Atmospheric neutrino fluxes and prompt neutrinos from heavy flavor

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JHEP 1611 (2016) 167
JHEP 1506 (2015) 110
Neutrinos produced in the atmosphere by cosmic ray interactions

Atmospheric flux intrinsically interesting, not just a background to the astrophysical flux!

Figure from https://astro.desy.de/

1998 SuperKamiokande discovery of neutrino oscillations
Neutrinos produced in the atmosphere by cosmic ray interactions

Inputs include:

• cosmic ray (CR) flux and composition
• Particle physics inputs: CR interactions with air nuclei to produce mesons/baryons that decay

Figure from https://astro.desy.de/
Plan

• Review the energy dependence of the atmospheric neutrino flux.

• Review some features of the “conventional flux” of neutrinos from pion and kaon decays. Compare and contrast with the flux from heavy flavor decays (“prompt flux”).

• Discuss some of the details of the flux at high energies – neutrinos from heavy flavor decays (predominantly charmed particles) where theoretical uncertainties are the largest.
Energy dependence of the CR all particle spectrum
traditional rescaling in other figures, by power of 2.7 or 3

From Table 1, Gaisser, Astropart. Phys. 35 (2012) 801
Energy dependence, schematically, neglecting break in power law of cosmic rays

Cosmic rays produce hadrons. They decay to neutrinos (low energy—all, high energy—few)

Scaling by approximate CR energy spectrum

\[ P_{\text{decay}}(E) = 1 - \exp\left(-\frac{D}{\gamma c\tau}\right) \]
\[ \simeq \frac{D}{\gamma c\tau} = \frac{E_c}{E} \]

\[ \phi \sim \frac{1.7}{E_{\text{GeV}}^{2.7}} \frac{cm^2 s sr GeV}{1} \]
Energy dependence, schematically, similar (with different critical energies)

Energy dependence,
schema
twice,
similar
(with
different
critical
ergies)

\[ E^{2.7} \phi_\nu \]

Scaling by approximate CR energy spectrum

Impact of the different lifetimes

Electron neutrino flux from K-short, Gaisser & Klein, Astropart. Phys. 64 (2015) 1.2 \times 10^5 \text{ GeV}
Features-conventional flux

- Angular dependence
- Flavor ratios

- Honda et al., Phys. Rev. D 83 (2011) and earlier work.
- MCeQ: e.g., Fedynitch et al., PoS (ICRC2017) 1019.

Conventional flux (charged mesons):
\[
\begin{align*}
\pi & \rightarrow \mu\nu_{\mu} \ (100\%) \\
K & \rightarrow \mu\nu_{\mu} \ (64\%) \\
K & \rightarrow \pi^0 \ell\nu_{\ell} \ (3 \text{ - } 5\%)
\end{align*}
\]

Neutral kaons:
\[
\begin{align*}
K_{L} & \rightarrow \pi^\pm \ell\nu_{\ell} \ (27 \text{ - } 41\%) \\
K_{S} & \rightarrow \pi^\pm e\nu_{e} \ (0.07\%)
\end{align*}
\]
Features-conventional flux

- Angular dependence
- Flavor ratios

Muons decay

Muons don’t decay

Features-conventional flux

- Angular dependence
- Flavor ratios

www2.slac.stanford.edu/vvc/cosmic_rays.html


At Kamioka, averaged over azimuth, including geomagnetic effects.
Features-prompt flux

• Angular dependence
• Flavor ratios

BERSS: Bhattacharya et al., JHEP 06 (2015) 110
Bhattacharya et al., JHEP 1611 (2016)
GMS: Garzelli, Moch and Sigl, JHEP 10 (2015) 115
GRRST: Gauld et al, JHEP 02 (2016) 130
Benzke et al., 1705.10386

Prompt flux:

\[ D^+ \rightarrow \ell^+ \nu_\ell X \ (16 - 17\%) \]
\[ D^0 \rightarrow \ell^+ \nu_\ell X \ (6 - 7\%) \]
\[ D_s \rightarrow e\nu_e X \ (6.5\%) \]
\[ D_s \rightarrow \tau \nu_\tau \ (5.5\%) \]

Assume flavor equality for electron neutrinos and muon neutrinos. Tau neutrinos are special!
Features-prompt flux

- Angular dependence
- Flavor ratios

\[ \nu_e : \nu_\mu : \mu = 1 : 1 : 1 \]

Isotropic up to high energies, since all of the D’s have “prompt” decays.

Prompt flux:

\[ D^+ \to \ell^+ \nu_\ell X \ (16 - 17\%) \]
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Cascade Equations

\[ \frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{\text{dec}}} + \sum S(k \rightarrow j) \]

\[ S(k \rightarrow j) = \int_{E}^{\infty} dE' \frac{\phi_k(E')}{\lambda_k(E')} \frac{dn(k \rightarrow j; E', E)}{dE} \]

e.g., \( pA \rightarrow DX \)

\[ \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \rightarrow jY; E_k, E_j)}{dE_j} \]

e.g., \( D \rightarrow \nu_\mu X \)

\[ \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j} = \frac{1}{\Gamma_K} \frac{d\Gamma(k \rightarrow jY; E_k, E_j)}{dE_j} \]

High enough energies that muons are “stable”.

\[ j = N, \pi, K, D, \nu_i, \mu \]

Need cosmic ray flux \( j=\text{N} \) and energy distribution of the final state particle.
We use Z-moments: spectrum weighted moments

\[ S(k \to j) = \int_{E}^{\infty} dE' \frac{\phi_k(E', X)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE} \]

\[ S(k \to j) = Z_{kj}(E) \frac{\phi_k(E, X)}{\lambda_k(E)} \]

\[ Z_{kj}(E) = \int_{E}^{\infty} dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE} \]

Approximate relation – flux factorizes so Z only depends on E.
Calculate the differential cross section or decay distribution, convolute with the flux, integrate to get Z.
Spectrum weights favor forward production of charm – want the largest E (charmed meson) given E’ (cosmic ray nucleon).
Approximate formulae

\[ \phi_{\ell}^{\text{low}} = \frac{Z_{NM} Z_{M\ell}}{1 - Z_{NN}} \phi_N \]

\[ \phi_{\ell}^{\text{high}} = \frac{Z_{NM} Z_{M\ell} \ln(\Lambda_M/\Lambda_N) \epsilon_c^M}{1 - Z_{NN} 1 - \Lambda_N/\Lambda_M} \frac{\epsilon_c}{E} \phi_N \]

\[ \Lambda_M = \lambda_M/(1 - Z_{M\ell M}) \]

Exponential atmosphere, 1D, approximate factorization of depth dependence.

\[ Z_{ND}, Z_{D\ell}, \Lambda_D \quad c \rightarrow s\mu^+\nu_\mu \quad c \rightarrow se^+\nu_e \]

\[ \epsilon_c^\pi = 115 \text{ GeV} \]
\[ \epsilon_c^K = 850 \text{ GeV} \]
\[ \epsilon_c^D \sim 10^8 \text{ GeV} \]

A numerical tool: MCEq

Dembinski et al., and Fedynitch et al., PoS (ICRC2017) 1019.

MCEq: numerical solution to cascade equations, Fedynitch et al., arXiv: 1503.0054

Error band around black curve shows SIBYLL error band.
See also, e.g., Barr et al., Phys. Rev. D 74 (2006).
Geomagnetic and 3D effects not included (shaded region below 20 GeV).
What is new in our prompt charm evaluation using the Z-moment method?


  Forward production means small-x in parton distribution function or dipole cross section.
Cross section for charm, b quarks
Compare with LHC data for charm

NLO perturbative for example. For the prompt flux from charm, need even larger rapidities.

LHCb, Nucl. Phys. B 871 (2013) 1; JHEP 03 (2016) 159
NLO QCD result for flux

BERSS: Bhattacharya et al., JHEP 06 (2015) 110 uses CT10 PDFs with no nuclear corrections. Nuclear corrections via nCTEQ15 parton distribution functions are significant.

Nuclear corrections in dipole model are 10-20% reduction. Here, updated Z-moments, gluon PDF, more dipole models for uncertainty band.
KT factorization
Comparison with other recent results

Use the broken power law for comparison with recent results from other groups
Prompt fluxes with different scaling

Suggested upper limit on prompt flux: 0.54 ERS from Radel and Schoenen for IceCube, ICRC 2015 (2015) 1079.
Tau neutrinos plus antineutrinos

\[ D_s \rightarrow \tau \nu_\tau \quad \tau \rightarrow \nu_\tau X \]
Summary

• If we had a completely reliable calculational method for charm production, we wouldn’t need three different approaches.

• Our new NLO pQCD results are lower than BERSS, because of nCTEQ15 PDFs for nitrogen, which have small-x suppression. There are still nuclear uncertainties.

• A limit of 0.54*ERS cuts into dipole model range of flux predictions, and kT factorization without nuclear corrections.

• Have not talked about intrinsic/spectator charm, see, e.g., Halzen and Wille, Phys. Rev. D94 (2016) 014014; Laha and Brodsky, 1607.08240.
LHCb update

LHCb, red updated with errata published in JHEP05 (2017) 074.