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Latest results from the EbyE NLO EKRT model

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Abstract

We review the results from the event-by-event next-to-leading order perturbative QCD + saturation + viscous hydrodynamics (EbyE NLO EKRT) model. With a simultaneous analysis of LHC and RHIC bulk observables we systematically constrain the QCD matter shear viscosity-to-entropy ratio $\frac{\eta}{s}(T)$, and test the initial state computation. In particular, we study the centrality dependences of hadronic multiplicities, $p_T$ spectra, flow coefficients, relative elliptic flow fluctuations, and various flow-correlations in 2.76 and 5.02 TeV Pb+Pb collisions at the LHC and 200 GeV Au+Au collisions at RHIC. Overall, our results match remarkably well with the LHC and RHIC measurements, and predictions for the 5.02 TeV LHC run are in an excellent agreement with the data. We probe the applicability of hydrodynamics via the average Knudsen numbers in the space-time evolution of the system and viscous corrections on the freeze-out surface.

Keywords:
heavy-ion collisions, next-to-leading order perturbative QCD calculations, saturation, dissipative fluid dynamics

1. NLO EbyE EKRT model and its tests

The EKRT model \cite{1,2} rests on the idea that primary particle production in high energy heavy-ion collisions is dominated by few-GeV gluons, minijets \cite{3}, whose production rates are computable from collinear factorization of perturbative QCD (pQCD) but controlled by the phenomenon of saturation locally in the transverse plane \cite{4,5,6}. The produced minijet densities can then be converted into initial conditions for relativistic fluid dynamics simulations. In NLO pQCD, the infrared- and collinear-safe quantity computed here is the transverse energy $E_T$ carried into a mid-rapidity window $\Delta y$ \cite{7,5} per transverse area $d^2r$ in A+A collisions at c.m.s-energy $\sqrt{s_{NN}}$ and impact parameter $b$,

$$\frac{dE_T}{d^2r}(p_0, \sqrt{s_{NN}}, A, \Delta y, r, b; \beta) \overset{\text{pQCD}}{=} T_A(r + b/2)T_A(r - b/2)\sigma(E_T)_{p_0, \Delta y, \beta} \overset{\text{saturation}}{=} \frac{K_{\text{sat}}}{\pi} p_0^3 \Delta y,$$

where the transverse momentum cut-off $p_0 \sim$ few GeV, and $T_A$ is the nuclear thickness function. The NLO quantity $\sigma(E_T)_{p_0, \Delta y, \beta}$ is computed using collinear factorization and the subtraction method \cite{8}. It contains the CTEQ6M parton distributions \cite{9} with EPS09s nuclear effects \cite{10}, 2 $\rightarrow$ 3 and UV-renormalized 2 $\rightarrow$ 2 parton scattering matrix elements \cite{11}, and the measurement functions to define the $E_T$. The minimum $E_T$ in $\Delta y$ is controlled by the parameter $\beta \in [0, 1]$, fixed to 0.8 here \cite{5}. Saturation here is the limit where $E_T$
production from \((n > 2) \rightarrow 2\) parton processes starts to dominate over the usual 2 → 2 ones. This can be cast into the form of the saturation condition appearing on the r.h.s. of Eq. (1), where \(K_{\text{sat}}\) is a free parameter [5].

Equation (1) gives the saturation momentum \(p_0 = p_{\text{sat}}(\sqrt{s_{NN}}, A, r, b; K_{\text{sat}})\) locally in the transverse plane. With a formation time \(\tau_s(r) = p_{\text{sat}}(r)^{-1}\) the initial local energy density is then

\[
e(r, \tau_s(r)) = \frac{dE_T}{d^2r} = \frac{K_{\text{sat}}}{\pi} [p_{\text{sat}}(r)]^4.
\]

The observation [6, 12] enabling the NLO EbyE EKRT model of Ref. [2] is that the obtained \(p_{\text{sat}}(r, b) \approx p_{\text{sat}}(T_A T_A)\) which dependence can be parametrized, see Eq. 29 in [2]. Then the \(T_A\)'s can be made to fluctuate EbyE: we sample the nucleon positions from the standard Woods-Saxon density, setting a Gaussian gluon

\[
\frac{K_{\text{sat}}}{\pi} [p_{\text{sat}}(r)]^4.
\]

...and the necessity of a hydro evolution in understanding the centrality systematics of this observable [2].

Furthermore, these constraints are obtained in the centrality region where the \(\delta f\) effects remain small in these observables [2]. Relative EbyE fluctuations of \(v_2\) measured by ATLAS provide a stringent \(\eta/s\)-independent test for the computed initial states. The EKRT model passes also this test remarkably well, demonstrating the necessity of a hydro evolution in understanding the centrality systematics of this observable [2].

As a measure of our hydro validity, we plot in Fig. 2f also (i) the average Knudsen numbers (Kn), expansion rate \((\theta = \partial_p u^\mu)\) per thermalization time \((\tau_s = 5\rho/(e+p))\) averaged over entropy density throughout the evolution \((T > 100\text{ MeV})\), and (ii) the shear stress over pressure \((\sqrt{\pi_{\mu\nu}\pi^{\mu\nu}}/p)\) averaged over the entropy flux through the freeze-out surface. This reflects the average \(\delta f\) corrections in the end of the evolution. The facts that these indicators increase towards peripheral collisions only gradually and that \(\langle\text{Kn}\rangle = O(1)\) speak for the hydro validity at least up to 50% centralities. Towards peripheral collisions, \(\langle\text{Kn}\rangle\) increases due to the increasing relative weight of the early stages where \(\langle\text{Kn}\rangle\) is large (see the \(T > 180\text{ MeV}\) curve).
2. Further predictions from the EbyE NLO EKRT model

We have made a series of predictions from the EbyE NLO EKRT model without any further tuning. For ALICE, we have computed the symmetric 2-harmonic 4-particle cumulants, $\text{SC}(m,n) = \langle \langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4) \rangle \rangle = \langle \langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3) \rangle \rangle$ normalized by $\langle \langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4) \rangle \rangle$ shown in Fig. 2b,c. Our best-fit $\eta/s$ parametrizations predict rather well the positive correlation seen by ALICE [24] in SC(4, 2) and also the trend of the negative correlation in SC(3, 2). We emphasize, however, the importance of a 1-to-1 comparison: we expect that once we include the multiplicity weighting assumed in the ALICE analysis, our prediction will be systematically closer to the data. In Fig. 2d we show a prediction of the $p_T$ dependence of SC(4, 2)/$\langle v_2^4 \rangle$ shown in Fig. 2e in turn suggests that the low-to-high-$p_T$ ratios of these normalized correlators might be able to distinguish between our best-fit $\eta/s$ parametrizations. Similarly, we have provided the STAR collaboration with our predictions for the centrality dependence of mixed harmonic correlators $C_{m,n,m+n} = \langle \langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3) \rangle \rangle$. As shown in [22], our best-fit parametrizations reproduce the $C_{2,2,4}$ rather well. However, we underestimate the measured $C_{2,3,5}$, which we believe is due to large $\delta f$ effects in this observable, possibly combined also with non-flow and rapidity effects which we cannot consider, yet. Further studies on this are ongoing.

Thanks to the predictive power of the EKRT model, we have also made predictions for the 5.02 TeV Pb+Pb run at the LHC [13]. Figure 3 shows our predictions for the multiplicity and flow-coefficient ratios. In the latter, notice the slight increase with increasing $n$. Again, as seen in the figure, the EbyE NLO EKRT model fares very well in the data comparison.

To conclude, the EbyE NLO EKRT model [2] explains consistently the bulk observables and various correlators at mid-rapidity in LHC and RHIC heavy-ion collisions. Its predictive power in cms-energy, centrality and nuclear mass number has been demonstrated with various observables. Via a multi-energy and multi-observable analysis we have managed to constrain the $\eta/s(T)$ ratio, for which two best-fit parametrizations have been identified. Similar results have been found also in Ref. [31]. Systematic further tests of the hydro results validity are, however still needed, especially in the case of more complicated correlators, as well as more work for including further dissipative phenomena.

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Fig. 3. EbyE NLO EKRT model predictions for 5.023 TeV Pb+Pb collisions [13]. (a) Centrality dependence of charged particle multiplicity, vs. ALICE data [25, 26]. (b) Predicted $\sqrt{s_{NN}}$ dependence of charged particle multiplicity from RHIC Au+Au to LHC Pb+Pb collisions vs. data from ALICE [25, 26], CMS [27], STAR [28] and PHENIX [29]. (c-e) Ratio of the flow coefficients $v_n$ in 5.023 TeV and 2.76 TeV Pb+Pb collisions, vs. ALICE data [30].

References