# Measurement of the neutrino-nucleon cross-section at multi-TeV energies with the IceCube Neutrino Detector

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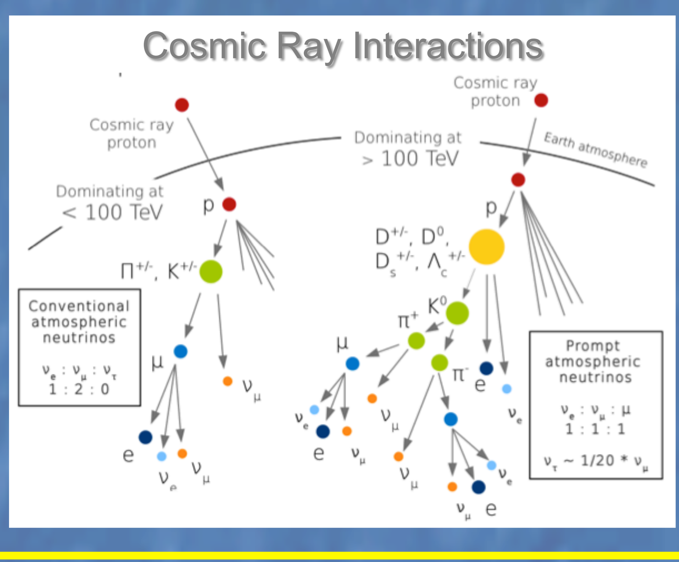
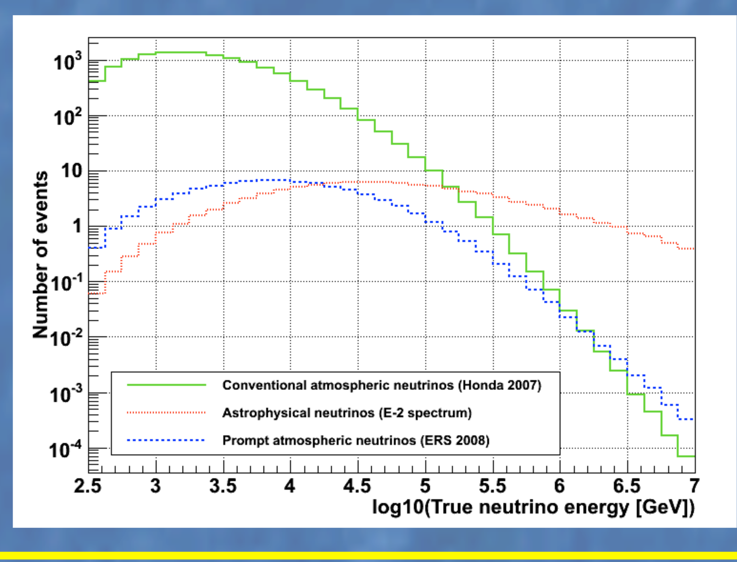
## Source: Muon neutrinos from cosmic rays

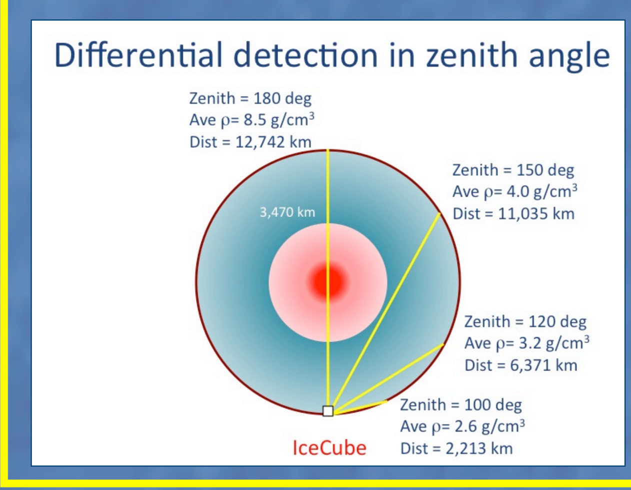
- **Flux of atmospheric and astrophysical $\nu_\mu$**
  - Isotropic cosmic rays interact with atmosphere [Gaisser, Elbert]
  - Resulting kaons and pions decay into "conventional" $\nu_\mu$ [Honda et al 2007]
  - Charm atmospheric neutrino component ("prompt") [ERS 2008]
  - "Astrophysical" neutrinos from the universe's acceleration mechanisms
  - Available flux is 98% conventional, 1.4% astrophysical, and 0.6% prompt

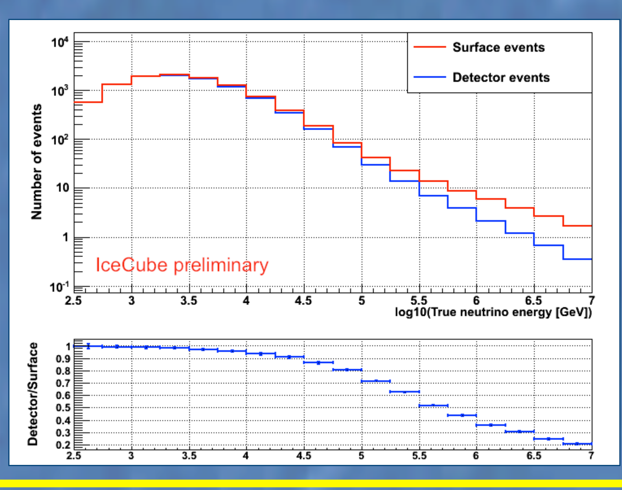


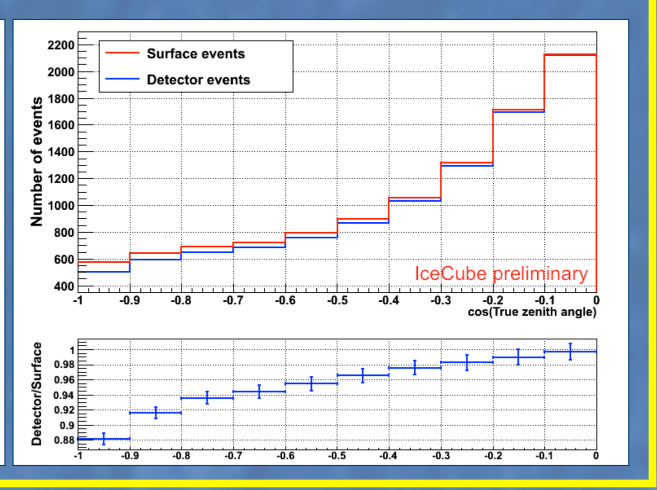




## Target: Earth

- **Earth density model: Preliminary Reference Earth Model [PREM 1981]**
  - Observe/measure neutrino absorption in the Earth
  - Differential density changes spectrum from surface to detector
  - Earth diameter = interaction length at ~40 TeV

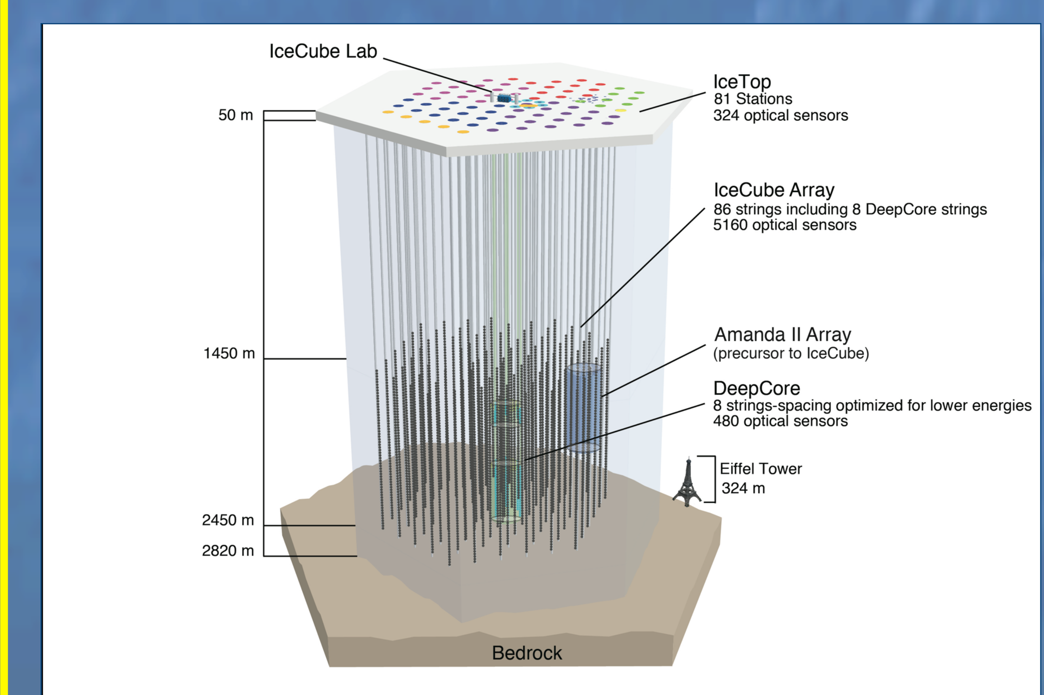



## Detector: IceCube Neutrino Detector

- **Neutrino astrophysics with world's largest neutrino telescope**
  - Detects Cherenkov photons from charged particles
- **Located at South Pole in deep clear glacial ice (1450 - 2450 m deep)**
  - 1 $km^3$ instrumented volume, or ~1 Gigaton
- **5160 optical sensors (digital optical modules, DOMs) deployed on 86 strings, 60 DOMs per string, 125-m grid, plus surface array IceTop**
  - Particle energy range ~ 10 GeV – 1 EeV ($10^9$ GeV)
  - Muon neutrino direction < $\pm$1 degree, muon energy $\pm$50%
  - Average detector uptime 99.8% taking data year-round
- **Collaboration of 300 members from 48 institutions in 12 countries**

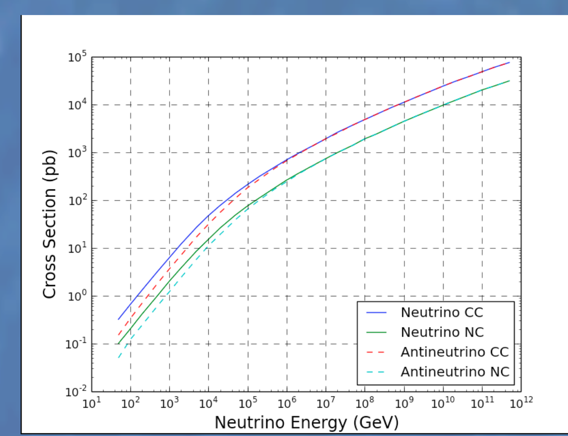



## References


- Cosmic rays: Gaisser, Astropart. Phys. 35 (2012) 801-806
- Cosmic ray knee correction: Elbert, DUMAND Summer Workshop Vol 2 (1978)
- Atmospheric neutrinos: Honda et al., Phys Rev D 75 (2007) 043006
- Prompt neutrinos: Enberg, Reno, & Sarcevic, Phys Rev D 78 (2008) 043005
- PREM: Dziewonski & Anderson, Phys. Earth Planet. Inter., 25 (1981) 297-356
- Neutrino model: Cooper-Sarkar, Mertsch, & Sarkar, JHEP 1108 (2011) 042
- Diffractive neutrinos: Seckel, Phys Rev Let 80 (1998) 5
- Truncated Energy: IceCube Collaboration, NIM A 703 (2013) 190-198
- Astrophysical neutrinos: IceCube Collaboration, ApJ 809 (2015) 98


## Cross section baseline

- **Total cross section for NC and CC interactions for $\nu_\mu$ and $\bar{\nu}_\mu$**
  - Assumes that NC and CC cross sections scale together
  - Result does not account for diffractive neutrinos [Seckel 1998]
- **Cooper-Sarkar, Mertsch, Sarkar [CSMS 2011]**
  - Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) formalism of next-to-leading-order (NLO) QCD for CC and NC cross sections using HERAPDF1.5
  - Sensitive to very small Bjorken-x (down to $10^{-5}$)
  - Energy range extended to 5 x $10^{20}$ eV (500 EeV)
  - Theoretical CC cross section ~47 pb at 10 TeV
  - Expected theoretical uncertainty ~5%

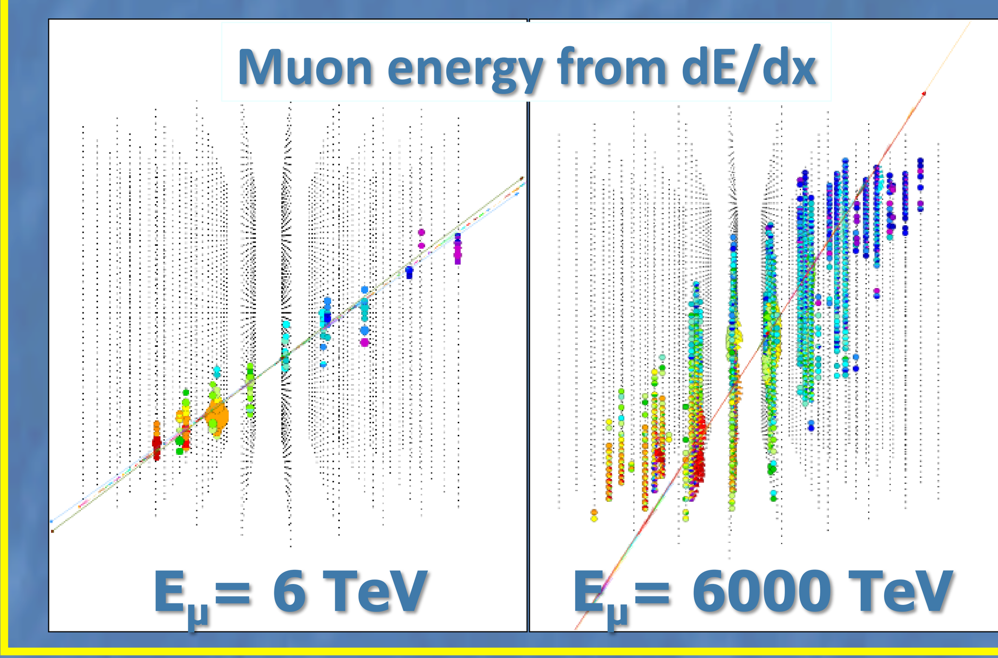


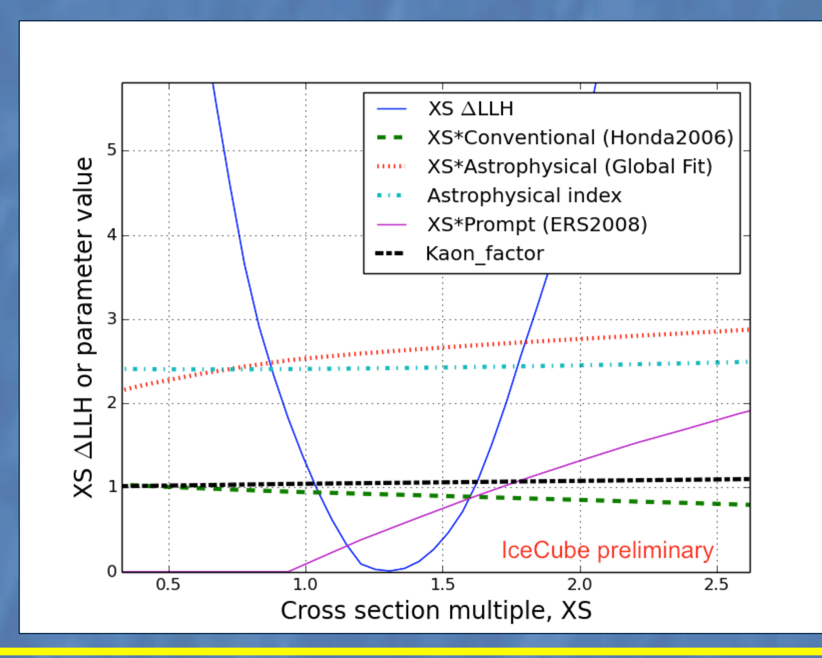

## Simulation

- **Source simulation from NeutrinoGenerator (NuGen)**
  - Monte Carlo that creates, propagates, and interacts up-going neutrinos
  - Can vary cross section models to generate expectations for fitter
- **Background simulation from CORSIKA**
  - Cosmic ray muon (down-going) events for background rejection
  - Signal to background ~ 1:$10^6$ events, final event selection purity 99.9%

## Experimental fit

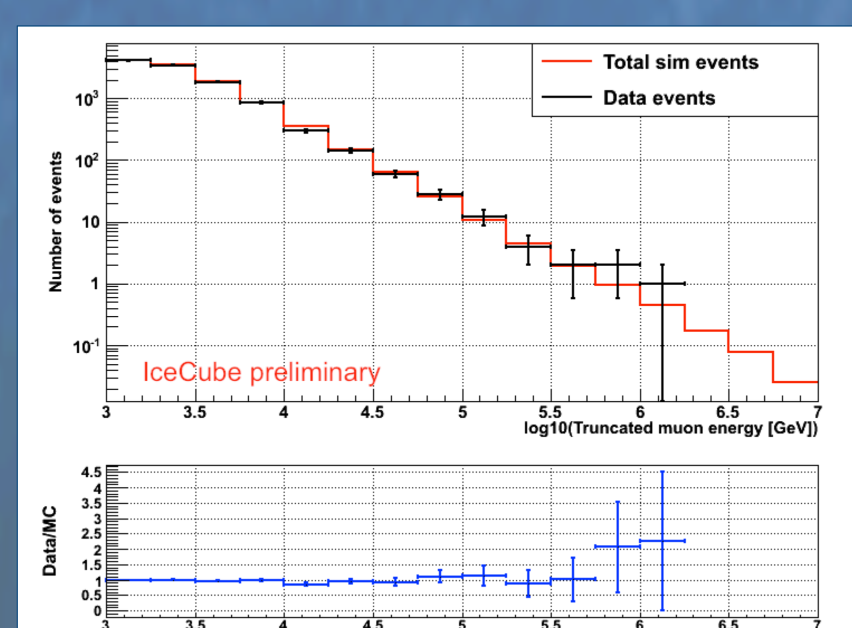
- **Event selection yielded 10,784 muon neutrinos in 2010 data year**
  - Muon energy determined by Truncated Energy method [IceCube 2013]
- **Two-dimensional LLH fit in muon energy and zenith angle**
- **Constrained by priors from other experiments**
  - Astrophysical and prompt fluxes from IceCube [IceCube 2015]
- **Fit result given as multiple of SM expectation from CSMS 2011**
  - Fit parameters included fluxes of conventional, astrophysical, prompt, plus $\nu_\mu\bar{\nu}_\mu$ ratio, kaon-pion ratio, DOM efficiency
  - Systematics included ice model, Earth model, atmospheric temperature model, and choice of astrophysical and prompt flux priors

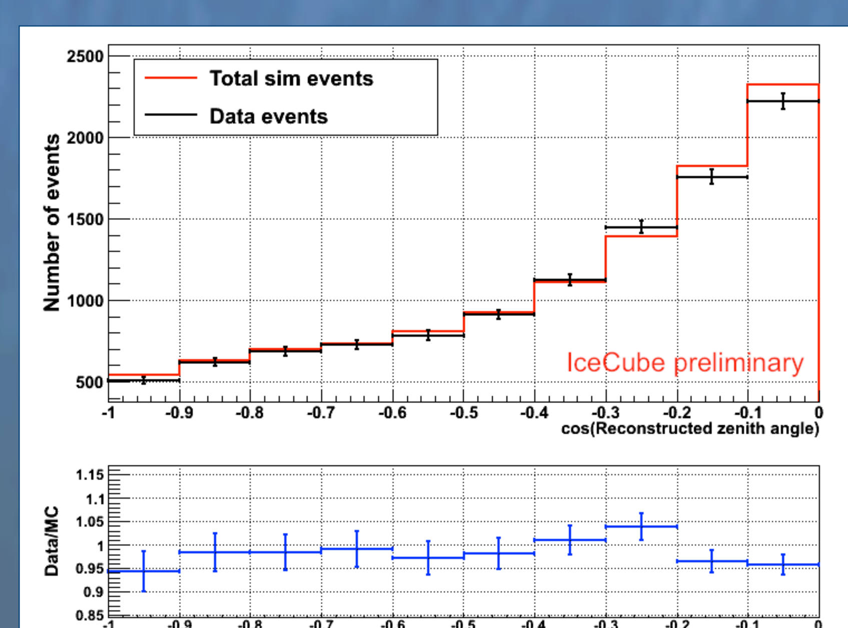



## Results

- **Total $\nu_\mu$-nucleon cross section = 1.30 $^{+0.30}_{-0.26}$ (stat.) $^{+0.32}_{-0.40}$ (syst.) times CSMS 2011 expectation**
  - **Energy range 6.3 TeV to 980 TeV**
- **In agreement with the Standard Model cross section at high energy**
- **Plans for follow-up analysis using 5+ years of data**

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