Measurement of Muon Neutrino Disappearance with IceCube/DeepCore

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for the IceCube Collaboration

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The IceCube Collaboration

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44 institutions/ 12 countries / ~ 310 authors

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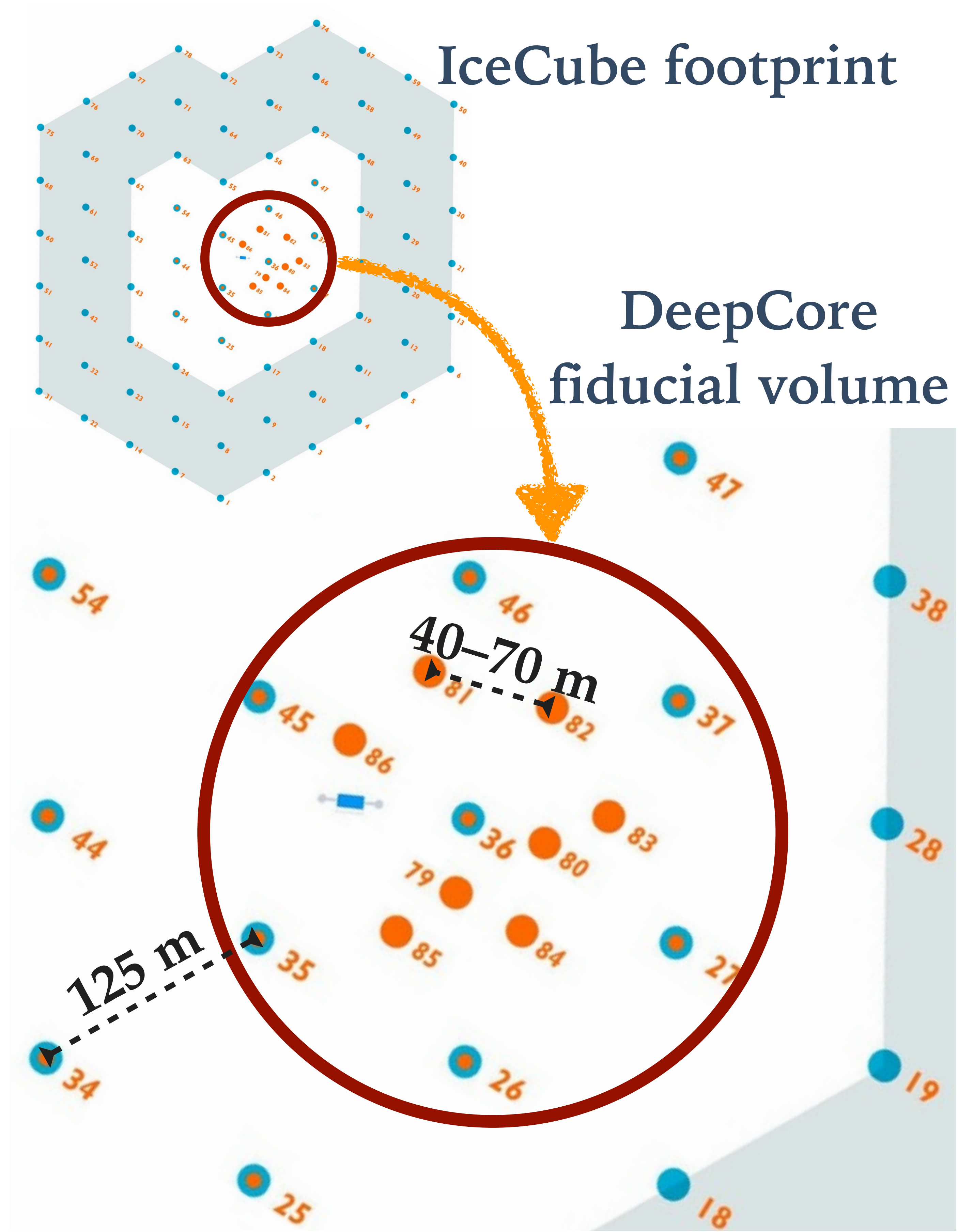
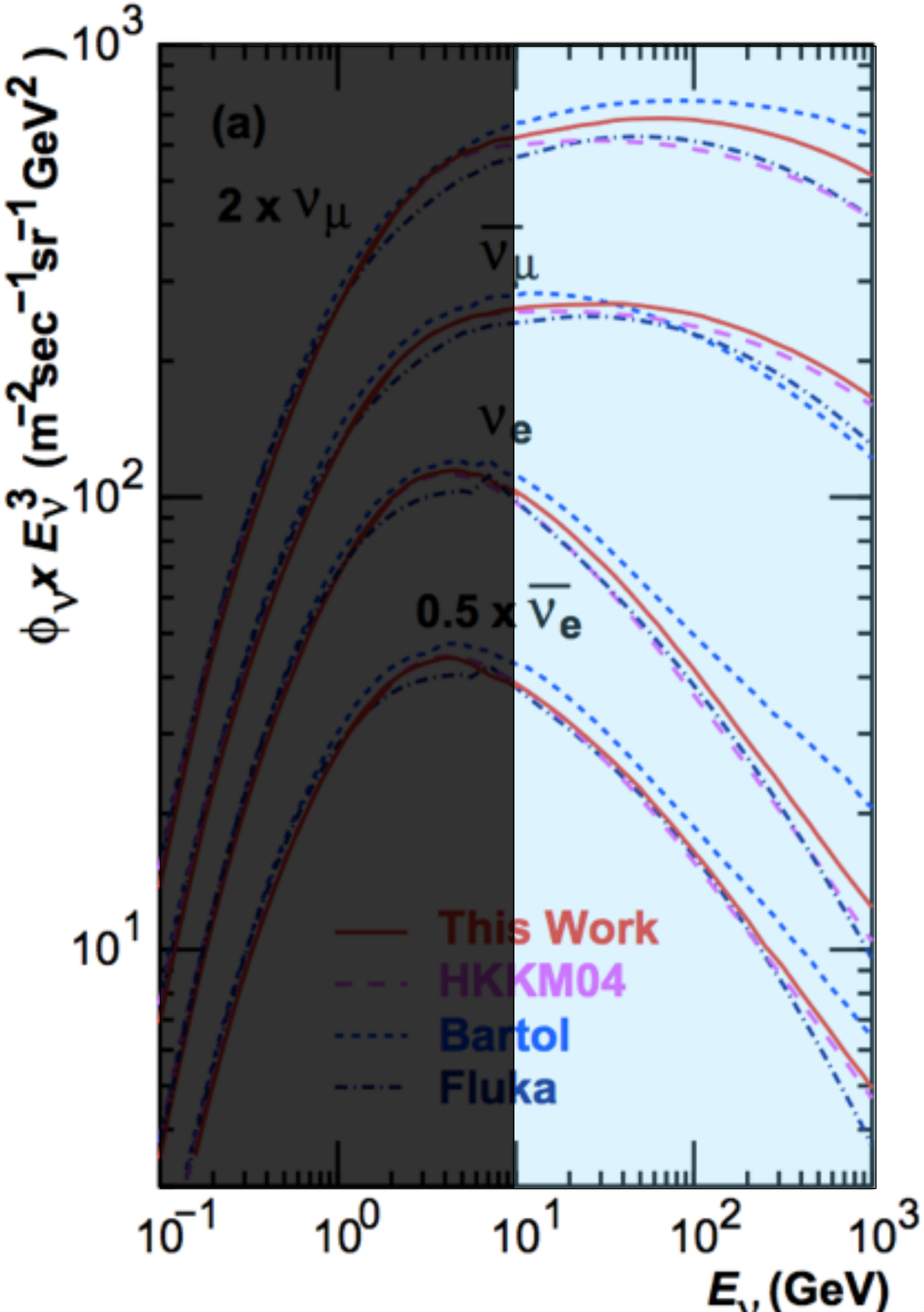
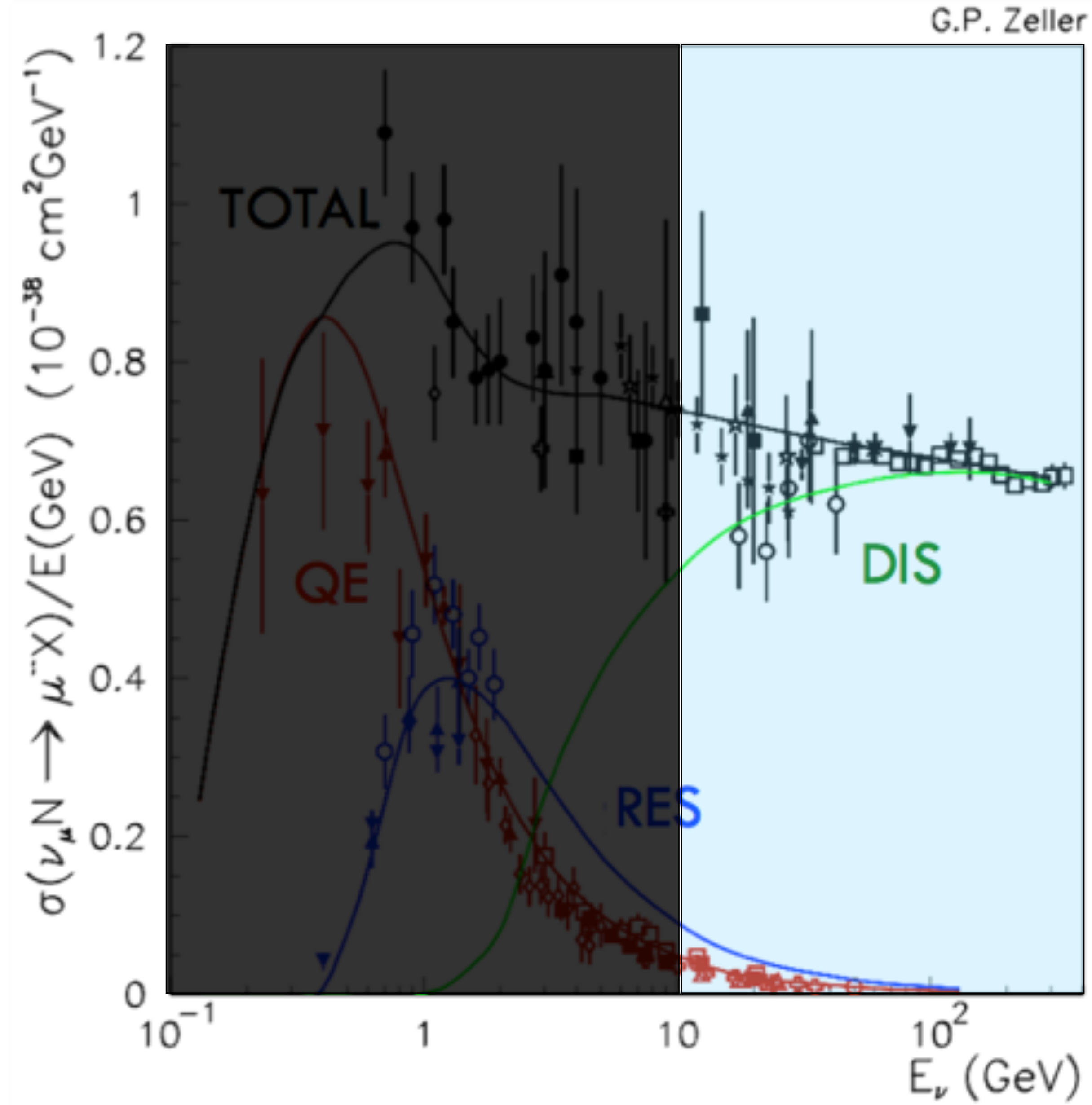
DeepCore

- Denser subarray
  - 7m vertical PMT separation
  - located in deep, clear ice
  - threshold $E_\nu \approx 10$ GeV
- Atmospheric muon rates are 10^6 higher than neutrino rates at trigger
  - use IceCube as active veto



Atmospheric Neutrinos

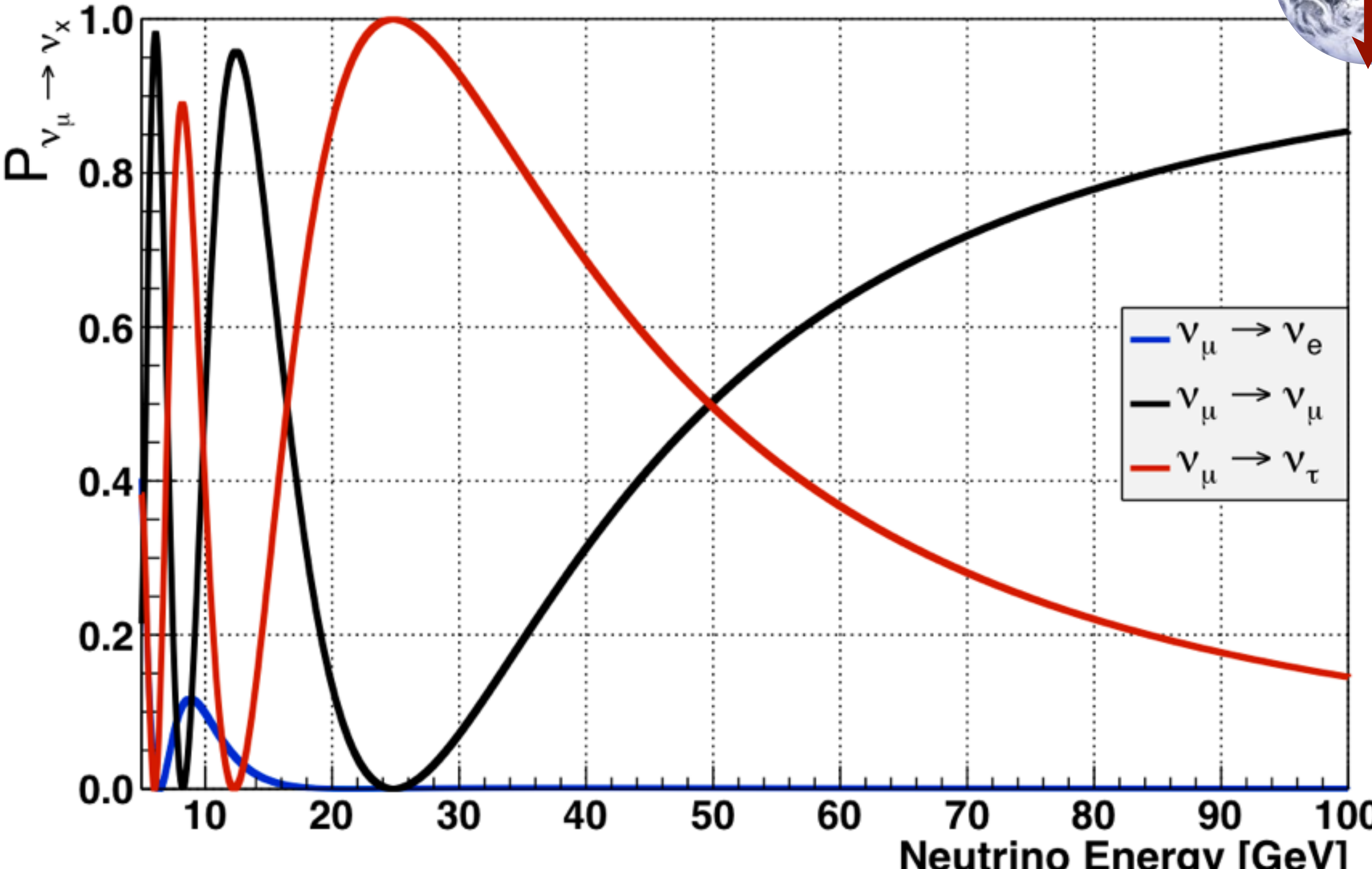


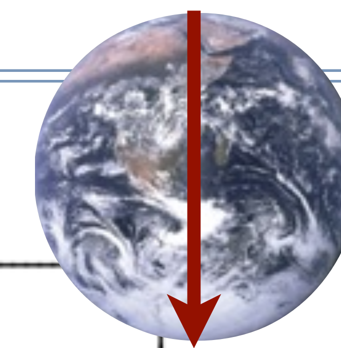


IceCube has high flux, primarily ν_μ
Interactions are almost always DIS

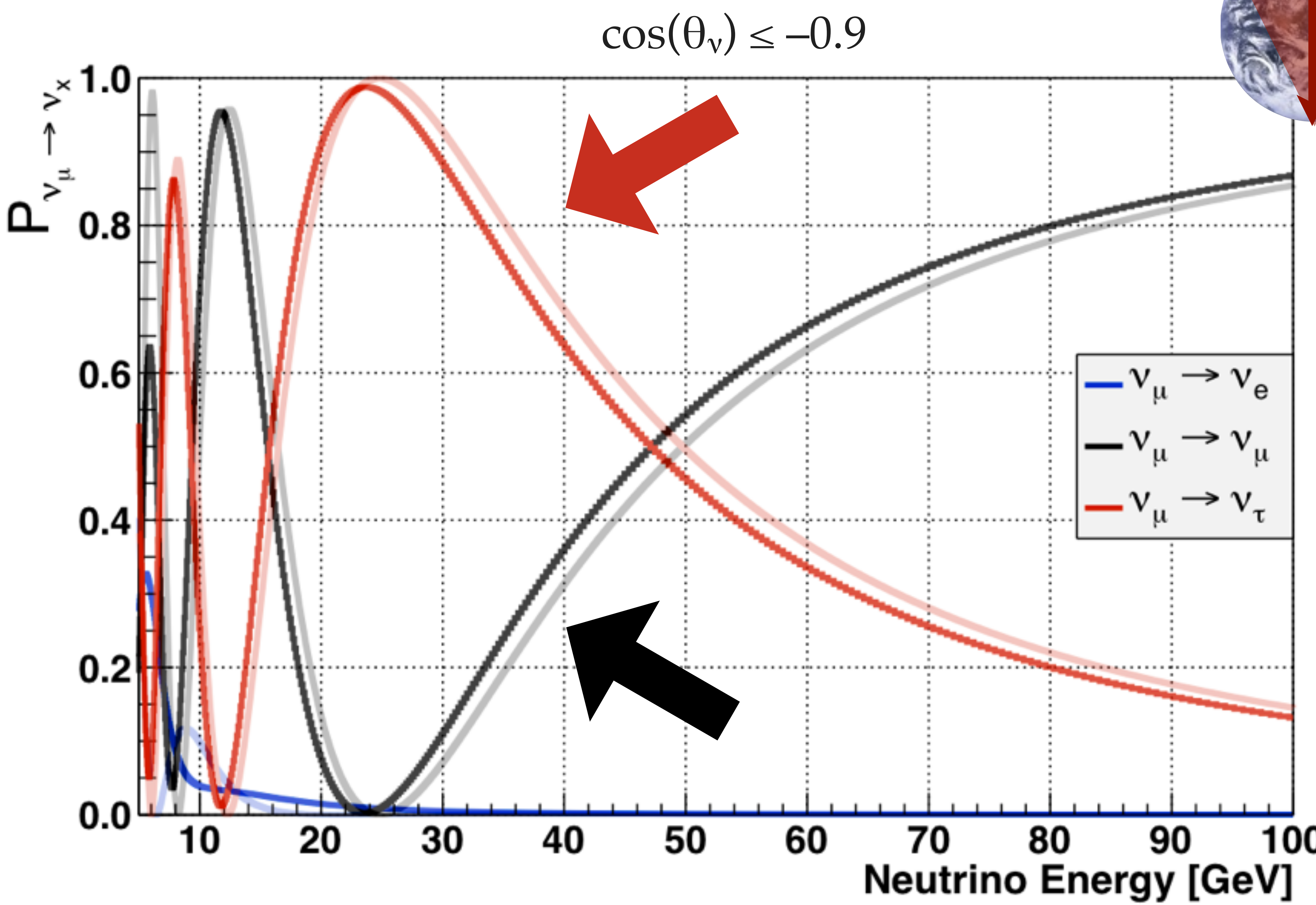
Atmospheric Oscillations

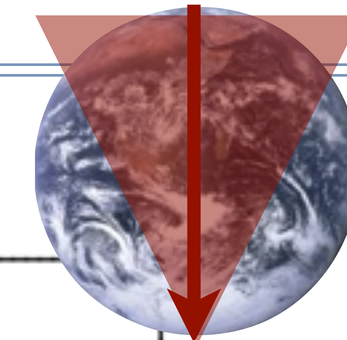
$\cos(\theta_\nu) = -1$





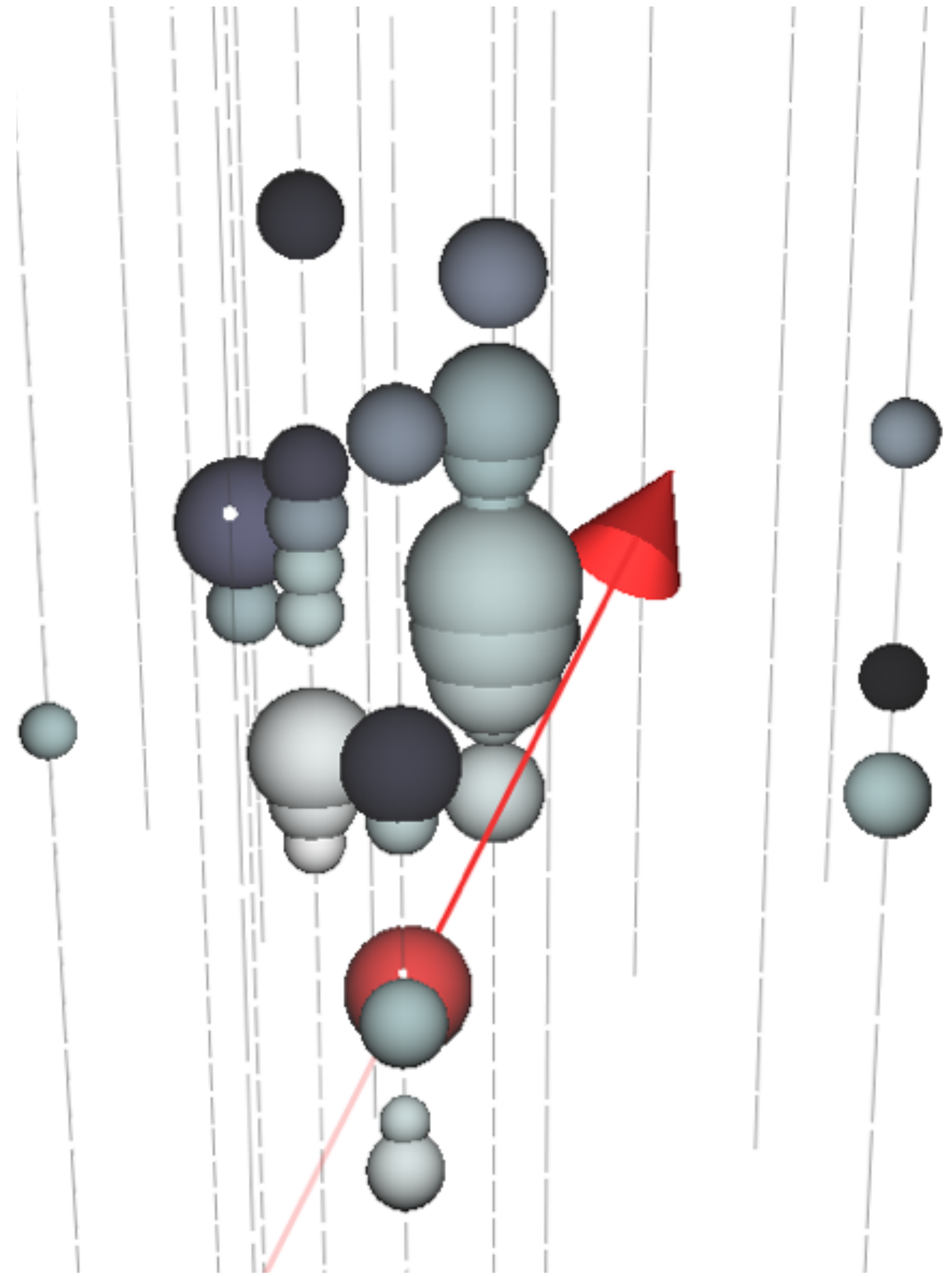
Atmospheric Oscillations





“Typical” Signal Event

- MC True information:
  - 27 GeV ν_μ (CC DIS)
  - 15 GeV outgoing muon
- Seen by a few strings
  - time shown by color (light to dark)
  - charge shown by size
- Reconstruction shown in red
  - muon travels from sphere to end of arrow
  - 25 GeV reconstructed energy



"Golden Sample" Event Selection

[IceCube, Phys. Rev. D 91, 072004 (2015)]

Neutrino-induced tracks

Atmospheric Muons

Neutrino-induced cascades

Dark Noise

- Signal: ν_μ with $E_\nu \leq 50$ GeV from charged current [CC] interactions
- Active IceCube Veto
  - reject events with ≥ 2 causally connected photons in veto region
  - these are tagged as "atmospheric muons" and used in background estimates
- Require many direct photons from muon†
  - used to distinguish tracks from cascades
  - improves performance of reconstructions

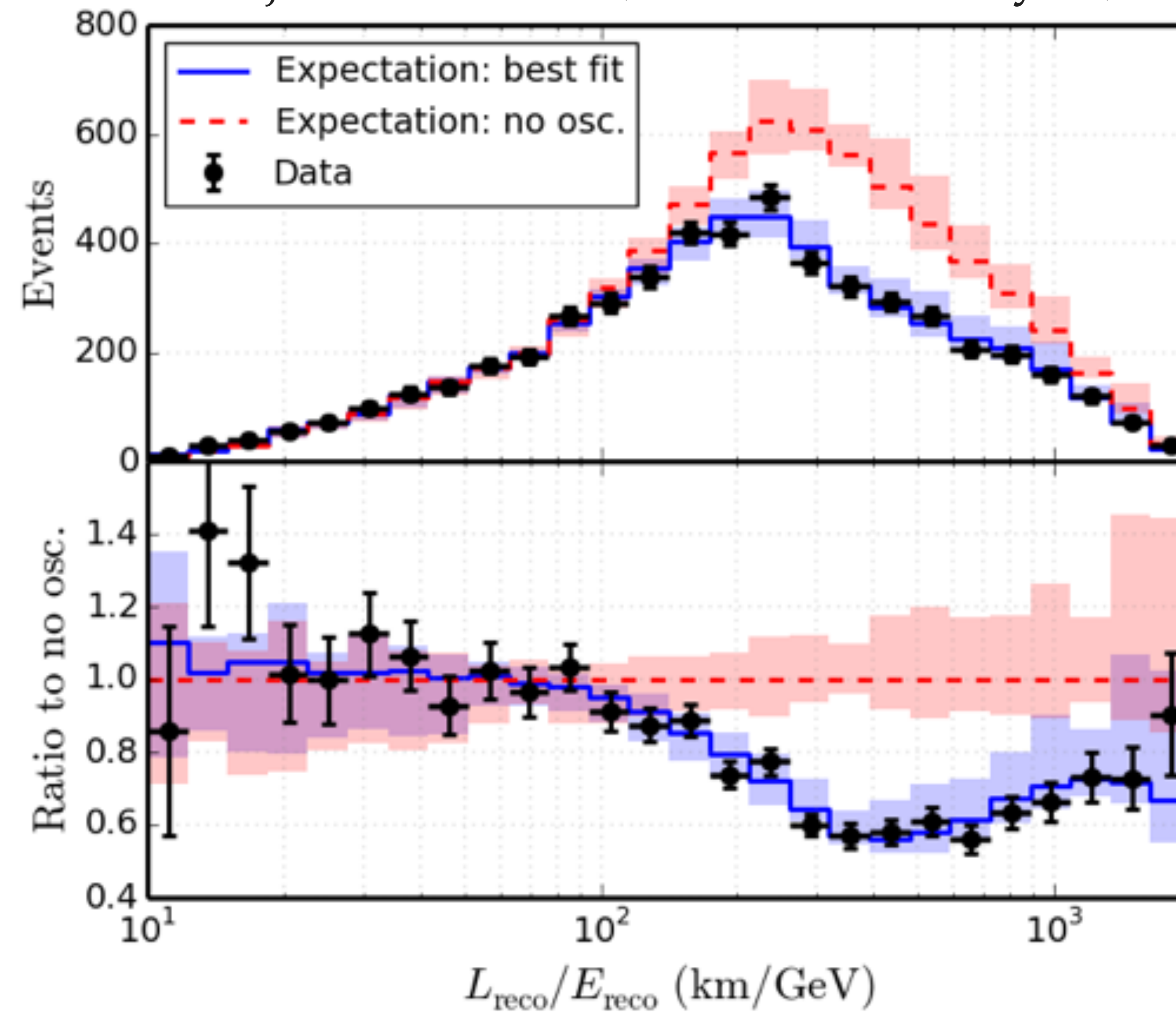
†Developed by Juan-Pablo Yáñez in collaboration with J. Brunner (Astropart.Phys.34:652-662,2011)

“Golden Sample” Oscillation Signature

[IceCube, Phys. Rev. D 91, 072004 (2015)]

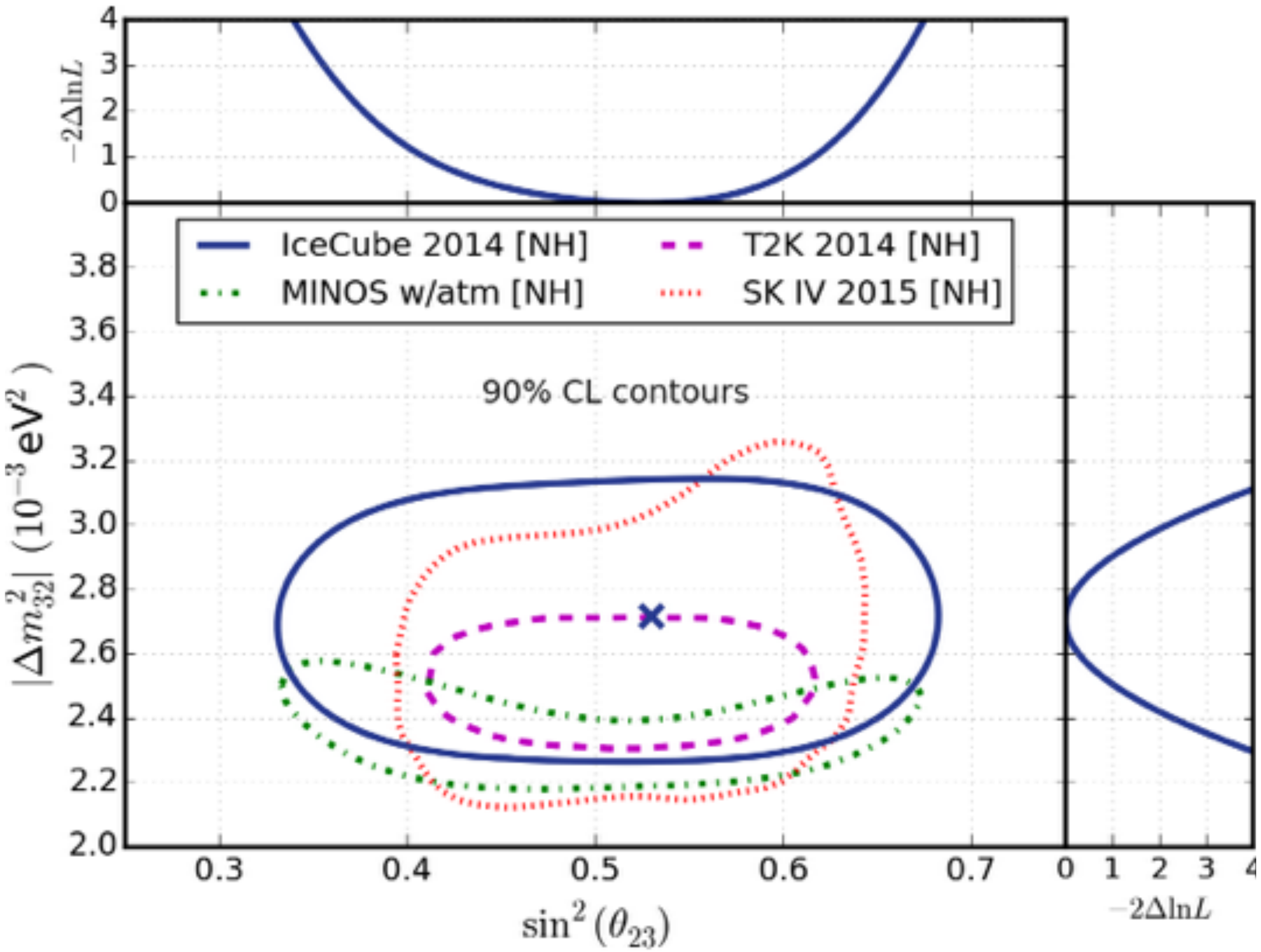
- Golden events only
  - up-going, track-like
  - 5174 events in 3 years
- Best fit to data from a 2D likelihood analysis
  - 8 bins in log(E)
  - 8 bins in cos(θ)
    - horizontal bin fixed for normalization
  - $\chi^2/\mathrm{dof} = 54.9/56$

Projection in L/E (not used in analysis)



Current ν_μ Disappearance Results

[IceCube, Phys. Rev. D 91, 072004 (2015)]



- Golden events only
  - up-going, track-like
  - 5174 events in 3 years
- Comparable with leading experimental measurements

		Best ± 68% CL
NH	$\sin^2(\theta_{23})$	$0.53^{+0.09}_{-0.12}$
	$\Delta m^2_{32}\ (10^{-3}\mathrm{eV}^2)$	$2.72^{+0.19}_{-0.20}$

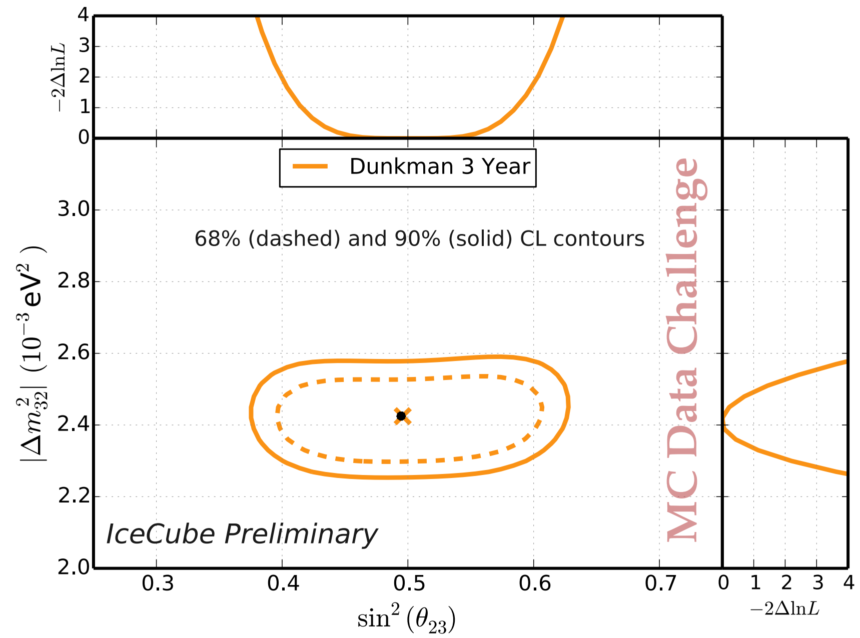
How will we improve our result?

- Get more high quality events
  - new reconstruction allows 10x statistics without degradation of resolutions
- Maximize the control sample
  - keep cascade-like events
  - keep down-going region
  - improves constraints on systematics
- Keep the good
  - use same data-driven approach for background estimation

IceCube Preliminary

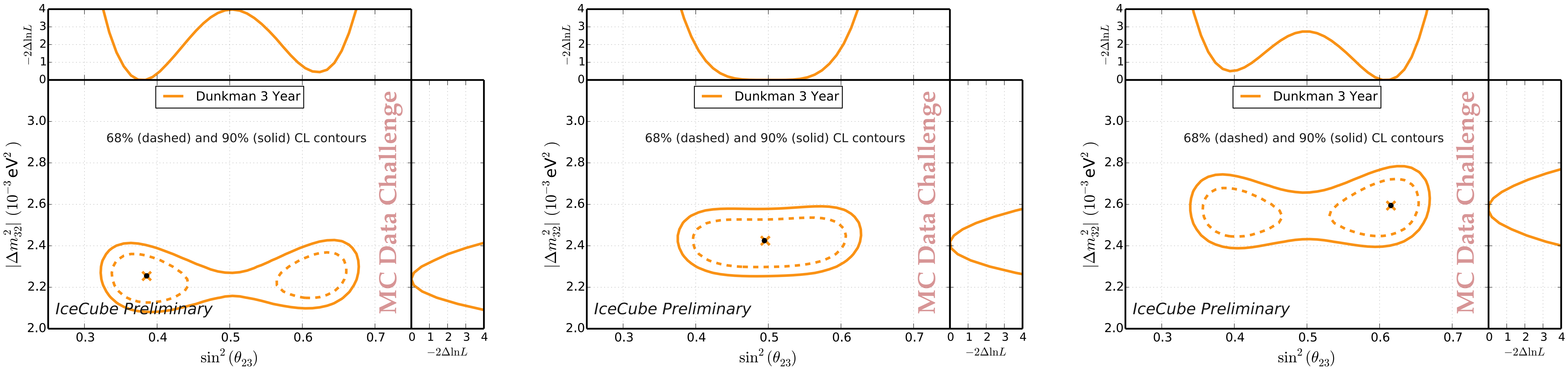
MC estimates only

Estimated Sensitivity of New Analysis



- Fit value agrees extremely well with injected value
  - this includes all systematics
  - also good agreement in all systematic/nuisance parameters

Estimated Sensitivity of New Analysis



- Fit value agrees extremely well with injected value
  - this includes all systematics
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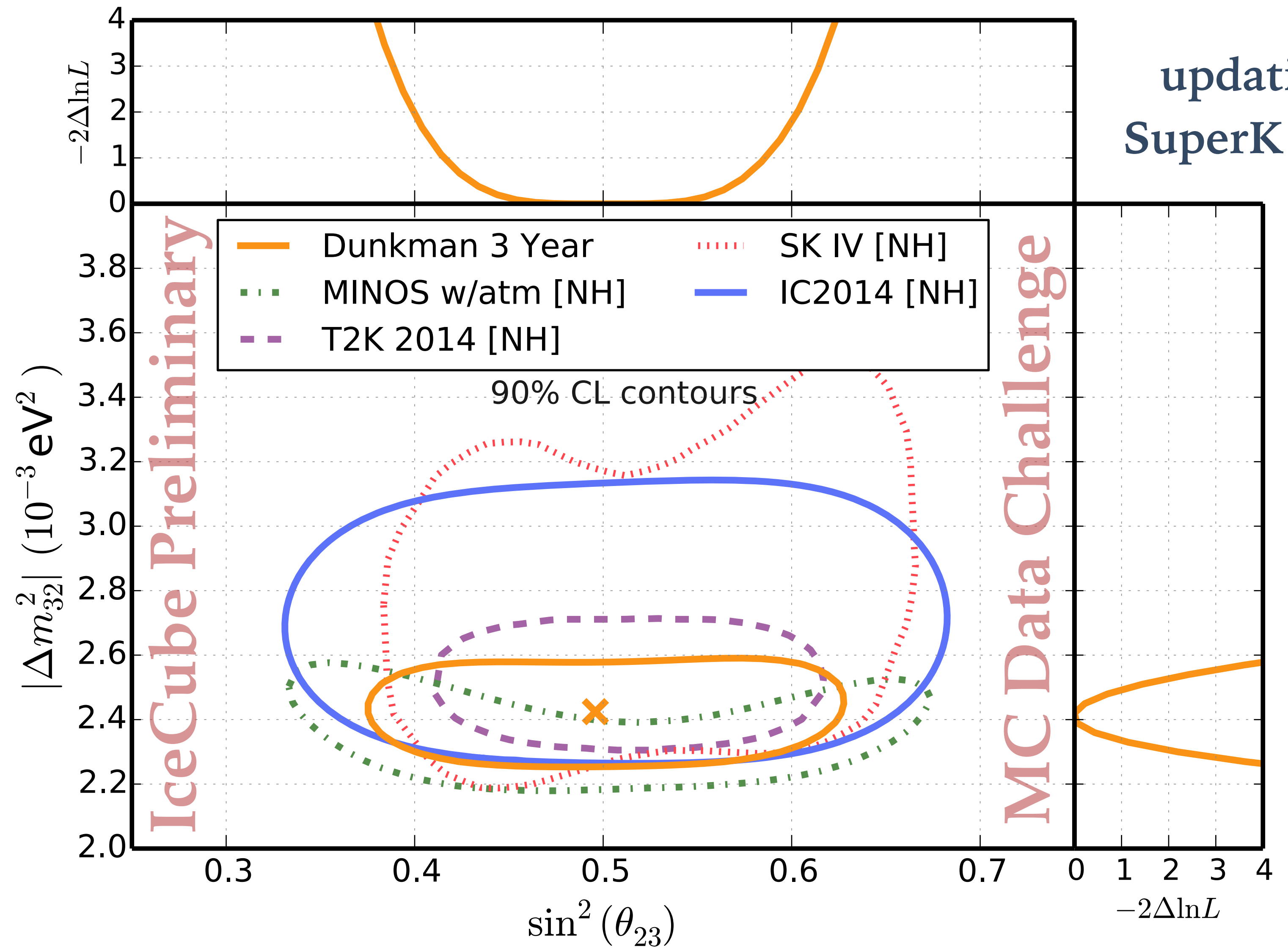
Comparing the Estimated Sensitivity



updating with new SuperK contours soon

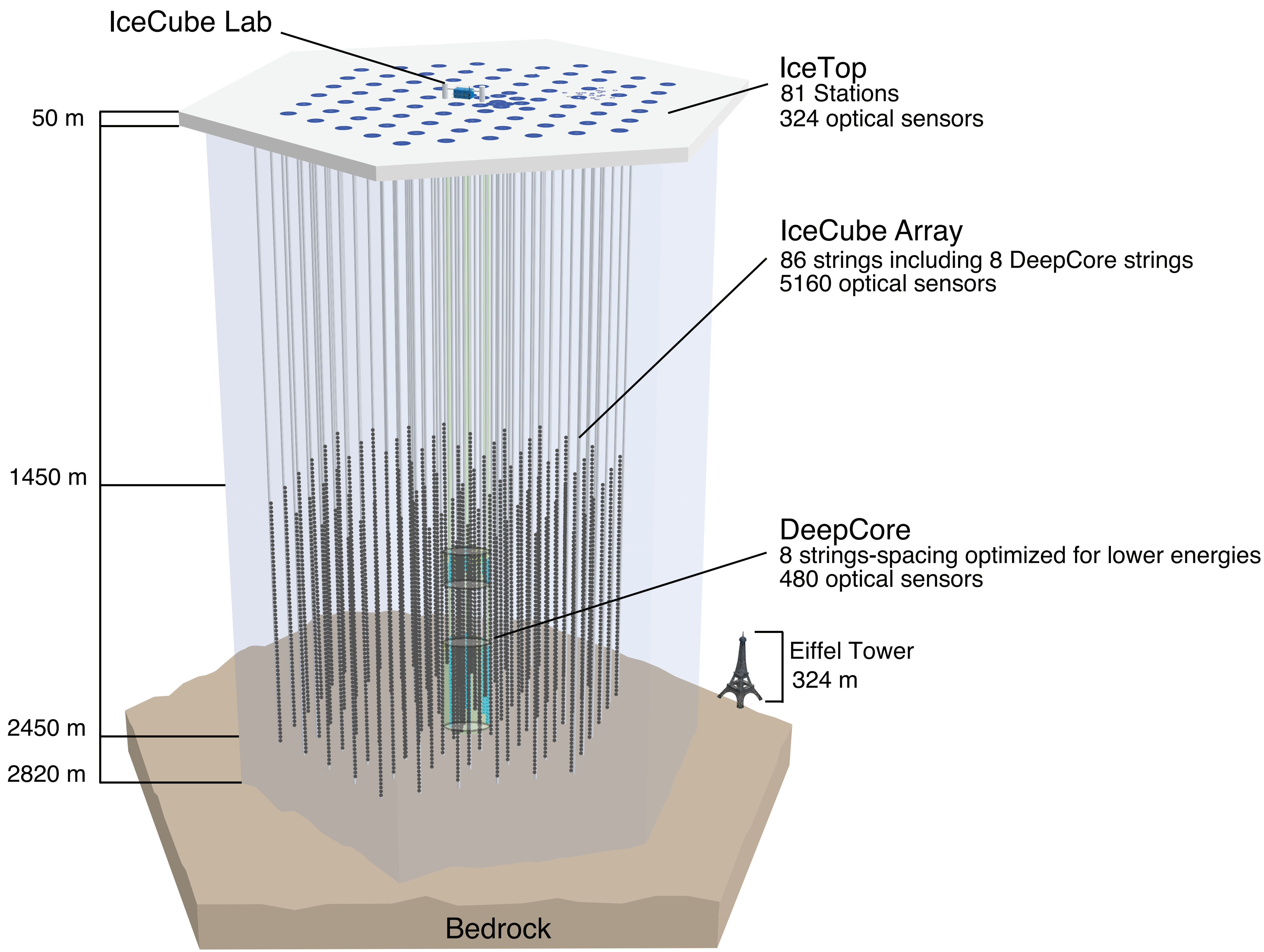
- Significant step forward from PRD result
    - major increase in mass splitting precision

Summary

- IceCube/DeepCore sees very many neutrino events
  - with three years of detector livetime, around 10^5 neutrino events pass low-level vetoes
  - current analysis uses subset of 5000 good neutrino-like events
- Current results are comparable with other experiments
  - updated analysis with 50,000 good neutrino-like events moves IceCube from comparable to competitive
- New results from IceCube/DeepCore coming soon!

Backup

IceCube in more detail

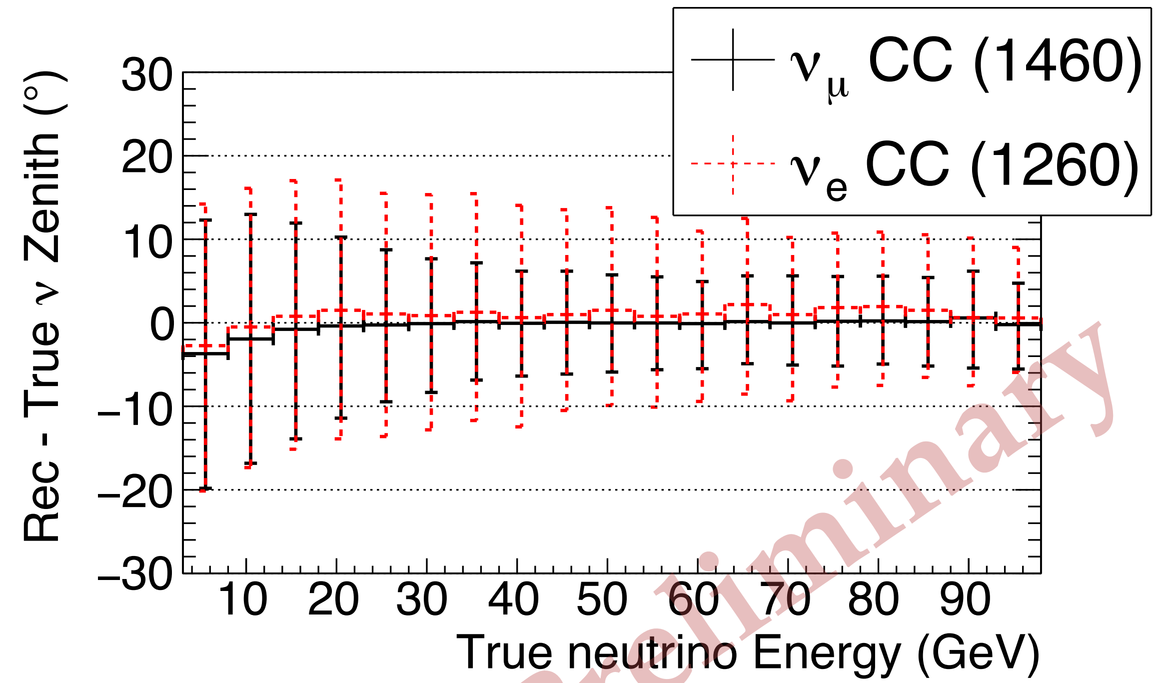


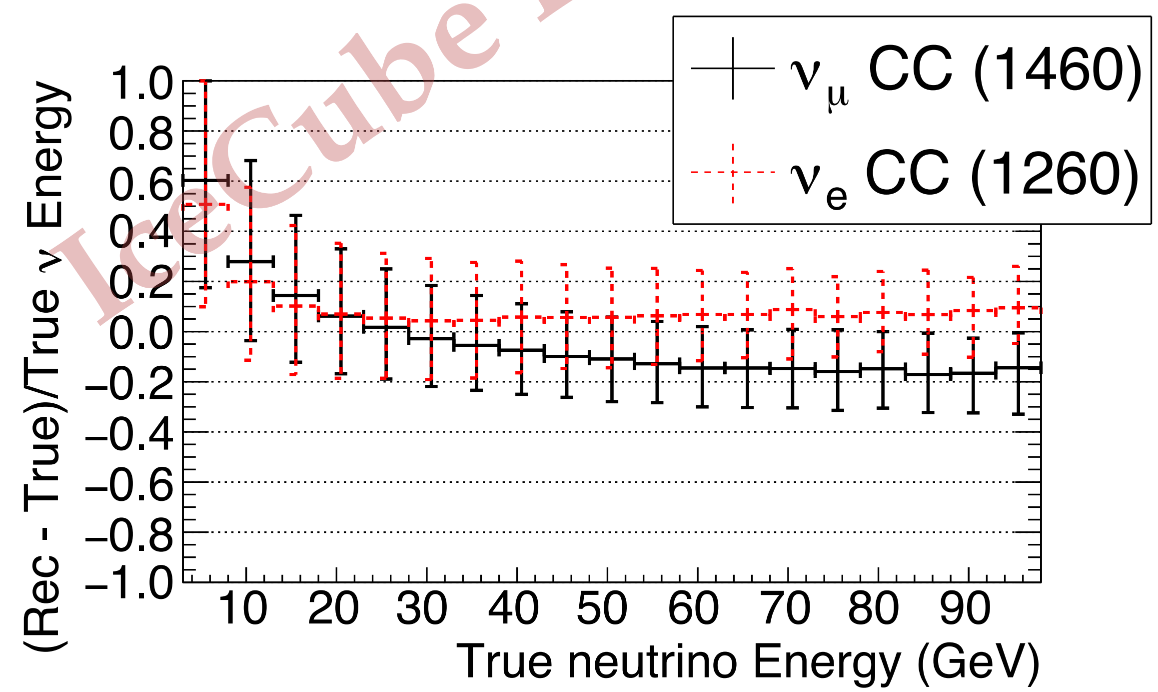
On-going Improvements: Reconstruction Methods

- Use un-scattered photons (current method)
  - Conveniently avoids many uncertainties from ice
  - Inconveniently rejects almost all triggered events
  - Conveniently, most triggered events are not neutrinos!
- Use all photons (my work)
  - Use estimated light yields from simulated ice model
  - Full likelihood reconstruction (8–10 dimensional space)
  - Fortunately keeps much higher fraction of neutrino events
  - Also keeps much higher fraction of non-neutrino events
  - Requires significantly more elaborate event selection

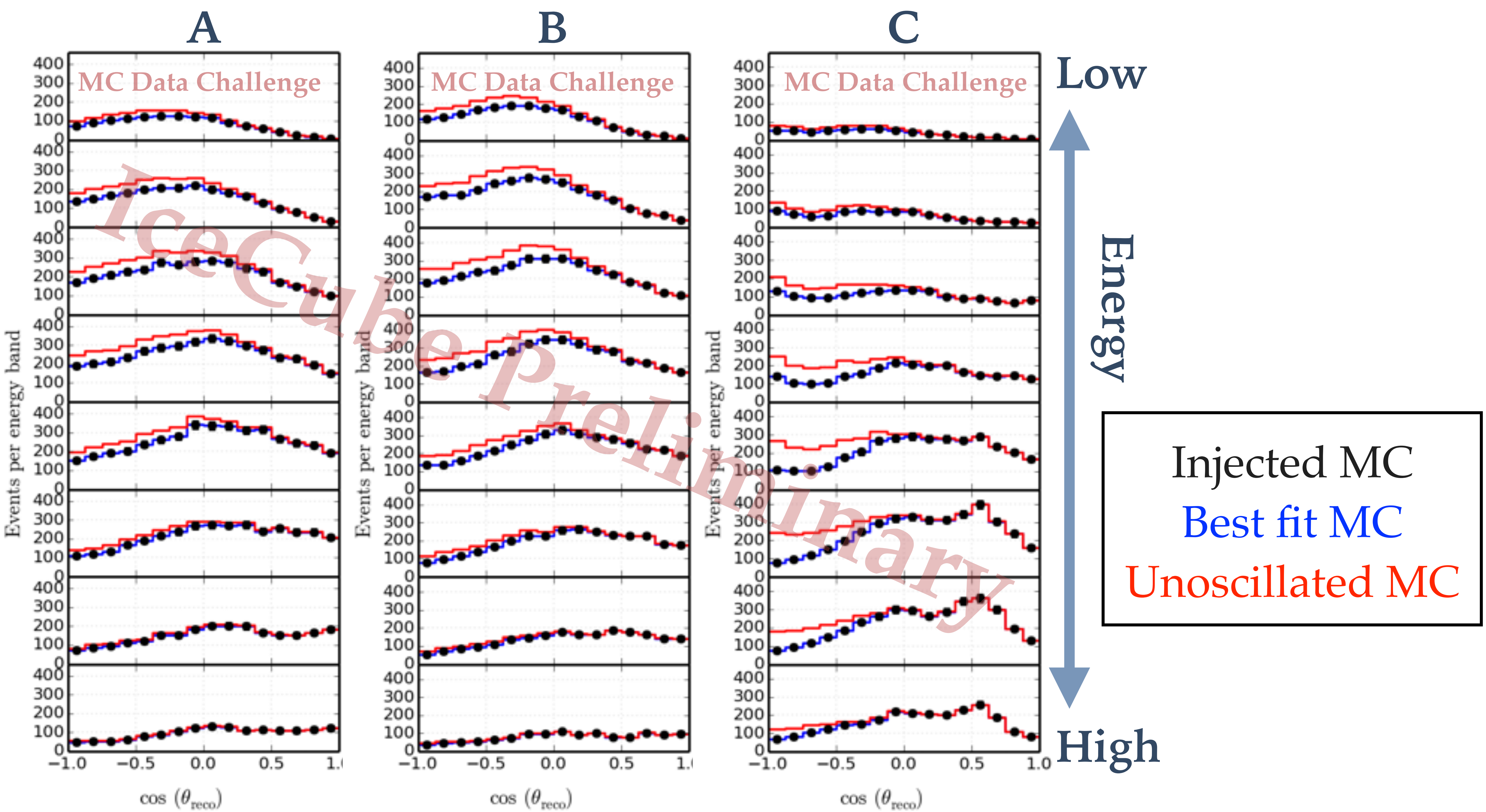
How can we improve?

- Get more high quality events
  - HybridReco/MultiNest allows 10x statistics without degradation of resolutions
- Maximize the control sample
  - improves constraints on systematics
  - keep cascade-like events
  - keep down-going region
- Some things are good already
  - follow Juan Pablo's method—take background sample from inverted veto of real data





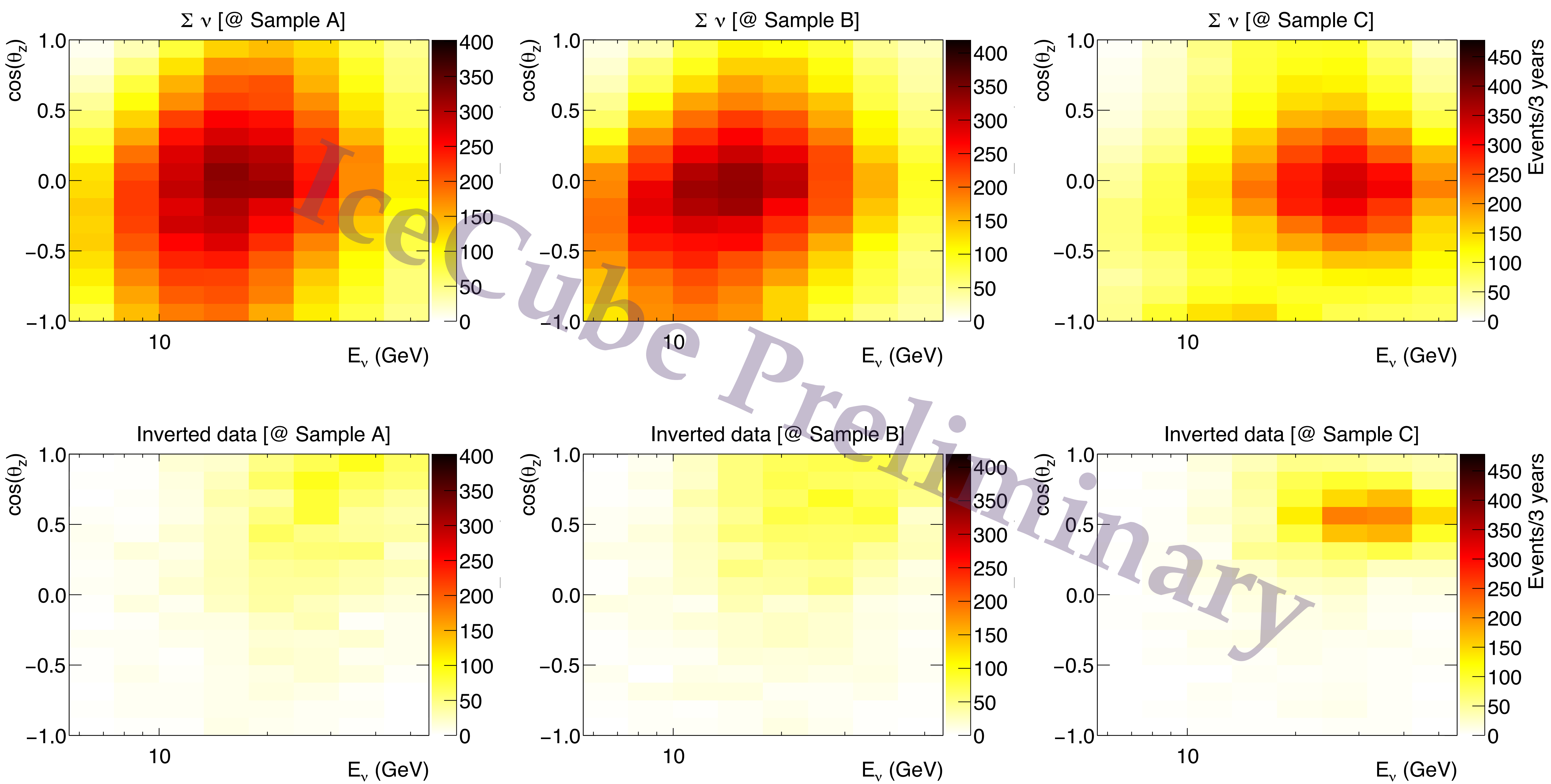
Example Fit Performance



Simulation split into three PID samples

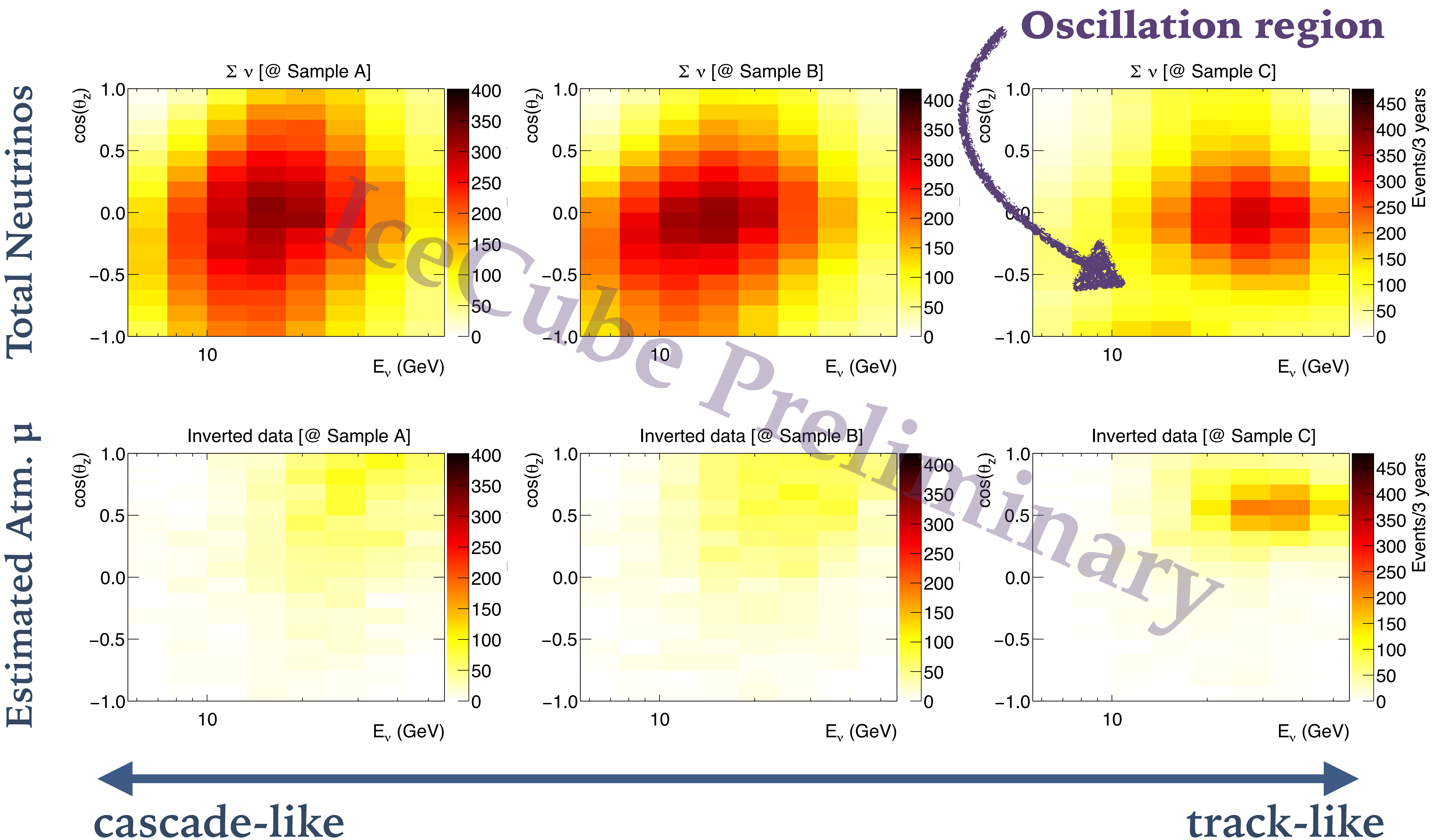
Total Neutrinos

Estimated Atm. μ



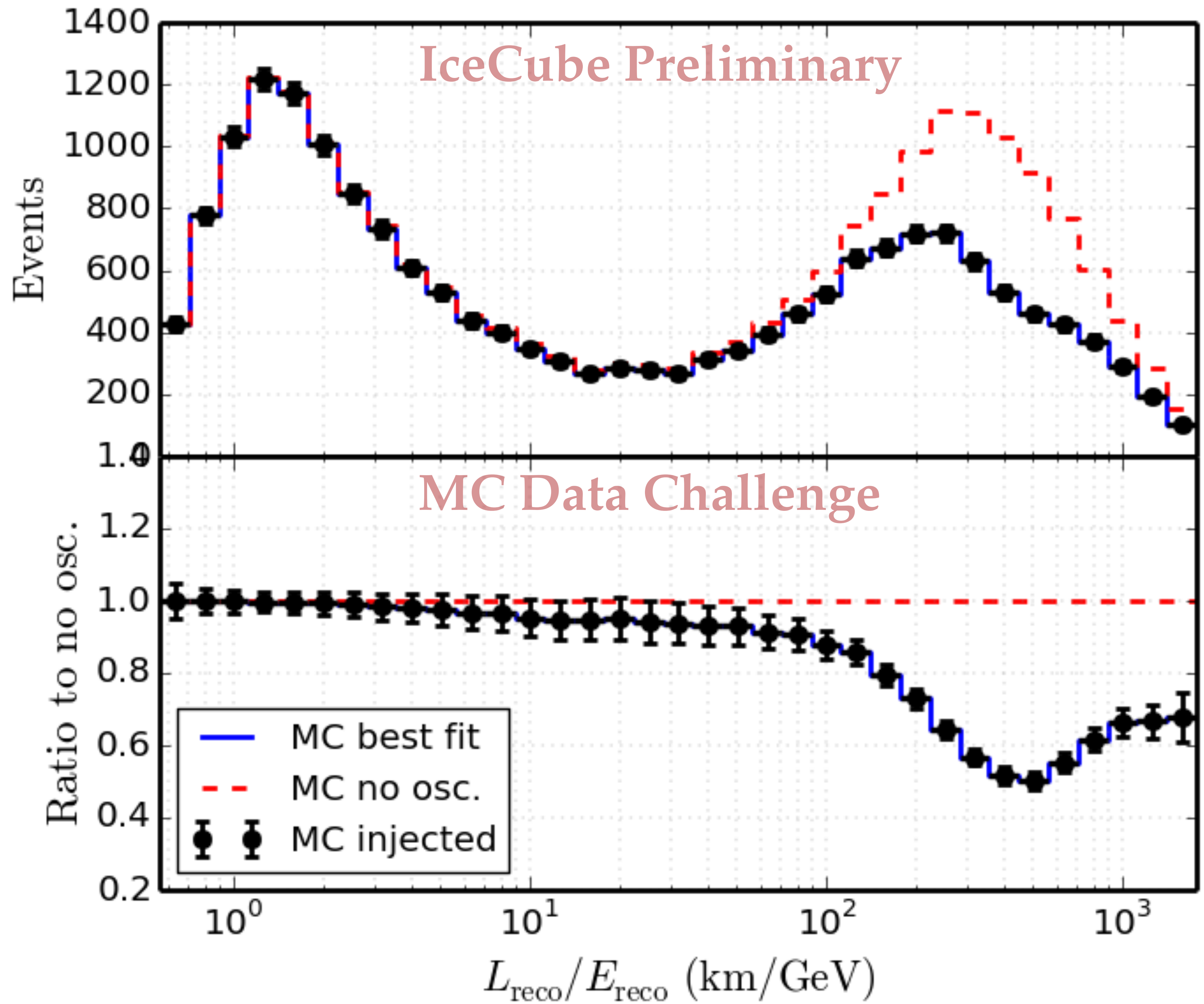
cascade-like track-like

Simulation split into three PID samples

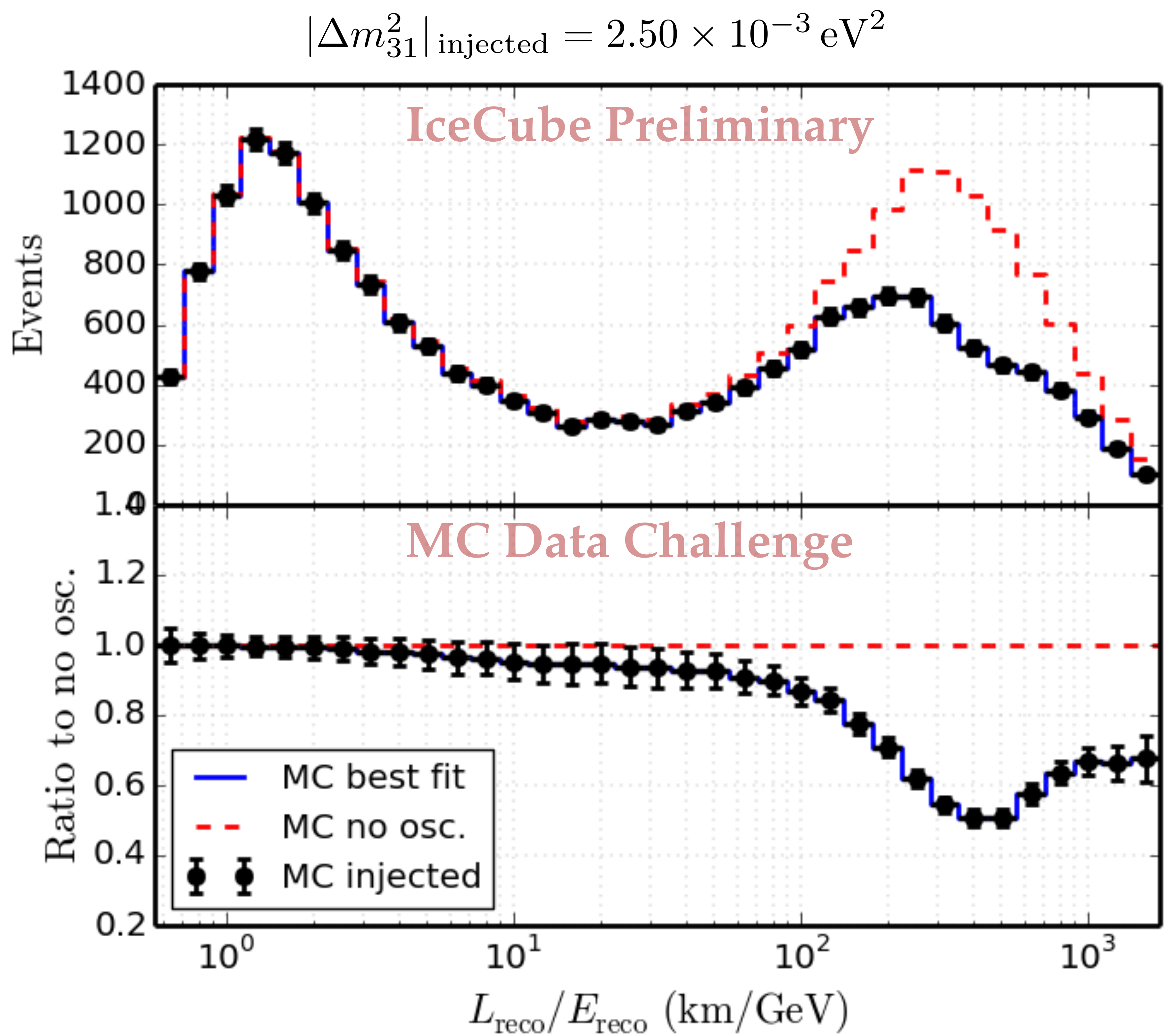


Mass splitting: PDG –1σ injected

$|\Delta m^2_{31}|_{\,\mathrm{injected}} = 2.33 \times 10^{-3}\,\mathrm{eV}^2$

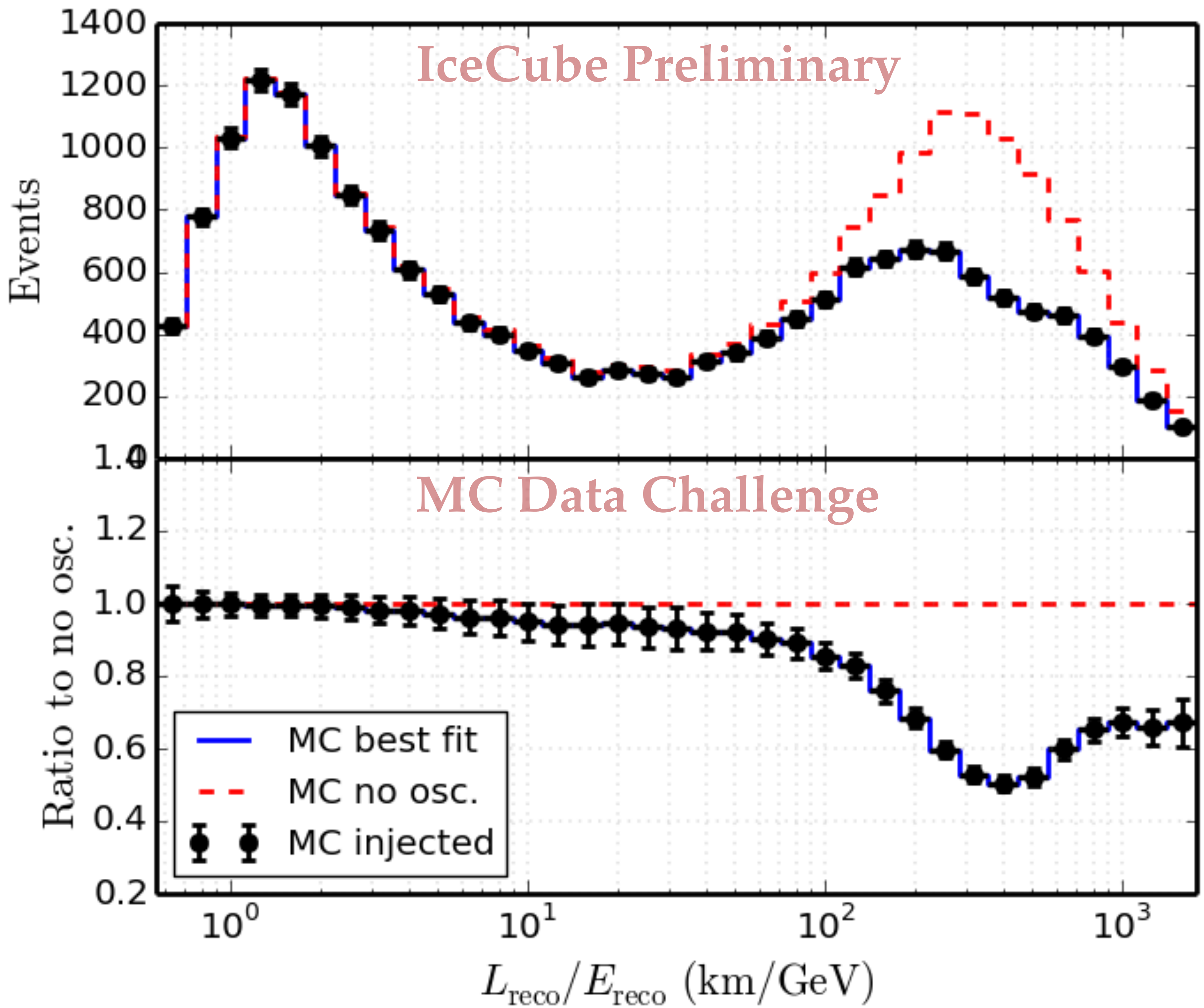


Mass splitting: PDG best fit injected



Mass splitting: PDG +1σ injected

$|\Delta m^2_{31}|_{\text{injected}} = 2.67 \times 10^{-3}\,\text{eV}^2$



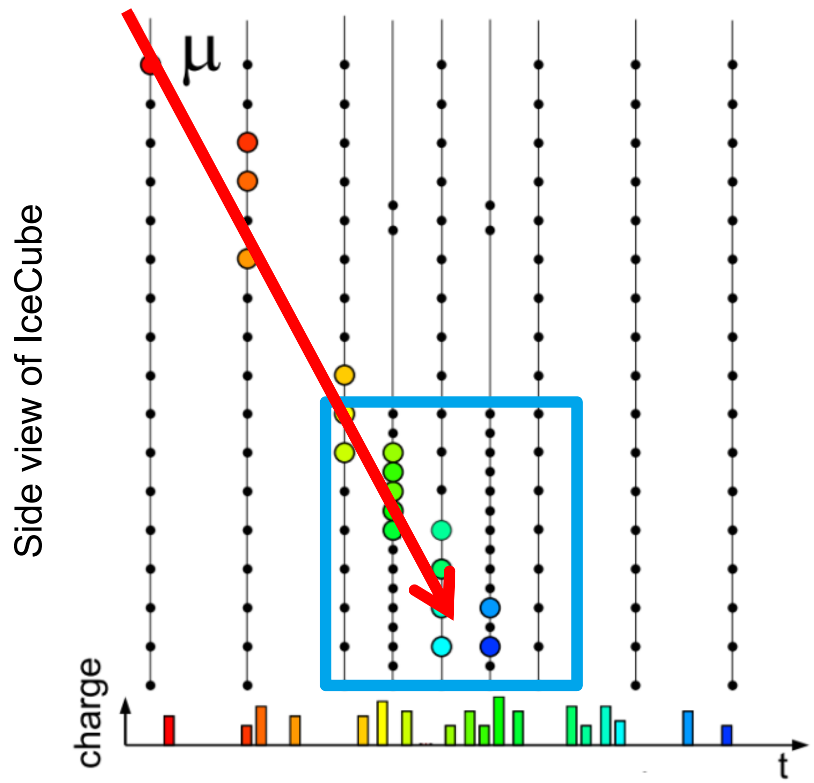
Backup 2

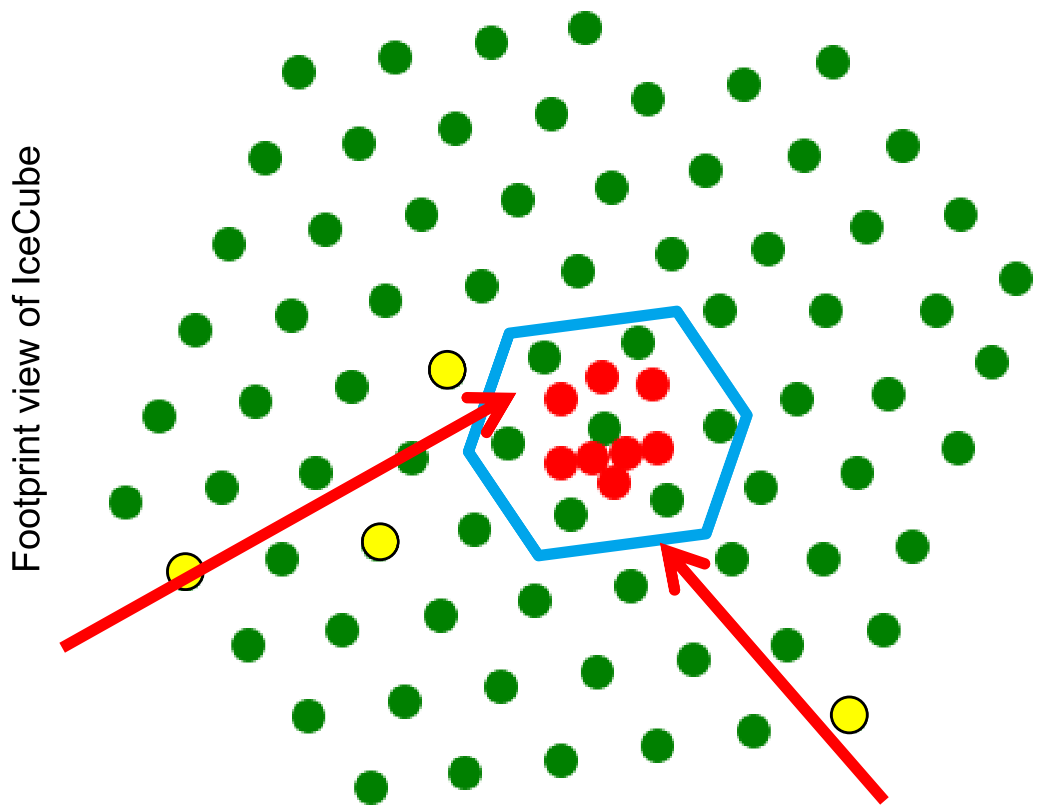
Juan Pablo's slides from Neutrino 2014

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



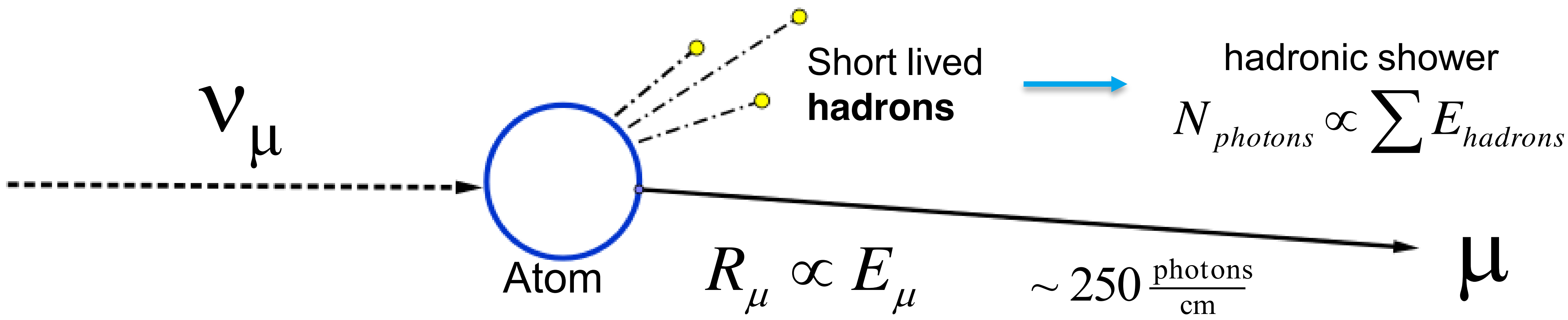


Veto is used to tag muons and use them to fit the atm. muon background in the result
This background is derived from data

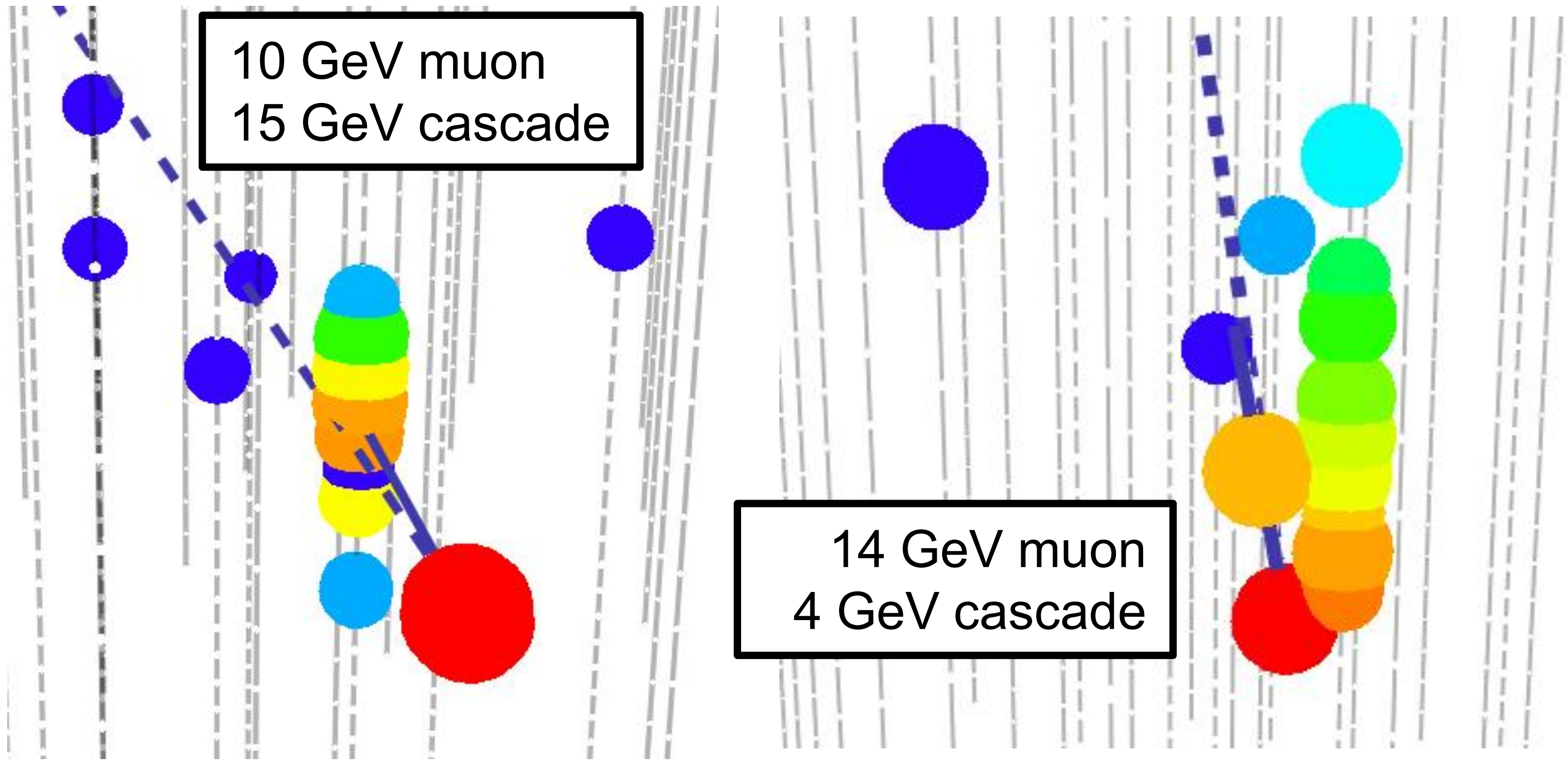
Neutrino signal

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

*All other interactions are background for this study



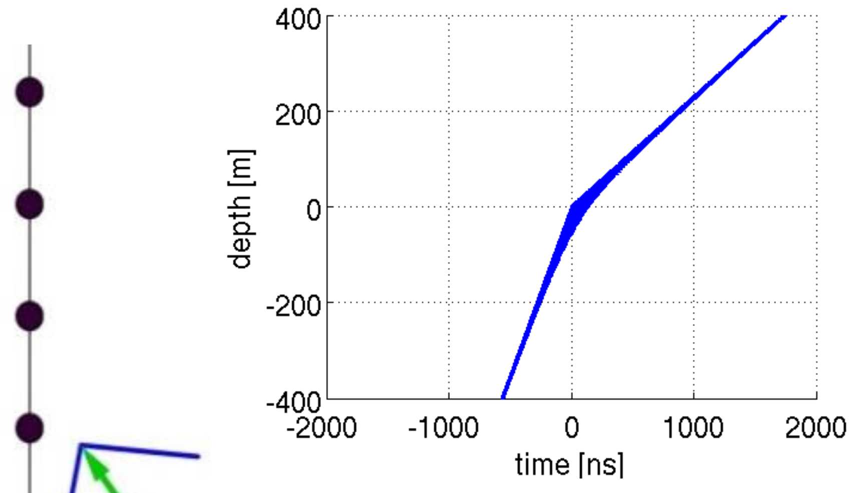
- Interactions in DC
  - DOMs triggered colored
  - Orange is early, **blue** is late
  - Dashed: neutrino direction
  - Solid line: muon
  - **Red**: interaction point

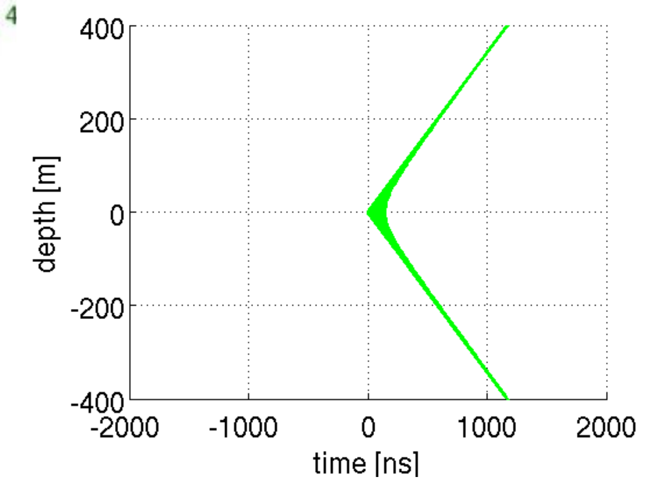


We need the **incoming direction** and **energy** of these signal neutrinos

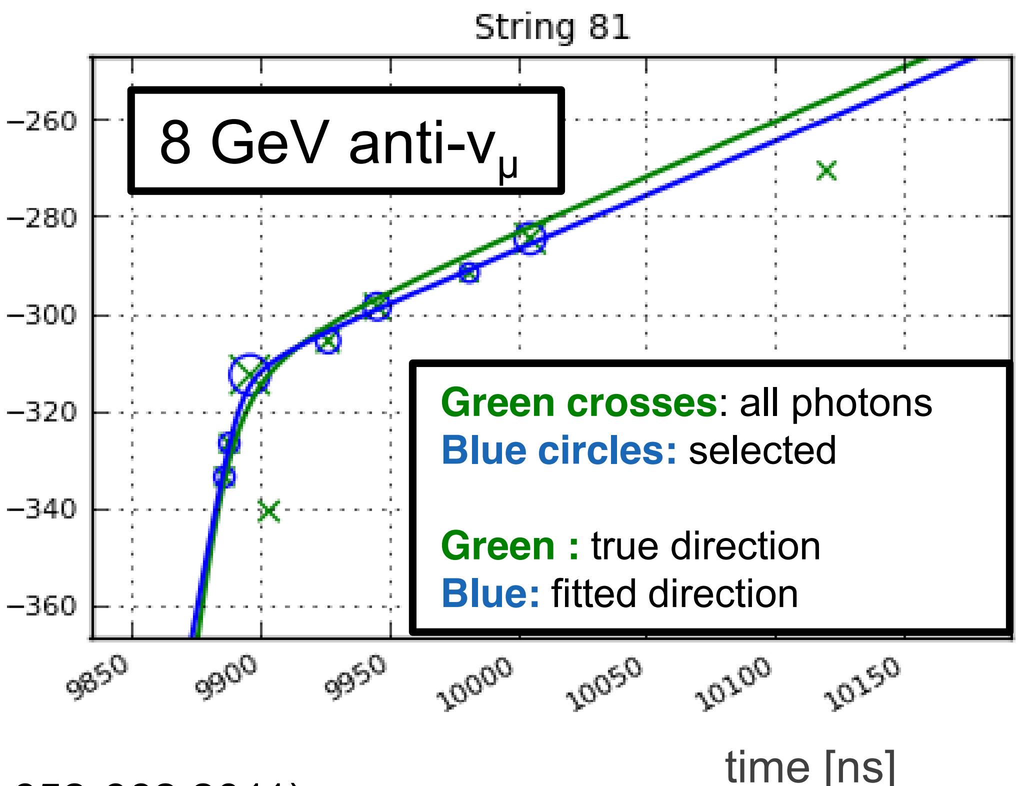
Selection and directional reconstruction: direct photons

- 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**

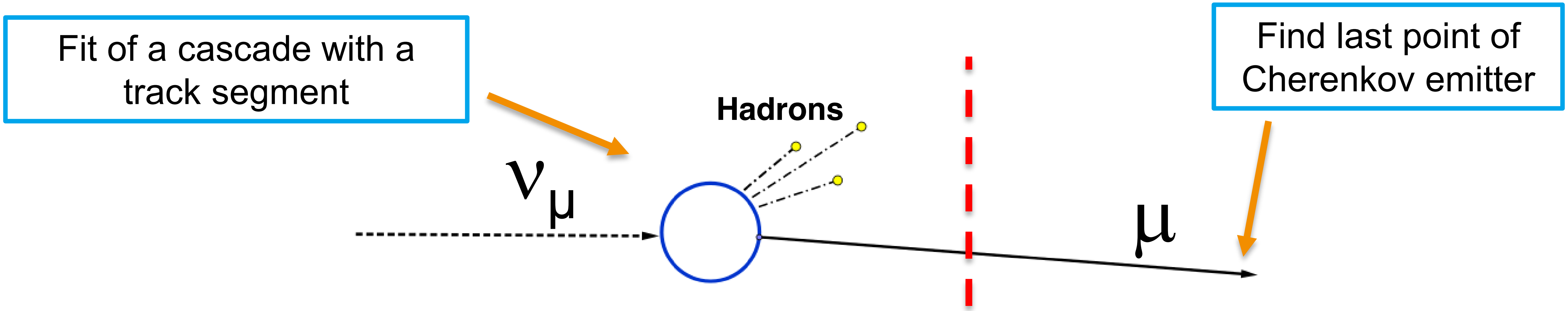


Idea developed in collaboration with J. Brunner* (Astropart.Phys.34:652-662,2011)

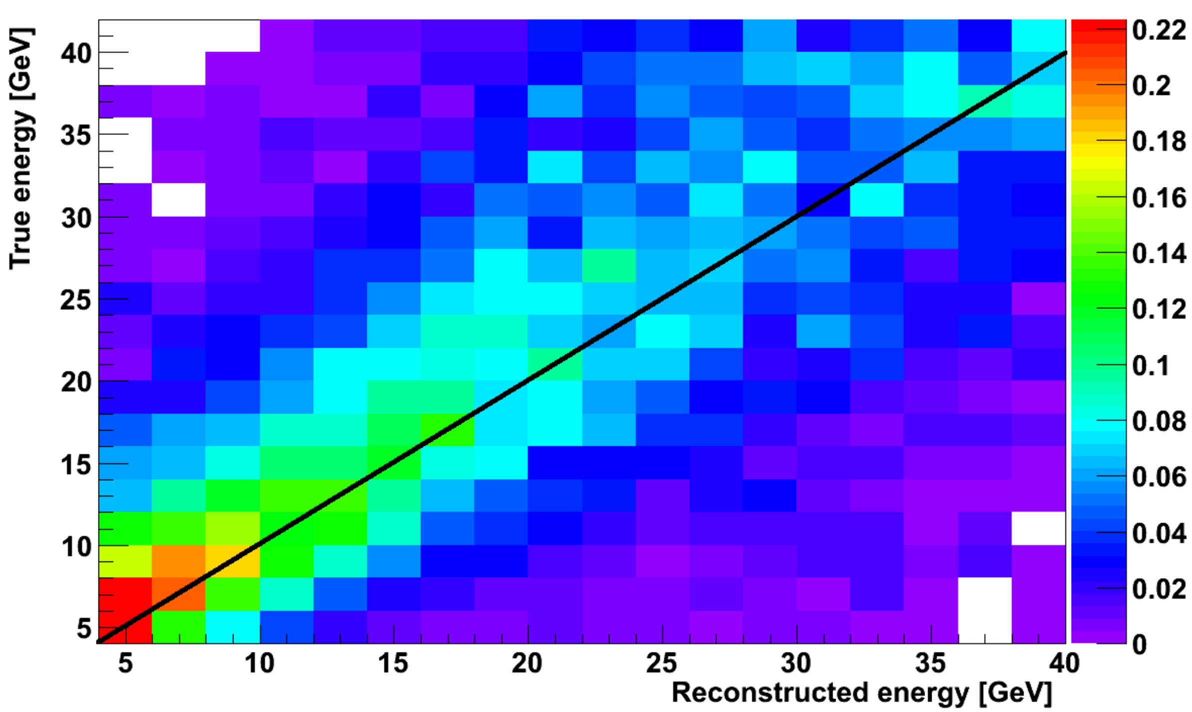
Constructing a full energy estimator

- Dividing the problem in two parts

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



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

Final neutrino sample

> Including 3 years of full detector configuration (IC86)
  - 953 days of detector livetime

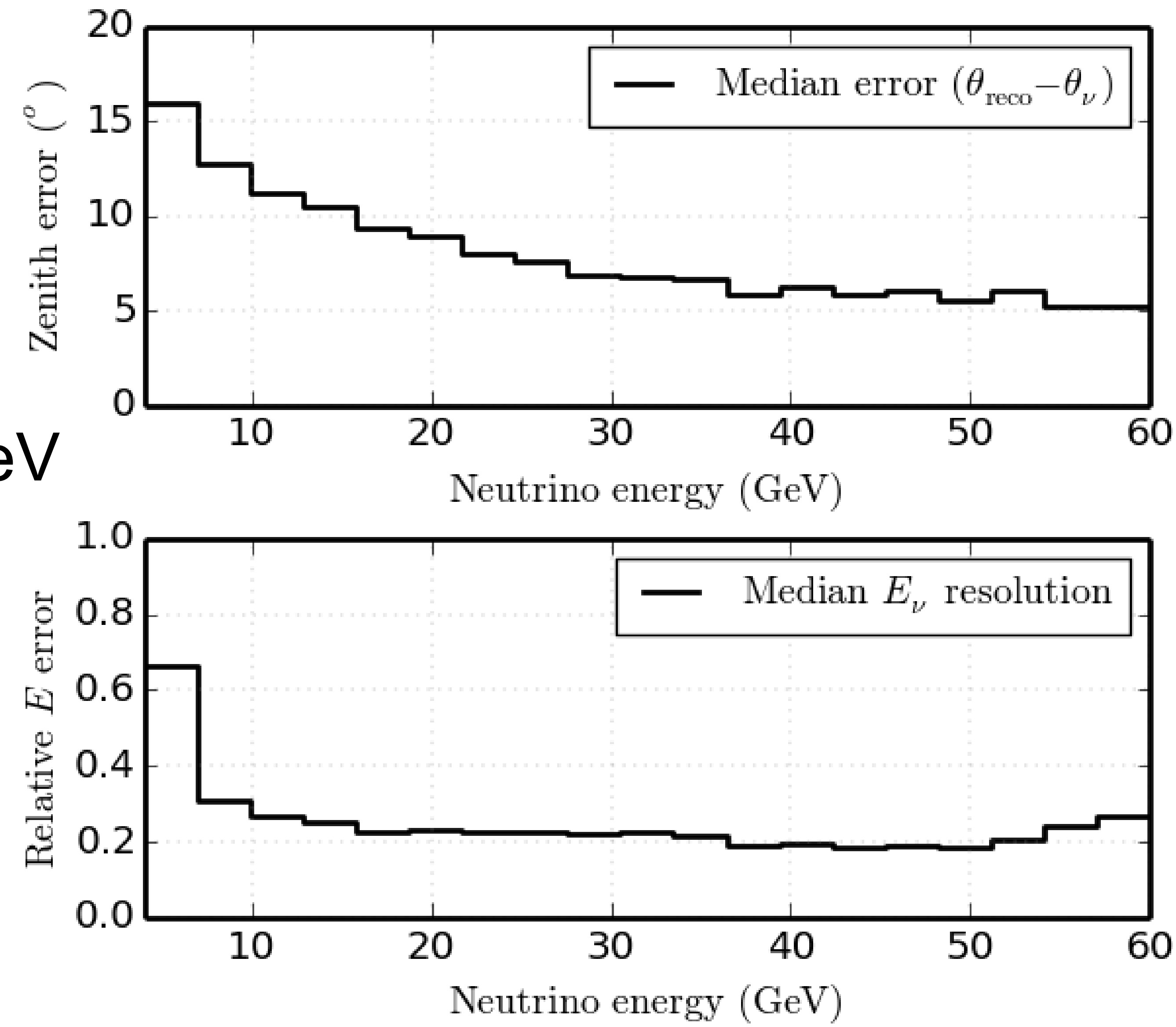
> MC expectation: ~ 7,000 events
  - Disappearance of ~ 1,900

> Energy threshold ~ 10 GeV

> Zenith angle: 12 deg. res. at 10 GeV
  - Low energy side: 15 deg. res.
  - High energy: 5 deg. res.

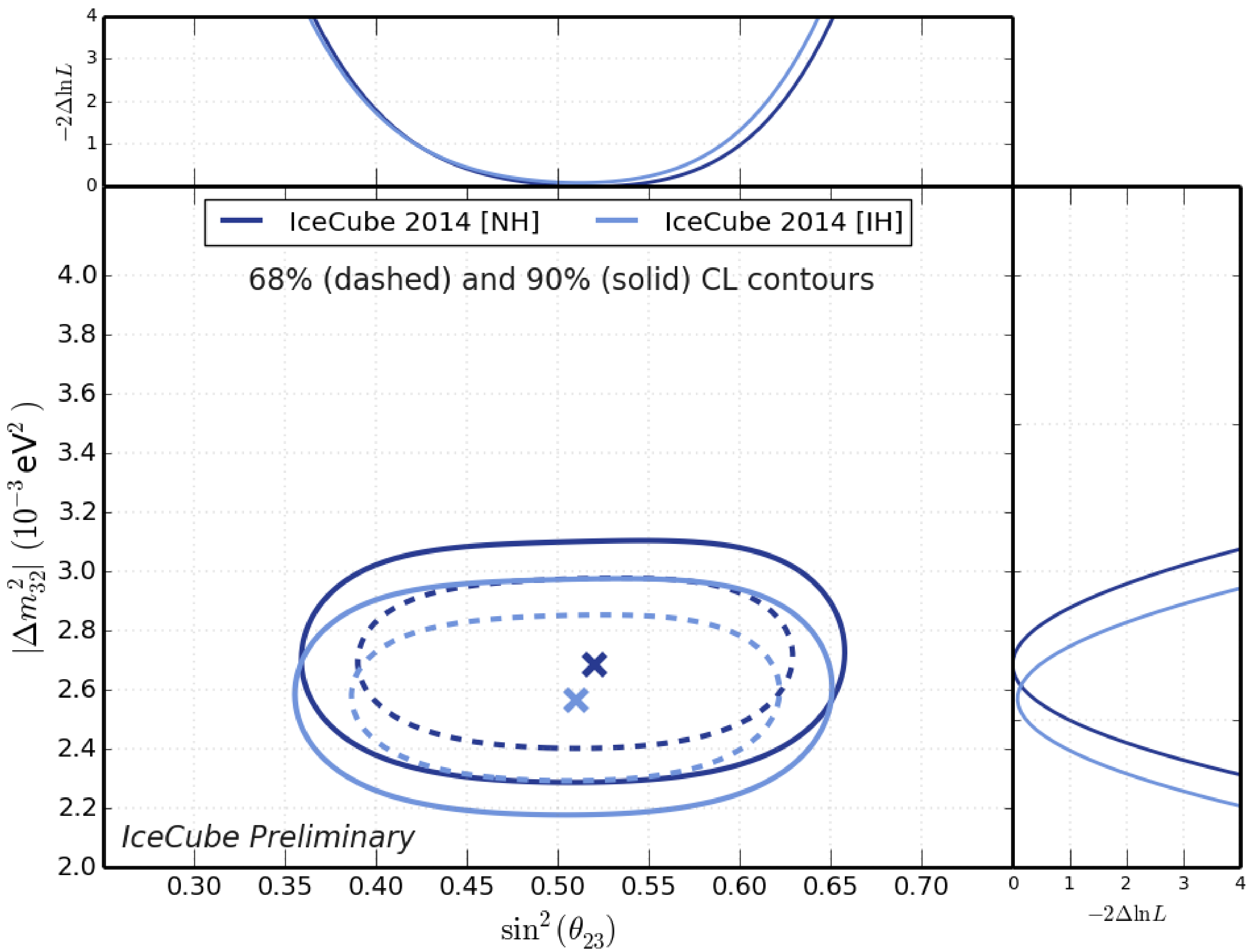
> Energy: 30% res. at 10 GeV
  - Not so reliable below 10 GeV
  - Above 50 GeV muons leave the detector

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

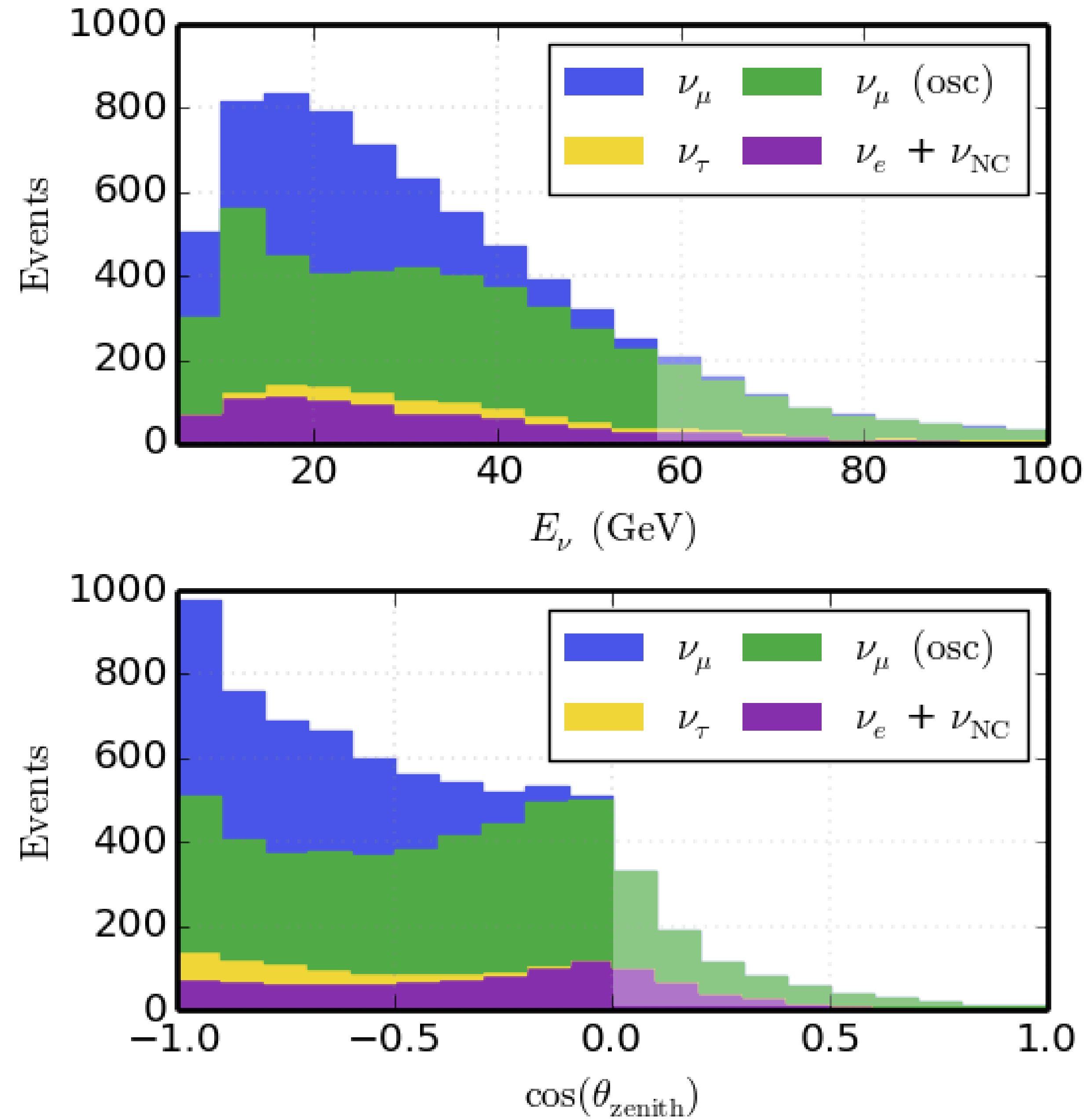
Parameter	Deviation at best fit
Flux at horizon	- 1 σ
Spectral index	+ 0.48 σ
ν_e deviation	- 0.62 σ
DOM eff.	+ 0.02 σ
Scattering in ice columns	+ 0.63 σ

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)
  - 953 days of detector livetime
- MC expectation: ~ 7,000 events
  - Disappearance of ~ 1,600
- Energy threshold ~ 10 GeV
- Zenith angle: 12 deg at 10 GeV
  - 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