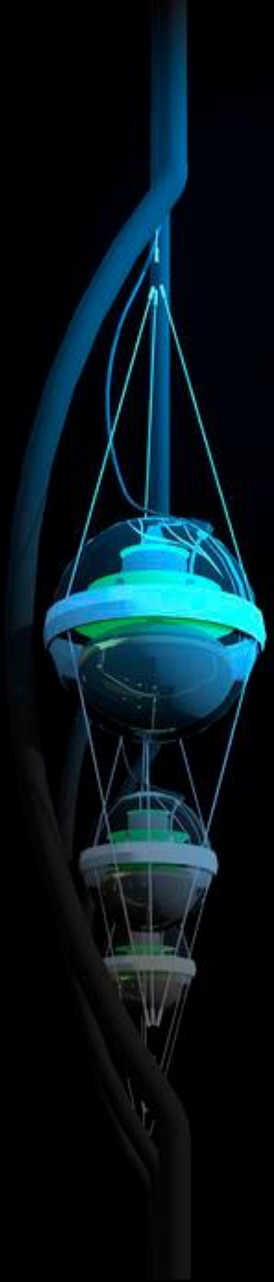


DeepCore oscillations results

First year of the full detector configuration

Juan Pablo Yáñez

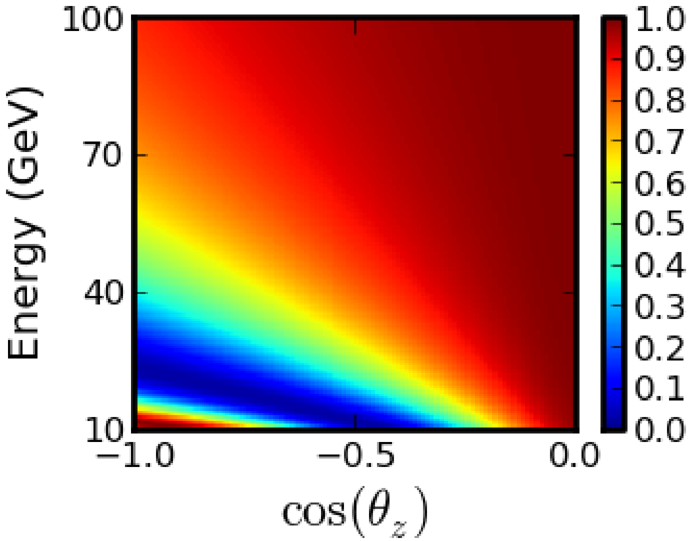
DESY

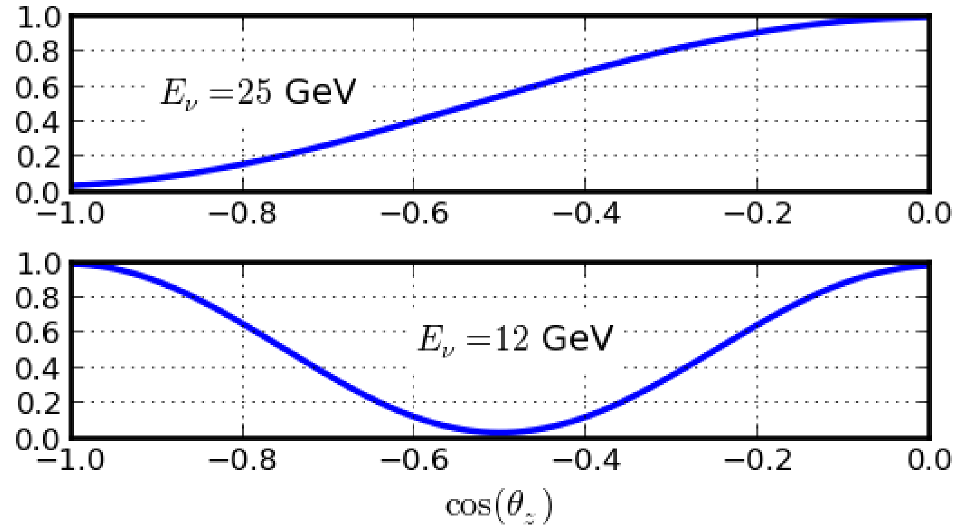
MANTS Meeting, October 2013, Garching

The searched effect

> Atm. Neutrinos crossing the Earth

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





Minimum at E ~ 25 GeV

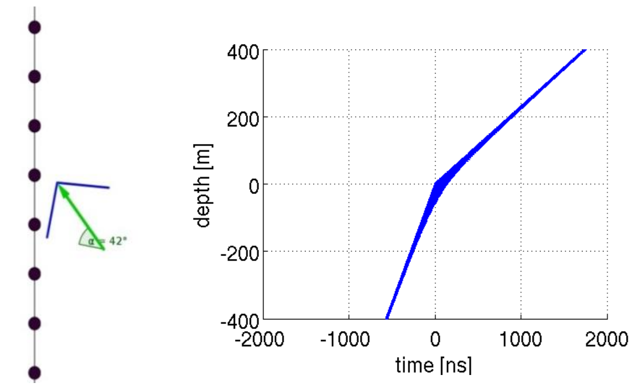
Minimum at
E ~ 10 GeV

Track the movement of the survival minimum to gain precision on measurement of **oscillation parameters**

Need to select and reconstruct **very low energy** events
Detector-related **systematics** can have a large impact
How to do it?

The 3-fold strategy

- SANTA*: find direct hits, build observables
  - Number of direct hits → **quality criterion**
  - Hyperbola projection orientation → **zenith angle**
  - **Limit impact of ice properties**



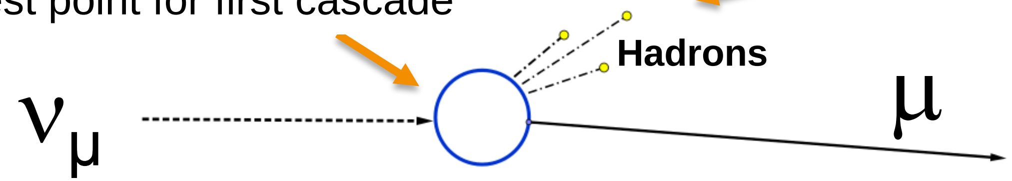
Idea developed in collaboration with J. Brunner (Astropart.Phys.34:652-662,2011), based on the BB-fit

***S**ingle-string **ANT**ares inspired **A**lgorithm

- A full energy estimator

Scale brightness → fit energy

Best point for first cascade

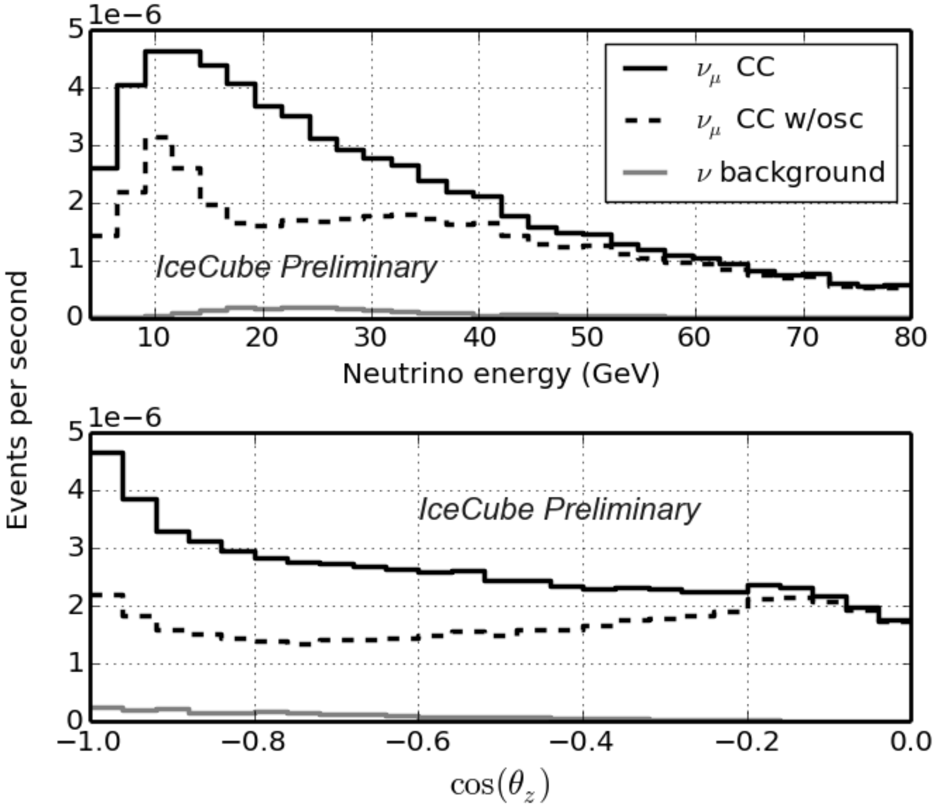


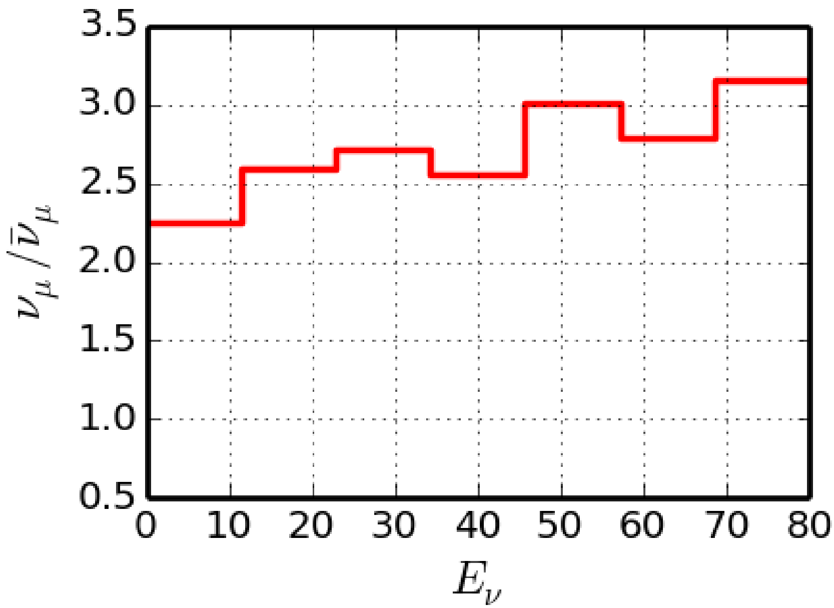
Find last point of Cherenkov emitter

- LLH fit: implement **(all – 1)** uncertainties as nuisance parameters
  - Weight related and **detector related** (total/relative light yield, acceptance)
  - Ice optical properties dependence included, but in a different fashion

Resulting neutrino sample

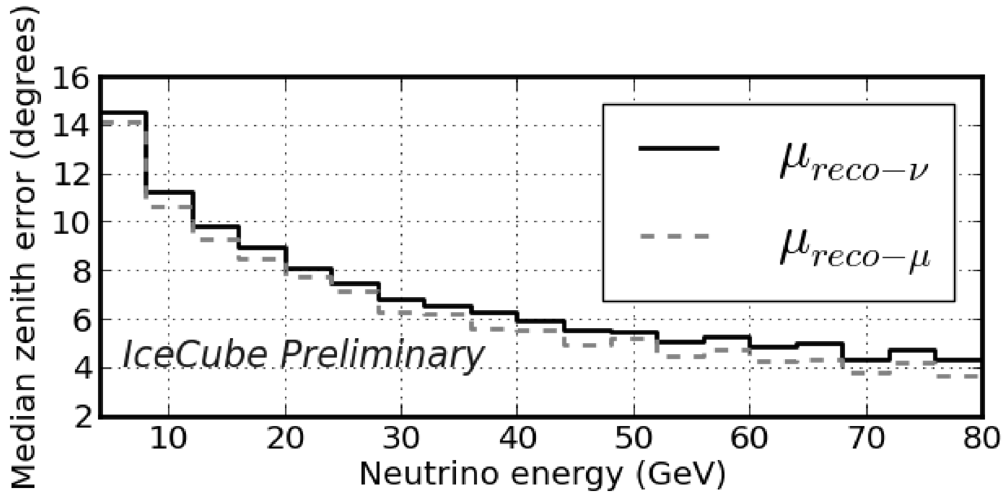
- ~ 2,000 events/year expected, disappearance of 500
  - Energy distribution peak ~12 GeV, a third of ν_μ sample with E < 20 GeV
  - Zenith acceptance enhanced for vertical events
  - Neutrino:antineutrino ratio > 2 for all E range



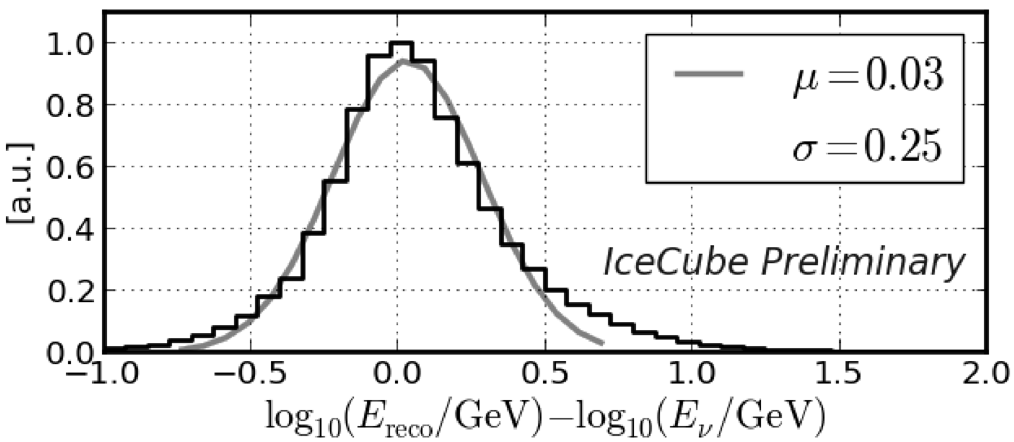


Estimators in final sample

- Energy and zenith resolution sufficient
  - Zenith angle resolution: 11 degrees at E=10 GeV, improving with E
  - Energy resolution of 0.25 in $\log_{10}(E/\text{GeV})$



Zenith angle from SANTA



Energy from step-wise approach

Best fit parameters from data

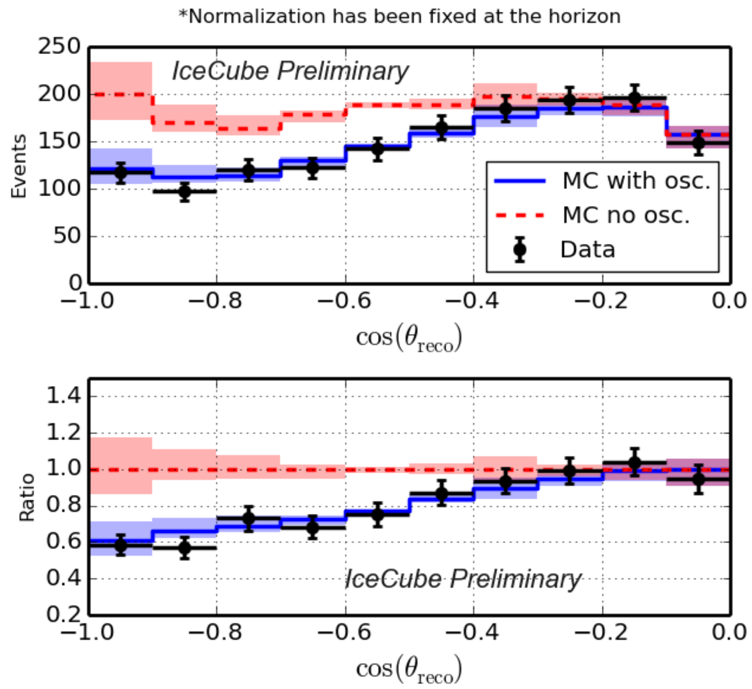
Parameter	Best fit point
$\sin^2(2\theta)$	1.0 (>0.94 at 68% CL)
Δm^2 (10^3 eV^2)	2.50 +/- 0.50

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

Analysis performed in 2-, **3-flavor vacuum scheme**: essentially the same results

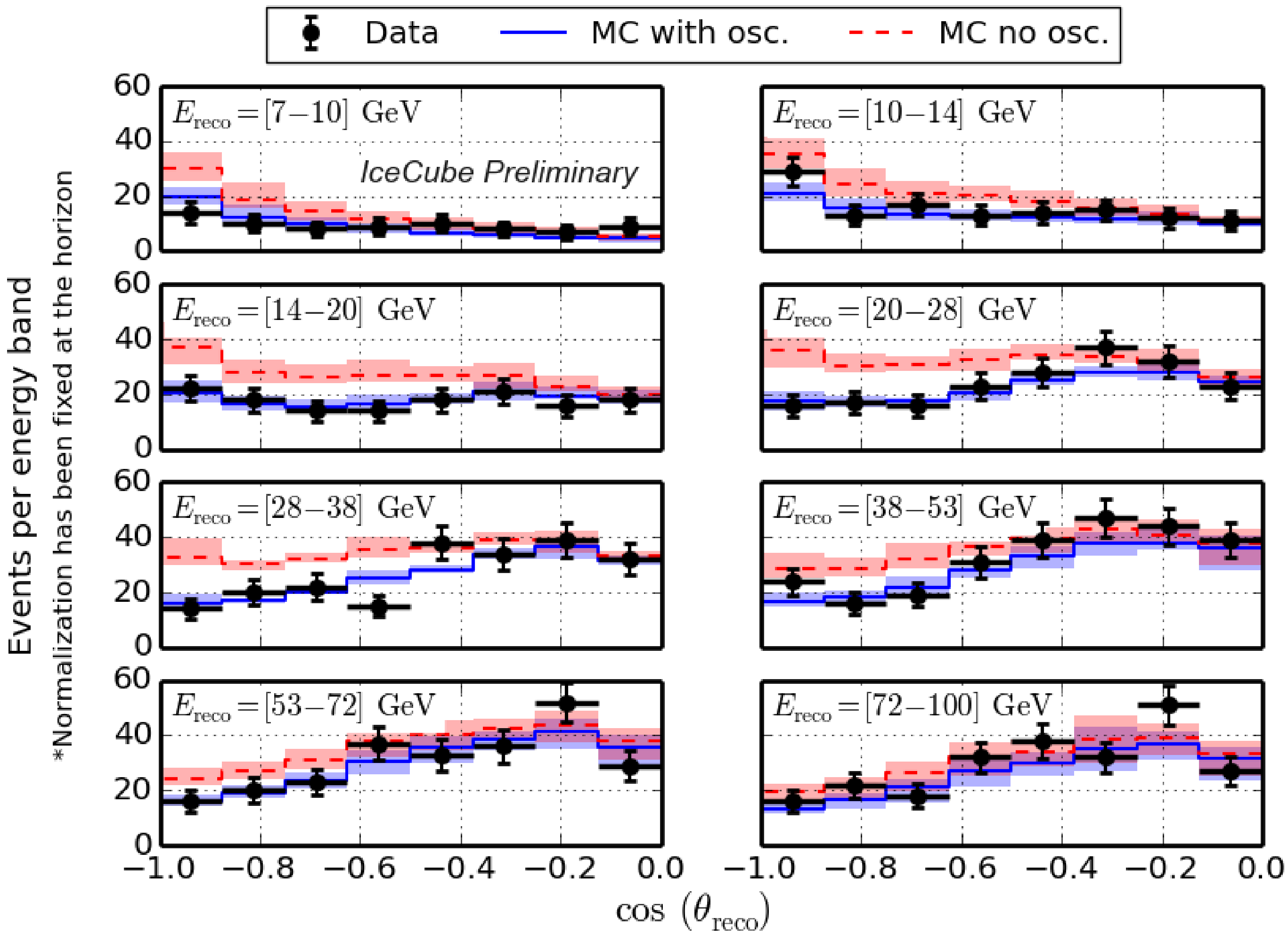
Parameter	Value at best fit point
Atm. μ	8 %
Spectral index	2.65+0.012
ν_e deviation	-0.5 %
DOM eff.	+2.7%
Relative QE	135 + 0.13 %
Scattering in ice columns	50 + 4 cm
Other oscillation parameters	Negligible

Data / MC agreement



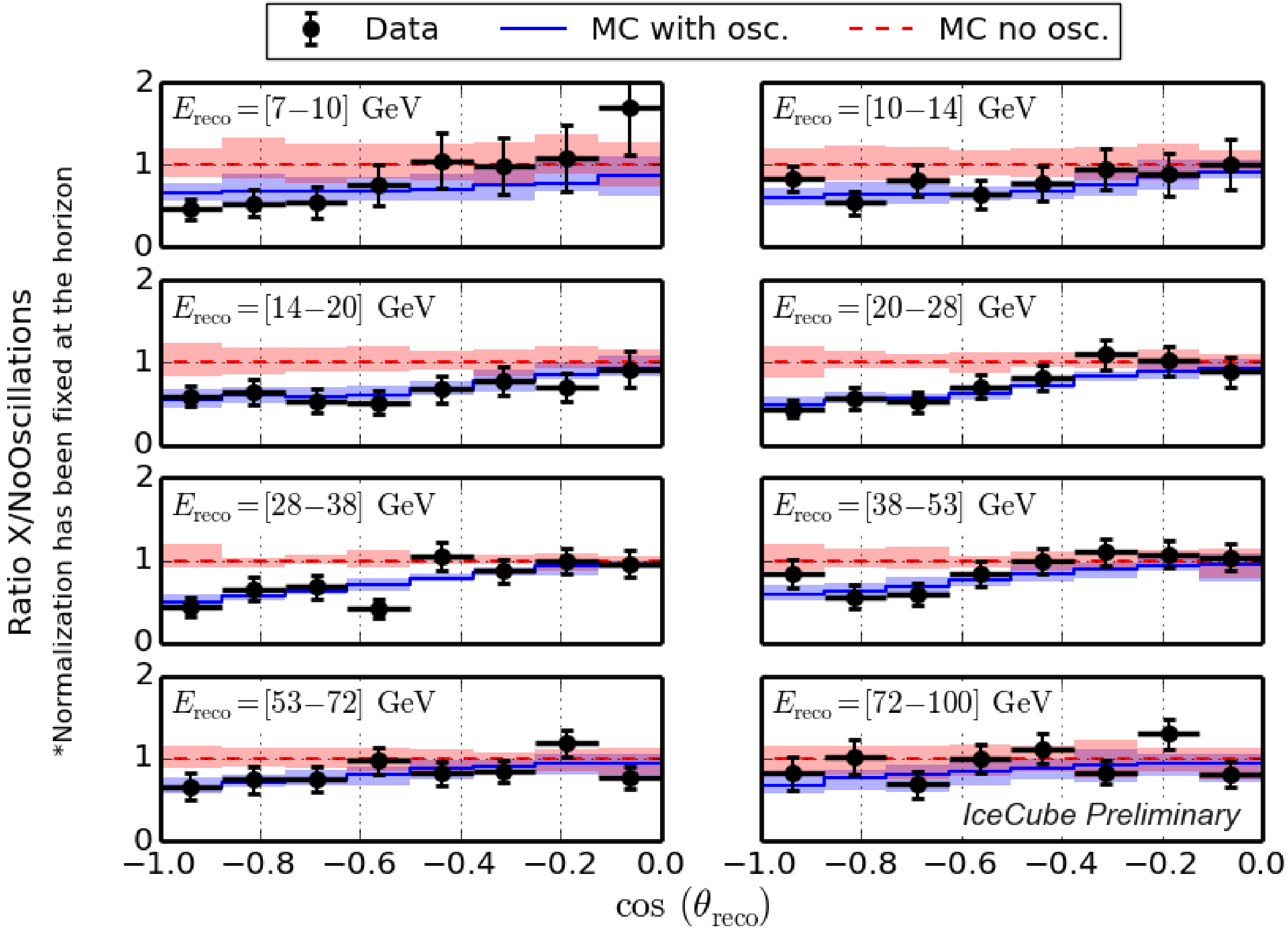
For all figures: bands indicate systematic uncertainties, MC expectation calculated using baseline values for nuisance parameters, **normalization fixed at the horizon (free in LLH)**

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



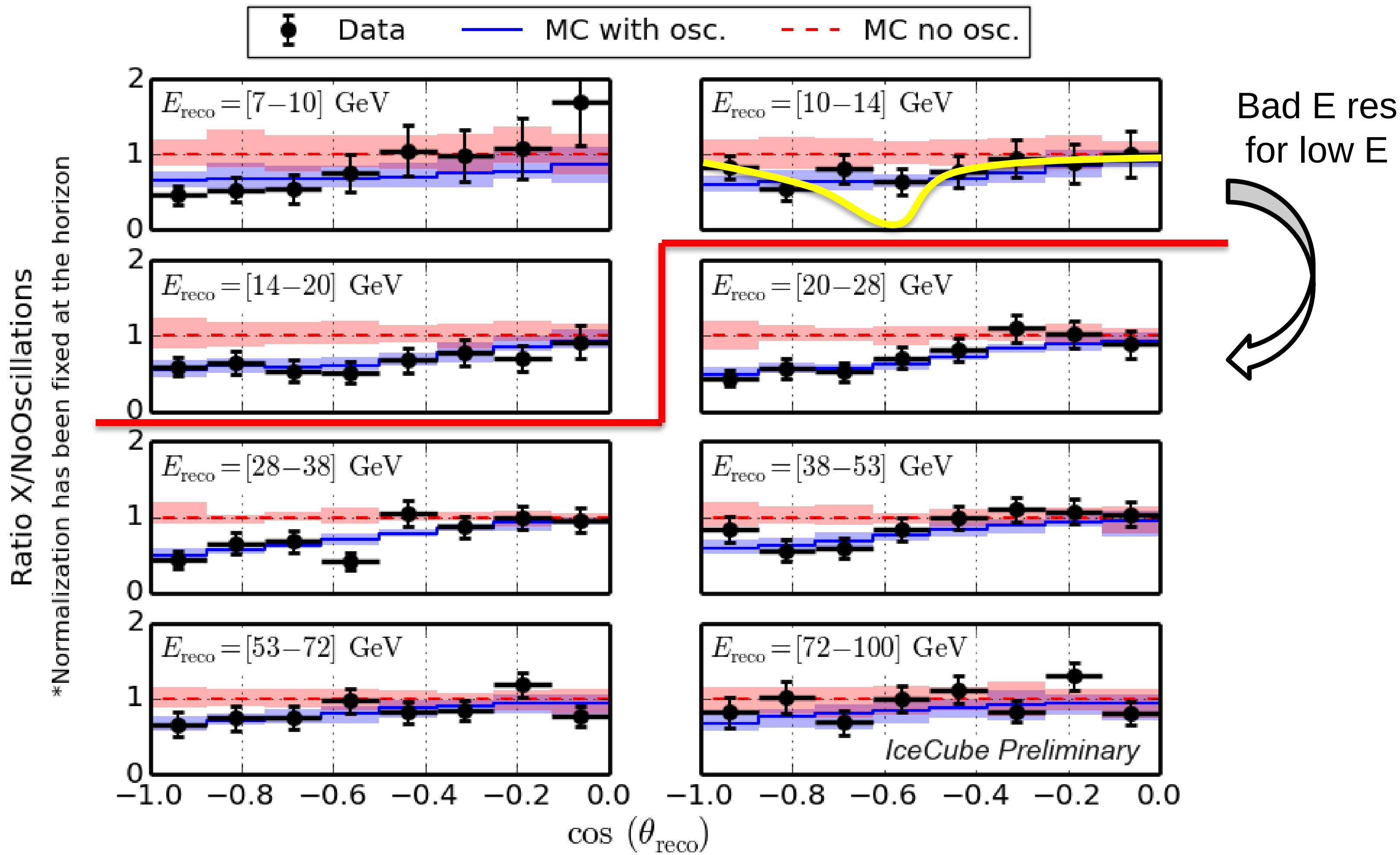
Bands indicate systematic uncertainties

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



Bands indicate systematic uncertainties

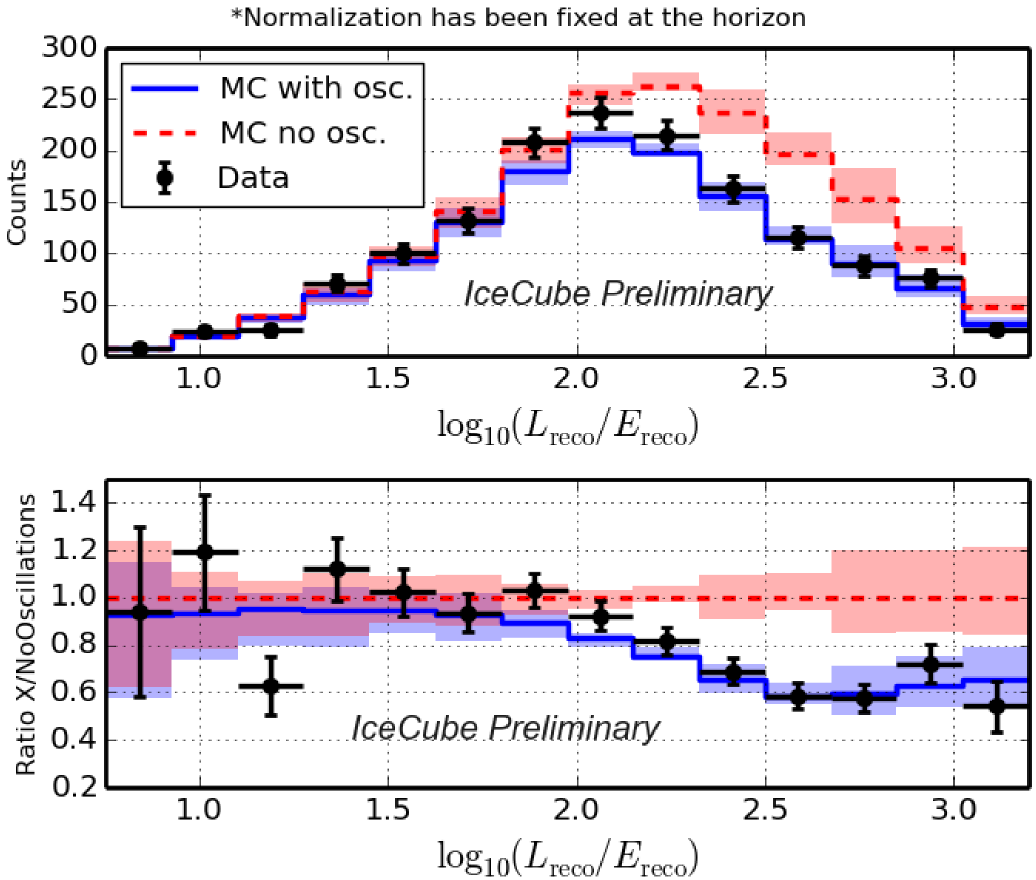
Ratio to no oscillations (bins as used in the likelihood)



Bands indicate systematic uncertainties

Effect as function of L/E

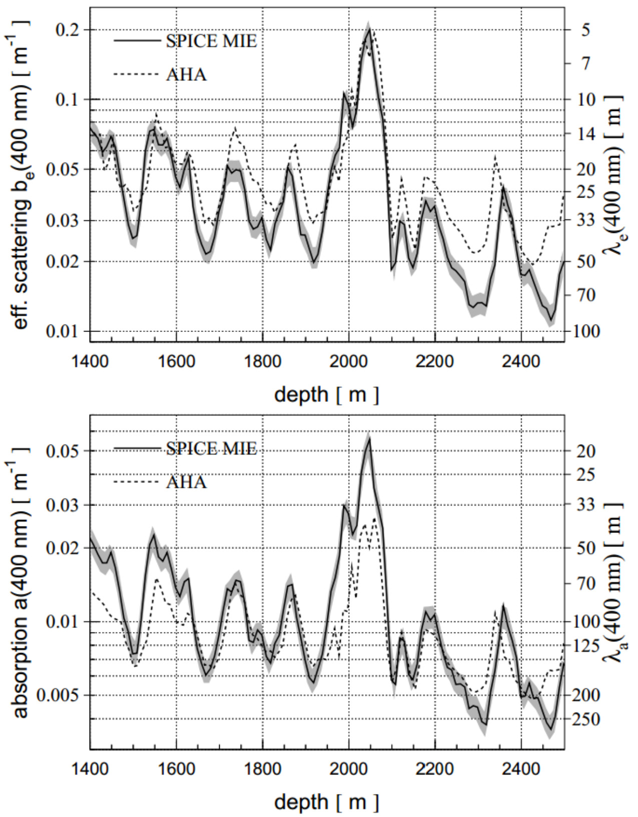
- Analysis is **not** performed in this variable, still instructive



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



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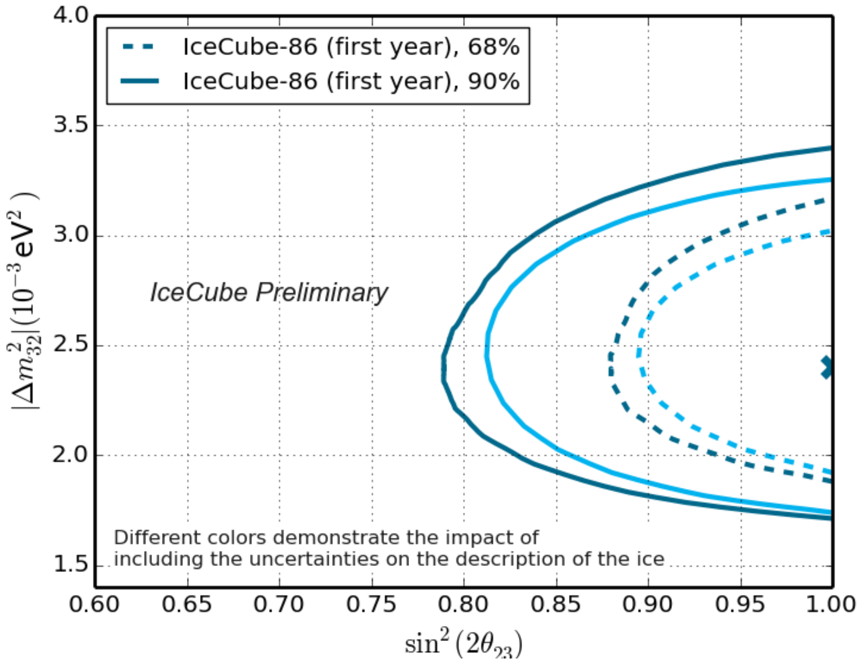
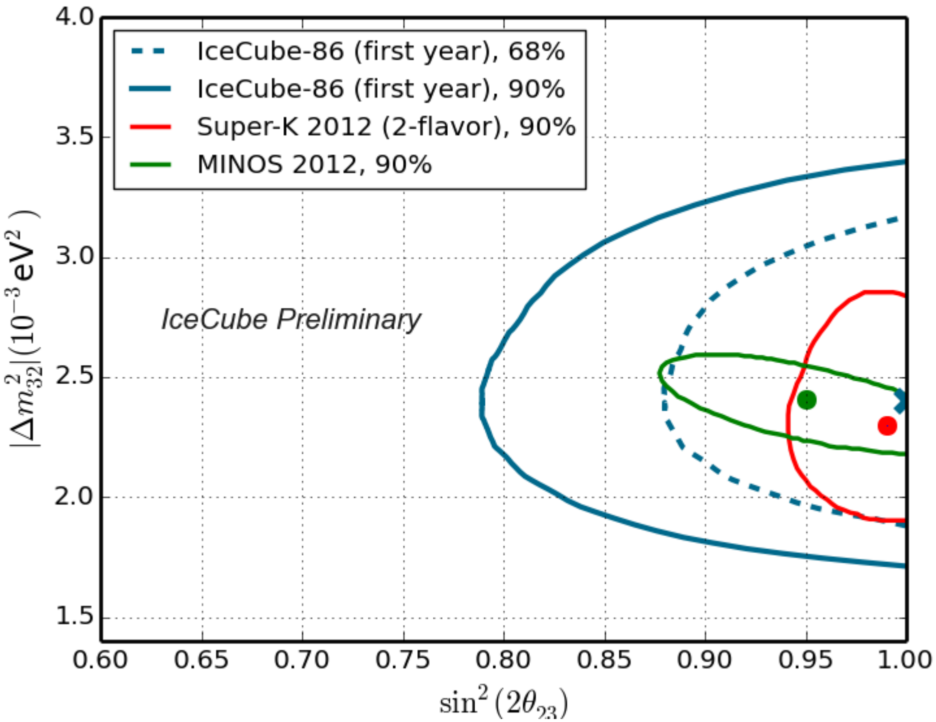


Comparison, conclusion, outlook

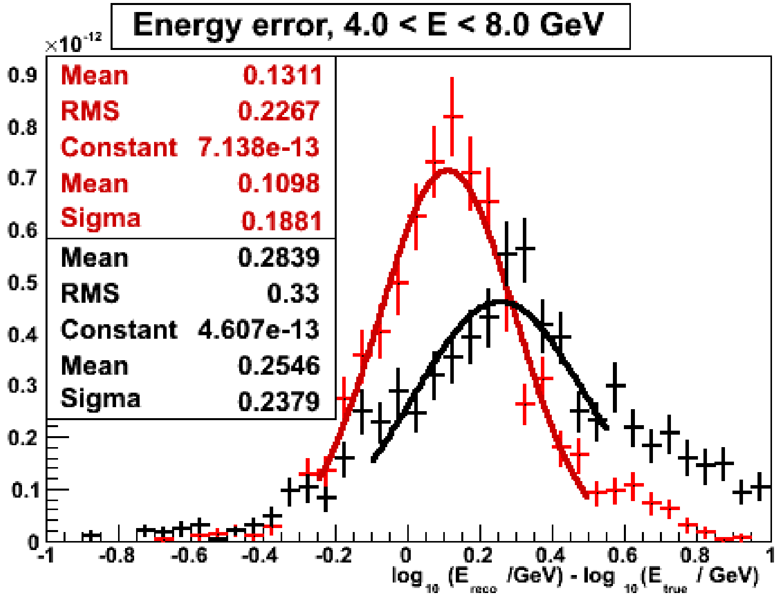
- Measured neutrino oscillations with IceCube DeepCore, full detector
  - Results compatible with best known values
  - Using new tools developed for the events of interest
  - Including energy and zenith estimator
  - Full treatment of systematic uncertainties
  - Very good agreement with MC

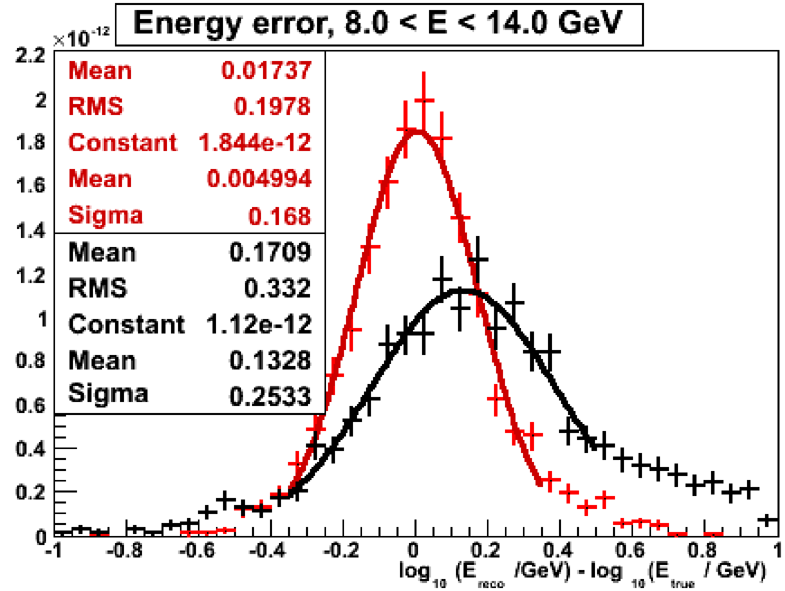


- Improvements in near future
  - **More data (2+ years available)**
  - Constrain the neutrino flux
  - Re-analysis of the quality demanded
  - Better MC at lower energies
  - **Integral energy estimator**

The energy estimator

- New strategy improves energy resolution
  - Good resolution down to neutrino energies of 6 GeV (final sample)
  - Changes in the most interesting region for gaining precision





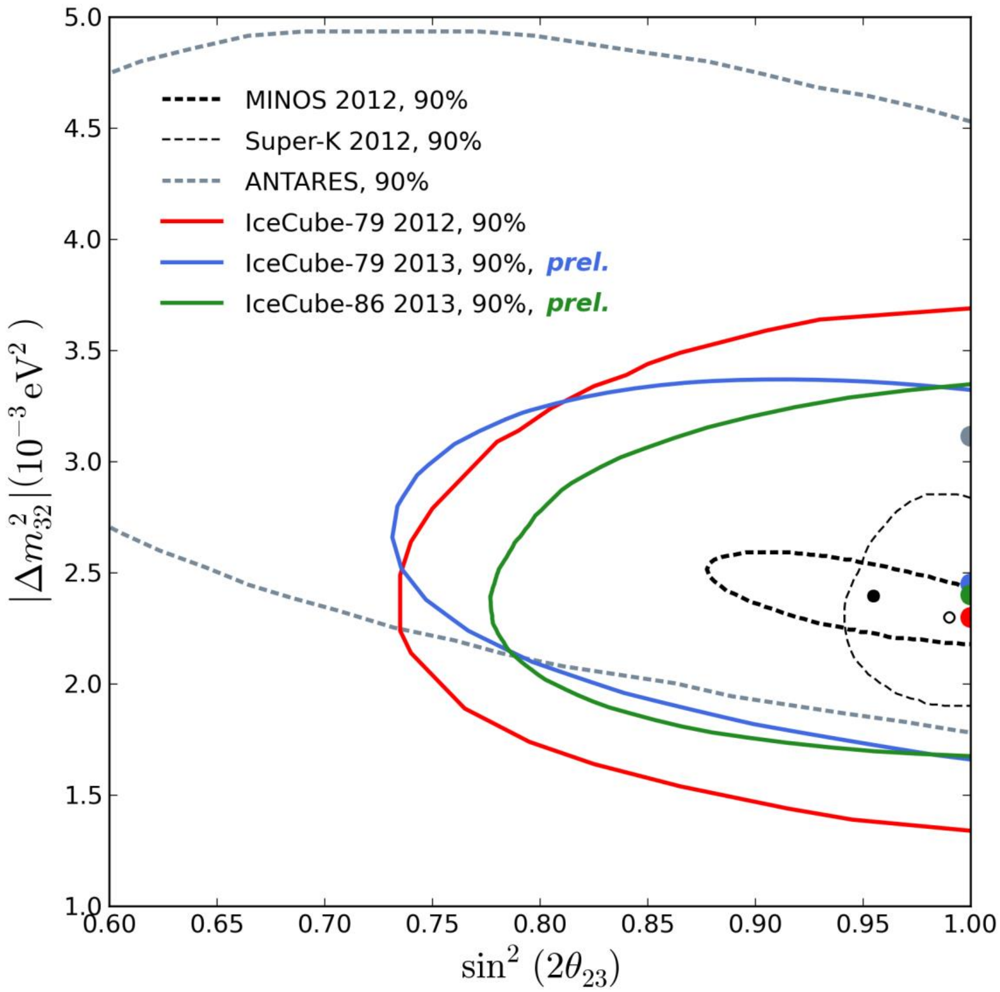
Black – current energy estimator // **Red** – improved energy estimator

Thank you for your attention

Backup slides

Improvements

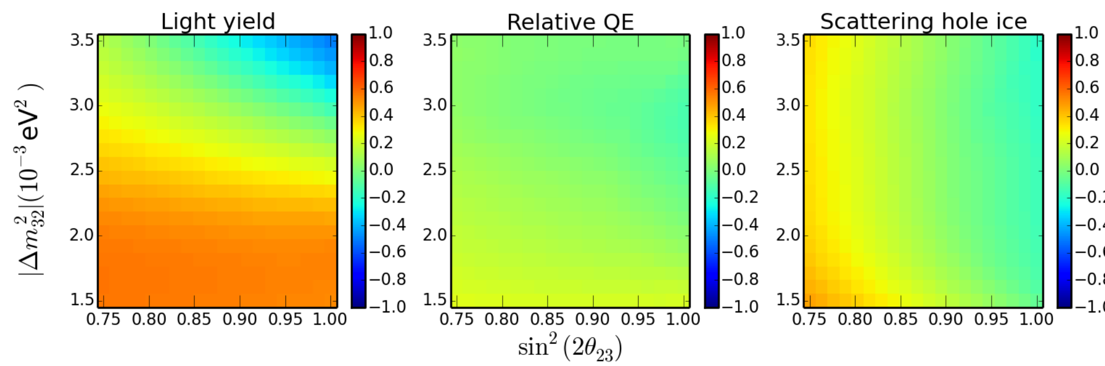
- All IC contours used one year of livetime

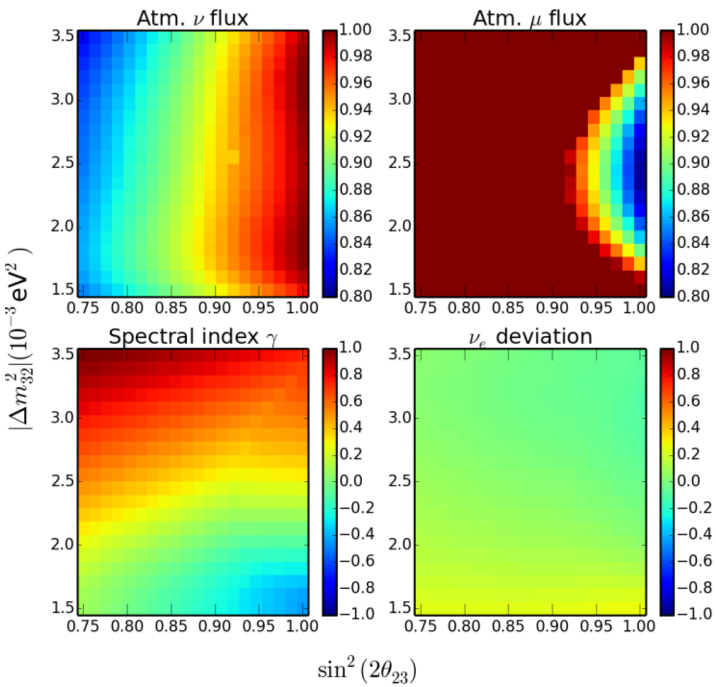


Studying the uncertainties

> Analyzing how the nuisance parameters move

- Color scale normalized to 1σ uncertainty
- One color = not relevant
- Pattern → parameter affected





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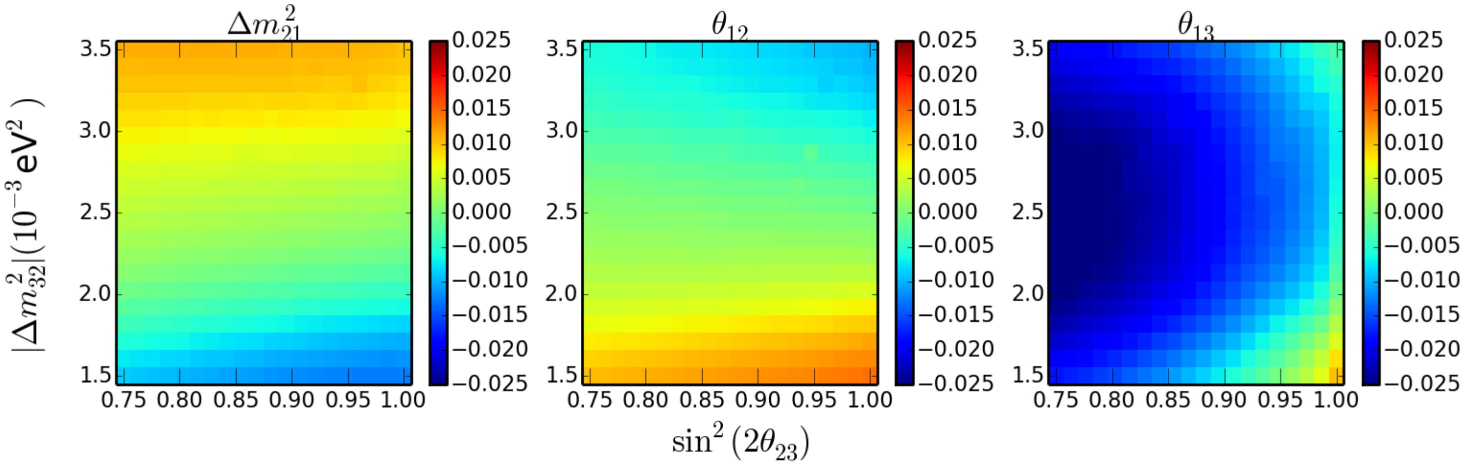
ν_e deviation	-0.5 %
DOM eff.	+2.7%
Relative QE	135 + 0.13 %
Scattering in ice columns	50 + 4 cm

Oscillation parameters

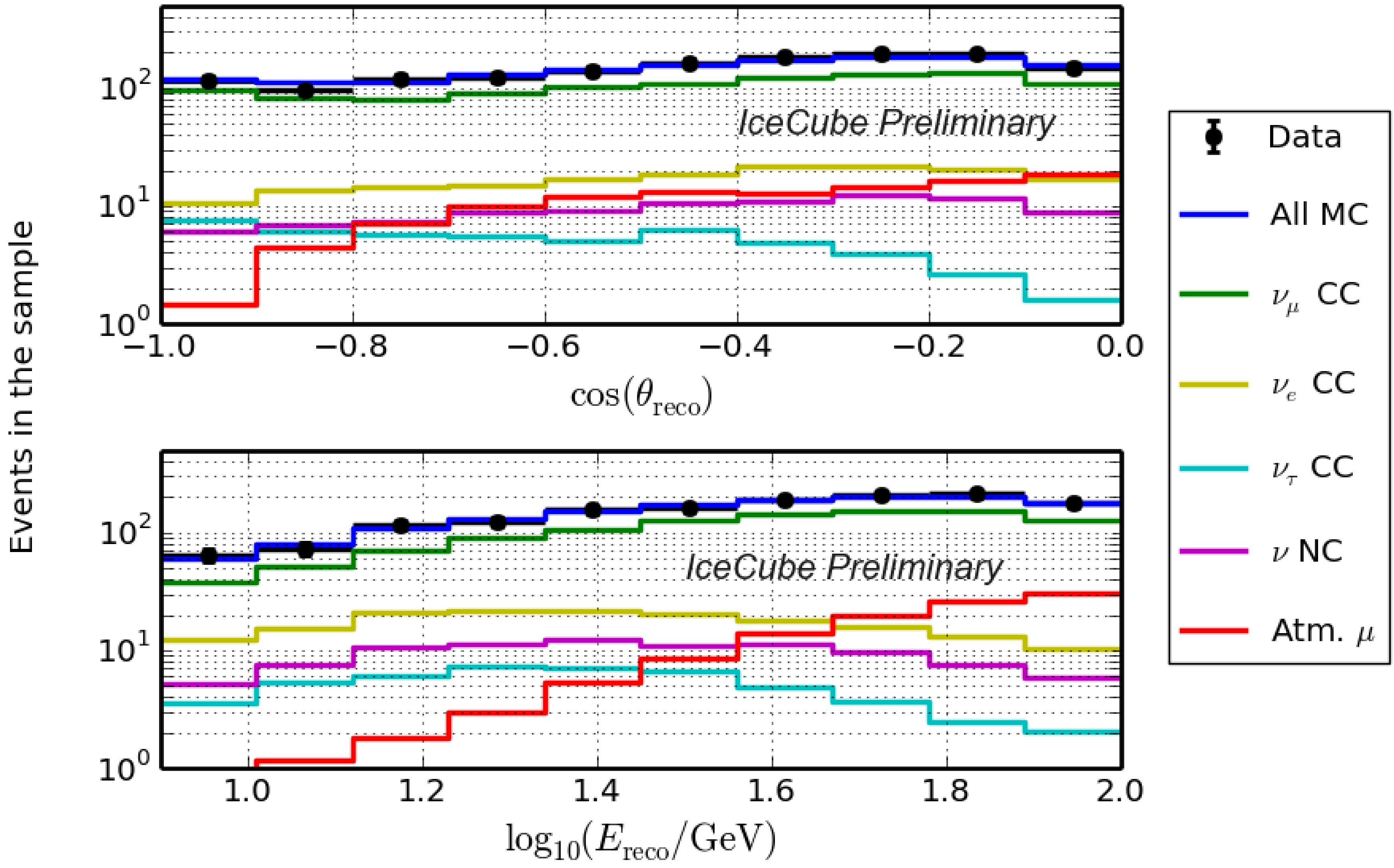
> Movement of the physics parameters in 3-flavor fit

- The oscillation parameters return to the injected value
- No sensitivity to them, can be left fixed (for computing speed)

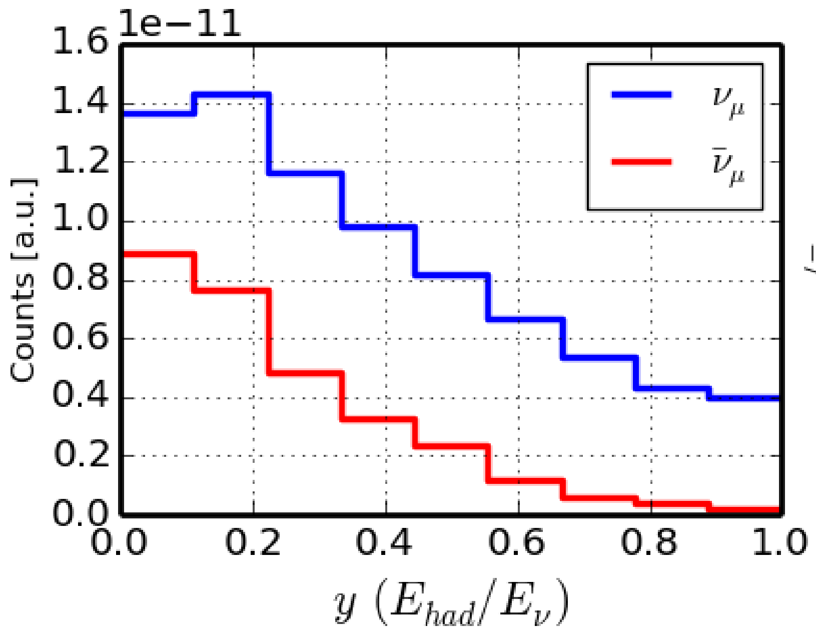


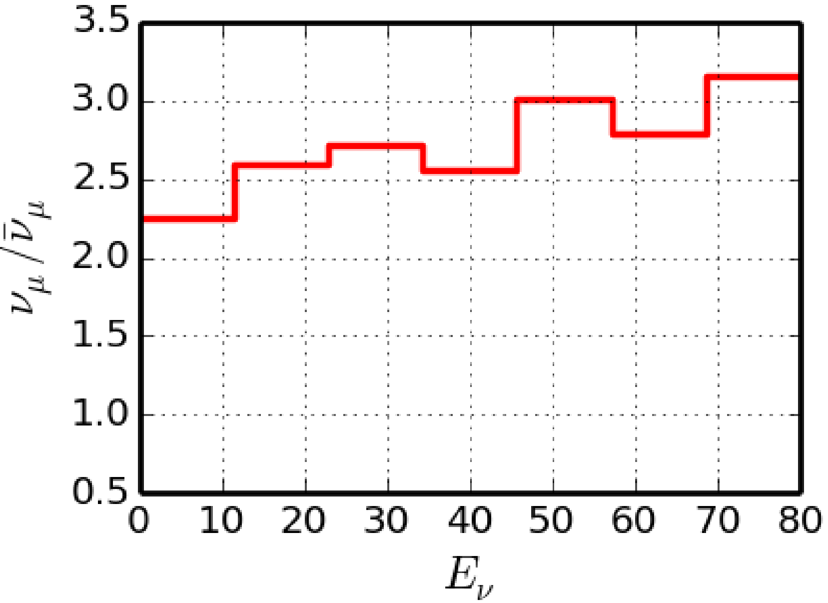
Note that the color scale goes between **[-0.025, 0.025]** standard deviations
The change is too small to notice otherwise

Composition of the data



Neutrino / antineutrino contributions



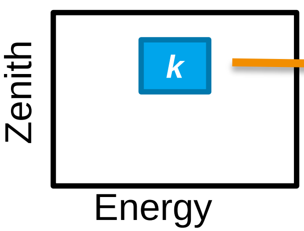


Implementing systematics from MC sets variations

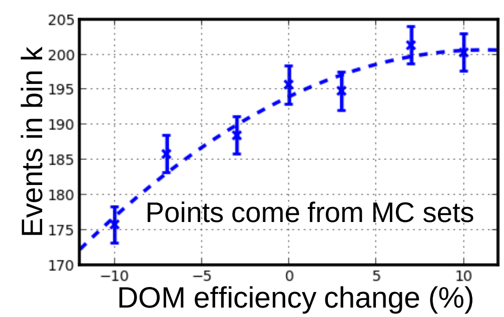
- Variations connected to the photon collection efficiency:
  - *f:* DOM efficiency
  - *g:* Relative quantum efficiency
  - *h:* Scattering in borehole ice (implemented as a change in the angular acceptance)
- The probability for a photon to be recorded by the ***i*-th DOM** is:

$$P_i = f \cdot g\left(i_{HQE,normal}\right) \cdot h\left(\theta_\gamma\right)$$

- 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

Uncertainties that cannot be parametrized

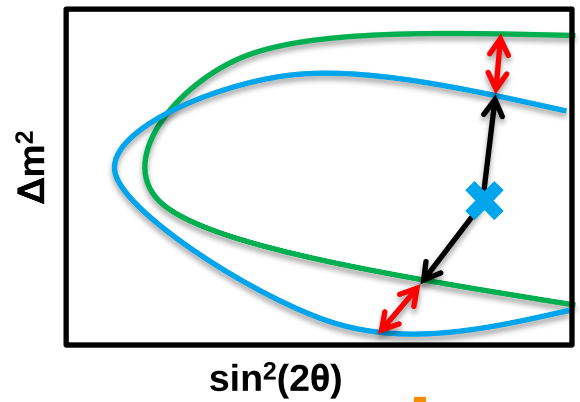
1. Produce contour plots for MC at a given confidence level ***X***
2. Calculate the deviation from different systematics wrt the baseline
   - Take the best fit as reference, and sweep the polar angle
   - Every direction has its own deviation
3. Add the deviations in quadrature (point by point), and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

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

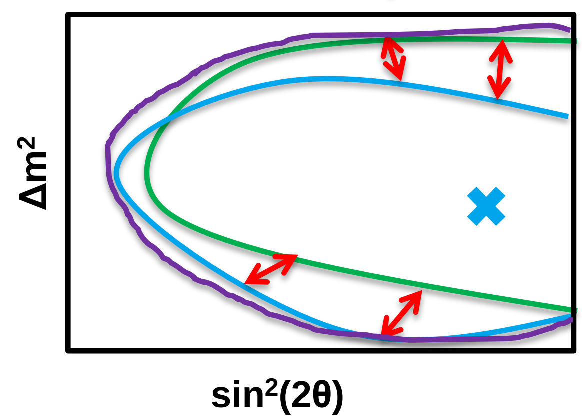
-- Baseline, 68% CL

-- Some systematic, 68% CL

2.



3.



> Not so easy (to implement, explain, follow)

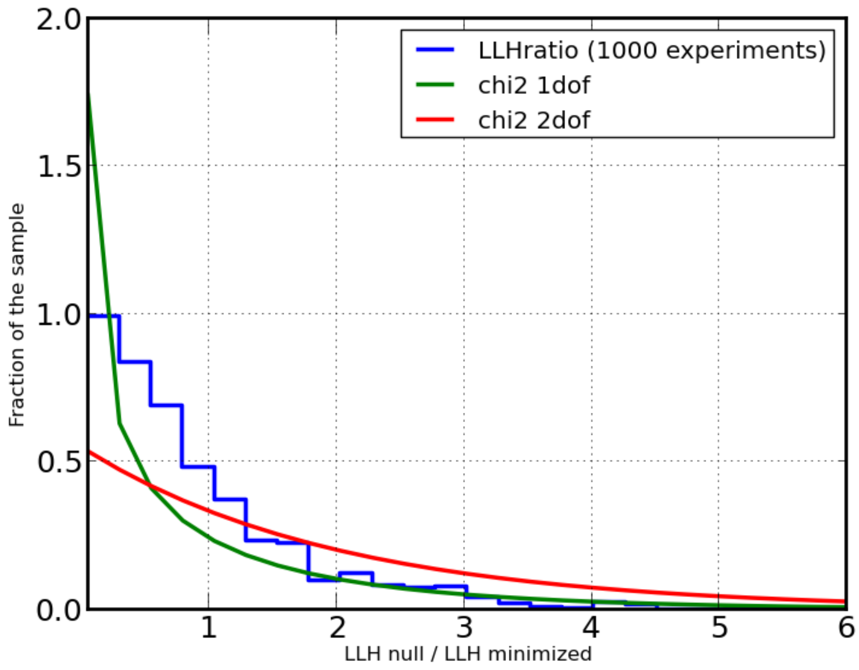
> Good for regions with different shapes
  - Contours grow only where is necessary
  - Regions where the result is very similar remain unchanged

> Presented at the Oscillations phone call, no objections by the group

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)