Cross section and inelasticity of multi-TeV neutrino interactions in IceCube

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Outline

• High-energy neutrino deep inelastic scattering

• IceCube Neutrino Observatory

• Earth absorption and cross section measurement

• Inelasticity distributions

• Future Possibilities with IceCube-Gen2
Neutrino Deep Inelastic Scattering

- At energies above \(\sim 10 \text{ GeV}\), neutrinos probe the quark and gluon structure of the nucleon.

- Kinematic variables:

\[
y = \frac{p \cdot q}{p \cdot k_1} = \frac{E_{\text{had}}}{E_\nu} \quad \text{(inelasticity)},
\]

\[
x = -\frac{q^2}{2p \cdot q} = \frac{2E_\nu E_\ell}{M E_{\text{had}}} \sin^2 \left(\frac{\theta_\ell}{2}\right) \quad \text{(Bjorken scaling variable)}.
\]

\[
Q^2 = -q^2 = 4E_\nu E_\ell \sin^2 \left(\frac{\theta_\ell}{2}\right) \quad \text{(4-momentum transfer squared)}.
\]
Cross Section & Kinematic Ranges

• At high energy, weak boson propagator causes $Q^2 \sim M_W^2 \sim 6 \times 10^4 \text{ GeV}^2$

• Typically $x \sim 10^{-3} \left( \frac{10^6 \text{ GeV}}{E_\nu} \right)$

• Ultra-high-energy neutrinos probe low-$x$ gluon structure where uncertainties are high and saturation may be important. Nuclear shadowing at low-$x$?

• Differential cross section:

Gluon PDFs:
Cross Section Calculations

- Total uncertainty on neutrino-nucleon DIS cross section typically no more than a few % from proton PDFs alone
- Uncertainties from c, b, t quark masses & nuclear shadowing not yet fully quantified at NLO at high energies
- IceCube uses HERAPDF1.5 ca. 2011, updated calculations are needed
Cross Section Measurements

- Accelerator based neutrino cross section measurements only extend up to $\sim 370$ GeV
- At energies from $\sim 10^3$ GeV to $10^7$ GeV, IceCube has the potential to measure:
  - Total cross section $\sigma$
  - Differential cross section $d\sigma/dy$ using $\nu_\mu$ starting tracks

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)
IceCube Neutrino Observatory
Neutrino Interaction Signatures

<table>
<thead>
<tr>
<th>Through-going Track</th>
<th>Starting Track</th>
<th>Shower</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CC</strong> $\nu_\mu N \rightarrow \mu X$</td>
<td><strong>CC</strong> $\nu_\mu N \rightarrow \mu X$</td>
<td><strong>CC</strong> $\nu_{e,\tau} N \rightarrow e, \tau X$</td>
</tr>
<tr>
<td>Outside detector</td>
<td>Inside detector</td>
<td>NC $\nu_{e,\mu,\tau} N \rightarrow \nu_{e,\mu,\tau} N$</td>
</tr>
</tbody>
</table>
Atmospheric and Astrophysical Neutrinos

• IceCube detects mostly atmospheric neutrinos below $10^5$ GeV
• Above $10^5$ GeV, mostly astrophysical neutrinos are detected
• Both can be absorbed as they pass through the Earth
Earth Absorption

• Energy/zenith angle-dependent absorption can be used to measure total cross section

Nature 551 (2017) 596-600
Cross Section Measurement (2017)

- Sample of 10,784 through-going tracks
- Constrain a total scaling of CC & NC neutrino DIS cross section:

\[
\frac{\sigma_{\text{meas.}}}{\sigma_{\text{SM}}} = 1.30^{+0.21}_{-0.19} \text{ (stat.)} ^{+0.39}_{-0.43} \text{ (syst.)}
\]

- Estimated energy range: 6 – 980 TeV

Nature 551 (2017) 596-600
Cross Section with Starting Tracks/Showers

- Sample of 103 starting tracks/showers up to 2 PeV
- Better energy resolution, but showers have poorer direction resolution
- Binned cross section results

Earth absorption region
**Inelasticity of Starting Tracks**

- Inelasticity of starting tracks can be determined from the energy loss profile in the detector.
- Difficult to disentangle hadronic shower and stochastic losses from muon.
- Random Forest method developed to reconstruct hadronic shower and muon energies.

*Phys. Rev. D 99, 032004 (2019)*
Energy/Inelasticity Resolution

- Resolution on \( \log_{10}(\text{total energy}) = 0.18 \)
- Resolution on inelasticity = 0.19
Inelasticity Distributions

- 2650 starting tracks analyzed
- Reconstructed inelasticity distributions agree well with nominal NLO calculations in energy bins from 1 TeV to 100 TeV
Mean Inelasticity Neutrino

- Mean inelasticity also agrees with atmospheric flux average between neutrinos/anti-neutrinos up to > 100 TeV
- Neutrino/anti-neutrino ratio 770 GeV to 21 TeV
  - $R = 0.77^{+0.44}_{-0.25}$
- Can be used to tune hadronic interaction models in cosmic ray air shower simulations

Neutrino-Induced Charm Production

• Charm production interactions have distinct inelasticity distribution

• Arise primarily from strange sea:

\[ \nu_\mu s \rightarrow cX\mu \]

• Zero charm production excluded at 91% CL in energy range from 1.5 TeV to 340 TeV

• Scaling on charm production cross section:
  • \( R = 0.93^{+0.73}_{-0.59} \)

Charm Interactions in Ice

- Charm interactions are occurring in IceCube’s sensitive energy range.
- Critical energy of charm hadrons in ice where interaction probability > decay probability:
  \[ \epsilon_{D^+} = 22 \text{ TeV}, \epsilon_{D^0} = 53 \text{ TeV}, \epsilon_{D^+_s} = 47 \text{ TeV}, \]
- Possibility to measure charm interaction cross section?
- No good calculations available.

- Charm production, semi-leptonic decay:
  \[ \nu_e N \rightarrow e X_1 D^{0,\pm} \rightarrow e X_1 X_2 \mu \nu_\mu \]
- Interactions suppress event rate.

IceCube-Gen2

- IceCube upgrade planned with 10x instrumented volume and more sensitive optical sensors
- Neutrino energies up to $10^{17}$ eV may be observed, equal to 14 TeV LHC center-of-mass energy
Potential Topics with IceCube-Gen2

- Precision cross section measurements, tests of low-x saturation models
- Neutrino-induced charm/bottom/top quark production
- Non-DIS interactions:
  \[ \nu_\mu N \rightarrow \mu^- W^+ N \]
- Physics beyond the standard model
  - Leptoquarks, low-scale QG, sphalerons, ...
Radio Neutrino Detection

- New techniques needed to make detection of neutrinos above $10^{17}$ eV a routine occurrence
- Askaryan Effect: Coherent radio emission from electromagnetic showers in ice
- ARA/ARIANNA/ANITA experiments have demonstrated the technology
- Inelasticity of $\nu_e$ could be measured from elongated showers due to the LPM effect
Summary

- Ultra-high-energy neutrino interactions are sensitive to low-x nuclear structure and physics beyond standard model
- Uncertainties in high-energy neutrino DIS not fully quantified yet
- Earth absorption can be used to constrain total cross sections up to $~10^{15}$ eV with IceCube
- Inelasticity distributions in IceCube agree well with current calculations, and are sensitive to heavy flavor production & interaction physics
- IceCube-Gen2 and radio detection will allow more powerful studies at the most interesting ultra-high neutrino energies around $~10^{17}$ eV