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Measurements of hadronic interactions at LHCb and their impact on photon/neutrino emission in UHECR sources

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Out in the universe, when ultra-high energy charged cosmic rays (UHECRs) propagate from their source and/or acceleration site, they may interact with the environment (gas), producing high-energy gamma rays and neutrinos. One of the main uncertainties in the prediction of the flux of gamma rays and neutrinos from such UHECR interactions is due to the modeling of hadronic interactions. Back here on Earth, the LHCb experiment at CERN employs a general-purpose forward spectrometer to primarily study heavy flavor physics at the Large Hadron Collider (LHC). The acceptance of the spectrometer covers the pseudorapidity range $2 < \eta < 5$ and the detector provides full tracking and particle identification down to very small transverse momenta. This makes LHCb ideal to study hadronic interactions similar to those undergone by UHECRs. The modeling of different astrophysical source scenarios involves the transport of CRs through magnetic fields, generating secondary particles from CR interactions in the local environment and tracking these interaction products through the universe to Earth. All these processes are implemented in CRPropa. Since recently, it also provides an interface to the general-purpose hadronic event generators. In this contribution, we summarize measurements of hadronic particle production done by LHCb and use them to evaluate the performance of the event generators employed in CRPropa. Based on these comparisons we determine which measurements could be performed by LHCb in the future to reduce the uncertainty in the hadronic interaction models and to provide better constraints on the modeling of astrophysical sources and transport.

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1. Introduction

The Monte Carlo code CRPropa [1] is widely used in simulations of interaction and propagation of ultra-high energy cosmic rays (CRs) in astrophysical scenarios. Recently, hadronic interactions have been included in CRPropa by directly calling hadronic interaction generators [2] and by sampling from precomputed cross-section and yield tables [3].

The LHCb experiment [4] measures hadronic particle production in various beam and energy configurations. The measurements most relevant for CRPropa are introduced here.

2. LHCb measurements

2.1 The LHCb experiment

The LHCb experiment [4, 5] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. The experiment was designed for the study of particles containing b or c quarks. The experiment is equipped an excellent tracking system, which includes the Vertex Locator (VELO), tracking stations and a dipole magnet. This, together with a particle identification system consisting of two Ring Imaging Cherenkov (RICH) detectors, electromagnetic and hadronic calorimeters, and muon chambers, allows the decay particles to be reconstructed and analyzed. Due to its forward geometry, the LHCb experiment is also an ideal tool for studying the interactions of the LHC beam with a fixed target. This is possible due to the fixed target system called SMOG (System for Measuring Overlap with Gas) [6, 7]. Through the SMOG system, the noble gases helium, neon and argon can be injected into the vacuum vessel of the VELO at a nominal pressure of about 2×10^{-7} mbar, which is two orders of magnitude higher than the nominal LHC vacuum pressure. This has been successfully exploited for precise luminosity determination using beam imaging techniques [7]. Between 2015 and 2018, the SMOG system was also used to study proton-nucleus and nucleus-nucleus collisions. For this purpose, several dedicated runs were performed with helium, neon and argon targets using proton and lead beams with beam energies ranging from 2.5 TeV to 6.5 TeV, resulting in center-of-mass energies of up to 110 GeV [8]. This flexible setup allows a broad physics program, providing important contributions to the study of the nucleon and nuclear structure as well as measurements of great interest to cosmic ray physics.

2.2 Antiproton production in pHe collisions

The SMOG system enabled the LHCb collaboration to perform measurements of the antiproton production cross-section in proton-helium collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\rm NN}} = 110\,\text{GeV}$ [9, 10]. In both measurements, information from the tracking system is used to select potential candidates with negative charge in the kinematic regions of interest. Additionally, particle identification information is employed to select a high-purity $\overline{p}$ sample.

For the measurement of prompt antiproton production, the response of the RICH system is used to calculate differences in log likelihoods between the proton and pion mass hypotheses, DLL$(\mathrm{p}-\pi)$ and the proton and kaon hypothesis, DLL$(\mathrm{p}-\mathrm{K})$. These differences in log likelihoods are then used to perform a template fit, which yields the prompt and non-prompt antiproton count. After accounting for the other background sources, such as interactions with residual gas in the beam pipe, the antiproton production cross-section is computed and compared to several generator predictions,

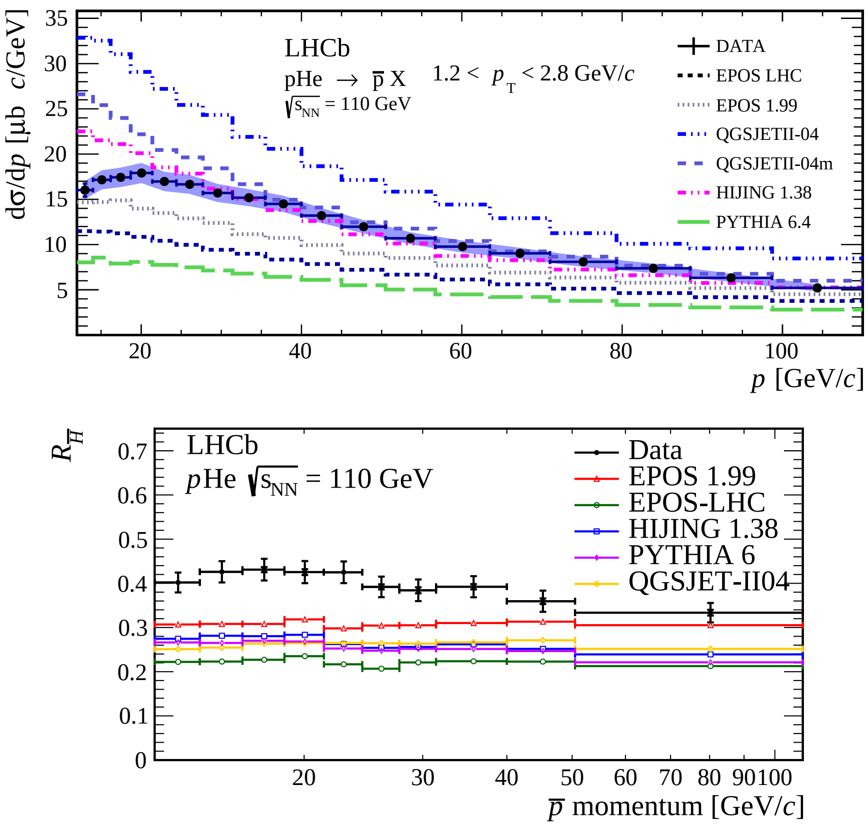

Figure 1: Antiproton production cross-section per He nucleus as a function of momentum. Upper panel: Prompt antiproton production [9], lower panel: ratio of prompt to non-prompt production [10].

as illustrated in Fig. 1. While the shapes are, except for low momentum, generally consistent, most event generators tend to either over- or underestimate the production cross-section, depending on the kinematic bin. The measured excess over the EPOS-LHC [11] prediction is specifically highlighted: $\sigma_{\rm vis}^{\rm LHCb}/\sigma_{\rm vis}^{\rm EPOS-LHC} = 1.08 \pm 0.07 \pm 0.03$, where the first uncertainty is due to luminosity and the second due to the uncertainty on the primary-vertex-reconstruction.

A subsequent measurement is performed to determine the ratio of detached (i.e. non-prompt) protons from hyperon decays to prompt protons $R_{\overline{H}}$. In this measurement, the impact-parameter (IP) resolution of the VELO is used to differentiate between prompt and detached antiprotons. The prompt and detached antiproton counts are then determined through a template fit of the distribution of the $\chi^2_{\rm IP}$ variable. These counts are then used to determine $R_{\overline{H}}$. The result, which is illustrated in Fig. **??**, indicates that the commonly used event generators tend to underestimate the antihyperon contribution to antiproton production.

2.3 Prompt long-lived charged particle production in pp collisions

Another way for the LHCb collaboration to contribute to open questions in astroparticle physics is to provide precision measurements of the production of light hadrons at the TeV scale in the forward region. These measurements are needed to further constrain generator predictions [13–15]

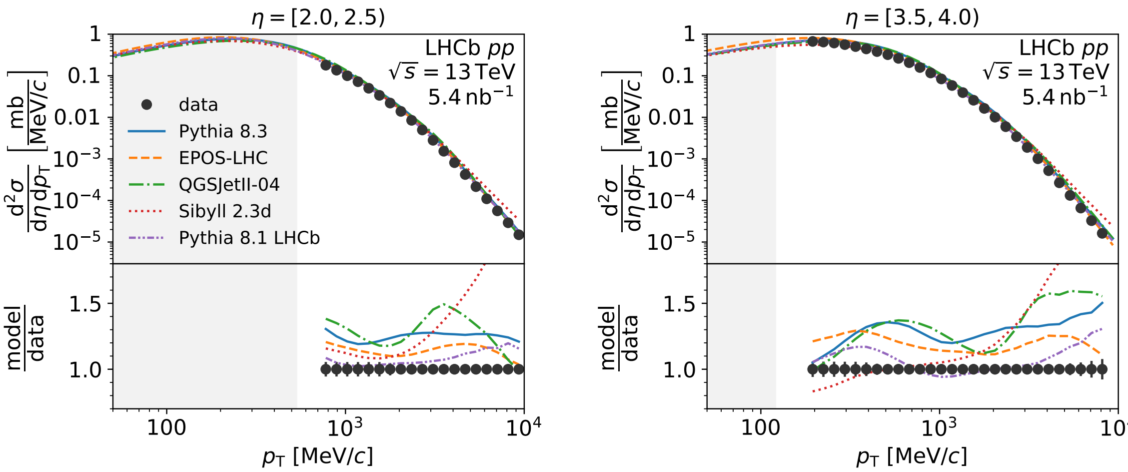

Figure 2: Differential cross-section of inclusive production of prompt long-lived charged particles in intervals of pseudorapidity, η, and as a function of transverse momentum, p_{T} . The error bars indicate the total uncertainty. The ratios of the model predictions and this measurement are shown in the lower panels. The lines labeled as Pythia 8.1 LHCb correspond to the occupancy-weighted simulated samples of this analysis. Left shows the kinematic interval $\eta \in [2.0, 2.5)$ and right the kinematic interval $\eta \in [3.5, 4.0)$ [12].

and to extrapolate them safely to even higher collision energies that are of interest in astroparticle physics.

The LHCb collaboration performed a measurement of the double-differential cross-section of prompt long-lived charged particles in pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV in intervals of η and p_{T}. Long-lived charged particles are defined as particles with a non-zero charge and a lifetime greater than 30 ps [16], which are electrons, muons, pions, kaons, protons, Σ^+, Σ^-, Ξ^- and Ω^- as well as their antiparticles. The determination of counts of prompt particles relies mostly on the tracking system as every track that passes the whole tracking system is considered a candidate. These candidates still contain a large fraction of backgrounds, namely fake tracks and tracks from secondary interactions, such as strange-hadron decays and interaction with the detector material. These contributions are estimated based on data and subtracted from the candidate counts. The resulting double-differential cross-section, which for two η intervals is illustrated in Fig. 2, indicates that the production cross-section of prompt long-lived charged particles is generally overestimated by the event generators.

2.4 Inelastic cross-section

The inelastic pp cross-section is a fundamental quantity for both the description of extensive air showers [11] and the modeling of the transport of cosmic ray particles in the interstellar medium [17, 18]. The LHCb collaboration provided a measurement of the inelastic pp cross-section at a center-of-mass energy of 13 TeV [19]. The measurement requires well reconstructed tracks within the geometrical acceptance of the LHCb detector, with the origin of the tracks lying within 200 mm longitudinally and 0.4 mm transversally of the average primary vertex position. Thus, the tracking system and especially the fine resolution of the VELO played an important role in this analysis. The inelastic cross-section was measured within the LHCb acceptance and

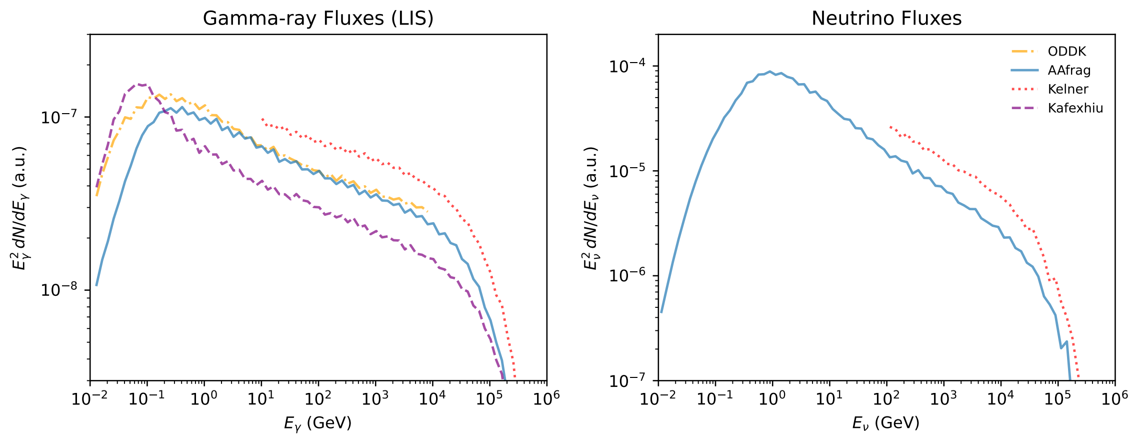

Figure 3: Example photon (left) and neutrino (right) production in astrophysical environments found in our Galaxy using different parameterizations of hadronic interactions. Reproduced from Ref. [3]

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then extrapolated to the full phasespace. The latter is reported as $\sigma_{\text{inel}} = 75.4 \pm 3.0 \pm 4.5$ mb, where the first uncertainty is experimental and the second due to the extrapolation. Using the same extrapolation methods, an update of an previously published inelastic cross-section is given for a center-of-mass energy of 7 TeV. It is reported as $\sigma_{\text{inel}} = 68.7 \pm 2.1 \pm 4.5$ mb, with the first uncertainty being experimental and the second due to the extrapolation.

3. Impact in astrophysical scenarios

Hadronic interactions of CRs are crucial for the multimessenger interpretation of astrophysical environments exhibiting particle acceleration. At acceleration sites, CRs interacting with ambient photon fields or gas are expected to produce non-thermal high-energy photons and neutrinos. In radiation-dominated environments, electromagnetic and photohadronic processes, such as $p\gamma \to pe^+e^-$, $p\gamma \to p\pi^0$ or $n\pi^- \to \gamma\nu$, may dominate above their respective production thresholds. However, in many astrophysical settings, hadron-hadron interactions play a significant role, with high-energy neutrinos from pion and kaon decays serving as key signatures of these processes. While strange and charm hadrons can also contribute [20], their contributions remain subdominant in astrophysical scenarios where the environments are transparent to pions and kaons.

An example of the impact of hadronic interactions on the fluxes of neutrinos and photons is shown in Fig. 3. The spectra shown here were calculated with CRPropa and include different parameterizations of hadronic interactions: *Kelner et al.* is based on SIBYLL 2.1 [21], *AAfrag* is based on QGSJet-II-04 [22]. Within the phasespace covered by LHCb, these models give very different predictions (see Fig. 2). According to Kelner et al., the relevant phasespace for the production of photons and neutrinos is $x_{\text{lab}} \sim 0.1$, with x_{lab} being the ratio of the energy of the secondary particle with the projectile energy in the lab frame. The acceptance of LHCb corresponds to $x_{\text{lab}} \sim 10^{-3} \ldots 0.1$. Tuning models to LHCb data could improve the model uncertainty also for the photon and neutrino fluxes, as the LHCb phasespace and very forward phasespace are connected

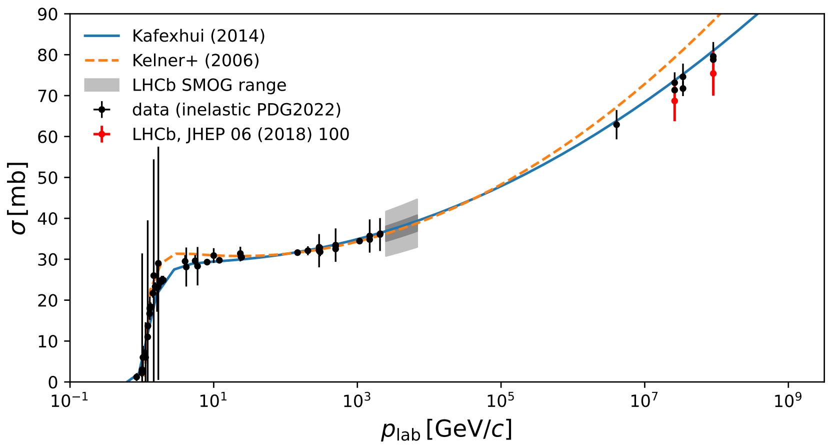

Figure 4: Inelastic cross-section in pp interactions as a function of the laboratory-system momentum. Models are used for the interaction length in propagation in the ISM [21, 26]. The gray band indicates the energy range where LHCb could provide measurements for various nuclei. The width illustrates a conservative (15%) and optimistic (5%) scenario for the uncertainty.

within the models. The measurements are particularly constraining when combined with very forward measurements of pion spectra like those from LHCf [23] or FASER [24].

The measurements of antiproton production Fig. 1) were motivated by the high-precision determination of the proton-antiproton production ratio $p/\overline{p}$ in cosmic rays with energies up to 350 GeV, which were performed by the PAMELA [23] and AMS-02 [25] experiments. The interpretation of these measurements was affected by large uncertainties on the antiproton production cross-section in the interstellar medium, which is mainly composed of hydrogen and helium. These uncertainties are particularly significant in the 10 to 100 GeV/c momentum range, where signatures of dark matter annihilation are also expected. The measurements of both the prompt antiproton production [9] and the cross-section ratio of antiprotons from antihyperons over prompt antiprotons $R_{\overline{H}}$ [10], performed by the LHCb collaboration, were therefore vital contributions, especially with no prior pHe data available.

In Fig. 4, an overview of the measurements of the inelastic cross-section in proton-proton interactions is shown. The Kelner parameterization slightly overestimates the cross-section at high energies, which results in an underestimation of the interaction length of CRs. While in the parameterizations the inelastic cross-section can be changed independently of the secondary particle yields, the two are intimately connected in microscopic models of the interactions such as QGSJet or Sibyll.

In addition to the high-energy measurement (red marker in Fig. 4), LHCb through the SMOG system also provides access to measurements of fixed-target collisions around 100 GeV center-of-mass. By swapping out the gases in the system, different collision systems can be studied with the same beam configuration. This would allow the models/parametrization for the extrapolation in atomic mass A. So far (including the upgraded SMOG system [8]) data for hydrogen (1), helium (4), neon (20) and argon (40) have been recorded.

4. Summary and Outlook

LHCb provides crucial measurements for CR science by studying hadronic interactions at forward rapidities, possibly reducing the uncertainties in modeling hadronic interactions. Using its SMOG system, LHCb can perform measurements across different target nuclei (e.g., H_2, He, Ar). Enabling future studies of the scaling of the particle spectra and total cross-sections with atomic mass A. Additionally, cross-section measurements at 6.8 TeV and 100 PeV in laboratory energy are possible. Apart from CR propagation, future measurements with oxygen beams will provide valuable input for improving air shower models used in CR simulations.

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