Beam energy scan using a viscous hydro+cascade model

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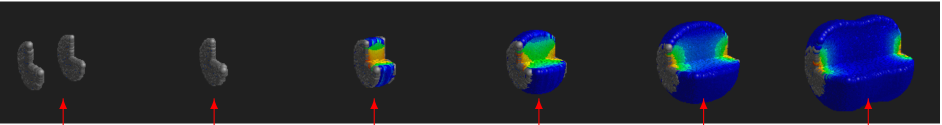
Theory and Modeling for the Beam Energy Scan, February 26-27, 2015

IK, Huovinen, Petersen, Bleicher, `arXiv:1502.01978`

Introduction: heavy ion collision in pictures

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



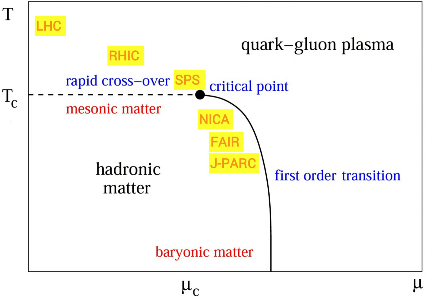
incoming nuclei — initial stage of the reaction — dense medium (QGP) — expansion — phase transition — hadrons

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

thermalization (initial state → hydrodynamic phase), particlization (hydrodynamic phase → hadronic cascade)

This study's 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 its EoS.

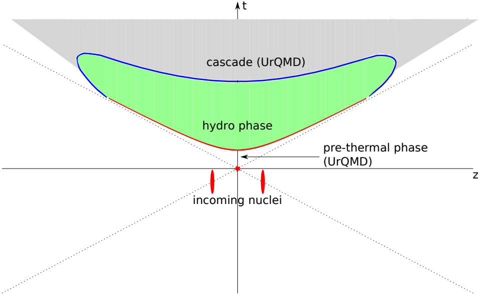


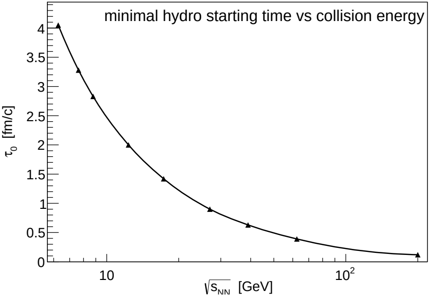
For Beam energy scan, we need a more elaborate model (vs. full RHIC):

1. 3D (non-boost-invariant) fluctuating initial state
   - CGC picture does not work as good as at full RHIC!
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 (pre-thermal) phase





Pre-thermal phase: UrQMD cascade [1],
which involves PYTHIA for $\sqrt{s} \gtrsim 10$ GeV scatterings

The scatterings are allowed until $\tau = \sqrt{t^2 - z^2} = \tau_0$ (red curve), $\tau_0 = \frac{2R}{\gamma v_z}$

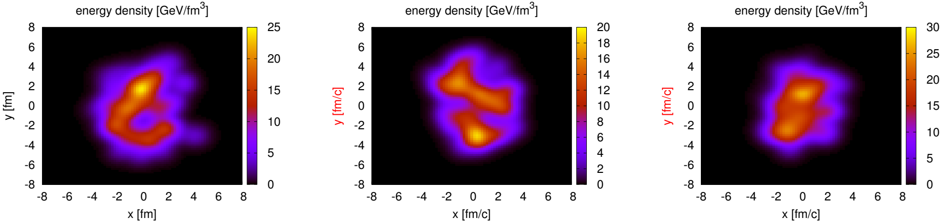
[1] M. Bleicher et al., J.Phys. G25 (1999) 1859-1896. `http://urqmd.org/`

“Thermalization”

At $\tau = \tau_0$ we deposit the energy/momentum P^α, baryon and electric charge N^0 of every particle into fluid cells:

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

Some typical initial energy density profiles in the transverse plane:



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:

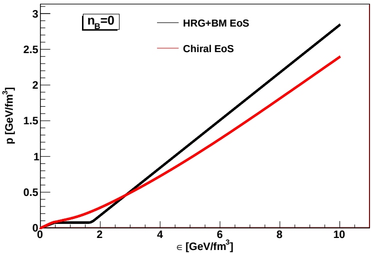
$$< u^\gamma \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\mathrm{NS}}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma \tag{3a}$$

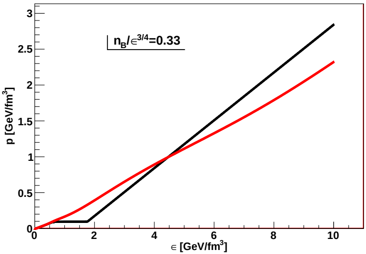
* Bulk viscosity $\zeta = 0$, charge diffusion=0

`vHLLE` code: IK, Huovinen, Bleicher, Comput. Phys. Commun. 185 (2014), 3016
`http://cpc.cs.qub.ac.uk/summaries/AETZ_v1_0.html`

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

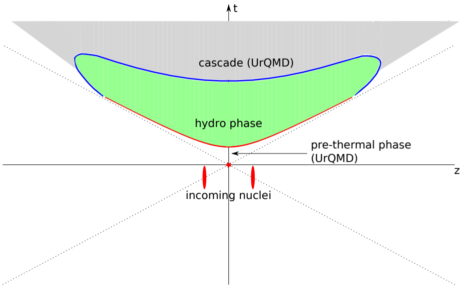




refs: J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G 38, 035001 (2011);
P.F. Kolb, J. Sollfrank, and U. Heinz, Phys.Rev. C 62, 054909 (2000).

Fluid$\rightarrow$particle transition and hadronic phase

$\varepsilon = \varepsilon_{sw} = 0.5$ GeV/fm^3 (blue curve), when the system is in hadronic phase:
$\{T^{0\mu}, N_b^0, N_q^0\}$ of hadron-resonance gas = $\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid



$\triangleright$ Momentum distribution from Landau/Cooper-Frye prescription:

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

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

$\triangleright$ Hadron gas phase: UrQMD cascade is employed after particlization surface.

*Huovinen and Petersen, *Eur.Phys.J.* A **48** (2012), 171

Results 1

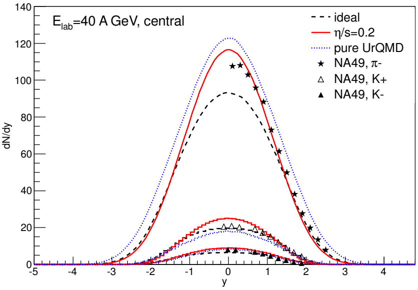
From the first round of simulations: fixed η/s, Chiral EoS

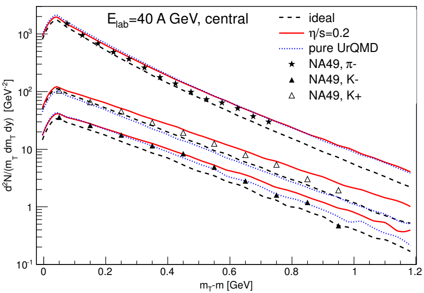
The rest of the parameters are fixed to their reasonable values:

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

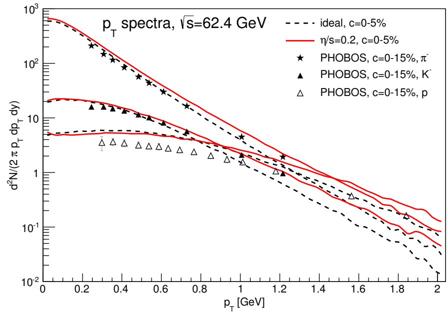
Results: $E_{\text{lab}} = 40$ A GeV Pb-Pb (SPS)

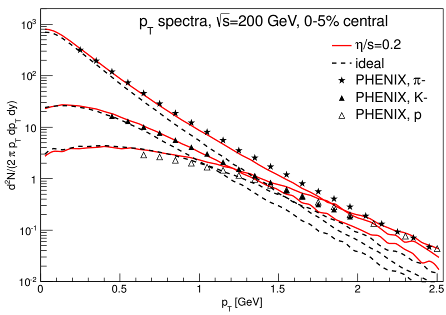
$\sqrt{s_{NN}} = 8.8$ GeV, 0-5% central collisions ($b = 0 \ldots 3.4$ fm)   (Chiral EoS only)





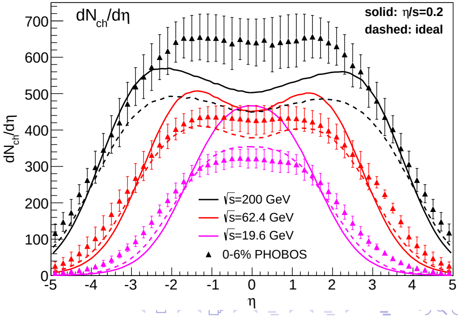
- viscous entropy production
- viscosity causes stronger transverse expansion



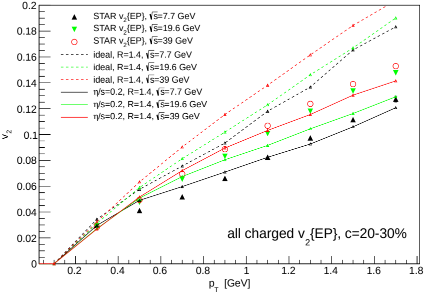


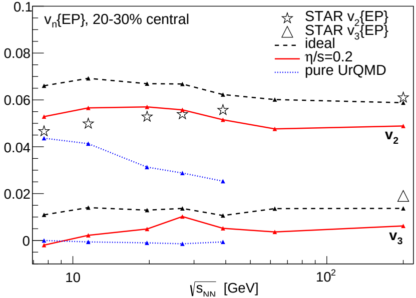
$dN/d\eta$+p_T **from existing RHIC data ($\sqrt{s_{NN}} = 19.6, 62.4, 200$ GeV Au-Au)**

Fine tuning is required for every energy individually to reproduce $dN/d\eta$ and v_2 (see next slide).



v_2 and v_3 at $\sqrt{s_{NN}} = 7.7\ldots200$ GeV Au-Au





- shear viscosity suppresses the elliptic flow (as expected)
- the suppression is too small for $\sqrt{s} < 30$ GeV and too large otherwise
- triangular flow is similarly suppressed

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

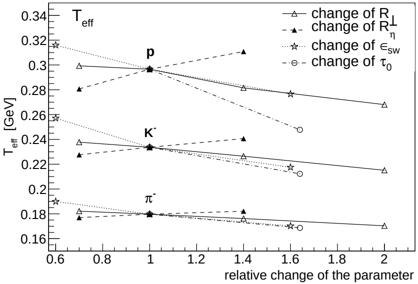
Parameter dependence

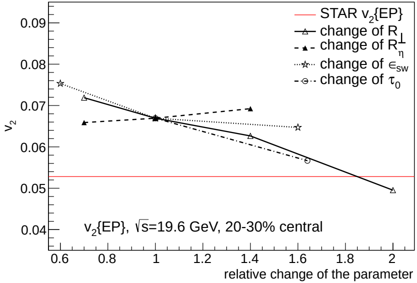
Response of the observables:

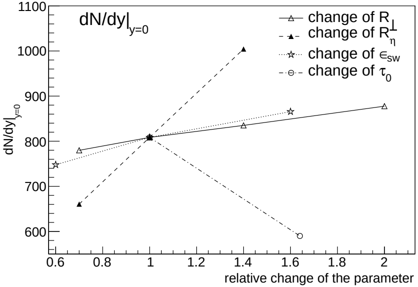
- T_{eff} from $\frac{dN}{m_T dm_T dy} = C \exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$ fit
- dN/dy in $|y < 0.2|$
- p_T integrated elliptic flow $v_2\{\text{EP}\}$

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

Defaults: $\eta/s = 0$, $R_\perp = R_\eta = 1$ fm, $\varepsilon_{\text{crit}} = 0.5$ 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	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$

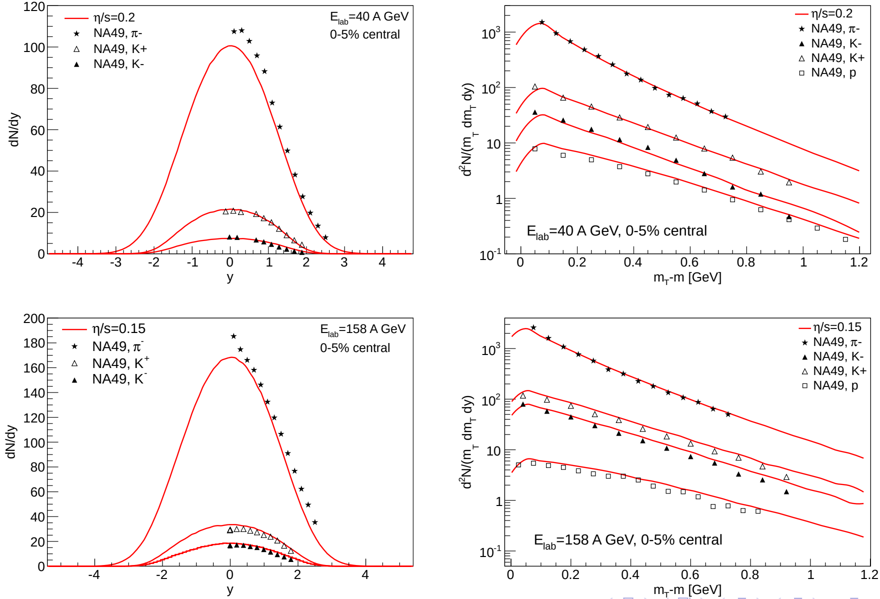
$\Downarrow$ visual adjustment to experimental data

Energy dependent model parameters:

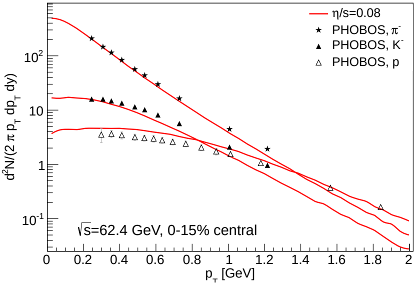
$\sqrt{s}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_z [fm]	η/s
7.7/8.8	3.2/2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
19.6/17.3	1.22/1.42	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

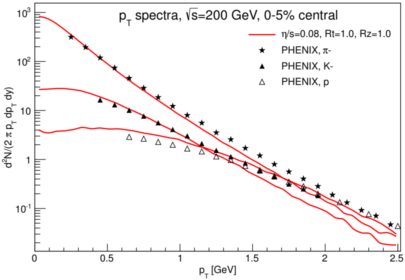
As a result...

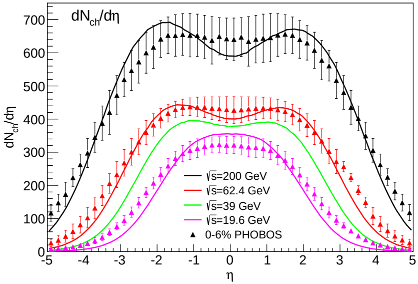
40 + 158 A GeV PbPb SPS ($\sqrt{s} = 8.8$ and 17.3 GeV)



RHIC BES + top RHIC

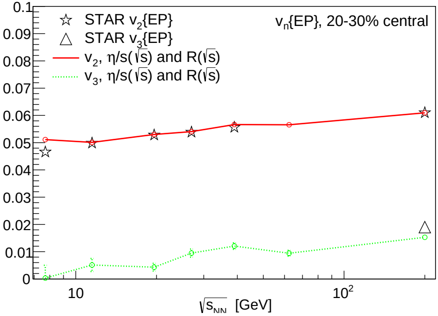






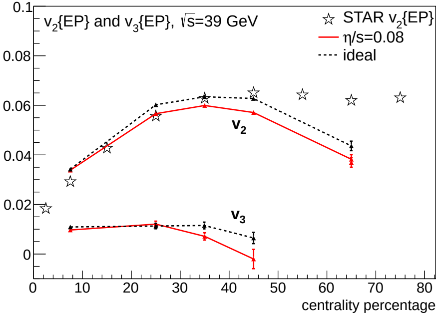
Elliptic and triangular flows at RHIC BES + top RHIC

v_2, v_3 vs collision energy



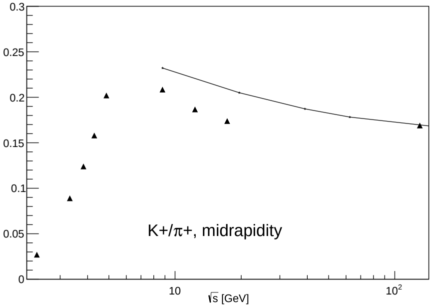
v_3: prediction!

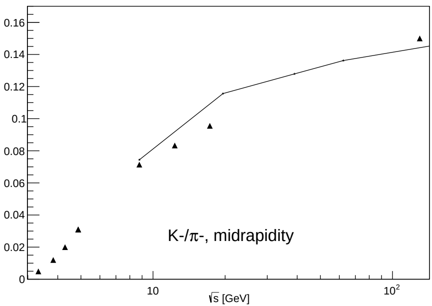
v_2, v_3 vs centrality



Peripheral events: the system is too small compared to the smearing radius, which results in decreased initial eccentricity ε_2.

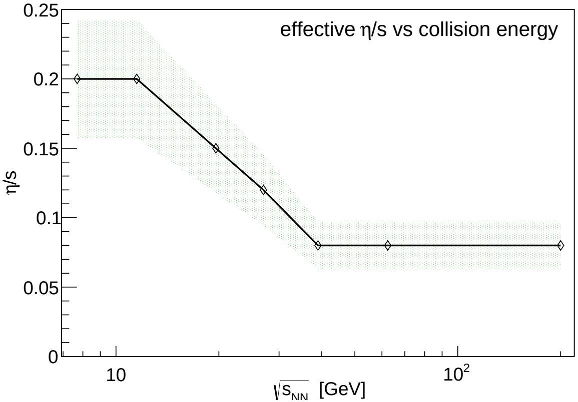
The Horn and the Step





An outcome of the adjustment to the data

Effective (constant) η/s in hydrodynamic phase



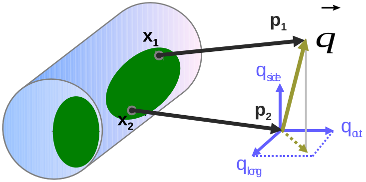
Green (error) band: estimated assuming that the parameters are varied such that v_2 stays the same and the inverse slope of p_T spectrum of protons changes within 5%.

! This is no actual error bar. That would require a proper χ^2 fitting of the model parameters (and enormous amount of CPU time).

Another prediction: femtoscopy

HBT(interferometry) measurements

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



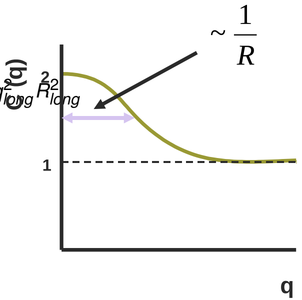
$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

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

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

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

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

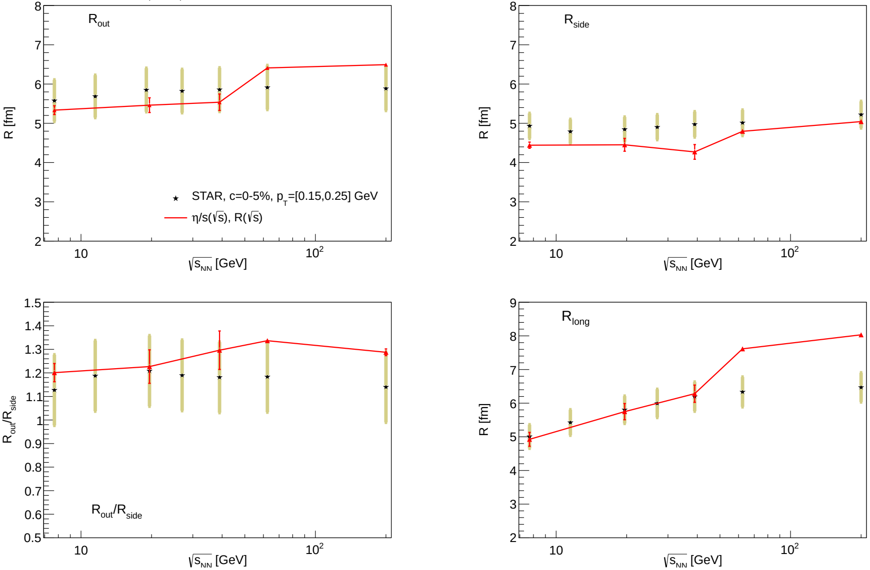


$R_{out}, R_{side}, R_{long}$ (HBT radii) correspond to *homogeneity lengths*, which reflect the space-time scales of emission process

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

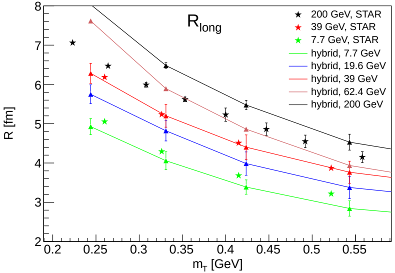
Femtoscopic radii from azimuthally integrated analysis

$\pi^-\pi^-$ pairs, $\langle k_T \rangle = 0.22$ GeV. Experimental data from STAR: `arXiv:1403.4972`



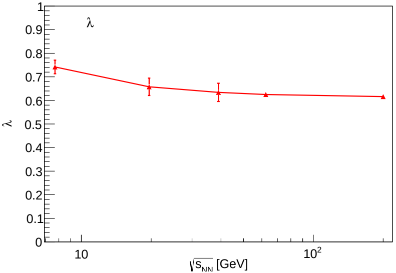
Theoretical error bars come from uncertainties in Gaussian fitting procedure

m_T dependence of $R_{\rm long}$



At higher energies, $R_{\rm long}$ at low-p_T overestimates the data

$\sqrt{s_{\rm NN}}$ dependence of the intercept parameter of the CF



Larger fraction of resonances produced at high energies, which lowers λ for pion pairs.

Addition to the Results 1:

EoS dependence

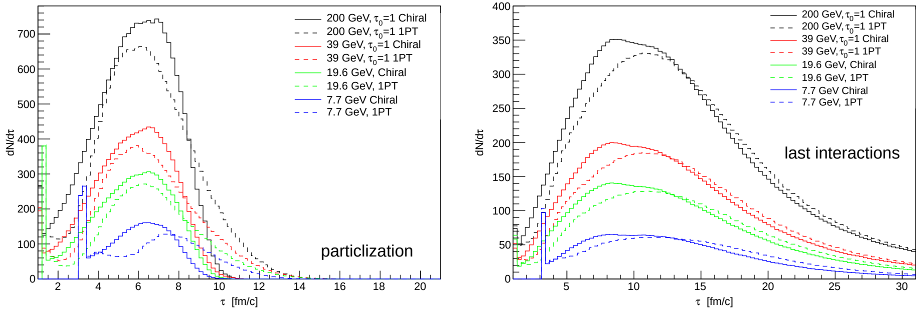
From the first round of simulations: fixed η/s,

$R_\perp = R_\eta = 1$ 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?

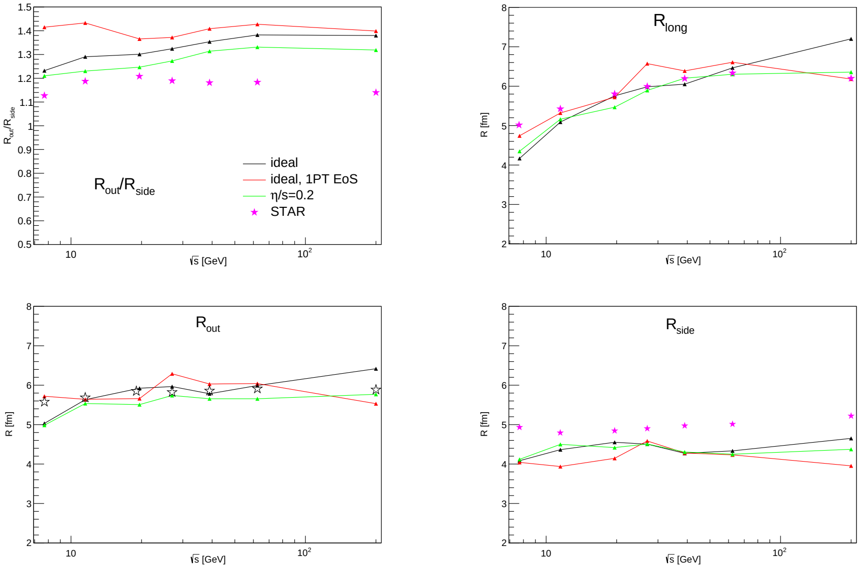
Yes: hydro phase in average lasts longer with `EoS Q`

Plots: τ distribution of hadrons sampled at the transition surface (left) and τ of last interactions (right)



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

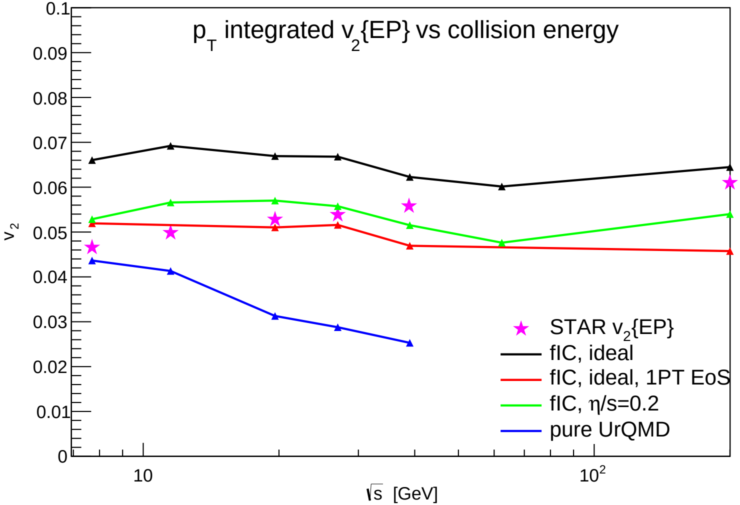
Femtoscopic radii: ideal hydro/Chiral EoS, ideal hydro/EoS Q, visc.hydro/Chiral EoS



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
- EoS at finite μ_B: Chiral model, EoS Q

Conclusions:

- Model applied for $\sqrt{s_{NN}} = 7.7 \ldots 200$ GeV A+A collisions.
- A fit to experimental data suggests $\eta/s = 0.2 \to 0.08$ when $\sqrt{s} = 7.7 \to 200$ 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.
- 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!