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Implementing hadronic interactions in CRPropa to study bursting sources of UHECRs

Leonel Morejon[a,*] **and Karl-Heinz Kampert**[a]

[a] *Bergische Universität Wuppertal,*
Gaußstraße 20, 42119 Wuppertal, Germany

E-mail: leonel.morejon@uni-wuppertal.de, kampert@uni-wuppertal.de

The study of Ultra-High Energy Cosmic Rays (UHECRs) via the multi-messenger approach is reaching a level that requires going beyond steady-state sources. Meeting this challenge requires improvements of the existing tools and defining new methods to accelerate the computations related to the propagation of UHECRs in extragalactic space and within the sources.

With this aim, the inclusion of hadronic interactions in the widely used code CRPropa has been completed allowing in-source propagation of UHECRs with all relevant interactions: magnetic, photonuclear, and hadronic. This contribution presents the implementation of hadronic interactions in CRPropa by exposing hadronic modelling softwares (e.g. EPOS-LHC, SYBILL, QGSJet) with the help of the code “chromo”. The impact on the performance of CRPropa is reported and compared to other methods used to simulate hadronic interactions. The physical interplay of hadronic and photohadronic interactions is discussed in the context of plausible scenarios of bursting sources.

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1. Introduction

Observations of extragalactic γ-rays over the last decade have revealed the abundance of extreme emissions with a relatively short time variablility. Previous measurements spanning multiple energy bands (radio emissions coupled with Fermi-LAT (GeV range), and H.E.S.S., MAGIC, VERITAS (TeV range)) have become more compelling with the recent announcement of the first detections of GRBs in the TeV range by MAGIC [1] and H.E.S.S.[2]. The gathered observations also exhibit plenty of short time scale variations of emissions, ranging days for radio galaxies such as M87 [3], minutes for blazars [4], and even seconds for GRBs[5]. To understand and explain the physics of the different emissions, a direct link to cosmic rays is needed.

Connections to astrophysical high-energy neutrinos have been explored by IceCube leading to establishing a flux level [6], determination of flavor composition [7], and the first evidence of neutrino - γ-ray temporal correlations with the remarkable TXS 0506+056 blazar [8–10]. Since flaring sources [11] have a much more stochastic distribution in the sky, their possible overabundance could explain why we were not able to identify neutrino point sources, yet. Establishing a direct connection between UHECRs and neutrinos would therefore indicate a common origin in flaring events.

Notwithstanding these observations, the modeling of UHECR sources has focused overwhelmingly on steady-state emission scenarios (see e.g. [12] and references therein). Candidate sources of UHECRs are constrained by the Hillas criterion for acceleration, and need to reach energies of no less than 100 EeV. These requirements are expected to be fulfilled by galaxy clusters, active galaxies, γ-ray bursts, and magnetars [12].

The project MICRO is french-german funded effort with the goal to develop the tools needed to simulate efficiently the emissions of bursting sources and predict the spectra of all messenger particles. Within this project, one of the milestones is to simulate the details of the sources, including magnetic effects and all particle interactions. For this purpose CRPropa [13] is a suitable simulation software well tested and capable of tracking particles in magnetic fields of varied characteristics while keeping track of the interactions and secondaries. This work presents the recent addition of a module to perform hadronic interactions in CRPropa by employing an existing python package (**chromo** [14]) to many of the state-of-the-art hadronic interaction generators (HIGs) available. The new module introduced here will be referred to hereon as Hadronic Interaction Module (HIM).

2. The Hadronic Interaction Module (HIM)

2.1 Implementation

The HIM consists of two portions: the *interaction sampling* and the *event generation*. The *interaction sampling* evaluates whether an interaction has occurred in a given propagation step of length d by sampling a random number p from a uniform distribution and computing the random interaction distance

$$d_{\text{int.}} = -\frac{\ln p}{\sigma\rho} \tag{1}$$

where ρ denotes the particle density (which is set by the user) and σ is the total inelastic cross section for proton-proton interactions. The evaluation of σ is provided in two ways: an evaluation

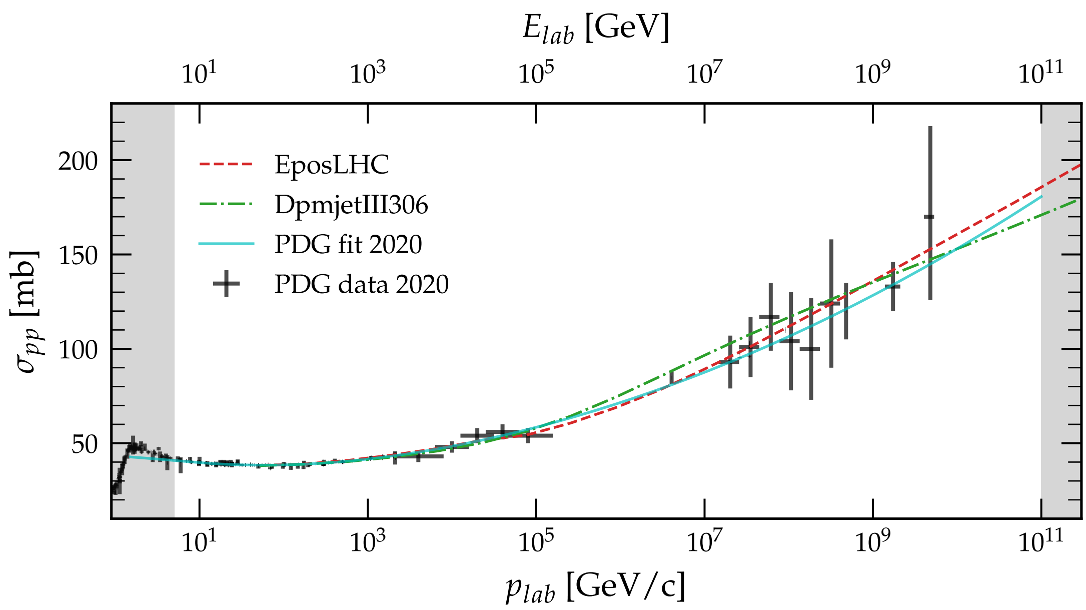
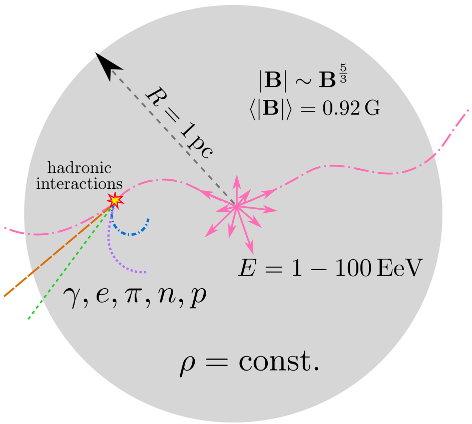


Figure 1: Cross section employed to sample the interaction length steps. More details can be found in the source material [15].

of the fit expression [15] and as provided by the HIG chosen for the simulations. The former method is provided as alternative because the latter can affect the duration of the event generation and extend the simulation time for specific HIGs (see Fig. 2). The comparison of the cross sections from these methods are shown in Fig. 1. The center of mass energy s for the evaluation of $\sigma(s)$ is computed from the primary cosmic ray being propagated and the mean kinetic energy of the target species (proton or nucleus). The energy distribution of the target species can be set to a thermal spectrum or a power-law distribution, as appropriate for the scenarios of interest. Both are cases where employing the mean energy is a good approximation [16].

The decision of performing an interaction within a propagation step, i.e. to decide whether the *event generation* portion is executed, is contingent on whether $d_{\text{int.}} \leq d$. The *event generation* portion consists of employing the frontend **chromo** [14] to generate an event with one of the available HIGs. **chromo** is a recently released frontend that provides a common interface to a sizeable number of frequently used hadronic interaction codes employed in astrophysical and air shower shower simulations (multiple versions of Dpmjet [17], Epos-LHC [18], QGSJet [19], Sibyll [20], and others). Besides the many available HIGs, the choice of **chromo** is justified by its availability as a Python [21] package tailored for efficiency and ease of use while avoiding the complications of less user friendly forms of parameter setting such as ASCII input cards, Fortran or C++ style interfaces. The *event generation* portion prepares the inputs describing the kinetics and interacting particle species from the relevant CRPropa tracked quantities and forwards them to the chosen HIG. Once the event is generated, the quantities describing the product particles and their kinematics are retrieved and a corresponding number of secondaries are injected into CRPropa. In addition, thinning steps are taken according to user settings which are provided for user customization.



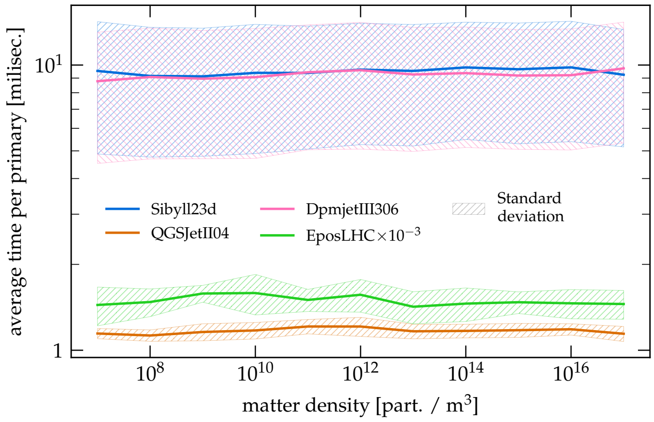


Figure 2: (Left) Illustration of simulated scenario (see text for full description). (Right) Average duration and variance of a batch of 30 CRPropa 3.2 simulations using only hadronic interactions for a variety of matter densities and employing four different HIGs.

2.2 Module Performance

The performance of the HIM is critical for simulating bursting sources scenarios since a large parameter space needs to be explored. To evaluate the time duration of simulations, a benchmark scenario was chosen which is typical for the intended (see for example [22]). Figure 2 (left) illustrates the benchmark source, represented by a blob of one parsec radius R with a homogeneous matter density and with a turbulent magnetic field following a Kolmogorov spectrum and with a root-mean-square of one gauss and a coherence length of 0.17 R. The injected protons follow a power law with spectral index of $\alpha = 1$ and with energies between 1-100 EeV. Only hadronic interactions were included and restricted to proton-proton interactions, thus the secondaries are not decaying and subject only to the magnetic field. As secondaries, only photons, electrons, pions, neutrons and protons and their anti-particles were considered as final state particles, however HIM allows restricting further the number of final state particles.

The comparison of simulation duration per primary particle is presented in Fig. 2 (right) for the benchmark described but with no magnetic field since the propagation of the secondaries does not reflect the time incurred in the hadronic interaction event generation itself. The different colors correspond to different HIGs, the lines represent the mean and the hatched region the variance of the duration of a batch of 30 simulations performed for fixed values of the matter density covering the shown range. The elapsed time per primary is effectively constant for all densities regardless of the HIG, however the differences between the lines are quite significant. Employing QGSJetII04 leads to the lowest durations per primary with ~ 1 ms, while simulations with EposLHC take about a thousand times more. The virtual independence on the matter density values indicates that the number of interactions of the secondary protons is not significantly larger than the number of injected ones, but could be affected for different parameter values like when choosing a harder injection spectrum or decreasing the energy threshold of secondaries tracked. Overall, this module performs reasonably well for the density ranges of interest here provided a suitable choice of HIG.

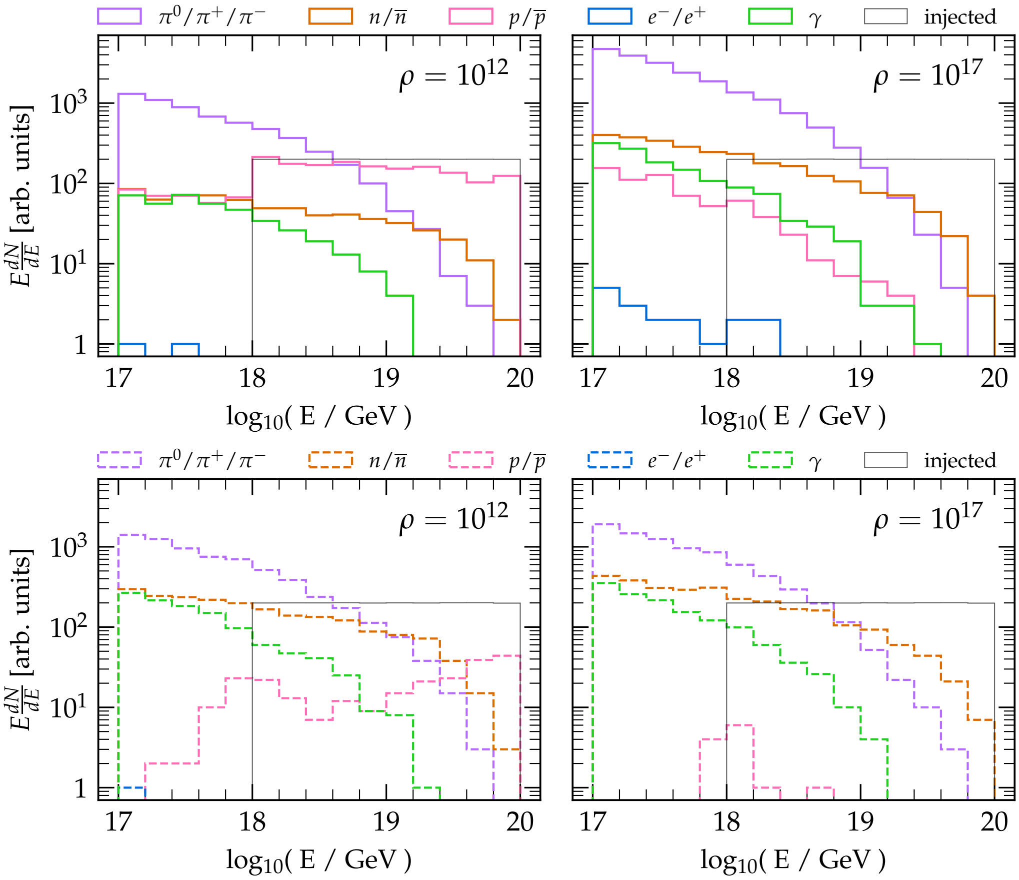


Figure 3: Secondary particle spectra produced in simulations without (top) vs with (bottom) magnetic field and employing two different values of the matter density: $10^{12}\,\mathrm{m}^{-3}$ (left) and $10^{17}\,\mathrm{m}^{-3}$ (right). See the text for details on the simulation scenario.

2.3 Example simulation of a source scenario

Figure 3 presents spectral densities of all escaping secondaries for two scenarios with different densities. The simulation scenario selected is the one presented in the previous subsection (see Fig. 2 left) employing Sibyll 2.3d as the HIG. The effect of the magnetic field is illustrated by contrasting the case where it is excluded (top) to the case where it is included (bottom) using the magnetic field parameters described in the previous subsection. In all figures the injected spectrum is the same and it is represented in the figures by a solid fine line. The spectra of the different secondaries are shown in distinct colors labeled in the figures.

The effect of the density is clearly visible in the spectra of all particles. Secondary protons barely interact before escaping the source as the spectrum (pink) is very similar to the injected one (see top-left plot) taking 66 % of the initial energy, whereas the secondaries take about 20 % of the injected energy. In contrast, for the larger density (top-right plot) most of the injected protons have interacted and only 2 % of the initial energy leaves as protons. However, the escaping secondaries (photons, pions, neutrons) take more than 70 % of the injected energy in correspondence to the increased number of interactions. The number of electrons and positrons are subdominant and are

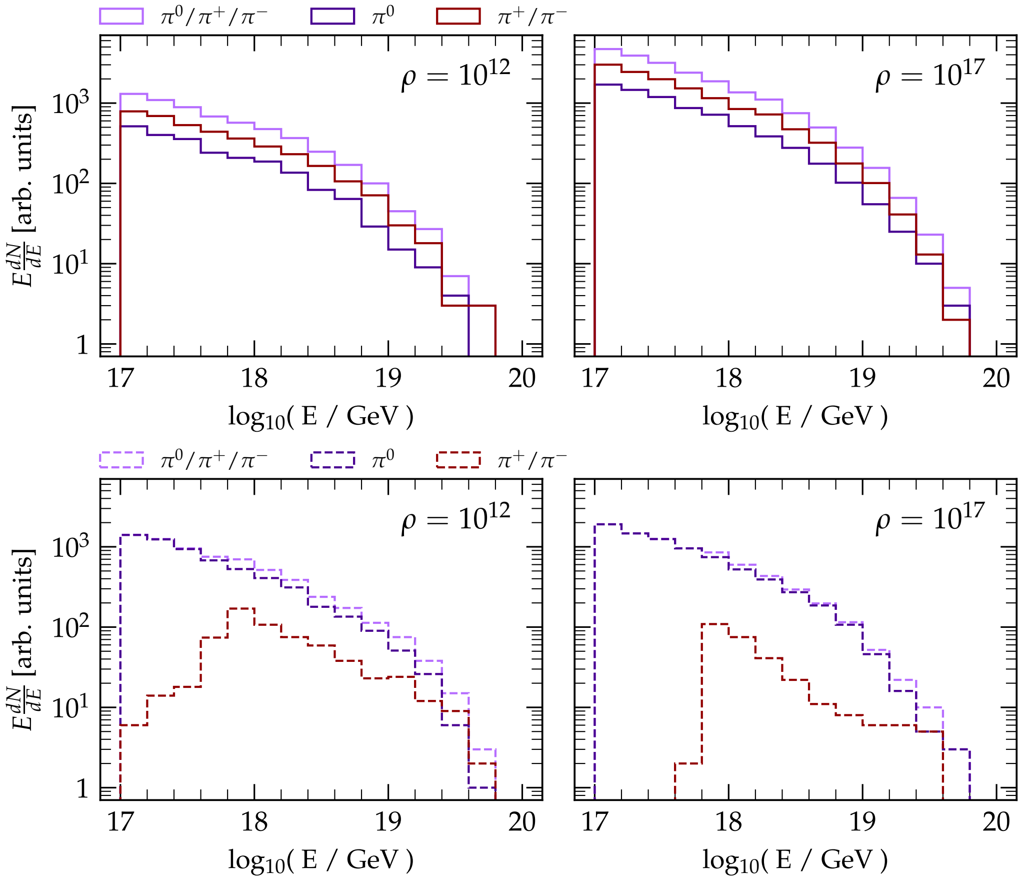


Figure 4: Secondary pion spectra produced in simulations without (top) vs with (bottom) magnetic field and employing two different values of the matter density: $10^{12}\,\mathrm{m}^{-3}$ (left) and $10^{17}\,\mathrm{m}^{-3}$ (right). See the text for details on the simulation scenario.

only slightly appreciable in the case of larger density.

The effect of the magnetic field has a similar result as expected, since it effectively increases the number of interactions by increasing the path of the particles inside the source before they can escape. Already in the lower density case (bottom-left plot) the suppression of the injected particles is considerable: escaping protons take 16 % of injected energy. The secondaries are consequently produced in larger amounts taking roughly 38 % which is relatively small, however, this reflects the magnetic confinement of charged pions in addition to the overproduction. Figure 3 shows the separate spectra of neutral and charged pions where the overproduction in this case is appreciable for the neutral pions, however the charged ones are strongly suppressed. Nevertheless, the production of photons and neutrons is doubled compared to the same density without magnetic field, much like it happens for neutral pions. In the case of larger density with magnetic field (bottom-right plot) such increase is, however, not as appreciable in the neutral particles as is also visible in Figure 3. This is to be expected since in the corresponding case without magnetic field protons almost completely interact and thus the addition of the magnetic field can only produce the additional energy redistribution of the remaining 2 % which escapes in the case without magnetic field. Furthermore, Figure 3 shows that charged pions are even more suppressed and escaping pions are made up almost entirely of neutral ones. It should be noted that after a few interactions of the protons the secondaries are produced at increasingly lower energies and contributing below the 0.1 EeV threshold set in these simulations. These make up an important part of the missing energy, however, they do not contribute to the escaping fluxes.

3. Summary and Outlook

The need for efficient simulation of bursting sources is evidenced by the abundance of examples of time variable emissions with relatively short duration and sizeable flux variations. Scenarios typical in bursting sources require very efficient simulation tools with the necessary interactions and up-to-date data. The project MultI-messenger probe of Cosmic Ray Origins (MICRO) is aimed at investigating such bursting scenarios and providing suitable tools suited for this purpose. This work presented one of the efforts within MICRO directed at including hadronic interactions in CRPropa for the simulation of bursting sources. The wide usage of CRPropa, its efficiency and its modular structure make it well suited for these type of simulations. The module for hadronic interactions (HIM) presented here constitutes an independent, optional code which employs **chromo**, a recently released package that provides a common interface to many softwares used in the simulation of hadronic interactions (like DPMJET, EPOS-LHC, QGSJet, SIBYLL, etc.). Examples of simulations provided here showcase the performance of HIM in different realisations of the phenomena of interest here. The efficiency of simulations using HIM is also illustrated and found to have an effect dependent on the hadronic interaction generator of choice: with a the best performance when employing QGSJetII04 and the worst when employing EposLHC. As next steps, we will implement dynamic source environments and study the prospects for identifying EHE photons and neutrinos from bursting sources.

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