Low $x$ and ultrahigh energy neutrino physics

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Outline

• Motivation: low x and ultrahigh energy neutrino astronomy
• Calculation of atmospheric prompt neutrino fluxes
• Comparison with IceCube observations

Based on work in collaboration with

Atri Bhattacharya, Rikard Enberg, Mary Hall Reno, Ina Sarcevic
arXiv:1502:01076
Important lesson from HERA:
Observation of strong growth of the proton structure function at small $x$.
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Why small $x$ is interesting?

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- Parton evolution needs to be modified to include potentially very large logs, resummation of $\log(1/x)$
- Further increase in the energy could lead to the importance of the recombination effects. Unitarity of the scattering amplitude.
- Modification of parton evolution by including non-linear or saturation effects in the parton density.
Mapping the Gluon Distribution

QCD fit analysis (default: NC, CC, LHeC only, following HERAPDF) with full experimental errors

The gluon is unknown at low $x$ and high $x$ – QCD: non-linear evolution, resummation. BSM: hi $M$ – HL-LHC!
Neutrino astronomy

• Universe not transparent to extragalactic photons with energy $> 10\ TeV$

• Weakly interacting: neutrinos can travel large distances without distortion
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Interaction lengths (at 1 TeV):

$$L_{\text{int}}^\gamma \sim 100 \text{ g/cm}^2$$

$$L_{\text{int}}^\nu \sim 250 \times 10^9 \text{ g/cm}^2$$
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Angular distortion

$$\delta \phi \simeq \frac{0.7^\circ}{(E_\nu/\text{TeV})^{0.7}}$$
Sources of high energy neutrinos

- Atmospheric: interactions of cosmic rays with nuclei in the atmosphere.
- Interactions of cosmic rays with gas, for example around supernova remnants. Interaction with microwave background (GZK neutrinos).
- Production at some source: Active Galactic Nuclei, Gamma Ray bursts.
- More exotic scenarios: WIMP annihilation (in the center of Sun or Earth), decays of metastable relic particles,...

Example AGN Cygnus A:

X ray

Radio image
Atmospheric neutrinos

Neutrinos in the atmosphere originate from the interactions of cosmic rays (etc. protons) with nuclei.

\( p + \text{Air} \)

\[ \pi, K, D, B \]

\[ \mu, \nu_\mu \]
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.
Sources of uncertainties for prompt atmospheric neutrinos:

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

Diagram for charm production in proton-proton collisions

In the collinear factorization:

\[
\frac{d\sigma^{pp\to c+X}}{dx_F} = \int dx_1 \, dx_2 \, dz \, g(x_1, \mu_F^2) \frac{d\sigma^{gg\to c\bar{c}}}{dz} \, g(x_2, \mu_F^2) \, \delta(zx_1 - x_F)
\]

where \( z = (m_c^2 - \hat{t})/s \) and \( g(x, \mu_F^2) \) is the gluon density in the proton.

\( x_F \approx 0.2 \) and \( x_2 \approx M_{cc}^2 / x_F s \)

At very high energies \( s \gg M_{cc}^2 \), \( x_2 \) is very small \( x_2 \ll 1 \)

\( x_2 \approx 10^{-4} - 10^{-9} \) and small scales
Charm production cross section

- Using NLO code by Cacciari, Frixione, Greco, Nason.
- Default set is CT10 Central.
- Charm quark mass $m_c = 1.27$ GeV
- Variation of factorization and renormalization scales with respect to $m_T^2 = m_c^2 + p_T^2$
- Comparison with RHIC and LHC data. Data are extrapolated with NLO QCD from measurements in the limited phase space region.

- Warning: need to extrapolate CT10 pdf down to very low $x$.
- PDF uncertainties not included in this plot.
- Based on collinear factorization, need to compare with kT factorization and dipole models with saturation.

Figure 1: The charm production cross section $pN \rightarrow c\bar{c} + X$ at NLO with $m_c = 1.27$ GeV using the CT10 parton distributions for a range of scales described in the text, with the central set with factorization and renormalization scales $M_F = 2.10^{1.6}m_T$ and $\mu_R = 1.10^{0.6}m_T$, respectively. Apart from experimental data points listed in table 1, results from HERA-B [43] and lower energy experiments summarized in [44] for $pN$ scattering are shown (labelled as Fixed target expts.). For comparison, we also show the lower and upper limits (grey fine-dashed curves) when the renormalization and factorization scales are made to vary proportionally to $m_c$ rather than to $m_T$.
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**UHE neutrino-proton cross sections**

Neutrino DIS CC cross section

\[
\frac{d^2\sigma^{CC}}{dx dy} = \frac{2G_F^2 M_N E_{\nu}}{\pi} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \cdot [xq(x, Q^2) + x\bar{q}(x, Q^2)(1 - y)^2]
\]

Since \( xq(x, Q^2) \sim x^{-\lambda} \) this implies that

Need extrapolations of parton densities to very small \( x \)

UHE neutrino cross sections important for IceCube

Contribution to the cross section in \( Q \) and \( x \) plane:

**Figure 7a**

- \( E_\nu = 10^6 \text{ GeV} \)
- \( Q^2 = M_W^2 \)
- \( \log_{10}(Q^2/1 \text{ GeV}^2) \)
- \( \log_{10}(x) \)

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Neutrino cross sections

Calculation of the neutrino cross section using the unified BFKL/DGLAP evolution (includes resummation effects at low $x$).

Behavior at high energies controlled dynamically by the resummed evolution equation, rather than the parametrized extrapolation.
Neutrino cross sections

Calculation of the neutrino cross section using the unified BFKL/DGLAP evolution (includes resummation effects at low $x$).

Comparison with latest estimates, I. Sarcevic et al.

BFKL/DGLAP unified calculation still works well, within the uncertainty bounds for DGLAP

LHC data do not provide (so far) additional strong constraints on PDFs (relevant for this process)

LHeC/FCC-eh can provide important input for the cross section evaluation.
Neutrino fluxes: comparison collinear vs saturation

Flux of $\nu_\mu + \bar{\nu}_\mu$

- Calculation does not include the PDF uncertainties.
- A bit of surprise: assuming the same initial cosmic ray flux NLO collinear calculation is lower than the calculation based on a dipole model with saturation…
- Different large x pdfs in the calculations. Should one move to NLO dipole model here as well?
- Gluon from CT10 is valence-like for low scales.
- LHeC/FCC-eh would provide an important constraint on the gluon in this context.
IceCube

• UHE neutrinos measured in IceCube Antarctic detector
• Neutrinos detected using Cherenkov light produced by charged particles after neutrinos interact
• Sensitivity to high energy >100 GeV neutrinos (>10 GeV with Deep Core)
IceCube results

988 day sample, 37 events observed (after selection with entering muon veto) with energies between 30-2000 TeV
Comparison of prompt flux with IceCube results

- IceCube results point to the hard spectrum of neutrinos.

- Experimental data are well above the atmospheric background, implying that the origin of IceCube is likely extraterrestrial (also incoming muon veto by IC).

- NLO calculation from charm gives reduced background (with respect to earlier calculations).

- Small x uncertainties in the evaluation of both the background production and interaction cross sections.

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Summary and outlook

• Precise low x gluon density important for the UHE neutrino physics. LHeC/FCC-eh constraints can significantly reduce the uncertainties.

• Small x gluon comes into play when evaluating the UHE neutrino DIS interaction cross section and for the production of the atmospheric neutrinos.

• Calculation of the prompt neutrino flux using NLO and new PDFs, matched to LHC and RHIC data.

• Prompt component is rather small. The IC data are significantly above, new calculation will change the evaluation of the significance of the astrophysical signal for IC. However, not all uncertainties are taken into account.

• Work in progress: nuclear pdfs, small x calculations including saturation, resummation; intrinsic charm. Estimate of LHeC, FCC-eh impact on the uncertainties of PDFs onto the calculation.
backup
Atmospheric neutrinos

- *Conventional*: decays of lighter mesons

\[ \pi^\pm, K^\pm \]
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Mesons loose energy
Atmospheric neutrinos

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Long lifetime: interaction occurs before decay

Mesons lose energy \implies\ Steeply falling flux of neutrinos

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

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

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

baryon \( \Lambda_c \)

![Diagram showing particles \( D^+, D^0 \) with quarks \( \bar{d}, c, \bar{u} \).]
Prompt neutrinos

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Short lifetime: decay, no interaction

\[ L_{\text{int}} > L_{\text{dec}} \]
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Flat flux, more energy transferred to neutrino

\[ \Phi_\nu \sim E_\nu^{-2.7} \]
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.

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

Differential charmed hadron cross section as a function of the energy:

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

Using Kniehl, Kramer fragmentation functions.
IceCube results

Two classes of events:

**Showers**: from secondary charged leptons and hadron dissociation

**Tracks**: events accompanied by an energetic muon (CC events with incoming $\nu_\mu$)

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

*IceCube Collaboration*

A 250 TeV neutrino interaction in IceCube. At the neutrino interaction point (bottom), a large particle shower is visible, with a muon produced in the interaction leaving up and to the left. The direction of the muon indicates the direction of the original neutrino.
Cosmic ray flux

Important ingredient: initial cosmic ray flux.

Cosmic ray flux can be traced to the particular behavior of the Gaisser cosmic ray primary fluxes—a significant deviation from the broken power-law follows a more steady behavior. This deviation before rising sharply at energies beyond the tens of PeV. In contrast, the Gaisser H3p flux, arises at the high energies using the broken power-law nucleon flux.

The ratio of the central lower limit) and (3.2 with earlier work, we show our results for the prompt lepton flux for the broken power-law is particularly important for the high energy prompt lepton flux. To allow for comparisons above the knee energy than when using the simple broken power-law parametrization. This feature is visible in figure 5a, which shows the all-particle flux to the nucleon flux, the H3a and H3p fluxes are shown along with the population in what we call the source populations, with spectral indices that vary by population and nucleus. We use here the parametrization by Gaisser in ref. [23] with three or four source populations to develop models for the cosmic ray composition.

Measurements, Gaisser [24] measure measurements from ATIC [25]: The all-nucleon cosmic ray spectrum as a function of energy per nucleon for the energy range of interest, $10^2$ to $10^{12}$ GeV, approximates a power-law with the break occurring at $E_\text{break} \approx 10^9$ GeV.

As discussed above, we use the charmed hadron spectral weights for the decay of charmed hadrons, which implies that only a small fraction of charm quarks produced in the inner zone of the source is ultimately released as charmed hadrons. The central $Z$-moments evaluated for the three respective cosmic-ray components are shown as a function of energy in figure 4a, with an average of three $Z$-moments, these $Z$-moments translate directly to the total prompt lepton flux (as shown in figure 4a).

The composition of the cosmic rays causes a much steeper drop in the nucleon flux with three or four source populations to develop models for the cosmic ray composition. The disambiguity in the normalization of the cosmic ray spectrum at high energies, overall the difference between the broken power-law and the simple power-law parametrizations is relatively small.

The differential cross sections by taking the $Z$-moments, in turn, translates directly to the total prompt lepton flux (as shown in figure 4a).

The composition of extragalactic cosmic rays cannot be described with two populations, but rather a mixed composition in the extragalactic population, while the extragalactic population of galactic cosmic rays is defined by three or four source populations. With these choices, at $E_\text{kin} = 10^8$ GeV (for $E < 5 \cdot 10^6$ GeV) and $E_\text{kin} = 10^9$ GeV (for $E > 5 \cdot 10^6$ GeV). With the fairly recent benchmark result when determining the prompt flux and correspondingly the event-rates and rates at IC.

The all proton extragalactic population (H3p), and for the broken power-law of eq. (48), the three curves show the moments evaluated for the three respective cosmic-ray components. The central $Z$-moments, in turn, translates directly to the total prompt lepton flux (as shown in figure 4a).

Simple power law used for comparison:

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