HYDRODYNAMICS from RHIC to LHC

based on arXiv:0712.0947 (nucl-th) with M. Chojnacki, W. Broniowski and A. Kisiel

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Motivation

i) the primary motivation/challenge for our work is development of a model describing soft-hadron production in the heavy-ion collisions at the RHIC energies in a complete and successful way (more than 95% of all produced hadrons are soft)

ii) on the basis of such a model, we may try to make predictions for the heavy-ion collisions at the LHC energies

our approach combines **well known elements** (Glauber model for the initial state, relativistic hydrodynamics for the intermediate evolution including hadronization, statistical/thermal model for the final emission stage) but each of those elements is **treated in quite sophisticated/modern way**, e.g. , the equation of state includes the QCD lattice results, the HBT radii are calculated with the two-particle Monte-Carlo method resembling very much the experimental procedure

iii) the use of the thermal event generator **THERMINATOR** for the final state implies that our approach may be applied straightforwardly to test the soft physics in detector simulations at LHC

Outline

1. Relativistic heavy-ion collisions at RHIC and LHC
2. Hydrodynamic approach
3. Results (fits) for RHIC
4. Predictions for LHC
5. Conclusions

1.1 LHC vs RHIC and SPS

SPS: Pb+Pb collisions at the maximal energy of
$\sqrt{s_{NN}}$ = 17.3 GeV

RHIC: Au+Au collisions at the maximal energy of
$\sqrt{s_{NN}} = 200 \approx 11.6 * 17.3$ GeV

LHC: Pb+Pb collisions at the maximal energy of
$\sqrt{s_{NN}} = 5500 \approx 27.5 * 200$ GeV = $318 * 17.3$ GeV

for soft phenomena dramatic changes between SPS and RHIC were expected (extended time evolution due to the softening of the equation of state)
– they were not confirmed

at the moment no dramatic changes are expected between RHIC and LHC – ???

1.2 Soft-observables

in our analysis we concentrate on the soft-hadronic observables in the midrapidity region

- transverse-momentum spectra
- the elliptic flow coefficient v_2

$$\frac{dN}{dy d^2 p_T} = \frac{dN}{dy\, 2\pi p_T\, dp_T} \left(1 + 2 v_2(p_T) \cos(2\phi_p) + ...\right).$$

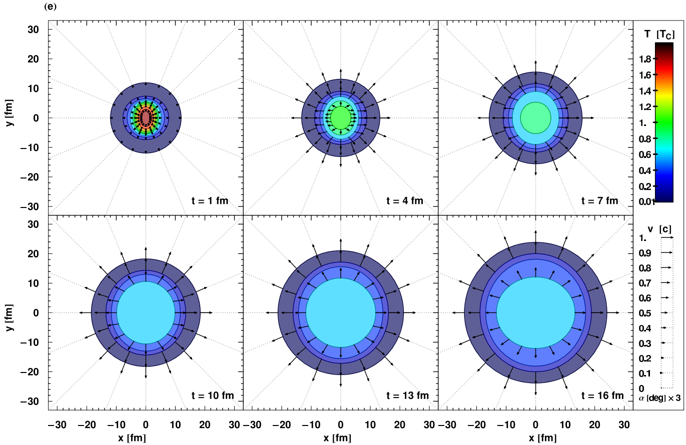
- the pion correlation functions, the HBT radii: $R_{\rm side}, R_{\rm out}, R_{\rm long}$

at RHIC there is a well known problem of simultaneous good description of those observables, this problem is related with application of relativistic hydrodynamics (very much successful in describing the spectra and v_2), another problem is related with early thermalization time used in hydro → so called RHIC puzzles

development of the hydrodynamic approach by: Heinz, Huovinen, Kolb, Heiselberg, Wiedemann, Hirano, Shuryak, Hung, Teaney, Bass, Nonaka, Hama, Kodama, Ruuskanen, Eskola, Rasanen, Tuominen, ...

1.3 Time evolution

typical hydro evolution in the transverse plane (videos by M. Chojnacki avaialable on the web)



2.1 Energy-momentum conservation laws

The relativistic hydrodynamic equations of perfect fluid follow from the assumption of local equilibrium and the conservation laws for the energy and momentum, which yield the relativistic Euler equations (3 eqs.) and the entropy conservation (1 eq.)

$$\begin{aligned} T^{\mu\nu} &= (\varepsilon + P)\, u^\mu u^\nu - P g^{\mu\nu}, \\ \partial_\mu T^{\mu\nu} &= 0, \end{aligned} \qquad \begin{aligned} u^\mu \partial_\mu (T u^\nu) &= \partial^\nu T, \\ \partial_\mu (s u^\mu) &= 0 \end{aligned}$$

ε - energy density, P - pressure, T - temperature,
u^μ - fourvelocity of the fluid element, s - entropy density

4 equations for 5 unknown functions, equation of state is needed, $s(T)$

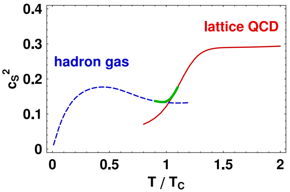
we consider a boost-invariant hydro model – reasonable approximation for midrapidity region, where we may also assume that $\mu_B \approx 0$

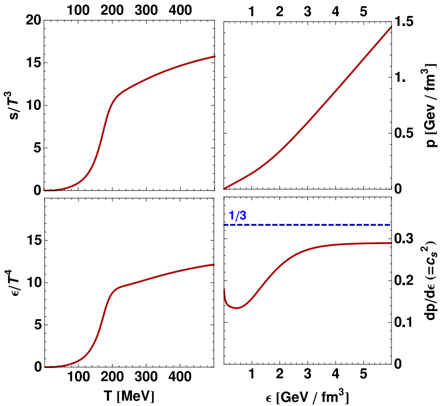
2.2 Equation of state

we use a formalism where EOS is encoded in the temperature dependent sound velocity function $c_s(T)$

the function $c_s(T)$ determines uniquely other thermodynamic functions

at low temperatures we use the hadron gas model, at high temperatures we use the lattice QCD results, in the transition region we make a simple interpolation





2.3 Initial conditions

Similarly to other hydrodynamic calculations we assume

$$s\left(\vec{x}_T\right) \propto \rho\left(\vec{x}_T\right) = \frac{1-\kappa}{2}\,\rho_{\mathrm{W}}\left(\vec{x}_T\right) + \kappa \rho_{\mathrm{bin}}\left(\vec{x}_T\right)$$

The case $\kappa = 0$ corresponds to the standard wounded-nucleon model
Bialas & Czyz, 1976
$\kappa = 1$ would include the binary collisions only.
The PHOBOS analysis of the particle multiplicities yields $\kappa = 0.14$ at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

further developments of our hydrodynamic approach will be based on GLISSANDO - Monte-Carlo version of the Glauber model - Broniowski, Rybczynski (previous talk), Bozek

2.4 Freeze-out with THERMINATOR

the freeze-out hypersurface Σ^μ is specified by the value of the final temperature $T = T_f$, the Cooper-Frye formula is then used to obtain the particle spectra

$$\frac{dN}{dy d^2p_\perp} = \int d\Sigma^\mu p_\mu f_{\rm eq}\,(p \cdot u)$$

this formula is used in the Monte-Carlo thermal generator THERMINATOR
A. Kisiel, T. Tałuć, W. Broniowski, WF, Computer Physics Communications **174** (2006)

all hadrons (including all known resonances) are produced on the hypersurface, the resonances decay in cascades leading to final stable hadrons such as pions, kaons and nucleons, for cylindrically asymmetric collisions and midrapidity, $y = 0$, the transverse-momentum spectrum has the following expansion in the azimuthal angle of the emitted particles

$$\frac{dN}{dy d^2p_T} = \frac{dN}{dy\, 2\pi p_T\, dp_T}\left(1 + 2v_2(p_T)\cos(2\phi_p) + ...\right)$$

2.4 Freeze-out

The correlation function for identical pions is obtained with the two-particle Monte-Carlo method, in this approach the evaluation of the correlation function is reduced to the calculation of the following expression

$$C(\vec{q},\vec{k}) = \frac{\sum_i \sum_{j\neq i} \delta_\Delta(\vec{q}-\vec{p}_i+\vec{p}_j)\delta_\Delta(\vec{k}-\frac{1}{2}(\vec{p}_i+\vec{p}_j))|\Psi(\vec{k}^*,\vec{r}^*)|^2}{\sum_i \sum_{j\neq i} \delta_\Delta(\vec{q}-\vec{p}_i+\vec{p}_j)\delta_\Delta(k-\frac{1}{2}(\vec{p}_i+\vec{p}_j))},$$

where δ_Δ denotes the box function with $\Delta = 5\,\mathrm{MeV}$. The correlation function is expressed with the help of the Bertsch-Pratt coordinates $k_T, q_{\mathrm{out}}, q_{\mathrm{side}}, q_{\mathrm{long}}$ and approximated by the Bowler-Sinyukov formula

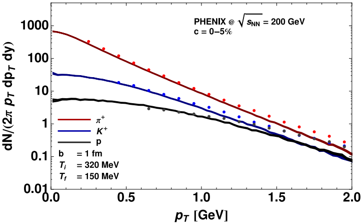
$$C = (1-\lambda) + \lambda K_{\mathrm{coul}}(q_{\mathrm{inv}}) \left[1 + \exp\left(-{R_{\mathrm{out}}}^2 q_{\mathrm{out}}^2 - {R_{\mathrm{side}}}^2 q_{\mathrm{side}}^2 - {R_{\mathrm{long}}}^2 q_{\mathrm{long}}^2\right)\right],$$

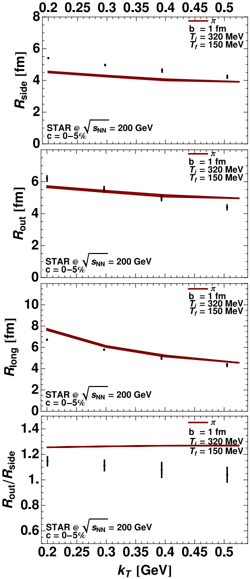
where $K_{\mathrm{coul}}(q_{\mathrm{inv}})$ with $q_{\mathrm{inv}} = 2k^*$ is the squared Coulomb wave function integrated over a static gaussian source.

3.1 RHIC central collisions

centrality class 0-5%
impact parameter $b = 1$ fm
initial central temperature T_i = 320 MeV
final freeze-out temperature T_f = 150 MeV

(single-freeze-out approximation)



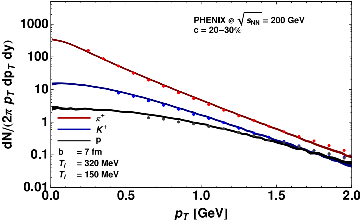


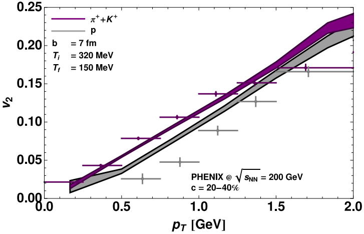
transverse-momentum spectra
elliptic flow $v_2 \approx 0$
HBT radii

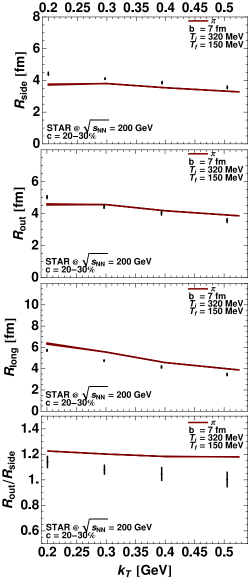
T_i is the main parameter

3.2 RHIC peripheral collisions

b = 7 fm, T_i = 320 MeV, T_f = 150 MeV







transverse-momentum spectra, v_2 and HBT radii

4.1 LHC central collisions

we expect that the main difference between RHIC and LHC is in the higher initial temperature, we consider three values: T_i = 400, 450, and 500 MeV

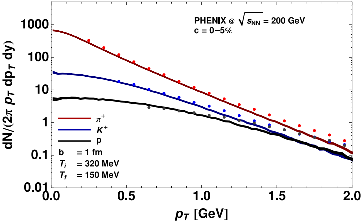
the presented results are obtained for T_i = 450 MeV

the final temperature is the same T_f = 150 MeV

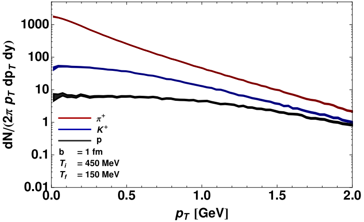
b = 1 fm, T_i = 450 MeV, T_f = 150 MeV

transverse-momentum spectra

RHIC



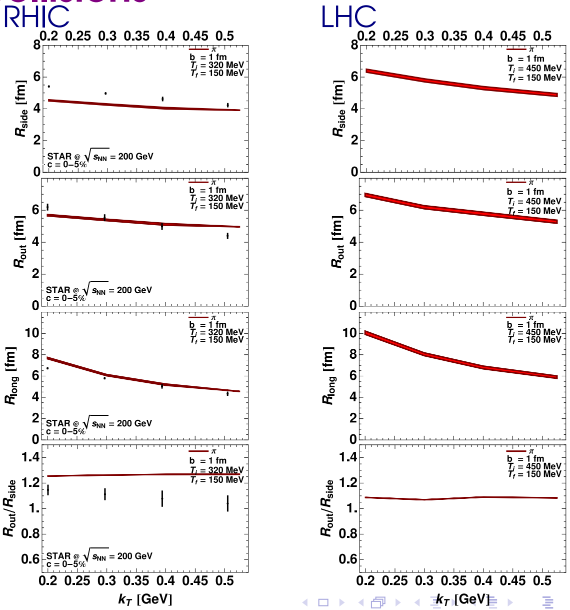
LHC



4.1 LHC central collisions

b = 1 fm, T_i = 450 MeV,
T_f = 150 MeV

HBT radii

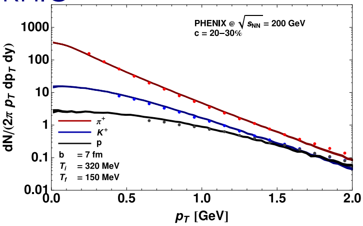


4.2 LHC peripheral collisions

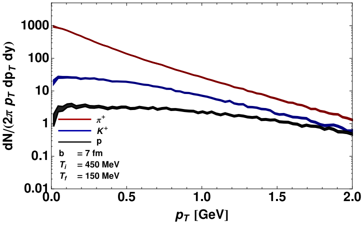
b = 7 fm, T_i = 450 MeV,
T_f = 150 MeV

transverse-momentum spectra

RHIC



LHC

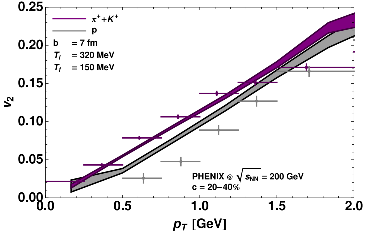


4.2 LHC peripheral collisions

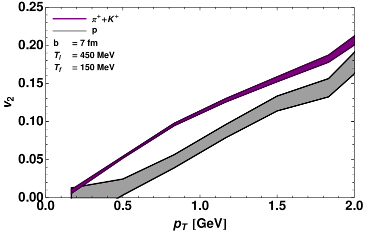
b = 7 fm, T_i = 450 MeV,
T_f = 150 MeV

elliptic flow v_2

RHIC



LHC

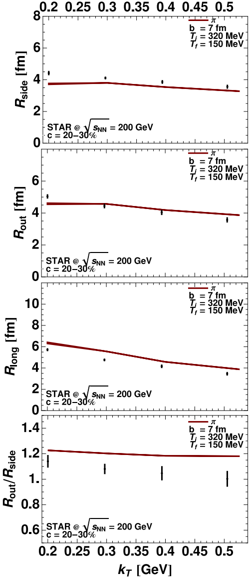


4.2 LHC peripheral collisions

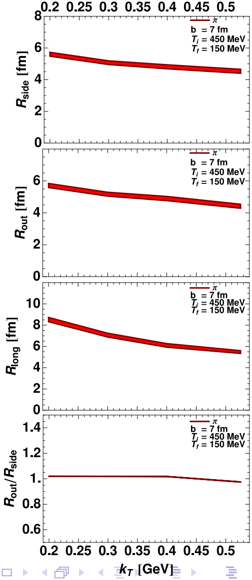
b = 7 fm, T_i = 450 MeV,
T_f = 150 MeV

HBT radii

RHIC



LHC



5. Conclusions

1. We achieved quite successful description of soft hadron production at RHIC
2. Extrapolation to higher energies indicates smooth changes of all studied quantities
3. Our approach may be used as the event generator to test the detector identification capabilities at LHC

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4. Even better fits for RHIC are possible with different initial conditions, e.g., initial transverse flow (work in progress with Broniowski and Chojnacki)
5. Initial 2D hydrodynamic expansion followed by 3D expansion (Bialas, Chojnacki, WF)
6. Dissipative effects (shear viscosity - Bozek, bulk viscosity - Torrieri)