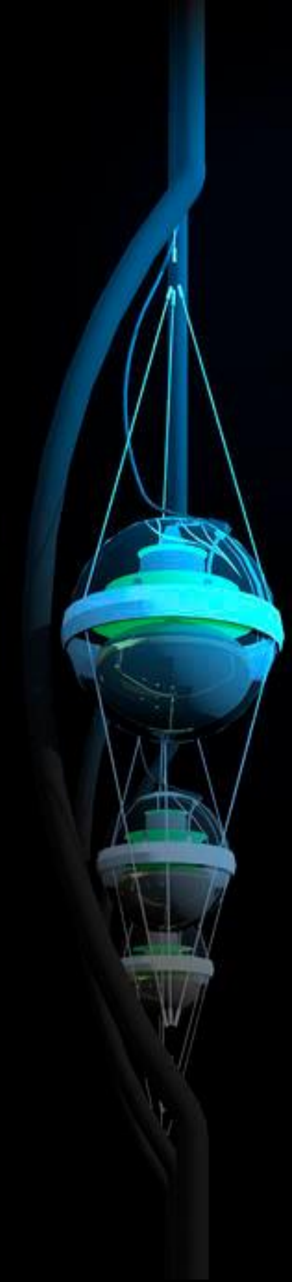


Neutrino Oscillations with IceCube DeepCore

Measurement of ν_μ disappearance with the full detector configuration

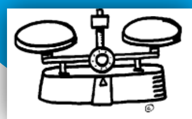
Juan Pablo Yáñez
DESY

Weak Interactions and Neutrinos Workshop
September 2013, Natal, Brazil

Searching for neutrino oscillations

> Oscillations in theory

Very **small mass** scale



+

Very **small** **Δm**

$\sigma_m^2 > m_1^2 - m_2^2$

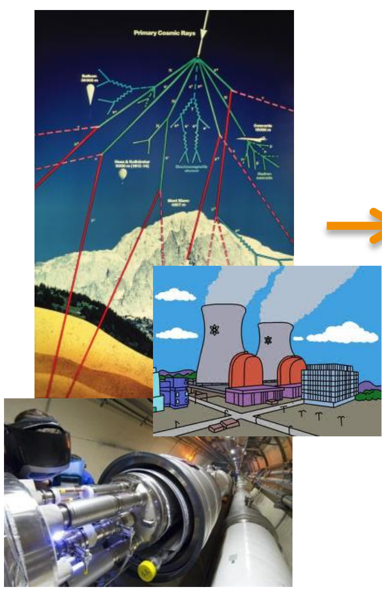
=

Oscillations

Effect depends in **energy** and **travel time**

> The disappearance channel in practice

Neutrino source



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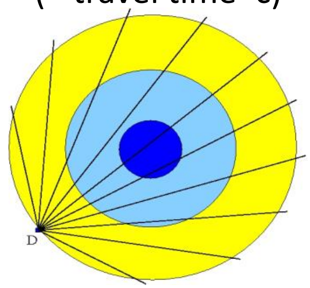
Propagation distance (≈ travel time ·c)



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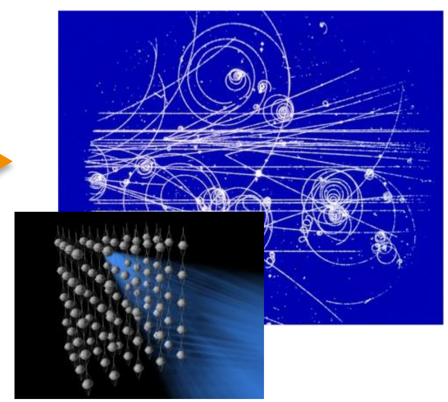
Detector

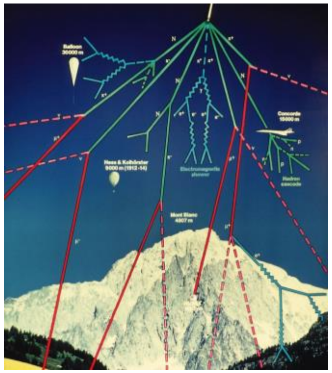


→

Assuming you understand the steps:
“Am I missing neutrinos?”

The experimental setup

Source: atmospheric neutrinos
CR (mostly protons) – nucleon interaction



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

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

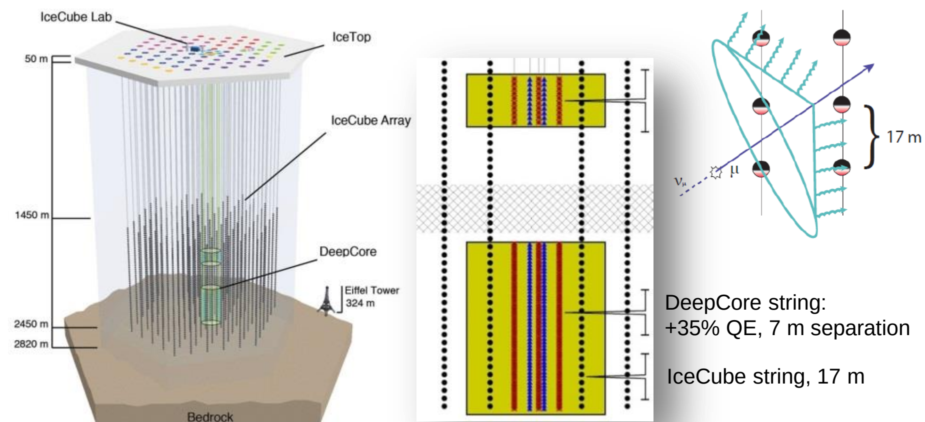
$$\downarrow \qquad\qquad \downarrow$$

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

- Travel distance of 20 – 12,700 km
- Wide energy range (MeV to PeV)

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

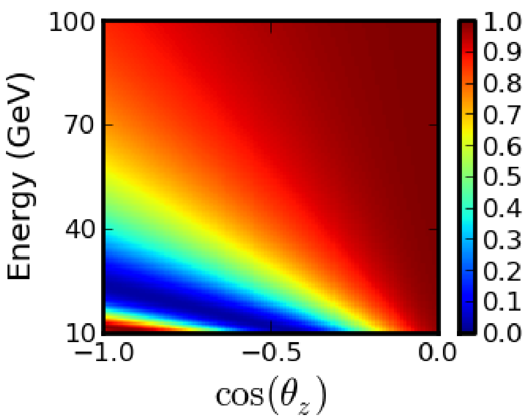
Detector: IceCube+DeepCore

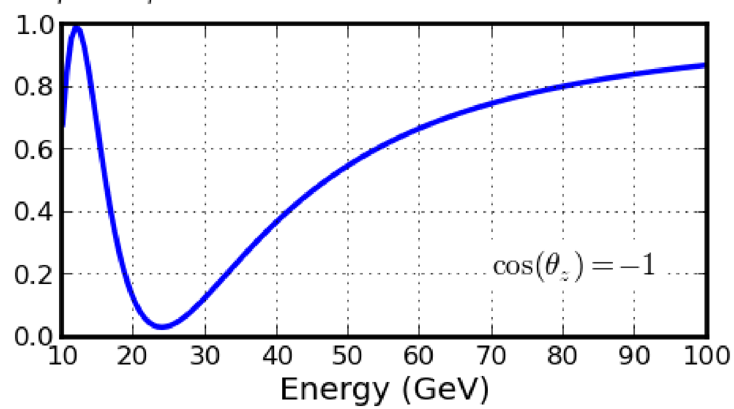


Triggers on thousands of neutrinos per year in signal region

The searched effect

$P(\nu_\mu \rightarrow \nu_\mu)$



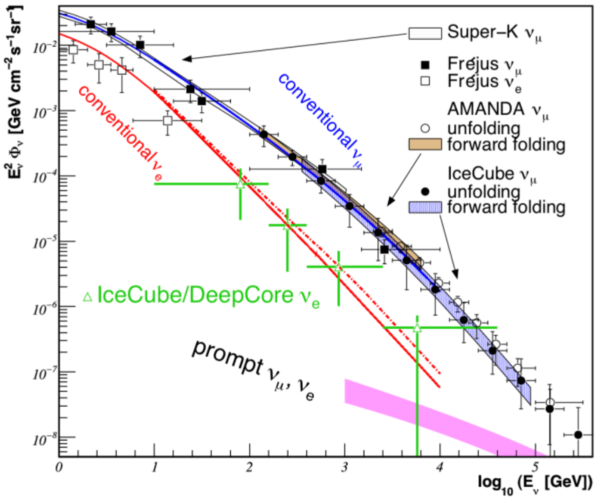


* “matter oscillations” are not discussed in this talk

What have we seen with DeepCore?

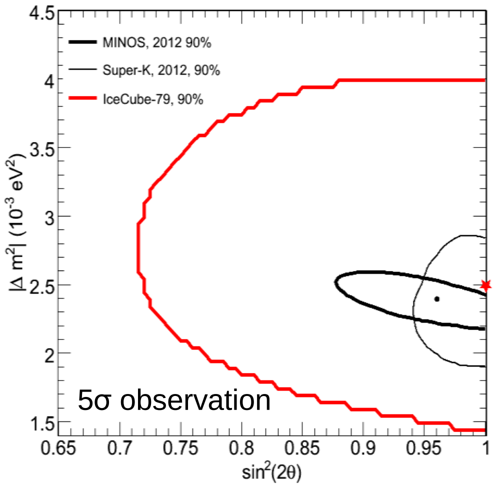
Measurement of ν_e

Phys. Rev. Lett. 110 (2013) 151105



Neutrino oscillations

Phys. Rev. Lett. 111, 081801 (2013)



Caveats

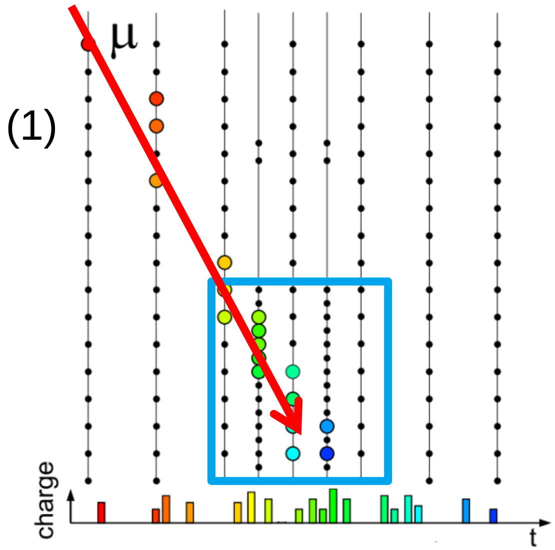
- First year of incomplete DeepCore
  - Event reconstructions in development
    - Oscillation results using tools for designed for TeV neutrinos
  - Focusing on the “high-energy” side (E>= 25 GeV)
  - Detector behavior still being understood
- Veto techniques started to be explored
- Large errors due to uncertainties in:
  - Optical properties of the medium (ice)
  - Absolute photon collection
  - Atmospheric neutrino flux
  - Neutrino cross sections

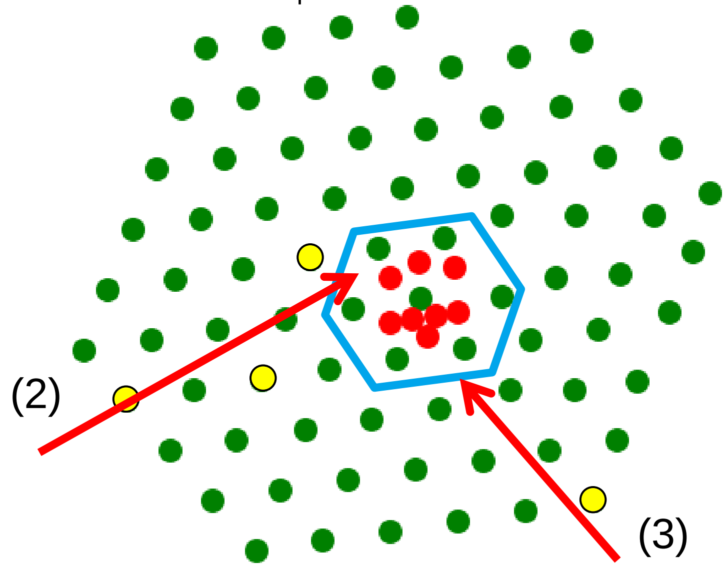
Introducing new strategies

Event selection and particle reconstructions

Selection of a neutrino sample: background rejection

- Rejection of atmospheric muon background based on veto capabilities
  - Location of first DOM pair (trigger)
  - Search for clusters of DOMs in veto region (1)
  - Count isolated but causally connected DOMs in veto region (2)
  - Search for individual hits in a narrow time window from known problematic directions (3)
  - Hints from “high-energy” reconstructions

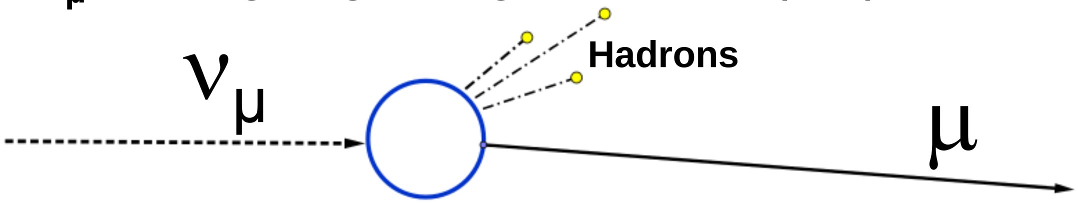




Next criterion: event quality. Need to define it!

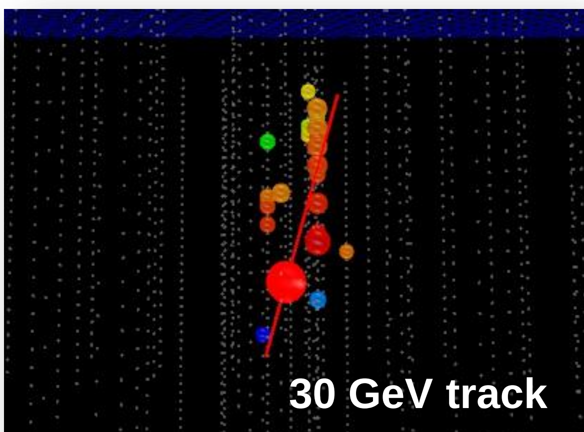
Revisiting the signal

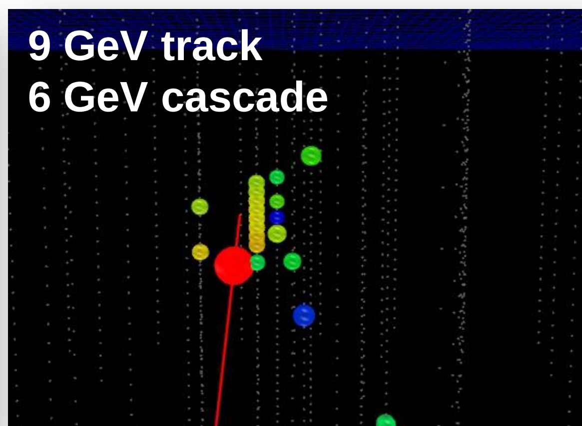
> The signal is ν_μ undergoing charged current (CC) interaction



- Neutral currents are background for IceCube oscillation analyses (no CC, NC cascade distinction)
- ν_e and ν_τ CC are also background

> Typical detector signature of ν_μ CC interaction at E_ν < 50 GeV



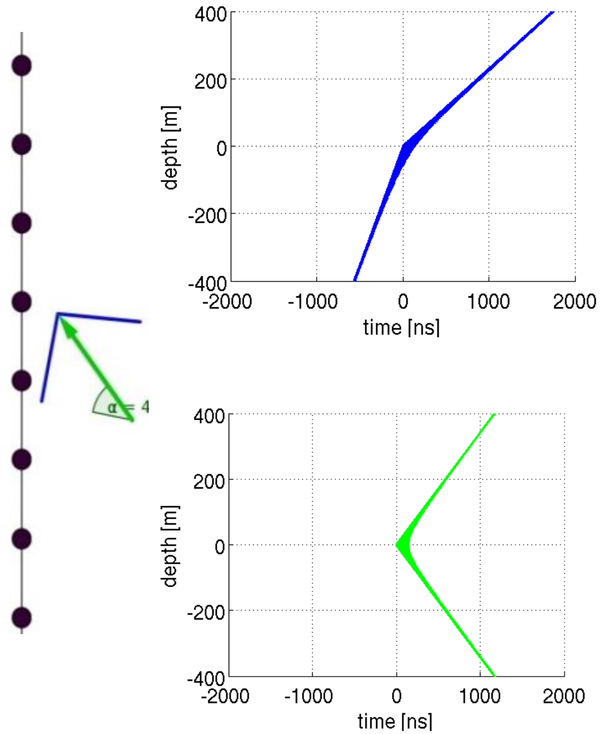


- Always a **mix** of track & cascade (entangled light)
- Few photons / channels
- Detector spacing matters
- Isolated hits can distort reconstruction tools

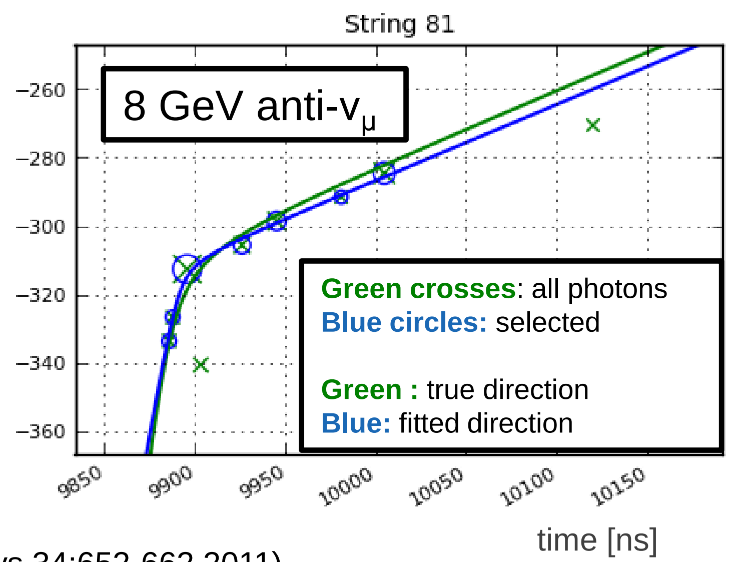
Very different from ν_μ CC of TeV energies in IceCube

The importance of *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**

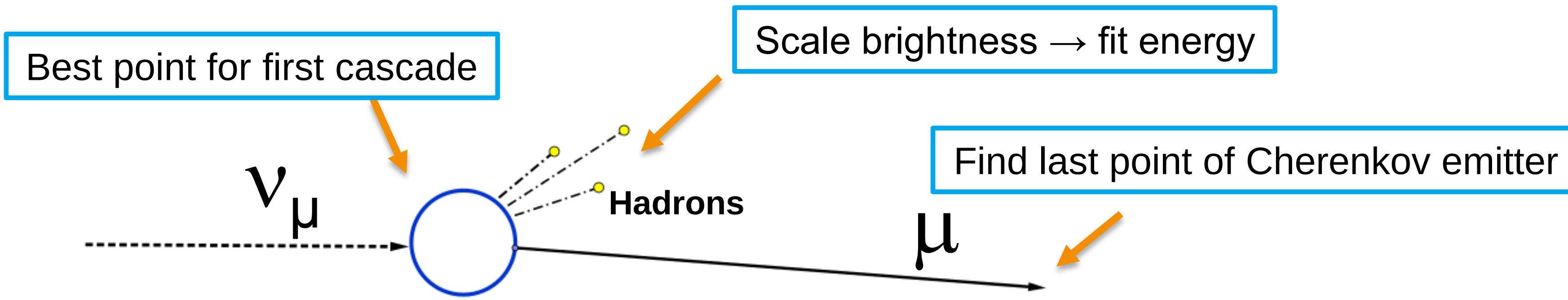


Idea developed in Collaboration with J. Brunner* (Astropart.Phys.34:652-662,2011)
Single-string **ANT**ares inspired **A**lgorithm

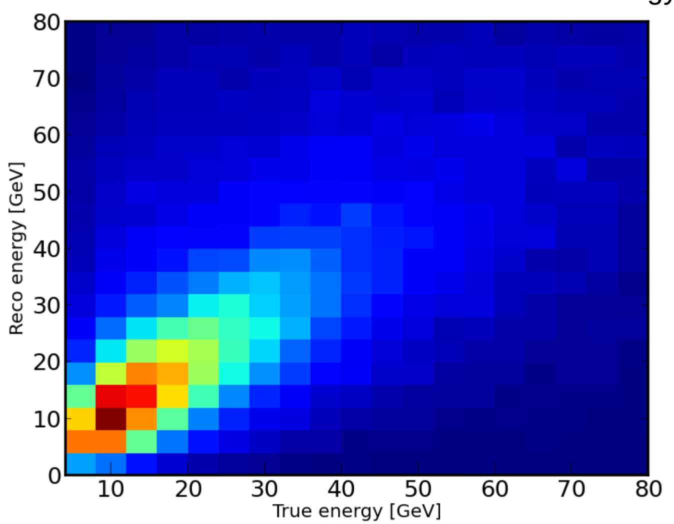
Constructing a full energy estimator

- Divide the problem, solve problems in steps

Energy proxy = Muon energy (track) + Energy of hadrons (cascade)



Correlation between reconstructed and true energy



- Uses all information available in the detector
- Step-wise approach
  - Requires separation of light from track/cascade
- Needs the parametrized light emission of particles
  - Optical properties of the ice included
  - All hadrons treated as a cascade

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

- Using a binned Poisson likelihood for a **3 flavor fit**
  - **2-D histograms** as a function of **energy** and **zenith angle**
  - **Systematic uncertainties** as nuisance parameters
- Systematic uncertainties included

$$E = [7{,}100]\ \mathrm{GeV}, \quad \cos\theta_z < 0$$

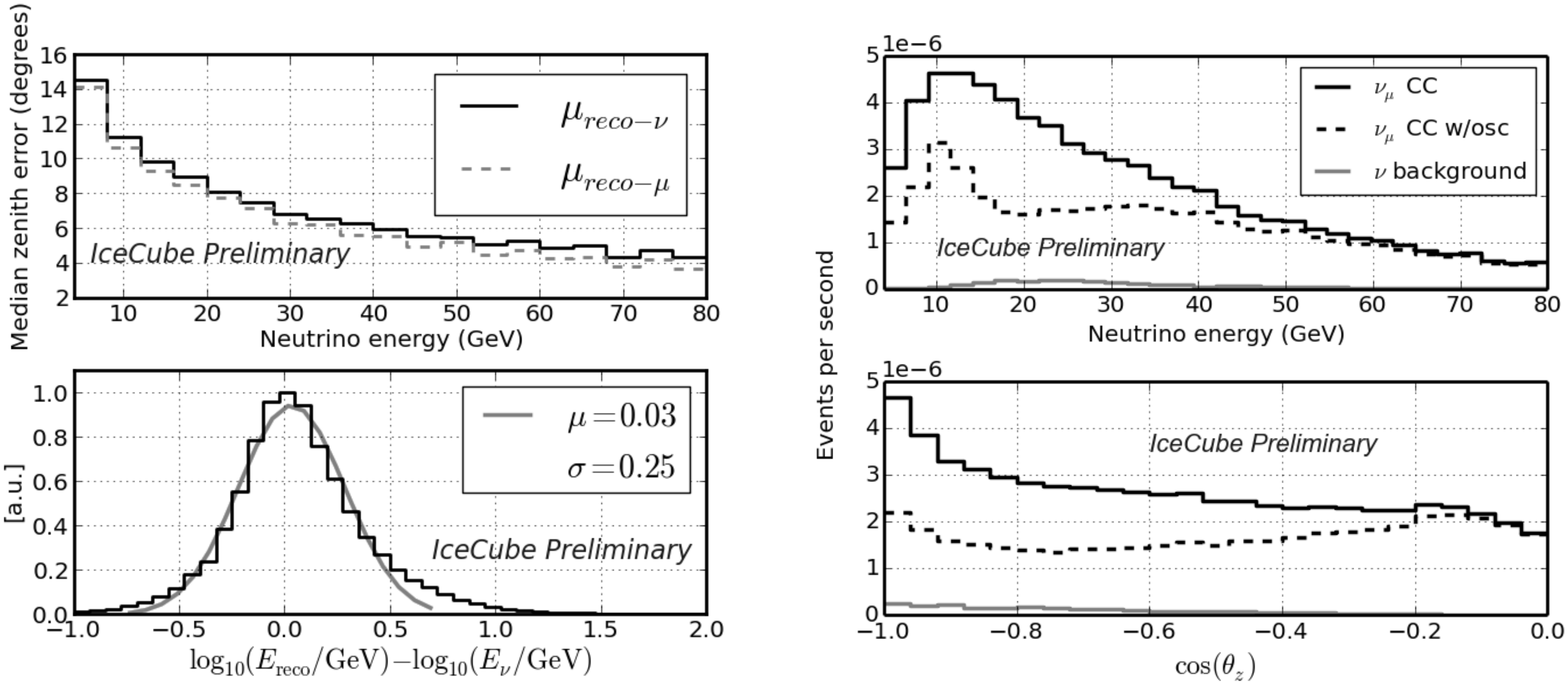
$$-\ln(L) \propto \sum_i t_i - d_i \ln t_i + \frac{1}{2}\frac{(\nu_i - \hat{\nu})^2}{\sigma_\nu{}^2}$$

Systematic uncertainty	Prior	Implemented
Atm. muon contamination	Flat prior, contamination [0, 10%]	Modifying the weights
Atm. Neutrino flux	From Honda 2006. Normalization left free. **Analyzing shape**	
ν_e/ν_μ deviation	$\sigma_n = 0.2$	
Spectral index (γ)	$\mu_\gamma = -2.65$, $\sigma_\gamma = 0.05$	
θ_{12}, θ_{13}, Δm^2_{21}	From Fogli et al. (arXiv:1205.5254)	
Photon collection eff.	$\sigma_{eff} = 10\%$	From discrete MC variations
DOM relative eff.	$\mu_{HQE} = 135\%$, $\sigma_{HQE} = 3\%$	
Scattering in ice columns	$\mu_a = 0.02$, $\sigma_a = 0.01\ \mathrm{cm}^{-1}$	

Results

The final neutrino sample

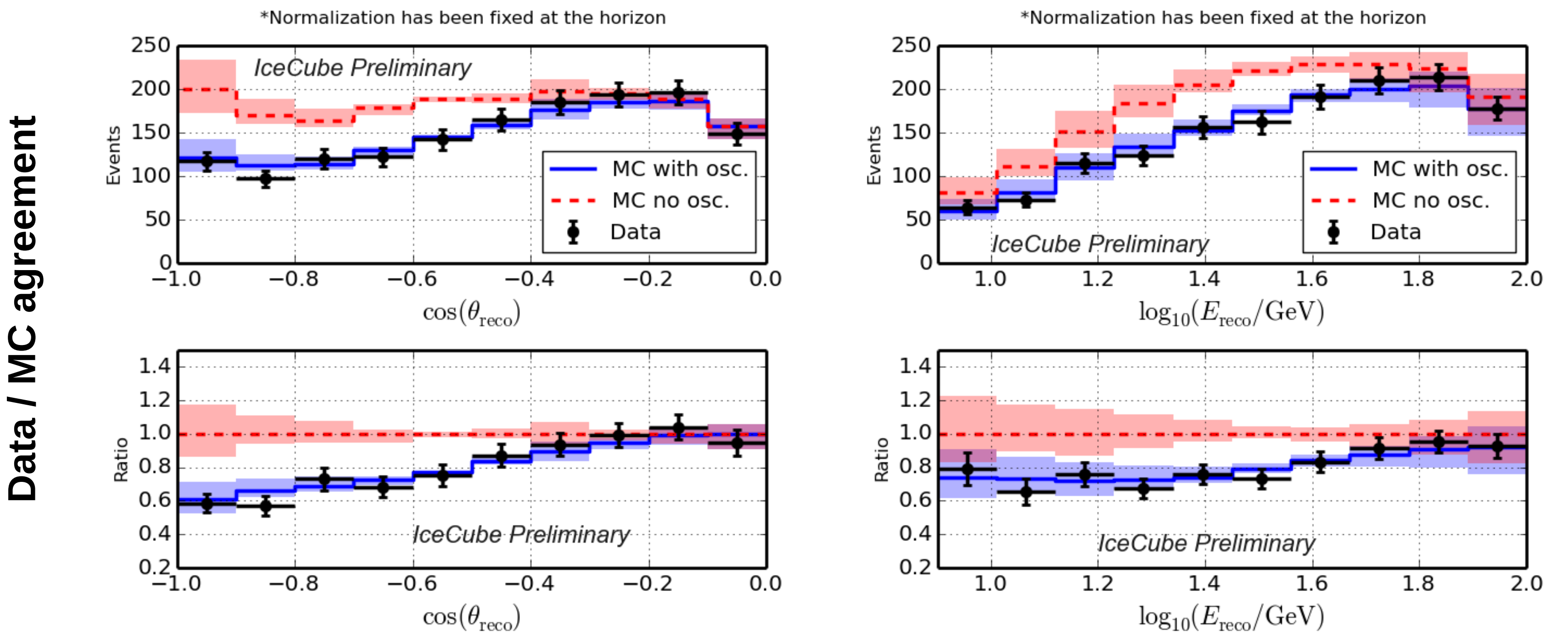
- Selection based on veto techniques and quality events
  - Focusing on reaching a well understood result
- ~ 2,000 events/year expected, disappearance of 500
  - Energy distribution peak ~12 GeV. Zenith acceptance enhanced for vertical events.
  - Zenith resolution better than 10 degrees. Energy resolution of 0.25 in $\log_{10}$(E/GeV)



Best fit parameters from data

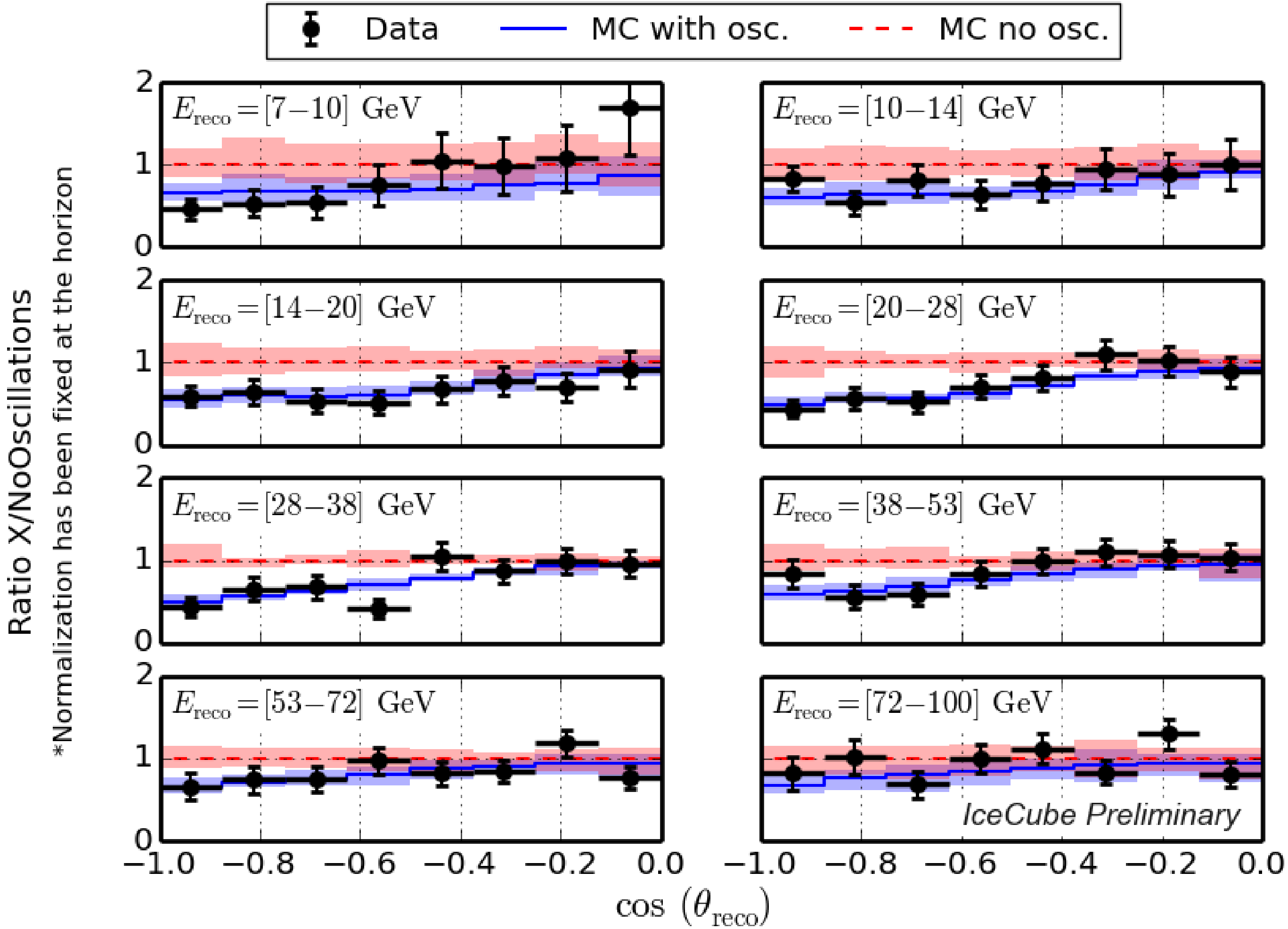
Parameter	Best fit point
$\sin^2(2\theta)$	1.0 (>0.94 at 68% CL)
Δm^2 $(10^3$ eV$^2)$	2.50 +/- 0.50

1487 events selected (2011-2012)
6σ rejection of no osc.
χ^2 = 48.8 / 54 dof



For all figures: bands indicate systematic uncertainties, MC expectation calculated using baseline values for nuisance parameters, **normalization fixed at the horizon (free in LLH)**

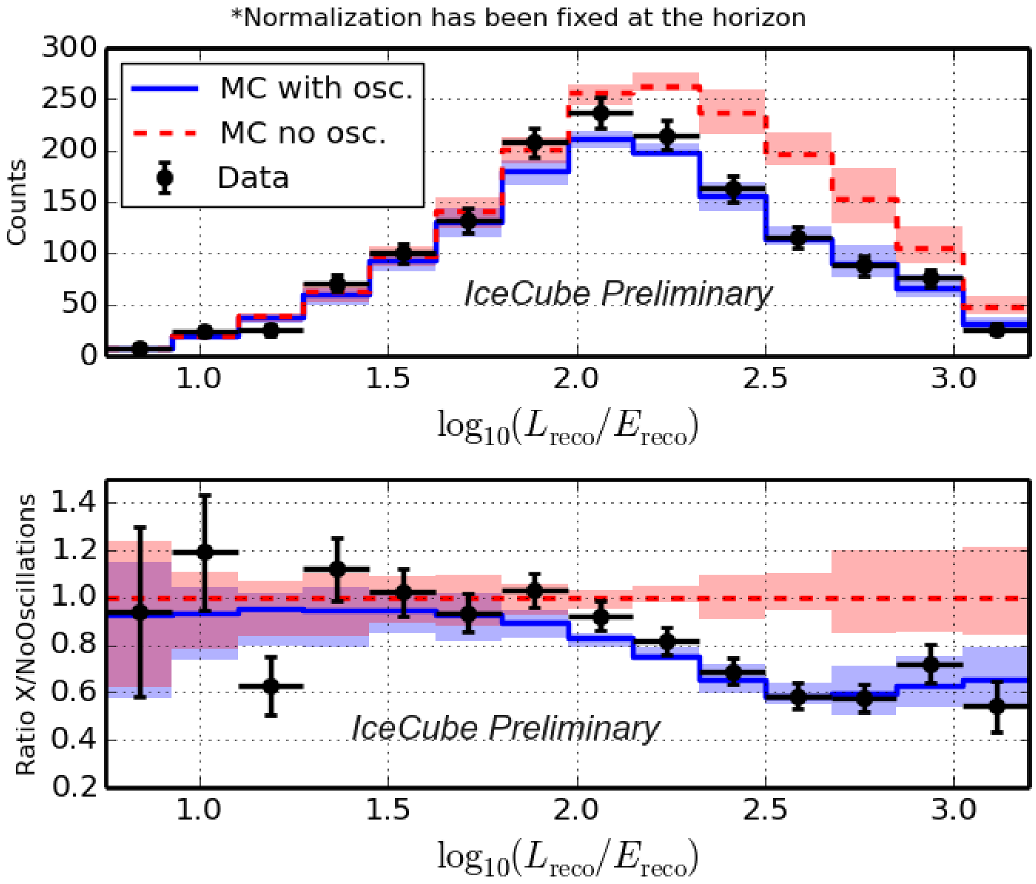
Ratio to no oscillations (bins as used in the likelihood)



Bands indicate systematic uncertainties

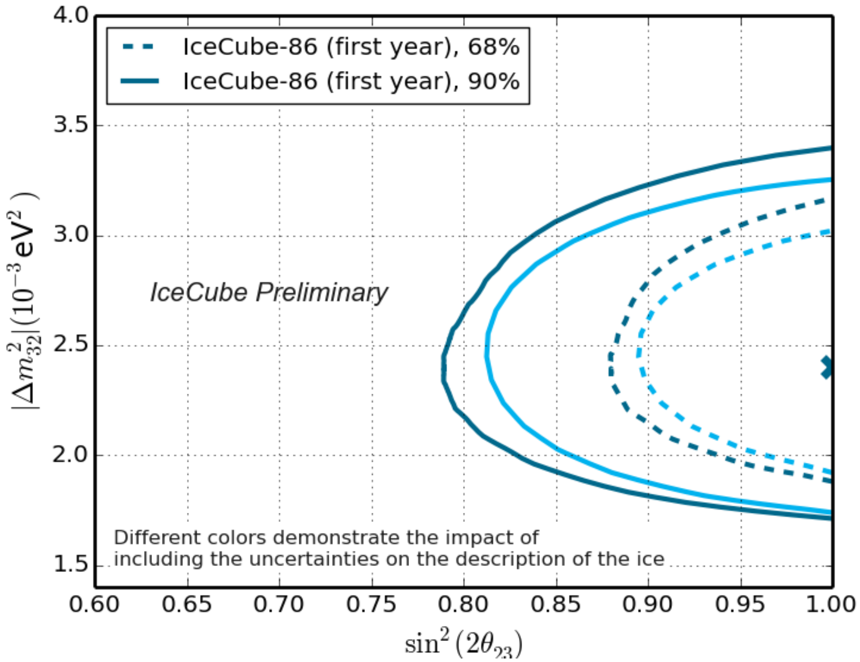
Effect as function of L/E

> Analysis is **not** performed in this variable, still instructive

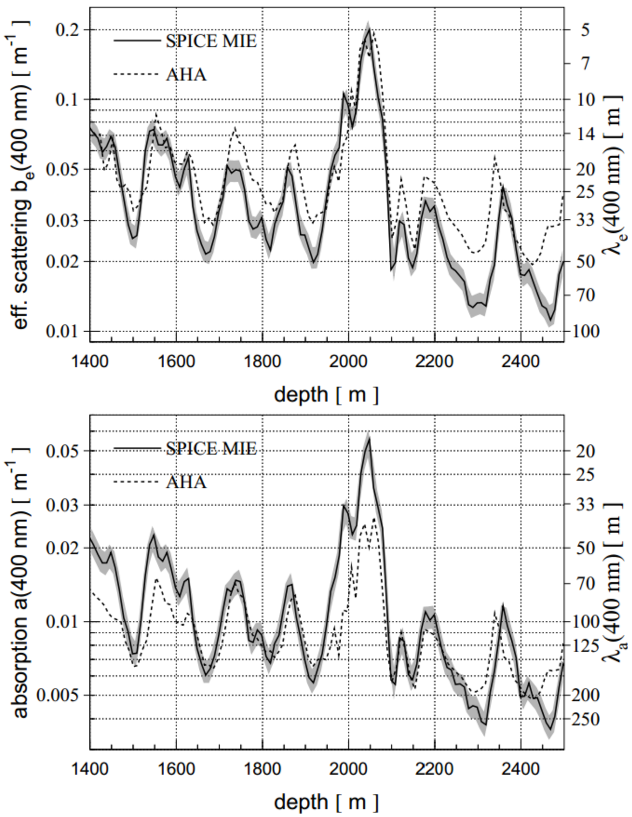


The last test: optical properties of the ice

- To include the medium uncertainties
  - Obtain the best fit from data
  - Produce MC with varied optical properties
  - Inject best fit, pass MC through analysis chain
  - Account for errors in confidence regions



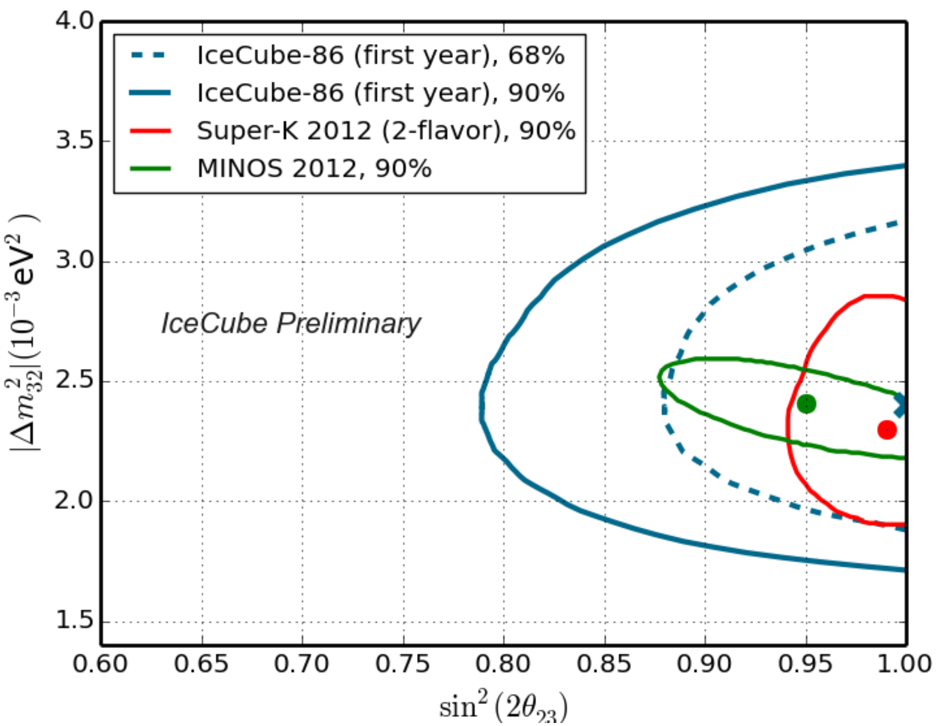
Optical properties of the medium



Nucl. Instr. Meth. A711 (2013) 73

Comparison, conclusion, outlook

- Measured neutrino oscillations with IceCube DeepCore (full detector)
  - Results compatible with best known values
  - Using new tools developed for the events of interest
  - Including energy and zenith estimator
  - Full treatment of systematic uncertainties
  - Very good agreement with MC



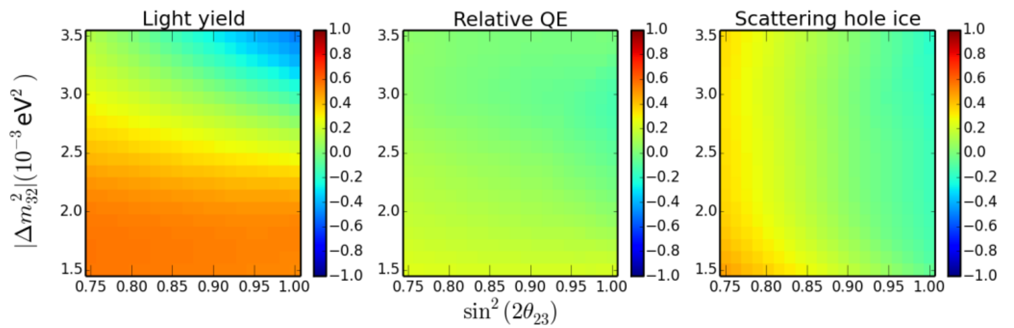
- Improvements in near future
  - Constrain the neutrino flux
  - Integral energy estimator (no steps)
  - Re-analysis of the quality demanded
  - Better MC at lower energies
  - **More data (2+ years available)**

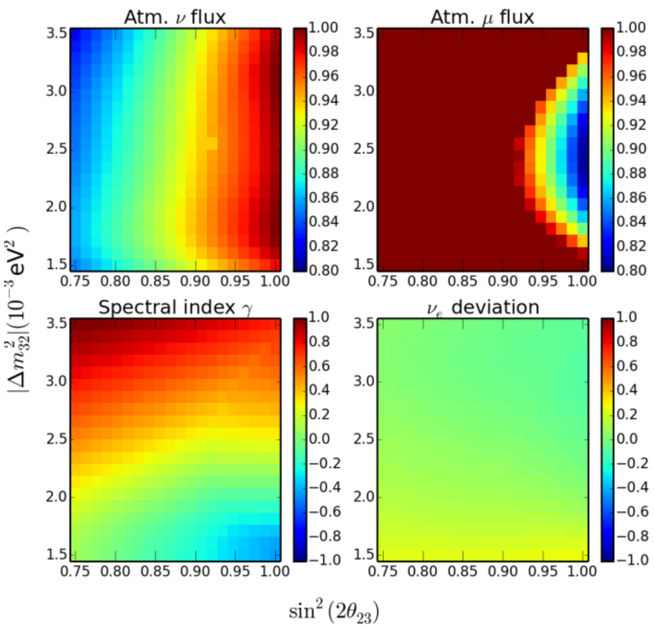
Thank you for your attention

Backup slides

Studying the uncertainties

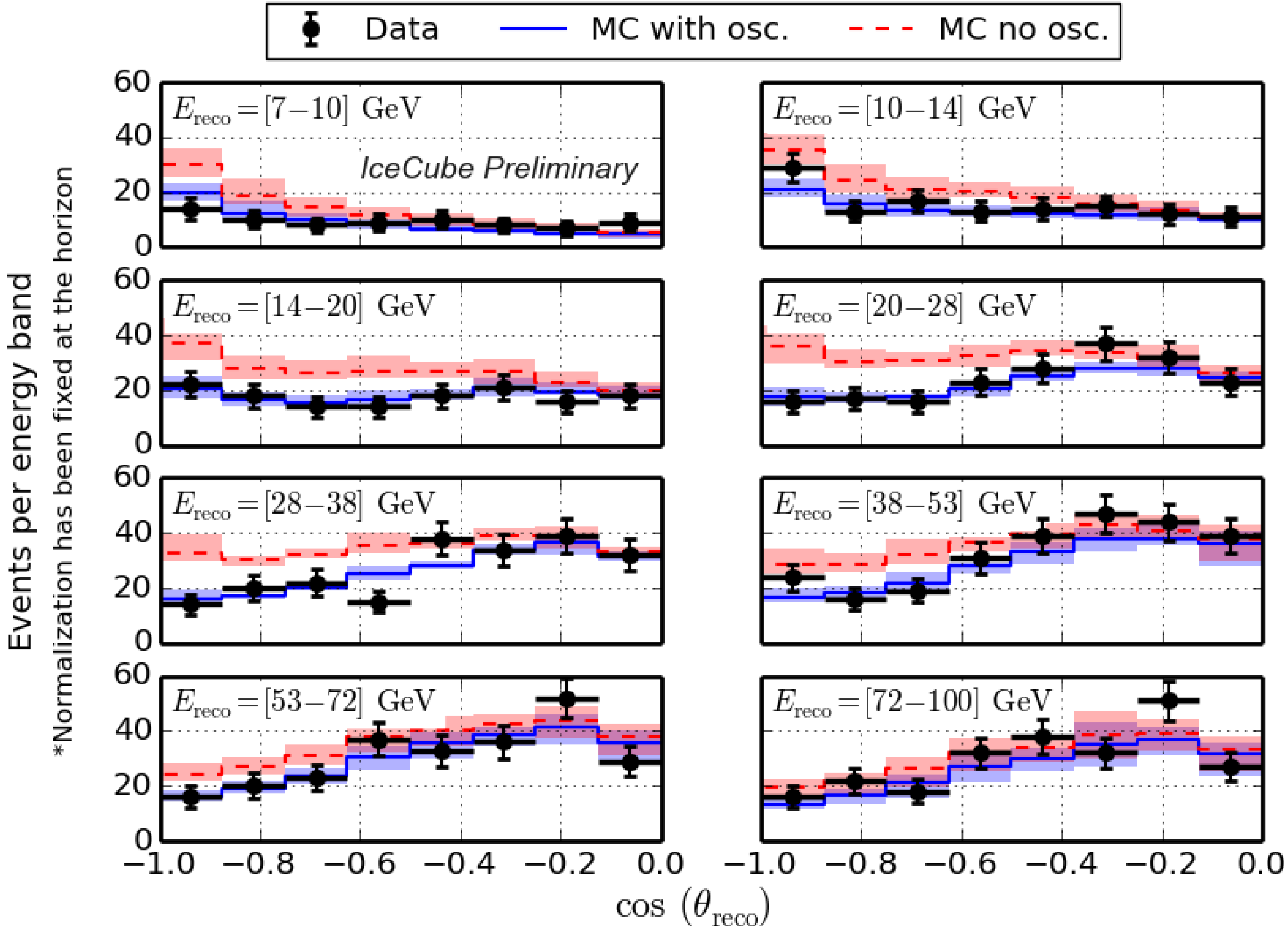
- Analyzing how the nuisance parameters move
  - Color scale normalized to 1σ uncertainty
  - One color = not relevant
  - Pattern → parameter affected





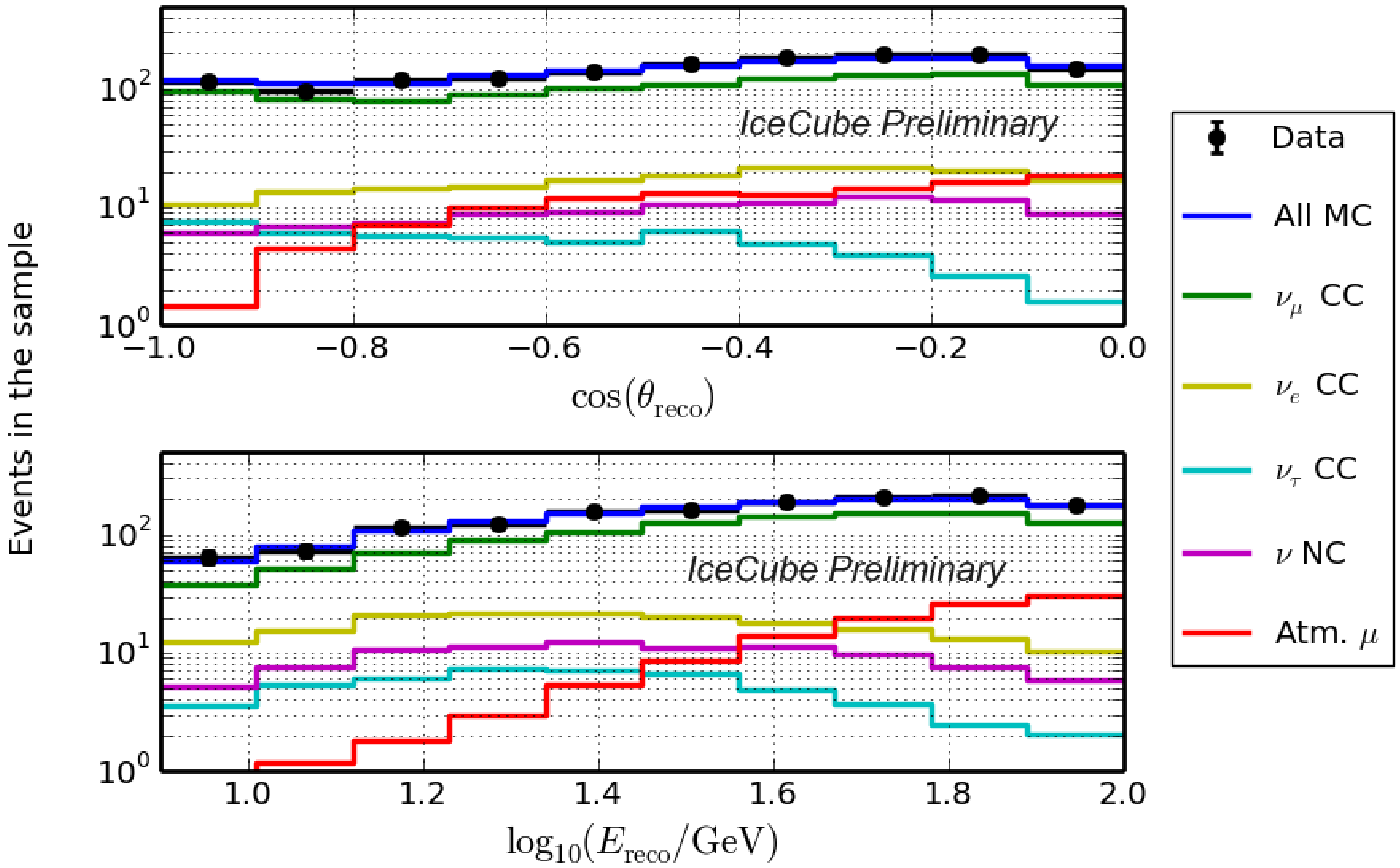
Parameter	Value at best fit point
Atm. μ	8 %
Spectral index	2.65+0.012
ν_e deviation	-0.5 %
DOM eff.	+2.7%
Relative QE	135 + 0.13 %
Scattering in ice columns	50 + 4 cm

Data / MC agreement (bins as used in the likelihood)

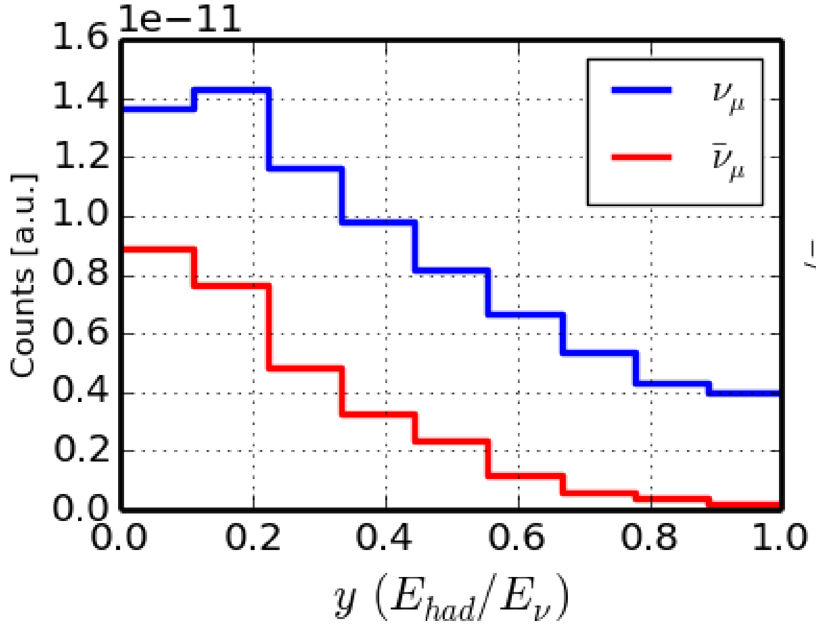


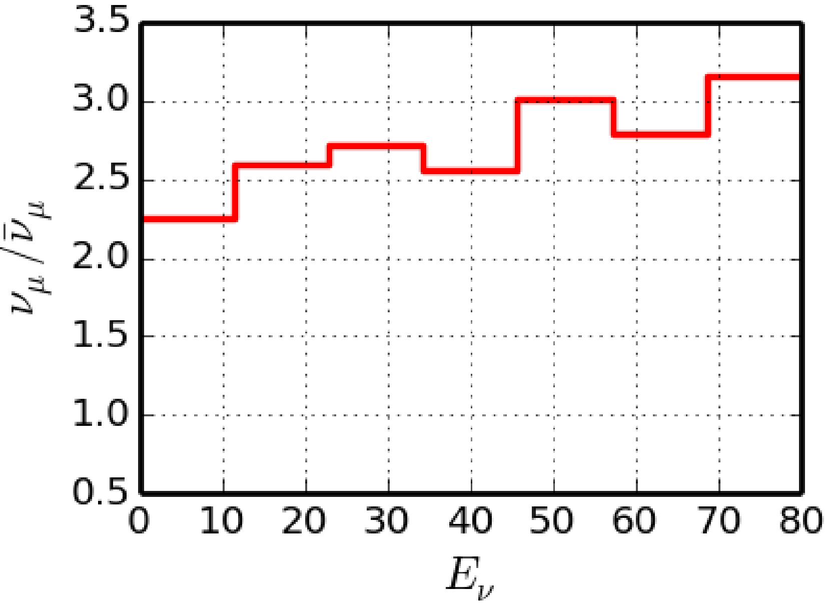
Bands indicate systematic uncertainties

Composition of the data



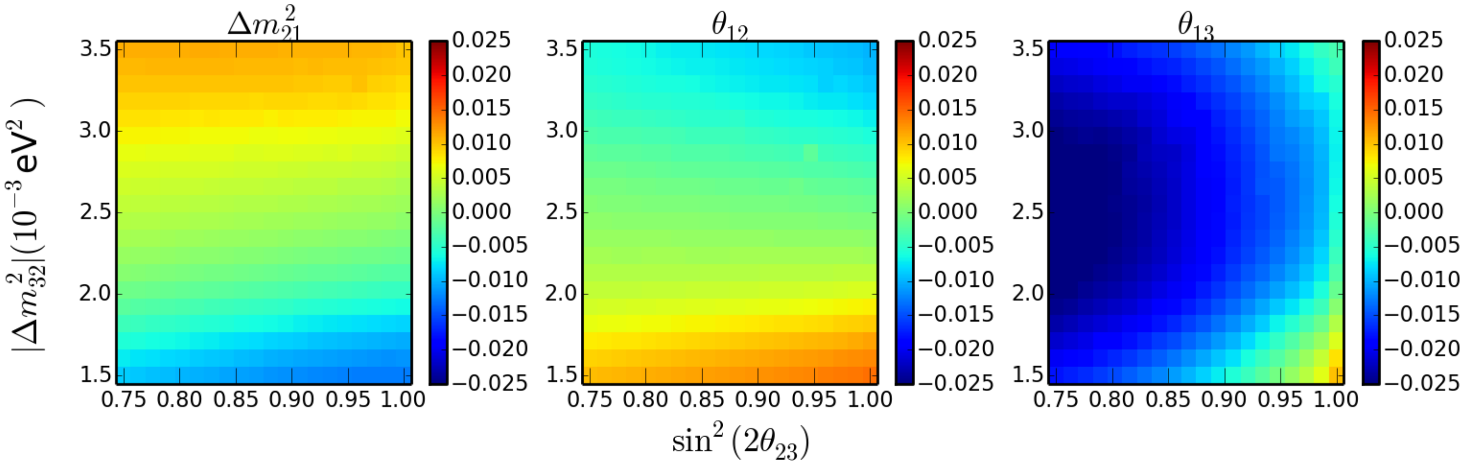
Neutrino / antineutrino contributions





Nuisance parameters: oscillations

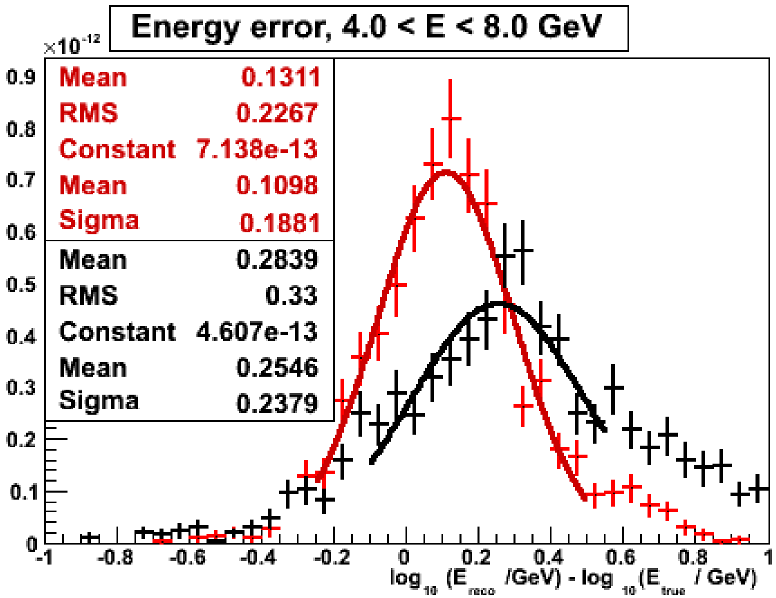
- Movement of the physics parameters

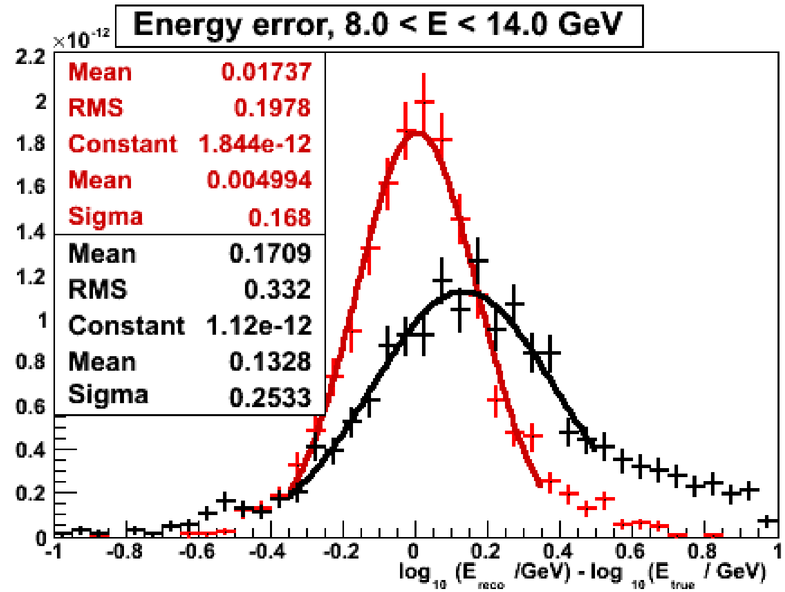


Important note: The color scale goes between [-0.025, 0.025] standard deviations
The change is too small to notice otherwise

Improved E reco for final sample

- Improvements before more data is included
  - Using the final sample of the analysis





Black – current energy estimator
Red – improved energy estimator

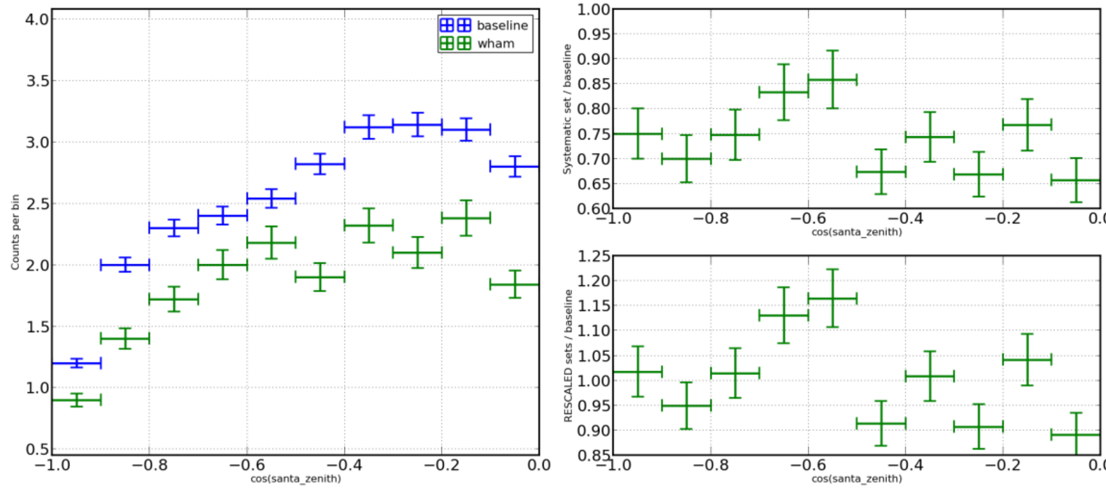
Work by Andrii Terliuk (DESY)

Testing the impact of the ice model

> Comparing the **observed zenith** for two final samples wrt ice model

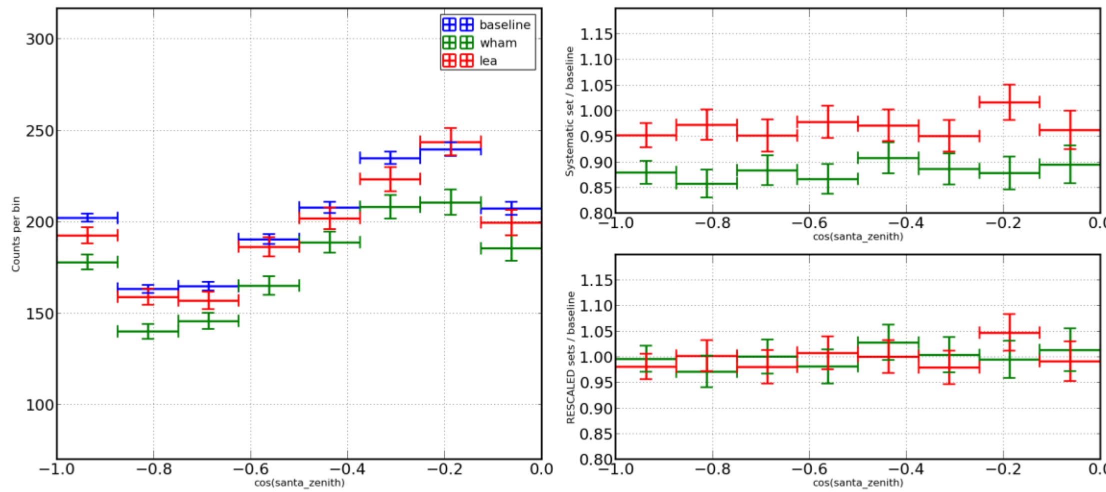
<u>IC79 oscillations (PRL)</u>

- Ice is a large systematic
- Deviations of up to 15%
- Different behavior for different zenith regions



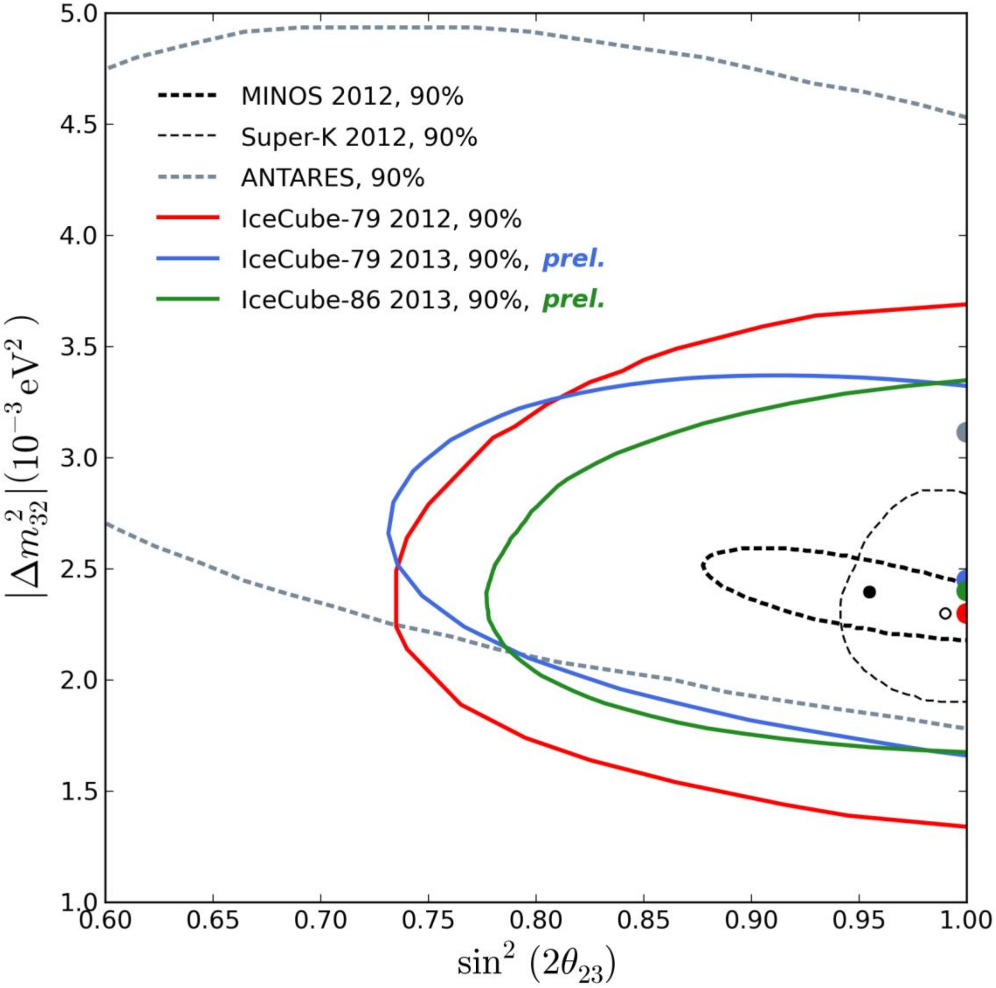
<u>IC86 using **SANTA**</u>

- Flat response: deviation from baseline is < 3% in bin counts
- After freedom of scaling is used, deviations are random, no clear tendency



Improvements

- All IC contours used one year of livetime

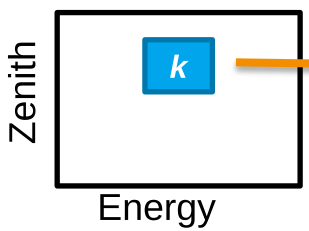


Implementing systematics from MC sets variations

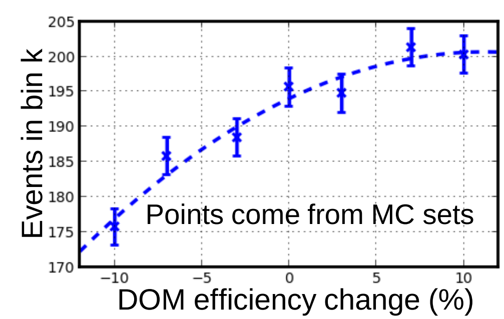
- Variations connected to the photon collection efficiency:
  - *f:* DOM efficiency
  - *g:* Relative quantum efficiency
  - *h:* Scattering in borehole ice (implemented as a change in the angular acceptance)
- The probability for a photon to be recorded by the ***i*-th DOM** is:

$$\mathrm{P}_i = f \cdot g\left(\mathrm{i}_{HQE,normal}\right) \cdot h\left(\theta_\gamma\right)$$

- In the analysis we look at binned 2-D histograms
  - The number of observed events can also be parametrized **for each bin (*k*) independently**

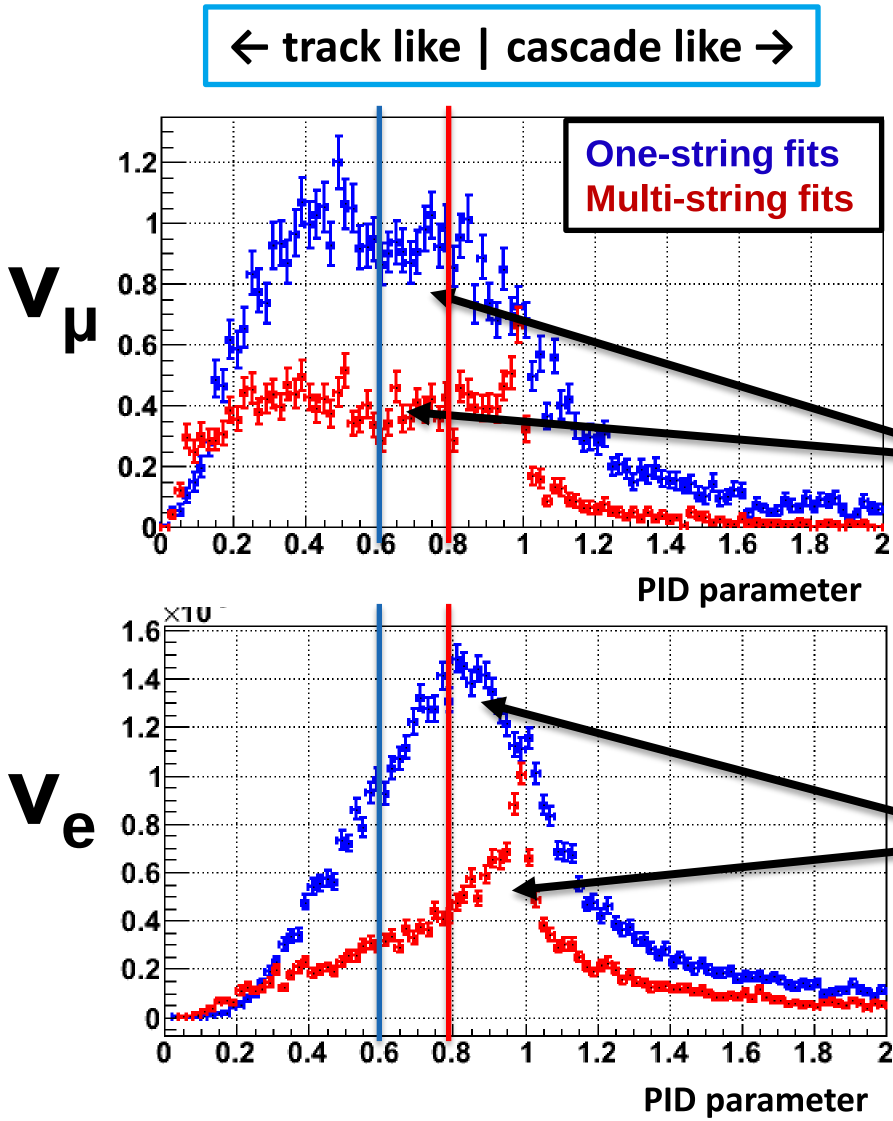


$$N_k = N_{k,baseline} \cdot \hat{f}_k \cdot \hat{g}_k \cdot \hat{h}_k$$



- Allows to access arbitrary variations on parameters that need simulations
  - Computationally expensive, but much faster than re-simulating events

Particle ID



- SANTA fits track and cascade hypotheses
- Cascade/track ratio used pick muon-like events

Flat distribution for ν_μ:
All have a muon + a cascade
Cascade light can dominate
No clear muon = no direction, remove

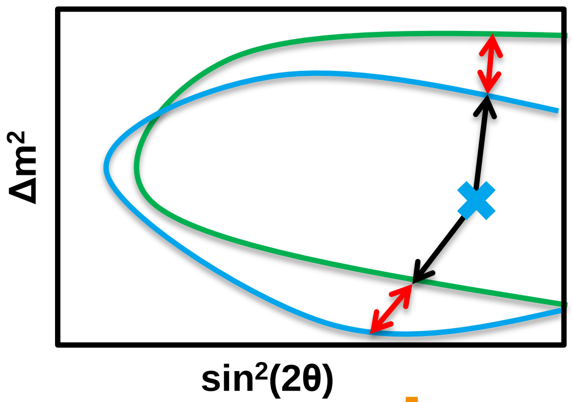
Peaked distribution for ν_e:
Behaves as expected
Different shapes for Multi-string,
Single-string, different cut values

Uncertainties that cannot be parametrized

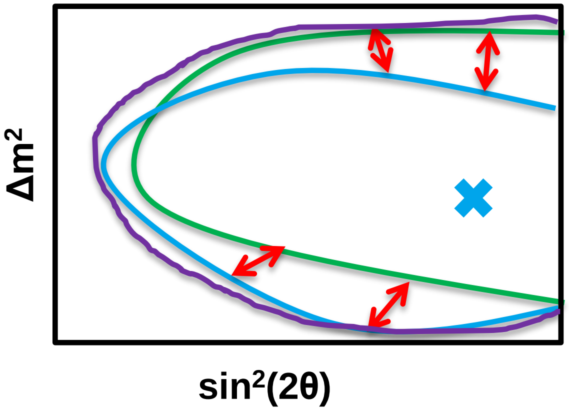
1. Produce contour plots for MC at a given confidence level ***X***
2. Calculate the deviation from different systematics wrt the baseline
   - Take the best fit as reference, and sweep the polar angle
   - Every direction has its own deviation
3. Add the deviations in quadrature (point by point), and sum them to the baseline contour.

-- Baseline, 68% CL
-- Some systematic, 68% CL

2.



3.



The result is that the **confidence regions grow** by adding the uncertainty of where the boundary really is

- Not so easy (to implement, explain, follow)
- Good for regions with different shapes
  - Contours grow only where is necessary
  - Regions where the result is very similar remain unchanged
- Presented at the Oscillations phone call, no objections by the group

What's the downside of the SANTA approach?

- The SANTA selection implies a strong reduction of the sample

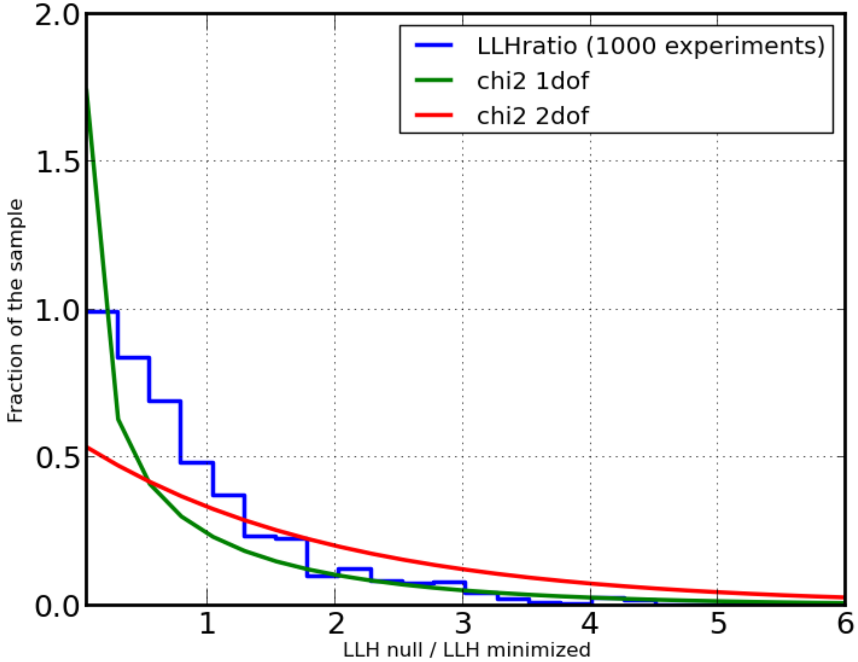
Events / year	Final level	Final level (removing vetos)
Expected NuMu (w/osc)	1,452	3,408
Disappeared NuMu (signal)	702	1,344

- With a perfect veto, the sample could be increased by 2
  - Improvements in veto algorithms can help gather statistics faster
- Making the SANTA selection weaker makes the fit less sensitive
  - Different schemes tested (increase sample by 70%), with no sensitivity improvement
- Analysis still sensitive to other sources of systematics
  - Addressed using nuisance parameters

Contours and proper coverage

> **Q**. Contours are obtained from the LLH ratio (Wilks theorem), is it valid?

A: It is not. For this to be valid, the test statistic would have to follow a χ^2 distribution with 2 degrees of freedom, but it doesn't.



- The LLH ratio distribution falls faster than a χ^2 with 2 d.o.f.
- If we use the LLH ratio, we over-cover.
- LLH ratio kept for now.
- Implementing Feldman-Cousins contours for the final result. Contours will shrink in some regions.

Distribution of the LLH ratio for 1000 mock data sets **with oscillations.**
The null hypothesis corresponds to the injected oscillation values (nuisance parameters free)
The alternative is to fit everything (oscillations + nuisance parameters)

Sample purity and stability

- Total atm. muons available amounts to ~ 6 days of livetime
  - About 7 events remain at final level (large weights)
  - Waiting for more MC would take months (being produced as we speak)
  - How pure is the sample? Is it possible to estimate? How to use what is available?

- Test the purity/stability
  - Mix all CORSIKA available (including different DOM efficiencies)

    Details will not be correct, but the overall shape of the distributions will be
  - Use variables where the 2 contributions are **separated**
  - Remove cut levels and fit

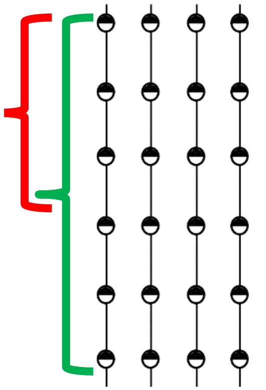
    a) normalizations of different contributions in such variables
    b) oscillations parameters (together with normalizations, in usual zenith & E)
  - Are the contributions stable? Can the oscillation parameters be extracted?

Sample purity and stability

> Variables used

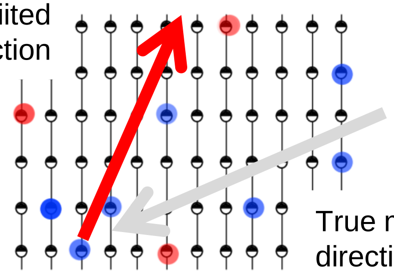
Depth of the first HLC pulse

Dominated by **atm. muons**

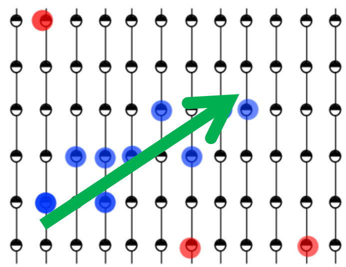


Neutrinos have a flat contribution

Average distance between DOM and track



Misreconstructed **muon**:
large average distance



Muon **neutrino**:
small average distance

> Veto cuts relaxed (all quality selections stay)

High energy reconstructions

- SPE fit with 7 iterations
- LineFit

Veto information

- Containment top/sides kept

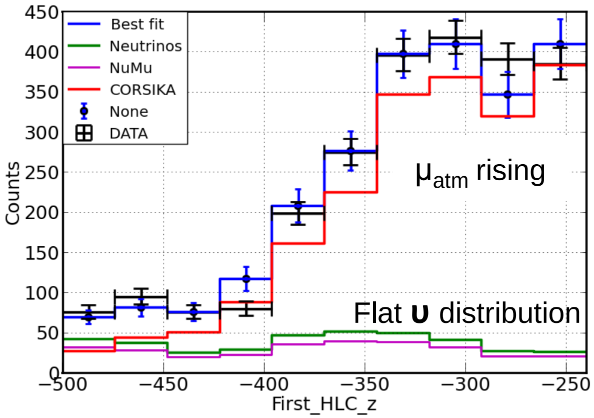
less contamination

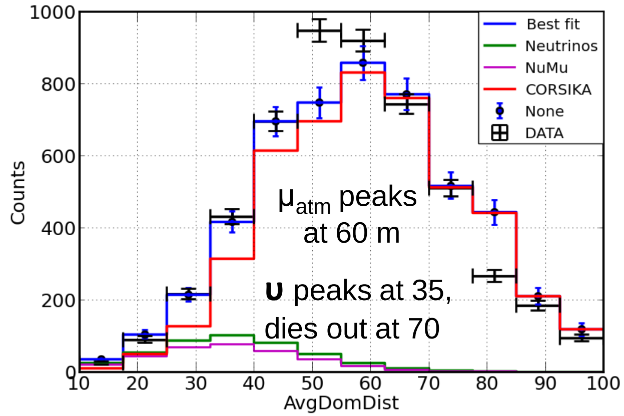
Divided in 4 steps:

1. No HE zenith & veto cuts
2. No HE zenith cuts & partial veto
3. cos(HE zenith) < 0.6 kept
4. **cos(HE zenith) < 0 kept**

Step 4 is the proposed final level

Step 1: Dominated by atmospheric muons





Remember: RED line has larger statistical errors than the data!

Each distribution fitted individually

Normalization values fitted

Dist \ Norm	all υ	υe	spectral index
AvgDOMdist	0,69	0,00	0,008
FirstHLCz	0,66	0,00	0,001

This number has a large error at this level, wait for the next one

> From here on you can do 2 different things (both done, see backup):

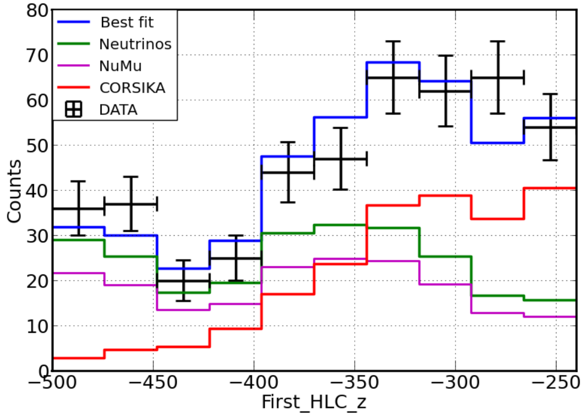
- Tighten the cuts on CORSIKA and signal and fit the distributions

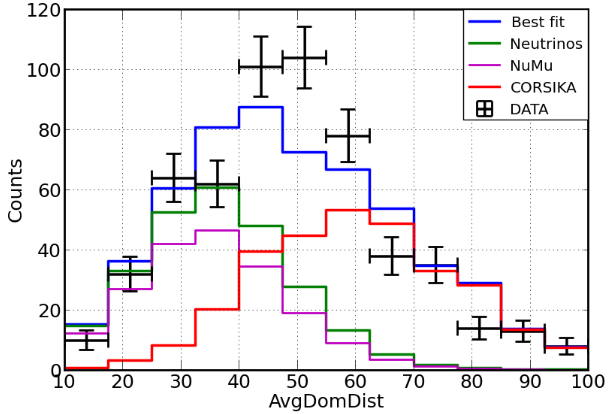
  Run into the same problem of low MC statistics

- Assume the CORSIKA sample will not be affected by the cuts; use these distributions
  - That is a rather **big assumption**! But without more MC, is worth the try
  - Done in order to have **an idea** of where the background lives
  - The neutrino normalization should be stable at the following steps: **in this one** the contribution is **too small to give a reliable estimate**.

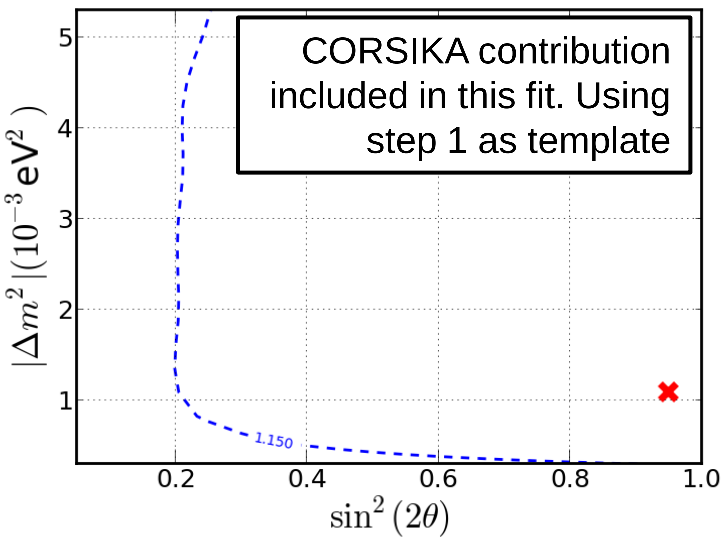
DESY

Step 2: Close to 1:1





Dist \ Norm	all ν	νe	spectral index
AvgDOMdist	0.58	0.01	0.014
FirstHLCz	0.58	-0.01	0.005

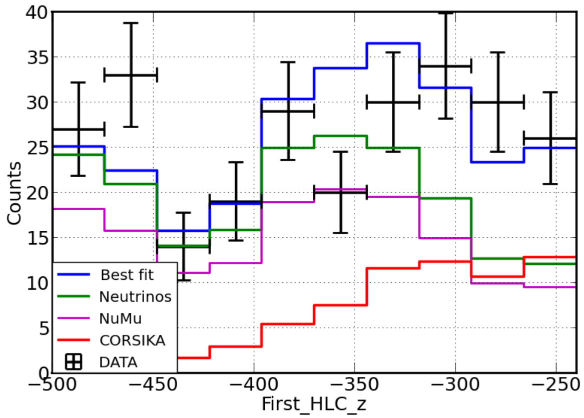


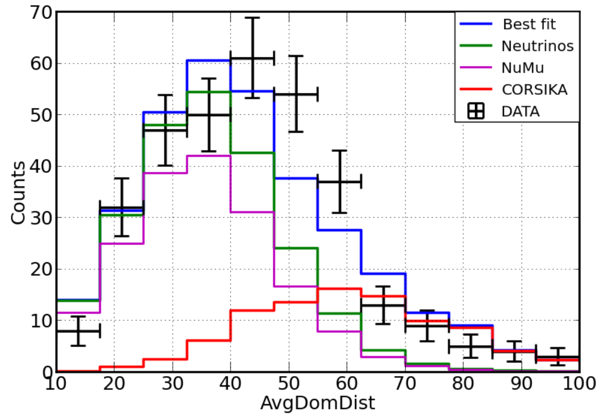
	all ν	νe	spectral index
Nuisance at best fit	0.59	0.01	-0.001

Fitting with <u>equal</u> background contribution
Very large uncertainty

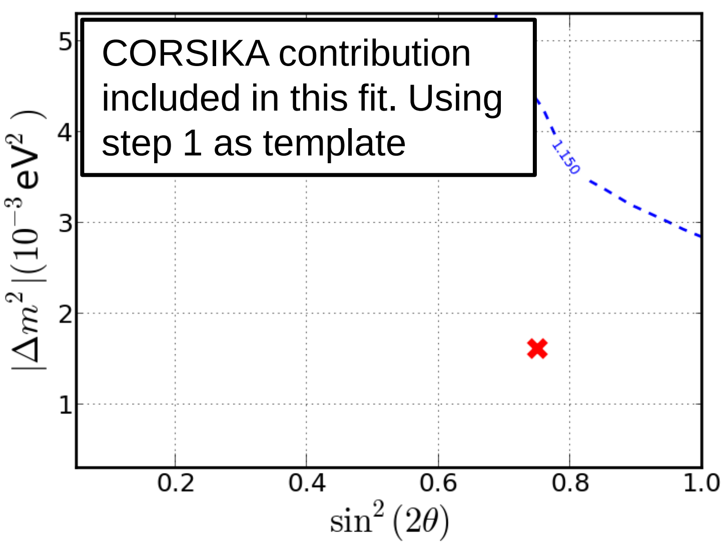
<u>Consistent results on the normalizations</u>

Step 3: Dominated by neutrinos (small contamination)





Dist \ Norm	all υ	υe	spectral index
AvgDOMdist	0.58	0.01	0.014
FirstHLCz	0.52	-0.01	0.008

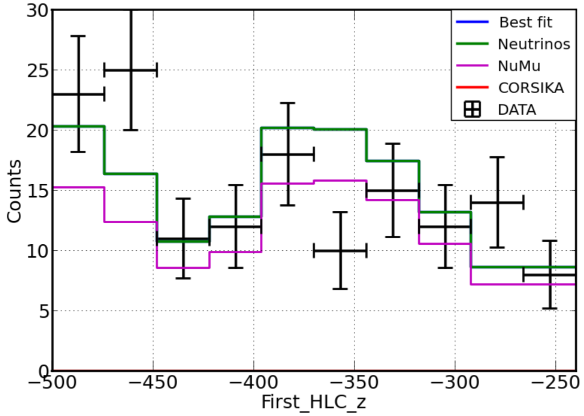


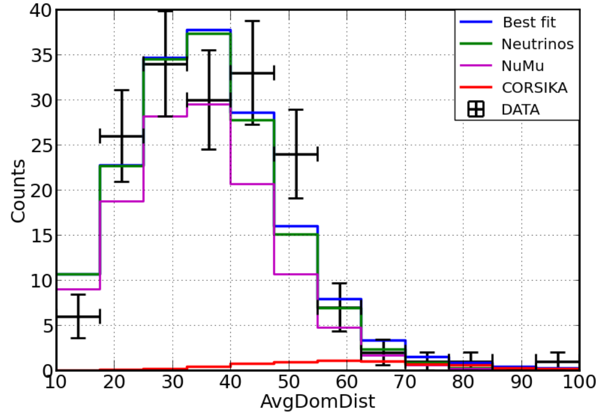
	all υ	υe	spectral index
Nuisance at best fit	0.52	-0.015	0.006

Fitting with <u>equal</u> background contribution
Very large uncertainty

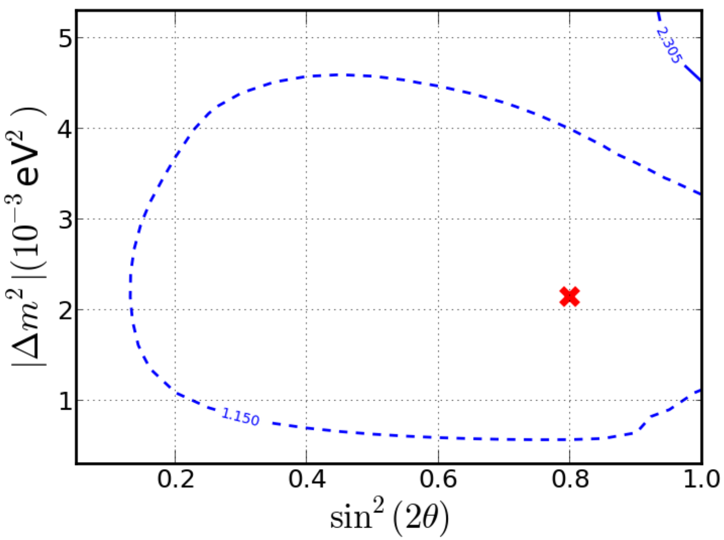
<u>Consistent results on the normalizations</u>

Step 4: Dominated by neutrinos (no contamination)





Dist \ Norm	corsika	all υ	υe	spectral index
AvgDOMdist	0.001	0.53	0.01	0.005
FirstHLCz	0.	0.52	-0.01	0.008



	corsika	all υ	υe	spectral index
Nuisance at best fit	0	0.51	0.002	-0.004

The fit prefers to put (almost) zero contribution of CORSIKA in both of the control variables and the oscillations fit.

The sample appears very clean to all variables