Effect of various particlization models on anisotropic flow and particle production using UrQMD hybrid model

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We discuss the effect of various particlization models available in the hybrid Ultra-relativistic Quantum Molecular Dynamics (UrQMD) event generator on different observables in non-central ($b = 5–9 \text{ fm}$) Au + Au collisions in the beam energy range 1A-158A GeV. Particlization models are used to switch fluid dynamic description to the transport description using various hypersurface criteria. In addition to particlization models, various equations-of-state (EoS) provided by UrQMD hybrid model were employed. The observables examined in this paper include excitation function of anisotropic coefficients such as directed ($v_1$) and elliptic flow ($v_2$), particle ratios of the species and shape of net-proton rapidity spectra at mid-rapidity. The results obtained here can be useful to predict as well as compare the measurements provided by the future experiments at FAIR and NICA once the data become available. We also make some comments on the best combination of particlization model and EoS which describe the experimental measurements best.

I. Introduction

Relativistic collisions of heavy-ions allow inspection of phase structure of the strongly coupled matter produced during the evolution of early universe in the laboratory. One of many objectives of these collisions is to locate the Quantum ChromoDynamics (QCD) critical point as well as the phase transition to the deconfined matter as per the various QCD predictions. High temperature and vanishing baryon chemical potential ($\mu_B$) region of the QCD phase diagram is fairly well explored in the experiments operated at Large Hadron Collider (LHC) [1–3] at CERN, Geneva and Relativistic Heavy Ion Collider (RHIC) [4, 5] at BNL, USA. On contrary, the realization of the QCD matter produced at high $\mu_B$ is rather limited and investigation of which will be performed in upcoming experiments at facilities such as Facility for Anti-proton and Ion Research (FAIR) [6, 7] at GSI, Germany and Nuclotron-based Ion Collider fAcility (NICA) [8] at JINR, Russia.

Due to the limitations posed by technologies few decades ago, previous experiments at these energies were incapable of addressing problems associated with the rare probes. Thus, in addition to this as well as for the optimal utilization of the new upcoming facilities, it is important to investigate the data available from previous experiments at similar beam energy regime as well as provide predictions for future experimental measurements. For the purpose of the latter, plethora of phenomenological models and simulation packages have been utilized to provide possible prospects for upcoming experiments.

In recent times, hybrid models are being extremely useful for the description of the expansion as well as evolution of strongly interacting matter in the heavy-ion collisions. In the hybrid models, the transport approach to explain the non-equilibrium dynamics is connected with hydrodynamical description to describe the fireball evolution. Such combination of approaches can be decisive in investigating various observables to extract QCD medium properties. Anisotropic flow is one such observable which describe the collective expansion of the medium and is quantified using Fourier expansion of the final state azimuthal distribution of the produced particles,

$$v_n = \langle \cos[n(\phi - \Psi)] \rangle$$

where the azimuthal angle and reaction plane angle are denoted by $\phi$ and $\Psi$ respectively whereas, directed flow ($v_1$) and elliptic flow ($v_2$) are various anisotropic coefficients.

Coming back to the hybrid models, UrQMD is one of the most popular event generator model and publicly available in hybrid format. After completion of fluid dynamic evolution, the later stage is described using transport approach as the medium is expected to be away from the equilibrium. The conversion of fluid-based description to the particle-based description is known as particlization which is a technical terminology. The Cooper-Frye procedure [9] is used to evaluate the particle distributions on the boundary where this conversion is performed. It is very important here to note that this switching of description is not freeze-out as in principle, after freeze-out there should not be any rescatterings and therefore, no need to have transport description [43]. There are various variants of hypersurfaces, particlization models are available in the UrQMD hybrid model. One can aim to extract some insights about the medium by observing the response of different observables to these variants. The choice of particlization

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model can further affect evolution of the particles after hadronization as well as freeze-out and hence observables, such as anisotropic flow, particle ratios, rapidity spectra and so on. Since there is no corresponding stage in real world to the particlization, it is important to look for best combination of particlization model with suitable EoS which explain the experimental data well.

To look for the possible signature of thermally equilibrated QCD medium, many experiments [10, 11] at variety of energies have investigated the elliptic flow coefficient of the hadrons. Even in low energy collisions at various beam energy ranges [12–14], $v_2$ has been studied by availing microscopic transport models [15–18]. The transition from out-of-plane top in-plane flow in terms of change of sign has been observed at low energies [19, 20]. In one of our previous work [21], the dependence of anisotropic flow has been studied using a hybrid UrQMD model for 6$A$ – 25$A$ GeV beam energies with hadron gas (HG) and chiral EoS. In another work [22], various flow coefficients of anisotropic momentum distribution and particle production has been analysed for HG, chiral and bag model (BM) EOS in the beam energy range $E_{\text{Lab}} = 1A – 158A$ GeV.

The directed flow, $v_1$ measures the deflection of the generated particles in the reaction plane. $v_1$ is worth investigating in relativistic nuclear collisions because of its sensitivity to longitudinal dynamics and the possibility of being formed before $v_2$ [23–25]. Due to the softening of the underlying EoS, the magnitude of $v_1$ is projected to vanish in the region of the phase transition, making it an interesting observable for research at RHIC-BES, FAIR, and NICA energies. Various experiments have been conducted in this direction during the last few decades. For example, at Alternating Gradient Synchrotron (AGS) [26–28] energies and less that that, at midrapidity range, the slope of $v_1$, which represents signal strength, displays linearity. Similar is not expected at higher beam energies because in previous studies [29–31], it is found out that slope at midrapidity is different than that at beam rapidity at energies higher than Super Proton Synchrotron (SPS) energy. The so-called structure "wiggle" appears to be sensitive to the underlying EoS, according to hydrodynamic model estimates [32–34]. Higher-order harmonics research has gotten a lot of interest in recent years, and it’s expected to reveal more information on the fireball that’s produced. The fourth-order harmonic coefficient, $v_4$, is known to be sensitive to intrinsic $v_2$ [35–37], thus it’s worth looking at it for a wider range of beam energies, which has also been done using the jet AA microscopic transport model JAM [24, 38]. It contains important information on the collision dynamics anticipated by hydrodynamical simulations.

Several event generator models to simulate the relativistic heavy-ion collisions are at the disposal of physicists in the market. However, almost none of them are capable of describing the experimental measurements under one framework. Thus, for better understanding of the precise measurements from upcoming experiments, it is imperative to have addressed their shortcomings and fix them as much as possible. As part of this attempt, one can employ various options available in a particular model and make efforts to extract the physics messages by performing qualitative or quantitative comparisons with existing experimental measurements.

In the present article, our aim is to investigate the effect of various particlization scenarios using multiple particlization models in UrQMD model for available nuclear equations-of-state variants. For this, we simulate non central (5 < b < 9 fm) Au - Au collisions using UrQMD model for beam energies ranging from 1A – 158A GeV for different particlization models and EoS. The chosen beam energy range spans existing GSI-SIS energy of the HADES experiment up to top SPS energy. The corresponding $<N_{\text{part}}>$ values in the selected impact parameter region of 5 < b < 9 fm cover approximately 10–40% centrality class [39]. Similar to our previous work, we compute various anisotropic coefficients, particle ratios and study net-proton rapidity distribution in the above-mentioned beam energy regime. Our objective is to find the best possible combination among the various permutations of UrQMD variants which describe the data best.

II. Model description

The working principle of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model can be found in Refs [17, 18, 40]. Simulation of nucleus-nucleus collisions is objective of the UrQMD model. Woods-saxon profile and Fermi gas model are employed to initialize the target and projectile nuclei in coordinate and momentum space. With the experimental inputs, namely, cross-sections and decay widths, the models incorporates the collisions as interactions among hadrons and resonances at low energies and string excitation and fragmentation at higher energies.

The UrQMD model is available in hybrid mode in which pure transport calculations to imitate the non-equilibrium conditions are coupled with hydrodynamics calculations using the SHASTA algorithm [41, 42] to model the intermediate hot and dense stage of the heavy-ion collision. As one of the crucial inputs to the hydrodynamics, initial conditions to account for non-equilibrium nature of early stage, incorporate the event-by-event fluctuations of the initial states. As soon as the two Lorentz contracted nuclei cross each other which corresponds to the time which make sure that all baryon scatterings and energy deposition has taken place, the hydrodynamics is switched on. This time act as lower bound for thermalization time. Right after this, the spectators are sent into the cascade and participant particles, which are "point like" in nature are mapped to hydrodynamical grid.

Now, the time is for hydrodynamical evolution where the equation-of-state (EoS) is important input. There are three EoS available in public version of UrQMD
UrQMD with measured directed flow for non-central (b = 5-9 fm) Au-Au collisions.

FIG. 1: (Color online) Comparison of directed flow of protons (upper two panels) and pions (bottom two panels) as a function of rapidity with experimental measurements at 40A and 158A GeV [44] at SPS for different EoS and particlization modes of UrQMD with measured directed flow for non-central (b = 5-9 fm) Au-Au collisions.
hybrid model. First one being the Hadron Gas (HG) EoS which is noninteracting gas of hadrons expressed by grand canonical ensemble and does not have any type phase transition. As the underlying degrees of freedom are same, the hydrodynamical and pure transport approaches can be compared on equal footings. The next EoS is Chiral + deconfinement EoS which incorporates both chiral as well as deconfinement phase transitions which is of cross-over type in nature for all finite net baryon densities. In addition to this, this EoS has partonic degrees of freedom. The occurrence of deconfinement transition is realized through quarks and Polyakov potential where as hadronic interaction administers chiral phase transition. Note that the partonic degrees of freedom only show up when the temperature is high enough. It has been seen that this EoS agrees well with the lattice QCD simulations at vanishing baryon chemical potential. The final available EoS is Bag Model (BG) which is combination of standard MIT bag model and improved version of \( \sigma - \omega \) model. The former is utilized for QGP phase whereas, the latter one is employed in case of hadronic phase. This EoS is available with inbuilt first order phase transition during which Gibbs' conditions are used to match both hadronic and partonic phases for equilibrium.

As times goes on, system starts to become dilute and fluid dynamical evolution would no longer be applicable. Therefore, the fluid description can be changed to particle description using Cooper-Frye formalism which is known as "Particlization". One of the crucial steps here is the determination of transition hypersurface. In the hybrid UrQMD model, depending on the type of hypersurface and switching criteria, there are three different particlization scenarios available for fluid to particle transition. The default scenario is known as gradual particlization scenario (GF) in which the slices of 0.2 fm thick undergo particlization when the energy density in all cells of that slice falls below five times the ground state energy density \( \epsilon_0 \). So, the particlization is performed slice by slice. The next scenario is Isochronous particlization (ICF) where the particlization takes place at the same time as soon as the energy density in all cells falls below the critical value (5\( \epsilon_0 \)). In these two cases, the hypersurface is isochronous in nature. Note that in the latter case, it is possible that the parts of the system may have become dilute as the transition can only be done once all cells have energy density below certain critical value. Therefore, the application of fluid dynamics would questionable in this case.

The last one is Iso-energy density particlization scenario (IEF), where the iso-energy density hypersurface is constructed numerically with the help of Cornelius routine \([43]\). Thereafter, the hydrodynamical fields are mapped to particles on this hypersurface using Cooper-Frye formalism once the energy density in all cells reaches below critical value. As discussed in Ref. \([43]\), this scenario is suitable to deal with event-by-event heavy-ion collisions analysis. The sampling algorithm described there, is very flexible in event-by-event calculations where the initial states of hydrodynamics changes widely.

### III. Results and Discussion

In this section, we present the outcomes of our investigation of dependence of various experimental observables on the available particlization models in UrQMD hybrid model. The study is performed using non-central Au + Au collisions for various beam energies in the range 1A–158A GeV and the results are compared with experimental measurements in similar kinematic regions wherever available. To begin with, we investigate the various flow coefficients for a range of beam energies using different particlization modes. Then we see the effect of particlization prescriptions on the particle production by looking at strange to non-strange ratio, baryon to mason ratio and more. Then we have a look at the net proton rapidity spectra for different particlization modes with combination to different EoS.

#### A. Anisotropic flow coefficients

In regards to the paper, study of anisotropic coefficients with respect to particlization models is important. The reason being the choice of hypersurface and switching criteria allow the fluid dynamic evolution to conclude at different times. This may affect the flow of the species as it will spend more or less time in evolution. Among various anisotropic flow coefficients, directed flow is believed to be sensitive to the longitudinal dynamics. So we estimate the directed flow of pions and protons as a function of rapidity for various participlization scenarios and equations of state as shown in Fig 1. The results are compared with the experimental data from NA49 experiment \([44]\) at SPS for similar centrality region (10–40\%) at 40 and 158A GeV. In case of pions for 40A GeV, all particlization scenarios favours the experimental result and do not show so much difference. If we look at pions and protons for higher beam energy at 158A GeV, the Iso-Energy particlization shows more favourable results compare to other two particlization modes. One interesting point to note here is that the so-called "wiggle" structure is less pronounced in the cases where IEF is employed compared to other two scenarios.

We choose slope of directed flow of protons as our next observable for investigation which is obtained by first-order polynomial fitting of differential direct flow \([v_1(y)]\) at the mid-rapidity. The slope of directed flow at mid-rapidity is interesting observable and contains insights about the medium properties. In Fig. 2, the results for proton with \( p_T < 2 \text{ GeV/c} \) are compared with the measurements of E895 \([26]\), NA49 \([44]\), and STAR \([45]\) experiments.

It can be seen that the slope of directed flow of protons does not show any sensitivity to the underlying degrees of freedom below 20A-30A GeV for all particlization sce-
FIG. 2: (Color online) Comparison of slope of the directed flow of protons as a function of beam energy at midrapidity for different EoS and particlization modes of UrQMD for non-central (b = 5-9 fm corresponds to approximately 10-40% central) Au-Au collisions with E895 [26] and STAR [45] experimental measurements in Au-Au collisions and with NA49 [44] experimental measurements in Pb-Pb collisions.

FIG. 3: (Color online) $p_T$ integrated elliptic flow $v_2$ of net protons, and pions as a function of beam energy at midrapidity (-0.5 < $y_{c.m.}$ < 0.5) for different EoS and particlization modes of UrQMD for non-central (b = 5-9 fm corresponds to approximately 10-40% central) Au-Au collisions. $v_2$ of net protons and pions for $p_T < 2$ GeV/c are compared with available E895 and NA49 experimental measurements [19, 44] respectively in the investigated beam energy range in Au-Au and Pb-Pb collisions.
respectively for all available centralities. Vertical bars on the data denote statistical uncertainties.

FIG. 4: (Color online) $K^-$ to $\pi^-$, and $K^+$ to $\pi^+$ ratio as a function of beam energy for different EoS and particlization modes of UrQMD for non-central (b = 5-9 fm corresponds to approximately 10-40% central) Au-Au collisions and their comparison with AGS [47], NA49 [48, 49], and STAR experimental measurements [50] in Au-Au, Pb-Pb, and Au-Au collisions respectively for all available centralities. Vertical bars on the data denote statistical uncertainties.

FIG. 5: (Color online) $K^-/\pi^-$ and $K^+/\pi^+$ ratio as a function of beam energy for different EoS and particlization modes of UrQMD for non-central (b = 5-9 fm corresponds to approximately 10-40% central) Au-Au collisions and their comparison with AGS [47], NA49 [48, 49], and STAR experimental measurements [50] in Au-Au, Pb-Pb, and Au-Au collisions respectively for all available centralities. Vertical bars on the data denote statistical uncertainties.
narios. This agrees with the claims made in one of our works which is due to the small life time of hydrodynamical phase. In our previous study, we observe a splitting among the comparison of various EoS [22], here, similar splitting is exhibited around 20–30 AGeV. This suggests, that various particlization models as well as EoS behaves different above this energy range, perhaps, indicating the threshold for possible onset of deconfinement. However, detailed study in this direction is in order to make any strong statement on this.

Moving on to elliptic flow ($v_2$) which was estimated for protons and pions and studied as a function of beam energies for different EoS and particlization models as shown in Fig. 3. The observable is compared with measurements from EOS/E895 [19] and NA49 [44] experiments. Similar to previous two observables, $v_2$ in case of IEF scenario show better agreement with experimental measurements at high beam energies whereas $v_2$ for ICF case diverges from the data even more than default GF scenario. Neither of the particlization model show any agreement with measured $v_2$ at low beam energies. One of the observations is that $v_2$ using Bag model shows non-monotonous behaviour irrespective of the particlization modes for both species. It seems because of the more realistic iso-energy density hypersurface in the IEF scenario, the results are in agreement with the experimental data.

**B. Particle ratios**

In this subsection, we proceed to study the effect of different particlization modes under different EoS on the particle production in the final state. Particle ratios might show sensitivity to the underlying particlization mode as various criteria for switching from fluid-based description to the particle-based description can alter the chemical composition of the system. Various particle ratios such as $K^+/\pi^+$ have been studied in literature, especially in central heavy-ion collisions and believed to be crucial to provide critical information about the medium such as onset of deconfinement [46]. Investigation of such ratios in non-central collisions can be interesting and might infer about the medium properties.

We start with the strange-to-non-strange particle ratios, such as $K^-/\pi^-$ and $K^+/\pi^+$ which is shown in Fig 4 as function of beam energies. The ratios are obtained for various particlization scenarios as well as EoS and compared with experimental data. As expected, the ratios are sensitive to the underlying particlization scenario. The unavailability of the data in the desired centrality classes mandate us to compare in three different classes in NA49 [48, 49] and STAR experiments [50] which covers the impact parameter region under study. Moreover, the ratio was also compared with measurements in various centrality classes to understand the centrality as well as beam energy dependence. There is a non-monotonous trend in the ratio $K^-/\pi^-$ when ICF scenario is used.

The particle to anti-particle ratios such as, $K^-/K^+$, $\pi^-/\pi^+$ and $P/P$ are estimated as function of beam energy and show in Fig 5. There is a monotonous trend in all three ratios for all cases of EoS and particlization modes. The ratios have shown excellent agreement with experimental measurements in IEF scenario for all three cases of EoS. Moreover, both in GF as well as ICF modes, the ratios $K^-/K^+$, $\pi^-/\pi^+$ have shown agreement with data but same can not be said in case of $P/P$. The ratios seem to be more sensitive to the particlization scenarios because of the possible change in the particle chemistry.

We also estimate the baryon to meson ratio namely, $P/\pi^+$ (shown as inverse for better visualization) and $\bar{P}/\pi^-$ which is shown in Fig 6. Agreement with the data is also seen in the case of IEF scenario for all EoS as depicted in Fig 6. In case of $\pi^+/P$, GF scenario is also able to reproduce the data compared to ICF mode. From both Figs 5 and 6, it is worth to note that there is almost no anti-proton production in ICF scenario even at higher beam energies which seems unrealistic. From this investigation, it seems quite visible that the IEF scenario brings out the more clarity in understanding and interpretation of the results.

Before closing, we want bring to the reader’s attention that the comparison of protons from UrQMD model with the experimental data should be accepted cautiously. In the region of low beam energy, $E_{lab} \lesssim 10$ A GeV, there is a non-negligible contribution of light nuclei production. Primordial nucleons calculated by the model still has contribution from bound nucleons. This involved all the proton observables in this article. This may not be as significant for anisotropic flow as it is for particle ratios. Since the flow coefficients are independent of proton multiplicity. As for particle ratios, this contribution is important as well as for net-rapidity distributions (see next subsection). The way out in such case is to coalesce final state nucleons in UrQMD into light nuclei. The basic principle for coalescence is to find out the nucleon clusters with small difference in momentum and position. Such study has its own importance, however, it is beyond the reach of this investigation.

**C. Net-proton rapidity spectra**

From the rapidity distributions of the net protons, the in-medium properties of stopped protons can be understood. It has been studied as promising variable for some time and in the studies performed in Refs. [52–56], it has been argued that irregularities at the mid-rapidity of the longitudinal spectra of net-protons can be consequence of the possible onset of the deconfinement. Possible reason behind this may well be the inherent softest point in the nuclear equation-of-state near phase transition. In the context of this paper, the particlization scenario also can play crucial role, since production of particles can be sensitive to the fluid to particle based description. Since such investigations, are primarily performed in central
collision, it is also equally important study in non-central collisions as well. In this investigation, the rapidity distribution of net-proton is estimated for beam energies 1A-158A GeV for various EoS and particlization scenarios. However, the rapidity spectra of net-protons in selected beam energies are shown in Fig 7. The simulated results are compared the experimental measurements from E917 [57] and NA49 [58] in centralities covering the impact parameter region under investigation. Even at the first glance one can see that rapidity spectra using ICF and GF scenario are not seem to be in the agreement with the measurements. However, IEF scenario seem to be performing quite well.

The shape of the rapidity spectra is quantified as a reduced curvature and its excitation function is studied in order to gain more insights and have more differential comparison. The reduced curvature is nothing but global minima or maxima at mid-rapidity i.e. double derivative of rapidity spectra at mid-rapidity. This quantity is similar to what was studied in Refs. [52–56] and named reduced curvature. In this analysis, the reduced curvature is estimated by fitting the rapidity spectra of net-protons at mid-rapidity using polynomial which is shown in Fig. 8. The reduced curvature of net-proton rapidity distributions for different particlization models and EoS compared with experimental measurements [57, 58]. The reduced curvature for measurements is also estimated in similar way as for simulations. The results with IEF scenario, for all three cases of EoS show nice agreement with data. In case of ICF scenario, the reduced curvature underestimates the experimental measurements in case of Hadron Gas and Bag Model EoS. In our previous work, we studied it for different EoS i.e. GF scenario and it disagrees with the data at high beam energies and same can also be observed in the same figure. One interesting observation from the above figure is that, there is very high sensitivity to the particlization scenario in case of Bag Model EoS at high beam energies, so much so
FIG. 7: (Color online) Rapidity spectra of net protons at 40 and 158A GeV beam energies for different EoS and particlization modes of UrQMD for non-central (b = 5–9 fm corresponds to approximately 10–40% central) Au-Au collisions and their comparison with the measured rapidity spectra of net protons in Au-Au and Pb-Pb collisions by E917 [57] and NA49 [58] Collaborations, respectively. Both simulation results and measurements are scaled for better visualization. Vertical bars on the data denote statistical uncertainties.

that we see large negative values of reduced curvature in case of ICF scenario and large positive values in case GF scenario. We would like to mention that the authors of refs [52–56] have subtracted contribution of nucleons bound in nuclei from primordial nucleons which we have not done in our analysis. Therefore, our results suffer from uncertainties due to contribution of bound protons.

IV. Summary

In this article, we have investigated different observables in non-central Au + Au collisions in beam energy range 1A–158A GeV for various particlization modes and nuclear EoS. In this investigation, we have employed three EoS, namely, Hadron Gas, Bag Model and Chiral + deconfinement EoS with particlization models...
such as Gradual (GF), Isochronous (ICF) and Iso energy density (IEF) particlization scenario. We started with anisotropic flow coefficient study for various particlization models for various EoS. We observed that irrespective of any EoS, IEF particlization scenario gives compelling and qualitative description of the experimental measurements in contrast with other two scenarios. In particular, experimental measurements of elliptic flow protons and pions were explained really well using IEF scenario at high beam energies. We also observed that directed flow using IEF scenario does not any "wiggle" structure in contrast to other two cases. The slope of the directed flow was examined as a function of beam energies for various particlization modes and EoS and it was seen that the IEF scenario help in reproducing the trend of the experimental data qualitatively.

Next, we investigated the effect of particlization models on particle production by estimating the particle ratios as choice of particlization mode can alter the particle chemistry of the system. We have observed that strange to non-strange ratio is qualitatively described by IEF and ICF scenario for all EoS cases. Moreover, in case of particle to anti-particle and baryon to meson ratios, IEF scenario describes the data reasonably well compared to other two scenarios. Surprisingly, we observed that for ICF scenario there was almost no anti-proton production at high beam energies which is unrealistic.

In the final section we concluded by investigating the reduced curvature of net protons, which is basically the quantification shape of rapidity at mid rapidity as function of beam energy. The reduced curvature obtained for IEF scenario gave consistent results with experimental measurement, even at high beam energies. The results here are important and would useful once more precise data become available in upcoming future.

From this investigation, particlization model dependent study has given more clarity on the suitability of the EoS in UrQMD model to examine various experimental observables. We have seen that choice IEF particlization scenario should be more realistic as it is providing compelling agreement with experimental results without being too sensitive to the underlying EoS. However, if one were to choose among the EoS then, both Hadron gas and Chiral EoS with IEF scenario would make good choice for more realistic combination. Having said that, examining other various observables using these combination would be helpful to make any strong claim.

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