The prompt atmospheric neutrino flux

Rikard Enberg

PAHEN, Naples, Sept 24, 2017
Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei

- Very large CMS energy $\rightarrow$ Hadron production: pions, kaons, D-mesons ...

- Interaction & decay $\Rightarrow$ cascade of particles

- Semileptonic decays $\Rightarrow$ neutrino flux

Credit: Astropic of the day, 060814
Conventional neutrino flux

- Pions (and kaons) are produced in more or less every inelastic collision

- $\pi^+$ always decay to neutrinos: $\text{BR}(\pi^+ \rightarrow \mu^+ \nu_\mu) = 99.98\%$

- But $\pi^\pm$, $K^\pm$ are long-lived ($c\tau \sim 8$ meters for $\pi^+$)
  - lose energy through collisions before decaying
  - neutrino energies are degraded

- This is called the conventional neutrino flux
Prompt neutrino flux

- Hadrons containing heavy quarks (charm or bottom) are extremely short-lived:
  - ⇒ decay before losing energy
  - ⇒ harder neutrino energy spectrum

- However, production cross-section is much smaller

- There is a cross-over energy above which prompt neutrinos dominate over the conventional flux

- This is called the prompt neutrino flux
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

Why are we interested?

- Atmospheric neutrinos are a background to extragalactic neutrinos
- Test beam for neutrino experiments
- Learn about cascades and the underlying production mechanism
- Higher energy pp collisions than in LHC: can maybe even learn something about QCD?
Calculations of the prompt flux

Recent:

M.V. Garzelli, S. Moch, G. Sigl, arXiv:1507.01570 (GMS)
PROSA Collaboration (Garzelli et al), arXiv:1611.03815
M. Benzke, M. V. Garzelli, et al., arXiv:1705.10386

Older but widely used:

A.D. Martin, M.G. Ryskin, A. Stasto, hep-ph/0302140 (MRS)
Calculations of the prompt flux

Recent:

- M.V. Garzelli, S. Moch, G. Sigl, arXiv:1507.01570 (GMS)
- PROSA Collaboration (Garzelli et al), arXiv:1611.03815
- M. Benzke, M. V. Garzelli, et al., arXiv:1705.10386

Older but widely used:

The IceCube events

The significance is sensitive to the prompt flux prediction

IceCube, arXiv:1311.5238
R. Enberg: The prompt neutrino flux
IceCube are using ERS

The shape of the ERS flux is used with overall normalization a free parameter

M.G. Aartsen et al., arXiv:1607.08006

R. Enberg: The prompt neutrino flux
Important message

QCD is crucial for some astrophysical processes:
- Atmospheric neutrinos
- Neutrino-nucleon cross-section @ high energy
- (Interactions in astrophysical sources?)

For example:
- What happens at small Bjorken-x? (Need very small x)
- Forward region (Hard to measure at colliders)
- Fragmentation of quarks $\rightarrow$ hadrons
- Nuclear effects in pA hard interactions
The calculation has many ingredients

- *Incident cosmic ray flux*
- Atmospheric density
- *Cross section for heavy quarks in pp/pA collisions at extremely high energy (perturbative QCD)*
- Rescattering of nucleons, hadrons (hadronic xsecs) (scattering lengths)
- Decay spectra of charmed mesons & baryons (decay lengths)
- Cascade equations and their solution (Semi-analytic: spectrum-weighted Z-moments)
Cosmic rays (CR)

- Knees and ankles $\rightarrow$ seems natural to associate different sources with different energy ranges of the CR flux
- Highest energies: Extragalactic origin? $\rightarrow$ GRBs, AGNs, or more exotic
- Lower energies: Galactic origin? $\rightarrow$ SNRs etc
Incident cosmic ray flux: nucleons

Solid red = Broken power law (old standard)
Dashed blue = Gaisser all proton (H3p)
Dotted green = Gaisser, Stanev, Tilav (GST4)

R. Enberg: The prompt neutrino flux
Calculating the neutrino flux

- To find the neutrino flux we must either solve a set of cascade equations given an incoming CR flux:

\[
\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \rightarrow NY)
\]
\[
\frac{d\phi_M}{dX} = S(NA \rightarrow MY) - \frac{\phi_M}{\rho d_M(E)} - \frac{\phi_M}{\lambda_M} + S(MA \rightarrow MY)
\]
\[
\frac{d\phi_\ell}{dX} = \sum_M S(M \rightarrow \ell Y)
\]

- \(X\) is the slant depth: “amount of atmosphere”
- \(\rho d_M\) is the decay length, with \(\rho\) the density of air
- \(\lambda_M\) is the interaction length for hadronic energy loss
- Here: semi-analytic solution (e.g. MCEq does it numerically)

- … or Monte Carlo simulate the cascade (e.g. SIBYLL)

R. Enberg: The prompt neutrino flux
Particle production

Particle physics inputs: energy distributions

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

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

along with interaction lengths, or cooling lengths

\[
\lambda_N(E) = \frac{\rho(h)}{\sigma_{NA}(E) n_A(h)}
\]

→ Need the charm production cross section \(d\sigma/dx_F\)
Problem with QCD in this process

Charm cross section in LO QCD:

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

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 \( x_1 \sim x_F \), \( x_2 \ll 1 \)

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

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

Very small \( x \) is needed for forward processes (large \( x_F \)!)

R. Enberg: The prompt neutrino flux
Problem with QCD at small $x$

- Parton distribution functions poorly known at small $x$
- At small $x$, must resum large logs: $\alpha_s \ln(1/x)$
- If logs are resummed (BFKL):
  power growth $\sim x^{-\lambda}$ 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 $x > 10^{-4}$!

- See Gao, Harland-Lang, Rojo, arXiv:1709.04922 for more on pdfs
Kinematic plane

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

Note LHeC!
Kinematic plane of NNPDF3.1

Figure 4: Typical kinematical coverage in the $(x, Q^2)$ plane for the datasets included in a global analysis, in this case NNPDF3.1. For hadronic observables, leading order kinematics are assumed to map each data bin to a pair of $(x, Q^2)$ values. The various datasets are clustered into families of related processes.

We can see that a global dataset provides a rather wide coverage in the $(x, Q^2)$ plane. The low-$x$ and $Q^2$ region is dominated by the inclusive HERA structure function measurements, which provide information down to $x \ll 3 \cdot 10^{-5}$. The high-$x$ region is covered by various processes, from fixed-target DIS structure functions at low $Q^2$ to collider jet, Drell-Yan and top quark pair production at large $Q^2$. The very high $Q^2$ region, up to a few TeV$^2$, is only covered by inclusive jet production data from ATLAS and CMS. Until relatively recently, most PDF fits were only based on DIS and fixed-target data, with some data from the Tevatron included. The breath of experimental information that is now included in the latest PDF fits is therefore quite impressive, with data from processes such as the $Z$ and the $t\bar{t}$ differential distribution only recently being considered for the first time.

In Table 1 (an extended version of Table 1 from [119]) we present another overview of the data entering a modern global PDF analysis. Here, we summarise the various hard scattering processes which are used to constrain PDFs in a global analysis. In each case we indicate the hadron-level process, the corresponding dominant parton-level process, as well as the partons which are constrained in each case and the corresponding range of $x$. Note that the latter are necessarily approximate, and only indicate in a qualitative way the $x$ region that dominates the PDF sensitivity of each measurement. The necessity to include as broad a
Small x

F2 measured at HERA (ZEUS) as a function of Bjorken-x.

Note the steep power-law rise

Can this rise continue?

Theoretical answer: no
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**
Bhattacharya et al (BEJKRSS, 2016): Redo QCD calculations in 3 ways

• **Standard NLO QCD with newest PDFs**
  - BERSS updated with RHIC/LHCb input, uses Nason, Dawson, Ellis and Mangano, Nason, Ridolfi

• **Dipole picture with saturation**
  - Approximate solution of Balitsky-Kovchegov equation
  - Update of ERS calc with new HERA fits + other dipoles

• **$kT$ factorization with and without saturation**
  - Resums large logs, $\alpha_s \log(1/x)$ with BFKL
  - Off-shell gluons, unintegrated PDFs (+ subleading…)
  - Kutak, Kwiecinski, Martin, Sapeta, Stasto (permutations)

*Include scale variations, PDF errors, charm mass, etc → Plausible upper and lower limits on xsec*

R. Enberg: The prompt neutrino flux
Also include nuclear shadowing

Partons are not in a free nucleon, but in a nucleus!

To estimate shadowing, we use PDFs:

- Eskola, Paukkunen, Salgado (EPS) for $^{16}$O
- nCTEQ15 for $^{14}$N
- CT14 for free protons

R. Enberg: The prompt neutrino flux
Nuclear effects

- Nuclear shadowing reduces flux by 10–30% at the highest energies.
- Effect is larger on the flux than on the total $\sigma(\text{cc})$ due to asymmetric $x_{1,2}$.
\[ \sigma(\text{cc}) \text{ and } \sigma(\text{bb}) \]

Data from RHIC, LHC and lower energies
Total cross sections well described by all calculations (at high energies), nuclear shadowing small

(Error bands=scale variations and PDF uncertainties)

R. Enberg: The prompt neutrino flux
Differential cross sections (LHCb)

LHCb measured D-meson production at 7 and 13 TeV
Kinematical range: $p_T < 8$ GeV, $0 < y < 4.5$

The flux is mostly sensitive to large $y$ and small $p_T$.

Cumulative fraction of Z-moment as function of $x_F$:

**Estimate**: 90% of $Z_{pD}$ given by

- $y > 4.9$ for $E_p = 10^6$ TeV
- $y > 5.7$ for $E_p = 10^7$ TeV
Comparison of NLO QCD


R. Enberg: The prompt neutrino flux
Prompt $\nu_\mu (=\nu_e = \mu)$ fluxes

We have calculated prompt neutrino fluxes using all these variations in QCD, nuclear effects, cosmic ray fluxes.

Also compare to other calculations:
- RE, Reno, Sarcevic (ERS) 0806.0418
- Bhattacharya et al (BERSS), 1502.01076
- Garzelli, Moch, Sigl, 1506.08025
- Gauld, Rojo, Rottoli, Sarkar, Talbert, 1511.06346

→ estimate of theoretical uncertainties
Compare with our BERSS NLO QCD and different cosmic ray fluxes

Difference to BERSS: $bb$ now included, modified fragmentation fractions, nuclear effects (here: nCTEQ15)

Overall: (30%, 40%, 45%) lower than BERSS at $(10^3, 10^6, 10^8)$ GeV
Influence of nuclear shadowing

Ratio of NLO QCD flux with and without nuclear effects
→ 20–30% suppression from $10^5$ to $10^8$ GeV for nCTEQ
  (only 4–13% for total cross section)
→ But much less for EPS (frozen at $x=10^{-6}$)
And now everything, using broken power law

ERS

Garzelli et al

BERSS

Gauld et al

R. Enberg: The prompt neutrino flux
Benzke et al GM-VFNS calculation

pQCD calculation in “General Mass – Variable Flavor Number Scheme” (GM-VFNS) M. Benzke, M. V. Garzelli, B. Kniehl, G. Kramer, S. Moch, G. Sigl, arXiv:1705.10386

The large pdf uncertainty at large energy arises from a particular set of CTEQ pdf fits (ct14nlo) – not constrained by data (but other sets do not show this – situation unclear)
And what does IceCube say?

A recent IceCube limit (3 yrs) on the prompt flux sets a limit at 90% CL of

$$0.54 \times (ERS \text{ modified with } H3p \text{ CR’s})$$

Best fit is still $$\phi_{\text{prompt}} = 0$$

L. Rädel & S. Schoenen (IceCube), PoS ICRC2015, 1079
Intrinsic charm

- “Normal” charm parton distribution is generated from gluon splittings
- There may be an “intrinsic” non-perturbative charm component in the nucleon
  [Brodsky, Hoyer, Peterson, Sakai, 1980]
- Would contribute charmed mesons at large xF
  [See e.g. Thunman et al; Bugaev et al.; Halzen and Wille…]

But there is hardly room in the data for that!
Or is there?
Conclusions

• The prompt neutrino flux poses one of the questions in neutrino astroparticle physics
  • How large is the flux?
  • Why hasn’t it been discovered?
  • What is the proper way to calculate it?

• We think we know what we don’t know – more accelerator and cosmic ray data needed!