Beam energy scan using a viscous hydro+cascade model

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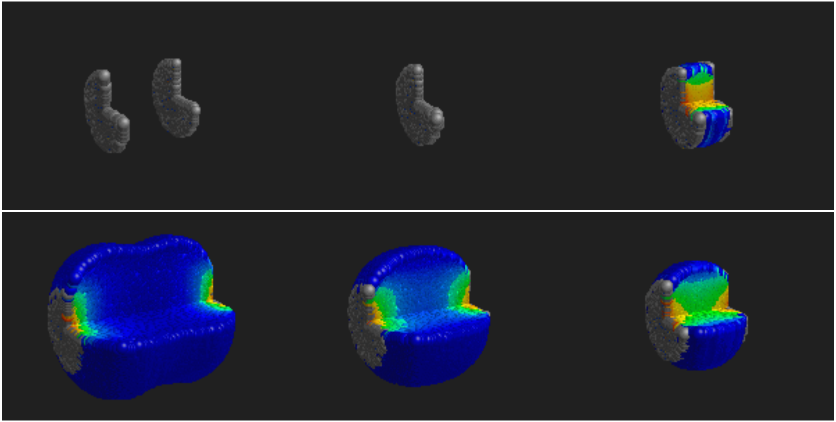
Introduction: heavy ion collision in pictures[1]



Typical size
10 fm $\propto 10^{-14}$m

Typical lifetime
10 fm/c $\propto 10^{-23}$s

10^{-8}sec after the collision: hadrons are detected

[1] https://www.jyu.fi/fysiikka/tutkimus/suurenergia/urhic/anim1.gif/image_view_fullscreen

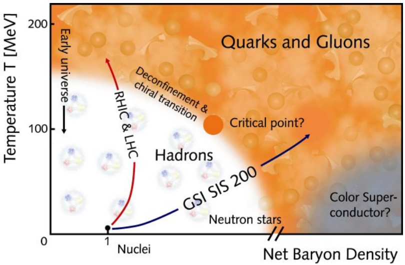
“Stages of Heavy Ion Collision”

1. Initial(pre-thermal) stage
   - Thermalization
2. Hydrodynamic expansion
   - Quark-gluon plasma phase
   - Phase transition
   - Hadron Gas phase
   - Chemical freeze-out
   - End of hydrodynamic regime
3. Kinetic stage
   Kinetic freeze-out
   $\Downarrow$
   Free streaming, then hadrons are detected

$\Leftrightarrow$

1. **Ingredients of hydro+cascade model**:

1. Initial stage model
   Enforced thermalization
2. Hydrodynamic solution
   - Equation of state for hydrodynamics
   - transport coefficients
3. Particlization and switching to a cascade



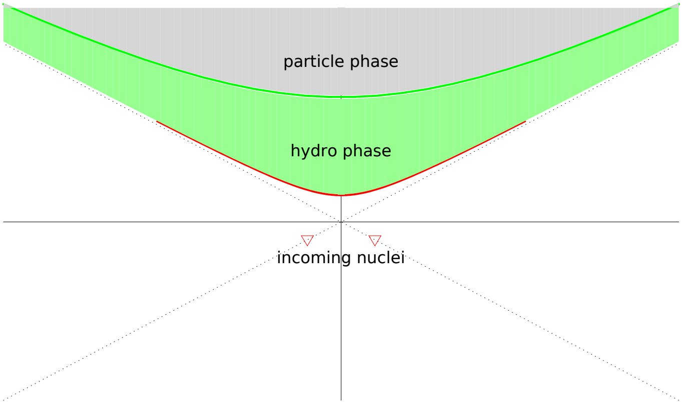
Ingredients essential for beam energy scan studies are marked red.

EoS reference: J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G 38, 035001 (2011).

1. **Ingredients of the model**:

1. Initial stage:
   UrQMD
2. Hydrodynamic solution
   - Equation of state for hydrodynamics:
     Chiral model coupled to Polyakov loop to include the deconfinement phase transition
     - good agreement with lattice QCD data at $\mu_B = 0$
     - Applicable also at finite baryon densities
   - transport coefficients
3. Particlization and switching back to cascade (UrQMD)

Initial conditions for hydrodynamic evolution



$\tau = \sqrt{t^2 - z^2} = \tau_0$ (red curve):
$\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid = averaged $\{T^{0\mu}, N_b^0, N_q^0\}$ of particles

Hydrodynamic stage

The hydrodynamic equations in arbitrary coordinate system:

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^{\mu}_{\nu\lambda} T^{\nu\lambda} + \Gamma^{\nu}_{\nu\lambda} T^{\mu\lambda} = 0, \quad \partial_{;\nu} N^\nu = 0 \qquad (1)$$

where (we choose Landau definition of velocity)

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - (p+\Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu} \qquad (2)$$

and $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

Evolutionary equations for shear/bulk, coming from **Israel-Stewart** formalism:

$$< u^\gamma \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma \qquad (3a)$$

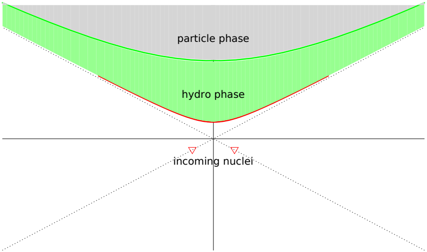
where

$$< A^{\mu\nu} >= (\frac{1}{2}\Delta^\mu_\alpha \Delta^\nu_\beta + \frac{1}{2}\Delta^\nu_\alpha \Delta^\mu_\beta - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta})A^{\alpha\beta}$$

* Bulk viscosity $\zeta = 0$, charge diffusion=0

Fluid→particle transition

$\varepsilon = \varepsilon_{sw} = 0.5$ GeV/fm^3 (end of green zone):
$\{T^{0\mu}, N_b^0, N_q^0\}$ of hadron-resonance gas = $\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid



▷ Momentum distribution from Landau/Cooper-Frye prescription:

$$p^0 \frac{d^3 n_i}{d^3 p} = \int \left(f_{\text{l.eq.}}(x,p) + \delta f(x,p) \right) p^\mu d\sigma_\mu$$

▷ Cornelius subroutine* is used to compute $\Delta\sigma_i$ on transition hypersurface.

▷ UrQMD cascade is employed after particlization surface.

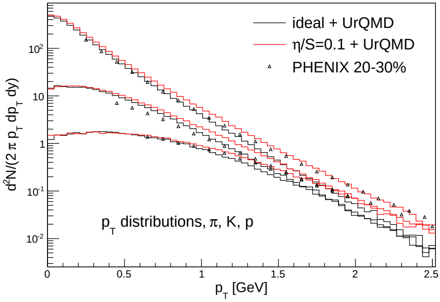
*Huovinen P and Petersen H 2012, *Eur.Phys.J.* A **48** 171

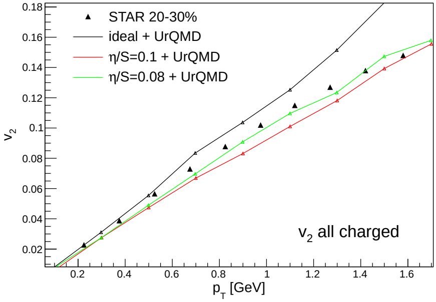
Model validation at top RHIC energy

Setup: smooth 3D initial conditions

$$\varepsilon(\tau_0, \vec{r}_T, \eta) = \varepsilon_{\mathrm{MCG}}(\vec{r}_T) \cdot \theta(Y_b - |\eta|) \exp\left[-\theta(|\eta| - \Delta\eta) \frac{(|\eta| - \Delta\eta)^2}{\sigma_\eta^2} \right]$$

Y_b is beam rapidity, parameters: $\Delta\eta = 1.3$, $\sigma_\eta = 2.1$
(chosen from the fit to PHOBOS $dN_{\mathrm{ch}}/d\eta$)

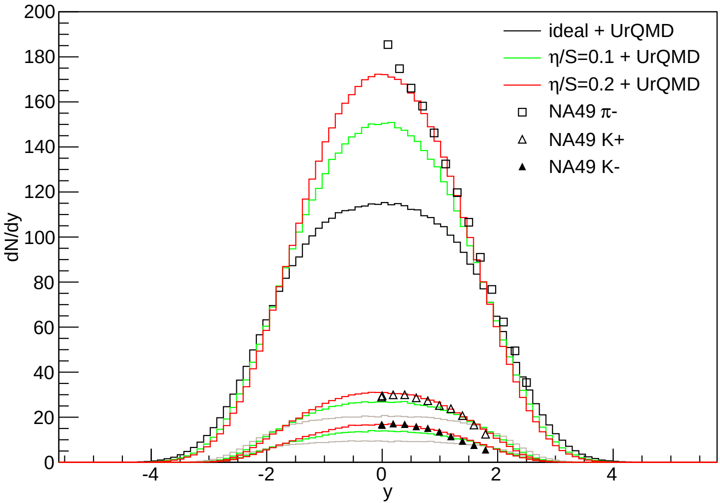




Beam energy scan (BES)

Results: $E_{\text{lab}} = 158$ A GeV Pb-Pb (SPS)

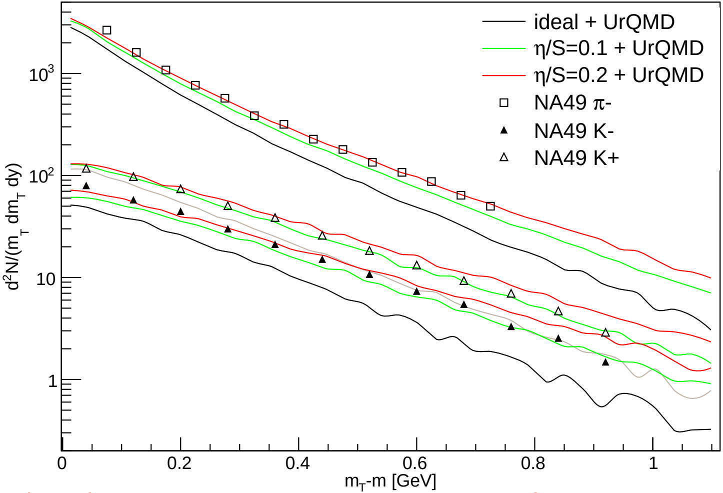
$\sqrt{s_{NN}} = 17.3$ GeV, 0-5% central collisions ($b = 0 \ldots 3.4$ fm)



→ strong viscous entropy production

Results: $E_{lab} = 158$ A GeV Pb-Pb (SPS)

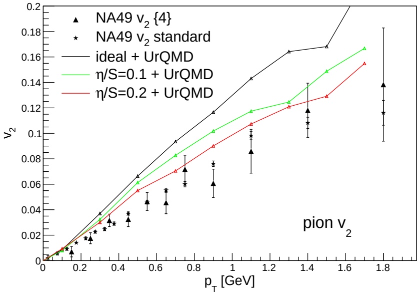
$\sqrt{s_{NN}} = 17.3$ GeV, 0-5% central collisions ($b = 0 \ldots 3.4$ fm)

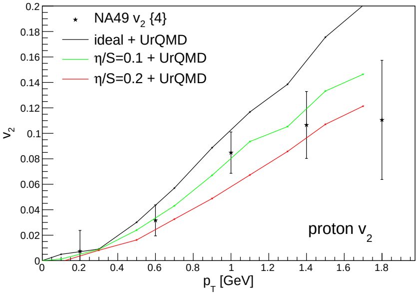


→ viscosity causes stronger transverse expansion

Results: $E_{\text{lab}} = 158$ A GeV Pb-Pb (SPS)

Mid-central events as defined by NA49 ($c = 12.5 - 33.5\%$)



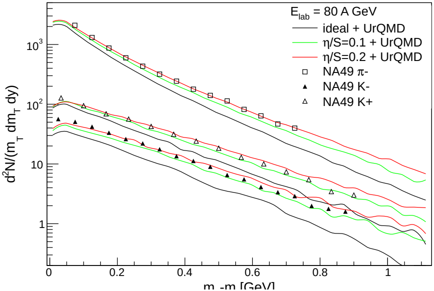


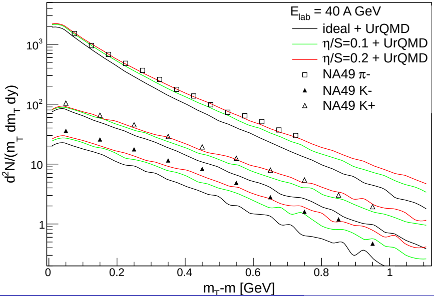
Results: $E_{\text{lab}} = 80, 40, 20$ A GeV Pb-Pb (SPS)

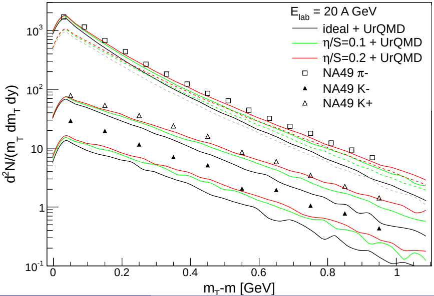
Corresp. $\sqrt{s_{NN}} = 12.3,\ 8.8,\ 6.3$ GeV

Pion & kaon pt-distributions for most central events ($c = 0 - 5\%$, $b = 0 \ldots 3.4$ fm)

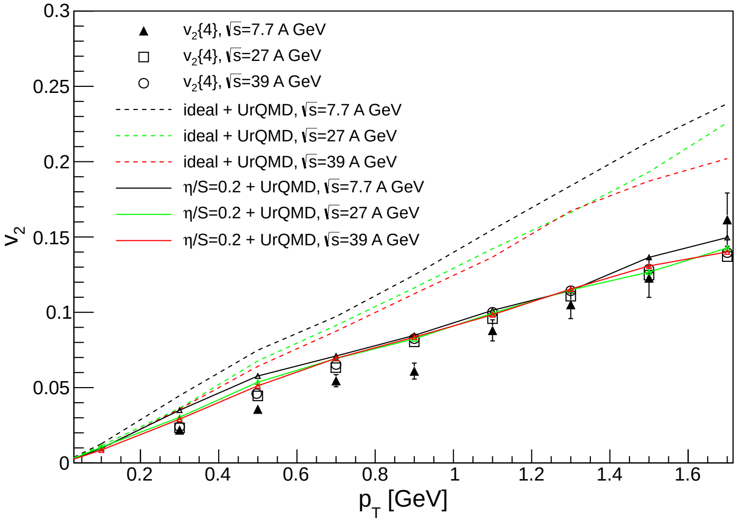
Overall good description with $\eta/S = 0.2$ except for K^- for lowest energies







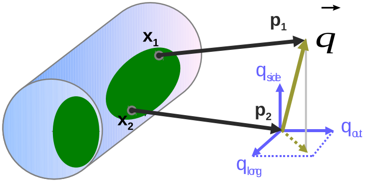
v_2 for BES at RHIC ($\sqrt{s_{NN}} = 7.7, 27, 39$ GeV Au-Au)



(20-30% central) $\eta/S \geq 0.2$ is required in hydro phase for all BES energies.

HBT(interferometry) measurements

The only tool for space-time measurements at the scales of 10^{-15}m, 10^{-23}s



$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

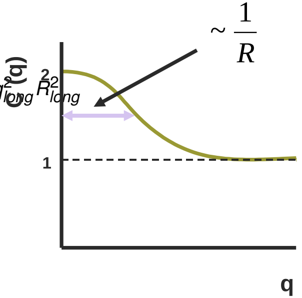
$$\vec{k} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2)$$

$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{\text{real event pairs}}{\text{mixed event pairs}}$$

Gaussian approximation of CFs ($q \to 0$):

$$C(\vec{k}, \vec{q}) = 1 + \lambda(k) e^{-q_{out}^2 R_{out}^2 - q_{side}^2 R_{side}^2 - q_{long}^2 R_{long}^2}$$

$R_{out}, R_{side}, R_{long}$ (HBT radii) correspond to *homogeneity lengths*, which reflect the space-time scales of emission process

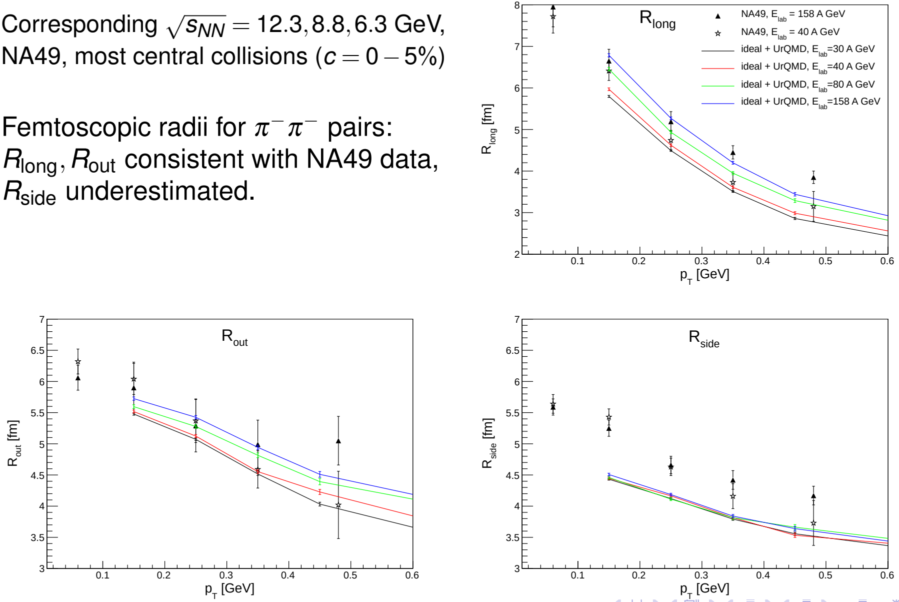


In an event generator, BE/FD two-particle amplitude (anti)symmetrization must be introduced

Femtoscopy at SPS energies

Corresponding $\sqrt{s_{NN}} = 12.3, 8.8, 6.3$ GeV, NA49, most central collisions ($c = 0 - 5\%$)

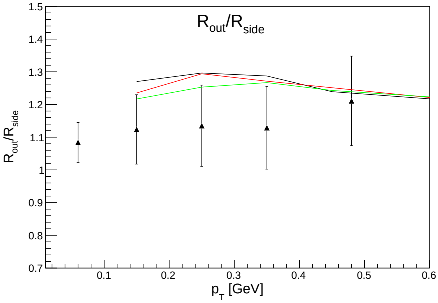
Femtoscopic radii for $\pi^- \pi^-$ pairs: $R_{\text{long}}, R_{\text{out}}$ consistent with NA49 data, R_{side} underestimated.

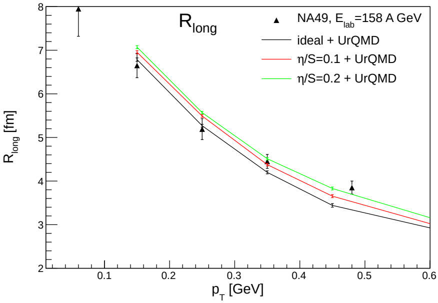


Femtoscopy at top SPS energy

$E_{\text{lab}} = 158$ A GeV SPS ($\sqrt{s_{NN}} = 17.3$ GeV)

Dependence on η/S

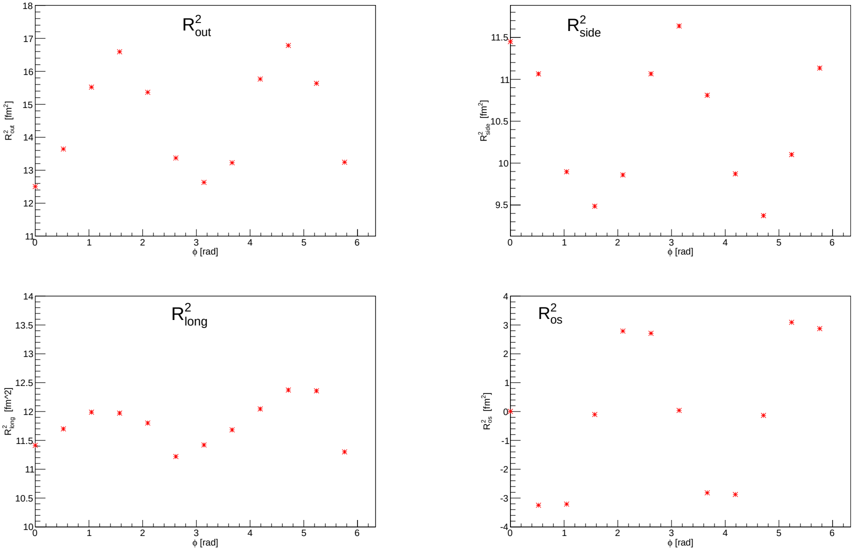




R_{long} is increased and $R_{\text{out}}/R_{\text{side}}$ is slightly improved by viscosity

Azimuthally-sensitive femtoscopy

$\sqrt{s_{NN}} = 7.7$ GeV, 10-30% central AuAu; $p_T = 0.15 \ldots 0.6$ GeV; $\phi = \psi_{\rm pair} - \Psi_{\rm RP}$



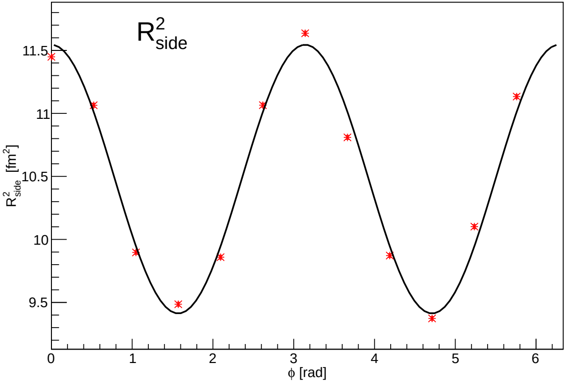
Azimuthally-sensitive femtoscopy

$$R_i^2(\phi) = R_{i,0}^2 + 2 \sum_{n=2,4,6\ldots} R_{i,n}^2 \cos(n\phi), \quad i = \text{out,side,long}$$

$$R_i^2(\phi) = 2 \sum_{n=2,4,6\ldots} R_{i,n}^2 \sin(n\phi), \quad i = \text{os}$$

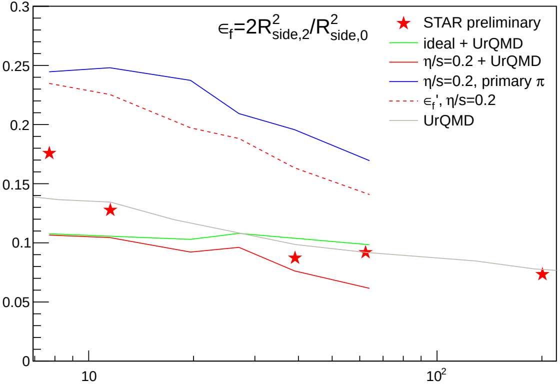
solid curve:
$R_{s,0}^2 + 2R_{s,2}^2 \cos(2\phi) \Rightarrow$

$$\varepsilon_f = 2\frac{R_{\text{side},2}^2}{R_{\text{side},0}^2}$$



F. Retiere and M. Lisa, Phys.Rev. **C**70:044907, 2004

Azimuthally-sensitive femtoscopy



STAR: C. Anson,
J.Phys. G**38**:124148,2011

10-30% central AuAu,
$p_T = 0.15 \ldots 0.6$ GeV

$$\varepsilon' = \frac{\int (y^2 - x^2) u^\mu \, d\sigma_\mu}{\int (y^2 + x^2) u^\mu \, d\sigma_\mu} \quad 1$$

[1] C. Shen, U. Heinz, Phys.Rev. C 85, 054902 (2012)
[2] UrQMD: M.A. Lisa, et al., New J.Phys.13:065006,2011

Rescatterings and resonance decays decrease the eccentricity

Summary

Viscous hydro + UrQMD model:

- 3+1D viscous hydrodynamics
- EoS at finite μ_B (Chiral model)

Conclusions:

- model validated at top RHIC energy, and applied for BES.
- shear viscosity in hydro phase improves description of
  - p_T-spectra
  - dN/dy
  - elliptic flow
  - femtoscopic radii
- v_2 from RHIC BES suggests $\eta/S \geq 0.2$

Summary

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Outlook:

- Effects of EoS with 1st order PT?

Thank you for your attention!

Extra slides

Viscous hydrodynamic equations

The hydrodynamic equations in arbitrary coordinate system:

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^{\mu}_{\nu\lambda} T^{\nu\lambda} + \Gamma^{\nu}_{\nu\lambda} T^{\mu\lambda} = 0 \quad (4)$$

where (we choose Landau definition of velocity)

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - (p + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu} \quad (5)$$

and $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

Evolutionary equations for shear/bulk, coming from Israel-Stewart formalism:

$$< u^\gamma \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma \quad (6a)$$

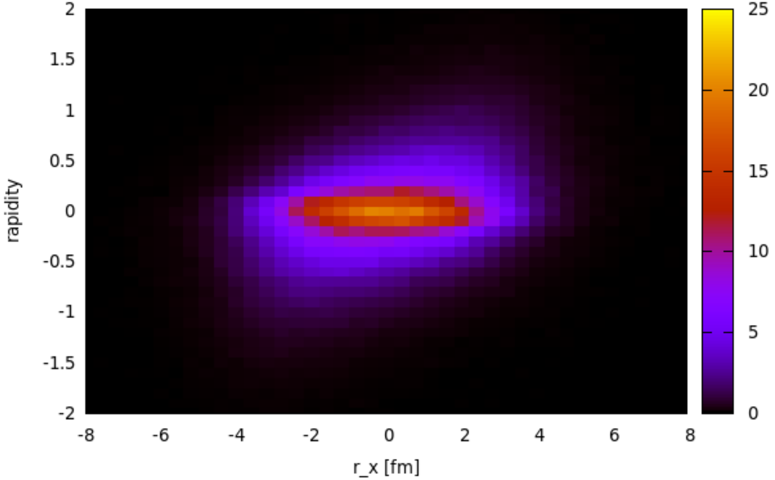
$$u^\gamma \partial_{;\gamma} \Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} - \frac{4}{3}\Pi\partial_{;\gamma}u^\gamma \quad (6b)$$

where

$$< A^{\mu\nu} >= (\frac{1}{2}\Delta^{\mu}_{\alpha}\Delta^{\nu}_{\beta} + \frac{1}{2}\Delta^{\nu}_{\alpha}\Delta^{\mu}_{\beta} - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta})A^{\alpha\beta}$$

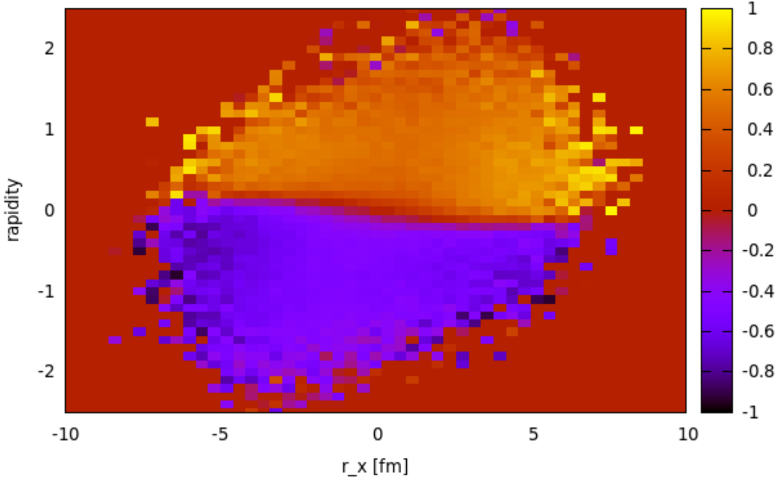
Typical smooth (event-averaged) initial condition for $E_{lab} = 168$ A GeV midcentral SPS collisions.

energy density [GeV/fm^3] distribution:



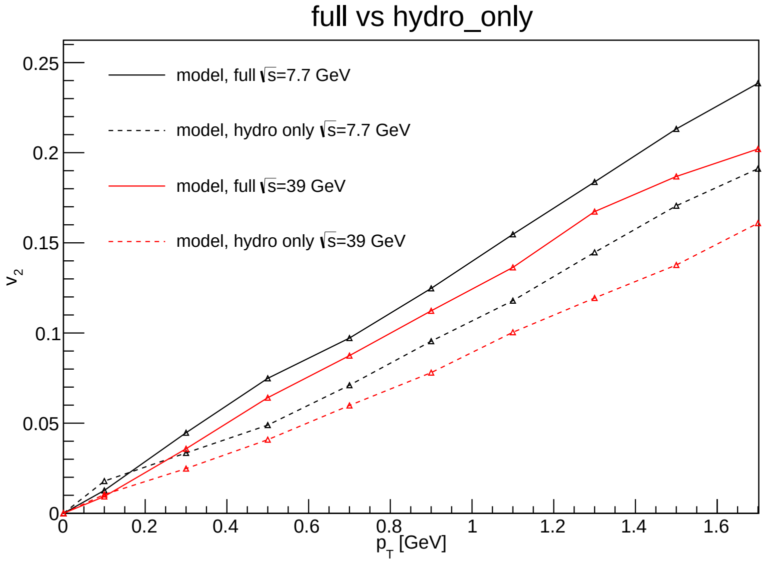
Typical smooth (event-averaged) initial condition for $E_{\rm lab} = 168$ A GeV midcentral SPS collisions.

v_η distribution (notice nonzero angular momentum!):



v_2 before and after the cascade

$\eta/S = 0$

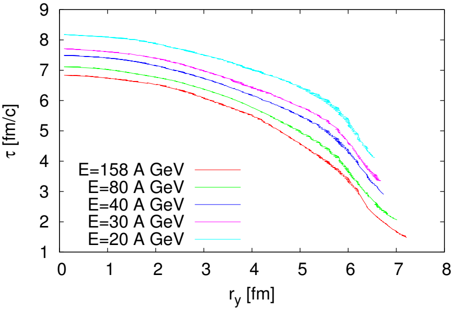


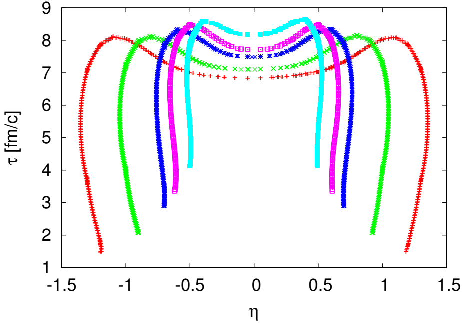
Transition surfaces

hydro→cascade transition

Most central collisions,
$E_{\text{lab}} = 20$ GeV (cyan)...158 GeV (red)
$\sqrt{s_{NN}} = 6.27 \ldots 17.3$ GeV

Transition criterion: $\varepsilon = \varepsilon_{\text{crit}} = 0.5$ GeV/fm^3, same for all energies





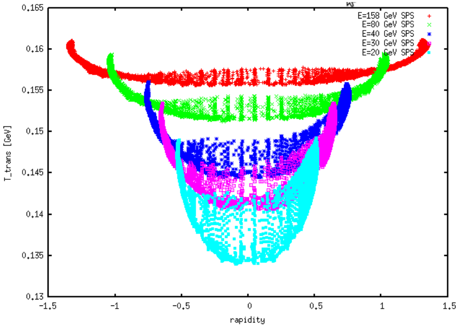
System squeezes in rapidity with decreasing collision energy,
hydro phase still lasts about 4.5 fm/c at lowest SPS energy.

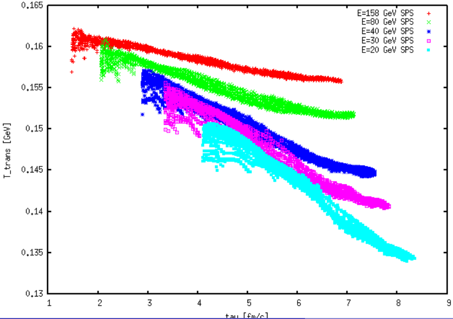
Thermodynamics on transition surface

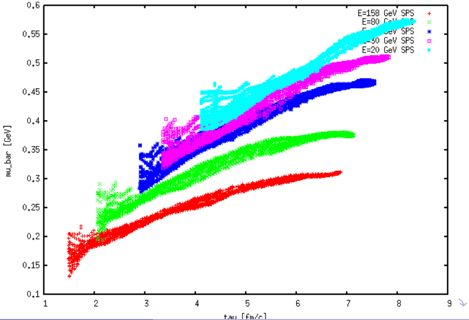
Procedure (for each surface element):

$$\{\varepsilon = \varepsilon_{\text{crit}}, n_B, n_Q\} \xrightarrow{EoS} \{T, \mu_B, \mu_Q, \mu_S\}$$

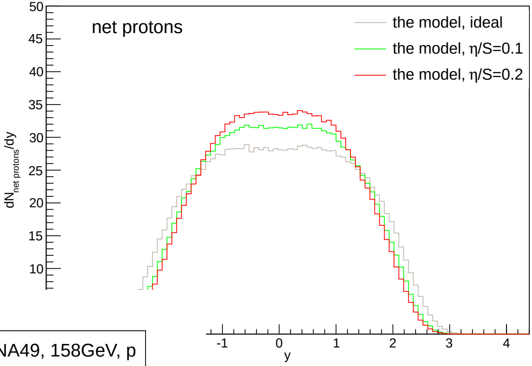
Most central collisions,
$E_{\text{lab}} =$20 GeV (cyan)...158 GeV (red)
T(rapidity) (top), $T(\tau)$ (bottom left), $\mu_B(\tau)$ (bottom right)





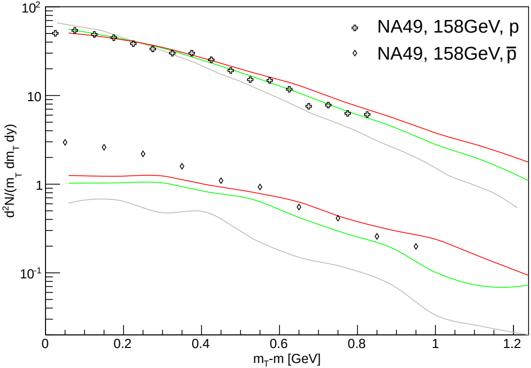


Results: 158 GeV SPS



protons & antiprotons

most central events
$(b = 0..3.4$ fm)

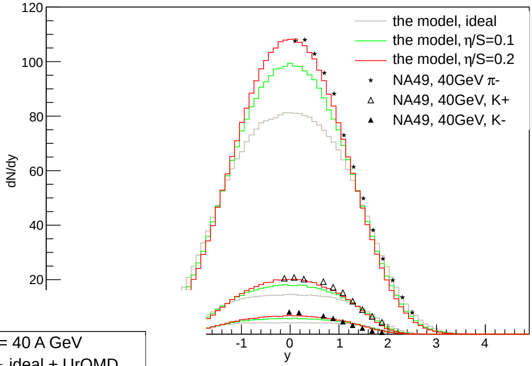


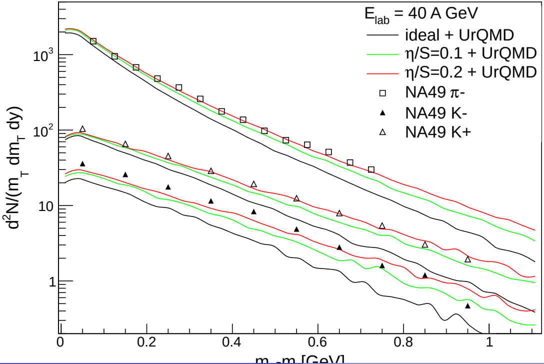
Hydrodynamic
$\tau_{start} = 1.42$ fm/c

Results: 40 GeV SPS

pions & kaons

most central events
($b = 0..3.4$ fm)



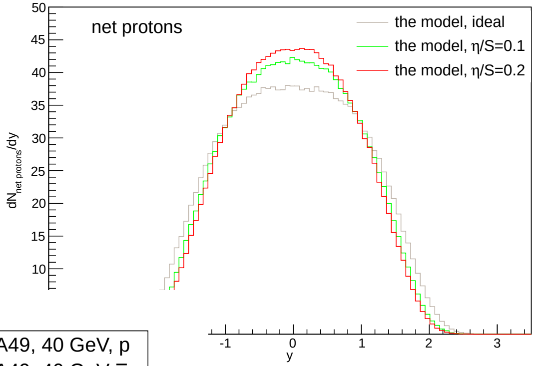


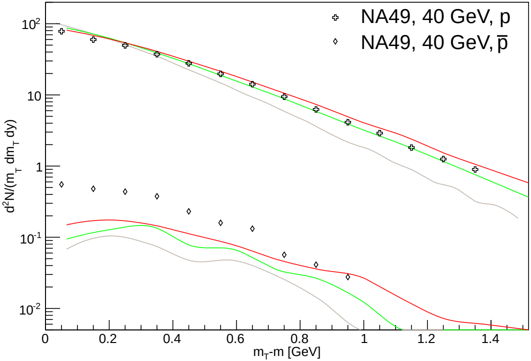
Hydrodynamic
$\tau_{start} = 2.83$ fm/c

Results: 40 GeV SPS

protons & antiprotons

most central events
($b = 0..3.4$ fm)



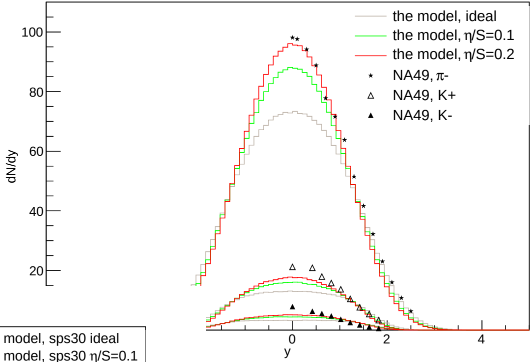


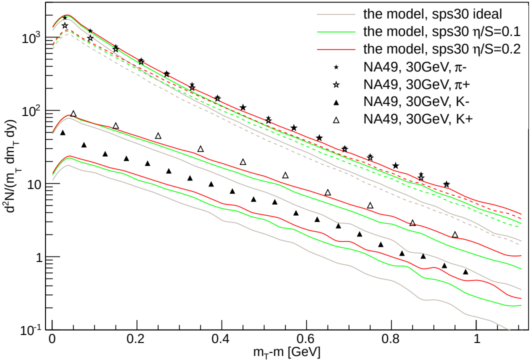
Hydrodynamic
$\tau_{\text{start}} = 2.83$ fm/c

Results: 30 GeV SPS

pions & kaons

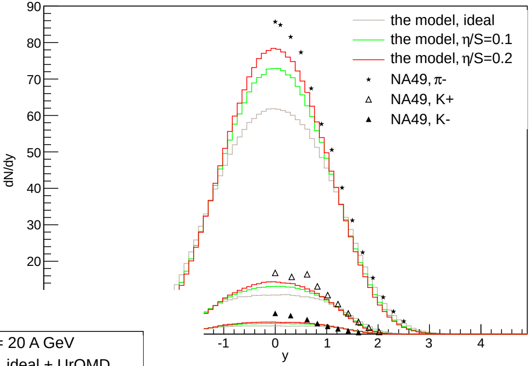
most central events
($b = 0..3.4$ fm)





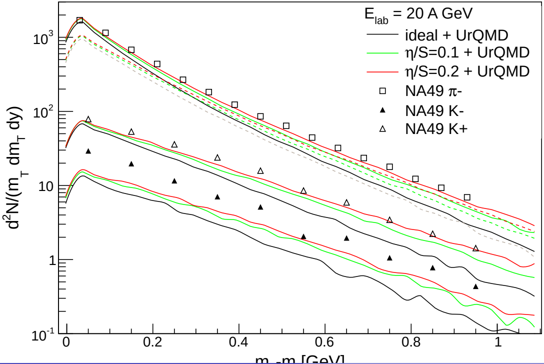
Hydrodynamic
$\tau_{\text{start}} = 3.28$ fm/c

Results: 20 GeV SPS



pions & kaons

most central events
($b = 0..3.4$ fm)



Hydrodynamic
$\tau_{start} = 4.05$ fm/c