Beam energy scan using a viscous hydro+cascade model: an update

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Outline

- Motivation
- Model description
- Results 1: the first round of simulations
- Results 2: adjustment to the data
- Addition to Results 1: EoS dependence

Some lessons from Au-Au RHIC/ Pb-Pb LHC

- Hydrodynamic/hybrid approach works very well
- $\eta/s \approx 1/(4\pi)$ at top RHIC with Monte Carlo Glauber IC,
- and somewhat larger value for 2.76 TeV PbPb LHC
- However, there are large uncertainties in η/s extraction from the initial state model, quantities to fit, model parameters.

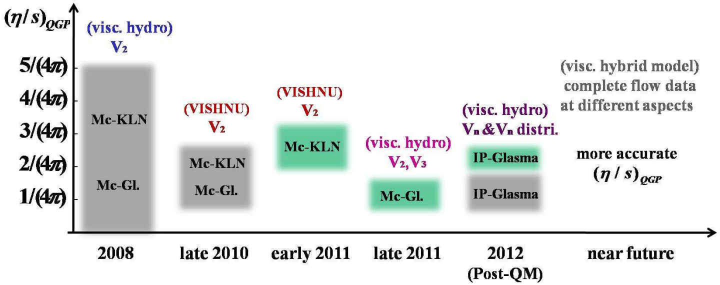
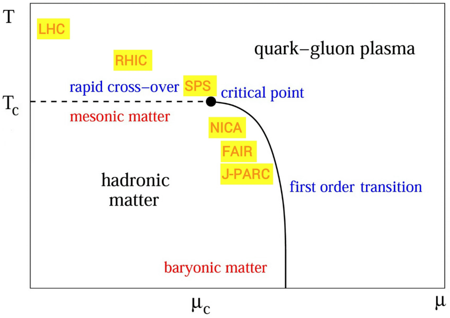


Figure: extracted η/s for top RHIC (grey bands), 2.76 TeV LHC (green bands).

Taken from Huichao Song, QM2012 proceedings `arXiv:1210.5578`

Motivation: apply a hybrid for RHIC BES, FAIR/NICA

to understand whether fluid is created at lower energies,
find its transport properties (η/s,...) and constrain EoS.



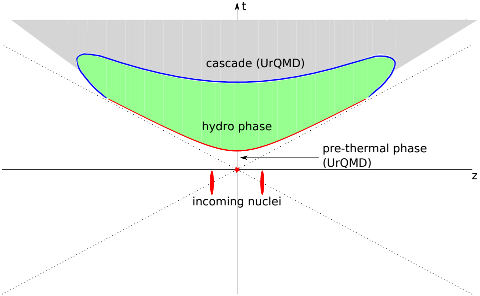
* plot provided by M. Gazdzicki

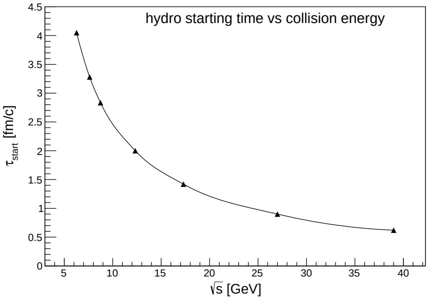
For Beam energy scan, we need a more elaborate model:

1. 3D (non-boost-invariant) fluctuating initial state
2. Baryon and electric charge densities
   - obtained from an initial state model
   - propagated in hydro phase and included in EoS
   - taken into account in particlization procedure

The model

Initial conditions for hydro phase





Pre-thermal phase: UrQMD

Hydro starts at $\tau = \sqrt{t^2 - z^2} = \tau_0$ (red curve):

$$\tau_0 = \frac{2R}{\gamma v_z}$$

At $\tau = \tau_0$ we deposit the energy/momentum, baryon and electric charge from particle to fluid cells:

$$\Delta P^{\alpha}_{ijk} = P^{\alpha} \cdot C \cdot \exp\left(-(\Delta x_i^2 + \Delta y_j^2)/R_\perp^2 - \Delta\eta_k^2 \gamma_\eta^2 \tau_0^2 / R_\eta^2 \right)$$

$$\Delta N^{0}_{ijk} = N^{0} \cdot C \cdot \exp\left(-(\Delta x_i^2 + \Delta y_j^2)/R_\perp^2 - \Delta\eta_k^2 \gamma_\eta^2 \tau_0^2 / R_\eta^2 \right)$$

Hydrodynamic phase

The hydrodynamic equations: local energy-momentum and charge conservation

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\nu\lambda} T^{\nu\lambda} + \Gamma^\nu_{\nu\lambda} T^{\mu\lambda} = 0, \quad \partial_{;\nu} N^\nu = 0 \tag{1}$$

where (we choose Landau definition of velocity)

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

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

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

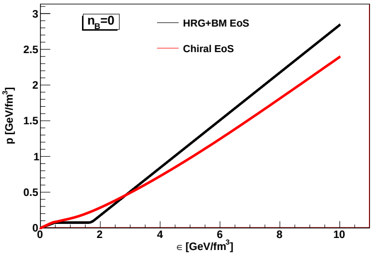
where $< A^{\mu\nu} >= (\frac{1}{2}\Delta^\mu_\alpha \Delta^\nu_\beta + \frac{1}{2}\Delta^\nu_\alpha \Delta^\mu_\beta - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta})A^{\alpha\beta}$

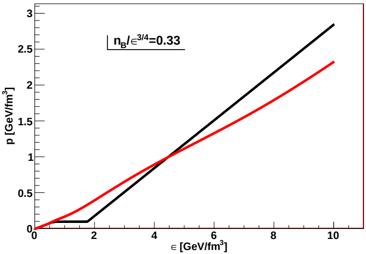
* Bulk viscosity $\zeta = 0$, charge diffusion=0

`vHLLE` code, see `arXiv:1312.4160` for the details of the code and its testing.

Equations of state for hydrodynamic phase

- Chiral model
  - coupled to Polyakov loop to include the deconfinement phase transition
  - good agreement with lattice QCD data at $\mu_B = 0$, also applicable at finite baryon densities
  - (current version) has crossover type PT between hadron and quark-gluon phase at all μ_B
- Hadron resonance gas + Bag Model (a.k.a. `EoS Q`)
  - hadron resonance gas made of u, d quarks including repulsive meanfield
  - the phases matched via Maxwell construction, resulting in 1^{st} order PT

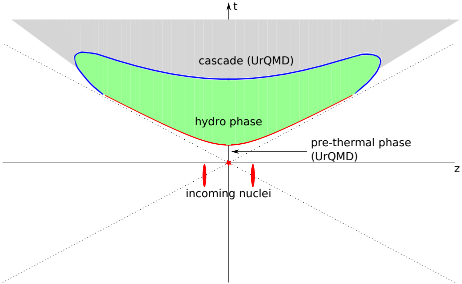




refs: J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G 38, 035001 (2011);
P.F. Kolb, J. Sollfrank, and U. Heinz, Phys.Rev. C 62, 054909 (2000).

Fluid→particle transition

$\varepsilon = \varepsilon_{sw} = 0.5$ GeV/fm^3 (blue curve):
$\{T^{0\mu}, N_b^0, N_q^0\}$ 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

Results 1

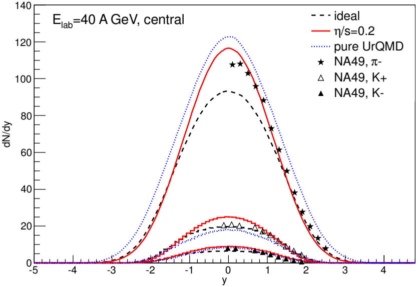
From the first round of simulations: fixed η/s, Chiral EoS

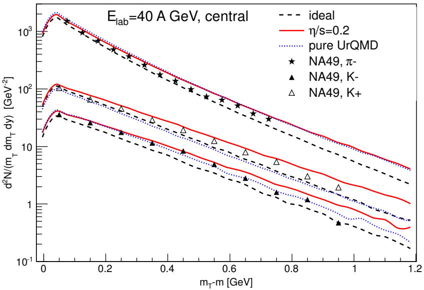
The rest of the parameters are fixed to their reasonable values:

$R_\perp = R_\eta = 1$ fm,
$\tau_0 = \max\left\{\frac{2R}{\gamma v_z}, 1\,\mathrm{fm/c}\right\}$
$\varepsilon_{\mathrm{sw}} = 0.5$ GeV/fm^3

Results: $E_{\mathrm{lab}} = 40$ A GeV Pb-Pb (SPS)

$\sqrt{s_{NN}} = 8.8$ GeV, 0-5% central collisions ($b = 0 \ldots 3.4$ fm) (Chiral EoS only)

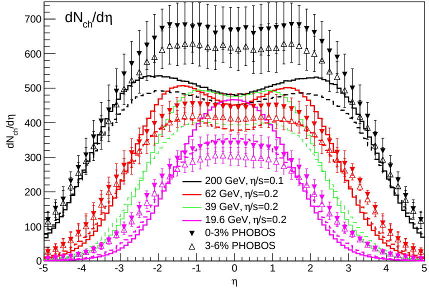


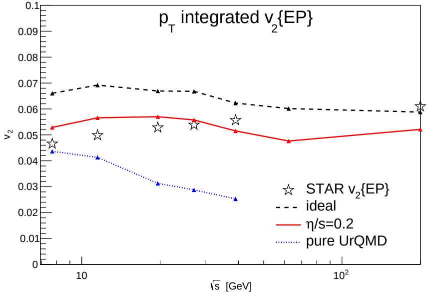


- viscous entropy production
- viscosity causes stronger transverse expansion

Going to $\sqrt{s} = 19.6 - 200$ GeV interval

Solid lines: $\eta/s = 0.2$ except for 200 GeV where $\eta/s = 0.1$





- fine tuning is needed for every collision energy individually

Results 2:

parameter adjustment to the data in BES region using Chiral EoS

!!! Observables in the model strongly depend on the details of the initial state for hydrodynamic expansion, because the hydro phase is shorter compared to full RHIC/LHC energies

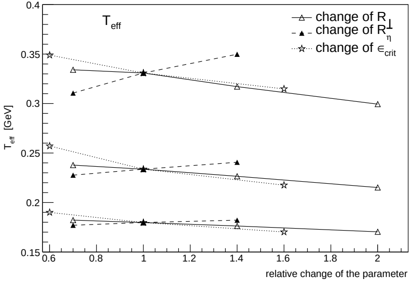
Parameter space exploration

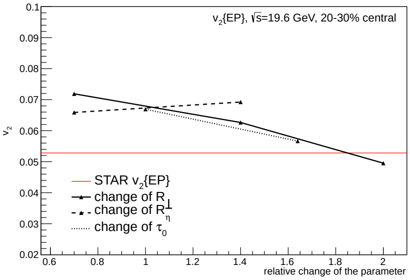
Response of the observables:

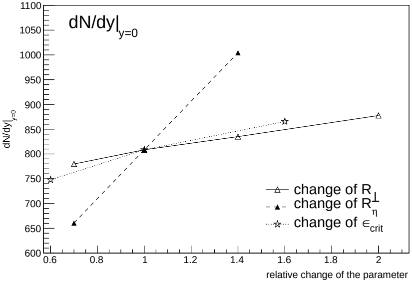
- $T_{\rm eff}$ from $\frac{dN}{m_T dm_T dy} = C \exp\left(-\frac{m_T}{T_{\rm eff}}\right)$ fit
- dN/dy in $|y<0.2|$
- p_T integrated elliptic flow $v_2\{\rm EP\}$

to the change of every individual parameter with respect to its default value.

Defaults: $\eta/s = 0$, $R_\perp = R_\eta = 1$ fm, $\varepsilon_{\rm crit} = 0.5$ GeV/fm^3.







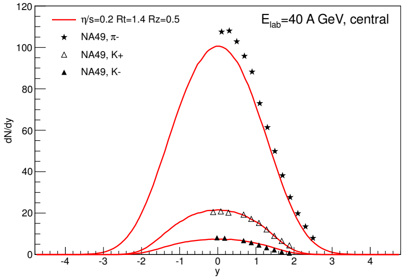
par. $\uparrow$	$R_\perp$	R_z	η/s	τ_0	$\varepsilon_{\rm crit}$
$T_{\rm eff}$	$\downarrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$
dN/dy	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$
v_2	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$

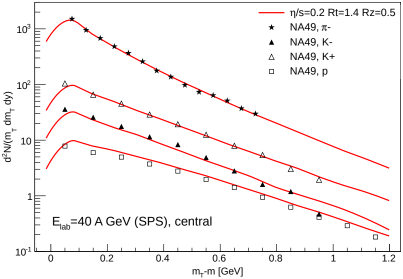
$\Downarrow$ adjusting to experimental data

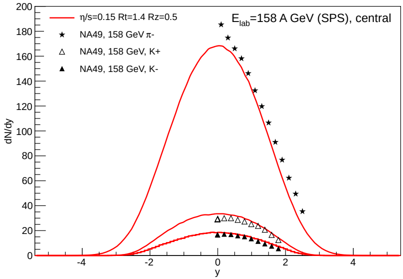
Energy dependent model parameters:

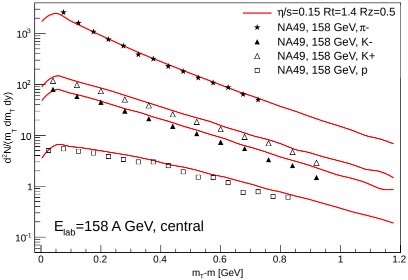
$\sqrt{s}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_z [fm]	η/s
7.7/8.8	3.2/2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
19.6/17.3	1.22/1.42	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

Results for 40 + 158 A GeV SPS

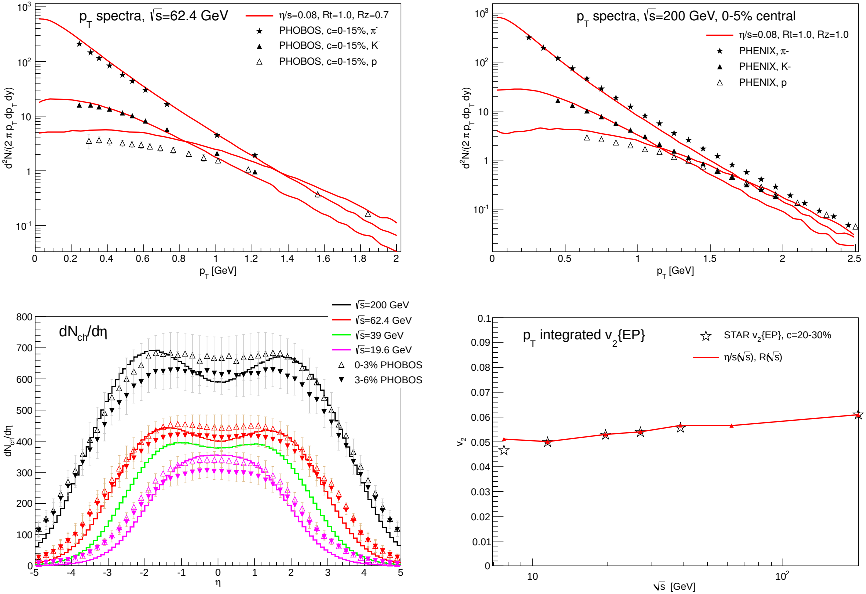




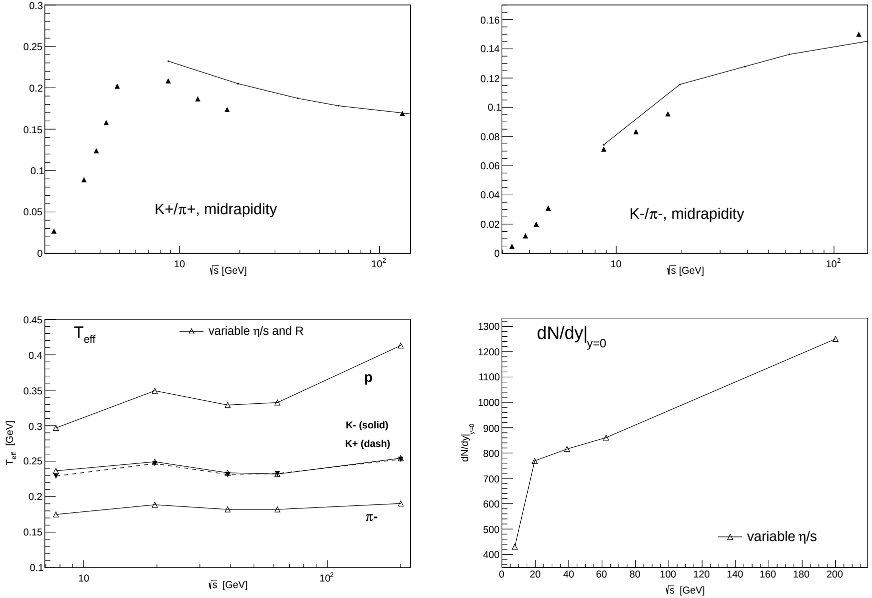




Results for RHIC BES + top RHIC

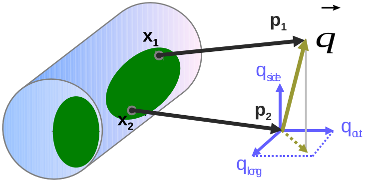


The Horn and the Step



HBT(interferometry) measurements

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



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

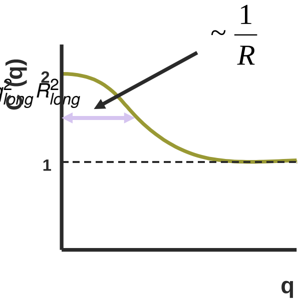
$$\vec{k} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2)$$

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

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

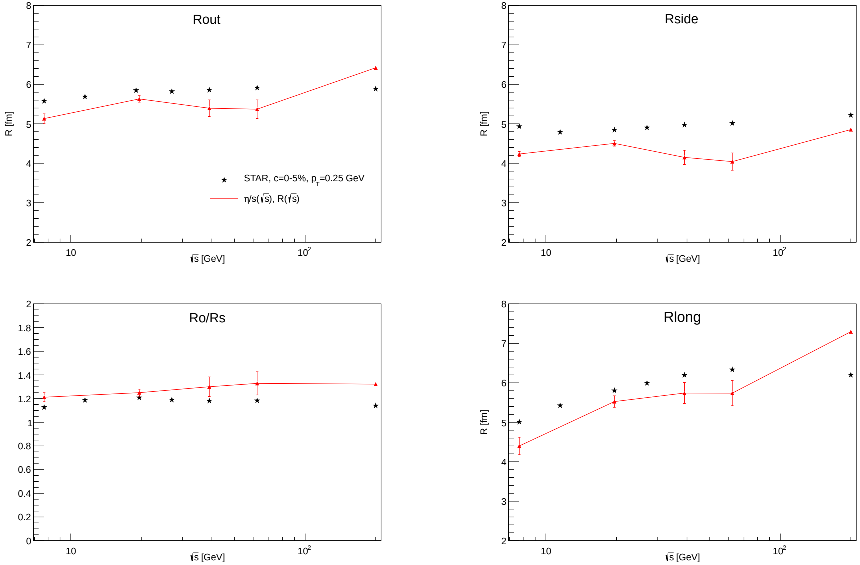
$$C(\vec{k}, \vec{q}) = 1 + \lambda(k) e^{-q_{out}^2 R_{out}^2 - q_{side}^2 R_{side}^2 - q_{long}^2 R_{long}^2}$$

$R_{out}, R_{side}, R_{long}$ (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

Femtoscopic radii



Addition to the Results 1:

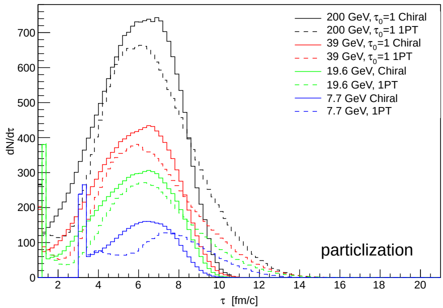
EoS dependence

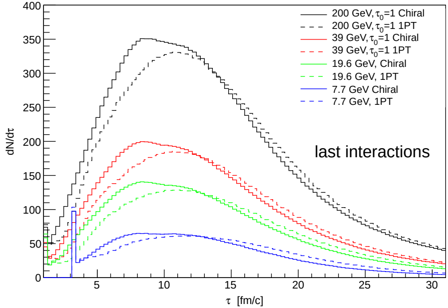
From the first round of simulations: fixed η/s,

$R_\perp = R_\eta = 1$ fm,
$\tau_0 = \max\left\{\frac{2R}{\gamma v_z}, 1\,\mathrm{fm/c}\right\}$
$\varepsilon_{\mathrm{sw}} = 0.5$ GeV/fm^3

Effects of the `EoS Q` compared to Chiral EoS?

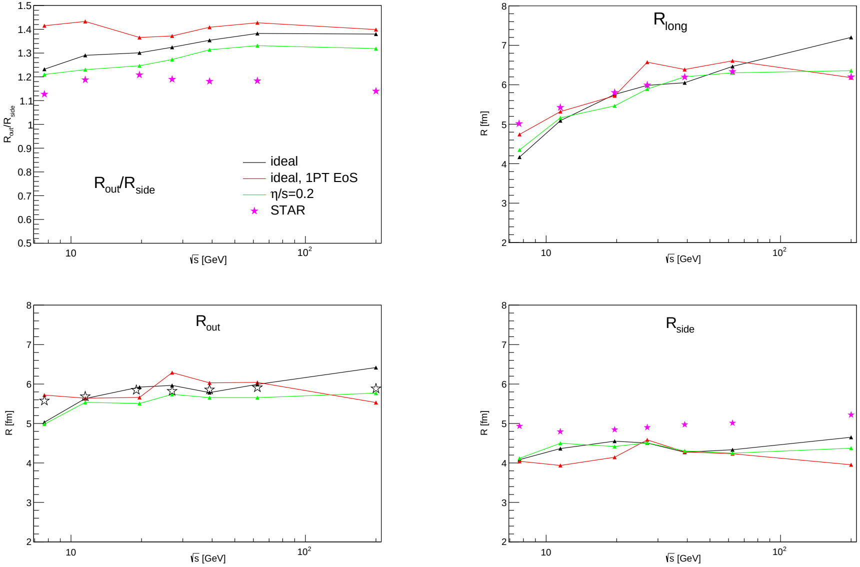
Yes: hydro phase in average lasts longer with `EoS Q`





Can we see it in femtoscopy (HBT), or any other observables?

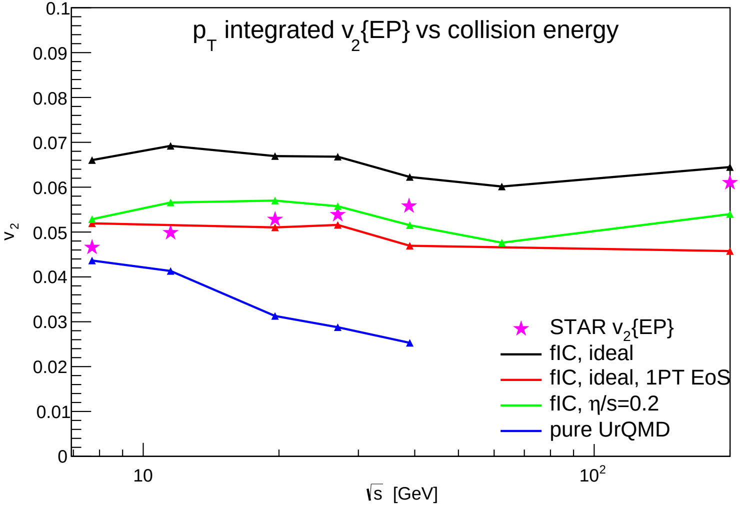
Femtoscopic radii: ideal hydro/Chiral EoS, ideal hydro/EoS Q, visc.hydro/Chiral EoS



Previous results for EoS dependence of HBT in hybrid UrQMD, see Q. Li et al., Phys.Lett.B674:111,2009

EoS dependence of the elliptic flow

ideal hydro/Chiral EoS, ideal hydro/EoS Q, visc.hydro/Chiral EoS, pure UrQMD



Summary

3+1D EbE viscous hydro + UrQMD model:

- pre-termal stage: UrQMD
- 3+1D viscous hydrodynamics, EbyE treatment
- EoS at finite μ_B: Chiral model, `EoS Q`

Conclusions:

- Model applied for $\sqrt{s_{NN}} = 7.7 \dots 200$ GeV A+A collisions.
- A fit to experimental data suggests $\eta/s = 0.2 \to 0.08$ when $\sqrt{s} = 7.7 \to 39$ GeV,
  modulo initial state (UrQMD) and EoS (Chiral model) used.
- This hints for μ_B dependent η/s or $\eta/(\varepsilon + p)$ being appropriate quantity.
- `EoS Q` is likely to be disfavored by the data (too small v_2 + too small $dN/d\eta$, slightly worse for HBT. Harder to compensate it by readjusting other model parameters)
- More experimental data and much more parameter space exploration is needed to extract η/s and other model parameters less ambiguously.

Work in progress.

Thank you for your attention!