Atmospheric prompt neutrino flux

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Outline

- Atmospheric neutrinos: conventional and prompt
- Cross section for charm production at forward rapidities: collinear, dipole and $k_T$ factorization calculations
- Prompt neutrino fluxes

Work in collaboration with

A. Bhattacharya, R. Enberg, Y. S. Jeong, C. S. Kim, M. H. Reno, I. Sarcevic
Neutrinos in the atmosphere originate from the interactions of cosmic rays (etc. protons) with nuclei.

\[ p + \text{Air} \rightarrow \pi, K \rightarrow \mu, \nu_\mu \]

(credit: www.hap-astroparticle.org/ A. Chantelauze)
Atmospheric neutrinos

- Conventional: decays of lighter mesons

\[ \pi^\pm, K^\pm \]

Mean lifetime: \[ \tau \sim 10^{-8} \text{ s} \]

Long lifetime: interaction occurs before decay

\[ L_{\text{int}} < L_{\text{dec}} \]

Long-lived mesons loose energy

Steeply falling flux of neutrinos

\[ \Phi_\nu \sim E_\nu^{-3.7} \]
Prompt neutrinos

- **Prompt**: decays of heavier, charmed or bottom mesons

  \[ D^\pm, D^0, D_s \]

  baryon \[ \Lambda_c \]

  Mean lifetime: \[ \tau \sim 10^{-12} \text{ s} \]

Short lifetime: decay, no interaction

\[ \mathcal{L}_{\text{int}} > \mathcal{L}_{\text{dec}} \]

Flat flux, more energy transferred to neutrino

\[ \Phi_{\nu} \sim E_{\nu}^{-2.7} \]
Prompt vs conventional flux

High energy atmospheric neutrino flux as a function of energy

- Conventional flux: constrained by the low energy neutrino data.
- Prompt flux: poorly known, large uncertainties. Essential to evaluate as it can dominate the background for searches for extraterrestrial high energy neutrinos.


conventional: decay of long lived pions and kaons: loose energy. Soft spectrum.
Sources of uncertainties:

- Initial Cosmic Ray flux: shape and composition
- Strong interaction cross section: framework (collinear, small x, saturation), parton distribution functions, nuclear effects, intrinsic charm
- Charm meson fragmentation
- Decay
- Interaction cross section of neutrino

From cosmic ray to neutrino detection
Frameworks for heavy quark production

• Standard NLO perturbative QCD collinear calculation.

• High-energy factorization with small $x$ BFKL/DGLAP resummed evolution, including saturation effects (through nonlinear evolution equation).

• Small $x$ dipole model with saturation.

Also:

Nuclear corrections.

$b$ quark contribution.
Heavy quark production in hadron collisions

Schematic representation of charm production in pp scattering:

\[ f_i(x_1, \mu) \quad \text{parton distribution function at scale } \mu \]
\[ \text{parametrized at scale } \mu_0 \]
\[ \text{evolved to higher scales with QCD evolution equations} \]

\[ x_1, x_2 \quad \text{longitudinal momentum fractions (of a proton momentum) of gluons participating in a scattering process} \]

\[ \hat{\sigma}_{gg \rightarrow c\bar{c}}(\hat{s}, \mu_F, \mu_R, \alpha_s) \quad \text{partonic cross section calculable in a perturbative way in QCD} \]

Factorization formula for cross section:

\[
\frac{d\sigma_{pp \rightarrow c+X}}{dx_F} = \sum_{i,j} f_i(x_1, \mu_F) \otimes \hat{\sigma}_{gg \rightarrow c\bar{c}}(\hat{s}, m_c, \mu_F, \mu_R) \otimes f_j(x_2, \mu_F)
\]
pQCD collinear calculation

\[
\frac{d\sigma_{pp \rightarrow c+X}}{dx_F} = \sum_{i,j} f_i(x_1, \mu_F) \otimes \hat{\sigma}_{gg \rightarrow c\bar{c}}(\hat{s}, m_c, \mu_F, \mu_R) \otimes f_j(x_2, \mu_F)
\]

For the cosmic ray interactions we are interested in the forward production: charm quark is produced with very high fraction of the momentum of the incoming cosmic ray projectile.

Other participating gluon will have very small fraction of longitudinal momentum:

\[
x_F \simeq \frac{E_c}{E_p} \quad x_F \gg x_2 \quad x_2 \sim \frac{M^2_{c\bar{c}}}{s}
\]

\[
s \gg M^2_{c\bar{c}}
\]

The cross section is sensitive to the domain of parton densities which are at very small values of \( x \). This is poorly constrained region.
Hybrid $k_T$ factorization calculation

Use $k_T$ factorization for heavy quarks with off-shell gluon and unintegrated parton density. Suitable for the high energy - low $x$ regime.

*Catani, Ciafaloni, Hautmann; Collins, Ellis; Levin, Ryskin, Shabelski, Shuvaev*

Since it is forward production, use ‘hybrid’ calculation: treat large $x$ gluon as collinear, and small $x$ gluon as off-shell.

\[
\sigma(pp \rightarrow q\bar{q}X) = \int \frac{d x_1}{x_1} \frac{d x_2}{x_2} \frac{d z}{z} d x_F \, \delta(z x_1 - x_F) \, x_1 g(x_1, M_F) \\
\times \int \frac{d k_T^2}{k_T^2} \delta^{\text{off}}(z, \hat{s}, k_T) f(x_2, k_T^2)
\]

Unintegrated gluon density obtained from the resummed small $x$ evolution equation with non-linear term

*Kutak, Sapeta; based on KMS (Kwiecinski, Martin, AS)*
Dipole model calculation

Mueller; Nikolaev, Zakharov; Kopeliovich, Tarasov; Raufes, Peng

At high energy the production of the heavy quark pair is viewed as interaction of

color dipole:

Gluon fluctuation into heavy quark-antiquark pair: color dipole

Interaction of the color dipole with the hadronic target.

Advantage of this framework: saturation and nuclear effects can be easily included as
multiple scattering of the color dipole off the target.
Heavy quark cross section in the dipole model:

\[
\sigma(pp \rightarrow q\bar{q}X) \simeq \int dy \ x_1 g(x_1, M_F) \sigma^{gp \rightarrow q\bar{q}X}(x_2, M_R, Q^2 = 0)
\]

Partonic cross section:

\[
\sigma^{gp \rightarrow q\bar{q}X}(x, M_R, Q^2) = \int dz \ d^2 \vec{r} |\Psi_g(z, \vec{r}, M_R, Q^2)|^2 \sigma_d(x, \vec{r})
\]

Dipole cross section:

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

\[
\sigma_d(x, \vec{r})
\]

gluon dipole

\[
\sigma_{d,em}(x, \vec{r})
\]

color singlet dipole

Dipole xsection constrained by collider data
Total charm production cross section

- NLO collinear calculation, HVQ, Nason, Dawson, Ellis; Mangano, Nason, Ridolfi

- Default parton distribution set is CT15 Central.

- Charm quark mass \( m_c = 1.27 \) GeV

- Variation of factorization and renormalization scales with respect to charm quark mass. Using range provided by Nelson, Vogt, Frawley

- Magenta-free nucleons, blue-nitrogen

- Comparison with RHIC and LHC data. Data are extrapolated with NLO QCD from measurements in the limited phase space region.

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**Table 1:** Total cross-section for \( pp(pN) \rightarrow c\bar{c}X \) in hadronic collisions, extrapolated based on NLO QCD by the experimental collaborations from charmed hadron production measurements in a limited phase space region.

| Expt.   | \( \sqrt{s} \) [TeV] | \( \sigma \) [mb] | |
|---------|----------------------|-------------------|
| PHENIX  | 0.20                 | 0.551\(^{+0.203}_{-0.231}\) (sys) |
| STAR    | 0.20                 | 0.797 ± 0.210 (stat)\(^{+0.208}_{-0.295}\) (sys) |
| ALICE   | 2.76                 | 4.8 ± 0.8 (stat)\(^{+1.0}_{-1.3}\) (sys) ± 0.06 (BR) ±0.1(frag) ± 0.1 (lum)\(^{+2.6}_{-1.6}\) (extrap) |
| ALICE   | 7.00                 | 8.5 ± 0.5 (stat)\(^{+1.0}_{-2.4}\) (sys) ± 0.1 (BR) ±0.2(frag) ± 0.3 (lum)\(^{+2.0}_{-1.6}\) (extrap) |
| ATLAS   | 7.00                 | 7.13 ± 0.28 (stat)\(^{+0.90}_{-0.66}\) (sys) ±0.78 (lum)\(^{+1.82}_{-1.90}\) (extrap) |
| LHCb    | 7.00                 | 6.100 ± 0.930     |
Total charm production cross section

- **kT**

- **dipole model**

- **BERSS**: Bhattacharya, Enberg, Reno, Stasto, Sarcevic: previous NLO calculation
- **AAMQS, Albacete, Armesto, Milhano, Quiroga-Arias, Salgado**: rcBK
- **Soyez**: based on Iancu, Itakura, Munier parametrization inspired by BK solution
- **Block**: phenomenological parametrization of the structure function
- **kT** calculation underestimates data at low energy.
- Need additional diagrams there (or energy dependent K-factor).
Nuclear corrections

**NLO pQCD**

Use of nuclear PDFs, nCTEQ and EPS

**Dipole model**

Glauber-Gribov formalism for nuclear rescattering

**k_T factorization**

Small $x$ evolution with the nonlinear density term enhanced by factor proportional to mass number $A$
Nuclear corrections

Nuclear modifications to the total charm production cross section are small:

10%-15% for charm
5%-10% for bottom

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$\sigma(pp \to c\bar{c}X)$ [\mu b]</th>
<th>$\sigma(pA \to c\bar{c}X)/A$ [\mu b]</th>
<th>$[\sigma_{pA}/A]/[\sigma_{pp}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2$</td>
<td>$M_{F,R} \propto m_T$</td>
<td>$M_{F,R} \propto m_c$</td>
<td>$M_{F,R} \propto m_T$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$3.84 \times 10^4$</td>
<td>$4.72 \times 10^4$</td>
<td>$4.03 \times 10^4$</td>
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<tr>
<td>$10^4$</td>
<td>$2.52 \times 10^2$</td>
<td>$3.06 \times 10^2$</td>
<td>$2.52 \times 10^2$</td>
</tr>
<tr>
<td>$10^5$</td>
<td>$8.58 \times 10^2$</td>
<td>$1.03 \times 10^3$</td>
<td>$8.22 \times 10^2$</td>
</tr>
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<td>$10^6$</td>
<td>$2.25 \times 10^3$</td>
<td>$2.63 \times 10^3$</td>
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<td>$10^7$</td>
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<td>$5.92 \times 10^3$</td>
<td>$4.90 \times 10^4$</td>
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<tr>
<td>$10^8$</td>
<td>$1.21 \times 10^4$</td>
<td>$1.23 \times 10^4$</td>
<td>$1.08 \times 10^4$</td>
</tr>
<tr>
<td>$10^9$</td>
<td>$2.67 \times 10^4$</td>
<td>$2.44 \times 10^4$</td>
<td>$2.35 \times 10^4$</td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>$5.66 \times 10^4$</td>
<td>$4.67 \times 10^4$</td>
<td>$4.94 \times 10^4$</td>
</tr>
</tbody>
</table>
Differential charm cross section

Differential charm cross section in proton-nucleon collision as a function of the fraction of the incident beam energy carried by the charm quark.

\[
\frac{d\sigma}{dE_h} = \sum_k \int \frac{d\sigma}{dE_k} (AB \rightarrow kX) D_k^h \left( \frac{E_h}{E_k} \right) \frac{dE_k}{E_k}
\]

\[ h = D^\pm, D^0(\bar{D}^0), D_s^\pm, \Lambda_c^\pm \]

Using Kniehl, Kramer fragmentation functions.
Differential charm cross section

- Parton saturation effects affect the differential cross section more than the integrated cross section.

- Reduction of the cross section, at large energy of the charm quark.

- Nuclear effects in nitrogen are non-negligible at these energies.
Differential charm cross section

Comparison of NLO pQCD, dipole model, and $k_T$ factorization

- NLO calculation and $k_T$ factorization calculation consistent with each other.

- Dipole calculation systematically above the other two: need for improvements in this model.
Comparison with LHCb 7 and 13 TeV

Transverse momentum distributions

• NLO pQCD and $k_T$ factorization consistent with each other.
• Bands on NLO pQCD calculation correspond to scale variation.
• Two lines in $k_T$ factorization correspond to the saturation/no-saturation calculation.
## Comparison with LHCb 7 and 13 TeV

Integrated cross section for charm-anticharm production at 7 and 13 TeV.

\[
1 < p_T < 8 \text{ GeV/c} \quad \quad \quad 2.0 < y < 4.5
\]

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\sigma(pp \to c\bar{c}X)$ [μb]</th>
<th>$k_T$</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7 TeV</strong></td>
<td>$1610^{+480}_{-620}$</td>
<td>$1730^{+900}_{-1020}$</td>
<td>$1619^{+726}_{-705}$</td>
</tr>
<tr>
<td><strong>13 TeV</strong></td>
<td>$2410^{+700}_{-960}$</td>
<td>$2460^{+1440}_{-1560}$</td>
<td>$2395^{+1276}_{-1176}$</td>
</tr>
</tbody>
</table>
Cosmic ray flux

Important ingredient for lepton fluxes: initial cosmic ray flux. Parametrization by Gaisser (2012) with three populations and five nuclei groups: H, He, CNO, Fe, MgSi
Cosmic ray flux

Multicomponent parametrization by Gaisser (2012) with three populations:

1st population: supernova remnants
2nd population: higher energy galactic component
3nd population: extragalactic component

\[
\phi_i(E) = \sum_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp \left[ -\frac{E}{Z_i R_{c,j}} \right]
\]

- \(a_{i,j}\) normalization
- \(\gamma_{i,j}\) spectral index
- \(R_{c,j}\) magnetic rigidity
- \(E_{c,\text{tot}} = Z e \times R_c\)

Converting to nucleon spectrum

\[
\phi_{i,N}(E_N) = A \times \phi_i(AE_N)
\]

for each component

This power law was used widely in previous evaluations of the prompt neutrino flux:

\[
\phi_p^0(E) = \begin{cases} 
1.7 E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\
174 E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV},
\end{cases}
\]
Neutrino fluxes

- Significant reduction (factor 2-3) due to the updated cosmic ray spectrum with respect to the broken power law.
- The reduction is in the region of interest, where prompt neutrino component should dominate over the atmospheric one.
- Black band: previous calculation.
- The updated fragmentation function reduces flux by 20%.
- B hadron contribution increases flux by about 5-10%.
- Nuclear effects: 20-35%.
- Combined effects: reduction by 45% at highest energies.
Neutrino fluxes

- Sizeable reduction of the flux due to the changes from linear to nonlinear evolution in $k_T$ factorization.
- Further reduction of the flux when nuclear effects in nitrogen are included.
Neutrino fluxes

Comparison with other calculations:

GMS: Garzelli, Moch, Sigl

GRRST: Gauld, Rojo, Rotolli, Sarkar, Talbert

Consistency within the error bands.
Predictions and IceCube limit

- NLO perturbative and $k_T$ factorization within the limit.
- Dipole model calculation is in slight tension with the IceCube limit.
- Overall the flux is well below the astrophysical flux measured by IceCube.
Summary and outlook

• Calculation of the prompt neutrino flux using NLO and new PDFs. Charm cross section matched to LHC and RHIC data. Consistent with LHCb data on forward charm production.

• Updated cosmic ray flux gives lower values (as compared with earlier ERS and BERSS evaluation) for the atmospheric neutrino flux.

• Nuclear effects in the target. Further reduction of the flux by about 20-35%. Estimate of nuclear corrections within the NLO pQCD consistent with the small x calculation.

• Alternative calculations: dipole and $k_T$ factorization. Small x resummation leads to enhancement, saturation to the reduction of the flux. Dipole model larger than other calculations at low energies, needs improvement.

• Other calculations also on the market: consistent but still large uncertainties. Largest uncertainties due to the QCD scale variation, PDF uncertainties and CR flux.

• Outstanding questions: fragmentation (forward production, hadronic-nuclear environment, differences between PYTHIA and fragmentation functions); intrinsic charm.
Backup
Hybrid $k_T$ factorization calculation

Unintegrated gluon density obtained from the resummed small $x$ evolution equation with non-linear term:

\[
 f(x, k^2) = \tilde{f}(0)(x, k^2) + \frac{\alpha_s(k^2)N_C}{\pi} k^2 \int_x^1 \frac{dz}{z} \int_{k_0^2}^{k^2} \frac{dk'^2}{k'^2} \left\{ \frac{f\left(\frac{x}{z}, k'^2\right) \Theta\left(\frac{k^2}{z} - k'^2\right) - f\left(\frac{x}{z}, k^2\right)}{|k'^2 - k^2|} + \frac{f\left(\frac{x}{z}, k^2\right)}{4k'^4 + k^4|z^\frac{1}{2}|} \right\} + \frac{\alpha_s(k^2)N_C}{\pi} \int_x^1 dz \tilde{P}_{gg}(z) \int_{k_0^2}^{k^2} \frac{dk'^2}{k'^2} f\left(\frac{x}{z}, k'^2\right) - \left(1 - k^2 \frac{d}{dk^2}\right)^2 \frac{k^2}{R^2} \int_x^1 \frac{dz}{z} \left[ \int_{k^2}^{\infty} \frac{dk'^2}{k'^4} \alpha_s(k'^2) \ln \left(\frac{k'^2}{k^2}\right) f\left(z, k'^2\right) \right]^2 \]

BFKL term with kinematical constraint

DGLAP with non-singular splitting

Nonlinear term responsible for taming the growth of the gluon density

Unintegrated parton density fitted to the inclusive structure function data at HERA

Two scenarios: linear and non-linear. Included A dependence in the nonlinear term.

Kutak, Sapeta; based on KMS (Kwiecinski, Martin, AS)