

Beam energy scan using a viscous hydro+cascade model

Iurii KARPENKO

Frankfurt Institute for Advanced Studies/
Bogolyubov Institute for Theoretical Physics

Strangeness in Quark Matter, 06-11 July 2015

IK, Huovinen, Petersen, Bleicher, Phys.Rev. C 91, 064901 (2015)

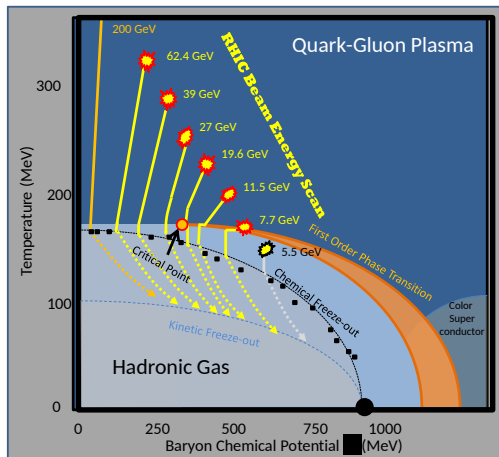


FIAS Frankfurt Institute
for Advanced Studies



Motivation

We want to understand whether fluid is created at lower energies, find its transport properties ($\eta/s, \dots$) and constrain its EoS.

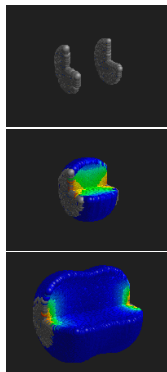


Picture taken from: G. Odyniec, Acta Phys. Polon. B 43, 627 (2012).

Tools

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

└────────── thermalization ─────────┘ └────────── particlization ─────────┘



- Initial state: **thick** pancakes
 - ▶ boost invariance is not a good approximation
→ need for 3 dimensional evolution
 - ▶ CGC picture does not work as well anymore
- Initial state: fluctuations
- Baryon and electric charges
 - ▶ obtained from the initial state
 - ▶ included in hydro phase
 - ▶ taken into account at particlization

Pictures taken from: <https://www.jyu.fi/fysiikka/tutkimus/suurenergia/urhic>

The model

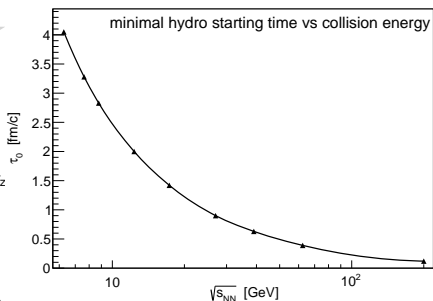
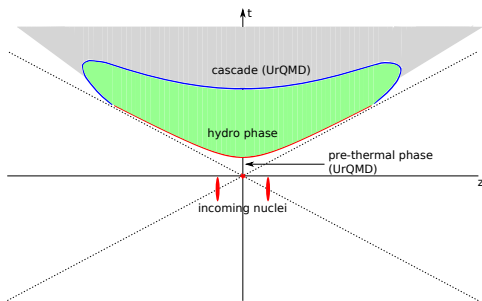
Initial (pre-thermal) phase

Pre-thermal evolution: 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)

The minimal value of τ_0 is

$\tau_0 = \frac{2R}{\gamma v_z}$, when two nuclei completely pass through each other.



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

“Thermalization”

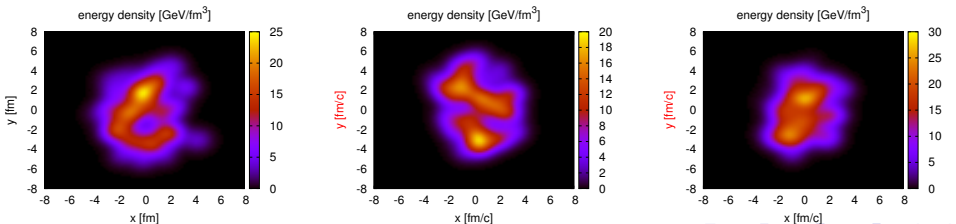
A single pre-thermal UrQMD event is used to create fluctuating initial state for an individual hydro evolution (hydro event).

The pre-thermal evolution does not lead to a thermalized state at τ_0 . Therefore, $\tau = \tau_0$ we deposit the energy/momentum P^α , baryon and electric charge N^0 of every particle into fluid cells according to:

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

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

Some typical initial energy density profiles in the transverse plane:



Hydrodynamic phase

The hydrodynamic equations: local energy-momentum and charge conservation

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

where (we choose Landau definition of velocity)

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

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

$$\langle u^\gamma \partial_{;\gamma} \pi^{\mu\nu} \rangle = -\frac{\pi^{\mu\nu} - \pi_{\text{NS}}^{\mu\nu}}{\tau_\pi} - \frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^\gamma \quad (3a)$$

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

vHLE code: free and open source. [Comput. Phys. Commun. 185 \(2014\), 3016](#)

http://cpc.cs.qub.ac.uk/summaries/AETZ_v1_0.html

<https://github.com/yukarpenko/vhllc>

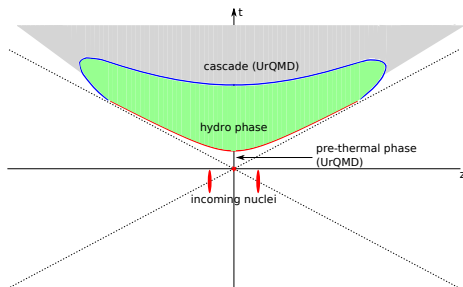
Properties of the fluid medium

- Equation of state: 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 confined and deconfined phases at all μ_B
- relaxation time $\tau_\pi = 5\eta/sT$

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

Fluid → particle transition and hadronic phase

$\varepsilon = \varepsilon_{SW} = 0.5 \text{ GeV/fm}^3$ (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



▷ Momentum distribution from Landau/Cooper-Frye prescription:

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

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

▷ **Hadron gas phase:** UrQMD cascade is employed after particlization surface.

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

Results 1

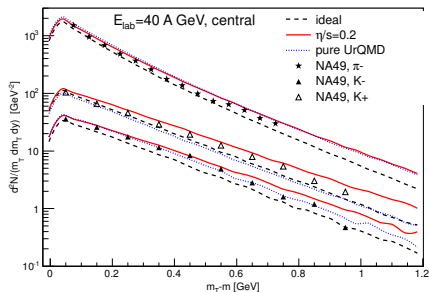
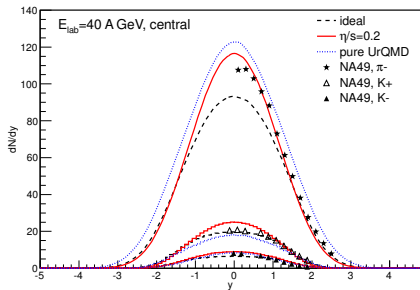
From the first round of simulations: fixed η/s , Chiral EoS

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

$$\begin{aligned}R_{\perp} &= R_{\eta} = 1 \text{ fm}, \\ \tau_0 &= \max \left\{ \frac{2R}{\gamma v_z}, 1 \text{ fm}/c \right\} \\ \epsilon_{\text{sw}} &= 0.5 \text{ GeV}/\text{fm}^3\end{aligned}$$

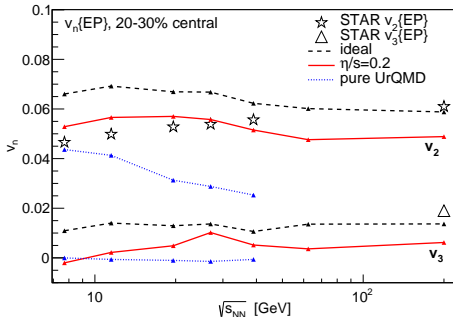
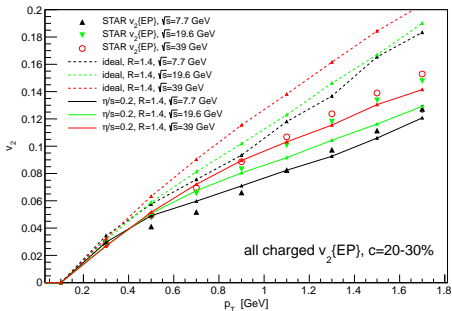
Results: $E_{\text{lab}} = 40$ A GeV Pb-Pb (SPS)

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



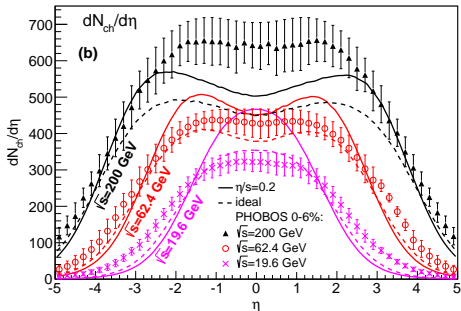
What do we observe here:

- viscous entropy production
- viscosity causes stronger transverse expansion
- The model approaches the data with $\eta/s = 0.2$



Going to more collision energies

- shear viscosity suppresses the elliptic and triangular flows (as expected)
- the suppression is too small for $\sqrt{s} < 30$ GeV and too large otherwise
- Fine tuning is required for every energy individually to reproduce $dN/d\eta$ and v_2 (see next slide).



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

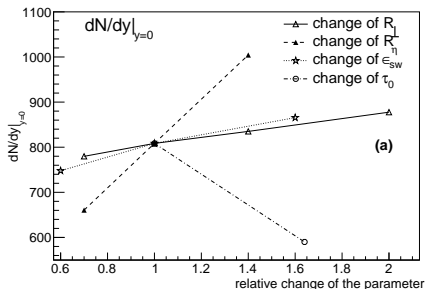
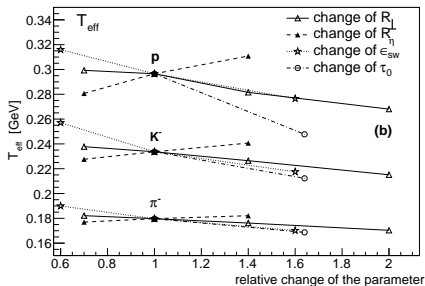
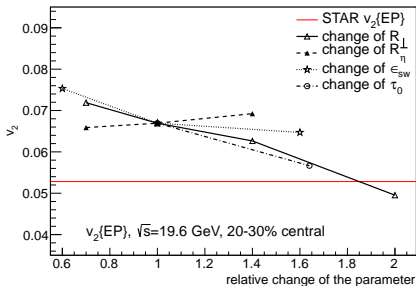
Parameter dependence

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,
 $\epsilon_{\text{crit}} = 0.5$ GeV/fm³.



How do the observables respond on the parameter variations

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

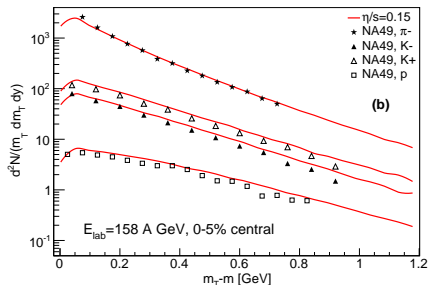
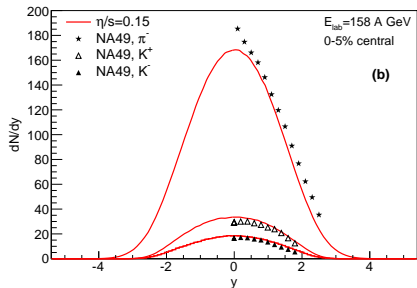
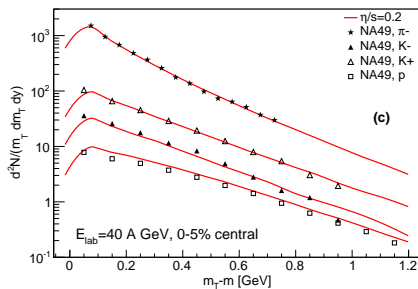
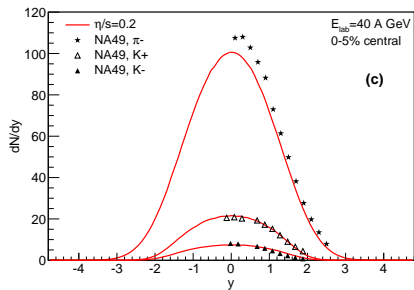
\Downarrow visual adjustment to experimental data

Energy dependent model parameters:

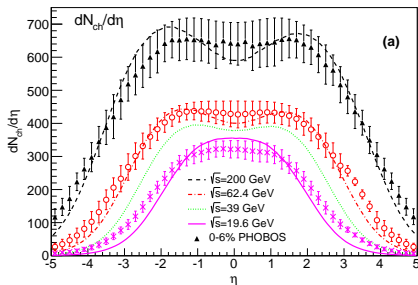
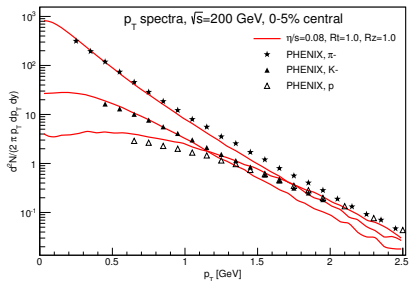
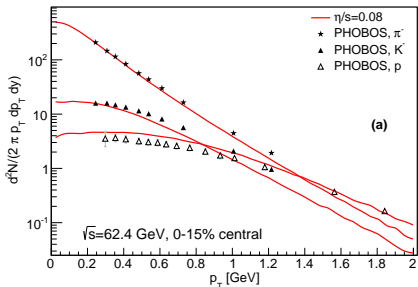
\sqrt{s} [GeV]	τ_0 [fm/c]	R_{\perp} [fm]	R_z [fm]	η/s
7.7/8.8	3.2/2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
19.6/17.3	1.22/1.42	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

As a result...

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

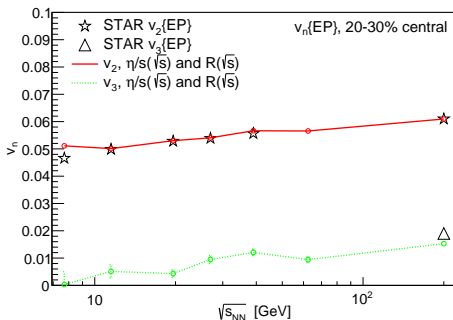


RHIC BES + top RHIC



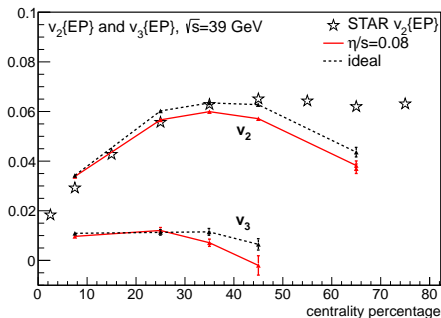
Elliptic and triangular flows at RHIC BES + top RHIC

v_2, v_3 vs collision energy



v_3 : prediction!

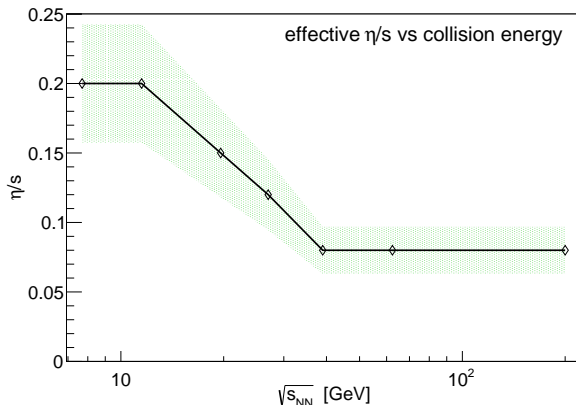
v_2, v_3 vs centrality



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

An outcome of the adjustment to the data

Effective (constant) η/s in hydrodynamic phase

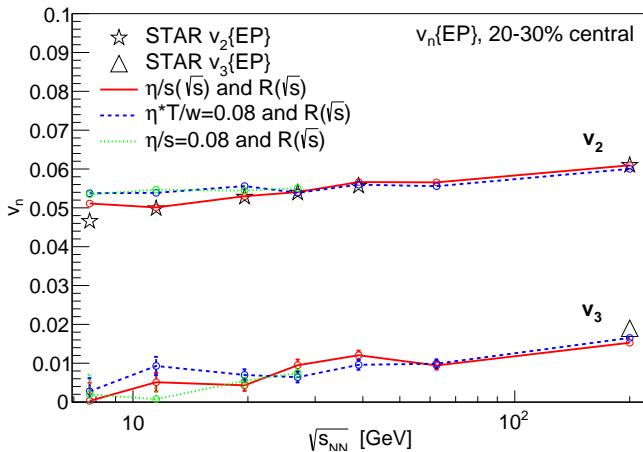


Green (error) band:
estimated assuming that
the parameters are varied
such that v_2 stays the
same and the inverse
slope of p_T spectrum of
protons changes within
5%.

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

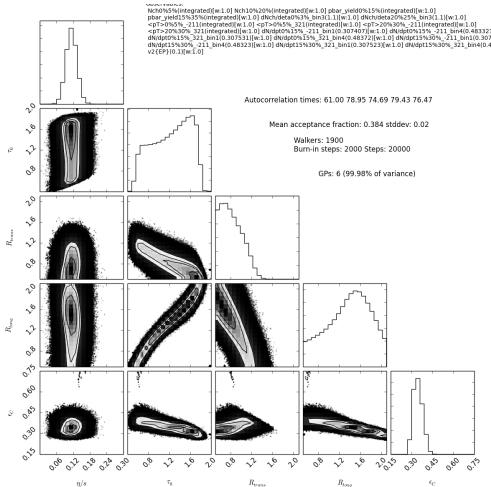
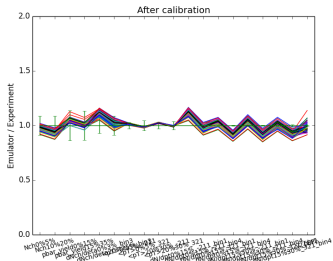
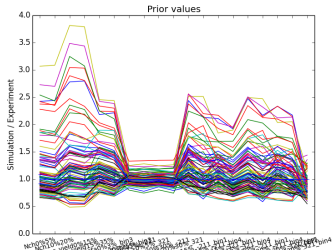
Fixed η/s vs fixed $T \cdot \eta/w$

Calculations show that there is no significant difference between fixed $\eta/s = 0.08$ (dashed green) and $T \cdot \eta/w = 0.08$ (dashed blue).



What's next? J. Auvinen, a comprehensive analysis at $\sqrt{s_{NN}} = 62.4$ GeV

Using the model + Gaussian processes (emulator) + Markov chain Monte Carlo



Results preliminary



Summary

3+1D EbE viscous hydro + UrQMD model:

- pre-thermal stage: UrQMD
- 3+1D viscous hydrodynamics
- EoS at finite μ_B : Chiral model, EoS Q

Conclusions:

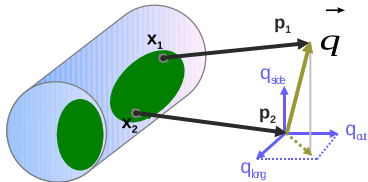
- Model applied for $\sqrt{s_{NN}} = 7.7 \dots 200$ GeV A+A collisions.
- A fit to experimental data suggests $\eta/s = 0.2 \rightarrow 0.08$ when $\sqrt{s} = 7.7 \rightarrow 200$ GeV, modulo initial state (UrQMD) and EoS (Chiral model) used.
- This hints for μ_B dependent η/s or $\eta/(\varepsilon + p)$.
- 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!

HBT(interferometry) measurements

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



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

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

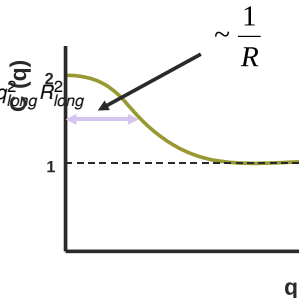
$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{\text{real event pairs}}{\text{mixed event pairs}}$$

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

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

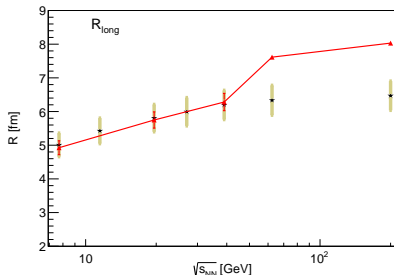
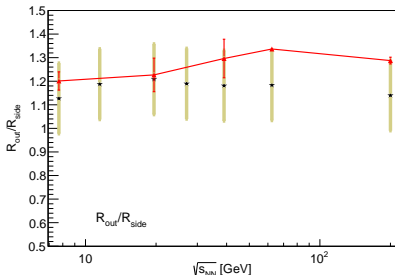
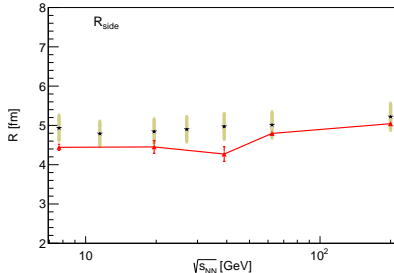
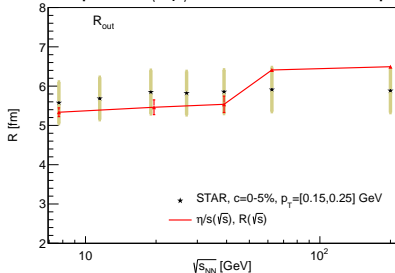
$R_{out}, R_{side}, R_{long}$ (HBT radii) correspond to *homogeneity lengths*, which reflect the space-time scales of emission process

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



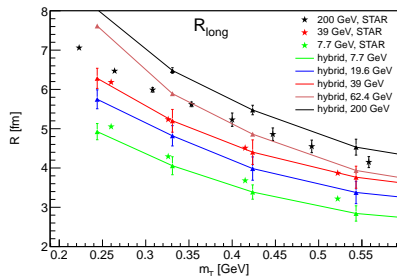
Femtoscopic radii from azimuthally integrated analysis

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



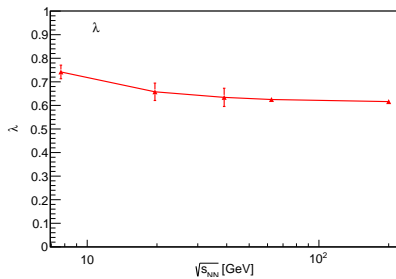
Theoretical error bars come from uncertainties in Gaussian-fitting procedure ▶

m_T dependence of R_{long}



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

$\sqrt{s_{\text{NN}}}$ 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

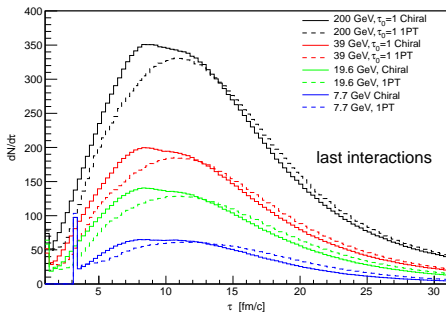
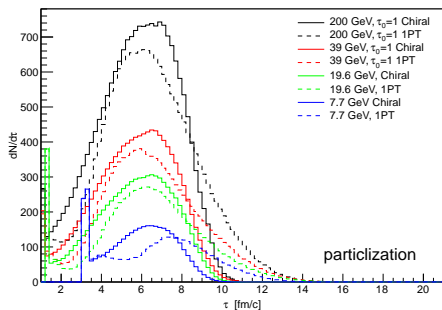
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Effects of the EoS Q compared to Chiral EoS?

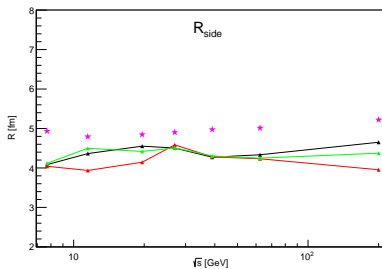
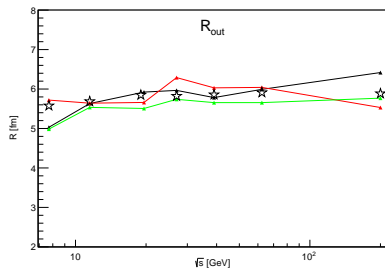
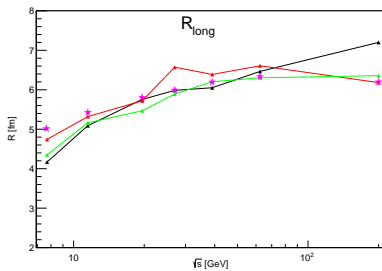
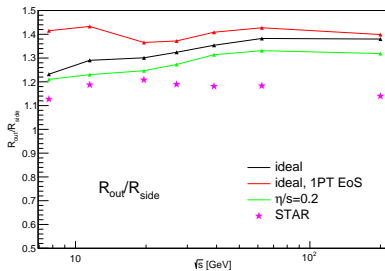
Yes: hydro phase in average lasts longer with EoS Q

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

