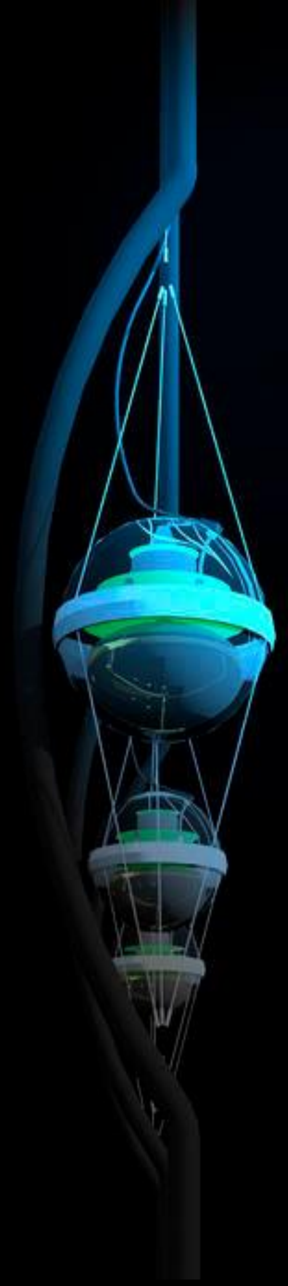


Results from atmospheric neutrino oscillations with IceCube/DeepCore

Measurement of ν_μ disappearance

Juan Pablo Yáñez
for the IceCube Collaboration
DESY

Neutrino 2014
June 2014, Boston, USA

juan.pablo.yanez@desy.de

Neutrino Oscillations in atmospheric neutrinos

- Neutrinos have peculiar properties
  - **Massive, but not too massive**
  - **Different masses, but not too different***
  - **Mixed, almost maximally mixed**

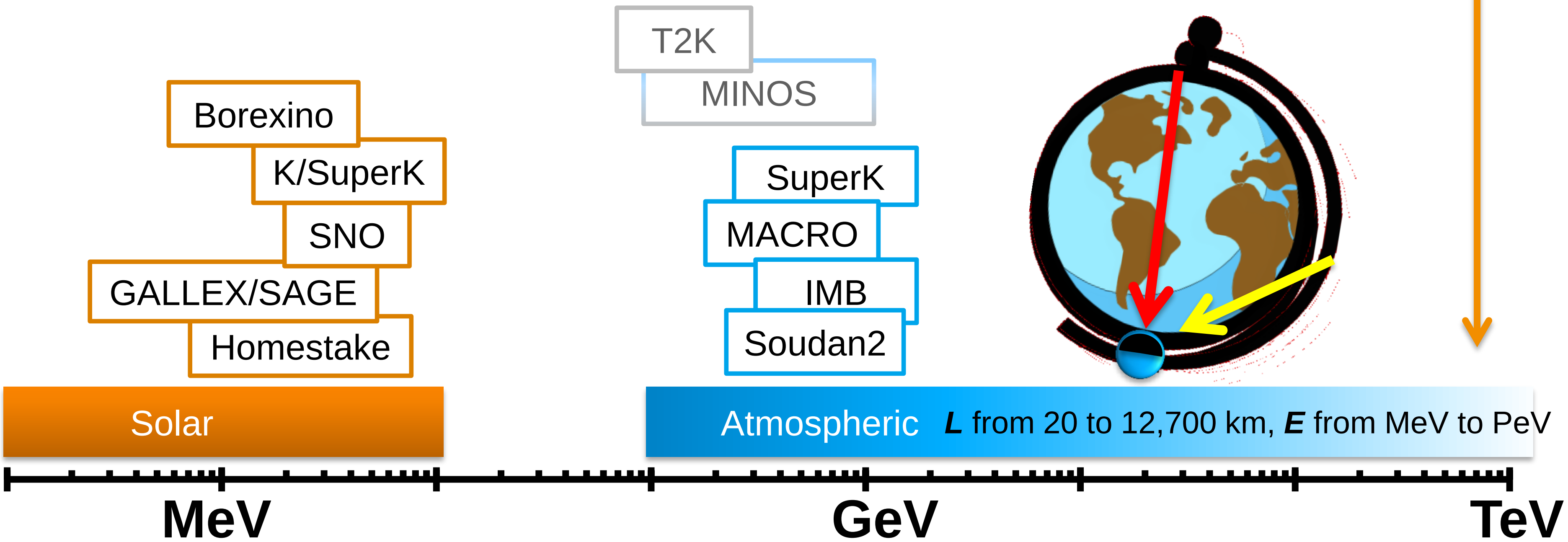
Neutrino oscillations

Described by a sum of factors of the form

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

3+2+1 physics parameters

- Nature has been kind to us
  - Naturally occurring neutrinos as a probe for oscillations (solar, atmospheric)



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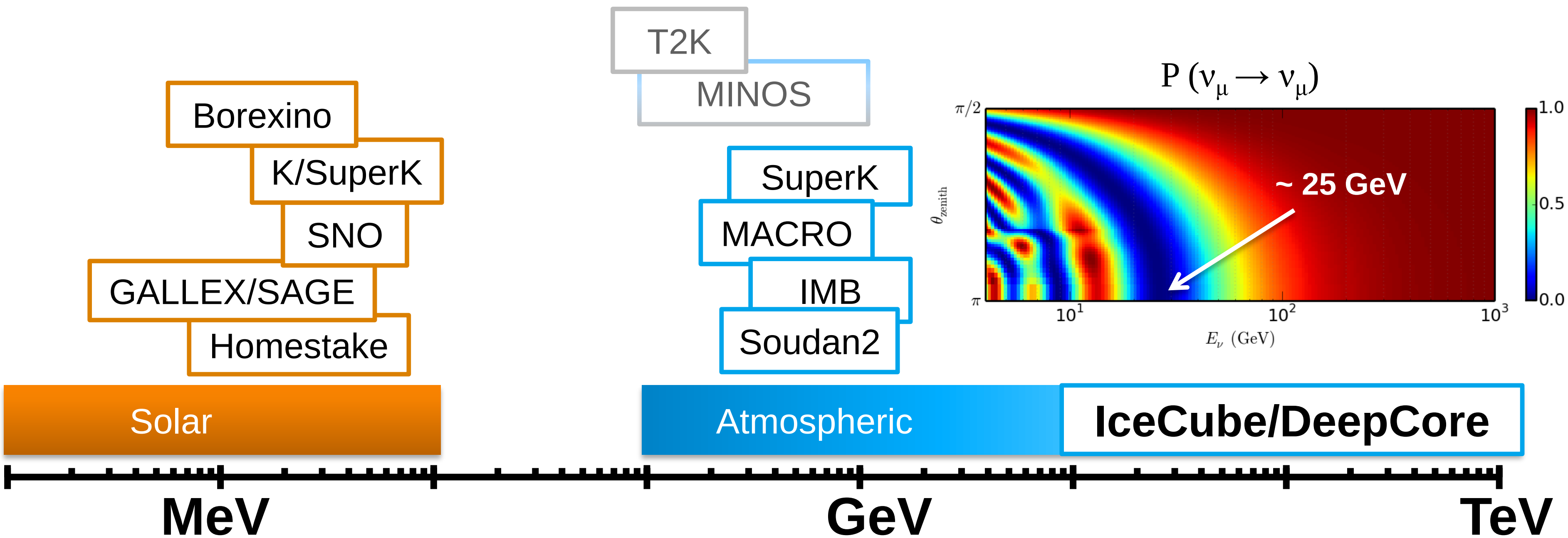
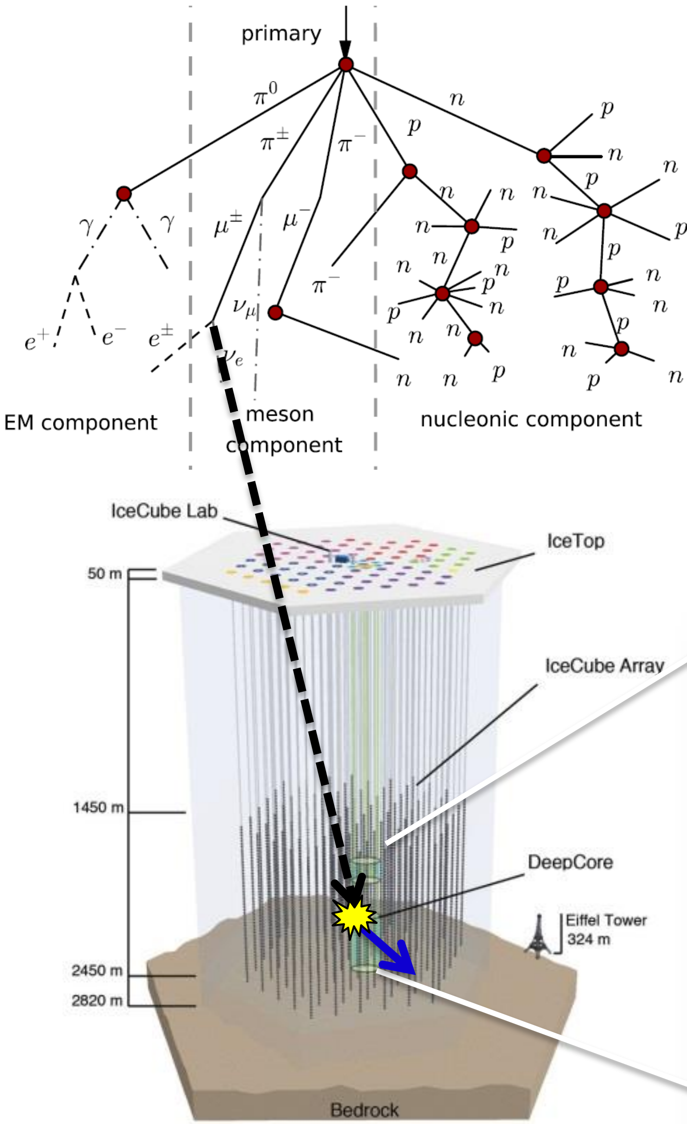


Atmospheric neutrinos in IceCube/DeepCore



$$\pi^+ \to \mu^+ + \nu_\mu, \quad \pi^- \to \mu^- + \overline{\nu}_\mu$$

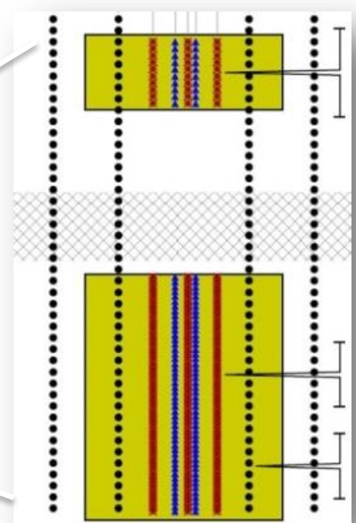
$$K^+ \to \mu^+ + \nu_\mu, \quad K^- \to \mu^- + \overline{\nu}_\mu$$

$$\downarrow \qquad \downarrow$$

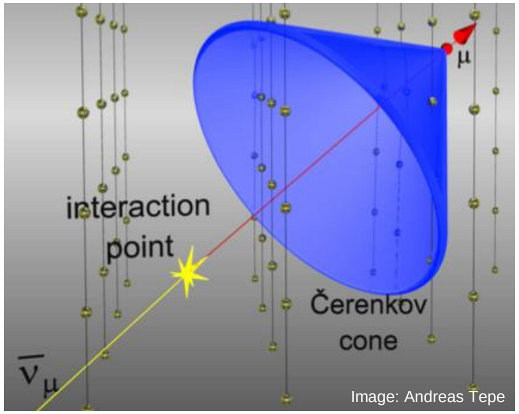
$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu, \quad \mu^- \to e^- + \overline{\nu}_e + \nu_\mu$$

Source of **signal ν_μ** and **background μ**

DeepCore sub-array
Detection E_{th} ~ 10 GeV
4π accpetance



Detection principle

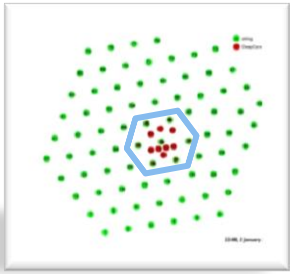


IceCube: 5,160 PMTs over ~ 1 km^3
DeepCore: ~ 600 PMTs over 0.02 km^3

IceCube detector

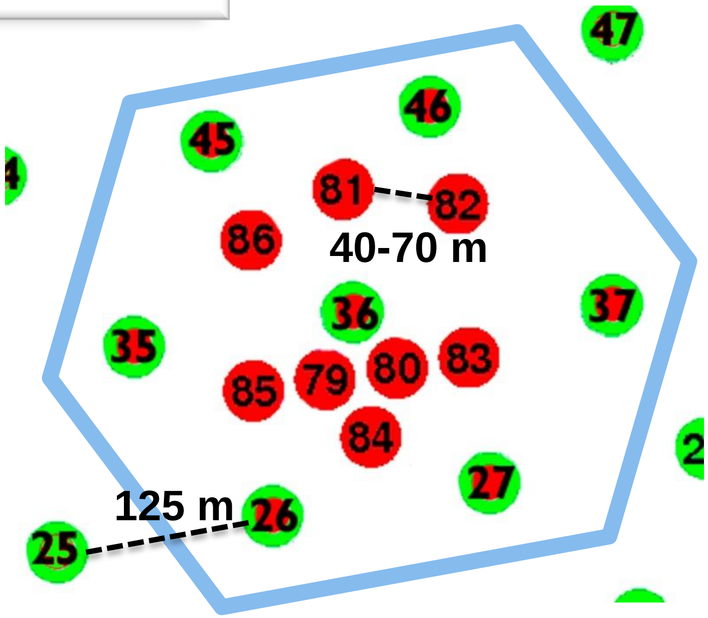
DESY

Measuring oscillations with IceCube/DeepCore



Footprint view of IceCube

DeepCore fiducial volume



- **Sparse detector**
  - Sensors separation from ~7 m to ~70 m
  - E_ν ~ 10 GeV → few photons in a few sensors
- Photons travel in a complex optical medium
  - Layered structure, varying scattering and absorption
  - Columns of newly formed ice at the drilled holes
- Sensors cannot be calibrated in-situ
  - Calibrated at the lab, now frozen in ice
  - In-situ tools fold in medium properties
- Atmospheric muons are detected at rates 10^6 higher than neutrinos
  - Non-negligible probability for faking a neutrino-like signature

Measuring oscillations with IceCube/DeepCore

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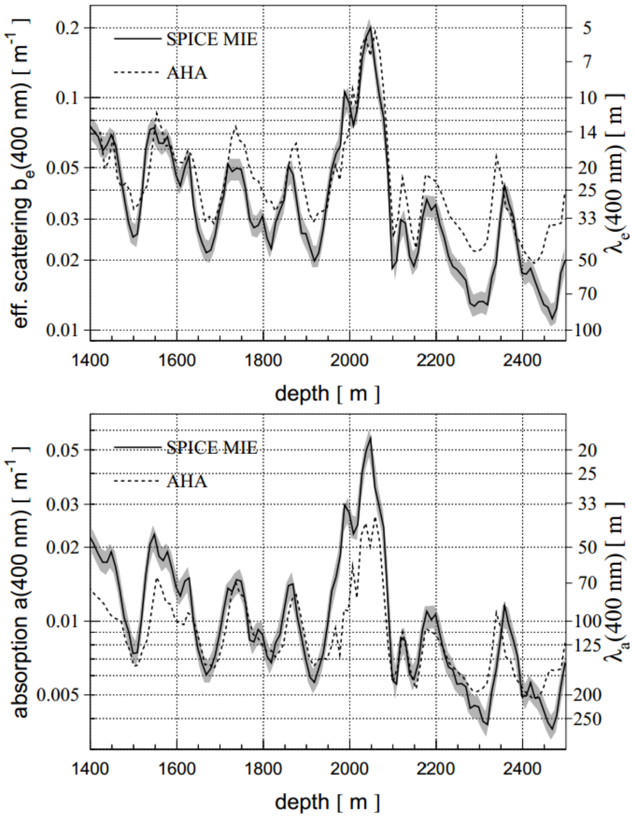
Optical properties of the medium



Nucl. Instr. Meth. A711 (2013) 73

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Inside of an IceCube string during refreeze, image taken by the Swedish camera system

Measuring oscillations with IceCube/DeepCore

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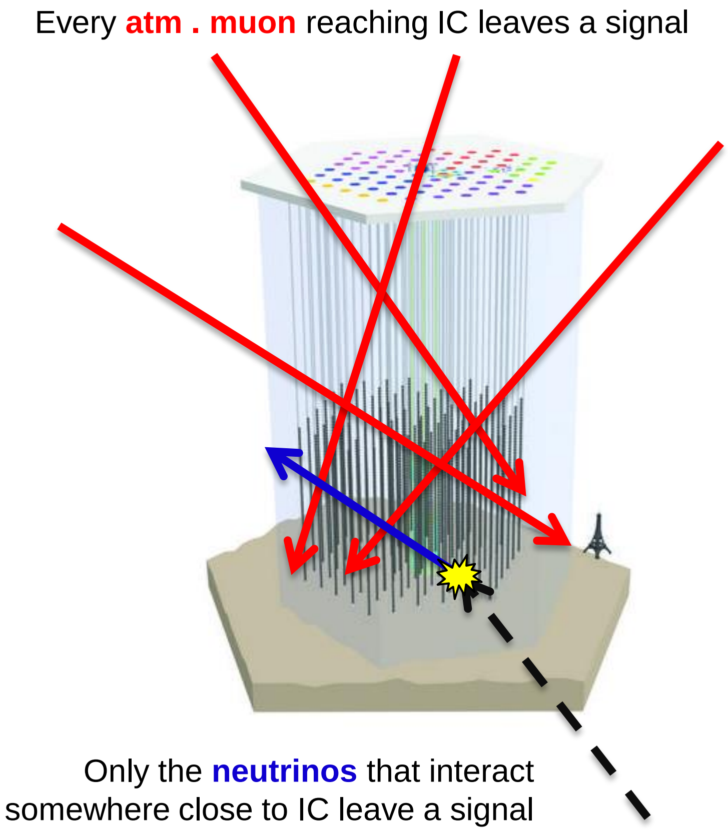

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Measuring oscillations with IceCube/DeepCore

- Sparse detector
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  - E_ν ~ 10 GeV → few photons in a few sensors
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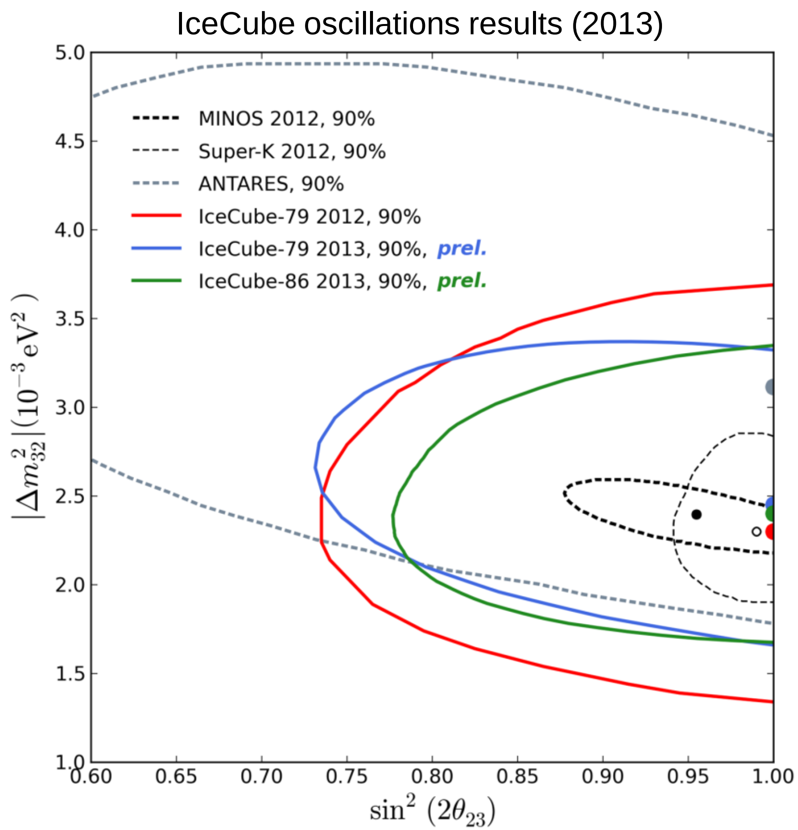
Nevertheless, IceCube triggers on **over 100,000 atm. neutrinos** every year.

It has the potential to make **statistically powerful** measurements of neutrino oscillations at energies **mostly unexplored.**

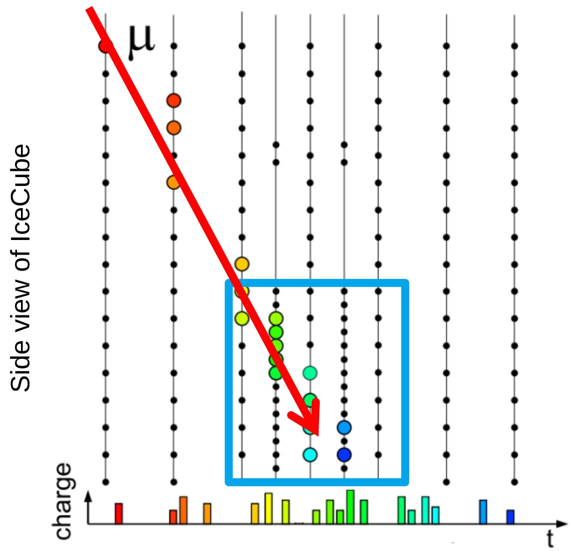


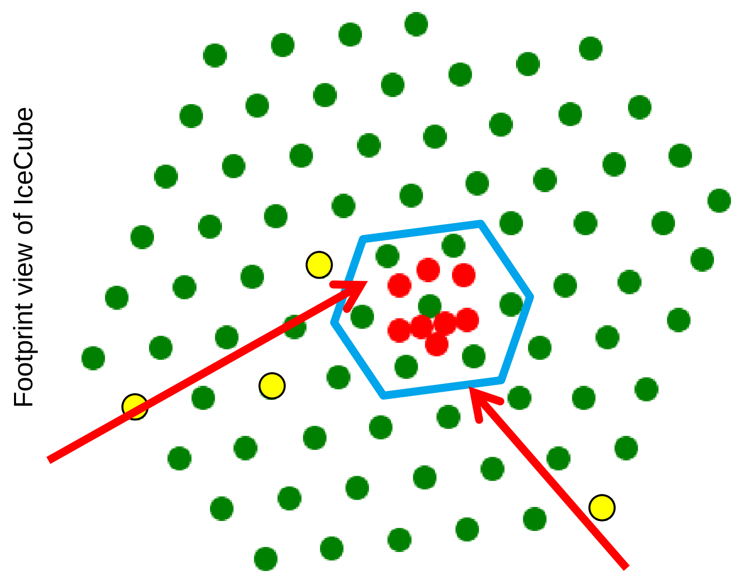
- Atmospheric muons are detected at rates 10^6 higher than neutrinos
  - Non-negligible probability for faking a neutrino-like signature

Addressing the challenges

Atmospheric muon background

- Use IceCube as a veto for DeepCore
  - Look for hits of muons entering the detector: tag and remove the events
  - Strategies:
    - Location of first DOM pair (trigger)
    - Count isolated but causally connected DOMs in veto region
    - Search for individual hits in a narrow time window from known problematic directions





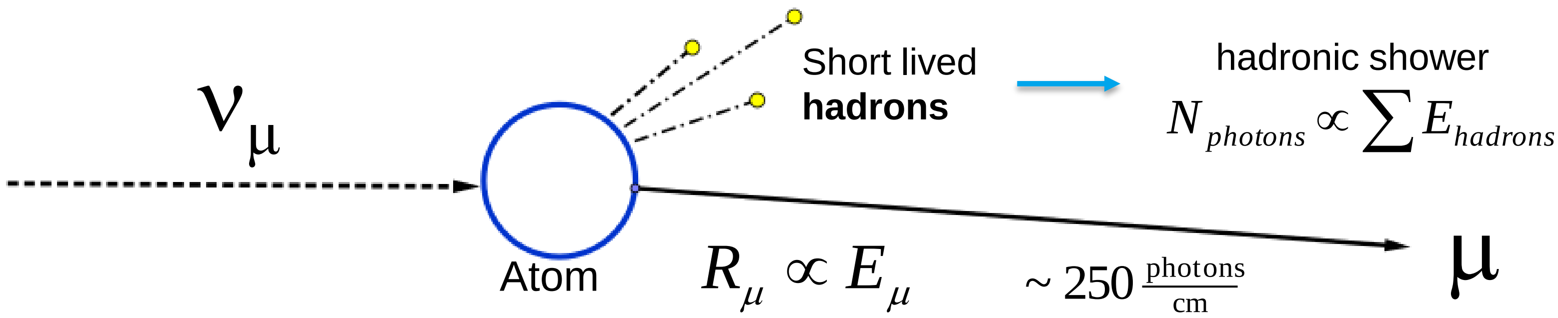
Veto is used to tag muons and use them to fit the atm. muon background in the result

This background is derived from data

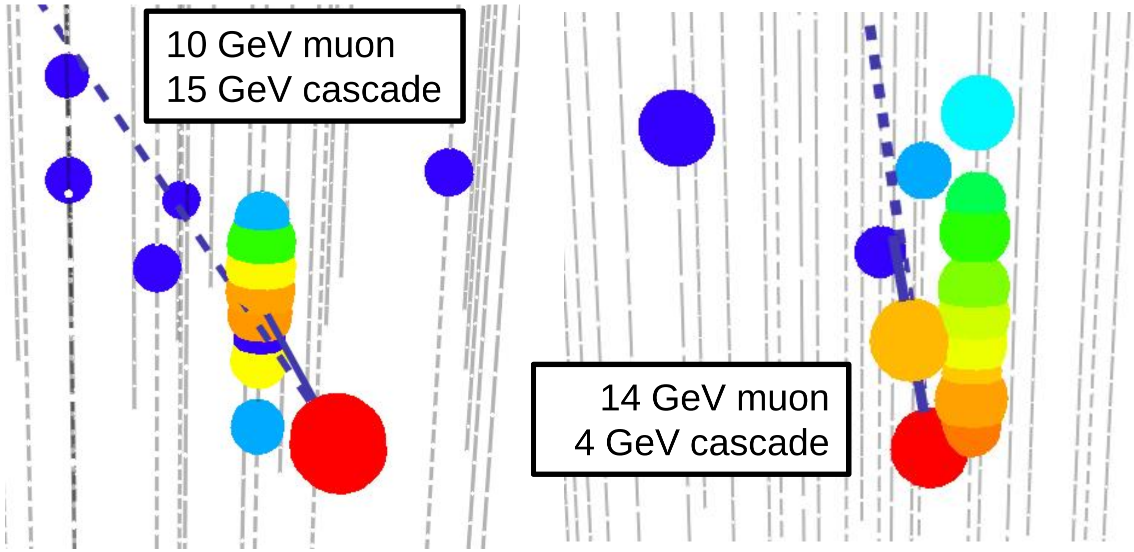
Neutrino signal

- Signal*: ν_μ of E ≤ 50 GeV in charged current (CC) interaction

*All other interactions are background for this study



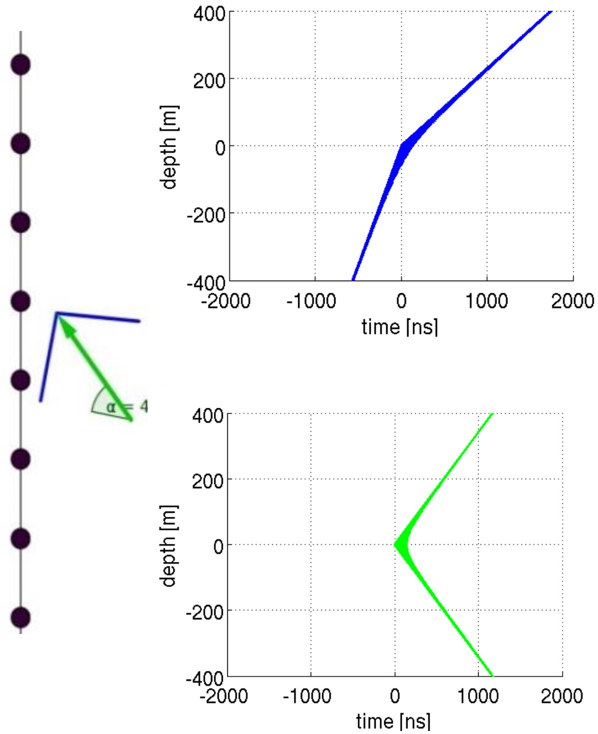
- Interactions in DC
  - DOMs triggered colored
  - **Orange** is early, **blue** is late
  - Dashed: neutrino direction
  - Solid line: muon
  - **Red**: interaction point



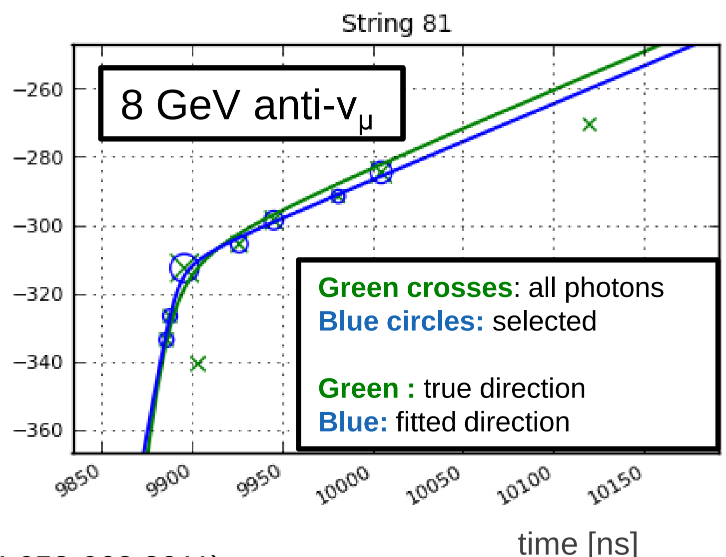
We need the **incoming direction** and **energy** of these signal neutrinos

Selection and directional reconstruction: direct photons

- Focus on the subset of neutrino events dominated by non-scattered photons
- Build observables that depend on them
  - Minimally distorted by medium properties/event variations



- Cherenkov light projected in string = hyperbolas
  - Search for patterns to get 2 variables:
  - Number of direct hits → **quality criterion**
  - Hyperbola orientation → **zenith angle**



Idea developed in collaboration with J. Brunner* (Astropart.Phys.34:652-662,2011)

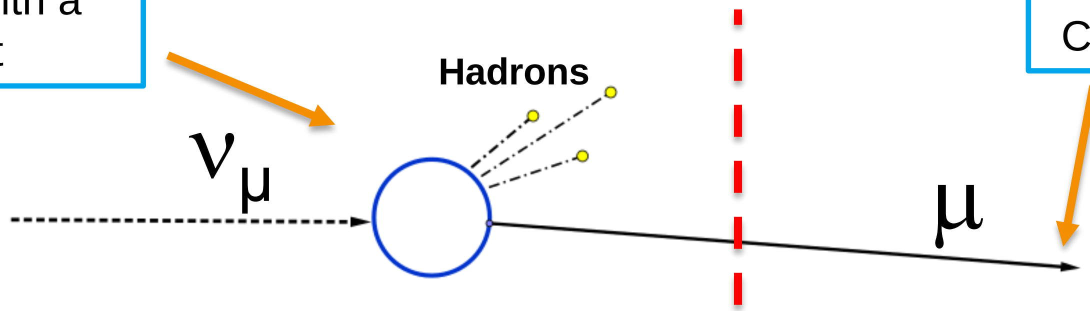
Constructing a full energy estimator

- Dividing the problem in two parts

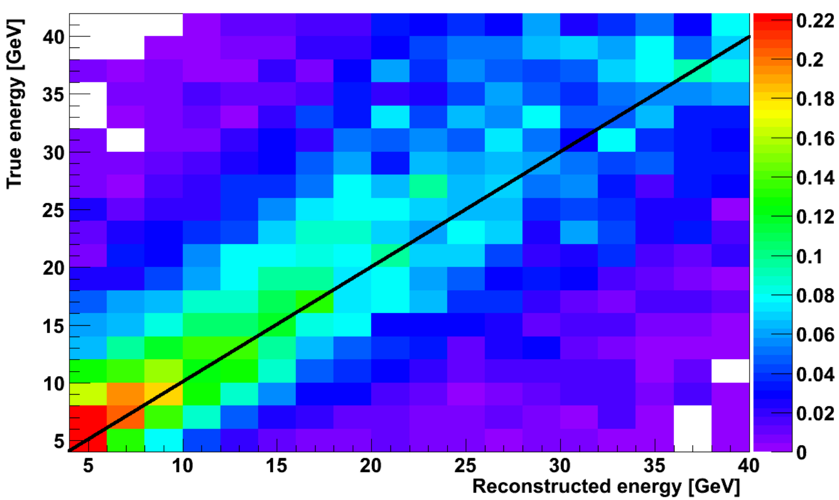
$$E_{\text{reco}} = E_{\mu}(R_{\mu}) + E_{\text{vertex}}(E_{\text{had}}, \vec{x}_{\text{vertex}})$$

Fit of a cascade with a track segment

Find last point of Cherenkov emitter



Correlation between reconstructed and true energy



- Takes all information available in the detector
- Uses the parameterized light emission of particles
  - Optical properties of the ice included
- Good resolution down to E_{ν} ~ 10 GeV

Fitting the oscillation parameters: θ_{23}, Δm^2_{23}

- Using a binned likelihood for a **3 flavor fit with matter effects**
  - **2-D histograms** as a function of **energy** and **zenith angle**
  - **Systematic uncertainties** as nuisance parameters
  - Other osc. parameters (θ_{12}, θ_{13}, Δm^2_{21}) fixed

    Using global fits from Fogli et al. (Phys.Rev.D86,013012)

$$E = [7, 56]\ \text{GeV}, \quad \cos\theta_z < 0$$

$$-\ln(L) \propto \sum_i t_i - d_i \ln t_i + \frac{1}{2}\frac{(\nu_i - \hat{\nu})^2}{\sigma_\nu{}^2}$$

- Systematic uncertainties included in the fit

Systematic uncertainty	Prior	Implemented
Atm. μ contamination	Unconstrained, free fit from data	Modifying the weights
Atm. ν flux *	From Honda 2011, Phys.Rev.D83:123001	
ν_e/ν_μ deviation	μ_n = Honda, $\sigma_n = 0.2$	
Spectral index (γ) *	μ_γ = Honda, $\sigma_\gamma = 0.05$	
Photon collection eff.	$\sigma_{eff} = 10\%$	From discrete MC variations
Scattering in ice columns	$\mu_a = 0.02\ \text{cm}^{-1}$, $\sigma_a = 0.01\ \text{cm}^{-1}$	
Modeling of bulk ice	Models in Nucl.Instr.Meth.A711,2013,73	Marginalization

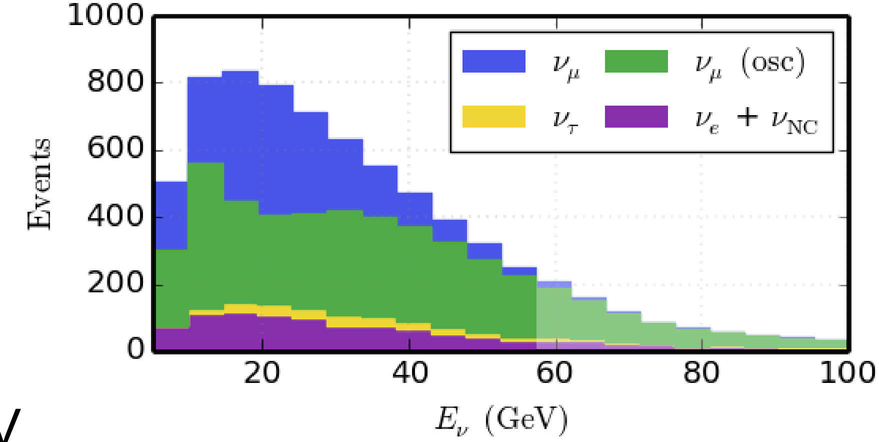
* Cross section uncertainty covered by these parameters

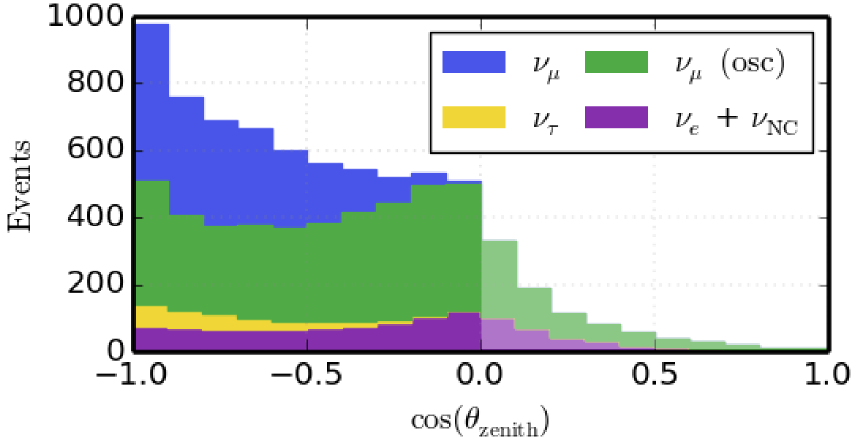
Results

Final neutrino sample

- Including 3 years of full detector configuration (IC86)
  - 953 days of detector livetime
- MC expectation: ~ 7,000 events
  - Disappearance of ~ 1,900
- Energy threshold ~ 10 GeV
- Zenith angle: 12 deg. res. at 10 GeV
  - Low energy side: 15 deg. res.
  - High energy: 5 deg. res.
- Energy: 30% res. at 10 GeV
  - Not so reliable below 10 GeV
  - Above 50 GeV muons leave the detector

MC prediction, **true** energy/zenith angle





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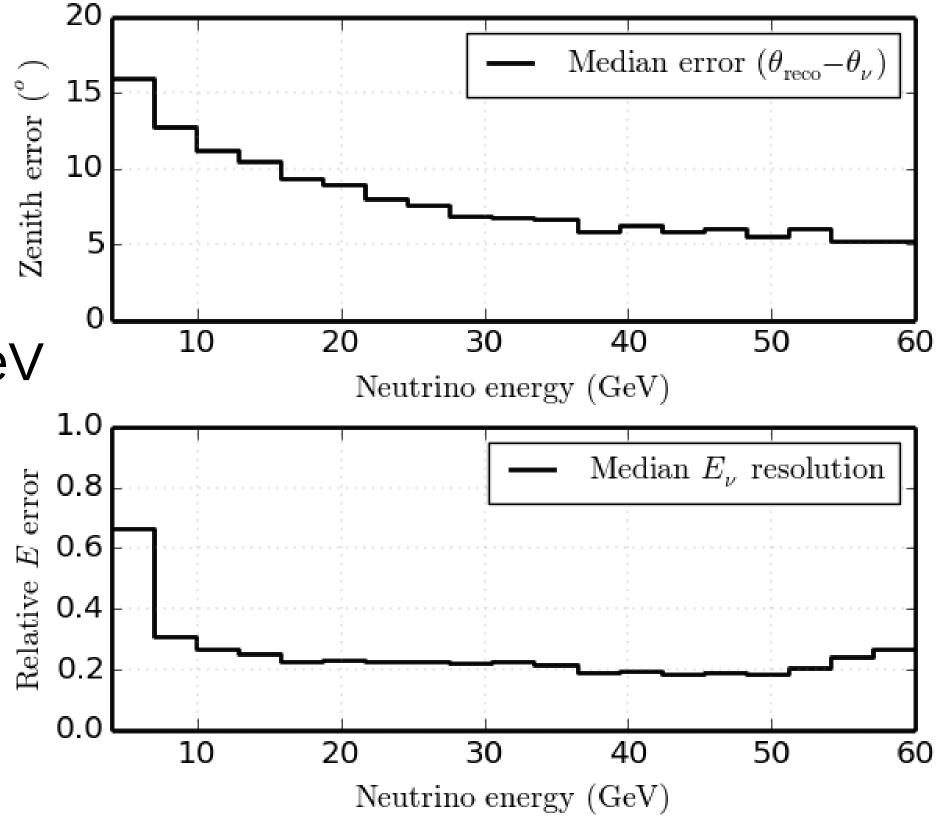
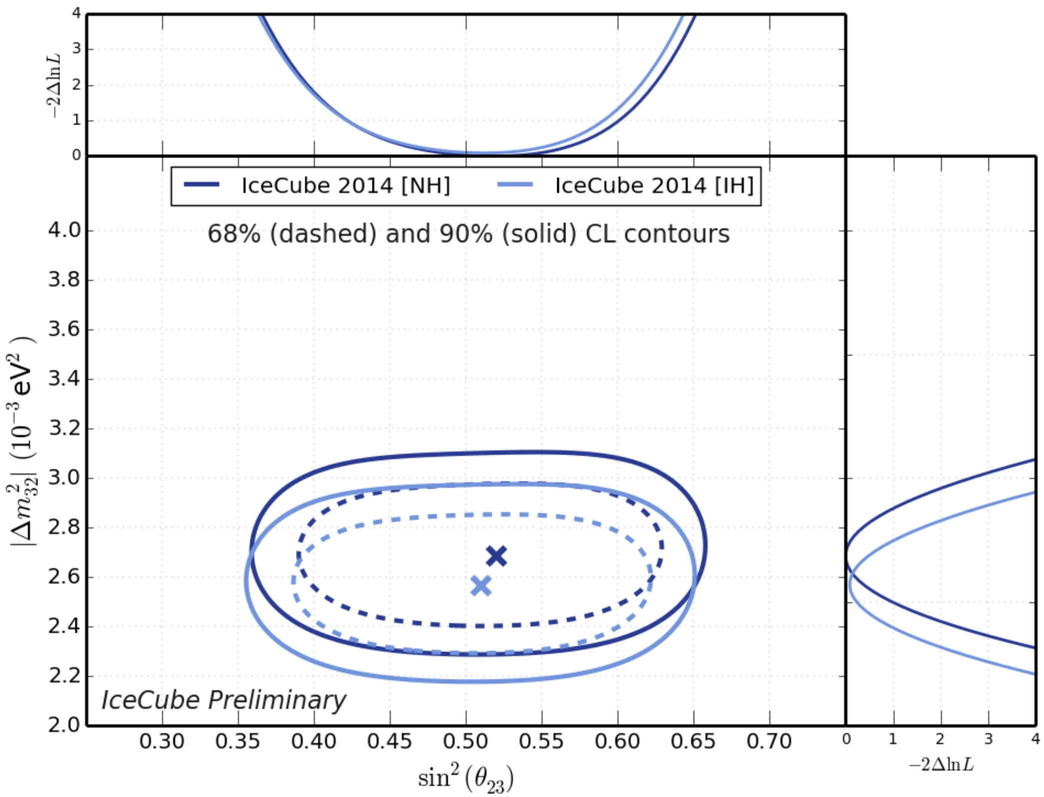
Resolutions of the final sample



Likelihood scan and profile

Parameter	Normal hierarchy		Inverted hierarchy	
	Best fit	68% CI	Best fit	68% CI
$\sin^2(\theta_{23})$	0.512	0.422 – 0.600	0.509	0.417 – 0.594
Δm^2_{32} (10^3 eV^2)	2.684	2.503 - 2.877	2.563	2.385 - 2.754

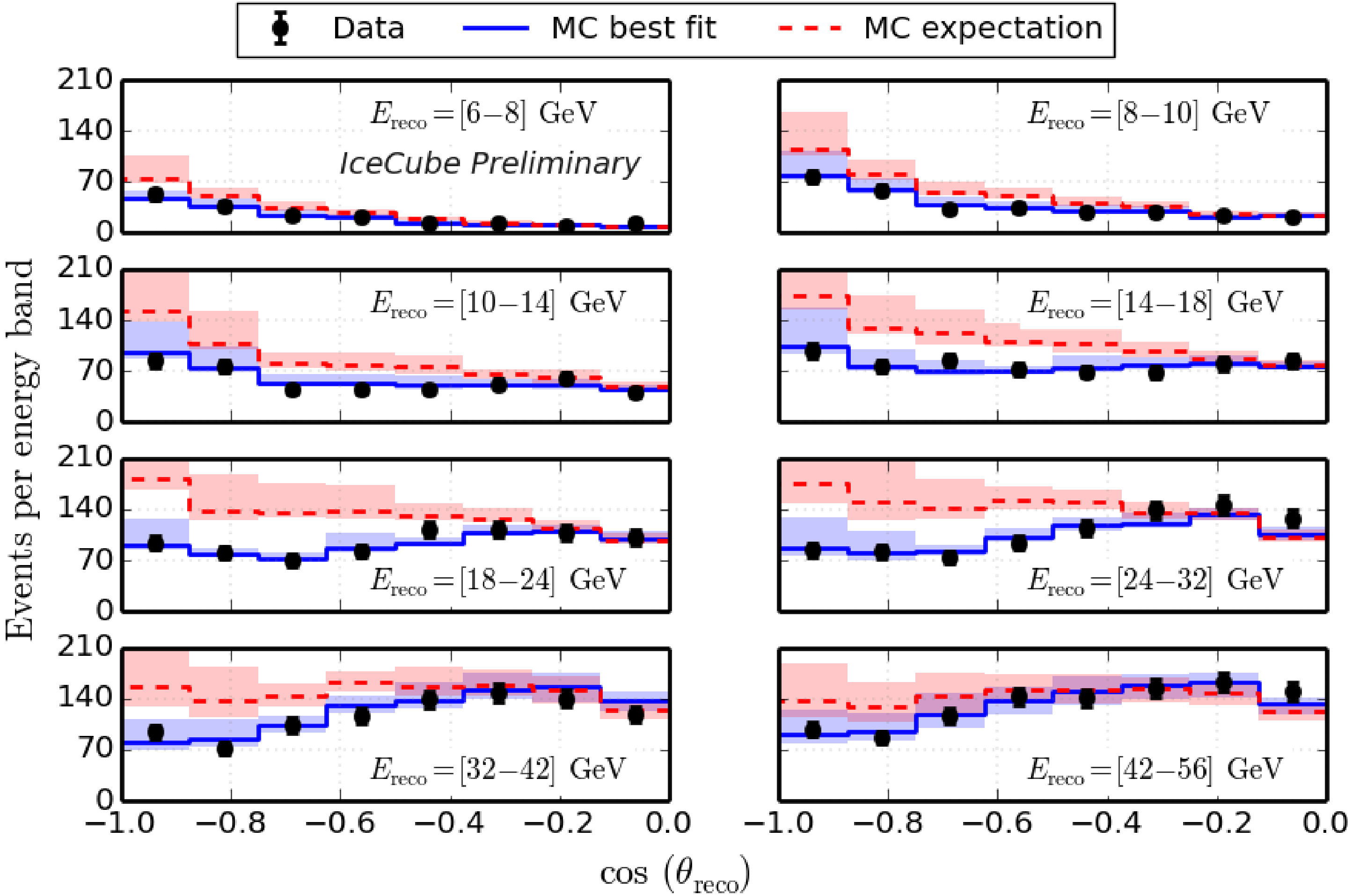


5293 events selected (2011-2014)
χ^2 = 45.5 / 56 dof
No preference for NH vs IH
1σ preference matter/vacuum

Parameter	Deviation at best fit
Flux at horizon	- 1 σ
Spectral index	+ 0.48 σ
ν_e deviation	- 0.62 σ
DOM eff.	+ 0.02 σ
Scattering in ice columns	+ 0.63 σ

Data / MC agreement (2D histogram analyzed)

- Solid lines: Best fit (with osc.) and MC expectation (no osc.)
- Bands: variations allowed by the systematic uncertainties **assumed**



Ratio to MC expectation (2D histogram analyzed)

- Solid lines: Best fit (with osc.) and MC expectation (no osc.)
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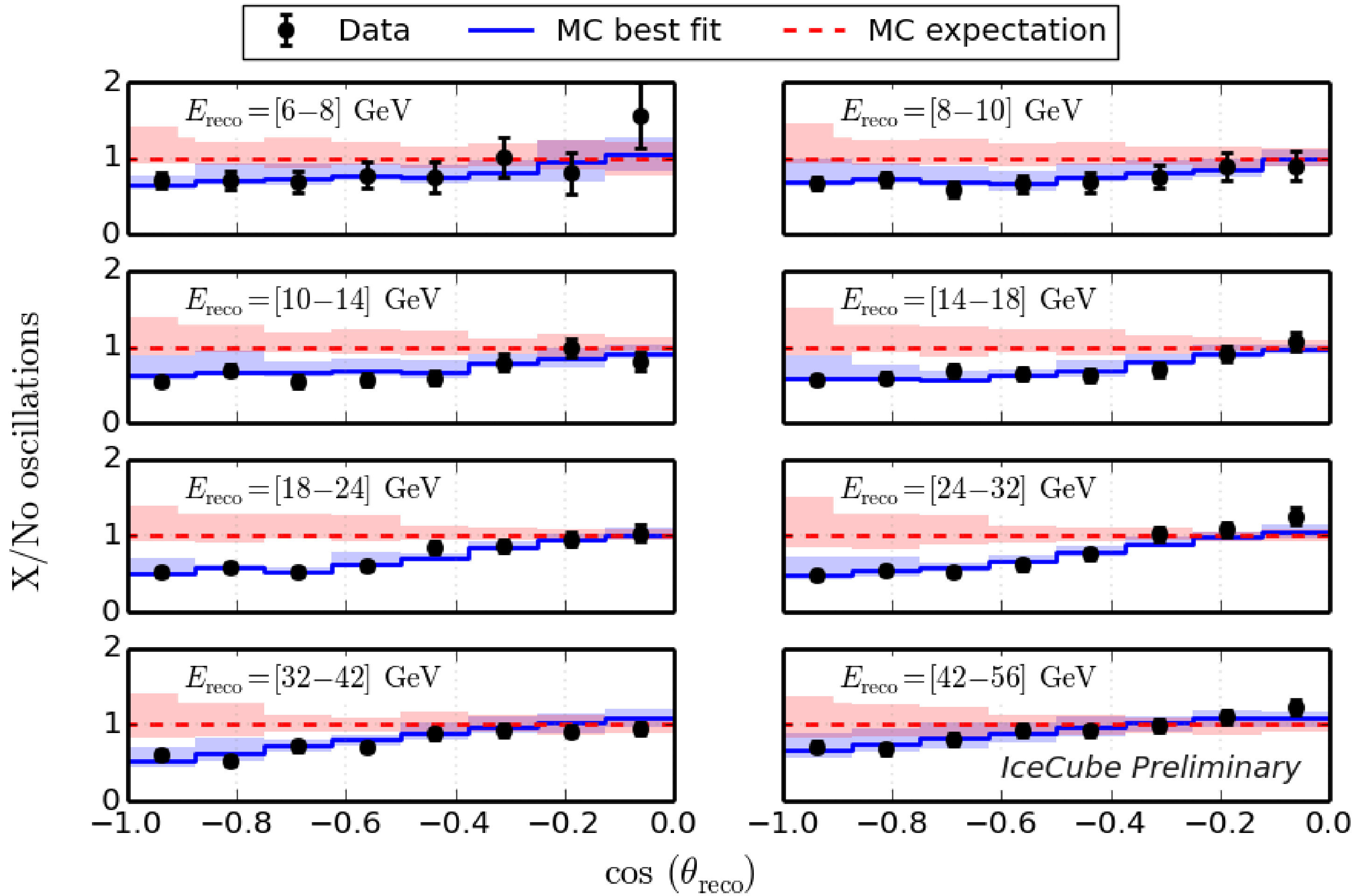
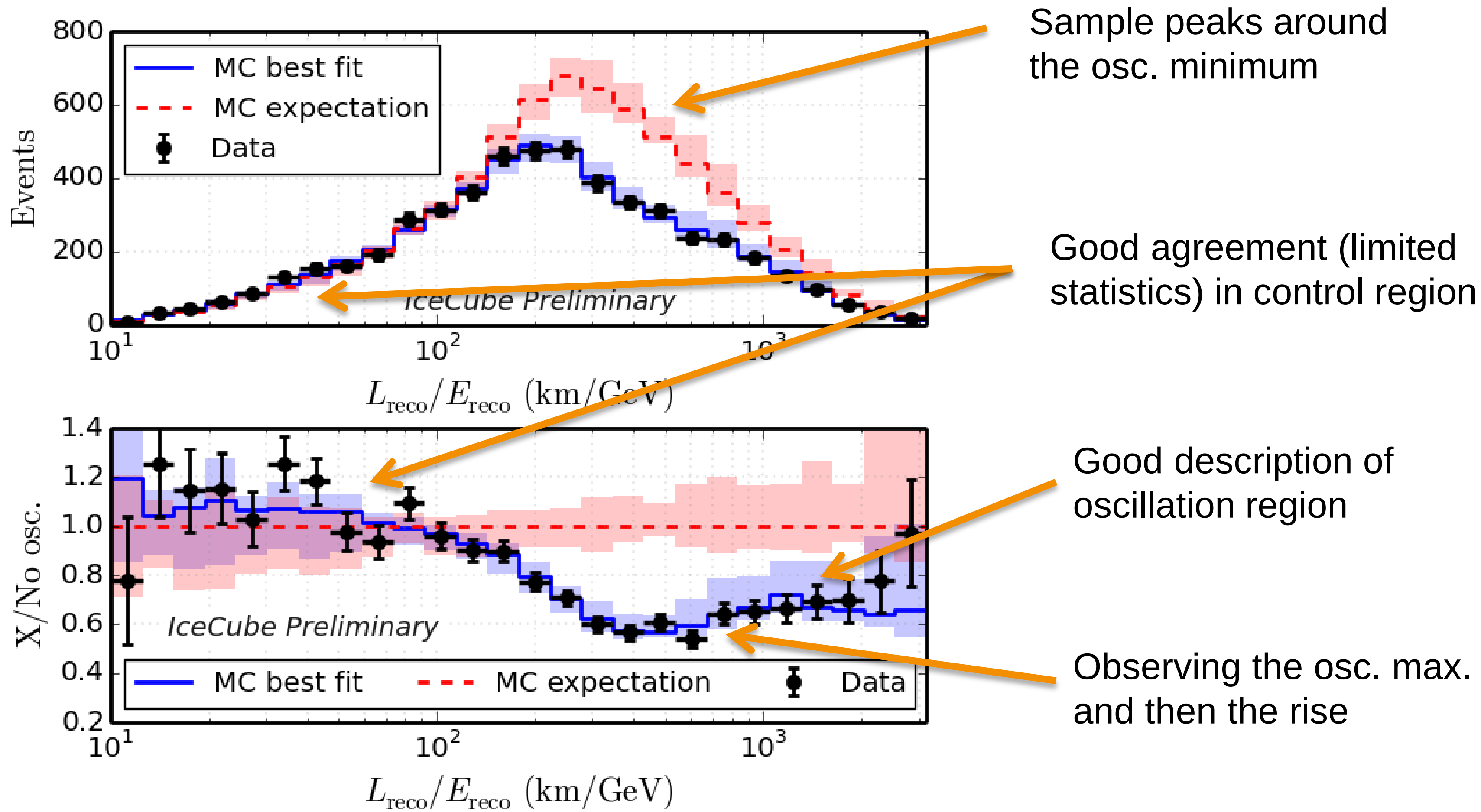


L/E display of the result

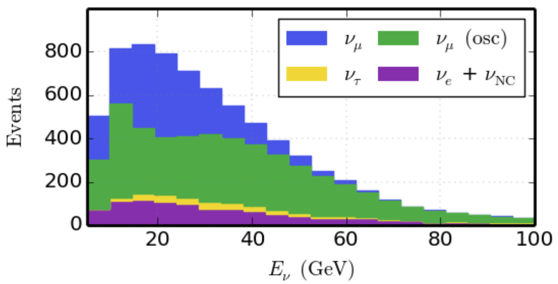
- Data as a function of reconstructed L/E

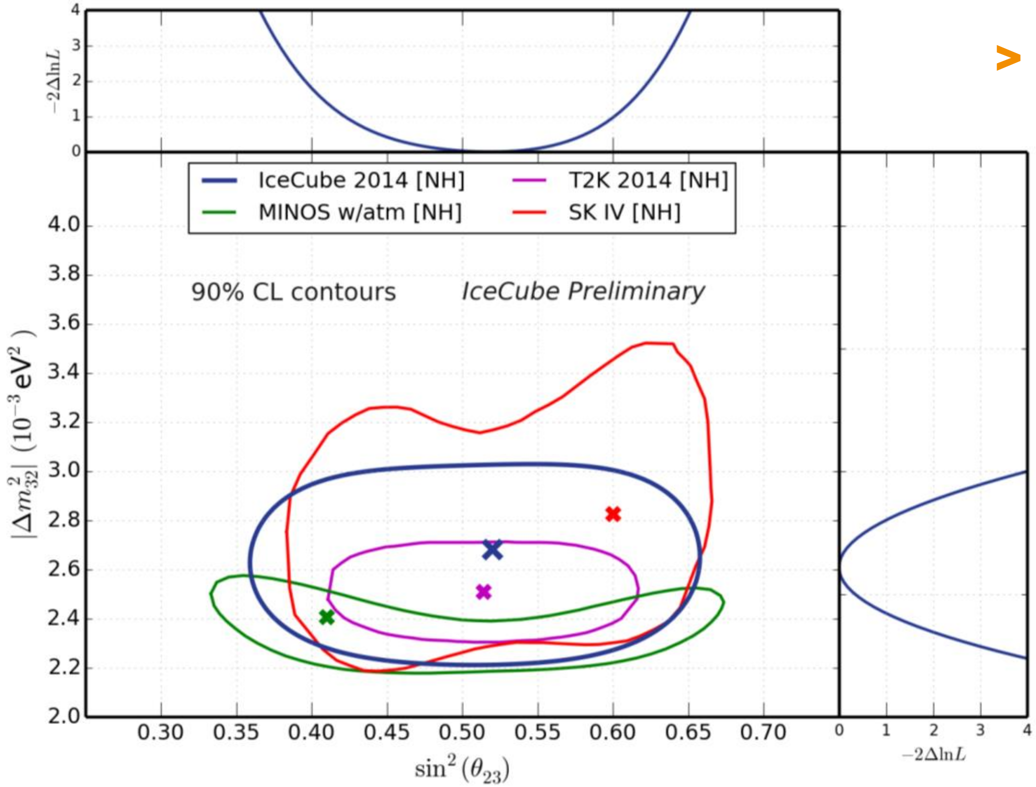


Comparison, conclusion, outlook

- Precision measurement of neutrino oscillations with IceCube/DeepCore
  - At the highest energies observed, test of 3-flavor paradigm
  - Results compatible with world's average (maximal mixing)
  - Systematic uncertainties under control, data/MC agreement
  - Not the final word on the subject

True energy distribution of final sample





- Constant improvements
  - Constrains on the neutrino flux
    (P.99) M. Schmitz, *Unfolding of the Muon Neutrino Energy Spectrum with IceCube*
  - Calibration/understanding of the ice
    (P.162) M. Jurkovič, *New Calibration Methods for IceCube, DeepCore and PINGU*
  - Reconstruction techniques
    (P.368) T. Arlen, J.P.A.M. de André, *Event reconstruction and Particle Identification for Low Energy Events in DeepCore and PINGU*
  - Cascade channel, selection efficiency
    (P.213) J.P.A.M. de André, *Sensitivity to ν_τ appearance with DeepCore and PINGU*
  - More data

... or an **extension.**

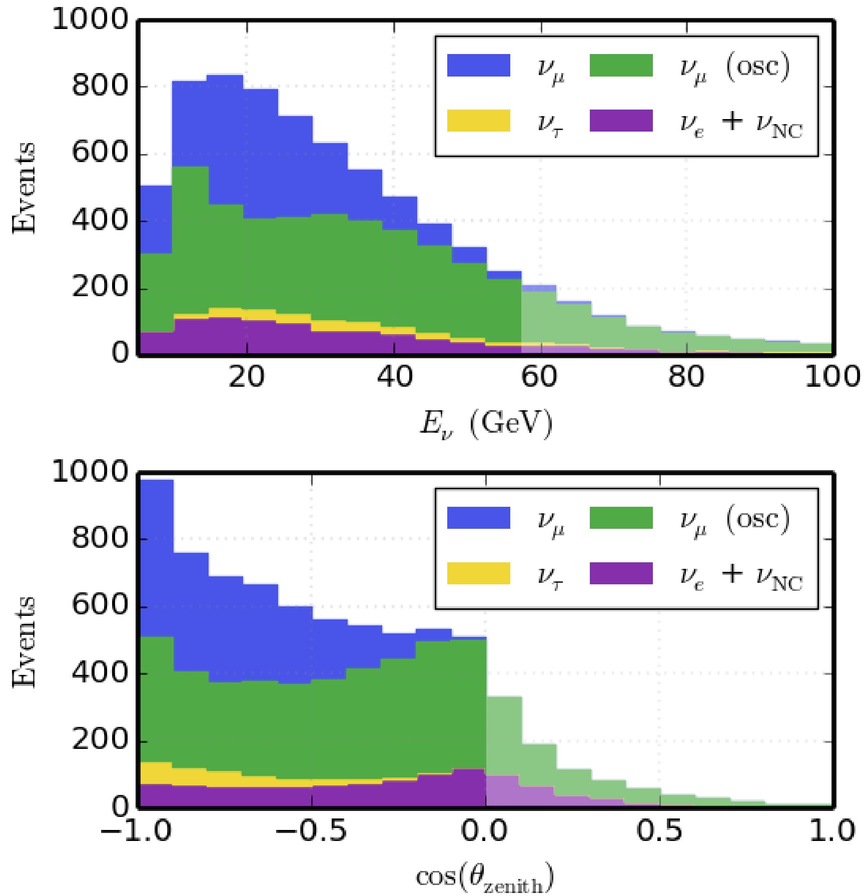
Backup slides

Final neutrino sample

- Including 3 years of full detector configuration (IC86)
  - 953 days of detector livetime
- MC expectation: ~ 7,000 events
  - Disappearance of ~ 1,900
- Energy threshold ~ 10 GeV

Component	Events in sample	
	Osc.	No osc.
ν_μ	3755	5900
ν_τ	273	-
ν_e	678	650
ν_{NC}	418	
Atm. μ	54	

MC prediction, **true** energy/zenith angle



Final neutrino sample, reconstructed observables

- Including 3 years of full detector configuration (IC86)
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  - Disappearance of ~ 1,600
- Energy threshold ~ 10 GeV
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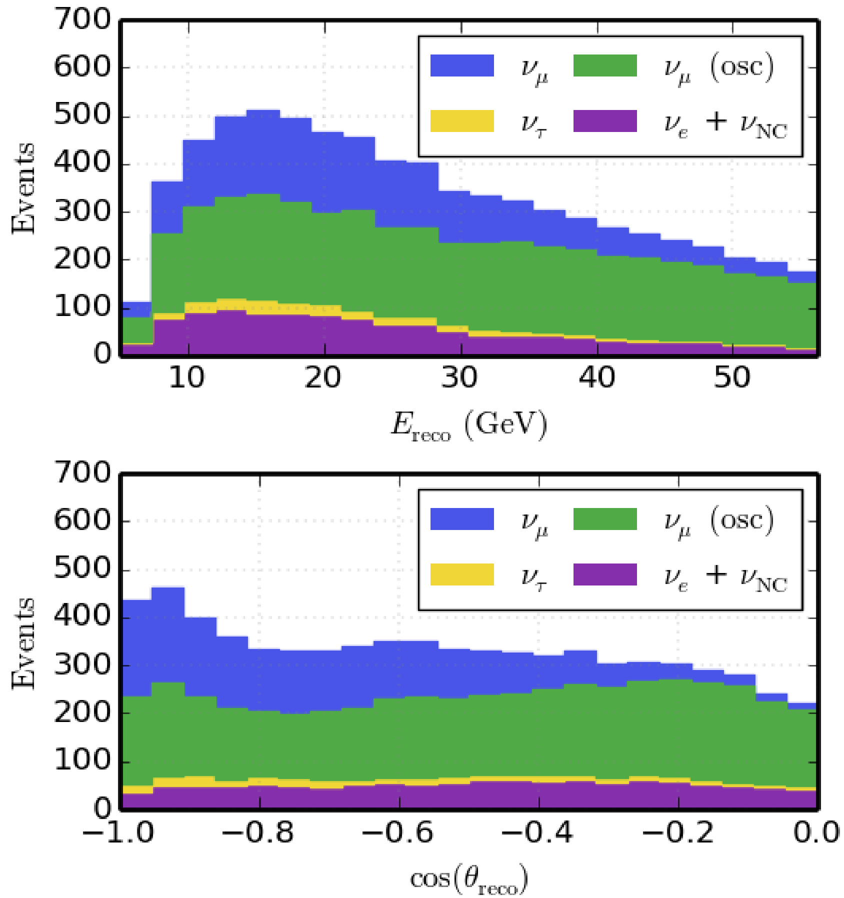
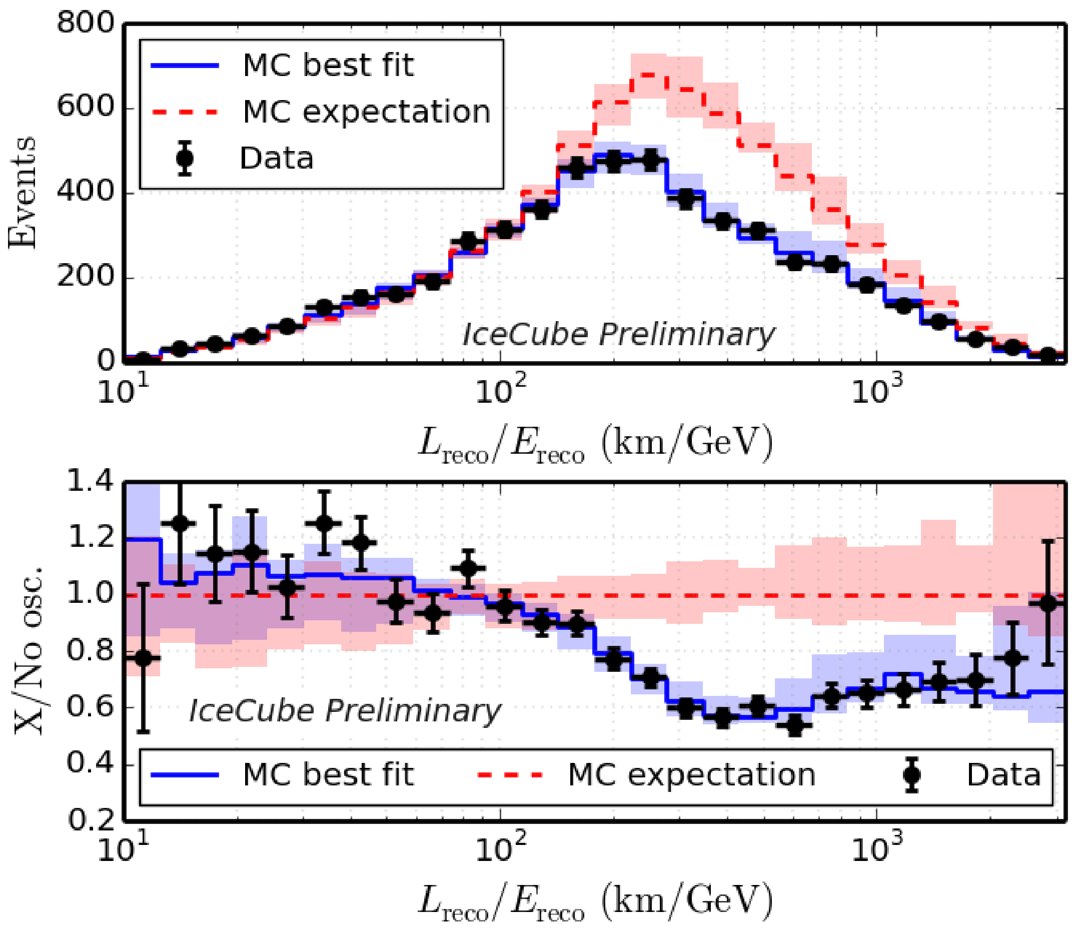
  - Low energy side: 15 deg. res.
  - High energy: 5 deg.
- Energy: 30% res. at 10 GeV
  - Strong bias below 10 GeV
  - Above 50 GeV muons leave the detector

MC prediction, **reconstructed** energy/zenith angle



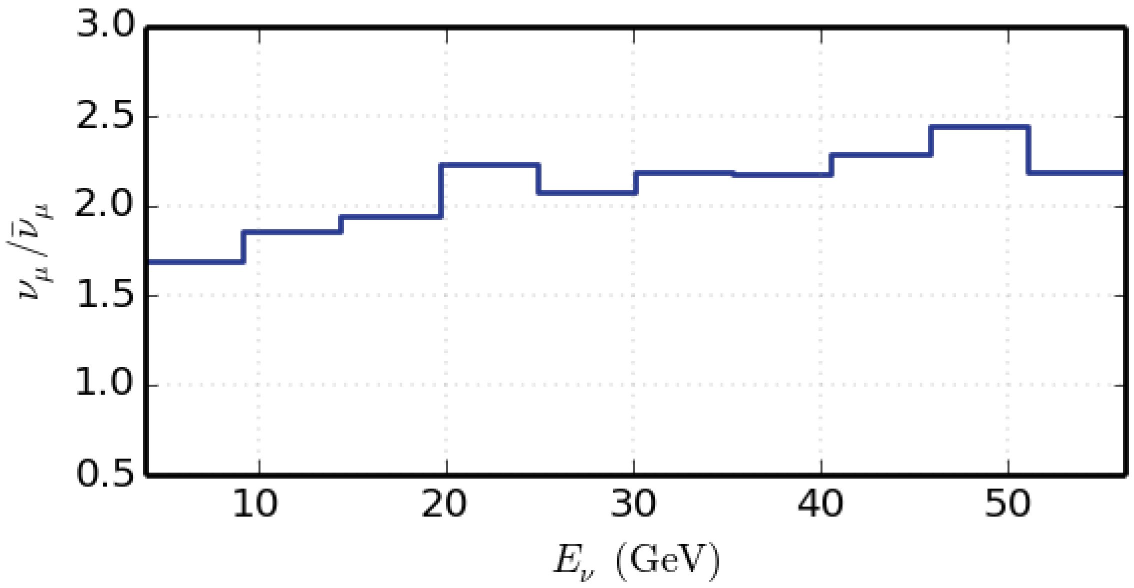
L/E display of the result

- Data as a function of reconstructed L/E



Neutrino:Antineutrino ratio

- Ratio of Nu:NuBar as a function of energy



Neutrino signal

- Signal*: ν_μ of E ≤ 100 GeV in charged current (CC) interaction

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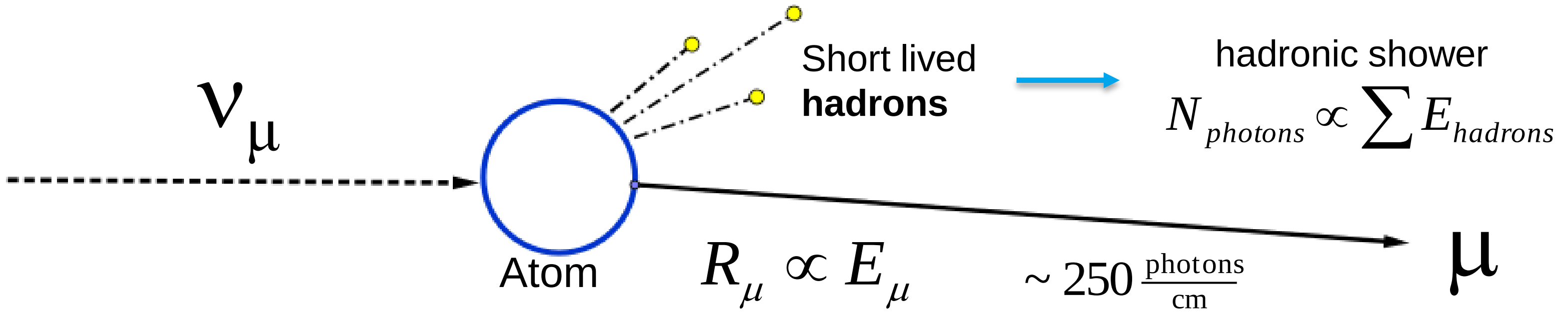

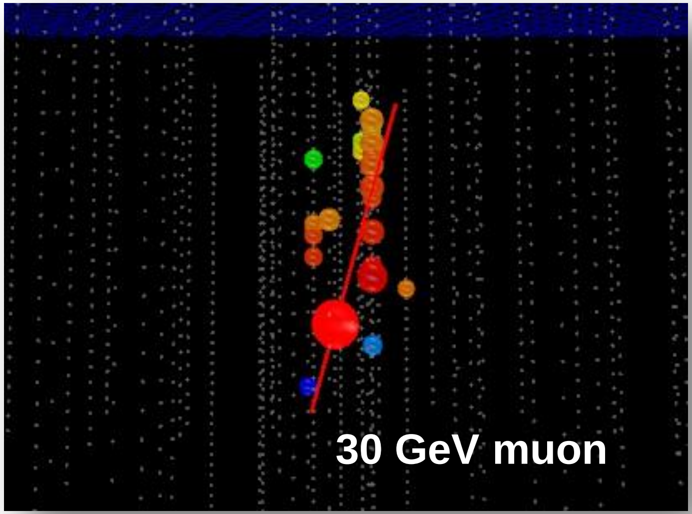

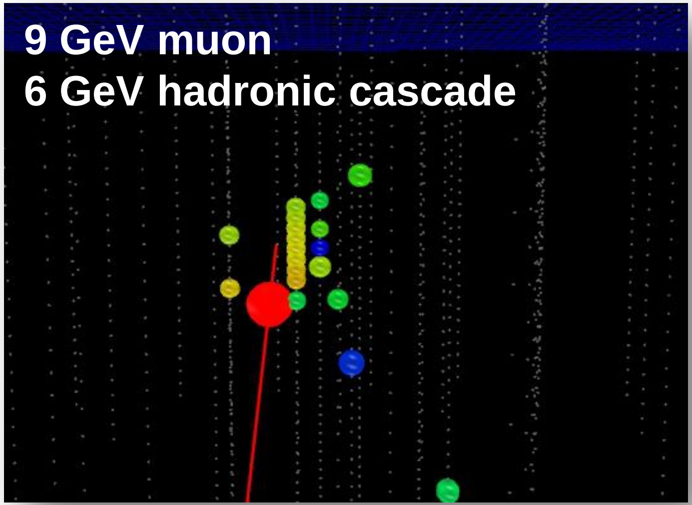

Cross sections from different models