The contribution of charm to high energy atmospheric neutrinos

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We will discuss the performance of the new version of the hadronic interaction model Sibyll 2.XX that also generates charm hadrons which decay and generate very high energy atmospheric neutrinos.

This talk is based on work done with Tom Gaisser, Ralph Engel, and especially by Felix Riehn and Anatoli Fedynitch. These results were presented by Riehn and Fedinitch at ISVHECRI 2014 last month.
The current high interest in the `prompt' neutrinos from charm is due to the detection by IceCube of a number of neutrinos of energy above 30 TeV, a fraction of which must be of astrophysical origin. If we can reliably estimate the contribution of charm to the atmospheric neutrino flux we can estimate better the flux of astrophysical neutrinos.
There are several previous estimates of the contribution of charm to the atmospheric neutrino flux:

Bugaev et al., PRD 58 (1998)  
Endberg, Reno, Sarcevich, PRD78 (2008)  
Fedynich, Becker-Tjus, Desiati, PRD86 (2012)  

ERS is the model used by IceCube to estimate the flux of astrophysical neutrinos. It is a very good estimate, except that it uses the cosmic ray flux used by TIG.

We are attempting to do a new calculation that agrees with all accelerator measurements of the charm production starting at low energies and including all LHC data. A special attention will be payed also to the cosmic ray flux energy spectrum.
Analytic and semi-analytic calculations of the atmospheric neutrino flux use the modified Elbert formula: see Gaisser's book and recent talks:

\[
\phi(E_{\nu}) = \phi(E_N) \times \left\{ \frac{A_{\pi \nu}}{1 + B_{\pi \nu} \cos(\theta)E_{\nu}/\epsilon_\pi} + \frac{A_{K \nu}}{1 + B_{K \nu} \cos(\theta)E_{\nu}/\epsilon_K} + \frac{A_{C \nu}}{1 + B_{C \nu} \cos(\theta)E_{\nu}/\epsilon_C} \right\}
\]

where the critical energy is 115 GeV for pions, 850 GeV for Kaons, 10 PeV for charm mesons.

The decay length for charged D mesons is 0.34 mm and 0.15 mm for neutral D mesons. Another significant difference is that pions and Kaons generate electron neutrinos through muon decays and Ke3 decays, D mesons lepton decay channels produce equal numbers of muon and electron neutrinos.
The new version of hadronic interaction model Sibyll 2.XX (not yet released) corrects several problems of Sibyll 2.1 that is widely used for air shower calculations, such as
- Very high interaction $pp$ cross section not consistent with the LHC cross section measurements is corrected
- implements parton shadowing to generate similar correct shower depth of maximum as Sibyll 2.1
- The excessive K+ production in p-Nucleus interactions that affects the atmospheric neutrino production is corrected
- Generates more baryon-antibaryon pairs to agree with the accelerator measurements

It also generates charm mesons and baryons
The new Sibyll includes
- multiple parton interactions
- hard and soft scattering
- diffraction dissociation
- Lund fragmentation of strings

We have added charm production to the hard scattering (perturbative QCD component). Since there is evidence in data also for non-perturbative component (leading charm particles and assymetry) we have also added charm to the valence quark scattering part of the code.

The charm production measurements from 250 GeV/c in the Lab to $\sqrt{s}$ of 7 TeV are compared to the charm production of Sibyll.
Almost full phase space coverage exists in these experiments.

Fixed target data
It is different in collider experiments. Different detectors cover different parts of the phase space.

For $|y| < 0.5$ in ALICE the central charm meson production is entirely due to pertubative processes.
LHCb measures D production in the central and forward regions. Sibyll reproduces the measurements well, although there is a little problem with very high transverse momenta.
Similar problem exists also with the measured charmed Lambda production. It is important because the $x$ distribution of Lambdas is very flat, which means after decay it generates high energy neutrinos.
Sibyll performance in the whole energy range. There is still not a full agreement between the total inclusive cross section and the central charm production measured by ALICE.
For calculations of the atmospheric muon and neutrino fluxes a matrix method developed by A. Fedinitch is used. It involves the all particles that Sibyll generates:

**Leptons**

\[ \mu^+, \mu^-, \tau^+, \tau^-, \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \]

**Mesons**

\[ K^+, K^-, K_L^0, K_S^0, \pi^+, \pi^-, D^+, D^-, D^0, \bar{D}^0, D_s^+, D_s^-, K^{*+}, K^{*-}, K^{*0}, \bar{K}^{*0}, D^{*+}, D^{*-}, D^{*0}, \bar{D}^{*0}, \eta, \eta^*, \eta_c, J/\psi, \omega, \phi, \pi^0, \rho^+, \rho^-, \rho^0 \]

**Baryons**

\[ p, \bar{p}, n, \bar{n}, \Delta^+, \Delta^{++}, \Delta^{++}, \Delta^+, \Delta^-, \Delta^+, \Delta^0, \bar{\Delta}^0, \Lambda^0, \bar{\Lambda}^0, \Omega^-, \bar{\Omega}^+, \Sigma^{*+}, \Sigma^{*-}, \Sigma^{*-}, \Sigma^{*+}, \Sigma^{*0}, \Sigma^0, \bar{\Sigma}^0, \Sigma, \bar{\Sigma}, \Sigma^+, \Xi^-, \Xi^+, \Xi^0, \Xi^0, \Xi^+_C, \Xi^+_C, \Xi^0_C, \Xi^{0+}_C, \Xi^{0+}_C, \Xi^{0+}_C, \Xi^{*0}_C, \Xi^{*0}_C, \Xi^{*+}_C, \Xi^{*+}_C, \Xi^{*0}_C, \Xi^{*0}_C \]
The MonteCarlo calculations we have done are folded with the fluxes of protons and neutrons in the primary cosmic cosmic rays that hit the atmosphere. This should generate the right ratio of neutrinos to antineutrinos in the atmospheric neutrino fluxes.

Comparison of the all nucleon fluxes in Gaissers model h3a and the fit GST to the TIG cosmic ray flux used in all previous calculations of atmospheric neutrinos including charm. The cosmic ray flux used in the calculation changes the shape of the atmospheric neutrino flux at high energy.
Contribution of different particle decays to the atmospheric muon flux. Note that the prompt muons start dominating over the conventional muon fluxes above 1 PeV, Note that the muon fluxes are multiplied by the muon energy cubed.
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In the case of muon neutrinos (and antineutrinos) the cross over is at slightly lower energy of about 500 TeV.
For electron neutrinos the crossover is at about 20 TeV, which means that prompt electron neutrinos contribute to all IceCube high energy neutrino events. This contribution, however, is not huge.
We compared our predictions for charm production at LHC to those of DPMJET II. While in the central region the two predictions are similar, in the forward regions DPMJET generates many more charm particles, while Sibyll is consistent with the experimental data in the whole phase space.
**Conclusions:** When this new version of Sibyll will be ready and could be used for all kinds of calculations?

We are currently happy with this version’s descriptions of \( pp \) interactions and the charm mesons and baryon production in them. We feel that more checking should be performed on p-nucleus collisions predictions. Luckily there is data on such collisions and we are concentrating on them now.

It will not be difficult (but is not done yet) to describe the charm baryons and mesons interactions.

I hope that by the end of the year we will be ready with the new Sibyll 2.XX model and it will become available after the first publication.

Thanks