"RHIC serves the perfect fluid" – Hydrodynamic flow of the Quark-Gluon Plasma*

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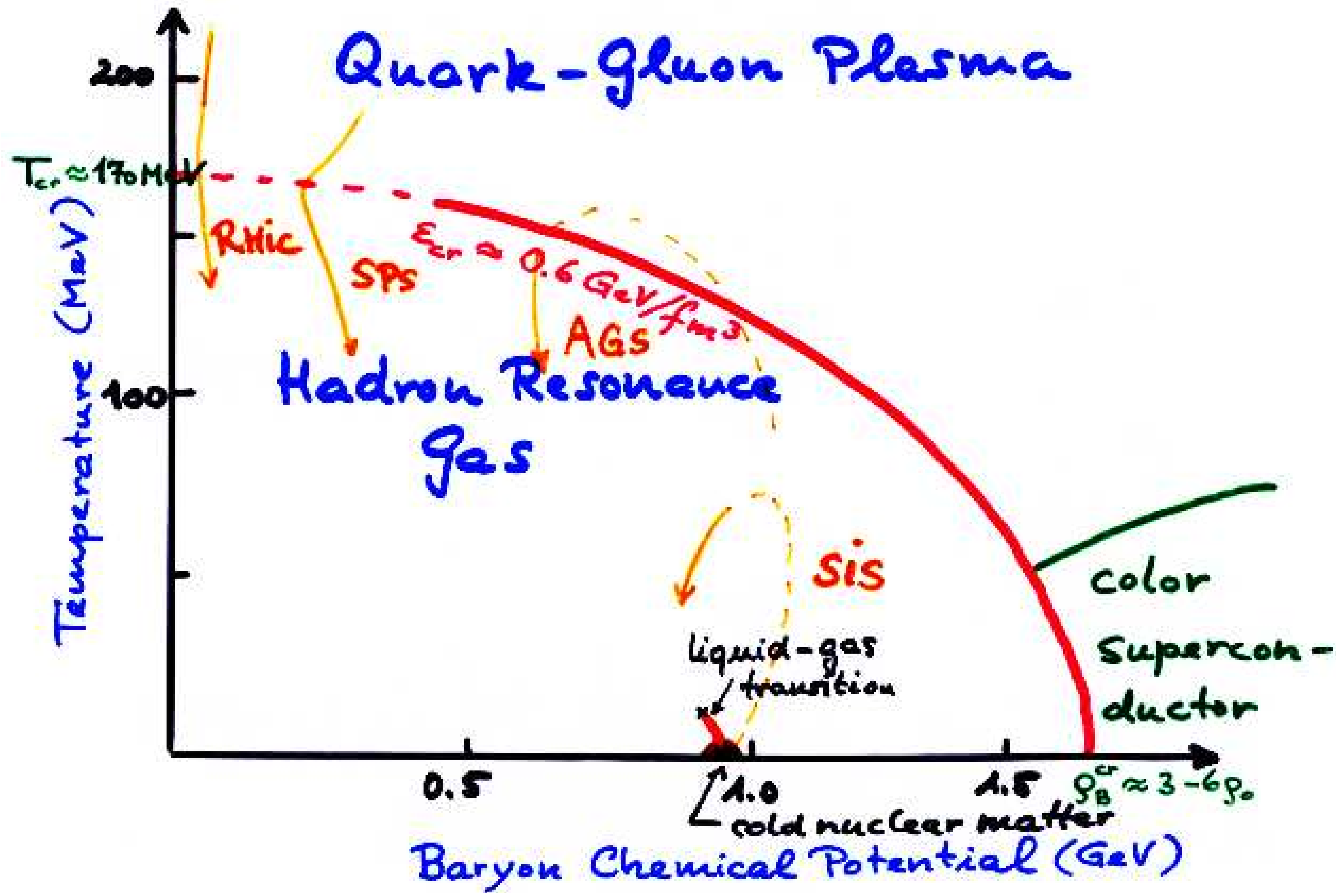
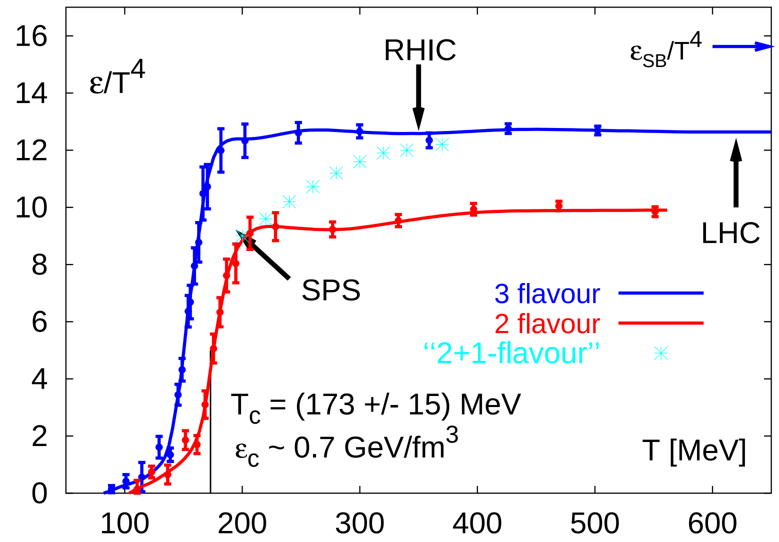
The QCD Phase Diagram and Heavy-Ion Collisions

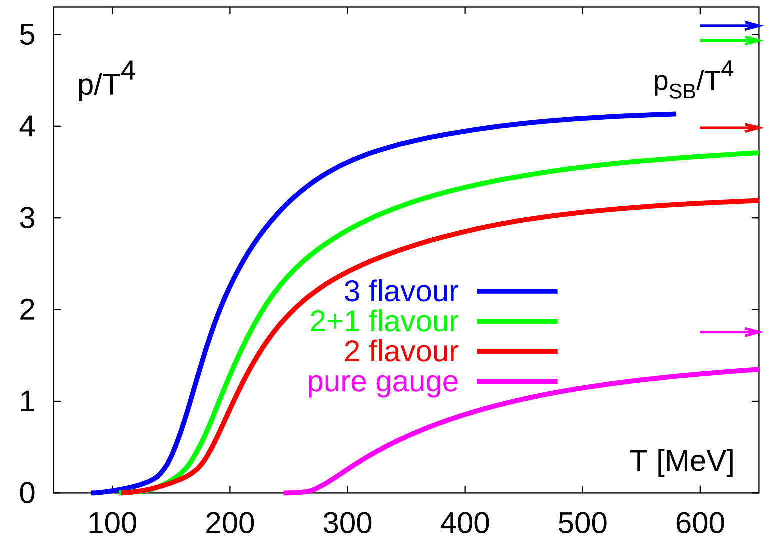


Particle Physics ↔ Heavy-Ion Physics ⟺ Atomic Physics ↔ Condensed Matter Physics

The QCD equation of state (EOS) at zero baryon density

F. Karsch and E. Laermann, hep-lat/0305025, in "Quark-Gluon Plasma 3"





- Critical temperature $T_{\rm cr} = 173 \pm 15\,\text{MeV}$ $(\approx 100\,000 \times T_{\text{center of sun}})$
- Critical energy density $\varepsilon_{\rm cr} \simeq 0.7\,\text{GeV/fm}^3$
- $\varepsilon \approx 0.8\,\varepsilon_{\rm SB}$ for $T \gtrsim 1.3\,T_{\rm cr}$, $\varepsilon \approx 3\,p$ for $T \gtrsim 2\,T_{\rm cr}$

$\Longrightarrow$ Weakly coupled QGP? NO!

Collective flow tests the Equation of State:

Hydrodynamic equations, ideal fluid limit:

($\dot{f}$ = time derivative in local rest frame, $\partial{\cdot}u$ = local expansion rate)

$$\dot{n}_B = -n_B\,(\partial{\cdot}u)$$

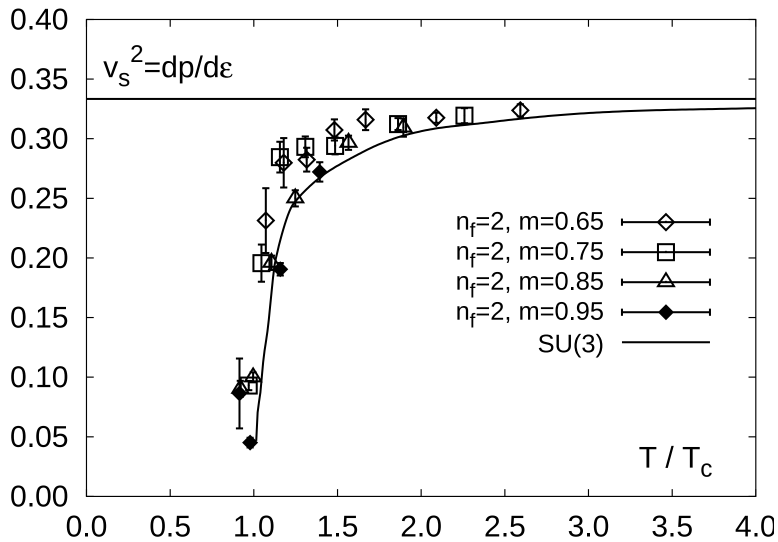
$$\dot{\varepsilon} = -(\varepsilon + p)\,(\partial{\cdot}u)$$

$$\dot{u}^\mu = \frac{\nabla^\mu p}{\varepsilon + p} = \frac{c_s^2}{1+c_s^2}\frac{\nabla^\mu \varepsilon}{\varepsilon}$$

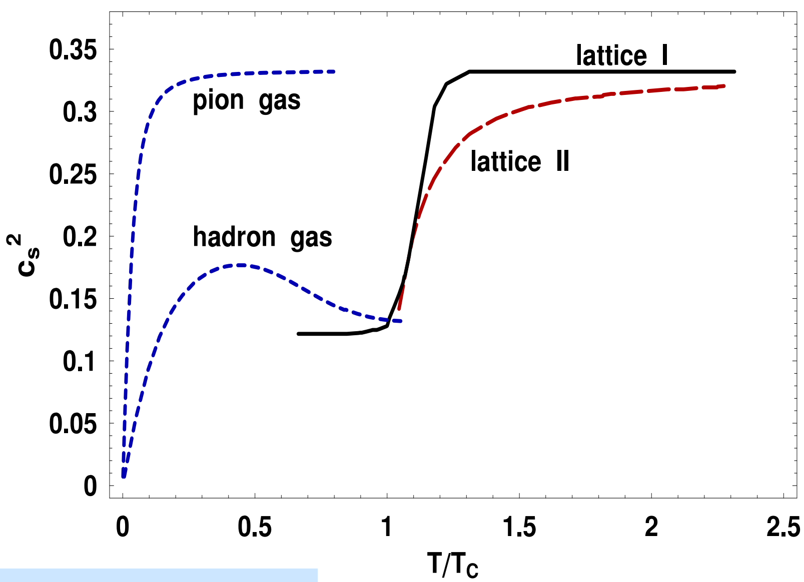
- flow driven by pressure gradients $\nabla^\mu p$
- acceleration $\frac{\nabla^\mu p}{\varepsilon + p}$ closely related to

speed of sound $c_s^2 = \frac{\partial p}{\partial \varepsilon}$

Karsch+Laermann, hep-lat/0305025



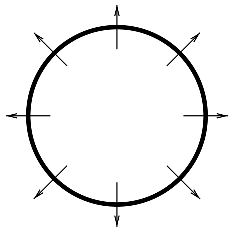
Chojnacki et al., nucl-th/0410036



"Softest point" near $T = T_{\rm cr}$.

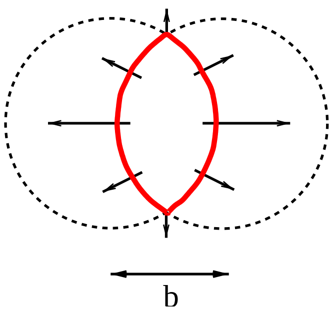
"Flavors" of transverse flow:

Radial flow:



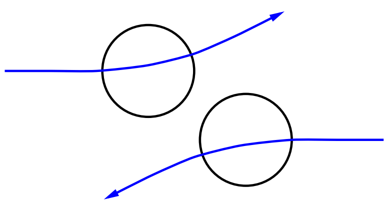
→ the only type of transverse flow in $b = 0$ collisions between equal spherical nuclei
→ integrates pressure history over entire expansion stage
→ observable via effect of $\langle v_\perp \rangle$ on slope of $m_\perp$ spectra

Elliptic flow ($b \neq 0$ or collisions between deformed nuclei, e.g. U+U):



→ peaks at midrapidity
→ requires spatial deformation of reaction zone at thermalization
→ magnitude of signal probes degree and time of thermalization
→ shuts itself off as dynamics reduces deformation (H. Sorge)
→ sensitive to Equation of State during first $\sim 5\,\mathrm{fm}/c$

Directed flow ($b \neq 0$, $y \neq 0$):



→ generated very early while nuclei penetrate each other
→ dominated by early non-equilibrium processes
→ becomes weaker with increasing collision energy

Flow = unavoidable consequence of thermalization!

QGP $\Longrightarrow$ an (approximately) thermalized system of quarks and gluons
$\Longrightarrow$ thermal pressure gradients $\Longrightarrow$ **collective flow**

Hydrodynamics – the natural tool to study flow:

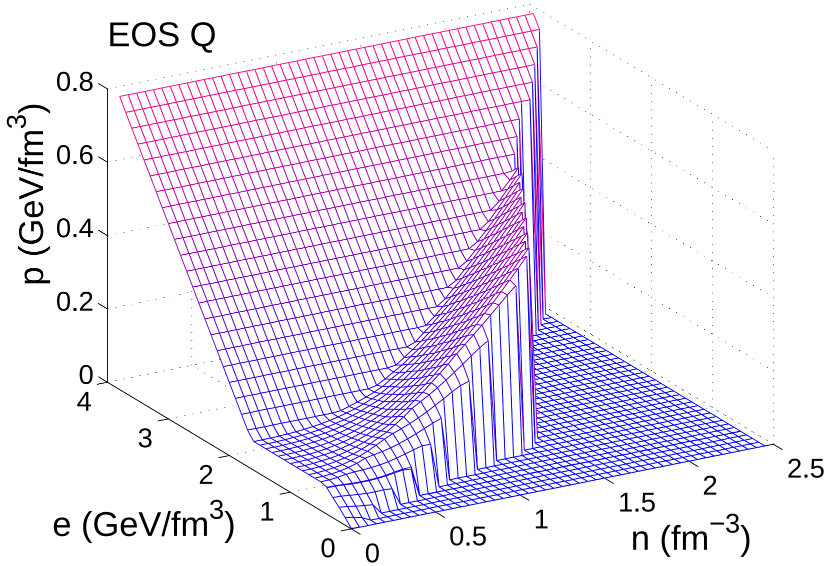
Relativistic Hydrodynamics:	Conservation of energy, momentum and baryon number	$\partial_\mu T^{\mu\nu} = 0$ $\partial_\mu j^\mu = 0$

with energy momentum tensor $T^{\mu\nu}(x) = (e(x)+p(x))\, u^\mu(x) u^\nu(x) - g^{\mu\nu} p(x)$
and baryon current $j^\mu(x) = n(x)\, u^\mu(x)$

Equation of state:

– EOS I: ultrarelativistic ideal gas, $p = \frac{1}{3}\, e$
– EOS H: hadron resonance gas, $p \sim 0.15\, e$
– EOS Q: Maxwell construction between
EOS I and EOS H

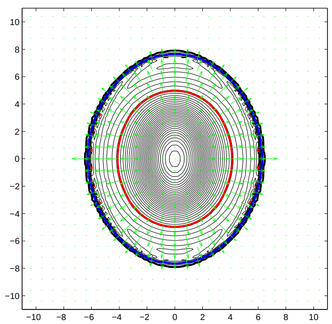
critical temperature $T_{\text{crit}} = 0.164$ GeV
$\Rightarrow$ bag constant $B^{1/4} = 0.23$ GeV
latent heat $\Delta e = 1.15$ GeV/fm^3



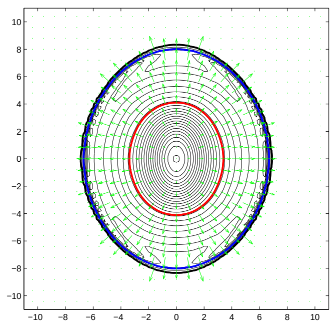
Implement exact longitudinal boost invariance for simplicity ($Y \approx 0$ only)

Radial and elliptic flow from hydrodynamics:

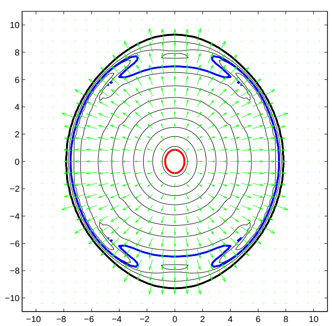
Au+Au at $b = 7$ fm



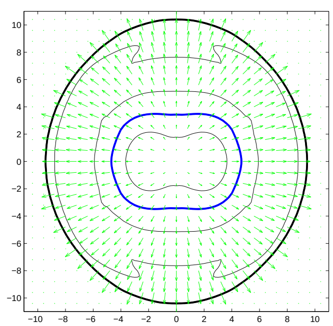
3.2 fm/c ($\epsilon_x = 0.160$, $\epsilon_p = 0.114$)



4.0 fm/c ($\epsilon_x = 0.127$, $\epsilon_p = 0.141$)



5.6 fm/c ($\epsilon_x = 0.067$, $\epsilon_p = 0.147$)



8.0 fm/c ($\epsilon_x = 0.003$, $\epsilon_p = 0.123$)

- when do elliptic and radial flow develop?
- how is elliptic flow related to the time-dependent spatial deformation $\epsilon_x = \frac{\langle\langle y^2 - x^2 \rangle\rangle}{\langle\langle y^2 + x^2 \rangle\rangle}$?
- how do radial and elliptic flow depend on the EOS?
- what is the source deformation at freeze-out?
- is there enough time before freeze-out to change sign of ϵ_x?

What is fitted, what is predicted?

Au+Au @ 130 A GeV:

$\tau_{\rm eq} = 0.6\,$fm$/c$, $e_{\rm max}(b{=}0) = 24.6\,$GeV/fm^3, $\langle e\rangle(\tau{=}1\,{\rm fm}/c) = 5.4\,$GeV/fm^3

$T_{\rm max}(b{=}0) = 340\,$MeV, $T_{\rm chem} = T_{\rm had} = 165\,$MeV, $T_{\rm dec} = 130\,$MeV

All fit parameters are fixed in central ($b{=}0$) collisions:

- Glauber model $\Rightarrow$ shape of initial transverse entropy and baryon density profiles $s(\boldsymbol{r},\tau_{\rm eq}), n_B(\boldsymbol{r},\tau_{\rm eq})$
  $\Rightarrow$ free parameters $s_0(\tau_{\rm eq})$, $n_0(\tau_{\rm eq})$, soft/hard fraction
- Measured p/π ratio $\Rightarrow$ fixes n_0/s_0
- Total charged multiplicity $dN_{\rm ch}/dy$ $\Rightarrow$ fixes product $\tau_{\rm eq}\cdot s_0(\tau_{\rm eq})$
- soft/hard fraction $\Rightarrow$ fixed through centrality dependence of $dN_{\rm ch}/dy$
- Shape of π, p spectra $\Rightarrow$ fixes decoupling temperature $T_{\rm dec}$ and radial flow $\langle v_\perp\rangle$
- Final radial flow $\langle v_\perp\rangle$ $\Rightarrow$ "fixes" $\tau_{\rm eq}$ [upper limit] (flow needs time and pressure to develop)
- Equation of State $\Rightarrow$ compute $e_0 = e_{\rm max}(b{=}0),\ T_{\rm max}(b{=}0)$ from $s_0,\ n_0$

Predictions (no additional parameters!):

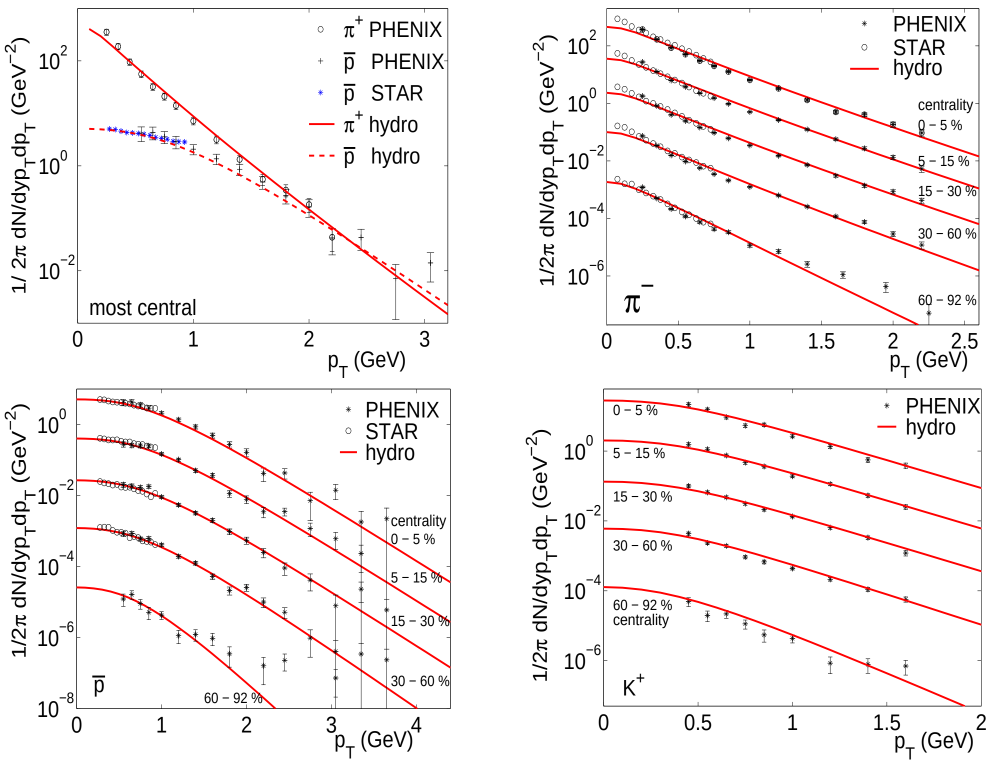
- All hadron spectra other than $p,\ \pi$ in $b{=}0$ collisions
- All hadron spectra and elliptic flow coefficients for non-central collisions at any impact parameter

Shortcomings of early hydro calculations (repaired in later versions):

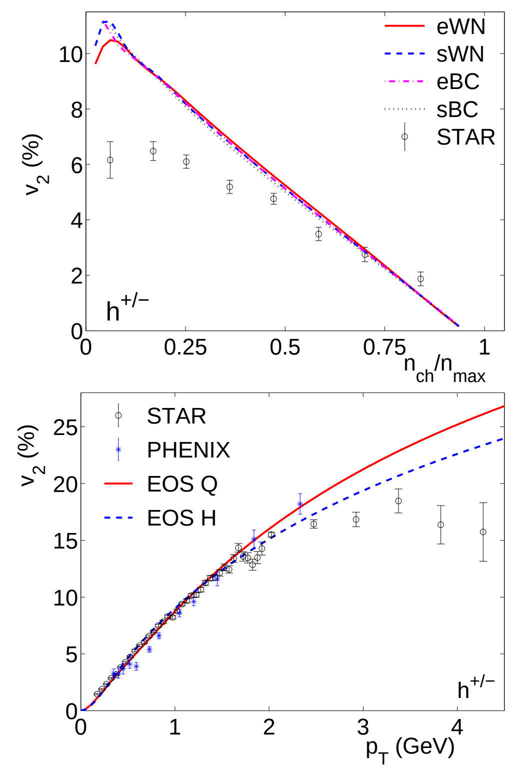
- EOS assumes chemical equilibrium all the way down to $T_{\rm dec}$
- No transverse dynamics before $\tau_{\rm eq}$

Successes of hydrodynamics at RHIC:

Single particle spectra from central and peripheral Au+Au @ 130 A GeV (STAR, PHENIX):



Centrality and momentum dependence of elliptic flow v_2 (STAR, PHENIX, PHOBOS):



Model parameters fixed with π, $\bar{p}$ spectra at $b = 0$; all other spectra predicted (UH & P.Kolb, hep-ph/0204061).

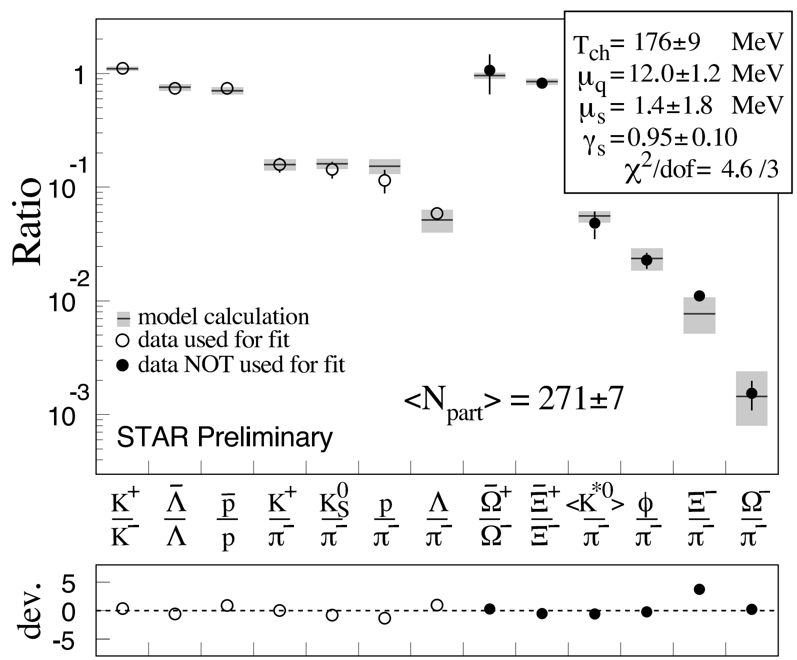
$$v_2 = \langle \cos(2\phi) \rangle$$

Final radial flow $\langle v_\perp \rangle > 0.5\,c \Longrightarrow$ bang!

Interlude: Chemical Freeze-out at $T_{\rm had} \simeq 170$ MeV

Central Au+Au @ 130 A GeV

(STAR Coll., G. van Buren, QM2002)



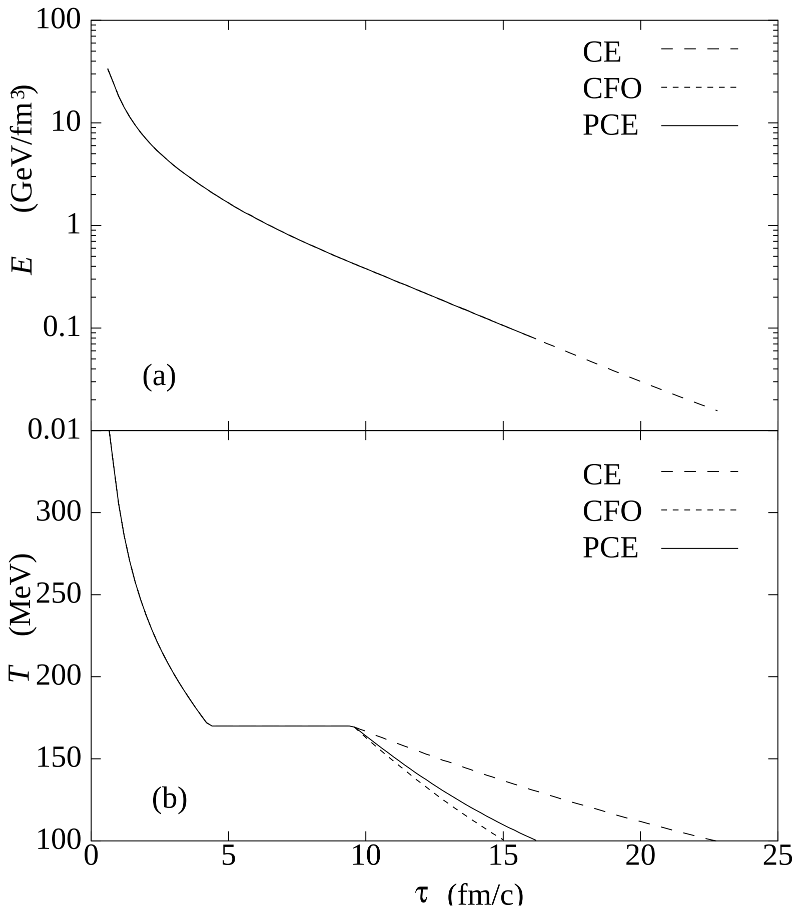
Abundance ratios of stable hadrons decouple in maximum entropy state of "apparent chemical equilibrium" with $T_{\rm chem} \simeq T_{\rm had} \simeq 170$ MeV

$\Longrightarrow$ Need non-equilibrium chemical potentials $\mu_i(T)$ for hadrons i to keep abundance ratios constant at $T < T_{\rm chem}$.

(R. Rapp, PRC 66 (2002) 017901
T. Hirano, PRC 66 (2002) 054905
D. Teaney, nucl-th/0204023)

Note: Hadron abundances are in statistical, not in kinetic chemical equilibrium!
Requires pre-hadronic phase with large strangeness correlation volume.

Expansion with non-equilibrium chemical potentials:

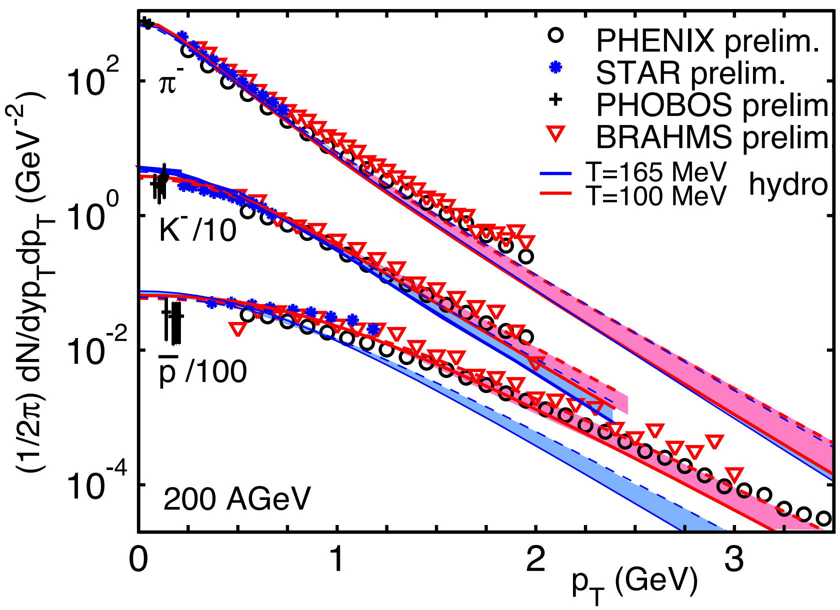


T. Hirano, PRC 66 (2002) 054905

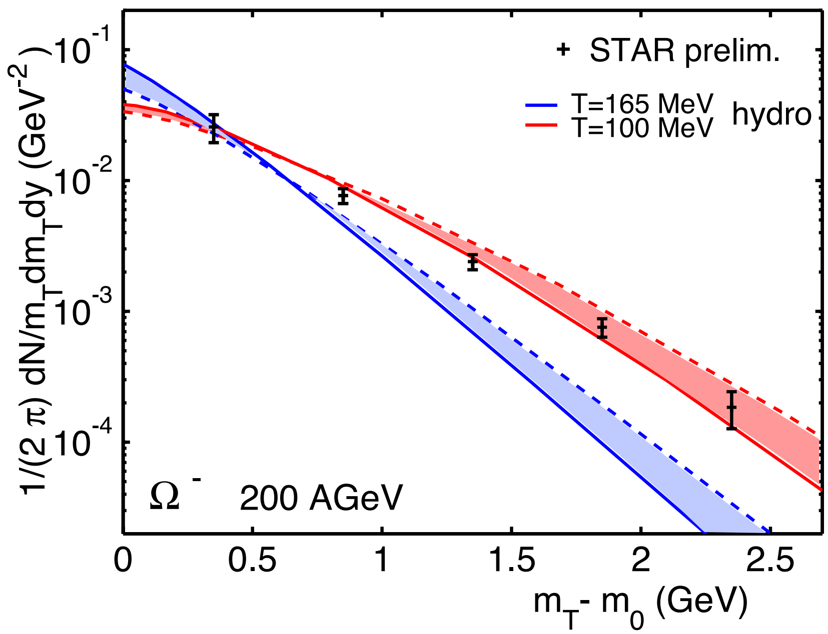
- Non-equilibrium hadronic potentials do not alter the equation of state $p(e)$
  $\Longrightarrow$ unchanged time evolution of energy density $e(\tau)$
- They do, however, change $e(T)$
  $\Longrightarrow$ same energy density corresponds to lower temperature
  $\Longrightarrow$ system cools faster
- Freeze-out at fixed energy density
  $\Longrightarrow$ same time, same flow, but lower temperature

200 A GeV Au+Au spectra and hydrodynamics

hydro: Kolb & Rapp, PRC 67 (2003) 044903



C. Suire (STAR), NPA 715 (2003) 470c



Hydro parameters: $\tau_{\rm eq} = 0.6\,\mathrm{fm}/c, \quad s_0 \equiv s_{\rm max}(b{=}0) = 110\,\mathrm{fm}^{-3}, \quad s_0/n_0 = 250$

$T_{\rm chem} = T_{\rm crit} = 165\,\mathrm{MeV}, \qquad T_{\rm dec} = 100\,\mathrm{MeV}$

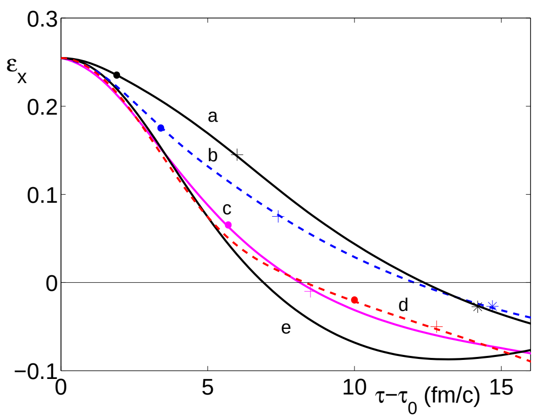
Note:
- Hydro does not create enough radial flow already at $T_{\rm c}$ to describe baryon spectra
- Multistrange baryons seem to fully participate in continued radial flow build-up during late hadronic phase!

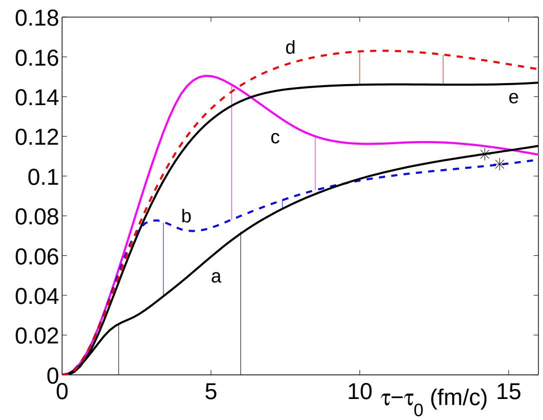
Evolution of anisotropies in Au+Au at $b = 7$ fm

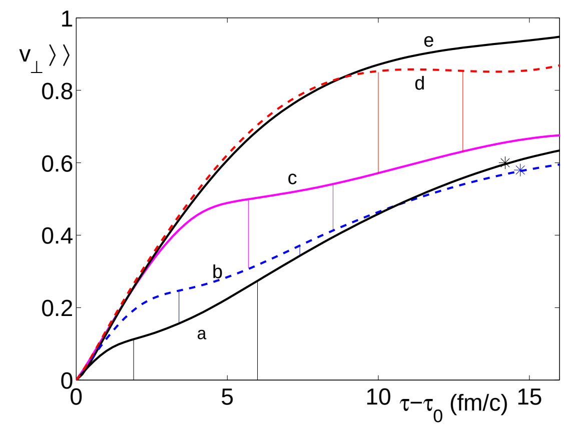
(P. Kolb, J. Sollfrank, U.H., PRC 62 (2000) 054909)

for various initial energy densities

a ≙ 9.0, b ≙ 25, c ≙ 175, d ≙ 25000 GeV/fm**3; e ≙ ideal gas limit







spatial eccentricity

momentum anisotropy

radial flow

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

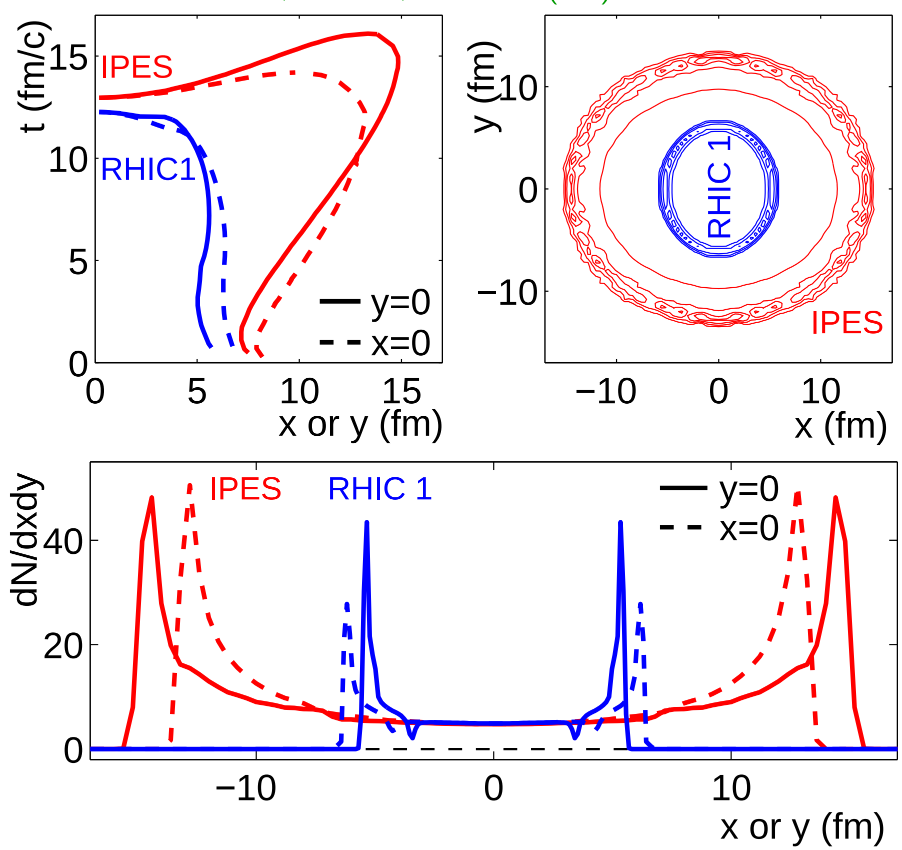
$$\epsilon_p = \frac{\langle\langle T^{xx} - T^{yy} \rangle\rangle}{\langle\langle T^{xx} + T^{yy} \rangle\rangle}$$

$$\langle\langle v_\perp \rangle\rangle = \frac{\left\langle\!\!\left\langle \gamma \, (v_x^2 + v_y^2)^{\frac{1}{2}} \right\rangle\!\!\right\rangle}{\langle\langle \gamma \rangle\rangle}$$

Final spatial eccentricity can be measured with asHBT:

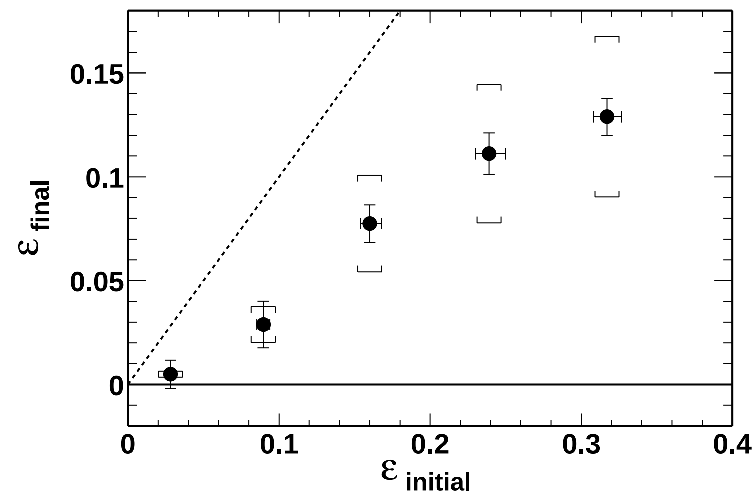
Hydro: Au+Au at $b = 7$ fm
$(\epsilon_x^{\text{initial}} = 0.25)$

UH, P. Kolb, PLB 542 ('02) 216



Data: Au+Au at 200 A GeV

STAR Coll., PRL 93 ('04) 012301



STAR: $\frac{\epsilon_x^{\text{final}}}{\epsilon_x^{\text{initial}}} = \frac{0.11 \pm 0.035}{0.22}$
$= 0.46 \pm 0.15$

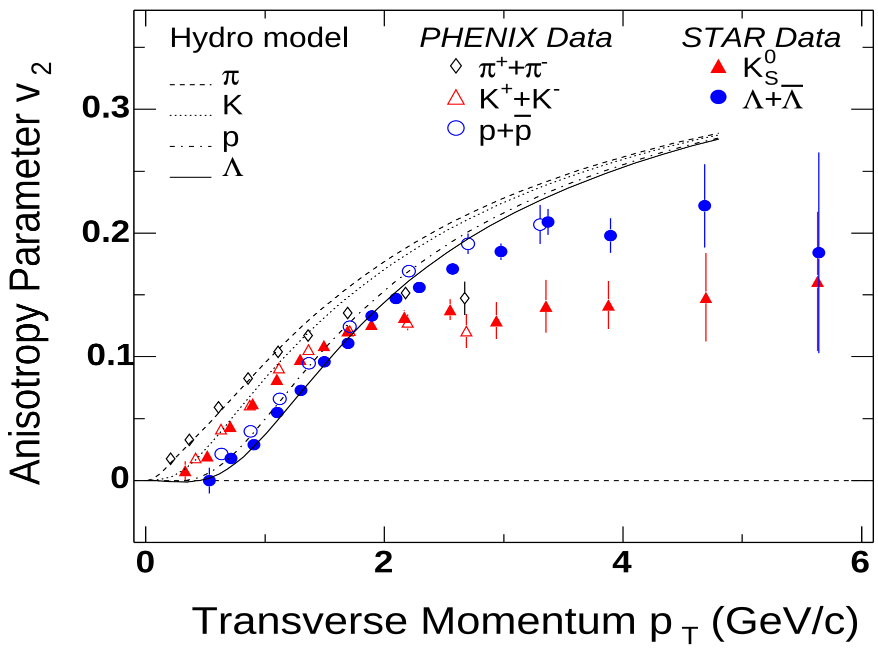
Hydro: $\frac{\epsilon_x^{\text{final}}}{\epsilon_x^{\text{initial}}} = \frac{0.14}{0.25} = 0.56$

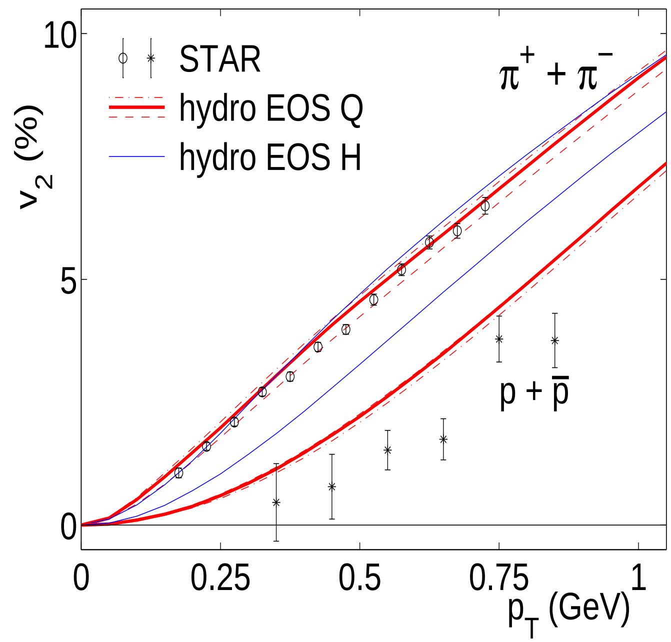
Note: Freeze-out distribution integrates over $\tau \Rightarrow$ $\epsilon_x(\tau > 12\,\text{fm}/c) < 0$, but $\epsilon_x^{\text{final}} > 0$!

Hydro gives consistent space-time evolution ("HBT puzzle" has another reason)

Rest mass dependence of differential elliptic flow (the “fine structure”)

STAR Coll., PRL 87, 182301 (2001) and PRL 92, 052302 (2004); PHENIX Coll., PRL 91, 182301 (2003)





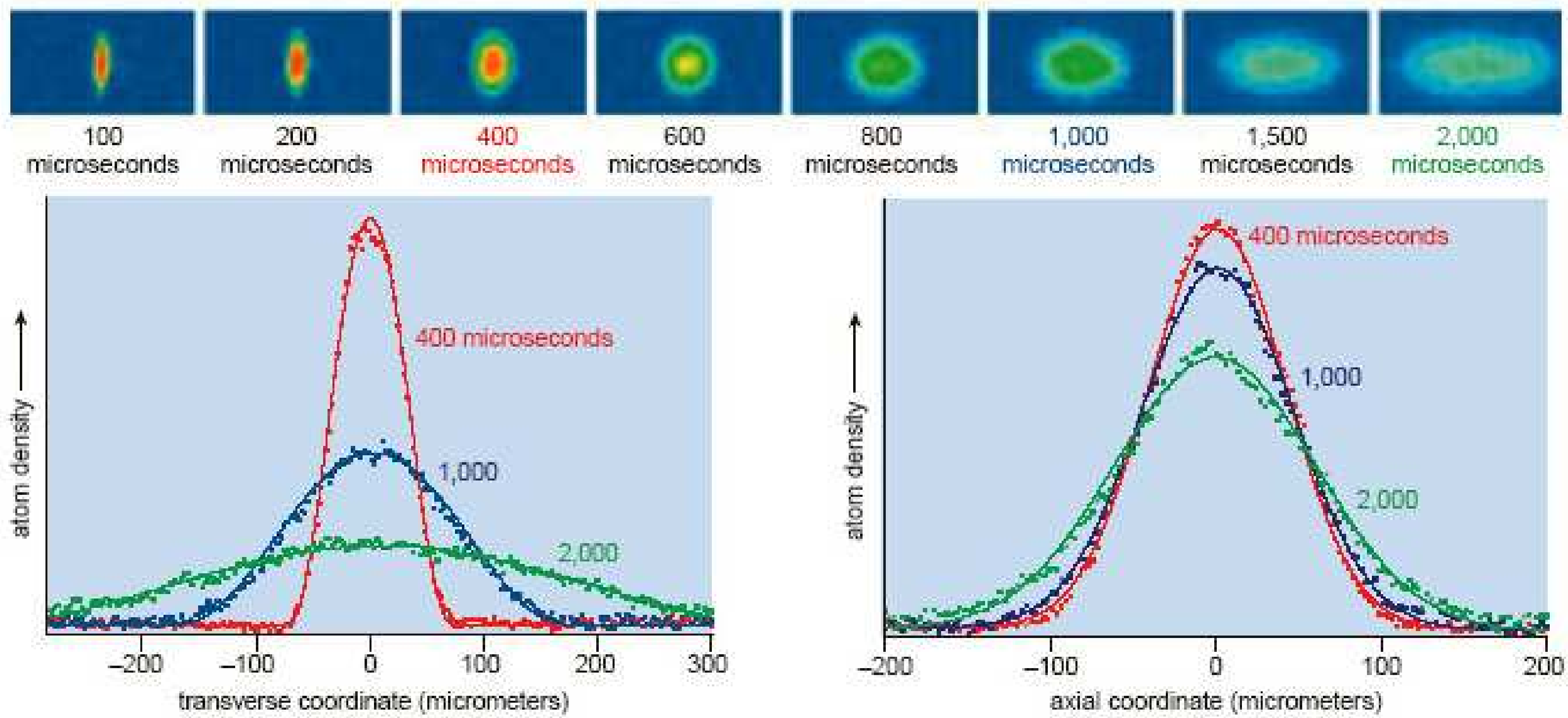
Data follow the hydrodynamically predicted rest mass dependence of $v_2(p_\perp)$ out to $p_\perp \sim 1.5\,$GeV for mesons and out to $p_\perp \sim 2.3\,$GeV for baryons

$\Longrightarrow$ bulk of matter ($> 99\%$ of all particles) behaves hydrodynamically!

Note: mass-splitting of v_2 (“fine structure”) sensitive to EOS!

Elliptic collective flow of strongly coupled atoms at $T = 10^{-6}$ K:

J.E.Thomas et al., Am. Scientist 92 (2004) 238



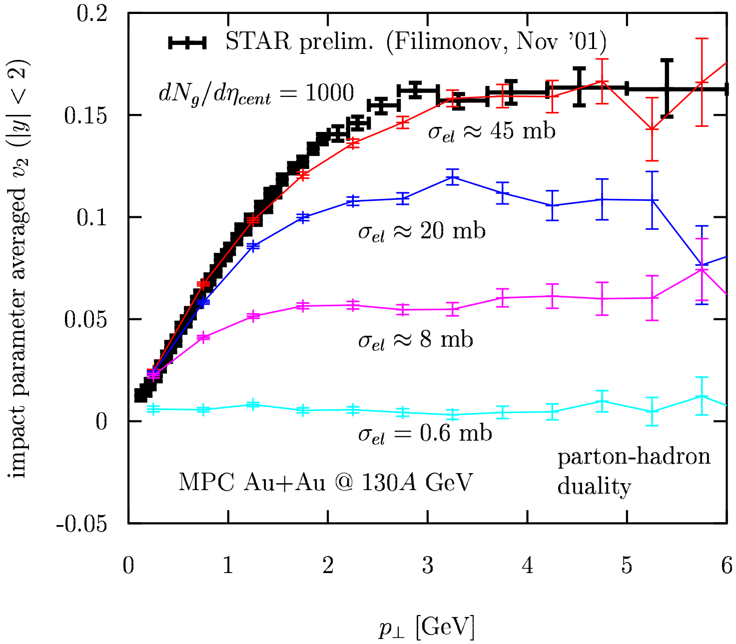
Interaction strength can be tuned (Feshbach resonance):

Strong interaction: elliptic collective flow

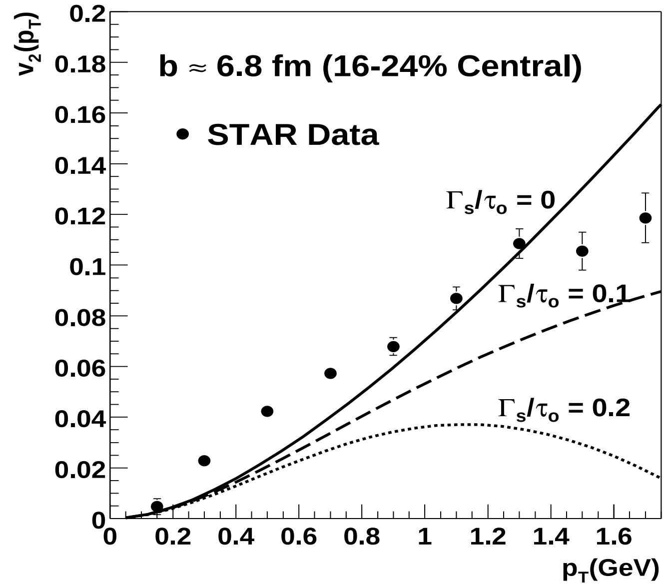
Weak interaction: ballistic expansion with aspect ratio $\rightarrow 1$

Breakdown of hydrodynamics at high $p_\perp$: upper limits for the QGP viscosity

D. Molnár and M. Gyulassy, NPA 697 (2002) 495



D. Teaney, PRC 68 (2003) 034913



$$\Gamma_s = \frac{4}{3}\eta/(T\cdot s)$$

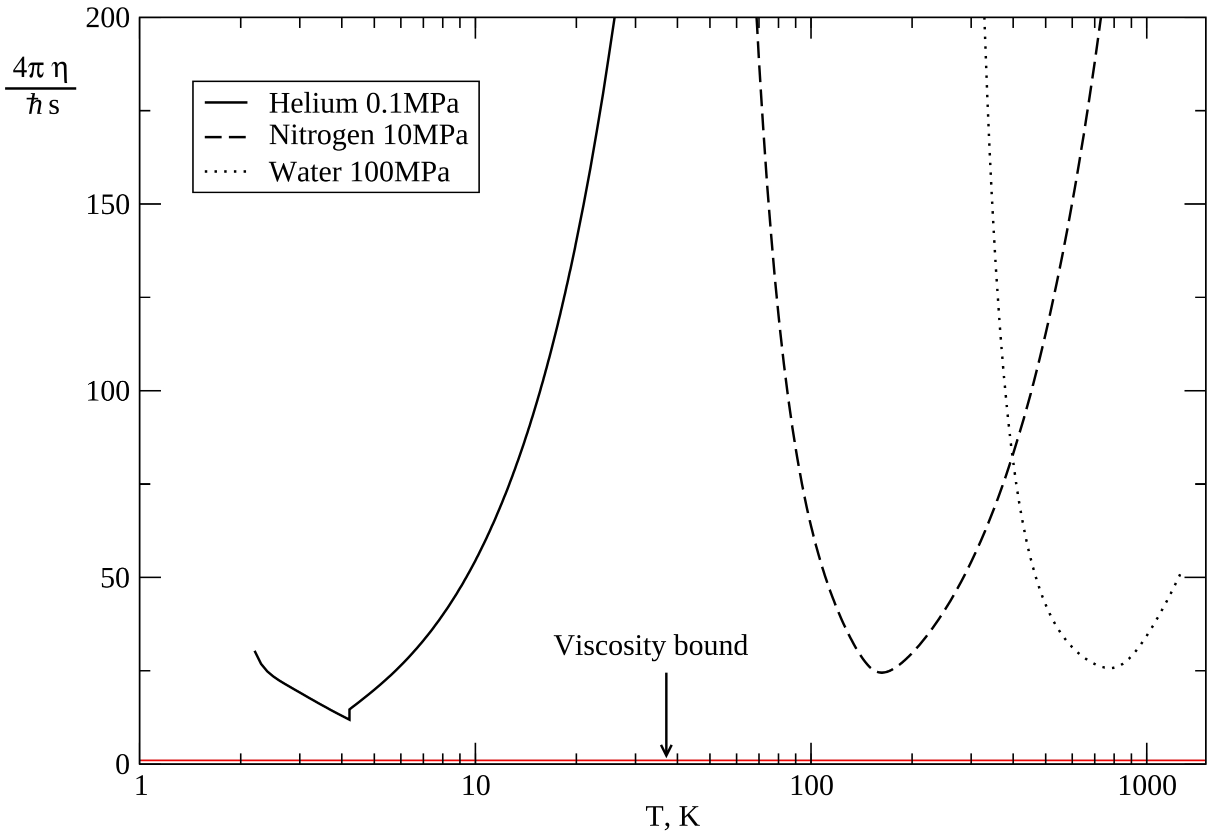
- For sufficiently (very) large $\sigma_{\rm el}$, $v_2(p_\perp)$ from covariant parton transport model MPC follows hydrodynamic curve at low $p_\perp$ and reproduces observed saturation at high $p_\perp$
- Similar pattern is seen in viscous hydrodynamics: viscous corrections increase $\sim p_\perp^2$
- v_2 data suggest $\frac{\Gamma_s}{\tau} < 0.1$, close to minimum viscosity $\frac{\eta}{s} = \frac{\hbar}{4\pi}$ (Son et al. 2002)

QGP seems to be the most perfect (real) fluid ever observed!

QGP – the most ideal fluid ever observed!

adS/CFT universal lower viscosity bound conjecture: $\boldsymbol{\frac{\eta}{s} \geq \frac{\hbar}{4\pi}}$

Kovtun, Son, Starinets, hep-th/0405231



Upper limit for QGP viscosity from Teaney's estimate is close to this bound!

More quantitative constraints on η require viscous hydrodynamics code.

Viscous relativistic hydrodynamics (Israel & Stewart 1979)

Include shear viscosity η, neglect bulk viscosity (massless partons) and heat conduction ($\mu_B \approx 0$); solve

$$\partial_\mu T^{\mu\nu} = 0$$

with modified energy momentum tensor

$$T^{\mu\nu}(x) = \big(e(x)+p(x)\big)u^\mu(x)u^\nu(x) - g^{\mu\nu}p(x) + \pi^{\mu\nu}.$$

$\pi^{\mu\nu}$ = traceless viscous pressure tensor which relaxes locally to 2η times the shear tensor $\nabla^{\langle\mu}u^{\nu\rangle}$ on a microscopic kinetic time scale τ_π:

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right)$$

where $D \equiv u^\mu\partial_\mu$ is the time derivative in the local rest frame.

Kinetic theory relates η and τ_π, but for a strongly coupled QGP neither η nor this relation are known $\Longrightarrow$ treat η and τ_π as independent phenomenological parameters. For consistency: $\tau_\pi\theta \ll 1$ ($\theta = \partial^\mu u_\mu =$ local expansion rate).

(1+1)-d viscous hydrodynamic equations

(Muronga & Rischke 2004, Chaudhuri & Heinz 2005)

Azimuthally symmetric transverse dynamics with long. boost invariance:
Use (τ, r, ϕ, η) coordinates and solve

- hydrodynamic equations for $T^{\tau\tau} = (e+\mathcal{P})\gamma_r^2 - \mathcal{P}$, $\quad T^{\tau r} = (e+\mathcal{P})\gamma_r^2 v_r$ (with "effective pressure" $\mathcal{P} = p - r^2\pi^{\phi\phi} - \tau^2\pi^{\eta\eta}$) together with
- kinetic relaxation equations for $\pi^{\phi\phi}$, $\pi^{\eta\eta}$:

$$\frac{1}{\tau}\partial_\tau\Big(\tau T^{\tau\tau}\Big) + \frac{1}{r}\partial_r\Big(r(T^{\tau\tau}+\mathcal{P})v_r\Big) = -\frac{p+\tau^2\pi^{\eta\eta}}{\tau},$$

$$\frac{1}{\tau}\partial_\tau\Big(\tau T^{\tau r}\Big) + \frac{1}{r}\partial_r\Big(r(T^{\tau r}v_r+\mathcal{P})\Big) = +\frac{p+r^2\pi^{\phi\phi}}{r},$$

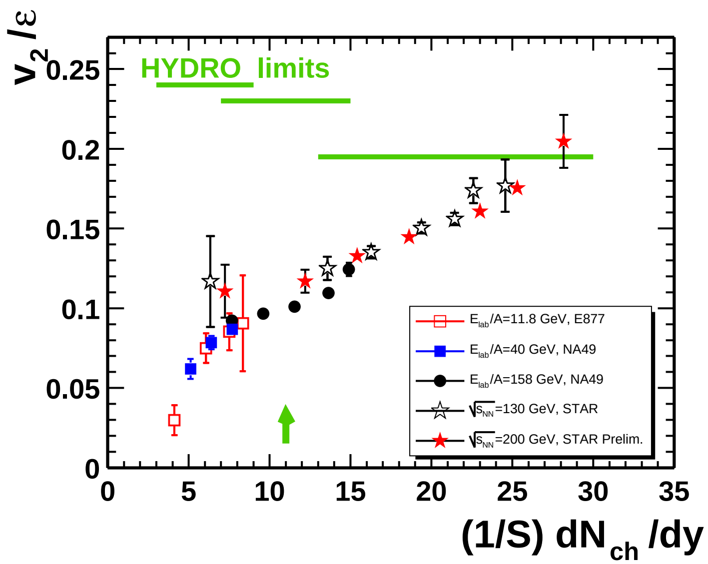
$$\Big(\partial_\tau + v_r\partial_r\Big)\pi^{\eta\eta} = -\frac{1}{\gamma_r\tau_\pi}\left[\pi^{\eta\eta} - \frac{2\eta}{\tau^2}\left(\frac{\theta}{3} - \frac{\gamma_r}{\tau}\right)\right],$$

$$\Big(\partial_\tau + v_r\partial_r\Big)\pi^{\phi\phi} = -\frac{1}{\gamma_r\tau_\pi}\left[\pi^{\phi\phi} - \frac{2\eta}{r^2}\left(\frac{\theta}{3} - \frac{\gamma_r v_r}{r}\right)\right].$$

Close equations with EOS $p(e)$ where $e = T^{\tau\tau} - v_r T^{\tau r}$ and $v_r = T^{\tau r}/(T^{\tau\tau}+\mathcal{P})$.

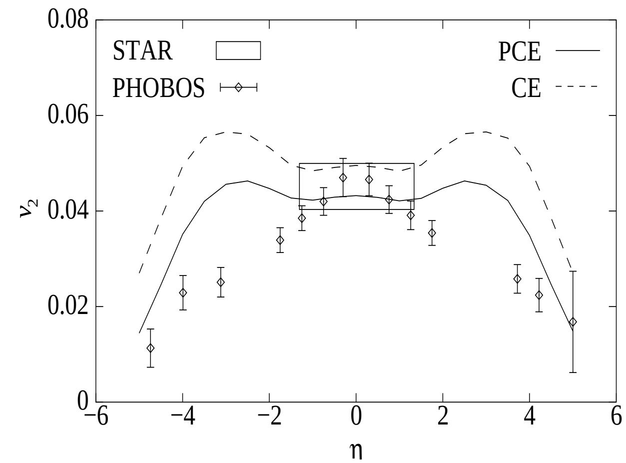
Limits of ideal fluid dynamics: smaller, less dense systems

STAR, PRC 66 ('02) 034904; NA49, PRC 68 ('03) 034903



3d hydro:

T. Hirano, PRC 65 ('02) 011901; 66 ('02) 054905



- $\frac{v_2^{\text{measured}}}{v_2^{\text{hydro}}}$ scales with $\frac{1}{S}\frac{dN_{\text{ch}}}{dy} \propto s_{\text{init}}$
- $e_{\text{init}} > 10\,\text{GeV/fm}^3$ needed for v_2 to saturate before hadronization and exhaust ideal hydro limit!
- hydrodynamics predicts non-monotonic v_2/ϵ: between AGS and RHIC it decreases, due to softening of EOS by quark-hadron transition (Kolb, Sollfrank, UH, PRC 62 (2000) 054909)
- data show instead monotonous increase of v_2/ϵ with $\sqrt{s}$!?

What's going on??

Breakdown of ideal hydro: the viscous hadron fluid

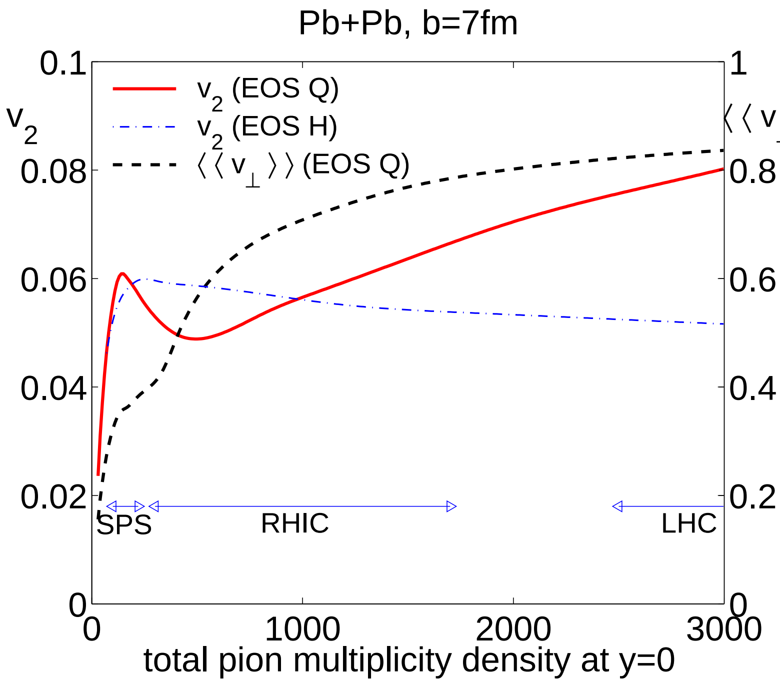
Excitation function of elliptic flow:

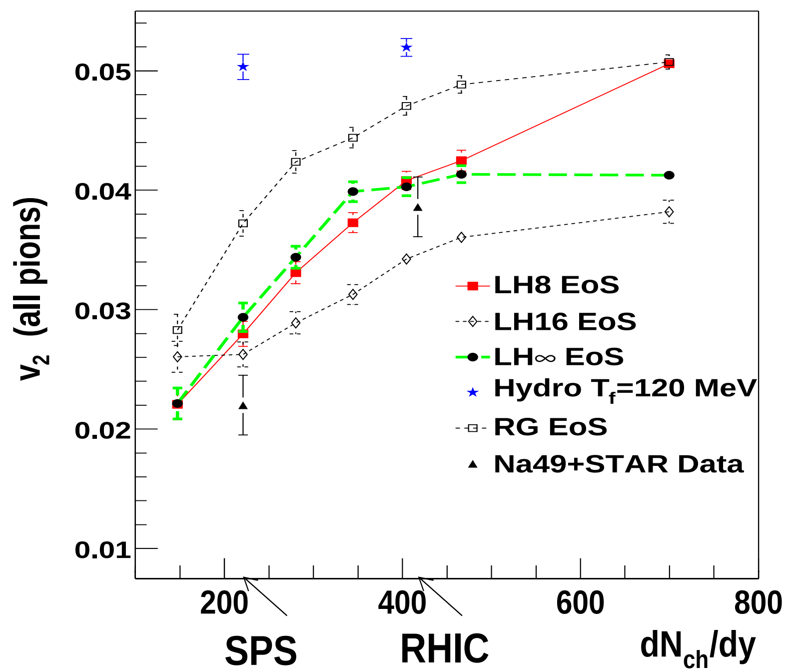
Ideal hydro

P. Kolb, J. Sollfrank, U.H., PRC 62 ('00) 054909

Hydro + RQMD

D. Teaney, J. Lauret, E. Shuryak, nucl-th/0110037





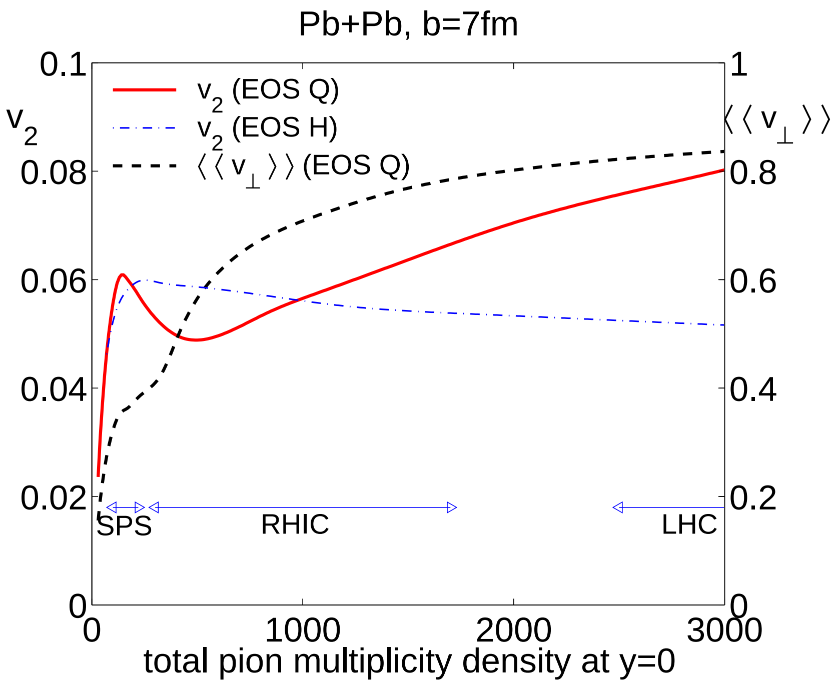
Hadron resonance gas is very viscous and does not respond strongly to spatial eccentricity $\Longrightarrow$ non-monotonic behaviour of v_2 resulting from dip in c_s^2 near phase-transition is erased!

$\Longrightarrow$ The inability of the viscous hadronic phase to build elliptic flow kills the phase transition signature!

“Saturation” of v_2: first hint of real “phase transition”?

Ideal hydro

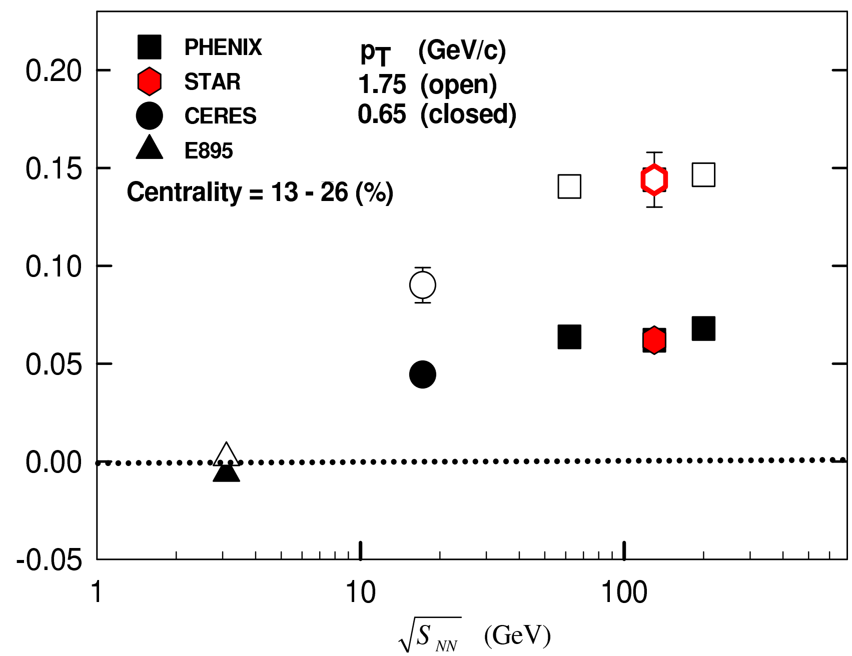
P. Kolb, J. Sollfrank, U.H., PRC 62 ('00) 054909



AGS, SPS and RHIC data

PHENIX Coll., nucl-ex/0411040

$(A{\approx}200) + (A{\approx}200)$, 13-26% centrality



“Saturation” of v_2 between $\sqrt{s_{NN}}{=}63$ and 200 GeV $\Longleftrightarrow$ signature of softening of EOS near phase transition?! (Sorge, PRL 82 (1999) 2048)

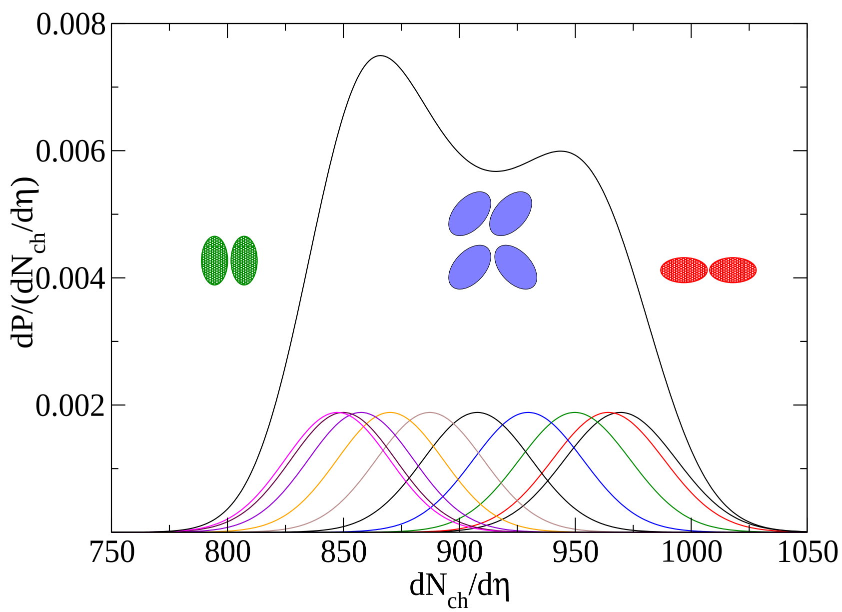
Beware! Many similar “phase transition signatures” have had a short shelf life . . .

But certainly worth investigating in more detail! (e.g. with U+U . . .)

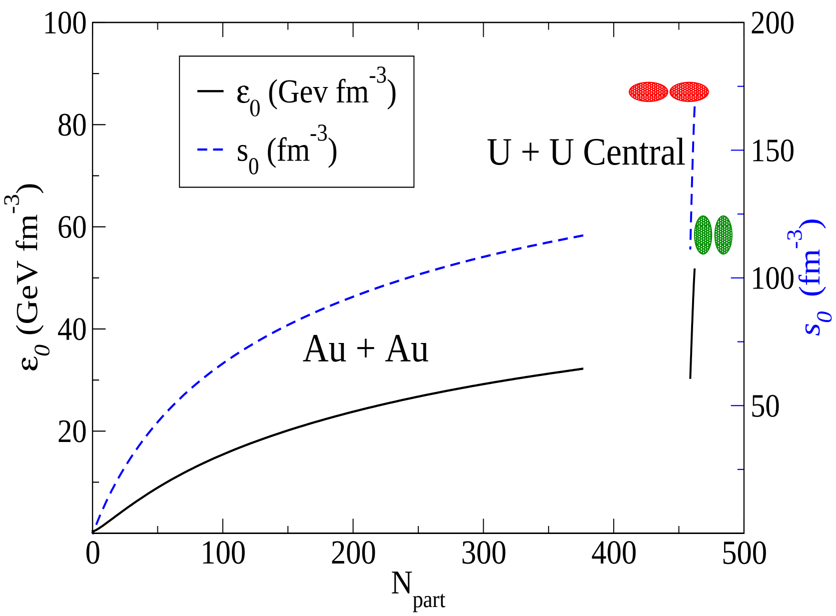
The ultimate test of hydrodynamics at RHIC: fully aligned ("zero spectators") U+U at 200 A GeV

A.J. Kuhlman, U.H., PRL 94 (2005) 132301, and nucl-th/0506088

Multiplicity distribution for full overlap U+U collisions at 200 A GeV

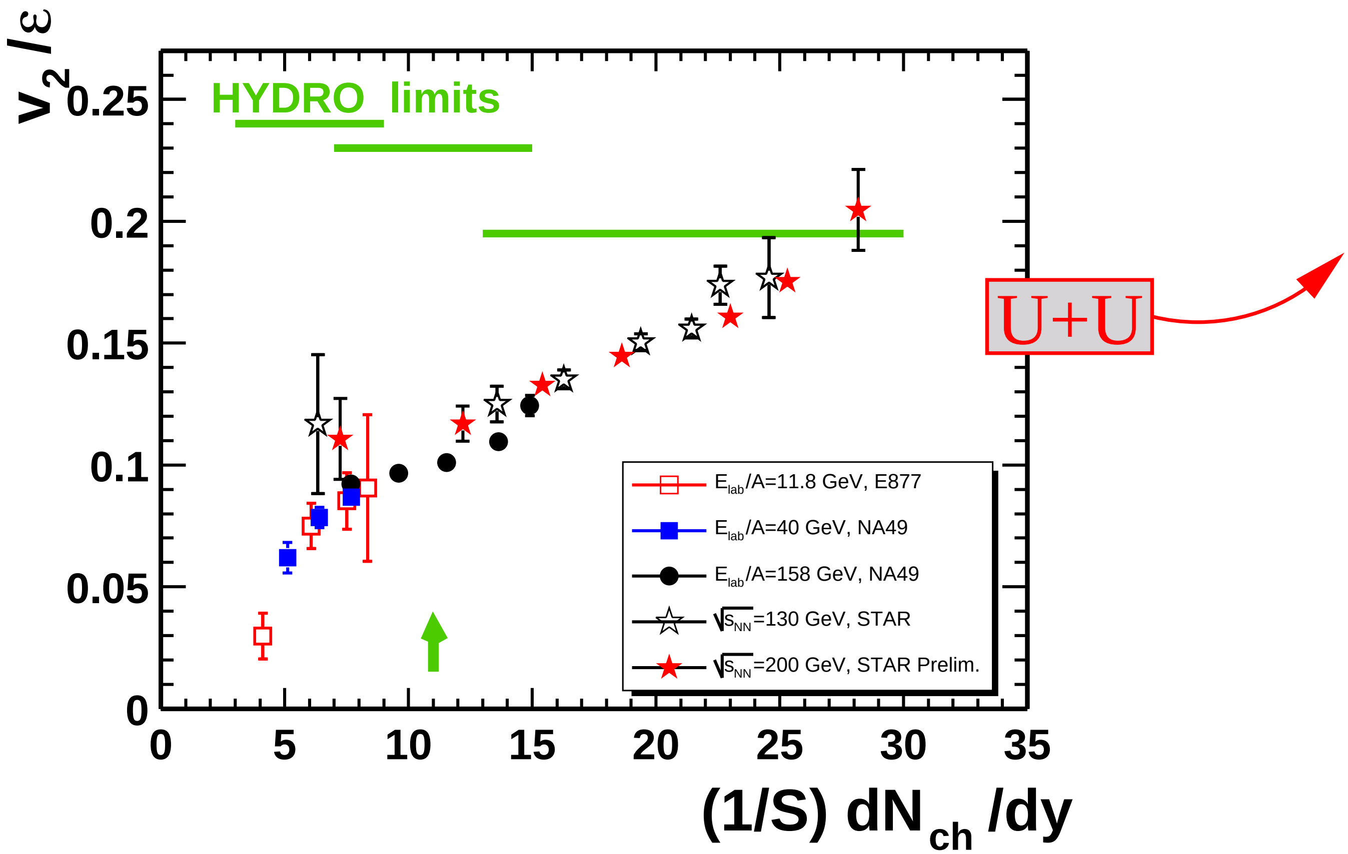


Initial maximal energy and entropy density for Au+Au and U+U collisions



- $dN_{\rm ch}/d\eta$ in head-on-head collisions $\approx 14\%$ larger than in side-on-side collisions
- e_0 in head-on-head U+U collisions $\approx 65\%$ larger than in side-on-side U+U and $b{=}0$ Au+Au!
- ϵ_x(side-on-side U+U) $\approx \epsilon_x(b{=}7\,\text{fm Au+Au})$, at 30% higher e_0

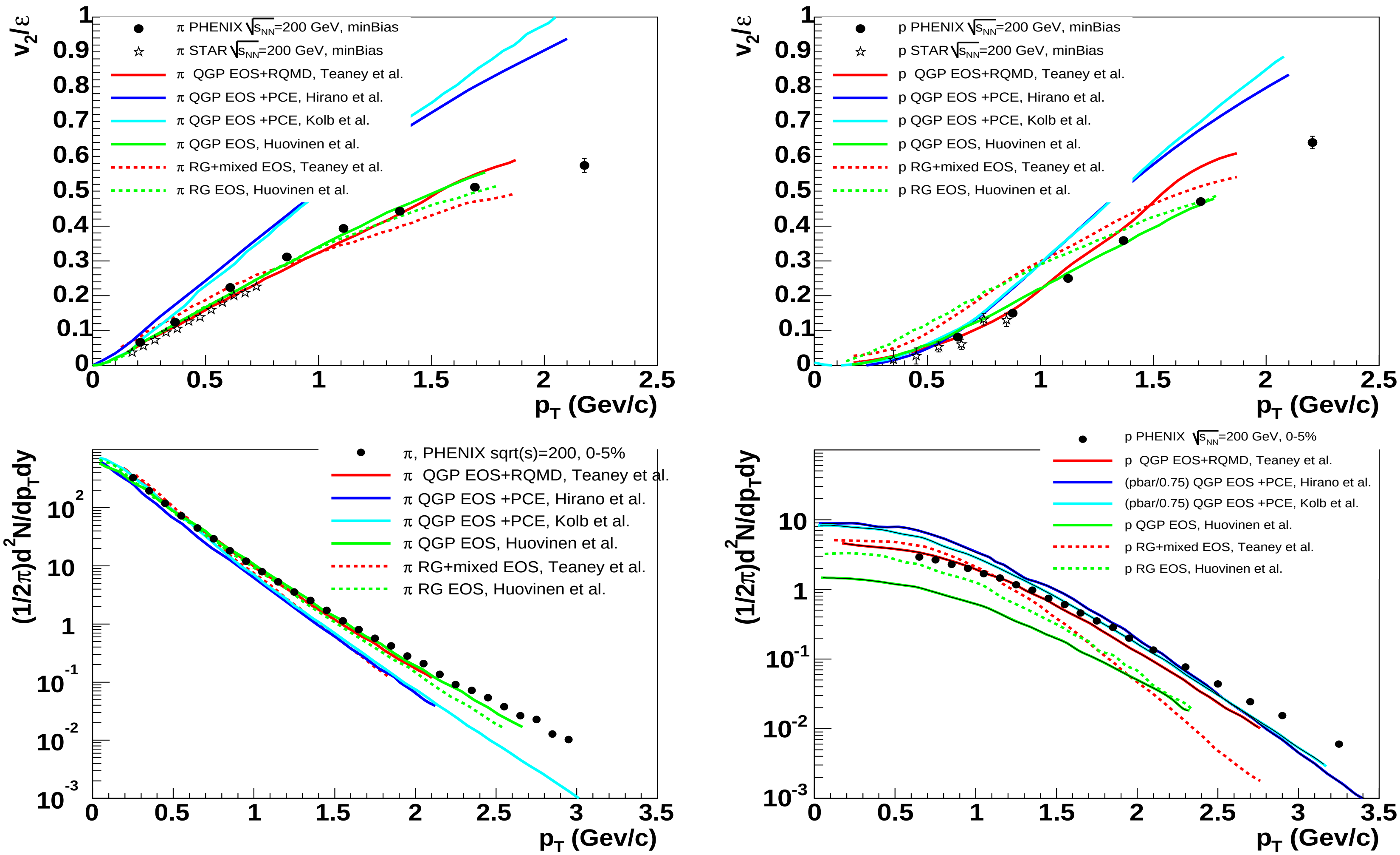
Initial entropy densities in U+U vs. Au+Au



The fine print on hydrodynamics:

PHENIX White Paper, NPA 757 (2005) 184

pions protons

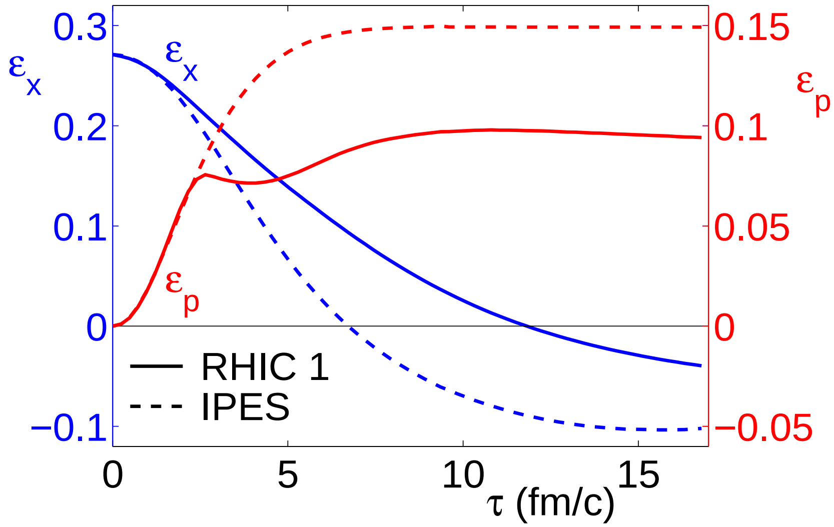


All theory curves use the same hydrodynamics and EOS in QGP phase!

How we deal with the hadron phase makes all the difference . . .

Redistribution of momentum anisotropy in the HG phase

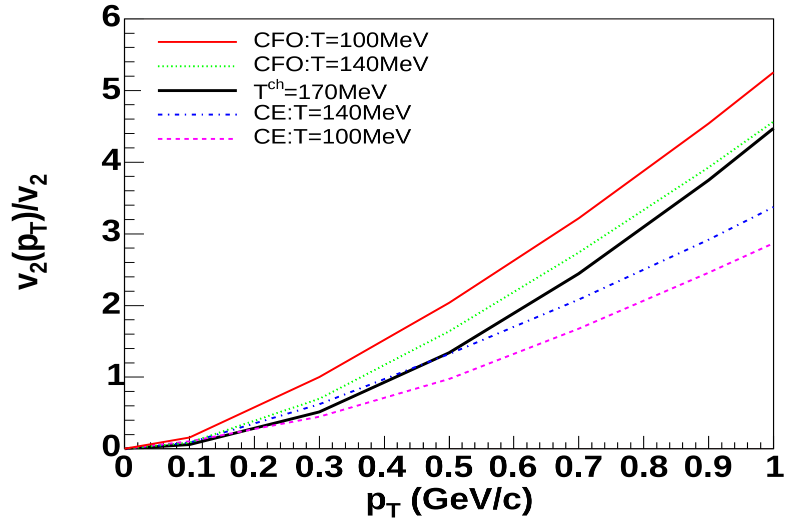
P.F.Kolb, U.H., PLB 542 (2002) 216



$$\epsilon_x = \frac{\langle\langle y^2 - x^2 \rangle\rangle}{\langle\langle y^2 + x^2 \rangle\rangle}$$ spatial anisotropy

$$\epsilon_p = \frac{\langle\langle T^{xx} - T^{yy} \rangle\rangle}{\langle\langle T^{xx} + T^{yy} \rangle\rangle}$$ momentum anisotropy

T. Hirano, M. Gyulassy, nucl-th/0506049



Pion elliptic flow for different hadronic EOSs and $T_{\rm dec}$

- Momentum anisotropy saturates ≈ when spatial eccentricity passes through zero.
- This happens before hadronization is complete.
- However, redistribution of momentum anisotropy in HG phase over p_T for different hadronic species reflects intricate interplay between thermal motion and radial flow and depends on chemical composition, viscosity and EOS of HG, $T_{\rm dec}$, . . .

$\Longrightarrow$ Quantitative interpretation of v_2 data requires detailed understanding of viscous hadronic dynamics!

$\Longrightarrow$ To extract early EOS signature (e.g. c_s^2 of QGP), reconstruct total momentum anisotropy (p_T^2-weighted elliptic flow) from hadron spectra:

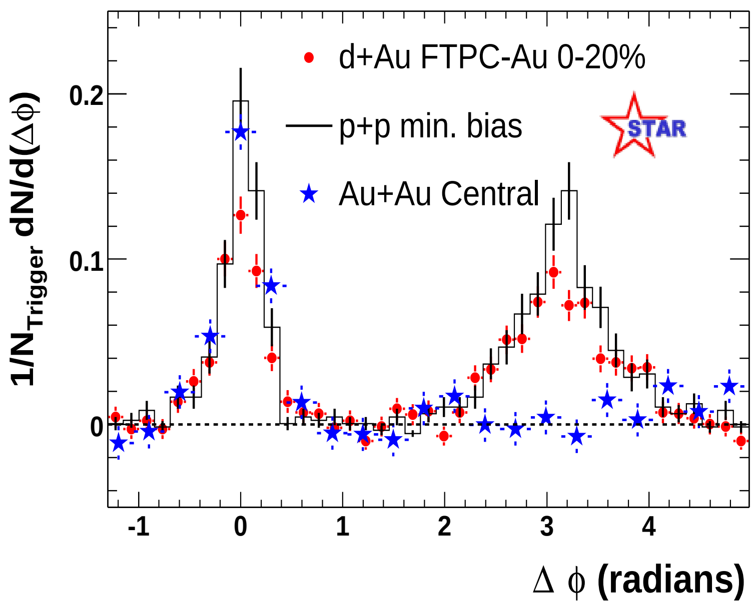
$$\epsilon_p = \frac{\langle\langle T^{xx} - T^{yy}\rangle\rangle}{\langle\langle T^{xx} + T^{yy}\rangle\rangle} = \frac{\sum_{\mathrm{i\in hadrons}} \int p_T^2 \cos(2\phi_p) \frac{dN_i}{dy\, p_T dp_T\, d\phi_p}\, d^2p_T}{\sum_{\mathrm{i\in hadrons}} \int p_T^2 \frac{dN_i}{dy\, p_T dp_T\, d\phi_p}\, d^2p_T}$$

May have to correct this for resonance decays.

Jet quenching in central Au+Au collisions:

STAR Coll., PRL 91 (2003) 072304

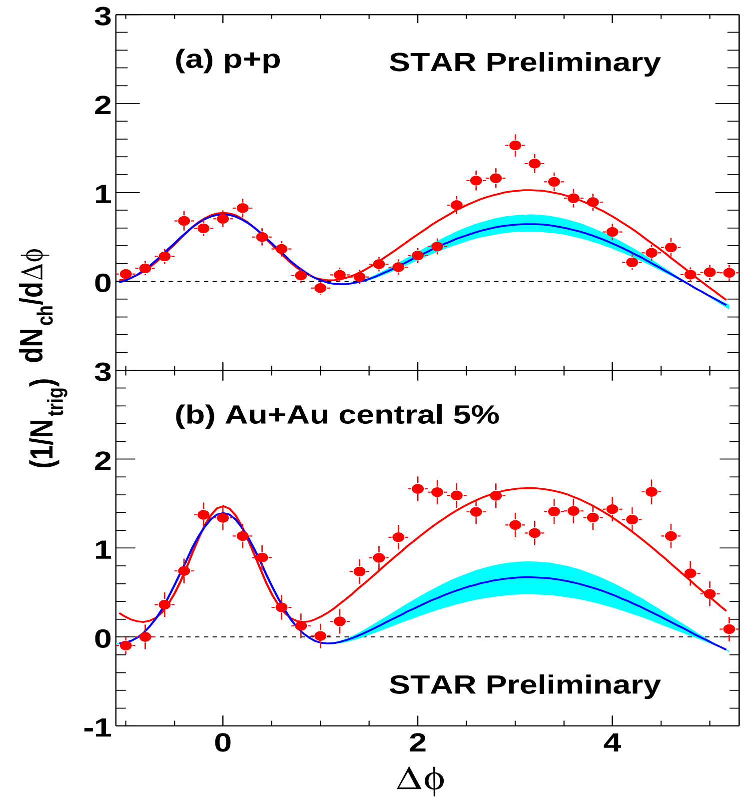
$p_T^{\rm assoc} > 2\,$GeV



- trigger particle for near-side jet has $4 < p_T < 6\,$GeV

STAR Coll., F. Wang, Quark Matter 2004

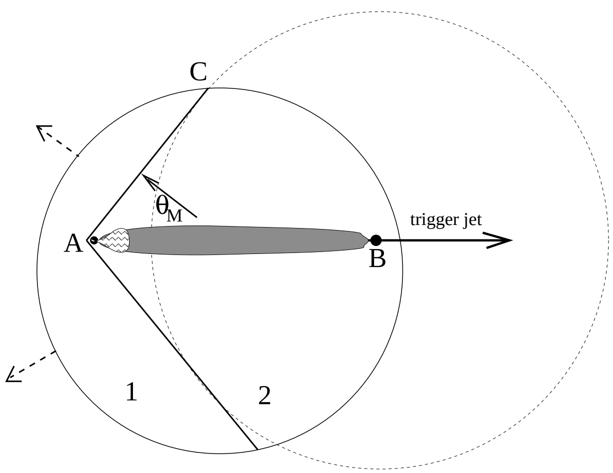
$0.15 < p_T^{\rm assoc} < 4\,$GeV



- away-side jet ($p_T > 2\,$GeV) visible in p+p and d+Au, but fully quenched in central Au+Au
- energy of quenched jet appears as additional multiplicity of low-p_T particles opposite to trigger particle
- $\Longrightarrow$ "thermalization" of intermediate-p_T jets!

Evidence for a "sonic boom"?!

Shuryak et al., hep-ph/0411315

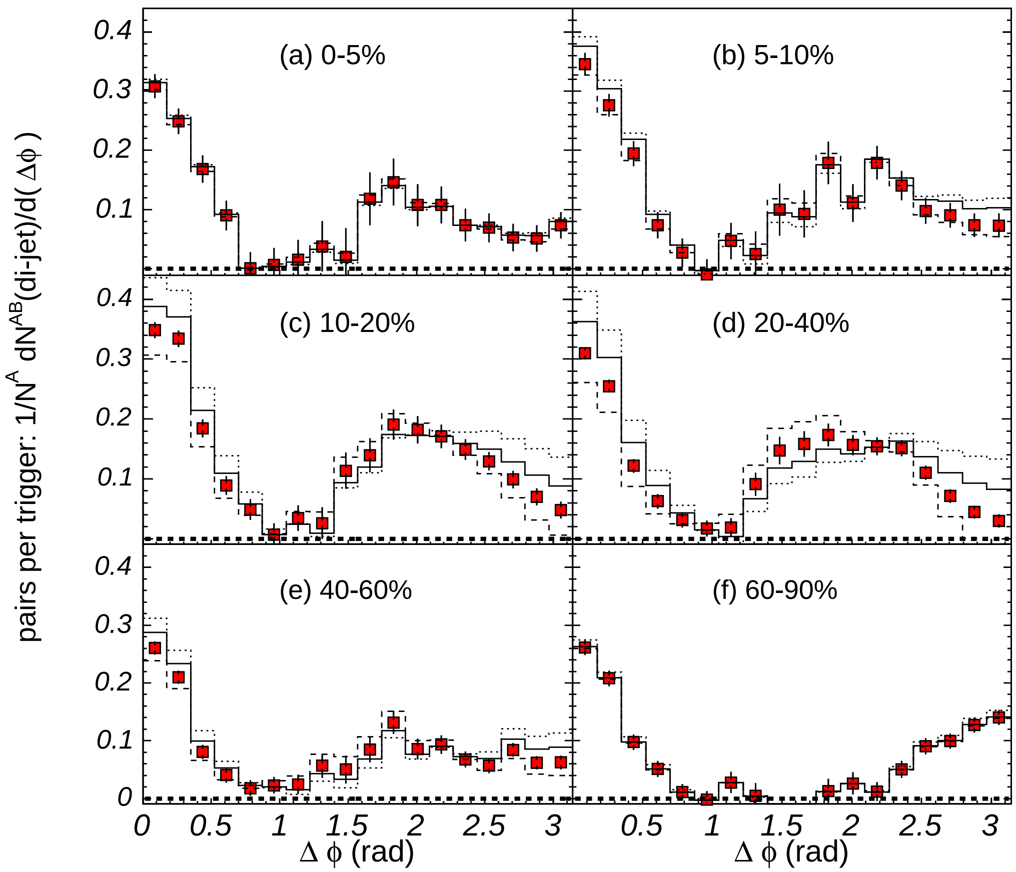


Away-side jet creates Mach cone at $\cos\theta_{\rm M} = \frac{c_s}{c}$

$\Longrightarrow$ $\theta_{\rm M} \approx 63^\circ \approx 1.1$ rad

PHENIX Coll., B. Jacak, ICPAQGP 2005

$1 < p_T^{\rm assoc} < 2.5\,\text{GeV} < p_T^{\rm trigger} < 4\,\text{GeV}$

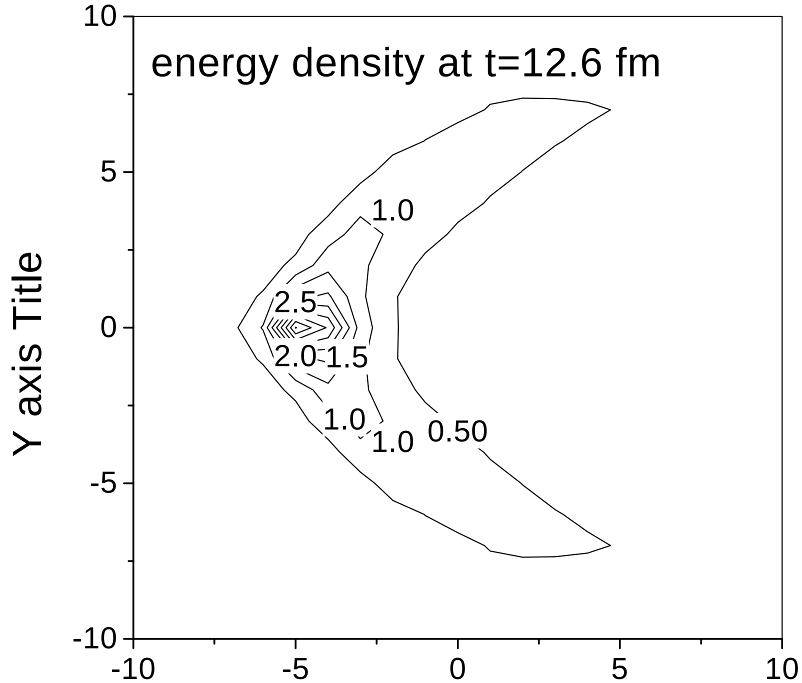


$\Uparrow$ $\Uparrow$

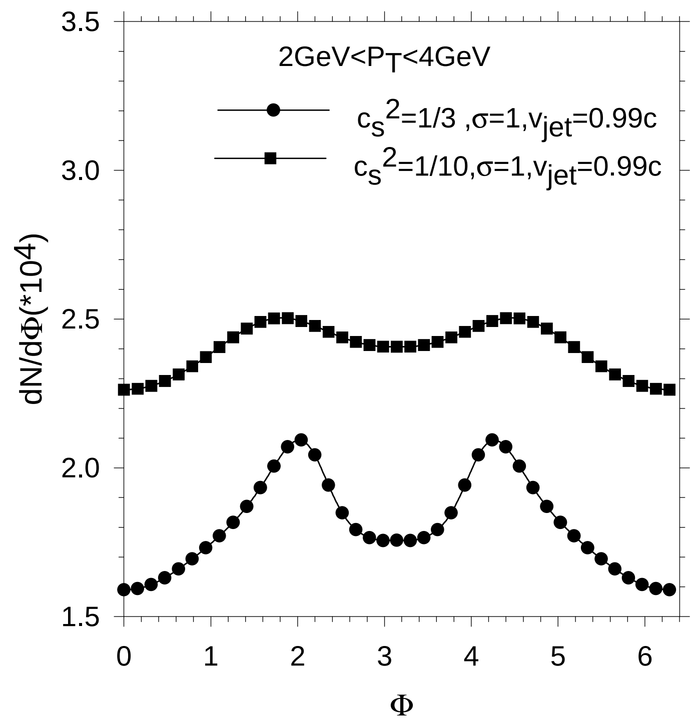
Hydrodynamic simulation of sonic boom

A. Chaudhuri and U.H., in preparation

Energy density contours:



$dN/d\phi$ for thermal photons:



(Away-side jet travels to the left)

Note: Mach cone angle sensitive to the speed of sound c_s^2 !

Conclusions

Collective flow patterns observed at RHIC provide

- Strong evidence for thermalization at $\tau_{\rm therm} < 1\,\text{fm}/c,\ e > 10\,\text{GeV/fm}^3$ $\Longrightarrow$ matter initially in QGP state.
- Strong evidence that QGP is strongly coupled plasma and behaves like an almost ideal fluid with low viscosity

Ideal fluid dynamics works at RHIC because QGP is created!

The late hadron gas phase is highly viscous.

Future needs:

- systematic studies to further constrain $\tau_{\rm therm}$ and EOS
- more hybrid simulations (H2H, . . .) to better describe late hadronic stage
- viscous hydrodynamics to better constrain transport coefficients of QGP from data

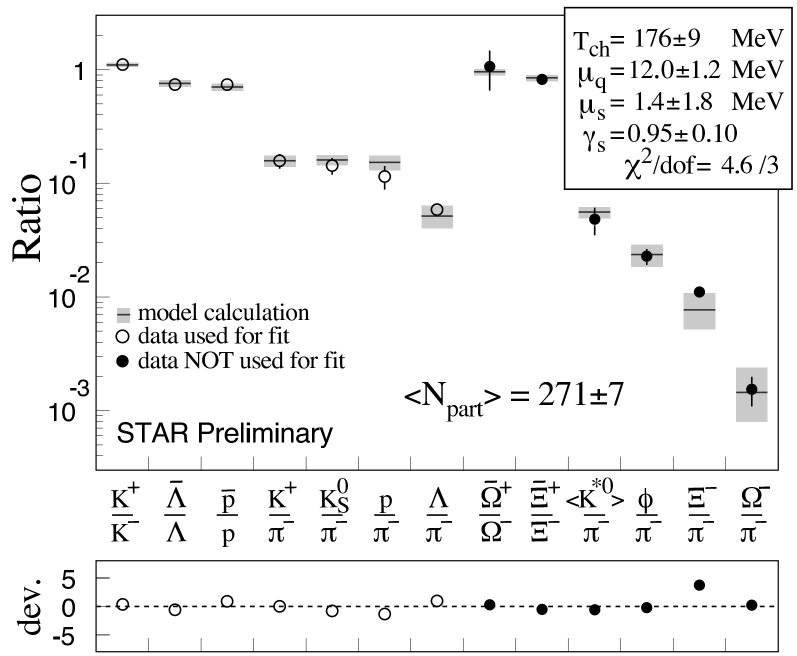
Supplements

Primordial Hadrosynthesis – Measuring $T_{\rm cr}$

Chemical Freeze-out at $T_{\rm had} \simeq 170$ MeV

Central Au+Au @ 130 A GeV

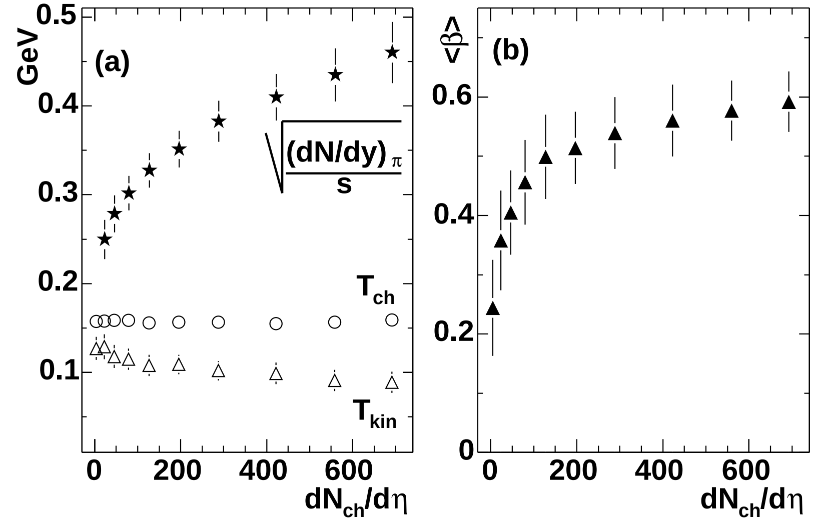
(STAR Coll., G. van Buren, QM2002)



Abundance ratios of stable hadrons decouple in maximum entropy state of "apparent chemical equilibrium" with $T_{\rm chem} \simeq T_{\rm had} \simeq 170$ MeV.

$T_{\rm chem}$ insensitive to expansion rate:

STAR Coll., PRL 92 (2004) 112301



$\Longrightarrow$ phase transition!

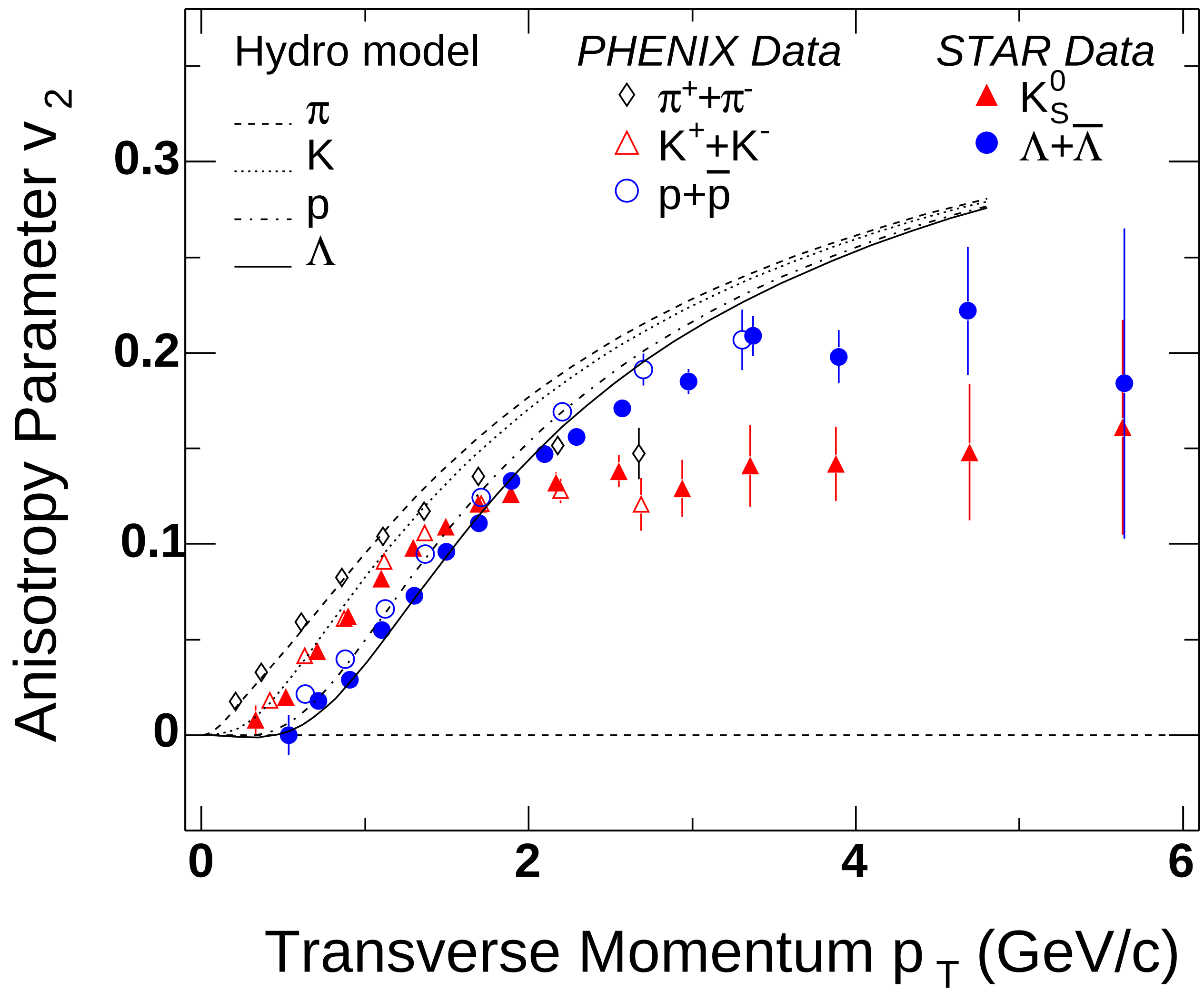
Note: Hadron abundances are in statistical, not in kinetic chemical equilibrium!
Requires pre-hadronic phase with large strangeness correlation volume.

Quark coalescence –

a first indication of color deconfinement

At intermediate p_T, mesons and baryons behave differently:

STAR Coll., PRL 87, 182301 (2001) and PRL 92, 052302 (2004); PHENIX Coll., PRL 91, 182301 (2003)



Parton coalescence:

Ko & Lin '02, Hwa & Yang '02, Greco et al. '03, Fries et al. '03, Molnár & Voloshin '03, Lin & Molnár '03

- Picture: - **coalescence of massive "dressed" valence quarks**
  - **no dynamical gluons**

- Basic equations: $qq \to \text{meson}$, $qqq \to \text{baryon}$

$$E\frac{dN_M(\boldsymbol{p})}{d^3p} = \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q \qquad |\psi_{\boldsymbol{p}}(\boldsymbol{q})|^2 \qquad f_\alpha(\boldsymbol{p}_\alpha, x) f_\beta(\boldsymbol{p}_\beta, x)$$

$$E\frac{dN_B(\boldsymbol{p})}{d^3p} = \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q_1 d^3q_2 |\psi_{\boldsymbol{p}}(\boldsymbol{q}_1, \boldsymbol{q}_2)|^2 f_\alpha(\boldsymbol{p}_\alpha, x) f_\beta(\boldsymbol{p}_\beta, x) f_\gamma(\boldsymbol{p}_\gamma, x)$$

hadron yield   space-time   wave-fn.   quark distributions

assumes: rare process, weak binding, factorizable 2-body and 3-body density matrix, smooth spacetime distributions, 3D hypersurface (sudden approx.)

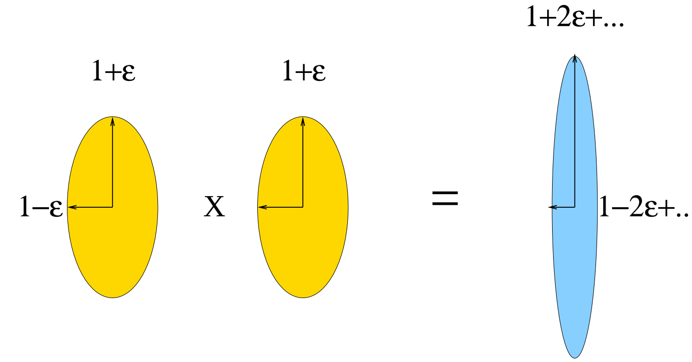
Can dominate over fragm. for $p_\perp < 4-5$ GeV   [Greco et al., Fries et al., PRL90 ('03)]

Quark number scaling at intermediate $p_\perp$: coalescence

D. Molnár and S. Voloshin, PRL 91 (2003) 092301

Narrow wave function limit ($\boldsymbol{q} = 0$): $\frac{dN_M}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^2$, $\frac{dN_B}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^3$

$$v_2^M(p_\perp) \approx v_2^a\left(\tfrac{p_\perp}{2}\right) + v_2^{\bar{a}}\left(\tfrac{p_\perp}{2}\right)$$
$$v_2^B(p_\perp) \approx v_2^a\left(\tfrac{p_\perp}{3}\right) + v_2^b\left(\tfrac{p_\perp}{3}\right) + v_2^c\left(\tfrac{p_\perp}{3}\right)$$



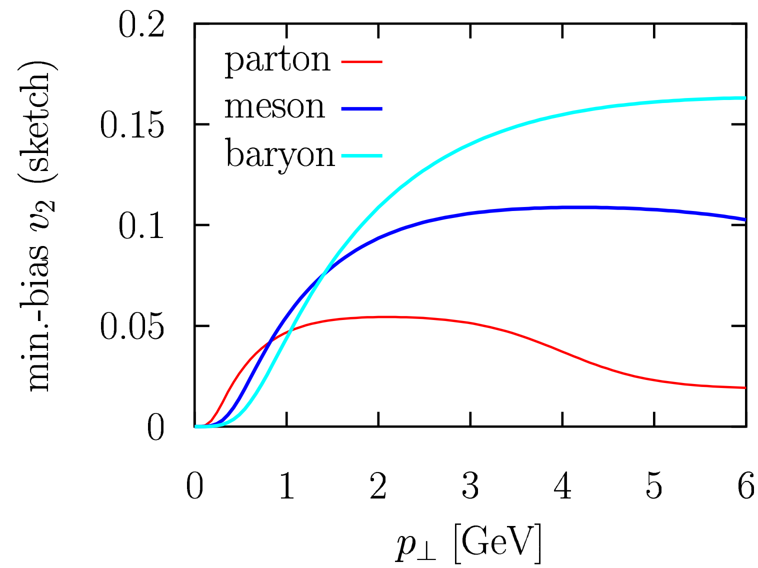
$\Rightarrow$ **Hadron v_2 amplified at high $p_\perp$:**

If all quark flavors have same v_2:

$3\times$ for baryons

$2\times$ for mesons

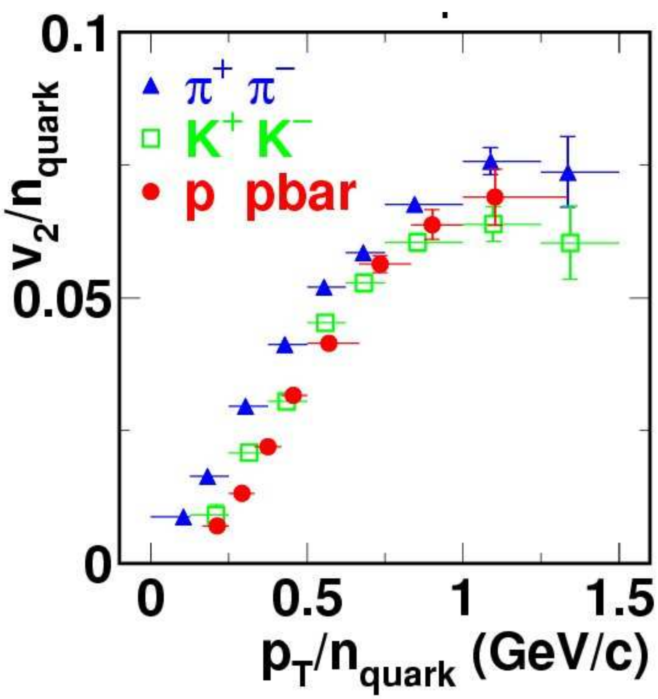
$$v_2^h(p_\perp) \approx n \times v_2^q(p_\perp/n)$$



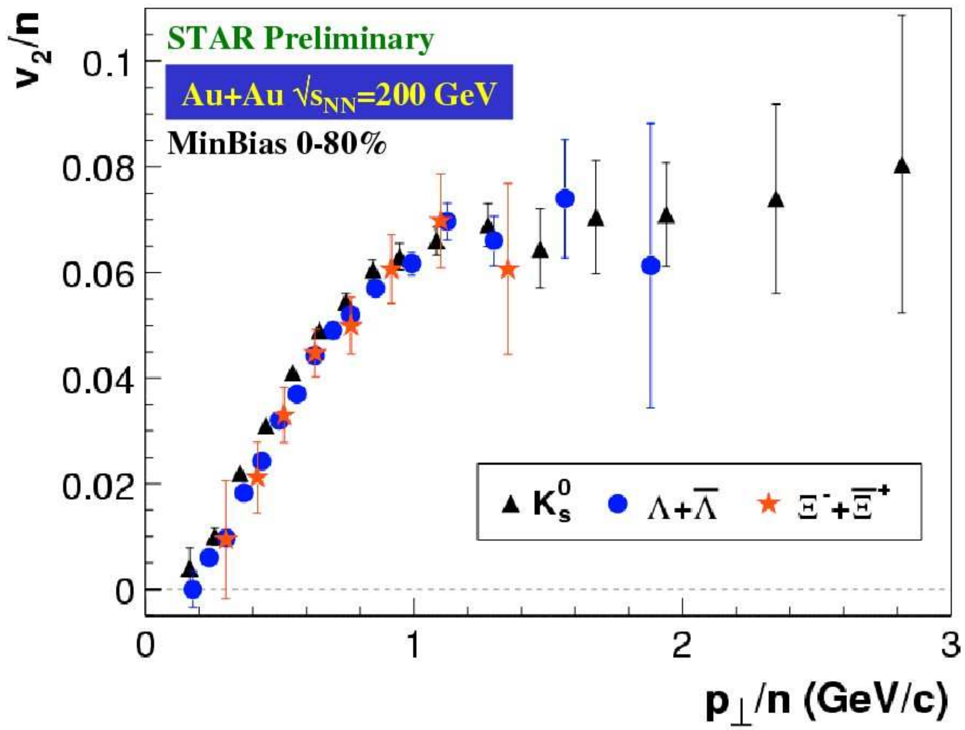
Note: Parton v_2 can be extracted only because it breaks away from hydro at high p_T!

Experimental extraction of parton elliptic flow

PHENIX Coll., PRL 91 ('03) 182301



J. Castillo (STAR Coll.), nucl-ex/0403027



- Coalescence predictions confirmed for $\pi, K, K_0, p, \Lambda, \Xi$
- RHIC data indicate $v_2^q \approx v_2^s$
- Parton elliptic flow follows hydro to $p_{T,\mathrm{break}} \approx 750\,\mathrm{MeV}$, saturates at $\approx 7\%$ in min. bias. collisions

Quark number scaling indicates dynamical role for deconfined quarks!

JET –

Jet Emission Tomography of the QGP

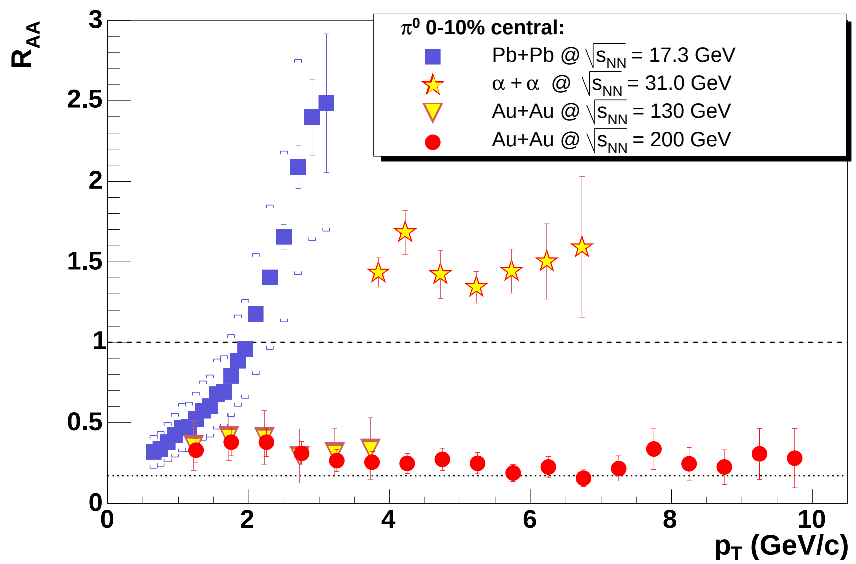
Suppression of high p_T hadron production in Au+Au:

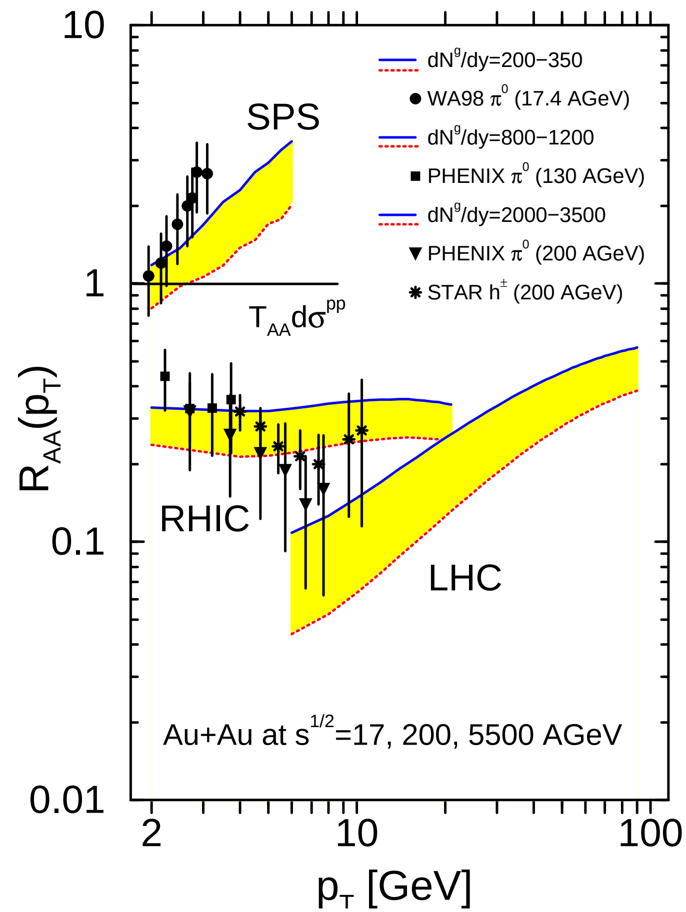
$$R_{AA}(p_T;b) = \frac{\frac{dN_{AA}}{dp_T}(b)}{N_{\rm coll}(b)\frac{dN_{pp}}{dp_T}}$$

M. Gyulassy and I. Vitev,
PRL 89 (2002) 252301

Au+Au at $\sqrt{s} = 130$ and $200\,A$ GeV

PHENIX Coll., PRL 88 (2002) 022301; PLB 561 (2003) 82





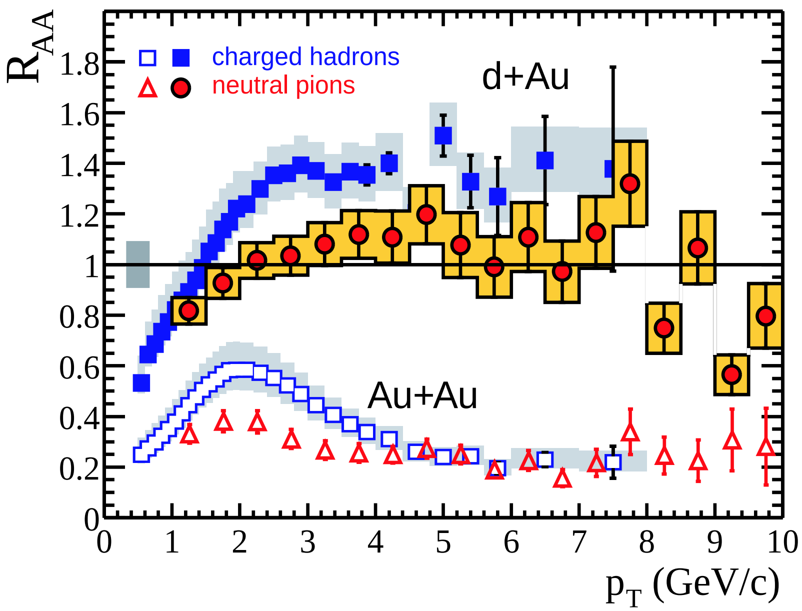
$\Longrightarrow$ $\boldsymbol{\frac{dN_g}{dy} = 1000 \pm 200}$

$\Longrightarrow$ $\boldsymbol{\langle e \rangle (\tau_0{=}0.2\,\mathrm{fm}) \approx 20\,\mathrm{GeV/fm^3}}$!

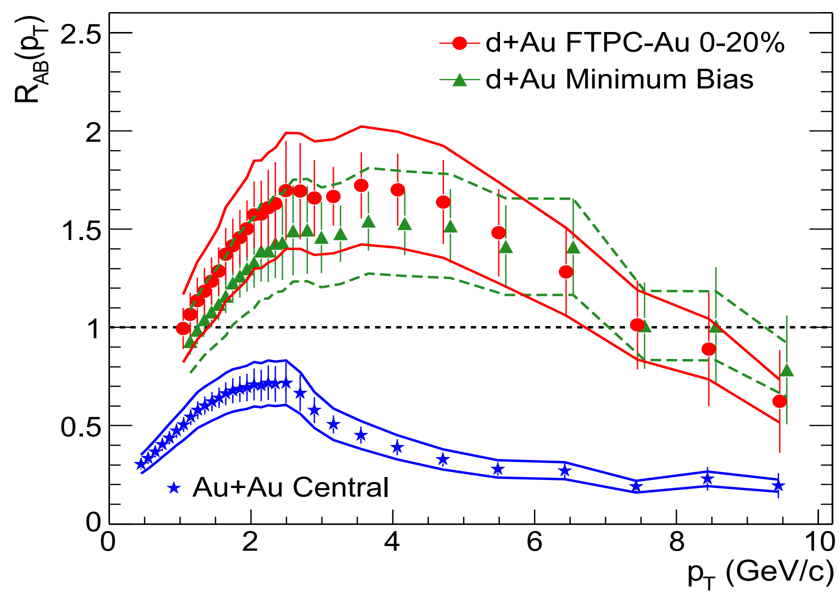
High-p_T suppression absent in d+Au $\Longrightarrow$ suppression in Au+Au not due to nuclear wavefunction (e.g. CGC) but a final state effect

No high p_T suppression in d+Au:

PHENIX Coll., PRL, nucl-ex/0306021



STAR Coll., PRL, nucl-ex/0306024



- as collision centrality increases, R_{AA} increases in d+Au (Cronin effect) but decreases in Au+Au

- high-p_T suppression absent in d+Au $\Longrightarrow$ suppression in Au+Au not due to nuclear wavefunction (e.g. CGC) but a final state effect

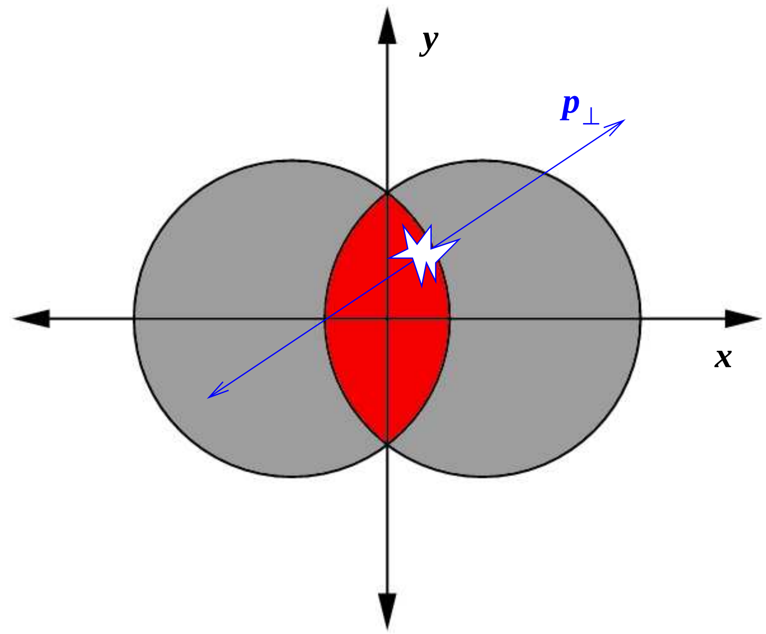
Quantitative Jet Emission Tomography (JET)?

What is needed to turn jet quenching into a tomographic precision tool?

Energy loss = (QCD cross section for induced gluon radiation)
× (path integrated density of scatterers)

In order to use energy loss to explore the density distribution of the medium, must first test that we correctly understand the QCD cross section with the medium.

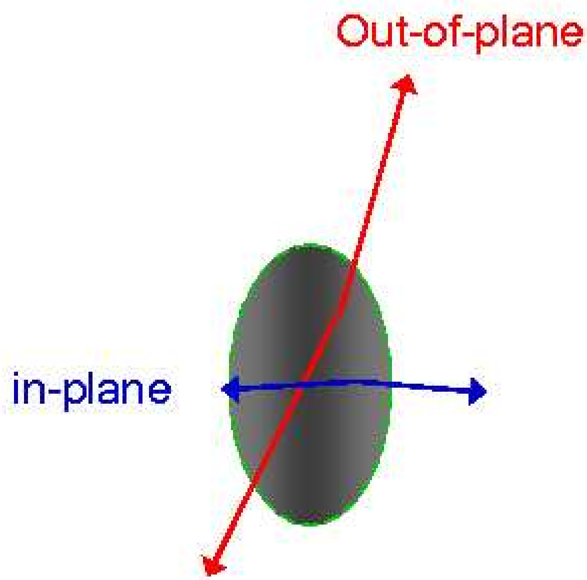
$\Longrightarrow$ Study energy loss as function of path length for fixed density distribution, by exploring angular dependence of jet quenching in a deformed source.

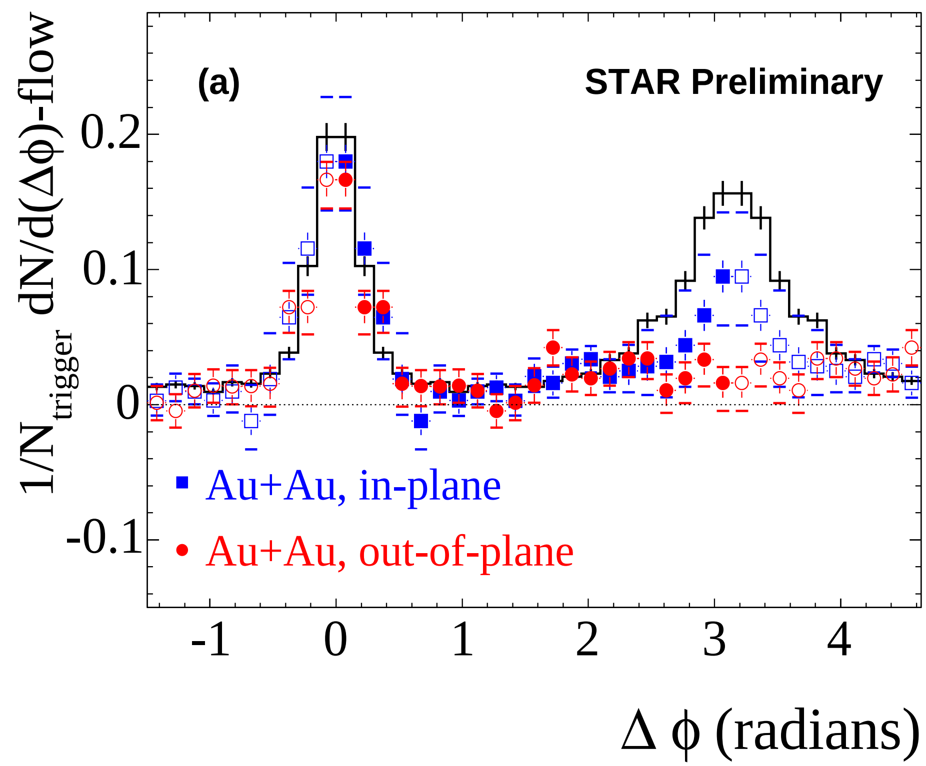


Path length dependence of parton energy loss:

STAR Coll., nucl-ex/0403018, Quark Matter 2004

Emission angle dependence:





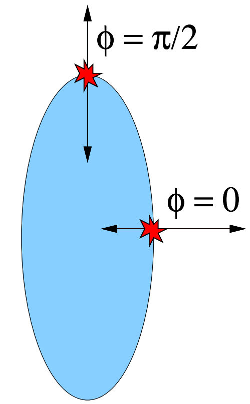
- medium opaque for colored particles
- energy loss increases strongly with path length

Energy loss of fast partons in Au+Au and U+U collisions

- Energy loss, ΔE, of fast parton is proportional to (Gyulassy *et al.*, *Quark Gluon Plasma 3*, p.123)

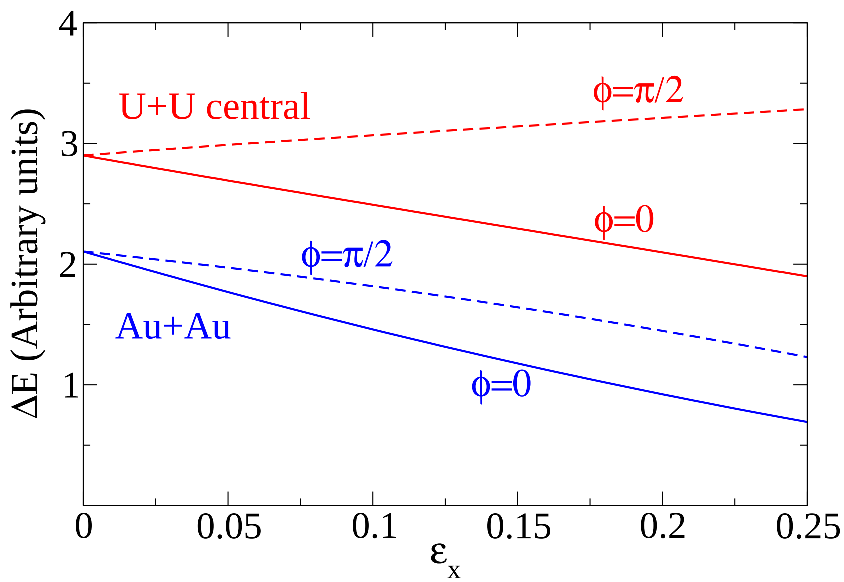
$$\Delta E \sim \int_{\tau_0}^{\infty} d\tau\ \rho(\boldsymbol{r}_\perp(\tau),\tau)\ (\tau-\tau_0)$$

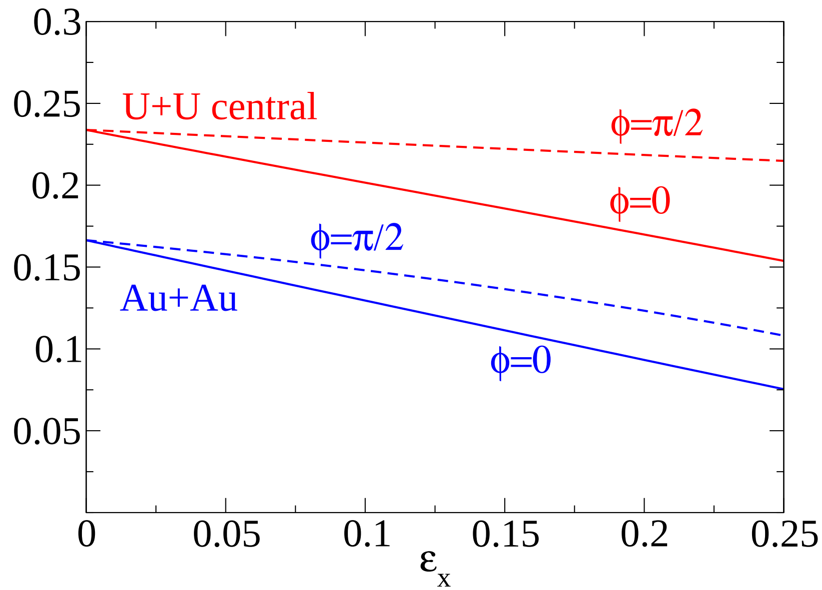
where $\boldsymbol{r}_\perp(\tau)$ denotes parton trajectory.



- Focus on away side jet created at "edge" of medium
- Consider two cases: *(i)* time-independent density $\rho_0 \equiv \rho(\boldsymbol{r}_\perp,\tau_0)$;
  (ii) dilution via longitudinal expansion, $\rho(\boldsymbol{r}_\perp,\tau) = \rho_0 \cdot \frac{\tau_0}{\tau}$

$\rho = \rho_0$ A.J.Kuhlman, U.H., PRL 94 (2005) 132301 $\rho = \rho_0\tau_0/\tau$





Summary

Key discoveries at RHIC at all wavelengths:

- strong radial and elliptic flow (also at SPS) (predicted)
- elliptic flow exhausts the ideal fluid limit (new) (predicted)
- strangeness enhancement and statistical hadronization at $T_c \approx 170\,\mathrm{MeV}$ (also at SPS) (predicted)
- suppression of high-p_T hadron production in Au+Au vs. Cronin enhancement in d+Au (opposite centrality dependence in Au+Au and d+Au) (new) (predicted)
- jet quenching by parton energy loss with energy redistribution to low p_T ("jet thermalization") (new) (predicted)
- universality of $\frac{v_2}{n_{\mathrm{val.}}}\left(\frac{p_T}{n_{\mathrm{val.}}}\right)$ (quark coalescence, elliptic flow is partonic) (new)

The picture begins to take shape . . .

- $v_2 \implies$ short thermalization time $\tau_{\rm therm} < 1\,{\rm fm}/c \implies$ matter initially in QGP state, $e_0 > 10\,e_{\rm cr}$, $T_0 \sim 2\,T_{\rm cr}$, lives $\sim 5-7\,{\rm fm}/c$ before hadronizing
- Bulk of matter created at RHIC $=$ almost ideal fluid with low viscosity $\implies$ QGP $=$ strongly coupled plasma
- $T_{\rm cr} \approx 170\,{\rm MeV}$ measured (statistical hadronization), consistent/w LQCD
- strangeness enhancement, quark number scaling of v_2, R_{CP} of identified hadrons at intermediate p_T indicate quark deconfinement
- jet emission tomography (JET) $\implies$ QGP is color opaque
- JET and hydro yield independent, consistent estimates for initial energy density $e_{\rm init} \approx 15\,e_{\rm cr} \approx 100\,e_{\rm nucl.mat.}$

but . . .

- some puzzles remain (HBT, v_2 at high p_T)
- detailed properties of QGP still to be explored (charm flow, quarkonium spectroscopy, thermal photons & dileptons, precision JET, QGP speed of sound and viscosity, . . .)

So far, RHIC has been a huge success, but . . .

We are not done yet!