Muon and Muon Neutrino Fluxes from Atmospheric Charm

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The charm contribution to the atmospheric fluxes of muons and muon neutrinos may be enhanced by as much as a factor of 10 when one includes the contributions of $D \to \pi, K \to$leptons and folds in uncertainties in the charm cross section and energy distribution. In the energy range considered here, from 100 GeV to 10 TeV, the charm contribution is small compared to the conventional flux of muons and muon neutrinos.

The fluxes of leptons from the decays of pions and muons produced by cosmic ray interactions in the atmosphere are known to within approximately $\pm 20\%$[1] at energies $\sim$ 1 GeV. At cosmic ray energies greater than a few GeV, charm-anticharm pairs can be produced. The semileptonic decays of charmed mesons and baryons which emerge from the cosmic ray interactions with air are additional contributions to the atmospheric lepton fluxes. Here, we present the charm contribution to the atmospheric lepton fluxes in the energy range of 100 GeV to 10 TeV. We evaluate the theoretical uncertainties associated with charm production and decay. We show that the lepton flux from charm decays has a factor of approximately ten uncertainty, but the uncertainty has little implication for the measured atmospheric muon and muon neutrino fluxes in this energy range.

Atmospheric leptons from pion and kaon decays are called "conventional" leptons. Leptons from charm decays contribute to the "prompt" flux. Recently, a new calculation of the prompt lepton fluxes by Thunman, Ingelman and Gondolo (TIG)[2] has appeared in the literature. Using a PYTHIA[3] based Monte Carlo, they have evaluated the contributions of semileptonic decays of charmed particles to the leptonic fluxes. One aspect of charm decays not included in other calculations is the decay chain of charm$\to \pi, K \to$leptons, called here "secondary" contributions. Each charm decay has an associated pion and/or kaon in the final state, which itself decays leptonically.

The calculation of prompt, conventional and secondary lepton fluxes can be done approximately using the Z-moment form of the cascade equations. Details of approximate solutions can be found in, for example, Ref. [4]. The general form for the flux of particles of type j, as a function of energy and slant depth in the atmosphere, X, is

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{(dec)}} + \sum_k S(k \to j) \quad (1)$$

where

$$S(k \to j) = \langle N_j \rangle \int_E^\infty dE_k \frac{\phi_k(E_k, X)}{\lambda_k(E_k)} \frac{dn_{k\to j}}{dE} \quad (2)$$

The quantities λ_j and $\lambda_j^{(dec)}$ are the interaction and decay lengths, $\langle N_j \rangle$ is the average particle multiplicity of type j, and $dn_{k\to j}/dE$, describes the energy distribution of particle j given its production by particle k with energy E_k. Z-moments are defined by

$$S(k \to j) \equiv \frac{\phi_k(E, X)}{\lambda_k(E, X)} Z_{kj}(E) \ . \quad (3)$$

The Z-moments Z_{kj} depend on particle type and energy.

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The starting point for the solution to the cascade equations is the cosmic ray flux, which we take as all protons with an energy behavior $\phi_p \sim E^{-2.7} - E^{-3}$, as in TIG. Given the cosmic ray flux, and the interaction and decay moments of TIG in Ref. [2], we can evaluate the conventional and prompt fluxes. Since our interest in is the "low energy" regime, 100 GeV$< E <$ 10 TeV, we include only $c = D^0$, $\bar{D}^0$, $D^{\pm}$ in our charm contribution. TIG have shown that these are dominant in this energy range. The new feature here is to include secondary decays: we have additionally, for example, $D \to \pi \to \mu$, so we need the decay moment $Z_{D\pi}$. As a first approximation, we rescale the decay moments for D's into neutrinos to account for hadronic branching fractions and multiplicities. The details of the D decay-moment inputs can be found in Ref. [5].

Our results for the fluxes of muons (particles plus antiparticles), including secondary decays, are shown in Fig. 1 for the vertical direction. The solid line indicated by P (prompt) include only D^0, $\bar{D}^0$ and $D^{\pm}$. The dashed lines are the TIG parameterization of their Monte Carlo results [2], which have significant Λ_c and $D_s^{\pm}$ contributions at high energies. At low energies, the D's dominate. The muon neutrino fluxes are similar. The prompt flux of muon neutrinos equal the prompt flux of muons. The conventional muon neutrino flux is approximately a factor of 10 suppressed relative to the muon flux. The secondary muon neutrino flux is about a factor of five suppressed relative to the secondary muon flux.

As can be seen from the figure, the secondary flux is approximately three orders of magnitude below the conventional one. As one goes to angles off the vertical, both the secondary and conventional fluxes increase, but in a constant ratio, while the prompt flux remains constant as a function of angle.

Uncertainties in the calculation of the charm cross section and energy distribution affect predictions of both the prompt and secondary fluxes. We estimate that the cross section data [6] can accommodate an additional factor of two in the theoretical prediction of TIG [2]. The energy distribution in the charm production cross section is another uncertainty. The energy distribution

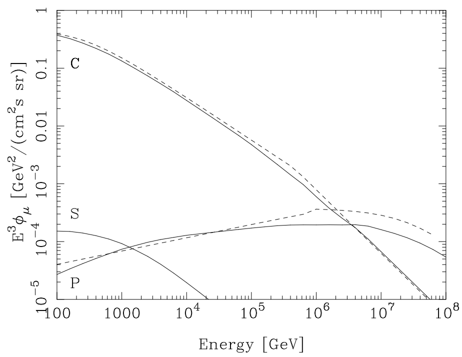

Figure 1. Conventional (C), prompt (P) and secondary (S) atmospheric muon plus antimuon flux in the vertical direction. The dashed lines are the approximate formulae of Ref. [2].

is usually written in terms of the charm particle energy divided by the incident nucleon (beam) energy: $x = E_c/E_b$, and in the scaling approximation, $d\sigma/dx \sim (n+1)(1-x)^n$. Next-to-leading order (NLO) perturbation theory, when fit to the $(1-x)^n$ distribution, has $n \sim 6 - 9.5$ for $E_b = 100 - 1000$ GeV, while experimental measurements yield $n \sim 4.9 - 8.6$ in the same energy range[6]. By using experimental rather than theoretical values for n, the charm flux can be enhanced by a factor of 1.5.

Finally, the charmed meson decay moment used for Fig. 1 is based on a parton V-A formula. If we use phase space instead of the V-A formula, the Z decay moment is enhanced by a factor of 2.4. Taken together, these enhancements can increase the secondary flux by a factor of 7, and the prompt flux by a factor of 3.

To estimate the effect of the high energy cross section on the low energy flux, we use a cross section which becomes $0.1\sigma_{pp}$ at high energies as suggested by Zas et al.[7], where σ_{pp} is the total pp cross section[8]:

$$\sigma^{c\bar{c}} = \frac{\sigma^{LE} \times 0.1\sigma_{pp}}{\sigma^{LE} + 0.1\sigma_{pp}} \qquad (4)$$

where σ^{LE}, for $E = 100 - 1000$ GeV, is the next-to-leading order (NLO) charm pair produc-

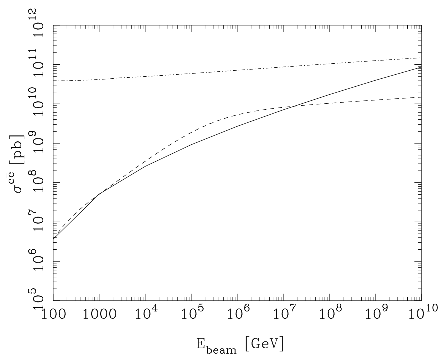

Figure 2. The charm-anticharm cross section according to Eq. (4) (dashed line). The solid line is the NLO charm cross section using CTEQ3 parton distribution functions with $\mu = m_c = 1.3$ GeV and the dot-dashed line is σ_{pp}.

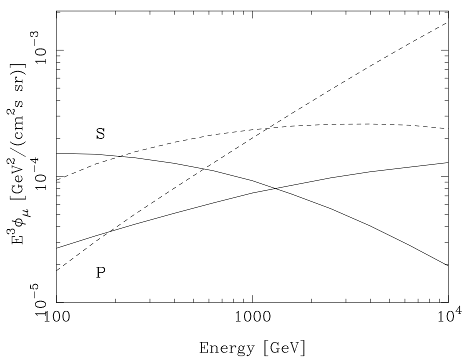

Figure 3. A comparison of the prompt (P) and secondary (S) muon fluxes using TIG parameters (solid line) and the fluxes computed using the cross section of Eq. (4) and a scaling energy behavior with $n = 4$.

tion cross section, evaluated at factorization and renormalization scales μ equal to $m_c = 1.3$ GeV, using the CTEQ3 parton distribution functions[9]. We use a power law extrapolation for $E > 1$ TeV. The cross section of Eq. (4) is represented by the dashed line in Fig. 2. As an extreme, we take $n = 4$ in $d\sigma/dx \sim (1-x)^n$, barely consistent with the low energy data. Our results for the muon plus antimuon fluxes are shown in Fig. 3.

In conclusion, there is a factor of about ten uncertainty in the prediction for the flux of muons from the decay of charm in the energy range 100 GeV-10 TeV. Relative to the prompt muon flux, the secondary decay contribution is significant, however, relative to the conventional flux, it is not. These conclusions also apply to the muon neutrino fluxes from charm decay. Because the conventional electron neutrino flux is small, the prompt flux is more important at 10 TeV than in the muon neutrino and muon case. This is a topic under further investigation by the present authors.

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