Neutrino absorption in the Earth and measurement of the neutrino-nucleon cross-section at multi-TeV energies with IceCube

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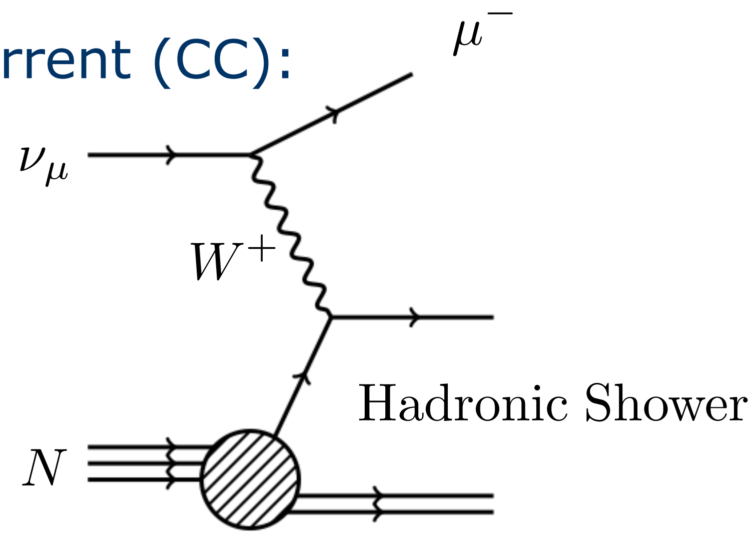
Outline

- Neutrino cross section: calculation and measurements
- Absorption of high-energy neutrinos in the Earth
- Measurement of the neutrino cross section with IceCube

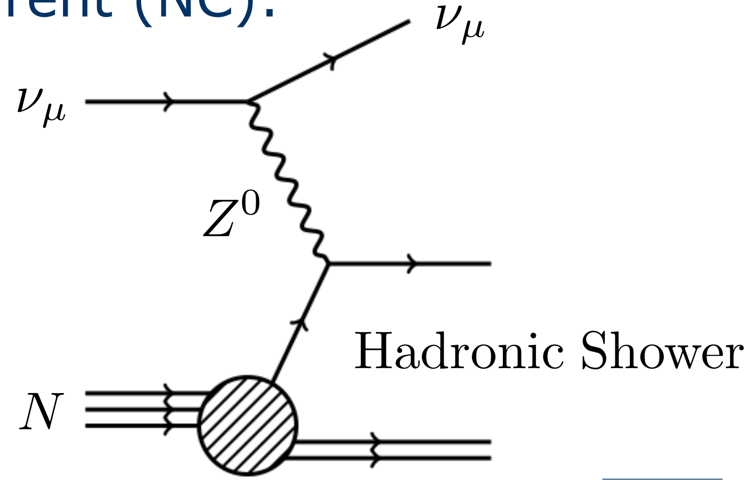
High-Energy Neutrino Interactions

- At high energies, neutrinos interact primarily with nuclei through weak charged and neutral-current processes
- At energies above ~10 GeV, neutrinos probe the quark and gluon structure of the nucleon: deep inelastic scattering (DIS)

Charged-current (CC):

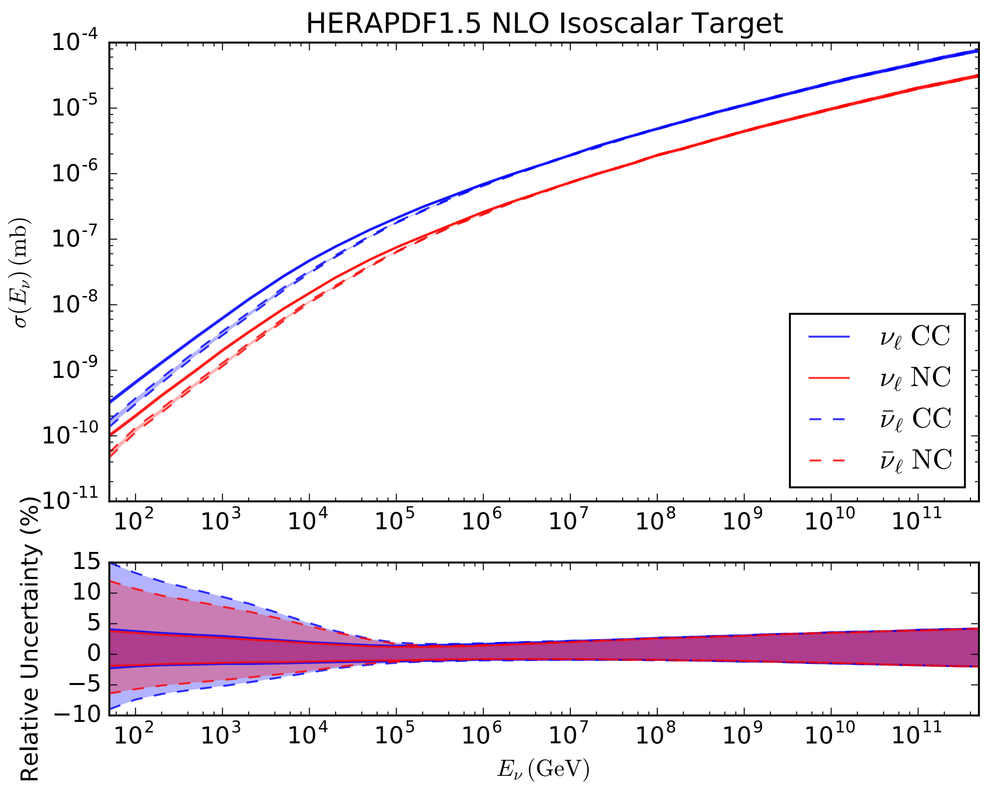


Neutral-current (NC):



Neutrino-Nucleon Cross Section

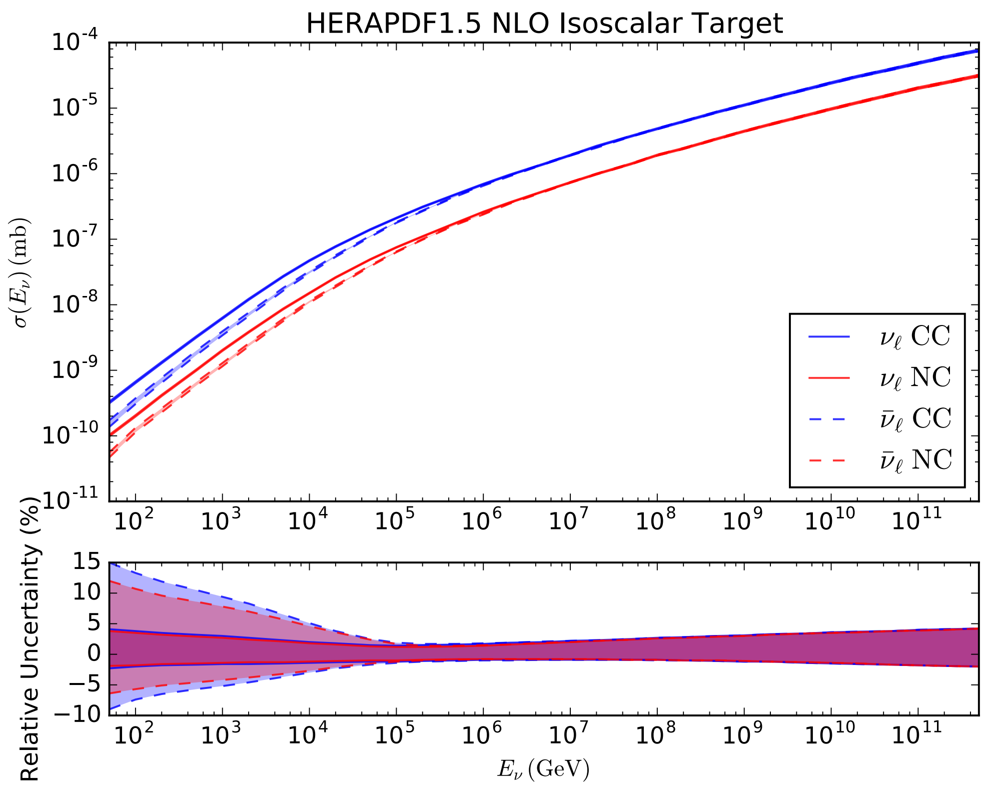
- Cross section rises linearly until its growth is slowed by the finite W,Z boson masses above ~10 TeV
- Above ~10 TeV, growth is governed by the behavior of sea quarks and gluons at low Bjorken-x
- Below this energy, the antineutrino cross section is smaller by a factor of 2
- NC cross section smaller than CC by a factor of 3



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

Neutrino-Nucleon Cross Section

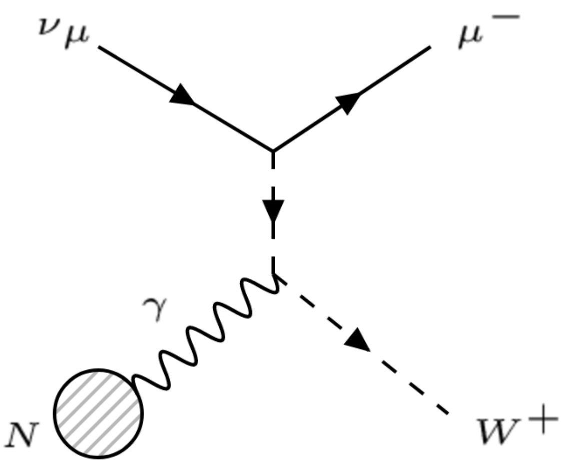
- Calculation relies on knowledge of nucleon structure as described through parton distribution functions (PDFs)
- Proton PDFs measured at the HERA ep collider can be used to predict the neutrino DIS cross section to high precision (< 5%) over a large energy range



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

Additional Effects on Cross Section

- Additional Standard Model effects may go beyond this uncertainty estimate
  - Nuclear shadowing
  - Treatment of heavy quark masses
  - Gluon saturation at ultra-high energies
  - Electromagnetic W-boson production in nuclear Coulomb field: $\nu_\mu N \to \mu^- W^+ N$



- Physics beyond the Standard Model may cause a large enhancement at high energies:
  - Low-scale quantum gravity models, leptoquarks…
  - LHC center-of-mass energy reached at 100 PeV neutrino energy

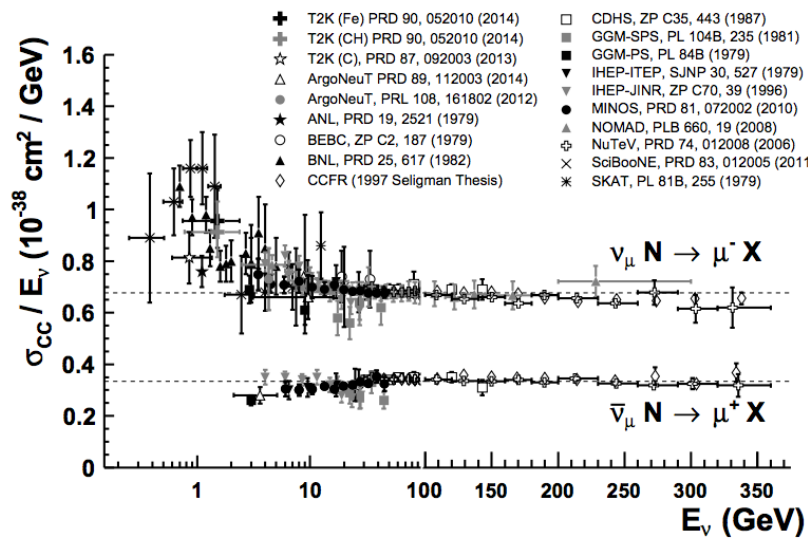
Previous Measurements

- Neutrino DIS cross sections measured up to 360 GeV in many accelerator-based experiments
- Measuring total cross section required knowledge of the absolute neutrino flux:

$$\frac{dN}{dE}(E) \propto \sigma(E)\Phi(E)$$

- In many experiments, absolute flux was calibrated by assuming the world-average measurement
- Neutrino telescopes can access much higher energies and don't need an absolute flux calibration

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



World average:

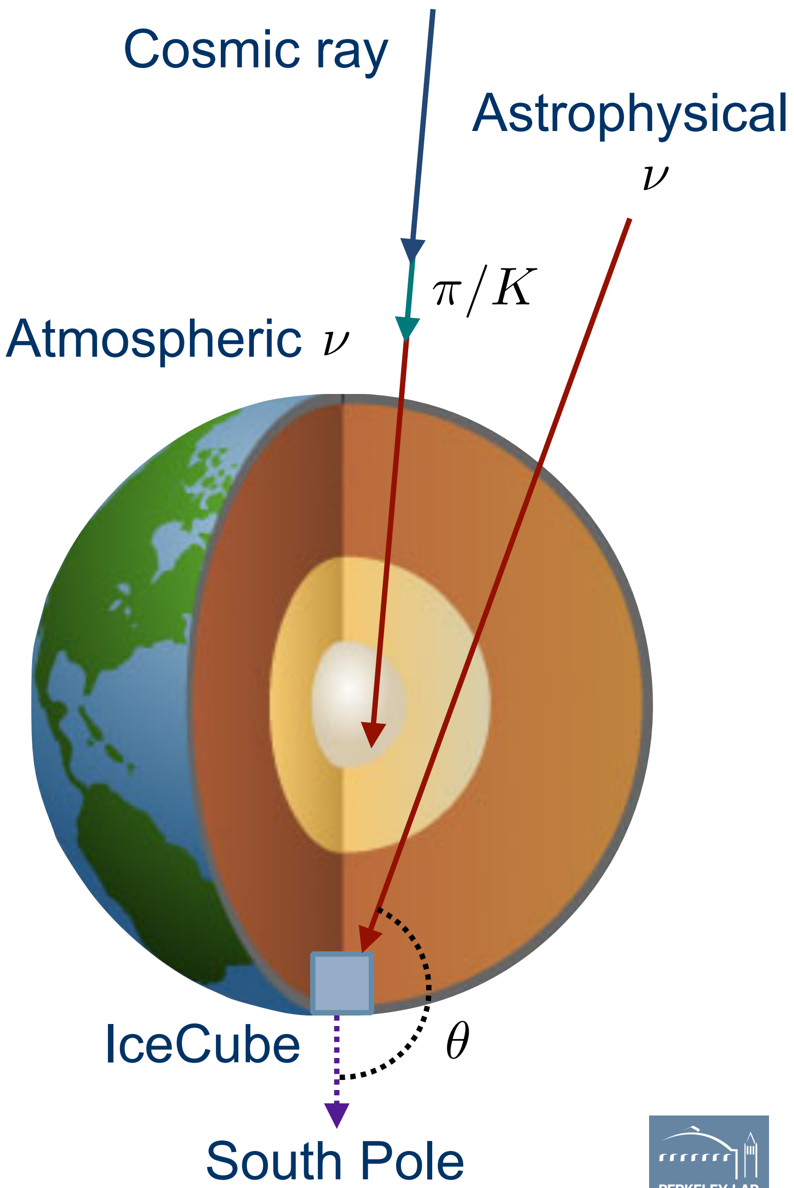
$$\frac{\sigma^{\nu,CC}}{E} = 0.677 \pm 0.014 \times 10^{-38}\,\text{cm}^2\,\text{GeV}^{-1}$$

Neutrino Absorption in the Earth

- Atmospheric and astrophysical neutrinos can be absorbed when passing through the Earth

- A 40 TeV neutrino has a mean free path of about one Earth diameter

- At the South Pole, IceCube can detect the variation in absorption as a function of zenith angle, θ



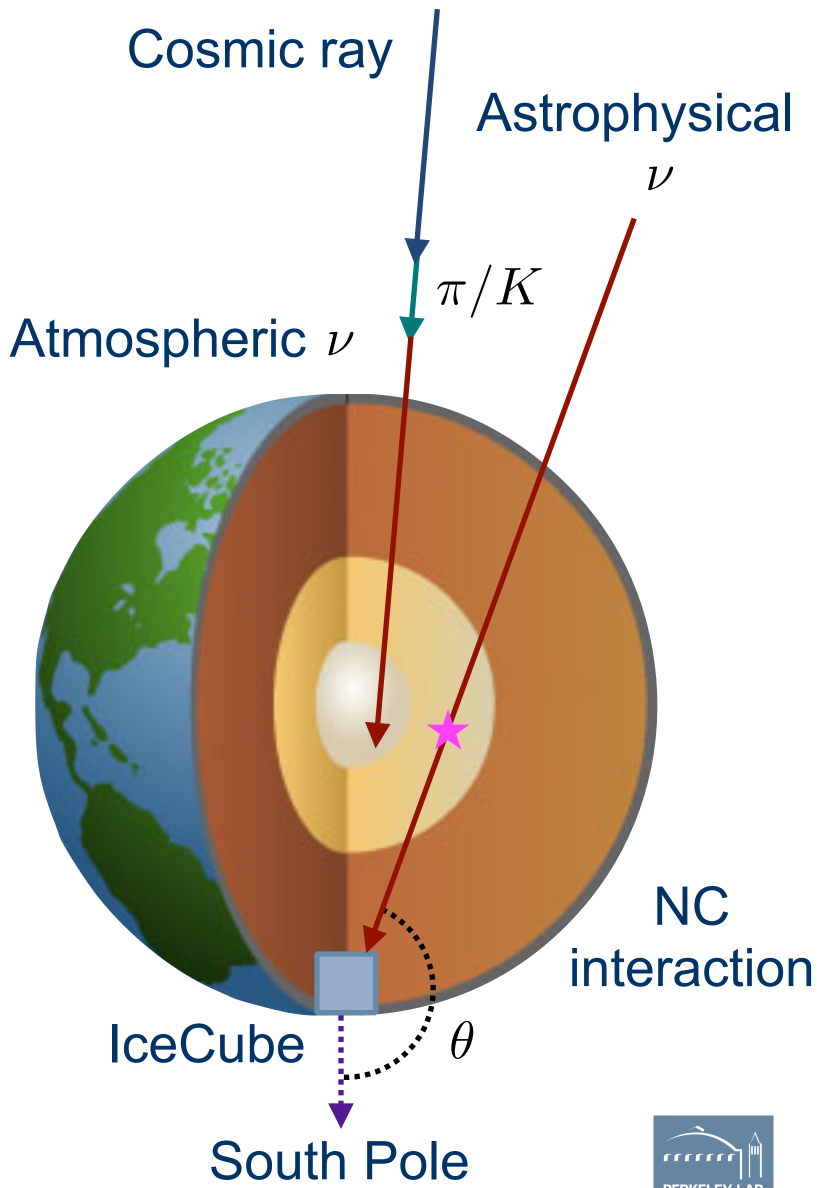
Neutrino Absorption in the Earth

- Flux attenuation approximately described by:

$$\frac{dN}{dE}(E,\theta) \propto \sigma(E)\Phi(E,\theta)e^{-\sigma(E)X(\theta)/M}$$

- Neutrinos can still be transmitted after neutral-current interactions, but with lower energy

- Treated through Monte Carlo simulation

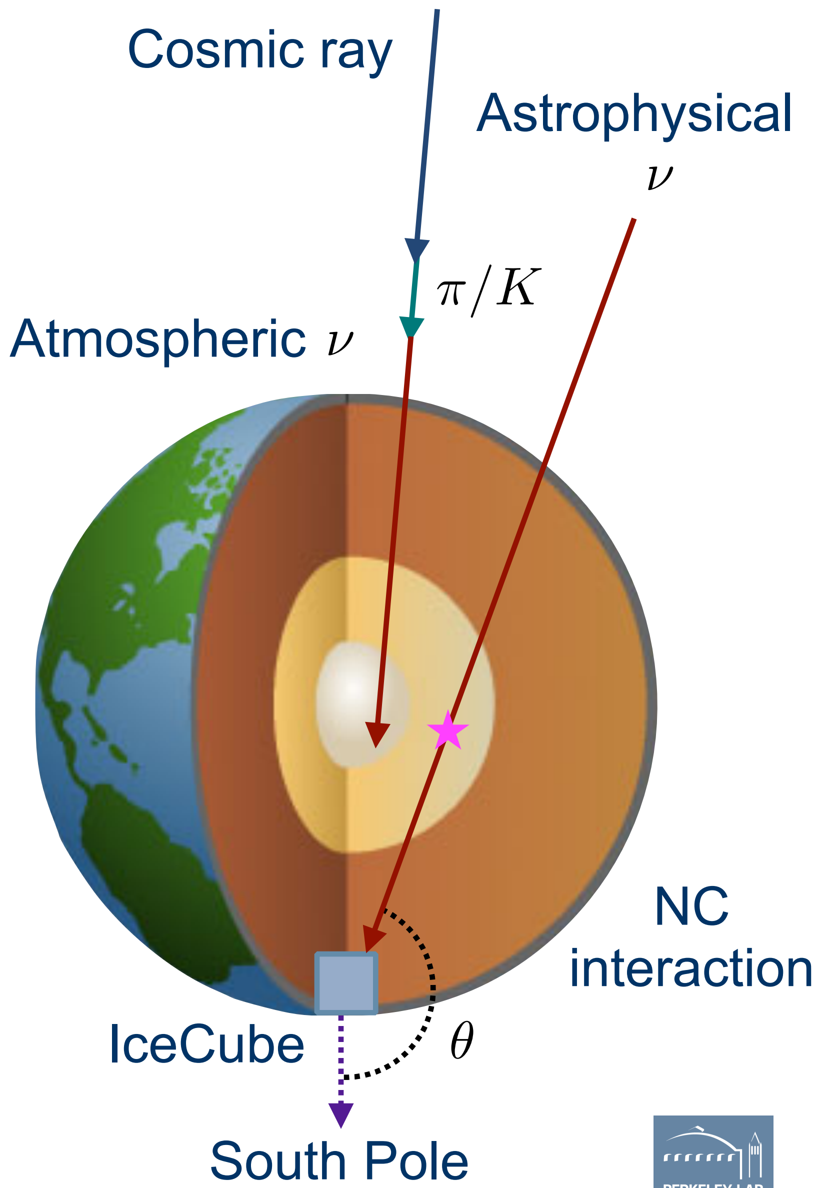


Neutrino Absorption in the Earth

- Flux attenuation approximately described by:

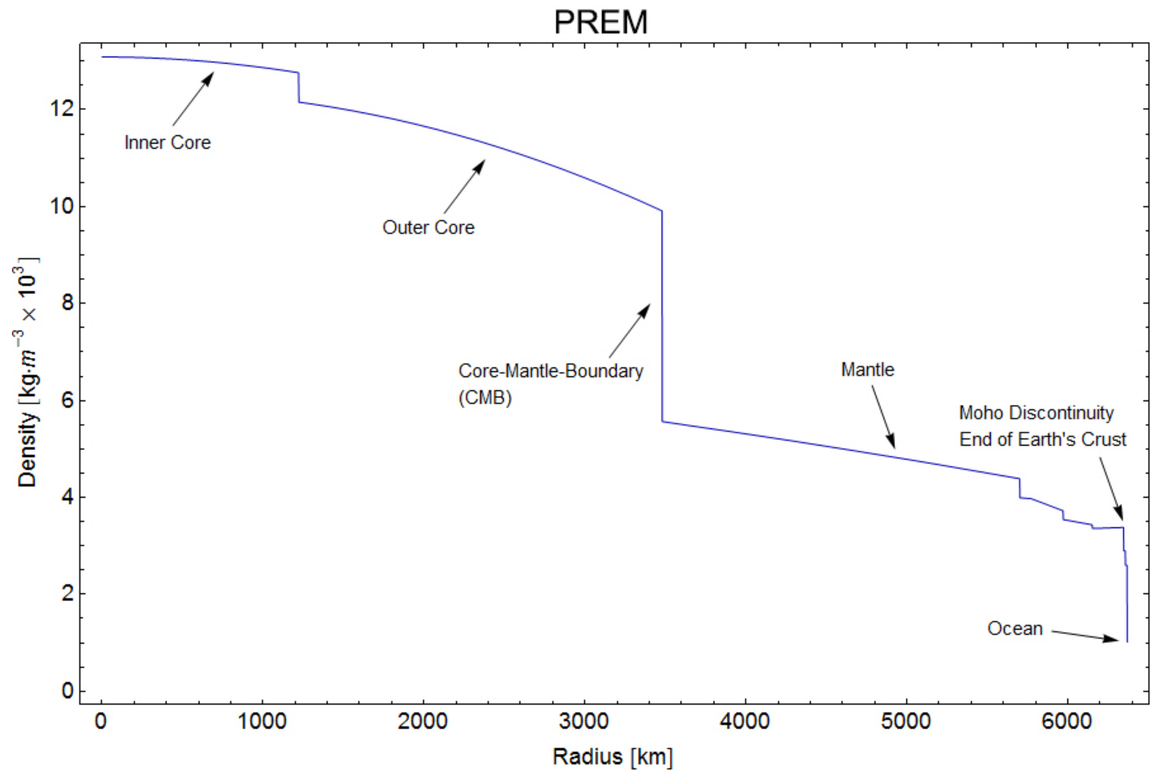
$$\frac{dN}{dE}(E,\theta) \propto \sigma(E)\Phi(E,\theta)e^{-\sigma(E)X(\theta)/M}$$

- Don't need to know absolute neutrino flux to measure cross section
- Must know column depth through the Earth and neutrino flux as a function of zenith angle



Earth Density Model

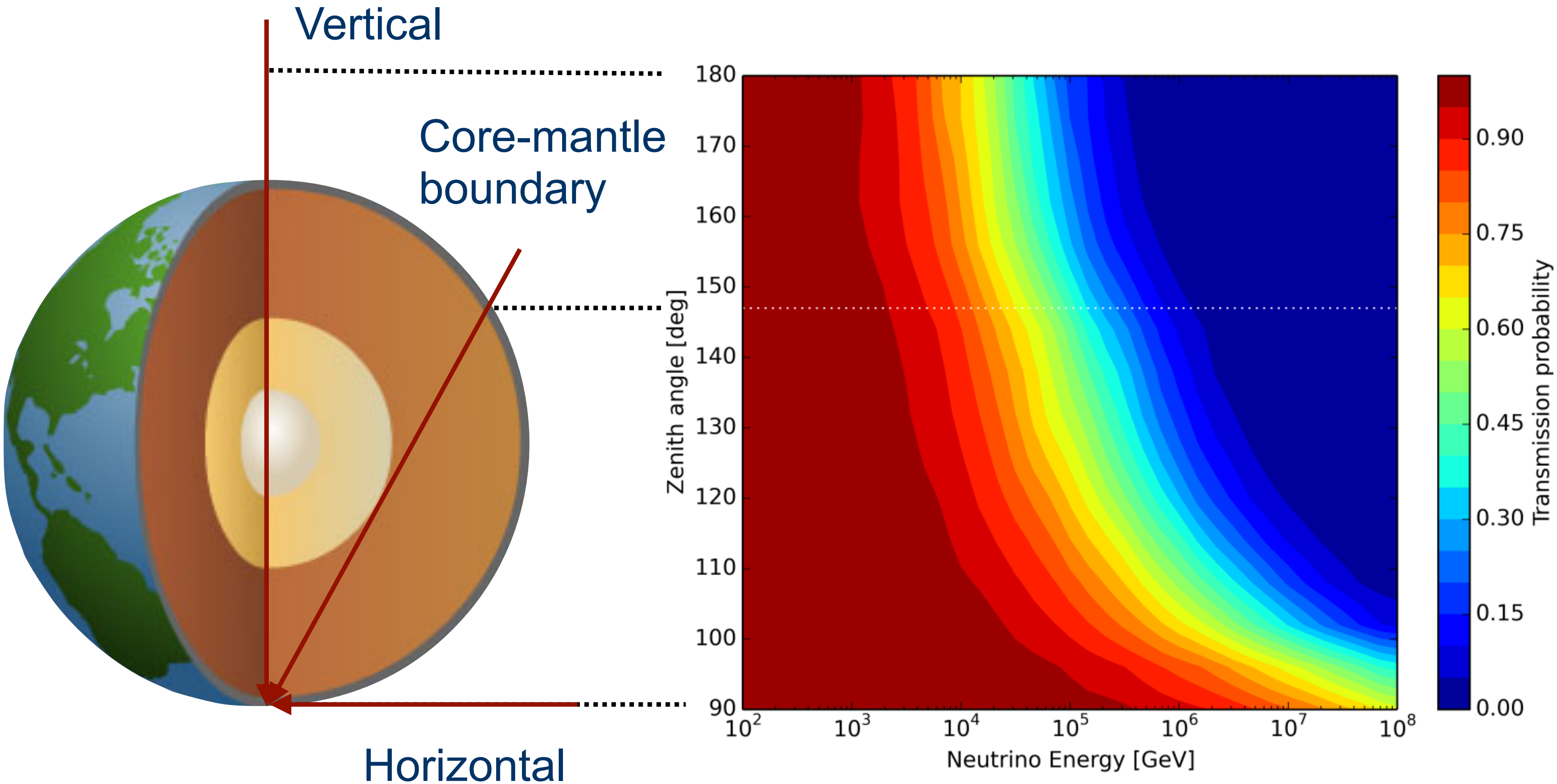
- Preliminary Earth Reference Model
- Seismic wave studies tightly constrain the density profile of the Earth
- Well-known mass and moment of inertia of the Earth provide additional constraints
- Column depth known to an accuracy of ~1-2%



A. M. Dziewonski and D. L. Anderson, Physics of the Earth and Planetary Interiors 25 (1981) 297–356.

Transmission Probability

- Monte Carlo calculation of neutrino transmission probability



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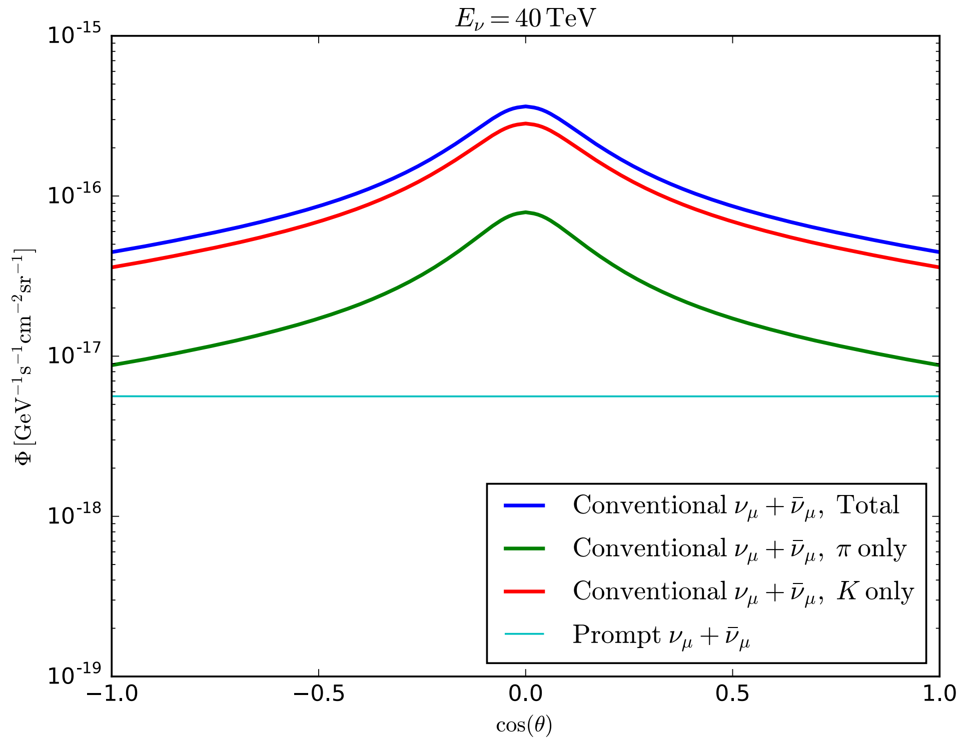
Atmospheric Fluxes

- Conventional atmospheric flux
  - Pion/kaon decays
  - Zenith-dependent (atmospheric density profile)
  - $\Phi(E) \sim E^{-3.7}$
- Prompt atmospheric flux
  - Charm hadron decays
  - Isotropic
  - $\Phi(E) \sim E^{-2.7}$
  - Not yet observed



Conventional flux calculation:

M. Honda et al.
Phys. Rev. D 75 043006 (2007)

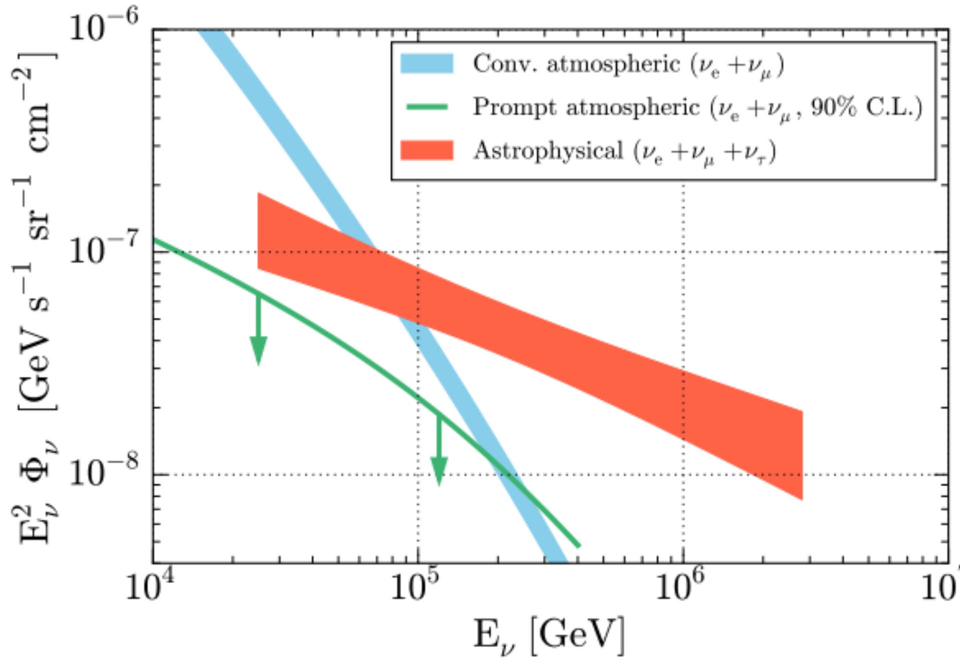
Prompt flux calculation:

R. Enberg, M. Reno, I. Sarcevic
Phys. Rev. D 78 043005 (2008)

Astrophysical Flux

- Isotropic; no large galactic contribution or point sources found yet

- Global analysis of IceCube data is consistent with a power-law flux from 20 TeV - 2 PeV

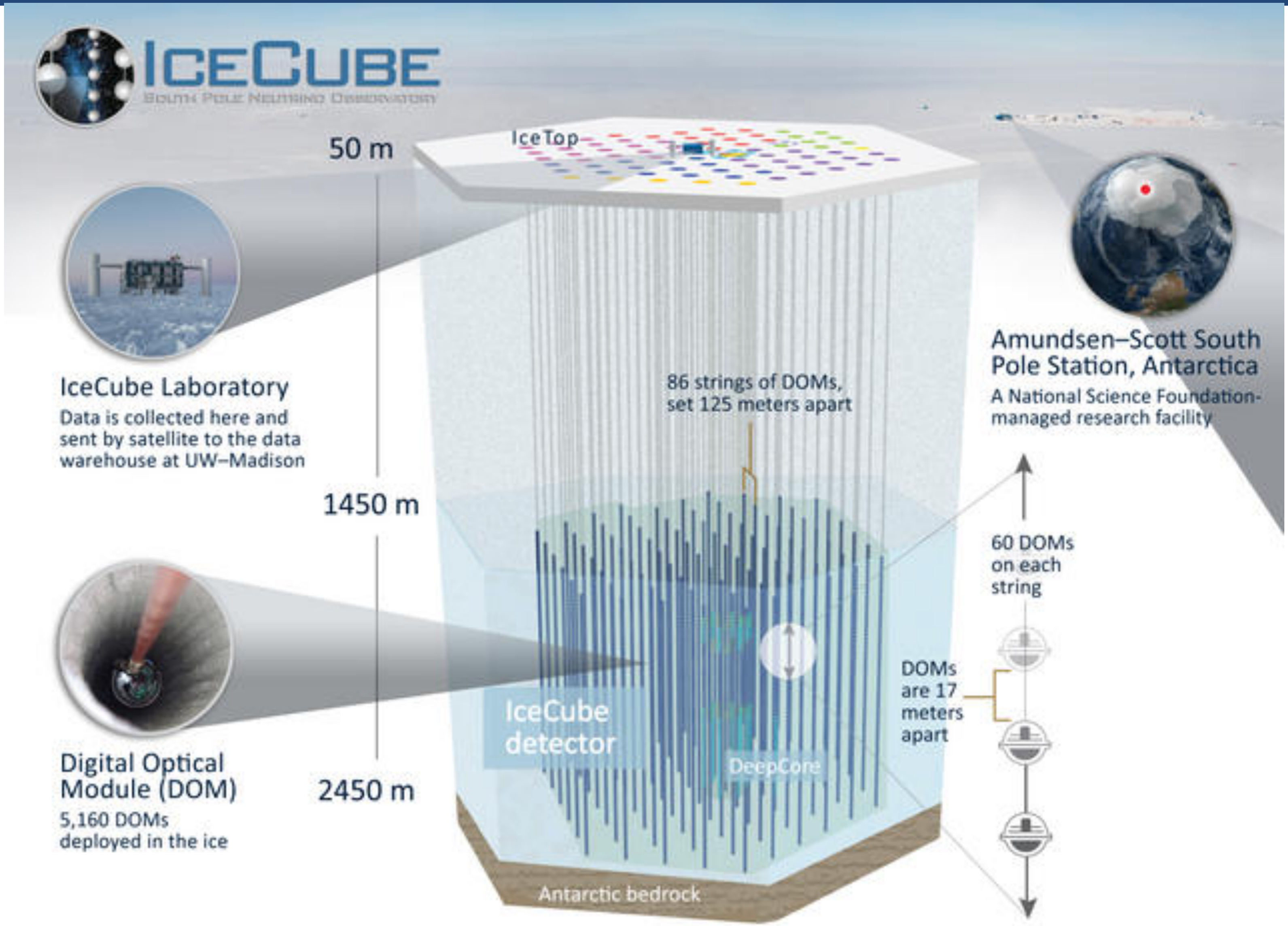


M. Aartsen et al. (IceCube Collaboration)
Astrophysical Journal 809, 98 (2015)

- Best-fit flux per flavor:

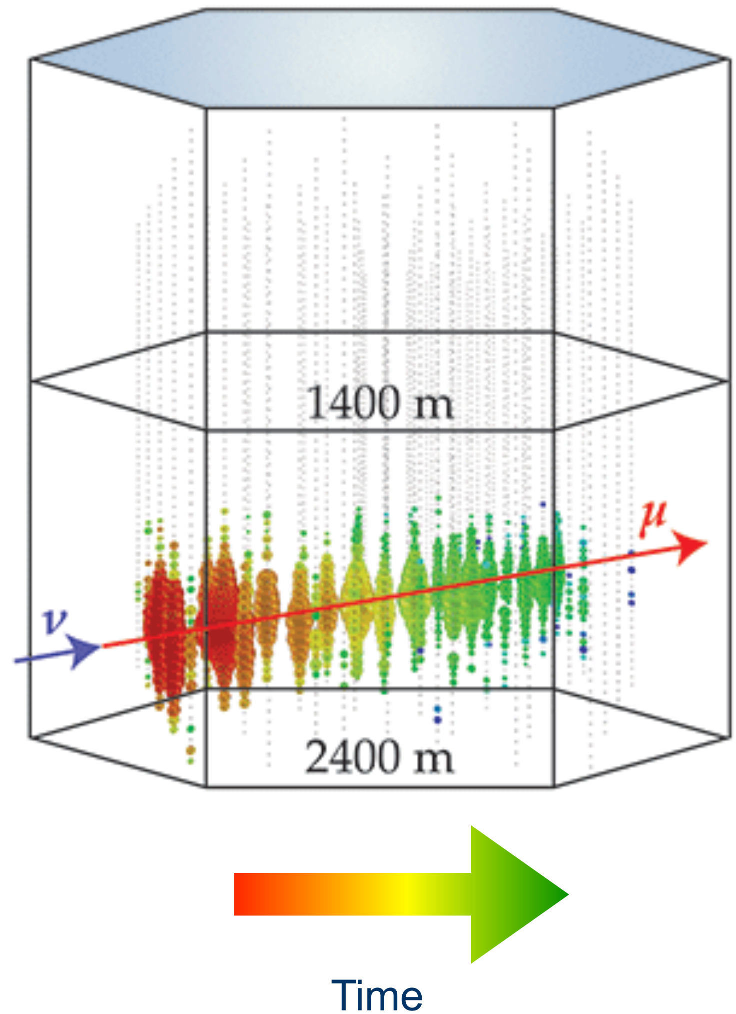
$$\Phi(E) = (2.2 \pm 0.4) \times 10^{-18} \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-2.50 \pm 0.09} \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$$

The IceCube Neutrino Observatory



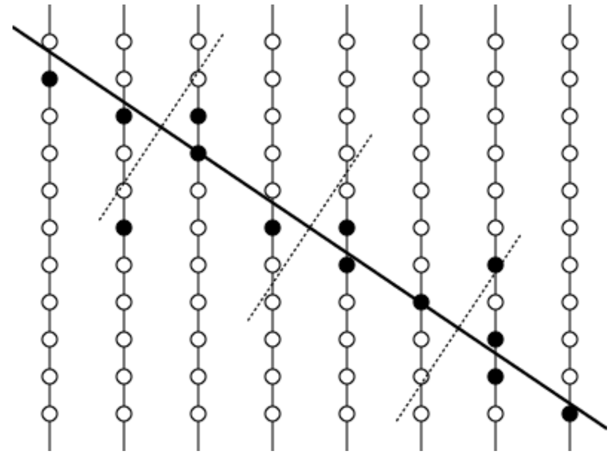
Data Sample

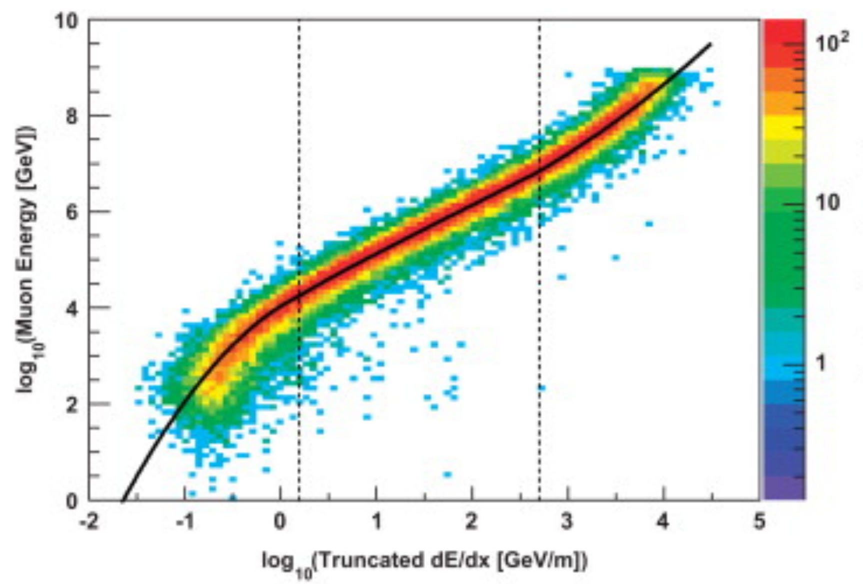
- Use a sample of upward going neutrino-induced muons
  - Cherenkov light recorded by DOMs
  - Timing information provides excellent angular resolution (< 1 degree)
- Negligible background of mis-reconstructed down-going cosmic-ray muons
- One year of data from 2010-2011 with the partially complete 79-string configuration of IceCube
- 10,784 events observed



Muon Energy Reconstruction

- Split muon track into bins and measure the mean energy loss rate, $\langle dE/dx \rangle$
- At energies > 1 TeV, $\langle dE/dx \rangle$ is correlated with muon energy
- Since muon energy losses are stochastic and have a large non-Gaussian tail, throwing out the largest 40% of bins improves performance
- Factor of ~2 muon energy resolution





R. Abbasi et al. (IceCube Collaboration)
NIM A703 (2013) 190–198

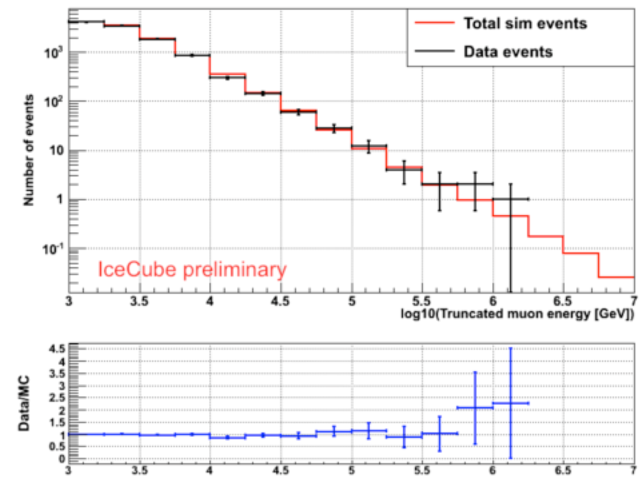
Measurement Method

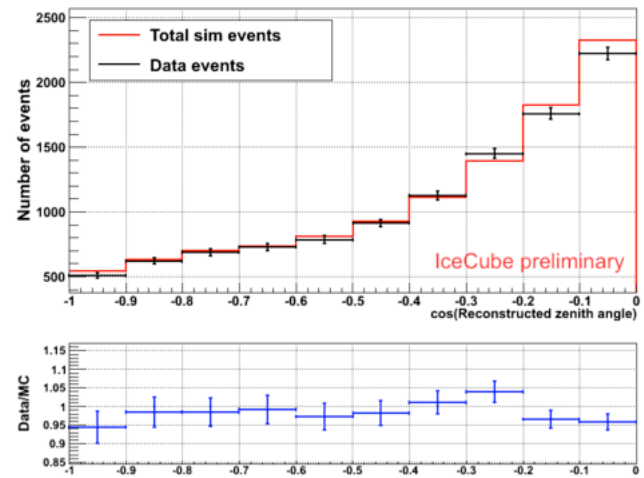
- Fit the 2D distribution of reconstructed muon energy and zenith angle

- Measure an overall scaling factor of the neutrino/anti-neutrino charged and neutral current cross sections:

$$R = \frac{\sigma_{\text{meas.}}}{\sigma_{SM}}$$

- Treat flux and detector systematic uncertainties as nuisance parameters





Systematic Uncertainties

- Systematics considered, in rough order of importance:
  - Ice model: light absorption and scattering
  - Atmospheric flux:
    - Pion/kaon production ratio
    - Neutrino/antineutrino ratio
    - Cosmic ray spectral index
  - Astrophysical flux:
    - Spectral index and normalization
  - DOM optical efficiency
  - Earth density profile
  - Atmospheric density profile

Fit Results

- Previous IceCube flux measurements used for prior constraints on nuisance parameters
- Since the Standard Model cross section was assumed, constrain cross section times flux normalization
- No large deviations from expected values of nuisance parameters

Result	Baseline/units	Nuisance Parameter Input & uncertainty σ	Nuisance Parameter Fit result
$\Phi_{\mathrm{Conv.}} \times \sigma$	Ref. [25] $\times R$ ($R = \sigma_{\mathrm{meas.}}/\sigma_{\mathrm{SM}}$)	1.0 ± 0.25	0.92 ± 0.03
$\Phi_{\mathrm{Conv.}}$ spectral index	Ref. [25] with knee	0.00 ± 0.05	$+0.007 \pm 0.001$
K/π ratio	Ref. [25] baseline	1.0 ± 0.1	1.05 ± 0.09
$\nu/\bar{\nu}$ ratio	Ref. [25] baseline	1.0 ± 0.1	1.01 ± 0.005
$\Phi_{\mathrm{prompt}} \times \sigma$	Ref. [26]$\times R$	$0.0^{+1.0}_{-0.0}$	$0.5^{+0.40}_{-0.34}$
$\Phi_{\mathrm{astro.}} \times \sigma$	Ref. [10]$\times R$	2.23 ± 0.4	$2.62^{+0.05}_{-0.07}$
Astrophysical index (γ)		2.50 ± 0.09	2.42 ± 0.02
DOM Efficiency	IceCube Baseline	1.0 ± 0.1	1.05 ± 0.01

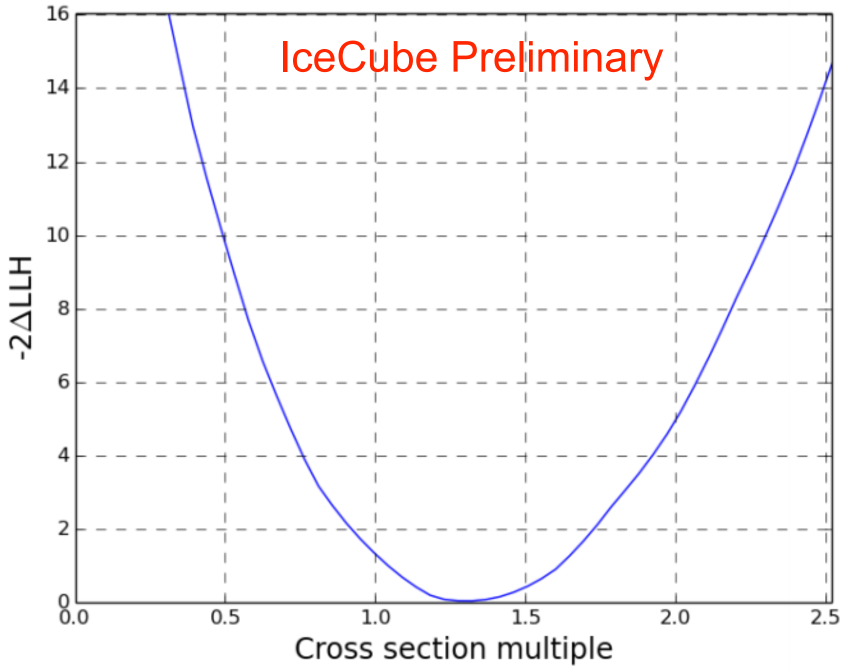
IceCube Preliminary

Cross Section Result

- Log-likelihood ratio scan across cross section multiple
- Zero absorption in the Earth strongly rejected
- Best-fit multiple of cross section:

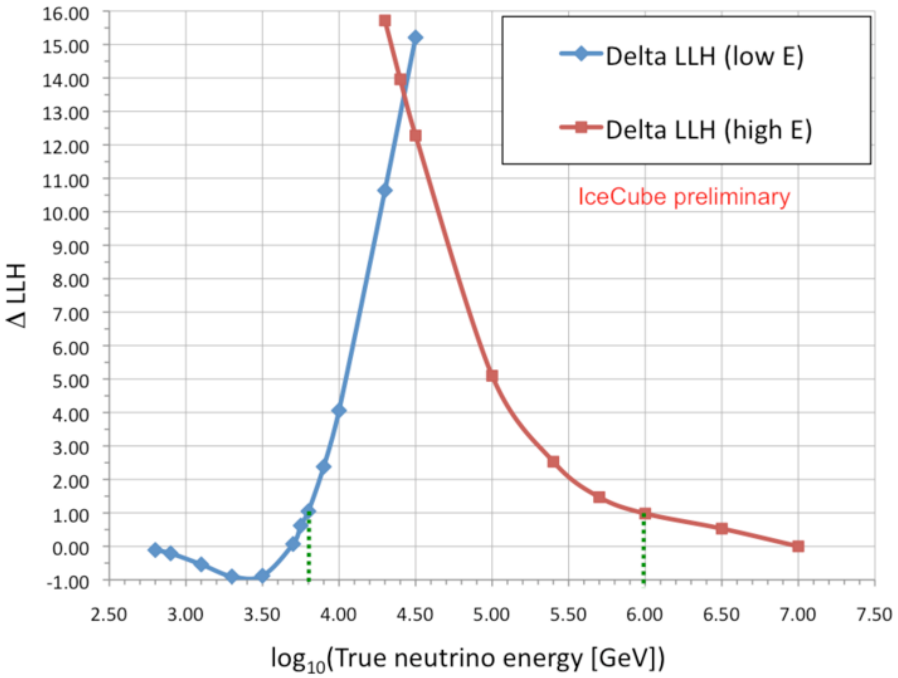
$$\frac{\sigma_{\text{meas.}}}{\sigma_{SM}} = 1.30^{+0.21}_{-0.19}\,(\text{stat.})\,^{+0.39}_{-0.43}\,(\text{syst.})$$

- Consistent with Standard Model cross section within statistical and systematic uncertainties



Sensitive Energy Range

- Over what energy range is there sensitivity to neutrino absorption?
- Consider the Earth to be transparent below a given low energy threshold
- Move the threshold upward until the log-likelihood ratio becomes $-2\Delta\mathrm{LLH} = 1$
- Repeat for a high energy threshold moving downwards
- Sensitive energy range:
  6 TeV - 980 TeV



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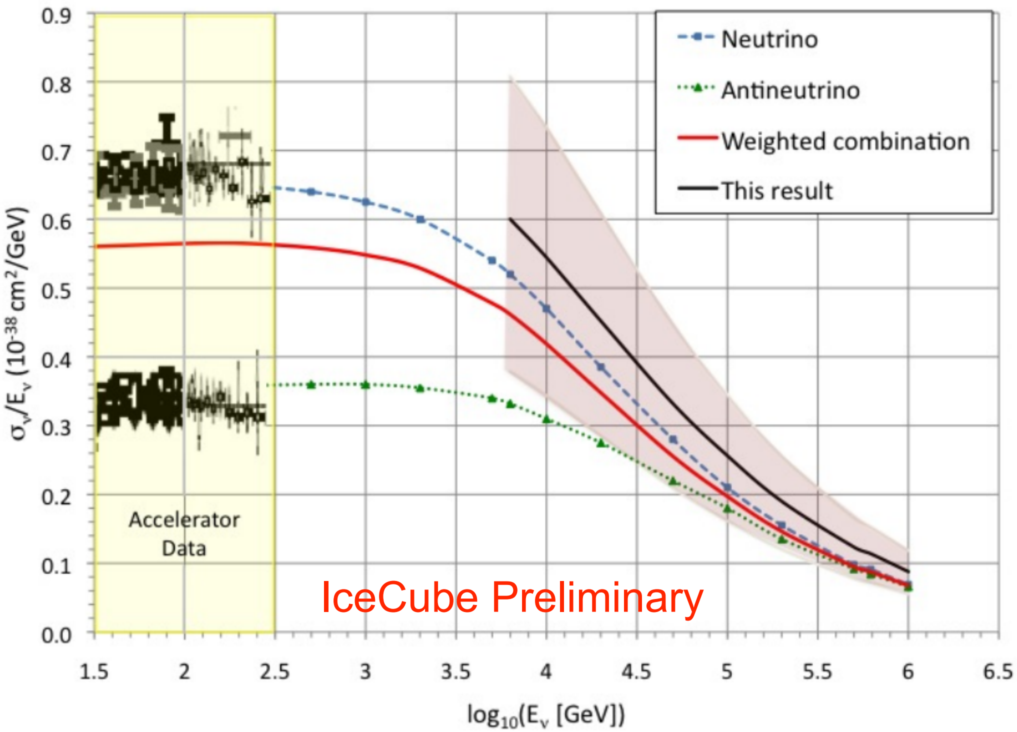
Comparison to Previous Results



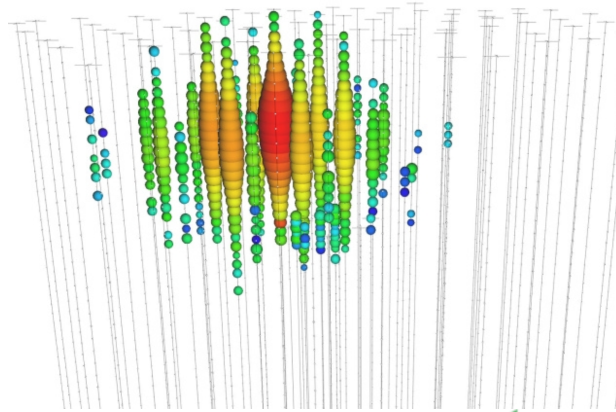
- 2 orders of magnitude higher in energy than previous accelerator-based measurements
- Measurement reflects a flux-weighted sum of neutrinos and antineutrinos
- First measurement where the DIS cross section is no longer linear in energy
- Consistent with current Standard Model calculations

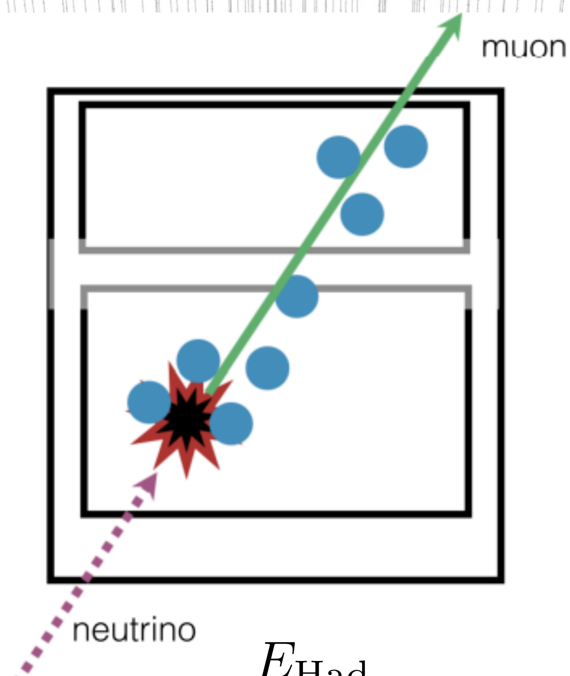
Future Directions

- 6 more years of data are available and could reduce uncertainties below 20% and enable a binned measurement across energy

- Additional neutrino detection channels are useful:
  - Cascades: Gain more high energy ν_e and ν_τ events
  - Starting tracks: Reconstruct inelasticity when the interaction vertex is contained; measure differential cross section, $d\sigma/dy$

2 PeV cascade

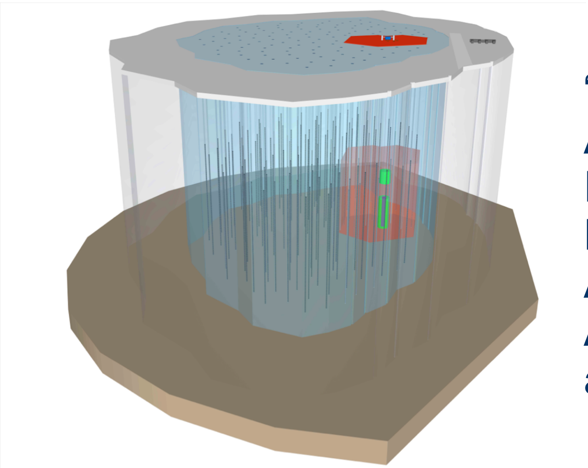




$$y = \frac{E_{\text{Had}}}{E_\nu}$$

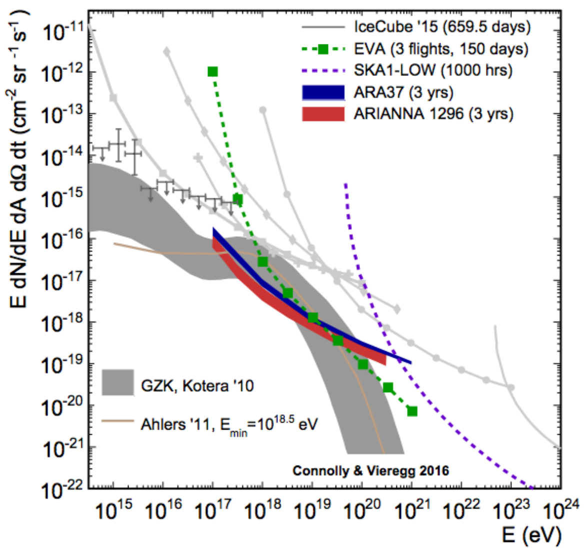
Future Directions

- The ~10 km^3 IceCube-Gen2 expansion could reach even higher energies



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

- Radio detection techniques (e.g. ARIANNA/ARA) could access the most interesting energies > 100 PeV using GZK neutrinos



See parallel by S. Klein on Wed. 6/21