Bulk quantities in nuclear collisions from CGC and hybrid simulations

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Introduction

As Fig. 1 shows, the current description of ultra-relativistic heavy-ion collisions involves different ingredients and can be divided in successive stages. The earliest times are dominate by strong color fields and large occupancy numbers and its dynamics is currently believe to be well described by a classical effective field theory, as the Color Glass Condensate (CGC) [1]. As the system approaches thermal equilibrium, the classical approximation should break down and the system is believe to start expanding hydrodynamically. Entropy production can happen at this stage in case one considers a viscous hydro expansion. At late times, with the system cooling down and becoming too dilute, it approaches a gas of ordinary hadrons with the dynamics described by kinetic theory.

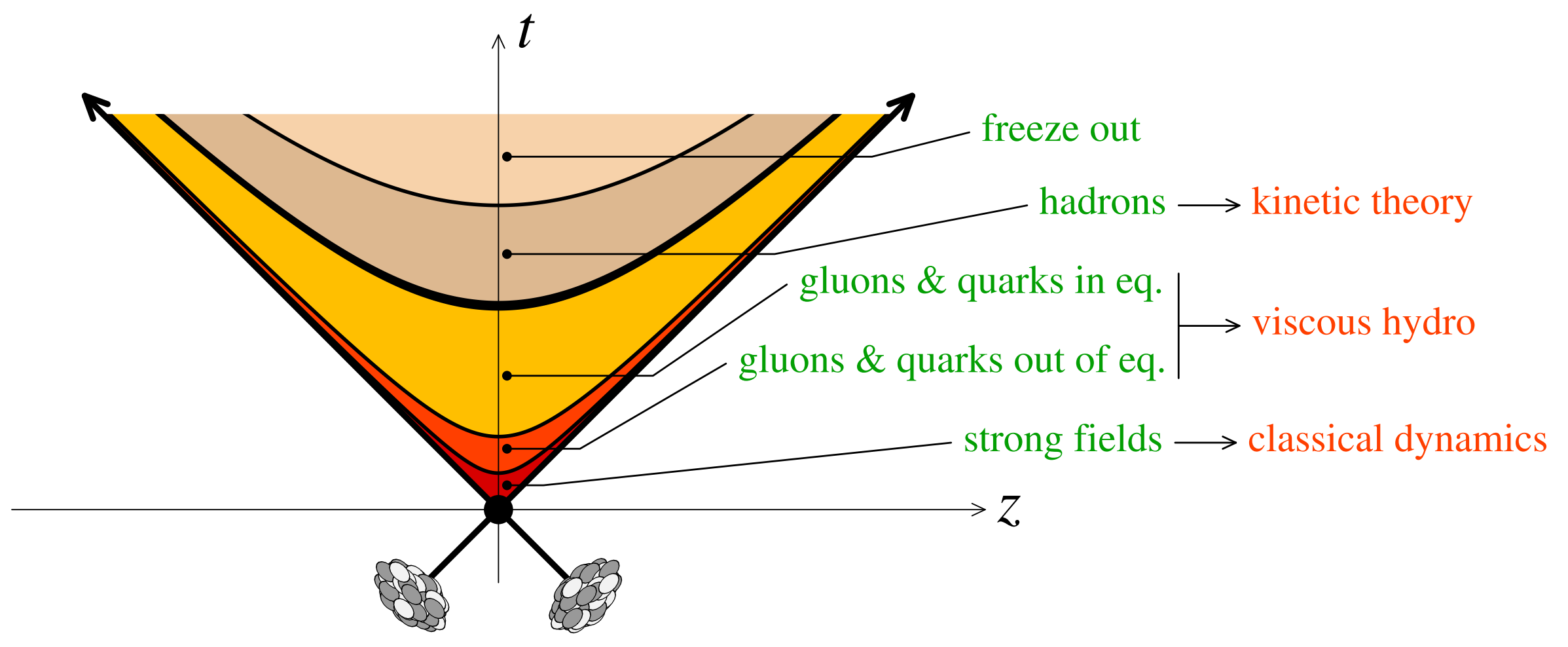

Figure 1: Successive stages of a heavy-ion collision.

Still, as the majority of the multiplicity observed in the detectors comes from the initial stages of the collision, it is common to directly compare particle distributions in the initial state with experimental data on bulk quantities like total multiplicity and its dependence on centrality, collision energy, and collision system under the assumption that subsequent evolution of the system will not change these bulk quantities.

In this work we compute global, bulk observables obtained separately from a purely CGC model, and a hybrid (hydro + transport) model simulation that shares the same initial state dynamics. This allows to assess the effects of hydrodynamic and hadronic evolution, and quantify to what extent initial condition models can be directly compared to experimental data. Only selected results are presented here. A complete version of this work can be found in [1].

Pure initial state model ("rcBK")

In the dilute-dense approximation of the CGC [2] the running coupling corrected cross section for production of gluons for a given impact parameter $\boldsymbol{b}$ with transverse momentum k_T at rapidity y can be written as [3]:

$$\frac{d\sigma}{d^2k\,dy\,d^2b} \sim \frac{N}{\boldsymbol{k}^2}\int d^2q\,d^2b'\,\overline{\phi}_{h_1}(\boldsymbol{q},x_1,\boldsymbol{b})\,\overline{\phi}_{h_2}(\boldsymbol{k}-\boldsymbol{q},x_2,\boldsymbol{b}-\boldsymbol{b}')\,\frac{\alpha_s\left(\Lambda^2_{\text{coll}}\,e^{-5/3}\right)}{\alpha_s\left(Q^2\,e^{-5/3}\right)\,\alpha_s\left(Q^{*\,2}\,e^{-5/3}\right)}\,,\quad(1)$$

where N is an overall normalization to be fixed by comparison with the experimental data. $\overline{\phi}_{h_i}(\boldsymbol{k},x,\boldsymbol{b})$ denotes the unintegrated gluon distribution (UGD), which encodes all dynamics of nuclear collisions in this model. As in previous studies [4], it is obtained from solving the running coupling Balitsky-Kovchegov (rcBK) equation.

Eq. (1) is the starting point for each calculation. In the case where hydrodynamic evolution is absent, one must still convert this spectrum of gluons into that of the hadrons which are measured. Here we use the Local-Parton-Hadron-Duality as fragmentation model, where distributions at partonic and hadronic level only change by a constant multiplicative factor.

Hybrid hydrodynamic model ("vhydro" & "ihydro")

In the case where collisions are described via a hybrid hydrodynamic model, the initial entropy density is chosen as being proportional to the gluon density from the CGC framework:

$$s_0(\boldsymbol{b}) \propto \left.\frac{dN_g}{d^2b\,dy}\right|_{y=0}\;;\qquad\text{where}\qquad \left.\frac{dN_g}{d^2b\,dy}\right|_{y=0} = \frac{1}{\sigma_s}\int d^2k\;[Eq\ (1)]$$

The corresponding energy density is then obtained by thermodynamic relations from an equation of state derived from Lattice QCD calculations, s95p-v1.2 [5]. Moreover, we:

- Assume zero initial shear tensor and bulk pressure, and no initial transverse fluid velocity;
- Assume early thermalization and start hydrodynamic evolution at $\tau_0 = 0.2$ fm;
- Consider ideal and viscous hydrodynamics evolution ("vhydro" and "ihydro", respectively); the resulting equations of motion in the dissipative case are the ones from the 2nd-order viscous hydrodynamics [6];
- Use the MUSIC code [7] to solve hydro equations with $(\eta/s(T), \zeta/s(T), T_{sw})$ corresponding to the maximum a posteriori parameters from a Bayesian analysis [8].
- Switch to the hadronic afterburner UrQMD [9] for cells with $T < T_{sw} = 151$ MeV.

Results

The (energy and system size independent) normalization of the rcBK and the vhydro simulations has independently been fixed to describe the central region of the hadronic multiplicity in Pb+Pb at 2.76 TeV; the same normalization from the vhydro simulation has been used for the ihydro simulation.

In Fig. 2 (left) we compare our results for each simulation with the data for the centrality dependence of charged hadrons produced in Pb+Pb collisions at 5.02 TeV. The difference from the pure-initial state and the hybrid simulation with viscous hydrodynamics is quantified in the right panel for several heavy-ion systems at RHIC and LHC energies.

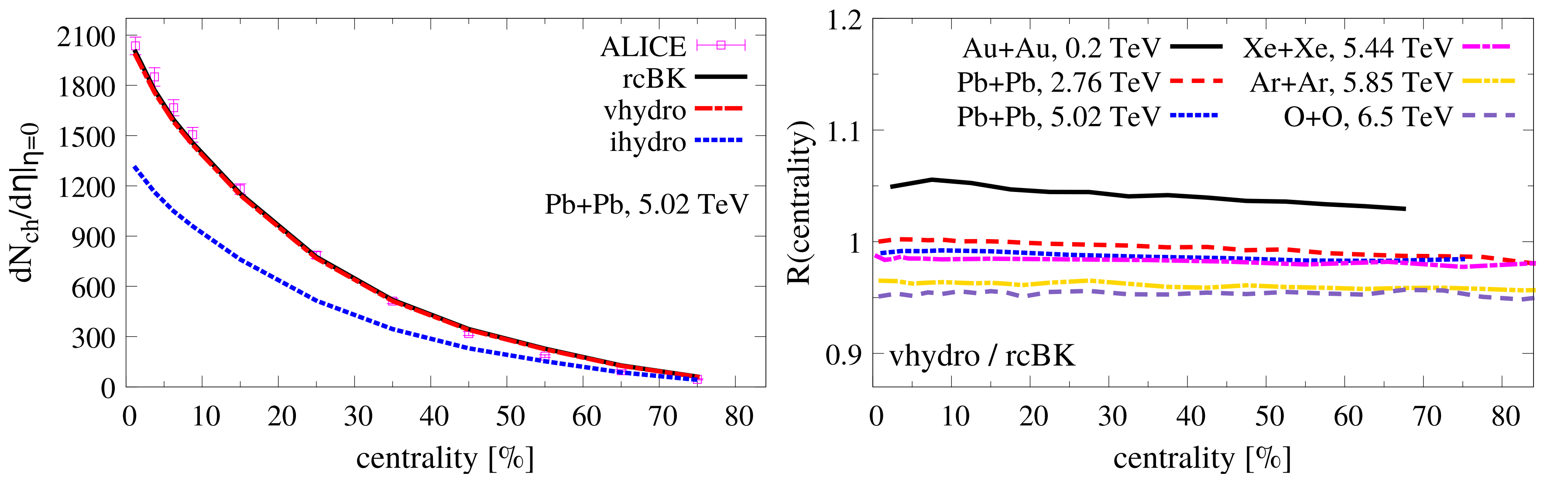

Figure 2: (left) Centrality dependence of charged hadron multiplicity from rcBK and vhydro simulations for Pb+Pb collisions at 5.02 TeV. The result for the hybrid model simulation assuming ideal hydro evolution (ihydro) ilustrate the production of entropy due to dissipative effects, ∼50% for most central collisions. (right) Ratio of the centrality dependence from the vhydro and the rcBK simulations for several heavy-ion systems from RHIC to LHC energies. After fixing an overall (energy and system size independent) normalization, both simulations do not differ more than ∼5%.

In Fig. 3 we compare the results of our simulations to the centrality dependence of transverse momentum in Pb+Pb collisions at 5.02 TeV and with the ratio of the transverse momentum in Xe+Xe and Pb+Pb collisions at 5.44 TeV and 5.02 TeV, respectively. We point out that the mentioned ratio could, perhaps, be used as a probe of viscosity effects on different collision systems and to investigate the onset of hydrodynamic behaviour in nuclear collisions.

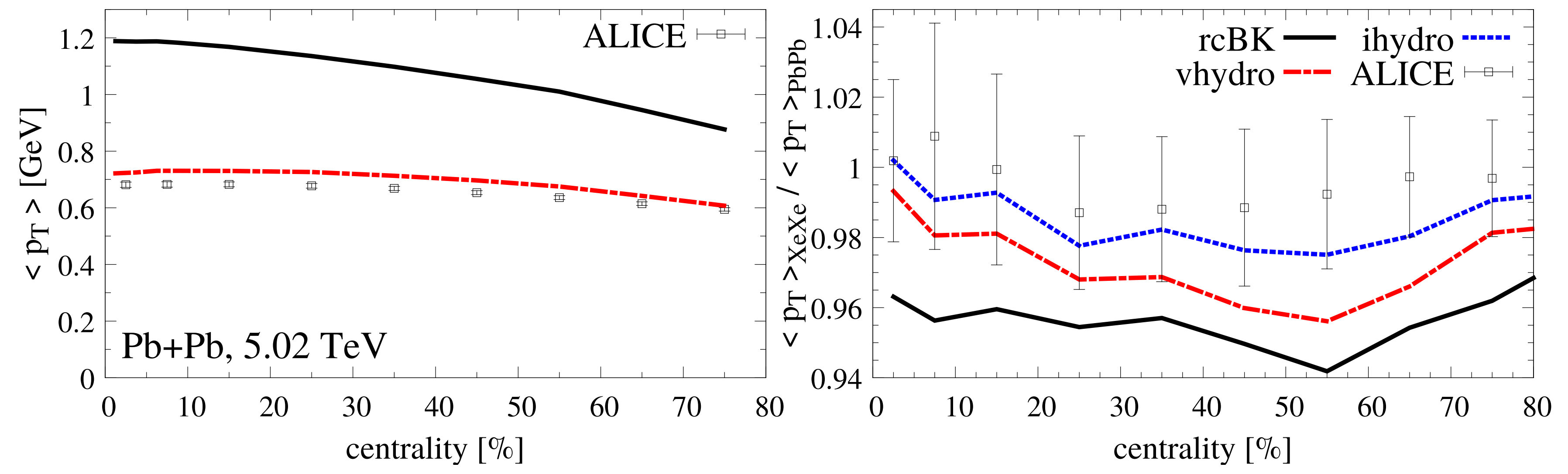

Figure 3: (left) Centrality dependence of the average transverse momentum of charged hadrons at mid pseudorapidity in Pb+Pb collisions at 5.02 TeV from the rcBK and vhydro simulations. The space-time evolution from the hydrodynamic phase allows for redistribution of energy decreasing the average transverse momentum per charged particle, bringing the curve closer to the experimental data. (right): Ratio of the average transverse momentum of charged hadrons at mid pseudorapidity in Xe+Xe collisions at 5.44 TeV and in Pb+Pb collisions at 5.02 TeV. The pure initial state model is clearly not in accordance with the available experimental data. The hybrid simulation with ideal hydrodynamics is compatible with the experimental data in all the measured range. The result with viscous hydro evolution is consistent within error bars up to ∼40% centrality.

Conclusions

- The centrality dependence of the charged particle multiplicity in the rcBK and the vhydro simulations do not differ more than $\sim 5\%$ from 0.1 TeV to 10 TeV. Therefore, such quantities are insensitive to the late stage dynamics.
- Assuming early time thermalization occurs, up to ∼50% of the final multiplicity observed in heavy-ion collisions can come from dissipative effects.
- Comparing the mean p_T in Pb+Pb collisions to the same quantity in other colliding systems (at similar energies) as a function of centrality could be considered for two purposes: to investigate the onset of hydrodynamical phase in high-energy heavy-ion collisions and to probe the effects of viscosity in different colliding systems.

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