Testing the Neutrino Mass Ordering with Multiple Years of IceCube/DeepCore

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- TAUP, July 2017 -

Deutsche Forschungsgemeinschaft

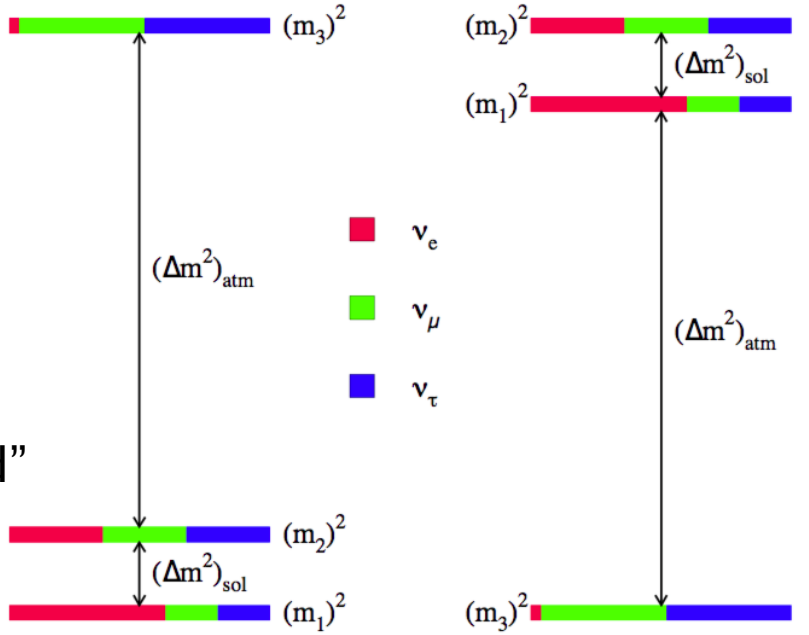
Bundesministerium für Bildung und Forschung

Neutrino Mass Ordering …

… what is it about and why should I care?

What is Neutrino Mass Ordering?

- Neutrinos are massive particles
- Masses are fundamental, unknown constants in SM
- NMO describes the ordering of these masses
- Only two possibilities remain: “Normal” or “Inverted”



(from: arXiv:1205.2671)

… and why should I care about it?

- Neutrino masses still not understood in SM (Nobel prize 2015)
- Ordering has impact on many fields of physics (cosmology, double-beta decay, absolute masses, CP violation…)
  - *W. Winter, Lake Louise Winter Institute, Feb. 2017*
- Many experiments (e.g. IceCube extension PINGU) aiming to measure NMO within next 5-10 years

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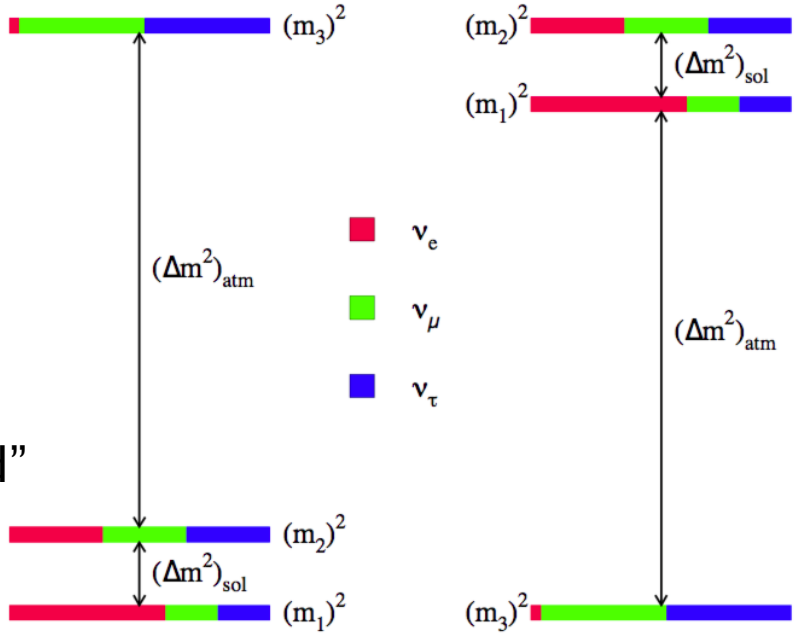

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… and why should I care about it?

Where can we get such neutrinos from to probe the NMO?

- Neutrin
- Orderir
  (cosmo
  - *W. Winter, Lake Louise Winter Institute, Feb. 2017*
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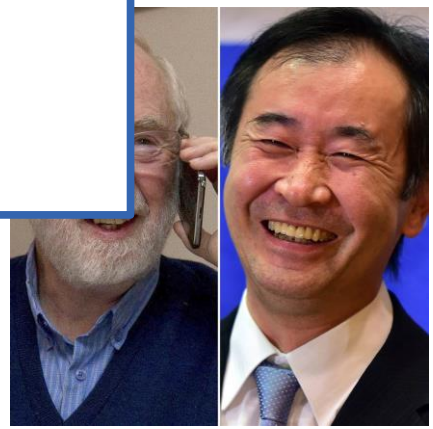
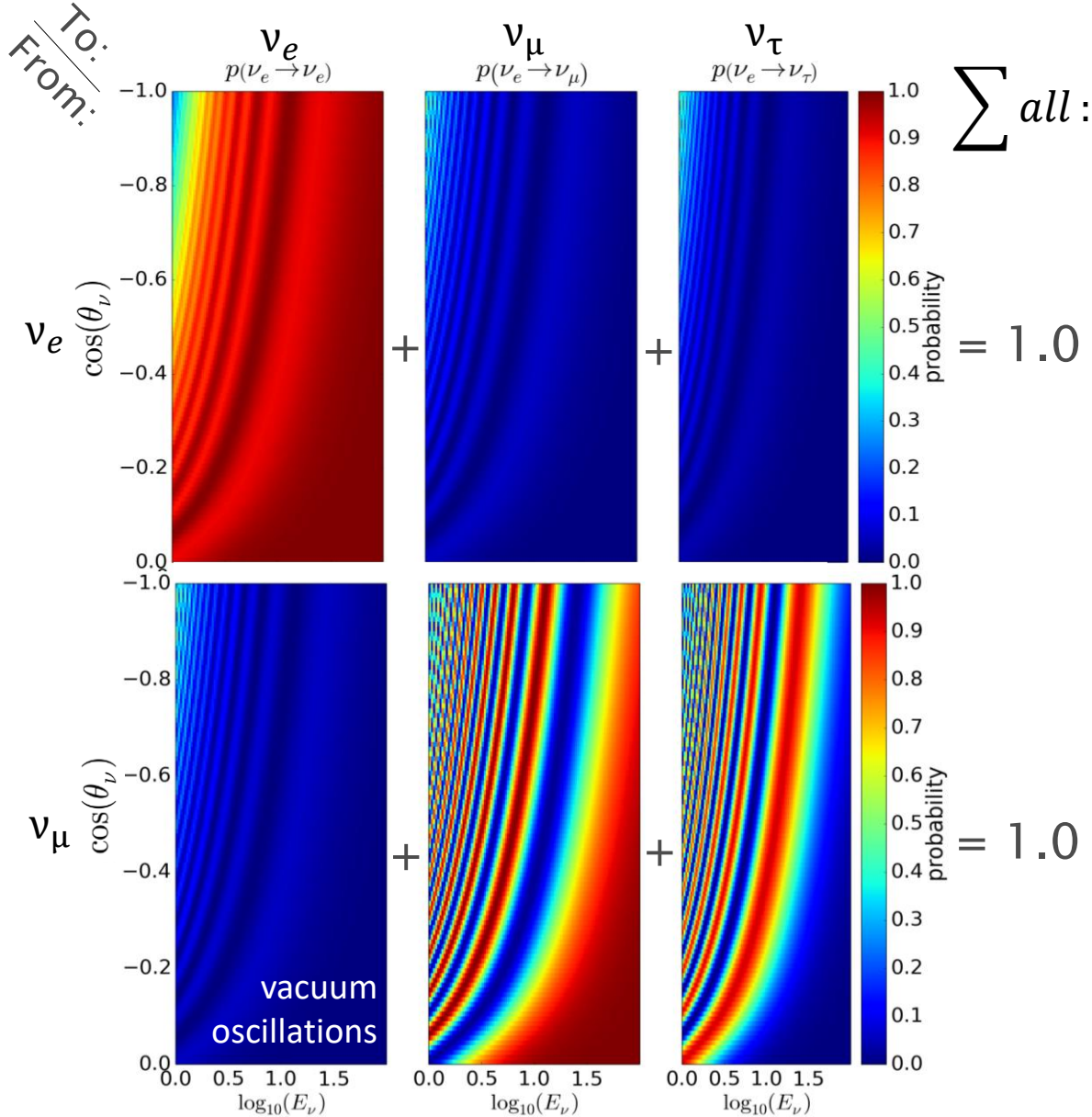
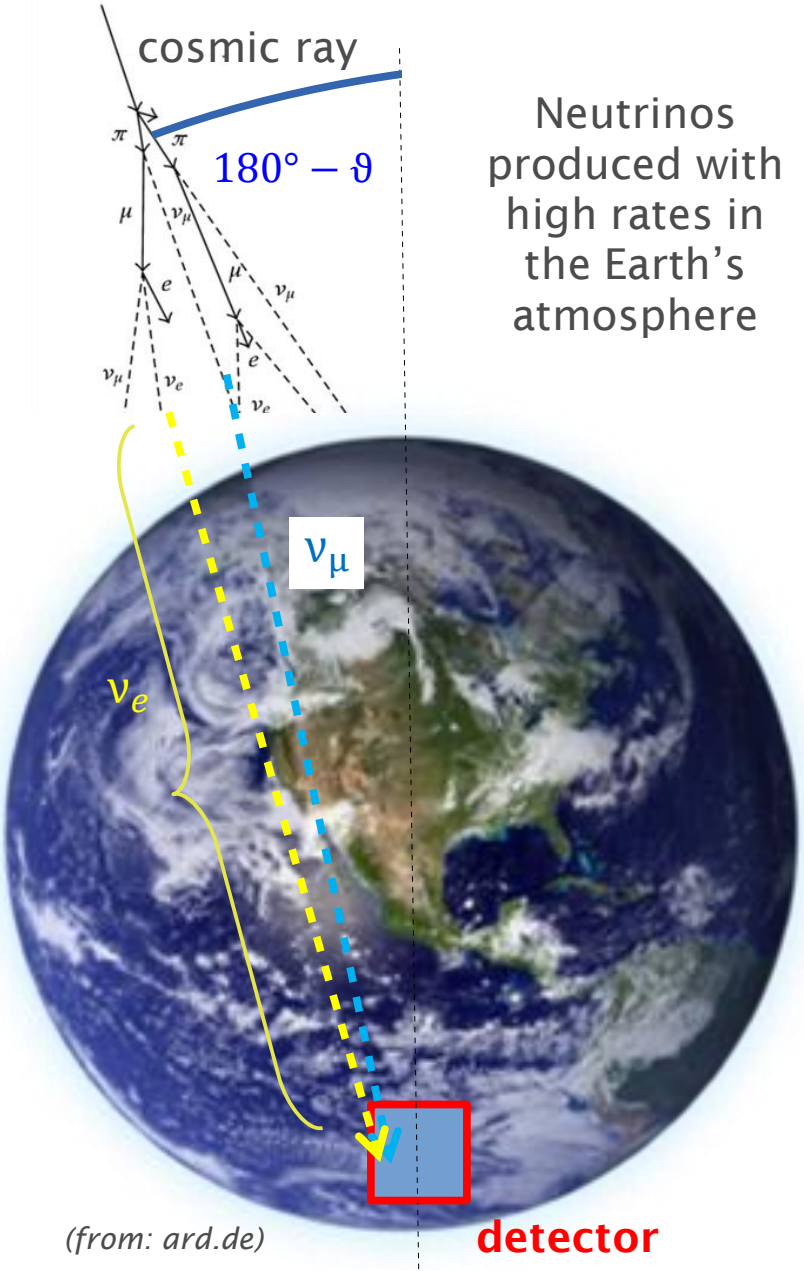


Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

Oscillation pattern for atmospheric neutrinos:





Neutrinos produced with high rates in the Earth's atmosphere

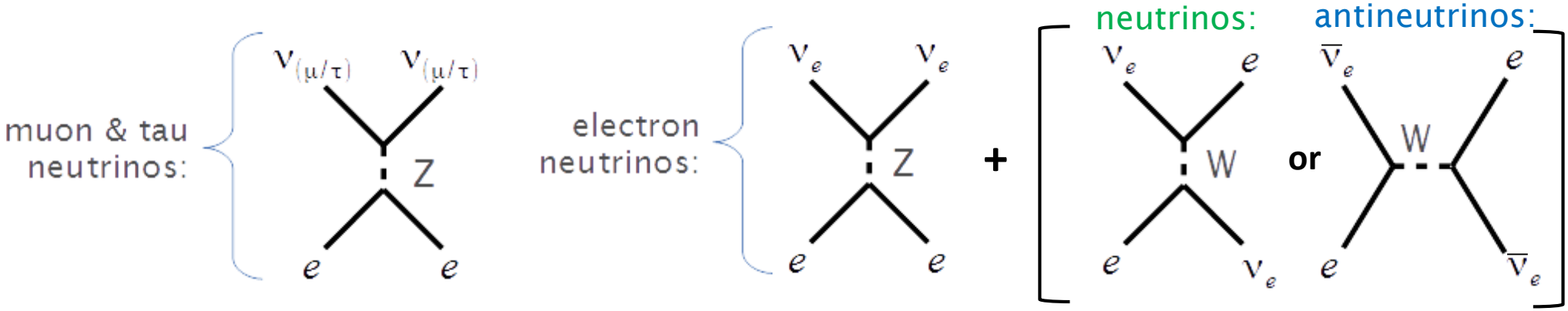
Matter Effects …

… as probe for the NMO

What does the ordering change?

Two matter effects during propagation through Earth:

- Interactions with electrons in the Earth (**MSW-Effekt**):



$$\sin(2\theta_M) = \frac{\sin(2\theta)}{\xi}$$

$$\Delta m^2_M = \Delta m^2_{\text{atm}} \cdot \xi$$

with:

$$\xi = \sqrt{\left(\sin^2(2\theta) + \left(\cos(2\theta) - \frac{A_{CC}}{\Delta m^2}\right)^2\right)}$$

$$A_{CC} = \pm 2\sqrt{2} \cdot G_F E_\nu N_e$$

+: neutrino
-: antineutrino

neutrino energy

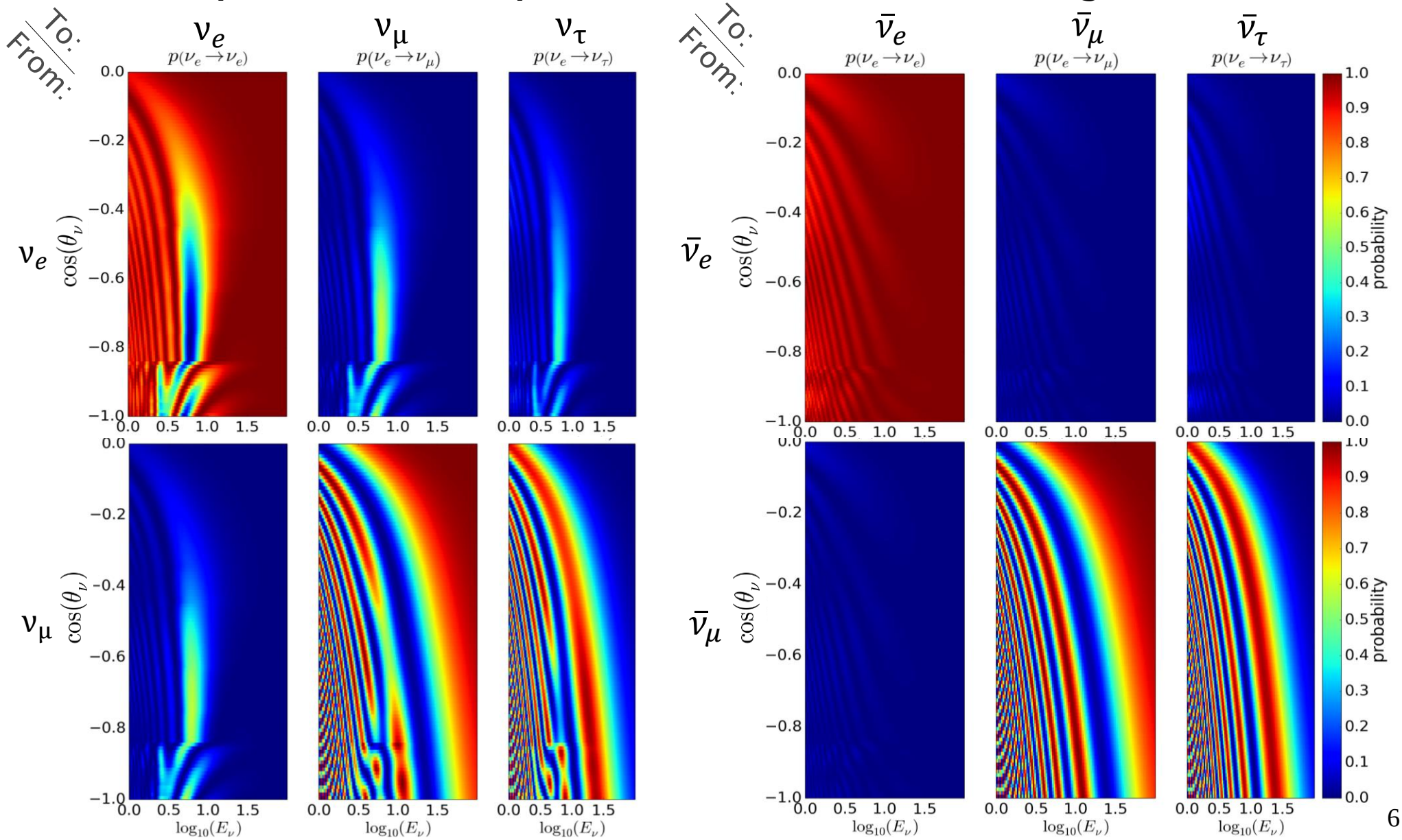
electron density

- **Parametric enhancement** due to non-homogeneous matter distribution:
  - Earth's core and mantle differ in matter density by a factor of ~2
  - Resonance occurring from periodicity of matter profile

Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

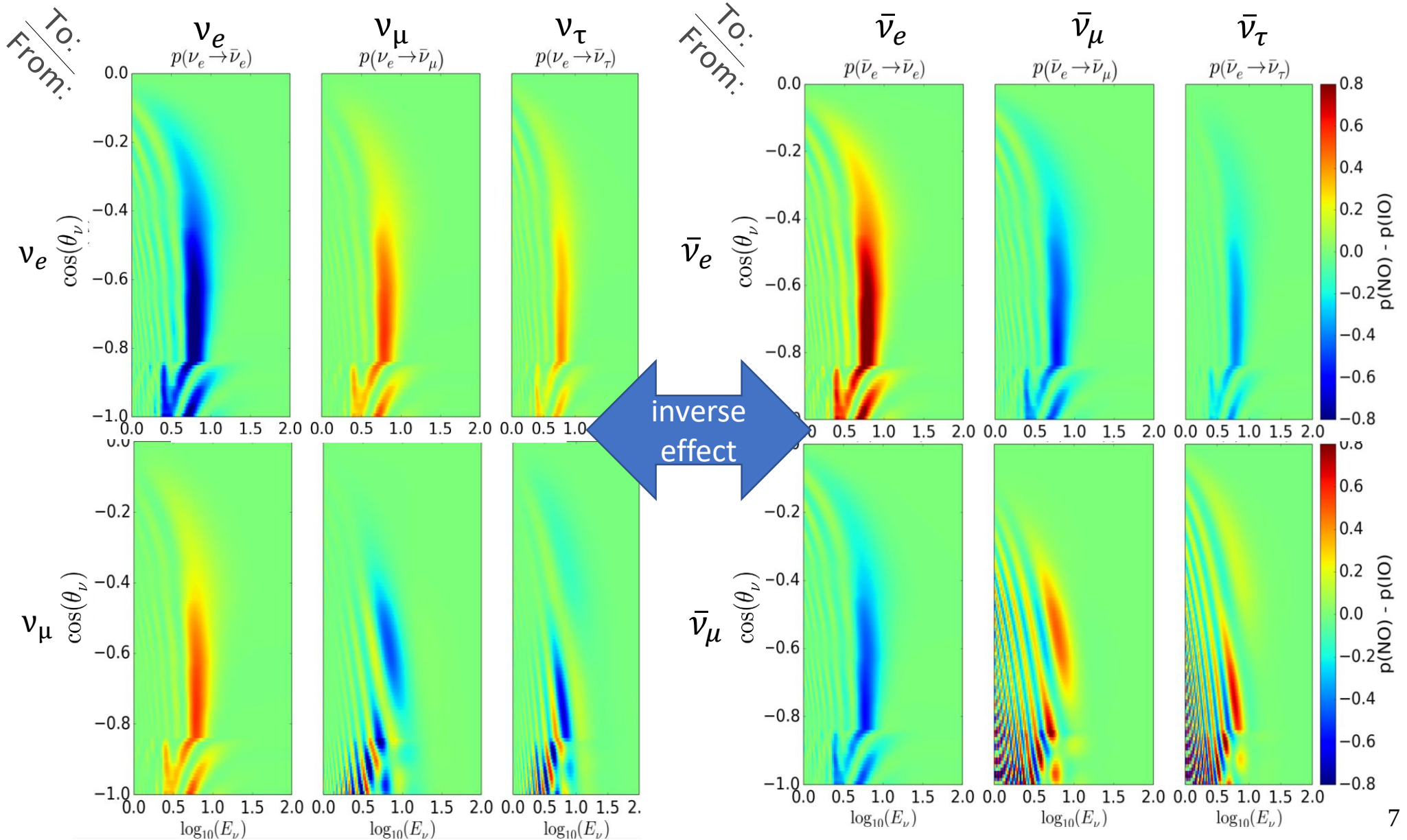
Oscillation pattern for atmospheric neutrinos (Normal Ordering):



Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

Differences between NO and IO for (anti-)neutrinos:



Atmospheric Neutrinos…

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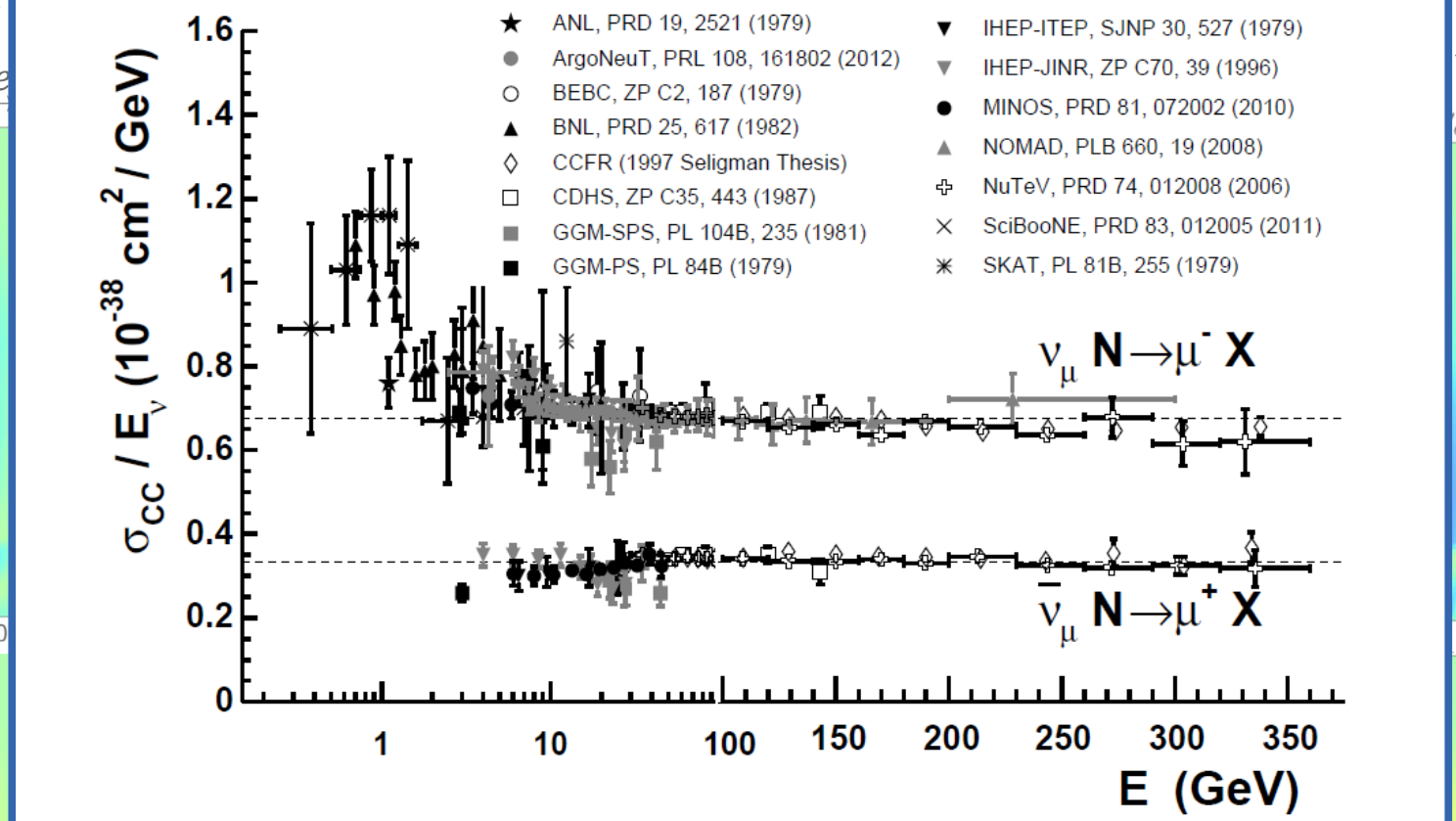
Differences

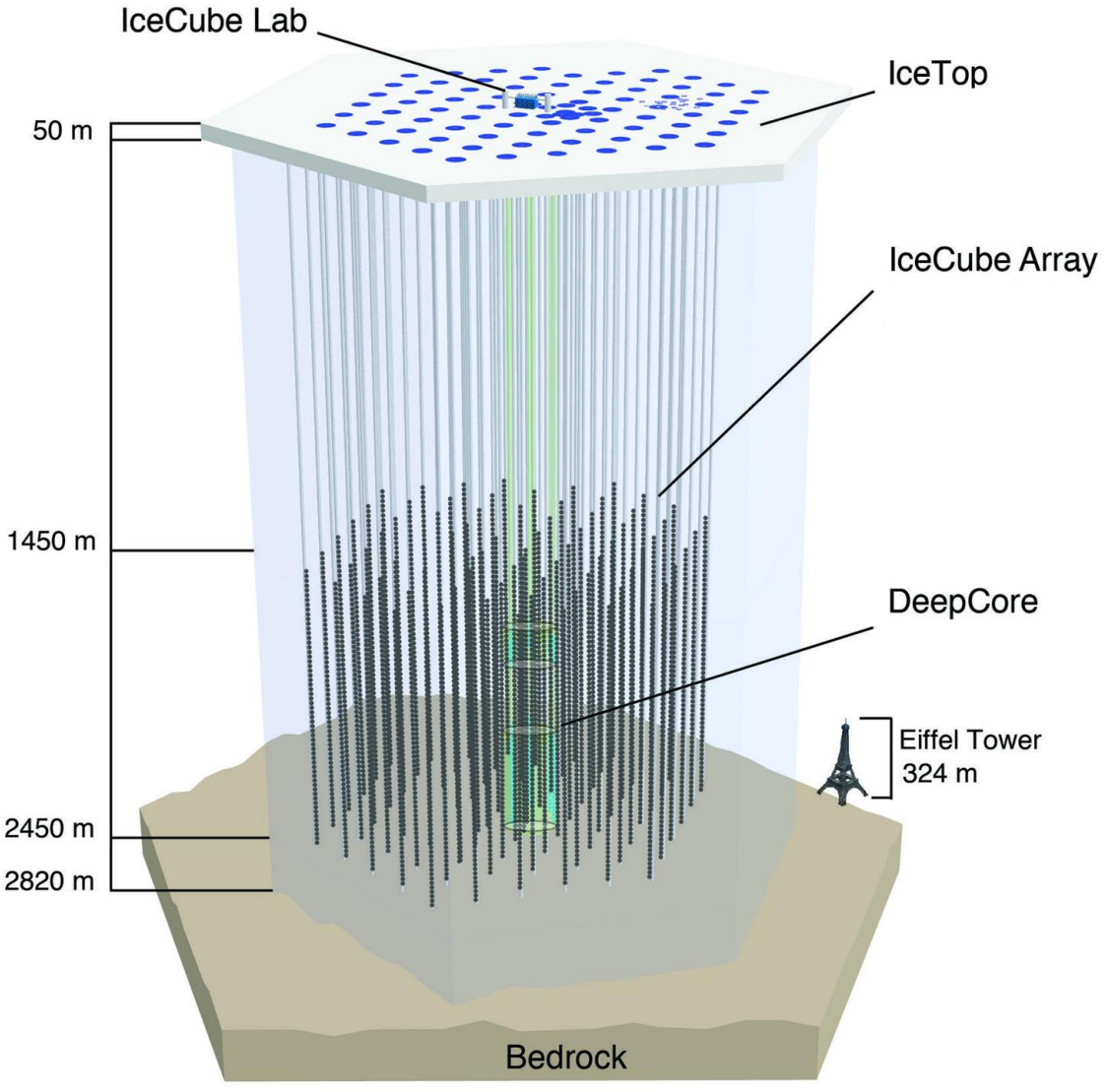


(from: : J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).)

Does that mean, the effect is invisible, if neutrino and anti-neutrino are not distinguishable?

The IceCube Neutrino Observatory…

… construction and setting of the experiment



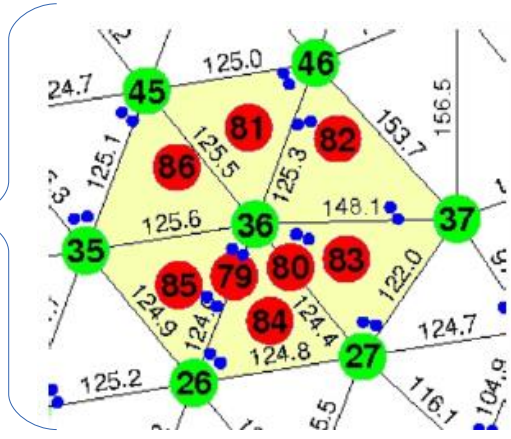
The IceCube Detector

- At Geographic South Pole
- Construction completed in 2010
- $\sim 1\ km^3$ size neutrino detector
- $1.5 - 2.5\ km$ depth
- 5160 PMTs at 86 strings (including Deepcore)
- Sees $E_\nu > 100\ GeV$

The DeepCore Subdetector

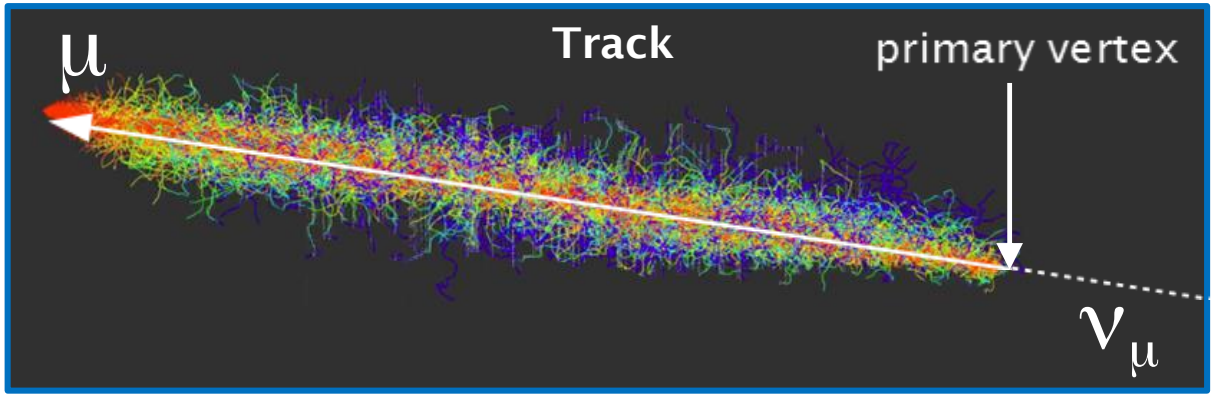
- 8 strings
- 460 high-QE PMTs (+35%)
- Sees $E_\nu > 5\ GeV$

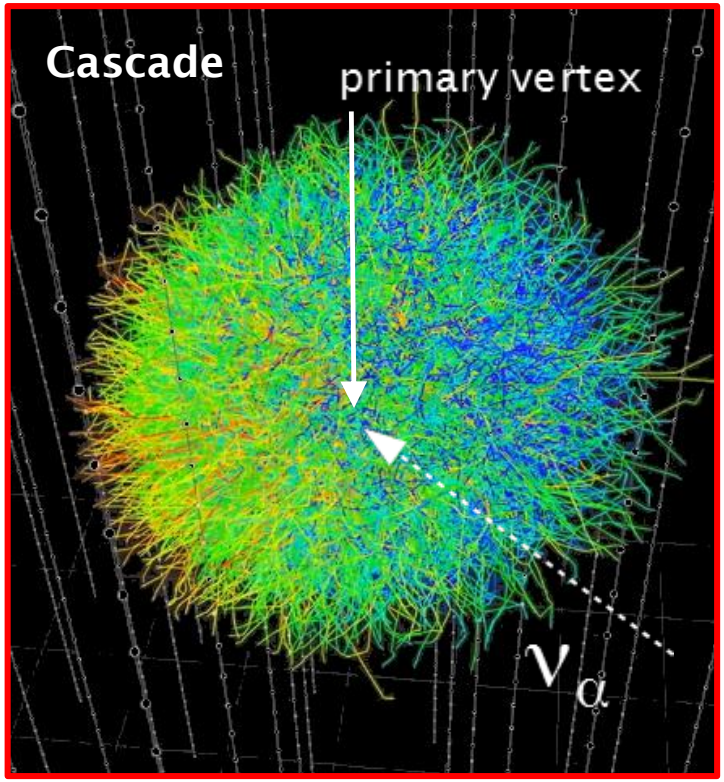
DeepCore, on-top view / string locations



Flavor Separation in IceCube…

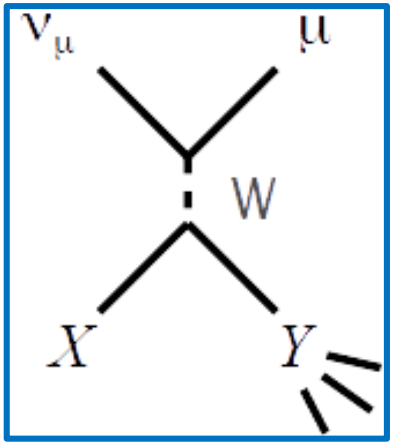
… using event topologies

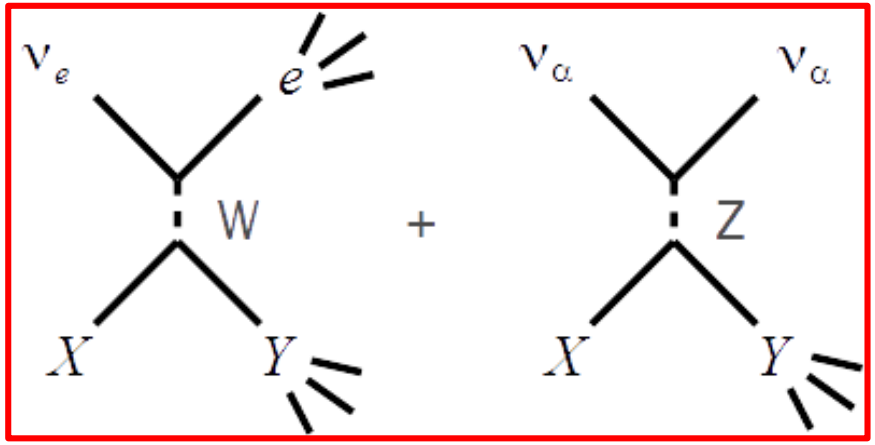




Two Event Topologies:

- Tracks and Cascades
- Physics behind tracks:
  - CC muon neutrinos
  - Atmospheric muons
- Physics behind Cascades:
  - CC electron /tau neutrinos
  - NC interactions
- Left: Cherenkov Photon propagation
- Easy to separate at >100GeV





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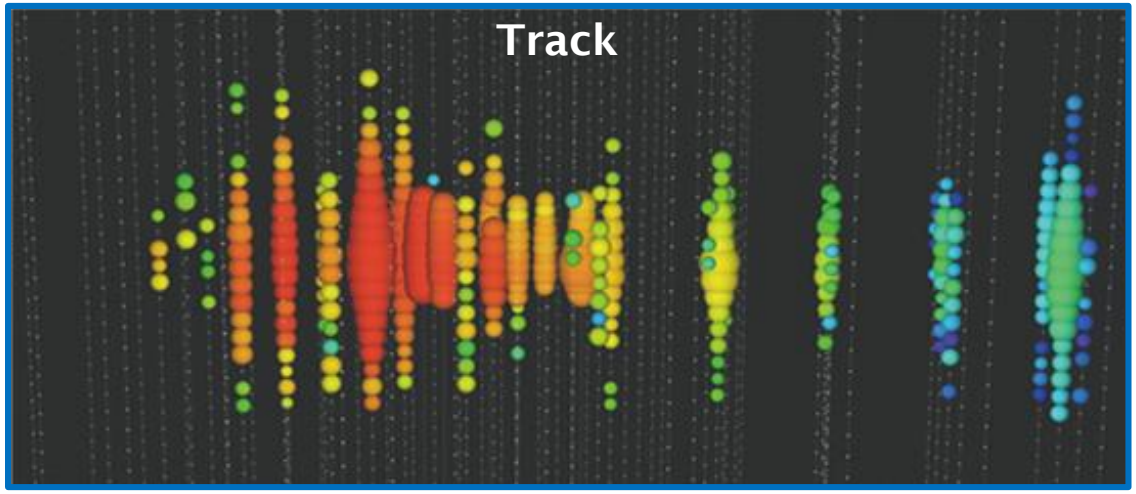

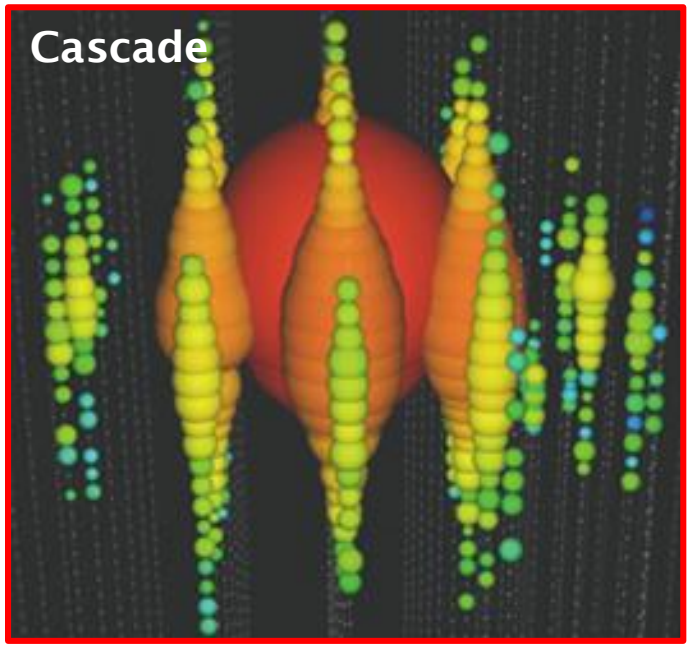

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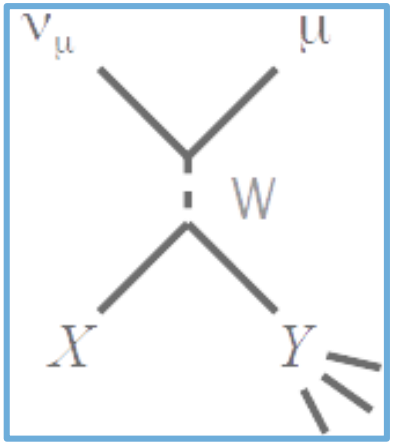

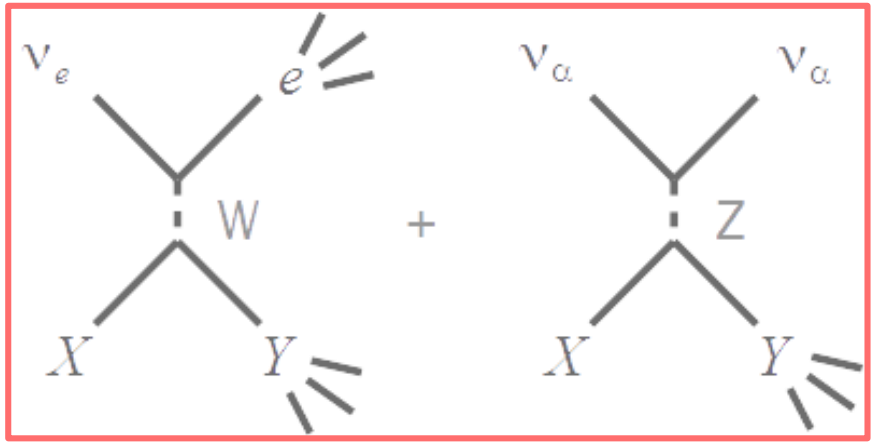

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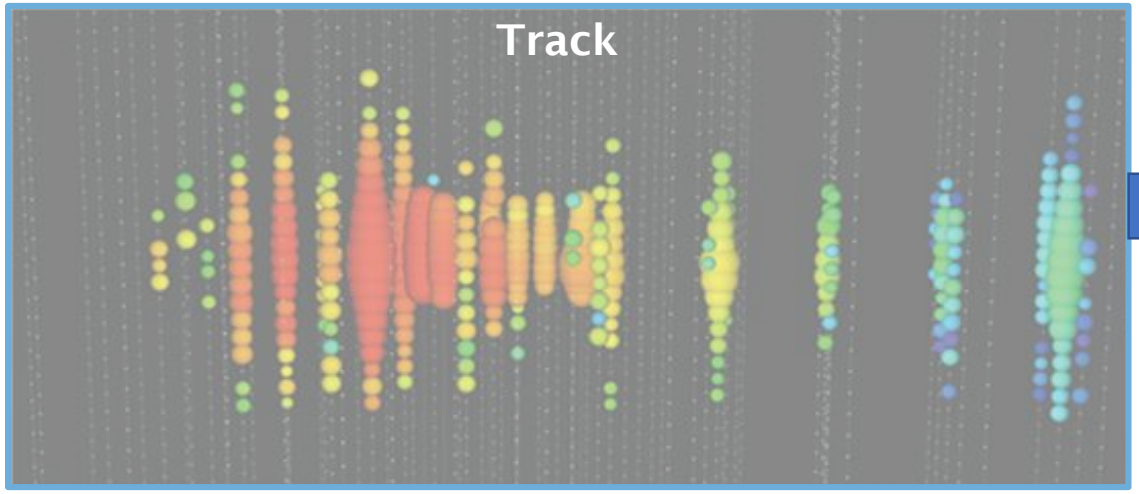
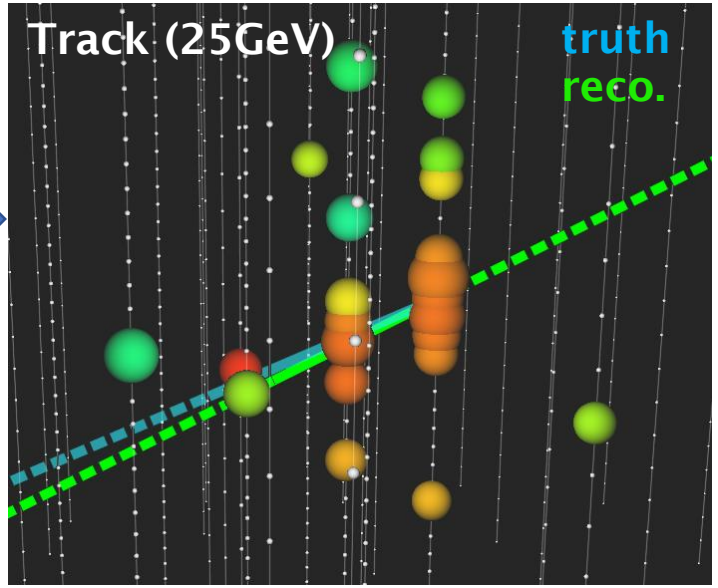
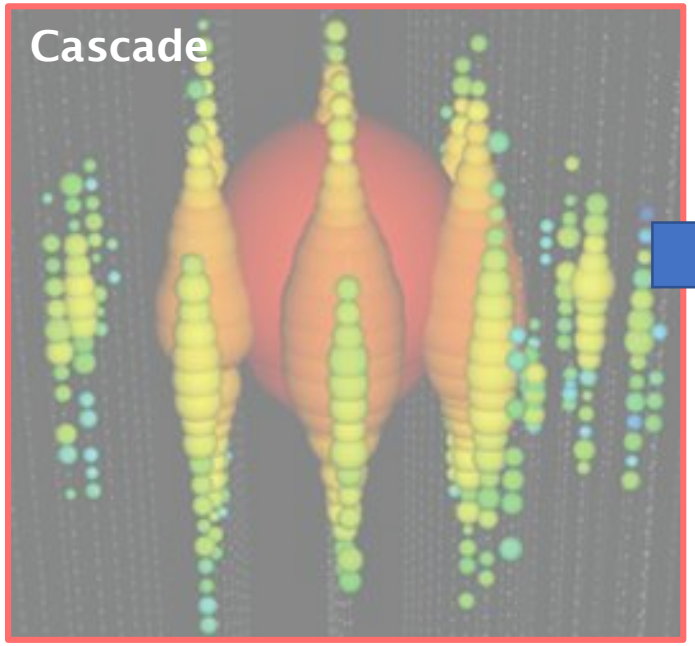
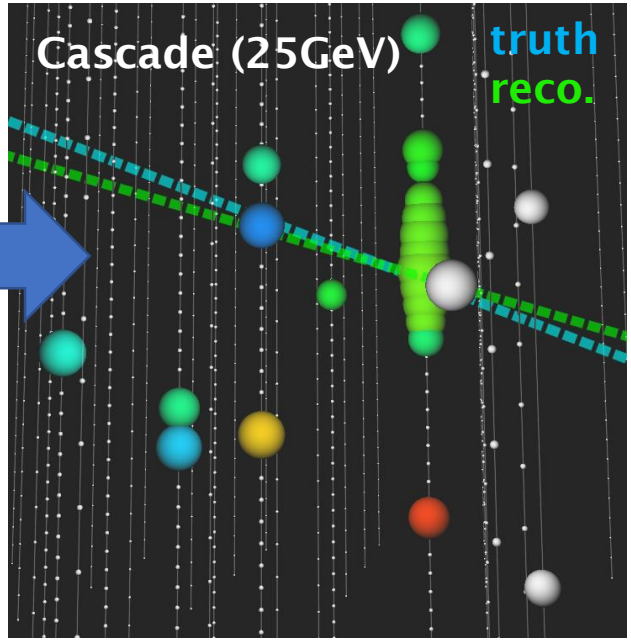








Separation at low energies:

- Weak separation power
- Separation of tracks and cascades statistical process
- Separated in reconstruction by likelihood difference:

$$\boldsymbol{PID} = \log(\mathcal{L}_{\text{track}}) - \log(\mathcal{L}_{\text{casc}})$$

- Fit simultaneously with: vertex, direction, energy

Idea of Mass Ordering Measurement…

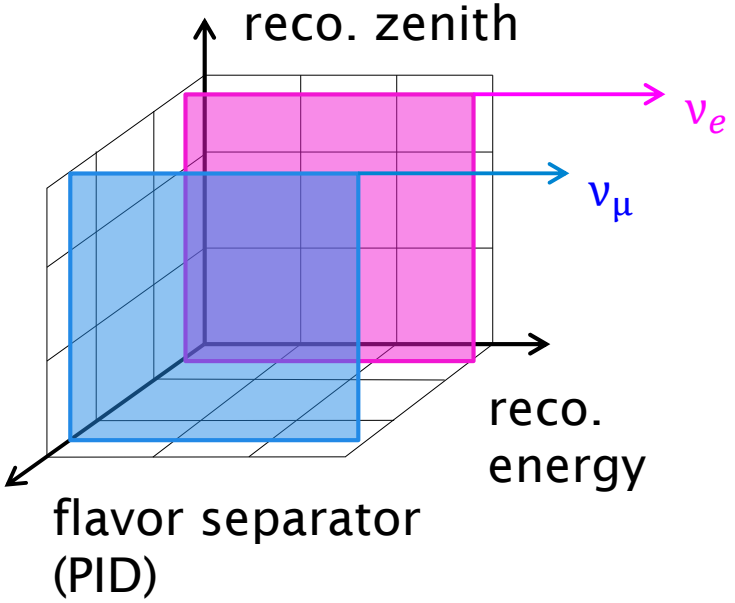
… with the IceCube/DeepCore detector

So, what do we need to measure for NMO?

1) **Neutrino Energy**
2) **Direction (zenith angle)**
3) **Flavor separator (PID)**

need to reconstruct these 3 quantities at extreme low energies (<10GeV)

(challenging energy regime for data selection and reconstruction)



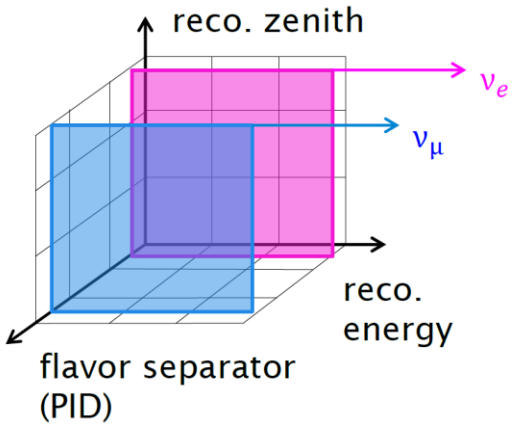
Analysis Method: 3D LLH Analysis

- Separate flavors within fitted diagram
- Fit oscillations for all flavors simultaneously
- Multiple years, high statistics, low-E sample
- Optimize Likelihood function:

$$LLH = -\sum_{i=1}^{N_{bins}} \log\left(p\left(obs_i \mid pred_i\left(\theta_{jk}, \Delta m_l^2, \boldsymbol{NMO}, \{p_k\}\right)\right)\right)$$

Idea of Mass Ordering Measurement…
… with the IceCube/DeepCore detector

How do we do this analysis?



Perform 2 parallel analyses on IceCube/DeepCore …

Analysis A
(similar to std. oscillations)

- 3 years of IceCube/DeepCore data
- Event-containment and quality cuts
- Focuses on:
  - energy range 5-80GeV
  - upgoing events only
  - 2 PID bins (tracks and cascades)
  - coarse binning
- Expect ~9k events per year

Analysis B
(high statistics, low energy tuned)

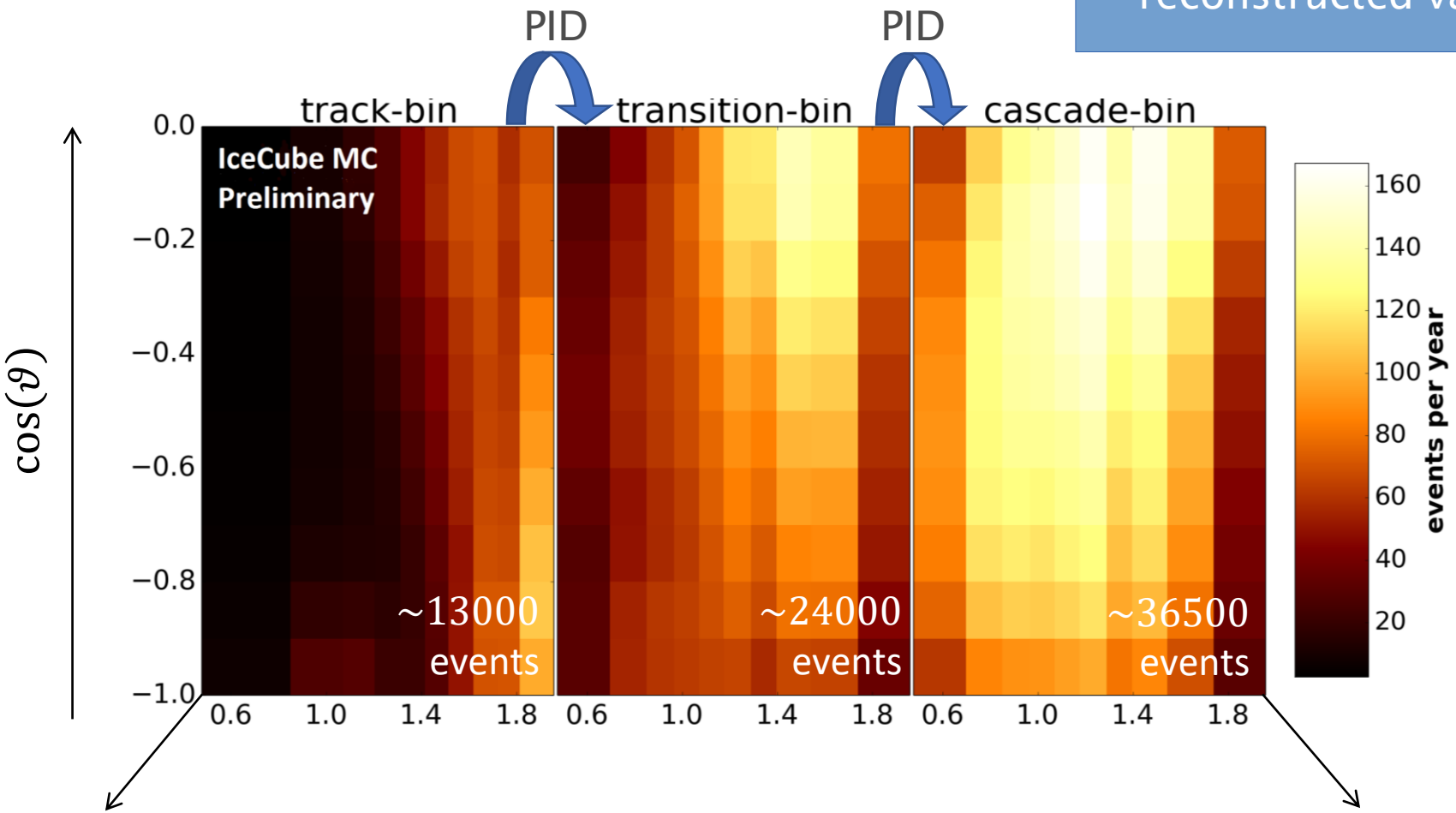
- 4 years of IceCube/DeepCore data
- Aiming to maximize statistics
- Focuses on:
  - energy range 4-90GeV
  - upgoing events only
  - 3 PID bins (+transition bin)
  - small, non-linear binning
- Expect ~22k events per year
- Focus on this in this talk!

Reconstructed Observables …

… inserting the NMO Likelihood

What do these 3D histograms look like?

shown for Analysis B in reconstructed variables



Reconstructed Observables …

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What do these 3D histograms look like?

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PID PID

Many processes contributing to the 3D histograms:

Signal:

- CC muon neutrinos (~55%)
- CC electron neutrinos (~20%)
- CC tau neutrinos (~5%)

Background:

- NC neutrinos (all flavors) (~10%)
- Atmospheric muons (~10%)
- Triggered detector noise (~0.1%)

with all components depending on systematic parameters

$\cos(\vartheta)$

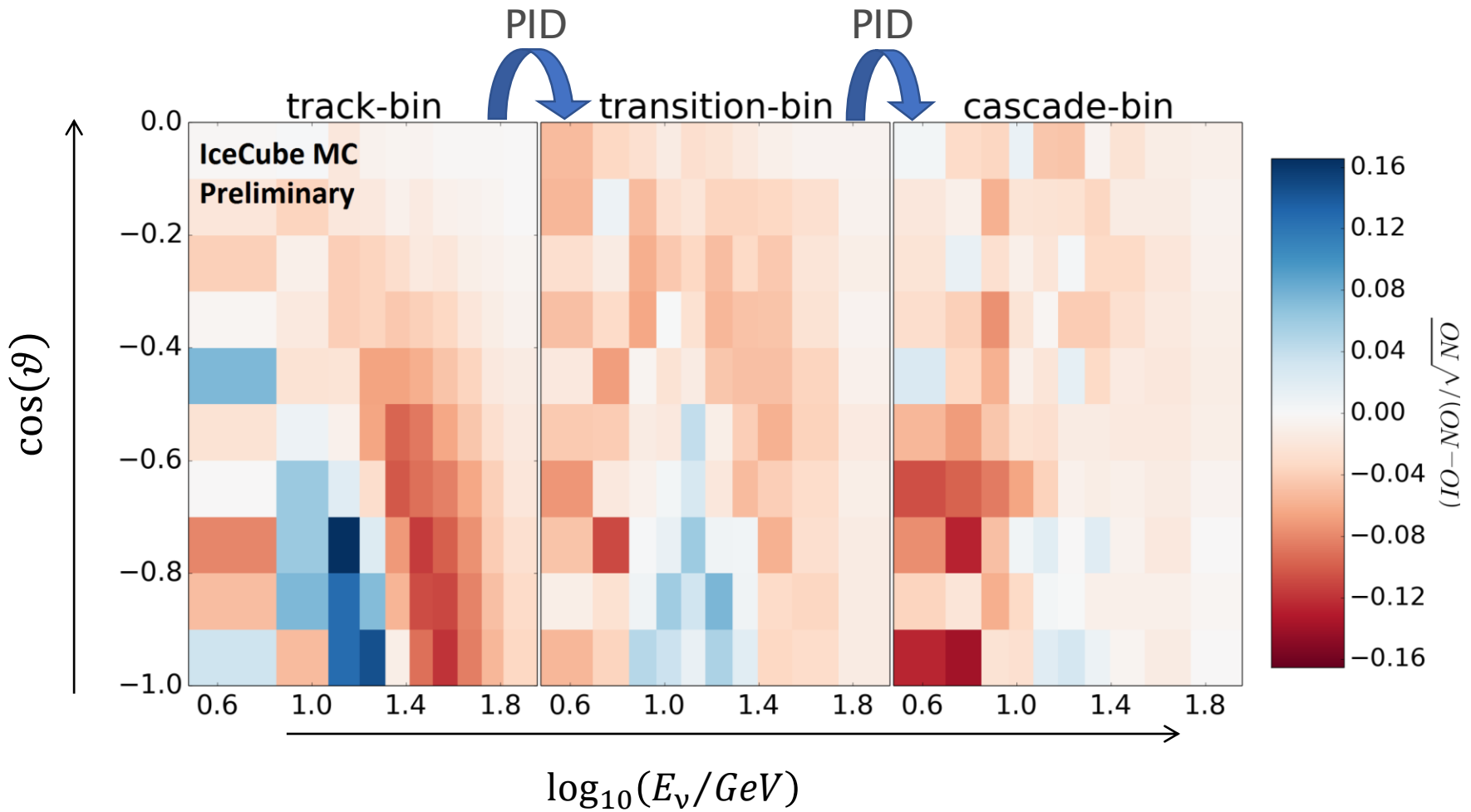
"track-like" → $\log_{10}(E_\nu/GeV)$ → *"cascade-like"*

Reconstructed Observables …

… inserting the NMO Likelihood

What is the signature we expect in these 3D histograms?

shown for Analysis B in reconstructed variables



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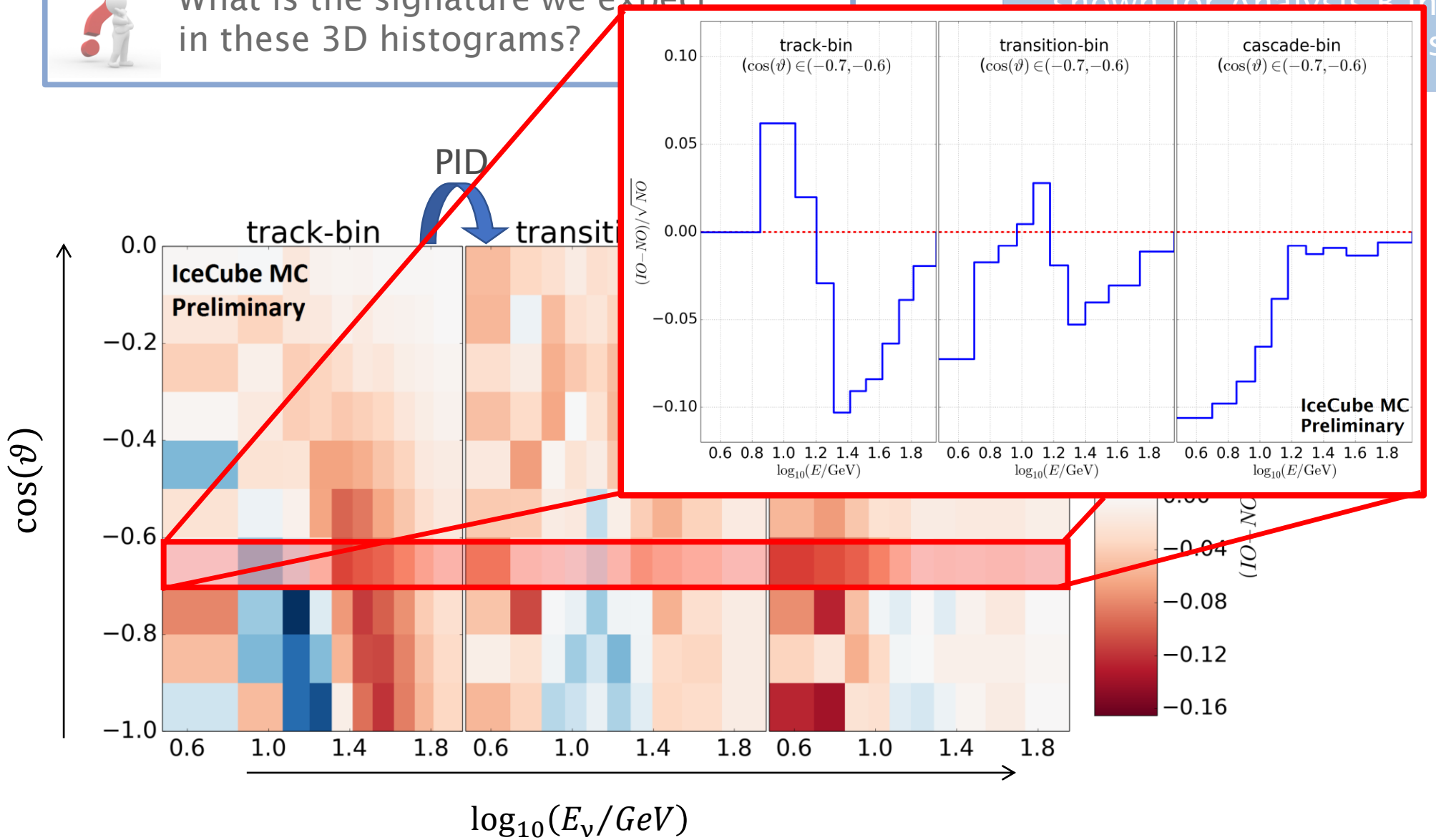


Systematic Influences …

… understanding detector and physics

How are systematic uncertainties treated in these fits?

Systematic Uncertainties included in fit of signal parameters

- Parametrize impact of systematic uncertainty on 3D histogram:
  - **Normalizations**
  - **Detector uncertainties**
  - **Oscillation parameters**
  - **Atmospheric flux uncertainties**
  - **Interaction uncertainties**
- Fit all uncertainties simultaneously with fit of NMO
- Reduces significance for NMO by inclusion of systematics

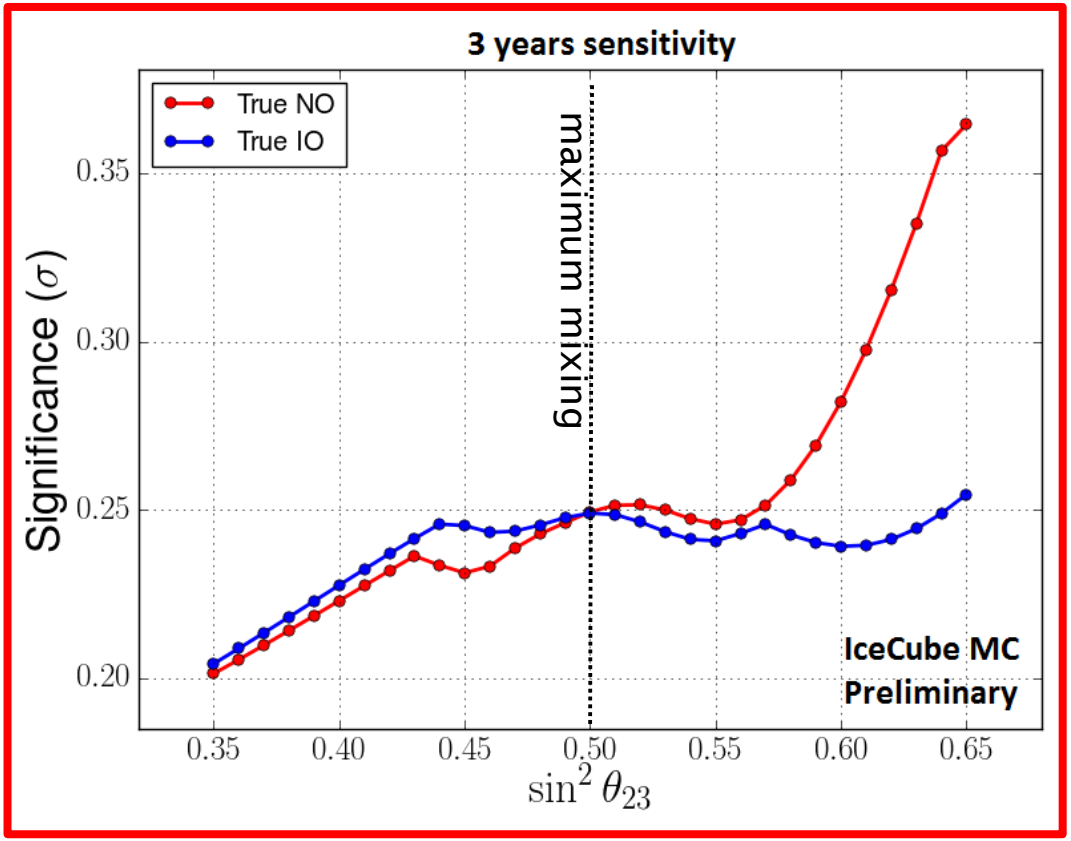
Name:	Explanation:
N_μ	Normalization of atmospheric muons
N_e	Normalization of electron neutrinos
N_{NC}	Normalization of NC interactions
$L_{scatter}^{holeice}$	Scattering length in re-frozen ice
ϵ_{PMTs}	Efficiency of photomultipliers
Δm_{23}^2	Atmospheric neutrino mass difference
θ_{23}	Atmospheric mixing parameter
γ_ν	Neutrino energy spectrum uncertainty
γ_μ	Muon energy spectrum uncertainty
σ_ν^{zenith}	Atmospheric zenith spectrum uncertainty
ν-$\bar{\nu}$-ratio	Neutrino-antineutrino ratio
M_A^{res}	Resonant interaction uncertainty
M_A^{qe}	Quasi-elastic interaction uncertainty

Sensitivity …

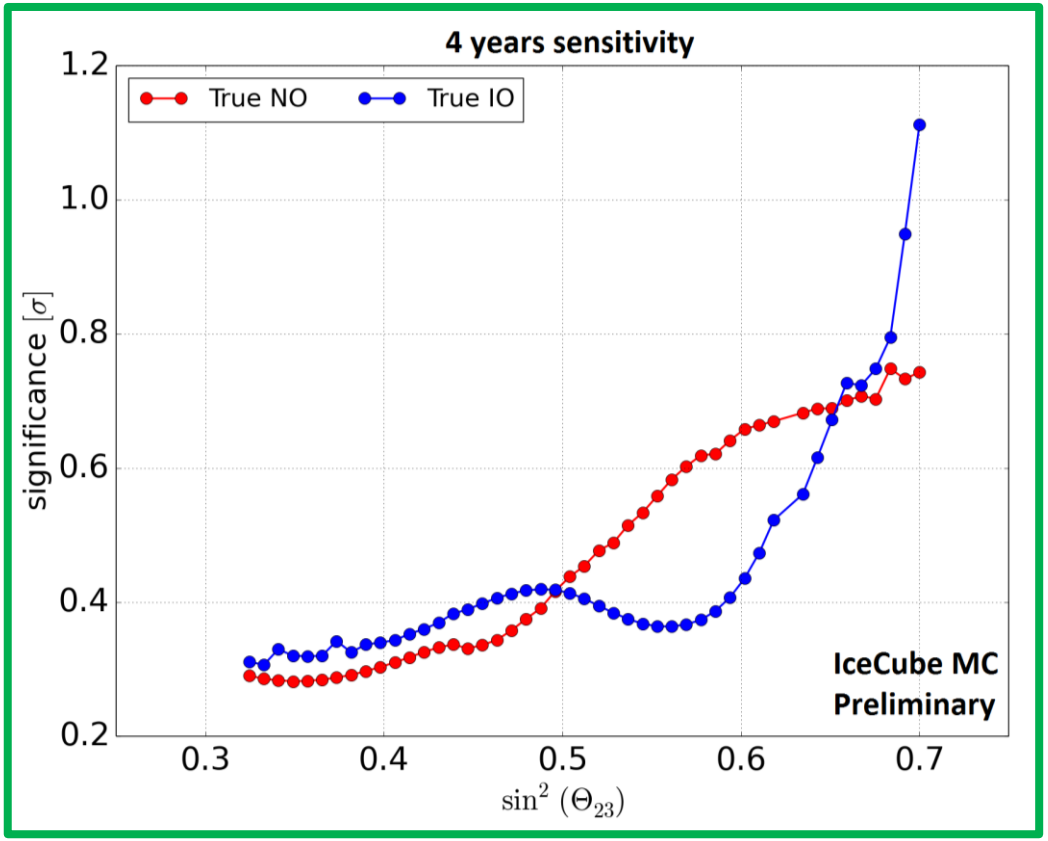
… of the 3 Observables inserting the oscillation LLH

How sensitive is DeepCore to NMO using multiple years of data?

Analysis A



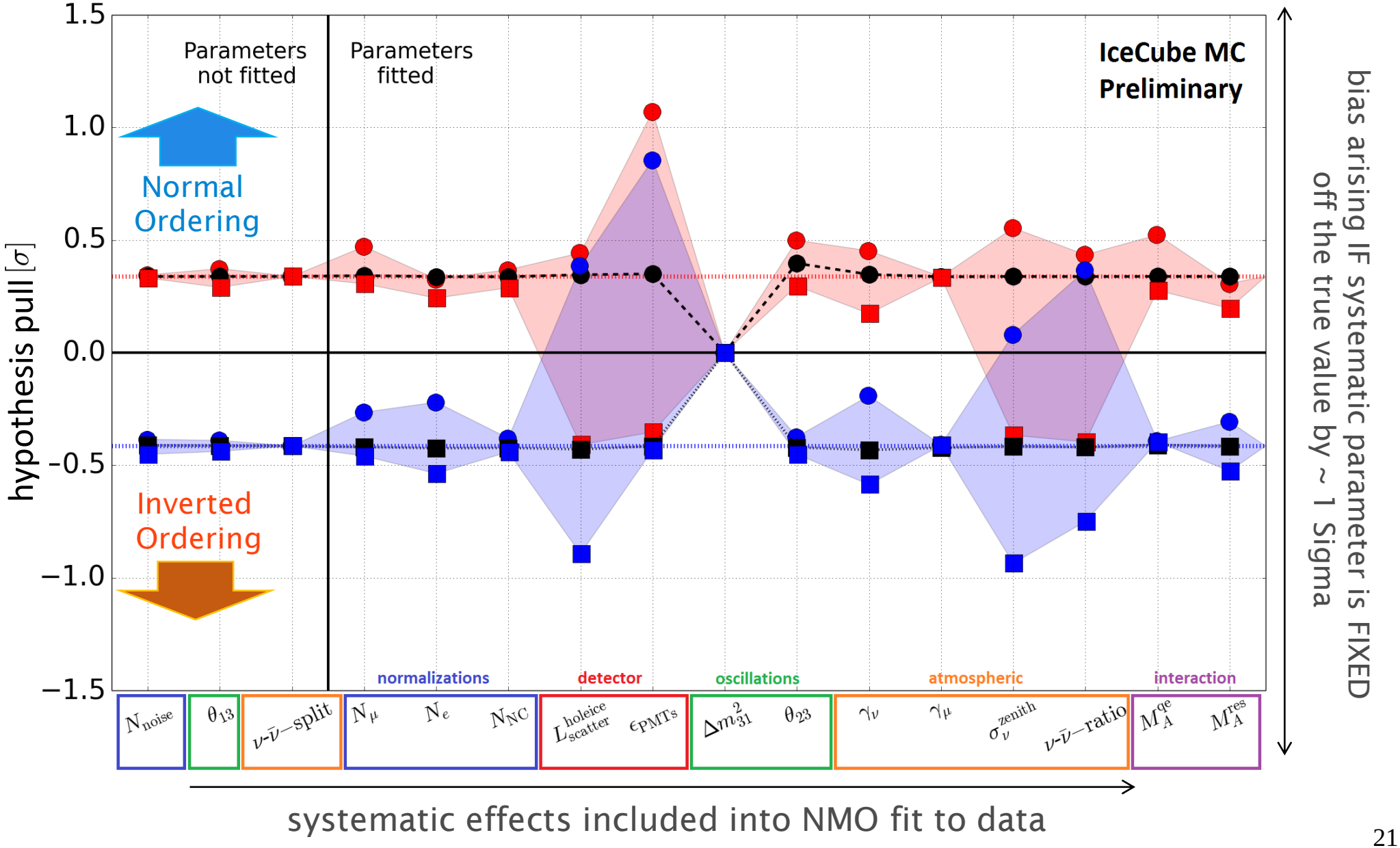
Analysis B



regarding strong θ_{23} dependence of sensitivity

Systematic Influences …

… understanding detector and physics



Summary & Outlook …

… and a short discussion

Summary

- NMO measurement is key goal of many future neutrino experiments (e.g. PINGU)
- Already currently running IceCube/DeepCore detector can explore this type of measurement
  - Extreme low-energy, ($E_\nu > 5\ GeV$), high-statistics data samples
  - Challenging energy regime for data selection and reconstruction
  - Test NMO with 2 independent analyses with different focuses
- Stand-alone sensitivity of $\sim 0.3 - 0.7\sigma$ (depending on value of θ_{23})
- Explore this type of measurement for future PINGU extension
  - Analysis chain, understanding and treatment of systematics
  - s. talk by Ken Clark later in this session (IceCube Gen2/Phase I)

Outlook

- Experimental DeepCore result on NMO in near future
- Also, sensitive to testing matter effects vs. vacuum oscillations

from: http://www.capteurdereve.fr/

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Thank you!
… any questions?

Outlook

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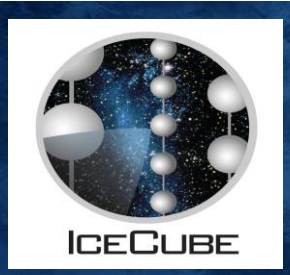


BACKUP

Reconstruction in IceCube…

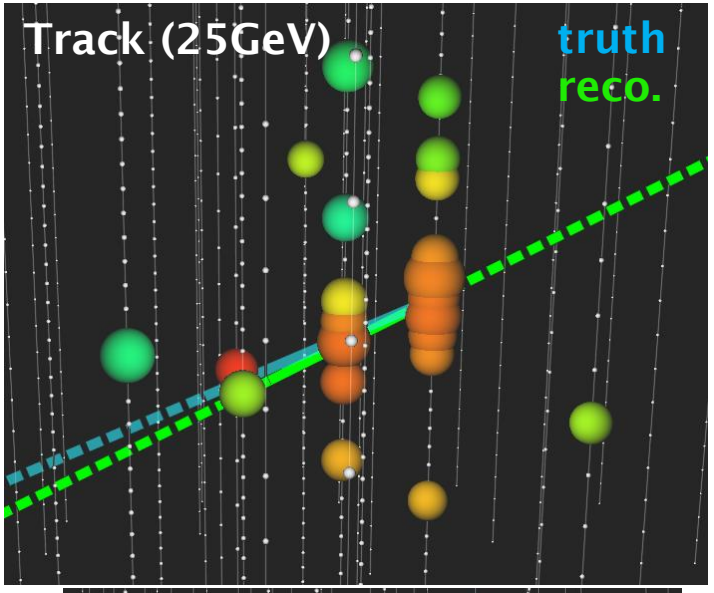
… at the lowest energies

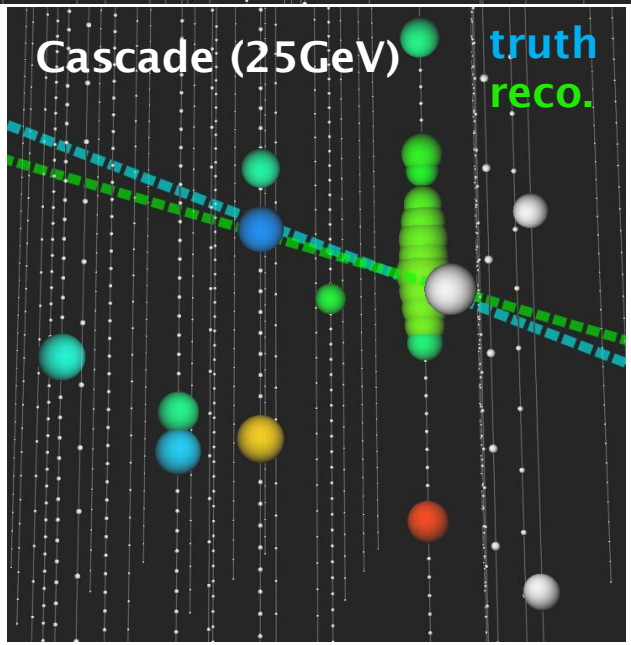
Event reconstruction based on Likelihood-Fit:

- Poissonian likelihood, comparing seen and expected photons in all optical modules:

$$\mathcal{L} = \prod_{i=1}^{N_{OM}} p\left(n_\gamma^{\text{seen}} \mid n_\gamma^{\text{expect}}(\text{hypothesis})\right)$$

- Expectation including ice properties and detector response
- Fitting cascade- and track+cascade-hypothesis
- For each hypothesis fit simultaneously: energy, direction, vertex, time, (tracklength)
  - reconstructed **energy** E_ν
  - reconstructed **zenith angle** ϑ_ν
- Separation of tracks and cascades using Log-Likelihood-Ratio (called PID):
  - $PID = \log(\mathcal{L}_{\text{track}}) - \log(\mathcal{L}_{\text{casc}})$





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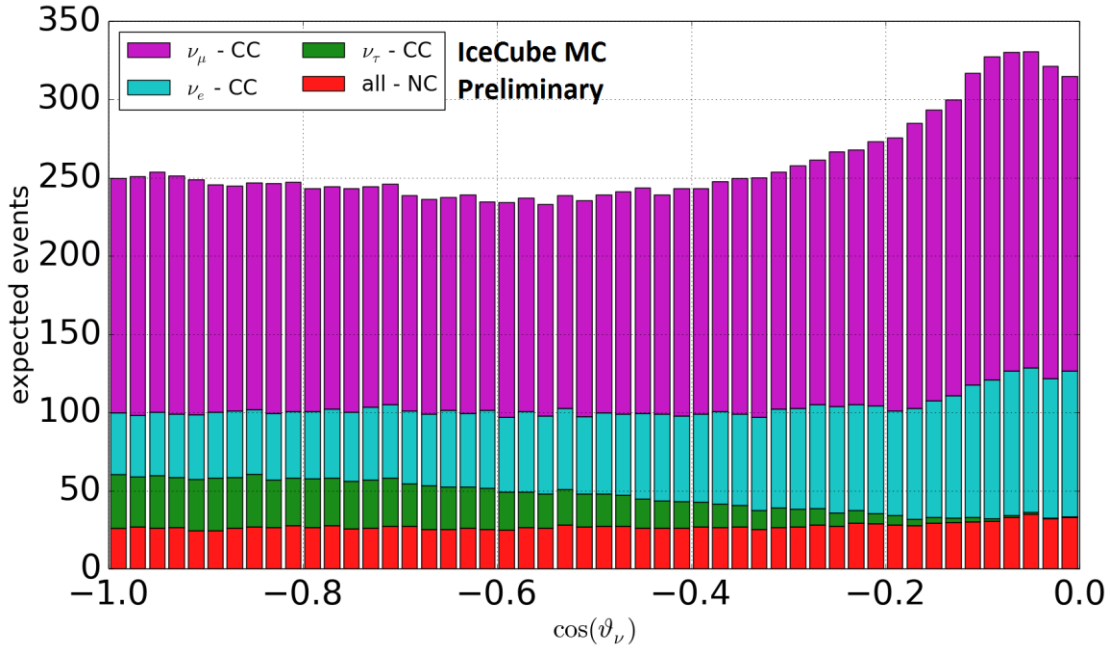
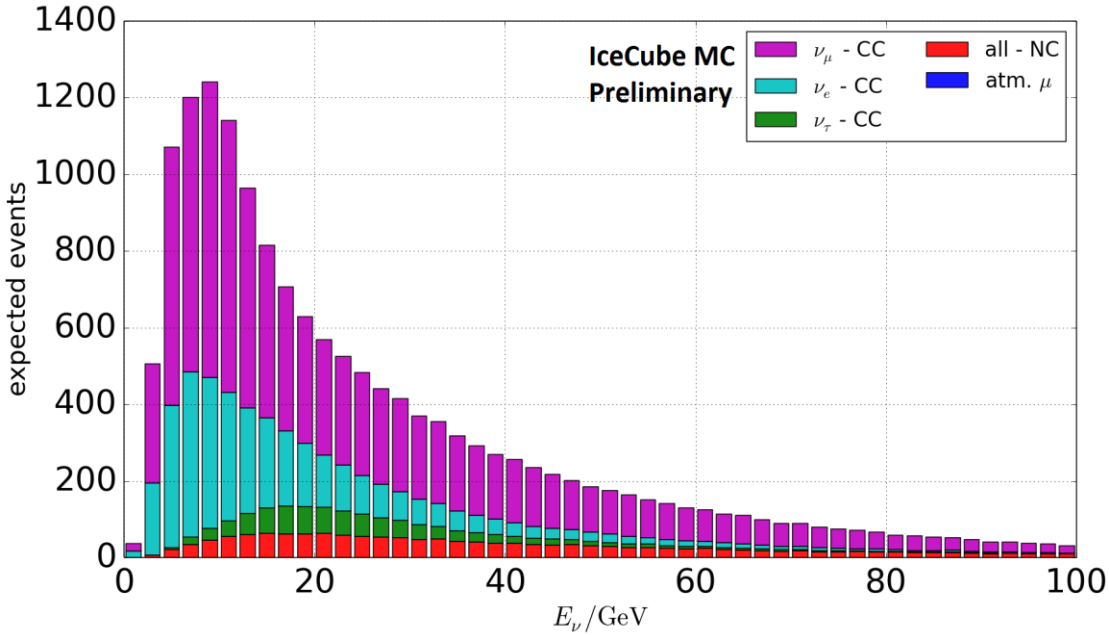


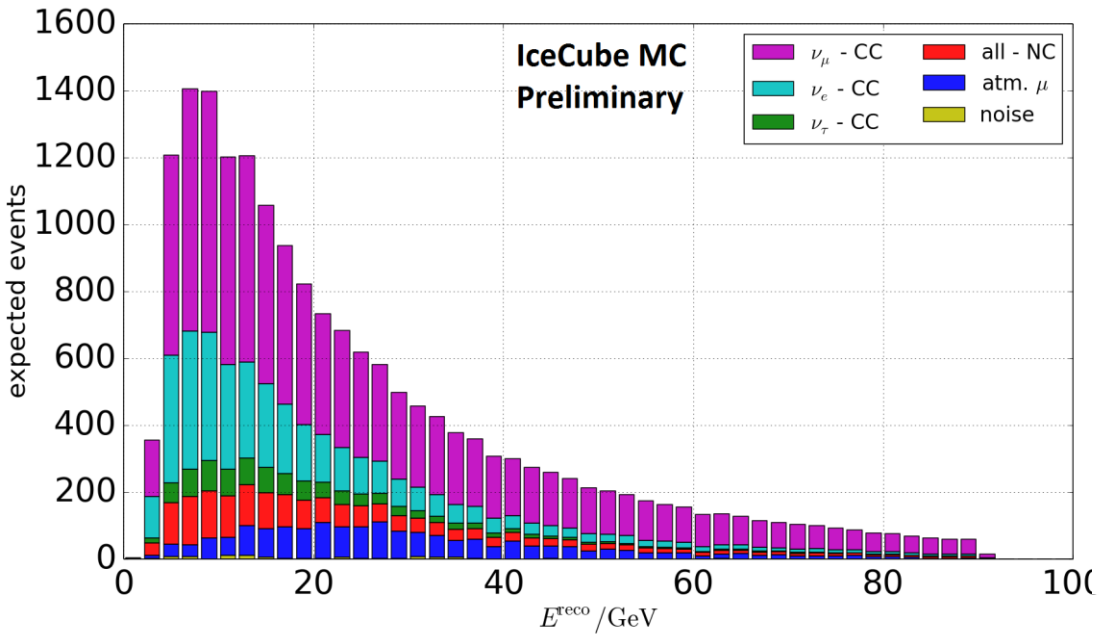


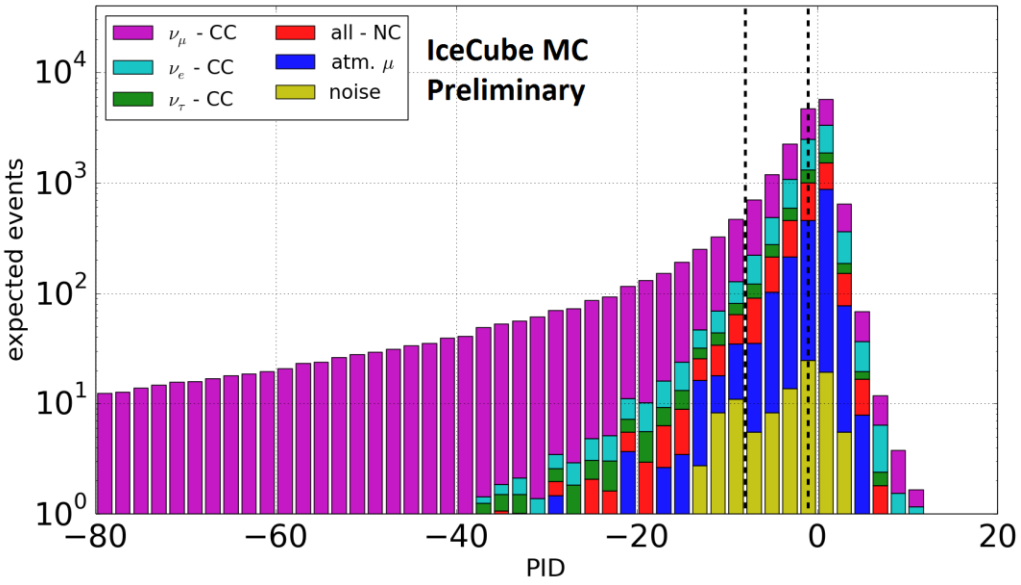
Distribution of …

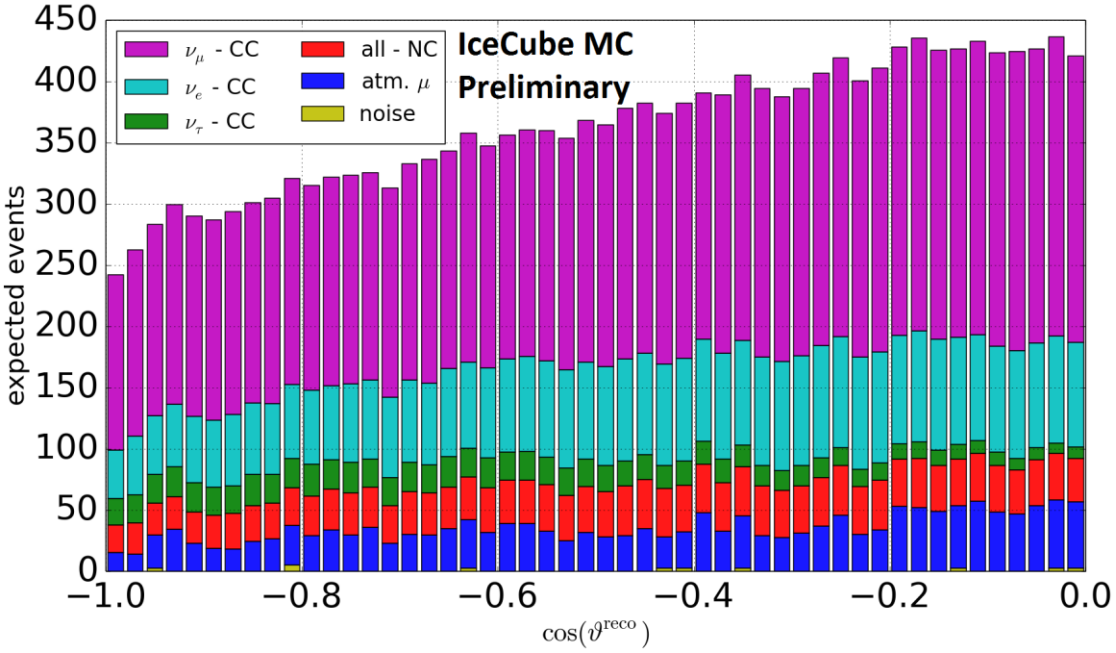
- true energy
- true zenith

… as predicted by IceCube Monte Carlo

BACKUP







Distribution of …

- reconstructed energy
- reconstructed zenith
- flavor separator (PID)

… as predicted by IceCube Monte Carlo