IceCubeによる大気ニュートリノ観測

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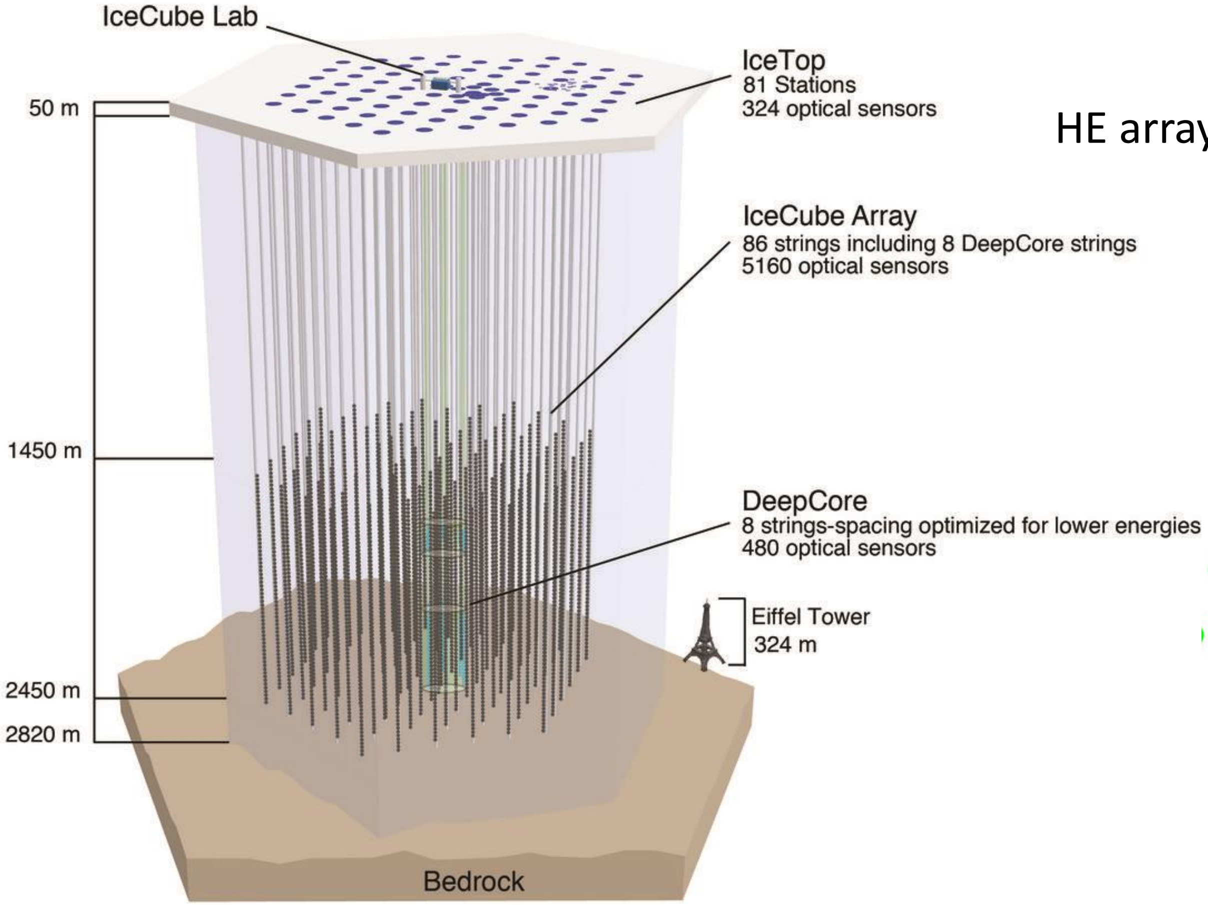
第29回宇宙ニュートリノ研究会「大気ニュートリノ」宇宙線研究所　柏の葉キャンパス

Outline

- Atmospheric neutrinos with IceCube
  - Measurements of atmospheric neutrinos
  - Application of atmospheric neutrinos?
    - Seasonal variation
    - Cross section measurement
- Atmospheric neutrinos with DeepCore
  - Neutrino oscillations

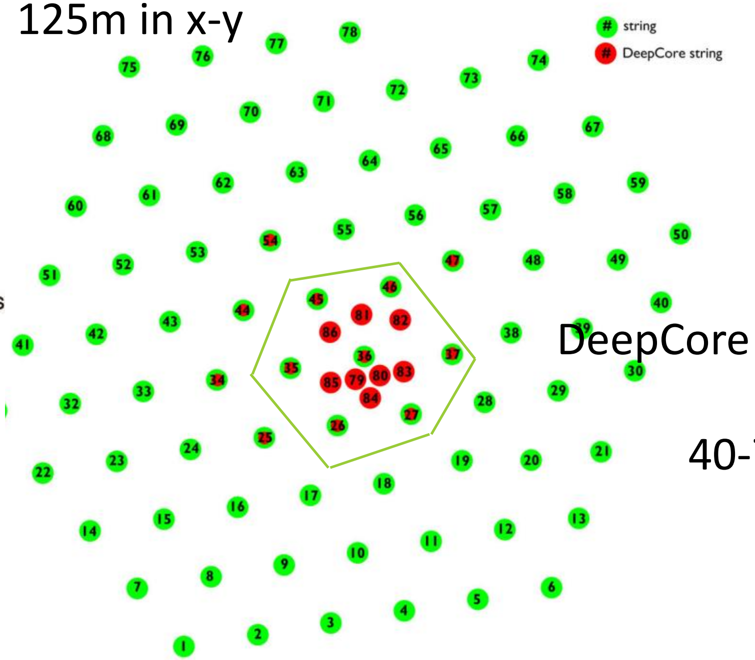
IceCubeとDeepCore検出器



HE array spacing

17m in z

125m in x-y

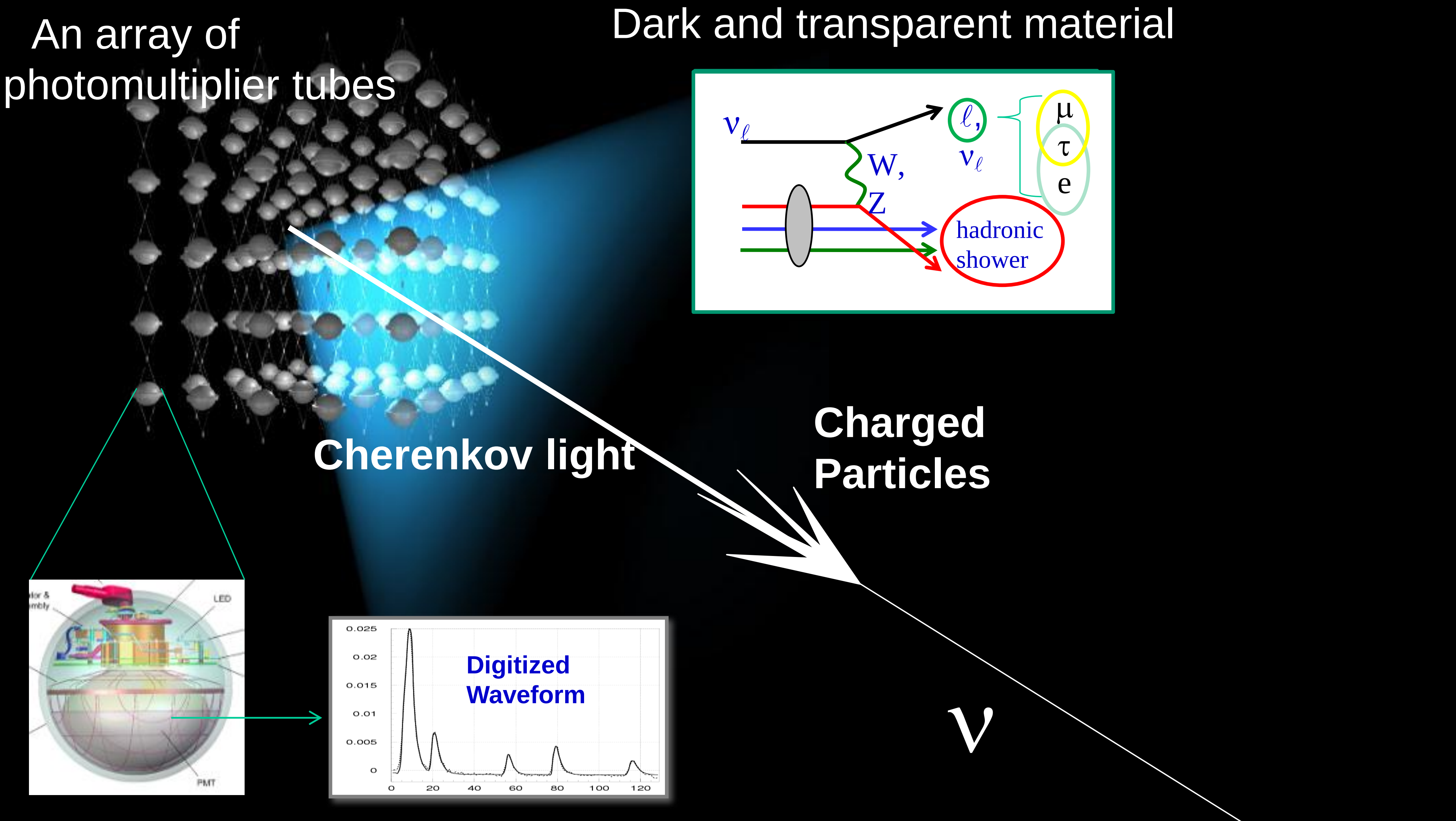


DeepCore spacing

7m in z

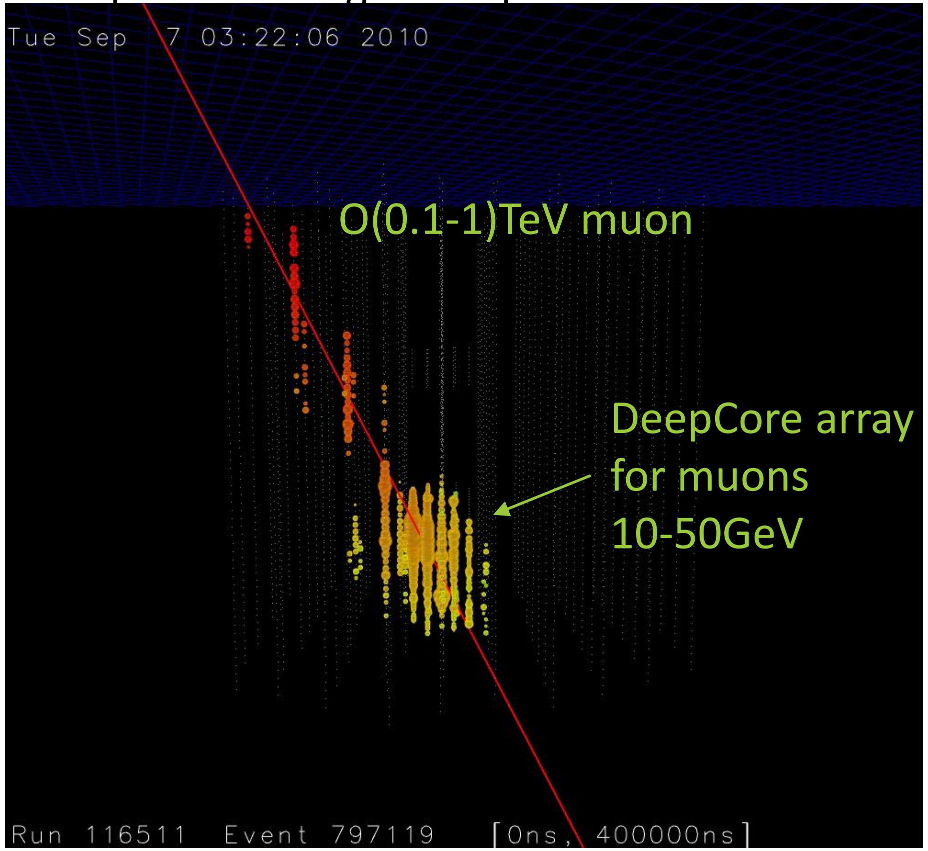
40-70m in x-y

Detection Principle

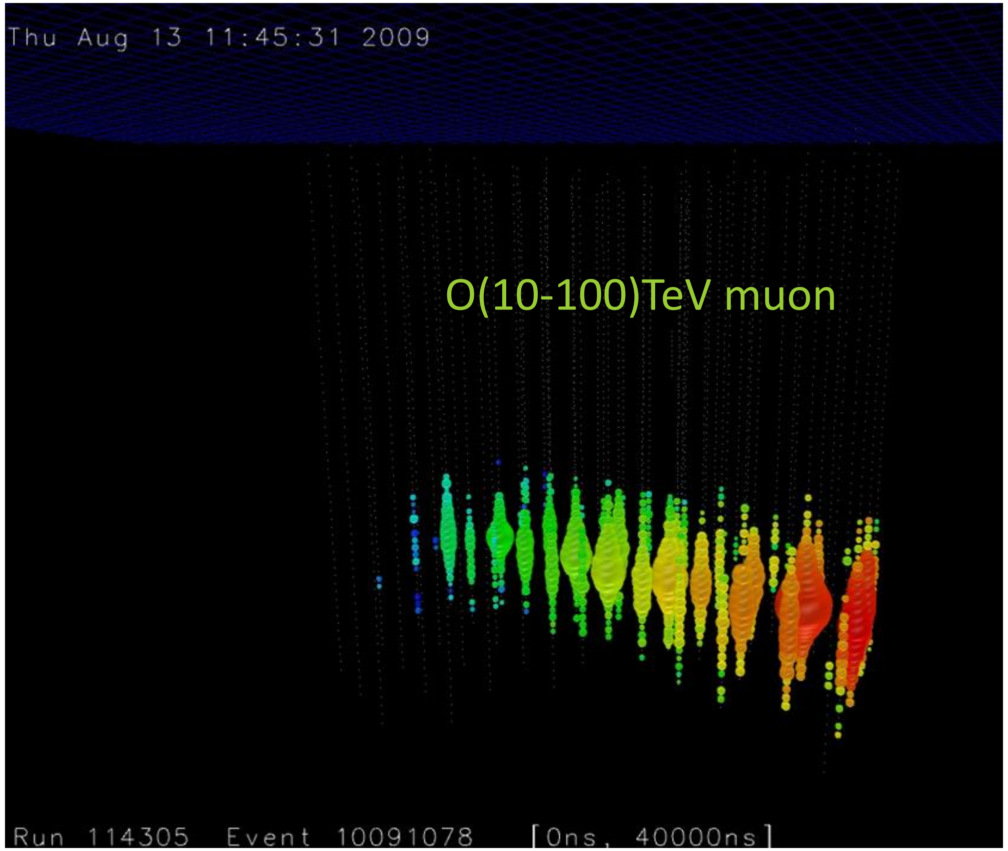


IceCubeとDeepCore検出器

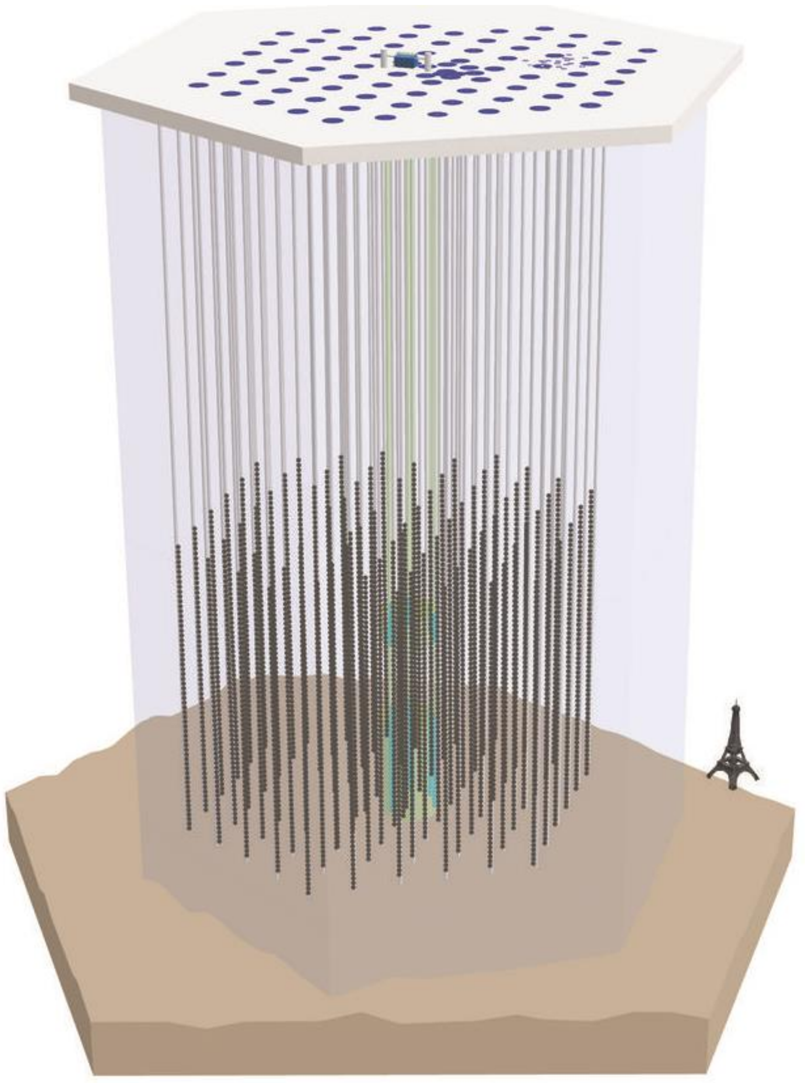
DeepCore Hitting atmospheric muon event



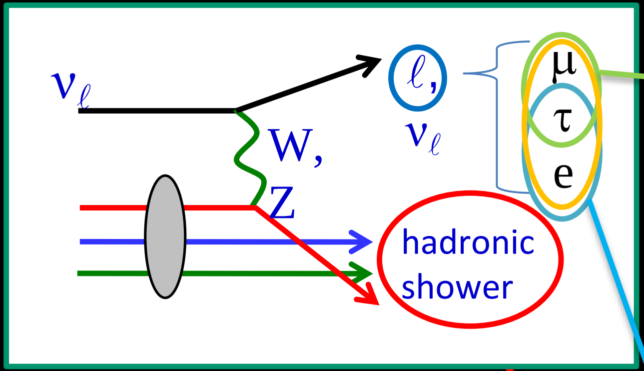
IceCube neutrino event



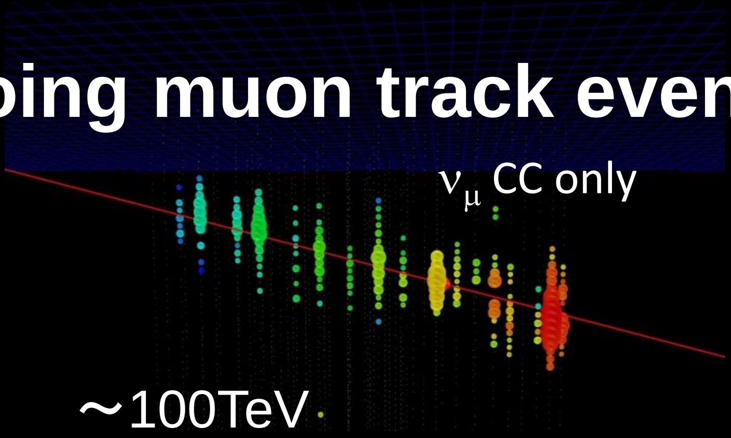
Atmospheric νs with IceCube



IceCube大気ν事象のselectionとPID



Up-going muon track event

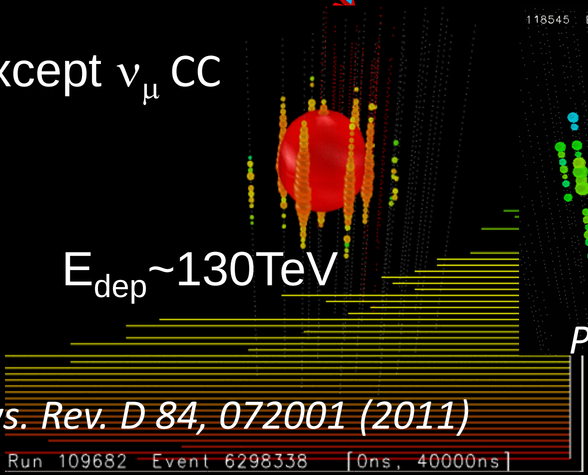


ν_μ CC only

～100TeV

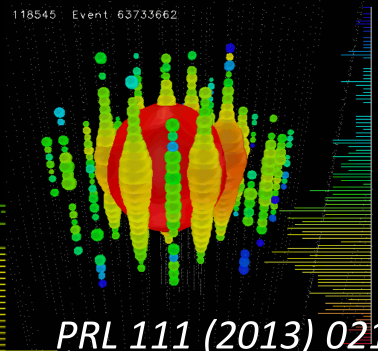
Cascade events

All except ν_μ CC



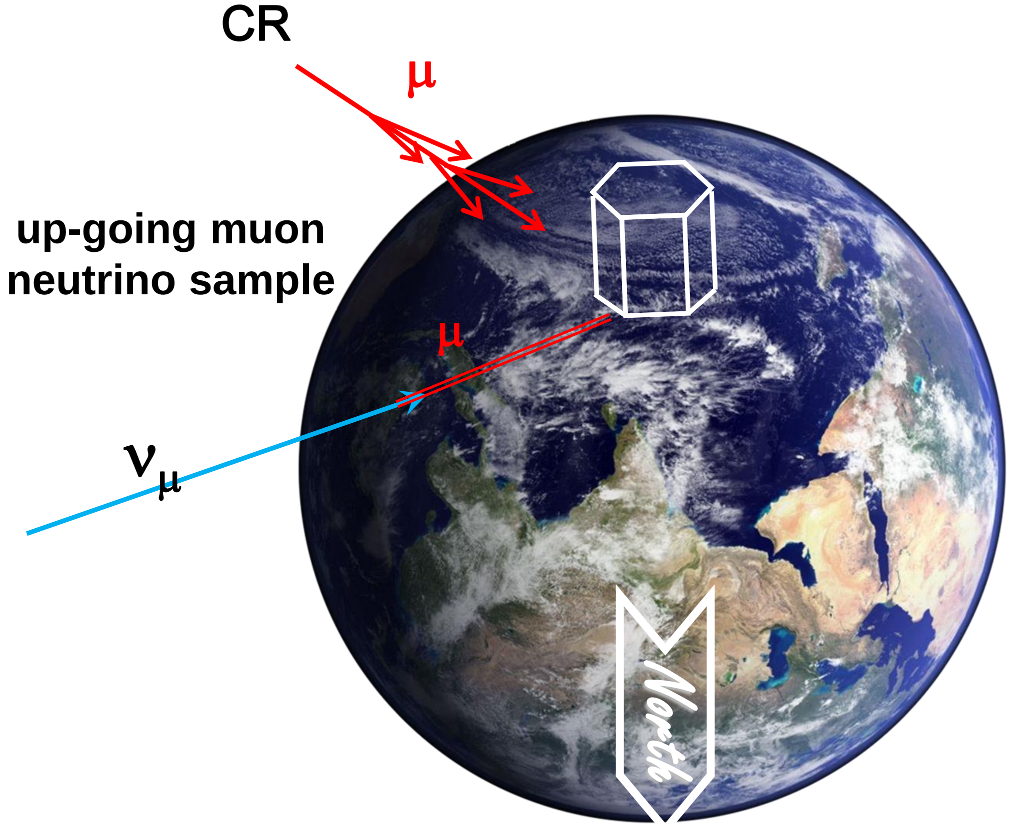
E_{dep}~130TeV

Phys. Rev. D 84, 072001 (2011)

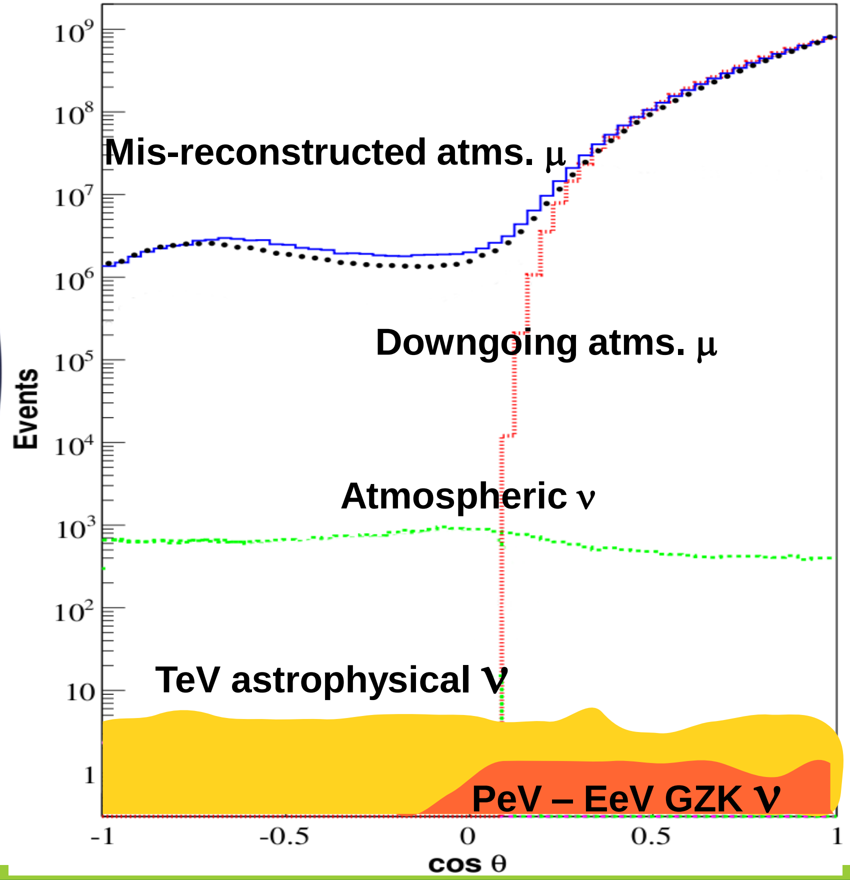


PRL 111 (2013) 021103

Upward-moving track channel

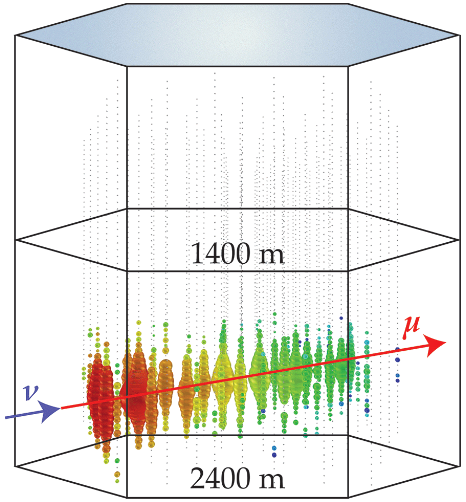


Trigger rates:
Atm. muons: ~3 kHz,
~200 atm. ν /day
(with E >100 GeV in IceCube)



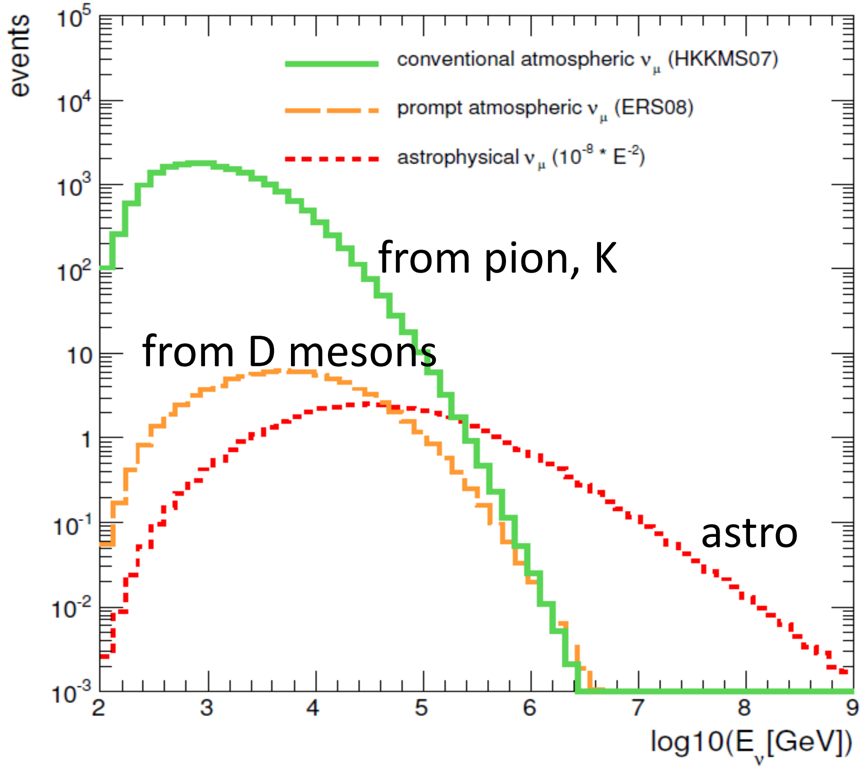
Energy regions

Select well reconstructed
upward going tracks



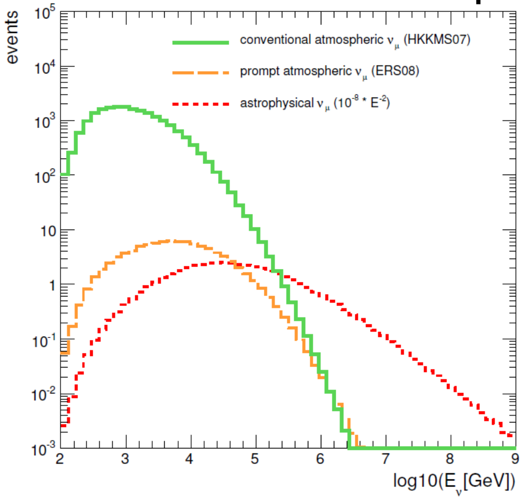
Physics 7, 88 (2014)

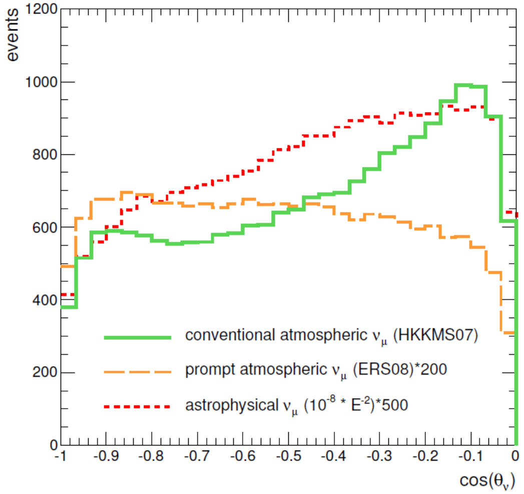
muon tracks from 50GeV-200TeV atmospheric neutrinos



~~Astrophysical and~~ Atmospheric ν_μ

MC expectations



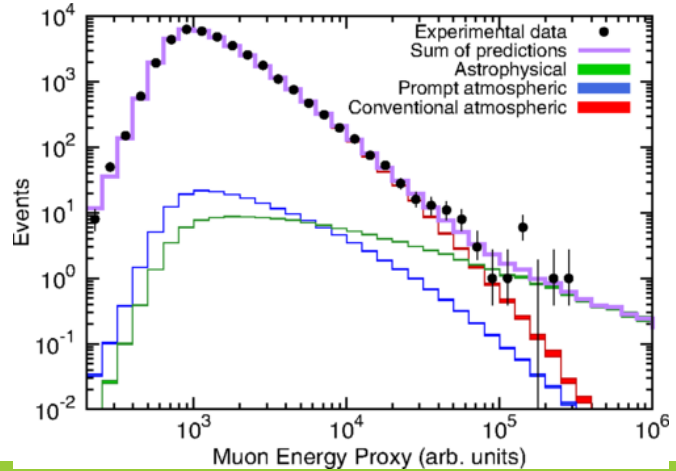


Dominant atmospheric ν induced events are measured

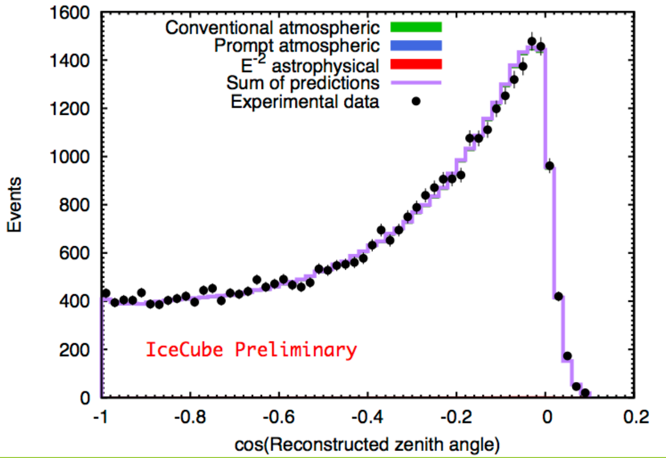
- 35000 events of 2 year sample 99.9% muon neutrino purity

HKKMS:Phys. Rev. D 70, 043008 (2004)
ERS:Phys. Rev. D 78, 043005 (2008)

Data:2010-2012 (2 years) fit results



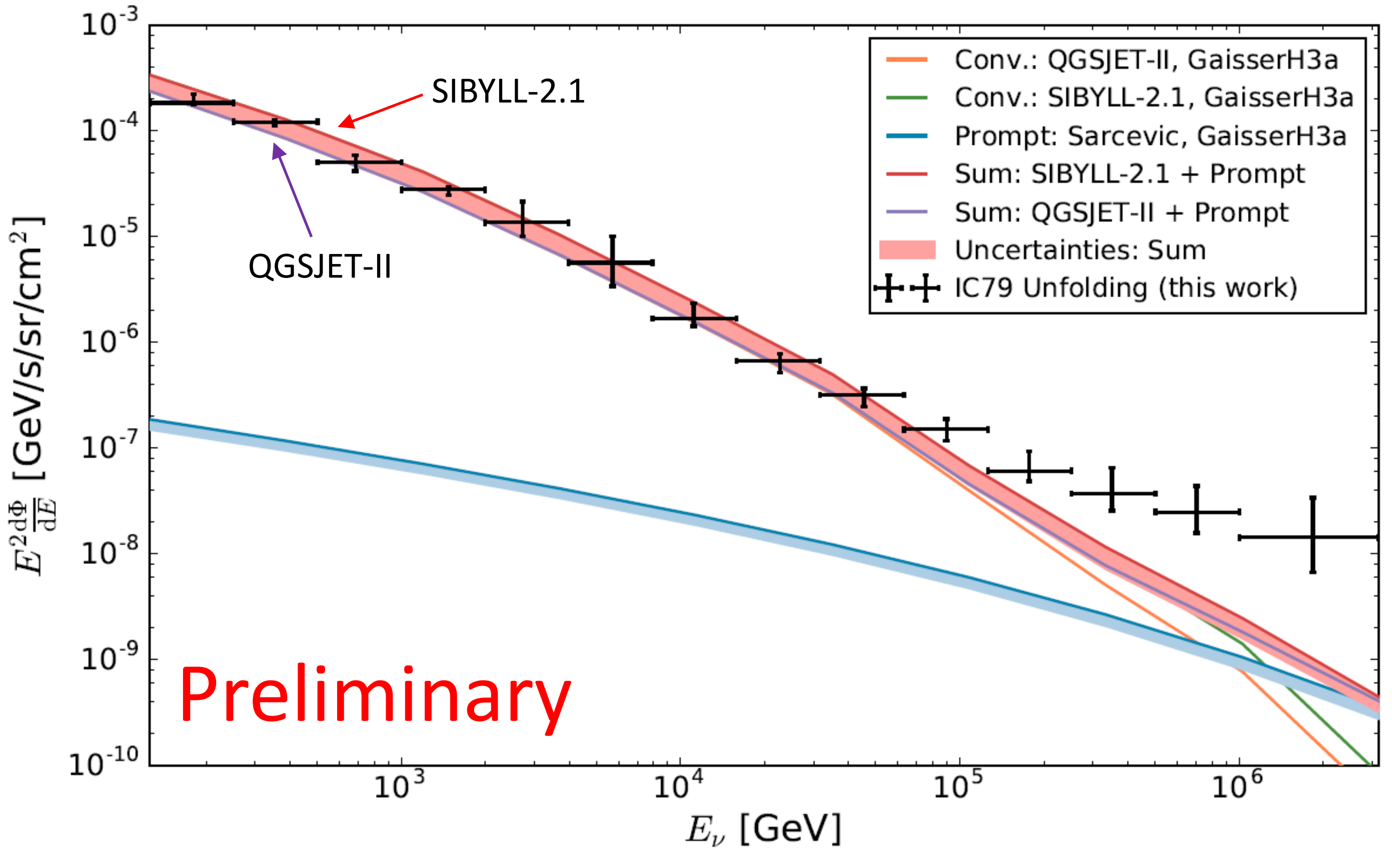
IceCube PRL(2015)



Parameter	Best fit
HKKMS07 normalization	$0.93^{+0.04}_{-0.04}$
ERS normalization	$0^{+1.05}$
Cosmic ray spectral index change	$-0.023^{+.001}_{-.0008}$
Detector optical efficiency	$+9.1^{-0.5\%}_{+0.5}$
Kaon production normalization	$1.15^{+0.08}_{-0.07}$

Unfolding of atmospheric ν spectra

The upward-going track sample can also be used to unfold the atmospheric nu spectra



solving inverse problem by
TRUEE (NIMA697, 133 (2013))

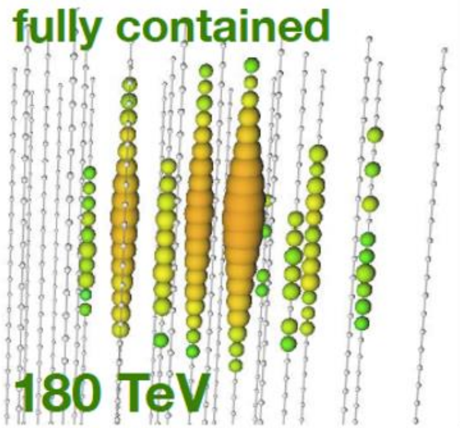
$$g(y) = \int_c^d A(y,x) f(x)\, \mathrm{d}x + b(y)$$

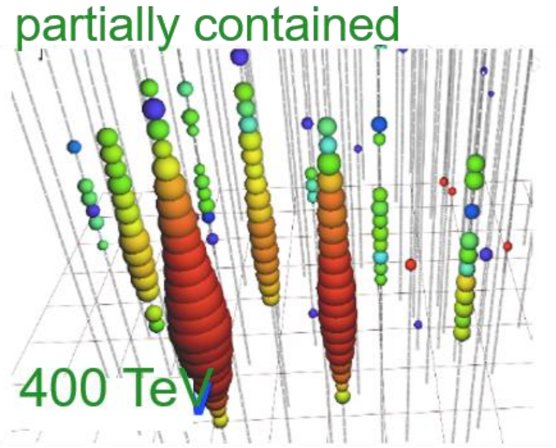
f(x): want to know
g(y) is the distribution of a measured variable y
A(y; x) is response function: gives the probability to measure a certain y under a given x.

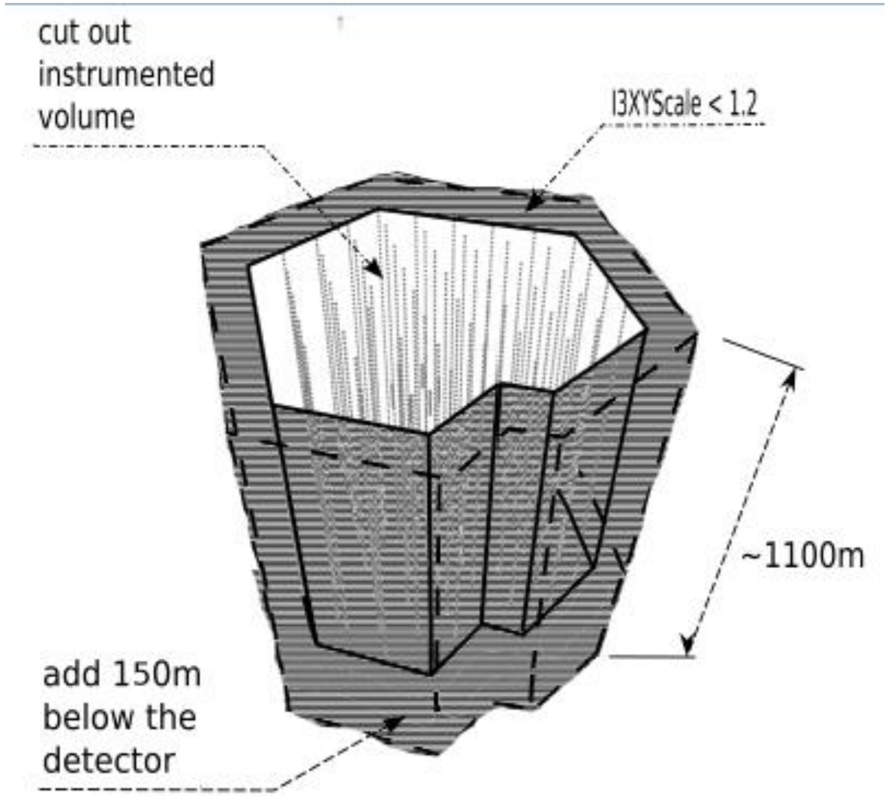
- limited by stat (energy bin size) and syst (y-axis)
- zenith angle dependent unfolding spectra with multiple years of data is under work

Cascade event selection

- Well reconstructed vertex positions in detector
- Effective detection volume limited compared to track

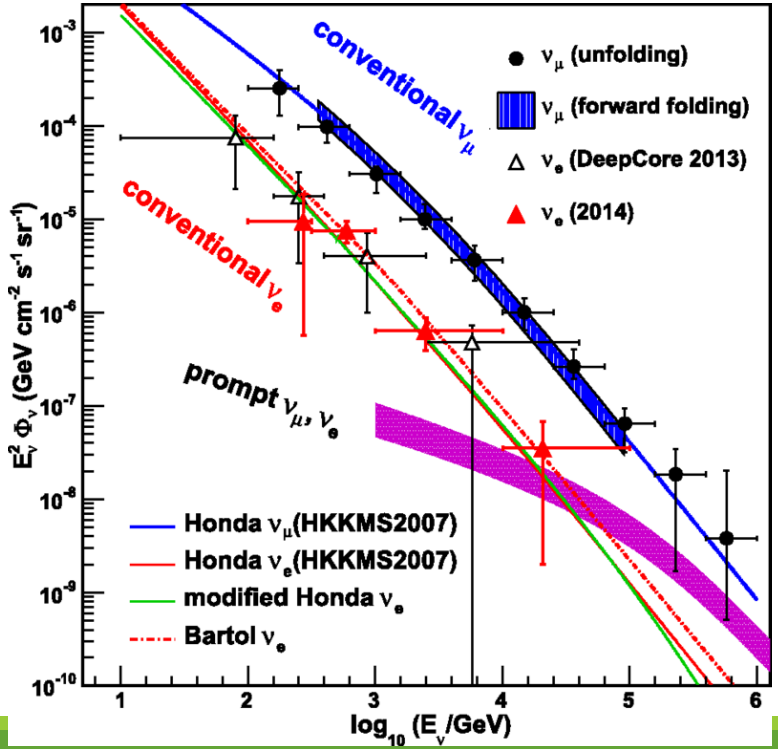






Atmospheric neutrinos ν_e with cascades

- Most ν_e come from the semileptonic decay of charged and neutral kaons
- The ν_e flux is lower than that of ν_μ and the ν_μ/ν_e ratio increases with increasing energy, reaching a factor of ~20 at 1 TeV.



1078 event observed in 0.3-14TeV

CR muons (115 events)

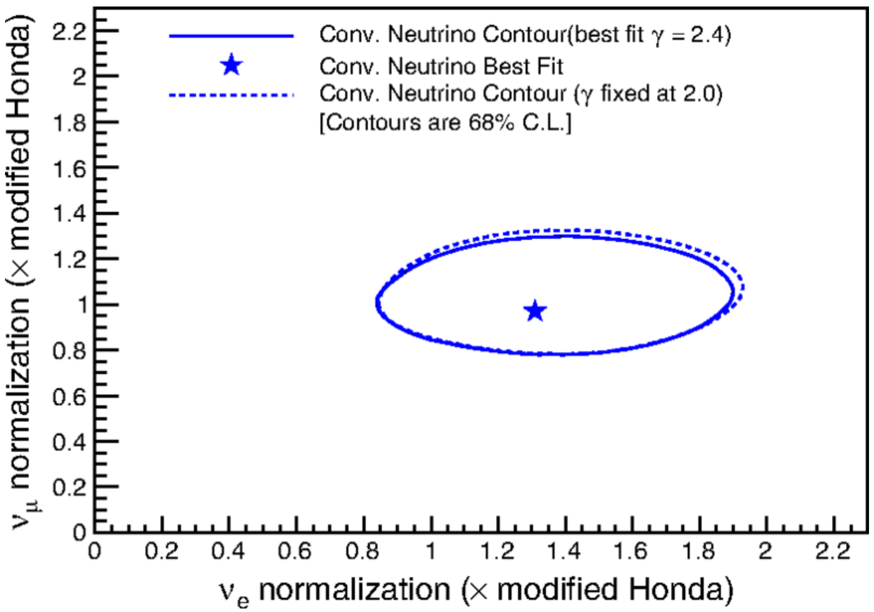
ν_μ rates (645 events)

ν_e rates (215 events)

Phys. Rev. Lett. 110, 151105 (2013)
PRD 91, 122004 (2015)

Best fit parameters

- Consistent within error, hint for more n_e (Kaons)?
- The flux ratio of ν_μ to ν_e at 1.7 TeV is $16.9^{+6.4}_{-4.0}$ compared with the Honda prediction of 23 and the Bartol prediction of 14. Further analysis is ongoing!

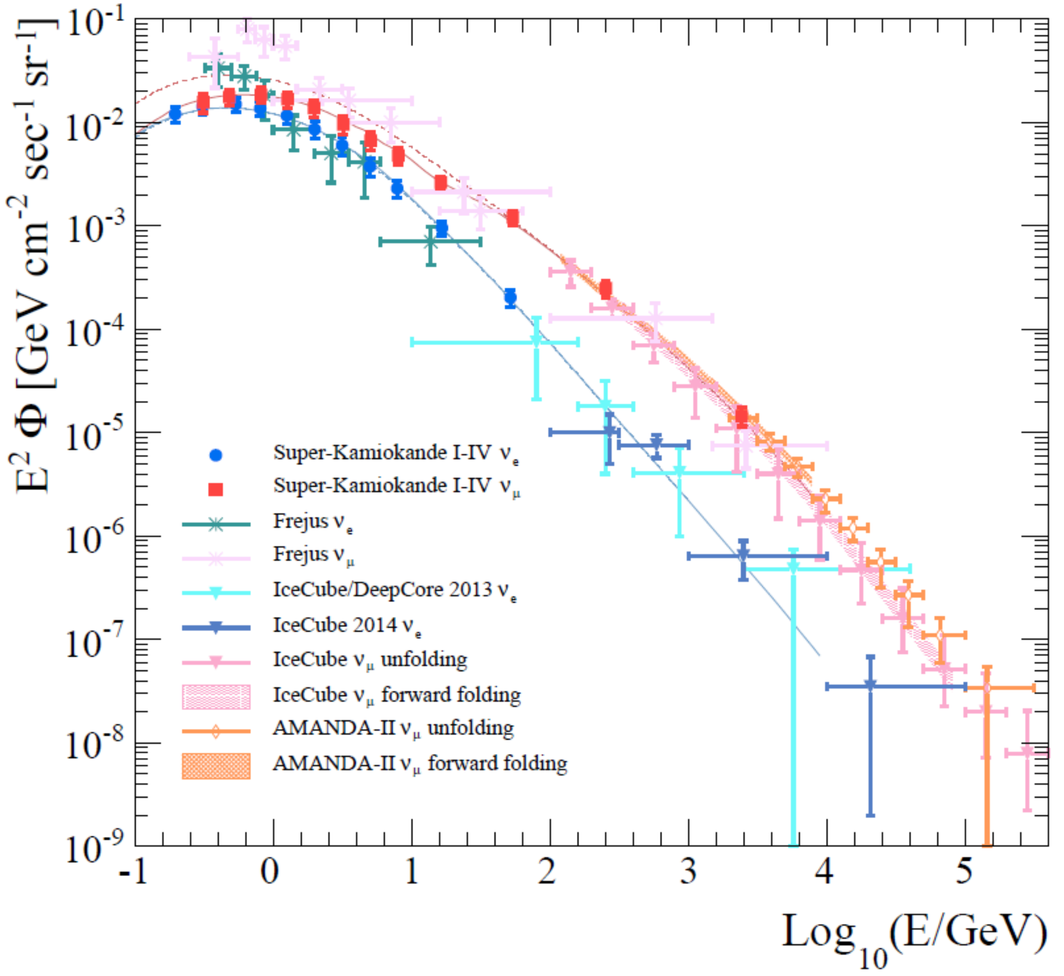


Parameters	Best fit
CR muon	115+28−27 events
Conventional ν_μ	1.0+0.2−0.1 × modified Honda
Conventional ν_e	1.3+0.4−0.3 × modified Honda
Prompt normalization	0.0+3.0−0.0 × modified ERS
Optical efficiency	−2.2% (±10% prior)
Ice parameters	+1.0 σ at scattering +10%

Honda:PRD **75**, 043006 (2007)

Bartol:PPD **70**, 023006 (2004)

Comparisons with SK



http://arxiv.org/pdf/1510.08127v1.pdf

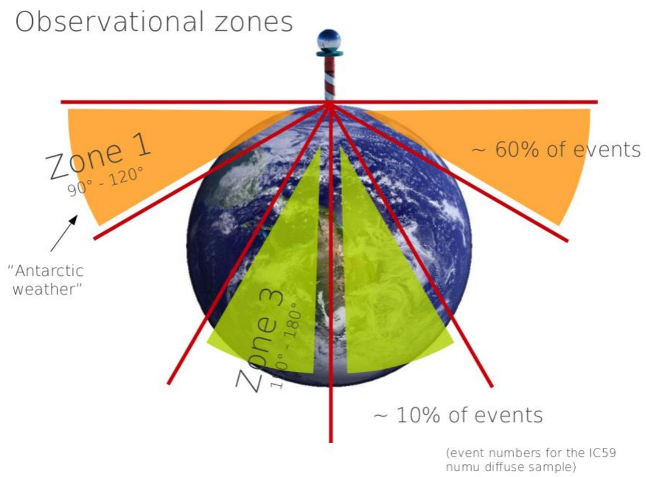
- Wide energy coverage of atmospheric neutrinos
- IceCube (stat.) errors still to be reduced

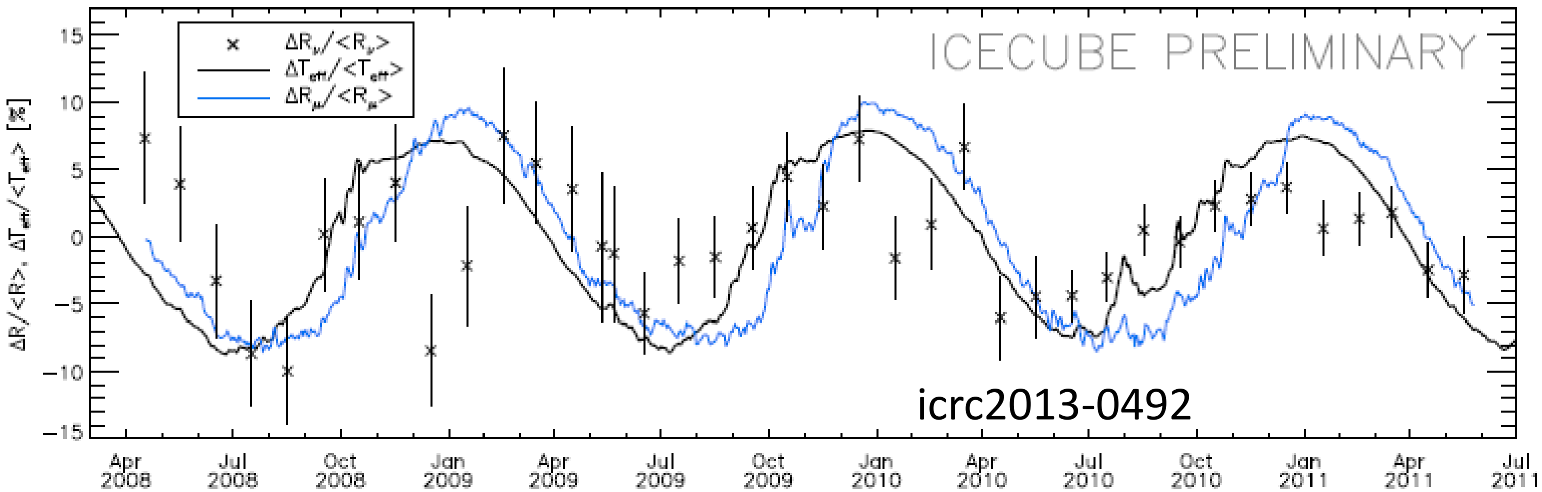
100GeV-PeV neutrino beam, any use?

Seasonal variation of atmospheric neutrinos

170 well-reconstructed neutrinos per day with energies above 100 GeV

Cleated upper region of atmosphere of which temperature monitored by satellite



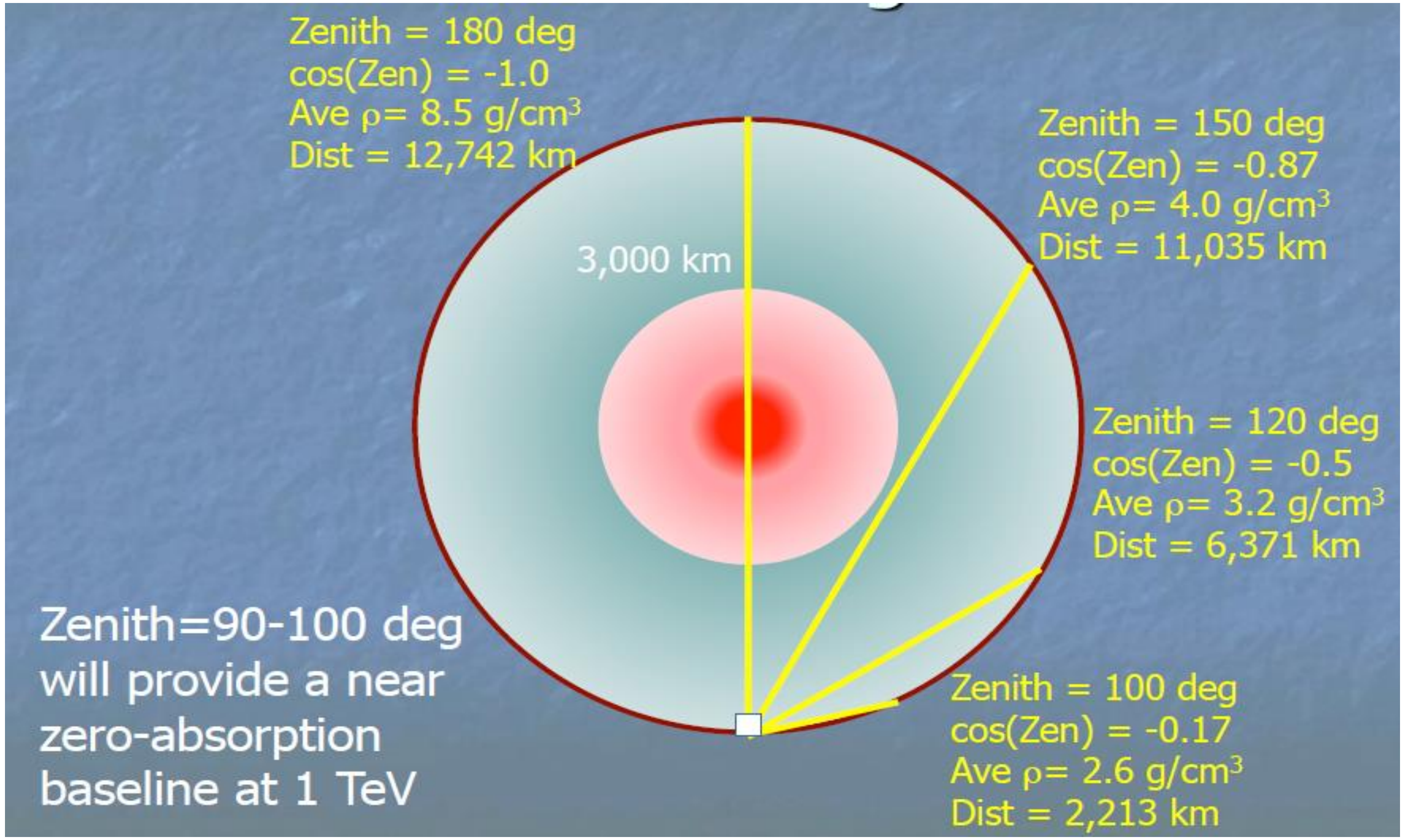


5% level variation, consistent with effective temperature and muon seasonal variation (slightly ahead), is observed

$$T_{\rm eff}(\theta) = \frac{\int dE_\nu \int dX \, P_\nu(E_\nu,\theta,X) A_{\rm eff}(E_\nu,\theta) T(X)}{\int dE_\nu \int dX \, P_\nu(E_\nu,\theta,X) A_{\rm eff}(E_\nu,\theta)}$$

The neutrino-nucleus cross sections

High energy neutrinos are absorbed in the Earth



Absorption effect

$$\mathrm{Rate} = \mathrm{V}\,\Omega\,\mathrm{T} \otimes N_A \sigma \otimes \phi(\mathrm{E}_\nu)\exp(-N_A \sigma\, \mathrm{X})$$

Aperture: Detector+ Geometry

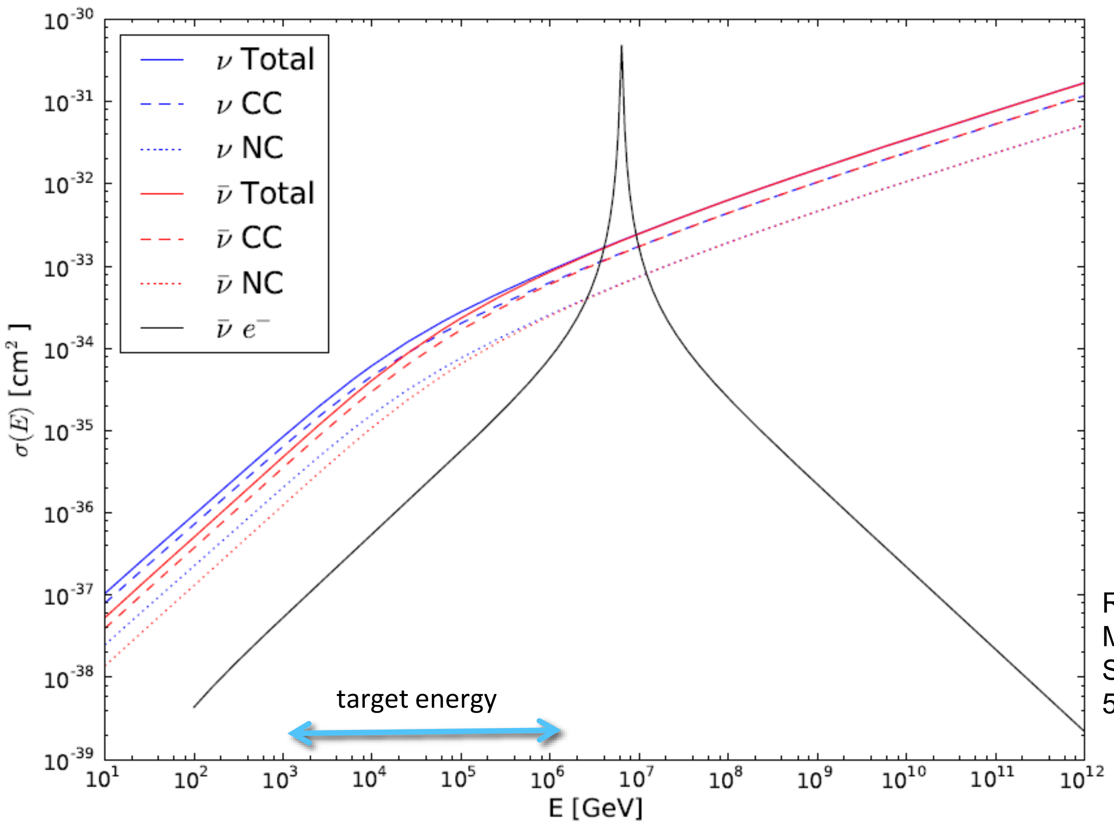
Interaction

Atmos/Astro ν flux

Absorption

Energy range

Reference model ‘CSMS’: A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, JHEP p. 1108:42 (2011) using HERAPDF1.5

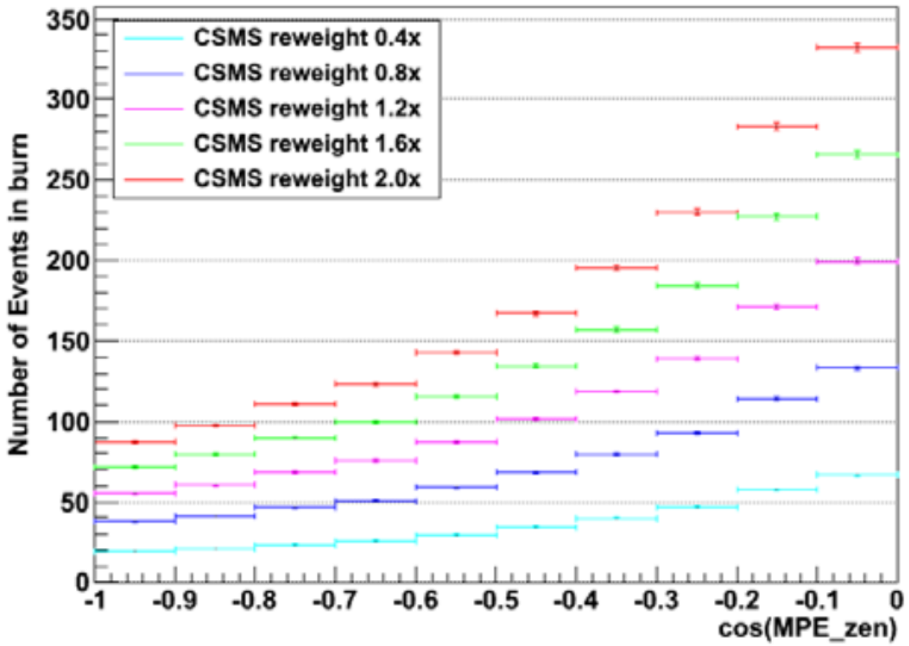


Raj Gandhi, Chris Quigg, Mary Hall Reno, and Ina Sarcevic. Phys. Rev. D, 58(9):093009 (1998)

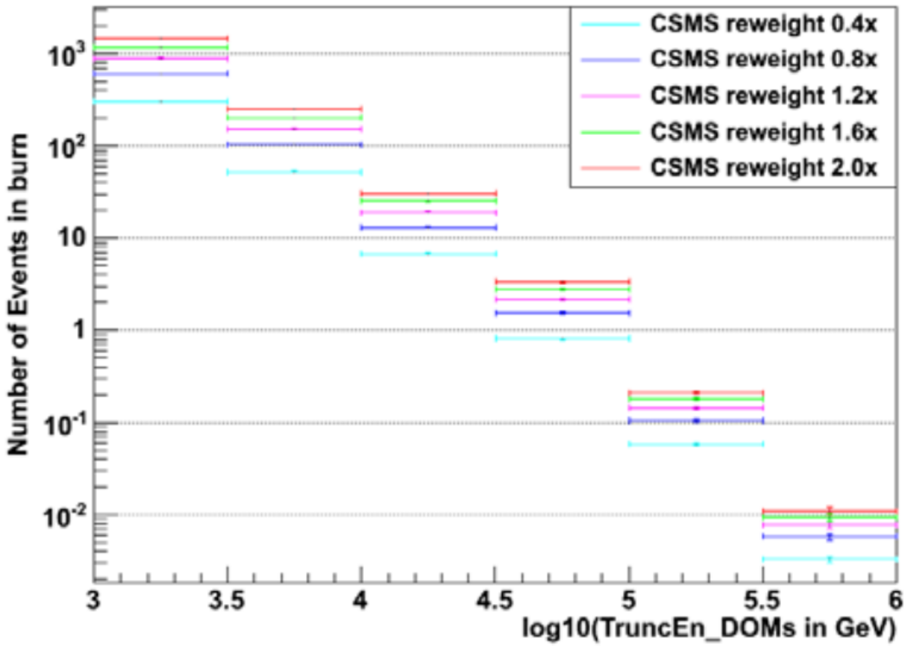
Figure 3.3: Neutrino-nucleon and antineutrino-electron scattering cross-sections as a function of neutrino energy from [67] based on data from [64]. From bottom to top at low energy, the cross-sections are for $\bar{\nu}$ NC, ν NC, $\bar{\nu}$ CC, $\bar{\nu}$ total, ν CC, and ν total. The resonance peaked at 6.3 PeV is the antineutrino-electron resonance.

Implication to the neutrino-nucleus cross sections

Expected event distribution as function of cos θ



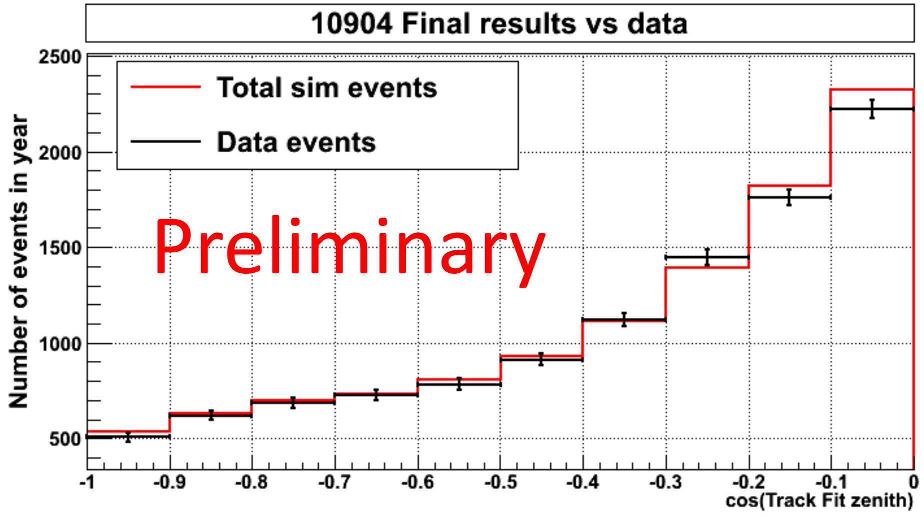
Expected event distribution as function of reconstructed energies

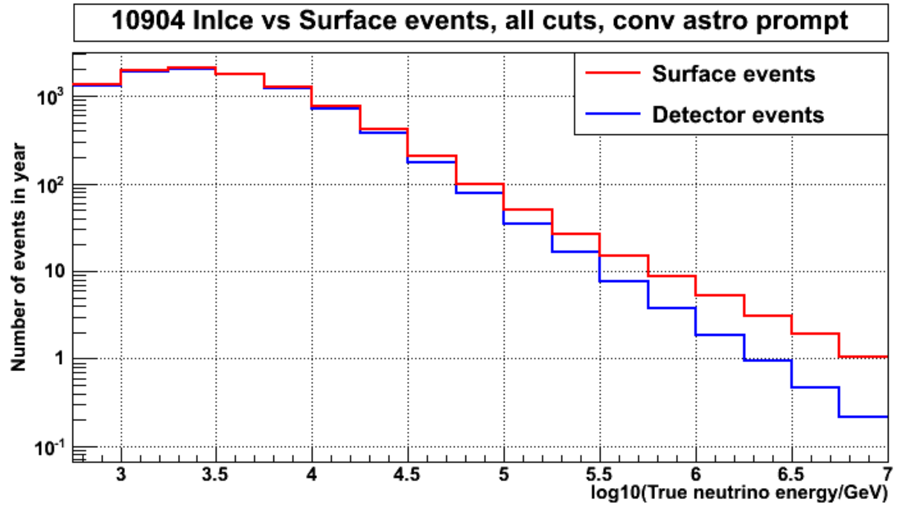


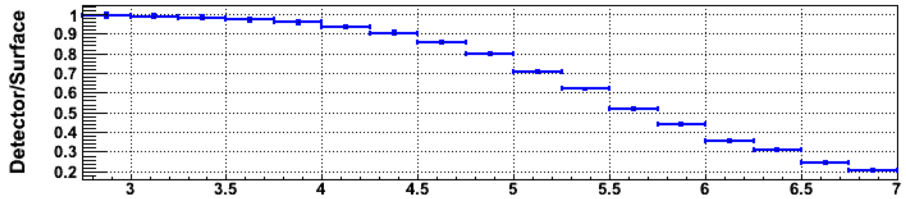
Reference model ‘CSMS’: A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, JHEP p. 1108:42 (2011) using HERAPDF1.5

Best fit cross section

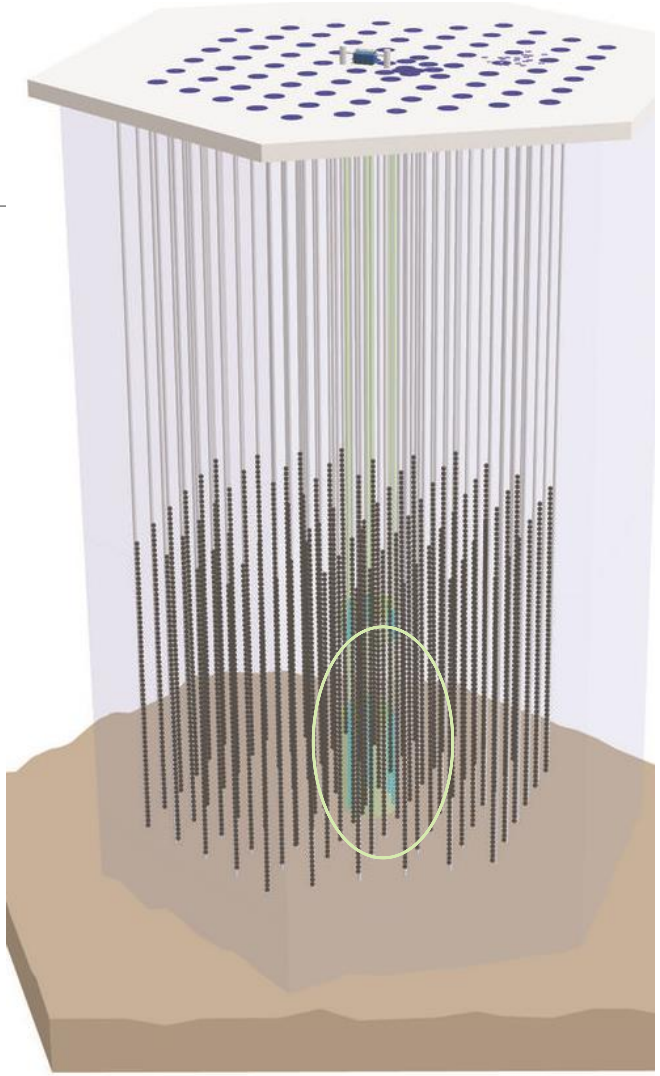
- 1.23xSM (+0.31-0.24 stat) (+0.34-0.37sys)
- Energy range: 1.4 TeV to 890 TeV (mean 21.6 TeV)
- "In agreement with Standard Model expectations within error"



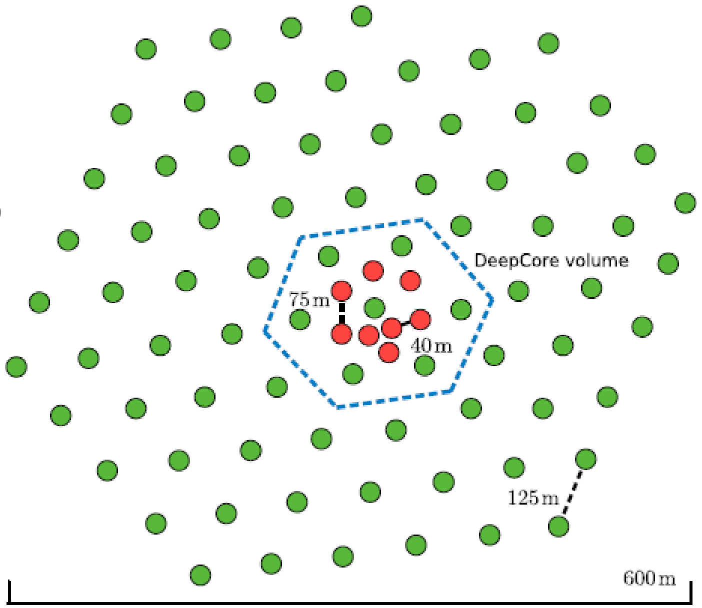




Atmospheric νs with DeepCore



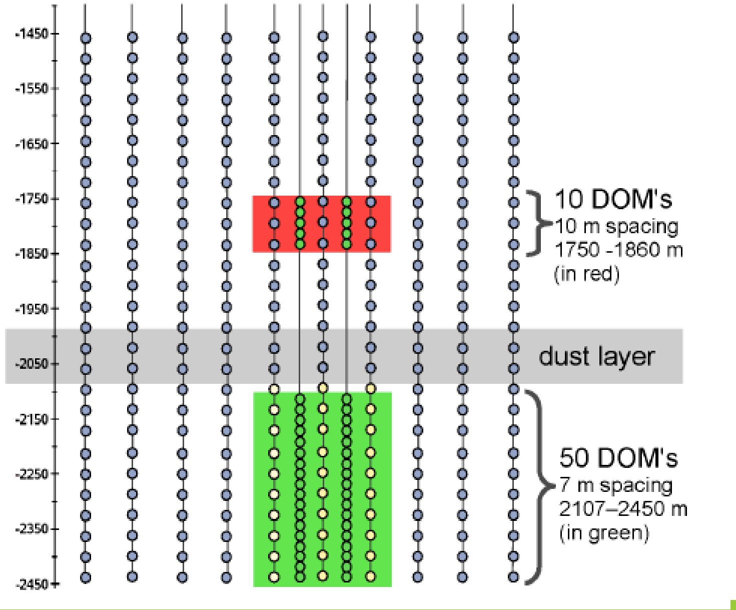
DeepCore oscillation analysis



8-DC strings and 7-IC strings forms a DC low E neutrino array

- Sample: nu mu CC interaction induced ***contained*** muon track
  - Use an active veto
  - Reconstruct neutrino zenith angle as proxy for L & E

- Analyses: To measure $\nu_\mu \rightarrow \nu_\mu$ survival pattern (absorption, but not due to νN interactions)
  - The pattern is convoluted with initial ν_μ flux, interaction probability, and detection probability in 15GeV-50GeV
  - Compare the flux with predictions with different oscillation parameters

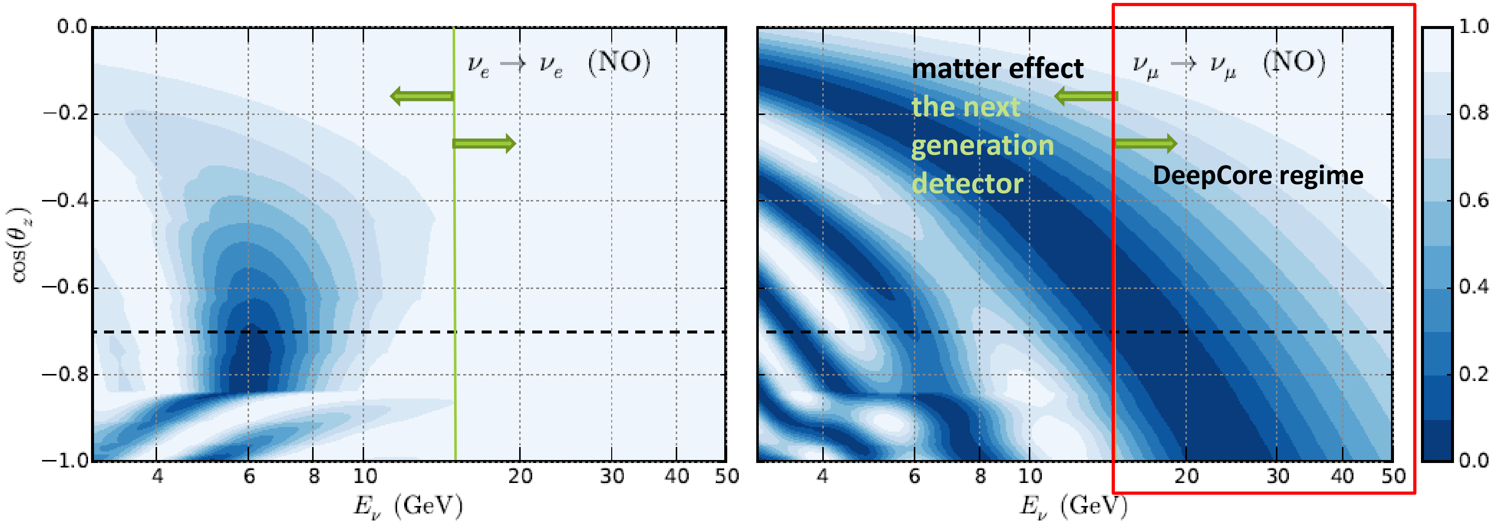


PHYSICAL REVIEW D 91, 072004 (2015)

What we want to measure?

➢Survival probability of muon neutrinos

Advances in High Energy Physics (2015) Article ID 271968 arXiv:1509.08404



Energy region 15GeV-50GeV

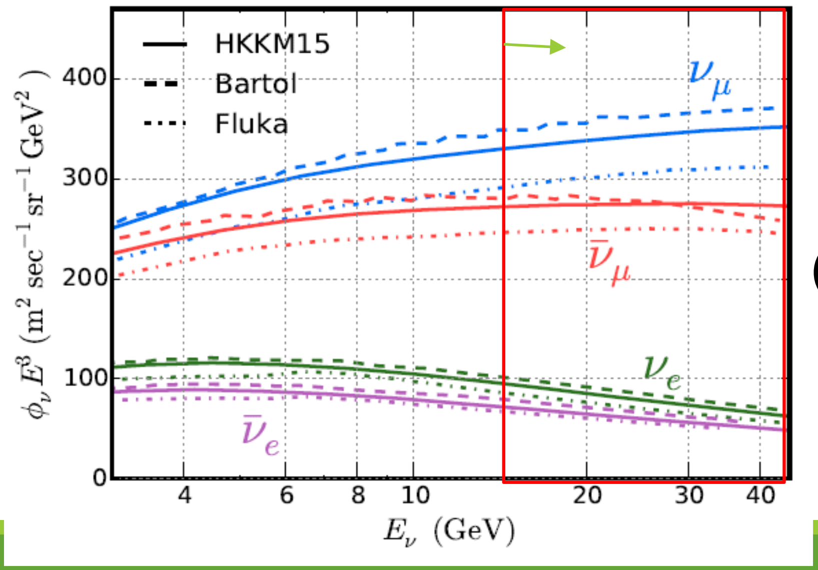
- Smooth disappearance pattern
- Independent of mass ordering
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ transitions

Measureable pattern

- These oscillation patterns are convoluted with ***initial atmospheric neutrino fluxes*** and ***interaction probabilities***

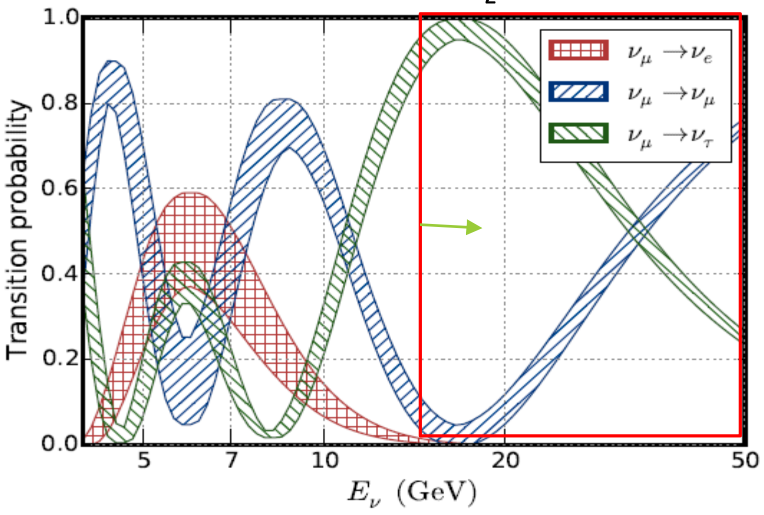
neutrino–nucleon DIS dominant

$$CR+N \to X+\pi^{\mp},\, K^{\mp}\,,$$
$$\pi^-,\, K^- \to \mu^- + \bar{\nu}_\mu\,,$$
$$\pi^+,\, K^+ \to \mu^+ + \nu_\mu\,,$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



$\otimes$

Slice at $\cos(\theta_z)$=-0.7



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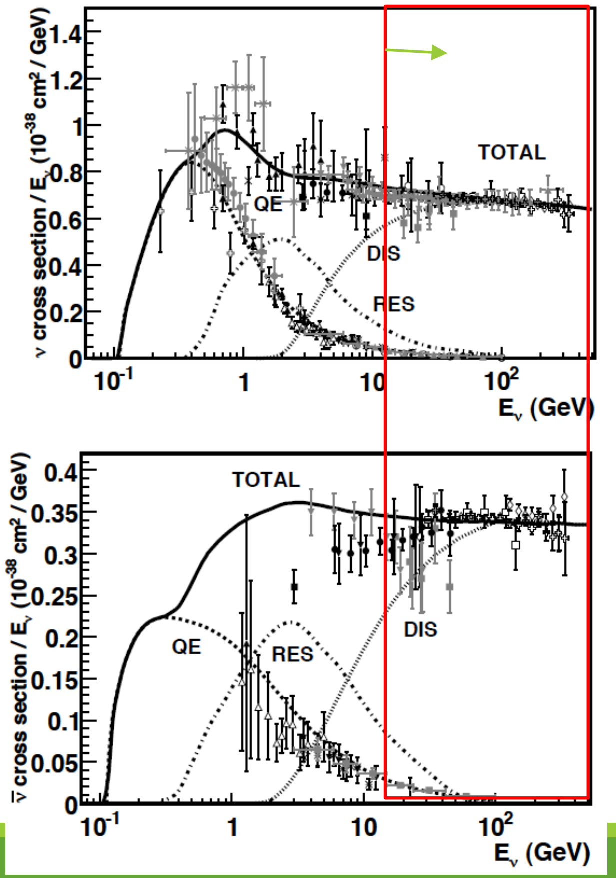
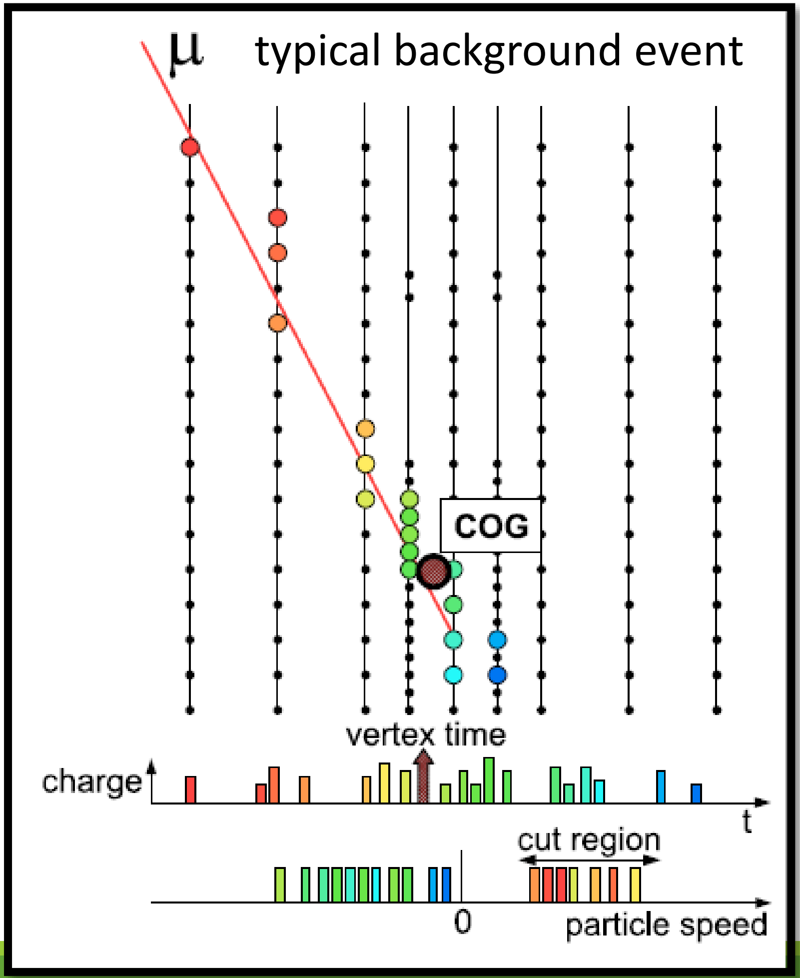


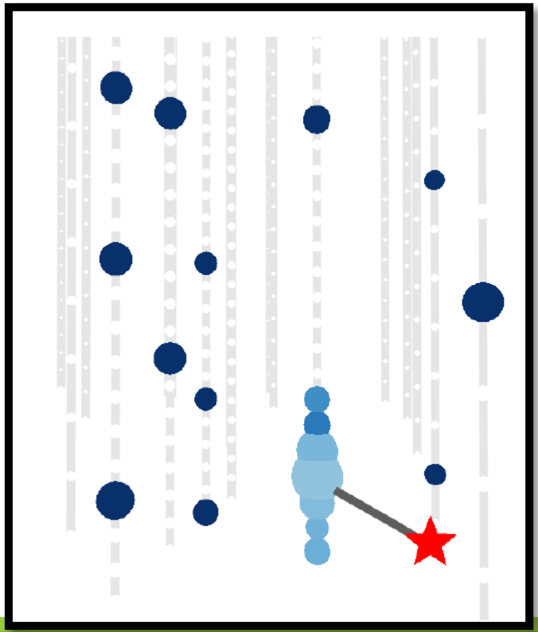
Event selection :veto

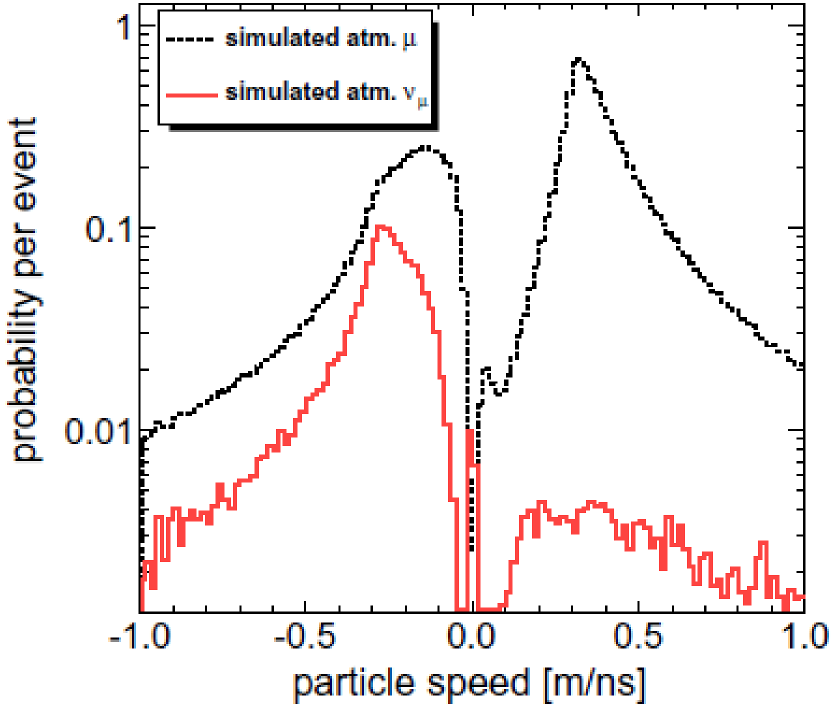
Triggered by DeepCore DOM hits

Large portion of background events are removed by IceCube array as an active muon veto



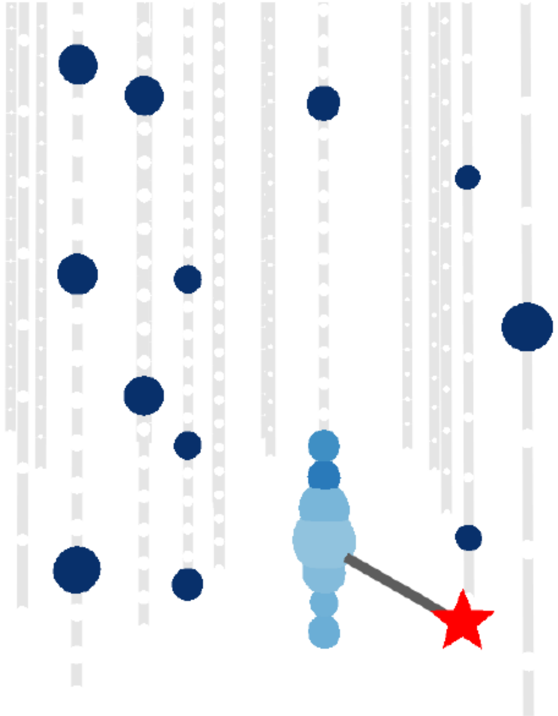
typical signal event
12 GeV muon neutrino

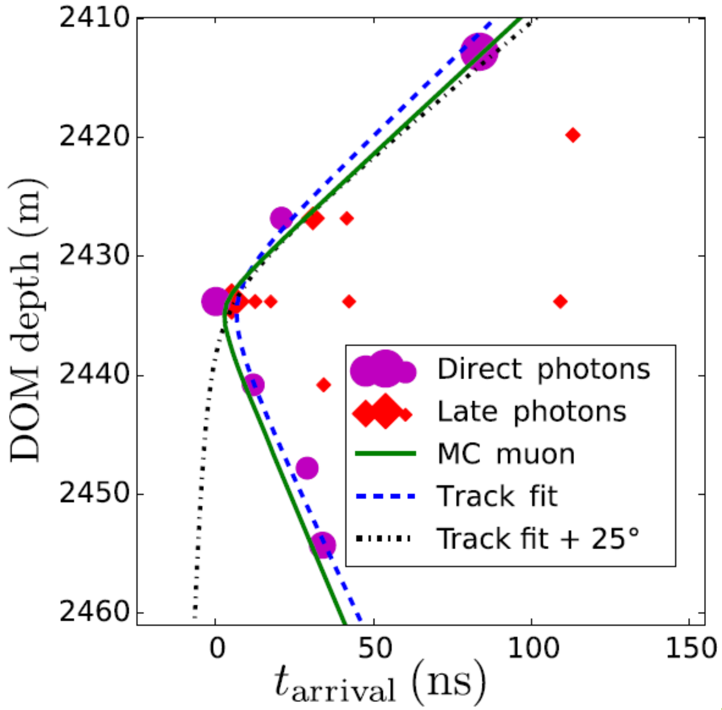


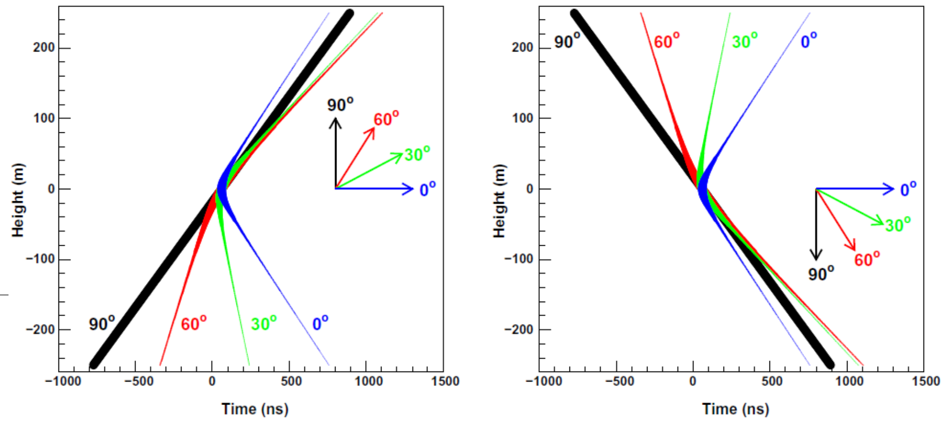


Reconstruction

- A simulated 12 GeV muon neutrino interacting in DeepCore
  - producing an 8GeV muon (42m) and a 4GeV hadronic shower
  - 7 signal induced photon hit DOMs







- Preferentially selects events that occur close to a string which reduces the impact of optical scattering in the ice using unscattered photon (30% of events)
- Directional reconstruction is based on chi2 fit with a hyperbolic function (assuming cascade / track+cascade) by only using unscattered (direct) photon's arrival time and recorded charge
- Retain only consistent with track hypothesis

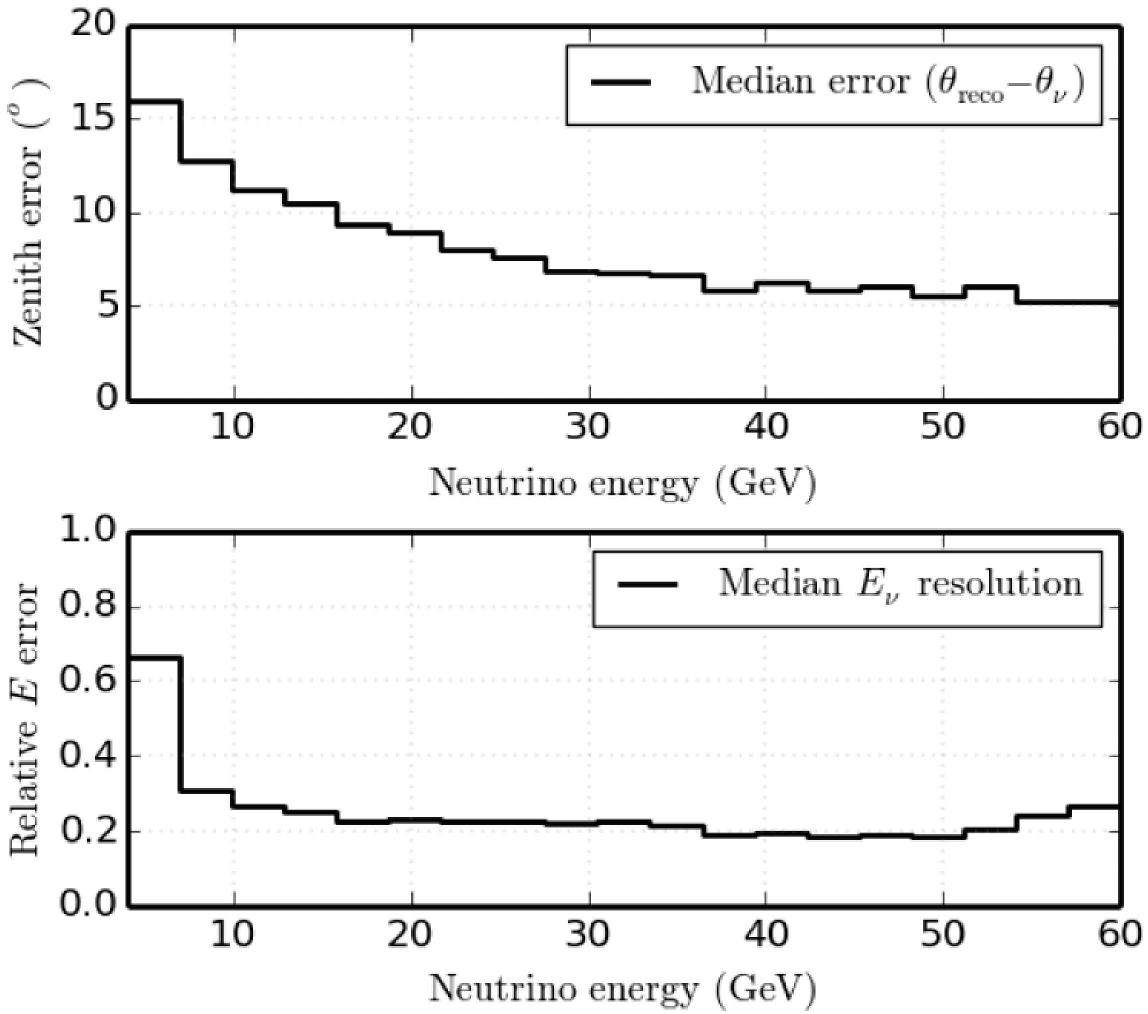
Reconstruction

- Energy reconstruction is performed using all connected hits

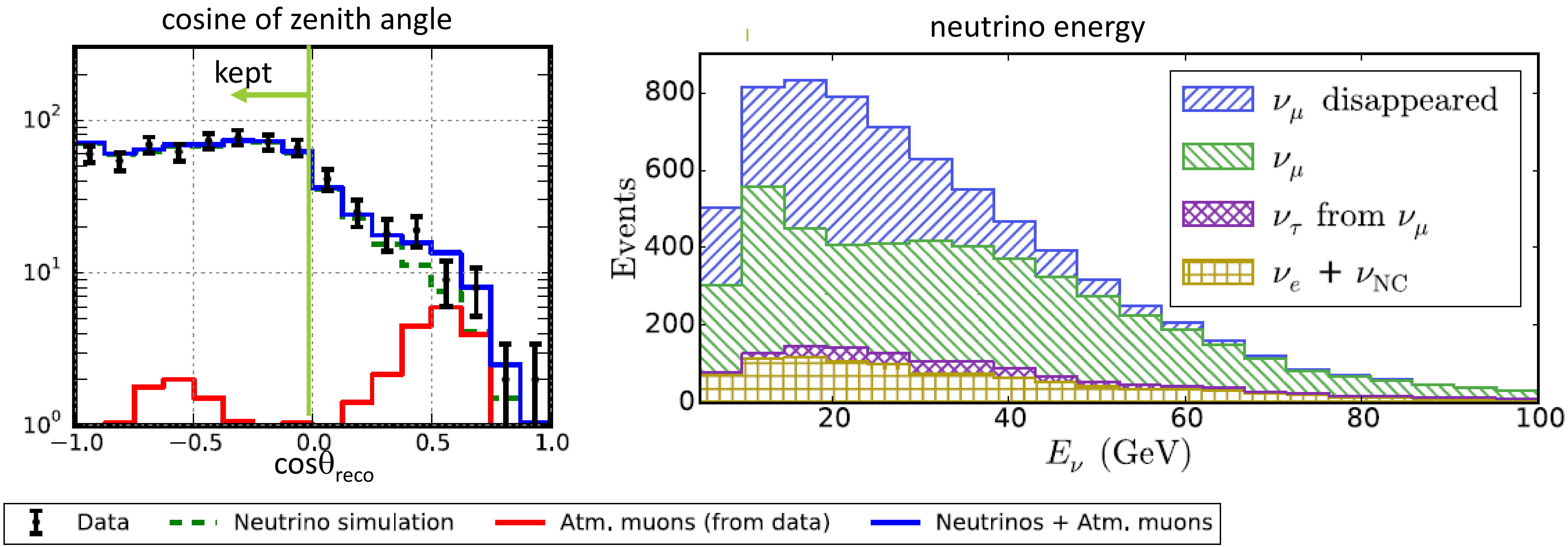
1. estimate range of muon track
   - LLH fit varying track length and vertex position with the given direction
2. add shower at the vertex

$E_\nu = E_{shower} + aR_{muon}$ $a = 0.226 GeV/m$

Median zenith angle and energy resolution
Resolutions for DeepCore (PRD)



Event distributions



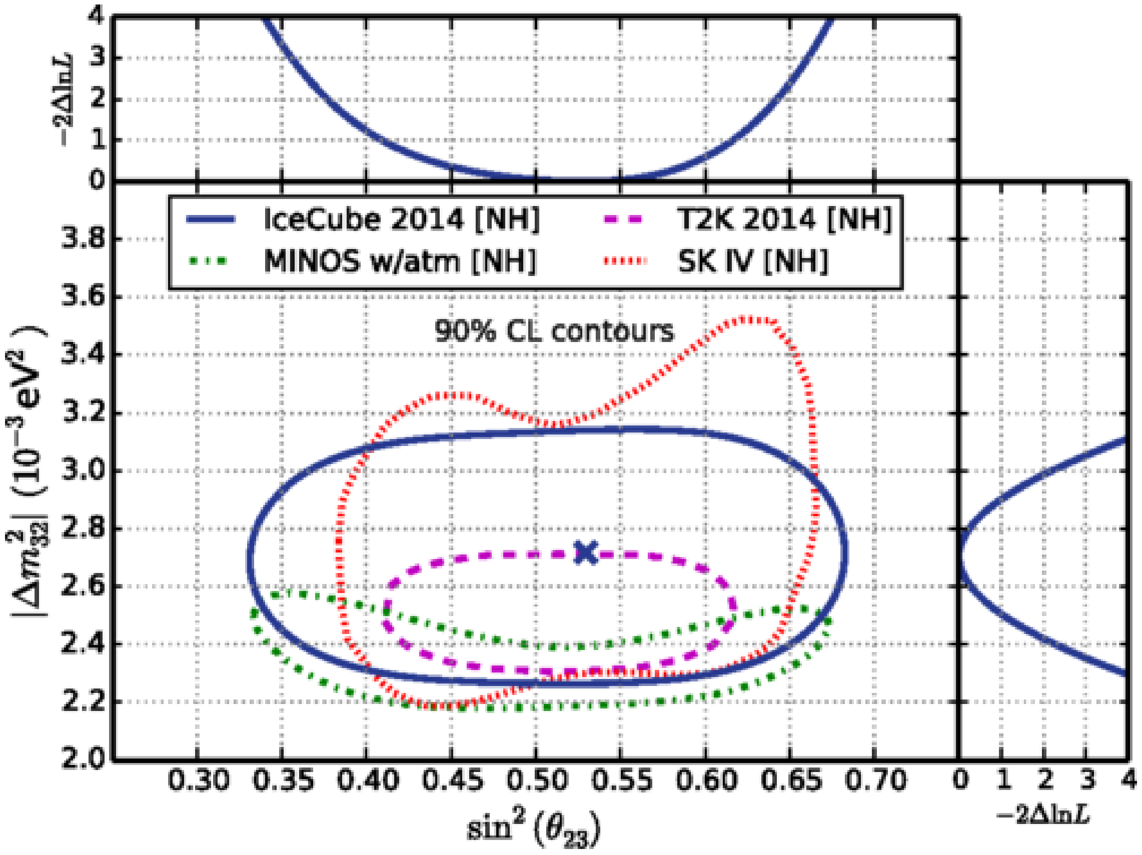
74% νμ CC, 13% νe CC, 8% neutral current interactions and 5% ντ CC, μ<5%: 80% DIS

Fit parameter estimation

A binned (8x8, $\log E_{reco}$ and $\cos\theta$) maximum likelihood is used that includes nuisance parameters for systematic uncertainties: The physics parameters of the fit are the mixing angle θ_{23} and mass splitting Δm^2_{32}

- 3 year data from May 2011 to April 2014, 953 days
- A total of 5174 events compared to an expectation of 6830 events assuming no oscillations
- E_{reco} between 6 to 56GeV and $\cos\theta$ between -1.0 to 0
- θ_{13} is treated as a nuisance parameter
- The remaining oscillation parameters are fixed to the values given in Phys. Rev. D 86, 013012

Fit results



Best fit parameters

$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

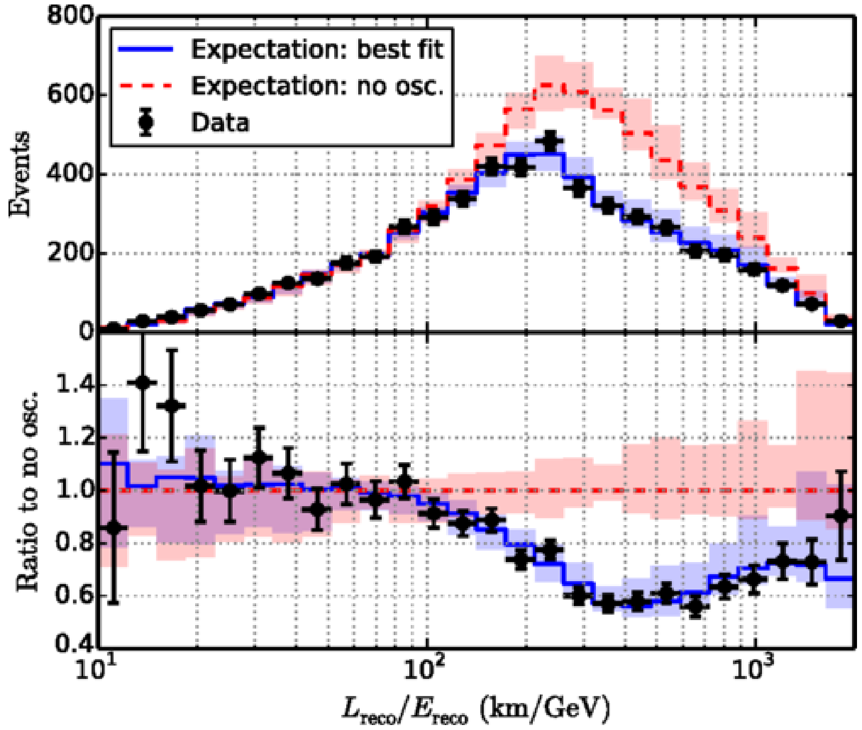
in 2D fit, chi2 = 54.9/56 dof

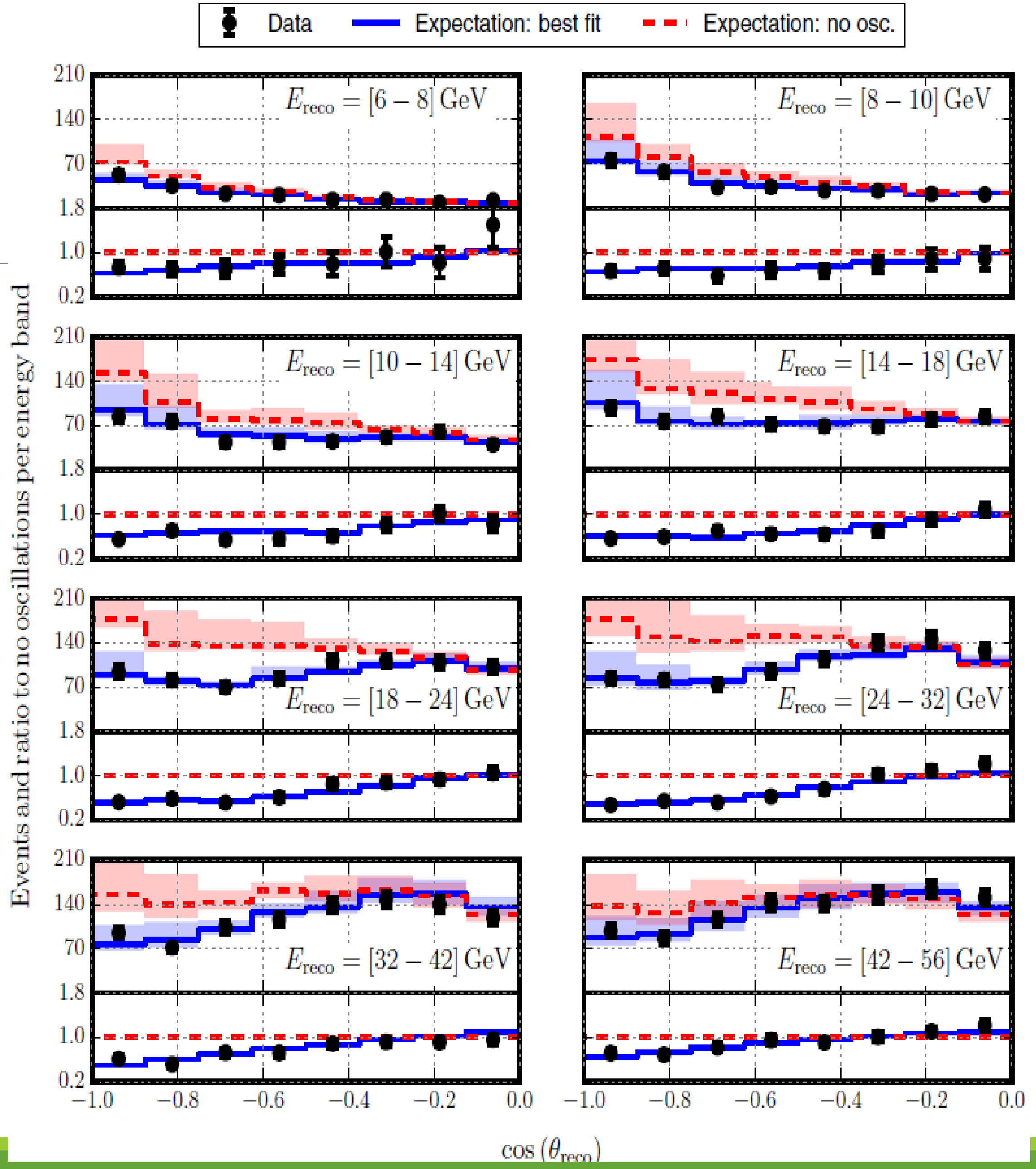
Size of statistical error only

$$\sigma(|\Delta m^2_{32}|) = ^{+0.14}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sigma(\sin^2\theta_{23}) = ^{+0.06}_{-0.08}$$

stat and syst similar sizes

Data/MC comparisons



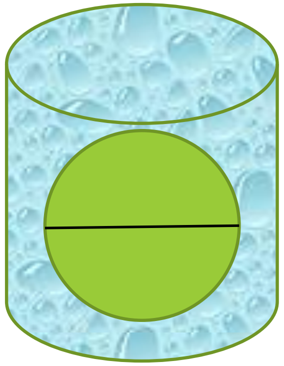


- Measuring in large L/E range
- Affected by different sys error than accelerator results
  - (Bands indicate estimated systematic uncertainties)

Uncertainties

	$\sin^2(\theta_{23})$	Δm^2_{31} (10^3 eV^2)
PRD errors	~ 0.1	~ 0.2
Hole ice (angular acceptance)	29.88%	2.34%
DOM eff	0.73%	19.06%
Gamma	0.13%	8.67%
NuE	0.05%	0.94%
Atm Mu	0.00%	0.72%
Hadronic energy scale	< 1 %	
Axial mass (non-DIS events)		

Preliminary



Next steps with DeepCore

Inclusion of cascade events

Improve event selection and analysis of more data sample (currently 3 years, until April 2014)

…

Summary

- IceCube measures atmospheric neutrinos in a wide energy region from 6GeV to 100TeV
- Track samples are main channel for atmospheric neutrino analysis
- Cascade channel is also being used. Absolute rate of each channel as well as relative rates gives additional flavor dependent information
- Using atmospheric neutrinos as wide energy band steady neutrino beam, more physics can be extracted with IceCube/DeepCore
  - Oscillation
  - Hadronic interaction
  - neutrino cross section
  - Earth core science

Backup

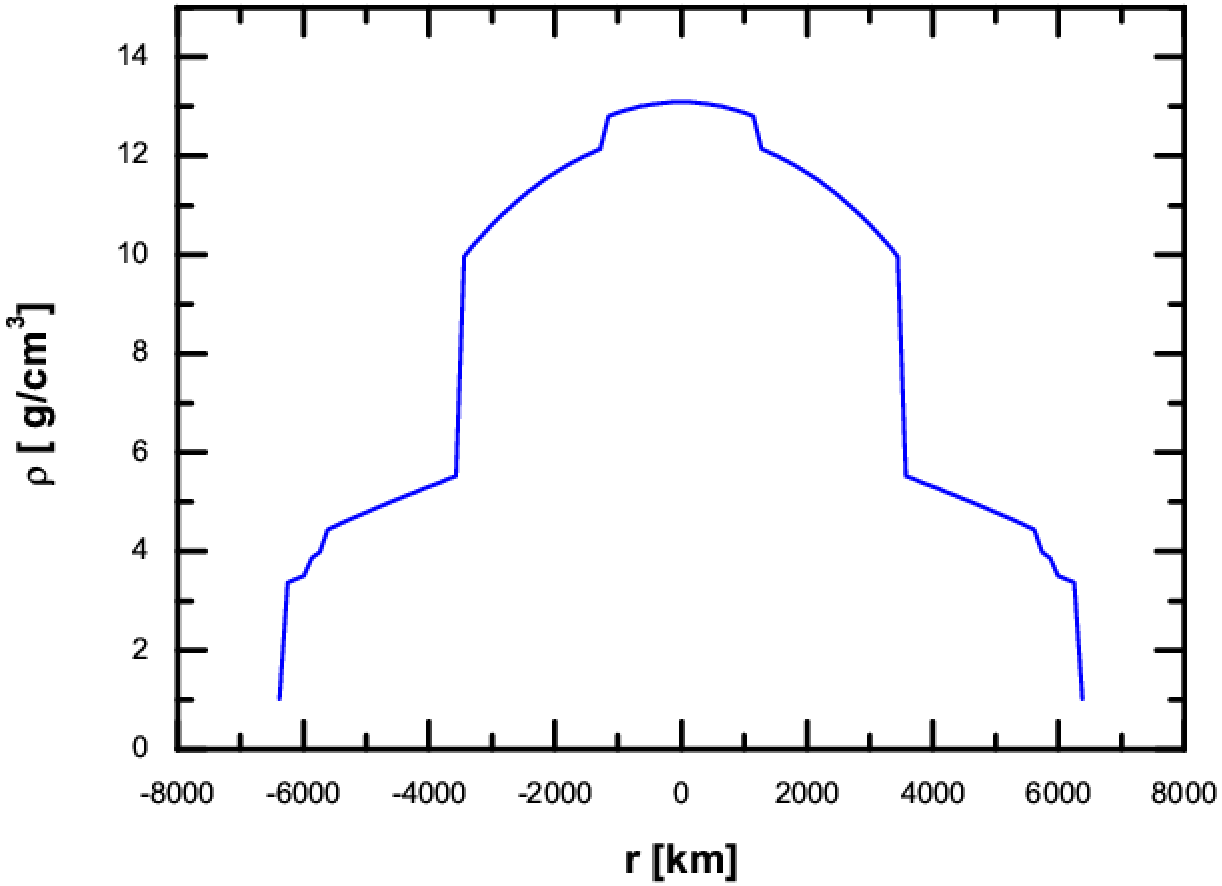
Trigger

the Simple Majority Trigger with 3 DOMs in the DeepCore Ąducial volume (SMT3) is used. The trigger requires a minimum of three DOMs in hard local coincidence (HLC) mode within a 2.5 μs time window: 200Hz

The standard deviation of the time of these pulses, σt, is also calculated. HLC signals outside a 3 σt time window from the mean, which match the hypothesis of a muon entering the DeepCore volume, are searched for. If two or more pulses are found the event is rejected.24hz

3 or more direct hits in at least one string which matches hypervola pattern

Earth profile



Earth matter effect on GeV neutrino propagation - Arcos, Yaithd Daniel Olivas et al. arXiv:1510.07103 [hep-ph]