# Atmospheric neutrino oscillations with IceCube/DeepCore $\nu_\mu$ disappearance

Andreas Groß
for the IceCube collaboration

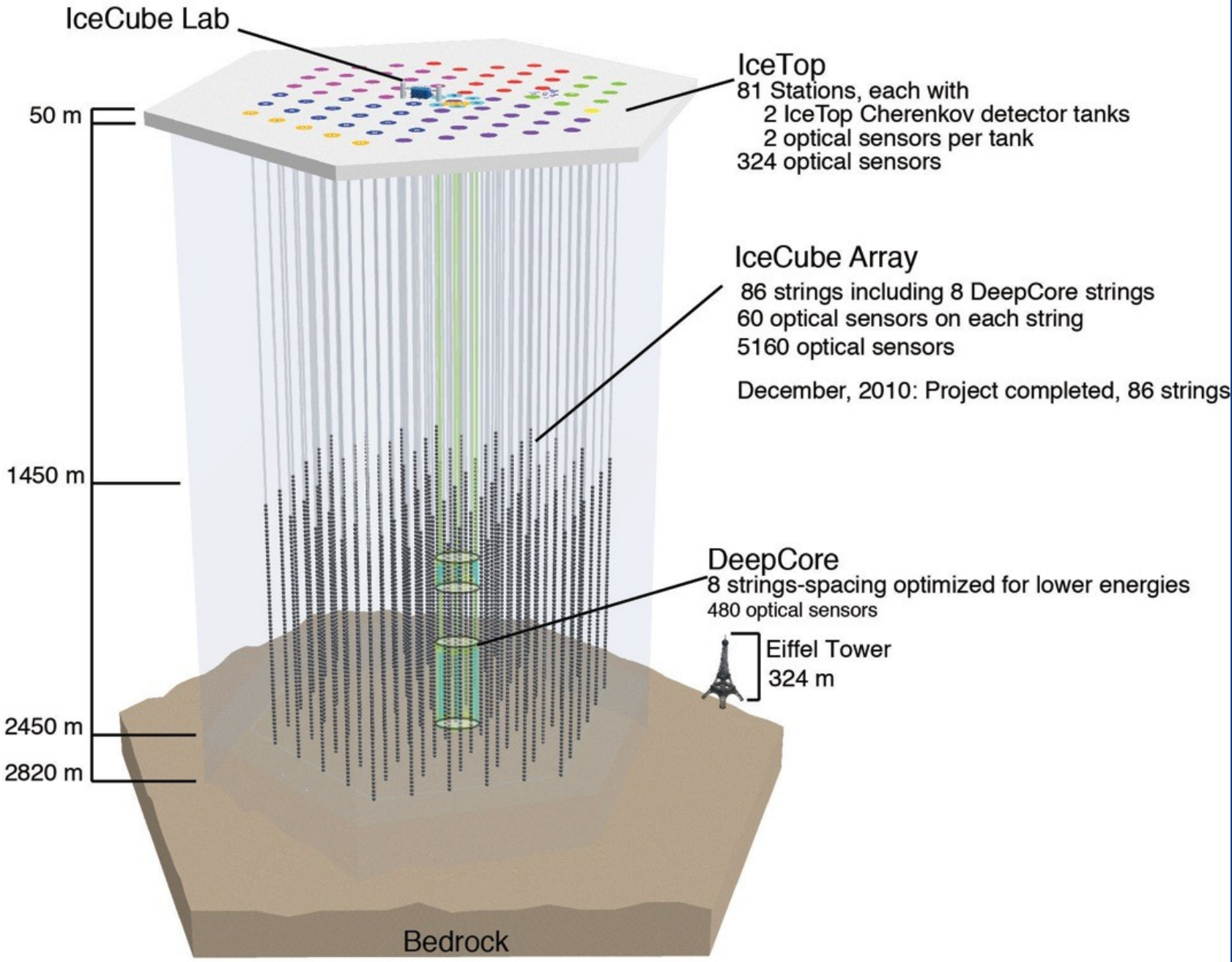
Neutrino Oscillation Workshop 2012
Conca Specchiulla

# The IceCube Collaboration


## International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

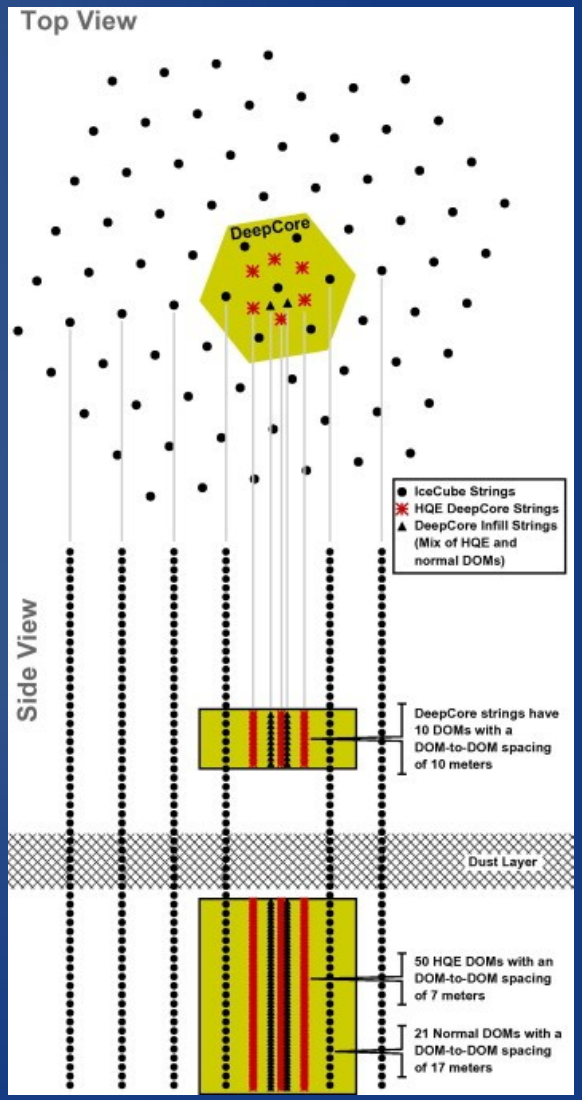
# The IceCube detector



# DeepCore
# atm. oscillations in neutrino telescopes

- DeepCore energies: 10-100 GeV
- Denser string spacing
- Covers first oscillation maximum @25 GeV
- 70 m string distance → 25 GeV muons can bridge strings
- String 79/80: 40 m infill

  ~10 GeV (2-string events)



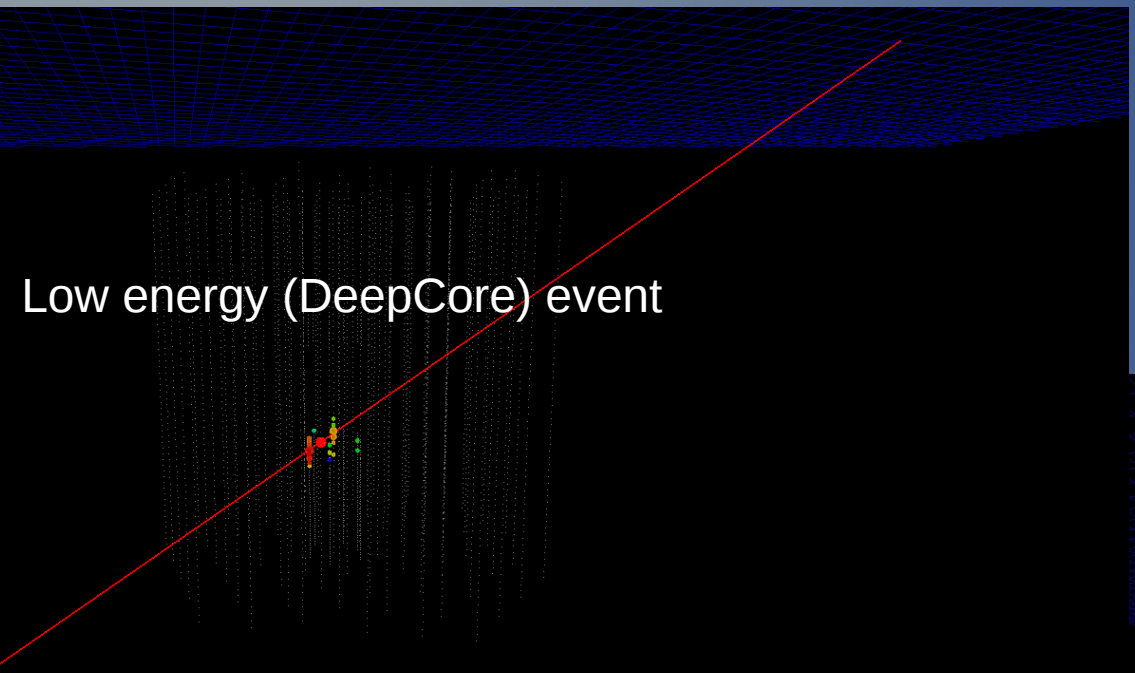
# Neutrino oscillations in DeepCore

- Energy threshold at trigger level ~ 10GeV
  - First oscillation maximum @25 GeV well covered
  - Large volume → High statistics available
- Challenges
  - Reconstructions: high energy methods not very efficient at 10 GeV
  - Systematic uncertainties: need to be controlled in order to have evidence for oscillations

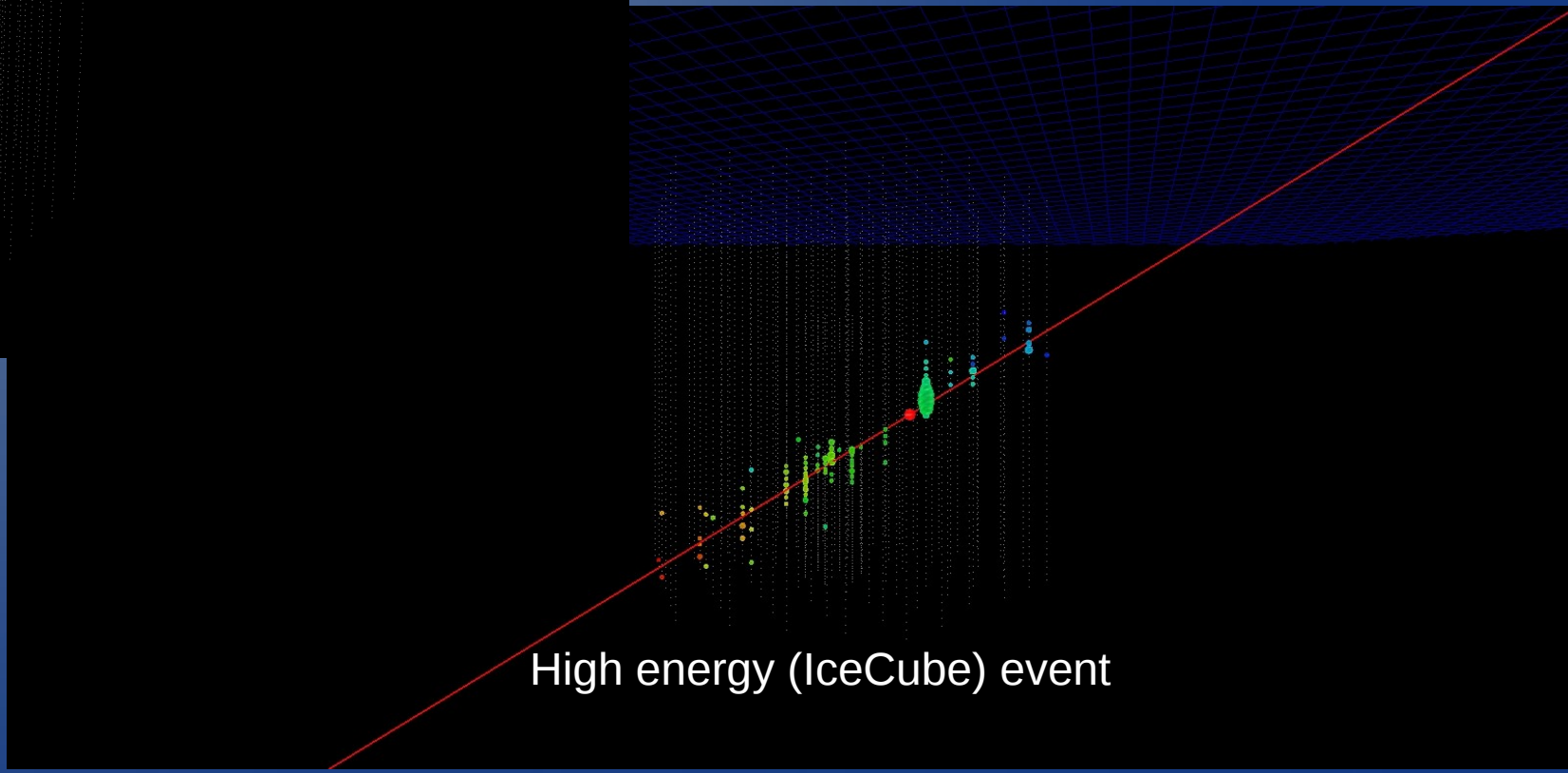
# Analysis strategy for 79-string data

- Use well-established reconstructions
  - Accept higher threshold of ~25-30 GeV
- Use a low-energy sample of DeepCore events for the signal and a high-energy sample of IceCube events
  - Same reconstruction methods are used
  - For some sources of systematics, the effects are correlated → high-energy sample puts constraints on these
- Use the covariance matrix method to cover correlations in systematic errors

# Some event displays

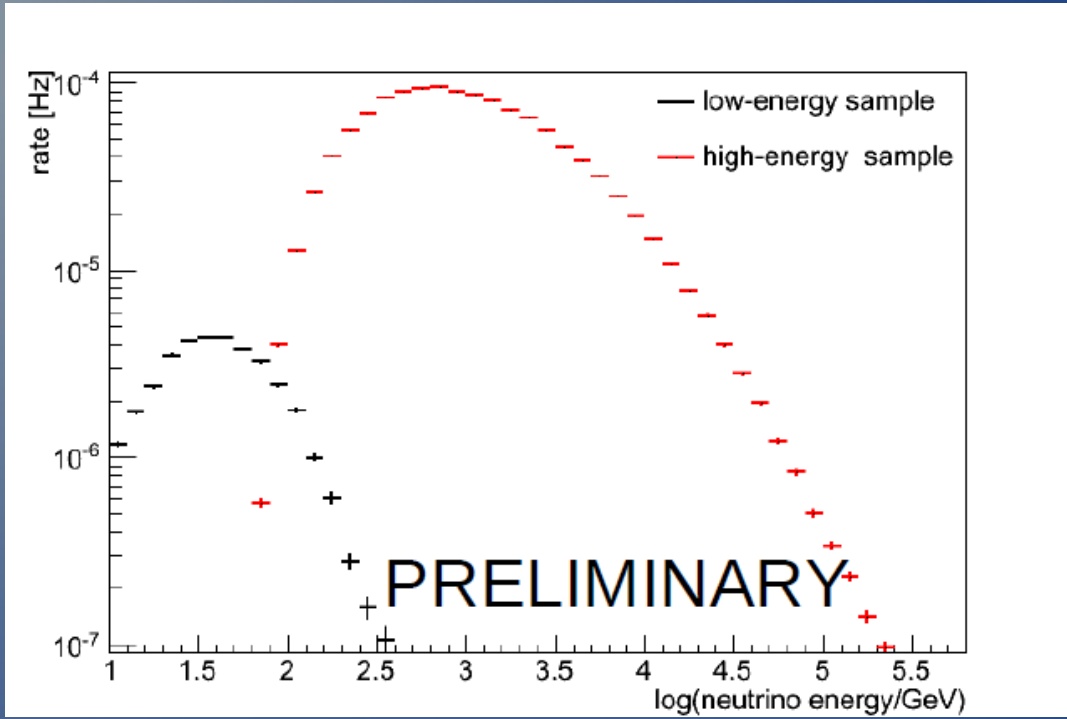


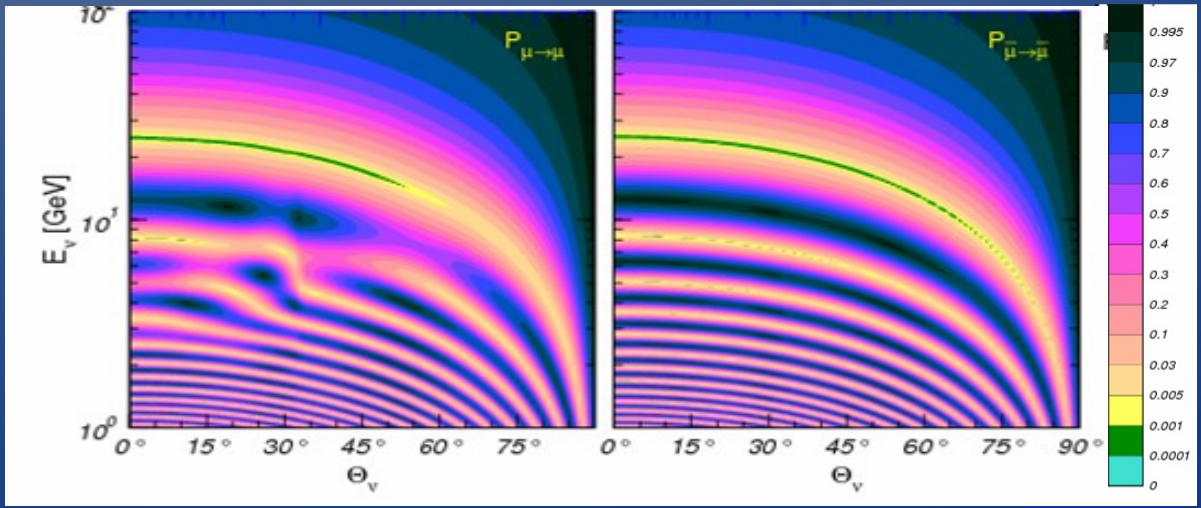
Low energy (DeepCore) event



High energy (IceCube) event

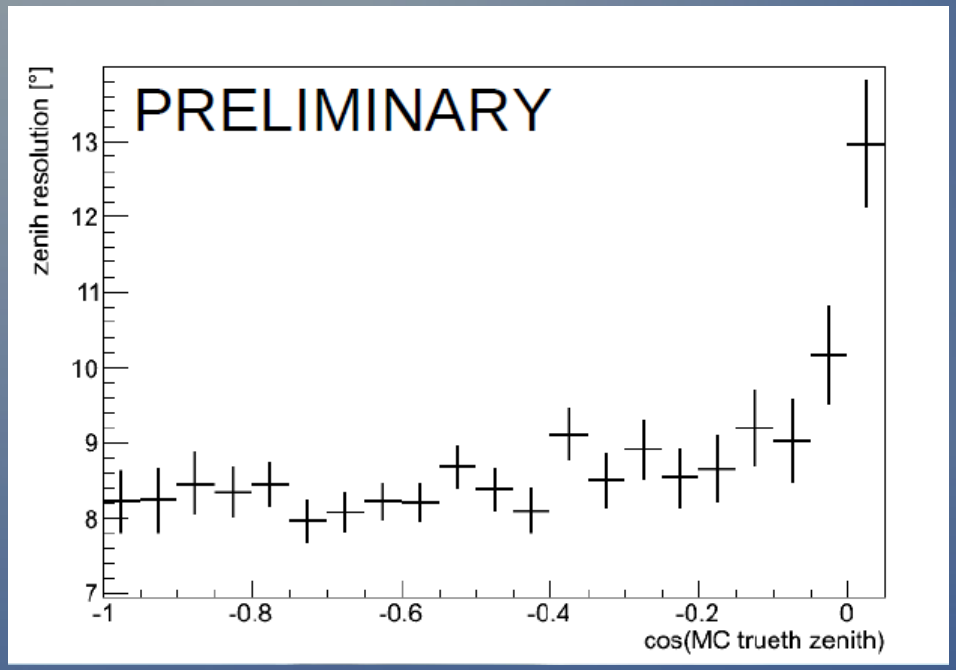
# Energy range: IceCube vs DeepCore

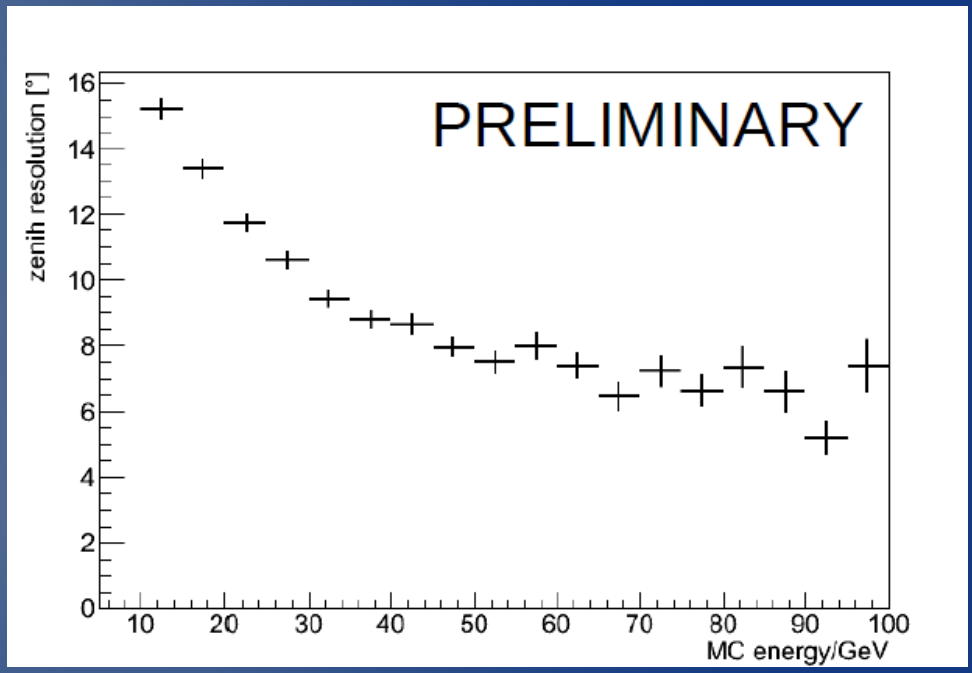



Oscillogram:
M. Maltroni, priv. com.
mofication from
Ahmedov et al,
JHEP06(2008) (2008) 1-49

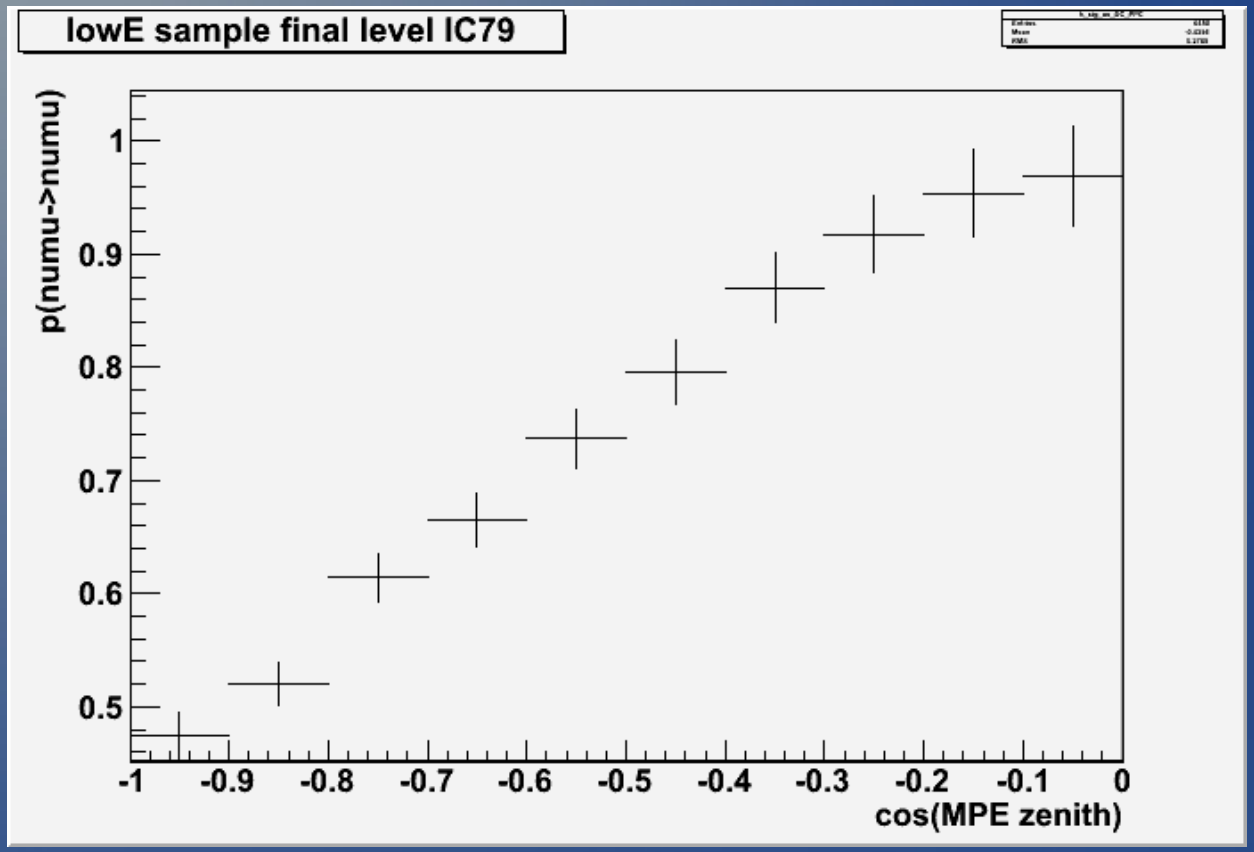
# Angular resolution at low energy




- Reminder: highE IceCube resolution ~ 0.5-1°
- Limiting factors:
  - Kinematic angle between muon and neutrino
  - Short tracks → short lever arm, harder to reconstruct

# Expected strength of oscillation effects

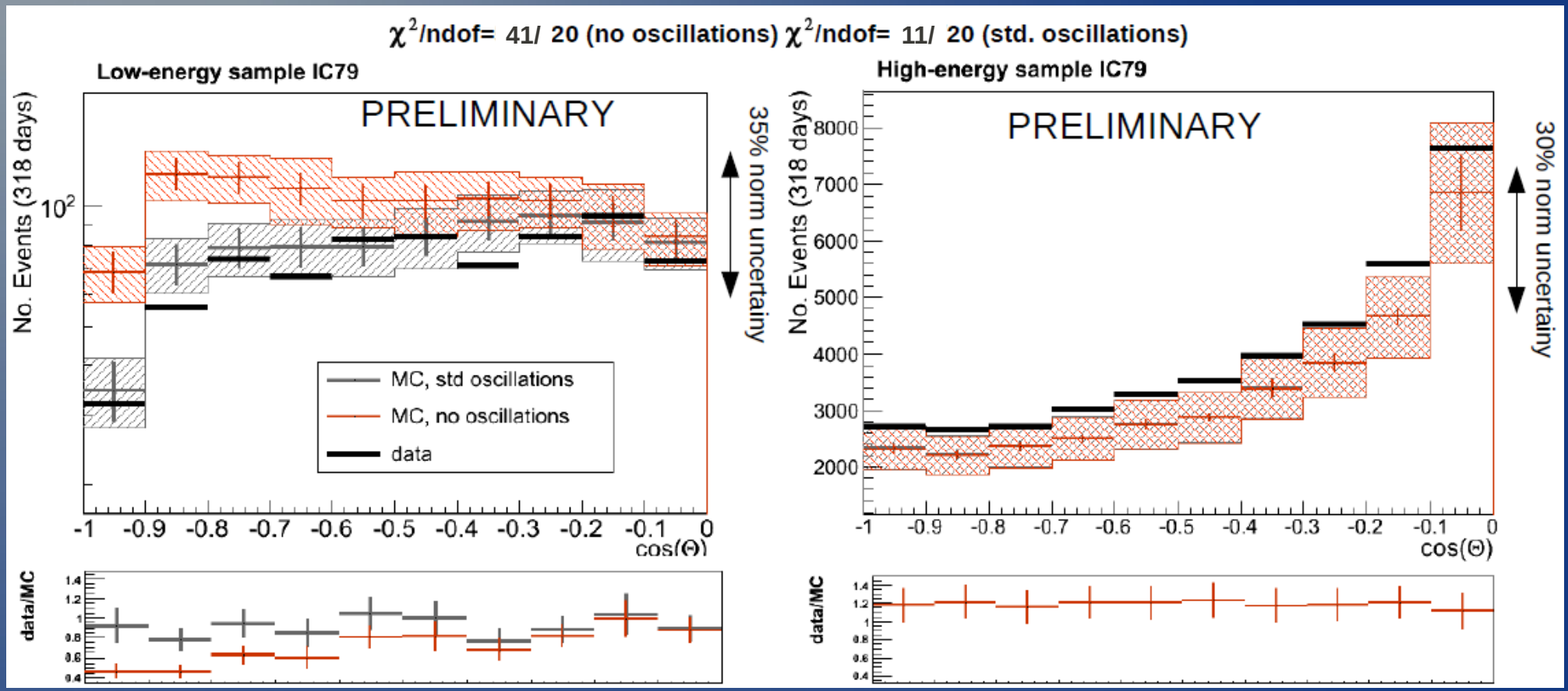



Smearing due to angular misreconstruction is taken into account in this plot.
Backgrounds are not included.

# Challenge: systematic errors

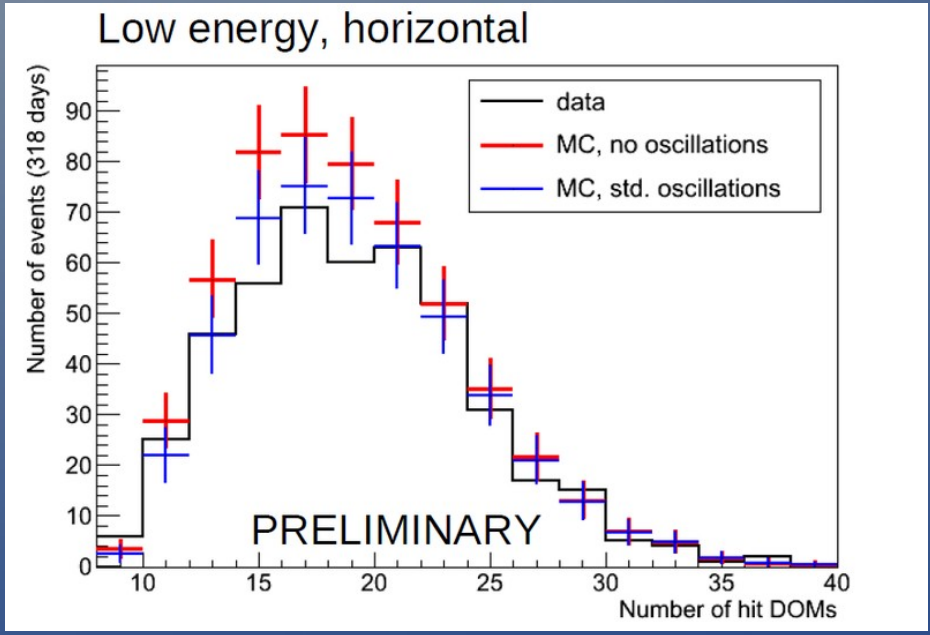
| Systematics source | Norm Low energy | Norm High energy | Correlated Low energy High energy | Uncorrelated Low energy High enegy |
|---|---|---|---|---|
| DOM efficiency | 10% | 15% | 10% | 5% |
| Ice model | 20% | 5% | 5% | 15% |
| Atm ν flux model | 5% | 7% | 5% | 2% |
| CR norm | 25% | 25% | 25% | 0% |
| CR index | 3% | 7% | 0% | 10% |
| **Total** | **35%** | **30%** | **28%** | **20%** |

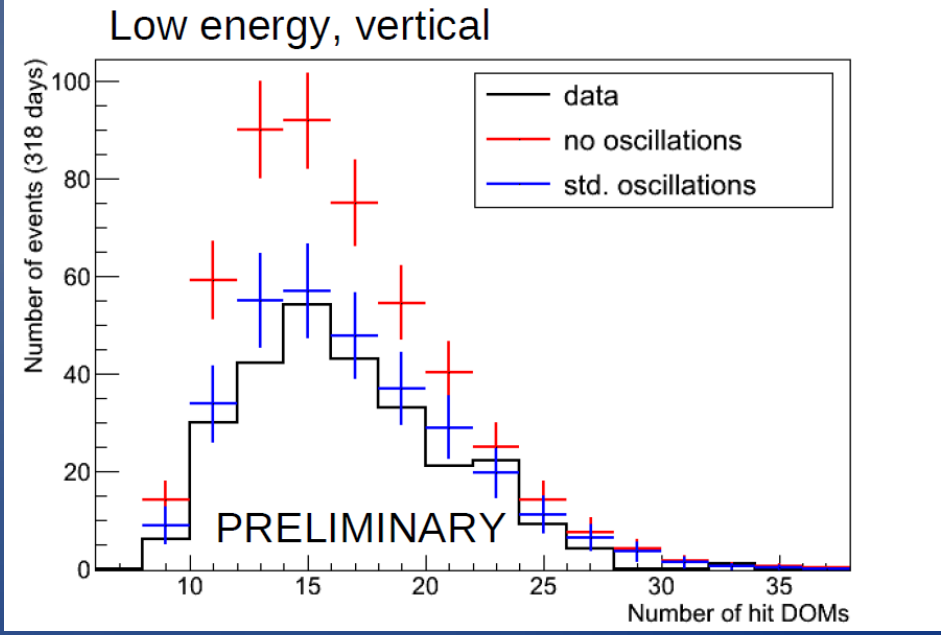
# Result: IceCube/DeepCore sees oscillations (5.6σ)




Significance obtained by MC experiments,
Covariance matrix covers systematic uncertainties and their correlations

# Further variable: number of DOMs (→ energy)




Expected effect for oscillations:
Deficit of vertical events at low energy
Present in data

Energy information not included
In statistical analysis

# About the oscillation parameters

- Our data is consistent with world average best fit (at 1 sigma level)
- Systematic uncertainties under detailed investigation
  - $\nu_\tau$ appearance
  - Cross check of the errors band assumptions
- Future improvements for IceCube oscillation analysis:
  - New reconstruction methods (various approaches in IceCube)
  - Inclusion of energy observable
  - More efficient event selection (e.g. BDT)
  - Inclusion of two additional DeepCore strings

# Summary and outlook

- First 5-sigma detection of neutrino oscillations by a high-energy neutrino telescope
- Oscillation parameter fit in agreement with world average
- Systematics under further investigation for parameter extraction
- Expected future improvements:
  - New analysis methods
  - Use of full IceCube detector (two additional DeepCore strings)
  - Work towards better constraints of systematic uncertainties

# Further outlook

- New project: PINGU (“precision IceCube next generation upgrade”)
  - ~20 additional infill strings
  - Target the 1-10 GeV energy range
  - Potential to measure hierarchy
  - Capabilities and design under investigation