Signature of intermittency in hybrid UrQMD-hydro data at 10 AGeV Au+Au collisions

Somen Gope\textsuperscript{a}, Buddhadeb Bhattacharjee\textsuperscript{b}

Nuclear and Radiation Physics Research Laboratory, Department of Physics, Gauhati University, Guwahati, Assam 781014, India

Received: 17 September 2020 / Accepted: 13 January 2021 / Published online: 30 January 2021
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Communicated by Evgeni Kolomeitsev

Abstract An attempt has been made, in the light of scaled factorial moment (SFM) analysis, to investigate hybrid UrQMD-hydro generated events of Au+Au collisions at 10 AGeV to realize the role of hydrodynamic evolution on observed intermittency, if any. \( \ln \langle F_q \rangle \) values for \( q = 2-6 \) are found to increase with increasing values of \( \ln M^2 \) indicating unambiguously the presence of intermittency in our data sample generated with both chiral and hadronic equations of state (EoS). Although various late processes like meson-meson (MM) and meson-baryon (MB) hadronic re-scattering and/or resonance decays are found to influence the intermittency index significantly, these process could not be held responsible for the observed intermittency in hybrid UrQMD-hydro data. Moreover, the signature of intermittency is also found to exists in different sets of data sample generated with a change in initial conditions such as the start time \((t_{\text{start}})\) and transition energy density (TED) of the UrQMD-hydro model confirming the robustness of the observed power law behavior \( F_q \propto (M^2)^{\alpha_q} \) in our various generated sets of hydro data.

1 Introduction

Correlated emission of produced particles of a nuclear collision results in preferential emission of particles over some preferred phase space bins of pseudorapidity \((\eta)\), azimuthal angle \((\phi)\), transverse momentum \((p_T)\) or any combination of these resulting genuine non-statistical (dynamical) fluctuation in the single particle density distribution spectra. A number of mathematical tools are available to extract and analyze these dynamical fluctuations to have an insight into the collision dynamics in general and particle production mechanism in particular.

Scaled factorial moment (SFM), \( F_q \), where \( q \) is the order of the moments, is one such tested and widely used mathematical tool, that filters out dynamical fluctuation from the mixture of statistical and dynamical one \([4,8,9]\). A power law behavior of \( F_q \) on diminishing phase space bin width \( \delta w \), or otherwise, on increasing number \( M \) of bins into which the phase space is divided, that is, \( F_q \propto M^{\alpha_q} \) is termed as intermittency where the exponent \( \alpha_q \) is called the intermittency index and denotes the strength of intermittent particle emission. Intermittency is a property connected with the scale invariance of the physical process and was used first in connection with the turbulence burst in classical hydrodynamics \([10–12]\).

In the study of the heavy-ion collisions, hydrodynamical approach remains the heart of the dynamical modeling of such collisions \([13]\). Hydrodynamics plays an important role in connecting the static aspects of the matter formed in the collision and the dynamical aspect of such collisions. The high elliptic flow values that have been observed at Relativistic Heavy Ion Collider (RHIC) that seems compatible with some ideal hydrodynamic prediction added additional importance to this approach during last decade \([14]\). Hydrodynamics is applied to matter under local equilibrium in the intermediate stage of the evolution of heavy-ion collision (HIC). In this approach a local correspondence between the
energy density and the multiplicity of the final hadrons is assumed.

The Ultra-Relativistic Quantum Molecular Dynamics (UrQMD) is a QCD based microscopic transport model of nuclear collision that is based on the phase space description of such collisions [15]. While at low energies collisions are better described in terms of hadronic interactions and resonance decays, at relativistic and ultra-relativistic energies quark and gluons degrees of freedom are introduced via the excitation and fragmentation of strings. The model has found to be highly successful in describing the experimental results of pp, pA and AA collision from SIS to LHC energies [16–18]. Several attempts [19,20] have been made to investigate non-statistical fluctuation using SFM technique with UrQMD generated data for different systems. However, such analysis of UrQMD data does not exhibit any signature of intermittency [19,24].

UrQMD-hydro, on the other hand, is a hybrid micro plus macro approach that incorporates transport and hydrodynamical description of heavy-ion collisions for more consistent portrayal of such events from the initial state of collision to final decoupling of hadrons. Here, the microscopic transport calculation for initial condition and freeze-out procedure is implemented with intermediate hydrodynamic calculations [14,15].

In this work an attempt has been made to analyze UrQMD-hydro generated all charged particles data using scaled factorial moment technique to realize the presence of intermittency, if any, in the data sample and hence to assess if the hydro plays any role on the observed intermittent type of emission of particles produced in a nuclear collision. Keeping in mind the large acceptance of the upcoming Compressed Baryonic Matter (CBM) experiment at Antiproton and Ion Research (FAIR), Germany as well as the facts that 10 AGeV is the highest achievable energy for A-A collision at SIS100 of FAIR [21] and according to hydrodynamical calculation, the deconfinement phase border is first reached around 10 AGeV [22,23], the present investigation is carried out with 10 AGeV Au+Au collisions MC data.

Further, it has been pointed by a number of workers [24–27] that the correlation among the emitted particles of heavy-ion collisions might washout due to a number of effects such as − effect due to dimensional projection from 3D hyperspace to 1D phase space (η, φ or pT), contribution from the isotropic decay of the metastable resonances etc. With the help of UrQMD model generated data for Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, it has been shown by J. Steinheimer et. al. [28,50] that due to last stage hadronic re-scattering for both stable and unstable particles, the momentum distribution (by 30%) as well as the particle multiplicity change significantly. It is therefore expected that for FAIR-CBM experiment, where a fireball of high net-baryon density is supposed to be created, the final state hadronic interaction and resonance decay would influence the observables of such collision quite significantly. Therefore, in this work an attempt has also been made to see the effect of final stage hadronic interaction and resonance decays on the observed intermittency by switching on and off the meson–meson (MM), meson–baryon (MB) scattering and resonance decays in UrQMD-hydro model.

2 Mathematical formalism

In the study of intermittency in one dimension, a pseudo-rapidity interval $\Delta \eta$ is divided into $M$ bins of equal width $\delta \eta = \frac{\Delta \eta}{M}$, where $\eta$ is defined as $\eta = -\ln(tan(\theta/2))$. Here, $\theta$ is the polar angle of each emitted charged particle of an event and is estimated as $\theta = \cos^{-1}(p_z/p)$.

If $n_m$ is the number of particles in the $m$th bin, where $m$ can take any value from 1 to $M$ (=10, say), the factorial moment $f_q$ of order $q$ is defined as [4,29,45]:

$$ f_q = \langle n_m(n_m-1)\ldots(n_m-q+1) \rangle $$

If the averaging in the above equation is performed over all events for a fixed bin, the procedure is called vertical averaging and gives fluctuation in event space. On the other hand, if $n_m$ is averaged over all bins for a fixed event, it is called horizontal averaging and provides information on fluctuation in phase space.

Assuming that the statistical contribution to the fluctuation in the spatial distribution of the charged particles is Poisson distributed, Bialas and Peschanski showed that the factorial moments of the multiplicity distribution of the entire sample of events are equivalent to the moments of the corresponding dynamical part only, irrespective of the nature of the statistical component [4,8]. In either method of averaging, if the probability distribution $P_n$ of $n_m$ can be expressed as a convolution of dynamical distribution $D(v)$ and the statistical (Poissonian) distribution, $f_q$ is shown to be a simple moment of $D(v)$, the statistical component is regarded as having been filtered out by $f_q$ estimation [46].

For a single event, the $q$th order scaled factorial moment is defined as:

$$ F_q = M^{-q-1} \sum_{m=1}^{M} \frac{n_m(n_m-1)\ldots(n_m-q+1)}{n(n-1)\ldots(n-q+1)} $$

where, $n$ is the multiplicity of an event. Thus, $n = \sum_{m=1}^{M} n_m$.

For an ensemble of events having varying multiplicity, the expression for scaled factorial moment is modified as:

$$ F_q = M^{-q-1} \sum_{m=1}^{M} \frac{n_m(n_m-1)\ldots(n_m-q+1)}{\langle n \rangle^q} $$
where, $\langle n \rangle = \frac{\sum_{n} N_{ev} n}{N_{ev}}$. $N_{ev}$ is the total number of events of the population.

The horizontally averaged normalized or scaled factorial moment is then expressed as:

$$\langle F_q \rangle = \frac{1}{N_{ev}} \sum_{i=1}^{M} M^{q-1} \sum_{m=1}^{M} n_m (n_m - 1) \ldots (n_m - q + 1) \langle n \rangle^q$$

(4)

In log–log plot, a linear increase of scaled factorial moment $\langle F_q \rangle$ with decreasing bin width $\delta \eta$ or otherwise, increasing number of bins $M$ into which the pseudorapidity space is divided confirms the power law behavior of the form $\langle F_q \rangle \propto M^{\alpha_q}$, thereby indicating the intermittent pattern of emission of particle in a nuclear collision.

Intermittency, in turn, is related to self similarity and fractal behavior of the emission spectra \cite{4,47–49}. The anomalous fractal dimension $d_q (= D - D_q$, where $D$ and $D_q$ are ordinary topological dimension and generalized fractal dimension respectively), is related to intermittency index $\alpha_q$ through the relation

$$d_q = \frac{\alpha_q}{(q - 1)}$$

(5)

A study on the order $q$ dependence of $d_q$ is quite informative about the particle production mechanism. It is claimed \cite{30,31} that an increase in $d_q$ with $q$ is associated with particle production via some branching mechanism. An order independence of $d_q$, on the other hand, is indicative of particle production via a phase-transition.

3 Results

The analysis was initiated by generating equal number of events $3.02 \times 10^4$ of UrQMD-hydro (default) \cite{32–34} and UrQMD (default) \cite{15,35,36} Monte Carlo (MC) events for central (0–5% $\equiv b \leq 2.0$ fm) \cite{37} Au+Au collisions at 10 AGeV. To examine the applicability of hybrid UrQMD-hydro model at SIS100 energy, another set of MC events for Au+Au collisions at 8 AGeV is generated and the transverse mass ($m_T$) spectra of $\pi^+$ at 10 AGeV is generated and the transverse mass ($m_T$) spectra of $\pi^+$ of the generated data is compared with the experimental $m_T$ spectra of $\pi^+$ of the experimental to our generated data. Compared published spectra by C. Spieles using UrQMD-hydro data with experimental spectra of E895

To minimise the projection effect, if any, the analyses of the UrQMD-hydro and UrQMD data using SFM technique are being carried out for all charged particles in two dimensional pseudorapidity-azimuthal ($\eta - \phi$) space. Initial shape dependence of the two dimensional density distribution spectrum (Fig. 2a, b) is removed by converting the pseudorapidity ($\eta$) and azimuthal angle ($\phi$) [$\phi = \tan^{-1}(p_y/p_x)$] values of every primary charged particle of each generated event to a
Fig. 2 Density distribution spectrum for a single event in 2D \( \eta - \phi \) space, b entire sample in 2D \( \eta - \phi \) space and c entire sample in 2D \( \chi(\eta - \phi) \) spaces

where, \( \eta_{\text{min}} = -5.0, \eta_{\text{max}} = 5.0, \phi_{\text{min}} = 0 \) and \( \phi_{\text{max}} = 6.28 \). Obviously, from Eq. (6), the values of \( \chi(\eta) \) and \( \chi(\phi) \) vary from 0 to 1. The two dimensional \( \chi(\eta - \phi) \) space is now divided into \( M_1 \times M_1 \) bins of equal width \( d\chi_\eta \times d\chi_\phi \) where \( M_1 = 1 \) to 10 and \( d\chi_\eta = \frac{\eta_{\text{max}}(\eta) - \eta_{\text{min}}(\eta)}{M_1} \) and \( d\chi_\phi = \frac{\phi_{\text{max}}(\phi) - \phi_{\text{min}}(\phi)}{M_1} \) [40,41]. Thus, the minimum and maximum values of \( d\chi_\eta \) and \( d\chi_\phi \) would be 0.1 and 1 respectively. Accordingly, the size of the smallest bin of the two dimensional \( \chi(\eta - \phi) \) space would be 0.1 \times 0.1 when it is divided into hundred square bins of equal size \( d\chi_\eta \times d\chi_\phi \). The single particle density distribution spectrum of two dimensional \( \eta - \phi \) space (Fig. 2b) is then replotted in two dimensional \( \chi(\eta - \phi) \) cumulant phase space as shown in Fig. 2c with UrQMD-hydro (default) and UrQMD (not shown) generated data. It could be readily seen from Fig. 2c that, as expected, the distribution is found to be flat in \( \chi(\eta - \phi) \) space and is free from any preferential emission thereby minimizing the scope of any error in our fluctuation studies due to initial (kinematic) shape dependence of the single particle spectra itself.

Equal number of events are then generated using random number generator (RAN-GEN) with same multiplicity as that of each event of UrQMD-hydro data with \( \chi(\eta) \) and \( \chi(\phi) \) values for each particle randomly generated between 0 and 1.

To estimate the scaled factorial moment in two dimensional cumulant \( \chi(\eta - \phi) \) space using the above formula (Eq. 4), as stated above, the two dimensional \( \chi(\eta - \phi) \) space is successively divided into \( M_1 \times M_1 \) = 1, 4, 9, 16, ...., 100 bins of equal width \( d\chi_\eta \times d\chi_\phi \). The number of particles populating each square bin is computed to estimate the corresponding SFM. The SFM estimated for each bin are then averaged for all bins and finally over all events to get \( \langle F_q \rangle \) for different values of \( M^2 \).

The two dimensional horizontally averaged scaled factorial moments \( \langle F_q \rangle \) of order \( q = 2 - 6 \) are then estimated for \( \chi(\eta - \phi) \) space with UrQMD-hydro, UrQMD and RAN-GEN generated data and the values of \( \ln \langle F_q \rangle \) are plotted against \( \ln M^2 \) in Fig 3a. From this plot, a clear signature of power law behavior of the form \( \langle F_q \rangle \propto M^{\alpha_q} \) for the estimated values of \( \langle F_q \rangle \) with the increasing number of phase space bin \( M^2 \) could be observed confirming the presence of intermittency in UrQMD-hydro (default) generated data with chiral equation of state (EoS). The error bars shown in these plots are estimated by considering them as independent statistical errors only and the effect of correlation of statistical errors for different bin size has not taken into consideration here. However, as pointed out by several other workers [42–44] exclusion of the correlation of statistical errors does not change the main results appreciably.

Moreover, it is evident from the inset plot of Fig. 3a that no such intermittency effect could be seen with UrQMD (trans-
Fig. 3 $\ln \langle F_q \rangle$ vs $\ln M^2$ plots for (a) UrQMD-hydro (default) events and UrQMD and RAN-GEN events (inset) and (b) for UrQMD-hydro events with hadronic and chiral equations of state (EoS). Solid straight lines are the best fitted lines to the data points.

Fig. 4 $\ln \langle F_q \rangle$ vs $\ln M^2$ in $\chi(\eta - \phi)$ space for UrQMD-hydro data with different start time ($t_{\text{start}}$). Solid straight lines are the best fitted lines for the data points.

Fig. 5 $\ln \langle F_q \rangle$ vs $\ln M^2$ in $\chi(\eta - \phi)$ space for UrQMD-hydro data with two different transition energy density (TED). Solid straight lines are the best fitted lines for the data points.

In hybrid UrQMD-hydro model, both the initial and final stages of the collision are described by transport UrQMD model [14], which does not exhibit any signal of intermittency. The observed intermittency in UrQMD-hydro (default) data could therefore be due to hydrodynamic evolution of the matter created in the collisions or/and due to use of chiral EoS.

To the best of our knowledge, no work on intermittency has been reported yet with UrQMD-hydro generated data and therefore to check the robustness of the observed power law behavior in the hybrid UrQMD-hydro (default) data, new sets of hybrid UrQMD-hydro events are generated by changing the initial conditions such as the start time ($t_{\text{start}}$) of hydrodynamic evolution and the transition energy density (TED), which is related to the end time of the hydrodynamic evolution. In hybrid UrQMD hydro model, while the two lorentz contracted nuclei pass through each other, the coupling between the UrQMD initial and hydrodynamic evolution takes place. $t_{\text{start}}$ is the initial time to begin the hydrodynamic evolution. In Fig. 4, $\ln \langle F_q \rangle$ vs $\ln M^2$ is plotted for different $t_{\text{start}}$ (1, 3, and 5 fm). It could readily be seen that while the general trend of power law behavior remains unaffected, the strength of intermittency indices decrease with the increase of $t_{\text{start}}$ (Table 1). For a fixed TED, a large $t_{\text{start}}$ means a shorter period of hydrodynamic evolution which in turn weakened the strength of intermittency.

The freeze-out or transition energy density (TED), on the other hand, is the energy density at which the system passes from the local equilibrium phase to the phase of non-equilibrium final state [52,53]. In other words, it is the energy density at which transition from hydrodynamic to transport description of HIC takes place and is expressed in terms of $\epsilon_f = 145 \text{ MeV/fm}^3$. A higher value of TED means early hadronization. A plot of $\ln \langle F_q \rangle$ against $\ln M^2$ for two different TED is shown in Fig. 5 and the power law of SFM on $M^2$ is readily evident in this case as well. The observed decrease in the intermittency index could be due to shorter hydrody-
Table 1: Intermittency index values for $q = 2-6$ for various systems using UrQMD-hydro model

| Systems                                      | $\alpha_2 \times 10^{-3}$ | $\alpha_3 \times 10^{-3}$ | $\alpha_4 \times 10^{-3}$ | $\alpha_5 \times 10^{-3}$ | $\alpha_6 \times 10^{-3}$ |
|----------------------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Hydro with chiral EoS                        | 1.20 ± 0.75               | 3.70 ± 0.78               | 8.40 ± 0.85               | 14.10 ± 0.94              | 20.80 ± 1.20              |
| Hydro with hadronic EoS                      | 0.20 ± 0.10               | 1.18 ± 0.32               | 3.50 ± 0.78               | 5.20 ± 0.94               | 11.38 ± 0.99              |
| Hydro with MM and MB scattering off          | 1.26 ± 0.90               | 5.31 ± 1.40               | 10.70 ± 1.46              | 18.10 ± 1.88              | 27.9 ± 2.46               |
| Hydro with resonance decays off              | 1.06 ± 0.61               | 3.82 ± 0.94               | 9.19 ± 1.02               | 17.23 ± 1.38              | 24.56 ± 1.93              |
| Hydro with both MM, MB and resonance decays off | 1.44 ± 0.90       | 5.38 ± 1.46               | 13.25 ± 1.40              | 20.20 ± 1.61              | 31.50 ± 2.54              |
| Hydro with $t_{\text{start}} = 1 \text{fm}$ | 1.20 ± 0.75               | 3.70 ± 0.78               | 8.40 ± 0.85               | 14.10 ± 0.94              | 20.80 ± 1.20              |
| Hydro with $t_{\text{start}} = 3 \text{fm}$ | 0.90 ± 0.78               | 3.26 ± 0.80               | 7.98 ± 0.90               | 13.29 ± 0.93              | 19.09 ± 1.14              |
| Hydro with $t_{\text{start}} = 5 \text{fm}$ | 0.72 ± 0.80               | 3.02 ± 0.81               | 7.43 ± 0.91               | 12.74 ± 0.94              | 18.53 ± 1.12              |
| Hydro with TED = 5 $\times$ $\epsilon_0$ fm | 1.20 ± 0.75               | 3.70 ± 0.78               | 8.40 ± 0.85               | 14.10 ± 0.94              | 20.80 ± 1.20              |
| Hydro with TED = 7 $\times$ $\epsilon_0$ fm | 1.00 ± 0.97               | 3.11 ± 0.99               | 8.10 ± 1.32               | 10.75 ± 2.01              | 19.11 ± 3.02              |
Intermittency index ($\alpha_q$) vs $q$ and b anomalous fractal dimension ($d_q$) vs $q$ for UrQMD-hydro data with chiral and hadronic EoS.

Fig. 6  a Intermittency index ($\alpha_q$) vs $q$ and b anomalous fractal dimension ($d_q$) vs $q$ for UrQMD-hydro data with chiral and hadronic EoS.

Dynamic evolution stage and/or more hadronic re-scattering due to longer final stage.

To ascertain the role of EoS (chiral/hadronic) in the observed intermittency in our hydro generated data, another set of UrQMD-hydro data was generated with hadronic EoS. The result of 2D analysis is presented in Fig. 3b for both the sets of data generated with hadronic and chiral EoS. A clear increase in the values of $\ln \langle F_q \rangle$ against $\ln M^2$ could be seen with UrQMD-hydro central (0–5%) data for both hadronic and chiral EoS. With chiral EoS, the intermittency indices $\alpha_q$ for $q = 2–6$ are found to be significantly larger than that of hadronic EoS data. The values of intermittency indices for different order of moments as estimated from this analysis with different sets of data are listed in Table 1. The errors in $\alpha_q$ are estimated by adding the errors in quadrature for three different bin widths [40]. The variation $\alpha_q$ against $q$ for UrQMD-hydro generated data with chiral and hadronic EoS are shown in Fig. 6a. The observed stronger intermittency in the data sample of UrQMD-hydro with chiral EoS than that of hadronic EoS data may be attributed to cascading particle production in partonic media produced due to the use of chiral EoS.

In Fig. 6b, the variation of $d_q$ with $q$ is shown for UrQMD-hydro generated data with both hadronic and chiral equation of states and is found to increase monotonically with the increase of $q$ for both the sets of data. A strong $q$ dependence of $d_q$ is suggestive of particle production via self-similar cascading mechanism indicating about the multifractal nature of the particle spectra. However, $d_q$ is consistently found to be larger in data sample with chiral EoS than that of hadronic EoS indicating the fact that particles of UrQMD-hydro data with chiral EoS occupy less phase space than that of hadronic EoS, or otherwise, particle emission is more preferential in partonic media than that of hadronic media.

The hadronic re-scattering and/or resonance decays have substantial impact on most of the hadronic observables, such as correlations and fluctuations [50,51]. Experimentally, one measures only final abundances of hadrons which includes both primordial particle production as well as contribution from the resonance decays. Production of resonances plays an important role for studying various properties of interac-
tion dynamics in heavy-ion collisions. Resonances, having short life time that subsequently decay into stable hadrons, as well as hadronic re-scattering can effect the final hadrons’ yields and their number fluctuations [51]. To evaluate the contribution of such processes on the observed intermittency, three new sets of UrQMD-hydro events are generated with (i) meson–meson (MM) and meson–baryon (MB) scattering off but resonance decays on, (ii) MM, MB scattering on but resonance decays off, and (iii) MM, MB, and resonance decays all off. \(ln(F_q)\) vs \(lnM^2\) plots for all such events are shown in Fig. 7a–c. It is readily evident from these figures that although all these late stage processes, such as hadronic re-scattering and/or resonance decays weaken the signatures of intermittency significantly, none of these processes are the cause of observed intermittent type of particle emission in our hybrid UrQMD-hydro generated data.

4 Summary

From the present investigation of two dimensional scaled factorial moments analysis on \(\chi(\eta, \phi)\) spaces, it is found that the data generated with UrQMD transport model or random generator do not exhibit any noticeable signature of self similarity or intermittency. On the other hand, the data of hybrid UrQMD-hydro event generator, which is a mixture of transport and hydrodynamic models, does exhibit intermittency both for hadronic and chiral EoS. The observed power law behavior seen in UrQMD-hydro data with both hadronic and chiral EoS, and not in UrQMD data, confirms that the observed intermittency is not associated with the nature of the medium produced in the heavy-ion collision, but on the mechanism of evolution of the medium produced in such collision. Although, the observed power law behavior is found to be invariant on the changes in initial conditions such as \(t_{\text{start}}\) and transition energy density of the hybrid UrQMD-hydro model, the intermittency index significantly changes due to the changes in initial condition. The particle production is found to be more preferential in UrQMD-hydro generated data with chiral EoS than that of hadronic EoS. In our effort to assess the effect of final state re-scattering and resonance decays on the strength of the intermittency, it is found that both hadronic re-scattering and resonance decays only weaken the strength of the intermittency. Thus, the multi particle correlations that could be observed with our UrQMD-hydro data can not arise due to late stage binary decays.

Acknowledgements The authors thankfully acknowledge the UrQMD group for developing UrQMD and UrQMD-hydro codes and allowing us to use the same for this work. The authors also acknowledge the Department of Science and Technology (DST), Government of India, for providing funds to develop a high-performance computing cluster (HPCC) facility, through the Project No. SR/MF/PS-01/2014-GU, which has been used to generated Monte Carlo (MC) events.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors’ comment: Unlike UrQMD, hybrid UrQMD-hydro model is not an open access code. Moreover, all necessary information about the data have already been provided in the manuscript in the form of table and figures and thus there is no need of providing raw data as such.]

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