Properties of hot dense matter from colliding nuclei*

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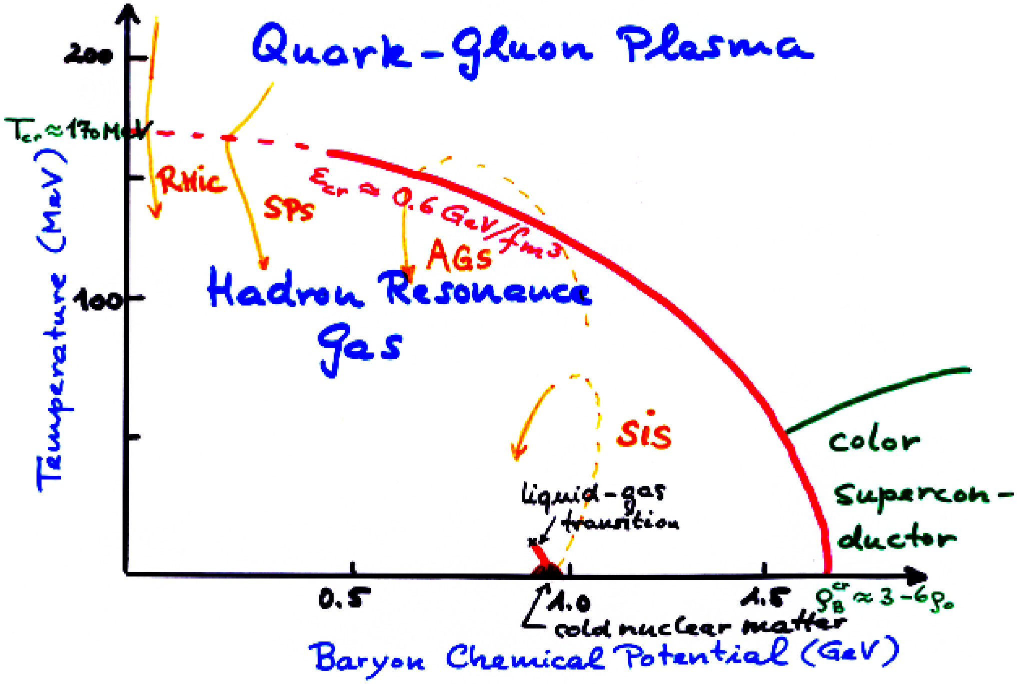
RHIC Goals:

- Create and study the Quark-Gluon-Plasma

  (= thermalized medium of deconfined quarks and gluons in which chiral symmetry is restored, i.e. $\langle\bar\psi\psi\rangle = 0$)

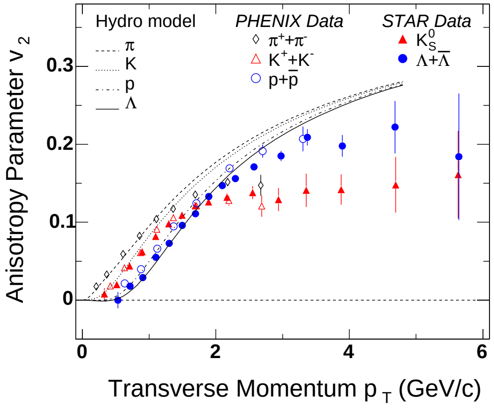
- Explore the QCD phase diagram:



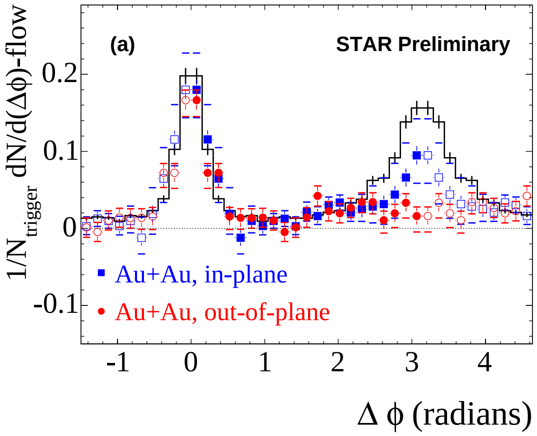
$\Longrightarrow$ **Condensed Matter Physics with Strongly Interacting Particles** (QCD instead of QED)

How to measure the properties of the created matter?

- explore its collective behaviour (radial and elliptic transverse flow)
  thermalization? equation of state? gas or liquid? viscosity? color conductivity?



- study how it affects calibrated hard probes (parton energy loss, JET, J/ψ suppression, charm flow, . . .)

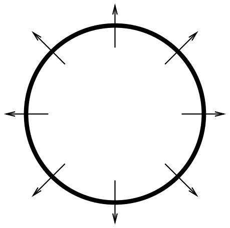


- measure its electromagnetic radiation

Flow – an unavoidable consequence of thermalization:

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

Radial flow:

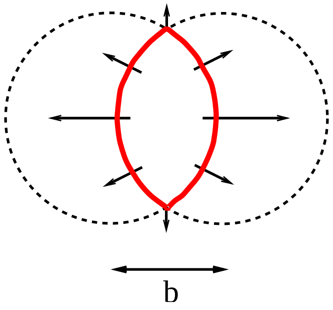


→ the only type of transverse flow in $b = 0$ collisions between equal spherical nuclei

→ 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

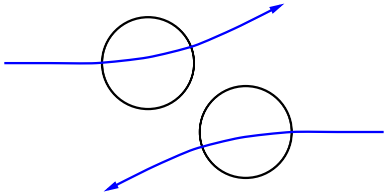
→ requires spatial deformation of reaction zone at thermalization

→ 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

Hydrodynamics – the natural tool to study flow:

Relativistic Hydrodynamics: Conservation of energy, momentum and baryon number

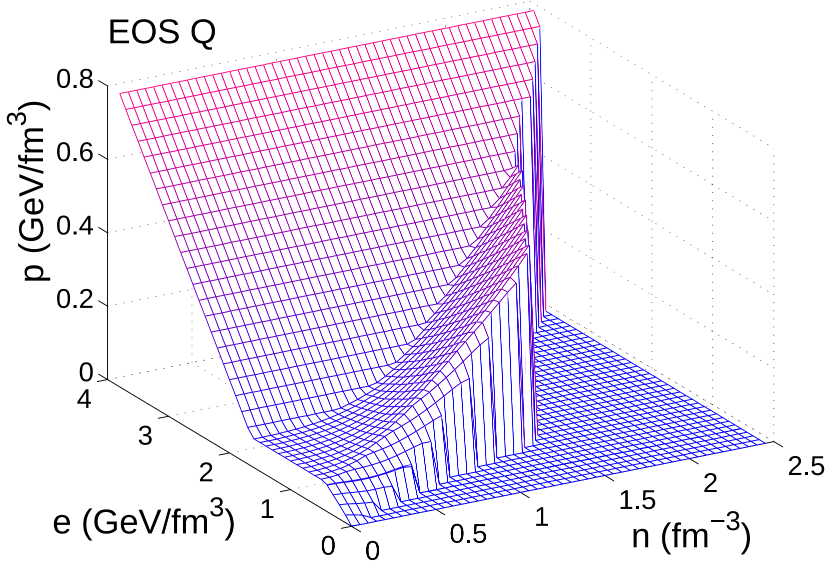
$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu j^\mu = 0$$

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

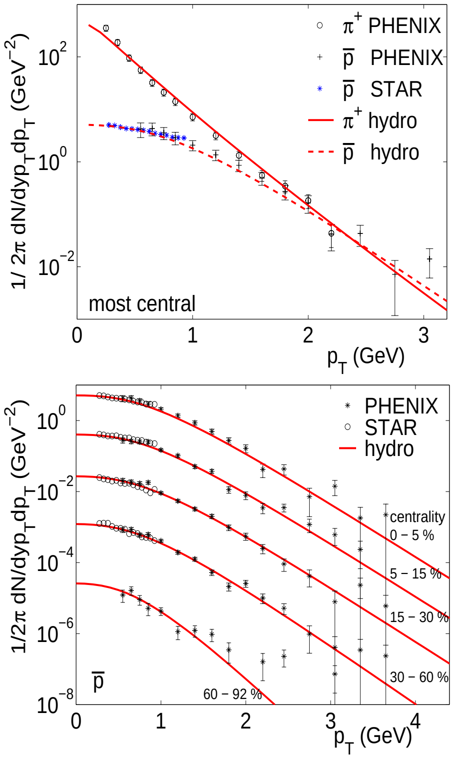
critical temperature $T_{\text{crit}} = 0.164$ GeV
$\Rightarrow$ bag constant $B^{1/4} = 0.23$ GeV
latent heat $\Delta e = 1.15$ GeV/fm^3



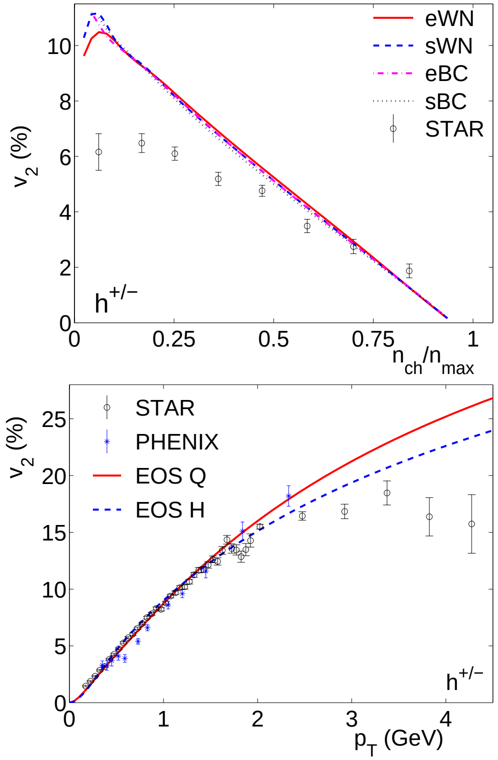
Implement exact longitudinal boost invariance for simplicity ($Y \approx 0$ only)

Hydrodynamic description of single-particle spectra:

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



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



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

What is fitted, what is predicted?

Au+Au @ 130 A GeV:

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

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

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!):

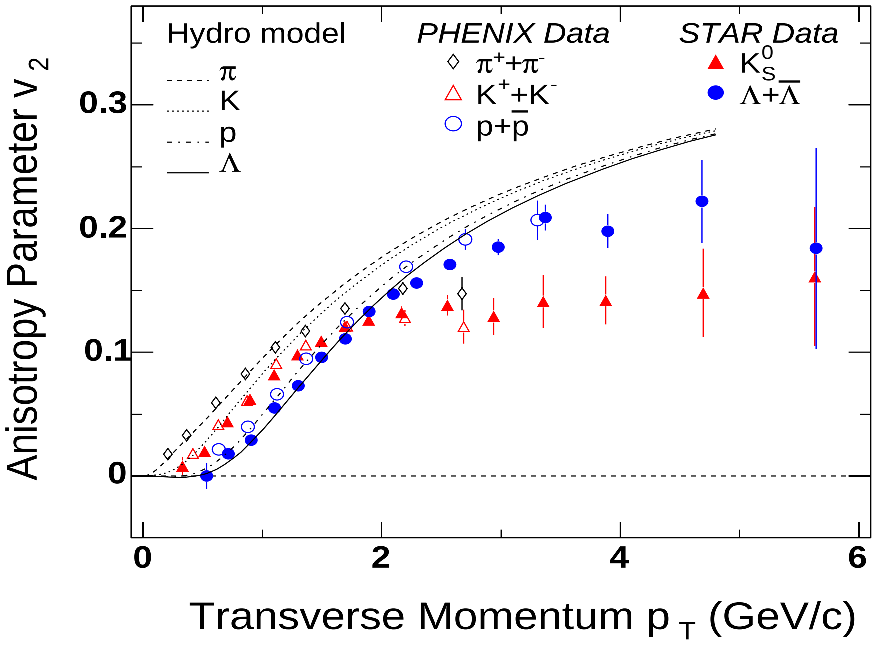
- All hadron spectra other than p, π in $b{=}0$ collisions
- All hadron spectra and elliptic flow coefficients for non-central collisions at any impact parameter

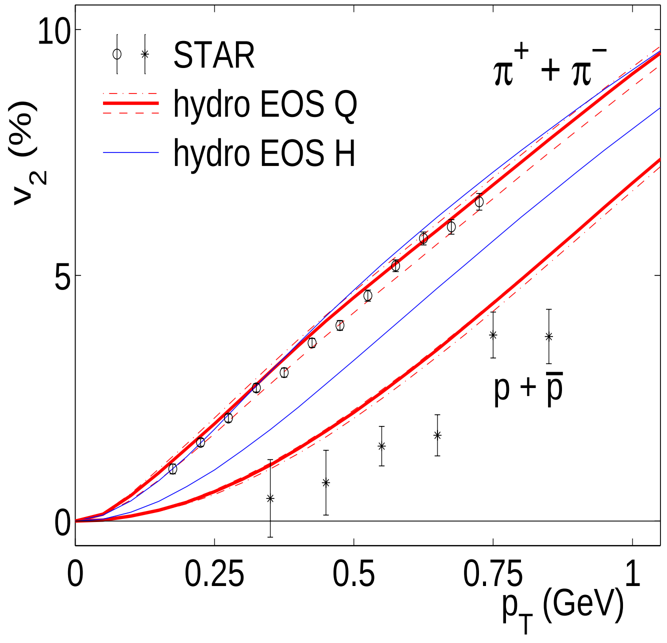
Shortcomings of early hydro calculations (repaired in later versions):

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

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)





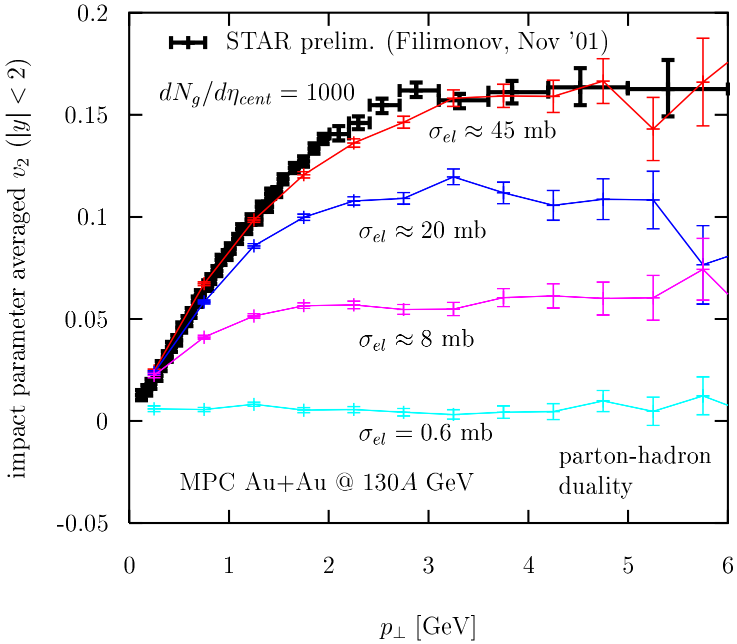
Data follow the hydrodynamically predicted rest mass dependence of $v_2(p_\perp)$ out to $p_\perp \sim 1.5$ GeV for mesons and out to $p_\perp \sim 2.3$ GeV for baryons

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

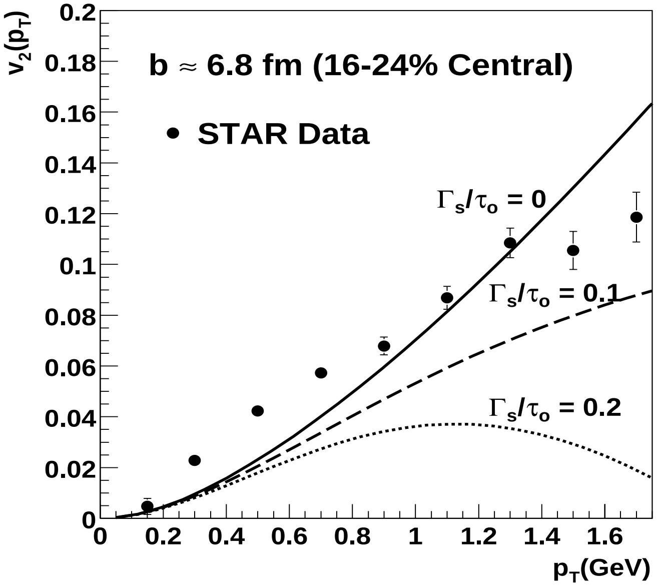
Note: mass-splitting of v_2 ("fine structure") sensitive to EOS!

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



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

- 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)
- More quantitative constraints on η require viscous hydrodynamics code

Why is this important?

- v_2 requires rescattering/reinteractions among produced matter $\Longrightarrow$ final state $\neq$ initial state
- microscopic studies (Zhang et al. 1999, Molnar & Gyulassy 2002): v_2 is a monotonic function of $\sigma\rho \sim 1/\lambda$; ideal fluid limit reached as $\lambda \to 0$
- v_2 data @ RHIC $\approx$ exhaust hydro limit $\Longrightarrow$ fast, efficient thermalization
- v_2 needs spatial deformation (rescattering maps ϵ_x onto v_2) $\Longrightarrow$ sensitive to early collision stage; data require $\tau_{\rm therm} \leq 1\,{\rm fm}/c$ (we use $0.6\,{\rm fm}/c$)
- since the hydrodynamic upper limit can only be approached from below and is $\approx$ exhausted by the data, the data provide stringent limits on viscosity and other transport coefficients
- since hydrodynamics works, we can use it to estimate initial energy density and lifetime of the plasma: $e_{\rm init} \simeq (10-20) \times e_{\rm crit}$, $T_{\rm init} \simeq 2 \times T_{\rm crit}$, $\tau_{\rm had} - \tau_{\rm therm} \simeq 5-7\,{\rm fm}/c$
- Theoretically, there exists only one viable concept that fits all of these properties: the QGP.
- RHIC data tell us that the QGP behaves like an almost ideal fluid and must therefore be strongly interacting.

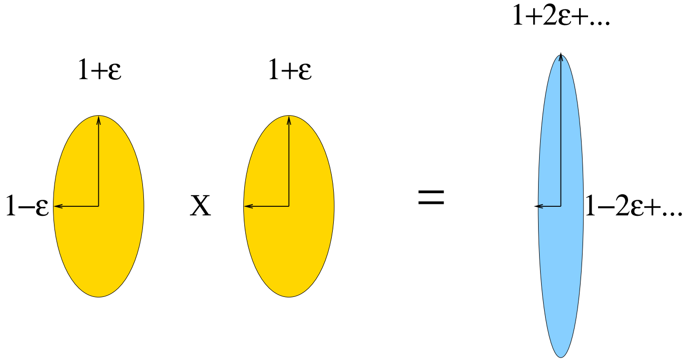
Quark number scaling at intermediate $p_\perp$: coalescence

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

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

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

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



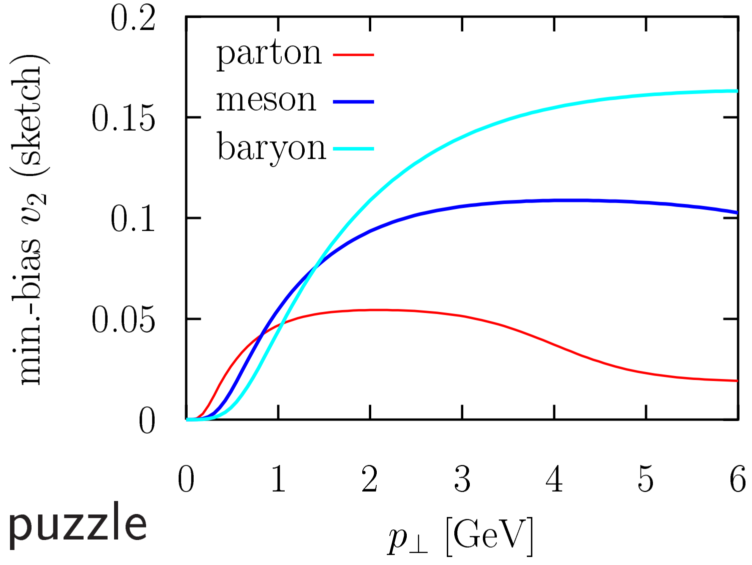
⇒ **Hadron v_2 amplified at high $p_\perp$:**

If all quark flavors have same v_2:

$3\times$ for baryons

$2\times$ for mesons

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

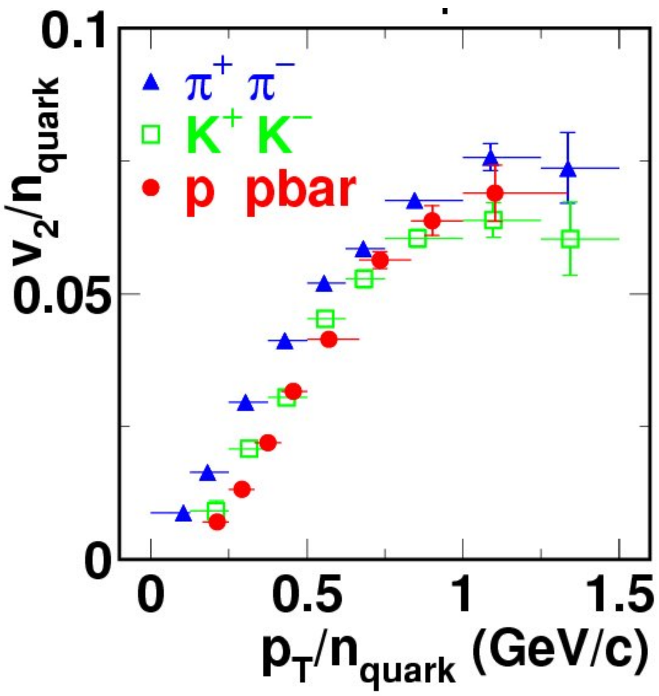


- This KEY EFFECT alleviates the opacity puzzle (smaller parton v_2 needed)

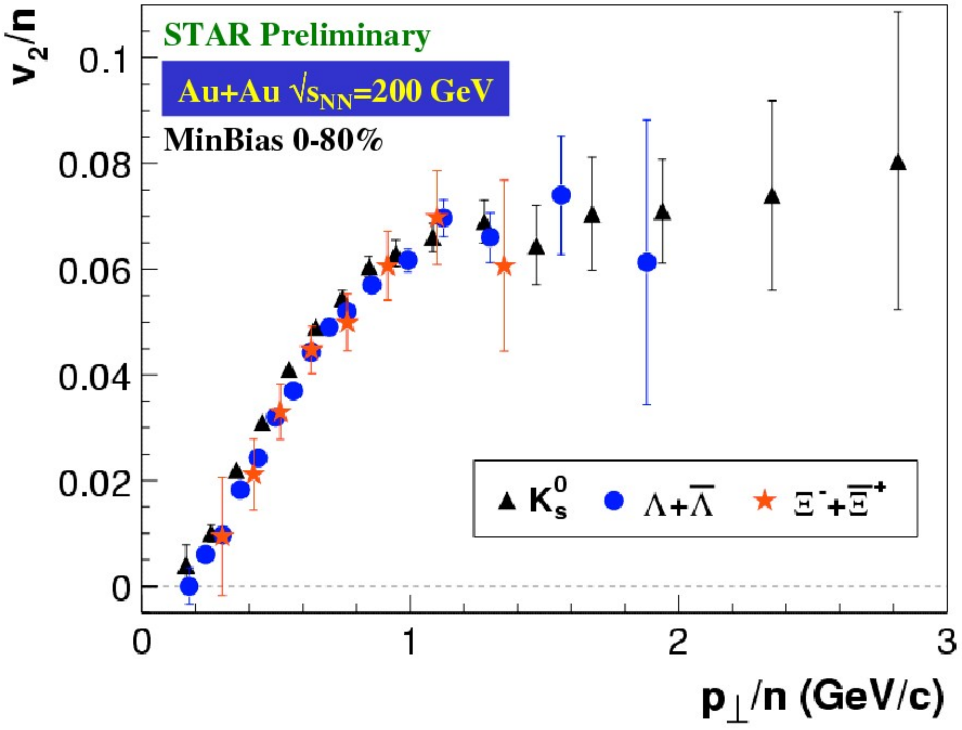
Note: Parton v_2 can be extracted only because it breaks away from hydro at high p_T!

Experimental extraction of parton elliptic flow (I)

PHENIX Coll., PRL 91 ('03) 182301



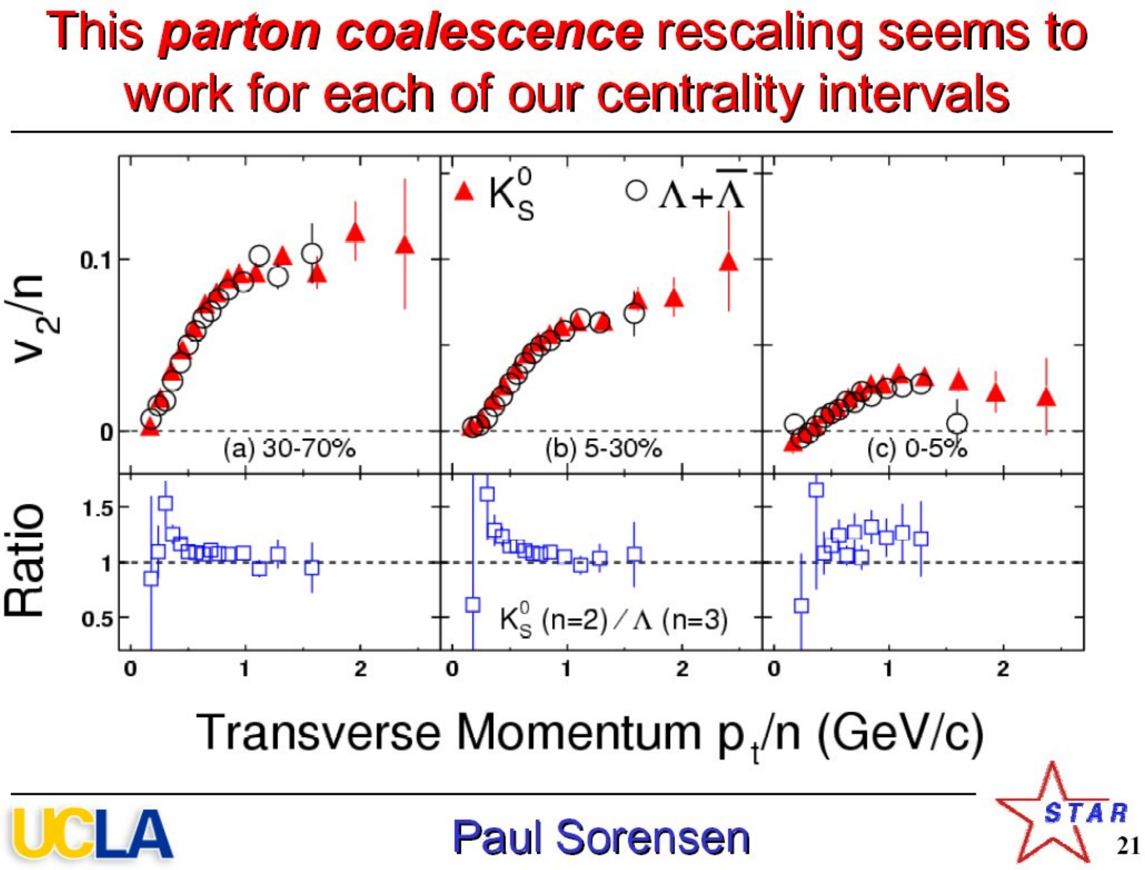
J. Castillo (STAR Coll.), nucl-ex/0403027



- 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

Experimental extraction of parton elliptic flow (II)

P. Sorensen (STAR Coll.), J.Phys. G30 ('04) S217



This ***parton coalescence*** rescaling seems to work for each of our centrality intervals

Paul Sorensen

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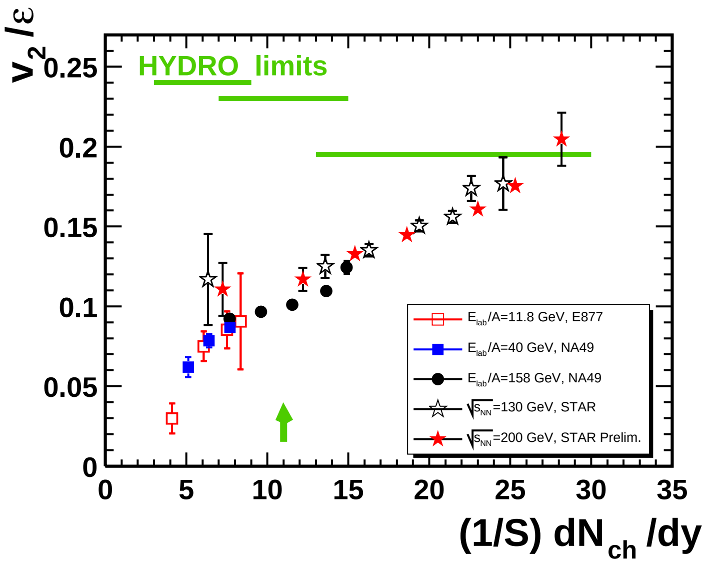
Note:
- Parton v_2 can be extracted only because it breaks away from hydro at high $p_\perp$
- Valence quark number scaling indicates quark deconfinement!

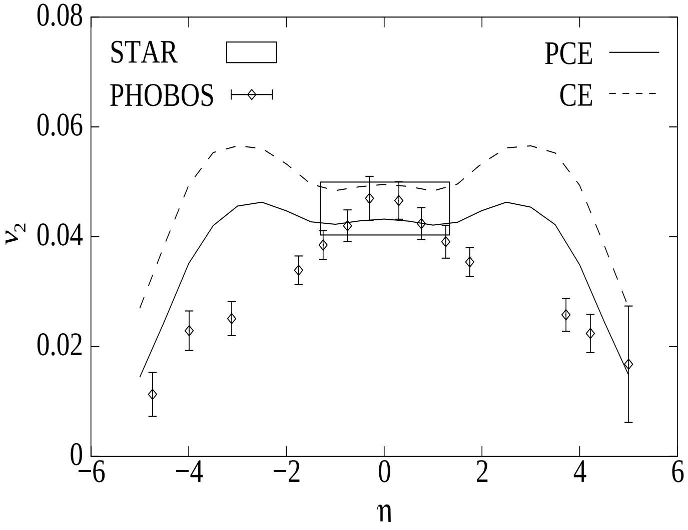
Limits of ideal fluid dynamics: smaller, less dense systems

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



3d hydro:

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



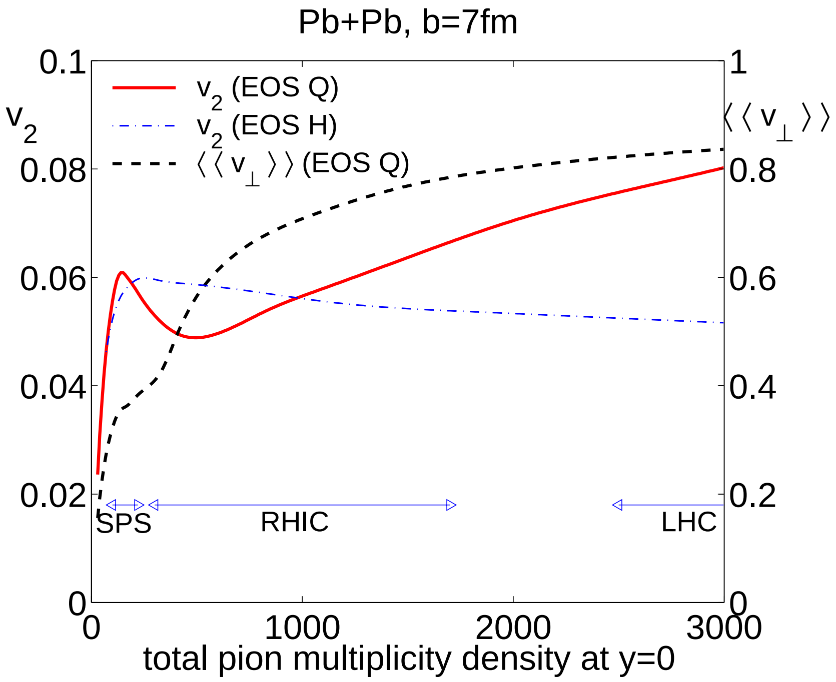
- $\dfrac{v_2^{\text{measured}}}{v_2^{\text{hydro}}}$ scales with $\frac{1}{S}\frac{dN_{\text{ch}}}{dy} \propto s_{\text{init}}$
- $e_{\text{init}} > 10\,\text{GeV/fm}^3$ needed for v_2 to saturate before hadronization and to exhaust ideal hydro limit!
- hydrodynamics predicts non-monotonic v_2/ϵ: between 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 $\sqrt{s}$ $\Rightarrow$ the inability of viscous hadronic phase to build elliptic flow kills the phase transition signature!

Breakdown of ideal hydro: the viscous hadron gas fluid

Excitation function of elliptic flow:

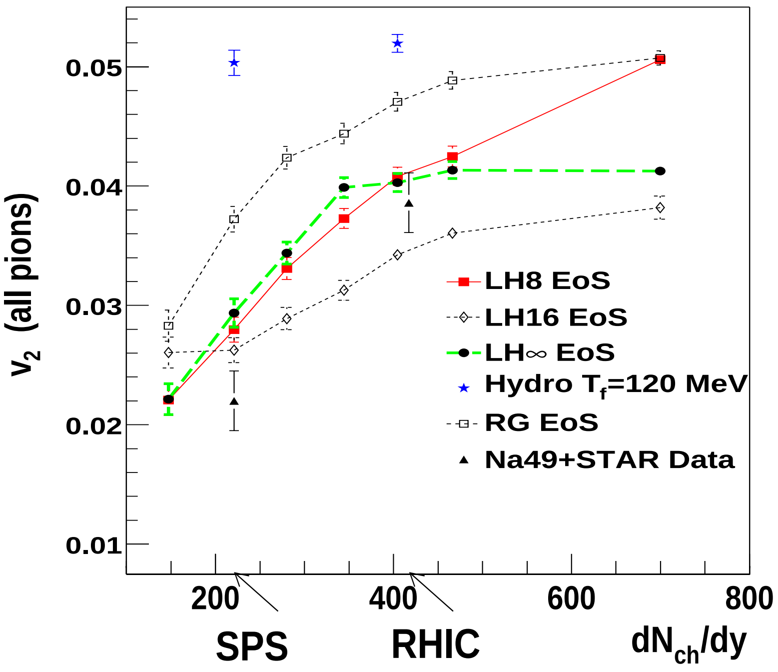
Ideal hydro

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



Hydro + RQMD

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

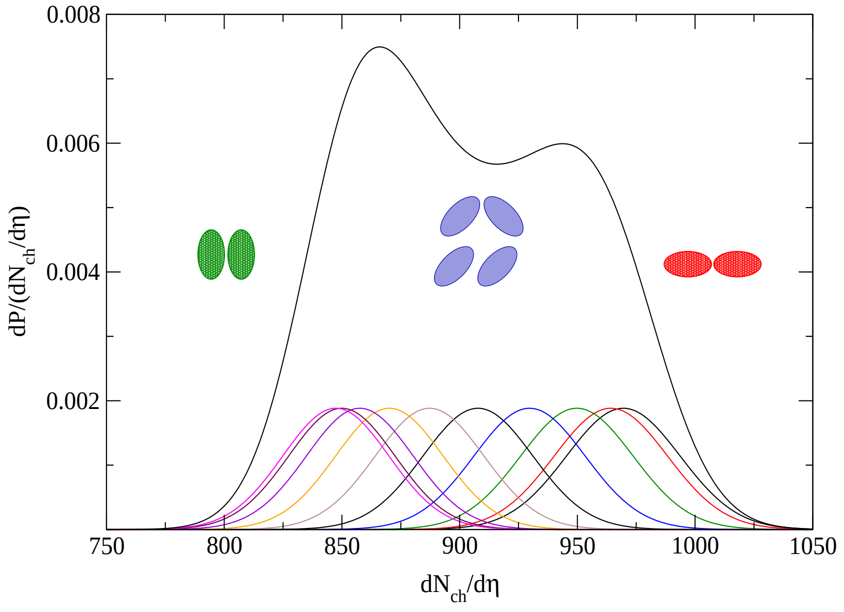


Hadron resonance gas is very viscous and does not respond strongly to spatial eccentricity $\Longrightarrow$ non-monotonic behaviour of v_2 resulting from dip in c_s^2 near phase-transition is erased!

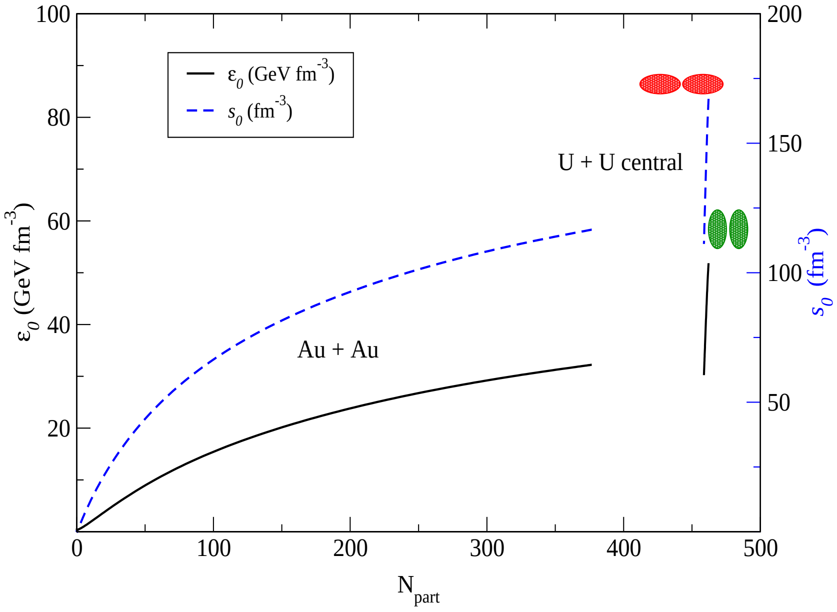
The ultimate test of hydrodynamics at RHIC: fully aligned (“zero spectators”) U+U at 200 A GeV

A.J. Kuhlman, U.H., in preparation

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



- $dN_{\mathrm{ch}}/d\eta$ 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) $\approx$ ϵ_x($b{=}7$ fm Au+Au), at 30% higher e_0

Suppression of high p_T hadron production in Au+Au:

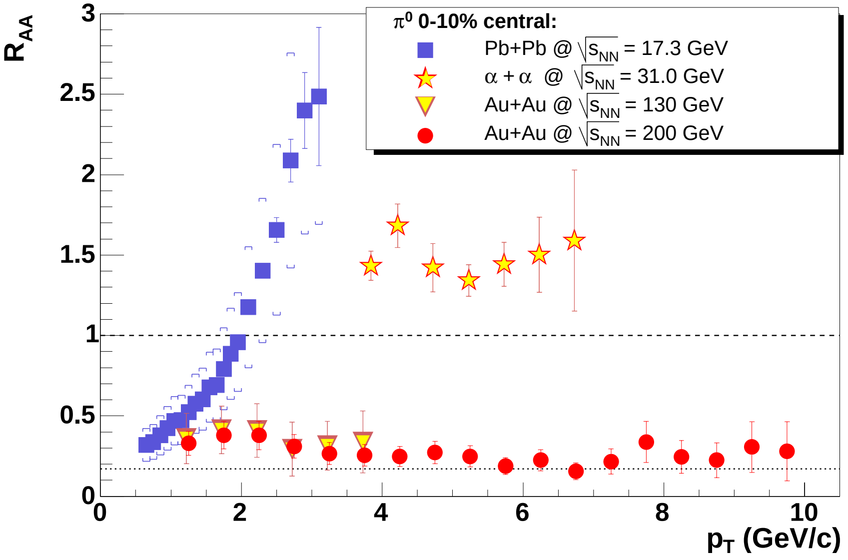
$$\boxed{R_{AA}(p_T;b) = \frac{\frac{dN_{AA}}{dp_T}(b)}{N_{\rm coll}(b)\frac{dN_{pp}}{dp_T}}}$$

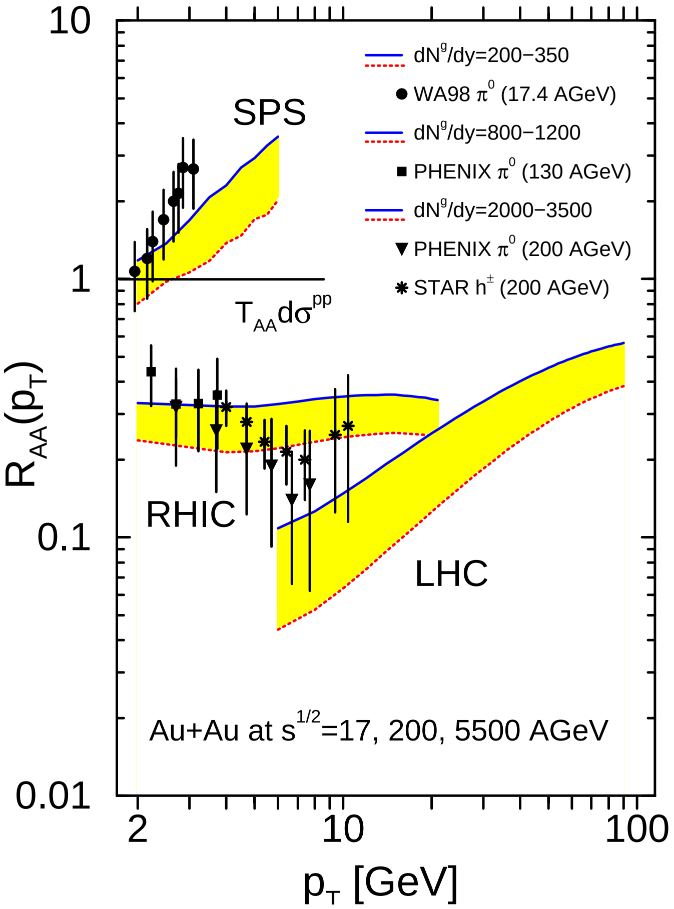
M. Gyulassy and I. Vitev,

PRL 89 (2002) 252301

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

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



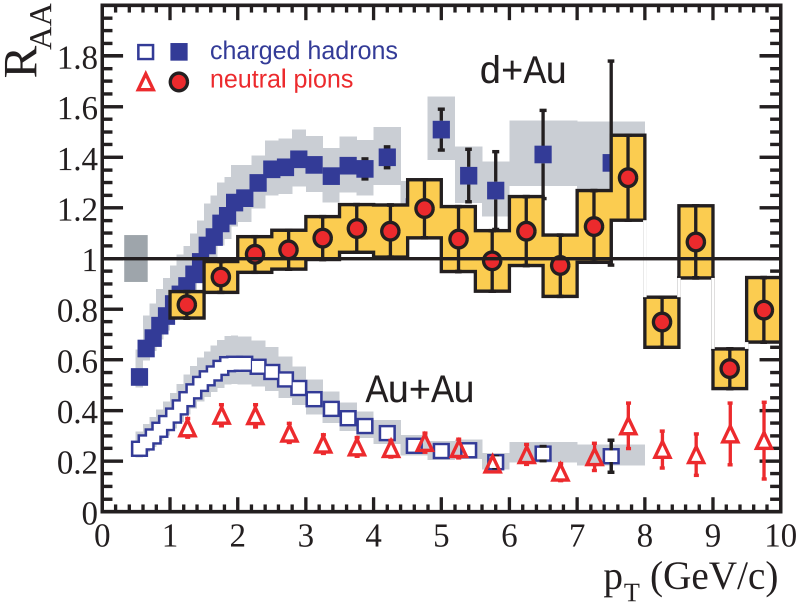


$$\Longrightarrow \quad \frac{dN_g}{dy} = 1000 \pm 200$$

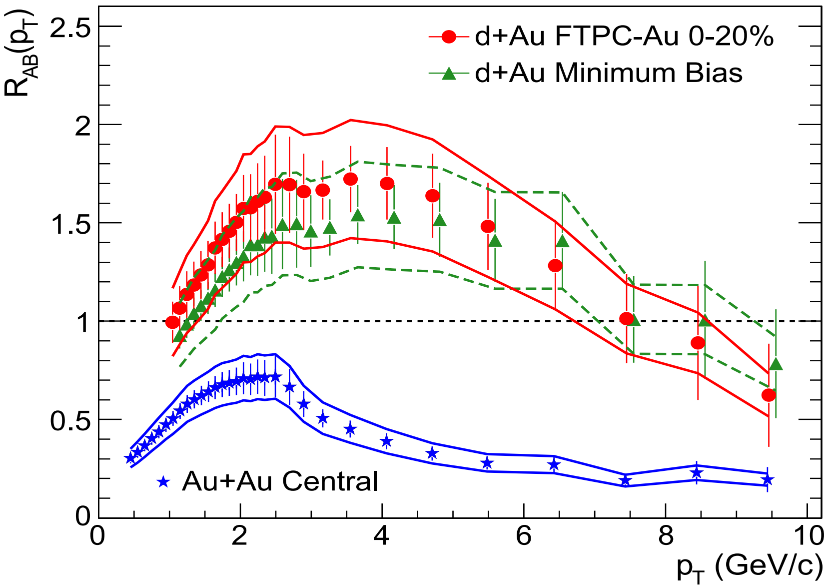
$$\Longrightarrow \quad \langle e\rangle(\tau_0{=}0.2\,\mathrm{fm}) \approx 20\,\mathrm{GeV/fm^3}\ !$$

No high p_T suppression in d+Au:

PHENIX Coll., PRL, nucl-ex/0306021



STAR Coll., PRL, nucl-ex/0306024



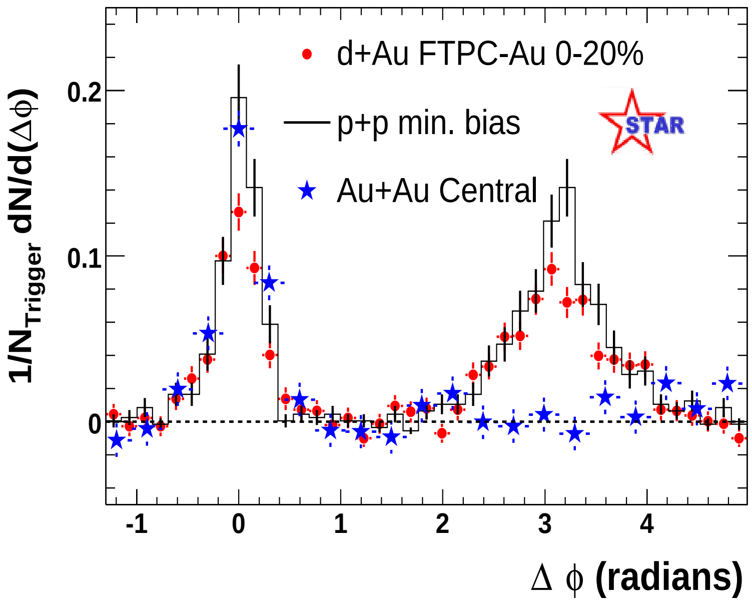
- as collision centrality increases, R_{AA} increases in d+Au (Cronin effect) but decreases in Au+Au

- 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

Jet quenching in central Au+Au collisions:

STAR Coll., PRL 91 (2003) 072304

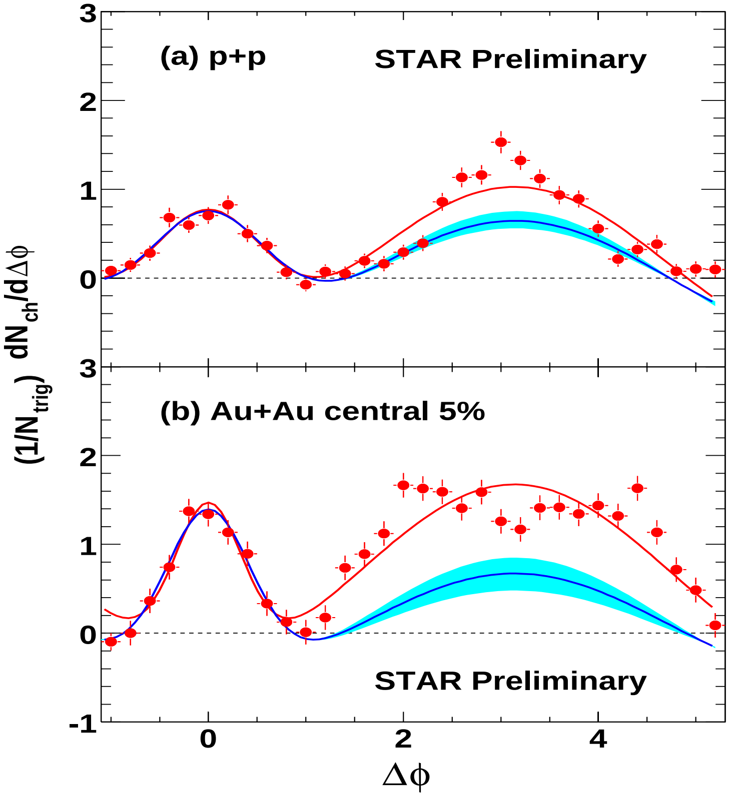
$p_T^{\mathrm{assoc}} > 2\,\mathrm{GeV}$



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

STAR Coll., F. Wang, Quark Matter 2004

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

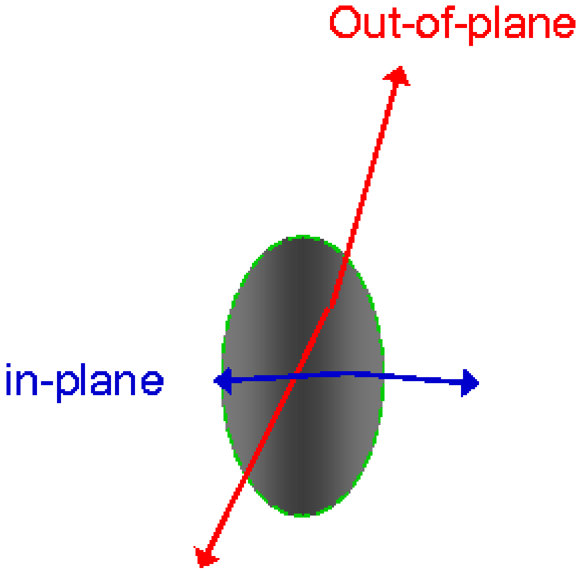


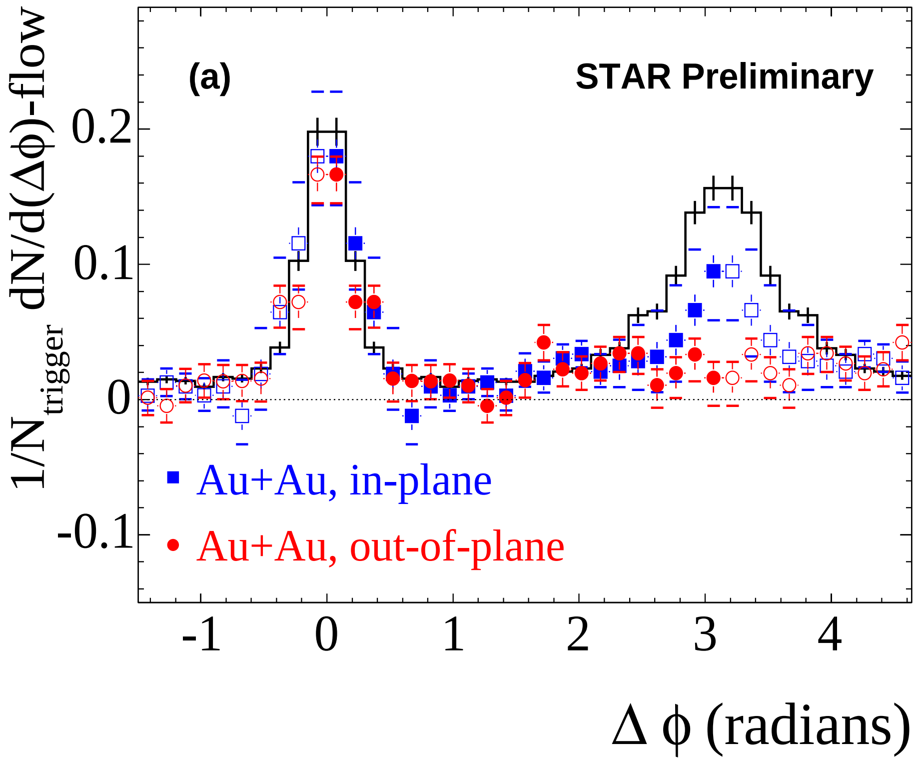
- away-side jet ($p_T > 2\,\mathrm{GeV}$) visible in p+p and d+Au, but fully quenched in central Au+Au
- energy of quenched jet appears as additional multiplicity of low-p_T particles opposite to trigger particle
- $\Longrightarrow$ “thermalization” of intermediate-p_T jets!

JET: Jet Emission Tomography
Path length dependence of parton energy loss:

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

Emission angle dependence:



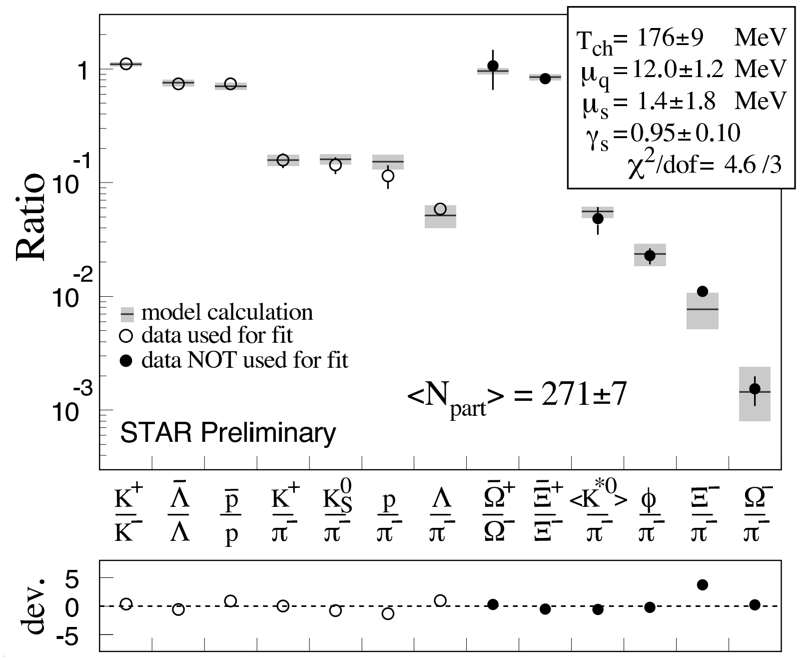


- medium opaque for colored particles
- energy loss increases strongly with path length

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

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 $T_{\mathrm{chem}} \simeq T_{\mathrm{had}} \simeq 170\,\mathrm{MeV}$

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

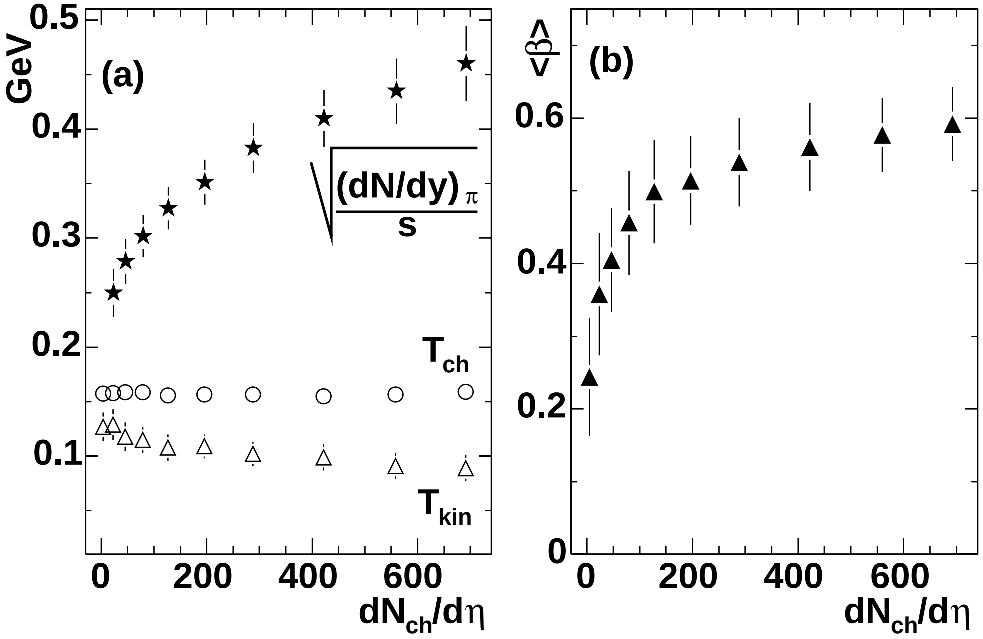
(R. Rapp, PRC 66 (2002) 017901
T. Hirano, PRC 66 (2002) 054905
D. Teaney, nucl-th/0204023)

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

Chemical vs. kinetic freeze-out: Evidence for a phase transition at $T_{\rm had} \simeq 170$ MeV

Central Au+Au @ 200 A GeV

(STAR Coll., PRL 92 (2004) 112301)



- Kinetic freeze-out temperature $T_{\rm kin}$ and radial flow velocity $\langle\beta_\perp\rangle$ depend on collision centrality, but $T_{\rm chem}$ does not!
- Centrality dependence of $T_{\rm kin}$ reflects centrality dependence of hydrodynamic expansion rate $\partial{\cdot}u$ through kinetic freeze-out criterium: $\tau_{i,\rm therm} = \frac{1}{\sum_j \langle v_{ij}\sigma_{ij}\rangle \rho_j} \simeq \tau_{\rm exp} = \frac{1}{\partial\cdot u}$.

Insensitivity of $T_{\rm chem}$ to collective expansion rate implies immediate chemical decoupling at hadron formation $\Longrightarrow$ chemical reaction rates must drop precipitously at $T_{\rm chem} = T_{\rm had}$ $\Longleftrightarrow$ Phase transition at $T_{\rm had}$!

So what are the properties of the hot dense matter formed at RHIC?

- It's thermalized: elliptic flow, hadron abundances, hadron spectra at $p_\perp < 2\,\text{GeV}/c$
- It's dense! $\langle e\rangle \approx 20-30\,\text{GeV}/\text{fm}^3$ at $\tau_0 = 0.2\,\text{fm}/c$, $\langle e\rangle \approx 10\,\text{GeV}/\text{fm}^3$ at $\tau_{\rm therm} = 0.6\,\text{fm}/c$ (elliptic flow, parton energy loss) $\Longrightarrow$ matter initially in QGP state.
- It's strongly coupled: $\tau_{\rm therm} < 1\,\text{fm}/c$ (elliptic flow) $\Longrightarrow$ not a perturbative quark-gluon gas
- It behaves like an almost ideal fluid with very low viscosity (elliptic flow, hadron spectra)
- It's very opaque to hard colored probes: parton energy loss, JET
- Evidence for deconfinement (indirect): quark-number scaling of v_2 and R_{CP} at intermediate $p_\perp$ (quark coalescence)
- Evidence for chiral symmetry restoration (indirect): flavor equilibration of hadron yields, disappearance of the ρ peak in e^+e^- spectra at SPS
- Evidence for a phase transition at $T_{\rm had} \approx 170\,\text{MeV}$: centrality independence of $T_{\rm chem} = T_{\rm had}$, rest mass dependence of v_2

What else would we like to find out?

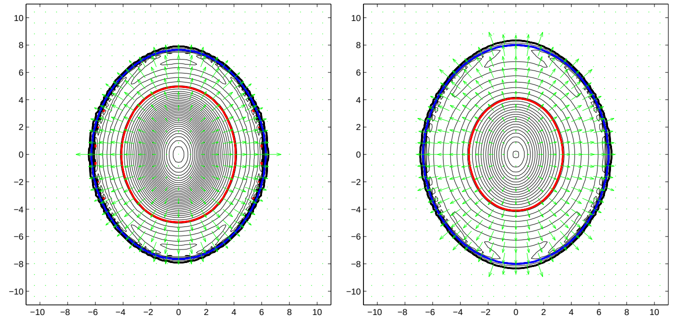
- Better constraints on τ_{therm} and EOS: precision flow studies and systematics (both theory and expt.)
- Better understanding of the interplay between the hydrodynamic early QGP and viscous late hadronic stages (more hybrid simulations (H2H, . . .))
- Better constraints on QGP transport coefficients of from data: requires more statistics (expt.) and a relativistic viscous hydrodynamic code (thy.)
- Hard evidence for deconfinement: charmonium and bottonium spectroscopy, direct photon spectra, quadratic path length dependence of non-abelian parton energy loss (precision JET)
- Hard evidence for chiral symmetry restoration: low mass dilepton spectra, hadron mass shifts in dense hadronic matter, constraints on chemical reaction rates in QGP phase from direct photons
- Phase transition or rapid cross-over? Event-by-event fluctuations
- Better understanding of QGP thermalization processes: Charm energy loss and flow; detailed exploration of gluon saturation physics ("color glass condensate") ideas at forward rapidities; new theory tools for strongly coupled plasmas; quantum transport theory

Beginning of a program of systematic precision studies of the QGP at RHIC!

Supplements

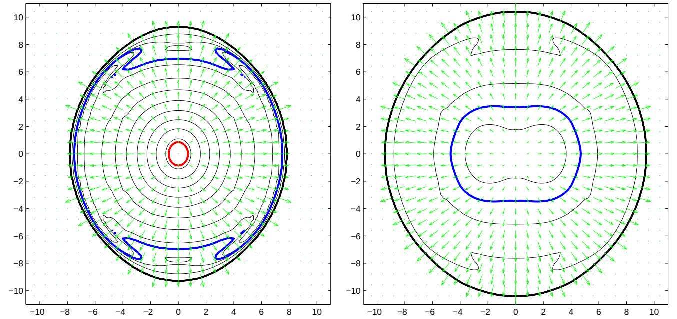
Radial and elliptic flow from hydrodynamics:

Au+Au at $b = 7$ fm



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

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

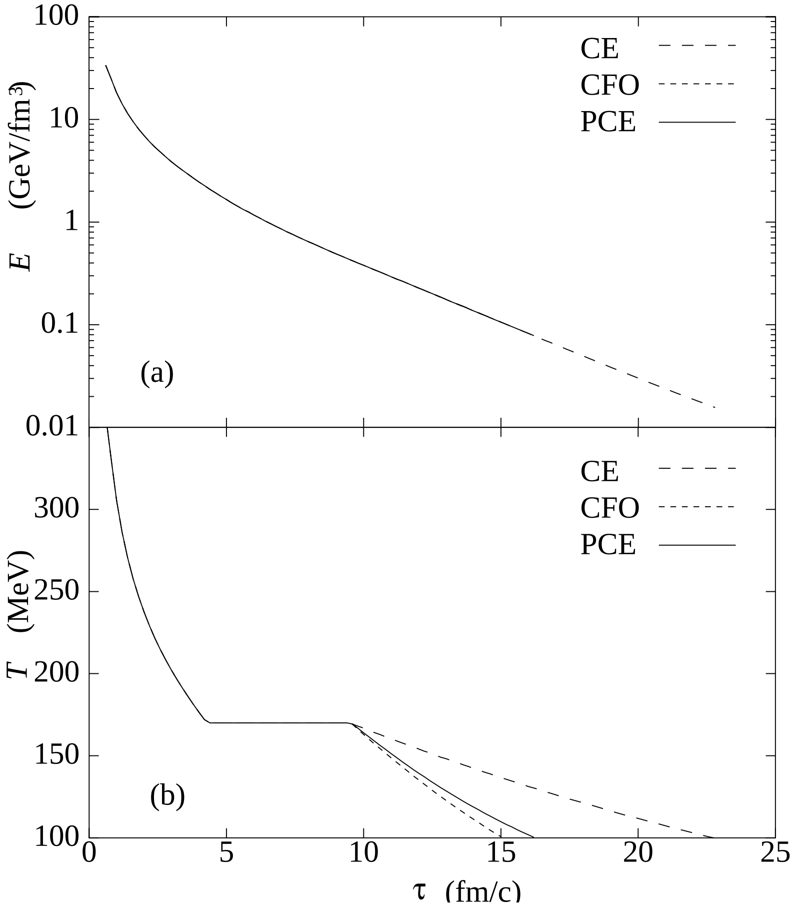


5.6 fm$/c$ ($\epsilon_x = 0.067$, $\epsilon_p = 0.147$)

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?

Expansion with non-equilibrium chemical potentials:

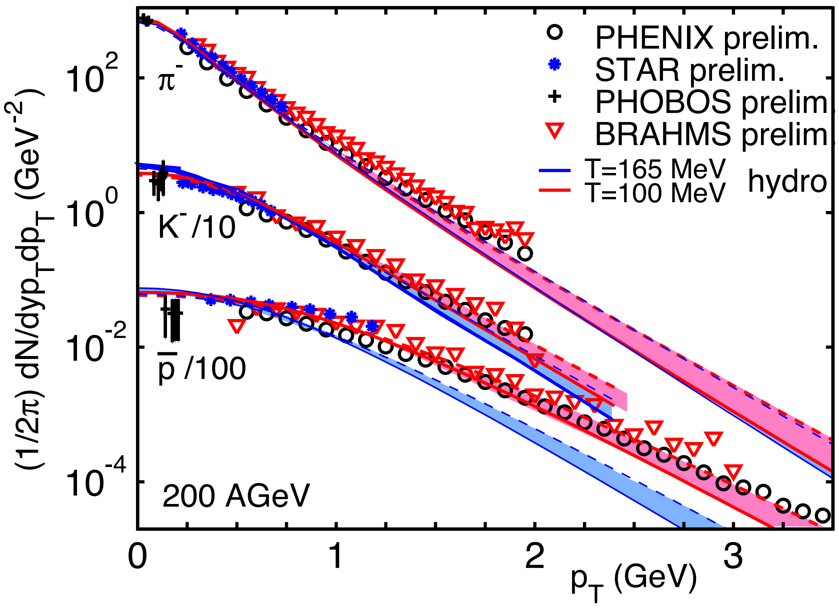


T. Hirano, PRC 66 (2002) 054905

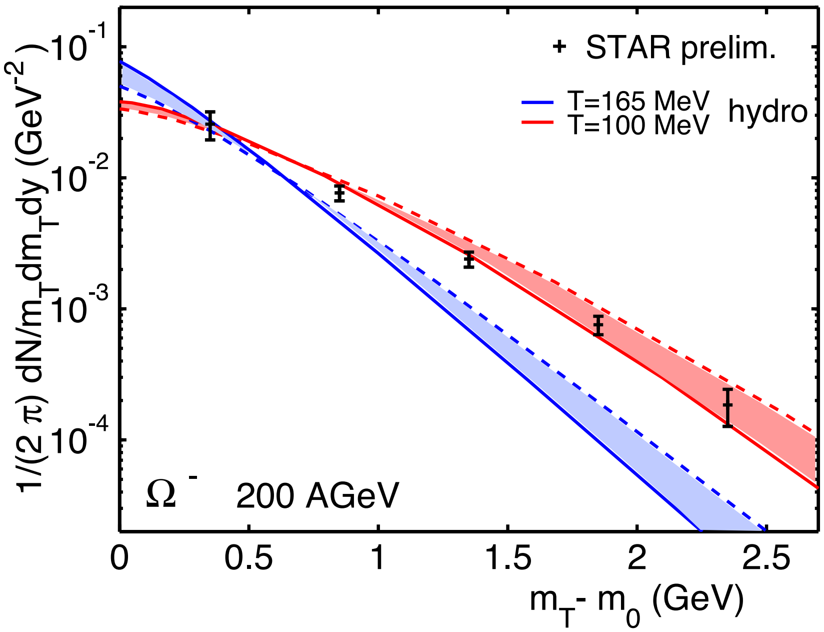
- Non-equilibrium hadronic potentials do not alter the equation of state $p(e)$
  $\Longrightarrow$ unchanged time evolution of energy density $e(\tau)$
- They do, however, change $e(T)$
  $\Longrightarrow$ same energy density corresponds to lower temperature
  $\Longrightarrow$ system cools faster
- 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: $\tau_{\rm eq} = 0.6\,{\rm fm}/c$, $s_0 \equiv s_{\rm max}(b{=}0) = 110\,{\rm fm}^{-3}$, $s_0/n_0 = 250$

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

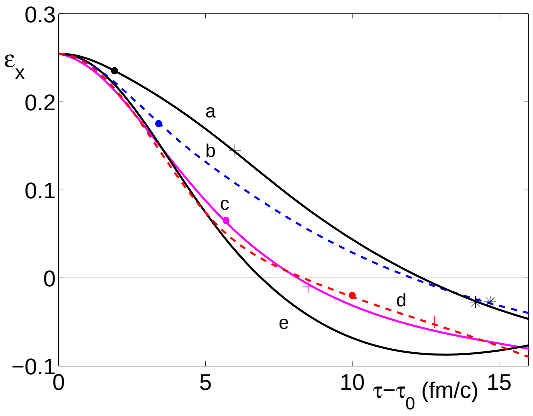
Note:
- Hydro does not create enough radial flow already at $T_{\rm c}$ to describe baryon spectra
- Multistrange baryons seem to fully participate in continued radial flow build-up during late hadronic phase!

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

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

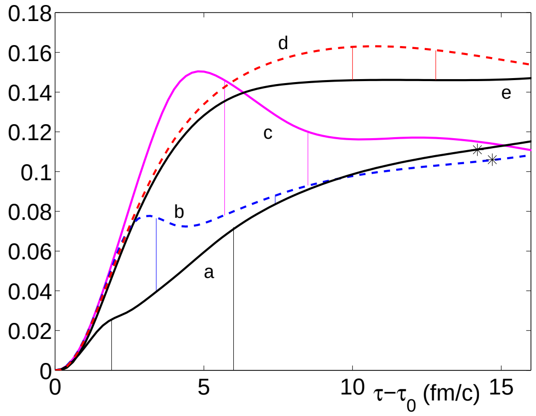
for various initial energy densities

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



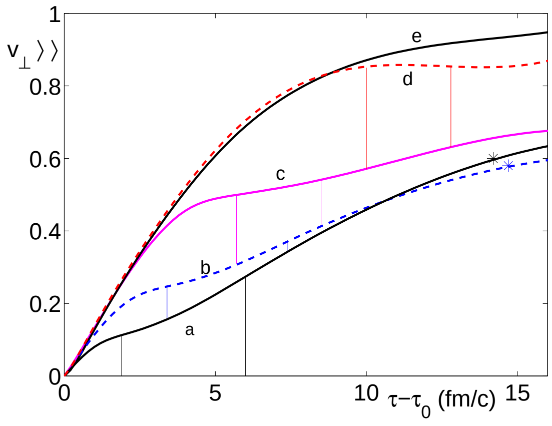
spatial eccentricity

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



momentum anisotropy

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



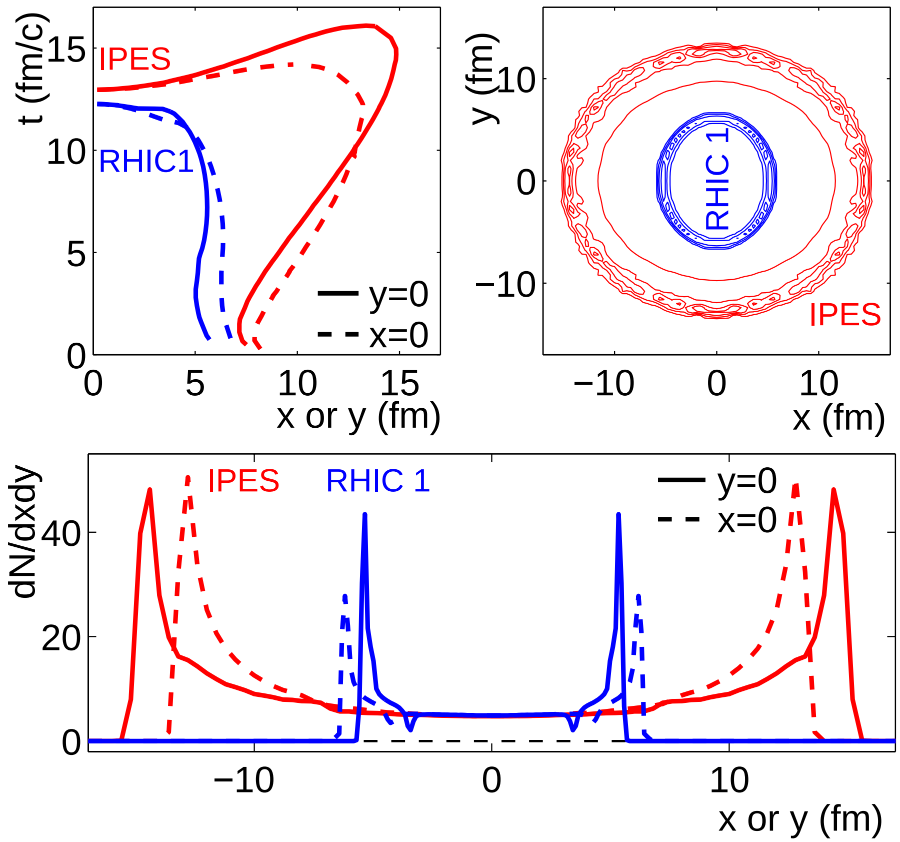
radial flow

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

Final spatial eccentricity can be measured with asHBT:

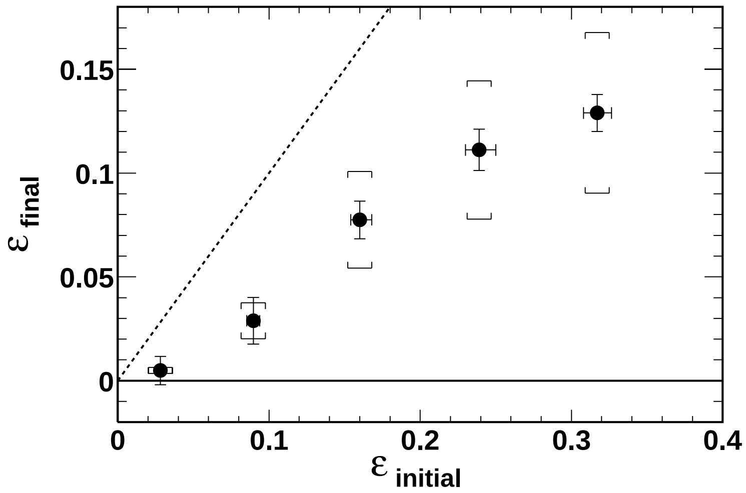
Hydro: Au+Au at $b = 7$ fm
$(\epsilon_x^{\text{initial}} = 0.25)$

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)

$dN/d\eta$ vs. centrality: Au+Au vs. central U+U

A.J. Kuhlman, U.H., in preparation