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

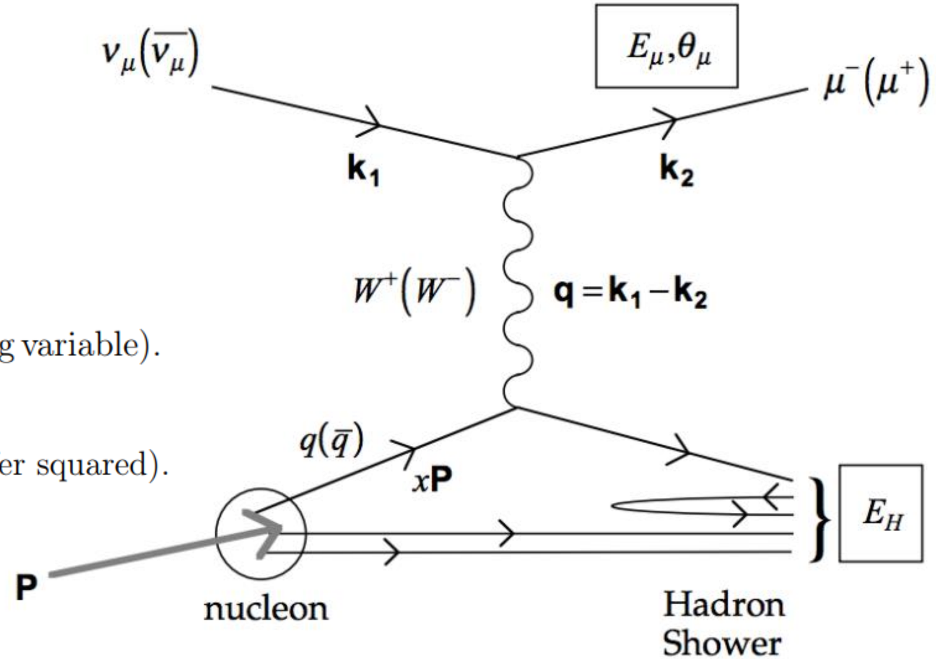
Neutrino Deep Inelastic Scattering

- At energies above ~10 GeV, neutrinos probe the quark and gluon structure of the nucleon
- Kinematic variables:

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

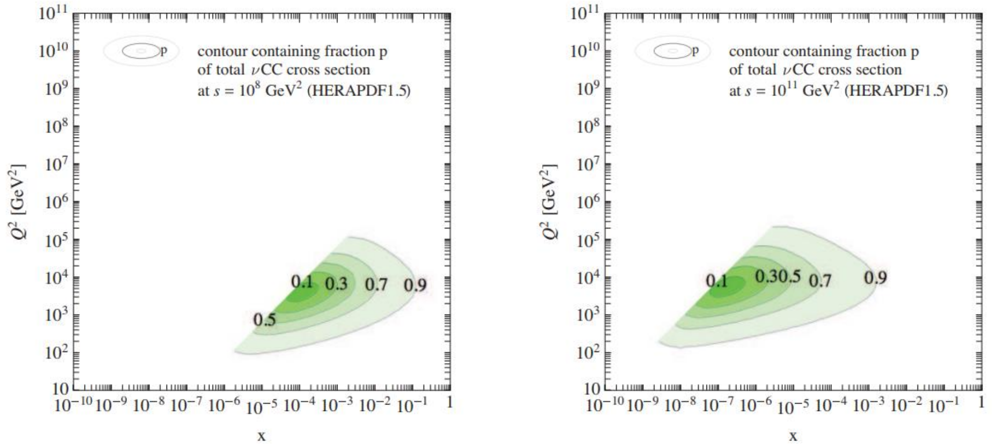
$$x = -\frac{q^2}{2p \cdot q} = \frac{2E_\nu E_\ell}{M E_{\rm had}} \sin^2\left(\frac{\theta_\ell}{2}\right) \quad \text{(Bjorken scaling variable)}.$$

$$Q^2 = -q^2 = 4E_\nu E_\ell \sin^2\left(\frac{\theta_\ell}{2}\right) \quad \text{(4-momentum transfer squared)}.$$

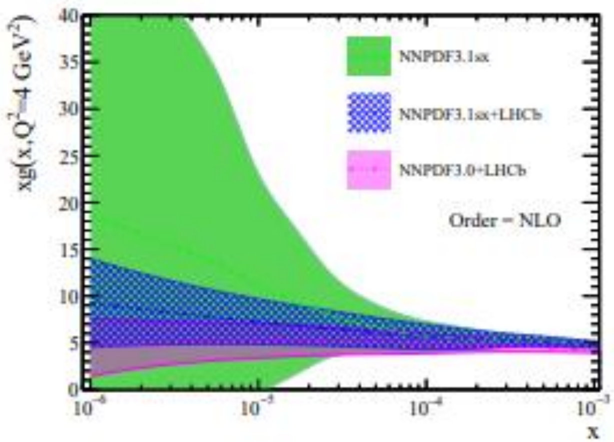


Cross Section & Kinematic Ranges

- At high energy, weak boson propagator causes $Q^2 \sim M_W^2 \sim 6 \times 10^4\ \mathrm{GeV}^2$
- Typically $x \sim 10^{-3} \left(\frac{10^6\ \mathrm{GeV}}{E_\nu}\right)$
- 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:



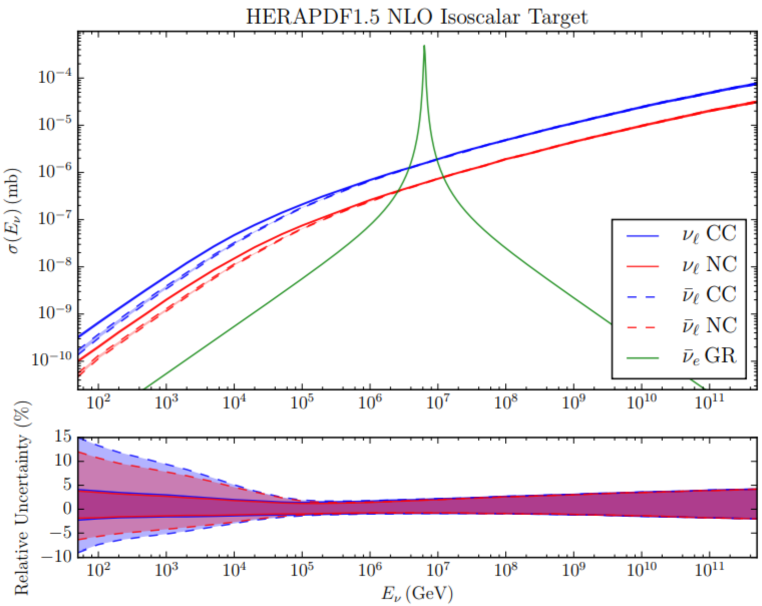
Gluon PDFs:

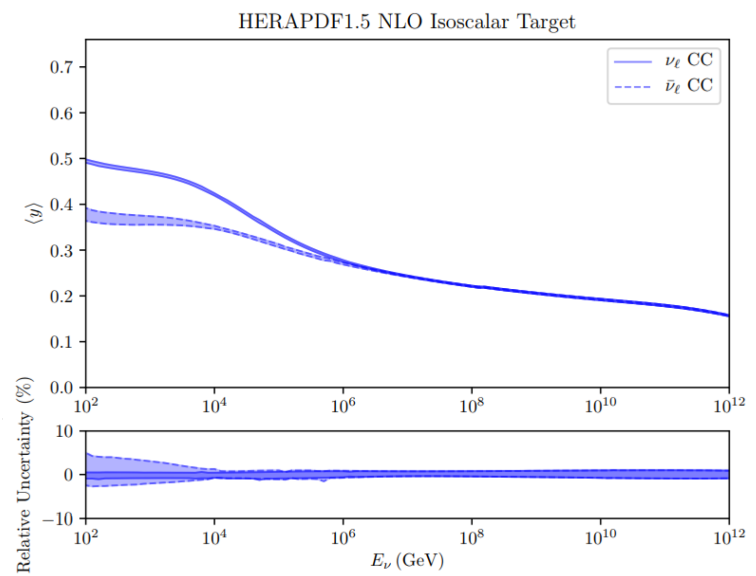


A. Cooper-Sarkar, P. Mertsch, S. Sarkar
JHEP 08 (2011) 042

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





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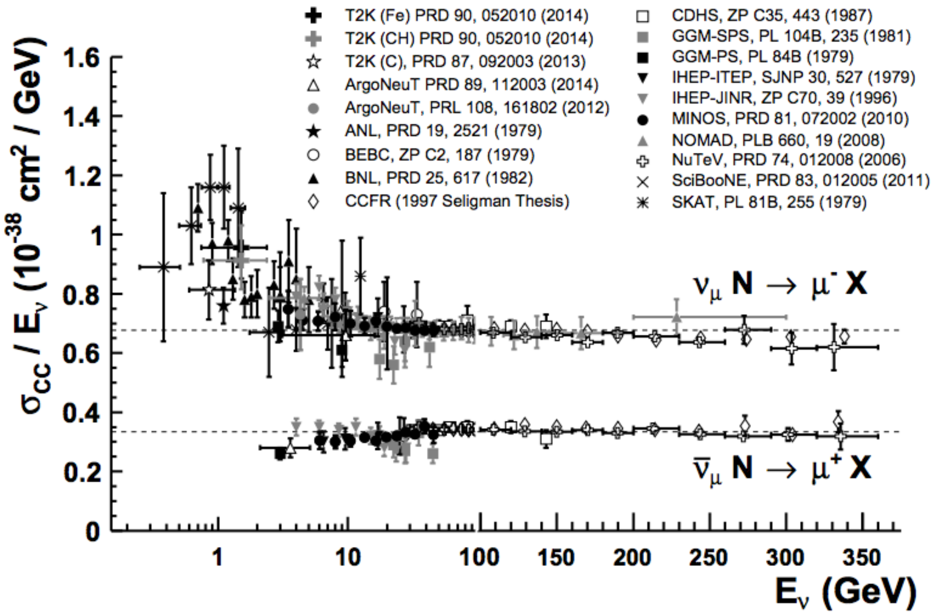
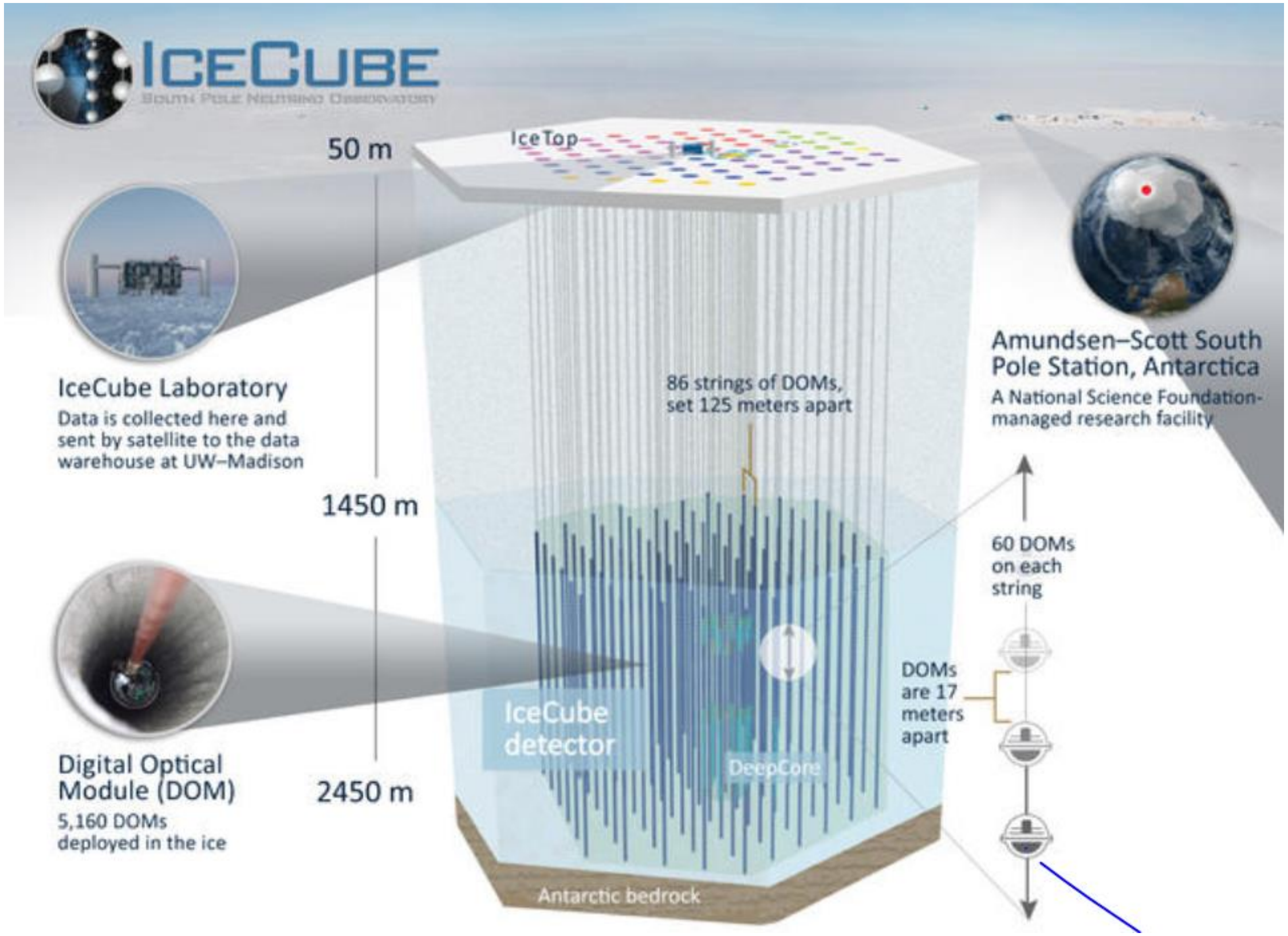
Cross Section Measurements

- Accelerator based neutrino cross section measurements only extend up to $\sim 370\ \mathrm{GeV}$
- At energies from $\sim 10^3\ \mathrm{GeV}$ to $10^7\ \mathrm{GeV}$, IceCube has the potential to measure
  - Total cross section σ through earth absorption
  - Differential cross section $d\sigma/dy$ using ν_μ starting tracks

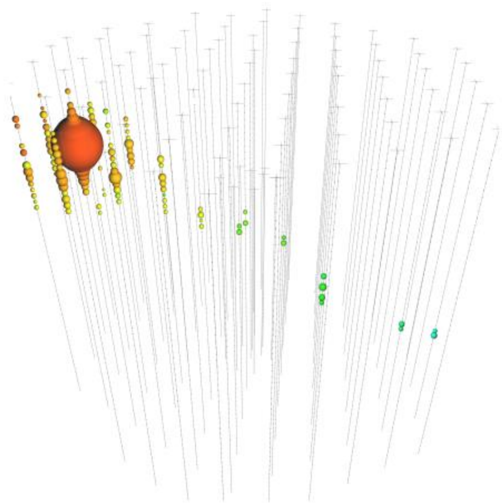
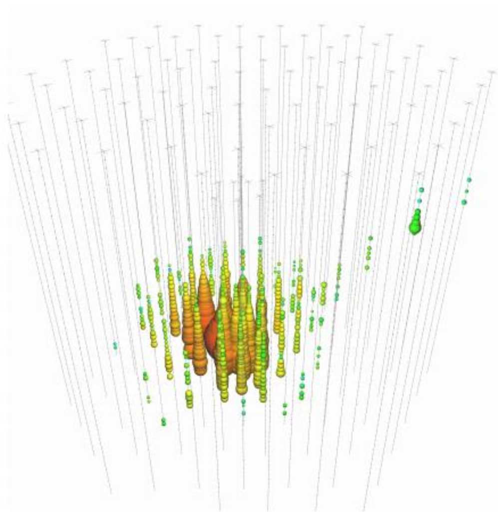
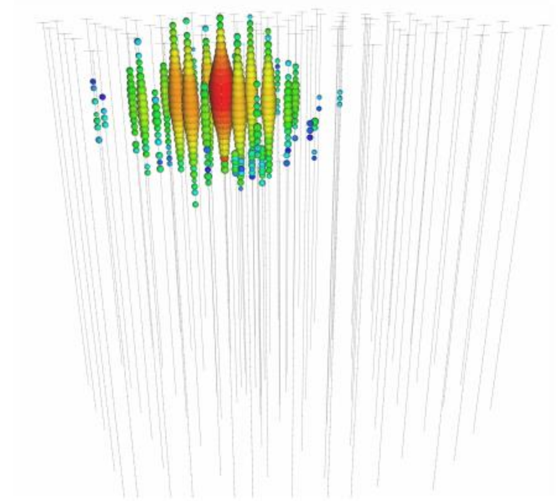


C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)

IceCube Neutrino Observatory

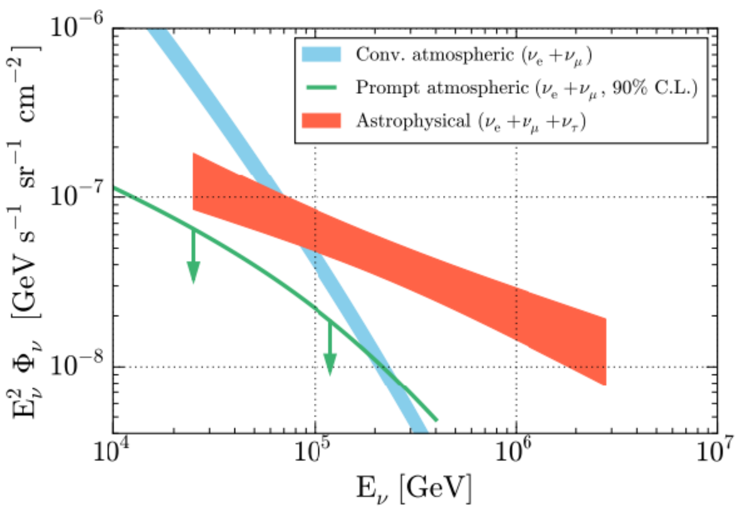


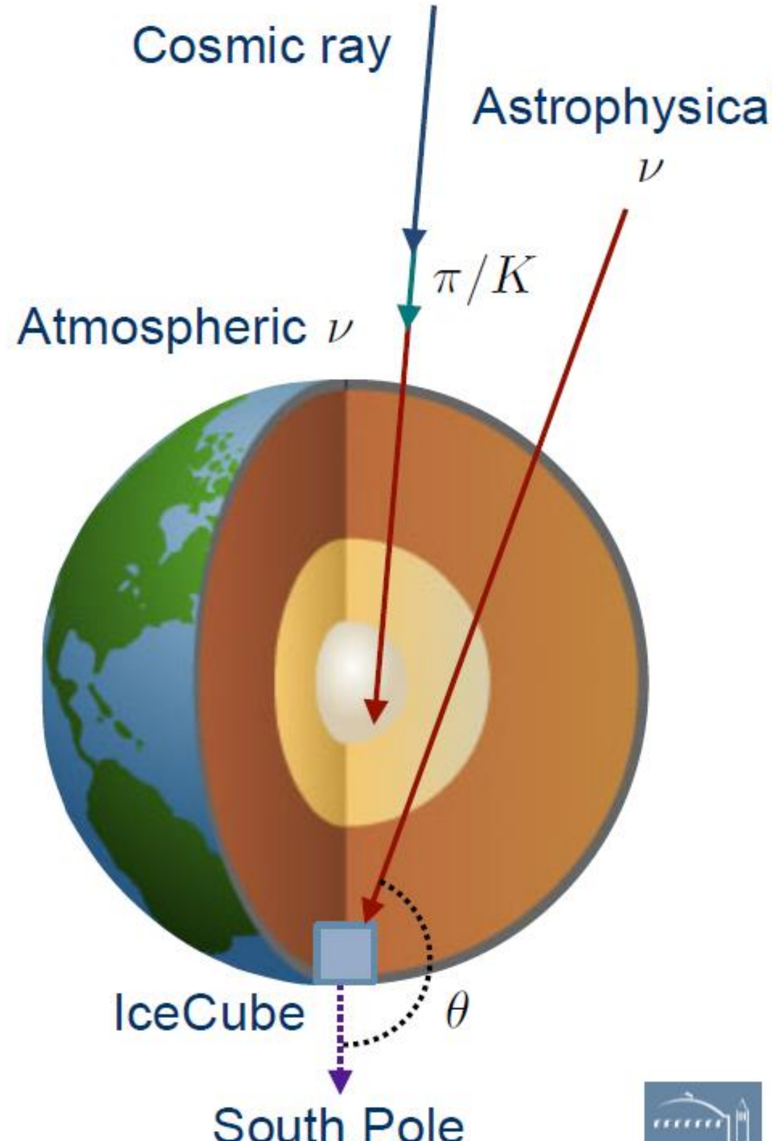
Neutrino Interaction Signatures

Through-going Track	Starting Track	Shower
		
CC $\nu_\mu N \to \mu X$ Outside detector	CC $\nu_\mu N \to \mu X$ Inside detector	CC $\nu_{e,\tau} N \to e, \tau X$ NC $\nu_{e,\mu,\tau} N \to \nu_{e,\mu,\tau} N$

Atmospheric and Astrophysical Neutrinos

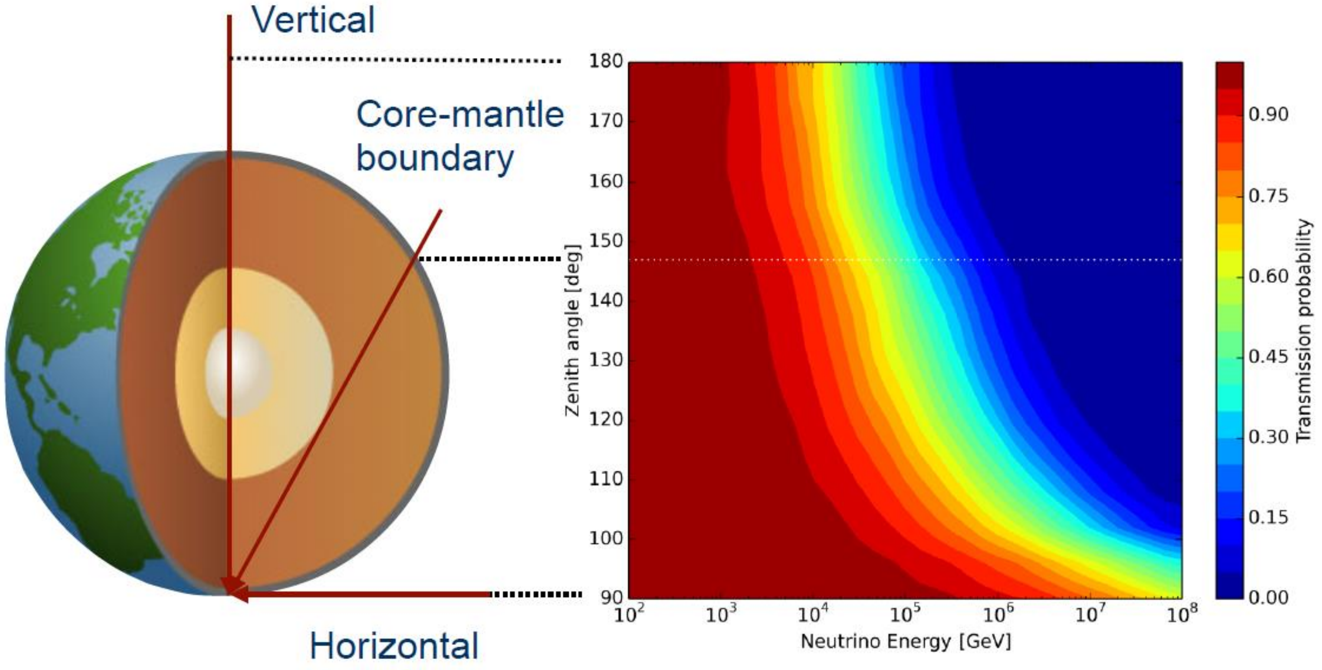
- IceCube detects mostly atmospheric neutrinos below 10^5 GeV
- Above 10^5 GeV, mostly astrophysical neutrinos are detected
- Both can be absorbed as they pass through the Earth





Earth Absorption

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



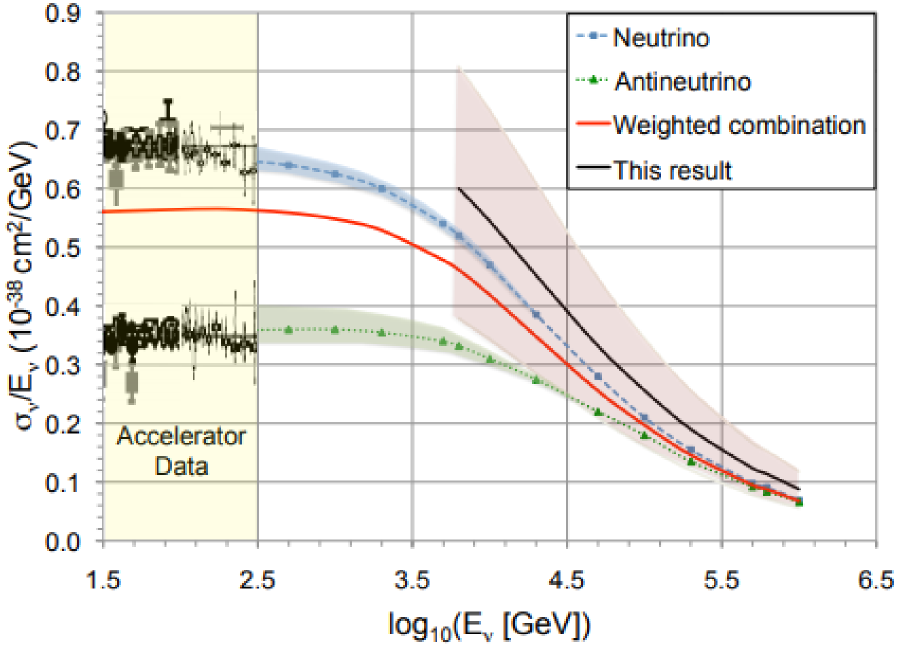
Nature 551 (2017) 596-600

Cross Section Measurement (2017)

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

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

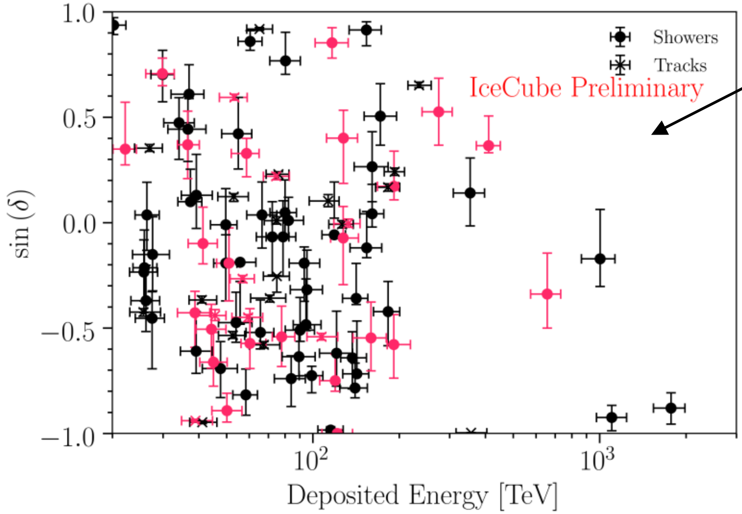
- Estimated energy range: 6 – 980 TeV



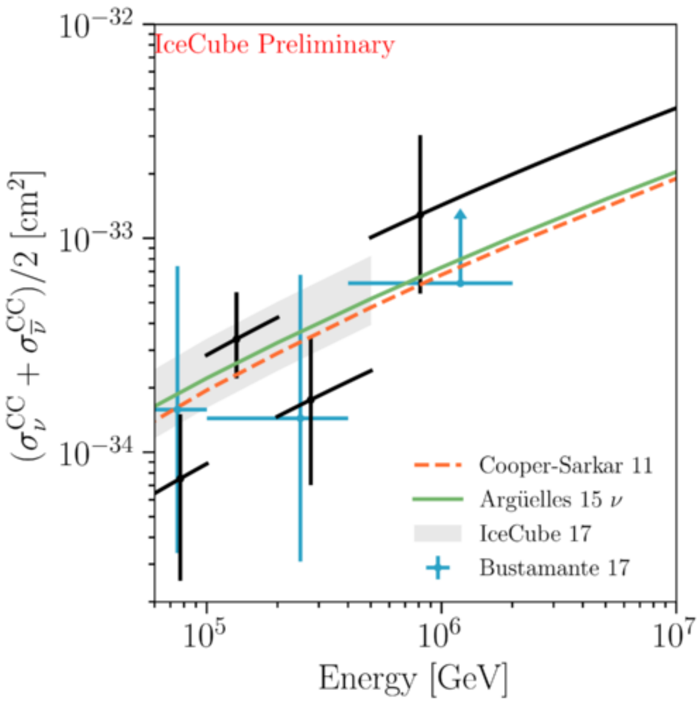
Nature 551 (2017) 596-600

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



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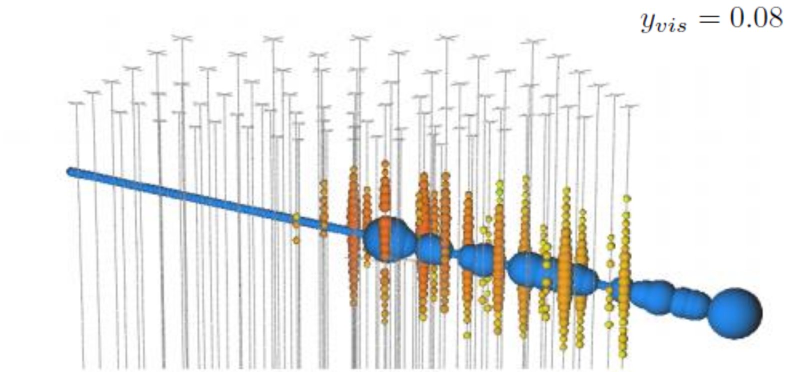
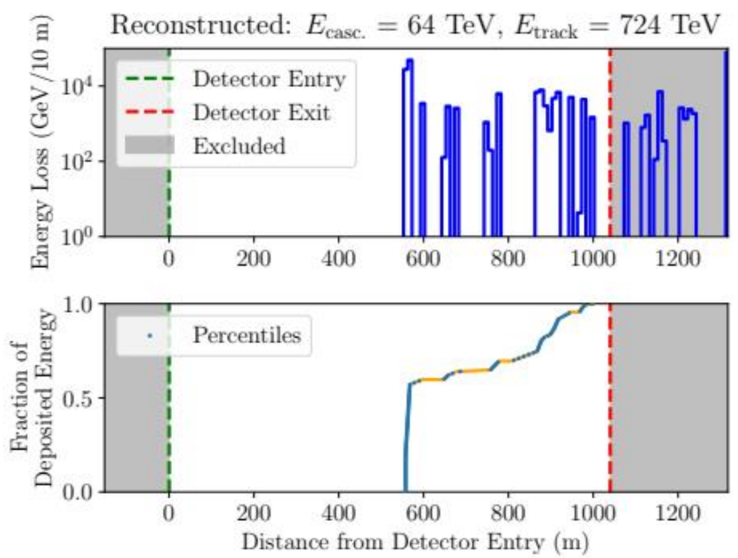
Inelasticity of Starting Tracks

- 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

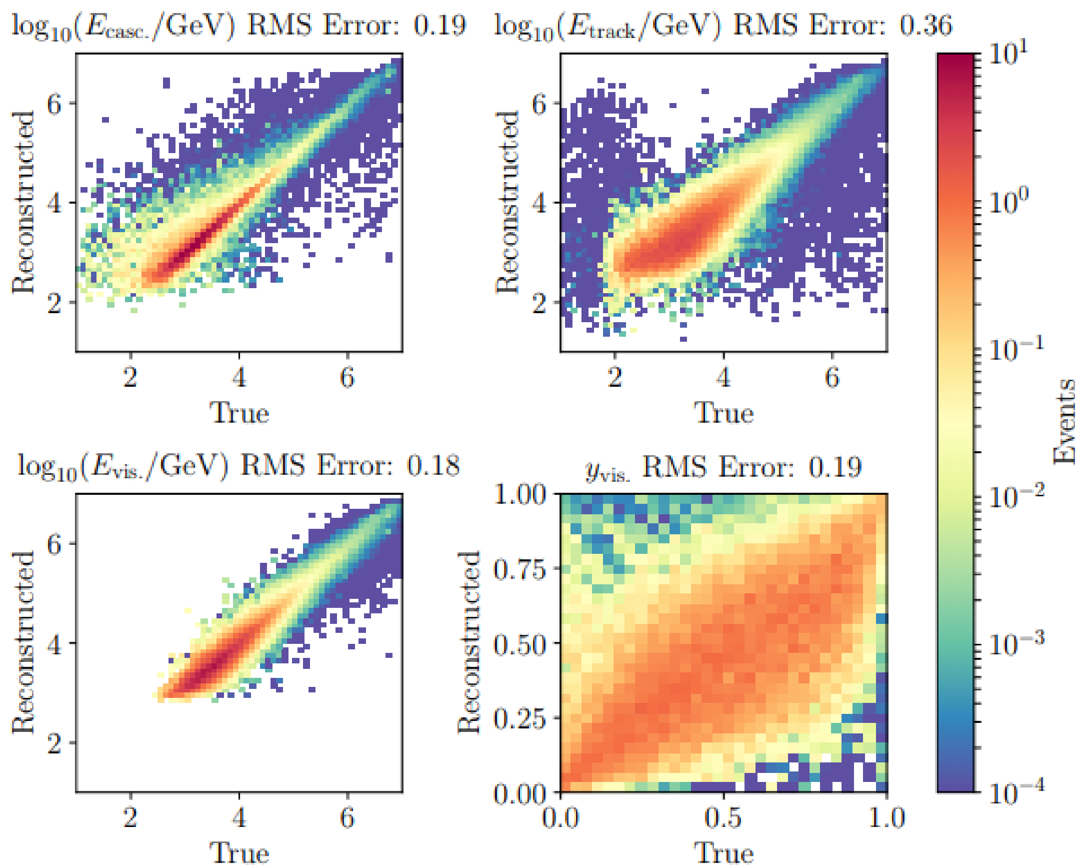




Phys. Rev. D 99, 032004 (2019)

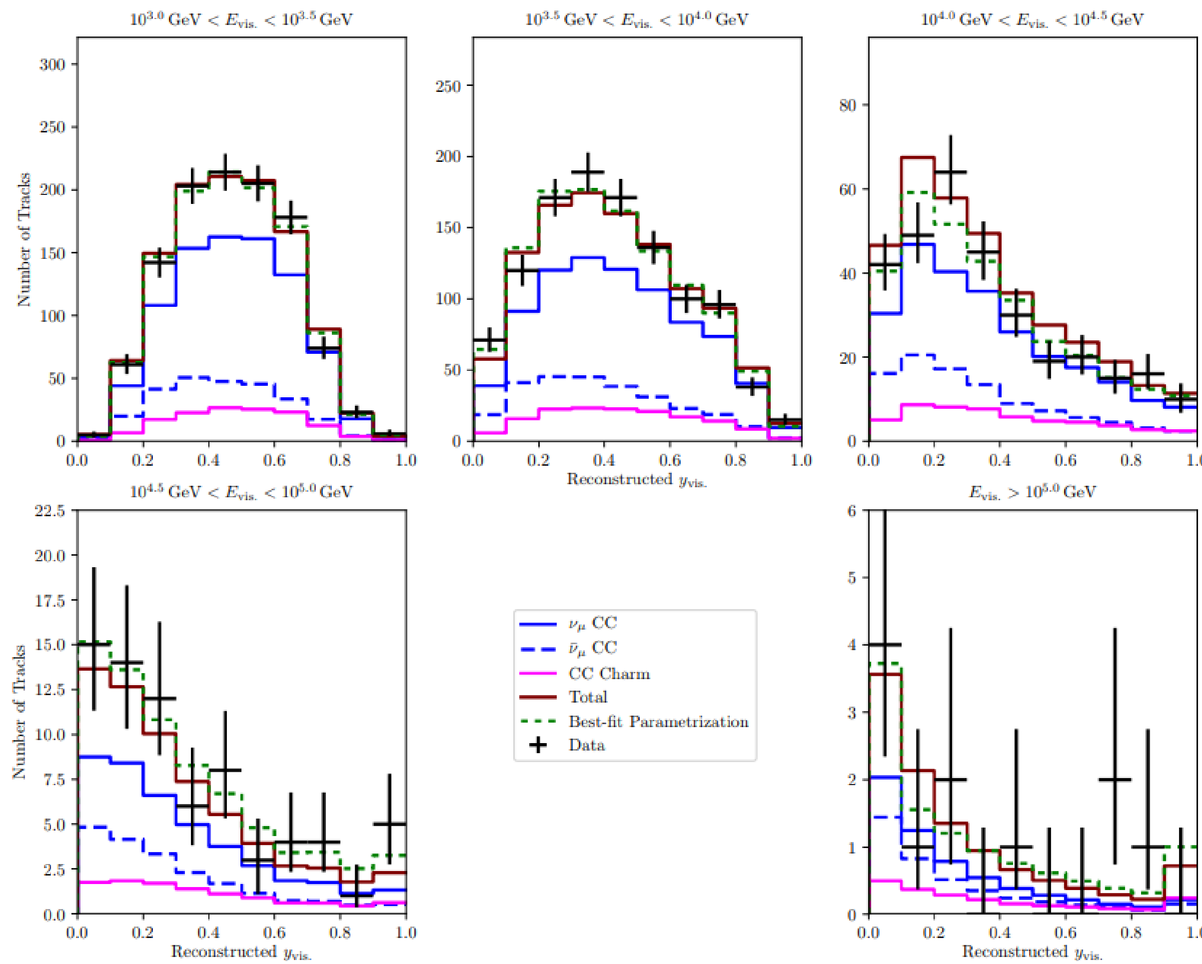
Energy/Inelasticity Resolution

- Resolution on log10 total energy = 0.18
- Resolution on inelasticity = 0.19



Inelasticity Distributions

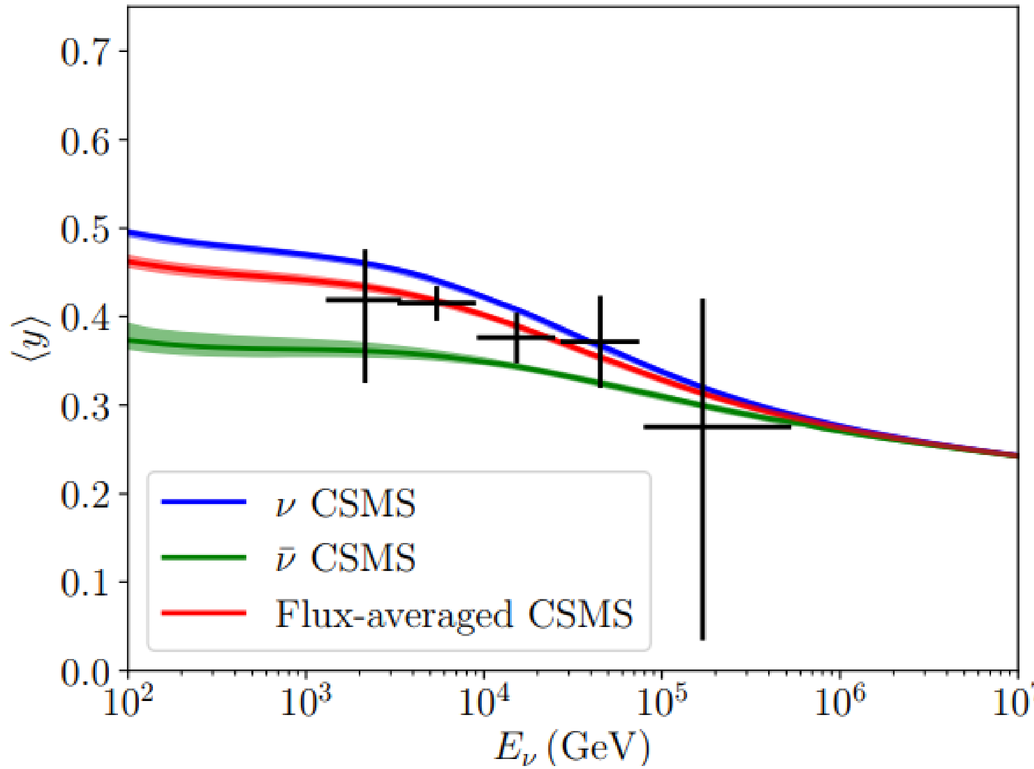
- 2650 starting tracks analyzed
- Reconstructed inelasticity distributions agree well with nominal NLO calculations in energy bins from 1 TeV to 100 TeV



Phys. Rev. D 99, 032004 (2019)

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



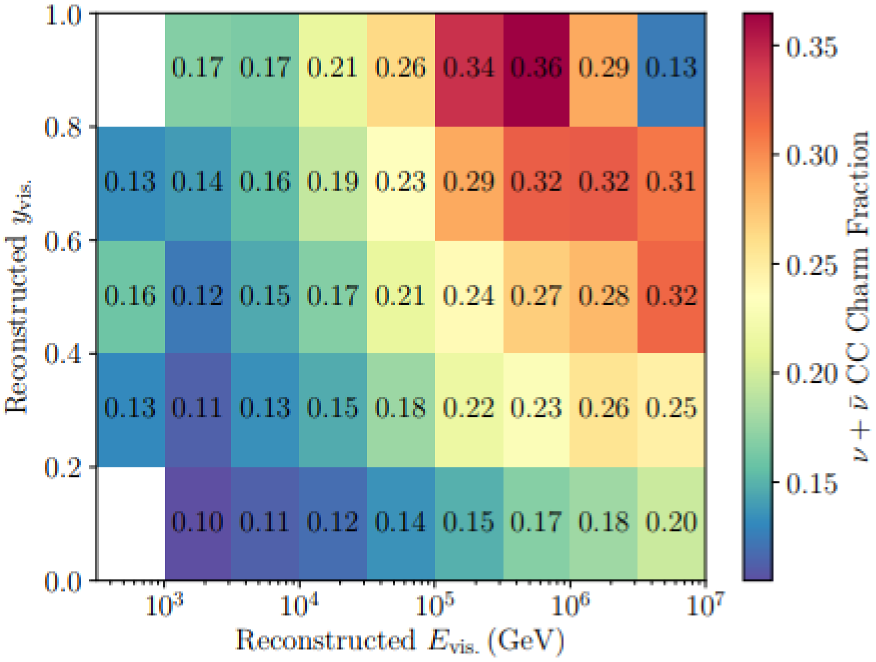
Phys. Rev. D 99, 032004 (2019)

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:
  - $R = 0.93^{+0.73}_{-0.59}$



Phys. Rev. D 99, 032004 (2019)

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:

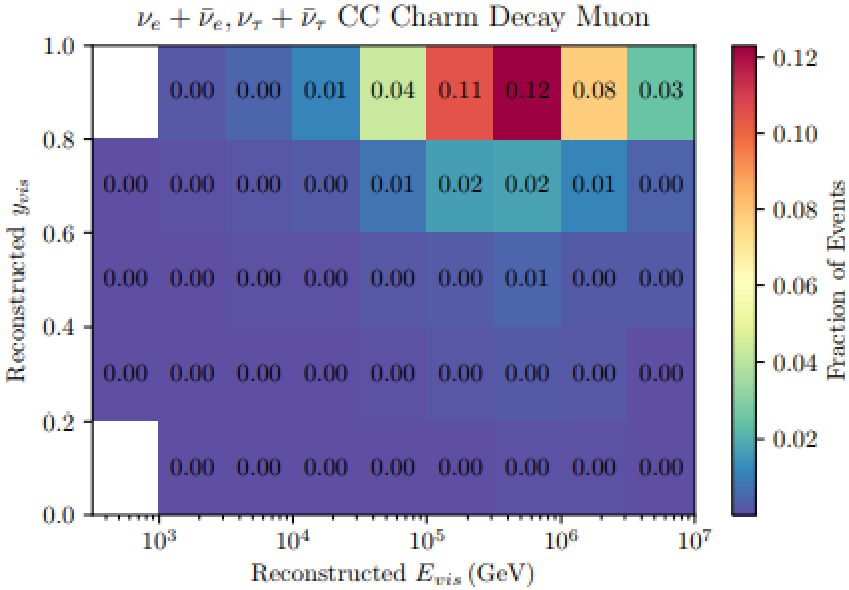
$$\epsilon_{D^+} = 22\text{ TeV},\ \epsilon_{D^0} = 53\text{ TeV},\ \epsilon_{D_s^+} = 47\text{ TeV},$$

- Possibility to measure charm interaction cross section?
- No good calculations available

- Charm production, semi-leptonic decay

$$\nu_e N \to e X_1 D^{0,\pm} \to e X_1 X_2 \mu \nu_\mu$$

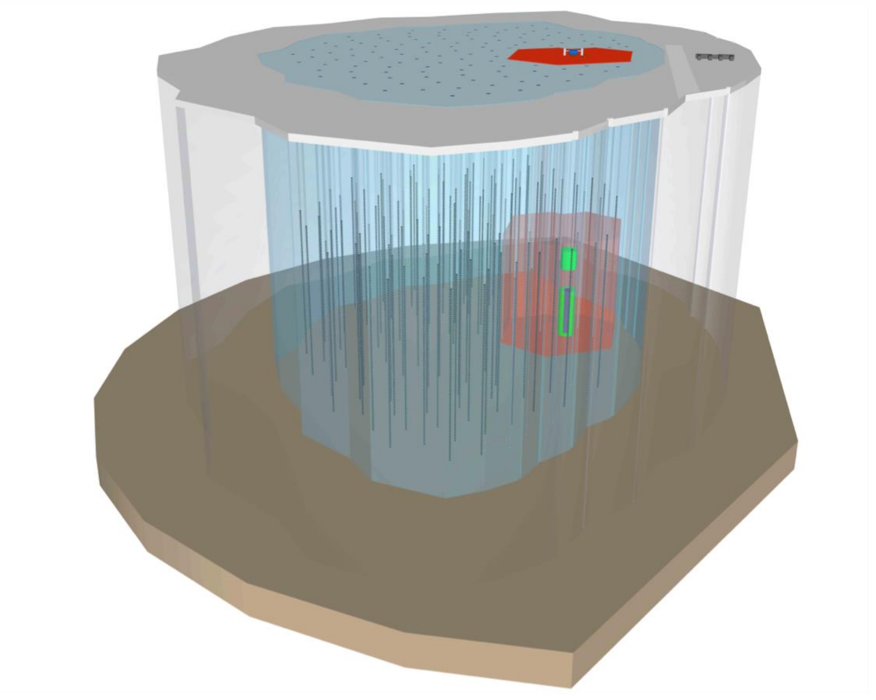
- Interactions suppress event rate



Phys. Rev. D 99, 032004 (2019)

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



"IceCube-Gen2:
A Vision for the Future of
Neutrino Astronomy in Antarctica" arXiv:1412.5106

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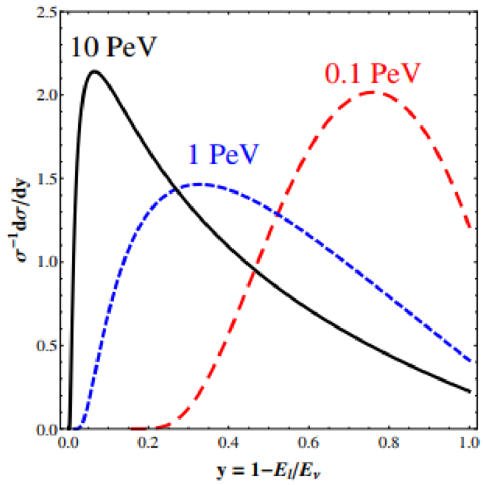
Potential Topics with IceCube-Gen2

- Precision cross section measurements, tests of low-x saturation models
- Neutrino-induced charm/bottom/top quark production
- Non-DIS interactions:

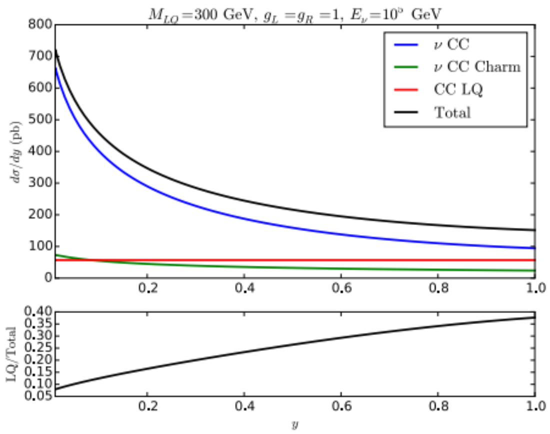
$$\nu_\mu N \to \mu^- W^+ N$$

- Physics beyond the standard model
  - Leptoquarks, low-scale QG, sphalerons, …



$$\nu_\ell b \to t \ell$$

Phys. Rev. D 95, 093002 (2017)

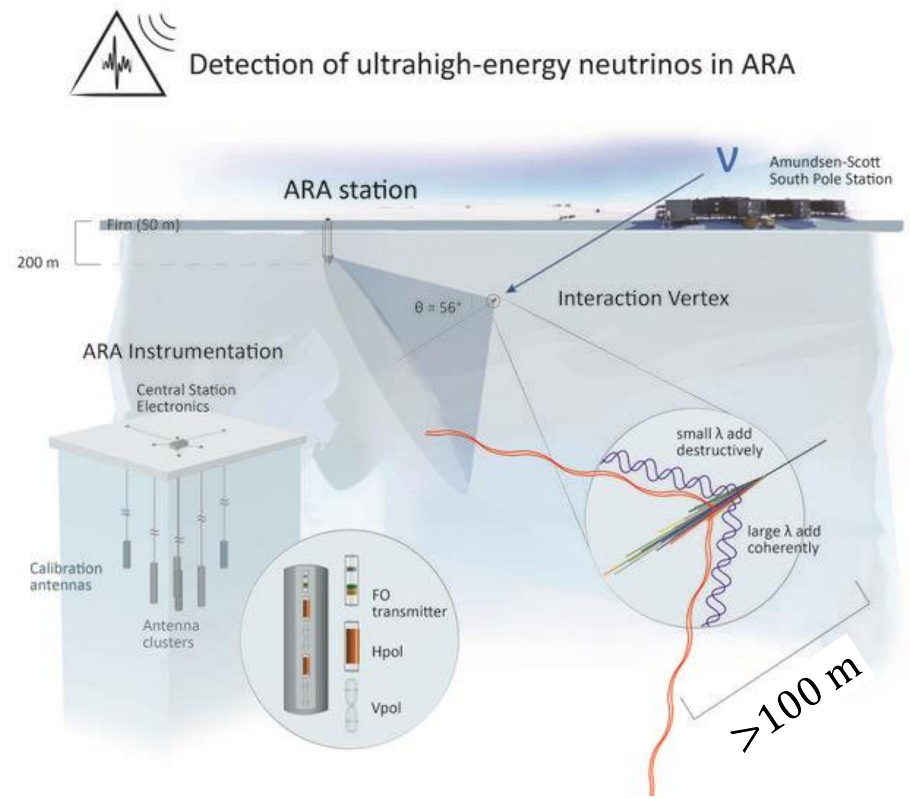


$$\nu_\mu N \to LQ \to \mu X$$

Phys. Rev. D 74, 125021 (2006)

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 ν_e could be measured from elongated showers due to the LPM effect



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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 $\sim 10^{15}\ \mathrm{eV}$ 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 $\sim 10^{17}\ \mathrm{eV}$