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MC-EKRT EVENT GENERATOR FOR INITIALIZING 3+1 D HYDRODYNAMICS

ABSTRACT

We present a Monte-Carlo implementation of the EKRT initial-state model [1]. Our new MC-EKRT event generator is based on collinearly factorized, dynamically fluctuating pQCD minijet production, supplemented with a saturation conjecture that controls the low-p_T particle production. Previously, the EKRT model has been very successful in describing low-p_T observables at mid-rapidity in heavy-ion collisions at RHIC and LHC energies [2, 3]. As novel features, our new MC implementation gives a full 3-dimensional initial state event-by-event, and includes dynamical fluctuations in the saturation and particle production. As a proof of principle study, we average a large set of event-by-event MC-EKRT initial conditions and compute the rapidity and centrality dependence of the charged hadron multiplicities for the LHC Pb+Pb and RHIC Au+Au collisions using 3+1 D viscous fluid dynamical evolution.

OUR A-B COLLISION, STEP BY STEP

1. Sample nucleus–nucleus impact parameter $\bar{b}_{AB}$.
2. Sample nucleon coordinates for the nuclei A and B.
3. Triggering condition: For any nucleons $a \in A$ and $b \in B$

$$\mathrm{d}(a,b) = \sqrt{(\bar{s}_a - \bar{s}_b)^2} \le \sqrt{\frac{\sigma^{NN}_{\text{trig}}}{\pi}},$$

where $\sigma^{NN}_{\text{trig}}$ is the nucleon–nucleon inelastic cross section.

4. Model the A-B collision as a collision of two parton clouds: Produce minijets ($p_T \ge p_{T0} = 1\,\text{GeV}$) with pQCD and collinear factorization from the nucleon–nucleon pairs.
5. Filter excess minijets, event by event, by local EKRT saturation and nucleon-level momentum conservation.
6. Feed the remaining minijets to hydro at proper time $\tau_0 = 1/p_{T0}$ with Gaussian smearing in the transverse coordinates and spacetime rapidity.
7. Run 3+1 D viscous hydro event by event (here testing with averaged initial states).
8. Compute observables.

MINIJETS FROM N-N PAIRS

1. For nucleons $a \in A$ and $b \in B$, the probability to produce $n \ge 0$ minijet pairs is:

$$P_n^{ab}(\bar{b}_{ab}) \equiv \frac{\left(T_{NN}(\bar{b}_{ab})\,\sigma^{ab}_{\text{jet}}\right)^n}{n!} e^{-T_{NN}(\bar{b}_{ab})\,\sigma^{ab}_{\text{jet}}},$$

where $\bar{b}_{ab} = \bar{s}_b - \bar{s}_a$ is the nucleon–nucleon impact parameter, T_{NN} is the nucleonic overlap function (Gaussian), and σ^{ab}_{jet} is the LO inclusive minijet production cross section.

2. Sample transverse momentum p_T and rapidities y_1 and y_2 for the produced minijets from $\frac{\mathrm{d}\sigma^{ab}_{\text{jet}}}{\mathrm{d}p_T^2\mathrm{d}y_1\mathrm{d}y_2}$ with nuclear PDFs that depend on the transverse location of each nucleon.
3. Sample spatial coordinates for the dijets from the product of the nucleon thickness functions $T_N(\bar{s}-\bar{s}_a) * T_N(\bar{s}-\bar{s}_b)$.

MINIJET CROSS SECTION

LO differential cross section of hard parton production:

$$\frac{\mathrm{d}\sigma^{ab}_{\text{jet}}}{\mathrm{d}p_T^2\mathrm{d}y_1\mathrm{d}y_2} = K\sum_{ijkl} x_1 f_i^{a/A}(\bar{s}_a, x_1, Q^2)\, x_2 f_j^{b/B}(\bar{s}_b, x_2, Q^2) \times \frac{\mathrm{d}\hat{\sigma}^{ij\to kl}}{\mathrm{d}\hat{t}},$$

where K accounts for higher order contributions, and $f_i^{a/A}(\bar{s}_a, x, Q^2)$ is a spatially dependent parton distribution function of parton flavour i in a nucleon a of nucleus A.

SPATIAL NUCLEAR PDFs – NEW!

Problem: Fluctuating $T_A(\bar{s}) \equiv \sum_{a=1}^{A} T_N(\bar{s}-\bar{s}_a)$ can grow very large $\Rightarrow$ EPS09s spatial nPDFs cannot be used.

Solution: Define the event by event fluctuating spatially dependent nPDF of the proton a bound in a nucleus A as

$$f_i^{a/A}(\bar{s}_a, x, Q^2) \equiv \exp\left(c_A(x,Q^2)\,\hat{T}^a_A(\bar{s}_a)\right) f_i^p(x, Q^2),$$

where $\hat{T}^a_A$ is a T_N-weighted average of the nuclear thickness function experienced by the nucleon a,

$$\hat{T}^a_A(\bar{s}_a) \equiv \sum_{b\neq a}^{A} T_{NN}(\bar{b}_{ab})\,.$$

The coefficient $c_A(x, Q^2)$ is set by normalizing to the global averaged nuclear modification (EPS09LO):

$$R_i^A(x,Q^2) = \left\langle \int \mathrm{d}^2\bar{s}\, \frac{\sum_{a=1}^{A} f_i^{a/A}(\bar{s}_a, x, Q^2)}{A f_i^p(x,Q^2)} \right\rangle_{\{A\}} \equiv F\left(c_A(x,Q^2)\right),$$

where $\langle\cdot\rangle_{\{A\}}$ is an average over all the sampled nuclei. The function F can be inverted numerically:

$$c_A(x,Q^2) \equiv F^{-1}\left(R_i^A(x,Q^2)\right).$$

MINIJET FILTERING EbyE – NEW!

The excessive minijet multiplicity is reduced by filtering the minijets simultaneously with a local EKRT saturation and momentum conservation. To keep collinear factorization valid from the highest p_T's down to as low a p_T as possible, we do the filtering in the order of the formation time $\tau = 1/p_T$, thus removing mainly the smallest-p_T minijets.

EbyE MC-EKRT SATURATION – NEW!

Towards the smallest p_T's, multiple minijet production populates the phase space so densely that $3 \to 2$, $4 \to 2, \ldots$ processes become as important as $2 \to 2$. This is the conjectured saturation limit here [2], which regulates the minijet production. In the current EbyE MC-EKRT set up, each candidate dijet is considered to have a spatial uncertainty area of radius $1/p_T^{\text{cand}}$ in the transverse plane around the sampled production point $\bar{s}^{\text{cand}}$. The candidate is compared with all of the previously accepted dijets with parameters p_T and $\bar{s}$, and if for any of them

$$\sqrt{\left(\bar{s} - \bar{s}^{\text{cand}}\right)^2} < \frac{1}{\kappa_{\text{sat}}}\left(\frac{1}{p_T} + \frac{1}{p_T^{\text{cand}}}\right),$$

the candidate dijet is rejected. The external parameter κ_{sat}, to be fitted from the data, acts as a “packing factor”.

MOMENTUM CONSERVATION – NEW!

Momentum conservation here is forced for each nucleon. If there are n accepted dijet processes with momentum fractions $(x_1^{(1)}, \ldots, x_1^{(n)})$ for nucleon 1 and m accepted processes for nucleon 2 with fractions $(x_2^{(1)}, \ldots, x_2^{(m)})$, then the candidate dijet process with momentum fractions x_1 and x_2 is accepted if

$$x_1 + \sum_{i=1}^{n} x_1^{(i)} \le 1 \quad \text{and} \quad x_2 + \sum_{i=1}^{m} x_2^{(i)} \le 1$$

3+1 D VISCOUS HYDRO

The accepted minijets are propagated as free particles to the proper time surface $\tau_0 = 1/p_{T0}$ ($= 0.2\,\text{fm/c}$) and spacetime rapidity $\eta = y$. The initial energy density profile for 3+1 D viscous fluid dynamical simulation is then obtained from minijet 4-momenta by summing over all the accepted minijets in an event:

$$e(\bar{s},\eta) = \frac{1}{\tau_0\,\mathrm{d}^2\bar{s}\,\mathrm{d}\eta}\sum_{i=1}^{N_{\text{jet}}} g_i(\bar{s},\eta)\, p_{T\,i}\cosh(\eta - \eta_i),$$

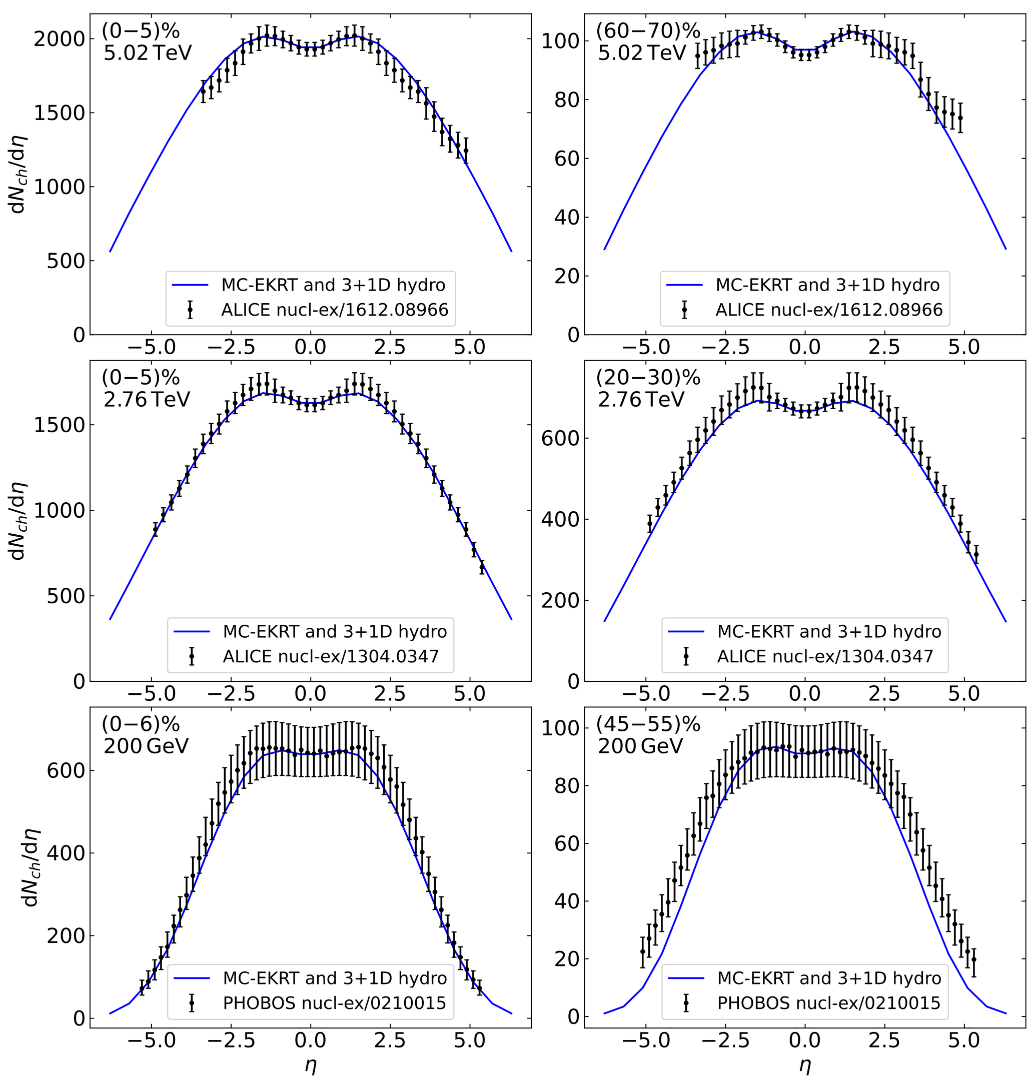
where $g_i(\bar{s},\eta)$ is a Gaussian-type smearing function

$$g_i(\bar{s},\eta) = \frac{1}{N} e^{-\frac{1}{2}\frac{(\bar{s}-\bar{s}_i)^2}{\sigma_T^2}}\, e^{-\frac{1}{2}\frac{(\eta-\eta_i)^2}{\sigma_L^2}}$$

where σ_T and σ_L are the transverse and longitudinal width parameters, and N is a normalization factor.

The events are divided into centrality classes according to the initial E_T. For each event, the energy density profile is converted to entropy density using the equation of state *s95p-PCE* with chemical freeze-out at 150 MeV. The event zaveraged entropy density is then converted back to energy density in each centrality class. The hydrodynamical evolution lasts until kinetic freeze-out temperature $T_{\text{kin}} = 130\,\text{MeV}$. We use a constant value $\eta/s = 0.12$ for the specific shear viscosity and omit the bulk viscous effects.

RESULTS



Charged particle multiplicity $\frac{dN_{ch}}{d\eta}$ as a function of pseudorapidity in central and peripheral events, compared with ALICE Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ and $2.76\,\text{TeV}$, and PHOBOS Au+Au data at $\sqrt{s_{NN}} = 200\,\text{GeV}$. Here the pQCD K-factors are 1.7, 1.9 and 3.2 for $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, 2.76 TeV and 200 GeV. The Gaussian widths $\sigma_T = 0.4\,\text{fm}$ and $\sigma_L = 0.5$ and saturation parameter $\kappa_{\text{sat}} = 2.5$ are kept constant.

REFERENCES

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