Beam energy scan using a viscous hydro+cascade model

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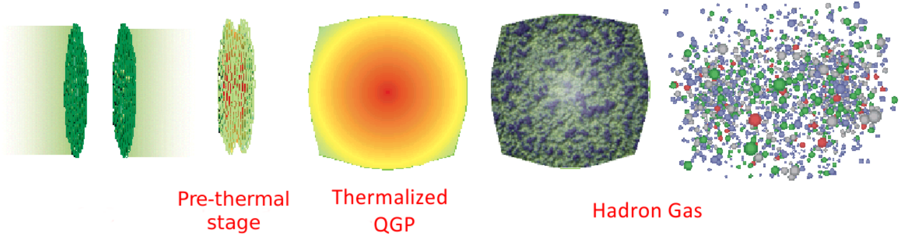
In collaboration with M. Bleicher, P. Huovinen, H. Petersen

Viscous hydro+cascade model

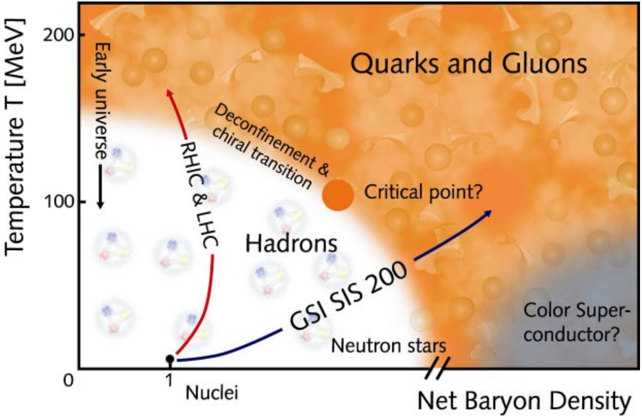


- 3D initial conditions at $\tau = \sqrt{t^2 - z^2} = \tau_0$
- 3+1D viscous hydrodynamic code
- transition surface from hydro to cascade: Cornelius algorithm [1]
- particle sampling according to DFs with non-equilibrium corrections from shear viscosity
- cascade: UrQMD

[1] authors: Pasi Huovinen and Hannu Holopainen

Reference: P. Huovinen, H. Petersen, arXiv:1206.3371 (published in EPJA)

Where do we want to apply it



Equation of state from Chiral model[2] 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

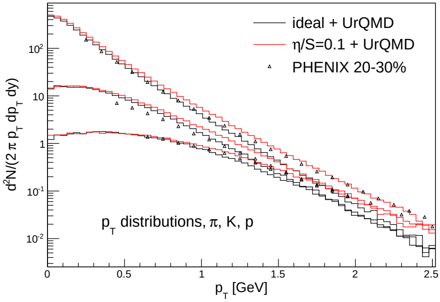
[2] J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G 38, 035001 (2011).

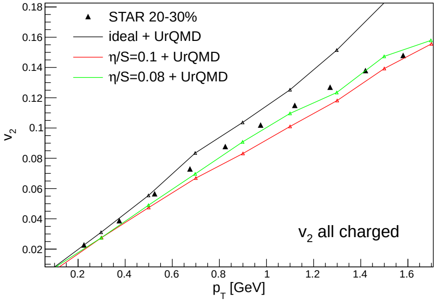
Validation at top RHIC energy

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 $dN_{\mathrm{ch}}/d\eta$)

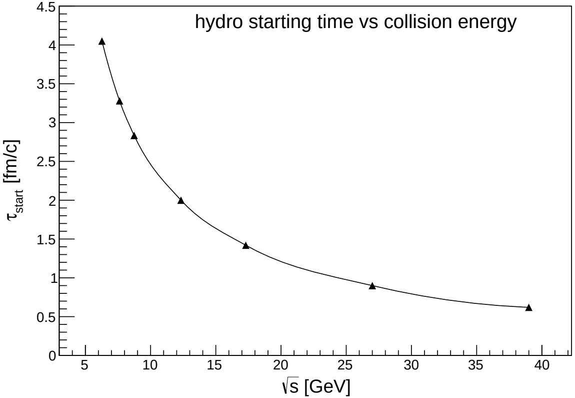




Beam energy scan (BES)

Initial conditions for hydrodynamic evolution

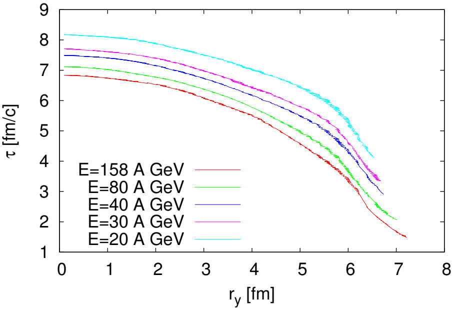
We generate smooth(event-averaged) 3D initial conditions from UrQMD.
Time to switch from particle to fluid description: $\tau = \frac{2R}{\gamma v_z} = \frac{2R}{\sqrt{(\sqrt{s}/2m_N)^2 - 1}}$
($t = 0$ when first NN collision happens)



Particle energies/momenta are converted to fluid $T^{\mu\nu}$ at $\tau = \tau_0$ hypersurface

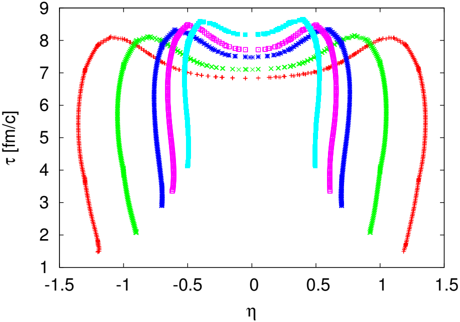
Transition surfaces

hydro→cascade transition



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

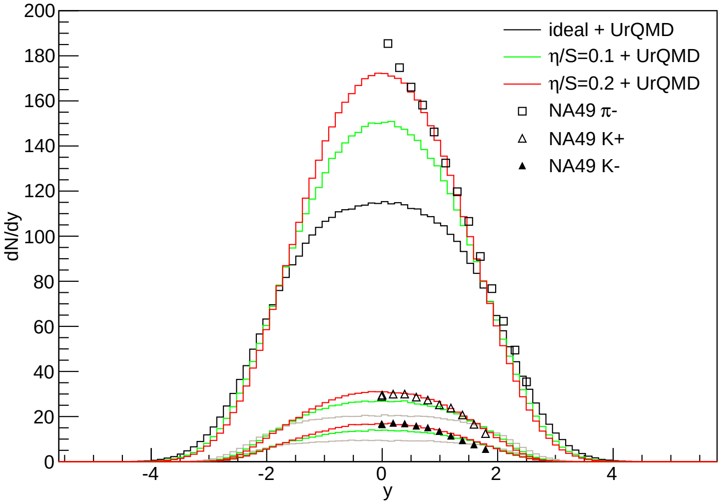
Transition criterion: $\varepsilon = \varepsilon_{\text{crit}} = 0.5$ GeV/fm^3, same for all energies



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

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

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



$\rightarrow$ strong viscous entropy production

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

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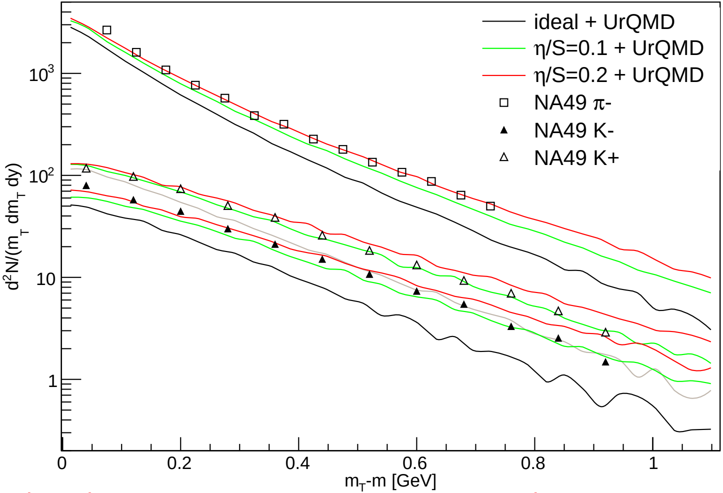
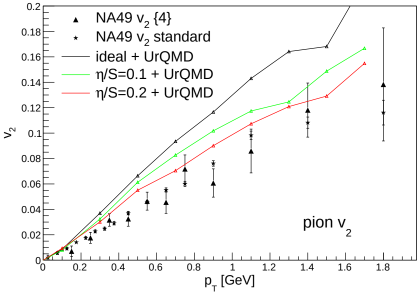
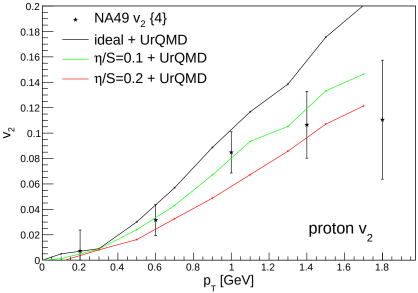


→ viscosity causes stronger transverse expansion

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

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



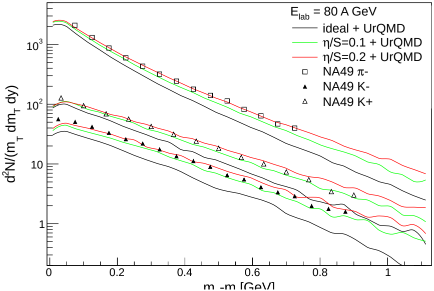


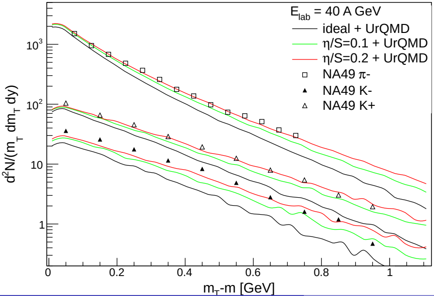
Results: $E_{\rm lab} = 80, 40, 20$ A GeV Pb-Pb (SPS)

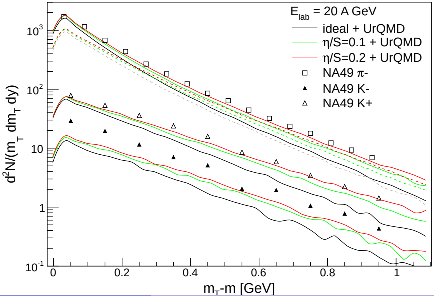
Corresp. $\sqrt{s} = 12.3,\ 8.8,\ 6.3$ A GeV

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

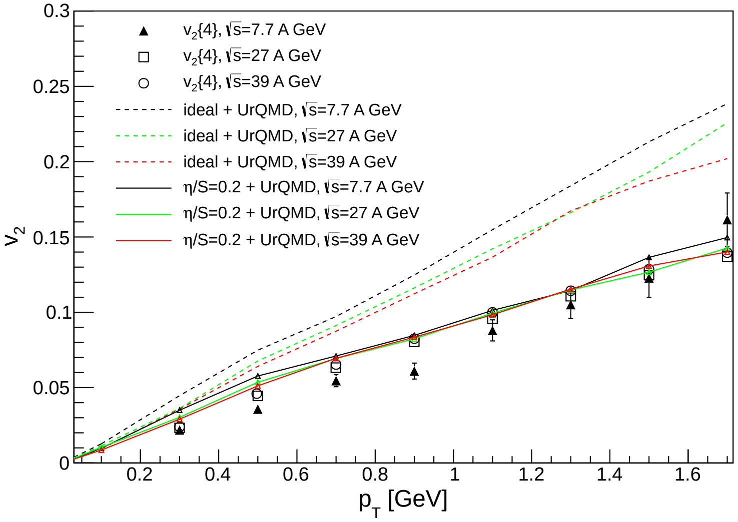
Overall good description with $\eta / S = 0.2$ except for K^- for lowest energies





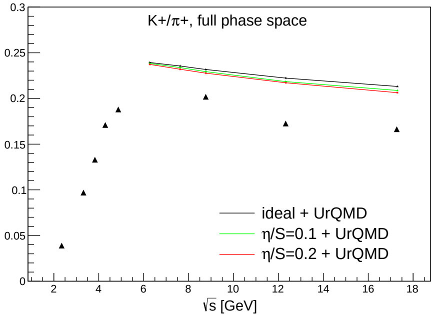


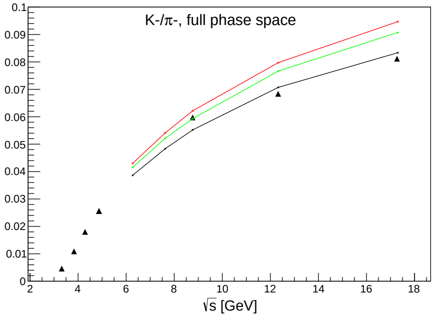
v_2 for BES at RHIC ($\sqrt{s} = 7.7, 27, 39$ A GeV Au-Au)



$\eta/S \geq 0.2$ is required in hydro phase for all BES energies.

K^+/π^+, K^-/π^- vs collision energy





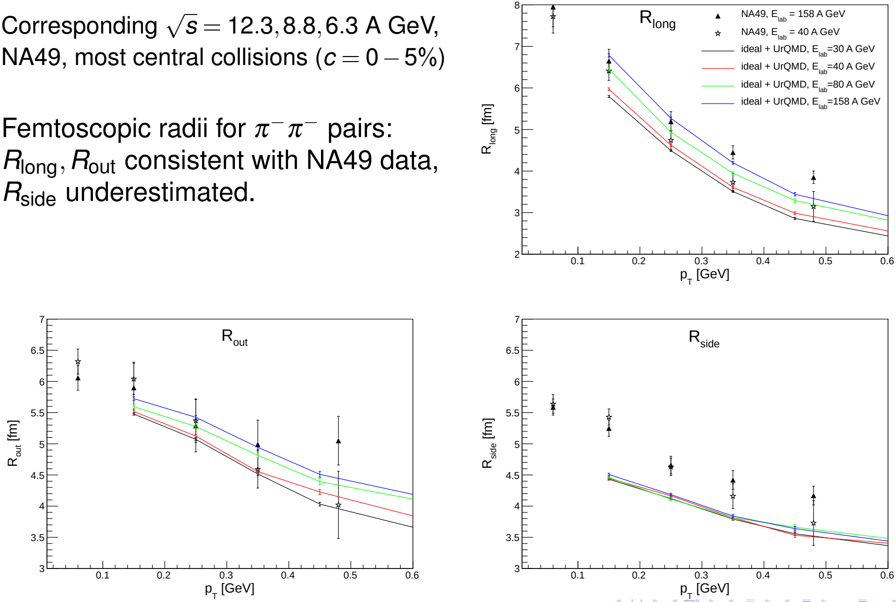
points: exp. data (from AGS, NA49, PHENIX)

$K+/\pi+$ decreases and $K-/\pi-$ increases due to additional entropy production in viscous hydro phase

Femtoscopy at SPS energies

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

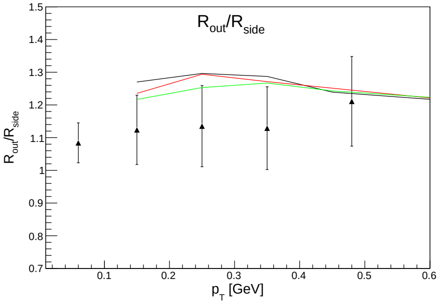
Femtoscopic radii for $\pi^- \pi^-$ pairs: $R_{\text{long}}, R_{\text{out}}$ consistent with NA49 data, R_{side} underestimated.

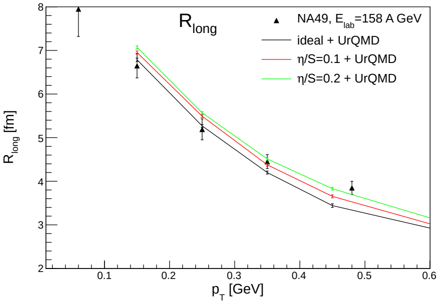


Femtoscopy at top SPS energy

$E_{lab} = 158$ A GeV SPS ($\sqrt{s} = 17.3$ A GeV)

Dependence on η/S





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

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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Thank you for your attention!

Extra slides

Viscous hydrodynamic equations

The hydrodynamic equations in arbitrary coordinate system:

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^{\mu}_{\nu\lambda} T^{\nu\lambda} + \Gamma^{\nu}_{\nu\lambda} T^{\mu\lambda} = 0 \tag{1}$$

where (we choose Landau definition of velocity)

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

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

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

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

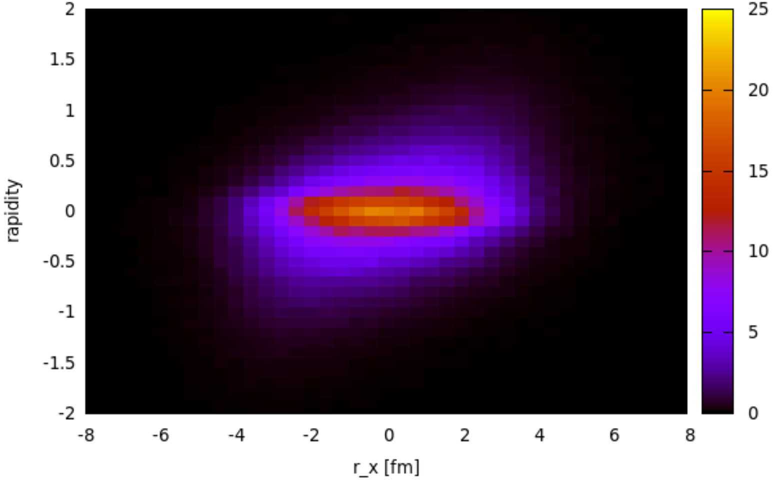
$$u^\gamma \partial_{;\gamma} \Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} - \frac{4}{3} \Pi \partial_{;\gamma} u^\gamma \tag{3b}$$

where

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

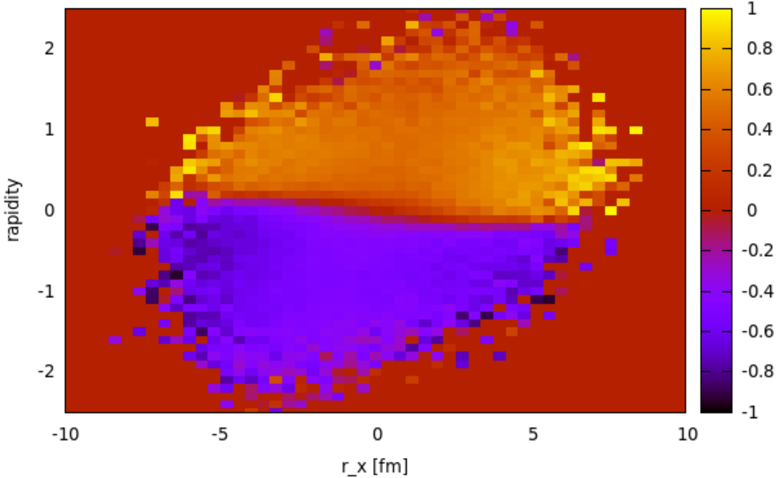
Typical smooth (event-averaged) initial condition for $E_{lab} = 168$ A GeV midcentral SPS collisions.

energy density [GeV/fm^3] distribution:



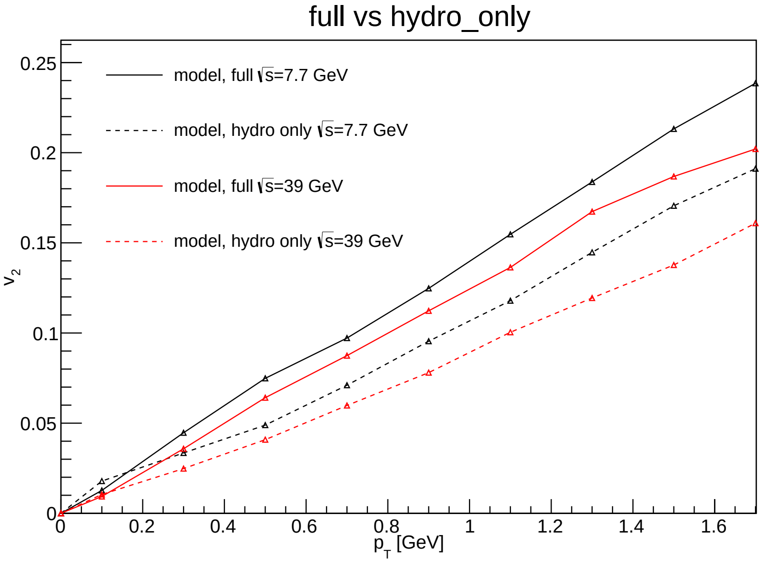
Typical smooth (event-averaged) initial condition for $E_{\text{lab}} = 168$ A GeV midcentral SPS collisions.

v_η distribution (notice nonzero angular momentum!):



v_2 before and after the cascade

$\eta/S = 0$



Thermodynamics on transition surface

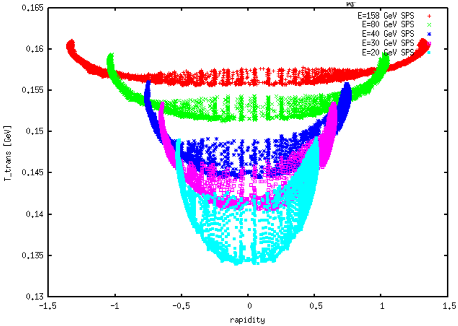
Procedure (for each surface element):

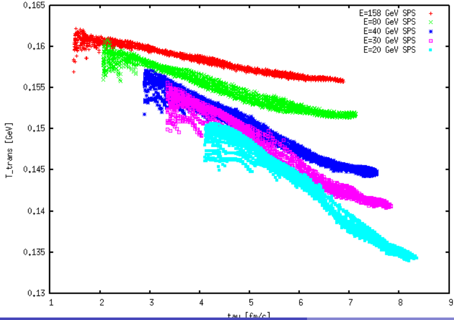
$$\{\varepsilon = \varepsilon_{\text{crit}}, n_B, n_Q\} \xrightarrow{EoS} \{T, \mu_B, \mu_Q, \mu_S\}$$

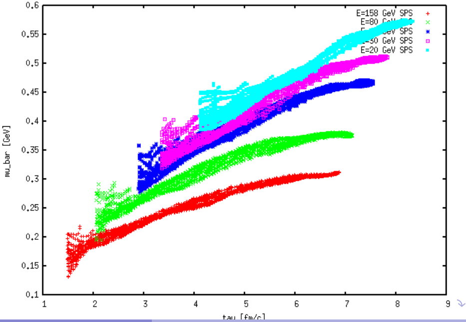
Most central collisions,

E_{lab} =20 GeV (cyan)...158 GeV (red)

T(rapidity) (top), $T(\tau)$ (bottom left), $\mu_B(\tau)$ (bottom right)



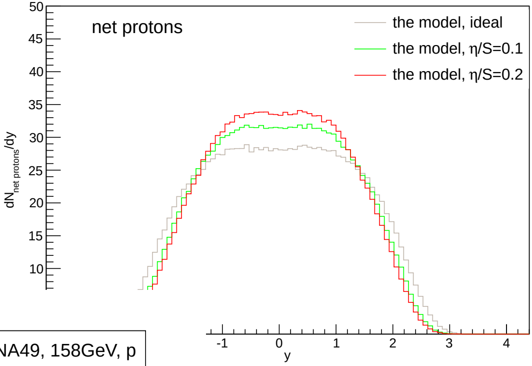


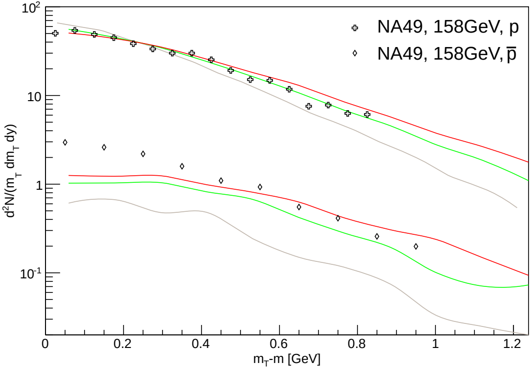


Results: 158 GeV SPS

protons & antiprotons

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



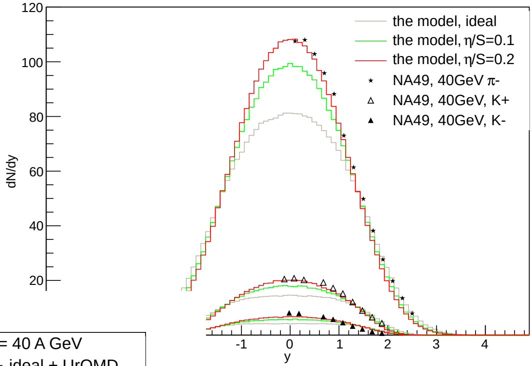


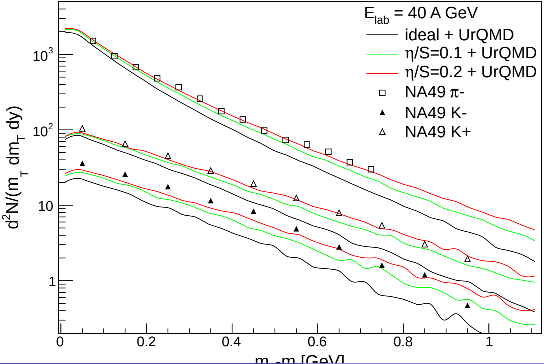
Hydrodynamic
$\tau_{start} = 1.42$ fm/c

Results: 40 GeV SPS

pions & kaons

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



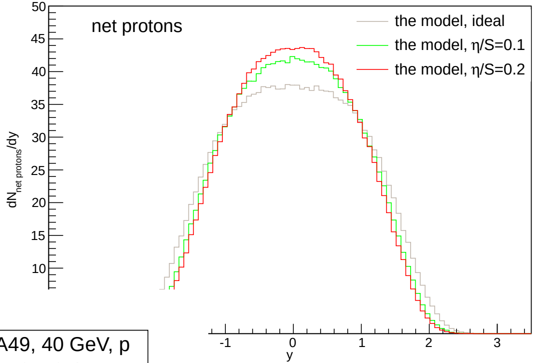


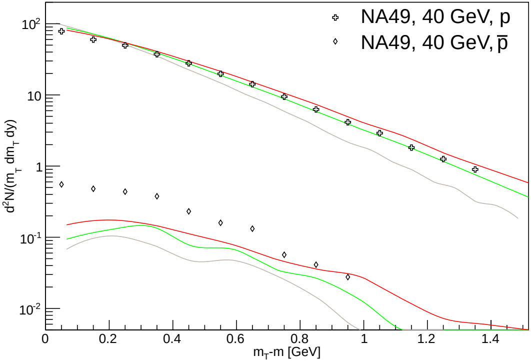
Hydrodynamic
$\tau_{start} = 2.83$ fm/c

Results: 40 GeV SPS

protons & antiprotons

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



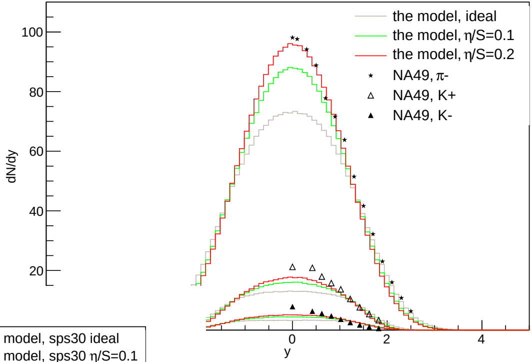


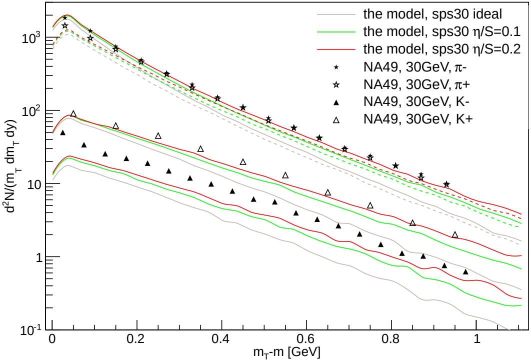
Hydrodynamic
$\tau_{\text{start}} = 2.83$ fm/c

Results: 30 GeV SPS

pions & kaons

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



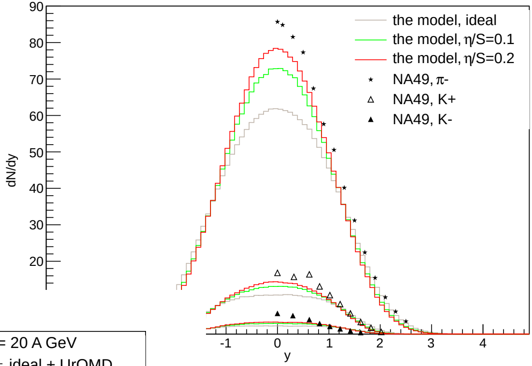


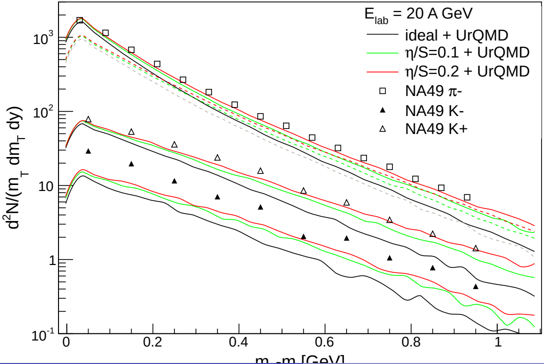
Hydrodynamic
$\tau_{\text{start}} = 3.28$ fm/c

Results: 20 GeV SPS

pions & kaons

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





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