Systematics for atmospheric neutrinos in IceCube

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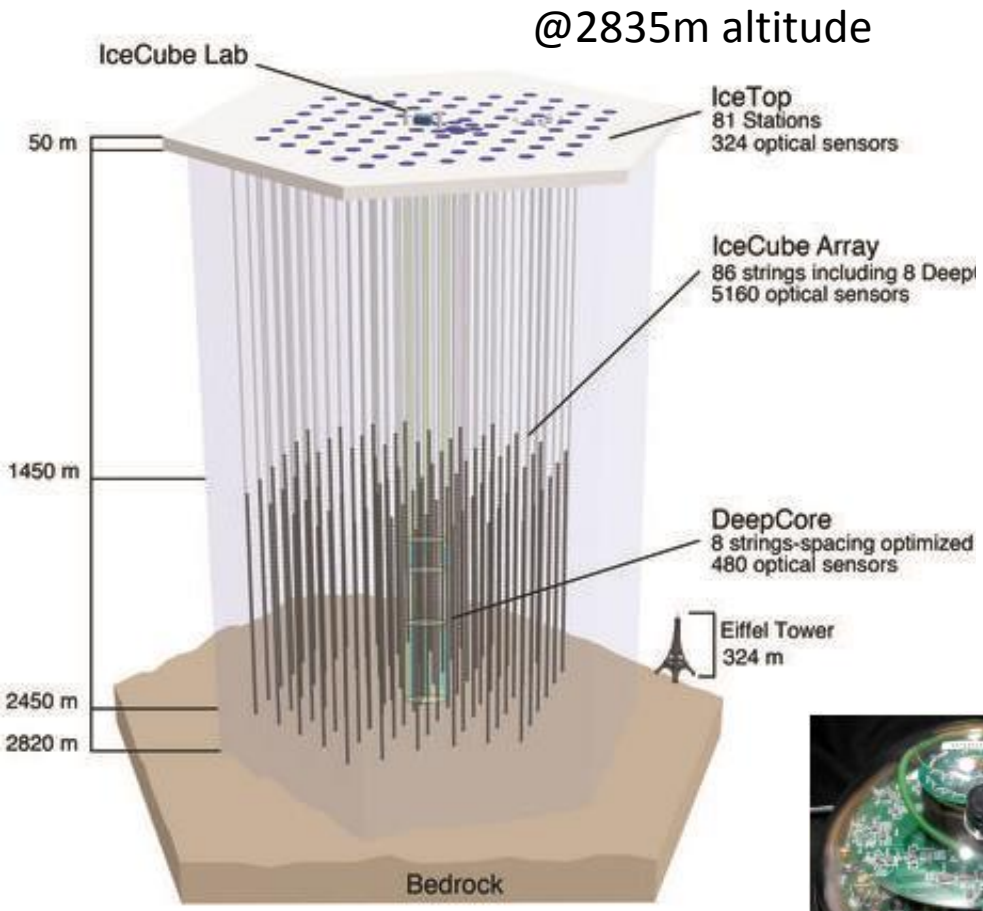
Outline

- IceCube Neutrino Observatory
- IceCube – DeepCore
- Major Systematics in IceCube
  - Detector systematics
    Digital Optical Module, Ice Property
  - νN interaction cross section
  - Atmospheric ν flux model
- Atmospheric Oscillation Analysis
  - ν_μ disappearance

IceCube neutrino observatory



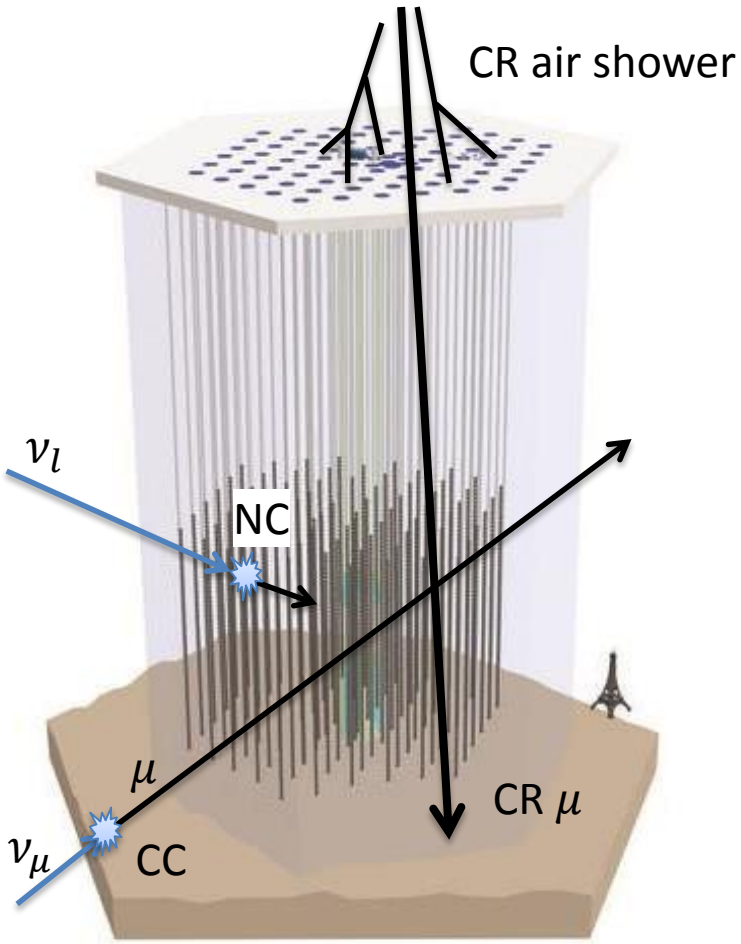
- 3D detector
  - Completed Dec 2010
  - IceTop:
    Surface array of ice tank
  - IceCube Array:
    In-ice array of DOMs
  - DeepCore:
    Infill array for low-E extension

10 inch PMT and
local DAQ electronics

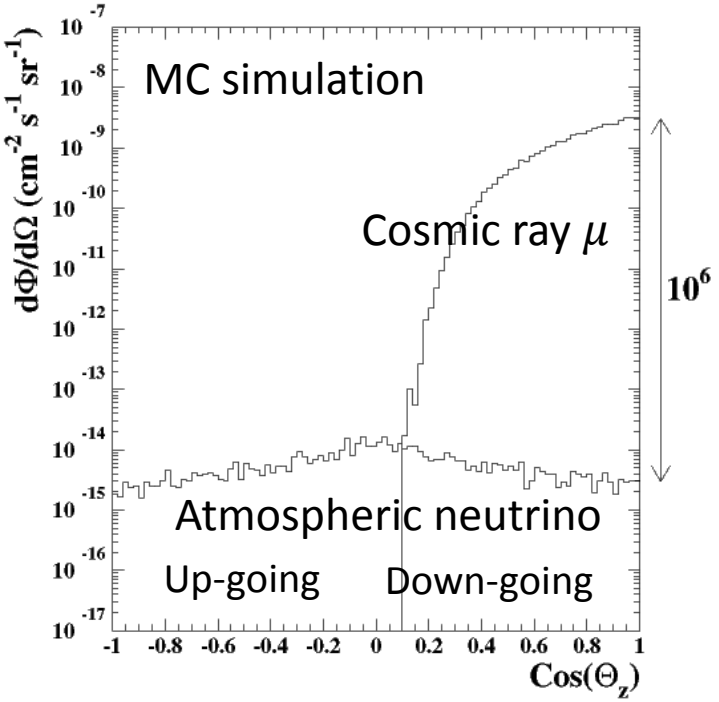
Digital Optical Modules

- 86 in-ice strings
- 60 DOMs per string
- 125m inter-string spacing

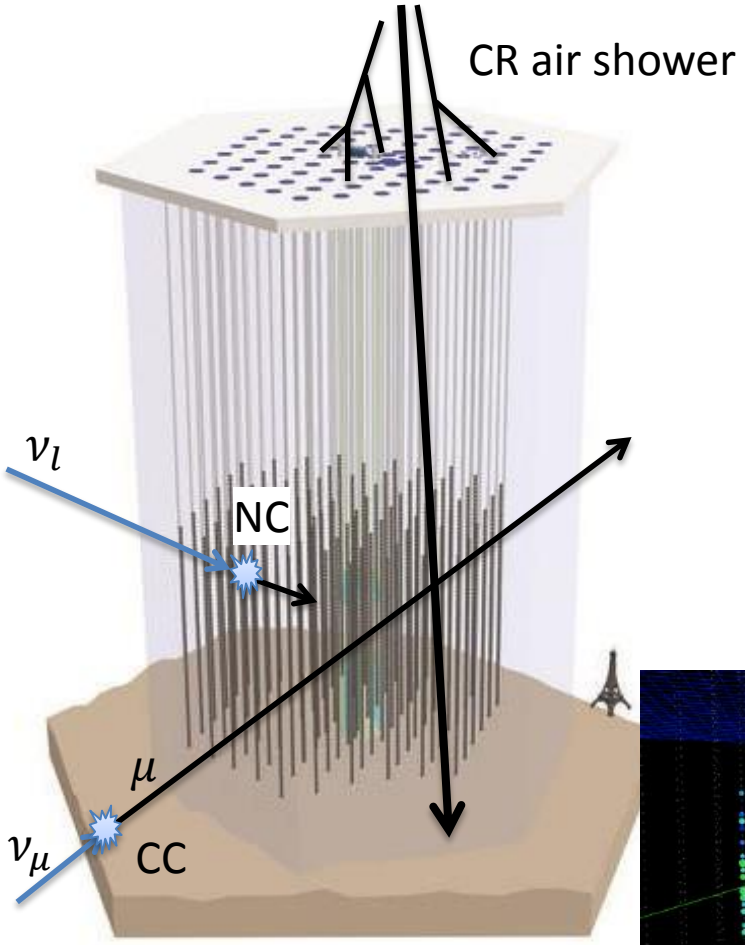
IceCube neutrino observatory



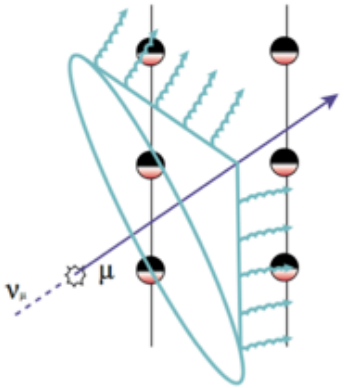
- IceCube measures
  - Cosmic Rays
    - air showers: >100 TeV, ~35 Hz
    - CR μ : > 1TeV, ~2.2kHz
  - Neutrinos: E_ν>100GeV
    - atmospheric: ~1 per million
    - astrophysical: ~1 per billion



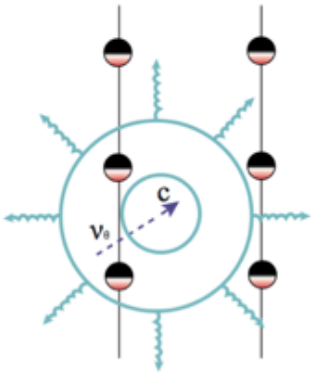
IceCube neutrino observatory



Detection principle of Neutrino Events

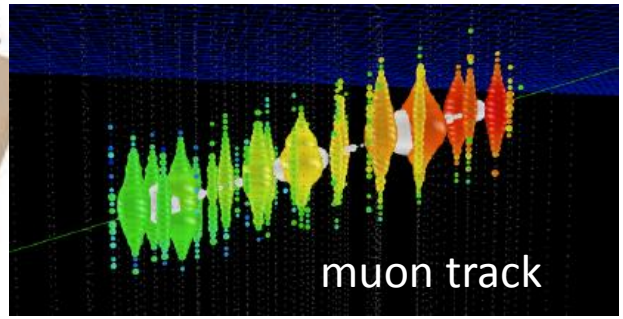


ν_μ CC-int

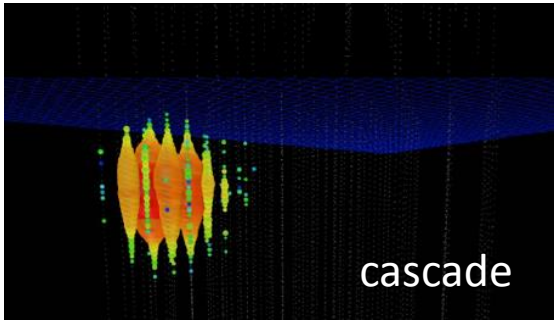


$\nu_{e,\tau}$ CC-int

$\nu_{\mu,e,\tau}$ NC-int

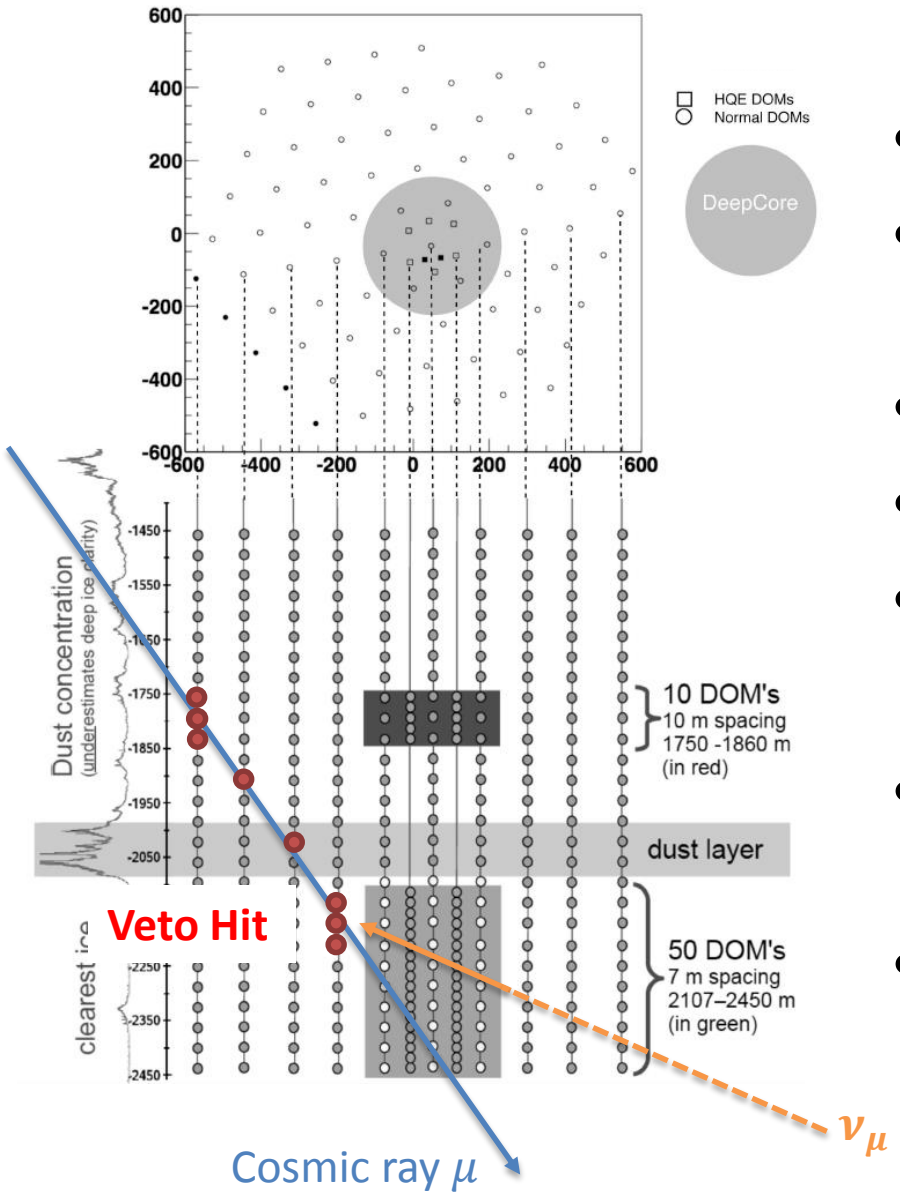


Limited energy resolution
(IceCube measures only dE_μ/dx)
Angular resolution <~1°



Energy resolution ~ 15%
Angular resolution 10°

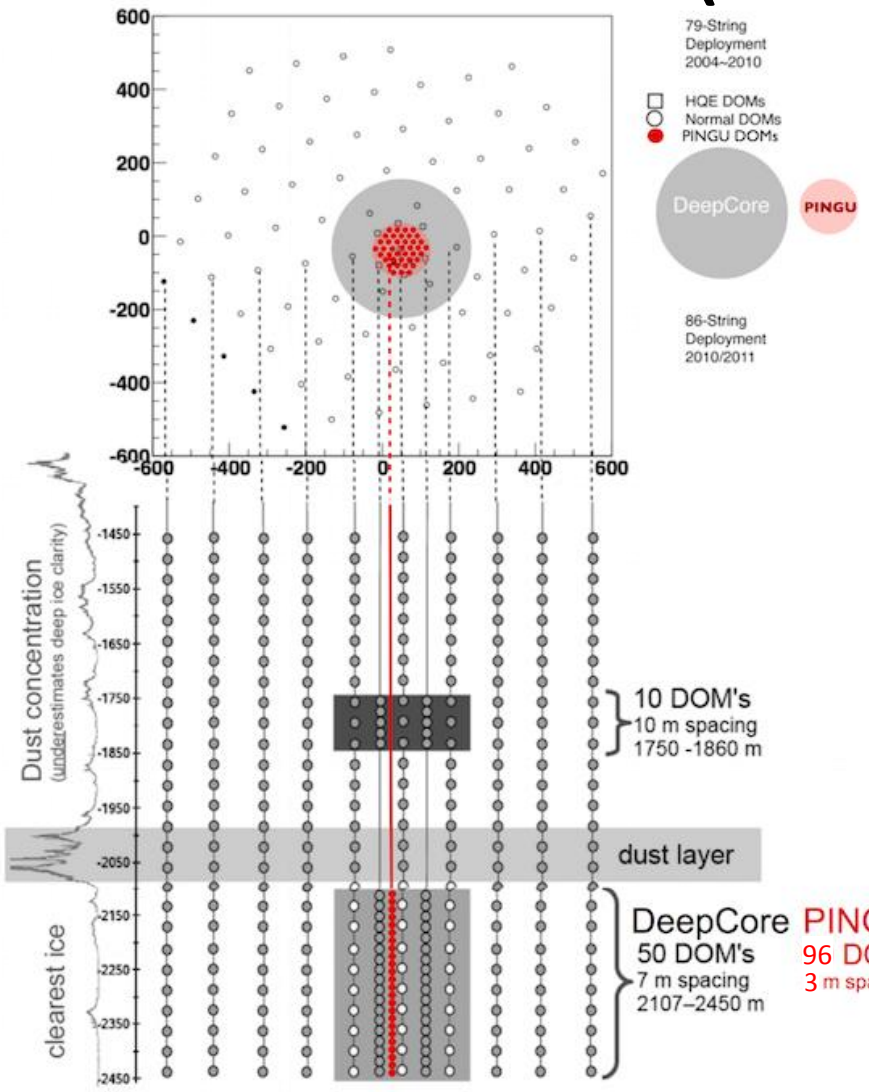
IceCube - DeepCore

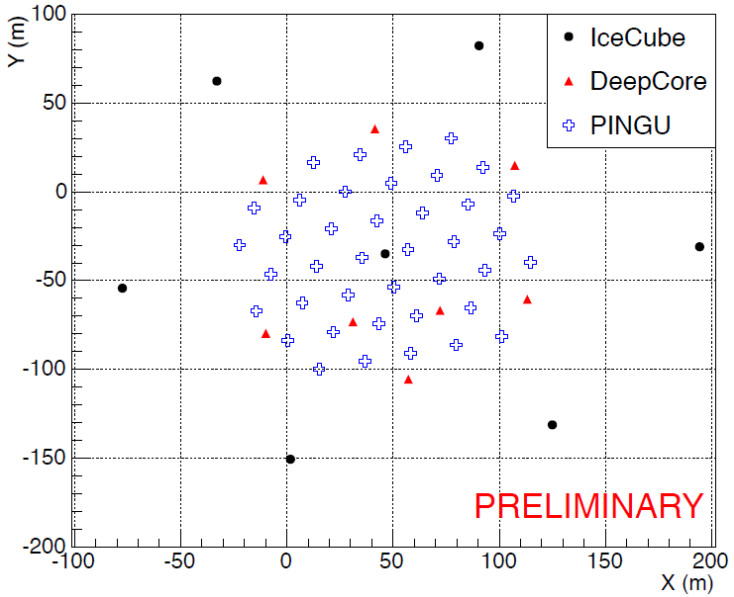


- 8 additional strings
- High Quantum Efficiency (QE) PMT
- 7m DOM vertical spacing
- 70m inter-string spacing
- In the clearest ice layer

- Use outer IceCube strings as Veto
- E_ν >10 GeV

PINGU (future upgrade)



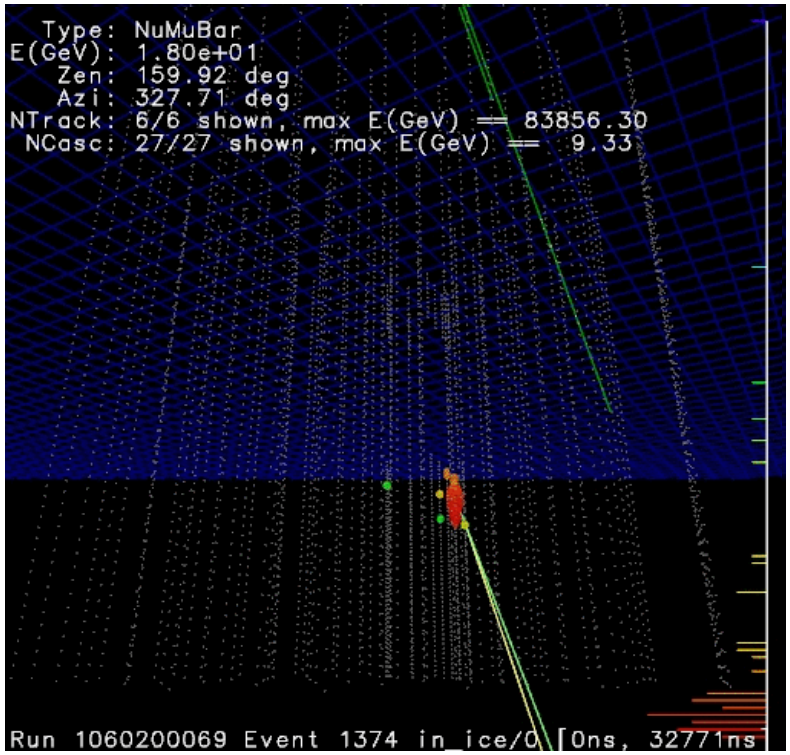


arxiv.org/abs/1510.05228

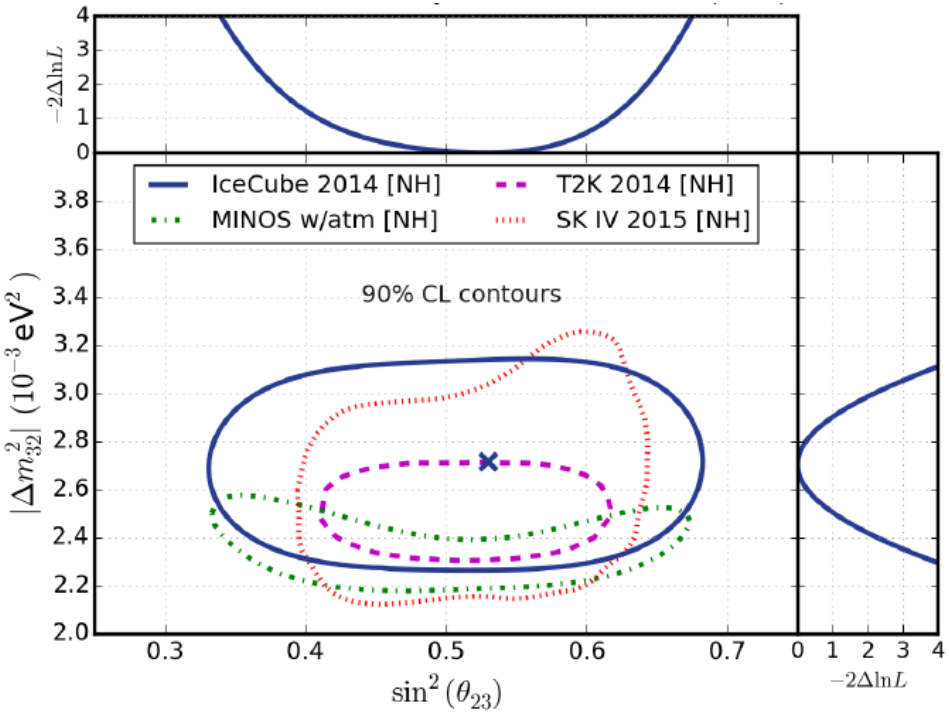
- 40 additional strings
- 96 DOMS per string with 3m DOM vertical spacing
- 22m inter-string spacing
- Energy threshold
  10 GeV → Few GeV

Letter of Intent: The Precision IceCube Next Generation Upgrade (PINGU)
arxiv.org/abs/1401.2046

IceCube - DeepCore

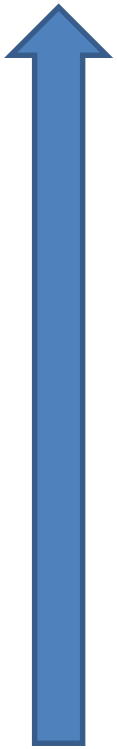


Phys. Rev. D 91, 072004, 2015



Major Systematics

large

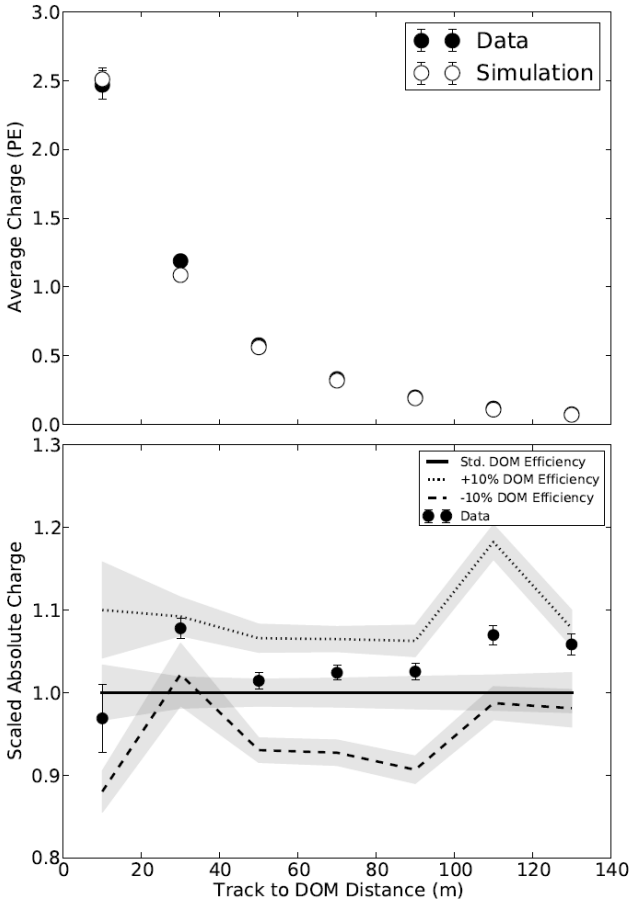


- Experimental Uncertainties
  - DOM Efficiency
  - Ice Property
- Atmospheric ν Flux
  - Normalization
    Spectrum index
    $\nu/\bar{\nu}$, ν_e/ν_μ
- νN Cross Section

DOM Light Detection Efficiency

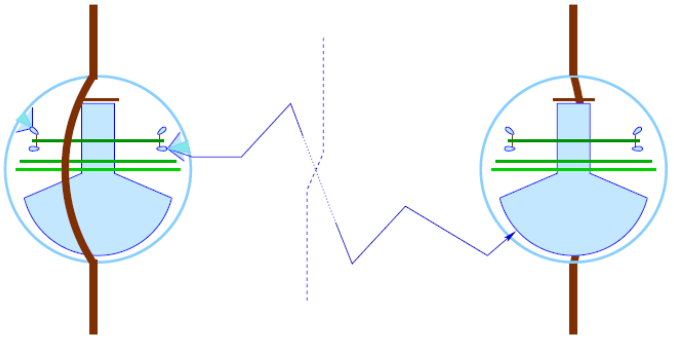
JINST 9, P03009 , 2014

Absolute charge measurements with minimum ionizing *quasi-horizontal* muons



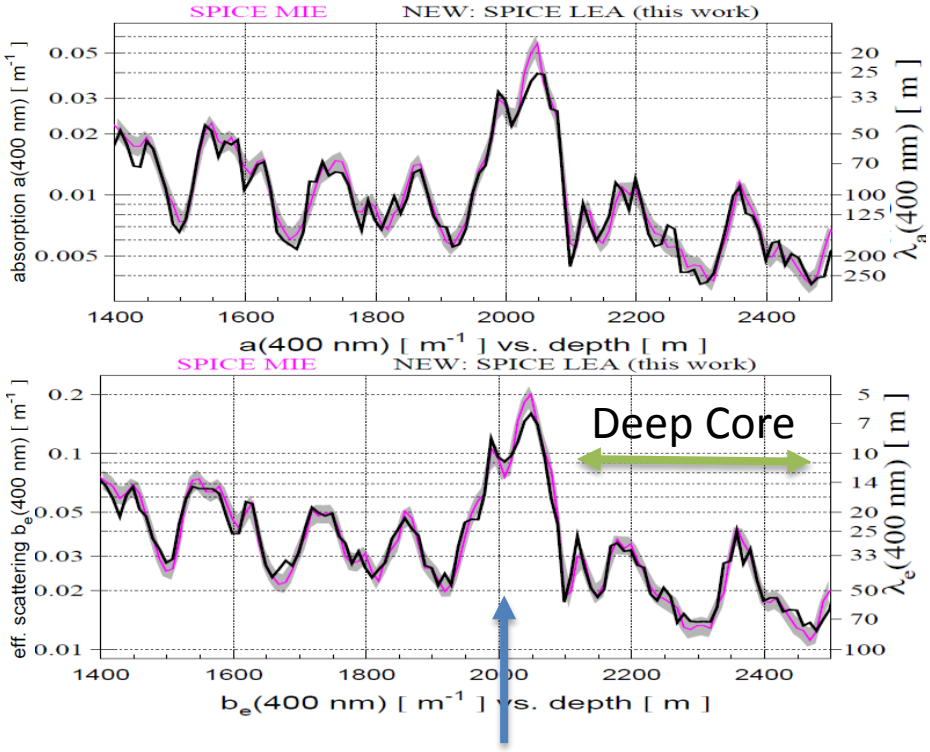
- Largest systematic at in-situ measurement
- Absolute Efficiency (~10%)
- Relative Efficiency (~3%) to DeepCore High QE DOM
- Create complete simulation sets with several values of efficiency
- Perform fit

Ice Property



Optical properties of the medium

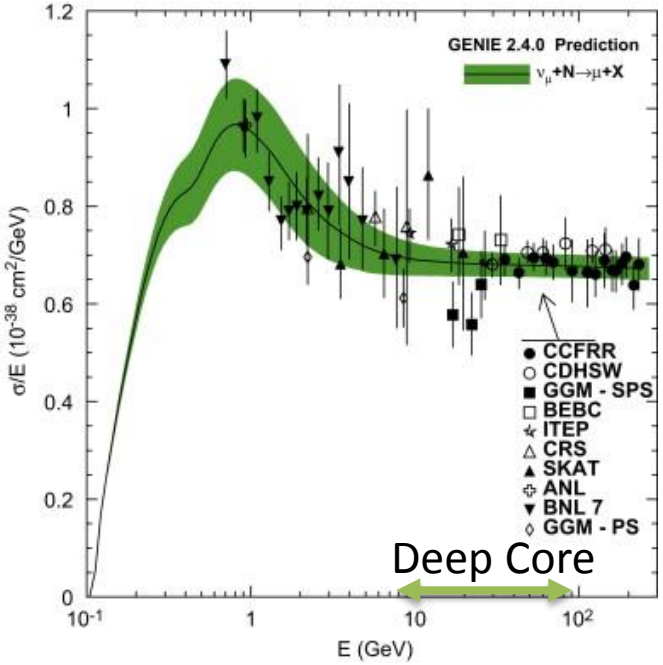
Dima Chirkin, UW-Madison, ICRC 2013



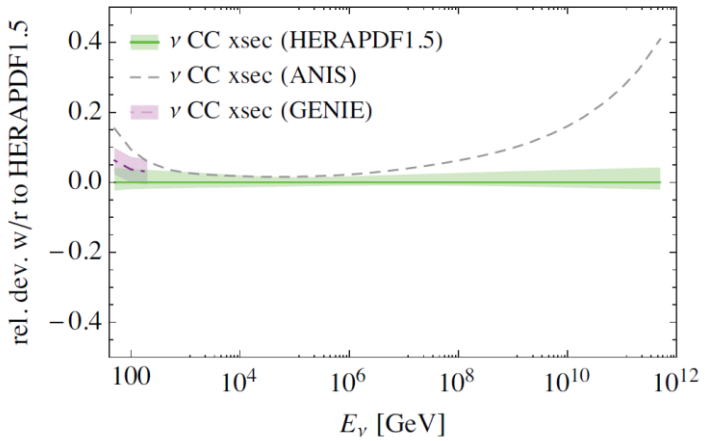
- Layered glacial ice
- Varying scattering and absorption (~10%)
- Angular acceptance of DOM in refrozen ice column (10%~30%)
- South Pole Ice Model (SPICE)
  - Model of Scattering and Absorption of light inside ice
  - Based on measurements by in-situ light source (LED) in DOMs
  - Includes optical anisotropy effect from ice flow and tilt
- Create complete simulation sets

Cross Section

GENIE, NIM A 614, 87, 2010
http://arxiv.org/abs/0905.2517



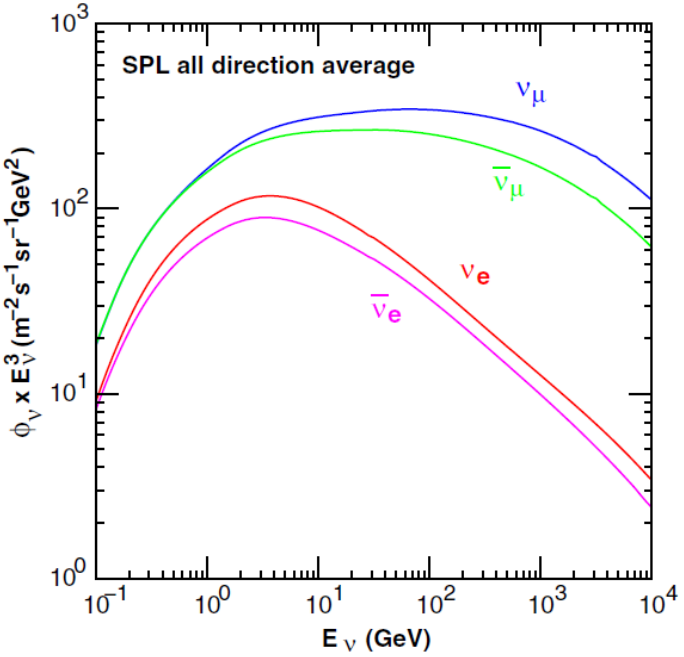
CSMS (Cooper-Sarkar, Mertsch, Sarkar)
http://arxiv.org/abs/1106.3723



- Neutrino Generator
  - GENIE: LE (<1TeV)
  - NuGen: HE (>100GeV) based on ANIS
- Systematics estimated in analysis (from GENIE)
  - Total cross section scaling, Free
  - Energy dependence, $E^{\pm 0.03}$
  - DIS cross section, 5%
  - Axial mass of non-DIS, CC-resonance 20% CC-quasi elastic $^{+25\%}_{-15\%}$
- CSMS (HERAPDF1.5)
  - current standard for HE NuGen simulation

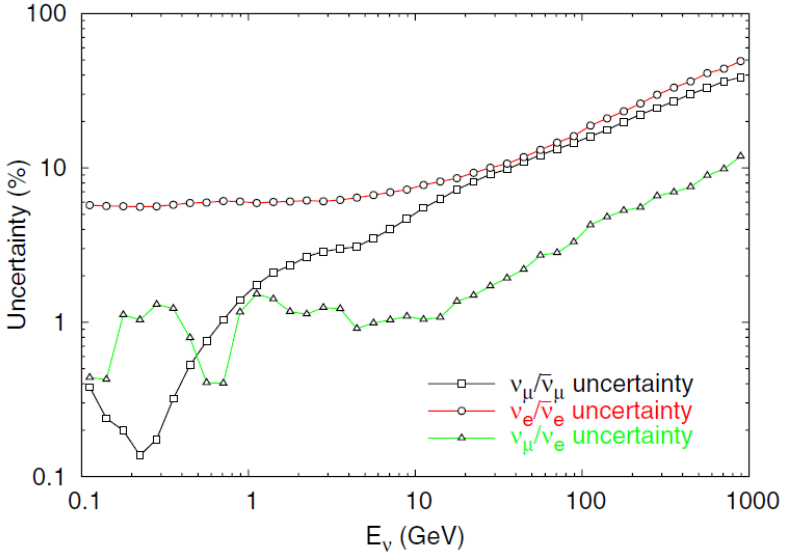
Atmospheric ν Spectrum Model

Honda et al.,
Phys. Rev. D 92, 023004, 2015



Honda 2015 atm ν flux as nominal value

GD Barr, TK Gaisser et al.,
Phys. Rev. D 74, 094009, 2006



Systematics from Barr et al.

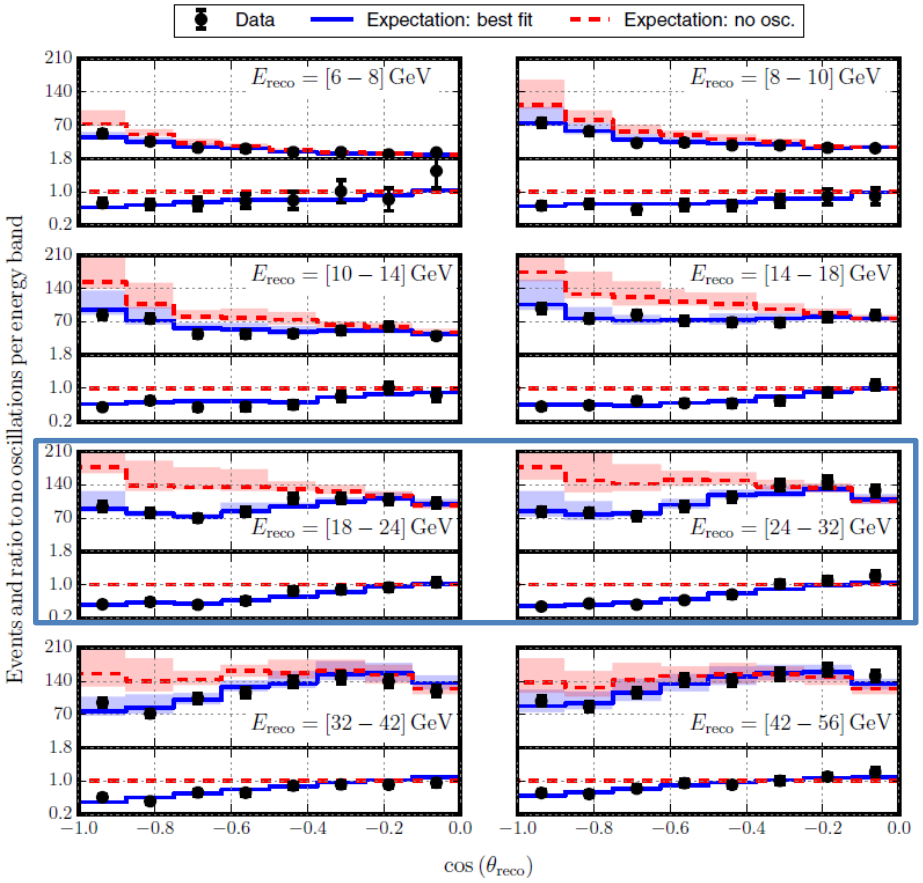
- Overall Normalization, Free
- Spectrum index, $E^{\pm 0.05}$
- $\nu/\bar{\nu}$, 10% *
- ν_e/ν_μ, 3%

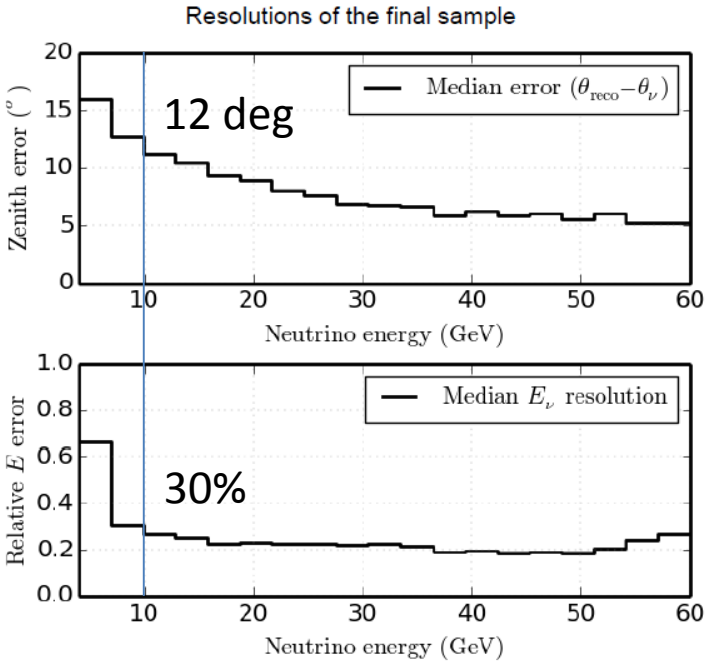
* Not included in PRD paper

Oscillation Analysis with DeepCore

Phys. Rev. D 91, 072004, 2015

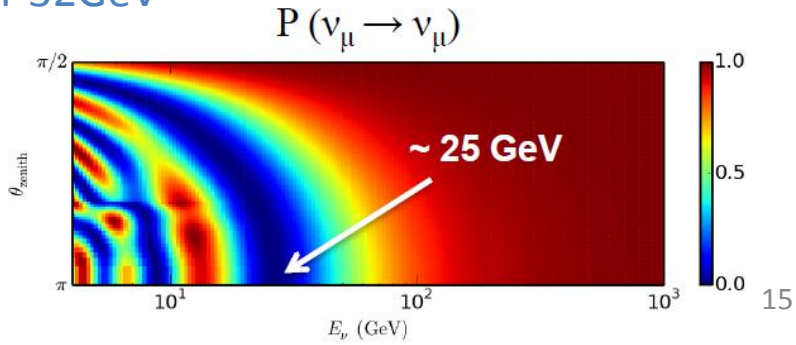
3 years of full IceCube 86 string, 953 days
MC expectation: ~7000 events
(disappearance of ~1900 events)





Juan Pablo Yanez, VLVNT 2015

18-24GeV
24-32GeV



Oscillation Analysis with DeepCore

Phys. Rev. D 91, 072004, 2015

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

$$sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

$$\left|\Delta m^2_{32}\right| = 2.72^{+0.19}_{-0.20} \cdot 10^{-3}\mathrm{eV}^2$$

Error from statistical only

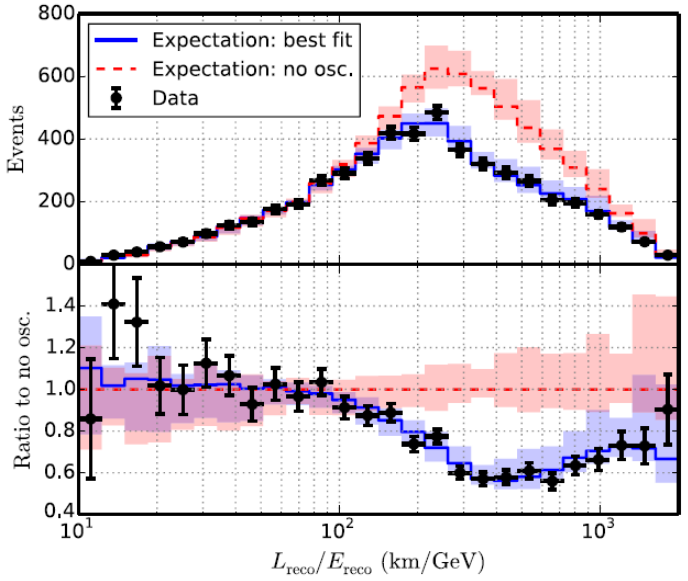
$$\sigma(sin^2(\theta_{23})) = ^{+0.06}_{-0.08}$$

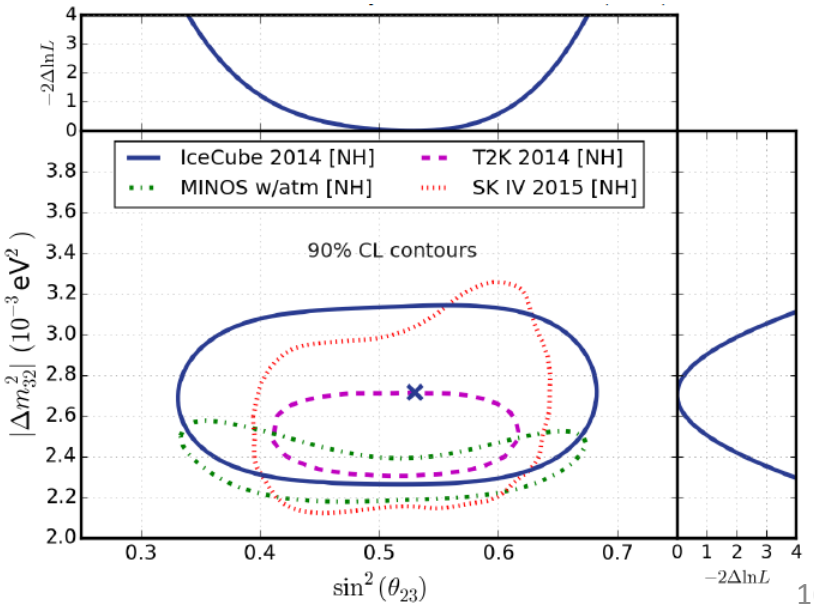
$$\sigma(\left|\Delta m^2_{32}\right|) = ^{+0.14}_{-0.15} \cdot 10^{-3}\mathrm{eV}^2$$

Systematics included as nuisance parameter

Nuisance parameter	Value at best fit (nominal)
DOM efficiency	0.997 (1.)
Scat. in ice columns [1/cm]	0.02238 (0.02)
Atm. μ contamination	0.034 (0.037)
Atm. ν flux	1.004
Atm. ν_e/ν_μ	1.005 (1.)
Spectrum index change	-0.002

Projected to Reconstructed L/E





*Actual fit is performed in 2D which will constrain systematics

Summary

- Detector systematics
  - DOM light detection efficiency $(1\sigma = \sim 10\%)$
  - South Pole Ice
    Scattering and absorption properties $(\sim 10\%)$
    Non-uniformity
      scattering in ice column → change DOM angular acceptance
      anisotropy from ice flow and ice tilt

  are controlled by in-situ calibration and are used to produce systematic simulation data sets
- Sub-dominant systematics are driven by theory
  - νN interaction cross section
  - Atmospheric ν flux model
- Oscillation Analysis (ν_μ disappearance)
  - Our best fits are compatible with other dedicated oscillation experiments

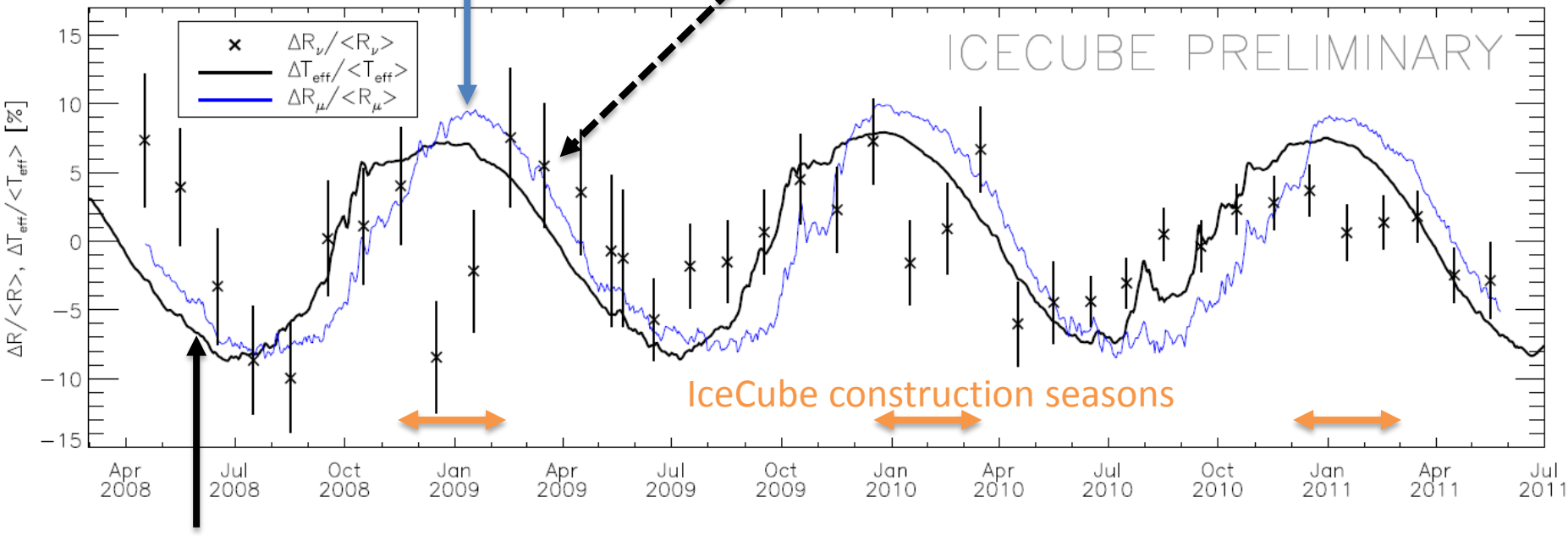

Thank you

BACK UP

Atmospheric ν_μ Seasonal Variation

Muon rate deviation

Neutrino rate deviation

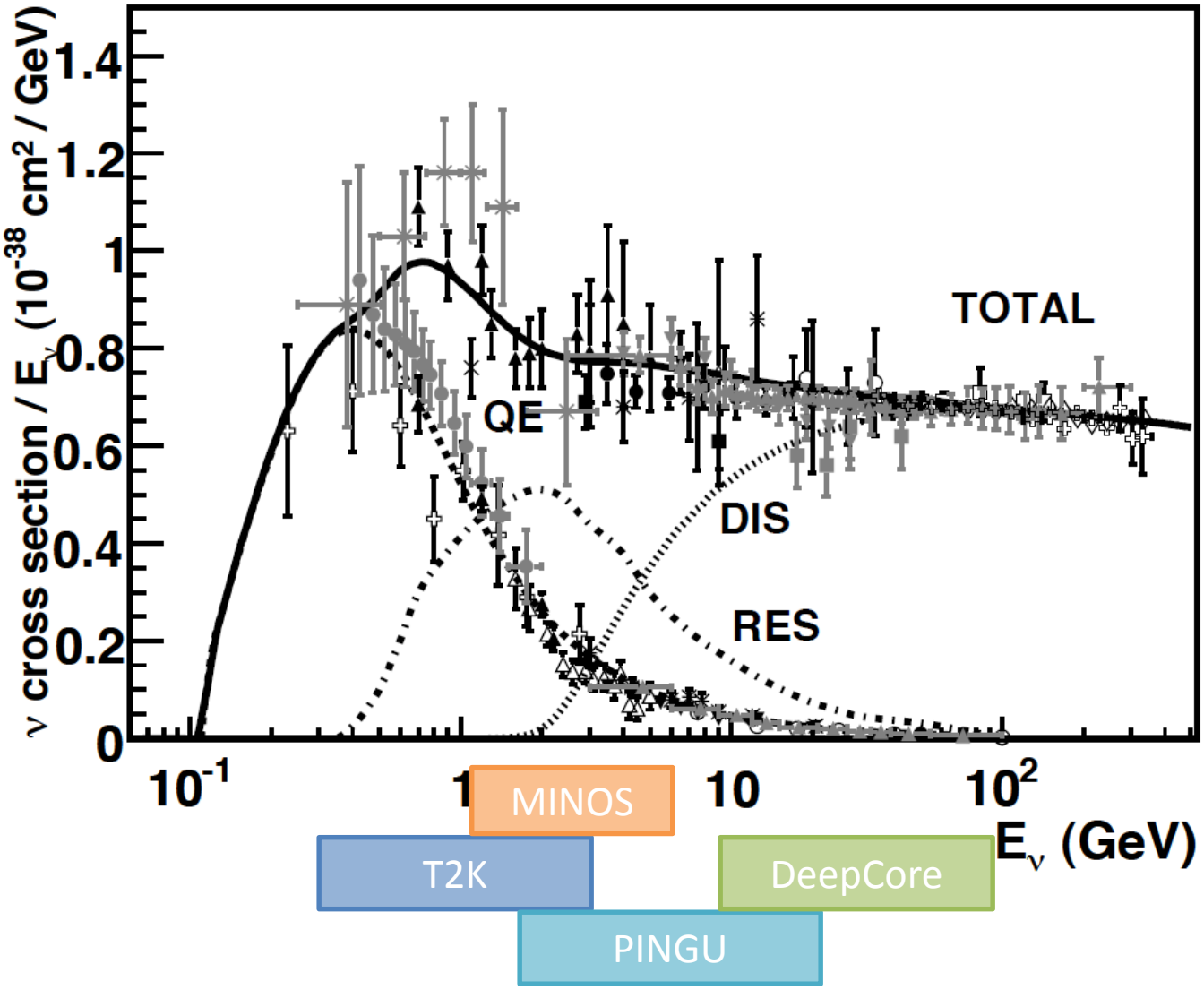


Temperature deviation

ICRC 2013

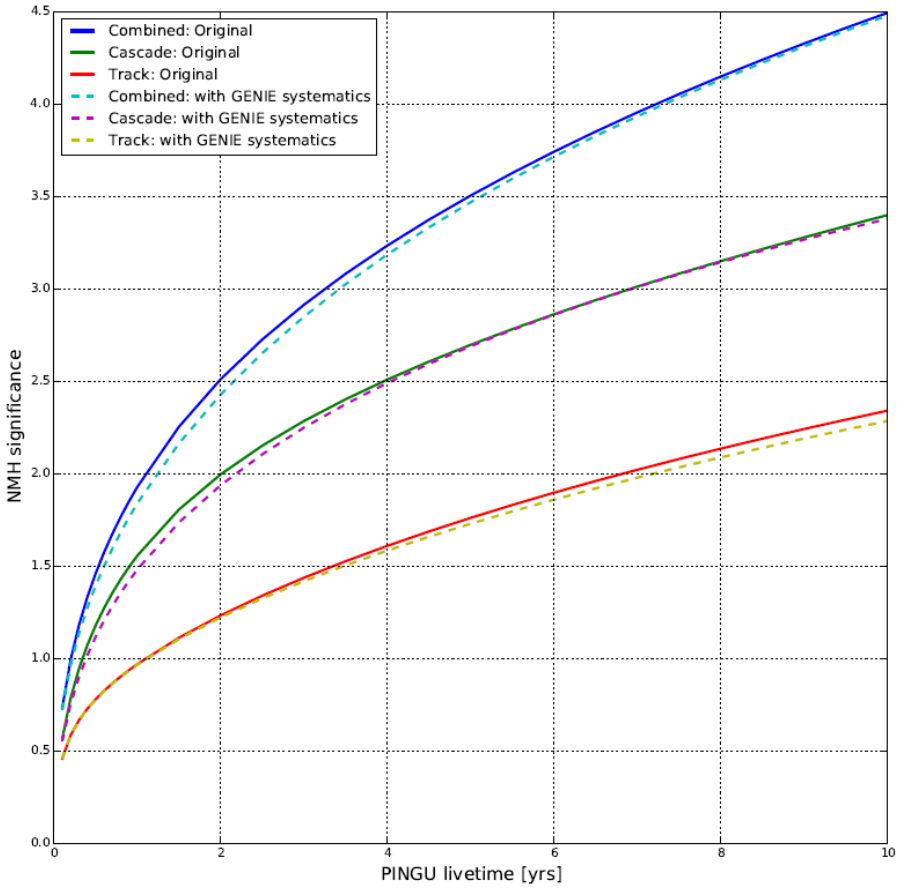
* Not included in PRD paper

Total neutrino CC cross sections



Impact of GENIE systematic in PINGU

- Largest impact from M_A in CCQE and CCRES
- Less impact from DIS systematics (its shape looks as other systematics, like spectrum index)

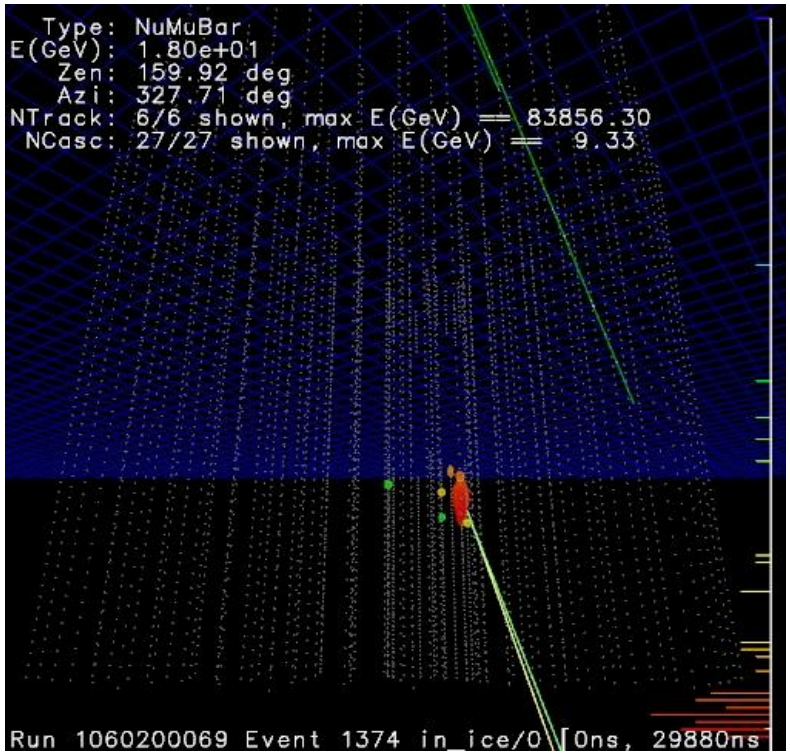


Joshua, NNN 2015

	impact (%)	
parameter	1 year	5 year
M_A^{CCQE}	5.9	1.0
M_A^{CCRES}	1.1	1.0
A_{HT}	0.1	0.0
B_{HT}	0.1	0.0
$C_{\nu 1u}$	0.1	0.0
$C_{\nu 2u}$	0.0	0.0

Reconstructing muon neutrinos in ice

Juan Pablo Yanez, 2014



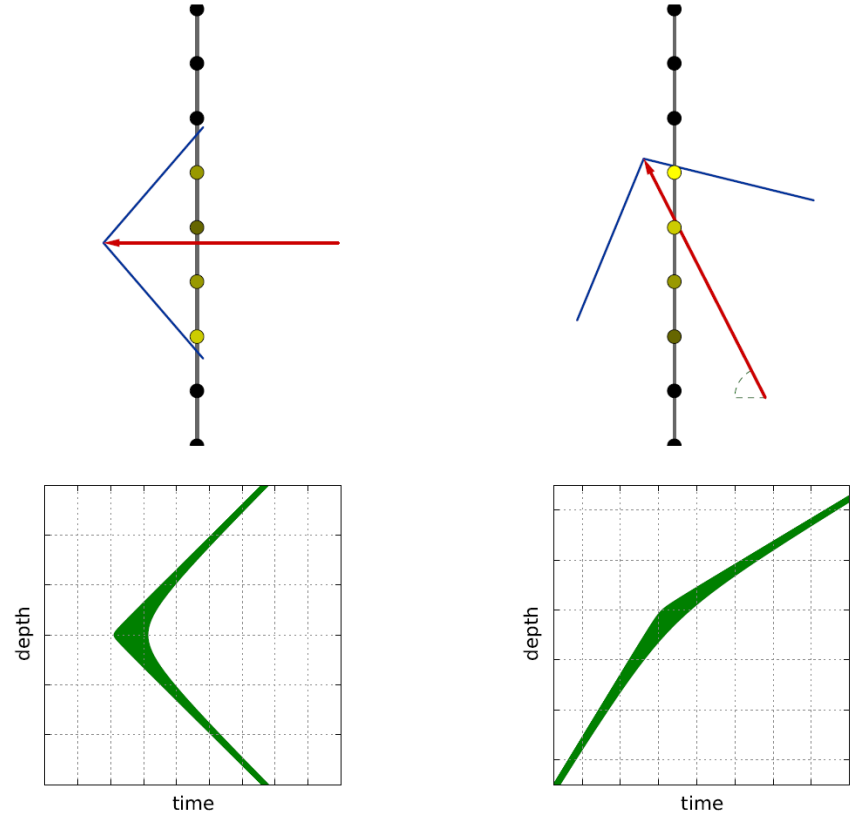
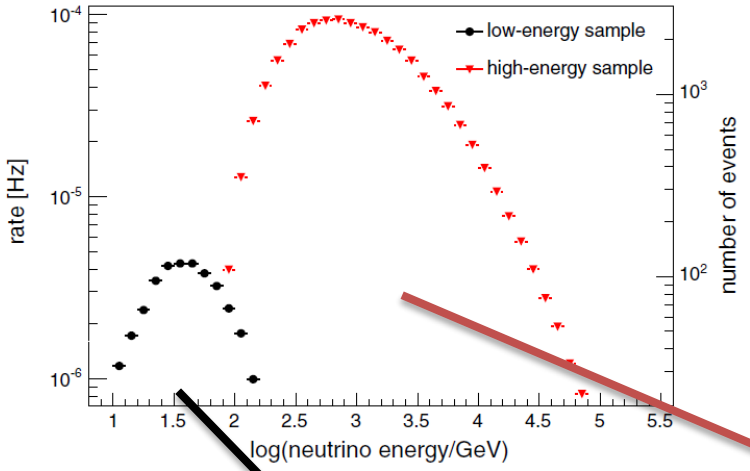


Figure 6.4: Formation of hyperbolic patterns. Top: diagrams depicting the differences in arrival time of photons to the DOMs as a function of the orientation of the Cherenkov emitter (red). Dark yellow means early signals, bright yellow means late. Bottom: hyperbolas formed by the intersection of Cherenkov light with the detector's strings for the two geometric configurations on top and a distance between $[0, 50]$ m between emitter and string.

Oscillation Analysis with DeepCore

Phys. Rev. Lett. 111, 081801, 2013



- IceCube 79 string (2010)
- 318.9 days
- Low energy sample
  - starting events in DeepCore
    719 events
- High energy sample
  - Entire IceCube
    39638 events

LE, DeepCore

HE, IceCube

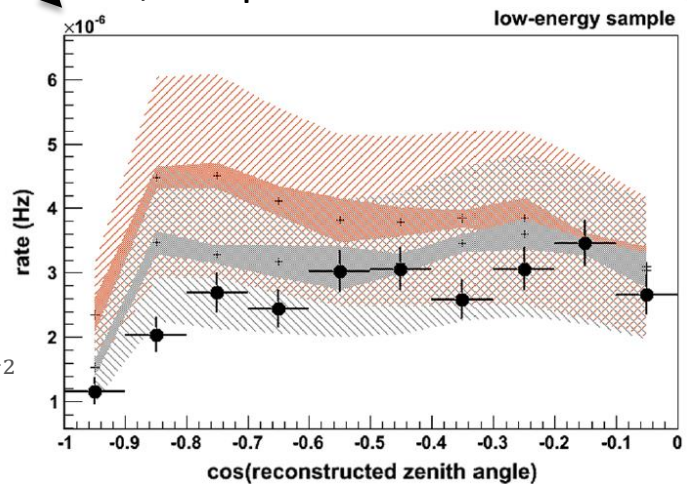
Non-oscillation

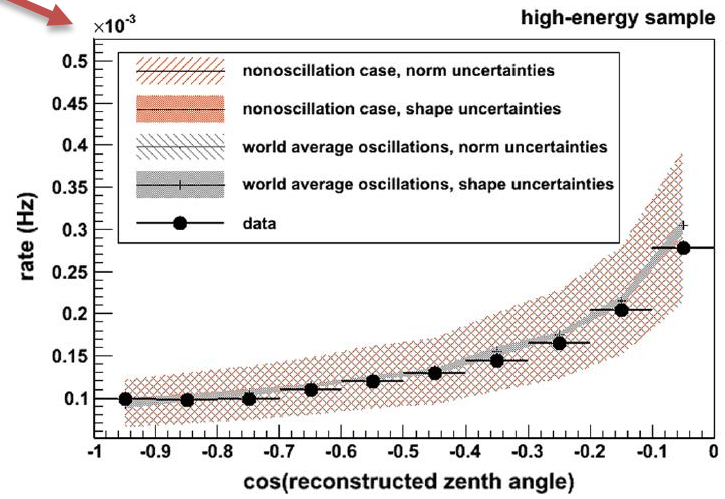
With Oscillation

world average:

$sin^2(2\theta_{23}) = 0.995$

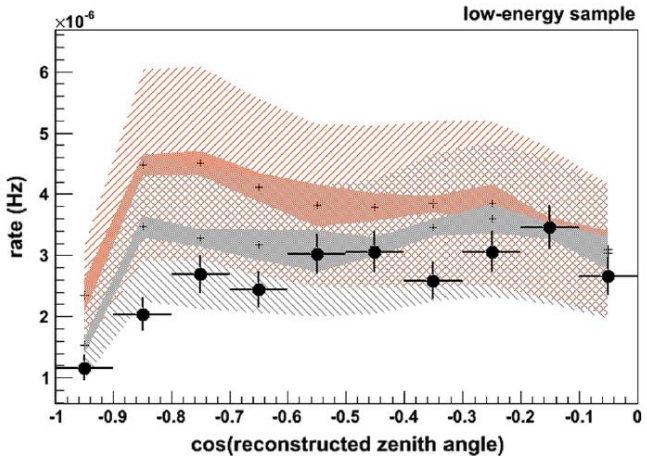
$|\Delta m^2_{32}| = 2.39 \cdot 10^{-3}\text{eV}^2$





Oscillation Analysis with DeepCore

Phys. Rev. Lett. 111, 081801, 2013



pull

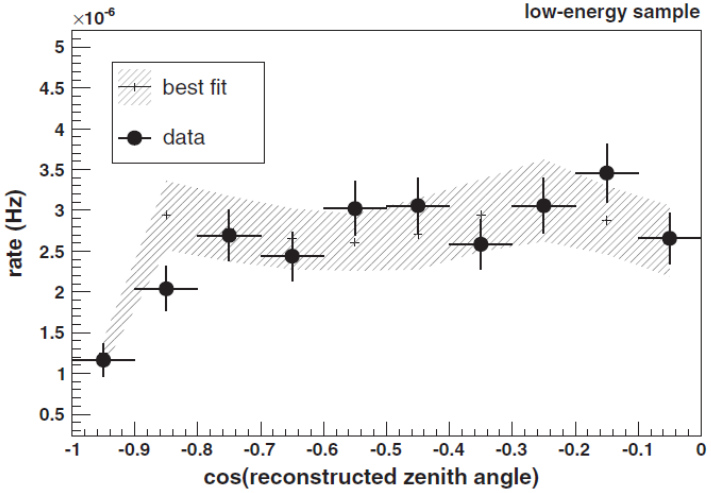
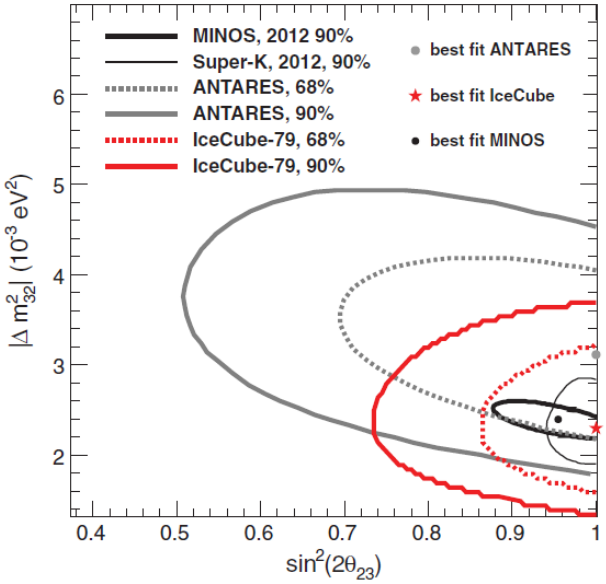


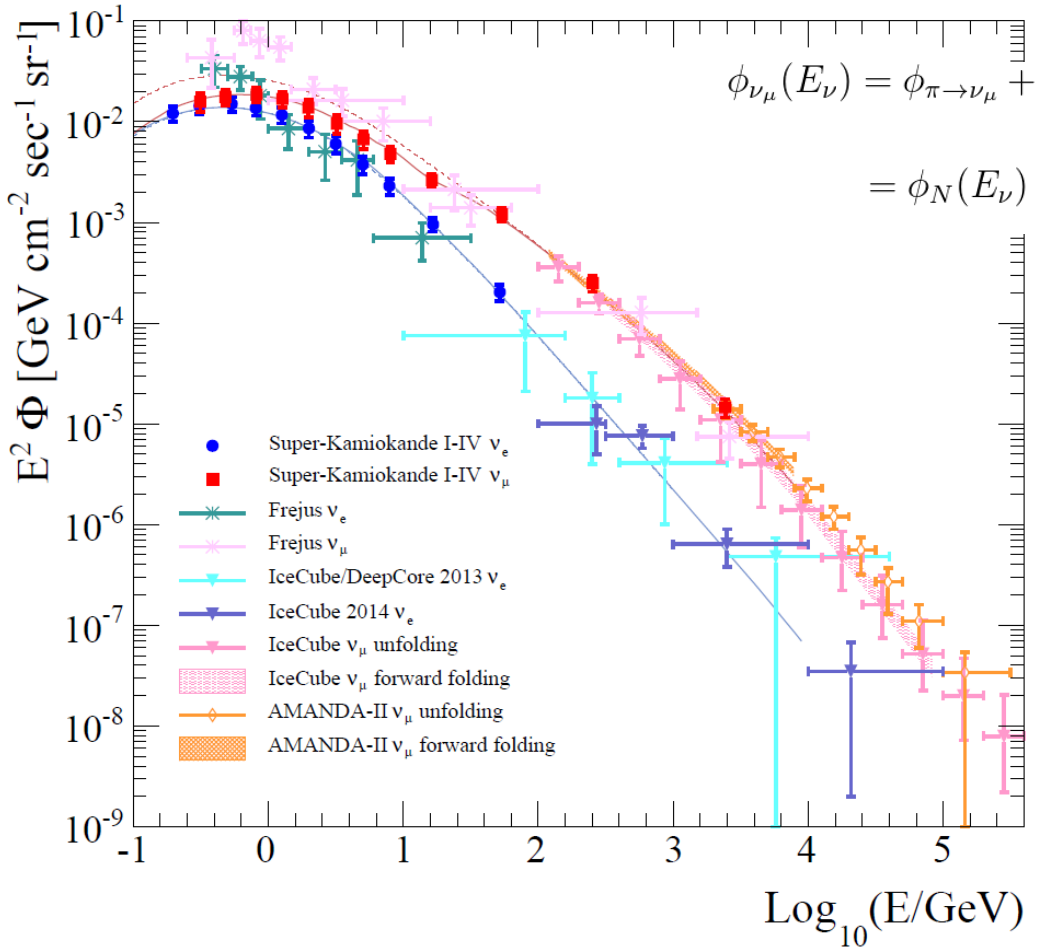
TABLE I. Pulls on the systematic uncertainties at the best-fit value of $|\Delta m^2_{32}| = 2.3 \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) = 1$.

Systematic uncertainty	Pull (standard deviations)
DOM efficiency	0.32
Ice model	−0.12
Atmospheric flux model	−0.59
Normalization	−0.82
Cosmic ray index or cross section	0.42
Relative efficiency of DeepCore DOMs	−0.01
Normalization of ν_e	−0.53



Atmospheric Spectrum (GeV to PeV)

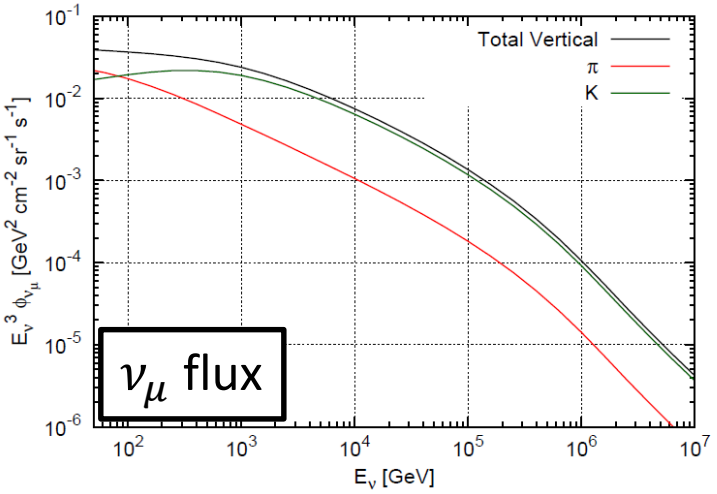
arxiv.org/1510.08127 SuperK Coll.



$$\phi_{\nu_\mu}(E_\nu) = \phi_{\pi\to\nu_\mu} + \phi_{K\to\nu_\mu}$$

$$= \phi_N(E_\nu) \times \left\{ \frac{Z_{N\pi} A_{\pi\nu}}{1 + B_{\pi\nu} \cos\theta^* E_\nu/\epsilon_\pi} + \frac{Z_{NK} A_{K\nu}}{1 + B_{K\nu} \cos\theta^* E_\nu/\epsilon_K} \right\}$$

[Gaisser, 1991]

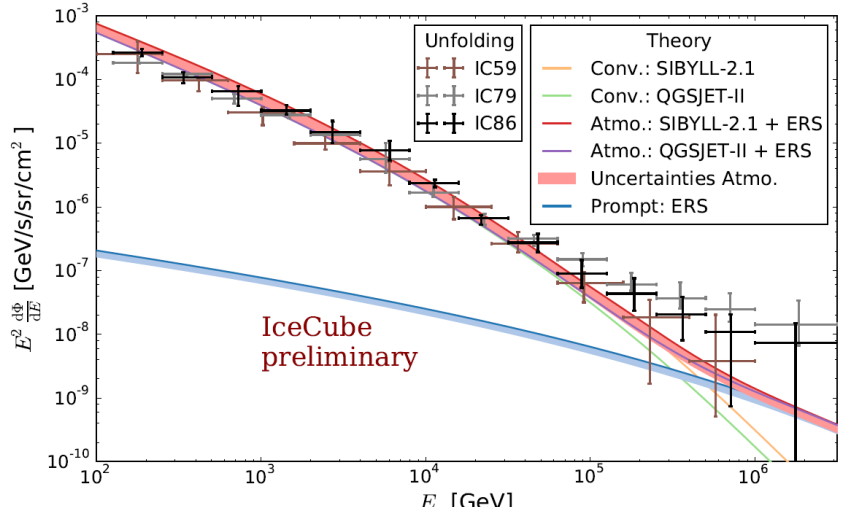


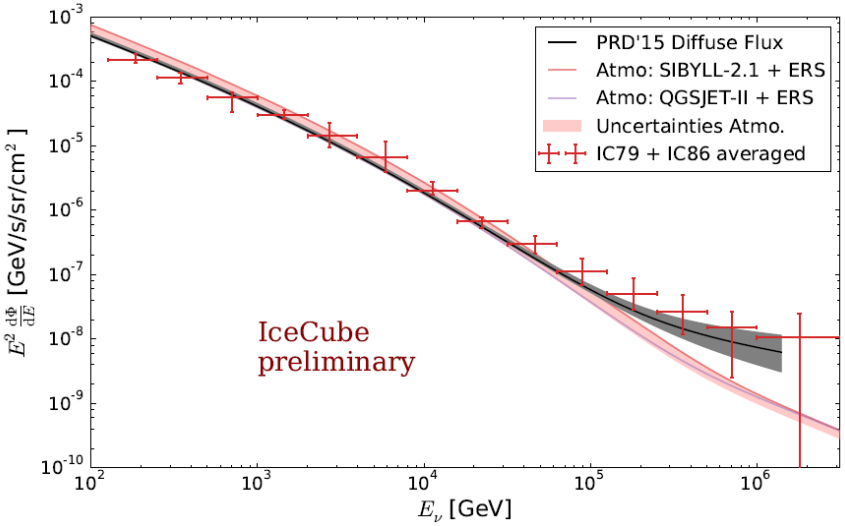
High energy extrapolation with CR knee

Kaons are main sources at high energy atm ν flux

Atmospheric ν_μ spectrum

Eur. Phys. J. C75, 116, 2015
ICRC 2015, Mathis et al





- IceCube 59+79+86 string 2009, 2010, 2011
- Up going pure ν_μ sample
  - zenith $> 86^o$
  - Track quality cut
  - ~200k events
- Reach to PeV energy range
- Sensitive to prompt and astrophysical components
- Systematics
  - DOM Efficiency 10%
  - Cross Section 5%
  - Cross check with different Ice Model

Atmospheric ν_e spectrum

Phys. Rev. Lett. 110, 151105, 2013

Phys. Rev. D 91 122004. 2015

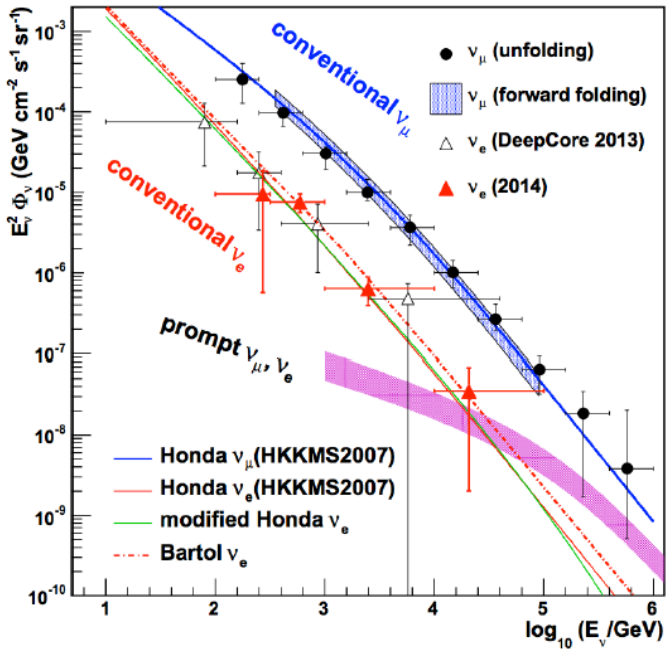
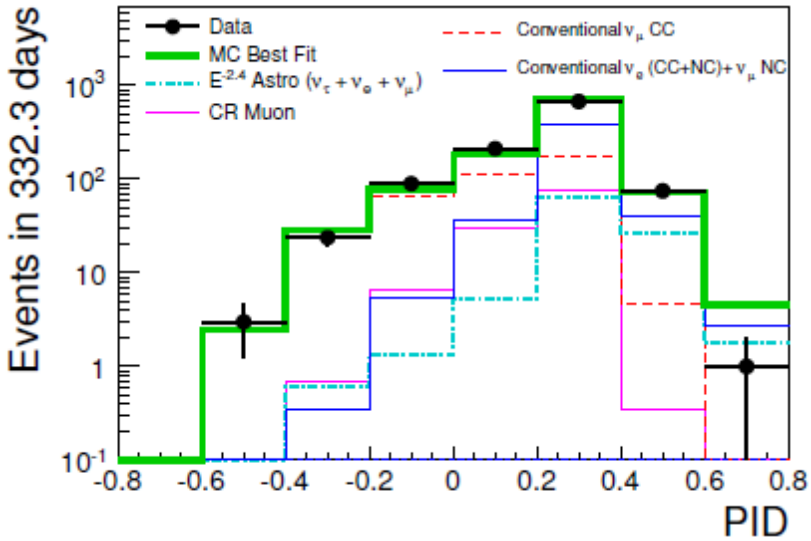


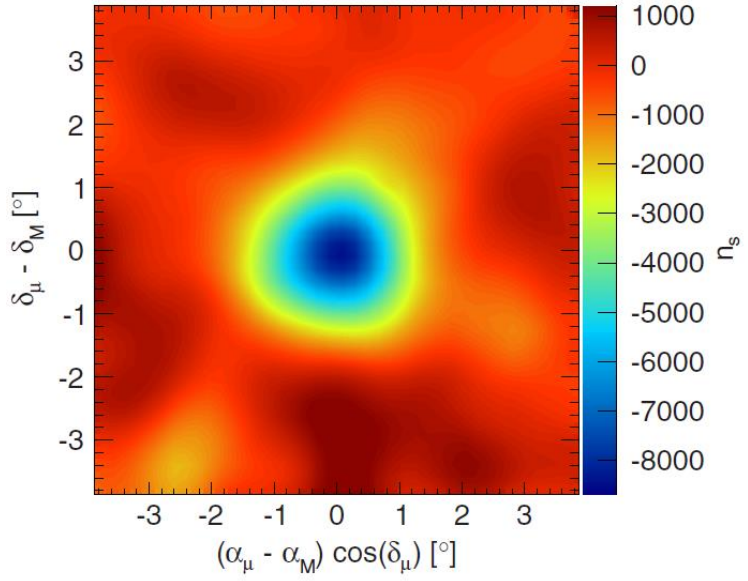
TABLE II. Systematic uncertainties.

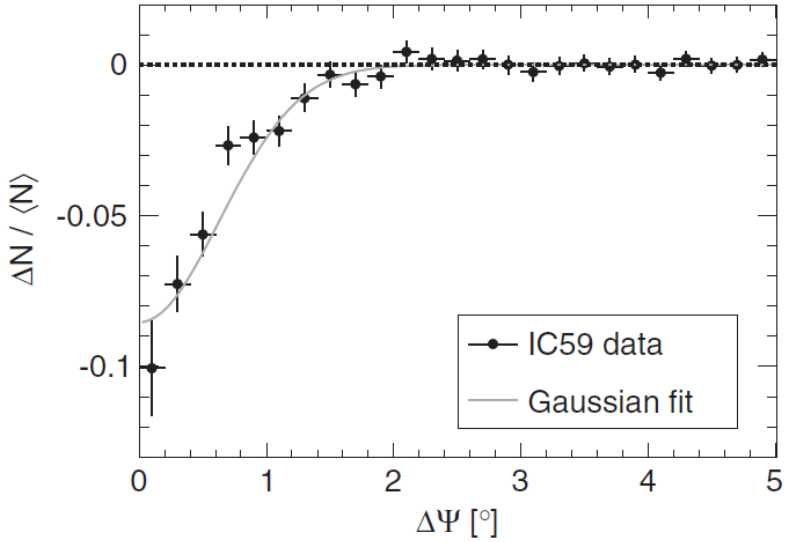
Source of uncertainties	atm. μ	atm. ν_μ	atm. ν_e
Ice properties	8%	6%	2%
DOM efficiency	30%	11%	10%
Cosmic-ray flux	33%	-	-
ν-nucleon cross section	-	6%	6%
Sum	45%	14%	11%

- Contained cascade event analysis
  - IceCube 79 string, 2010
    - Deep Core
    - Use IceCube as muon veto
  - IceCube 86 string, 2011
    - Entire IceCube
    - Multi channel analysis

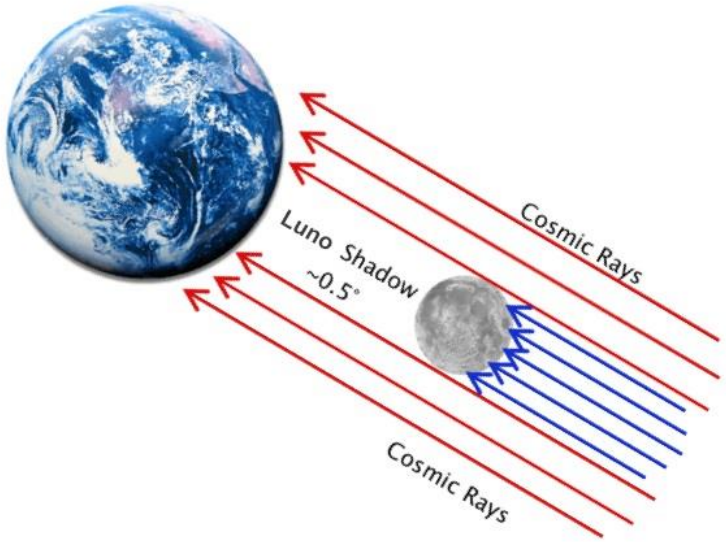


High Energy Muon Pointing Resolution





Phys. Rev. D 89 102004, 2014



Ice Column

Martin Rongen, VLVNT 2015