Neutrino absorption in the Earth and measurement of the neutrino-nucleon cross section with IceCube

Sandra Miarecki, Spencer Klein, Gary Binder

Lawrence Berkeley National Laboratory and UC Berkeley

For the IceCube Collaboration

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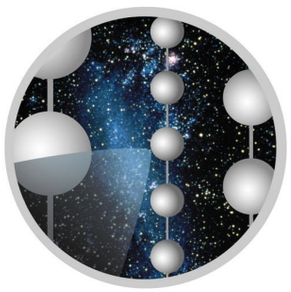
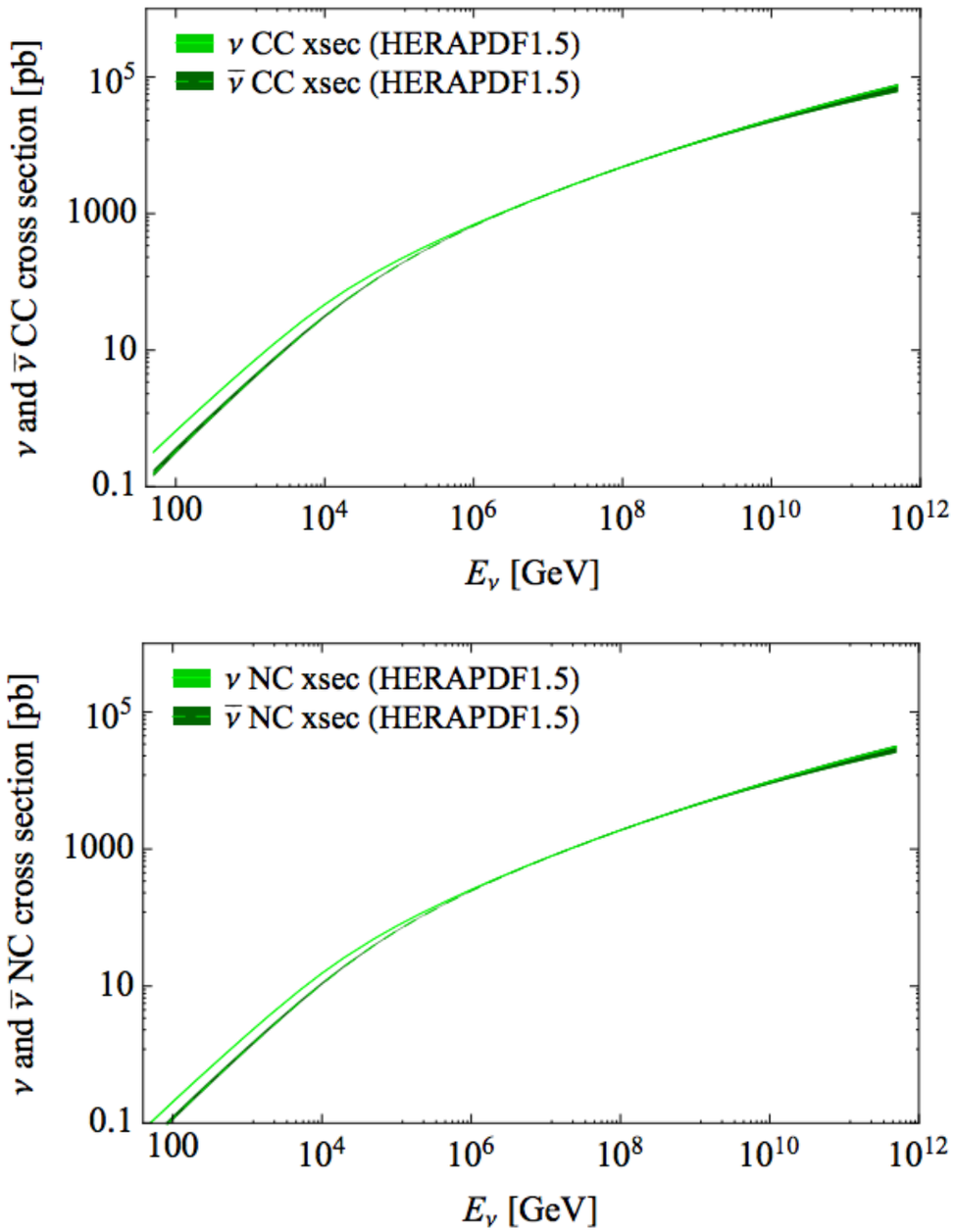


Neutrino-Nucleon Cross Section

- At energies above ~10 GeV, neutrinos resolve the parton structure of the nucleon —deep inelastic scattering
- The DGLAP formalism in QCD is used to predict and fit parton distribution functions (PDFs) at collider experiments
- Only a few percent uncertainty in the neutrino cross section up to ~1 EeV is allowed by PDF fits to HERA data
- Several effects could change this picture:
  - Gluon saturation and nuclear effects
  - Physics beyond the Standard Model: leptoquarks, extra dimensions, …



"The high energy neutrino cross-section in the Standard Model and its uncertainty" Cooper-Sarkar, Mertch, Sarkar JHEP 08 (2011) 042

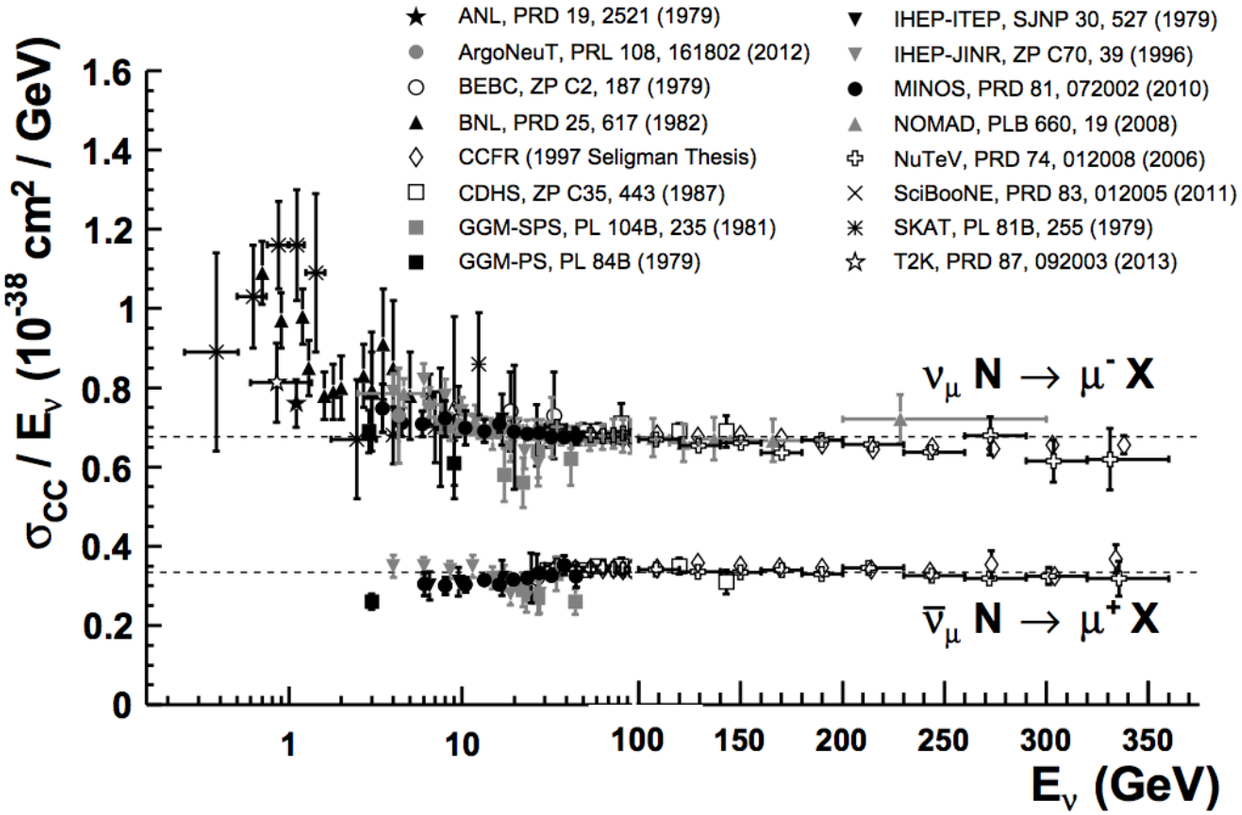
Previous Measurements

- Measurements of the neutrino cross section from accelerator neutrino beams extend up to 360 GeV

- These rely on (sometimes poor) knowledge of the absolute flux of the neutrino beam to obtain the correct normalization of the cross section

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

- Neutrino telescopes can extend this measurement up to higher energies by observing the attenuation of neutrino fluxes in the Earth



PDG 2014
"Neutrino Cross Section Measurements"
Chin. Phys. C, 38, 090001 (2014)

Earth Absorption

- The propagation of atmospheric and astrophysical neutrinos through the earth breaks the degeneracy between cross section and flux

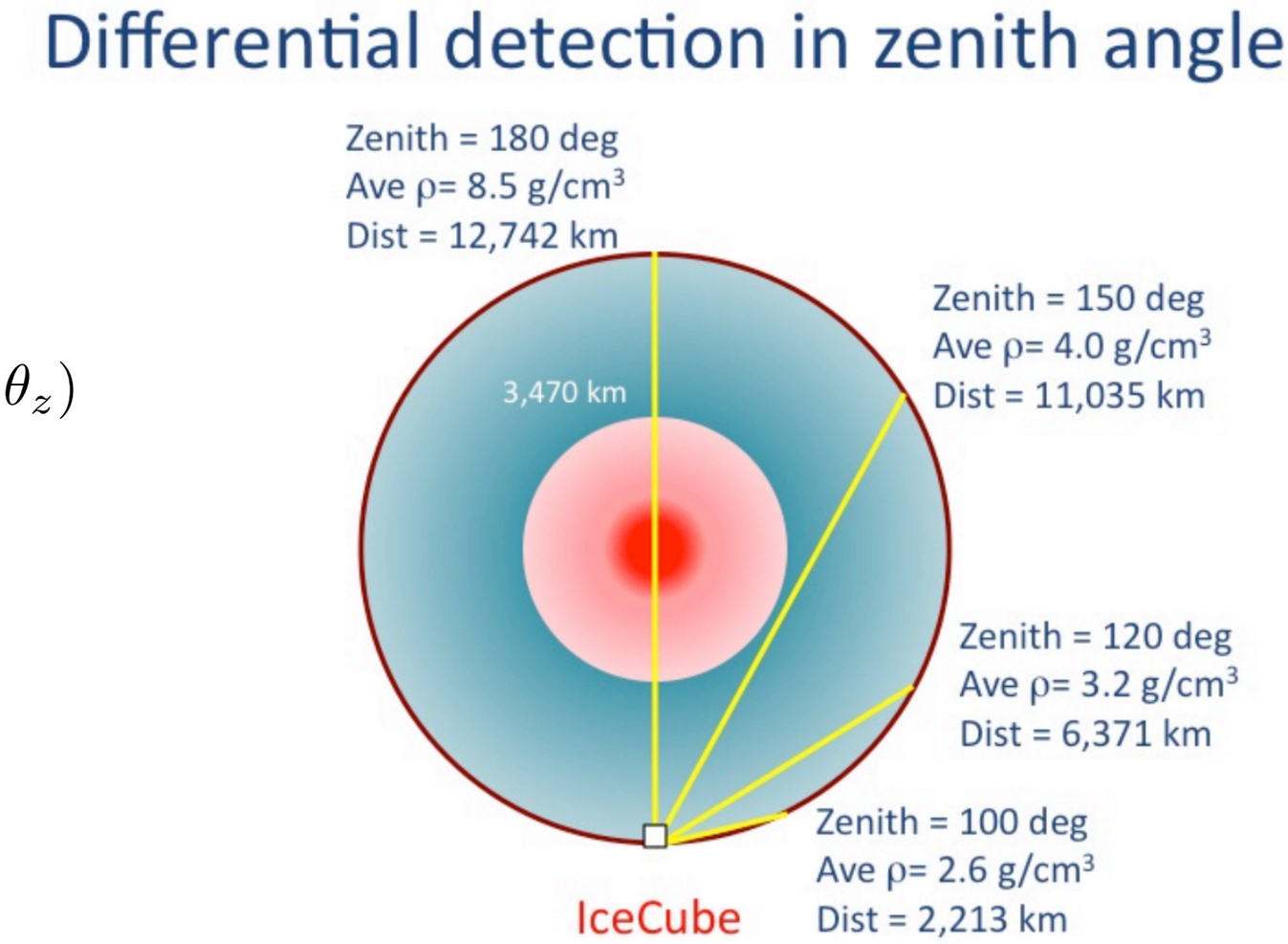
- Neutrino fluxes are attenuated:

$$\frac{dN}{dEd\Omega} \propto \sigma(E)\Phi(E,\cos\theta_z)P(E,\cos\theta_z)$$

$$P(E,\cos\theta_z) \approx e^{-\sigma(E)X(\theta_z)/M_N}$$

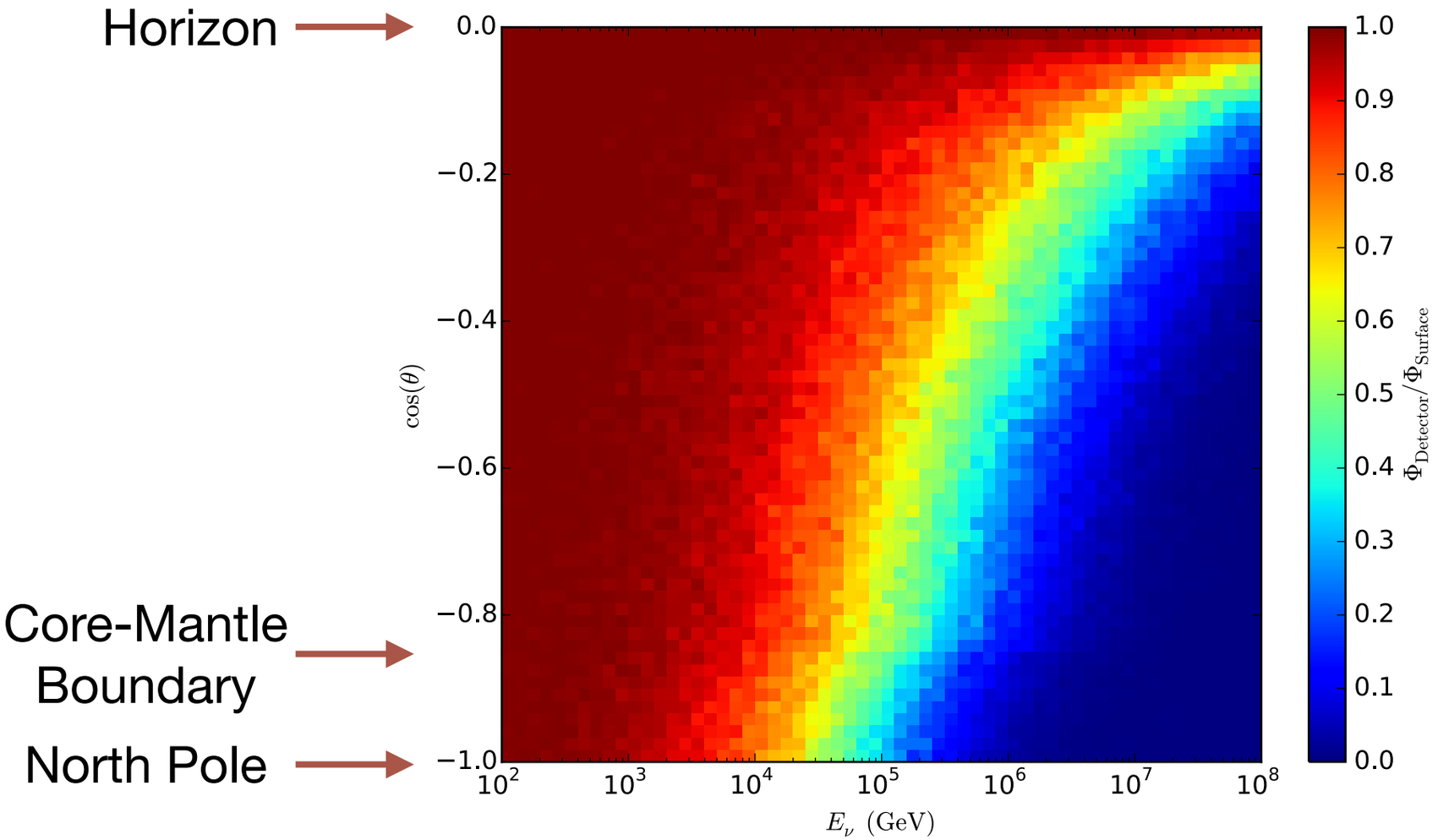
- Neutral-current interactions complicate attenuation, requiring a full Monte Carlo calculation

- Knowledge of the zenith-angle behavior the flux and the density profile of the Earth is necessary



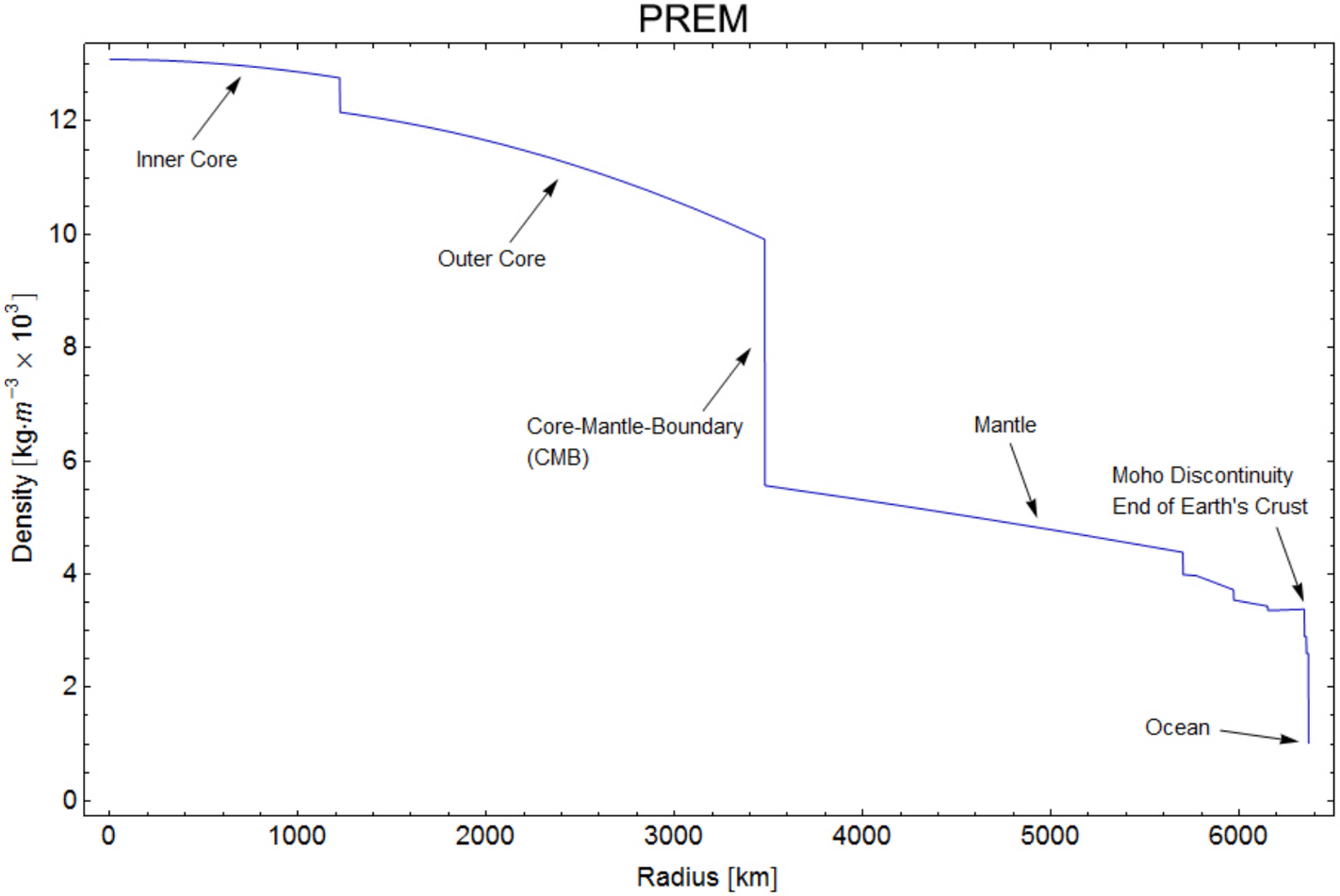
Attenuation Factor

- 50% attenuation occurs at ~30 TeV for vertical up-going neutrinos at the South Pole



Earth Model

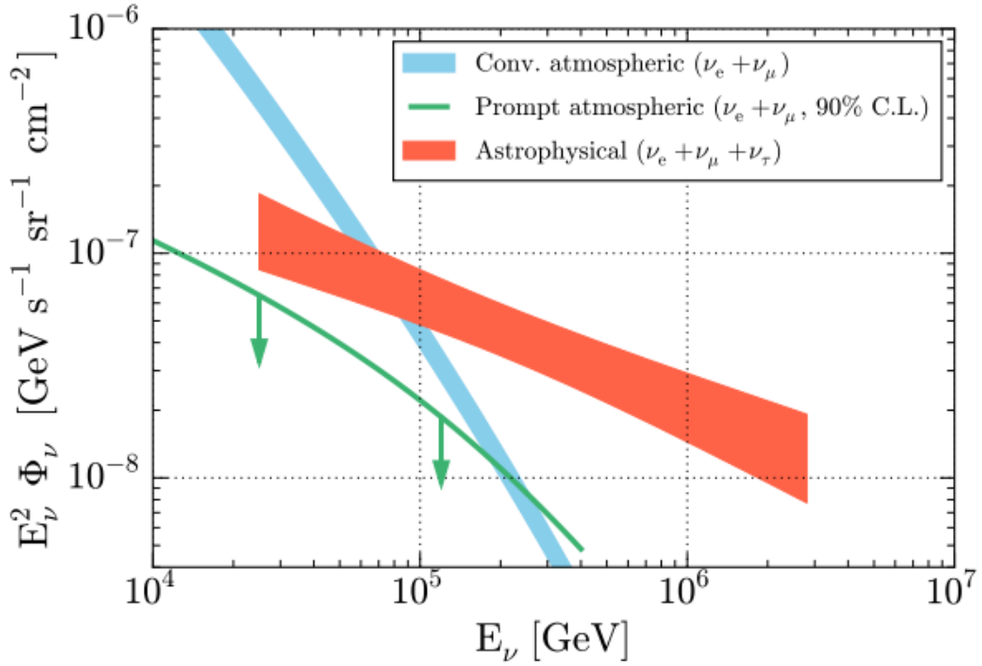
- ~5% uncertainties in the density and radius of various layers derived from seismological data
- Possible deviations constrained be preserving the well known total mass of the earth and moment of inertia.



Neutrino Fluxes

- Need to carefully parametrize uncertainties on both atmospheric and astrophysical fluxes
- Rely on previous IceCube flux measurements
- Because these have assumed the Standard Model cross section and have essentially only measured an event rate, the derived normalization of fluxes is really only a constraint on the product of cross section and flux

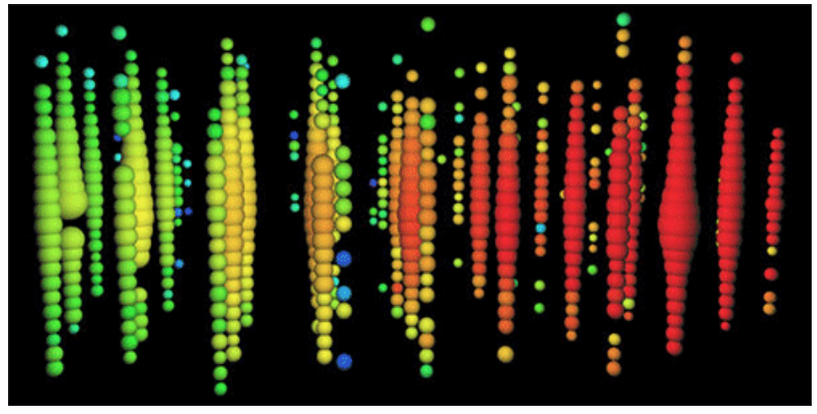
Flux Parameter	Uncertainty
$\frac{\sigma}{\sigma_{\mathrm{SM}}}\Phi_{\mathrm{Conv.}}$	1.0 ± 0.25
$\Delta\gamma_{\mathrm{Cosmic\ Ray}}$	0.0 ± 0.05
K/π factor	1.0 ± 0.10
$\nu/\bar{\nu}$ factor	1.0 ± 0.10
$\frac{\sigma}{\sigma_{\mathrm{SM}}}\Phi_{\mathrm{Prompt}}$	$0.0^{+1.0}_{-0.0}$
$\frac{\sigma}{\sigma_{\mathrm{SM}}}\Phi_{\mathrm{Astro.}}$	2.23 ± 0.4
$\gamma_{\mathrm{Astro.}}$	2.5 ± 0.09

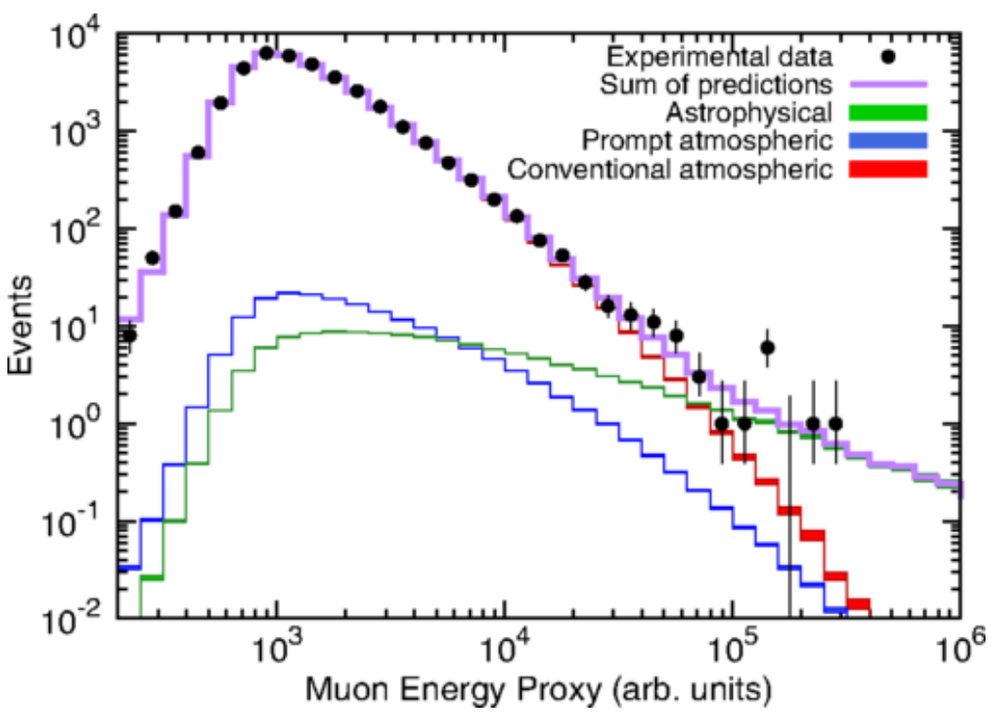


"A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube"Astrophysical Journal 809, 98 (2015)

Data Sample

- Using the same selection of up-going neutrino induced muons used to observe the northern sky astrophysical neutrino flux
- Currently, only using one year of data from the 79 string configuration taken in 2010 - 2011
- Using truncated dE/dx for muon energy estimation
- Method:
  - Likelihood fit of the 2D muon energy proxy and cos(zenith) distribution
  - Parametrize (most) systematic uncertainties
- Goal: Constrain one overall scaling factor of the CC/NC and $\nu_\mu/\bar{\nu}_\mu$ cross sections from the Standard Model





"Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube"
Phys. Rev. Lett. 115, 081102 (2015)

Systematics

Importance

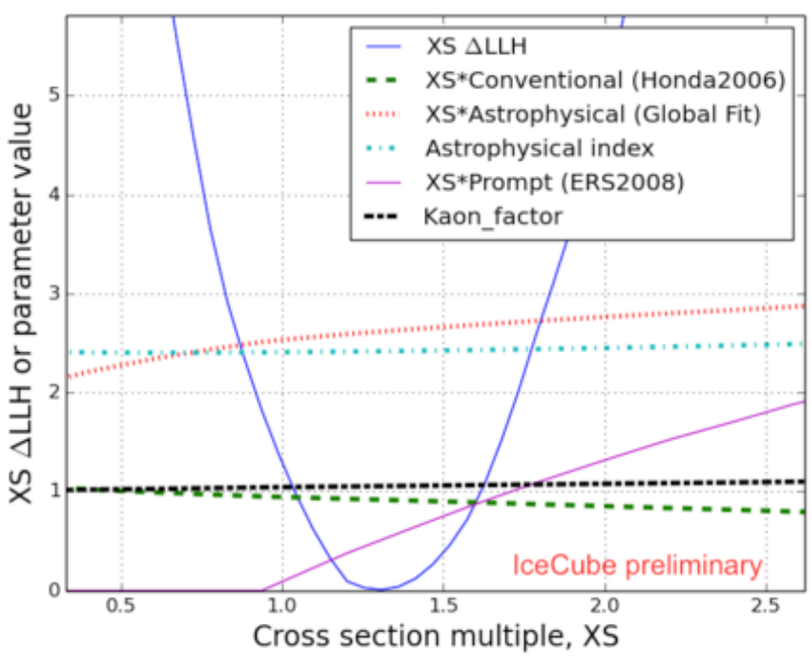
Systematic Uncertainty	Treatment
Ice Model	Discrete 10% scaling of the bulk ice scattering and absorption coefficients
Astrophysical Flux	Discrete choice of different measurements of the astrophysical power law index and normalization
Atmospheric Fluxes	Continuous parametrization of spectral index, pion/kaon, neutrino/anti-neutrino, and prompt flux uncertainties
Optical Efficiency	Continuous parametrization; largely an overall scaling uncertainty
Earth Density Model	Discrete 10% changes in layer radii and density
Atmospheric Temperature	Discrete choice of US Standard Atmosphere or NRLMSIS00 model with seasonal and latitude temperature variations
Hole Ice	Turning hole ice on or off

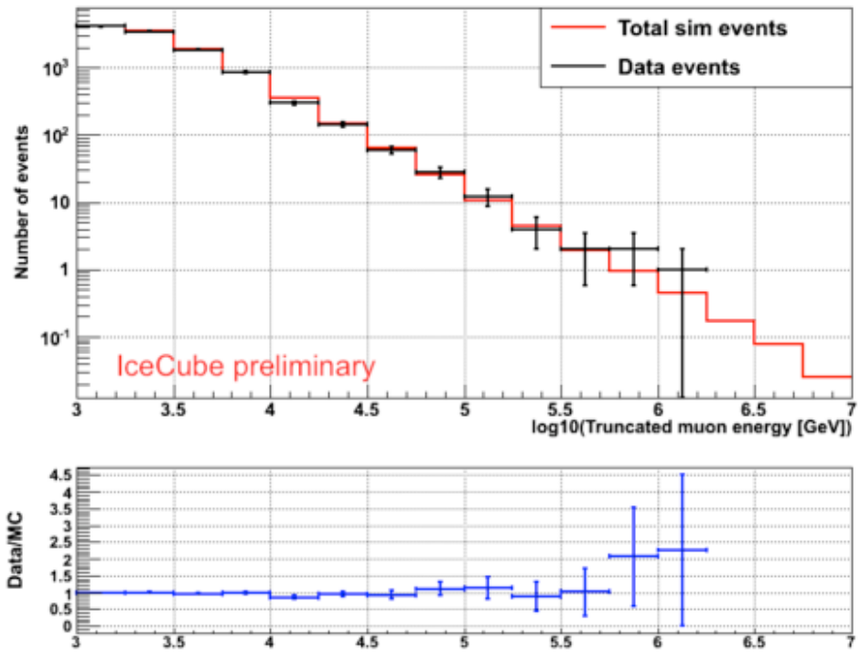
Final Result

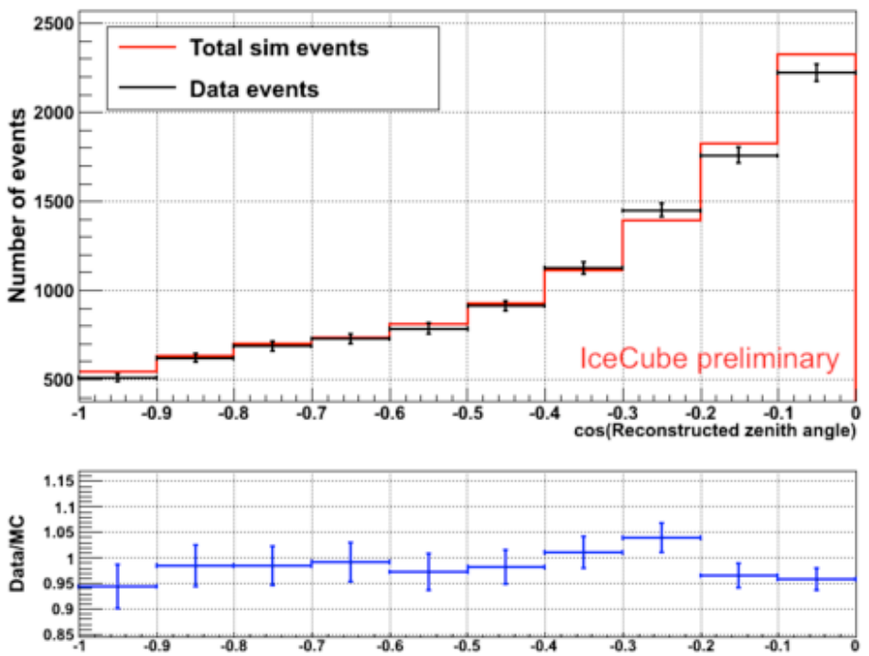
- 10,784 events observed in one year
- Best-fit energy and zenith distributions:
- Cross section multiple:

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} = 1.30^{+0.30}_{-0.26}\,(\mathrm{stat.})\,^{+0.32}_{-0.40}\,(\mathrm{syst.})$$

- Preliminary: final systematic error estimate still under review
- Likelihood profile:



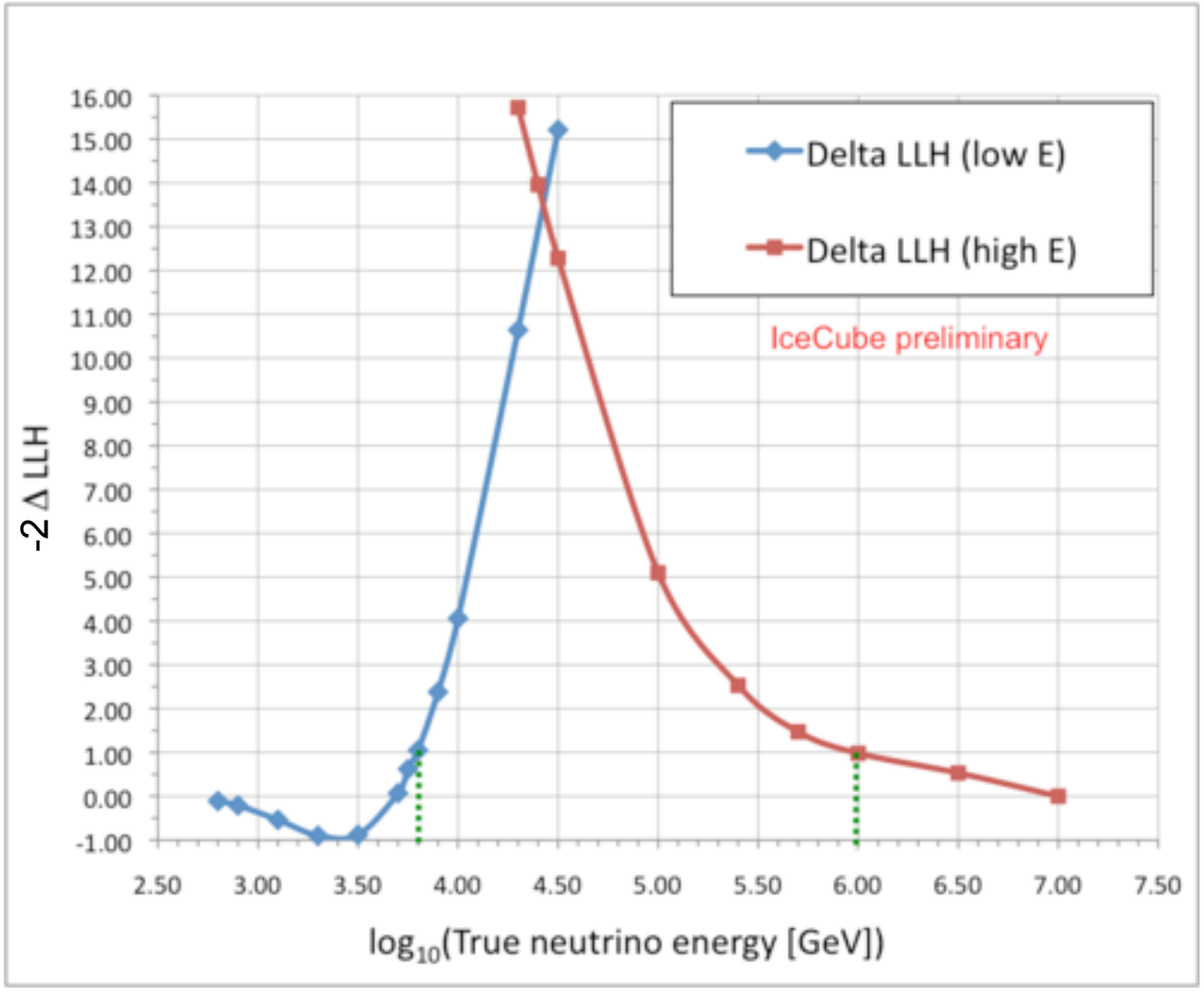




Energy Range

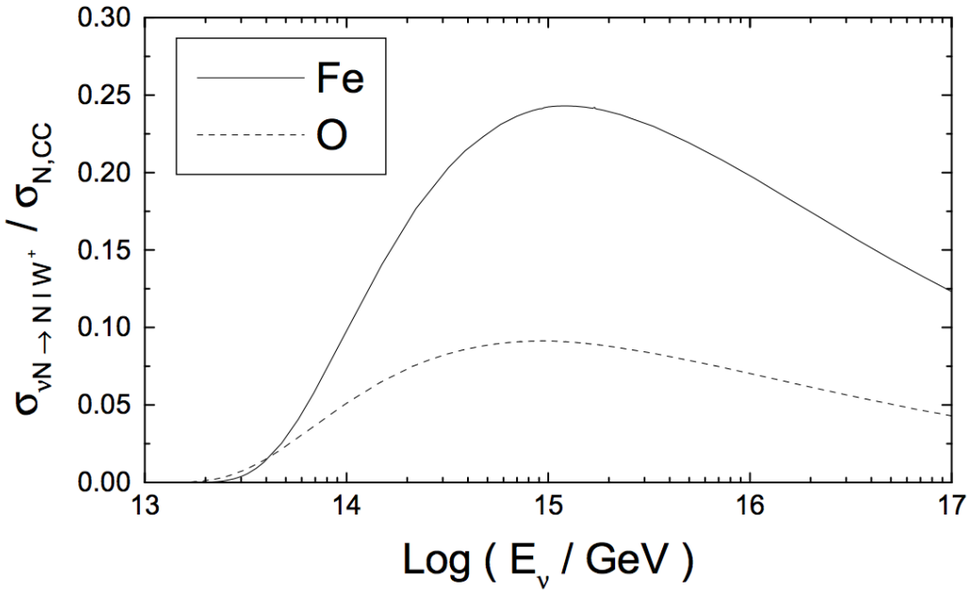
- Over what energy range are we sensitive to the cross section?
- Consider the earth to be transparent below a certain neutrino energy threshold
- Move the threshold until $-2\Delta\mathrm{LLH} = 1$
- The same can be done for a high energy threshold
- Sensitive energy range:

  $6.3\,\mathrm{TeV} - 980\,\mathrm{TeV}$



Future Steps

- 5 more years of data are waiting to be analyzed
- Do a binned measurement of cross section across energy
- Perform specific model tests
  - W boson production in nuclear Coulomb field may be observable
    - $\nu_\mu N \to \mu^- W^+ N$
    - Produces a unique signature depending on the composition of the Earth's interior
  - Non-Standard Model scenarios



"Neutrino-photon reactions in astrophysics and cosmology" Phys.Rev.Lett.80:900-903,1998

Summary

- IceCube can perform a measurement of neutrino cross section completely independent of uncertainties on the normalization of the neutrino flux or detection efficiency
- Sensitive up to ~1 PeV with 1 year of data
- Need to rely on previous measurements of the atmospheric and astrophysical flux to constrain the energy and zenith dependent uncertainties on the neutrino flux
- Systematics-dominated; ice model and flux uncertainties drive result
- More data should alleviate these issues
- Paper in progress