Neutrinos from charm production in the atmosphere

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Based on
+ work in progress w/ Reno, Sarcevic, & K. Kutak
Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei

- Hadron production: pions, kaons, D-mesons ...

- Interaction & decay \(\Rightarrow\) cascade of particles

- Semileptonic decays \(\Rightarrow\) neutrino flux

INFN-Notizie No.1 June 1999
Prompt vs conventional fluxes of atmospheric neutrinos

Pions & kaons: long-lived ⇒ lose energy before decay

Charmed mesons: short-lived ⇒ don't lose energy ⇒ harder spectrum

≈ $10^{5.5}$ GeV


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and smaller background rates from conventional atmospheric neutrinos allow a very precise energy reconstruction to the higher-energy regime. Events with cascade higher statistics than this data sample and an expansion of the physical flux is presented in Fig. 4.

Waxman-Bahcall bound. The limit on a di-muon flux predictions are not yet in reach with the current sensitivity. These limits are below the prediction by Bugaev et al. (RQPM) [3], but other prompt neutrino flux predictions. These limits are below the prediction by Bugaev et al. (QGSM) [6] and follow the slightly di-muon flux predictions in comparison to prompt flux expectations.

Figure 3 shows the limits on several prompt neutrino predictions. These limits are similar in normalization to the expected flux of conventional atmospheric neutrinos. The worsening of the analysis sensitivity by 5%. The limits only reach up to 360 TeV, which is slightly above the Enberg et al. prediction marks its theoretical uncertainty. The hatched area represents the envelope containing all limits on the di-muon flux.

The completed IceCube detector will provide much larger than the flux calculation. Preliminary upper limit derived on a generic atmospheric neutrino flux from charm is the end of the sensitive energy range defined by a primary cosmic-ray spectrum and composition [5]. This analysis produced an improved parameterization of the primary cosmic-ray spectrum and composition [5]. This analysis produced an improved parameterization of the primary cosmic-ray spectrum and composition [5].

The atmospheric neutrinos are the major background to e.g. the recent observed high-energy events.

A. Schukraft for IceCube, arXiv:1302.0127
Problem with QCD in this process

Charm cross section in LO QCD:

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

where

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

CMS energy is large: \( s = 2E_p m_p \) so \( x_1 \sim x_F, x_2 \ll 1 \)

- \( x_F=1: \) \( E=10^5 \rightarrow x \sim 4 \cdot 10^{-5} \)
- \( E=10^6 \rightarrow x \sim 4 \cdot 10^{-6} \)
- \( E=10^7 \rightarrow x \sim 4 \cdot 10^{-7} \)

- \( x_F=0: \) \( E=10^5 \rightarrow x \sim 6 \cdot 10^{-3} \)
- \( E=10^6 \rightarrow x \sim 2 \cdot 10^{-3} \)
- \( E=10^7 \rightarrow x \sim 6 \cdot 10^{-4} \)

So very small \( x \) is needed for forward processes (large \( x_F \)!)
Problem with QCD at small $x$

- Parton distribution functions poorly known at small $x$

- At small $x$, large logs must be resummed: $[\alpha_s \log(1/x)]^n$

- If logs are resummed (BFKL):
  power growth of gluon distribution as $x \rightarrow 0$

- Unitarity would be violated (T-matrix > 1)
How small $x$ do we know?

- We haven’t measured anything at such small $x$

- E.g. the MSTW pdf has $x_{\text{min}} = 10^{-6}$

- But that is an extrapolation!

- HERA pdf fits: $Q^2 > 3.5$ GeV$^2$ and $x > 10^{-4}$!
Kinematic plane

HERA: $x_{\text{min}} \sim 10^{-4}$ used for PDF fits ($Q^2 \sim 3.5 \text{ GeV}^2$)

Note LHeC!
Parton saturation

- **Saturation** to the rescue:
  - Number of gluons in the nucleon becomes so large that gluons recombine
  - Reduction in the growth

- This is sometimes called the **color glass condensate**

- Non-linear QCD evolution: **Balitsky-Kovchegov equation**
Charm production

- We need charm production cross section $d\sigma/dx_F$

- We use the dipole picture (see backup slides), and a solution of the Balitsky-Kovchegov equation

- Cross section at large energy suppressed relative to NLO QCD
Uncertainties in charm cross section

Different charm mass, factorization scale, pdf choice


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Total cross section, $pp \rightarrow cc$

Very different energy dependence!

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Gluon pdfs: very small $x$

GJR-V is a new pdf: **extrapolated** down to $x = 10^{-9}$

CTEQ3 was used in original calculation

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Theoretical uncertainties

Given all these uncertainties, can we get a better handle on how uncertain our prediction is?

Especially important given that this is a major background for IceCube and affects their significance calculations.

We are investigating the variation in theoretical predictions using different approaches.
Updating the prediction

Three issues:

• Saturation prediction
  • Compare previous calculation with
    • Running-coupling BK (numerical solution, AAMQS)
    • BK/DGLAP matching (numerical solution)
• Fixed order prediction using small-\(x\) PDF
  • Use NLO QCD with NLL resummation (FONLL)
• Nuclear dependence of incoming cosmic ray flux
  • Previously used proton flux only. Assess impact of using e.g. polygonato flux with mixture of elements

Work in progress (RE, Reno, Sarcevic, et al.)
Backup slides
Dipole frame picture of DIS

It is convenient to use the dipole frame:

→ Go to frame where the photon has very large lightcone $q^+$ momentum (e.g. proton’s rest frame)

Then the photon fluctuates into a color dipole before hitting the target and the dipole scatters on the proton:

Fluctuation is long-lived at small $x$:
Very useful in small-$x$ physics
DIS at small $x$ in dipole picture

The factorization is different from “standard” pQCD:

$$\sigma(\gamma^* N) = \int_0^1 dz \int d^2 r |\Psi_T(z, r, Q^2)|^2 \sigma_{q\bar{q}N}(x, r)$$

Dipole cross section from BK eqn

The wave function for the fluctuation is given by:

$$\left| \Psi^f_T(z, r, Q^2) \right|^2 =$$

$$e_f^2 \frac{\alpha_{em} N_c}{2\pi^2} \left[ (z^2 + (1 - z)^2) \epsilon^2 K^2_1(\epsilon r) + m_f^2 K^2_0(\epsilon r) \right]$$

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Generalize to hadron-hadron

Generalized to dipole picture for heavy quark production in hadron-hadron collisions by Nikolaev, Piller & Zakharov; Raufeisen & Peng; Kopeliovich & Tarasov

\[ \frac{d\sigma(pp \rightarrow Q\bar{Q}X)}{dy} \approx x_1 G(x_1, \mu^2) \sigma_{pQ\bar{Q}} \]

Gluon distribution of the projectile hadron → gives dipole

Scattering of this dipole on the target hadron
Dipole cross section from BK

Iancu, Itakura and Munier: model for $\sigma_d$ from the BK equation:

- Saturated region when the amplitude approaches one
- Color transparency region when it approaches BFKL result

\[
\mathcal{N}(rQ_s, Y) = \begin{cases} 
\mathcal{N}_0 \left( \frac{\tau}{2} \right)^{2\gamma_{\text{eff}}(x,r)}, & \text{for } \tau < 2 \\
1 - \exp \left[ -a \ln^2 (b\tau) \right], & \text{for } \tau > 2
\end{cases}
\]

where \(\tau = rQ_s, Y = \ln(1/x)\), \(\gamma_{\text{eff}}(x, r) = \gamma_s + \frac{\ln(2/\tau)}{\kappa \lambda Y}\)

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

Fitted to HERA data at small $x$: good description

(we use an update by Soyez for heavy quarks)