NEUTRINO MASS HIERARCHY with PINGU

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TECHNISCHE UNIVERSITÄT MÜNCHEN

Heisenberg-Programm
Bundesministerium für Bildung und Forschung

thanks to, J. Leute, A. Gross, S. Odrowski, A. Palazzo, D. Franco

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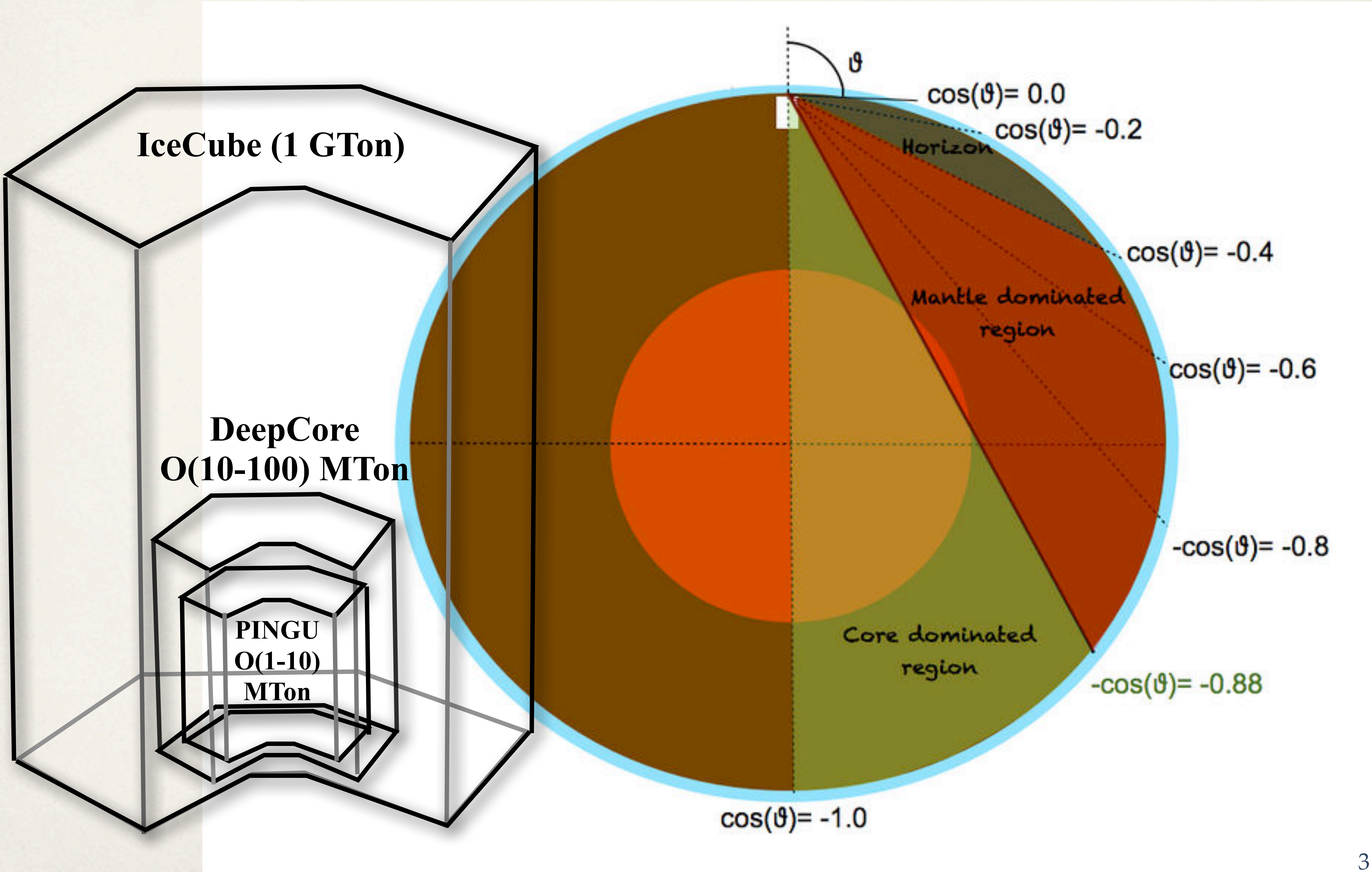
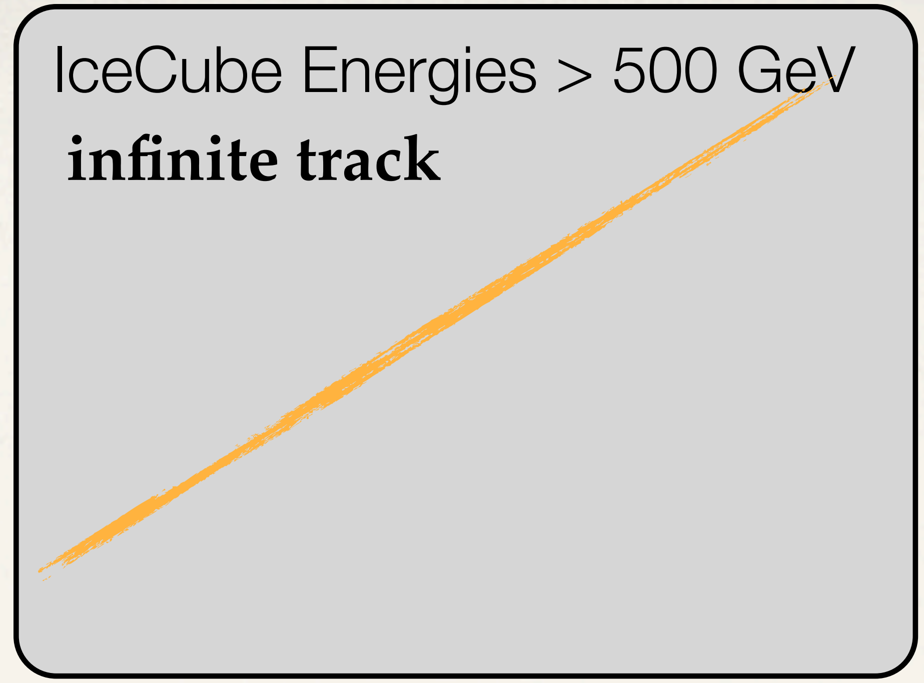
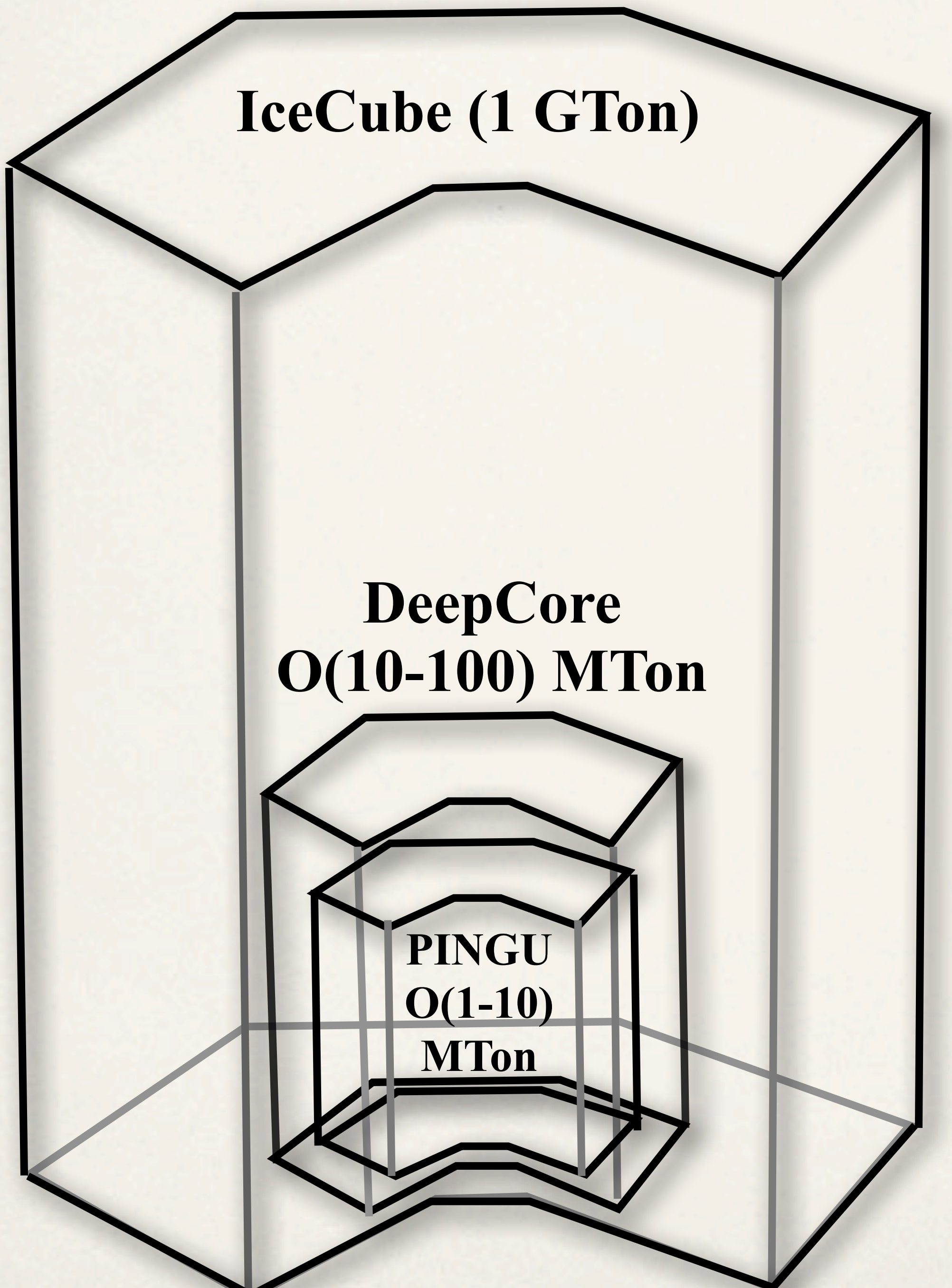
PINGU

SOUTH POLE

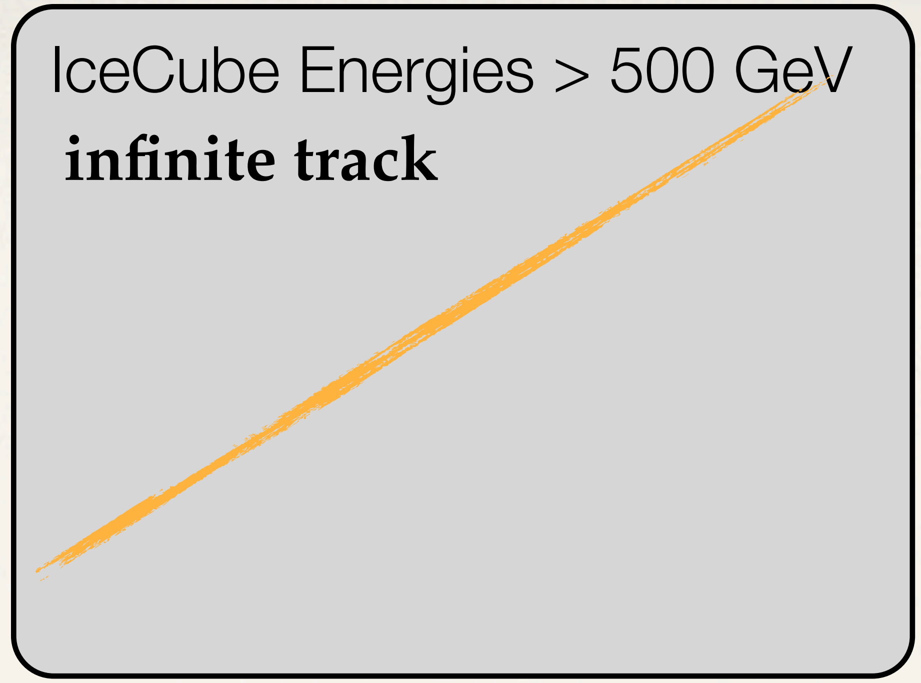


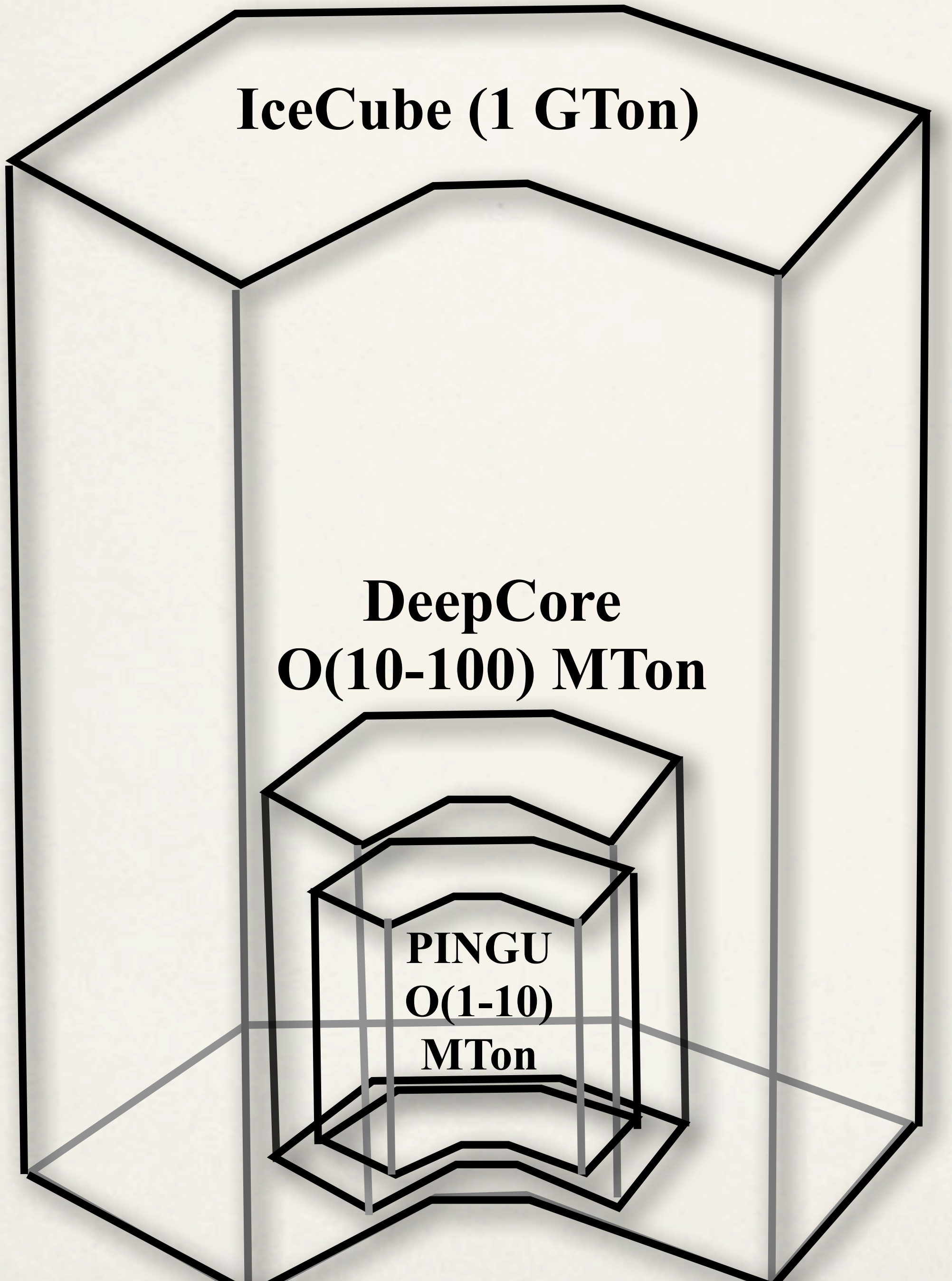
Topology


IceCube Energies > 500 GeV
infinite track


IceCube (1 GTon)
DeepCore
O(10-100) MTon
PINGU
O(1-10)
MTon

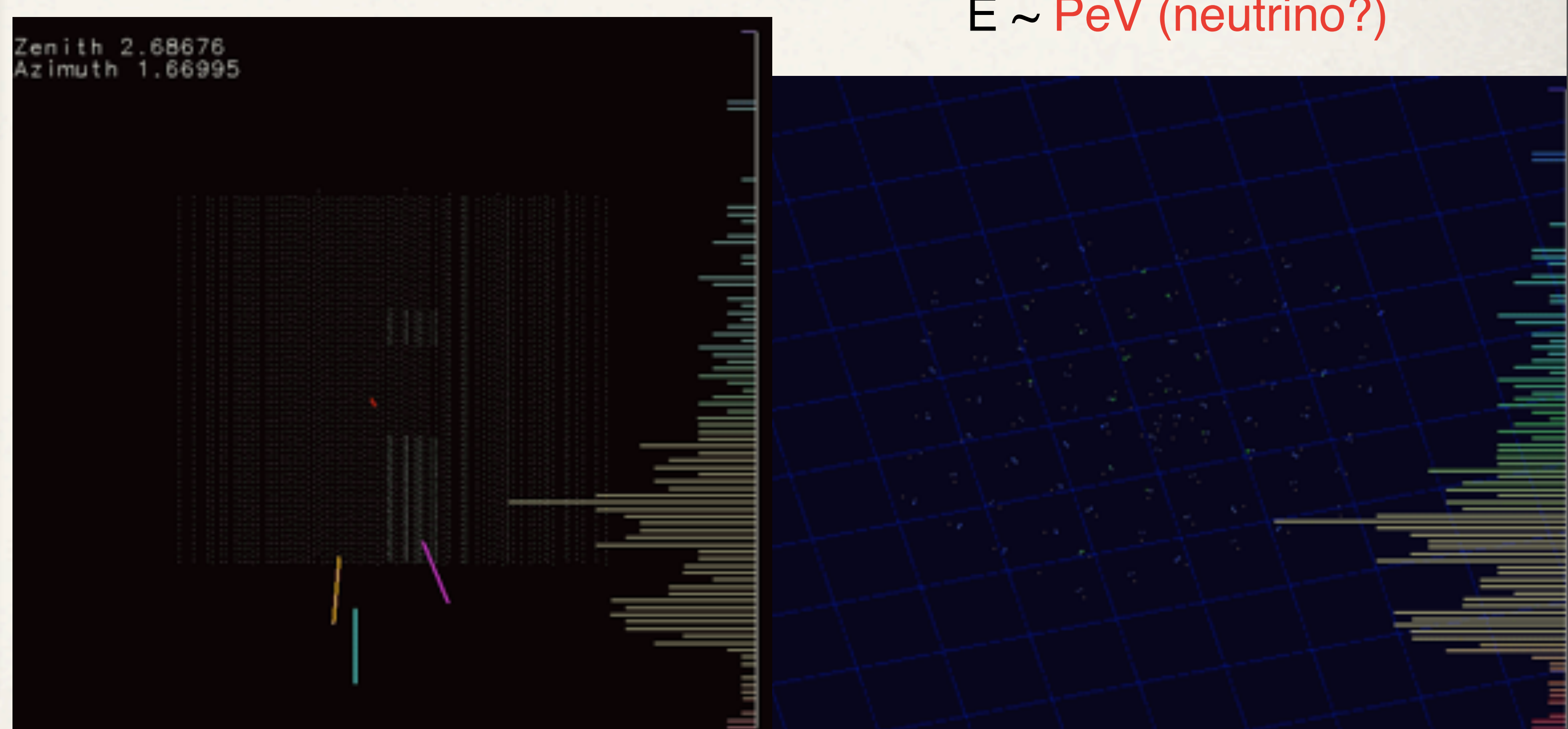
Topology



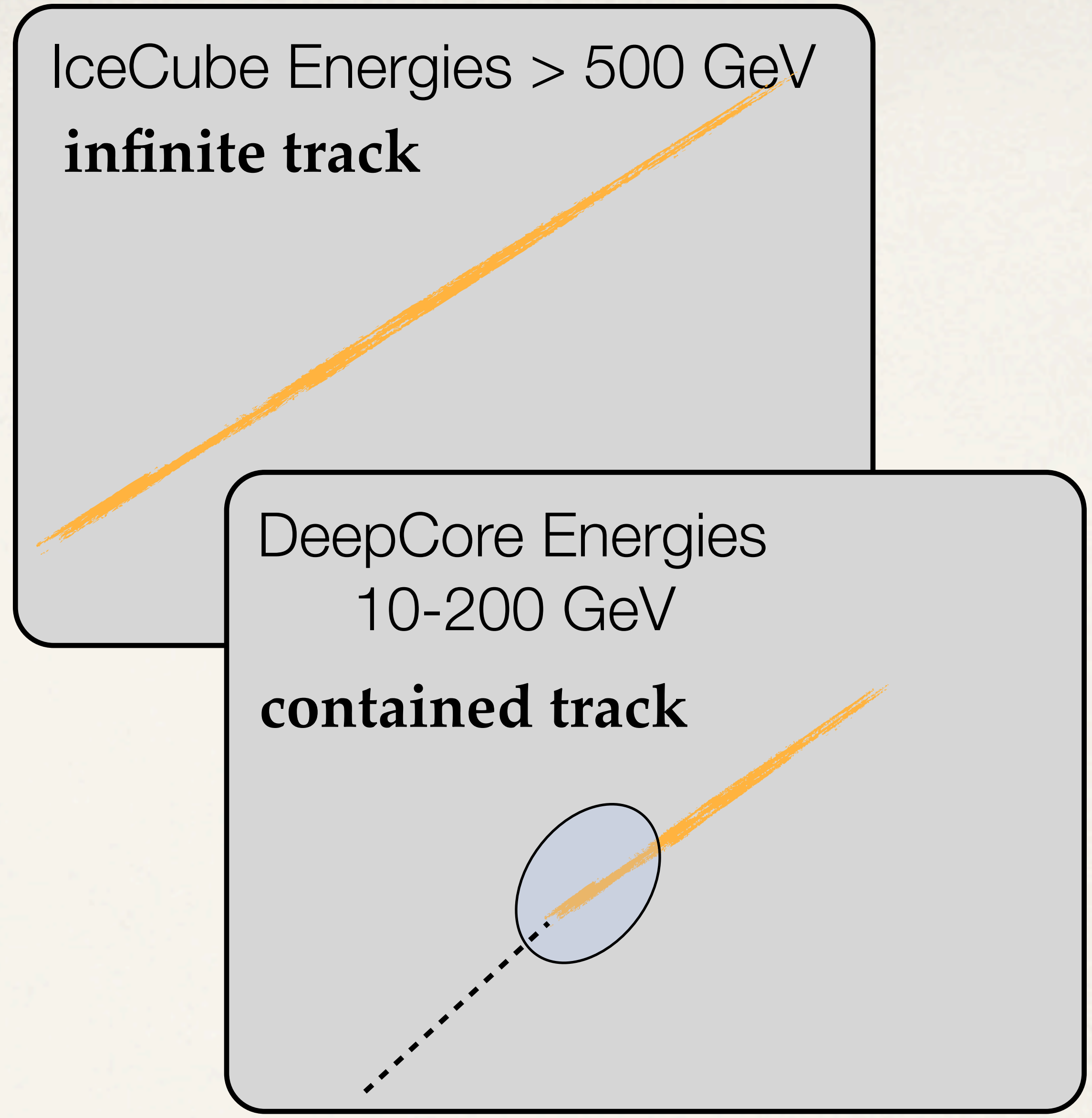


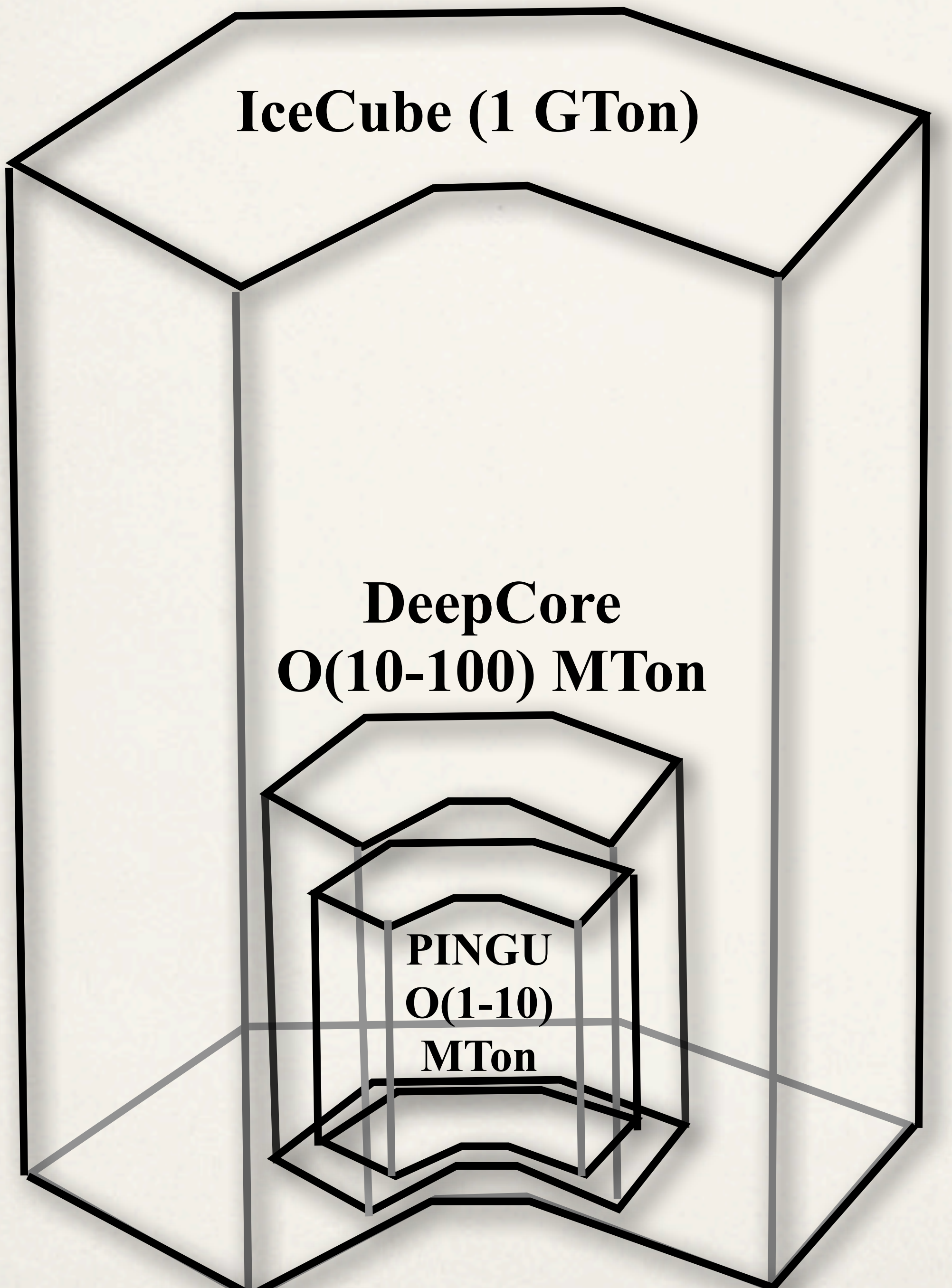
contained cascades

E ~ PeV (neutrino?)

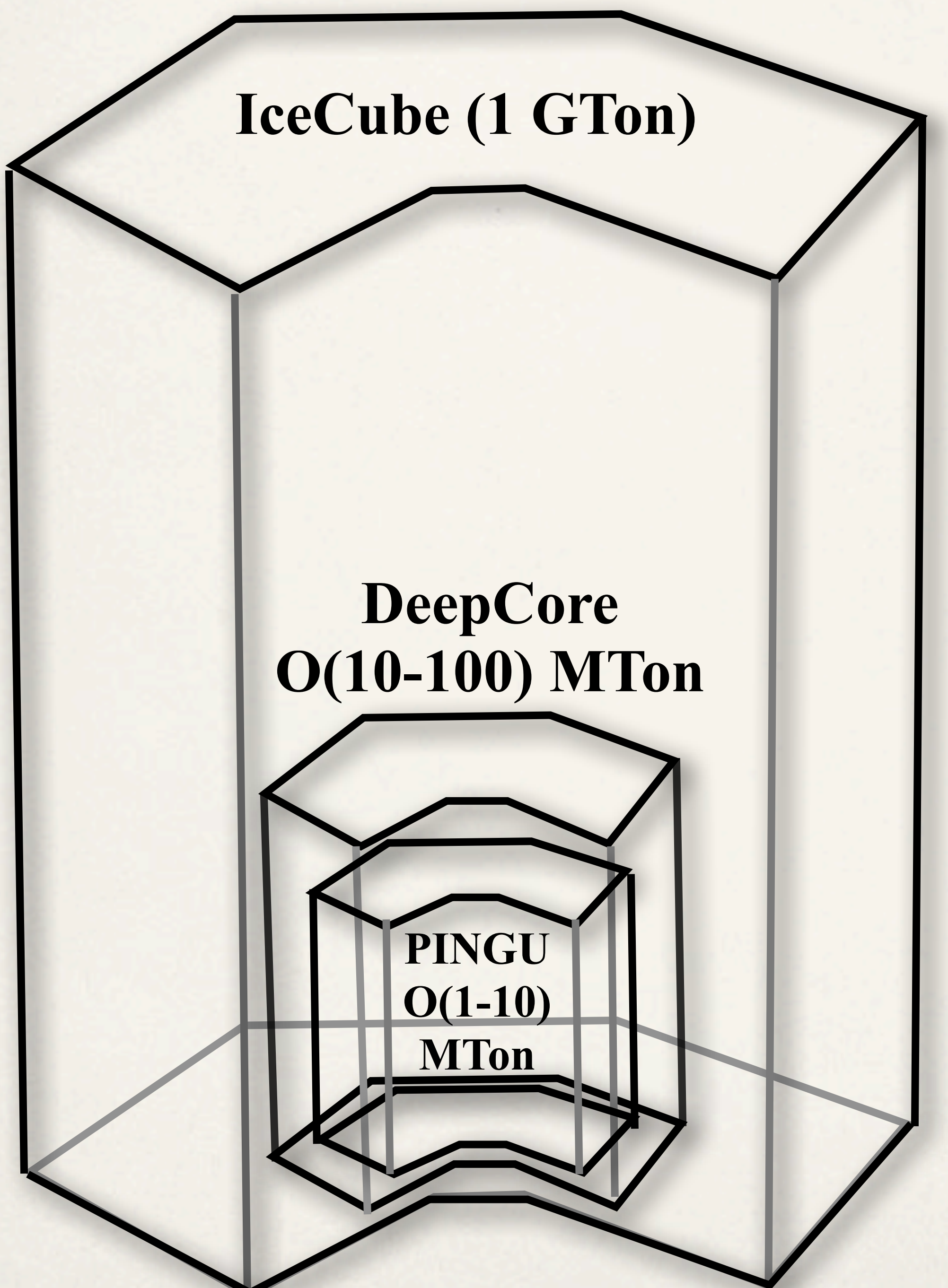


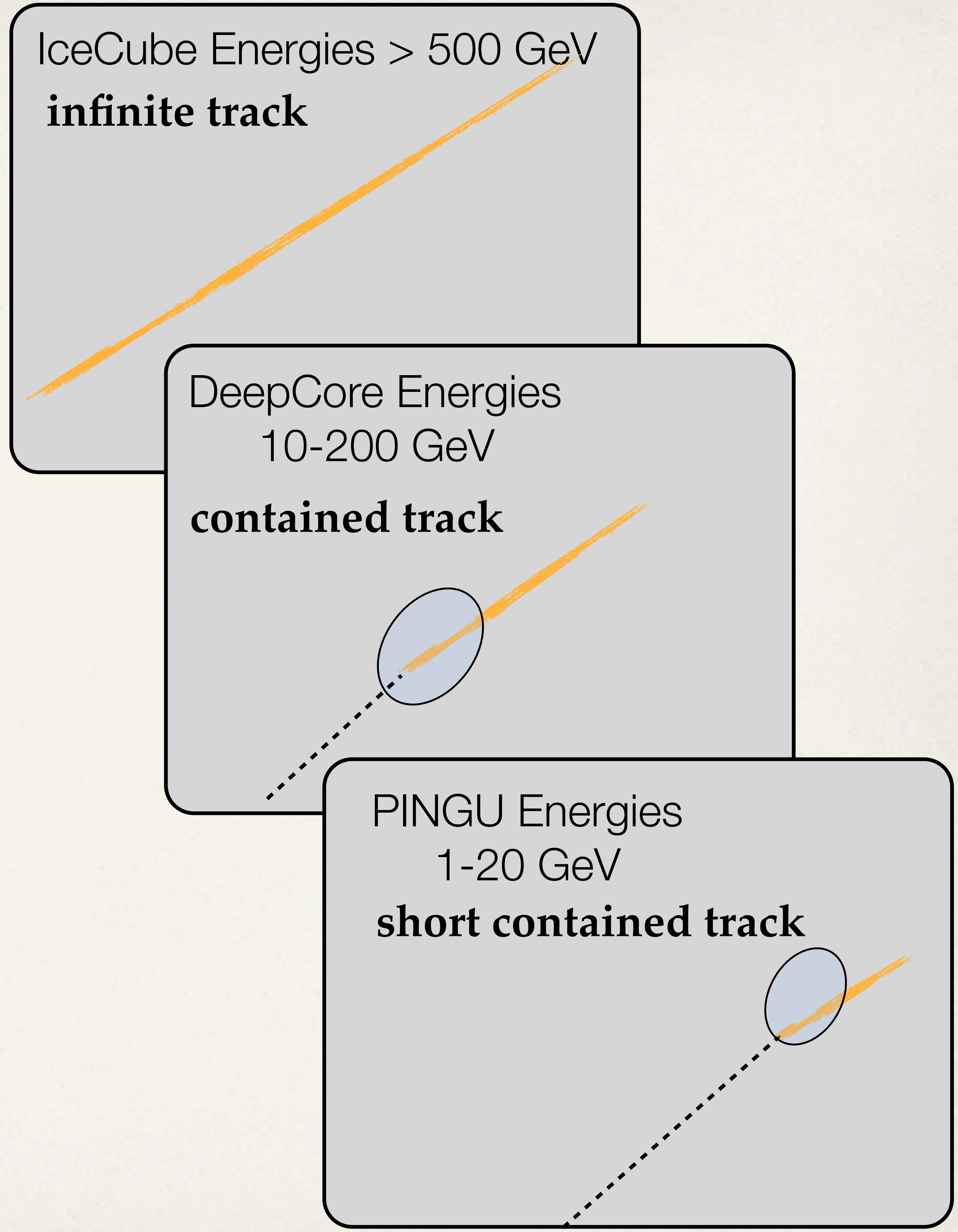
Topology


IceCube Energies > 500 GeV
infinite track
DeepCore Energies
10-200 GeV
contained track

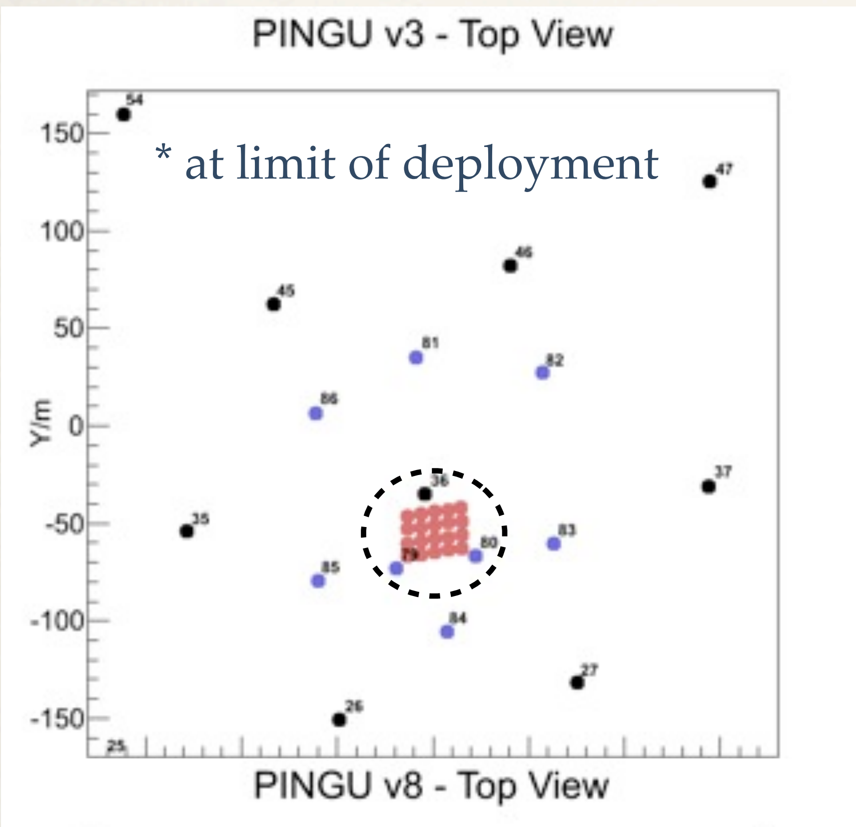

IceCube (1 GTon)
DeepCore
O(10-100) MTon
PINGU
O(1-10)
MTon

Topology

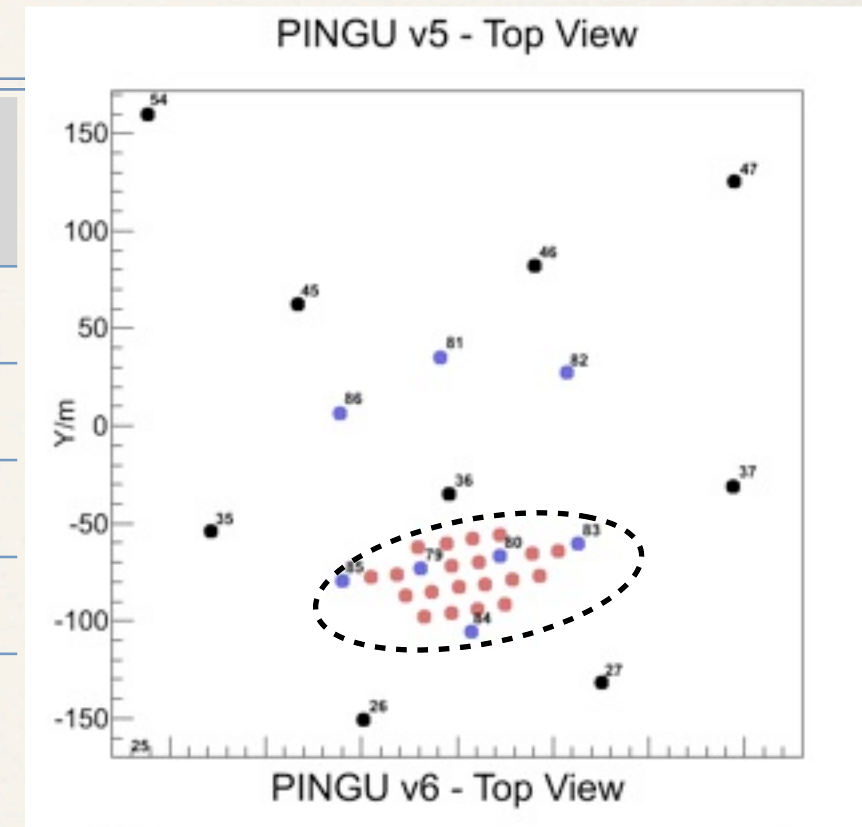

IceCube (1 GTon)
DeepCore
O(10-100) MTon
PINGU
O(1-10)
MTon

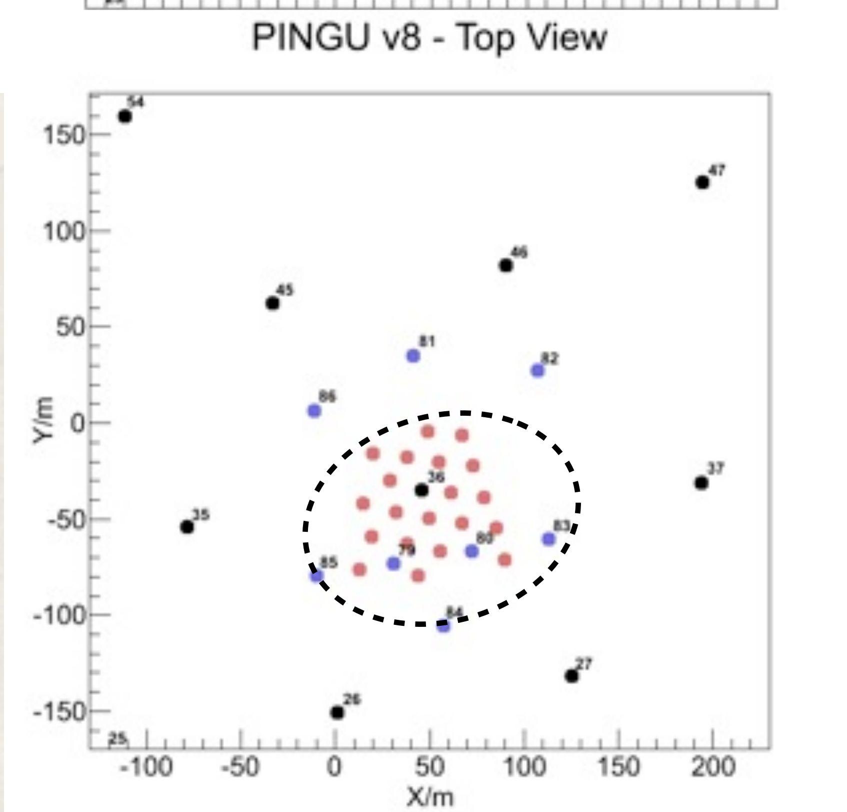

IceCube Energies > 500 GeV
infinite track
DeepCore Energies
10-200 GeV
contained track
PINGU Energies
1-20 GeV
short contained track

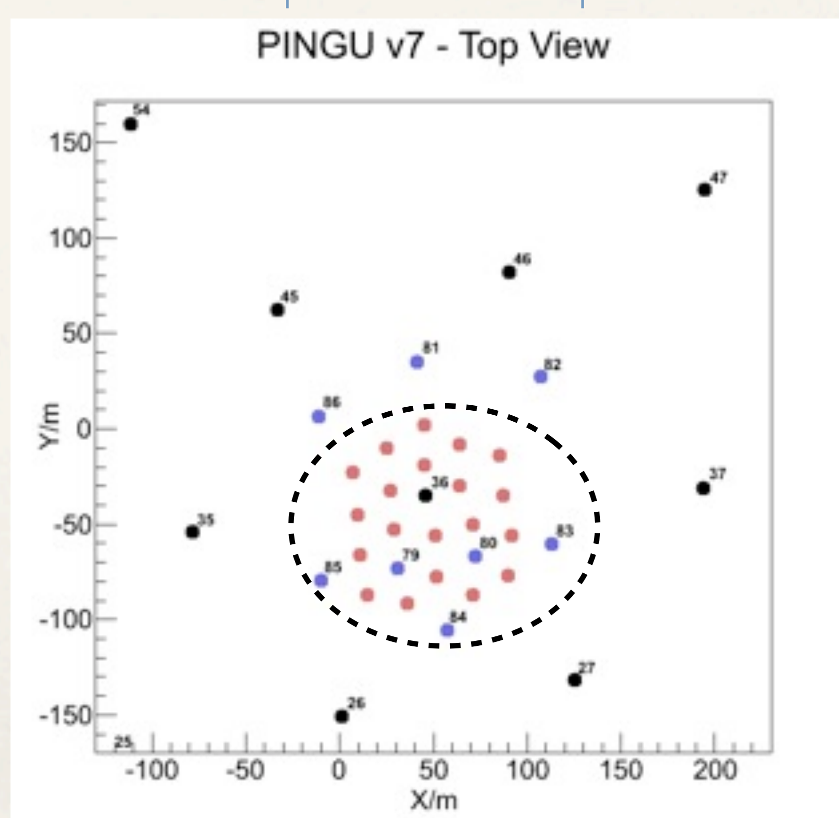
A Range of Geometries for PINGU

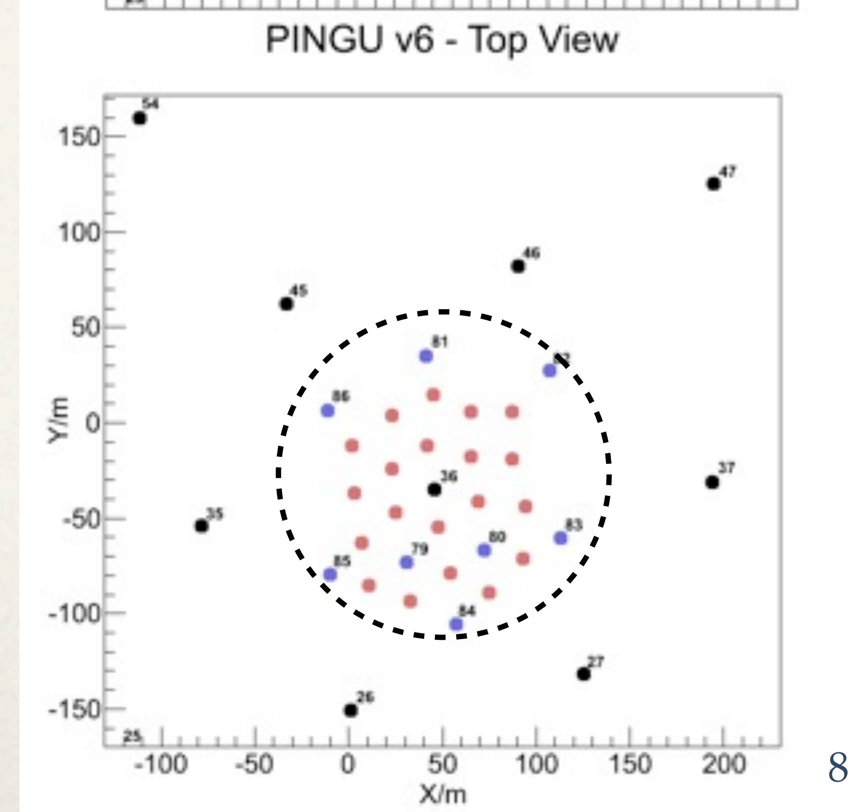


string spacing	DOM spacing	version
7m	3m	v3
14m	5m	v5
18m	5m	v8
22m	5m	v7
26m	5m	v6







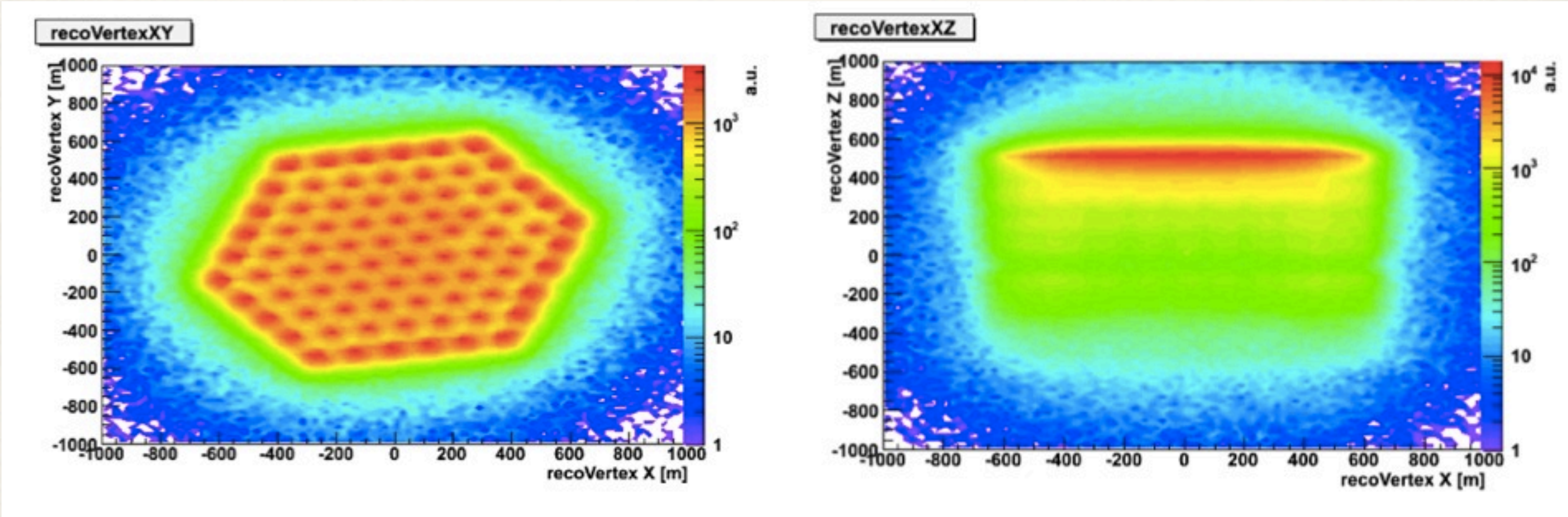


DeepCore: lessons for PINGU

- Atmospheric background fight by **containment and reconstruction.**
- Electron neutrinos: detected! very important component for PINGU/ORCA. This is not equivalent to a flavor identification though.
- Muon neutrinos disappearance -> oscillation analysis with high significance but not that high precision yet. More in the pipe-line (samples with 10x more statistics). Competitive with world-best values?
- How to propagate and make diagnostic of systematic uncertainties: one strategy completely implemented (see poster from A. Gross).
- Test on full simulation chain for assessment of single systematic and sensitivities (see poster from J. Leute).

DeepCore: Rejection of atmospheric background

Corsika background (IC80) reconstructed vertex



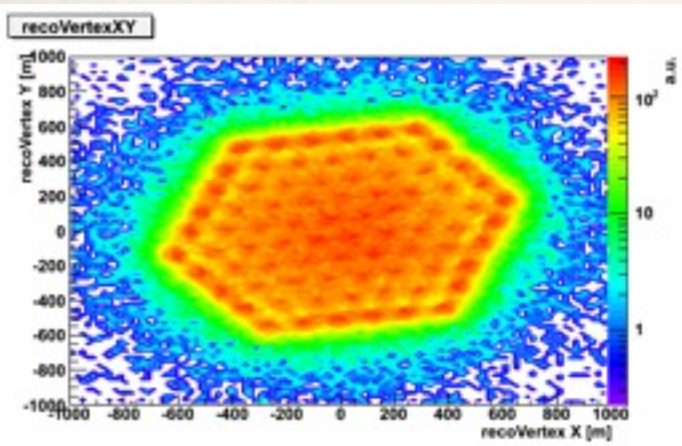
from DeepCore design study meeting in Stockholm, 2008

DeepCore: Rejection of atmospheric background

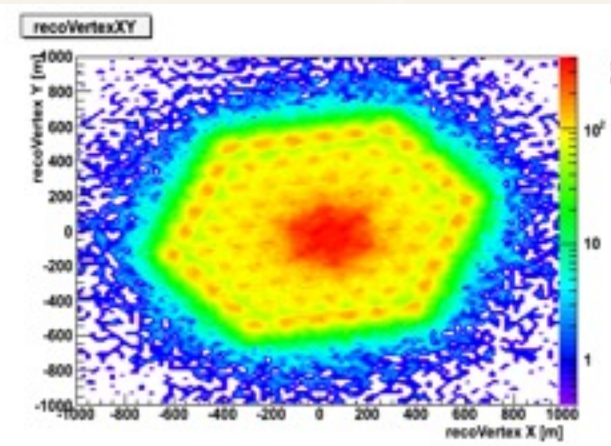
IC80 + 12 strings DeepCore

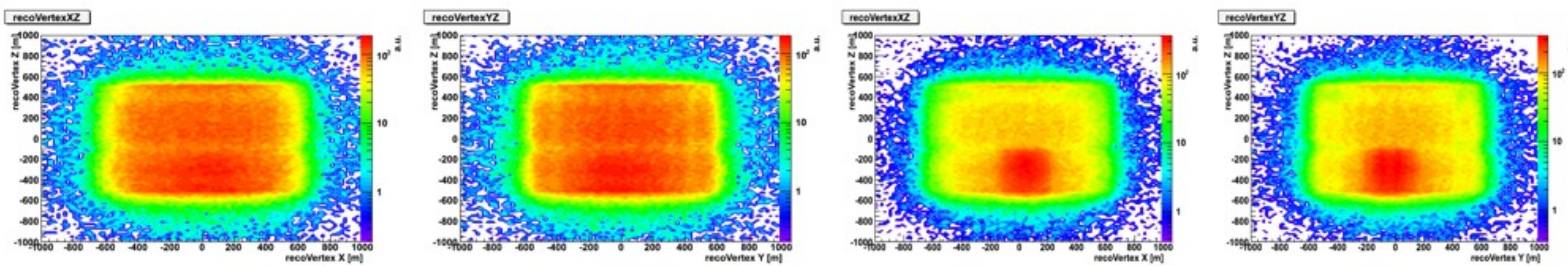
IC80 ν - vertex

ν - vertex



- MonteCarlo simulation
- 4π neutrino simulation
- E [5 GeV – 50 TeV]
- E^{-2} spectrum



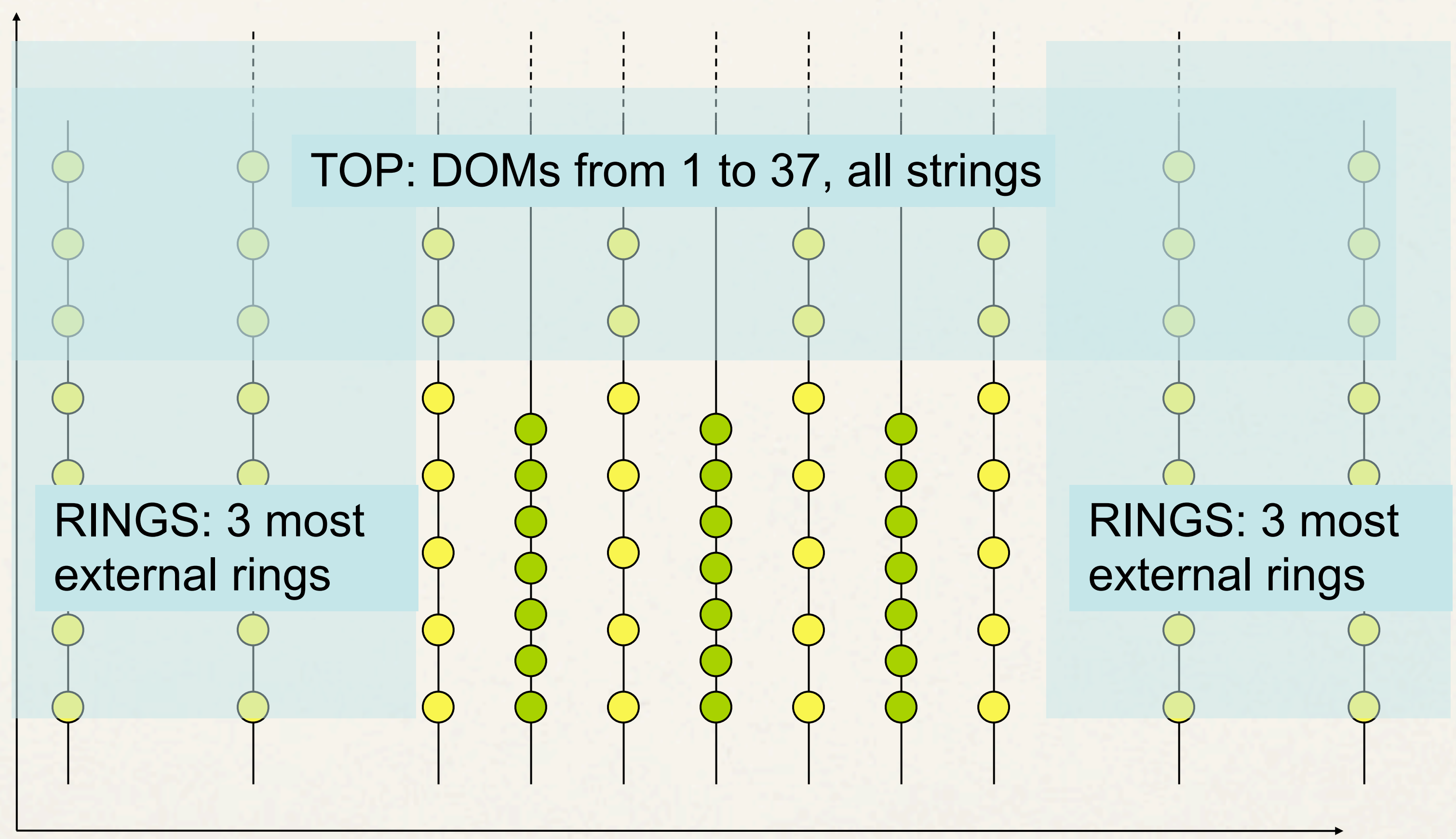


Actual DC: 8 strings

from DeepCore design study meeting in Stockholm, 2008

DeepCore: Rejection of atmospheric background

Containment cuts: enough for the reduction of the first 3 - 4 order of magnitude atmospheric background



from DeepCore design study meeting in Stockholm, 2008

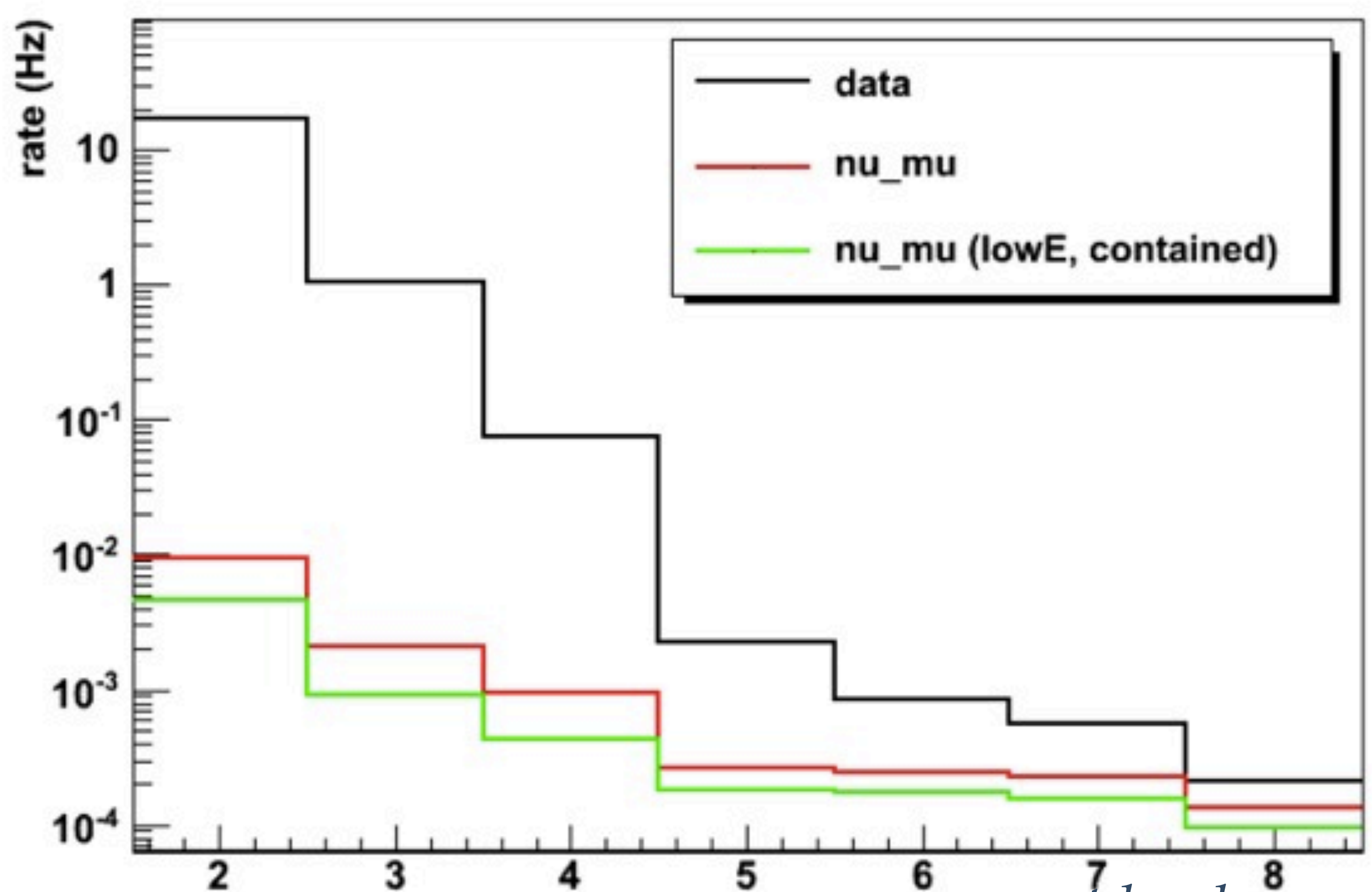
DeepCore: Rejection of atmospheric background

Containment cuts: reduction of the first 3 - 4 order of magnitude atmospheric background.
Various study performed in this direction, new variables at mature stage.

Example of analysis progression:
Up to L5, with containment only

Signal efficiency in DC:
~10-20% for a high pure sample (>95%).

for example, IC79 DC study



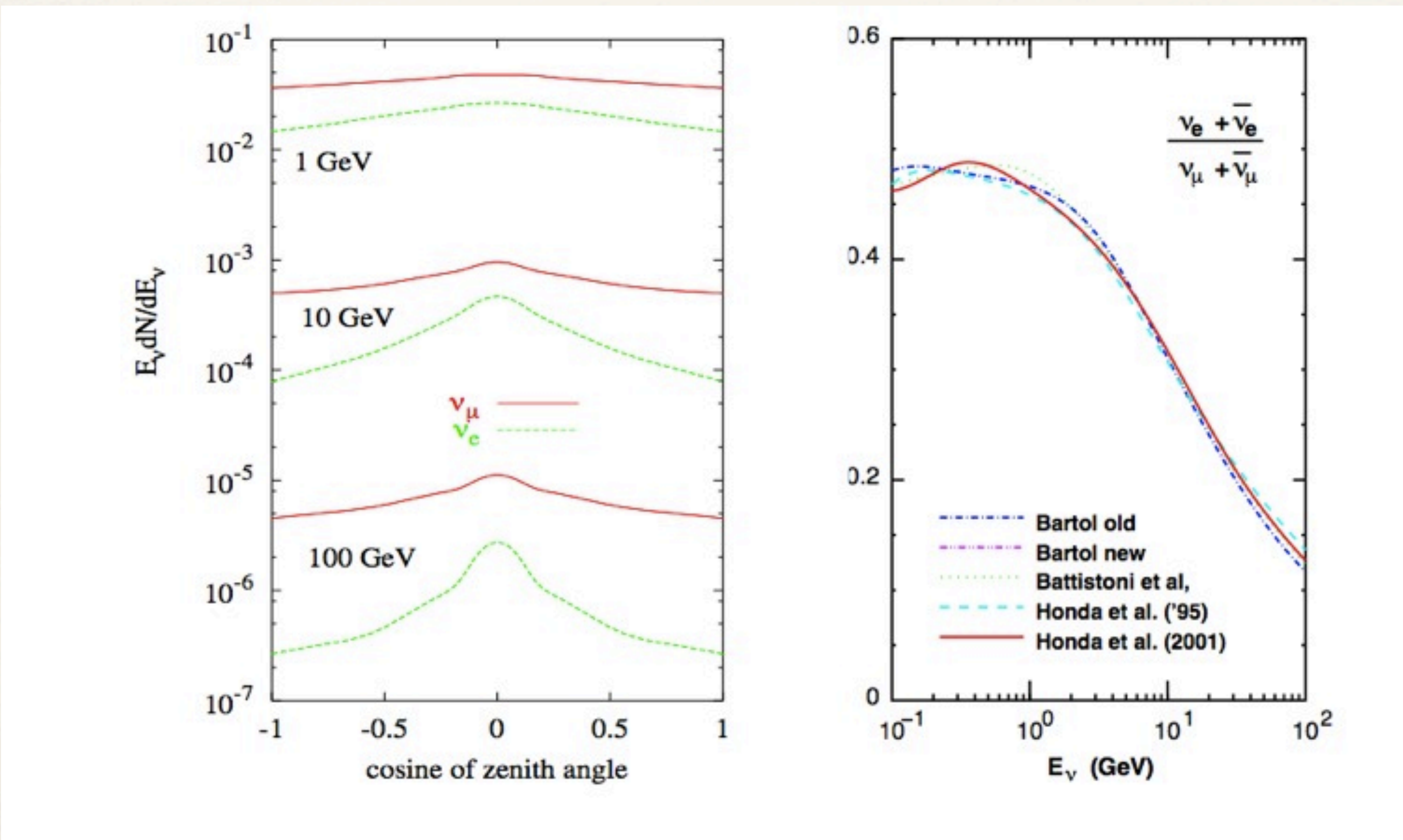
cut level

DeepCore: electron neutrinos

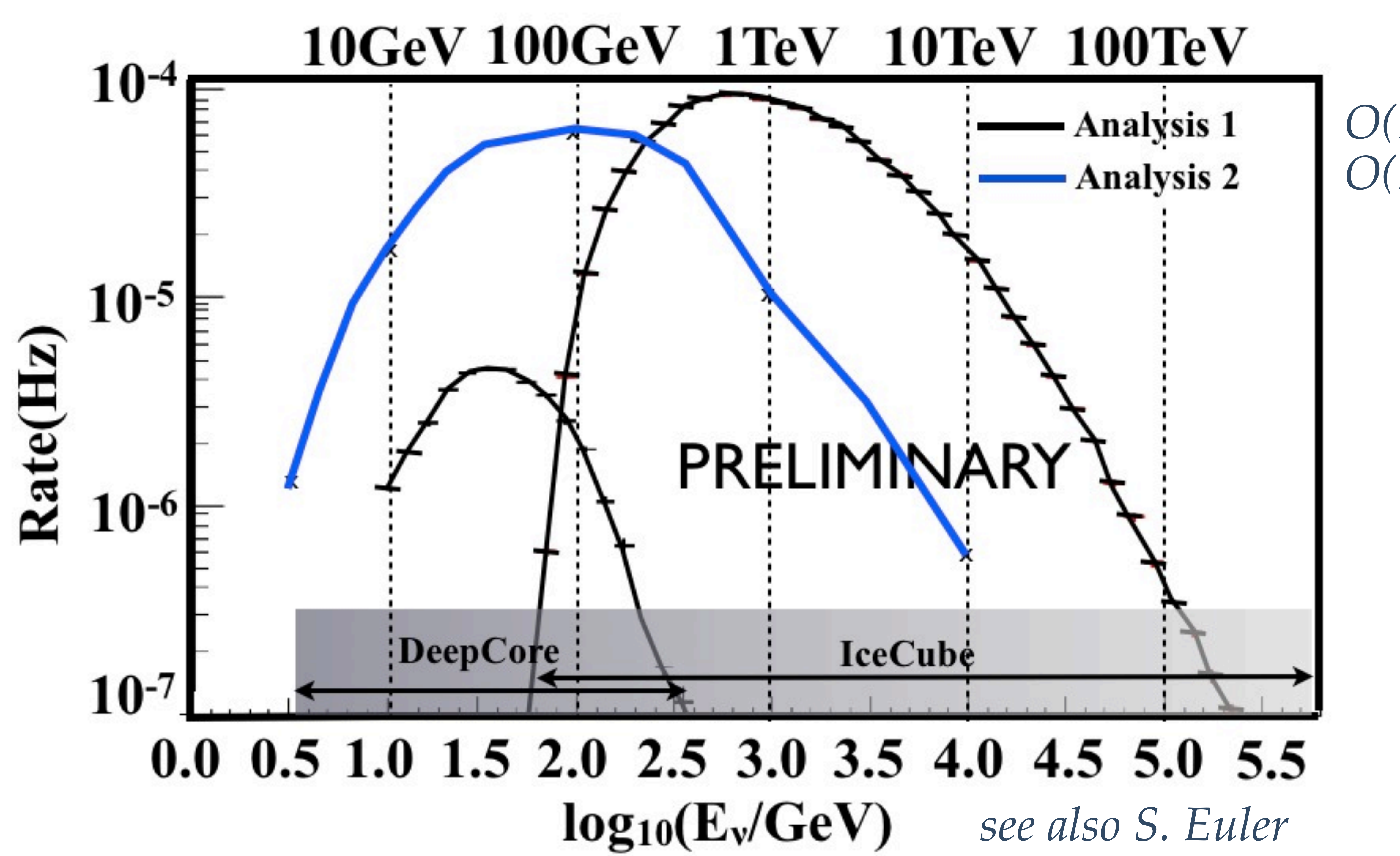
for PINGU/ORCA:

at lower energy electron neutrinos are more !!!

T.K. Gaisser and M. Honda, arxiv.org/pdf/hep-ph/0203272v2.pdf



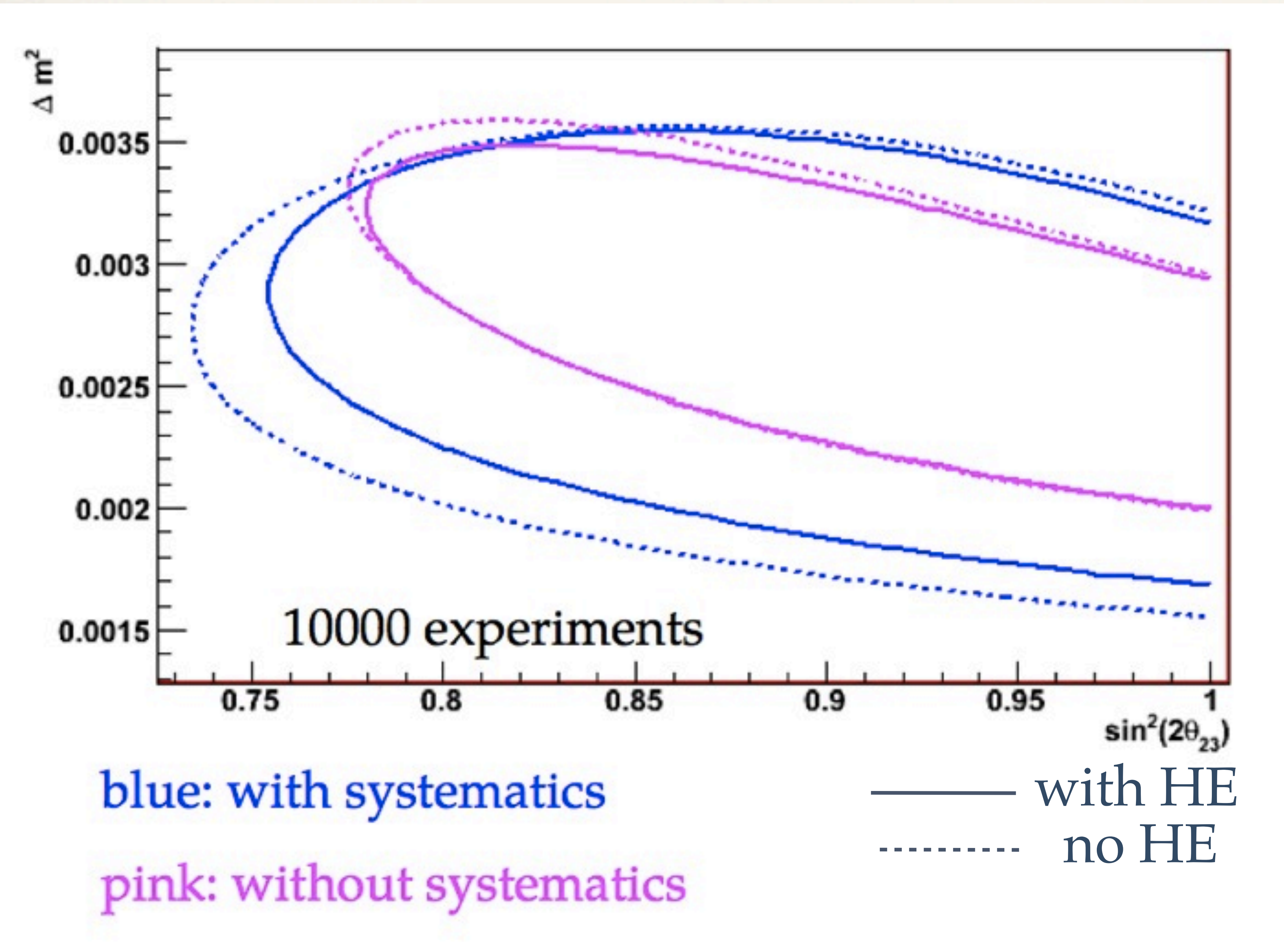
DeepCore - muon neutrino disappearance: much more to come!



O(10³)
O(10⁴)

see also S. Euler

DeepCore: atmospheric neutrino oscillation, impact of a "control-region" data stream

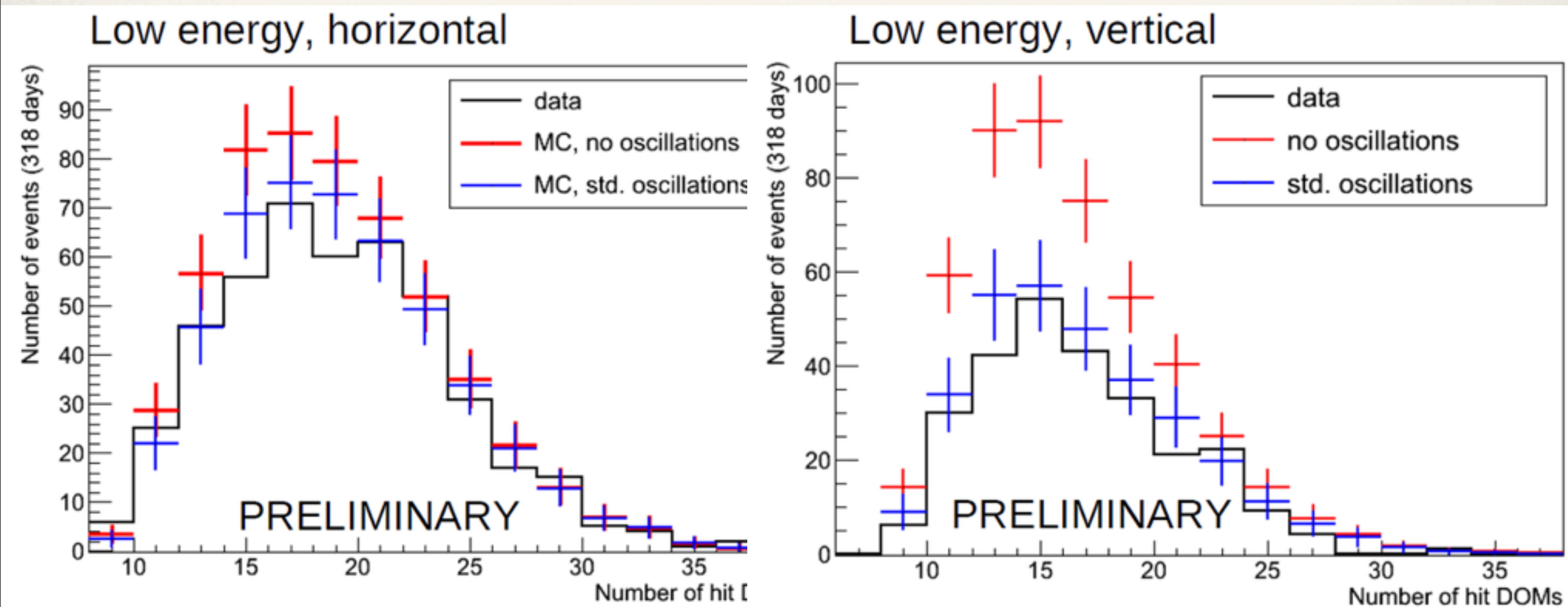


***for PINGU**: control-region (off-sources) data streams can be used to mitigate the impact of systematic uncertainties.*

***IceCube & DeepCore** can be used in a GLOBAL analysis.*

see J. Leute poster

DeepCore: muon neutrino disappearance, energy estimator has an impact!

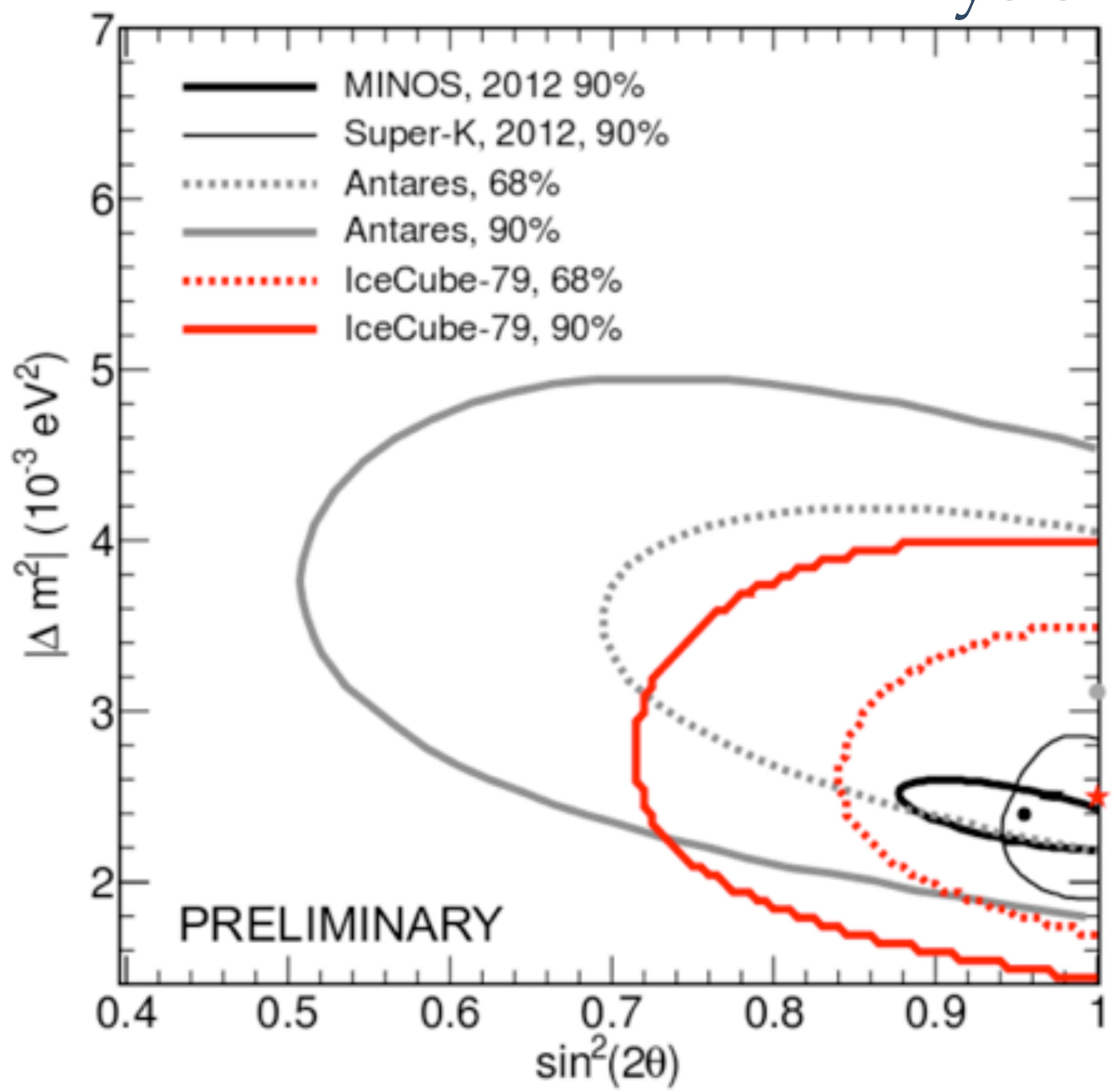


DeepCore: atmospheric neutrino oscillation only zenith

$|\Delta m^2| = [2.5 \pm 0.5(\text{stat}) \pm 0.3(\text{syst})]\ 10^{-3}\text{eV}^2$

$\sin^2(2\vartheta_{23}) > 0.92$ (68% CL)

Analysis 1

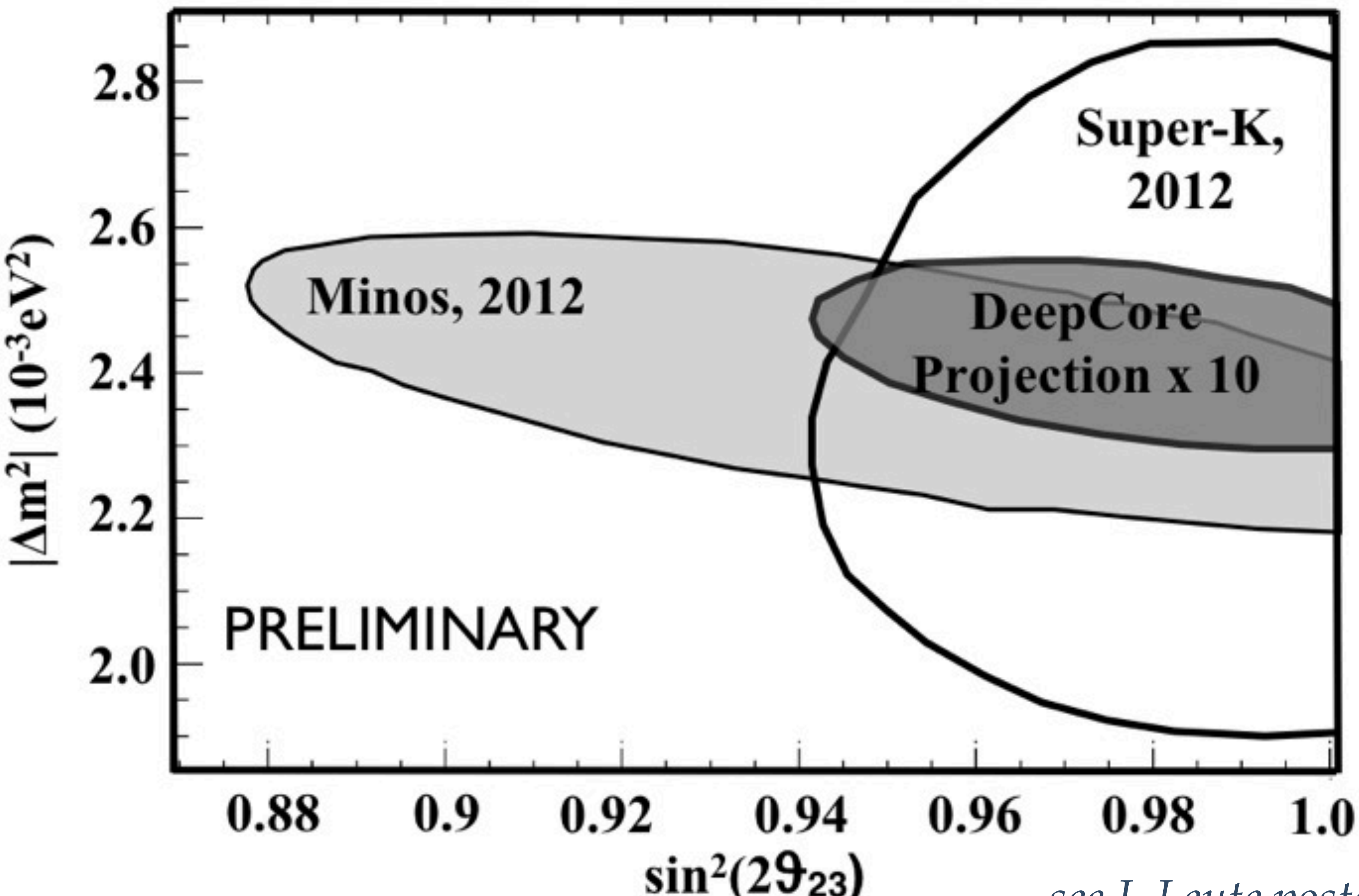


Statistical Errors: improved (see Analysis 2)
Systematic Uncertainties: if 10 times more statistics, then systematic uncertainties dominate.

Experimental systematic uncertainties are the largest one, work on-going to neil them down.

IF systematic uncertainties reduced, power of statistics of huge volume will **win**.

DeepCore: atmospheric neutrino oscillation
are we going to beat the world best fit values?



see J. Leute poster

Projected sensitivity

Analysis 1 where:

- systematics 50% reduced
- 3 bins in true energy
- 10x neutrinos

PINGU
(Precision IceCube Next Generation Upgrade) or Neutrino Mass Hierarchy using Atmospheric Neutrinos

- Hardware
- Reconstruction of the signal: status
- Neutrino mass hierarchy
- Uncertainties
- Approaching sensitivity calculation

PINGU: Hardware

IceCube legacy hardware with various modifications

Minimize cost and risk:

- Simplify Design of DOM electronics
- Simplify Design of Down Hole Cables
- Streamline Deployment
- Use freeze-in proven components from IC
- Work on-going on the break-outs of the cable

Cable cost: ~50% less expensive then IC cables

angular acceptance	as in IC
sensitivity	high QE DOMs (like DC)
timing resolution	as in IC
dynamic range	as in IC (or less)
dark noise	as in IC (HQE)
data rate expected	as in IC
DOM spacing	under study: 6-17 m
# DOM / string	60-80
# Strings	16-20 (unless requested more)
Depth/Environment	as in IC

PINGU: Hardware

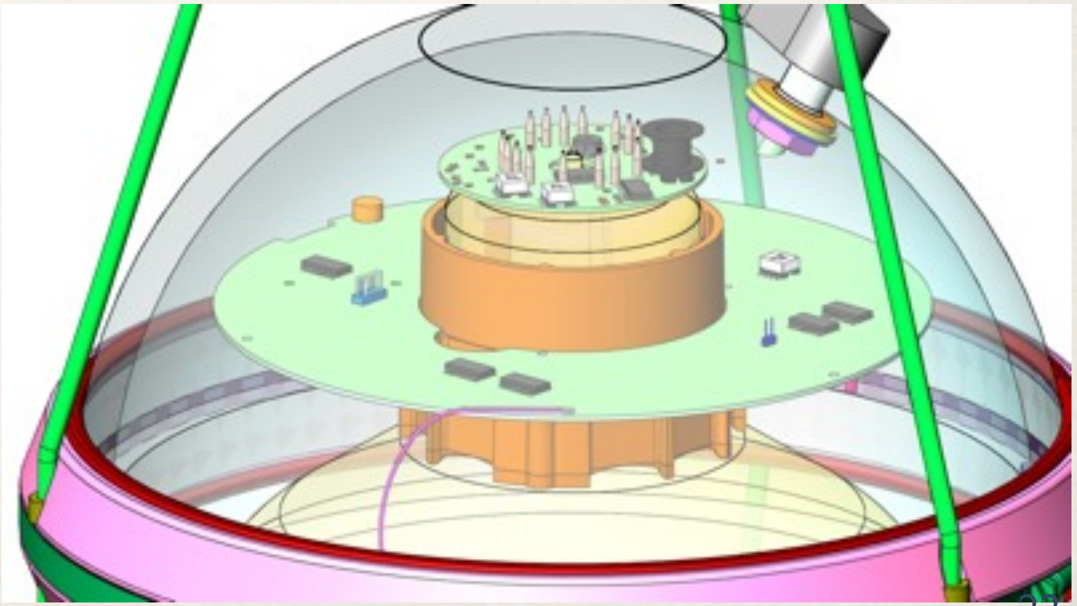
PINGU DOM = **PDOM**

Minimize cost and risk:

- Reduce (50%) power consumption for each single PDOM
- Parts kept: sphere, penetrator, PMT, collar, gel, harness, HV generator and base, quad cable technology
- Parts under new development: digitizer (ADC), circuitry, flasher (LED), FPGA logic, power supply
- Upgrade (partly already planned for IceCube): DAQ (and few others I don't know …)
- prototyping on-going

PDOM cost: ~30% less expensive then IC

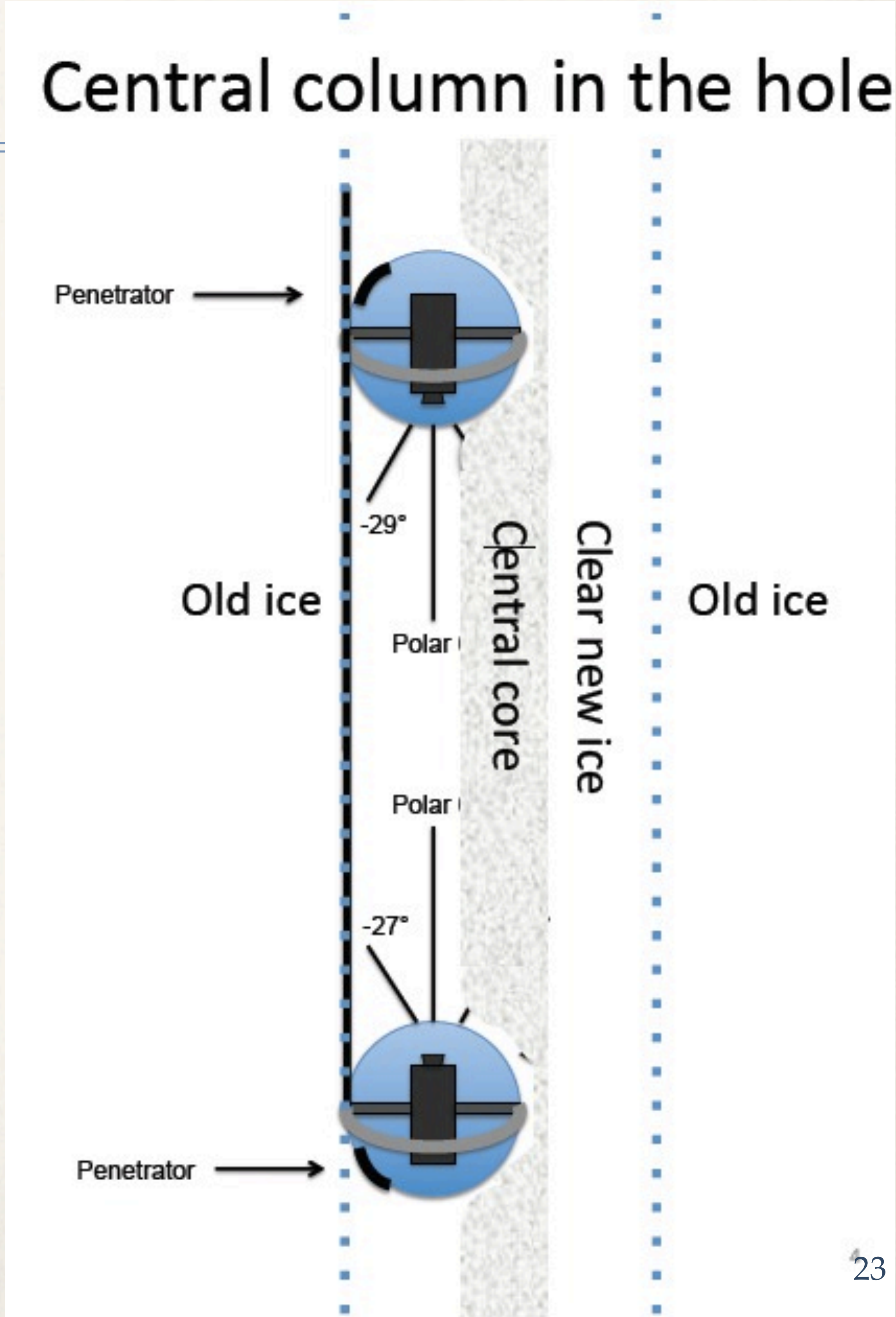
also alternative designs under study



PINGU: the hole ice

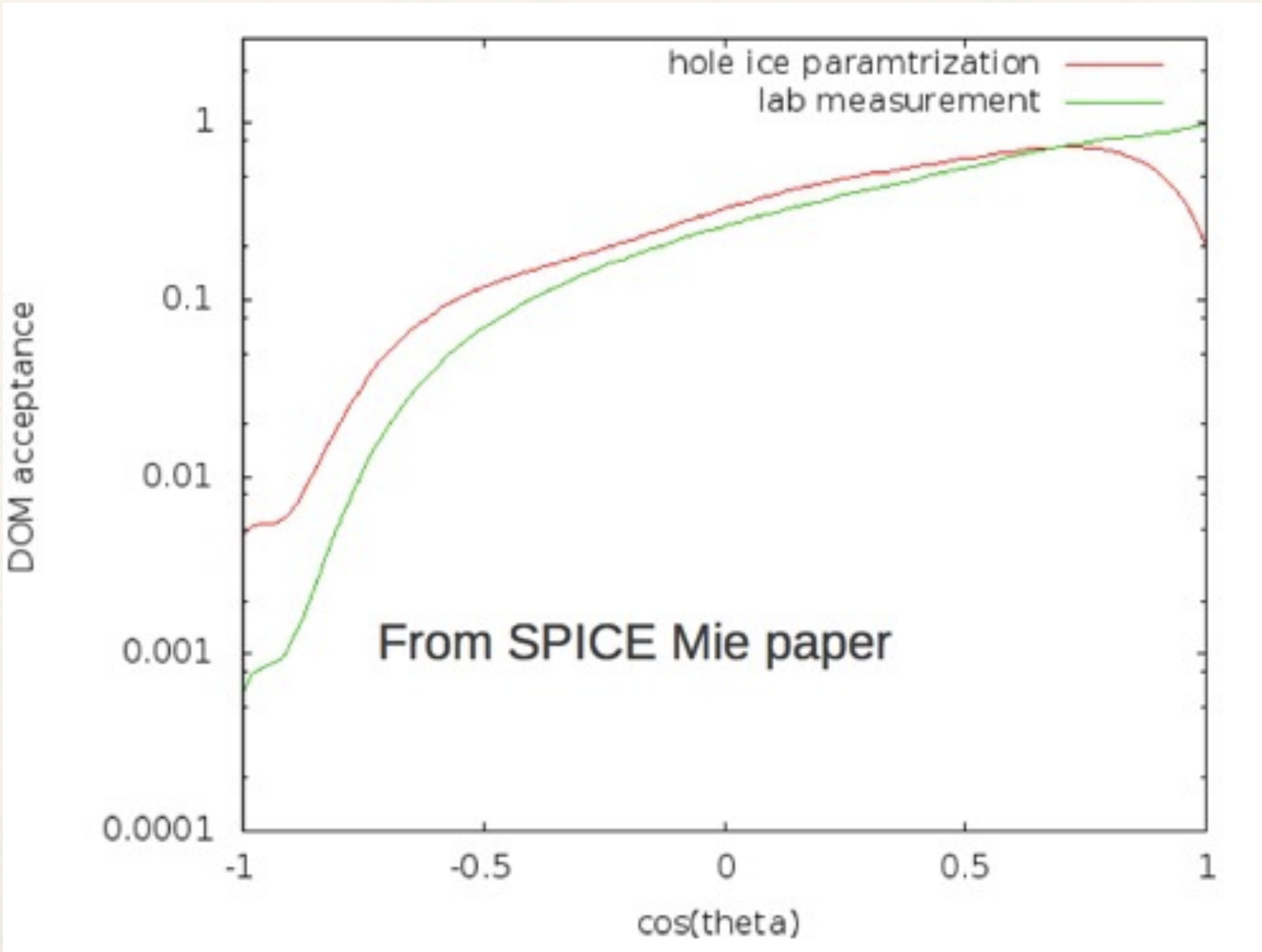
The water in the IceCube drilled holes was not degassed, natural refreezing process allowed.

Air bobbles trapped into a central core. Additional systematic uncertainty.



PINGU: the hole ice

In IceCube, hole ice is modeled in simulation by changing DOM angular acceptance. This works good enough for the moment (tested on oscillation analysis for example).



PINGU: the hole ice, calibration

But for PINGU, we want and we can do BETTER!

Ideas under study:
- add degassing / filtering stage
- addition of clean / degassed water to the hole after drilling
- control the refreezing

Improve *in-situ* calibration: improve LED-flasher system
Minimum pulse width 7ns -> 1ns

~5° -> 1° aim accuracy

30° FWHM beam -> 1° or diffuse beam

~30% uncertainty in brightness -> brightness measured with integrated photodiode (under study)

see also P. Berghaus et al. poster

PINGU: possible time-line (based on IceCube experience)

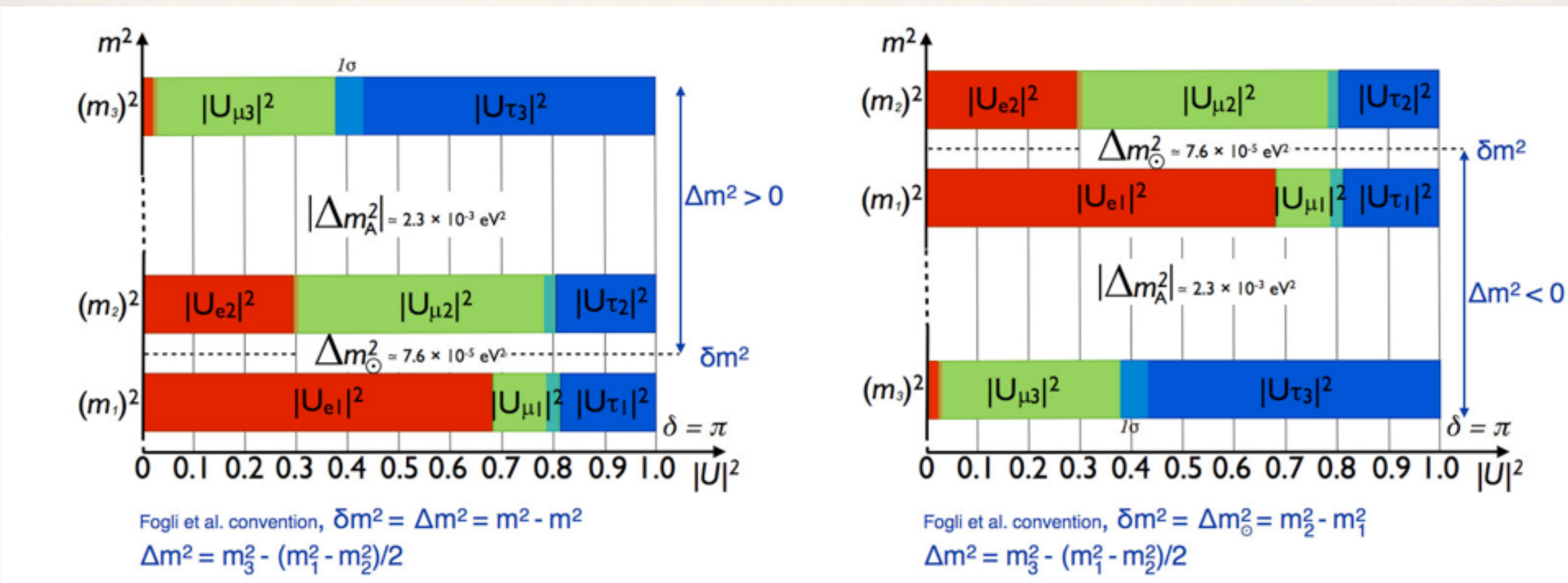
- Fall 2012/early 2013, LoI preparation / submission
- 2013 feasibility - optimization study of PINGU
- Fall 2013, Proposal for construction of PINGU to various funding agences
- Mar, April 2014, Proposal approval (!)
- May 2014, Begin "pre-spending"
- Summer 2014 -> Mar 2015 Procurement
- Sept 2015, Ship to pole 1
- Winter '15-'16 Deploy season 1
- Sept 2016, Ship to pole 2
- Winter '16- '17 Deploy season 2

Atmospheric neutrino mixing

convenient convention (Fogli et al., http://arxiv.org/abs/hep-ph/0506083)

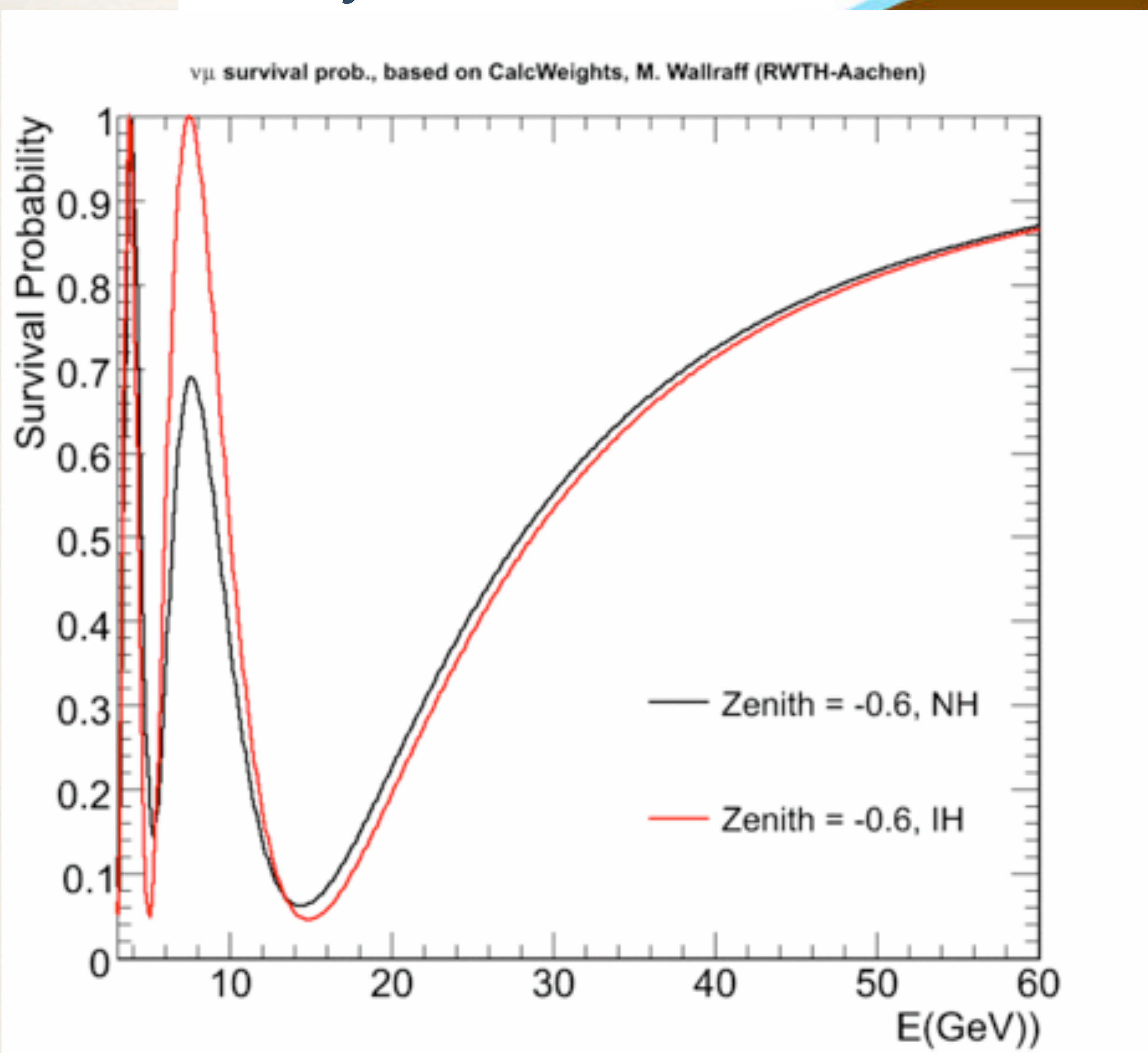
$\Delta m^2 = |m_3^2 - (m_1^2 + m_2^2)/2| \qquad \delta m^2 = m_2^2 - m_1^2 > 0$

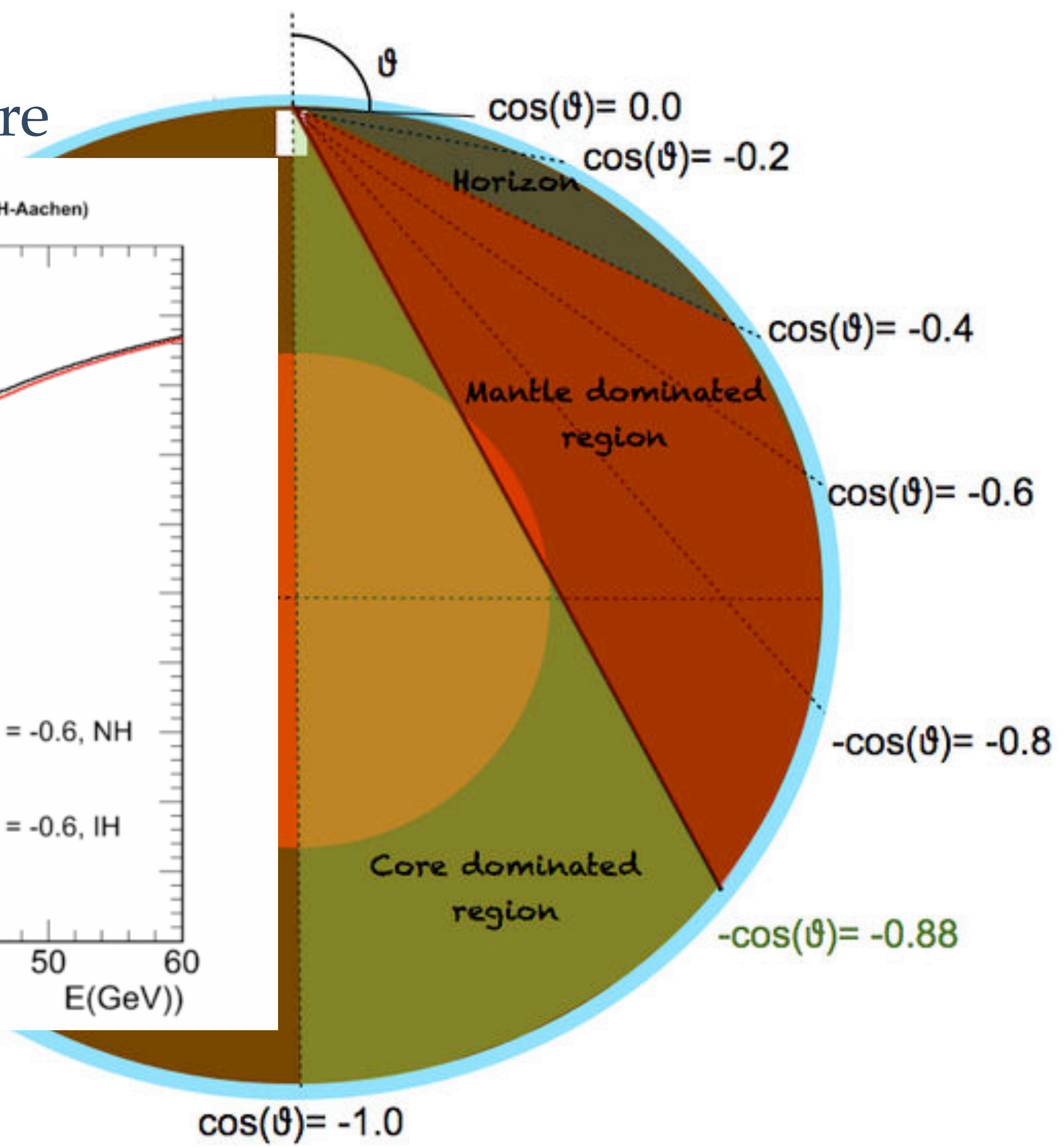
to invert the hierarchy: $+\Delta m^2 \to -\Delta m^2$



Atmospheric neutrino oscillation

Note: only neutrinos here





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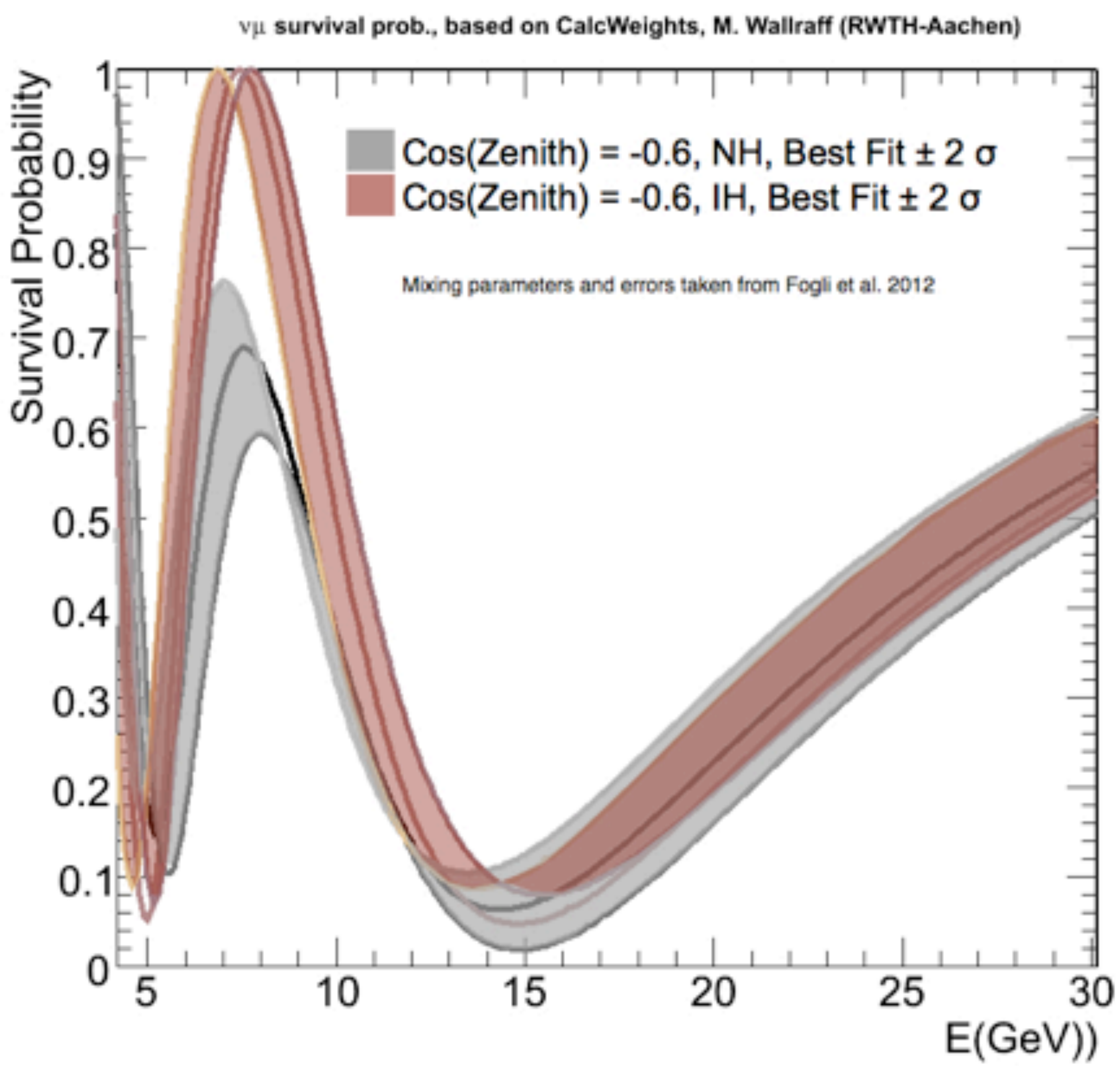
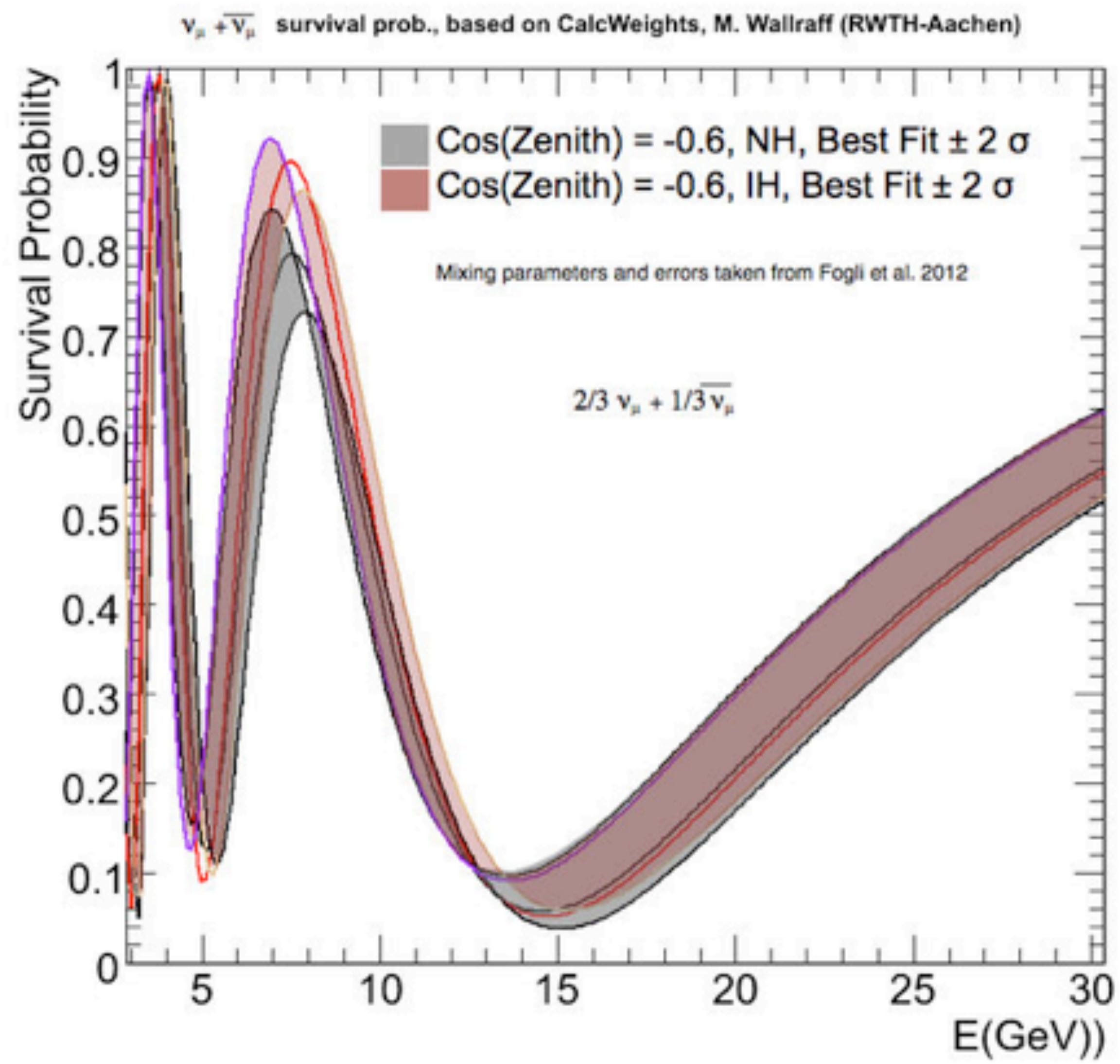


with anti-neutrinos also

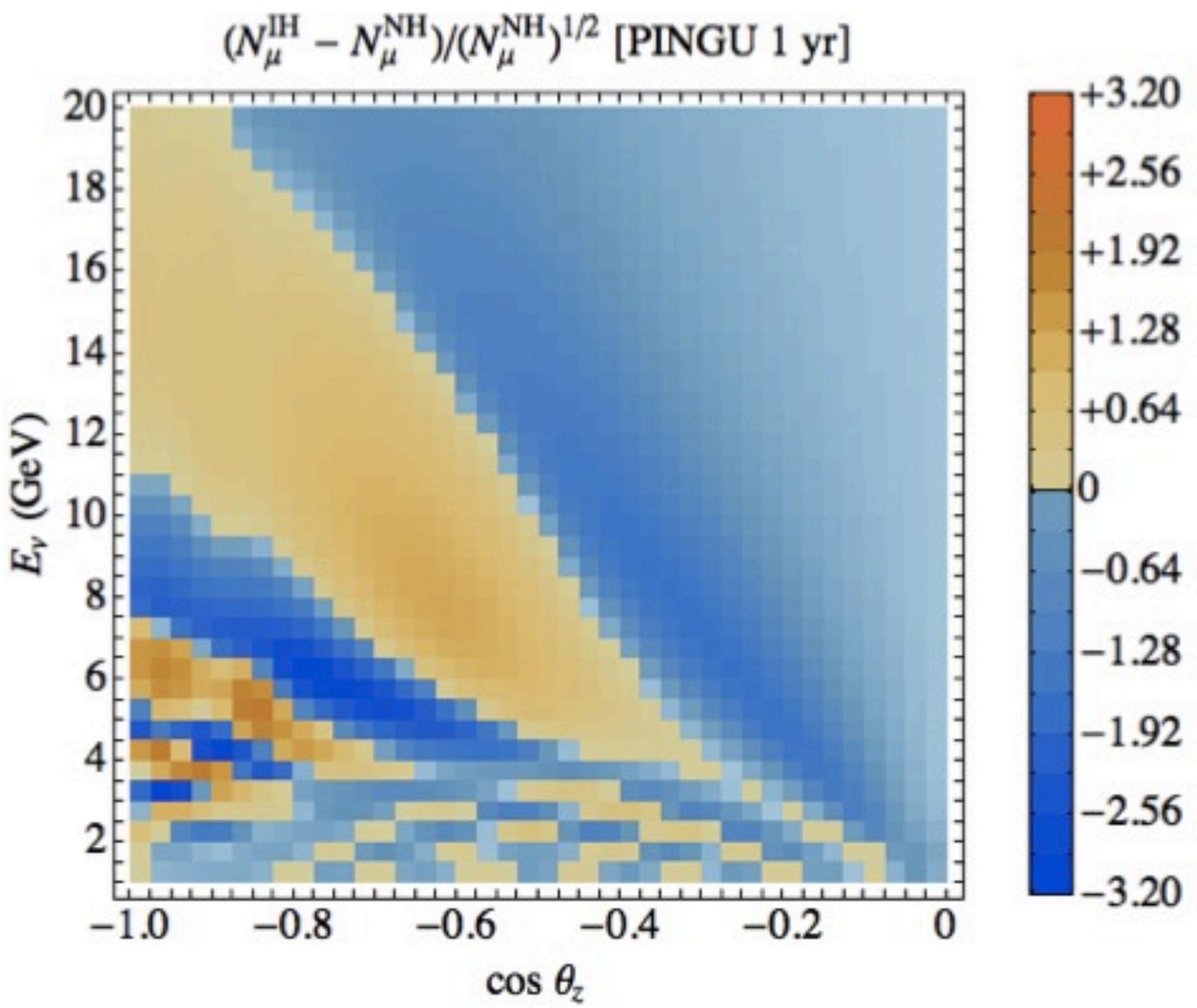


NO PANIC:

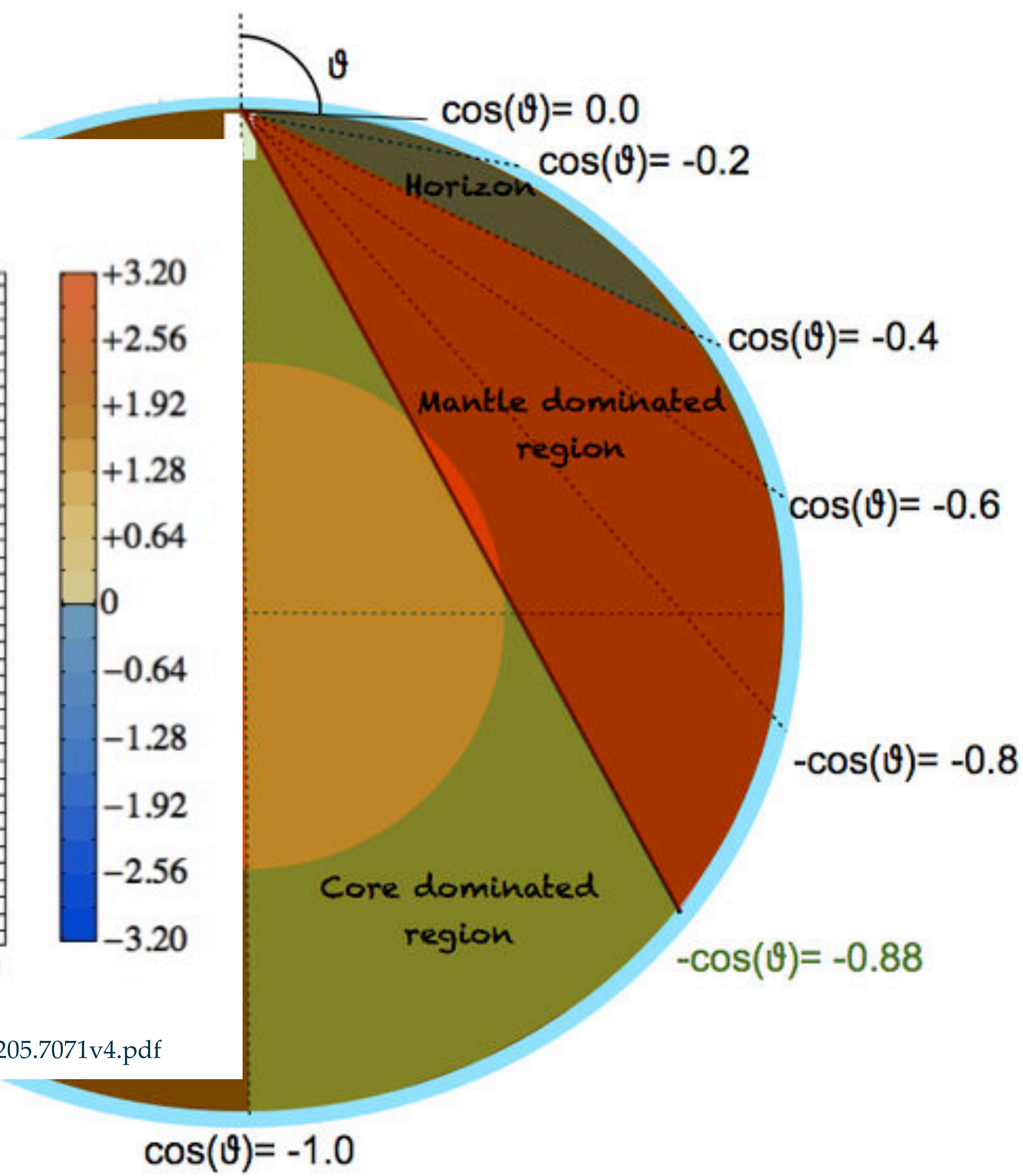
1- these are correlated uncertainties (control region strategy)

2- we will have better values

Atmospheric neutrino oscillation



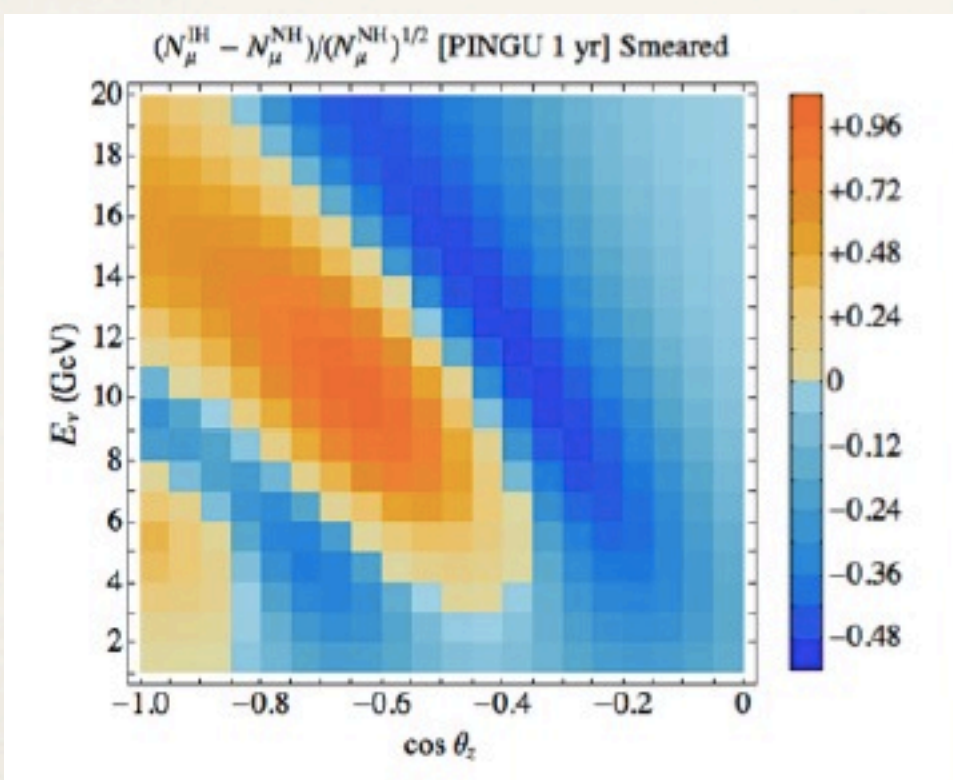
E. Akhmedov,, S. Razzaque, and A. Smirnov, http://arxiv.org/pdf/1205.7071v4.pdf

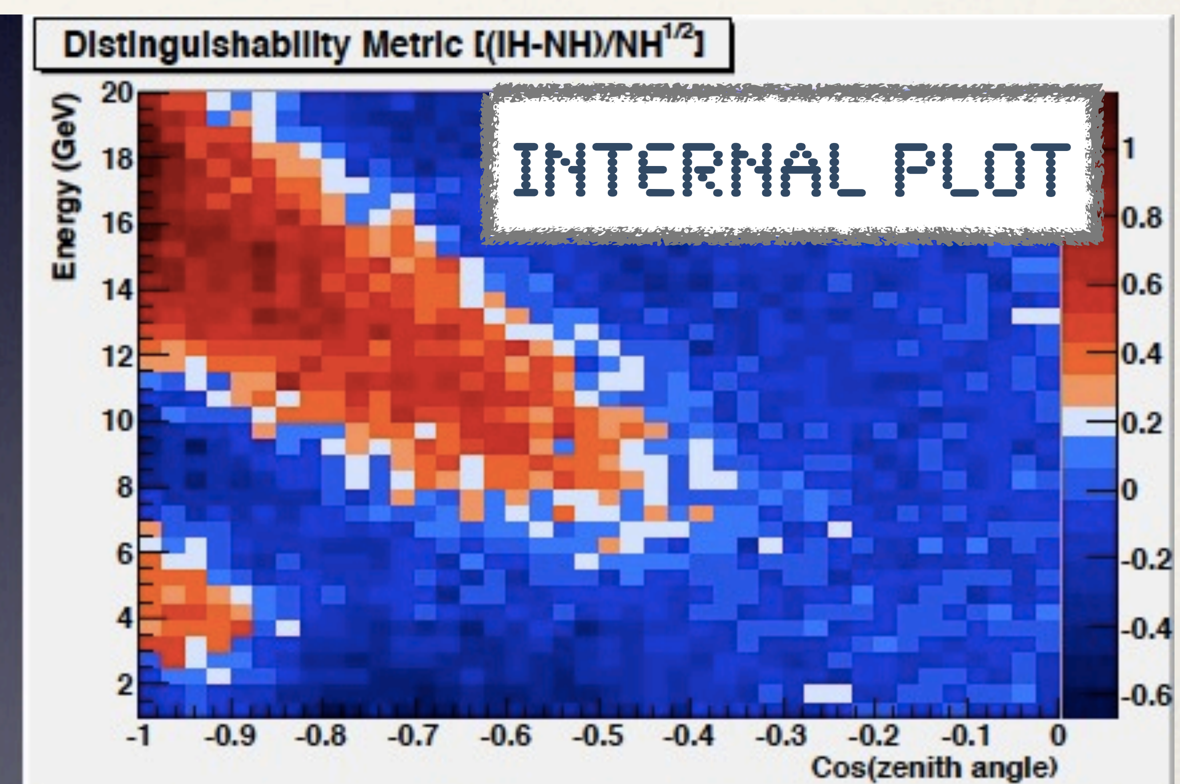


NMH on atmospheric neutrinos: where-is-the-signal?

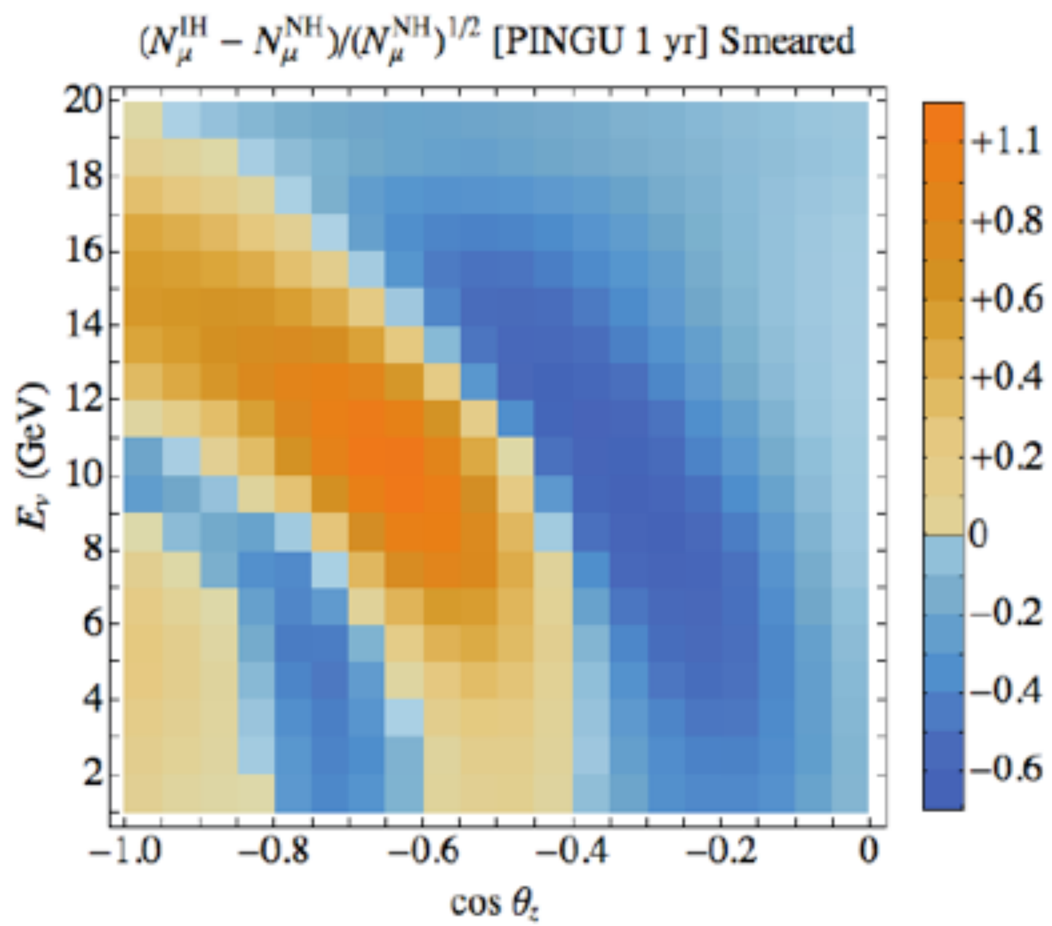
From the figures above to real case one needs to consider:

- resolutions of reconstructed events (2 GeV, 11.25 deg)





What do we simulate?



E. Akhmedov,, S. Razzaque, and A. Smirnov, http://arxiv.org/1205.7071

main focus on muon neutrinos

simulating 1-80 GeV

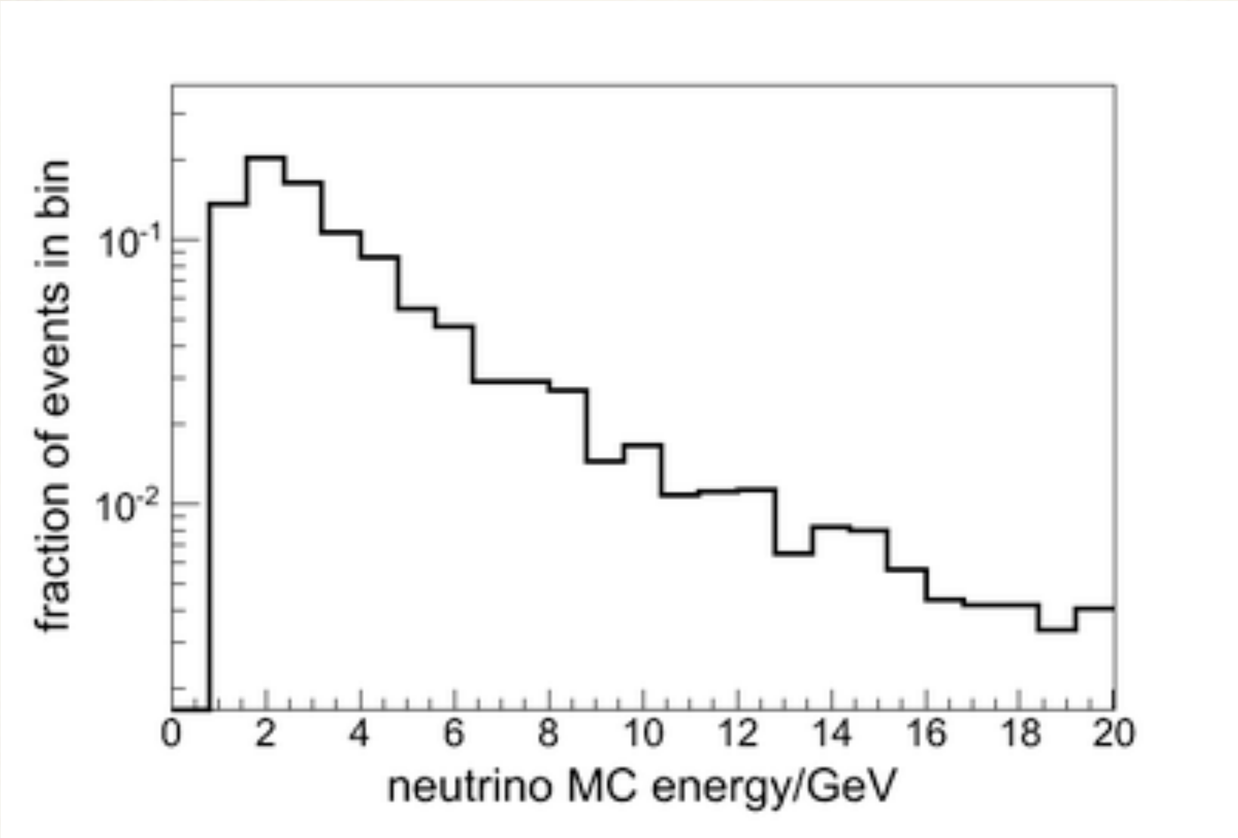
(most important range 1-20 GeV)

all-sky

different 20 string geometries

(simulation of larger geometries possible if 20 strings are not enough)

What do we simulate?



main focus on muon neutrinos

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(most important range 1-20 GeV)

all-sky

different 20 string geometries

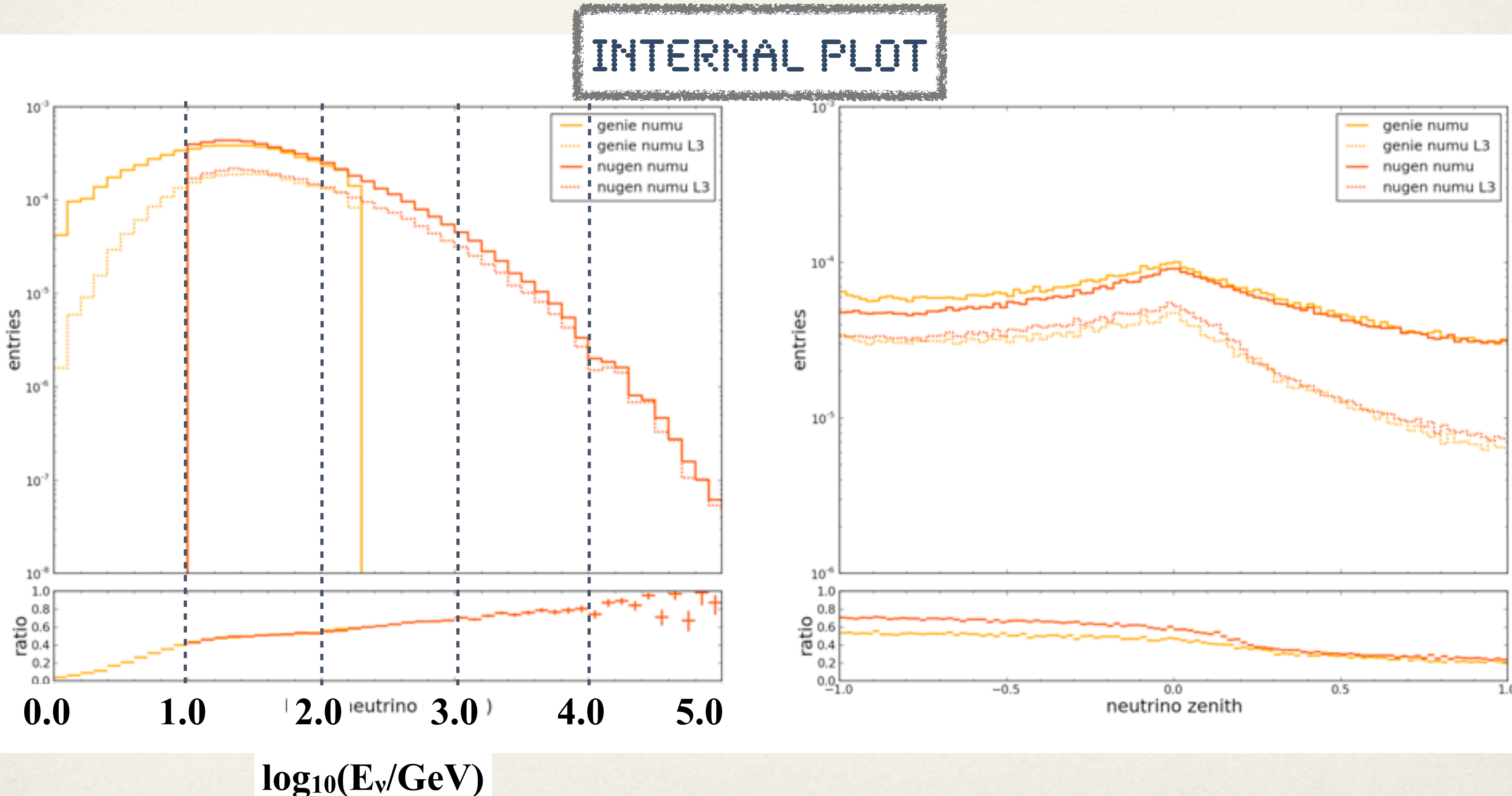
(simulation of larger geometries possible if 20 strings are not enough)

Simulation Setup

- benefits from experience with IceCube and DeepCore
- part of icetray
- neutrino generator: genie instead of nugen
- direct photon propagation
- event weighting to account for oscillations and atmospheric spectrum

Genie Neutrino Monte Carlo Generator

http://www.genie-mc.org



from S. Euler

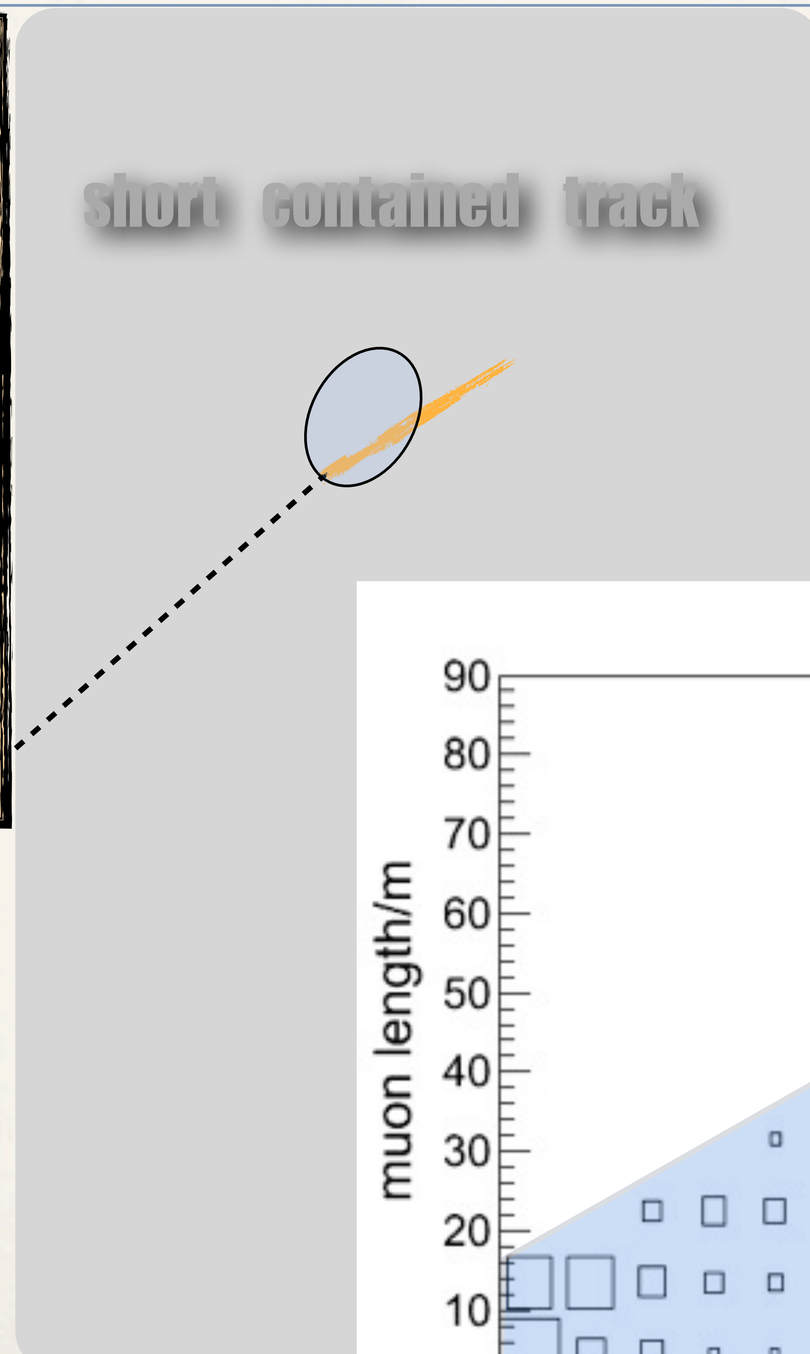
How do the events look like?

Hadronic cascade matters

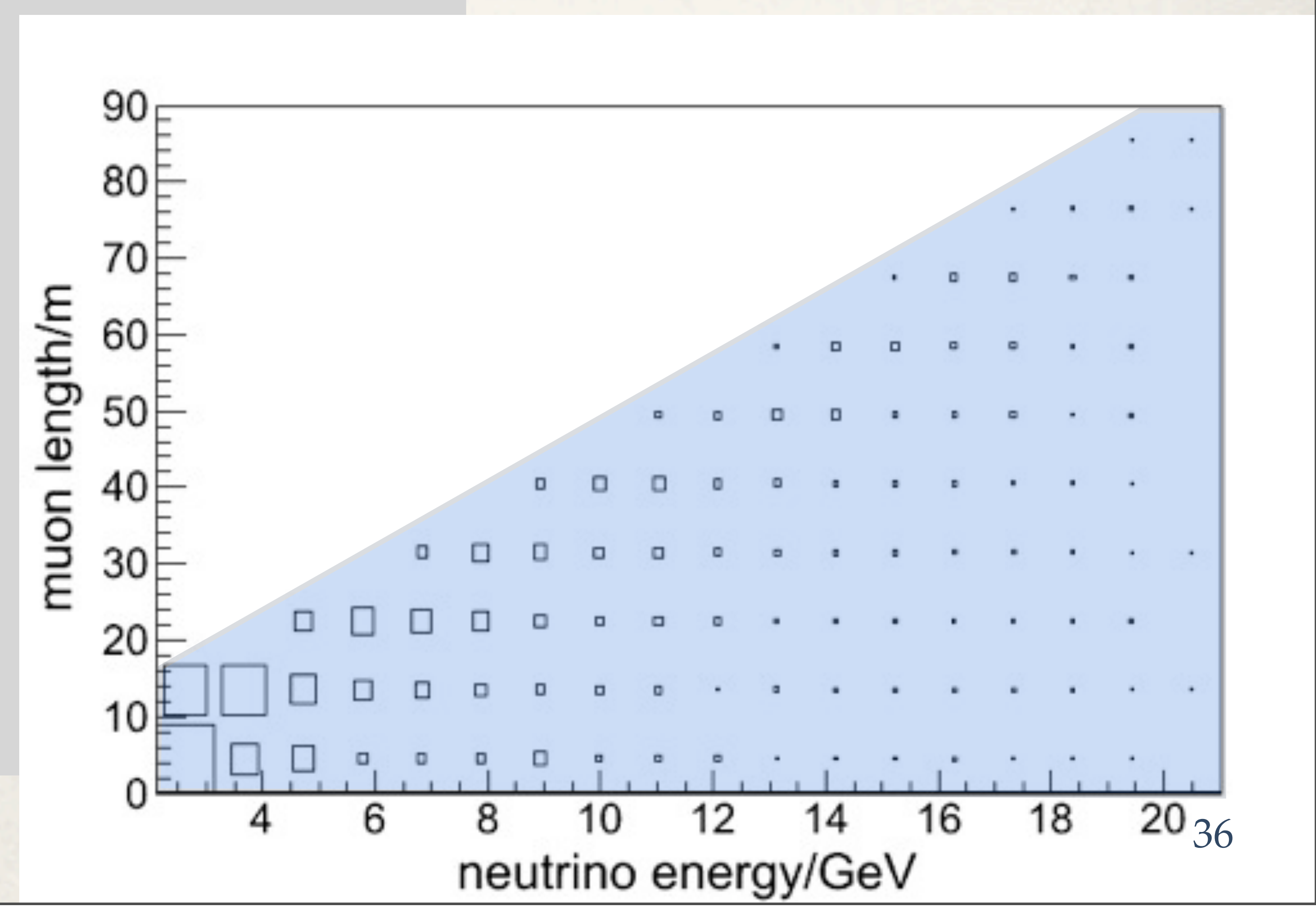
Infinite track hypothesis is a bad approximation

identification of events with tracks more difficult

(larger impact of scattering?)

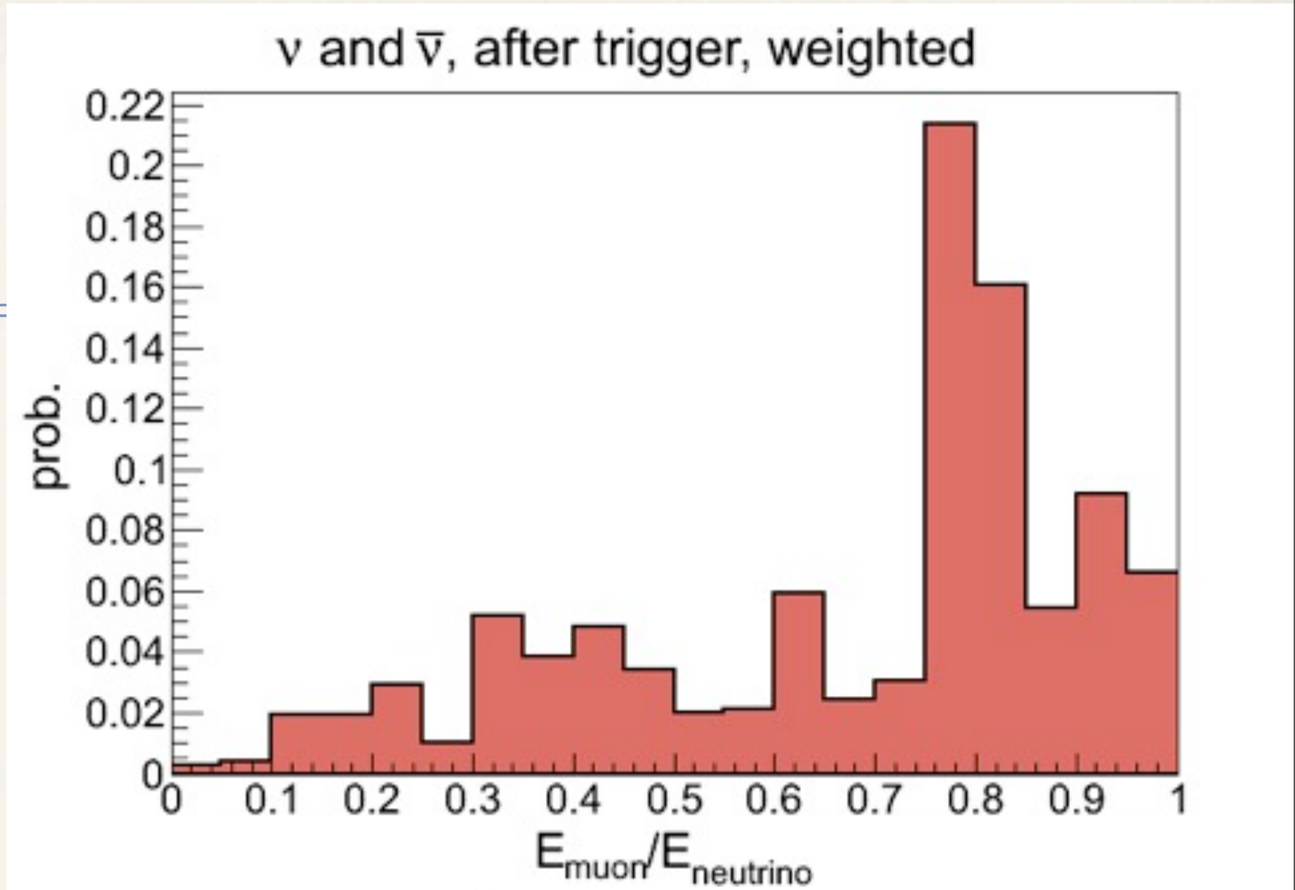


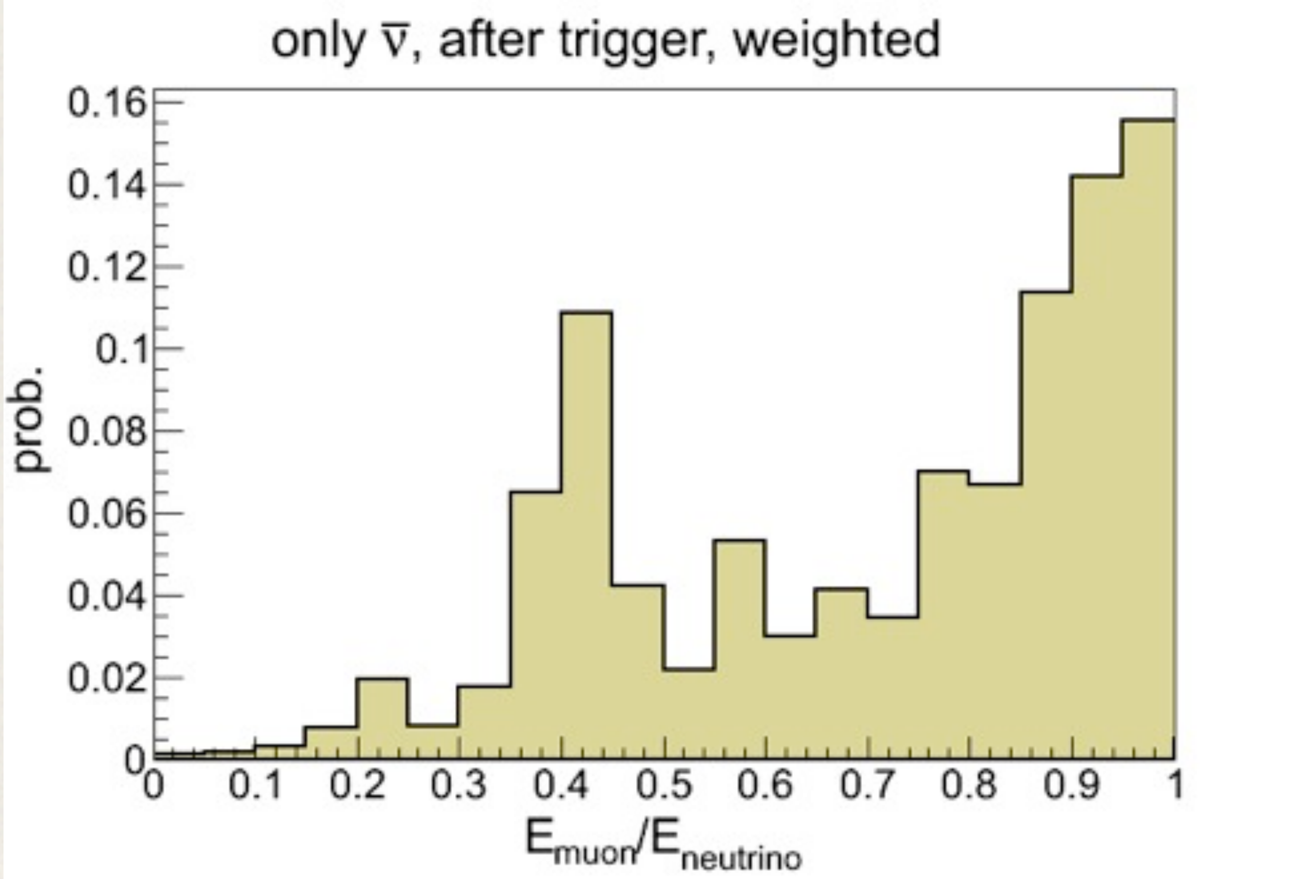
PINGU
Energies

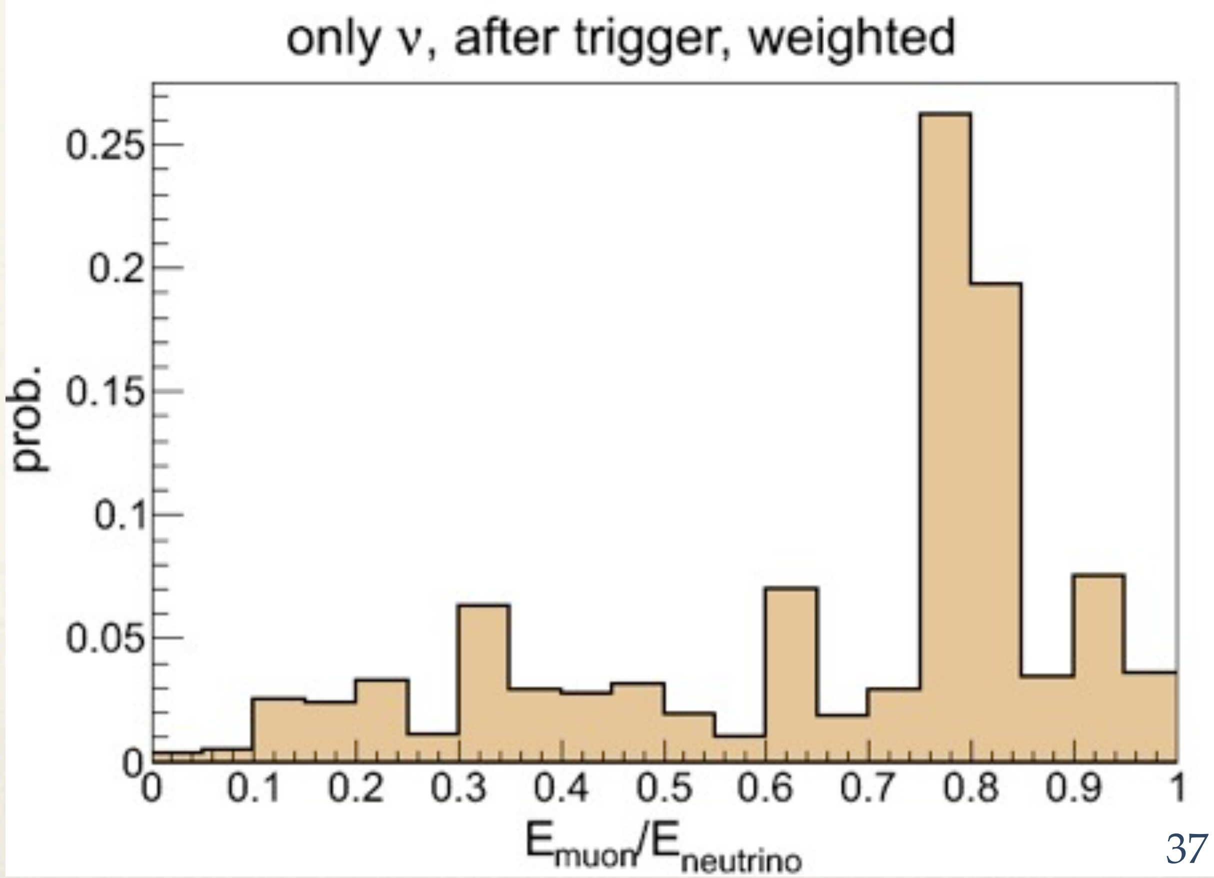


How do the events look like?

SMT3, nhit in PINGU > 6
Inelasticity will help, let's start to use it in DeepCore already !



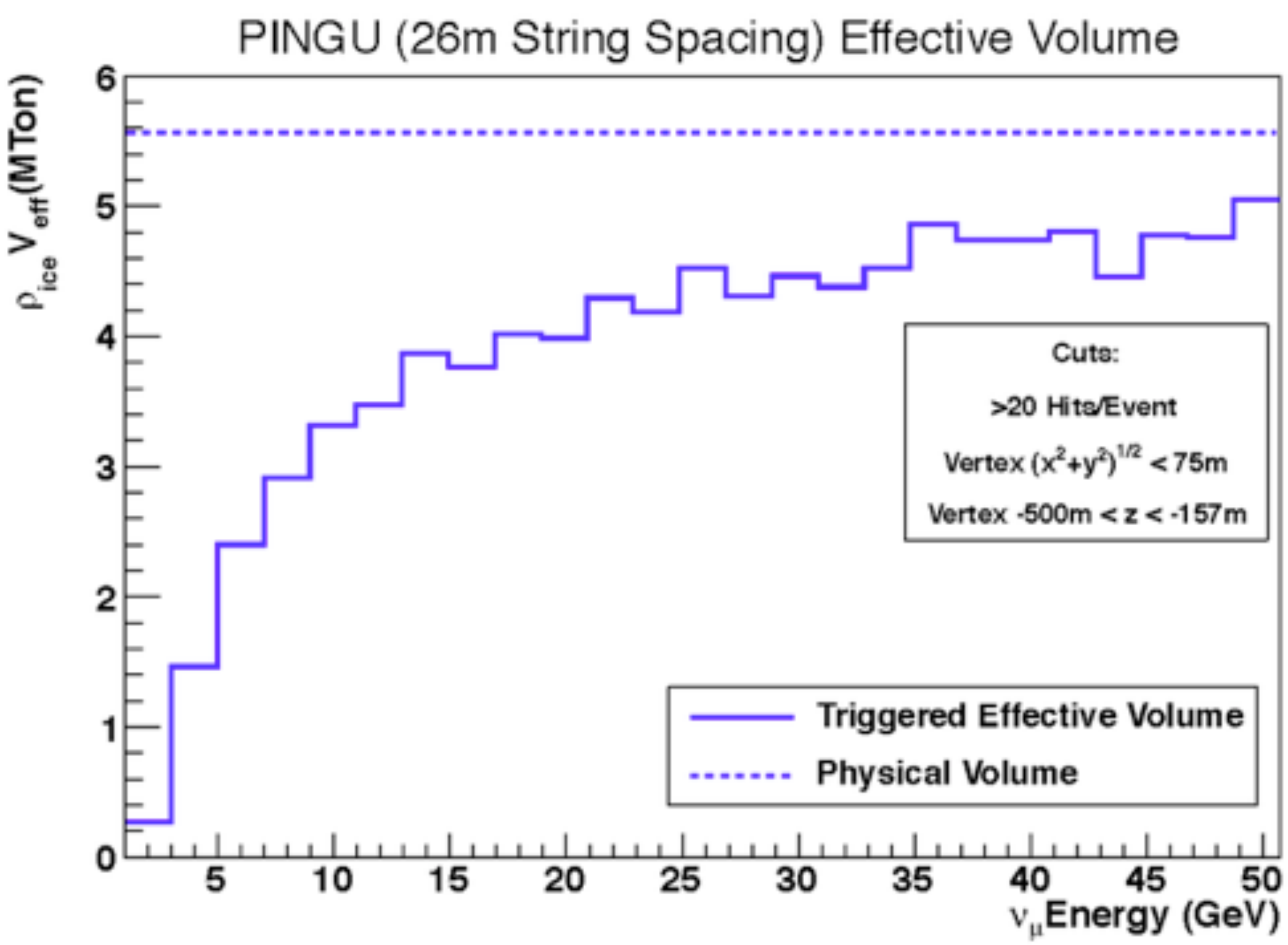


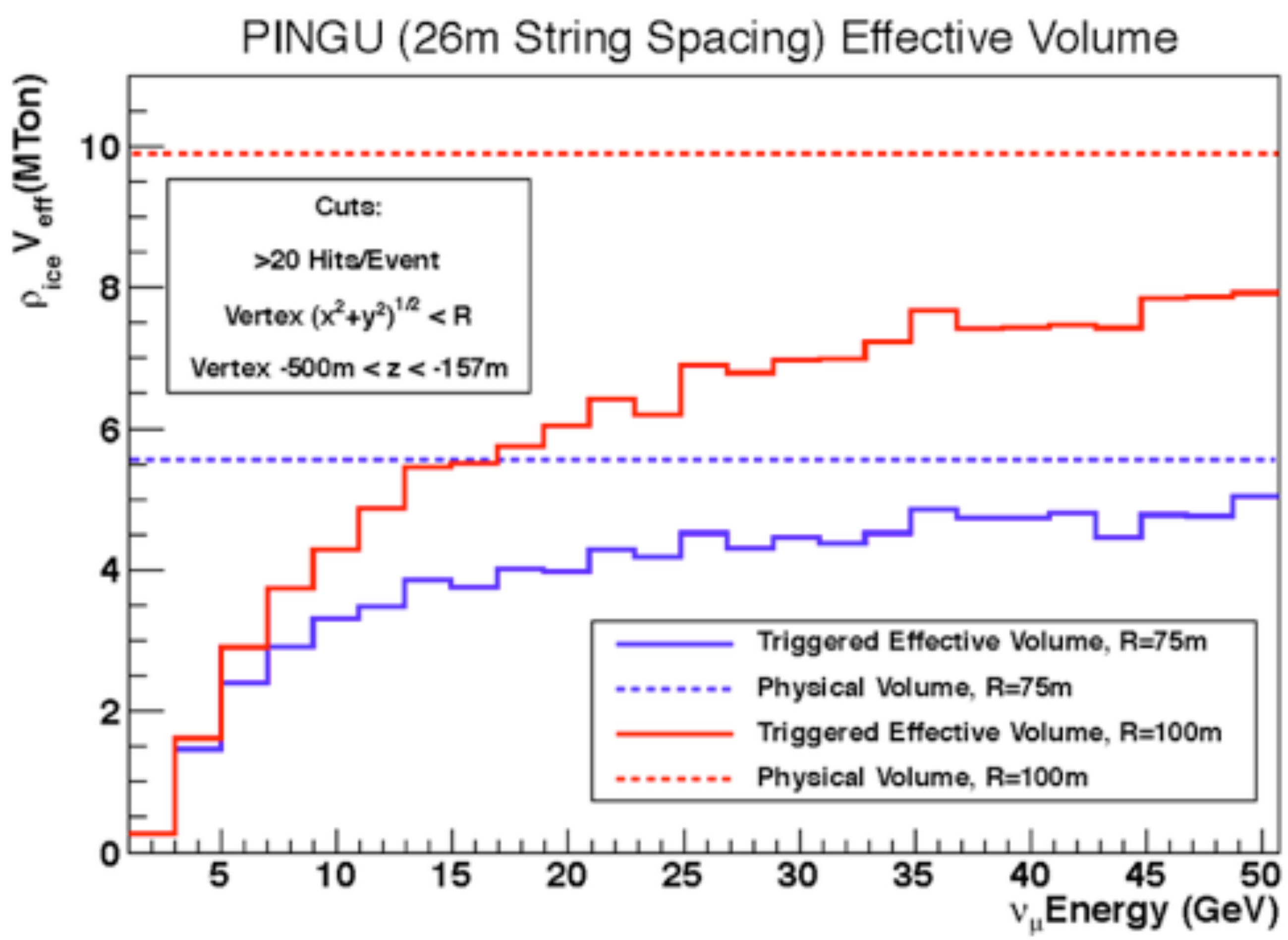


Comparison of Geometries

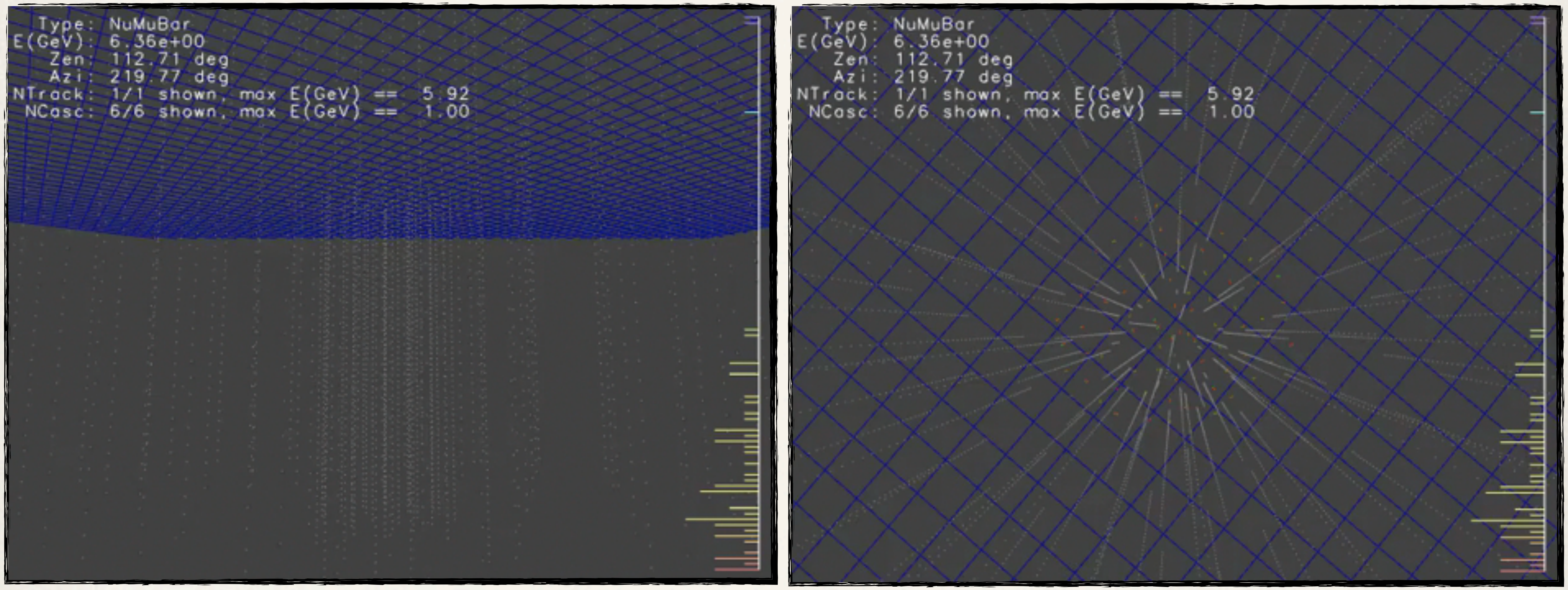
- currently using a cut on the number of hits to indicate that the events can be reconstructed
- alternative figures of merit to be investigated in the future
  - effective volume using direct hits (?) (matters for first-guess reconstructions but not so much for high-level ones)
  - effective volume after reconstruction
  - effective volume with benchmark background rejection

Comparison of Geometries



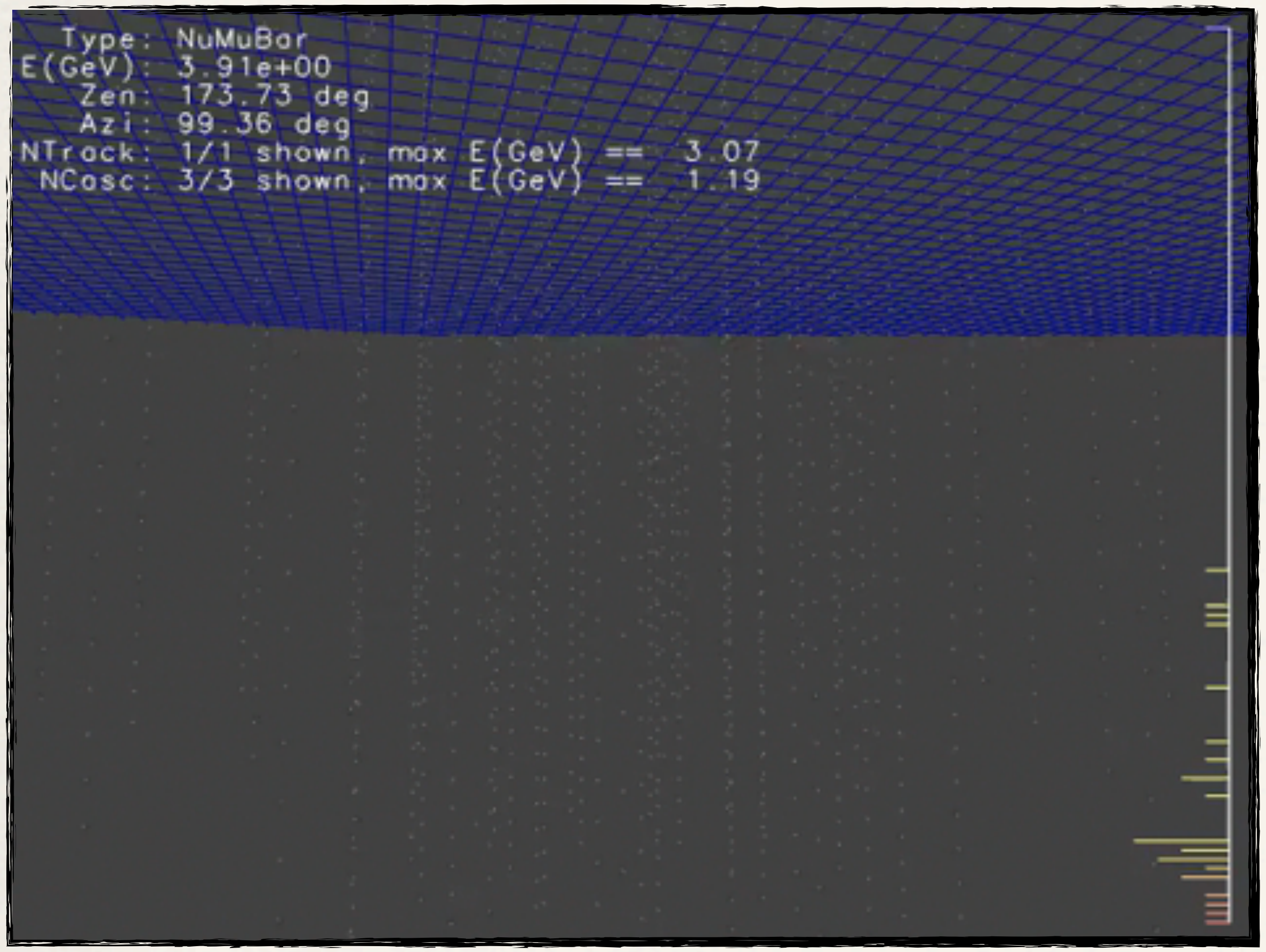


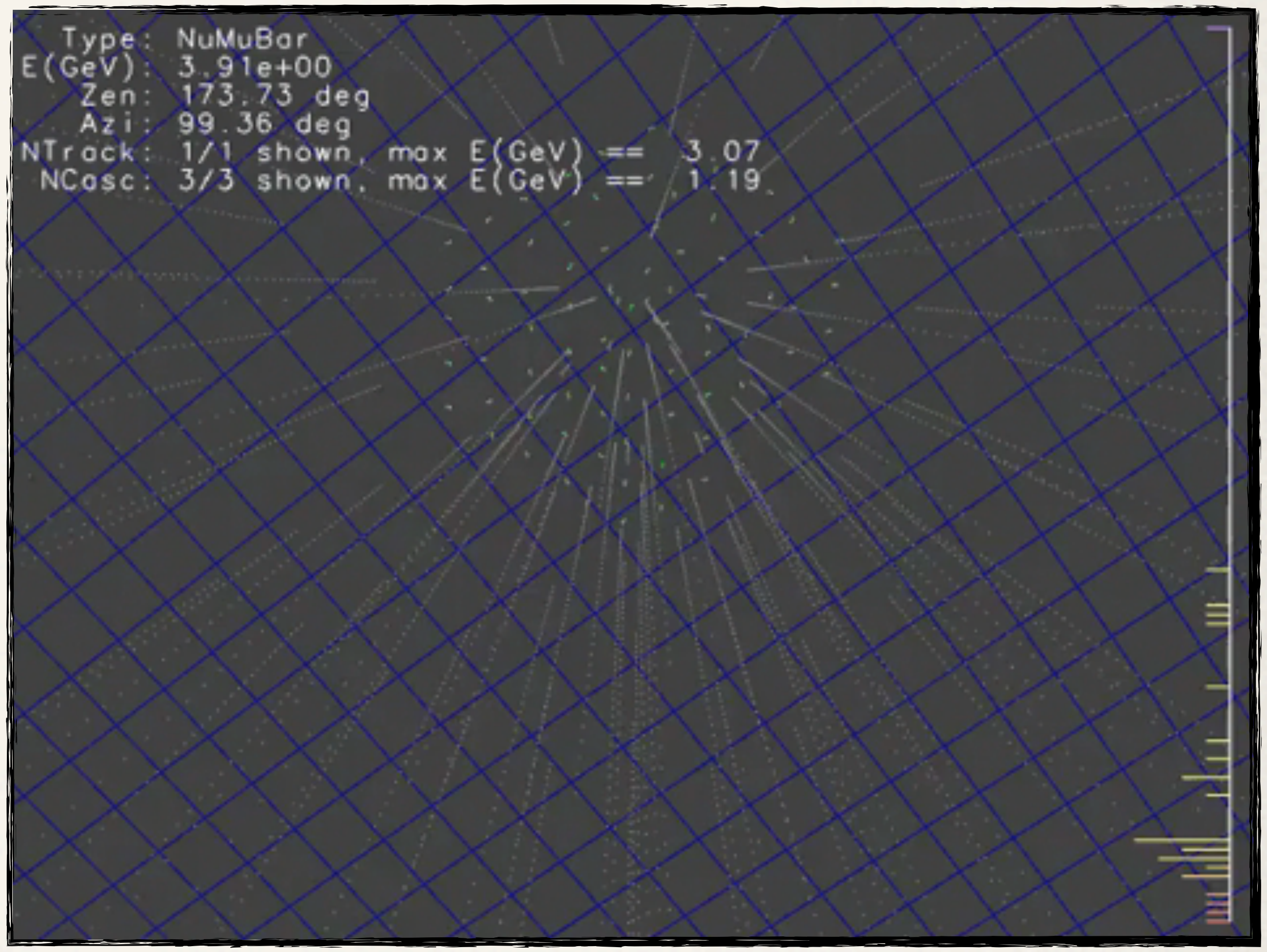
Example Events - Geometry v6



this is a mc event (of course!) - all hits are „physics“ hits - colors indicate time (red - blue) - size of hits indicates charge - the yellow/green line shows the neutrino/muon direction

Example Events - Geometry v6





this is a mc event (of course!) - all hits are „physics“ hits - colors indicate time (red - blue) - size of hits indicates charge - the yellow/green line shows the neutrino/muon direction

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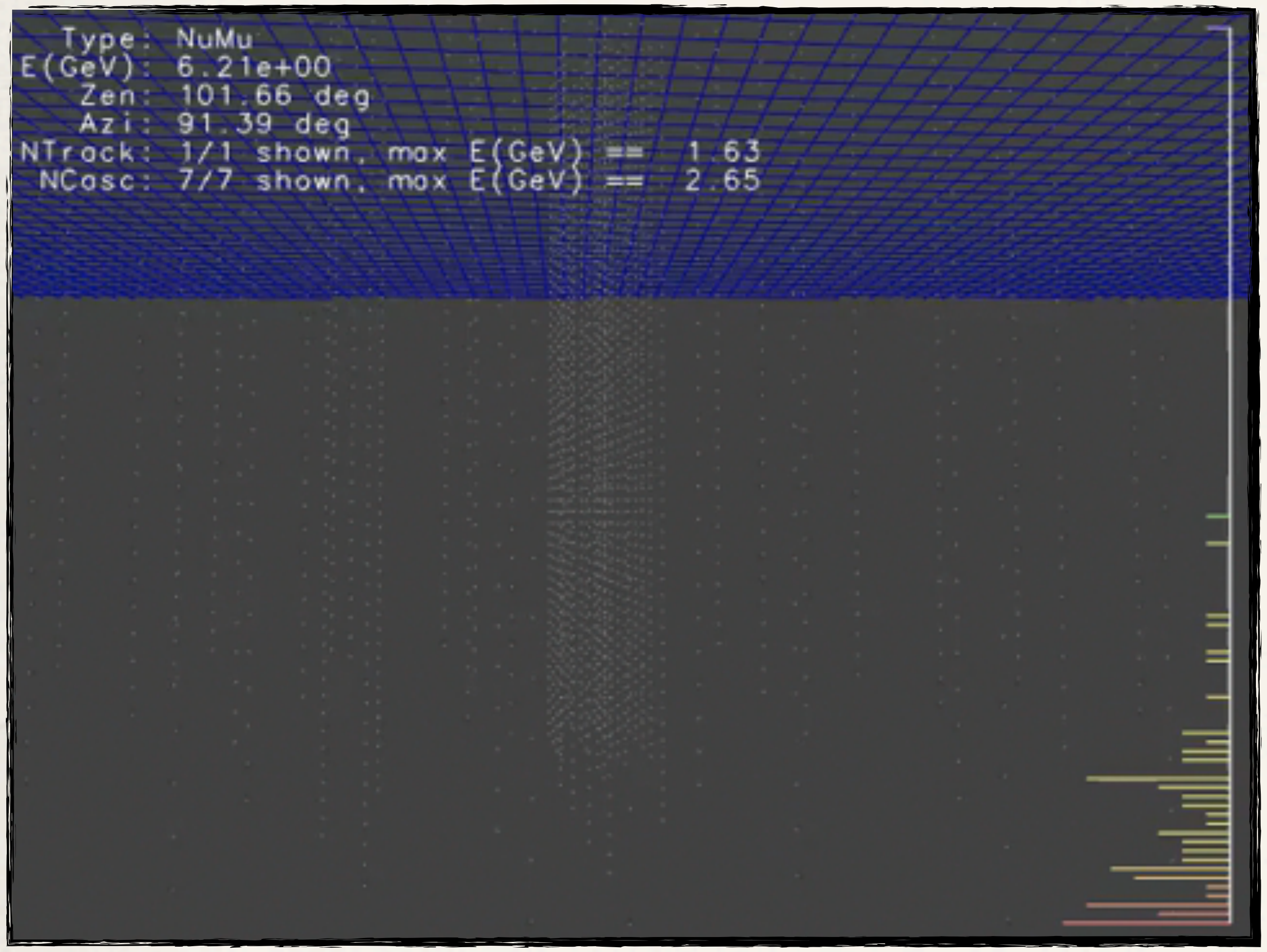

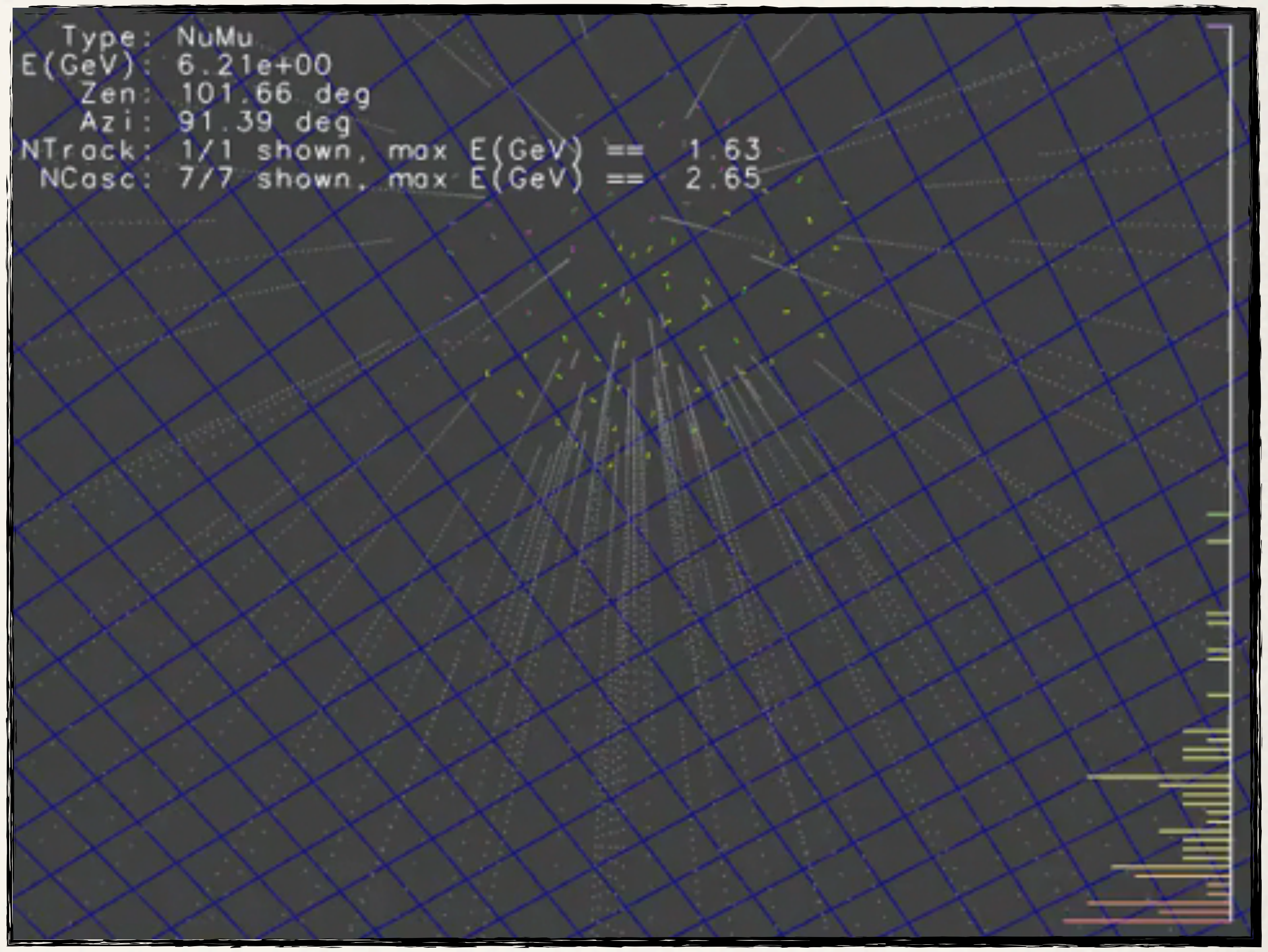

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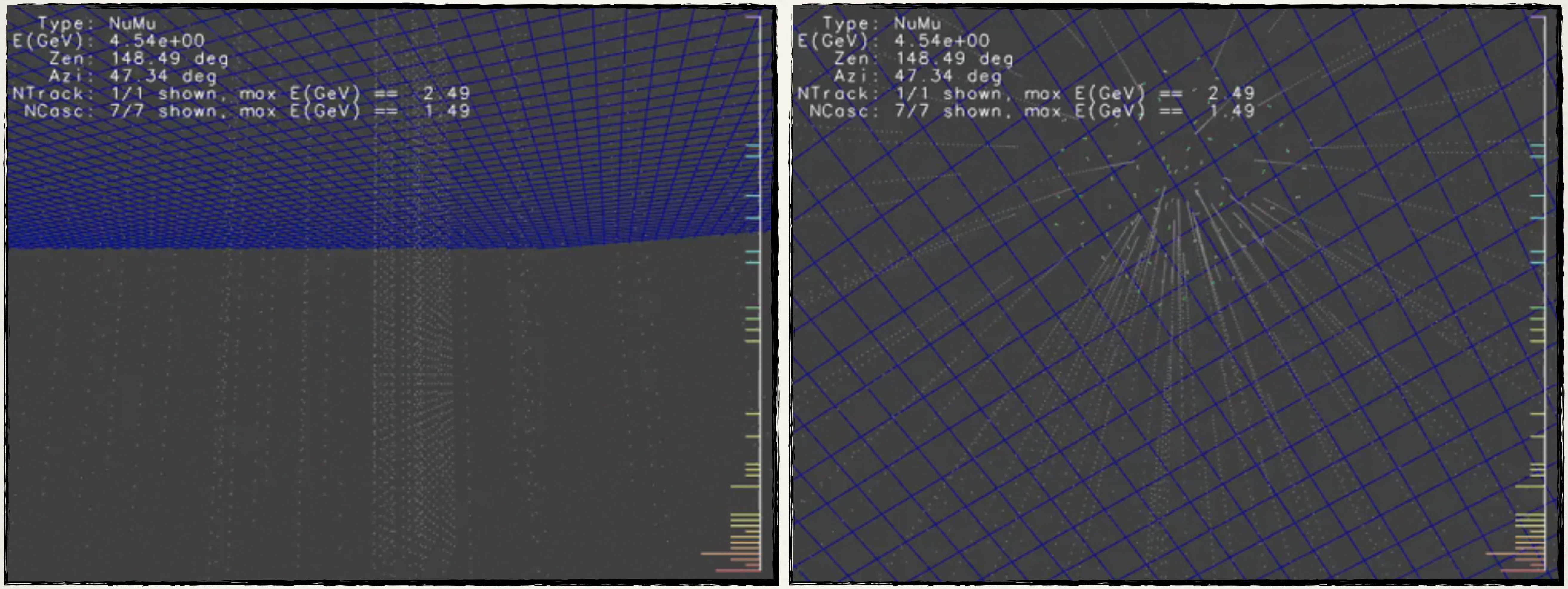

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Reconstruction

First-Guess Reconstruction → seed for → **Likelihood Reconstruction**

These reconstructions do not take the ice properties or the event topology into account.

Possibilities under investigation:

LineFit - straight line fit through the hits ignores Cherenkov cone and scattering
SANTA - uses the geometry of the Cherenkov cone and a stringent hit cleaning (as in ANTARES paper)
JAMS - a simple pattern recognition algorithm used in AMANDA

may apply several llh reconstructions with increasing complexity

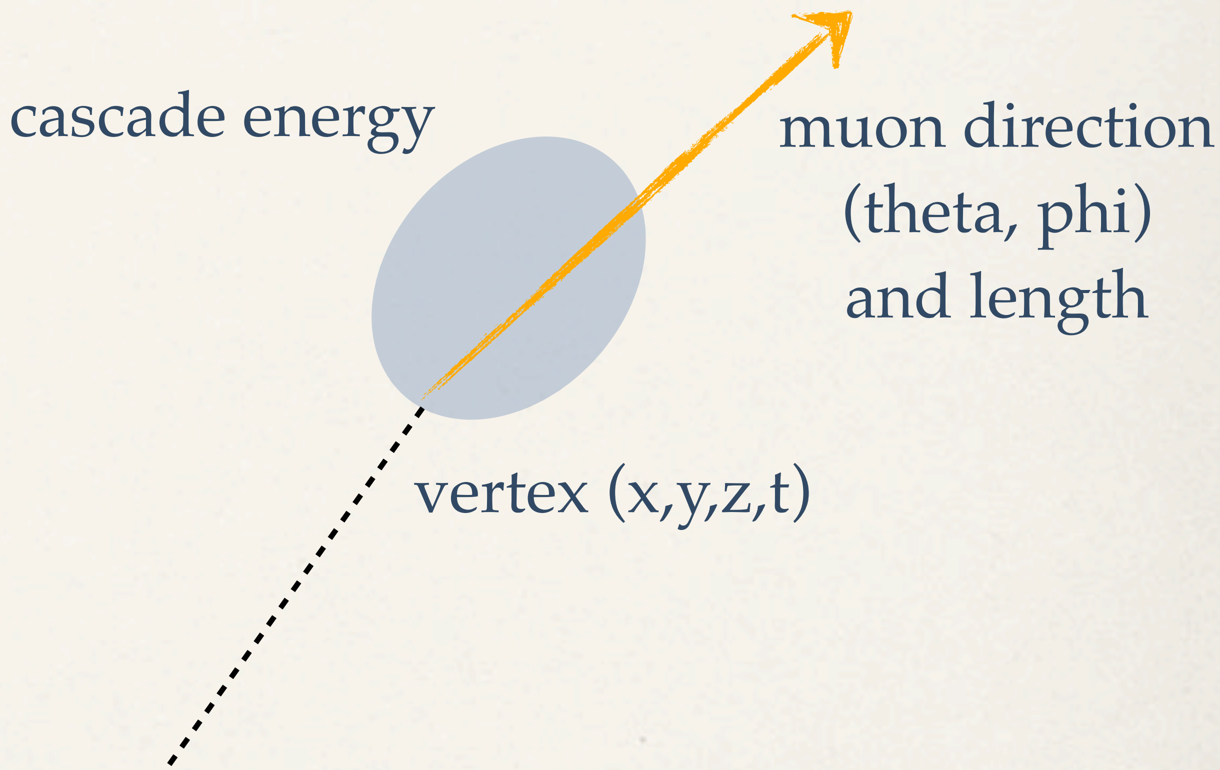
using ice properties and event topology

high-end likelihood reconstruction on next slide

see P. Berghaus et al poster

Likelihood Reconstruction of contained events

- Reconstruct the full event:
  - hadronic cascade + muon track
- Use tabulated pdfs for photon arrival times -> best possible use of ice information
- Under comparison and study many different options: from first look energy resolution looks promising, track resolution still problematic …. but tomorrow is another day and things will look differently!



Sensitivity calculation: one path (work on-going)

NMH measure is nothing else then an **oscillation analysis** with an extra sign

STEP 1: Define the input parameters

- Zenith distribution of atmospheric neutrinos in the signal region
- Energy distribution of atmospheric neutrinos in the signal region
- Consider the use of control region (DeepCore, IceCube streams) for possible mitigation and self-constrain of uncertainties

- List of uncertainties

The ensemble of **nuisance parameters**
for neutrino mass hierarchy measurement, preliminary list

From other experiments		PINGU specific	
Primary CR flux (AMS, BESS, …)	M. Sajjad Athar, M. Honda et al., http://arxiv.org/abs/1210.5154	DOM efficiency	improved in-situ calibrations
Geomagnetic field, interaction model	M. Sajjad Athar, M. Honda et al., http://arxiv.org/abs/1210.5154	Ice optical properties	hole ice water purification
Atmospheric neutrinos zenith, energy, composition	M. Sajjad Athar, M. Honda et al., http://arxiv.org/abs/1210.5154	Background?	electron neutrinos?, see reconstruction
Earth Profile (PREM, …)	under study		
Neutrino Interaction cross section	starting with GENIE under study		
Mixing parameters	degeneracies		
CP violation	probably not a bit problem		

Sensitivity calculation: one path (work on-going)

STEP 2: Define the analysis strategy

- reconstruction
- background rejection

Fitting procedure: various approaches to be compared.
Using both zenith and energy distributions, construct the $\Delta\chi^2$ between the NH and IH case. What to fit?

1) fit ($\pm \Delta m^2$, $\sin^2 2\Theta$), all the other mixing param marginalized
2) fit $\pm \Delta m^2$ all the other mixing param marginalized, uncertainties treated as nuisance parameters
3) fix the Δm^2 value to the best fit value (like all the others) and fit the sign only

Sensitivity calculation: one path (work on-going)

STEP 3: Propagate the uncertainties

various approaches to be compared.
- covariance matrix approach
- pull / nuisance minimization
- full MonteCarlo approach (test impact of non gaussian uncertainties)

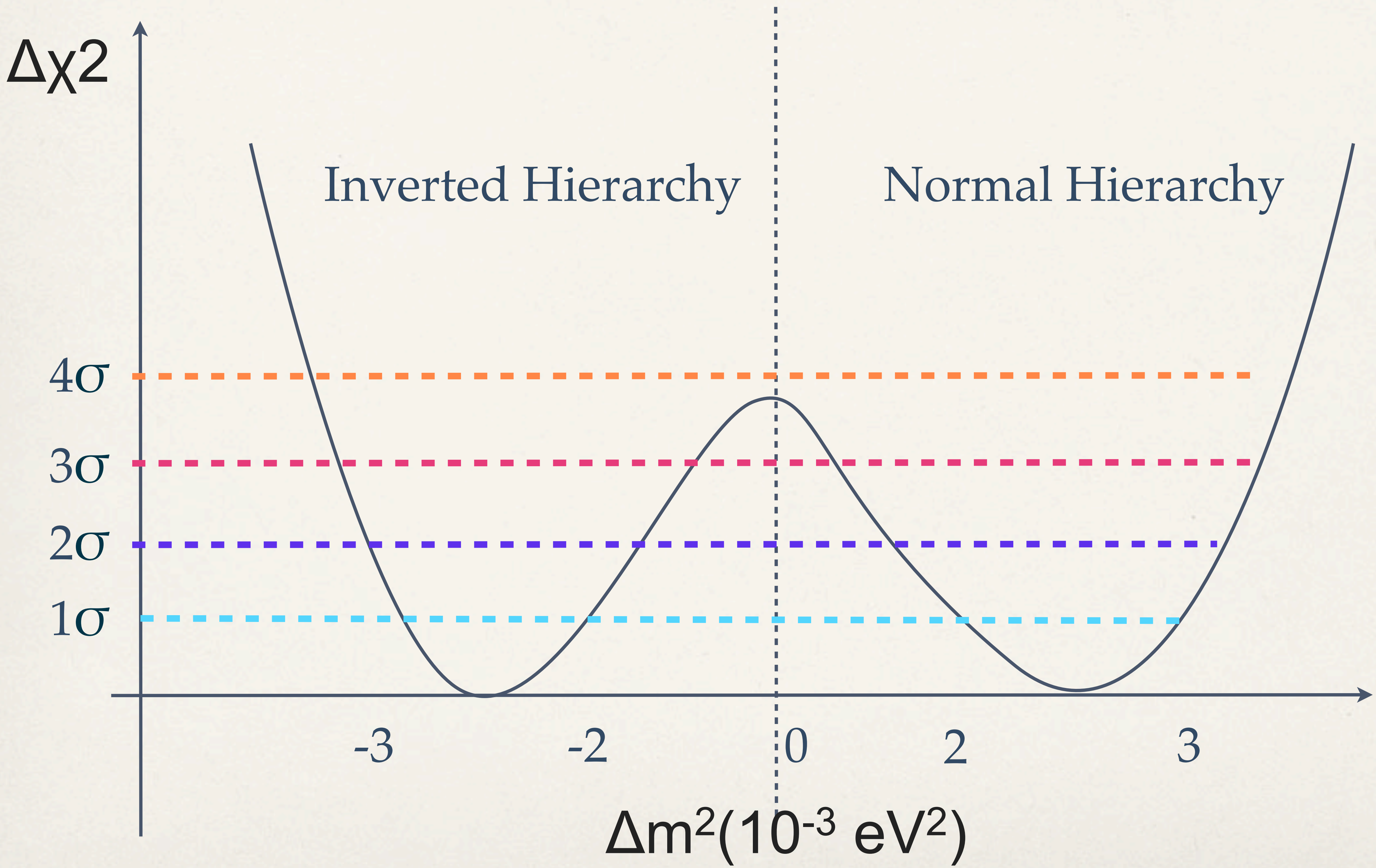
STEP 4: Generate N pseudo-experiments to build up the test statistics (see J. Leute poster)

STEP 5: Visualize the sensitivity, dependencies vs uncertainties (degeneracies) and possible progression vs life time.

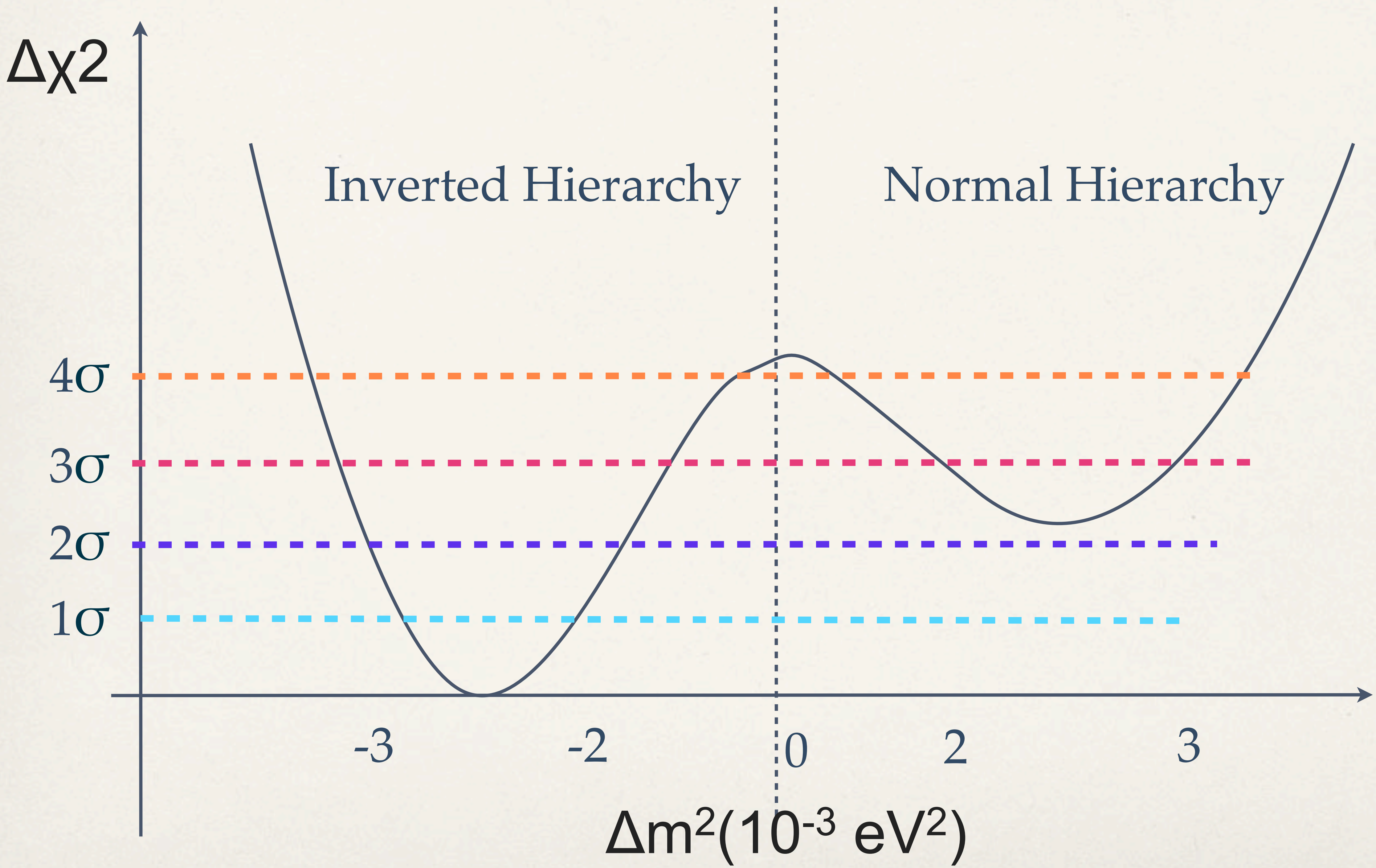
How could look like a sensitivity plot?

this scenario is for an experiment NOT sensitive to NMH

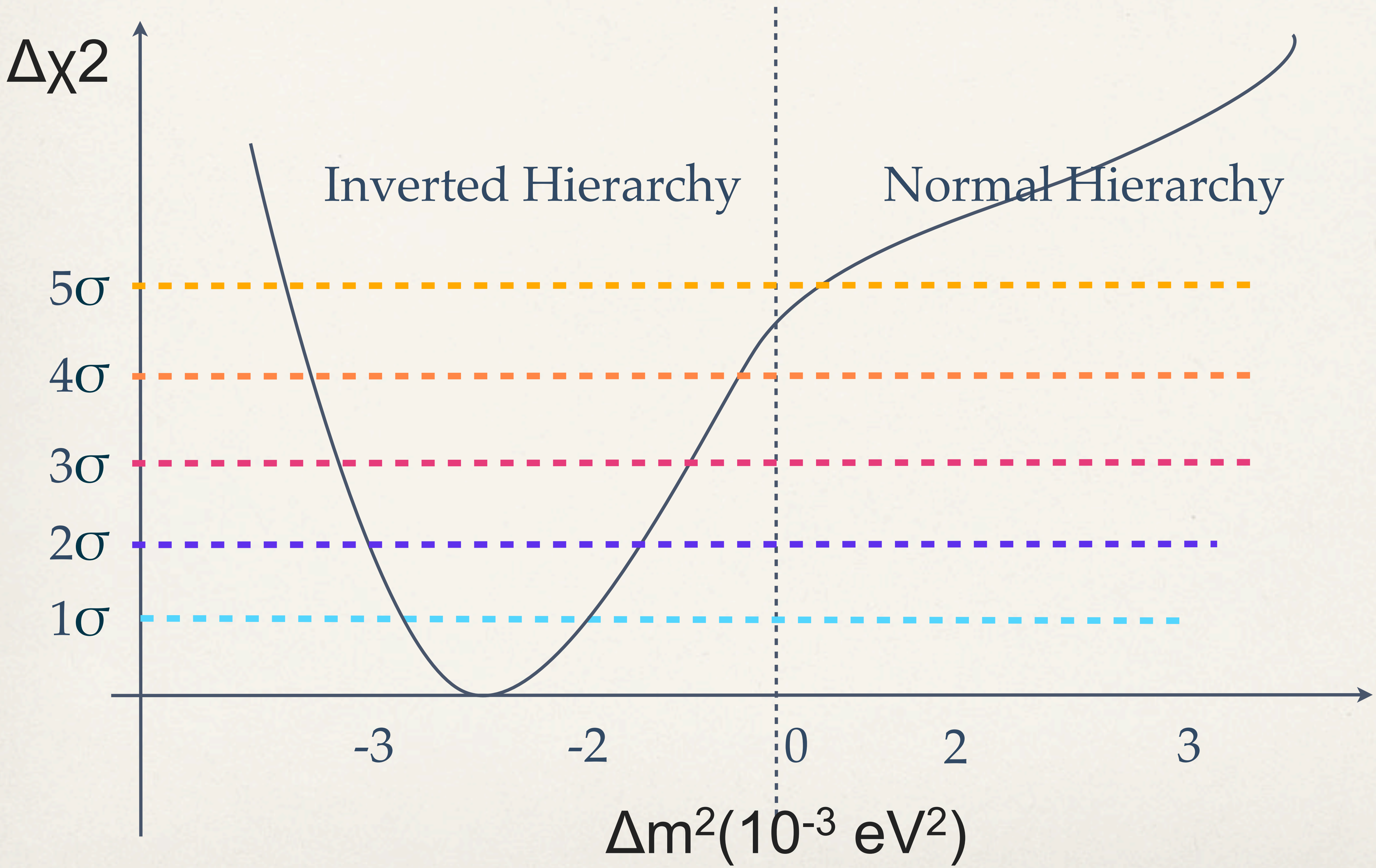
1D representation



this scenario is for an experiment sensitive to NMH indicating IH at 2 sigma level

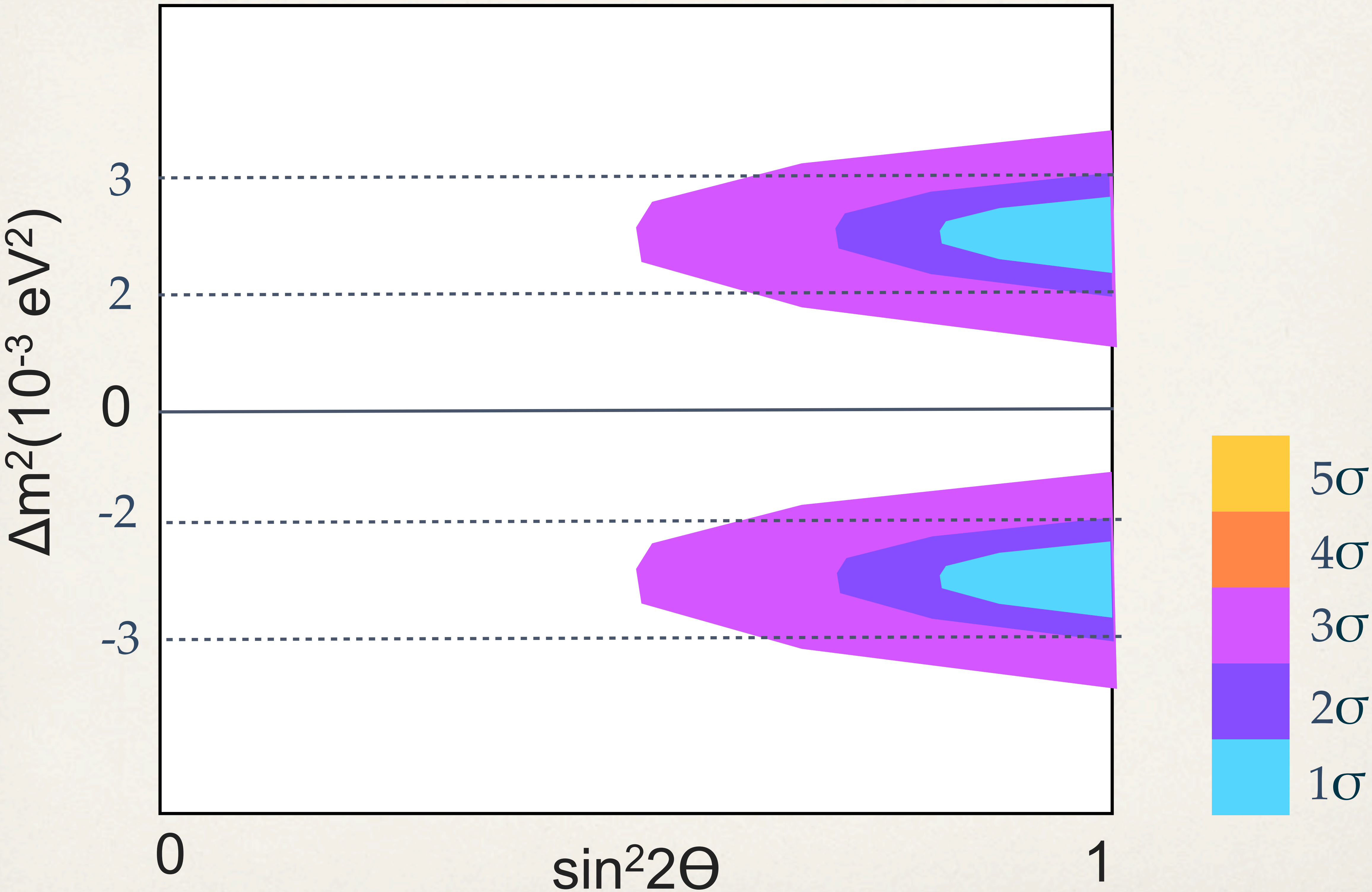


this scenario is for an experiment sensitive to NMH indicating IH at 5 sigma level

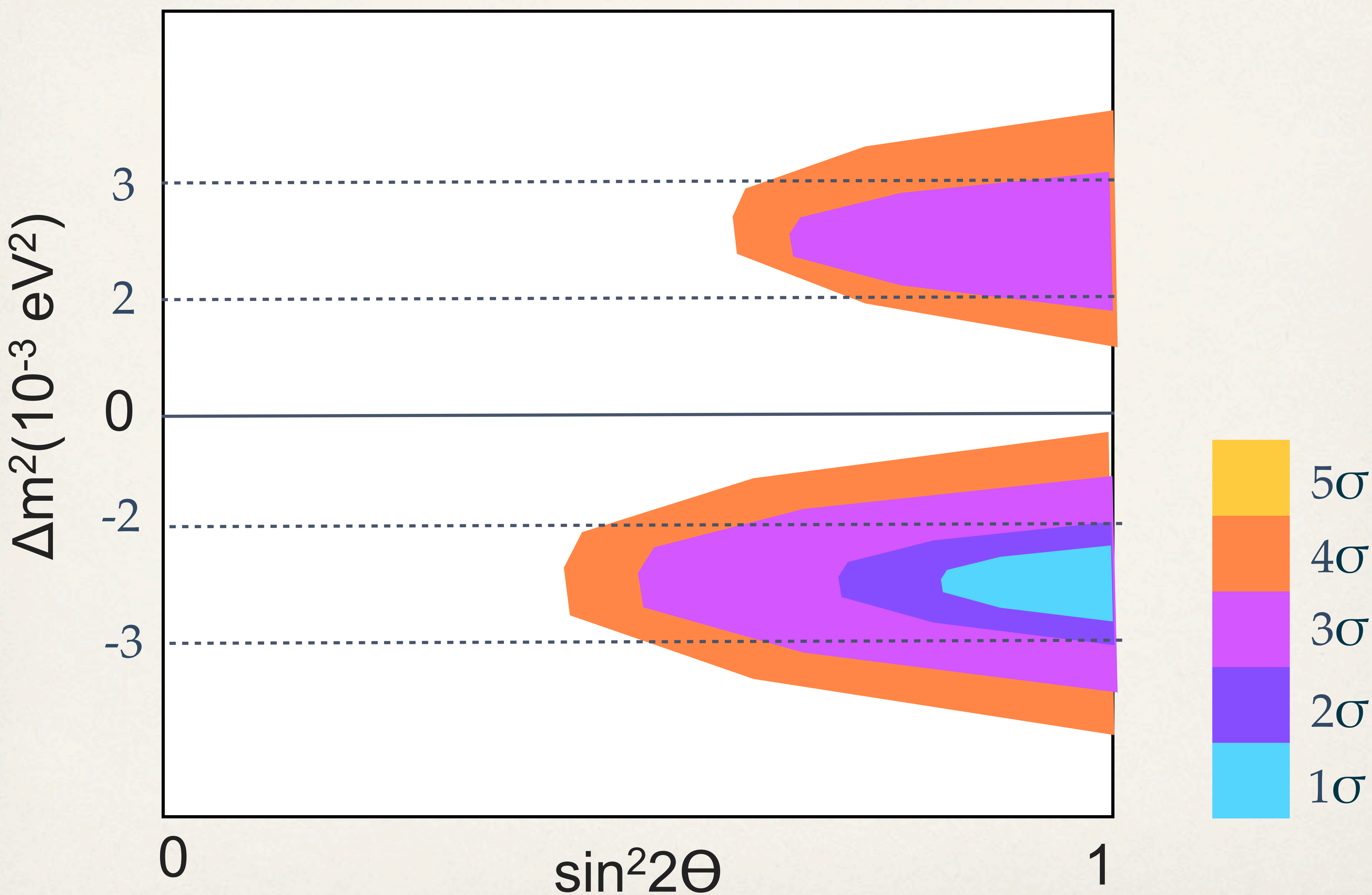


2D representation

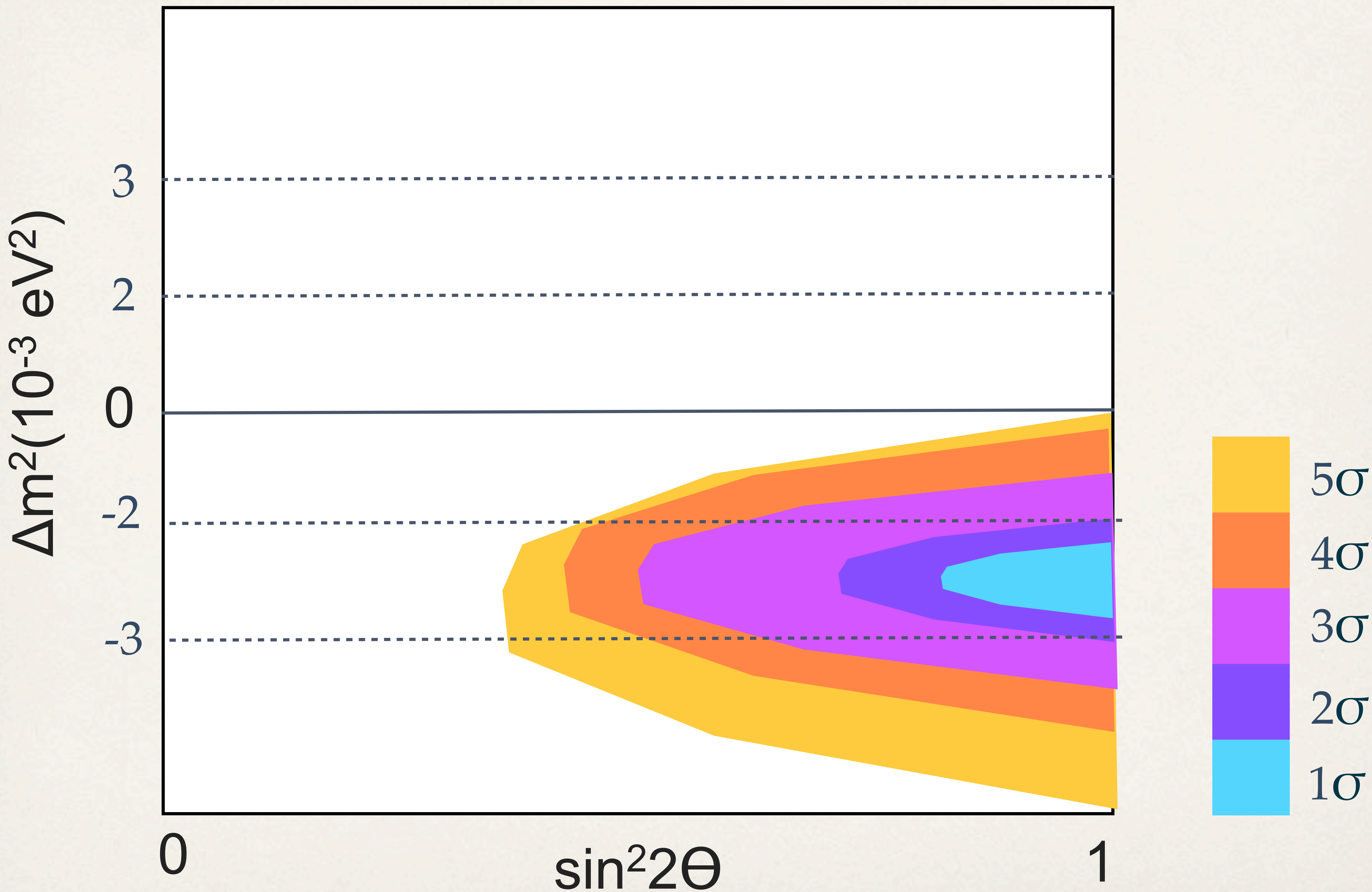
this scenario is for an experiment NOT sensitive to NMH



this scenario is for an experiment sensitive to NMH indicating IH at 2 sigma level



this scenario is for an experiment sensitive to NMH indicating IH at 5 sigma level



Questions to be answered by the sensitivity study

- Role of life-time vs signal efficiency vs volume: optimization to be performed for best (or enough) sensitivity

- Role of uncertainties: do we really need a high precision? the parameter space ($\pm \Delta m^2$, $\sin^2 2\Theta$) is large; for NMH is enough that one of the two regions get disfavored

- Role of degeneracies: to be quantified and carefully study

- Which uncertainties can be mitigated via the use of DeepCore and IceCube off-signal streams?

- and probably much much more ….

Questions to be answered by the sensitivity study

All of this makes the sensitivity study to NMH for PINGU a large but very exiting project. We are learning a lot!

We hope to have all the full sensitivity / feasibility study this for next Spring / Summer