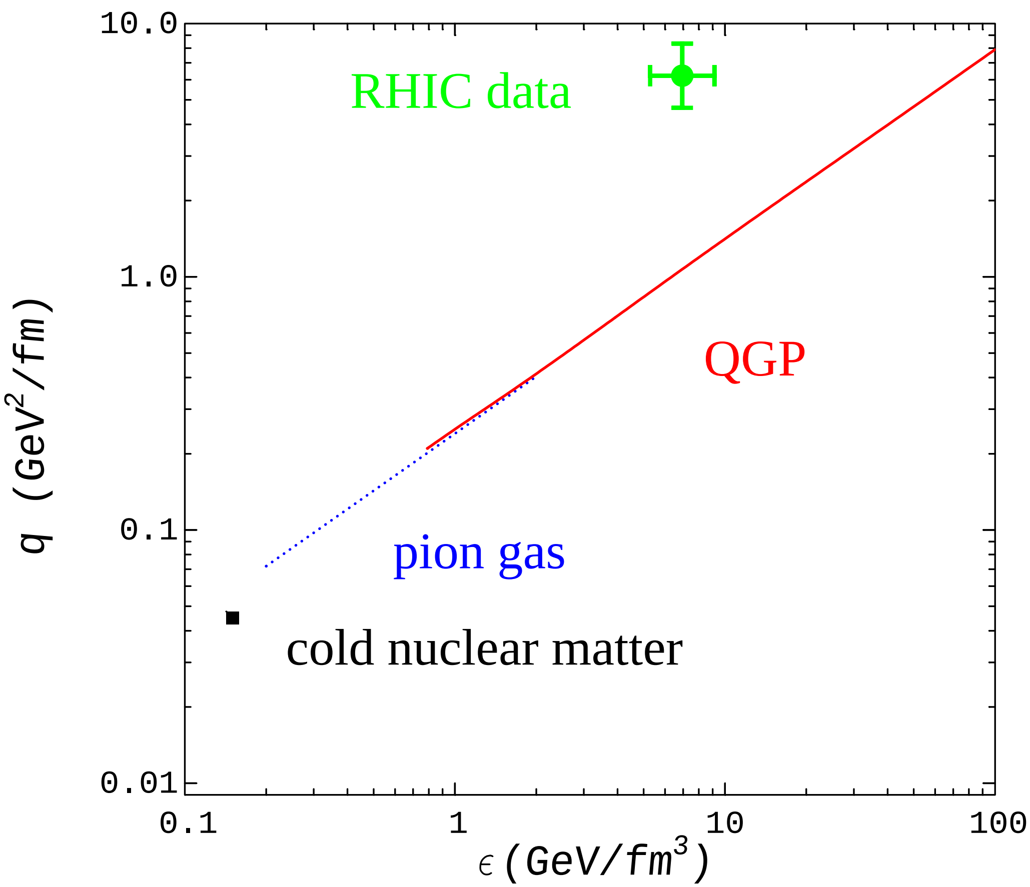


source: Star White Paper (2005)

Jet Quenching: Theory

energy loss governed by

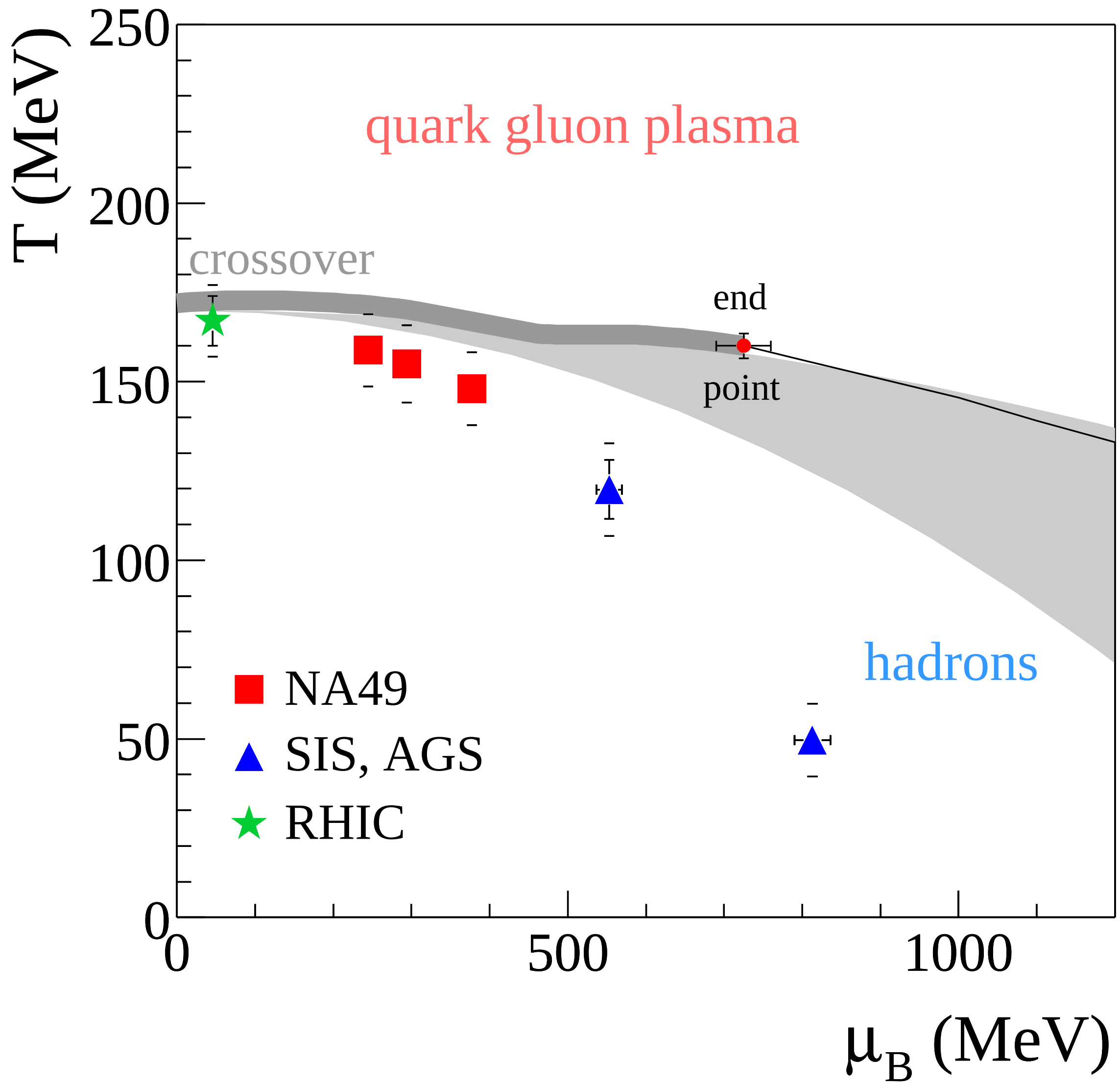
$$\hat{q} = \rho \int q_\perp^2 \, dq_\perp^2 \, \frac{d\sigma}{dq_\perp^2}$$



larger than pQCD predicts?

source: R. Baier (2004)

Phase Diagram: Freezeout



Summary (Experiment)

Matter equilibrates quickly and behaves collectively

Little Bang, not little fizzle

Initial energy density in excess of 10 GeV$/\mathrm{fm}^3$

Conditions for Plasma achieved

Evidence for stronly interacting Plasma ("sQGP")

Fast equilibration $\tau_0 \ll 1$ fm

Strong energy loss of leading partons