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12 years of HYDJET++ generator: history and the latest results

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Abstract. It has been dozen years since HYDJET++ Monte-Carlo event generator for the simulation of relativistic heavy ion collisions was developed. Now the generator is widely used for the simulation of nucleus-nucleus interactions from NICA to LHC energies. The model calculations on soft and hard probes of quark-gluon plasma (including collective flow, different kinds of particle correlations, jets, D and B mesons etc.) agree well with the experimental data. In this paper the selected main results and the very new ones are presented.

1. Introduction. HYDJET++ two components' model

The detailed description of the HYDJET++ Monte-Carlo event generator can be found in [1]. HYDJET++ was developed twelve years ago (version 2.0), it is freely available via internet [2] and the latest version is 2.4.

The HYDJET++ model has two components: first part for soft processes and second part for hard ones. The soft part of the HYDJET++ has no evolution stage from the initial state until hadronization, but represents a thermal hadron production already at the freeze-out hypersurface accordingly with the prescriptions of ideal hydrodynamics taken from the another event generator FAST MC [3]. On the other hand, the hard jet part of the HYDJET++ is based on PYTHIA [4] and PYQUEN [5] Monte-Carlo event generators. PYTHIA and PYQUEN simulate parton-parton collisions, parton radiative energy loss and process of hadronization.

2. HYDJET++ model results at the RHIC and LHC energies

HYDJET++ model can be used to analyze soft and hard physics in relativistic heavy ion collisions and for descriptions of the experimental data.

2.1. Soft physics results

Originally HYDJET++ Monte-Carlo event generator version 2.0 was tuned (multiplicity, transverse momentum $p_{\rm T}$ and rapidity y spectra, elliptic flow coefficient v_2 etc.) for the AuAu collisions at center-of-mass energy per nucleon pair $\sqrt{s_{\rm NN}}$ = 200 GeV [1] at the RHIC

(Relativistic Heavy Ion Collider). HYDJET++ generator simulation has a good agreement with RHIC experiments results on the physical observables.

Later the predictions for the physical observables in PbPb collisions at the LHC (Large Hadron Collider) energy were done [6, 7].

When the first experimental results with heavy-ion collisions at the LHC were available we have applied HYDJET++ model with tuned input parameters to reproduce the data from PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. We could see that the HYDJET++ event generator allows to reproduce the LHC experiments data on centrality and pseudorapidity η dependence of charged particle multiplicity, trasnverse momentum p_{T} spectra, nuclear modification factor R_{AA}, $\pi^{\pm}\pi^{\pm}$ correlation radii in central PbPb collisions, and p_{T}- and η-dependencies of the elliptic flow v_2 [8].

Triangular v_3 flow for soft component is introduced via a special modification of the freeze-out hypersurface from the version 2.2 of HYDJET++ model. Modulation of the final freeze-out hypersurface with the appropriate fitting triangular coefficient was done [9]. This modulation is not correlated with the direction of the impact parameter of the collision, and two independent "main" lower azimuthal harmonics, elliptical v_2 and triangular v_3, being obtained as a result. Interference between v_2 and v_3 harmonics gives as "overtones" both even and odd higher azimuthal harmonics (v_4, v_5, v_6, v_7 etc). This modification allows HYDJET++ to reproduce the LHC experimental data on p_{T}- and centrality dependencies of the anisotropic flow coefficients v_2, v_3 and v_4 up to $p_{\mathrm{T}} \approx 5$ GeV/c and 40% centrality in PbPb collisions. Also we see the good agreement of the HYDJET++ simulation with the basic trends for pentagonal v_5 and hexagonal v_6 flows at the LHC.

The analysis of dihadron angular correlations measured at the LHC in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV was done with the HYDJET++ model [10]. Our simulation shows that the extraordinary structure called a "ridge" in dihadron angular correlations could appear just as the simple interplay of independent v_2 and v_3 harmonics.

Another study of our group [11] favors the idea that the main features of the hexagonal flow v_6 can be understood in terms of the interplay of fully independent elliptic and triangular flows in HYDJET++ model.

HYDJET++ event generator was used to study the triangular flow v_3 of charged inclusive and identified hadrons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with centralities 0–50% [12]. We have found mass ordering effect, the v_3 flow of mesons was stronger than that of baryons for the particles with transverse momentum up to $p_{\mathrm{T}} \approx 2$ GeV/c. The interplay of hard and soft processes leads to breaking of this mass ordering of triangular flows v_3, because jet particles start to dominate in spectra of heavy hadrons at larger transverse momentum compared to those of light hadrons. The resonance decays can modify the spectra towards the number-of-constituent-quark (NCQ) scaling fulfillment for triangular flow v_3, whereas jets are the main reason of the scaling violation in heavy-ion collisions at the LHC energies.

Event-by-event harmonic flow coefficients v_2 and v_3 fluctuations measured in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV are interpreted within the HYDJET++ model [13]. We can see that the very simple modification of the HYDJET++ model via introducing additional distribution over spatial anisotropy parameters permits HYDJET++ model to reproduce both elliptic and triangular flow fluctuations.

The influence of geometric and dynamical anisotropies on the development of flow harmonics and, simultaneously, on the second- and third-order oscillations of femtoscopy radii were tested with HYDJET++ model [14]. The merely geometric anisotropy provides the results which anticorrelate with the experimental observations of either v_2 (or v_3) or second-order (or third-order) oscillations of the femtoscopy radii. Decays of resonances dramatically increase the emitting areas but do not change the phases of the radii oscillations. In contrast to the spatial deformations, the dynamical anisotropy alone provides the correct qualitative description of the flow and the femtoscopy observables simultaneously. Both types of the anisotropy are needed to match quantitatively the experimental data of PbPb collisions at the LHC energies.

The correlation of the average multiplicity of particles emitted in the forward hemisphere with the multiplicity of particles emitted in the backward hemisphere (FB-correlation) in PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV was studied with HYDJET++ event generator [16]. HYDJET++ model reproduces quite well observed dependence of FB-correlation. We can see that FB-correlations for the hard jet component of HYDJET++ are stronger than those for the soft hydrodynamic components and (in the most central collisions) they are determined mainly by the hard component. Anyway both (soft and hard) components of the model should be used simultaneously to reproduce the correct dependence of the strength of FB-correlations on the centrality of PbPb collisions.

2.2. Hard physics results

It was shown that HYDJET++ event generator allows to reproduce the LHC experiments data on nuclear modification factor $R_{\rm AA}$ of charged hadrons up to transverse momentum $p_{\rm T} \approx 100$ GeV/c [8].

The hard part of HYDJET++ generator, PYQUEN model [5] was used to simulate medium-modified inclusive jet production in PbPb collision at $\sqrt{s_{\rm NN}} = 2.76$ TeV with respect to the corresponding pp data [15]. It was shown that the contribution from wide-angle radiative energy loss dominates. Anyway taking into account collisional loss is also necessary to match the experimental data.

HYDJET++ event generator was used for the phenomenological analysis of charmed meson and charmonium production in PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [17, 18]. HYDJET++ reproduces $p_{\rm T}$ and v_2 spectrum of J/ψ mesons with another freeze-out parameters than for inclusive hadrons, but for D mesons with the same ones. Thus it was shown that the main part of D mesons, unlike J/ψ, seems to be in a kinetic equilibrium with hot hadronic matter.

The various mechanisms of $B^{\pm}$ meson suppression were analyzed with HYDJET++ model [19]. We can see that the contributions of nuclear shadowing and jet quenching into mechanisms of $B^{\pm}$ meson suppression are comparable at transverse momentum $p_{\rm T} \approx 10$ GeV/c. The relative contribution of jet quenching becomes stronger with increasing of transverse momentum and totally dominates at $p_{\rm T} > 30$ GeV/c. Since $B^{\pm}$ meson suppression factor $R_{\rm AA}$ due to jet quenching (nuclear shadowing) decreases (increases) with transverse momentum, the interplay between the two effects results in a weak (roughly constant) transverse momentum dependence of $R_{\rm AA}$. As we know LHC experimental data show the same trend.

3. HYDJET++ model tuning for the NICA energies

Very soon the heavy-ion physics program of the NICA (Nuclotron-based Ion Collider fAcility) will be started with planned energies of collisions from 3 to 11 GeV per nucleon pair. As it was already mentioned, HYDJET++ event generator originally was designed rather for very high energies (RHIC and LHC) than for intermediated energies like NICA ones. In particular, the soft component of HYDJET++ is based on the parametrization of the hydrodynamic equations assuming the complete local thermalization of the system. However such a condition may be not fulfilled at NICA energies. Also the contribution of the hard jet component at NICA energies will be extremely small. Nevertheless, nowadays we are starting to explore and tune HYDJET++ model to low energy front of the high energy physics.

Our first point was to achieve HYDJET++ description of multiplicity and transverse momentum $p_{\rm T}$ spectra of the different kinds of particles at NICA energies. For this task we have used the experimental data by STAR [20] for AuAu collisions at $\sqrt{s_{\rm NN}} = 7.7$ and 11.5 GeV. We have found that HYDJET++ model reproduces quite well transverse momentum $p_{\rm T}$ spectra for identified charged hadrons (π^+, π^-, K^+, K^-, p and $\overline{p}$) in AuAu collisions at these energies with centrality 0–5%. Figure 1 demonstrates this for $\sqrt{s_{\rm NN}} = 7.7$ GeV.

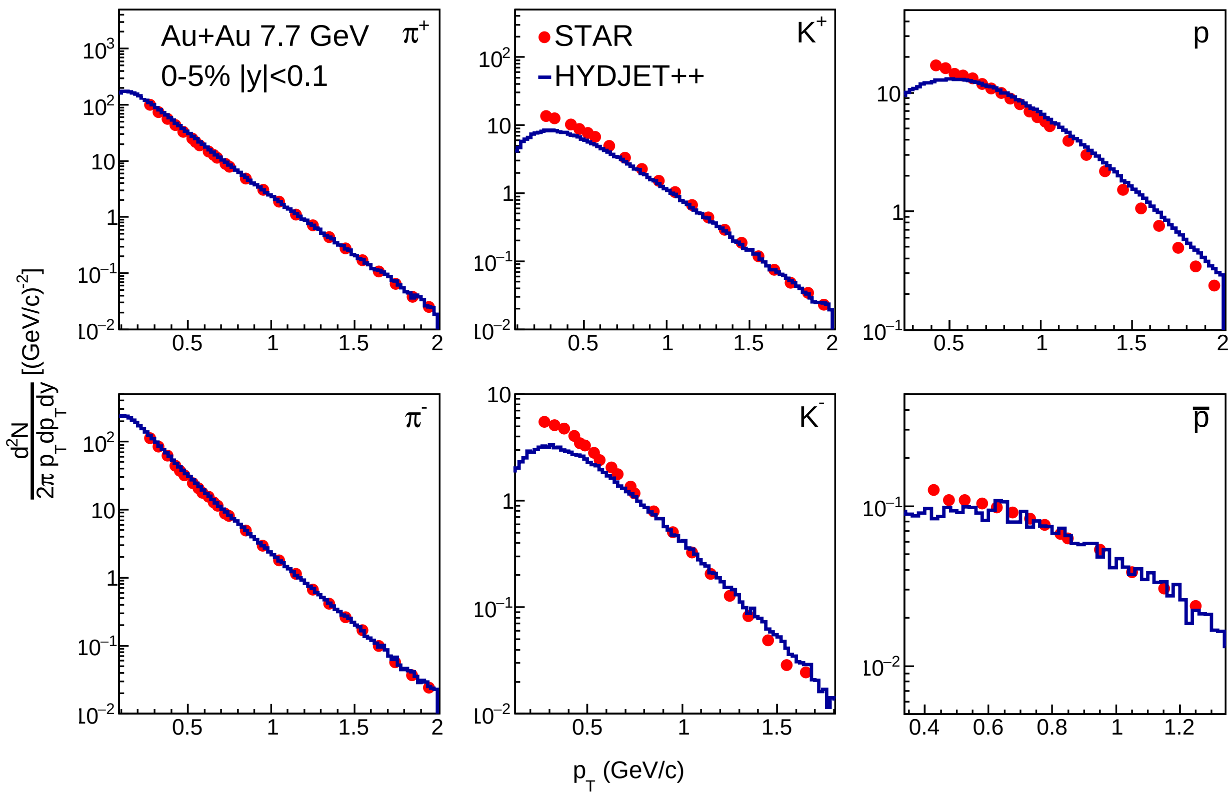

Figure 1. Mid-rapidity $|y| < 0.1$ transverse momentum p_T spectra for π^+, π^-, K^+, K^-, p and $\overline{p}$ in AuAu collisions at $\sqrt{s_{NN}} = 7.7$ GeV with centrality 0–5%. Points are the experimental data by STAR [20], histograms are HYDJET++ results.

Table 1. Multiplicity densities dN/dy for $|y| < 0.1$ in AuAu collisions at $\sqrt{s_{NN}} = 7.7$ GeV with centrality 0–5% for different kinds of particles by the data of the STAR experiment [20] and by the simulation with HYDJET++ model. STAR errors are based on the combined statistical and systematic uncertainties, statistical errors for HYDJET++ are negligible.

Particle	STAR	HYDJET++
π^+	93.4 ± 8.4	93.2
π^-	100 ± 9.0	103
K^+	20.8 ± 1.7	14.6
K^-	7.7 ± 0.6	5.5
p	54.9 ± 6.1	50.4
$\overline{p}$	0.39 ± 0.05	0.37

Table 1 shows the multiplicity densities dN/dy for $|y| < 0.1$ in AuAu collisions at $\sqrt{s_{NN}} = 7.7$ GeV with centrality 0–5% for different kinds of particles by the data of the STAR experiment [20] and by the simulation with HYDJET++ model. The different types of hadron yields obtained with HYDJET++ agree with the experimental data within 10% accuracy for pions and protons, but the underestimation of the kaon yield is near 30%. The results for $\sqrt{s_{\rm NN}} = 11.5$ GeV are the similar.

Thus, the first studies show that HYDJET++ event generator can be used to estimate various physical observables at NICA energies. The prospects for HYDJET++ applications in the domain of NICA energies are still under investigation.

4. Conclusions

HYDJET++ Monte-Carlo event generator allows one to describe a number of physical observables at relativistic heavy-ion collisions from NICA and RHIC to LHC energies. Further developing of the model can give us the possibility to continue this interesting activity of understanding of the very deep properties of the matter.

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