Prompt Neutrino Fluxes from Charm Production in the Atmosphere

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Atmospheric Neutrino

- Cosmic rays interact with air nuclei in the atmosphere and produce hadrons.
- Hadrons subsequently decay producing neutrinos.
  \[ \text{Atmospheric neutrino} \]
  \[ e.g.) \quad pp \rightarrow \pi^+ + X \]
  \[ \downarrow \]
  \[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow (\bar{\nu}_\mu, \nu_e, e^+) \nu_\mu \]
- Atmospheric neutrinos are the background to astrophysical neutrinos.
Conventional Neutrino Flux

- Neutrino flux from pion and kaon decay is called the **conventional** flux.
- K, π – long-lived particles – interact before the decay  
  ⇒ suppress the neutrino production at high E
Neutrino flux from the decay of the charmed hadrons is called the **prompt** flux. e.g.) D-mesons

- The charmed hadrons are short-lived particles.
- The resulting neutrino flux less depends on energy.
Cascade equations

The neutrino flux is obtained by solving the coupled cascade equations for nucleon, meson and lepton fluxes.

\[
\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \rightarrow NY) \quad \phi_N(E) - \text{nucleon flux}
\]

\[
\frac{d\phi_M}{dX} = S(NA \rightarrow MY) - \frac{\phi_M}{\lambda_M} - \frac{\phi_M}{\lambda_M^{\text{dec}}} + S(MA \rightarrow MY)
\]

\[
\frac{d\phi_l}{dX} = \sum_M S(M \rightarrow lY) \quad M = D^\pm, D^0, \bar{D}^0, D_s^\pm, \Lambda_c^\pm \quad \text{for prompt fluxes from charm}
\]

The function \( S \) is responsible for the generation.
Cascade equations

- generation function

\[ S(k \rightarrow j) = \int_{E}^{\infty} dE_k \frac{\phi_k(E_k)}{\lambda_k(E_k)} \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j} \]

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

\[ = \frac{1}{\Gamma_k} \frac{d\Gamma(k \rightarrow jY, E_j)}{dE_j} \quad \text{for decay} \]

dn/dE – the energy distribution of the final state particle.
**Z-moments**

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

\[
Z_{kj} \equiv \int_E^\infty dE_k \frac{\phi_k(E_k, X)}{\phi_k(E_j, X)} \frac{\lambda_k(E_j)}{\lambda_k(E_k)} \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j}
\]

Assumption : \(\phi_k(E, X) = E^\beta \phi_k(X)\)

\[
Z_{kj}(E) = \int_E^\infty dE_k \left( \frac{E_k}{E_j} \right)^\beta \frac{\lambda_k(E_j)}{\lambda_k(E_k)} \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j}
\]

Approximate Lepton Fluxes

\[
\phi_l^{\text{low}} = Z_{Mi} \frac{Z_{NM}}{1 - Z_{NN}} \phi_N
\]

\[
\phi_l^{\text{high}} = Z_{Mi} \frac{Z_{NM}}{1 - Z_{NN}} \frac{\ln(\Lambda_M / \Lambda_N)}{1 - \Lambda_N / \Lambda_M} \frac{\epsilon_M}{E} \phi_N
\]

\[
\Lambda_i = \lambda_i / (1 - Z_{ii}) \quad i = N, M
\]

The lepton flux can be obtained by interpolating these two solutions.
• The essential input to the neutrino flux evaluation is the charm production cross section.

• The charm production cross section can be calculated
  1) in the perturbative QCD,
  2) in the dipole model,
  3) with non-perturbative “intrinsic charm” production.
Charm Production Cross Section in QCD

The cross section for charm pair production

\[ \frac{d\sigma_{LO}}{dx_F} = \int \frac{dM_{c\bar{c}}^2}{(x_1 + x_2)s} \sigma_{gg\rightarrow c\bar{c}}(\hat{s})G(x_1, \mu^2)G(x_2, \mu^2) \]

\[ x_{1,2} = \frac{1}{2} \left( \sqrt{x_F^2 + \frac{4M_{c\bar{c}}^2}{s}} \pm x_F \right) \]

At high energies, \(x_1 \sim x_F\) and \(x_2 \ll 1\).

E.g.) at \(E_p = 1\) PeV, \(x_2 \sim 10^{-6}\) for \(x_F \sim 1\).

\(x_2\) become smaller at higher energy.
Gluon distribution at small $x$

The gluon distribution increases rapidly as $x$ becomes small.

At the high density region, gluons can be overlapped and recombined.
→ Saturation effect

K.Golec-Biernat – conf. proceeding
arXiv:0812.1523
Color Dipole Model

The virtual photon splits into a quark-antiquark pair (color dipole) before scattering on the proton.

C. Ewerz et al, JHEP03 (2011) 062

$$\sigma_{\gamma^* N} (x, Q^2) = \sum_f \int_0^1 dz \int d^2 r \left| \Psi(z, r, Q^2) \right|^2 \hat{\sigma}_{q\bar{q}N} (r, x)$$

$$\Psi(z, r, Q^2)$$ - fluctuation

$$\hat{\sigma}_{q\bar{q}N} (r, x)$$ - interaction of a dipole with a target
PP collisions in the dipole model

The differential cross section for heavy quark production from proton-proton collision

$$\frac{d\sigma}{dy}(pp \rightarrow Q\bar{Q}X) = x_1 G(x_1, \mu^2)\sigma^{gp}(x_2, \mu^2, Q^2)$$

The partonic cross section in the dipole model

$$\sigma^{gp}(x_2, \mu^2, Q^2) = \int dz d^2r \left| \Psi^Q_G(z, r) \right|^2 \sigma_{dG}(x, r)$$

$$\Psi^Q_G(z, r)$$ - splitting of gluon to dipole

$$\sigma_{dG}(x, r)$$ - interaction of q\bar{q} pair from a gluon with the target nucleon
PP collisions in the dipole model

\[ \sigma_{dG}(x, r) = \frac{9}{8} \left[ \sigma_d(x, zr) + \sigma_d(x, (1 - z)r) \right] - \frac{1}{8} \sigma_d(x, r) \]

\[ \sigma_d(x, r) = a \left( \frac{x}{x_0} \right)^{\lambda(r)} r^{b r+c} \quad \text{for } r \leq 0.5 \text{ and } r > 1.8 \]

\[ = a \left( \frac{x}{x_0} \right)^{\lambda(r)} \left( 1 + r^{b} - c e^{d r^e} \right) \quad \text{for } 0.5 < r \leq 1.8 \]

\[ \lambda(r) = -0.196 + 0.11r - 0.127 r^2 + 0.044 r^3 \quad (r < 1.8) \]

\[ = -0.39 + 0.182 r - 0.0325 r^2 + 0.00224 r^3 \quad (r \geq 1.8) \]

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YSJ, C. S. Kim, M. V. Luu and M. H. Reno, 
JHEP 11 (2014)025
Cosmic Ray Flux for Nucleon

Prompt Flux in Dipole Model

- New dipole cross section from the recent F2 parameterization – increases the flux by ~15%.
- The effect of CR spectrum – above 1 PeV, reduction in flux is by a factor of 3-4.
Intrinsic charm

Charm can be produced from non-perturbative fluctuation of nucleon and it goes into a charmed baryon-meson pair.

\[ p \rightarrow \Lambda_c^+ + D^0 \]

\[ \Rightarrow \text{Meson-Baryon Model (MBM)} \]

In the MBM, \( \Lambda_c^+ \) is produced through \( D^0 \Lambda_c^+ \) and \( \bar{D}^{*0} \Lambda_c^+ \).

T.J. Hobbs, J.T. Londergan and W. Melnitchouk, PRD 89 074008 (2014) (HLM)
Intrinsic charm production cross section

\[ \frac{d\sigma_{\Lambda_c}}{dx_F} \approx \sum_{M=D, D^*} f_{\Lambda_c M}(x_F) \sigma_{tot}^{M_p} \]

\[ \sigma_{tot}^{D_p} \approx \sigma_{tot}^{D^*_p} \approx 20 \pm 10 \text{ mb} \]

\( f_{\Lambda_c M} \) - splitting function

T.J. Hobbs, J.T. Londergan and W. Melnitchouk, PRD 89 074008 (2014) (HLM)
Prompt Flux – Intrinsic charm

\[ E^3 \phi \left[ \text{GeV}^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \]

Energy [GeV]

Preliminary
Conclusion

• The prompt flux with more realistic cosmic ray nucleon spectrum is reduced relative to the prompt spectrum using the broken power law. At 1 PeV, the reduction in flux is about a factor of 3.

• The dipole cross section from the $F_2$ parameterization by Block et al increase the flux about 15%.

• Intrinsic charm contribution based on the Hobbs et al MBM results may be important. – work in progress

• More update
  – with separate lepton flavors
  – with bottom quark contribution
  – with other models for intrinsic charm
Prompt flux: DM vs. NLO QCD

\[ E^3 \phi_y [\text{GeV}^2 \text{cm}^2 \text{s}^{-1} \text{sr}^{-1}] \]

vs.

Energy [GeV]

Preliminary