Charm production in DPMJET

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Abstract. In this work, charm production in the DPMJET hadronic jet simulation is compared to experimental data. Since the major application of DPMJET is the simulation of cosmic-ray-induced air showers, the version of the code integrated in the CORSIKA simulation package has been used for the comparison. Wherever necessary, adjustments have been made to improve agreement between simulation and data. With the availability of new muon/neutrino detectors that combine a large fiducial volume with large amounts of shielding, investigation of prompt muons and neutrinos from cosmic ray interactions will be feasible for the first time. Furthermore, above $\gtrsim 100$ TeV charmed particle decay becomes the dominant background for diffuse extraterrestrial neutrino flux searches. A reliable method to simulate charm production in high-energy proton–nucleon interactions is therefore required.

Keywords: cosmic ray detectors, cosmic rays, neutrino detectors

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1. Introduction

During recent years neutrino detectors, notably IceCube and ANTARES, as well as large air shower arrays, such as the Pierre Auger Observatory and the Telescope Array, have been advancing or completing their construction. These large detectors are sensitive to an energy region in which contributions from prompt charm decays in cosmic ray showers cannot be neglected and may constitute an interesting signal as well as a significant background. In the case of searches for diffuse fluxes of astrophysical neutrinos in neutrino telescopes, the signal must be separated at high energies from the background of atmospheric neutrinos.

Atmospheric neutrinos from π and K meson decays, whose spectrum approximately follows the power law $E^{-3.7}$ above 100 GeV, can be rejected using cuts on energy-correlated variables. However, the spectrum of prompt neutrinos is expected to be harder and correspond to the primary cosmic ray spectrum, since charmed mesons tend to decay promptly without interacting in the atmosphere (see, e.g., [1,2]). Consequently, this contribution needs to be known and separated from the signal, which is generally assumed to follow a power law of $\approx E^{-2}$, characteristic of Fermi acceleration processes [3]. It is therefore essential to achieve a precise understanding of the expected charm-induced lepton flux and angular distribution, in order to identify it in the data above 100–1 PeV, where the contribution of the softer component from light meson decays becomes negligible. For this purpose, the entire air shower needs to be simulated.

One of the most widely used cosmic ray shower simulation software packages in high-energy astrophysics is CORSIKA [4]. It offers the user the choice between several high-energy hadronic jet simulations but does not yet officially support propagation and decay...
of charmed particles. In order to remedy this situation, first the viability of one of the available models for the simulation of charm has to be demonstrated.

The consistency of charm simulation with experiment was first verified in 1995 using the standalone version of DPMJET [5]. The best available measurements at the time were those from the LEBC hydrogen bubble chamber that took data at CERN and Fermilab during the late 1980s using proton beams of 400 GeV and 800 GeV, respectively [6, 7]. Since then, a significant amount of new experiments have taken place, most notably in fixed target runs at Fermilab, but also using various types of colliders and most recently the HERA-B detector at DESY [8]. In this work, the version of DPMJET integrated in CORSIKA was used, running in first-interaction mode. This was done to directly evaluate its applicability to air shower simulation and to ensure compatibility with the standalone version.

2. Charm production in the dual parton model

2.1. The dual parton model

There are two mechanisms in any model for hadron production: soft particle production and hard collisions. Both components are part of the DPMJET hadron production models used in this work. Soft hadron production cannot be rigorously derived from QCD, the gauge field theory of strong interactions. Most theoretical efforts use Regge theory for a systematic description of soft hadron production. The so-called hard component of particle production can be derived from perturbative QCD. QCD perturbation theory within the QCD improved parton model can only be applied at moderately large transverse momenta ($p_{\perp}$). One feature of soft hadron production at small $p_{\perp}$ values is represented by exponentially decreasing transverse momentum distributions. The QCD improved parton model predicts another component of the transverse momentum distributions, decreasing like a power law, and thus less steeply than an exponential function, at large $p_{\perp}$.

The dual parton model DPM [9] and the closely related quark gluon string model QGSM [10, 11] construct hadron production from fragmenting strings. Here we will describe the structure of this mechanism in hadron–hadron collisions. Since it is not possible to describe the soft component of hadron physics using perturbative QCD, ’t Hooft introduced a new expansion parameter [12]. First, QCD is generalized from the gauge group SU(3) to SU($N_c$) with $N_c$ representing the number of quark ‘colours’. The idea was to use $1/N_c$ as an artificial expansion parameter, and later set $N_c = 3$ for physical applications. One then finds that the Feynman graphs can be characterized by a two-dimensional surface, and the Feynman expansion can be regrouped as a sum over surface topologies. The leading order corresponds to planar graphs; the next order for two-to-two amplitudes involves a cylindrical topology. It has been shown [13] that there is a one-to-one correspondence between the terms of this topological expansion and the terms of Reggeon field theory RFT [14]. The second theoretical concept entering DPM is duality [15] and the dual topological unitarization DTU [16]. The third ingredient of DPM is the coloured parton model.

The leading contribution to soft hadron production in the DPM corresponds to the production of two chains. The two chains arise from the unitarity cut of the Pomeron exchange diagram. Located at the end of either chain are the valence quarks and diquarks.
of the two protons. The valence diquarks have antitriplet colour, while the colliding protons as well as the two produced chains are colour neutral. Particle production occurs via fragmentation of the two quark–diquark chains. In order to arrive at a quantitative model, we have to specify the probability \( \rho_1(x) \) that the interaction separates the proton into a valence quark with momentum fraction \( x \) and a valence diquark with the remaining momentum fraction \( (1-x) \). These longitudinal momentum fractions are given by Regge asymptotics. Valence quarks in baryons as well as in mesons follow \( x-1/2 \), valence diquarks in baryons \( (1-x)^{3/2} \) and sea quarks \( x^{-1} \) distributions. Combining these, we obtain for the distribution in a proton

\[
\rho_1^p = c_p^1 x^{-1/2} (1-x)^{3/2},
\]

and in a meson (valence quarks follow the same distribution as their corresponding antiparticles)

\[
\rho_1^m = c_m^1 x^{-1/2} (1-x)^{-1/2},
\]

where the coefficients \( c_p^1 \) and \( c_m^1 \) normalize the distributions to unity.

This two-chain model already describes hadron production at low energies quite successfully. Many Monte Carlo models therefore started with two-chain models. However, at higher energies more and more discrepancies between the model and experimental data appear. One example is that the measured transverse momentum distributions can only be explained by including a hard component in the hadron production. Also, from a theoretical point of view, the pomeron total cross section (using the so-called supercritical pomeron) violates the unitarity principle. Therefore, the model has to be unitarized.

The DTUJET [17] and PHOJET [18,19] Monte Carlo models use an eikonal unitarization scheme. DTUJET and PHOJET, respectively, are used for the elementary interactions in DPMJET-II and DPMJET-III. Both models have multiple soft and hard chains as demanded by the unitarization method.

DPMJET-II [20] and DPMJET-III [21] use the Glauber model to describe hadron–nucleus and nucleus–nucleus collisions. Here, we will not present any details about the Glauber model and refer the reader instead to the original publications cited above.

### 2.2. Charm production in DPMJET and CORSIKA

The paper by Battistoni et al [5] gives the first description of DPM charm production. They used a version interfaced to the cosmic ray cascade code HEMAS [22], which has since then been phased out. There, DPM was implemented in form of the Monte Carlo event generator DPMJET-II [21], which itself is based on earlier work [23]–[25].

In [5], hard charm production was tested against NLO perturbative calculations [26] and differential charm production cross sections were compared to experimental data, mainly from the LEBC-EHS and LEBC-MPS collaborations [6,7]. Hadronic jet simulation with DPMJET-II is available in the CORSIKA cosmic ray transport code [4]. However, the official CORSIKA version at the time DPMJET-II was implemented had no provision for the propagation of charmed hadrons. Instead, all charmed hadrons not decaying within the hadronic jet simulation itself were handled by substituting strange quarks for charm. Charm production from DPMJET-II and other jet simulations is expected
to become available in the official CORSIKA release [29] in the near future. Earlier, an unofficial modified version was provided to the authors [27], in which charm was no longer suppressed. Our work is mostly based on this version, in which, however, one crucial parameter was erroneously changed with respect to the original DPMJET. The comparisons with experiment shown below demonstrate both the influence of correcting this parameter and the modifications made subsequently to the main DPMJET code (see figures 3 and 4).

DPMJET-II is also integrated in the FLUKA hadron cascade code [28]. We are not aware of any charm calculations using FLUKA-DPMJET-II, but this might change soon. All modifications to charm production described in this paper are similarly applicable to FLUKA.

2.3. Charm production in elementary hadronic collisions

In DPMJET-II there are three different mechanisms by which production of heavy flavours like charm can occur: (i) charmed quarks produced at the ends of hard and semihard chains (minijets), (ii) charmed quarks produced at the ends of soft sea chains and (iii) charm production inside the chain decay. Only the first mechanism (i) is founded on the solid theoretical basis of perturbative QCD; the other two mechanisms are phenomenological models used for charm and prompt muon production within cosmic-ray-induced cascades.

2.4. Charm production at the ends of hard and semihard chains (minijets)

Regarding this component, nothing in DPMJET-II was changed with respect to the older version described in [5]. Therefore, we do not need to repeat the details given there. However, it should be mentioned that in that work a detailed comparison was presented between the results of the DPMJET-II Monte Carlo at large transverse momenta and the corresponding NLO QCD calculations, showing excellent agreement between the two. For hadronic and nuclear collisions at laboratory energies beyond the TeV range, this is the dominant mechanism of charm production.

2.5. Charm production at the ends of soft sea chains

In DPMJET, charm production at the end of soft sea chains is considered as the non-perturbative limit of minijets. The parton transverse momentum distributions of minijets and soft sea chains are joined smoothly at the threshold transverse momentum between the two. A certain fraction of the soft sea chain ends carry heavy flavours. At high energies, the probability $P_{c\bar{c}}$ for production of a $c\bar{c}$ sea quark pair approaches the corresponding value for semihard chains, while at low energies $P_{c\bar{c}}$ decreases as required by phenomenological considerations. DPMJET uses

$$P_{c\bar{c}} = C \int_{m_q}^{E_R} 2E_\perp e^{-b_c E_\perp} dE_\perp,$$

with

$$b_c = b + 1.3 - \log_{10} \left( \frac{E_{CM}}{1 \text{ GeV}} \right).$$
An additional constraint is given by the requirement that $P_{c\bar{c}}$ should not exceed the corresponding probability for minijets.

### 2.6. Charm production inside the soft chain fragmentation

DPMJET-II uses the Lund model PYTHIA for chain fragmentation [30]. Within this model, a quark–antiquark pair $q_i \bar{q}_i$ leading to string breakup is produced via quantum mechanical tunnelling. The tunnelling probability can be worked out as a function of the transverse mass $m_\perp$ of the pair [30], with the result that $c\bar{c}$ pair production is highly suppressed: $u\bar{u}:d\bar{d}:s\bar{s}:c\bar{c} = 1:1:0.3:10^{-11}$. There are other models for string fragmentation with larger $c\bar{c}$ production probabilities, but none in which charm production inside the soft chain could not be neglected.

In DPMJET-II the picture remains the same, with one exception: the $c\bar{c}$ probability near a valence diquark at the end of a diquark–quark or diquark–antidiquark chain is not negligible. This effect was demonstrated in hadroproduction by fixed target experiments such as SELEX [31,32]. The leading particle shares a valence quark with the incident hadron, while the non-leading one does not. Therefore leading particles are copiously produced at large $x_F$ in the forward region of the incident hadron, resulting in an asymmetry between leading and non-leading particles. This phenomenon is referred to as the leading quark effect [33]. SELEX finds in the fragmentation region of protons and $\Sigma^-$-hyperons $\Lambda^+_c$ charmed hyperons with a comparatively flat Feynman-$x$ ($x_F$) distribution. In a fit to $(1 - |x_F|)^\alpha$, $\alpha$ is about 2.5. Without a new mechanism, DPMJET generates this distribution with an $\alpha$ of about 7. Better agreement with SELEX can be achieved by introducing, adjacent to a diquark, $c\bar{c}$ pairs with increased probability. In order to retain the standard PYTHIA code, this change was done in a special routine of DPMJET-II. The comparison of SELEX data and the modified version of DPMJET is shown in section 3.3.

### 3. Comparison with experimental data

#### 3.1. Collision scaling of charm production

In DPMJET, nuclear collisions are treated with a Monte Carlo formulation of the Glauber model [20,21]. This model contains two important numbers: the number of participants $N_{\text{part}}$ and the total number of collisions $N_{\text{coll}}$. Soft particle production scales rather well with $N_{\text{part}}$, whereas hard particle production (for instance at large $p_\perp$) scales with $N_{\text{coll}}$. The latter phenomenon is commonly referred to as collision scaling. All charm production, because of the large mass difference of the quarks involved, is expected to follow collision scaling.

This behaviour can be reproduced in experimental data. Fermilab experiment E789 [34] measured neutral D-meson production in p–Be and p–Au collisions, finding the production cross section to behave like

$$\sigma(A) = \sigma_0 A^\alpha,$$

with $\alpha = 1.02 \pm -0.03 \pm 0.02$ and the ratio

$$R = \frac{\sigma(\text{Au})/197}{\sigma(\text{Be})/9} = 1.06 \pm 0.11 \pm 0.07.$$

The consistency of these values with unity corresponds to collision scaling.
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Figure 1. Total open charm production cross-section measurements, taken from [35] and references therein, represented by markers. The corresponding values from the DPMJET simulation are indicated by the dotted line.

Table 1. Comparison of collision scaling in DPMJET-II with the results from HERA-B [8] (all cross sections in mbarn).

|       | p–p | p–nitrogen | HERA–B       |
|-------|-----|------------|--------------|
| $D^+\sigma_{pN}$ | 0.0112 | 0.0144 | 0.0202 ± 0.0022 ± 0.0024 ± 0.0018 |
| $D^0\sigma_{pN}$ | 0.0350 | 0.0445 | 0.0487 ± 0.0047 ± 0.0049 ± 0.0044 |
| $D_s\sigma_{pN}$ | 0.0051 | 0.0068 | 0.0185 ± 0.0064 ± 0.0037 ± 0.0017 |

The HERA-B Collaboration [8] measured $D^0$, $D^+$, $D_s^+$ and $D^{**}$ in p–C, p–Ti and p–W collisions. They parametrize the production cross sections as

$$\sigma_{p-A} = \sigma_{p-N}A^\alpha,$$

and obtain $\alpha = 0.99 \pm 0.04 \pm 0.03$, in agreement with collision scaling.

DPMJET-II in its original form included charm production in which collision scaling was represented rather poorly. This has been corrected in the version used in this paper.

In table 1 we compare the $\sigma_{p-N}$ cross sections obtained from DPMJET-II in p–p and p–nitrogen collisions with the ones obtained by the HERA-B Collaboration. Taking into account experimental errors (as given in the table), we find good agreement, meaning that collision scaling as simulated in DPMJET-II corresponds to that found experimentally.

3.2. Total charm production cross section

Figure 1 shows the total open charm production cross section as measured, along with the corresponding values from DPMJET. It can be seen that the simulation reproduces
the actual values reasonably well, considering that the errors in the experimental values are quite large.

3.3. Differential cross sections

Precision measurement of differential charm production cross sections at low transverse momentum $p_\perp$ and Feynman-$x_F = p_L/p_{L\text{max}}$ requires comprehensive instrumental coverage of the interaction region, especially in the direction of the beam. Since this is difficult to achieve in collider experiments, relevant data are almost exclusively provided by fixed target set-ups. In the past, various experiments have been conducted using different types of particle beams. In the following, we will restrict ourselves to the discussion of results that were obtained with proton beams. Even though statistics for proton–nucleus interactions are relatively low compared to those for meson beams [37], these are the processes that are the most relevant in cosmic-ray-induced air showers. Moreover, we consider data in the low $p_\perp$ region most relevant for air showers.

Figure 2 shows the simplest case, a proton beam impinging on hydrogen nuclei in the LEBC bubble chamber. These results were already used in the first comparison between DPMJET and experimental data in 1995 [5]. Taking into account the limited statistics going into the experimental result, agreement between experiment and simulation is satisfactory.

An important aspect of charm hadroproduction is the leading quark effect described in section 2.6, by which production of hadrons which share a common diquark with the incoming projectile is favoured. The extent of this effect has been demonstrated by the SELEX collaboration using beams of protons, $\pi^-$ and $\Sigma^-$. In the forward $x_F$ region, production of $\Lambda^+_c$ was found to be significantly enhanced over its antiparticle for $p$ and $\Sigma^-$ beams, whereas for the $\pi^-$ beam no asymmetry was observed. Including this effect in the latest version of DPMJET leads to good agreement with the experimental result, as shown in figure 3.

Since the original publication only gave absolute event numbers [36], and no value for the charm production cross section was published by the collaboration, in figure 3 an additional systematic error was added to the experimental result in order to account for uncertainties in the estimate. In [6], the value for $\Lambda_c$ production was found to be

$$1.4 \, \mu\text{barn} \leq \sigma(pp \rightarrow \Lambda^+_c/\bar{\Lambda}^-_c)B(\Lambda_c \rightarrow 3 \text{ charged}) \leq 6.1 \, \mu\text{barn},$$

which, together with the fraction of $\Lambda_c$ to total open charm

$$\sigma \left( \frac{\Lambda^+_c/\bar{\Lambda}^-_c}{cc} \right) = 0.28 \pm 0.21$$

and the total open charm production cross section from [37]

$$\sigma(pp \rightarrow cc) = 25 \, \mu\text{barn},$$

results in an estimate for the charm production at SELEX energies (540 GeV) as $7 \pm 5.25 \, \mu\text{barn/nucleon}$. This is consistent with the value obtained from simulating charm production in DPMJET (9.5 $\mu\text{barn/nucleon}$).

Finally, the simulation was compared to data from HERA-B [8]. Even though the kinematic region covered by the detector was limited to $-0.15 < x_f < 0.05$ and
Figure 2. LEBC hydrogen bubble chamber measurements, sum over all D-mesons. Values are taken from \cite{6} and \cite{7}. Top left: 400 GeV $p_{\perp}^2$, top right: 400 GeV $x_F$, bottom left: 800 GeV $p_{\perp}^2$, bottom right: 800 GeV $x_F$. In this case, results from the corrected version (cf. figures 3 and 4) are identical to DPMJET(new).

$p_{\perp} < 3.5$ GeV c$^{-1}$, the result represents the most accurate measurement of open charm production using a proton beam. Figure 4 shows the comparison with our simulation. Even though there appear to be slight discrepancies in the individual data points, the result from DPMJET agrees well with the fit to the data presented by the HERA Collaboration in their publication in summer 2007.

SELEX used a mixture of copper and carbon targets, and HERA-B alternated between carbon, titanium and tungsten. In each case, the target thickness was a small fraction of the proton interaction length. To simplify the simulation, in DPMJET nitrogen nuclei were used as target material. This is legitimized by the fact that, as noted above, collision scaling was verified both in experiment and simulation. The individual diagrams have been scaled to represent the cross section values per nucleon.

4. Conclusion

Charm production in DPMJET has been checked against experimental data from both fixed target and collider experiments. Since the primary purpose of DPMJET is
Figure 3. SELEX measurements of $\Lambda_c$ production parameters and asymmetry for a 540 GeV proton beam on a mixed C/Cu target. Top left: $\Lambda^+_c x_F$, top right: $\bar{\Lambda}^+_c x_F$, bottom left: $p^2_\perp$ for all $\Lambda_c$, bottom right: asymmetry between $\Lambda^+_c$ and $\bar{\Lambda}^+_c$ production as a function of $x_F$. Asymmetry values higher than 1 are the result of the likelihood method used to analyse the data. All measurements taken from [36]. The error bars have been extended with respect to the original paper to reflect uncertainties in the absolute $\Lambda_c$ production cross section, for which a value of $7 \pm 5.25 \mu$ barn/nucleon was assumed (see text). Shown are the result from the old release version of CORSIKA, the version with the corrected parameter (bugfix) and the newest version in which leading quark effects are implemented. For more information about the different versions, see section 2.2. For the $\bar{\Lambda}^+_c$, the parameter-corrected result is identical to the new version, while in the asymmetry plot it is identical to the old version.

Simulation of cosmic-ray-induced air showers, the comparison was restricted to proton–nucleon interactions at low $p_{\perp}$, which, however, represent the by far dominant contribution to charm production. The total open charm cross section is consistent with experimental values, even though systematic errors on measurements are very large, especially at high energies.

Comparison of simulation to differential distributions from fixed target experiments show reasonable agreement. Since 1995, new data have become available that show hard
collisions playing a much larger role than previously assumed. Those results, most notably from the SELEX collaboration concerning charmed baryon asymmetries, but also collision scaling in $c\bar{c}$ production, were incorporated into the code.

In summary, charm production in DPMJET has been updated, reflecting the latest experimental results and is now consistent with all available measurements. All simulations have been performed with the DPMJET version integrated in the CORSIKA air shower simulation package. It thus allows us for the first time to generate Monte Carlo simulations of the prompt component in cosmic ray air showers. The precise effect of prompt contributions on muon and neutrino fluxes, as well as a study of meson–nucleon collisions, will be the subject of a later paper.

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