Muons and neutrinos from atmospheric charm, theoretical considerations

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Atmospheric neutrino production

Cosmic ray interactions with air nuclei,

Production of mesons: pions, kaons, charmed mesons,

Meson interaction and decay.

Here, review of atmospheric flux calculation, with emphasis on charm production.

\[
c \rightarrow s\mu^+\nu_\mu \quad c \rightarrow s\nu_e\nu_e
\]

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


Same production mechanism for accelerator beams, inside astrophysical objects, cosmogenic neutrino flux.
Atmospheric neutrino flux

- Review how the flux scales with energy, for “conventional” and “prompt” neutrino fluxes.

- Theoretical considerations in the “prompt” flux from charm. (Results from ERS (2008) and work in progress with I. Sarcevic and R. Enberg.)

IceCube Results

Measurements in progress.
IceCube, Abbasi et al, PRD83 (2011) 012001
Atmospheric lepton flux

- Cosmic ray flux – energy spectrum and composition (first approximation, protons)
- CR interaction cross section with air nuclei (A = 14.5)
  - Regeneration of CRs
  - Production of mesons, including the energy distributions
- Meson interactions and decays, including energy distribution of leptons
- Coupled transport equations of CRs, mesons and leptons

**REFS**, e.g.,

- Cosmic Rays and Particle Physics, T. Gaisser, Cambridge U Press
Cosmic ray flux

\[ \phi \sim \frac{1.7}{E_{\text{GeV}}^{2.7}} \frac{1}{\text{cm}^2 \text{s sr GeV}} \]

approximately isotropic above 30 GeV, (I will call them protons or N)

“knee”, change in energy behavior


\[ \sigma_{N \text{ air}} = 300 \text{ mb} \]
\[ \lambda_N \approx 80 \text{ g/cm}^2 \]

Altitude of interaction: approx. 15 km

\[ X_v = \int_h^{\infty} \rho(h') \, dh' \]
pA collisions produce hadrons and eventually leptons (etc)

\[ pA \rightarrow \pi^\pm \]
\[ \quad \rightarrow \pi^0 \]
\[ \quad \rightarrow K^\pm \]
\[ \quad \rightarrow K_L, K_S \]
\[ \quad \rightarrow D^\pm \ldots \]

\[ \pi^- \rightarrow \mu \bar{\nu}_\mu \quad B = 100\% \]
\[ \pi^0 \rightarrow \gamma \gamma \quad B = 98.8\% \]
\[ K^- \rightarrow \mu \bar{\nu}_\mu \quad B = 63.5\% \]
\[ K_L \rightarrow \pi \ell \bar{\nu}_\ell \quad B(K_{e3}) = 38\%, \quad B(K_{\mu3}) = 27.2\% \]

“conventional atmospheric flux” from pions and kaons
Conventional and prompt 

\[ \pi^\pm \quad c\tau_0 \quad [\text{cm}] \quad D^\pm \quad c\tau_0 \quad [\text{cm}] \]

<table>
<thead>
<tr>
<th></th>
<th>( \pi^\pm )</th>
<th>( D^\pm )</th>
<th>( K^\pm )</th>
<th>( D^0 )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c\tau_0 ) [cm]</td>
<td>730</td>
<td>0.028</td>
<td>371</td>
<td>0.013</td>
<td>30,000</td>
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**Decay lengths for relativistic particles**

<table>
<thead>
<tr>
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<th>( \gamma c\tau_0 ) [m]</th>
<th>( \gamma c\tau_0 ) [m]</th>
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<tbody>
<tr>
<td>( \pi^\pm )</td>
<td>( 52 \ E/\text{GeV} )</td>
<td>( 1.5 \times 10^{-4} \ E/\text{GeV} )</td>
</tr>
<tr>
<td>( K^\pm )</td>
<td>( 7.5 \ E/\text{GeV} )</td>
<td>( 7 \times 10^{-5} \ E/\text{GeV} )</td>
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\[ \rho = \rho_0 e^{-h/h_0} \quad \rho_0 \simeq 2 \times 10^{-3} \ \text{g/cm}^3, \ h_0 \simeq 6.4 \ \text{km} \]

“Critical energies” for vertical mesons: decay lengths=h0

\[ E_c^\pi = 290 \ \text{GeV} \quad E_c^{D^\pm} = 10^8 \ \text{GeV} \quad \varepsilon_c^\pi = 115 \ \text{GeV} \]

\[ E_c^K = 2 \ \text{TeV} \quad E_c^{D^0} = 2 \times 10^8 \ \text{GeV} \quad \varepsilon_c^K = 850 \ \text{GeV} \]
Transport equations

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

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

For which particles? High enough energies that muons are “stable”.

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

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

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

Need cross section and energy distribution of the final state particle.
Conventional lepton flux

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

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

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

Z-factor approximately independent of \(X\)

\[\phi_N(E, X) = \exp(-X(1 - Z_{NN})/\lambda_N)\phi_N(E, 0), \quad Z_{NN} \simeq 0.4 \quad \text{attenuated flux}
\]

Another example – pion decay to neutrinos:

\[\phi_\pi \simeq Z_{N\pi} \times \text{factor} \times \phi_N(E, 0)
\]

\[\phi_\nu \simeq P_{\pi \to \nu}^{\text{dec}} Z_{\pi\nu} \times \text{factor} \times \phi_\pi
\]

High energy: \(P_{\pi \to \nu}^{\text{dec}} = 1 - \exp(-ct/\gamma c\tau) \simeq E_\pi^c/E\)

Low energy: \(P_{\pi \to \nu}^{\text{dec}} \simeq 1\)

“low energy” charm up to very high energies!

Example: proton to proton

\[
\frac{1}{\Lambda_N} = \frac{1 - Z_{NN}}{\lambda_N}
\]

\[Z_{N\pi} = 0.1
\]

\[Z_{\pi\nu} = 0.06
\]

\[E_\pi^c = 115 \text{ GeV}
\]

\[E_c^D \sim 10^8 \text{ GeV}
\]
Approximate formulae

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

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

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

For prompt lepton flux: electron and muon neutrinos (and antineutrinos) and muons (essentially stable), need:

\[ Z_{ND}, Z_{D\ell}, \Lambda_D \]
E.g., Honda et al., PRD 75 (2007), using DPMJET-III, for Kamioka, calibrated to observed atmospheric muon flux, incl 3-dim & geomagnetic corrections. See also Barr et al., PRD 70 (2004).
Prompt muons/neutrinos: uncertainties from production of charm
charm contributions using parton distribution functions

PDF = parton distribution function

\[ \sigma(pp \rightarrow c\bar{c}X) \simeq \int dx_1 \, dx_2 \, G(x_1, \mu)G(x_2, \mu)\hat{\sigma}_{G\bar{G}\rightarrow c\bar{c}}(x_1 x_2 s) \]

One approach, pQCD with PDFs.

\[ x_1, x_2 : \]
\[ x_F = x_1 - x_2 \]
\[ x_F \simeq x_E = E/E' \]
\[ x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \quad E \sim 10^7 \text{ GeV} \rightarrow x_2 \sim 10^{-6} \]

Disadvantage: need gluon PDF in low x, not very big Q range.

Necessarily involve extrapolations at low x (sometimes explicit, sometimes implicit).
What about large logarithms? \( \ln(1/x) \)
Prompt muons/neutrinos: uncertainties from production of charm
ccharm contributions with dipole approach

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

heavy quarks:
\[ \gamma^* \rightarrow c\bar{c} \]
\[ c\bar{c}\ N \rightarrow c\bar{c}X' \]

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

- Golec-Biernat & Wusthoff (GBW, PRD 59 (1999))
- Data show as small x that the virtual photon-proton cross section scales: dipole model includes this scaling (Stasto, Golec-Biernat & Kwiecinski, PRL 86 (2001))
- Improved QCD motivated form – Balitsky-Kovchegov (BK) evolution
- Modified for gluon -> charm anticharm pair
Dipole approach

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

- Kramer-Kniehl (KK) and Peterson fragmentation functions for c-quark to charmed mesons.
Results for prompt lepton flux (vertical) with dipole model evaluation

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

Conventional in vertical direction

Uncertainties include: charm mass, gluon PDF, dipole parameters, scales

Prompt flux: dipole model and others

Range of predictions

DM=our dipole model
NLO QCD=Pasquali, Reno, Sarcevic, PRD 59 (1999)
Atmospheric neutrinos-angular dependence

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

Conventional flux from Gaisser-Honda.

IceCube Results- it is time for a new perturbative QCD calculation with PDFs…. 

Higher energies in accelerators

• With the PDF approach:
  – Need new comparisons, with updated PDFs, with new measured high energy cross sections.

High rapidity most important for prompt flux calculation.

Range of cross section predictions from theory still quite large (mass of charm quark, scale dependence).
Modern PDFs – still extrapolations….

Still question of composition of CRs, proper treatment of Air target for prompt calc.
Work in progress

• With the PDF approach:
  – Improvements to hard scattering with the Fixed Order Next-to-Leading Log (FONLL) approach, which matches resummed logs \( \log(pt/mc) \) to fixed order result.

Need low-ish pT, high rapidity. E.g., for \( 10^8 \) GeV, rapidity around 5-7 for pT less than 10 GeV.

Work in progress - kinematics
Charm to mesons-Fragmentation


KK=Kramer & Kniehl

\[ x = x_c \] \[ x_c = \frac{E_c}{E_p} \]

\[ x = x_E \]

BCFY (solid)

KK (dot–dash)

\[ E = 10^6 \text{ GeV, NLO} \]

\[ m_c = 1.5 \text{ GeV} \]
High pT muons from charm

• See L. Gerhardt and S. Klein, ICRC 09 and 0909.0055,
• Look for charm production at “high pT” where high is larger than 6 GeV for 1 TeV muons: separation of the muon from charm decay and the muons from shower core.
• Muons from the conventional flux are at lower pT and thus lower separation between muon from pion/kaon and shower core.
• Sensitive to the cosmic ray composition.
• Potential to pick out the charm contribution at lower energies than a PeV because of the separation.
• FONLL calculation is the way to go here.
Final Remarks

• Atmospheric flux calculations are especially well developed in the lower energy regime where pions and kaons are the dominant intermediate states.

• At higher energies, there is still room for refinements of the calculations –
  – Theoretical evaluation of charm production, including energy distribution.
  – Will be informed by LHC data on charm production, and on small x PDFs, high rapidity.
  – Potential for extracting lower energy prompt flux from muon separations in IceCube.

• Atmospheric lepton flux is a background to diffuse neutrino flux searches, but interesting in its own right.
Diffuse astrophysical neutrinos – where are they?
Unflavored – prompt – electromagnetic decays to muons

\[ \eta, \eta', \rho^0, \omega \ldots \]

Illana, Lipari, Masip and Meloni, arXiv:10105084
First: conventional lepton fluxes (vertical), to show contributions

\[ \phi_N \sim E^{-2.7} \]

\[ \phi_{\nu}^{\text{low}} \sim E^{-2.7} \]

\[ \phi_{\nu}^{\text{high}} \sim E^{-3.7} \]

Fig. from Thunman, Ingelman and Gondolo, (TIG) Astropart. Phys. 5 (1996)
Used PYTHIA and JETSET.
Dipole cross section

- Iancu, Itakura and Munier, based on analytic approximate solutions in two different regions, with Soyez parameter updates.

\[ \sigma_{Gp \rightarrow Q\bar{Q}X} = \int dz \, d^2r |\Psi^Q_G(z, r)|^2 \sigma_{dG}(x, r) \]

\[ \sigma_{dG}(x, r) \quad \text{related to} \quad \sigma_d = \sigma_0 N(rQ_s, Y) \]

\[ Q_s = Q_0(x_0/x)^{\lambda/2} \]

\[ Y = \ln(1/x) \]

\[ \tau = rQ_s \]

\[ N(rQ_s, Y) = \begin{cases} N_0 \left( \frac{\tau}{2} \right)^{2\gamma_{\text{eff}}(x, r)} , & \text{for } \tau < 2 \\ 1 - \exp \left[ -a \ln^2(b\tau) \right] , & \text{for } \tau > 2 \end{cases} \]

\[ \gamma_{\text{eff}}(x, r) = \gamma_s + \frac{\ln(2/\tau)}{\kappa\lambda Y} \]