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TeV–PeV hadronic simulations with DAMPE

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Cosmic ray research field has entered a brave new world of precise direct measurements in the multi-TeV energy domain thanks to the success of the newest space-borne instruments. DAMPE is a satellite astroparticle detector aimed at probing cosmic ray electrons and gamma rays from few GeV to 10 TeV and cosmic ray nuclei between 10 GeV and few hundred TeV with unprecedented energy resolution. It was successfully launched in December 2015, providing, in particular, the first direct observation of a break in a cosmic ray electron plus positron spectrum around 0.9 TeV. DAMPE presents a unique opportunity of directly measuring the cosmic ray spectrum and composition close to the knee region. However, one of the most challenging limitations on the precision of such measurement arises from the simulation of hadronic interactions in the detector. In spite of the utmost thick and finely segmented calorimeter onboard DAMPE, the cosmic ray proton and nuclei energy measurements still rely significantly on the hadronic Monte Carlo simulation. In this contribution, we discuss the challenges of the hadronic Monte Carlo detector simulation for TeV–PeV particles and review the existing solutions. We also present an in-house software tool which allows connecting the high-energy hadronic event generators, used in CORSIKA and implemented in the CRMC package, to the GEANT4 tool kit. Finally, we discuss preliminary simulation results with DAMPE setup based on this tool. Comparison with the alternative FLUKA simulation is presented as well.

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1. Introduction

The new epoch in space astroparticle physics started with a bloom of calorimetric space experiments aimed at directly measuring cosmic rays at multi-TeV energies. The recently launched DAMPE satellite [1] together with CALET [2] and ISS-CREAM [3] instruments on board International Space Station share similar conceptual design. In particular, they include a particle tracker detector followed by a thick fine-grained calorimeter for precise cosmic ray spectrum and composition measurements. While at sub-TeV energies the magnetic spectrometer technology is proven the most precise for cosmic ray spectra measurements, extending it to higher energies appears to be hardly feasible at least in the following decade, due to the difficulties of installing and maintaining superconducting magnets in space. Hence, the "calorimetric" approach will likely dominate in the nearest future at the highest energy frontier, TeV–PeV range, and will be exploited for the next generation spaceborne astroparticle missions, including High Energy cosmic Radiation Detection (HERD) facility [4], planned for launch in 2025.

The DAMPE instrument boasts the deepest calorimeter ever used in space with about 32 radiation lengths and ∼1.6 nuclear interaction lengths thickness [1, 5]. It allows measuring cosmic ray electrons and gamma rays with unprecedented energy resolution of about 1% at 100 GeV. With a relatively large acceptance of $\sim 0.3\ m^2 \times sr$ it allowed the first direct observation of a break in the cosmic ray electron plus positron spectrum at ∼0.9 TeV [6]. DAMPE is also an excellent instrument for measuring cosmic ray protons and nuclei, detecting about 80 protons at 100 TeV and about one proton of 1 PeV per year. However, in spite of its very thick calorimeter, the hadronic interactions from cosmic ray protons and nuclei still can not be fully contained in the detector, depositing on average 30–40% of energy in the detector at 100 TeV. As a result, estimation of proton/nuclei energy and effective acceptance relies significantly on the hadronic Monte Carlo simulation of the detector. A similar problem is inherent to other calorimetric experiments in space and will persist in the future missions. Hence, achieving the most precise simulation of hadronic interactions at TeV–PeV energies becomes crucial for the success of space astropartlce experiments in the forthcoming decade.

The proceeding is structured as follows. In Section 2 we discuss state-of-the-art of high-energy hadronic simulation approaches. Next, in Section 3 we introduce the developed interface which allows linking the GEANT4 detector simulation tool kit with the high-energy hadronic event generators and discuss preliminary results based on it with the DAMPE simulation. Conclusions are given in Section 4.

2. State of the art

Currently, two most popular detector simulation tool kits are widely used in astroparticle and high-energy physics, GEANT4 [7] and FLUKA [8, 9]. Hadronic models employed in GEANT4 have been validated up to LHC energies, with typical accuracy of tens of percent in most cases. At $\sim$ 10 TeV and higher (laboratory frame) these models lack some sufficient components and can no longer be considered fully reliable. A more consistent approach to hadronic simulations at highest energies is implemented in FLUKA, by introducing the Dual Parton Model (DPMJET) [10, 11] in conjunction with the Glauber formalism, which is used in particular for Ultra High Energy Cosmic

Ray air shower simulations up to 10^{20} eV [12, 13]. While FLUKA appears to be currently the most attractive code for TeV–PeV hadronic simulations with space astroparticle missions like DAMPE, there is a strong demand in the community of including state-of-the-art high-energy hadronic event generators, used in particular in CORSIKA [14], into the GEANT4 tool kit. Authors identify at least a few major reasons for that. First, due to the absence of ground beam facilities with energies above 10 TeV, hadronic models and interaction cross-sections have relatively unknown accuracy at TeV–PeV energies. Henceforth, in any high-energy astroparticle experiment it is crucial to compare at least a few different available models, like DMPJET [15], EPOS [16], SIBYLL [17, 18] or QGSJETII [19], to estimate the effect of systematic uncertainties related to hadronic interactions modelling. Second, to avoid bias due to different simulation implementations, it is important to perform model comparison using exactly the same detector geometry model and data processing chain, i.e. in the same simulation framework. The GEANT4 tool kit in turn offers a transparent way of implementing custom physics models combined with a wealth of state-of-the-art particle propagation codes and extensive user support. Last but not least, GEANT4 offers a straightforward machinery for implementing the precise detector geometry, in particular through conversion from CAD engineering drawings [20, 21, 22], which is crucial for accurate comparison of simulation with experimental data. Should be noted though that the software with similar CAD import functionality has been recently developed for FLUKA as well, through the integration with DAGMC libraries [23].

For the purpose of high-energy simulations (100 TeV and higher) with DAMPE, we developed an approach and implemented a software for connecting the high-energy hadronic models used in CORSIKA into GEANT4. The rest of the proceeding is dedicated to the developed approach.

3. Geant4–CRMC interface

The GEANT4 interface to high-energy hadronic event generators is implemented for the first time using the CRMC package [24], as shown in Figure 1. CRMC can be considered as a C++ wrapper on top of Fortran code of DPMJET, EPOS, SIBYLL and QGSJETII. Should be noted that for technical reasons related to the software implementation and some inherent code dependencies, different versions of DPMJET model are employed in FLUKA and CRMC, described in [10] and [15] respectively.

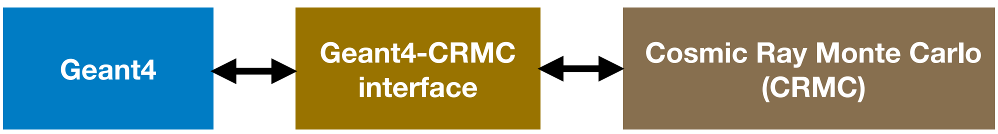

Figure 1: Schematics of Geant4–CRMC interface.

The developed interface connects CRMC to GEANT4 as a custom physics list. The interface was originally developed inside the DAMPE simulation framework, while later it was entirely disentangled from DAMPE code, allowing using it in arbitrary GEANT4 program. In particular, feasibility tests of the GEANT4–CRMC interface were successfully performed with the HERD detector simulation framework.

A typical particle generation flow is shown in Figure 2. For an inelastic hadronic interaction in GEANT4, the description of projectile particle and target nucleus (their PDG ID [25] and momenta) is transferred to the interface. Then, it is forwarded by the interface to CRMC which generates an inelastic interaction. Finally a set of secondary particles and their momenta is transferred back to GEANT4 for subsequent particle propagation.

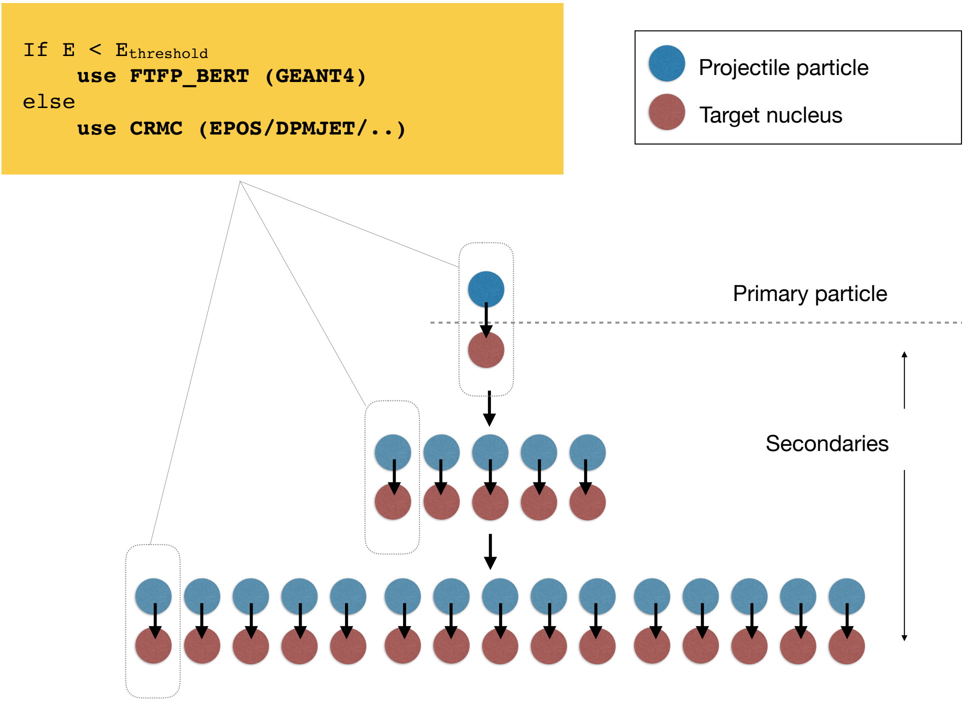

Figure 2: Illustration of hadronic interaction cascade in Geant4 linked to CRMC through the developed interface.

Depending on the interaction energy, an inelastic scattering is sampled either by an internal GEANT4 model (FTFP_BERT) or one of the CRMC models. The threshold energy is chosen well within the validity range of both CRMC and GEANT4 hadronic models, between $\sim$100 GeV and $\sim$1 TeV. In particular, DPMJET is considered reliable in the relativistic regime, above 5–10 GeV/A [12]. This roughly corresponds to 100 GeV proton kinetic energy in proton–ion collision (laboratory frame). Hence, we set a conservative value of 200 GeV as a baseline threshold. In addition, we tested another threshold value of 300 GeV and found no significant differences in the shower shape characteristics of the corresponding simulated Monte Carlo samples with respect to the samples obtained with the baseline threshold. Worthwhile mentioning, normally a smooth sampling between different models is employed in GEANT4 code in the transition regions between models. However, even with the fixed GEANT4–CRMC threshold no "step" effect is observed in the simulation. In other words, no significant difference between GEANT4 (FTFP_BERT) and CRMC (DPMJET, EPOS) physics models is seen in the energy range between 100 GeV and 1 TeV.

Preliminary simulation of the ultra high energy (100 TeV – 1 PeV) proton Monte Carlo samples using CRMC was performed in DAMPE for the cosmic ray proton analysis [26]. These samples were used as a cross check for the baseline FLUKA samples at this energy range, in order to assess the effect of systematic uncertainties related to hadronic simulations. As an example, Figure 3 shows the average fraction of energy deposited by protons in the DAMPE calorimeter after passing the trigger selection, as a function of true proton energy.

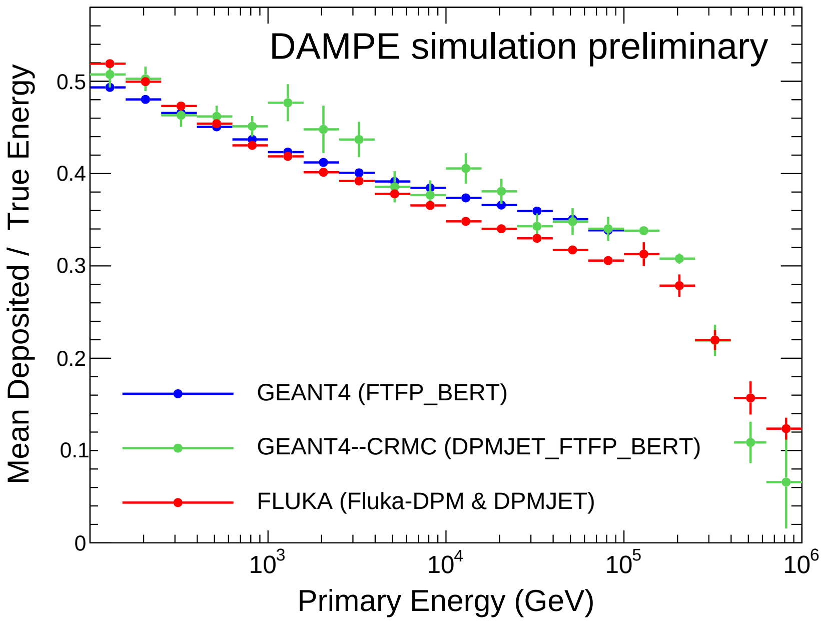

Figure 3: Ratio of deposited and true proton energy in the DAMPE calorimeter obtained with different simulation packages and hadronic models. For GEANT4–CRMC the combination of FTFP_BERT (GEANT4) and DPMJET (CRMC) models is used. At ∼200 TeV and higher energies the saturation of calorimeter readout leads to a drop of the ratio. A hard limit of 100 TeV is imposed on the application of FTFP_BERT and other native hadronic models in GEANT4 (blue graph). The CRMC sample has relatively low statistics since it was predominantly used as a cross-check for the baseline FLUKA sample at 100 TeV and higher energies.

As seen in Figure 3 the CRMC (DPMJET) model shows good agreement with GEANT4 (FTFP_BERT), while some differences between FLUKA and GEANT4 (with or without CRMC) can be seen. In particular, FLUKA predicts softer decrease of the deposited energy fraction compared to CRMC, at 200 TeV and higher energies. On the other hand, no significant differences were observed while replacing the DPMJET model with EPOS in CRMC. This brings us to conclusion that the difference between FLUKA and GEANT4–CRMC is likely due to the different treatment of low-energy hadronic interactions in two codes, rather than the high-energy ones. In particular, a Fritiof model [27] combined with Bertini and Binary cascade models at low energies [7] were used in GEANT4–CRMC up to 200 GeV, while Fluka-DPM model was used in FLUKA up to 20 TeV [28]. Finally, partial difference between CRMC and FLUKA due to some inevitable discrepancy of geometry implementations in two frameworks can not be completely excluded.

Further investigation of GEANT4–CRMC interface is now underway in DAMPE in cooperation with theory experts from GEANT4 and CORSIKA. In particular, it is planned to study the hadronic simulations with this interface using a simplified detector geometry, without the effects of readout electronics in the simulation, up to PeV energy. Such simulations can be compared, for example, with more established FLUKA simulations using a similar setup, in order to ensure the correct integration of high-energy hadronic event generators, implemented in CRMC, into GEANT4. As a next step, it is foreseen that public version of GEANT4–CRMC interface will become available in the future.

Finally, the developed interface connecting the state-of-the hadronic models and the GEANT4 framework represents a unique opportunity of validating the models with the multi-TeV data of DAMPE and other (future) space astroparticle missions. Such validation is possible thanks to the fine-segmented thick calorimeters on board these instruments, comparable in scale and granularity to those of LHC experiments.

4. Conclusions

A new era of direct cosmic ray measurements in space at TeV–PeV energies has begun with the launch of DAMPE and similar calorimetric detectors in space. In the upcoming decade, the cosmic ray experimental research in the transition from galactic to extragalactic origin will be likely dominated by such experiments. However, a key challenge of these instruments is the precise simulation of hadronic interactions in the detector, which directly affects the accuracy of cosmic ray proton and nuclei measurements. Two main simulation tool kits exist on the market for such task, GEANT4 and FLUKA. While the latter one is considered more accurate at mutli-TeV energies, in particular thanks to the implementation of DPMJET code, it lacks some flexibility of adding other state-of-the art hadronic simulation codes, including EPOS, SIBYLL and QGSJETII. The GEANT4 tool kit on the other hand offers versatility of implementing and changing between different physics models and a bounty of applying the most precise detector geometry model. However, the major problem of GEANT4 in this view is that it lacks native hadronic models applicable beyond $\sim$ 10 TeV (laboratory frame). In this proceeding we present the developed approach connecting the high-energy hadronic event generators (DPMJET, EPOS, SIBYLL, QGSJETII) and GEANT4. Namely, the software interface is developed allowing to plug the models into GEANT4 tool kit through the CRMC package. The interface is implemented as a custom hadronic model class which can be plugged inside arbitrary GEANT4 program. Preliminary simulations based on it were performed in DAMPE and used in the cosmic ray proton analysis, recently submitted for publication in Science Advances. Comparison with other simulation codes shows good agreement with a native GEANT4 hadronic model, FTFP_BERT, in the region where latter one is applicable. Some discrepancy with FLUKA is observed on the other hand, likely due to the difference in sampling of low-energy hadronic interactions and possibly in the detector geometry implementation in two frameworks. In addition, the feasibility of using the interface with other experiments was successfully tested with the HERD software framework. Further tests of the code are planned with a simplified detector geometry to ensure correct harmonisation of hadronic models, implemented in CRMC, with the GEANT4 framework. Afterwards, a public release of the developed code is foreseen in the future. Finally, the developed interface represents a unique opportunity for verifying and optimising the high-energy hadronic models with the precise TeV–PeV data of current and future space astroparticle instruments.

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