QCD in Astrophysics: Atmospheric Neutrinos from Charm

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Cosmic Accelerators

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Cosmic Rays
Atmospheric Neutrinos

- Cosmic ray nucleons interact with nucleons in the atmosphere producing mesons (pions, kaons, D-mesons, etc)
- Mesons can further interact or decay
- Decay of mesons results in neutrino flux
- Neutrinos from pion decay represent the so-called “conventional” atmospheric neutrino flux
- Neutrinos from charmed meson decay represent the “prompt” neutrino flux
Neutrino Fluxes at Earth

Enberg, Reno and Sarcevic, Phys. Rev. D79, 043005

Neutrino flux is obtained by solving the evolution equations for nucleon, meson and neutrino fluxes:

\[ \frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \rightarrow NY) \]

\[ \frac{d\phi_M}{dX} = S(NA \rightarrow MY) - \frac{\phi_M}{\rho d_M(E)} - \frac{\phi_M}{\lambda_M} + S(MA \rightarrow MY) \]

\[ \frac{d\phi_\ell}{dX} = \sum_M S(M \rightarrow \ell Y) \]

The primary nucleon flux is given by:

\[ \phi_N(E) = \begin{cases} 
  1.7 E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\
  174 E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV}
\end{cases} \]
$S(k \rightarrow j)$ is the regeneration function for pions, kaons and D-mesons,

$$S(k \rightarrow j) = \int_{E}^{\infty} \frac{\phi_{k}(E_{k})}{\lambda_{k}(E_{k})} \frac{dn(k \rightarrow j; E_{k}, E_{j})}{dE_{j}} dE_{k}$$

$dn/dE_{j}$ is the meson (pion, kaon, D-meson) production or decay distribution:

$$\frac{dn(k \rightarrow j; E_{k}, E_{j})}{dE_{j}} = \frac{1}{\sigma_{kA}(E_{k})} \frac{d\sigma(kp \rightarrow jY, E_{k}, E_{j})}{dE_{j}}$$

$$\frac{dn(k \rightarrow j; E_{k}, E_{j})}{dE_{k}} = \frac{1}{\Gamma_{k}} \frac{d\Gamma(kj \rightarrow jY, E_{j})}{dE_{j}}$$
We define the Z-moments:

\[ Z_{kj} = \int_{E}^{\infty} dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_{had}^{\prime}(E)}{\lambda_{had}^{\prime}(E')} \frac{dn(kp \rightarrow jY; E', E)}{dE}. \]

- The propagation of proton flux over distance \( X \) is given by

\[ \left( \frac{d\phi_N}{dX} \right)_{\text{cool}} = - \frac{\phi_N}{\lambda_{had}^N} + Z_{NN}^{had} \frac{\phi_N}{\lambda_{had}^N} - \frac{\phi_N}{\lambda_{EM}^N} + Z_{NN}^{EM} \frac{\phi_N}{\lambda_{EM}^N} \]

- The Z-moment is defined by

\[ Z_{NM} = \int_{0}^{1} dx_E x_E^{\alpha - 1} \frac{dn_{N \rightarrow M}}{dx_E} \]

where \( \frac{dn}{dx_E} \) is the energy distribution of the meson M produced by N (or from M decay).

- Meson flux is determined by solving the evolution equation:

\[ \frac{d\phi_M}{dX} = - \frac{\phi_M}{\lambda_{dec}} - \frac{\phi_M}{\lambda_{had}} - \frac{\phi_M}{\lambda_{rad}} + Z_{MM} \frac{\phi_M}{\lambda_{had}} + Z_{NM} \frac{\phi_N}{\lambda_N} \]
Charm contribution to atmospheric neutrinos can be calculated using parton distribution functions or in a dipole model which includes saturation effects.
Charm Production and Cross Sections using pQCD and PDFs

\[ \frac{d\sigma}{dx_F} = \int \frac{dM_{cc}^2}{(x_1 + x_2)s} \sigma_{gg \to cc}(\hat{s}) G(x_1, \mu^2) G(x_2, \mu^2) \]

The total charm cross section in pQCD is given by:

\[ \sigma(pp \to c\bar{c}X) = \int dx_1 dx_2 G(x_1, \mu^2) G(x_2, \mu^2) \tilde{\sigma}_{gg \to c\bar{c}}(x_1 x_2 s) \]

where

\[ x_{1,2} = \frac{1}{2} \left( \sqrt{x_F^2 + \frac{4 M_{cc}^2}{s}} \right) \pm x_F \quad (x_F = x_1 - x_2) \]

For high energies we need gluon PDF in low x, and low Q range.
The problem of small $x$}

Gluon distribution grows rapidly as $x \to 0$: gluons start overlapping
and may start recombining: saturation of cross section
Charm Production: dipole approach

\[ \gamma^* \rightarrow q\bar{q} \]
\[ q\bar{q}N \rightarrow X \]

heavy quarks:

\[ \gamma^* \rightarrow c\bar{c} \]
\[ c\bar{c}N \rightarrow c\bar{c}X \]

\[ \sigma_T (\gamma^* N) = \int_0^1 dz \int d^2r |\Psi_T(z, r, Q^2)|^2 \sigma_{dN}(x, r) \]

• Dipole model fits small x data HERA data (Stasto, et al., PRL 86 (2001))
• Improved QCD motivated form - Balitsky-Kovchegov (BK) evolution
• Modified for gluon -> charm anticharm pair
Dipole picture

Al Mueller showed how to formulate the BFKL equation in the dipole picture: evolution by dipole splitting

\[
\begin{align*}
\includegraphics[width=0.3\textwidth]{dipole_splitting1} + \includegraphics[width=0.3\textwidth]{dipole_splitting2} &= \includegraphics[width=0.3\textwidth]{dipole_splitting3}
\end{align*}
\]

DIS at small $x$ is then calculated as dipole splitting folded with scattering of one of the dipoles:

\[
\begin{align*}
\includegraphics[width=0.3\textwidth]{dipole_scattering}
\end{align*}
\]
Differential cross section for heavy-quark production

\[
\frac{d\sigma}{dy} = x_1 G(x_1, \mu^2) \sigma_{Gp\rightarrow Q\bar{Q}X}(x_2, \mu^2, Q^2)
\]

where \( \sigma_{Gp\rightarrow Q\bar{Q}X} \) is partonic cross section calculated in the dipole model,

\[
\sigma_{Gp\rightarrow Q\bar{Q}X} = \int dz d^2 \vec{r} |\psi_Q^G(z, r)|^2 \sigma_{dG}(x, \vec{r})
\]
Dipole cross section that describes interactions of heavy quark-antiquark pair fluctuation of the gluon with the target nucleon is given by

\[
\sigma^N_{GQQ\bar{Q}}(x_2, r) = \frac{9}{8} [\sigma_d(x_2, zr) + \sigma_d(x_2, (1 - z)r)]
\]

where:

\[
\sigma_d(x, r) = \sigma_0 \mathcal{N}(rQ_s, Y)
\]

and

\[
\mathcal{N}(rQ_s, Y) = \left( \frac{\tau}{2} \right)^{2\gamma_{eff}(x, r)} \quad \text{for} \quad \tau < 2
\]

\[
\mathcal{N}_0(rQ_s, Y) = 1 - \exp \left[ -a \ln^2(b\tau) \right] \quad \text{for} \quad \tau > 2
\]

\[
\tau = rQ_s
\]

\[
Y = \ln \left( \frac{1}{x} \right)
\]

\[
\gamma_{eff}(x, r) = \gamma_s + \frac{\ln(2/\tau)}{\kappa \lambda Y}
\]
FIG. 4: The NLO QCD $pA \to c\bar{c}X$ differential cross section as a function of Feynman $x_F$ for PRS [14] compared to the dipole model (DM) result for incident proton energies of $10^3$, $10^6$, $10^9$ GeV. The thicker lines are PRS and the thinner lines with the same color are DM at the same energy.
We calculate the Z-moments for charm production taking into account the effects of parton saturation at high energies.


To compute the Z-moments for pp we use the parametrization of the rapidity distribution,

\[ \frac{dN}{dx_E} = 0.12(1-x_E)^{2.6}x^{-2} \]

<table>
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<tr>
<th>( M )</th>
<th>( Z_{M\nu} )</th>
<th>( Z_{NM} )</th>
<th>( Z_{NM}^\gamma )</th>
<th>( c\tau ) [cm]</th>
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<tr>
<td>( \pi^\pm )</td>
<td>0.061</td>
<td>0.55</td>
<td>0.13</td>
<td>780</td>
</tr>
<tr>
<td>( K^\pm )</td>
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<td>0.055</td>
<td>0.0065</td>
<td>370</td>
</tr>
<tr>
<td>( D^\pm )</td>
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<td>( 2.4 \times 10^{-3} )</td>
<td>–</td>
<td>( 3.2 \times 10^{-2} )</td>
</tr>
<tr>
<td>( D^0 )</td>
<td>0.017</td>
<td>( 5.6 \times 10^{-3} )</td>
<td>–</td>
<td>( 1.2 \times 10^{-2} )</td>
</tr>
</tbody>
</table>
Prompt Neutrino Flux


DM=dipole model
GH=Gaisser-Honda
TIG=Thunman et al.
(PDF + pythia, small x extrapolation)
Prompt Neutrino Flux

FIG. 7: The effect of fragmentation on predicted $\nu_\mu + \bar{\nu}_\mu$ fluxes. The solid lines are DM and NLO QCD (the latter multiplied by two to separate the lines) with Kniehl–Kramer fragmentation. The dashed lines are without fragmentation.
Atmospheric neutrinos
angular dependence

Muon neutrino plus antineutrino flux, from our dipole model “prompt” calculation.

Conventional flux from Gaisser-Honda.

IceCube measurement of Neutrino Flux
Conclusions

- Charm contribution to atmospheric neutrinos is important at high energies ($E > 10^5 \text{GeV}$).
- Perturbative QCD calculation of charm contribution to atm neutrinos is sensitive to PDF’s at small $x$ $\rightarrow$ dipole approach incorporates parton saturation effects.
- Measurements of atmospheric neutrinos at high energies can provide valuable information about small-$x$ physics (small $Q$).
- Cosmic neutrinos can be used as probes of QCD.