Oscillation Research with Cosmics in the Abyss

KM3NeT Collaboration

ORCA overview

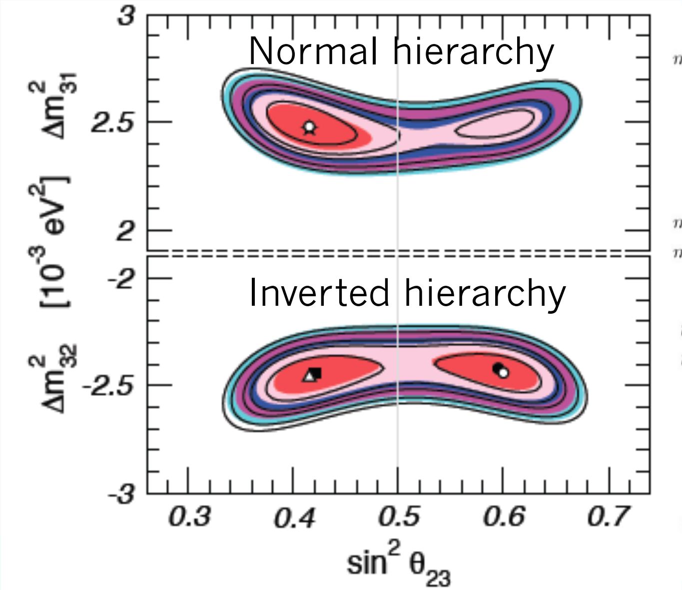
Antoine Kouchner (APC)
Catania, 05/12/2012

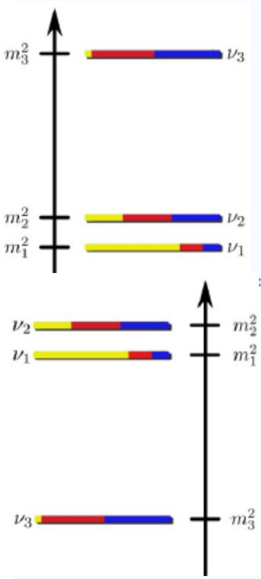
[ALL PRELIMINARY]

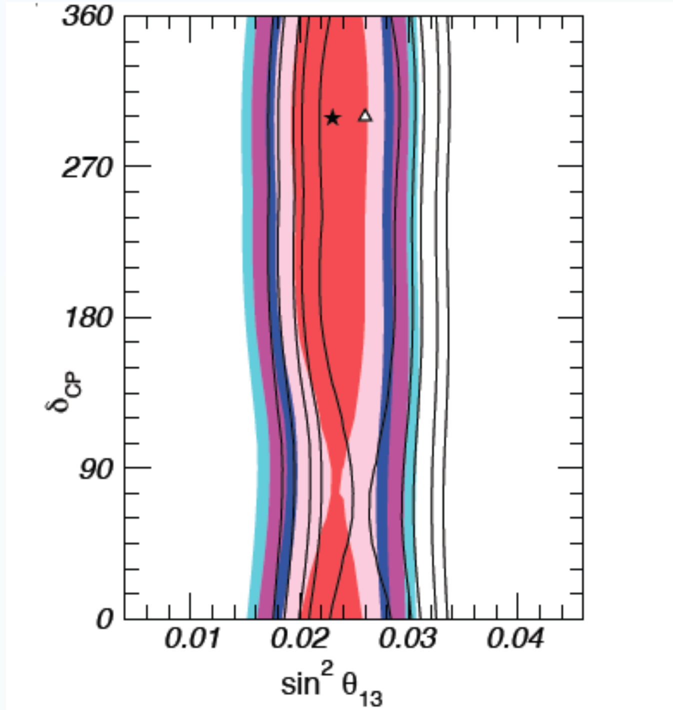
Outline

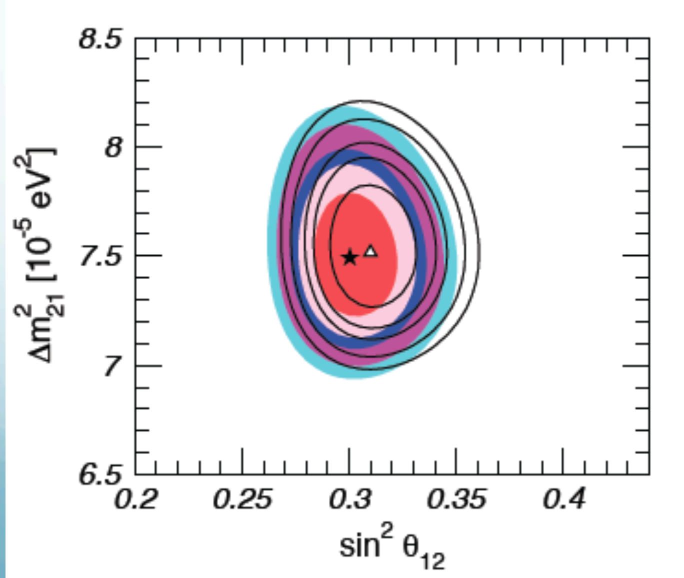
- What is it about?
  - Introduction
  - Akhmedov et al. paper
- First achievements with ANTARES
- Organization of ORCA
- Working lines
  - Systematics and sensitivity studies (Veronique)
  - First simulation chains
  - Algorithmic Aspects (direction and energy) (Agata, Apostolos)
  - Global fit approach (Aart)
- Outlook

Status









- All parameters are measured to fair precision except for the mass hierarchy and the CP phase.

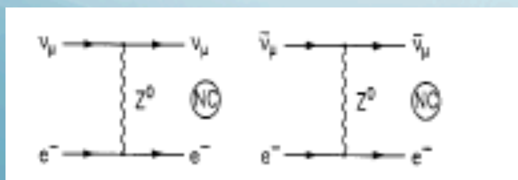
M. C. Gonzalez-Garcia et al., 1209.3023

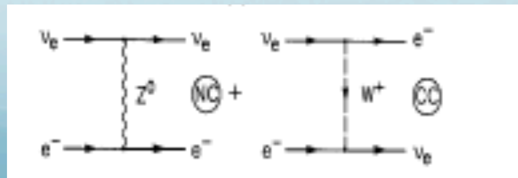
Long baseline experiments

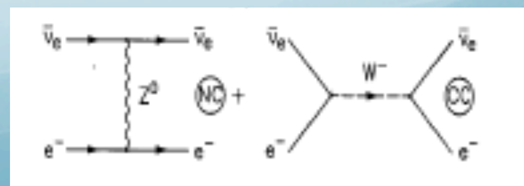
- « Standard approach » :probe $\nu_\mu \leftrightarrow \nu_e$ governed by Δm^2_{13}

$$P_{\mu e} = \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right) + \text{“subleading”}$$

- Insensitive to the sign of Δm^2_{13} at leading order.
- Matter effects (MSW) come to the rescue
- Earth density variations also affect the oscillations
- Different effect for neutrinos and antineutrinos
- Atmospheric neutrinos: effect measurable $\sigma(\nu) \approx 2\,\sigma(\overline{\nu})$





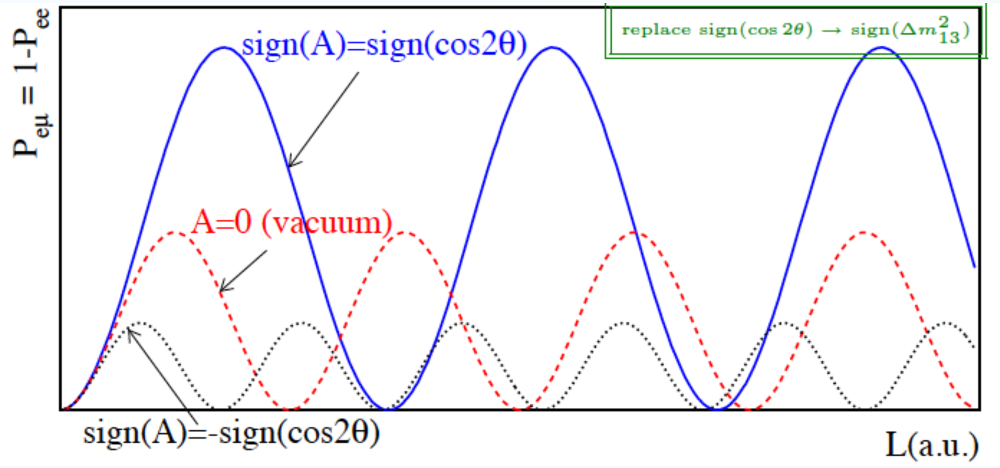


(Constant density) Matter effects

$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}^{\rm eff}\sin^2\left(\frac{\Delta_{13}^{\rm eff}L}{2}\right),$$

$$\sin^2 2\theta_{13}^{\rm eff} = \frac{\Delta_{13}^2\sin^2 2\theta_{13}}{(\Delta_{13}^{\rm eff})^2},$$

$$\Delta_{13}^{\rm eff} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta_{13}^2\sin^2 2\theta_{13}},$$



$A \equiv \pm\sqrt{2}G_F N_e$ is the matter potential.
- >0 for neutrinos
- <0 for anti-neutrinos

Requirements:

$\Delta_{13} \sim A$ matter potential must be significant not overwhelming

L large enough – matter effects are absent near the origin

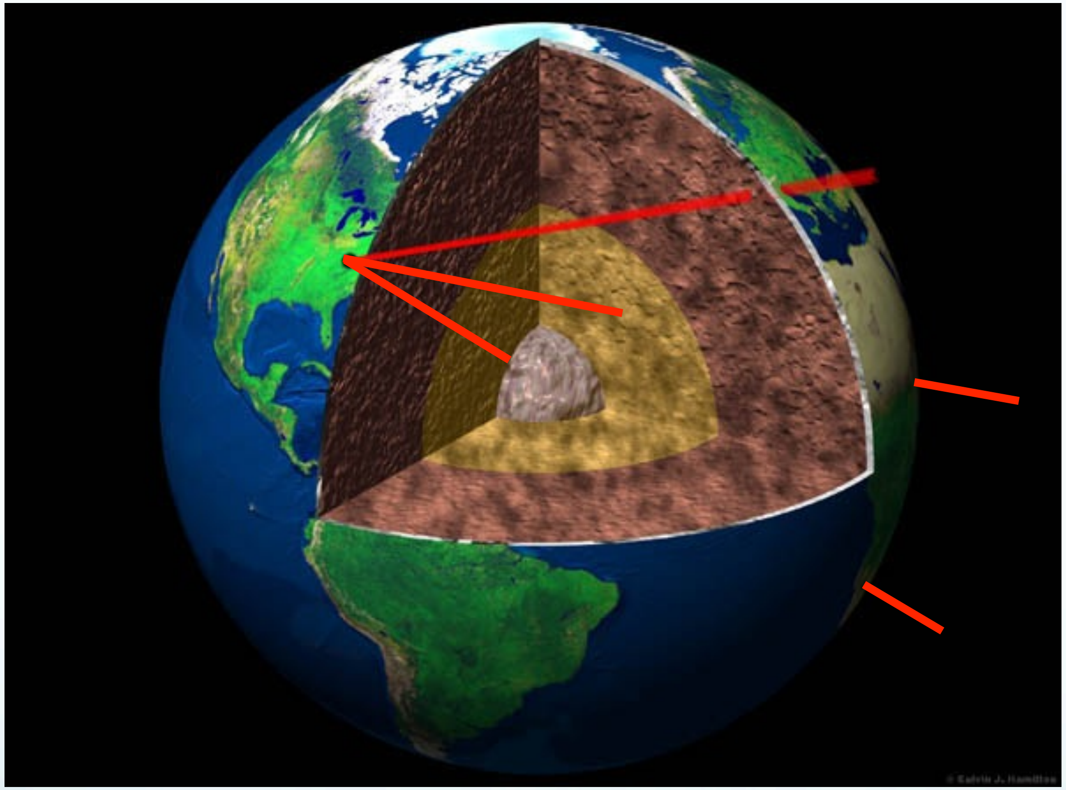
Matter resonance: A ➔ $\Delta_{13}\cos 2\theta_{13}$

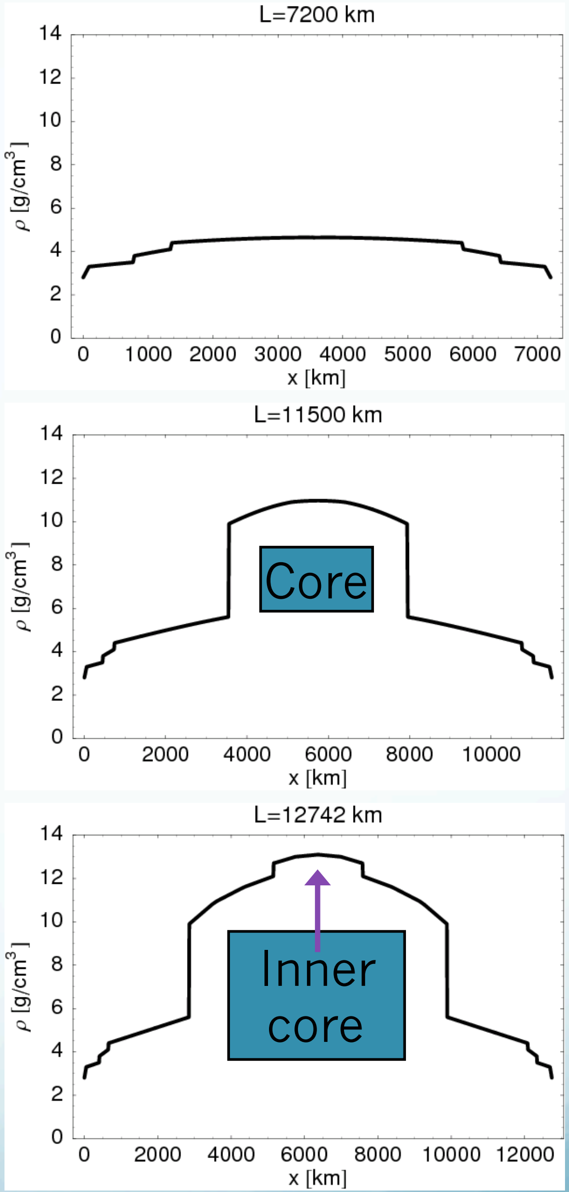
In this case:
- Effective mixing maximal
- Effective osc. frequency minimal

Resonance energy:

$$E_{\rm res}\,[\mathrm{GeV}] \sim 13\,200\,\cos 2\theta\,\frac{\Delta m^2\,[\mathrm{eV}^2]}{\rho\,[\mathrm{g/cm}^3]}$$

Earth density profile



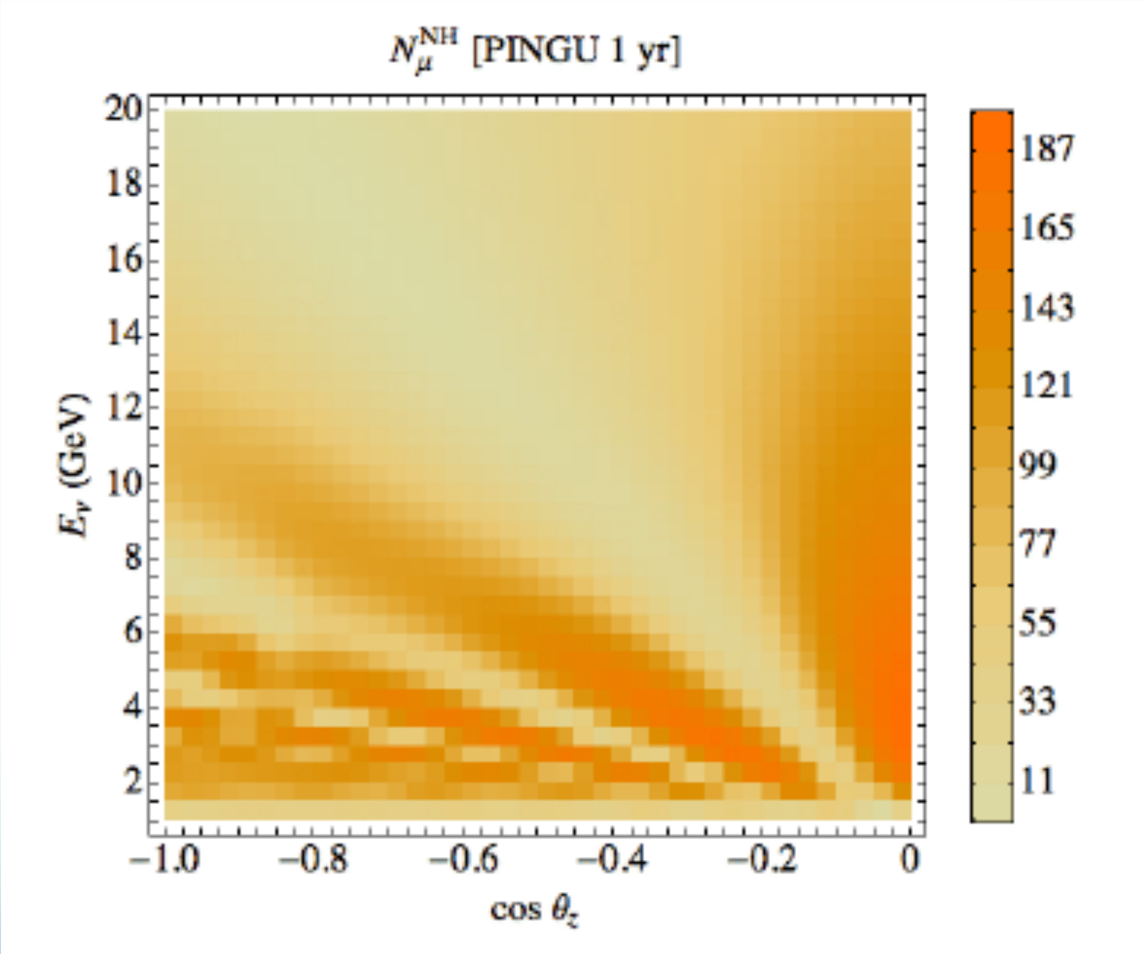


(PREM: Preliminary Reference Earth Model)

For ν_μ appearance:
- $\rho \sim 4.7$ g/cm^3 (Earth's mantle): $E_{res} \sim 7$ GeV
- $\rho \sim 10.8$ g/cm^3 (Earth's outer core): $E_{res} \sim 3$ GeV

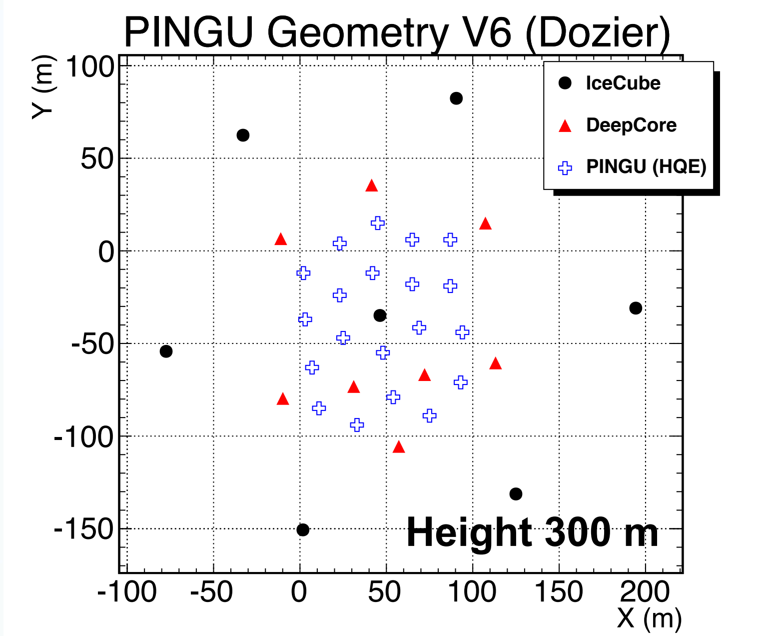
Akhmedov-Razzaque-Smirnov paper

hep-ph > arXiv:1205.7071 (v4)



Uses a large PINGU effective volume

PINGU possible configuration

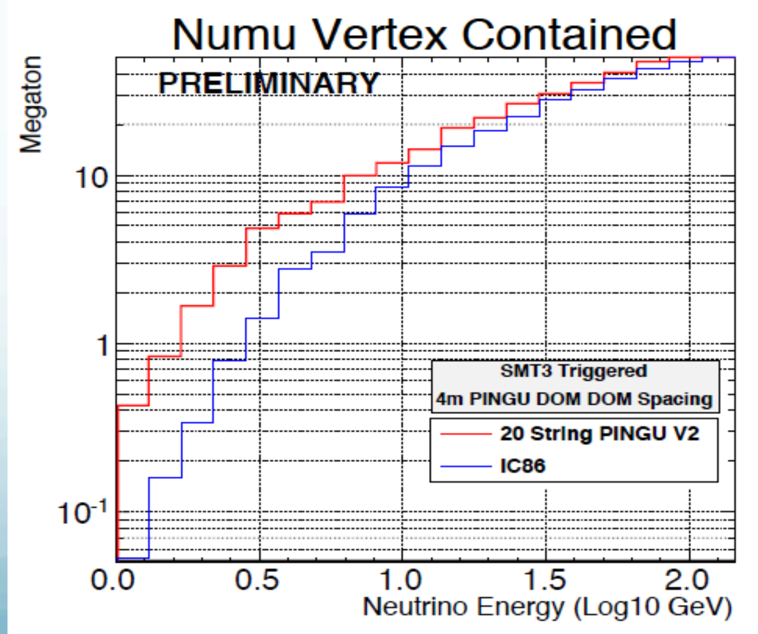


- Phased IceCube Next-Generation Upgrade

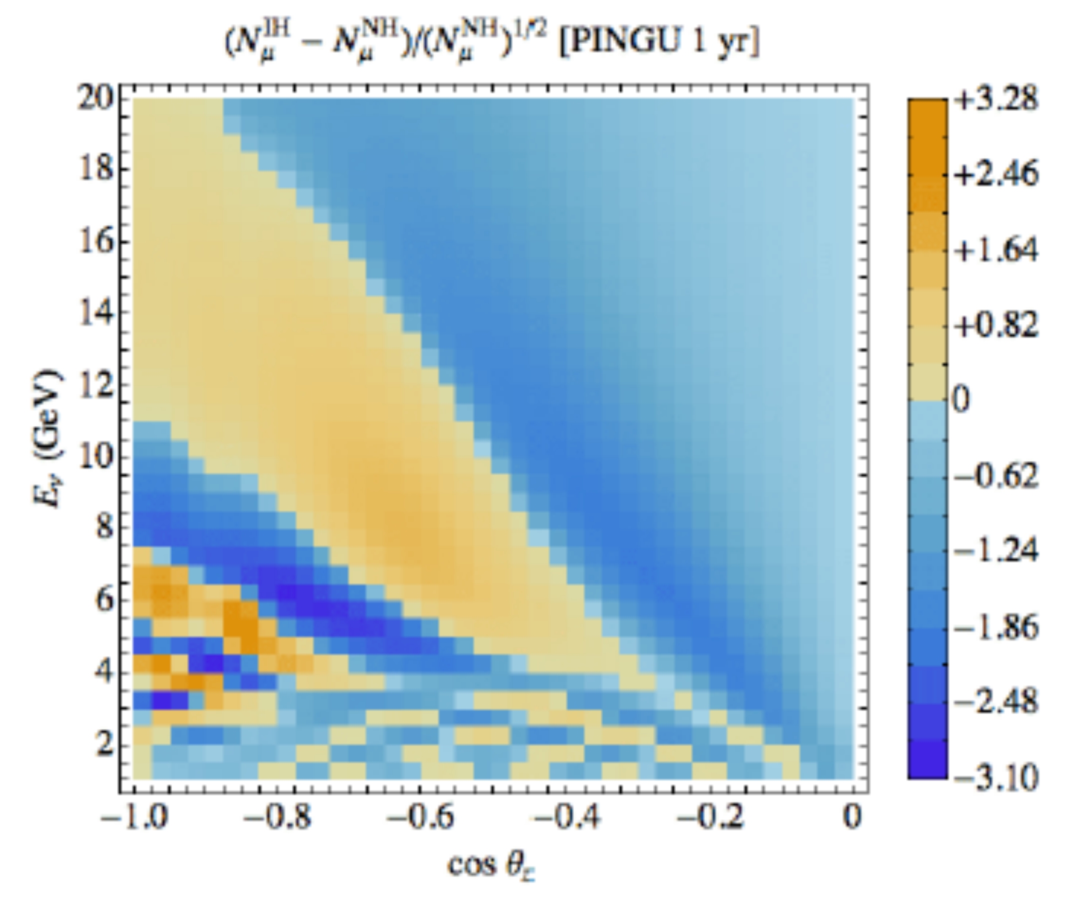
- Add 20 strings in Deep Core region
- Vertical distance between OM~5m

- Expected energy threshold at 1 GeV

- Other configurations under study



ARS: Inverted vs Normal



Perfect resolution

$$S^{tot} = \sqrt{\sum_{ij} S_{ij}^2} = \sqrt{\sum_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{\sigma_{ij}^2}}$$

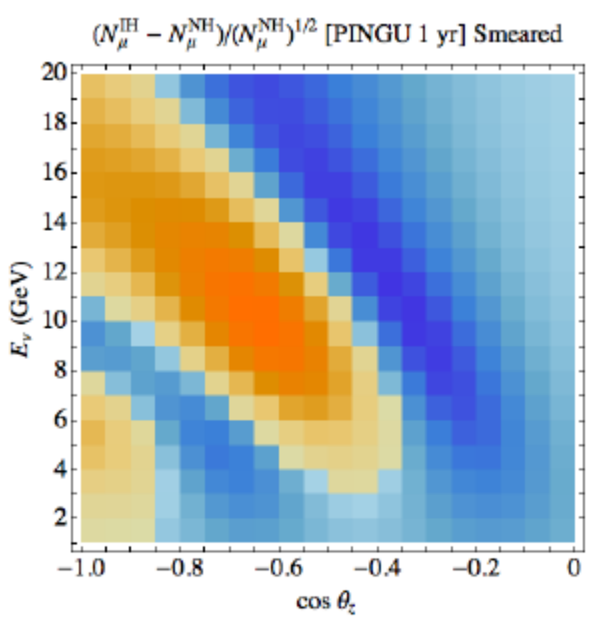
$$\sigma_{ij}^2 = N_{ij}^{NH} + (f N_{ij}^{NH})^2$$

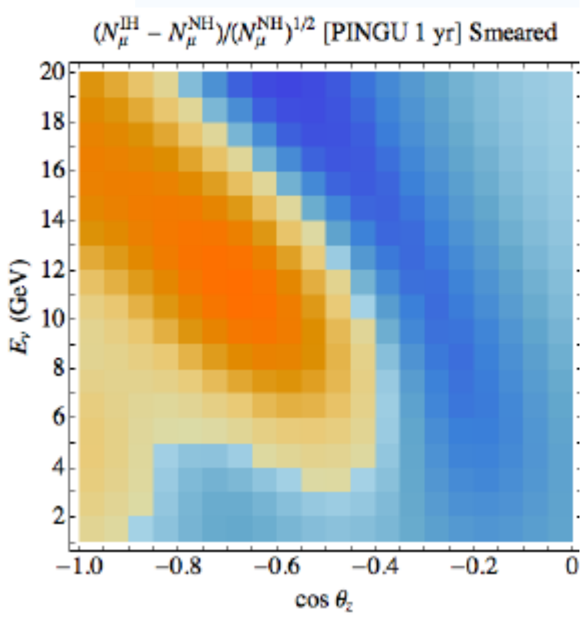
Uncorrelated systematics

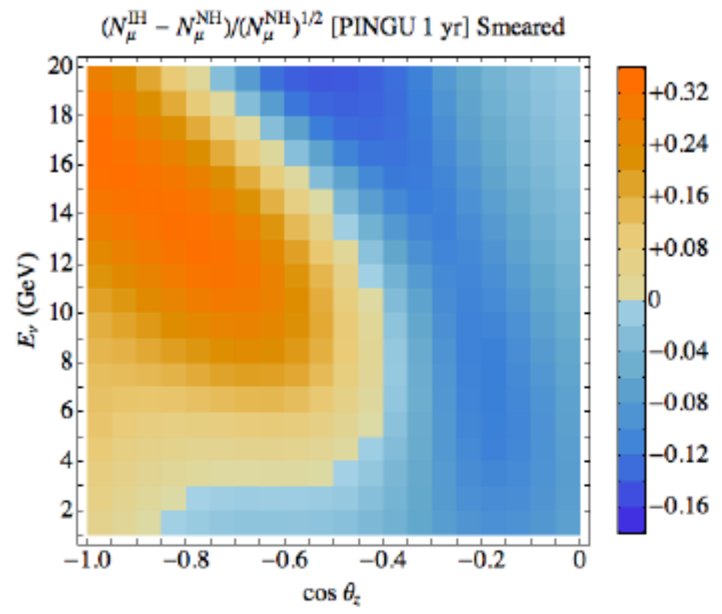
S=45.5σ (f=0%)
S=28.9σ (f=5%)
S=18.8σ (f=10%)

In 5 years

ARS: Inverted vs Normal







σE=2 GeV, σθ= 11.25°

S=16.3σ (f=0%)
S=11σ (f=5%)
S=7.2σ (f=10%)

σE=3 GeV, σθ= 15°

S=10.4σ (f=0%)
S=7σ (f=5%)
S=4.5σ (f=10%)

σE=4 GeV, σθ= 22.5°

S=7.2σ (f=0%)
S=4.5σ (f=5%)
S=3.0σ (f=10%)

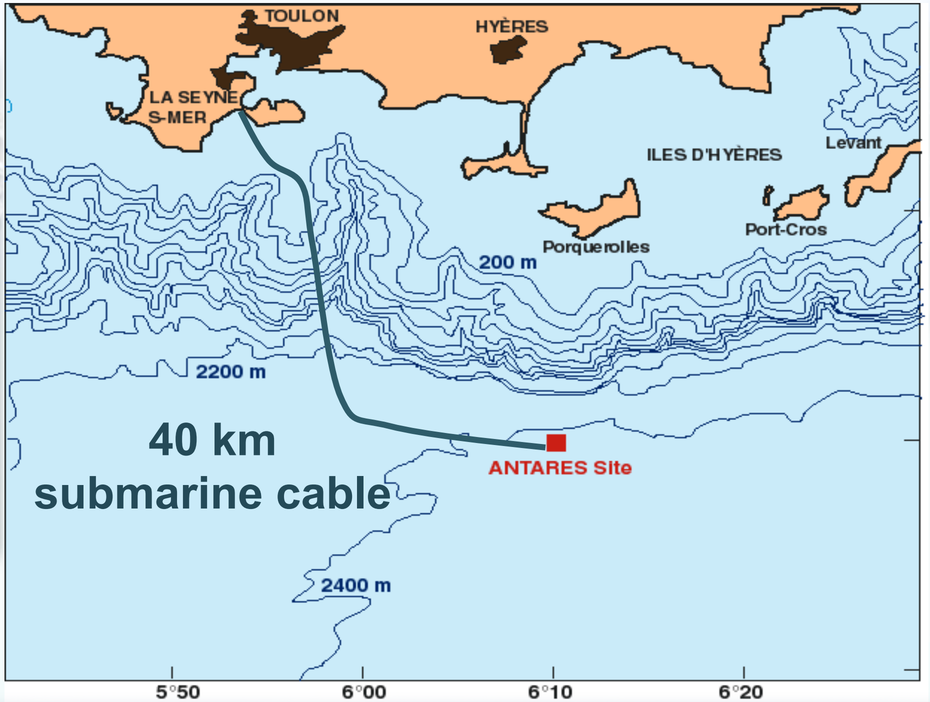
5 years

Mass hierarchy measurements

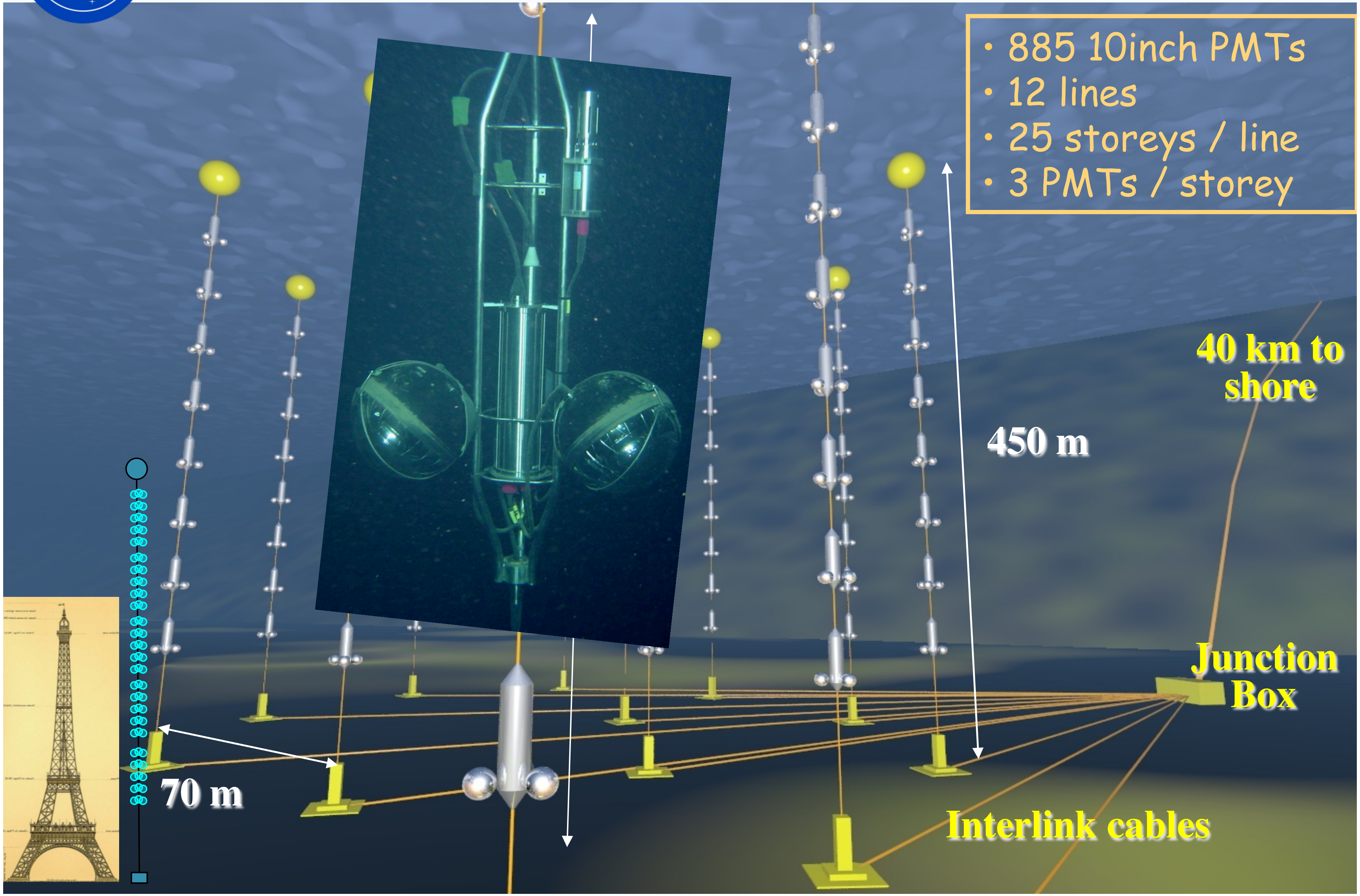
From J. Brunner

Project	Neutrino source	Detector	Goal	Problem
NOvA	LBL 810 km	14 kt tracking calorimeter	2σ for some values of δ ; 2020	Parameter degeneracy
Daya Bay II Reno II	Reactor 60 km	50 kt liquid scintillator	3σ in 2023	E_ν resolution & absolute scale
PINGU / ORCA	Atmosphere	1-10 Mt	3-5σ in ?	E_ν resolution Systematics
INO	Atmosphere	50 kt magnetized iron calorimeter	3σ in 2030	Low statistics 10 years needed
T2 Hyper Kamiokande	LBL 295 km	1 Mt water	3σ in 2030	Parameter degeneracy
LBNE	LBL 1300 km	10 kt Liquid Argon	2-5σ in 2030	Parameter degeneracy
LAGUNA Glacier	LBL 2300 km	20 kt Liquid Argon	5σ in 2030	Beam line from CERN
LAGUNA LENA	LBL 2300 km	50 kt Liquid scintillator	5σ in 2030	Beam line from CERN

The ANTARES Site & Infrastructure



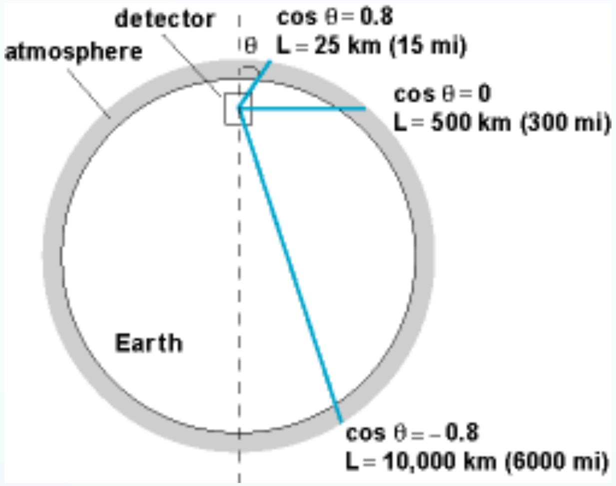
The ANTARES detector



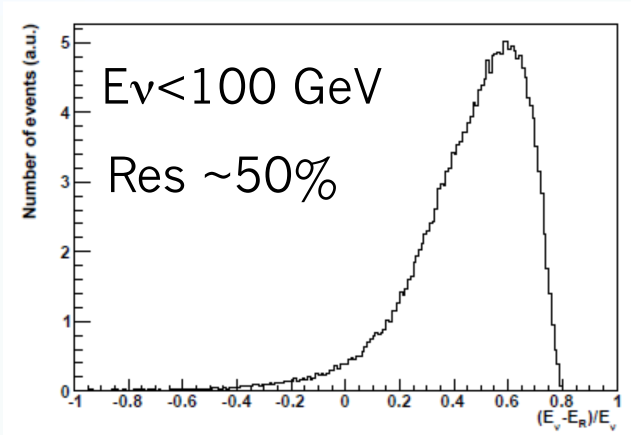
Oscillations with Atmospheric Neutrinos

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m_{32}^2 \cos\Theta}{E_\nu}\right)$$

$L = 2\ R_{Earth} \cos\theta$, from track fit

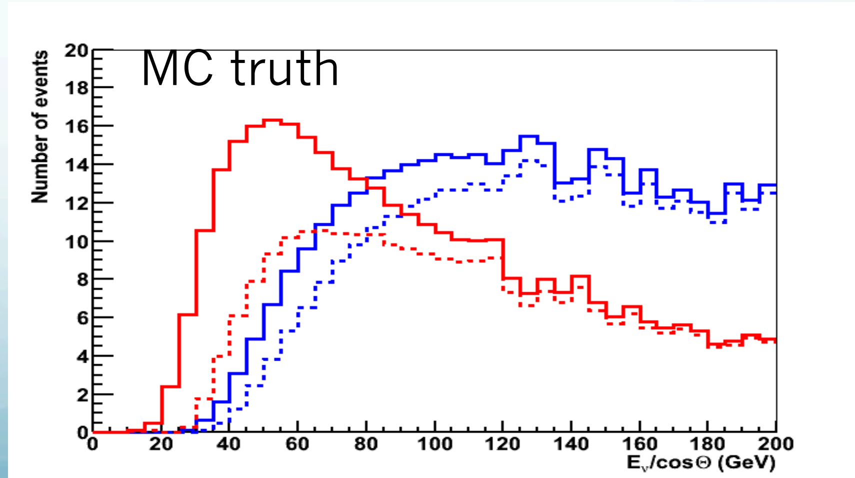


Eν from muon range



Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)

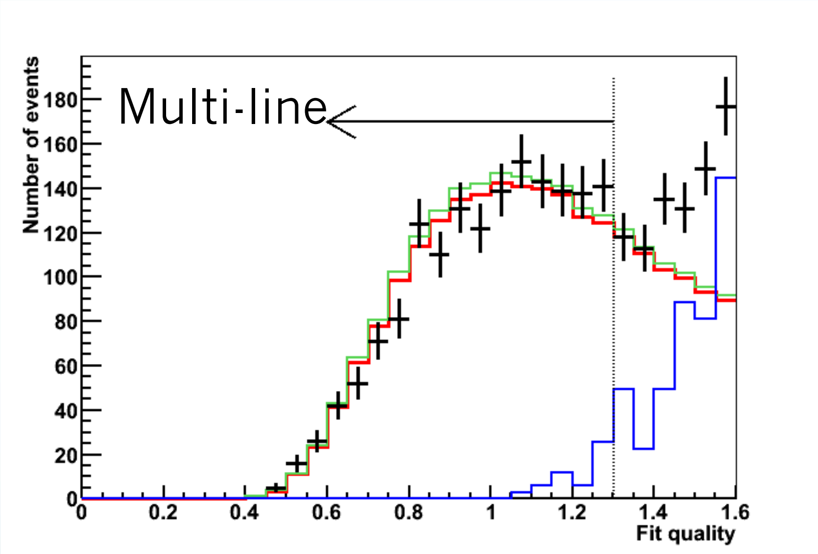
Larger effect on single-line (low energy) than multi-line (higher energy) events

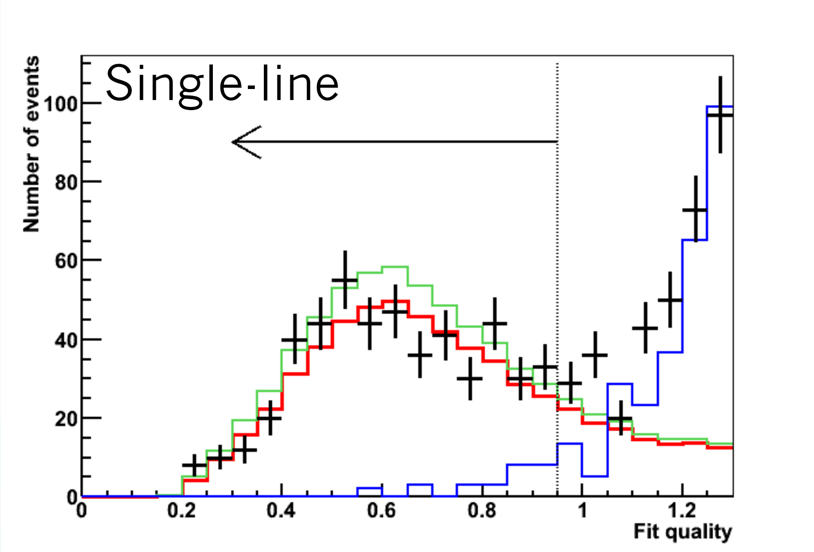


Neutrino Oscillations: Track Selection

Special low energy fit for single-line events (>7storeys, do not fit azimuth)

Select pure sample of atmospheric neutrinos (<5% muon contamination)





Zenith angle resolution:
0.8 degrees for multi-line events
3 degrees for single-line events

Neutrino Oscillations: Result

2008-2010 data (863 days):

No oscillation: χ^2/NDF = 40/24 (2.1%)

Best fit: χ^2/NDF = 17.1/21

$\Delta m^2 = 3.1\ 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.00$

Systematics:

(Absolute normalisation free)

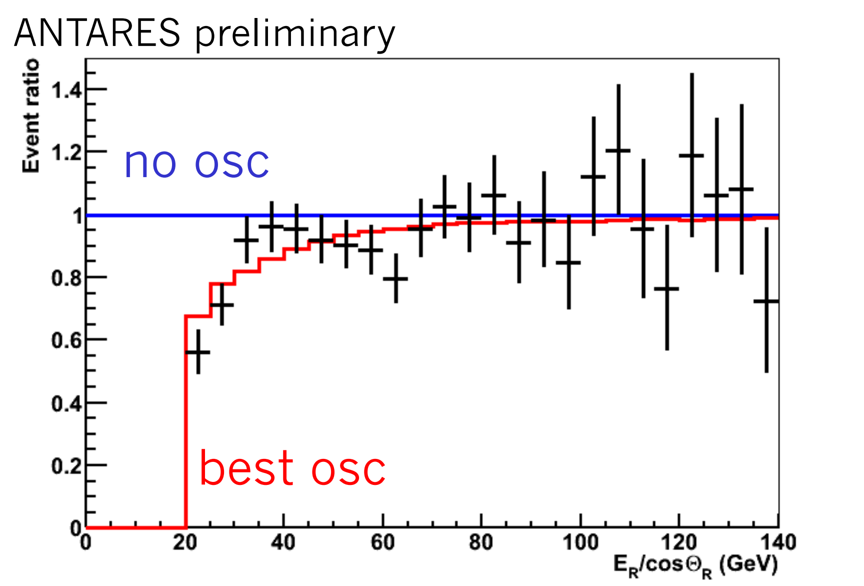
Absorption length: ±10%

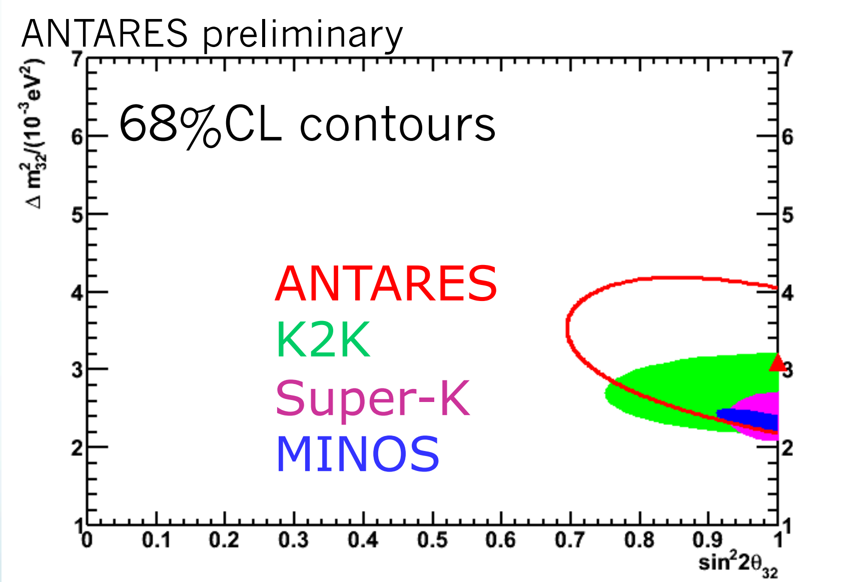
Detector efficiency: ±10%

Spectral index of ν flux: ±0.03

OM angular acceptance

5% error on slope vs $E_R/\cos\vartheta_R$



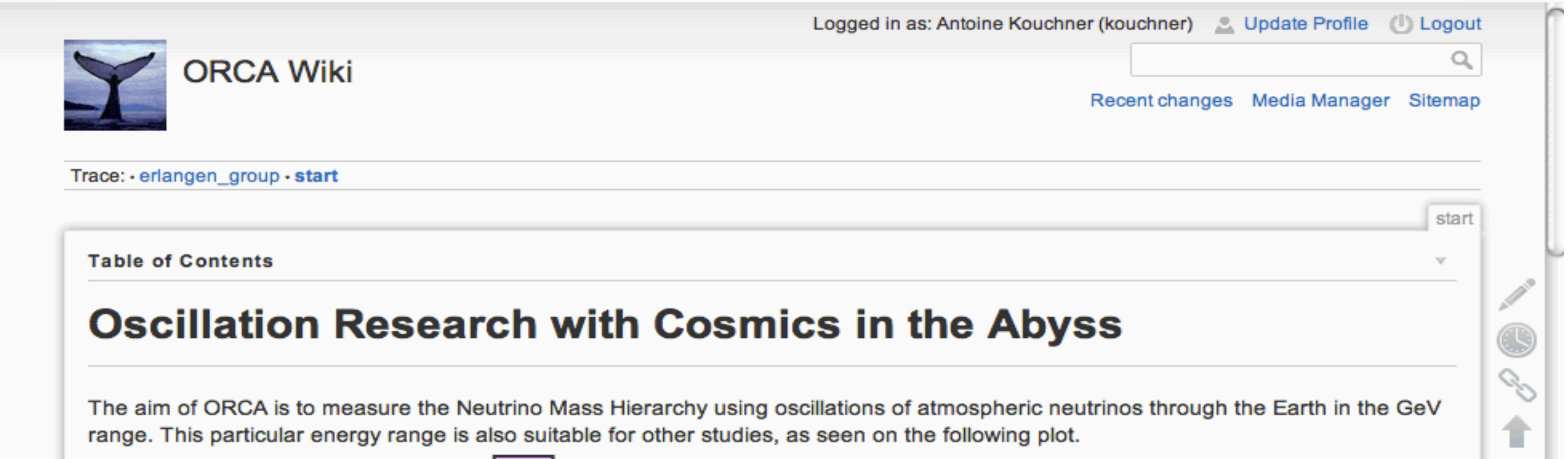


Assuming maximal mixing: $\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}\ eV^2$

Published in Phys. Lett. B 714 (2012) 224.

ORCA : organization

- Work performed within the KM3NeT collaboration (phase I) + a few other interested neutrino physics colleagues
- Coordination: A.Kouchner & A. Tsirigotis
- Mailing list: orca-l@in2p3.fr
- Wiki page : https://sbgorcawiki.in2p3.fr/doku.php



ORCA: organization

ORCA

Go to parent category | iCal export | View

Project ORCA
Managers: Kouchner, A.; Tsirigotis, A.

December 2012

05 Dec ORCA workshop (protected) New!

November 2012

06 Nov ORCA-PINGU common call

October 2012

25 Oct ORCA videoconference (protected)
05 Oct ORCA get-together (protected)

September 2012

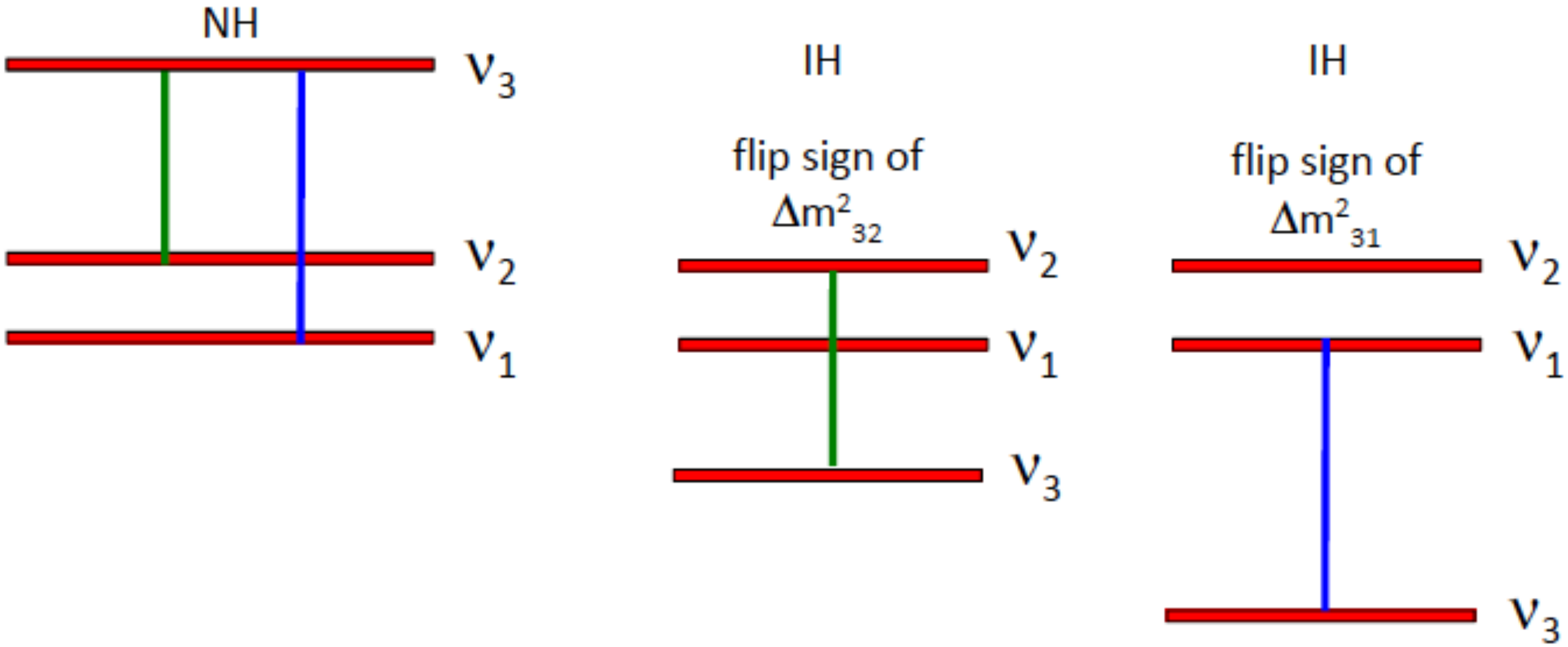
18 Sep ORCA videoconference (protected)
06 Sep ORCA kick-off meeting (protected)

Working lines

- Systematics and sensitivity studies
- First simulation chains
- Algorithmic Aspects
- Global fit approach

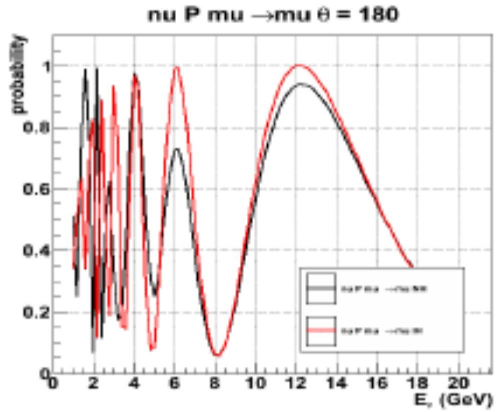
Next meeting in Marseilles January 29-31, 2012

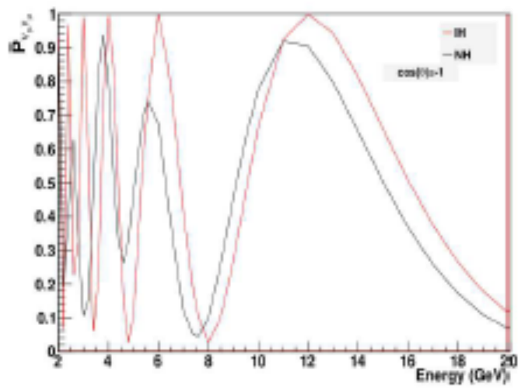
Definition of Inverted Hierarchy



Using globes: flipping Δm^2_{31} 'natural' (it is an input parameter)

Reading Ohlsson & Snellman: flipping Δm^2_{32} seems 'natural'





Definition of Inverted Hierarchy

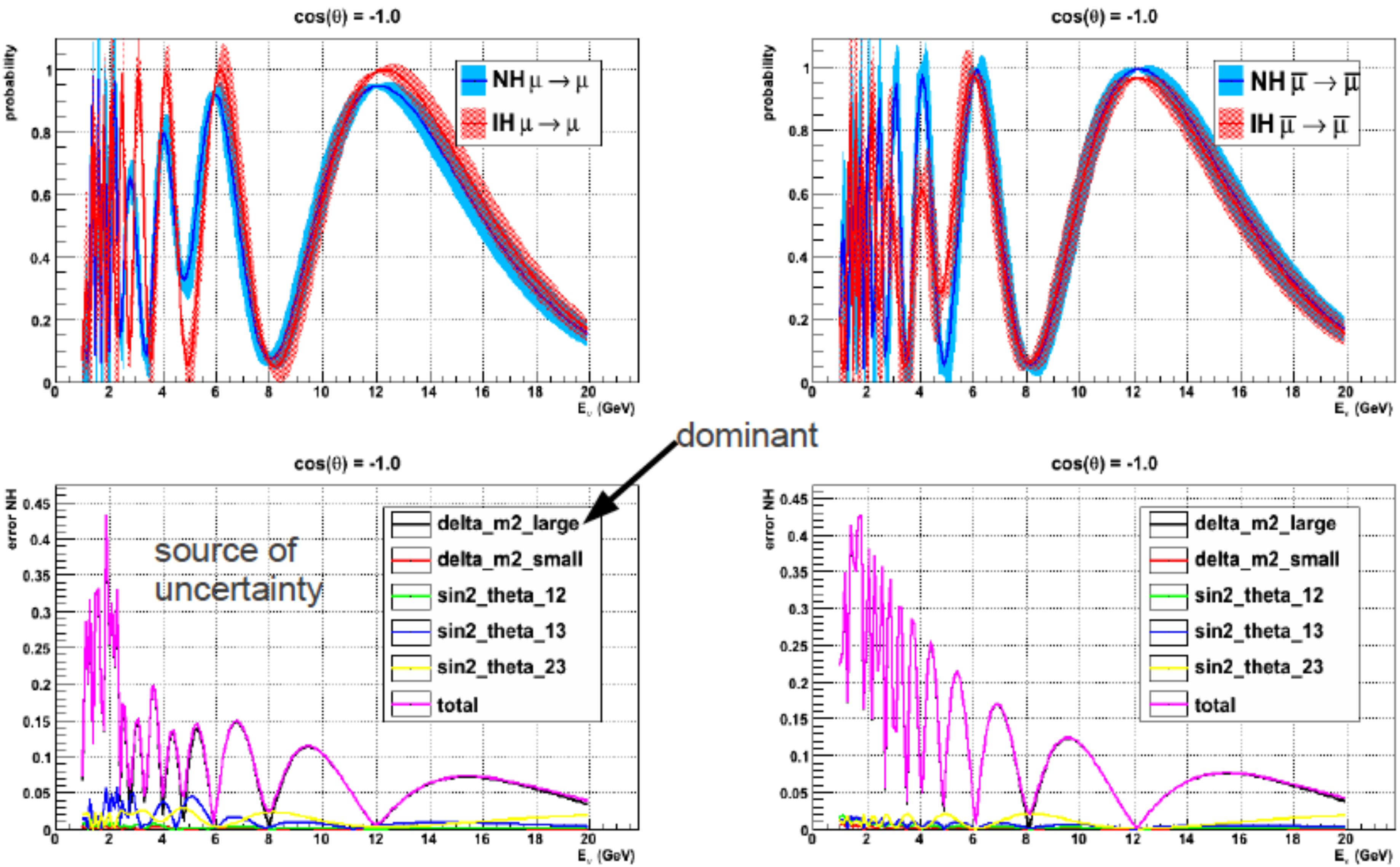
- A most reasonable choice:

flip the sign of $\Delta m^2_{large} = m^2_3 - (m^2_2 + m^2_1)/2$

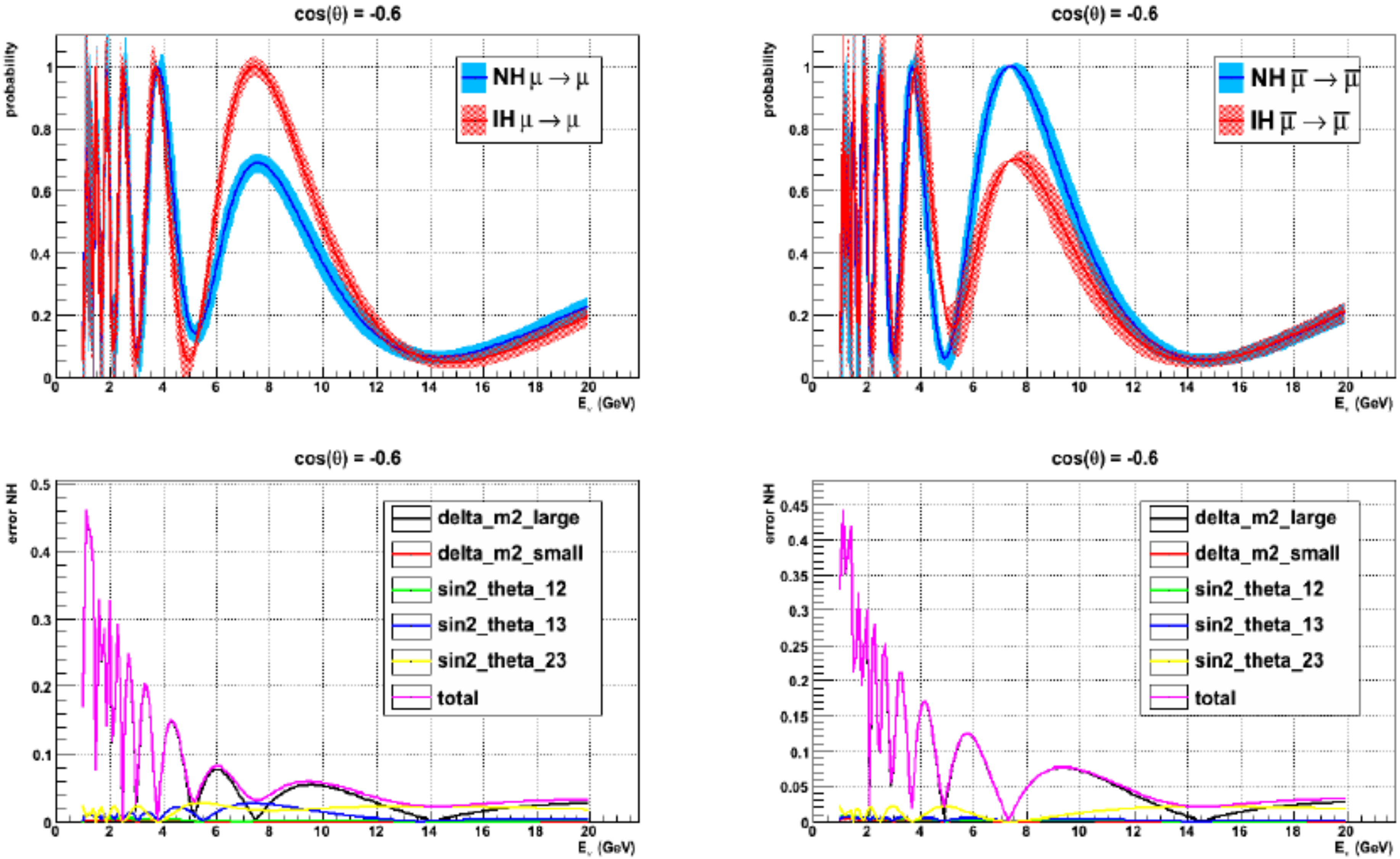
Parameter	Central value	1σ allowed range
$\delta m^2/10^{-5}$eV (NH or IH)	7.54	7.32-7.8
$\sin^2\theta_{12}/10^{-1}$(NH or IH)	3.07	2.91-3-25
$\Delta m^2/10^{-3}$eV (NH)	2.43	2.33-2.49
$\Delta m^2/10^{-3}$eV (IH)	2.42	2.31-2.49
$\sin^2\theta_{13}/10^{-2}$(NH)	2.41	2.16-2.66
$\sin^2\theta_{13}/10^{-2}$(IH)	2.44	2.19-2.67
$\sin^2\theta_{23}/10^{-1}$(NH)	3.86	3.65-4.10
$\sin^2\theta_{23}/10^{-1}$(IH)	3.92	3.7-4.31
δ/π (NH)	1.08	0.77-1.36
δ/π (IH)	1.09	0.83-1.47

Table 1: Result of the global 3ν oscillation analysis. Remember that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. Taken from [12]

Plots with uncertainties

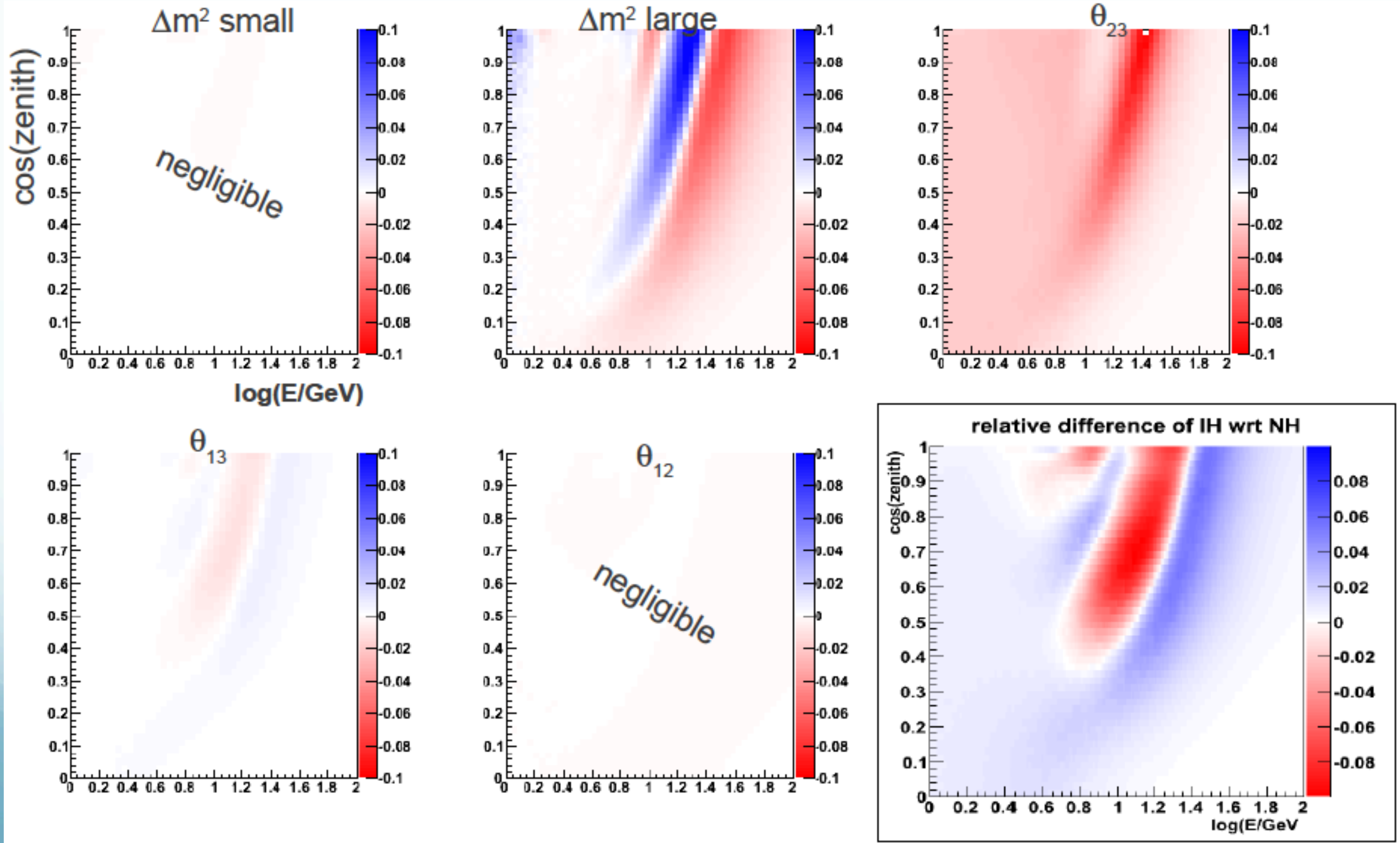


Plots with uncertainties

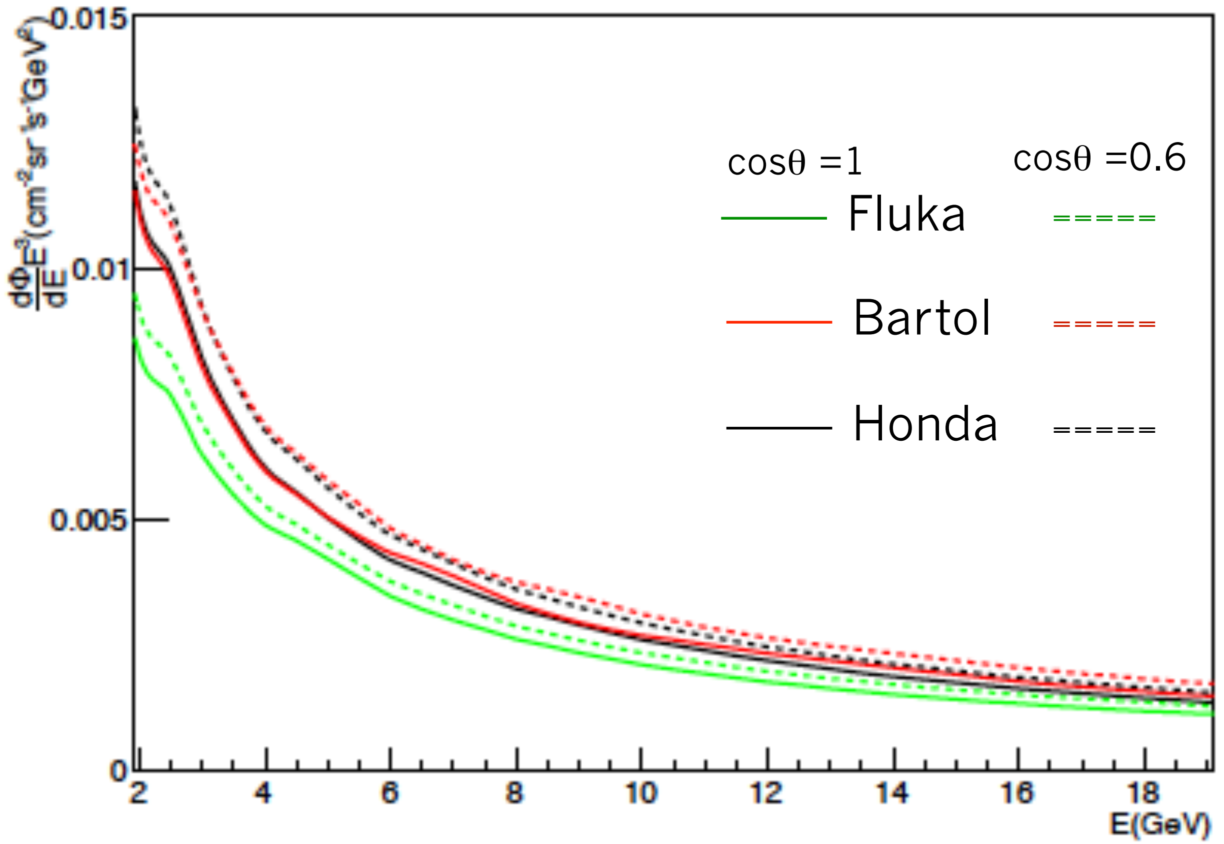


Oscillation parameter uncertainties

25% energy resolution and kinematics included



Atmospheric neutrino fluxes

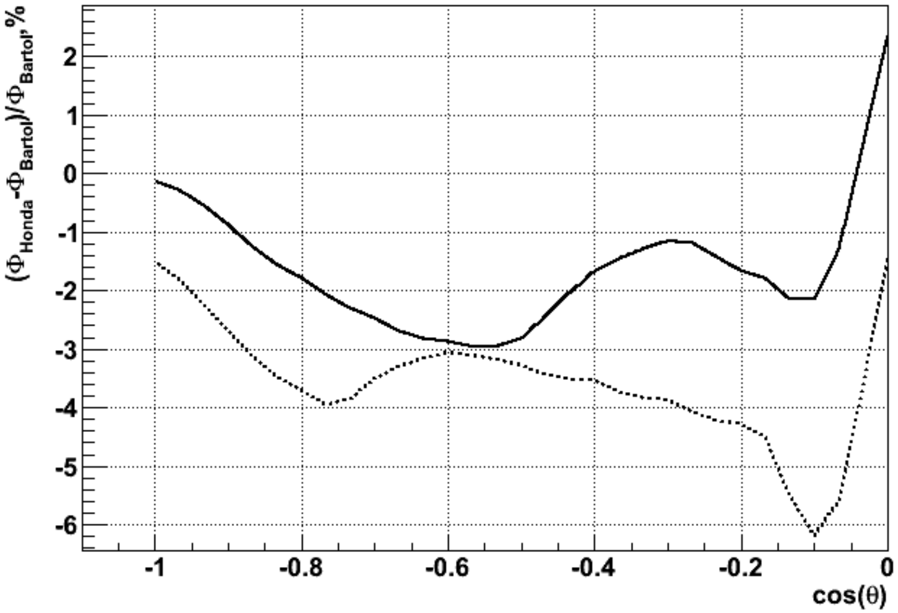


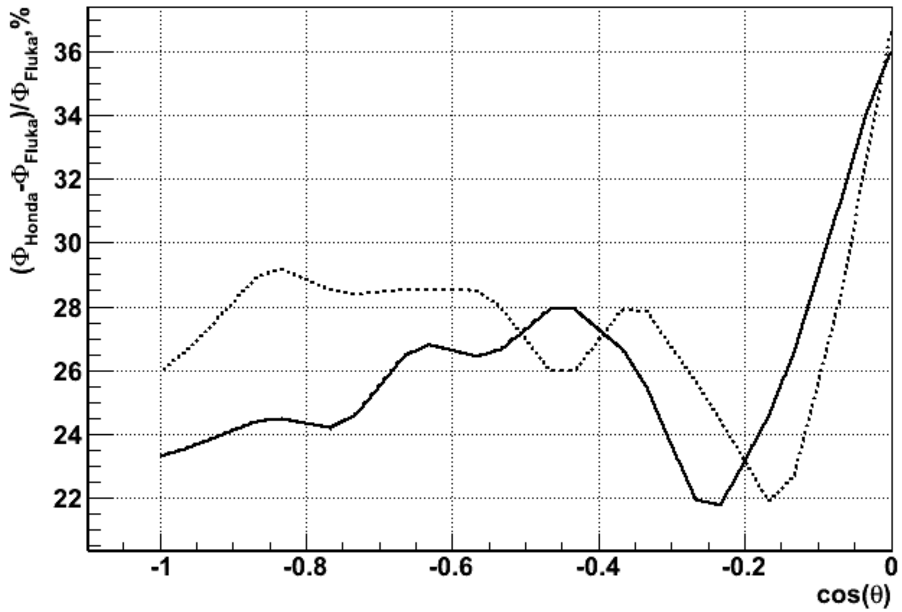
The fluxes used here are not the latest ones for each model. But today 20% uncertainties still remain from one group to another.

Comparison of fluxes

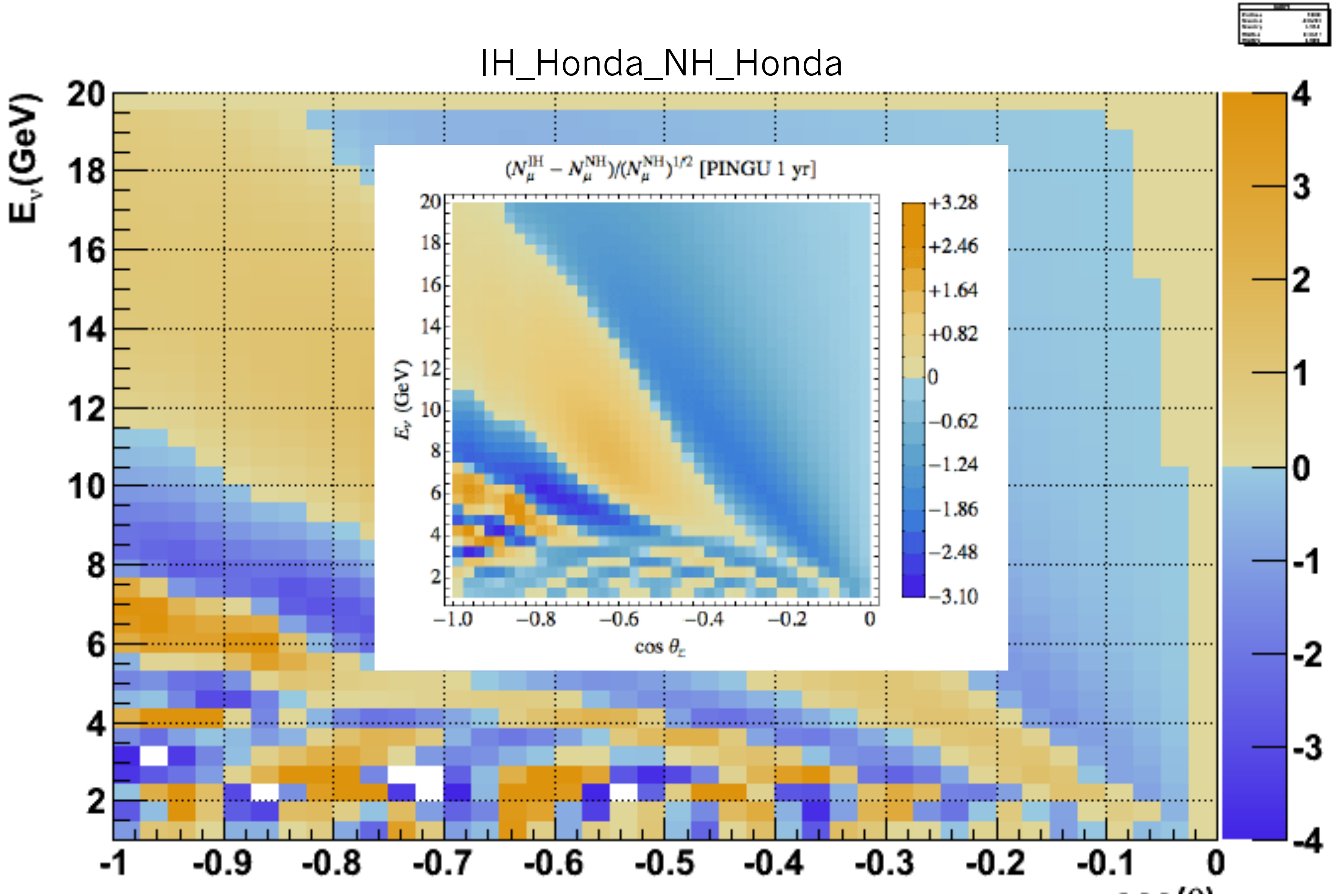
===== 5 GeV

══════ 10 GeV

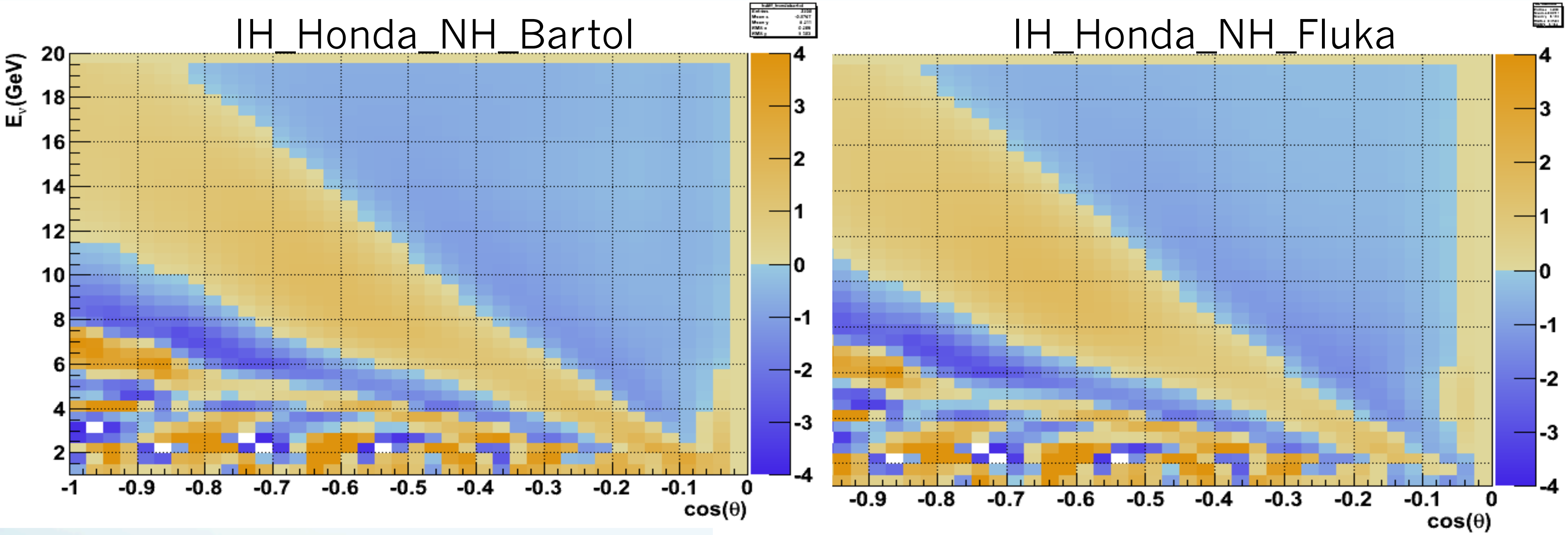




Fluxes as systematics

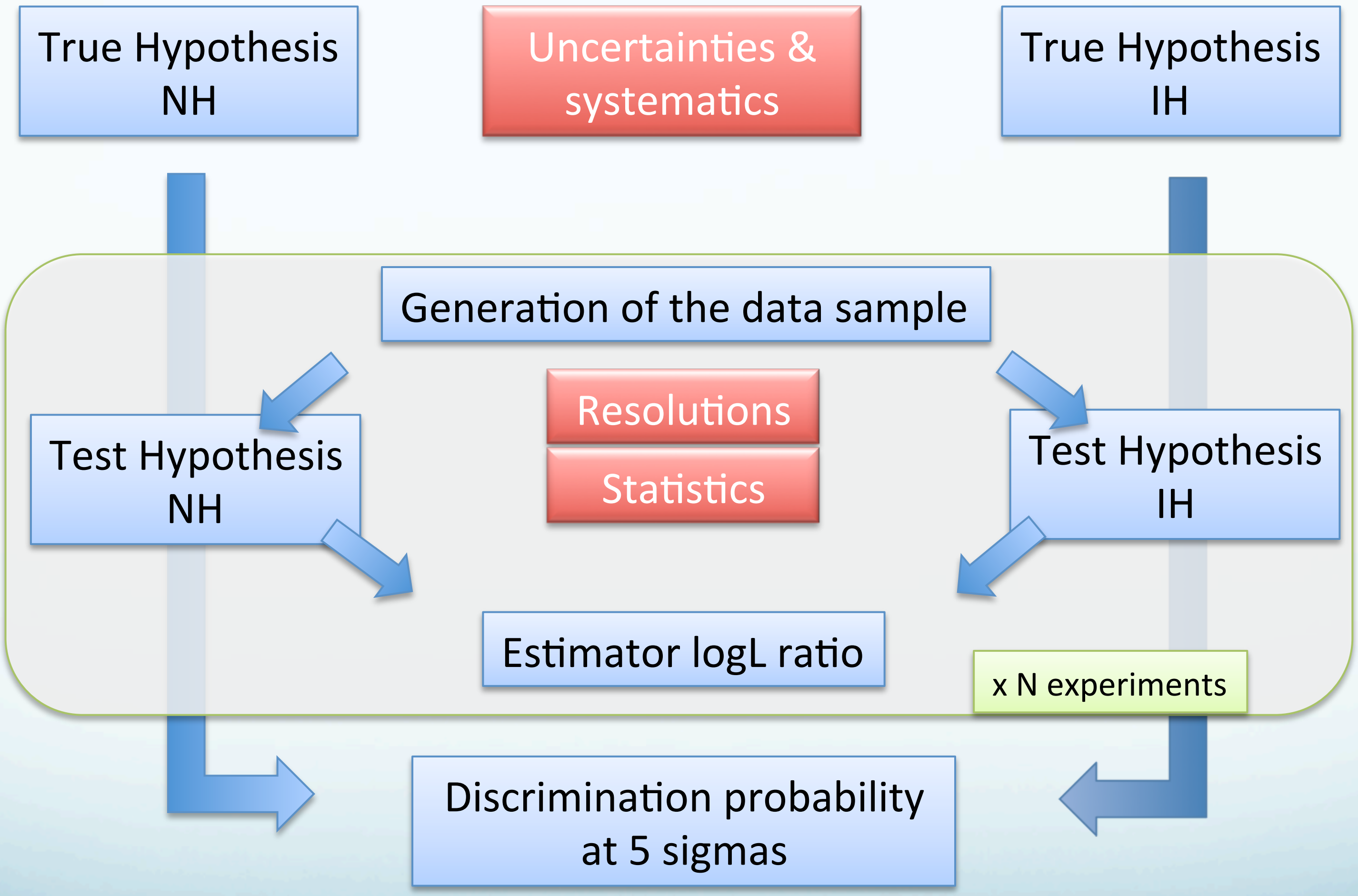


Fluxes as systematics



Impact of the atmospheric neutrino flux is reduced.
Probability to misidentify the mass hierarchy because of the differences of the neutrino spectrum shape is small (modulo normalization!)

Statistical method for MH discrimination



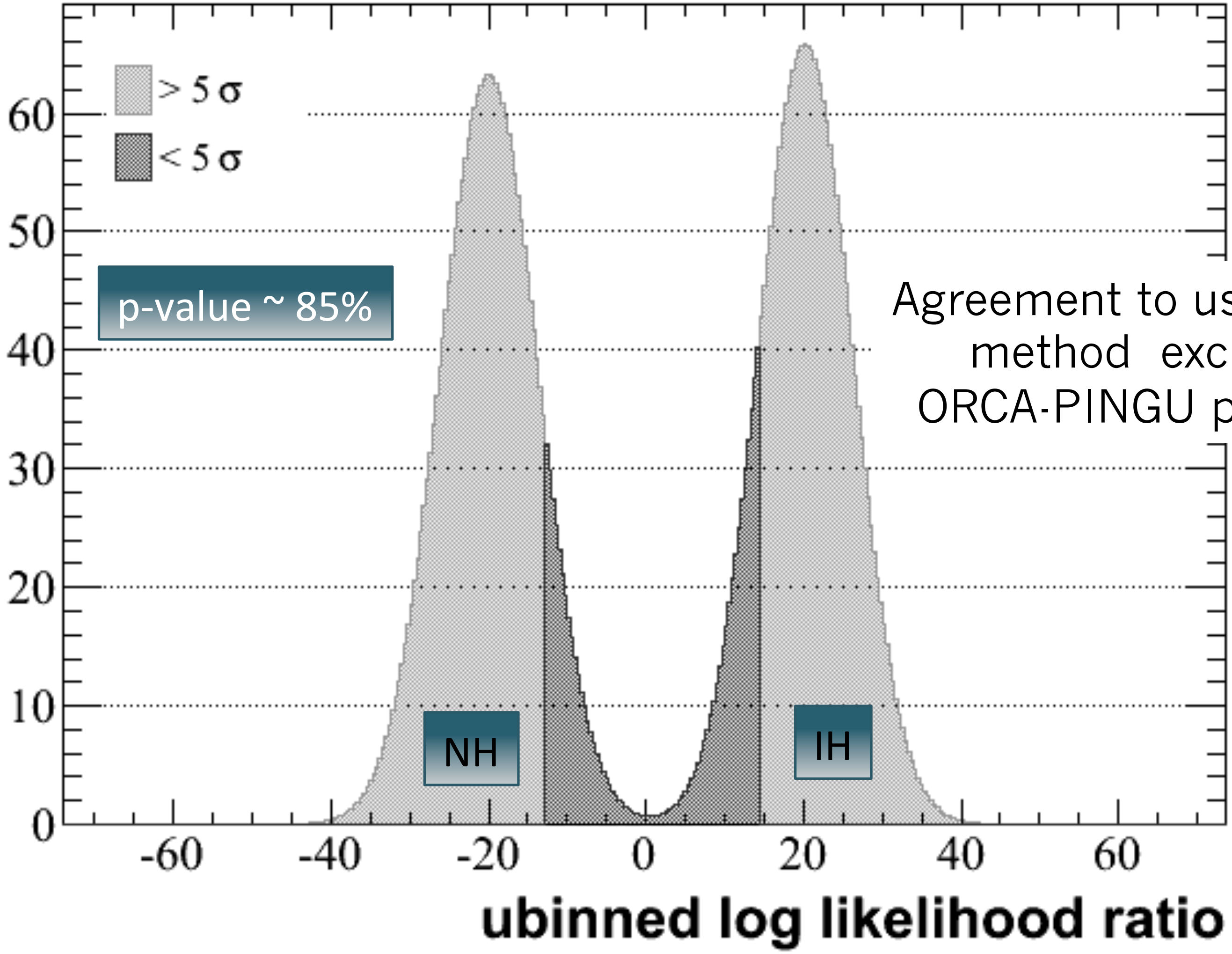
$$L_j = \frac{(e^{-\mu_j} \mu_j^n)}{n!} \times \prod_i \mathrm{pdf}_j(E_i, \theta_i)$$

$$\eta = \log(L_{NH}/L_{IH})$$

Probability to reach 5 σ

An example:

Energy resolution = 5 GeV
Angular resolution = 15 degree



Agreement to use the same method exchanging ORCA-PINGU parameters

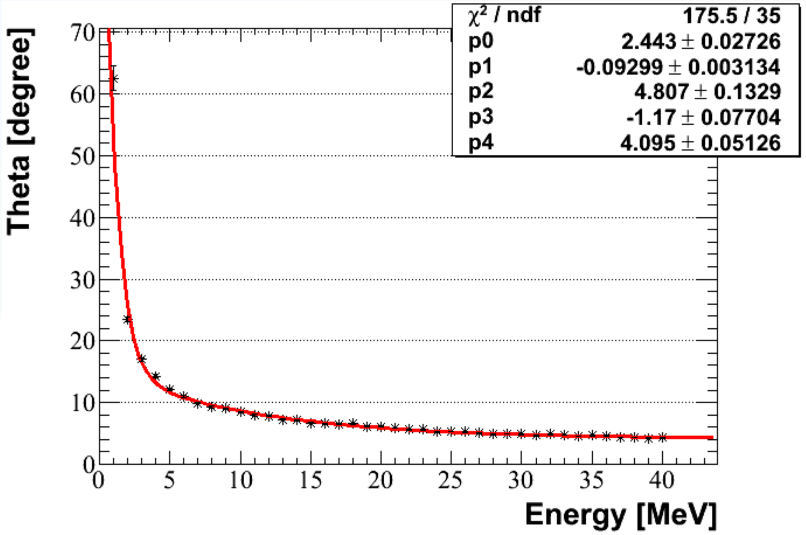
Results for different resolutions

Effective PINGU mass (Akhmedov et al.):

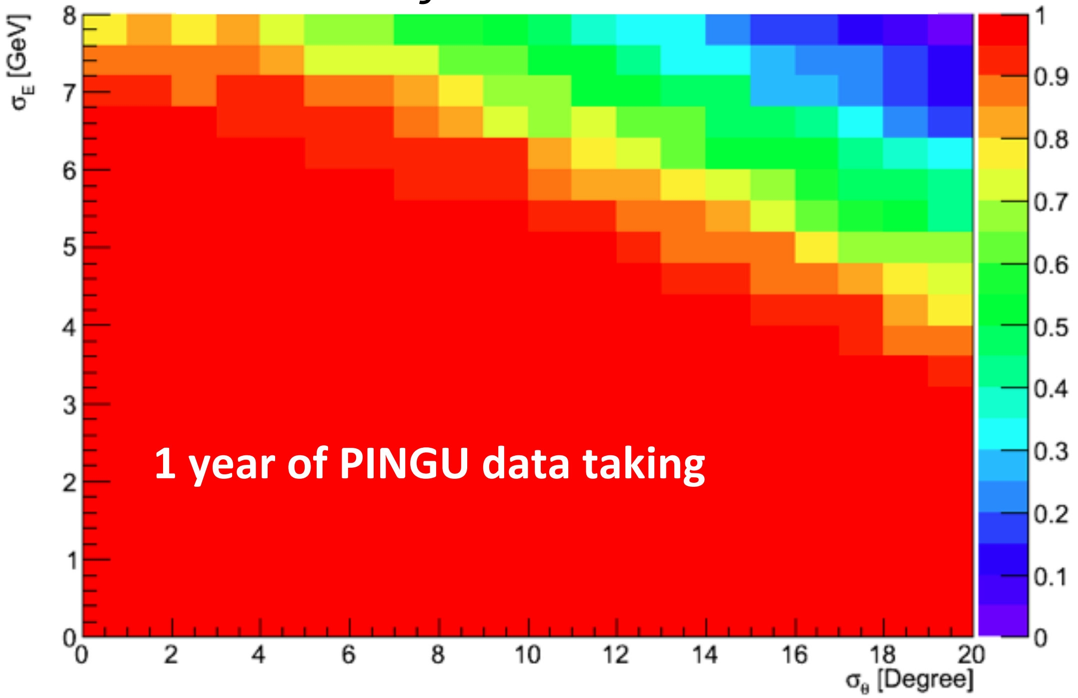
$M_{eff}(E) = 14.6 \times [\log(E_\nu/\mathrm{GeV})]^{1.8}$ Mt

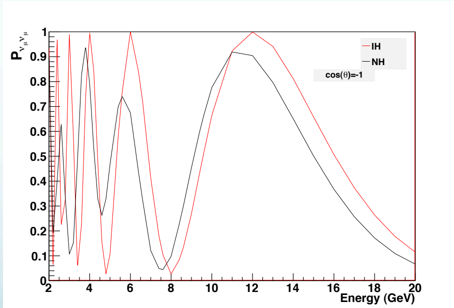
Neutrino-Muon scattering angle – parameterized

$\sigma_\alpha = \mathrm{Exp}(p_0 + p_1 x E) + \mathrm{Exp}(p_2 + p_3 x E) + p_4$



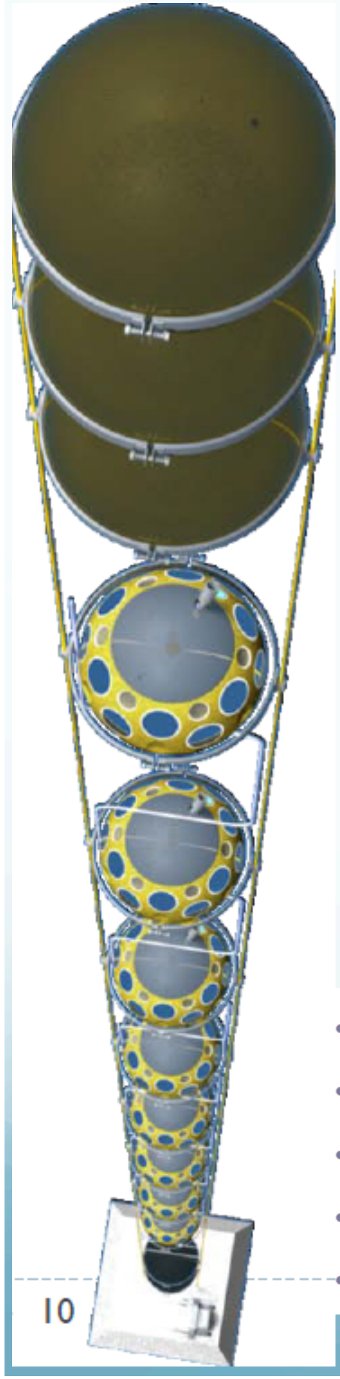
Probability to reach a 5 σ effect





Too favorable case here...

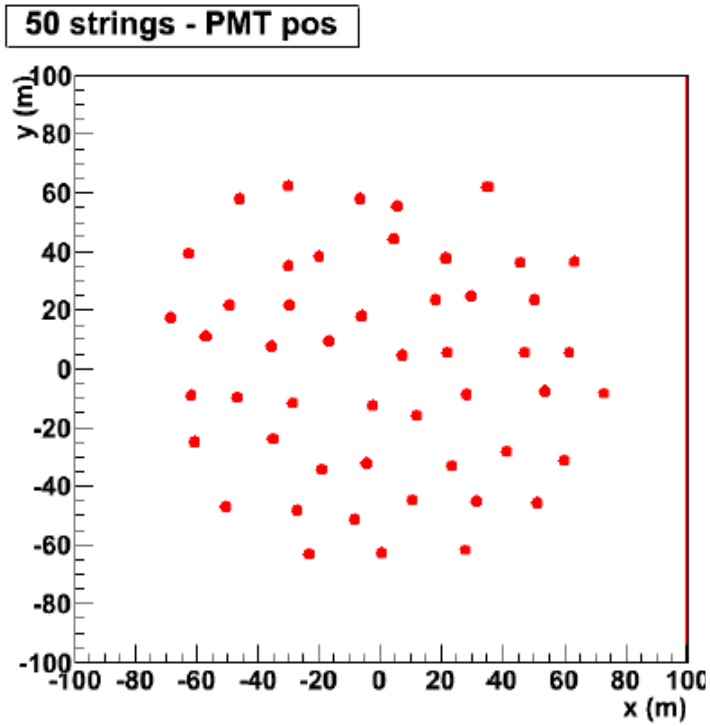
Possible ORCA detector



- ORCA detector:
  - 50 strings 20m spaced
  - 20 DOM/string spaced 6m

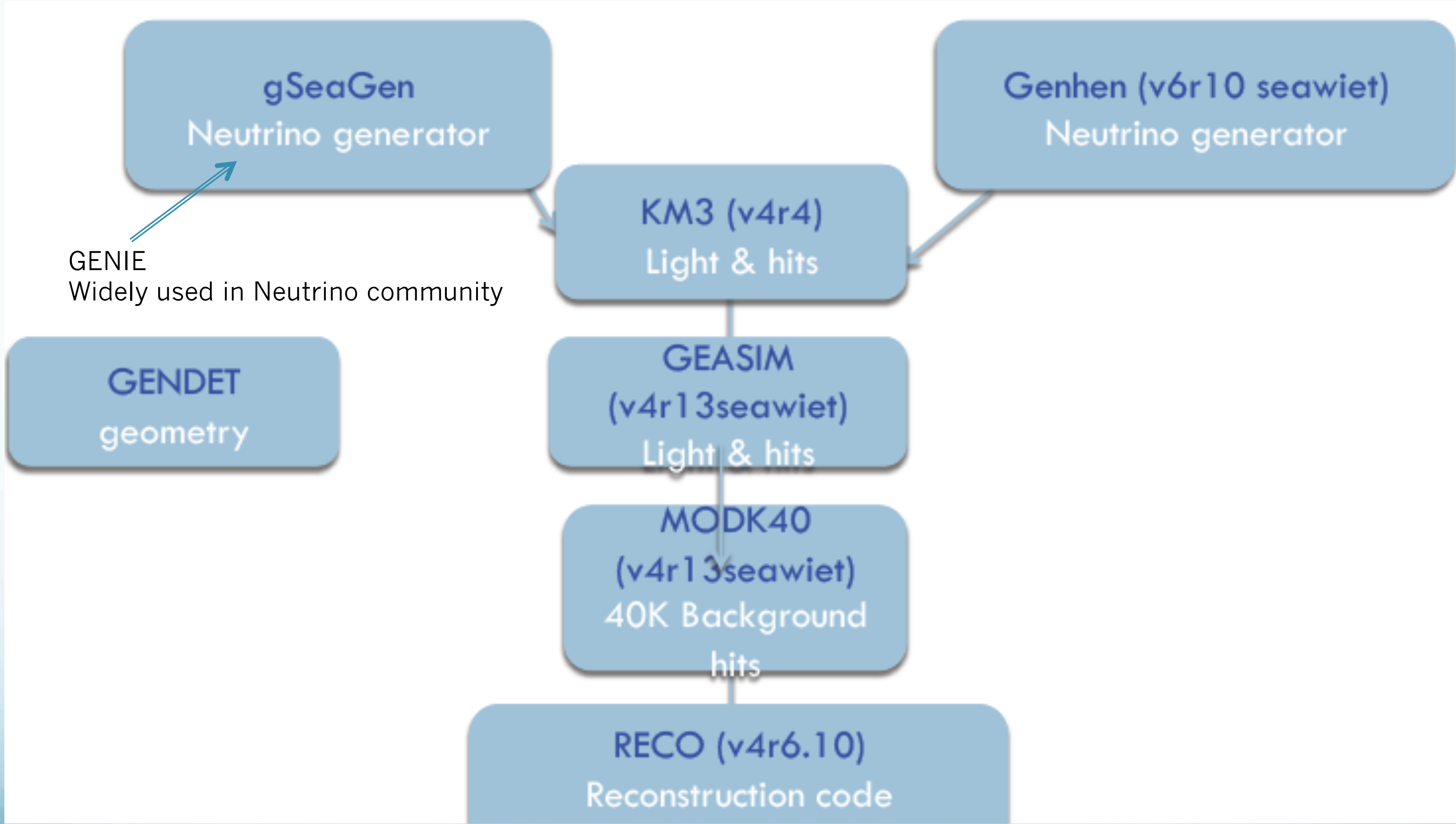
Instrumented volume:

$\Pi \times 70^2 \times\ 114 = 1.75$ Mt



- Multi-PMT DOM
- 31 small PMTs
- Almost uniform coverage
- Photon counting
- All electronics inside

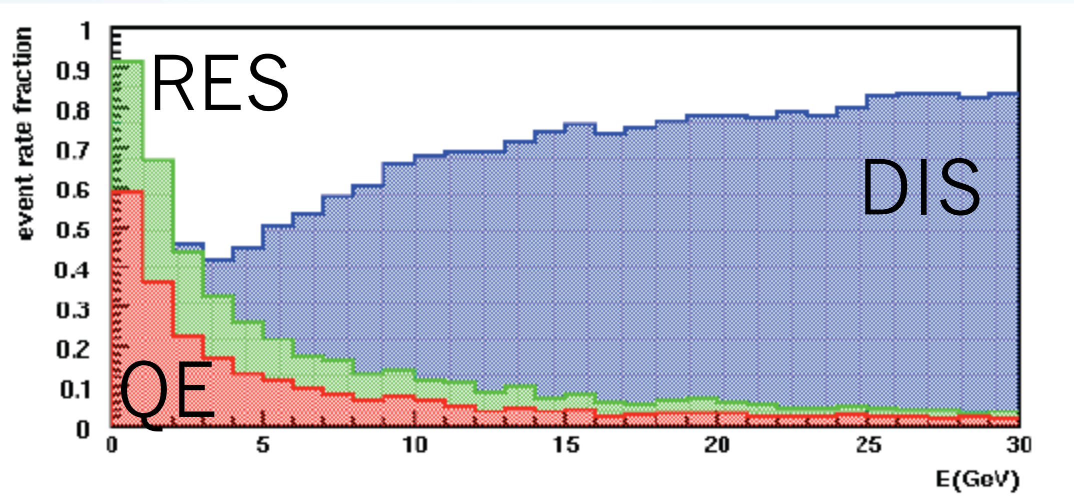
Simulation chain

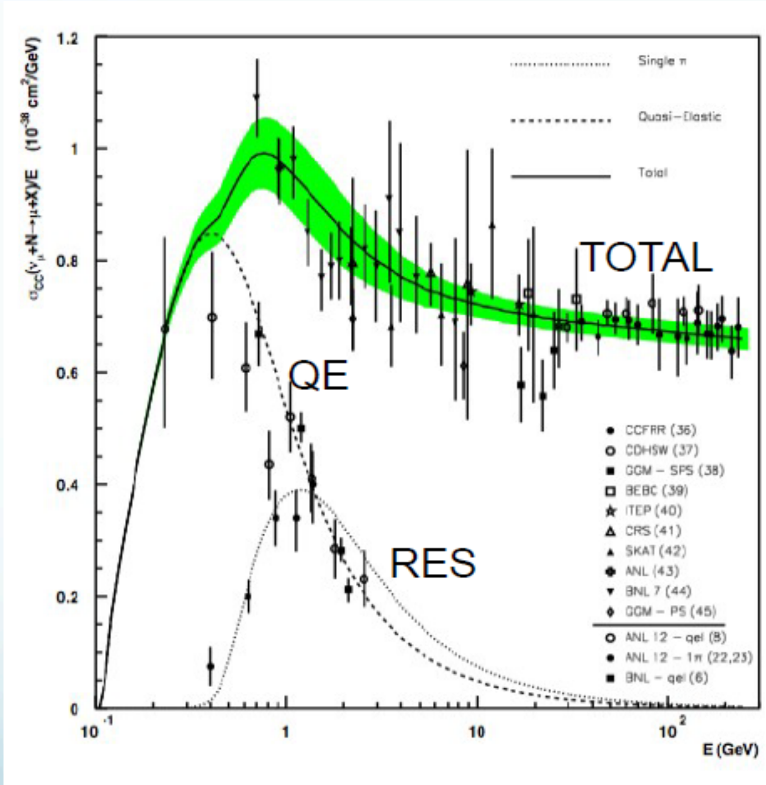


Neutrino Interactions

- Shifted energy region of interest
  - ANTARES : 50 GeV – 1 PeV
  - ORCA : 1 GeV – 50 GeV
- Three main contribution
  - Quasi-elastic
  - Resonant
  - Deep inelastic

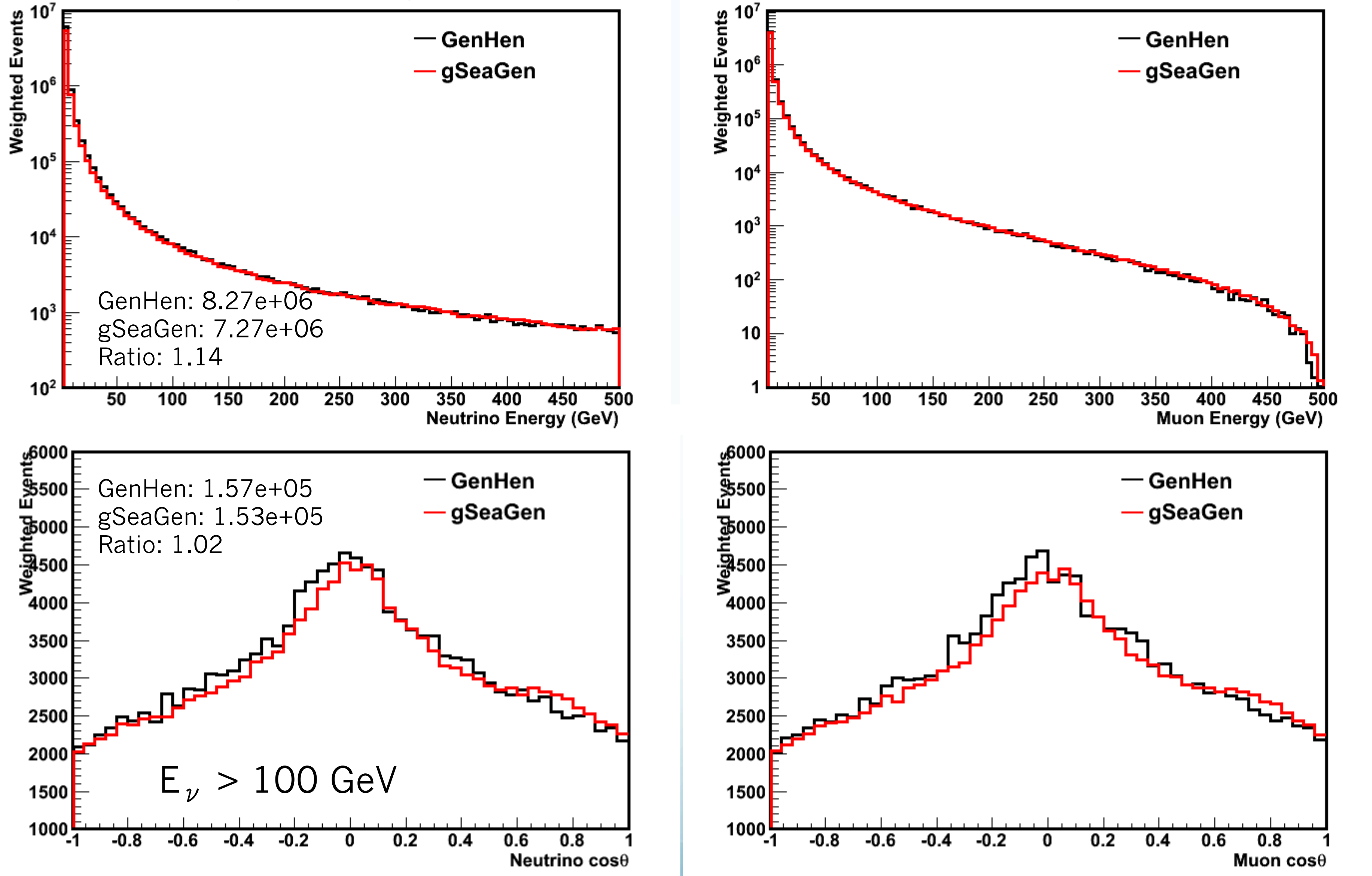
ANTARES tool Genhen has all three incorporated



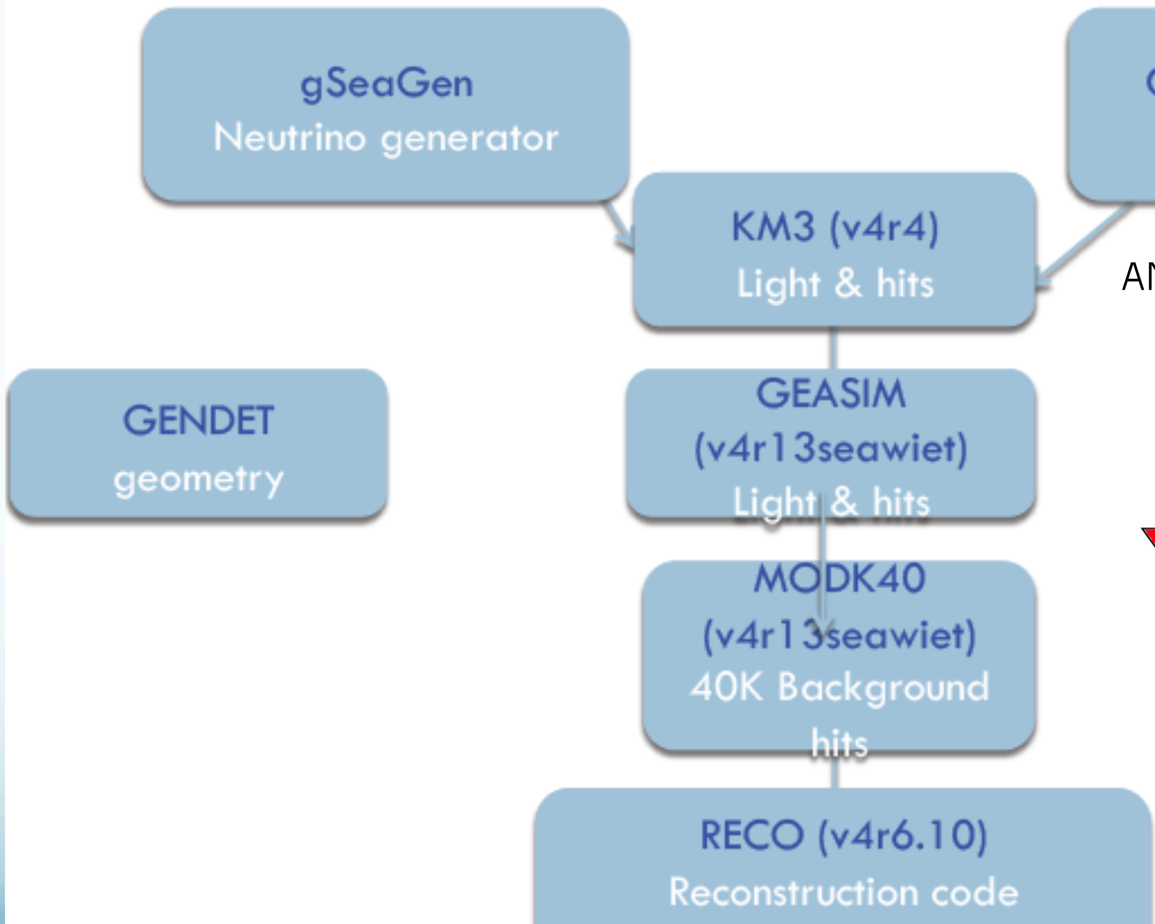


Genhen vs Genie (generation level)

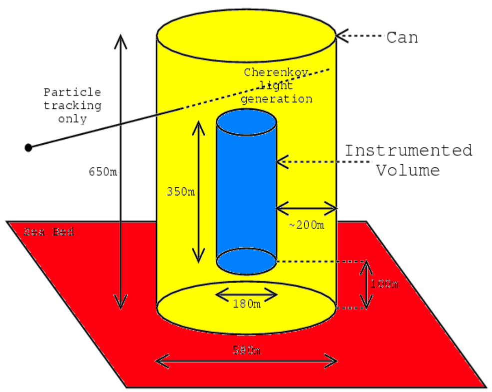
Bartol Flux ν_μ + anti-ν_μ (Kamioka Solar Minimum), 1 year



Simulation chain



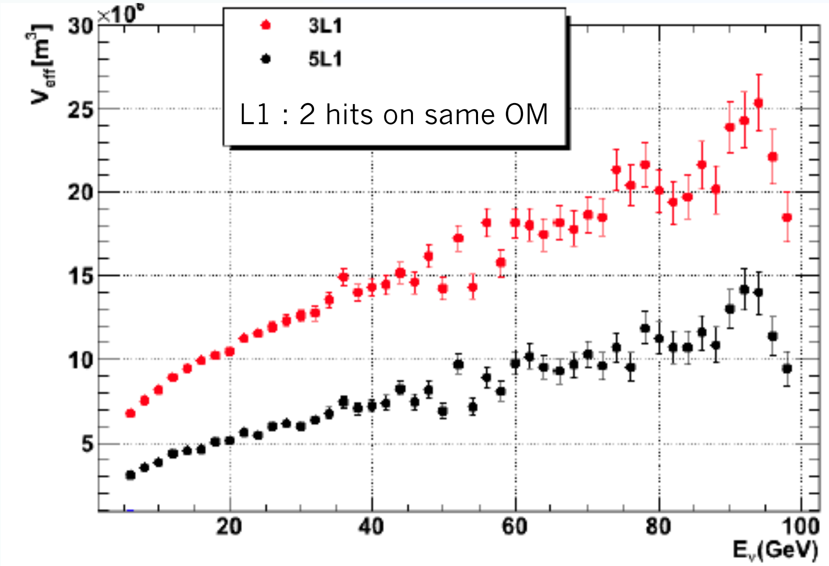
ANTARES scheme



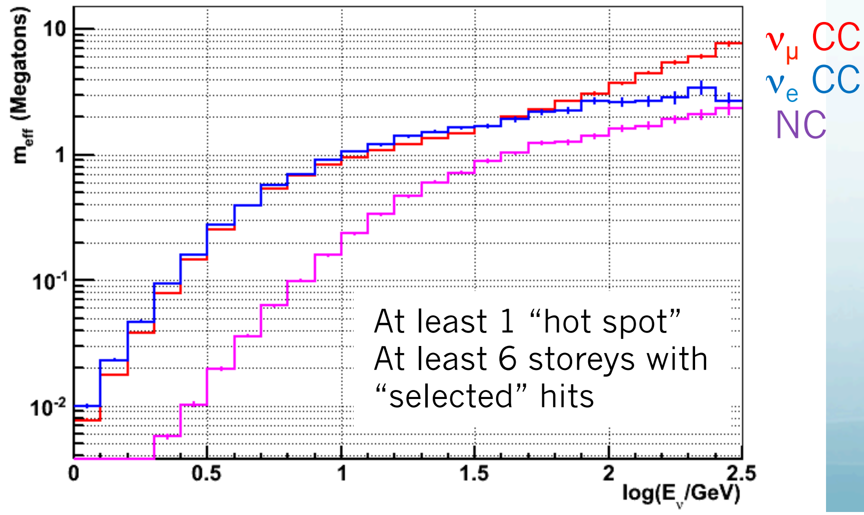
Events generated inside can volume: ~110 Mton

Effective volumes at trigger level

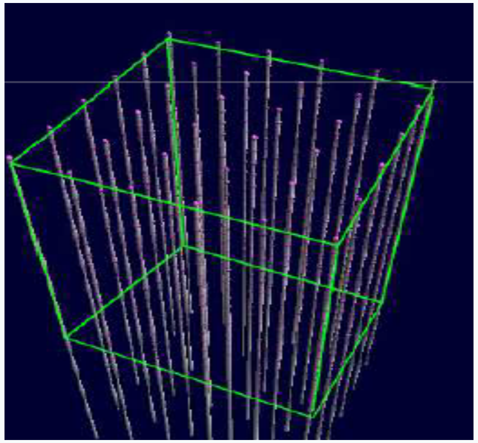
All events in can (edge effect)

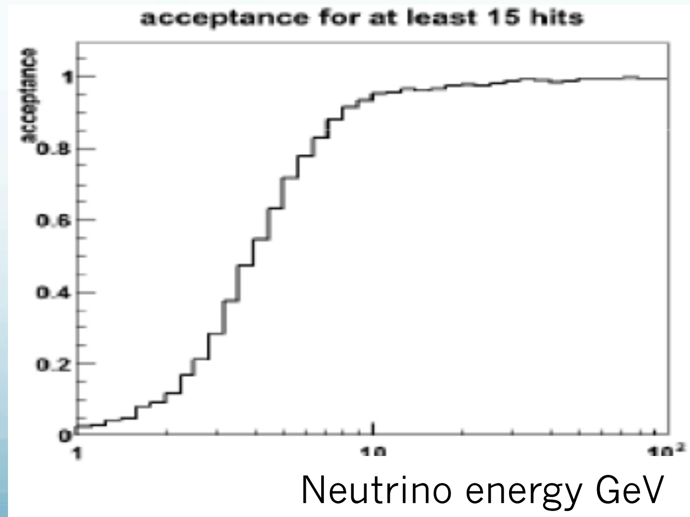


Antares OMs 1.5 Mton instrumented



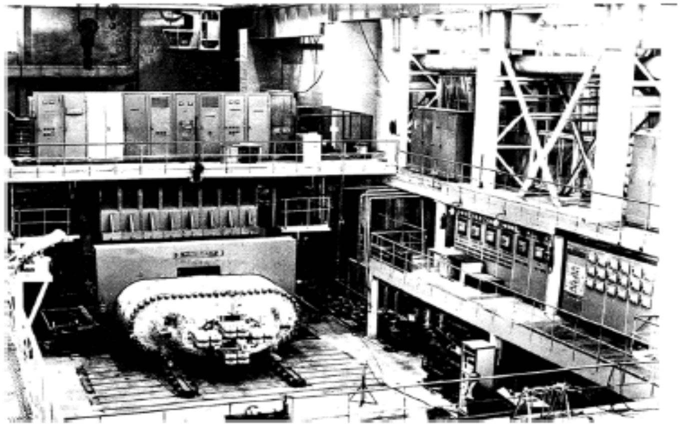
Alternative: work only with contained events
Ex: Detector 6x6 strings, spacing 20m
20 Oms per srting, spacing 6 m
Fiducial volume 1Mton

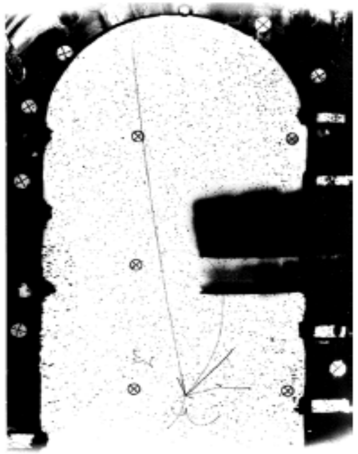


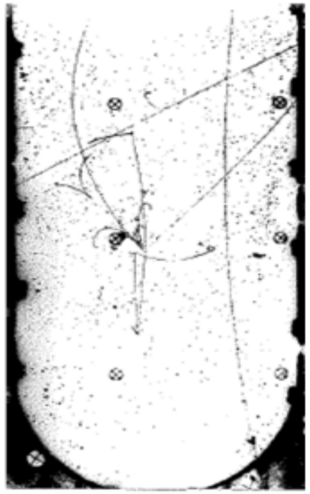


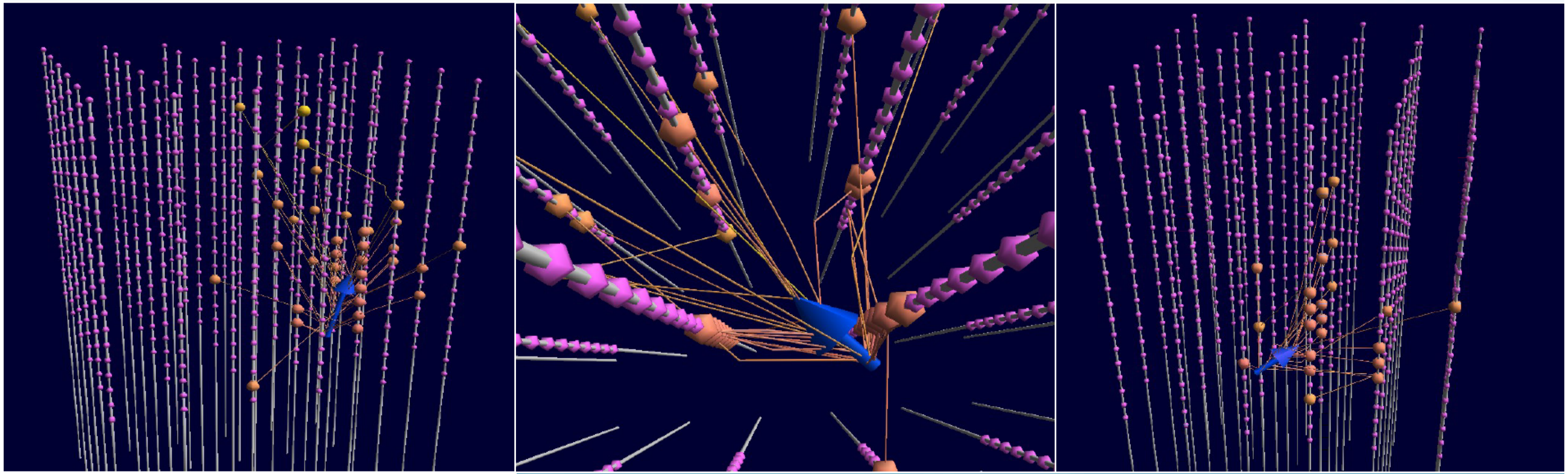
What do we want to reconstruct?

Events from the SKAT bubble chamber (2-30 GeV target CF_3Br)

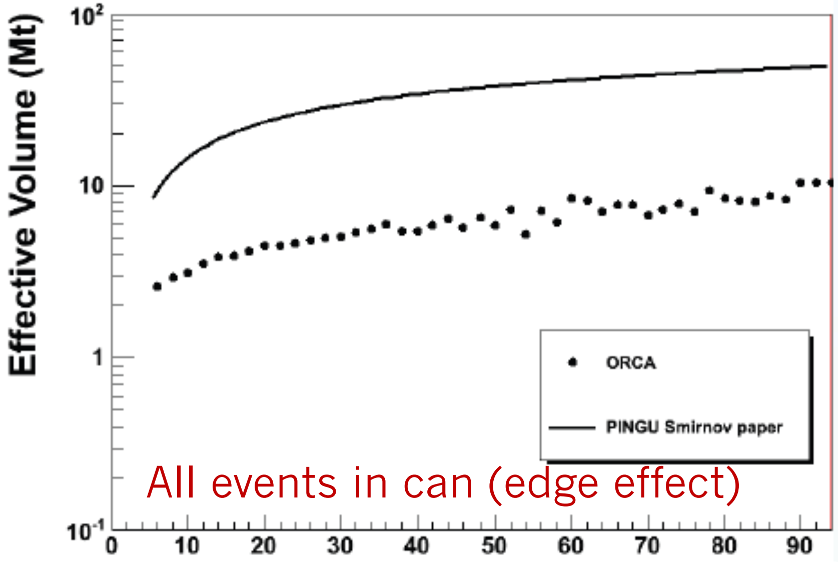


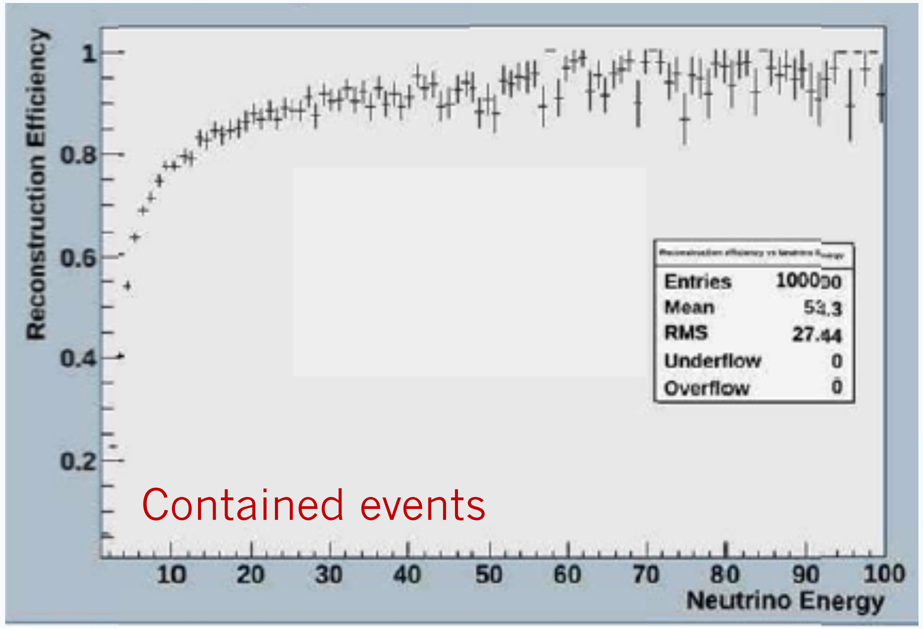


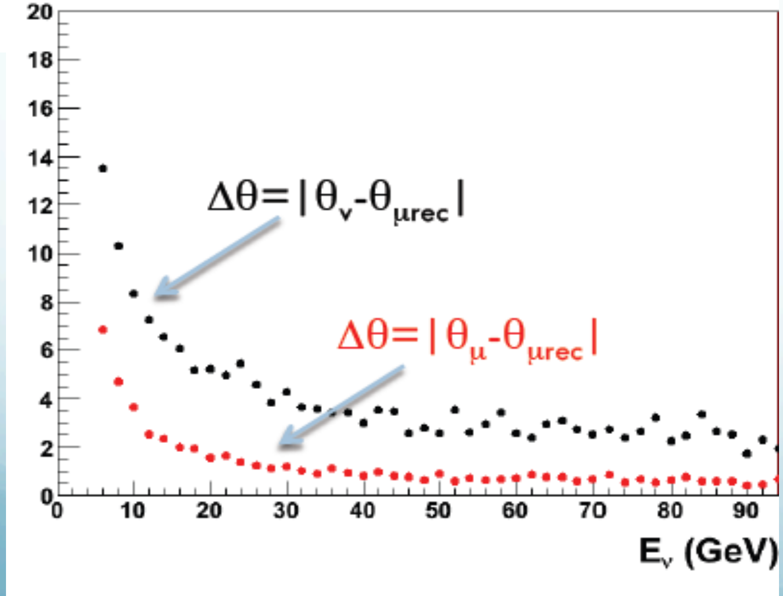


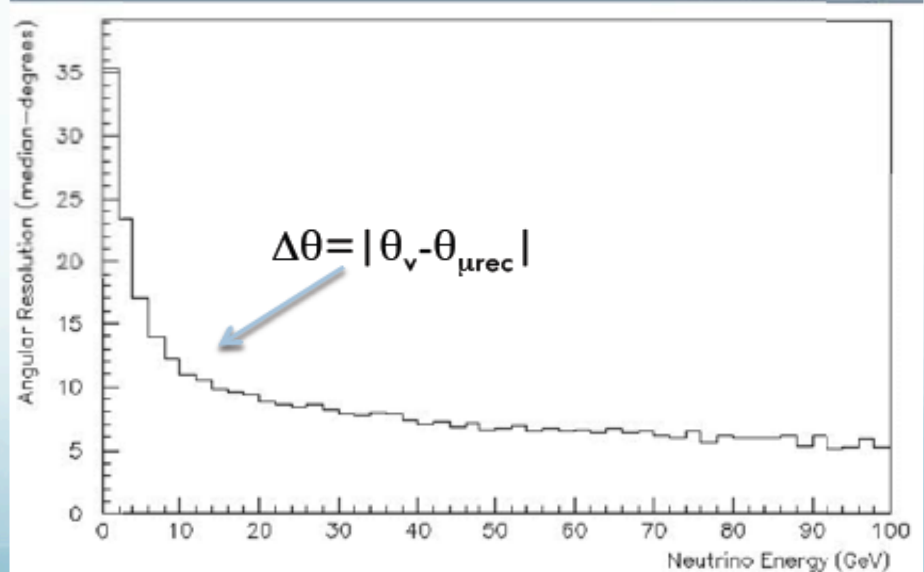


First reconstruction attempts (not optimized)







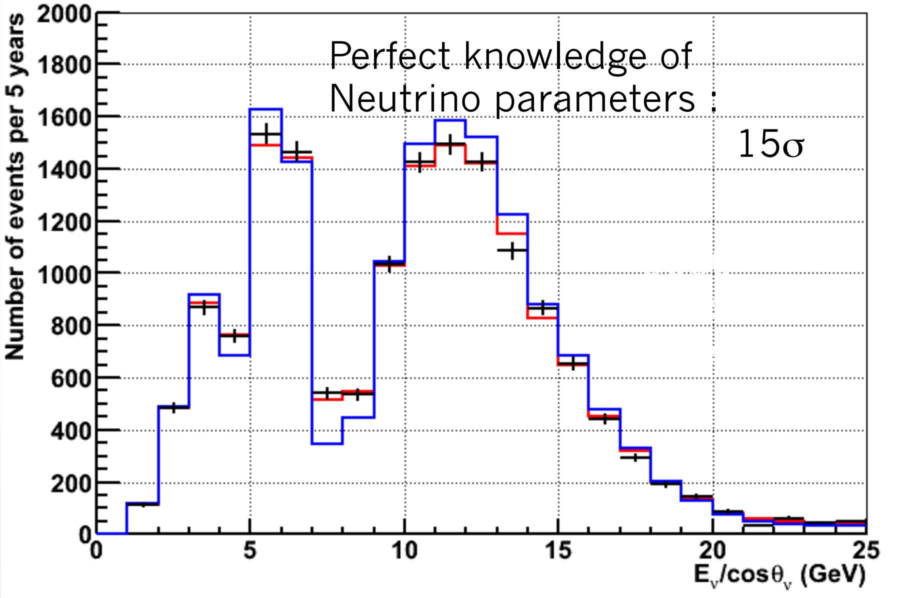


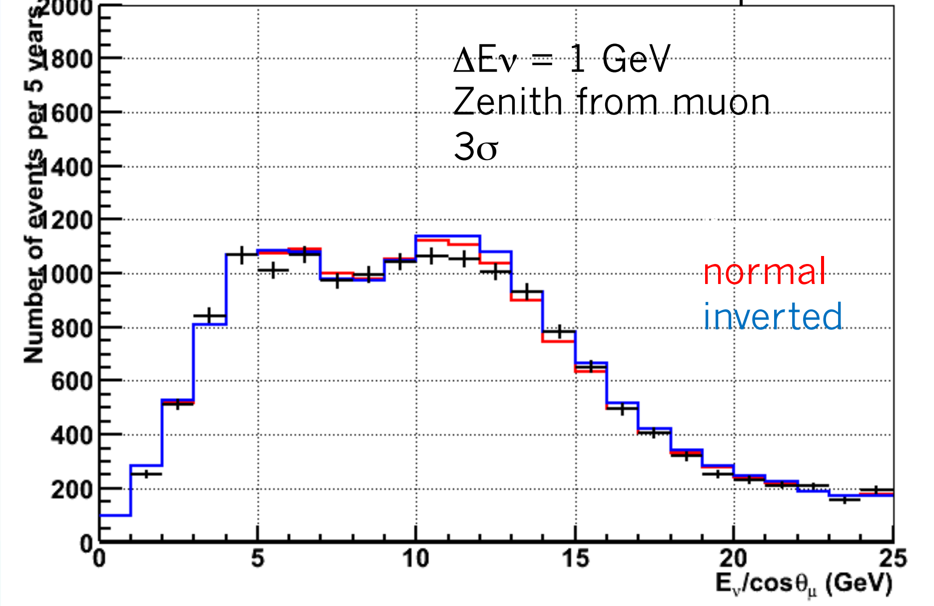
Promising, but what energy resolution for these events?

Observable E/cosθ (ANTARES-Bbfit analys.)

- sub-optimal but easier to get feeling for size of the effect

Antares OMs 1.5 Mton instrumented + semi-contained events in these plots



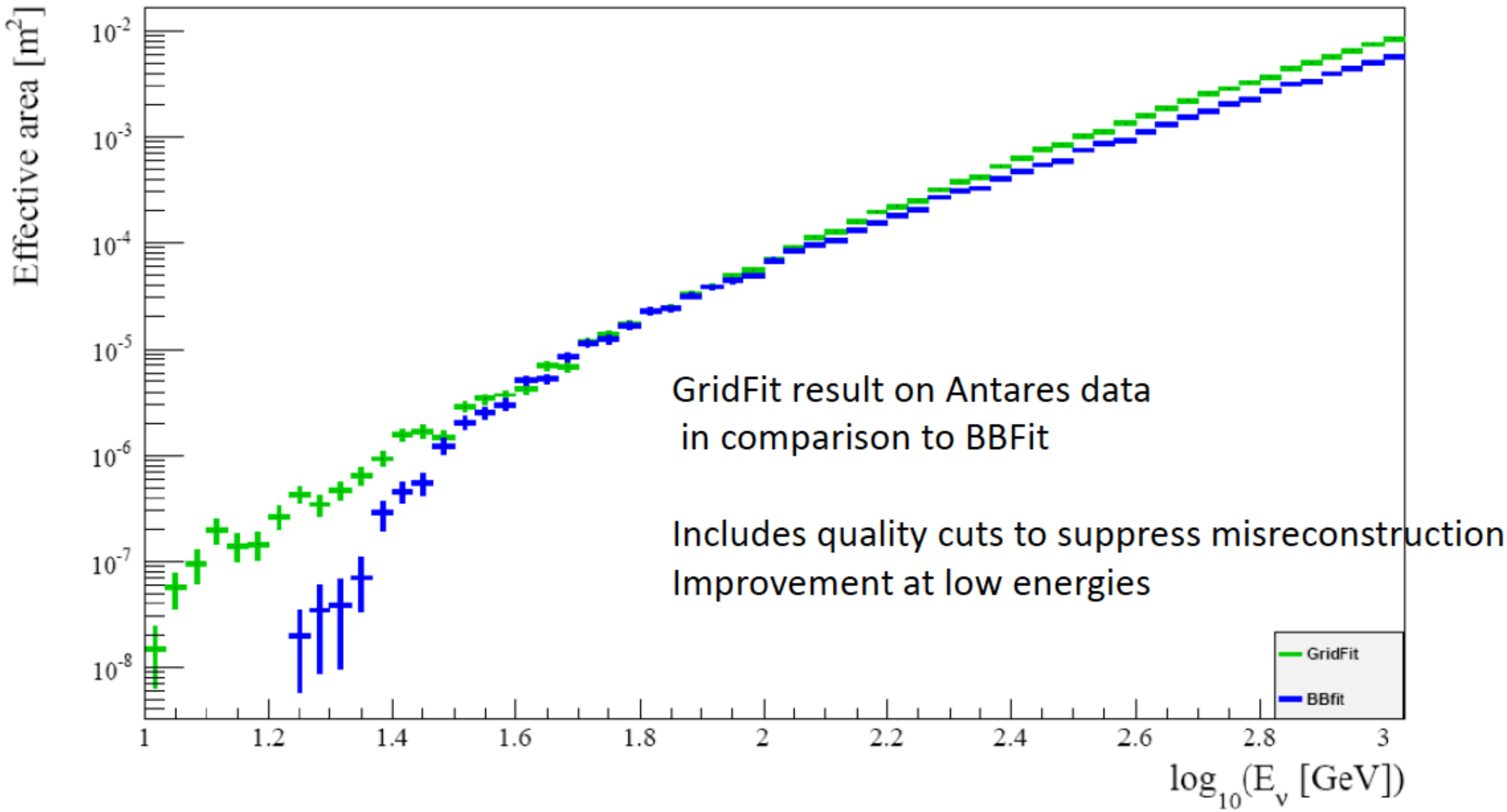


Resolution in energy and direction are key parameters !

- Optimal path length resolution σ(L) from ΔL/√12 to ΔL => σ(E)≈ 1 - 3 GeV
- Reconstruction of associated hadronic shower will improve. To be quantified.

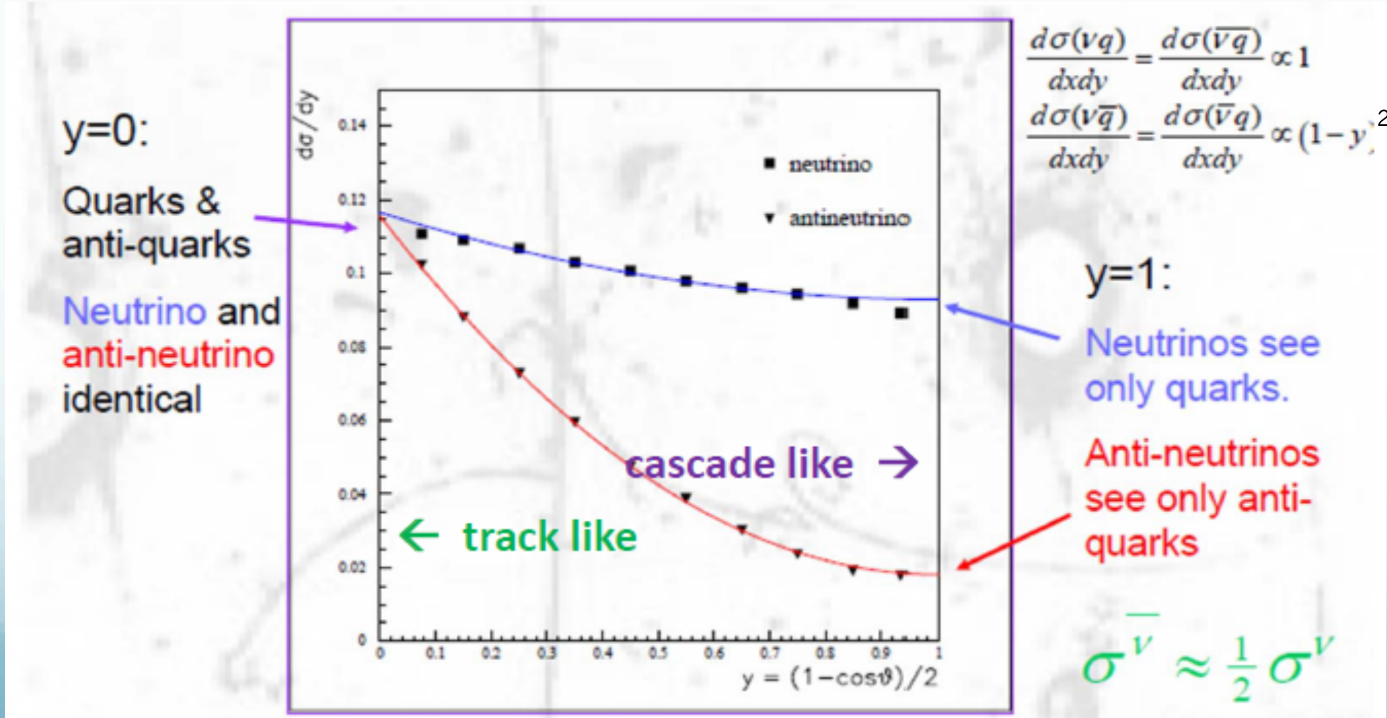
First improvements (gridfit)

Hit selection:
Correlated hits between neighboured stories/next-to neighboured stories



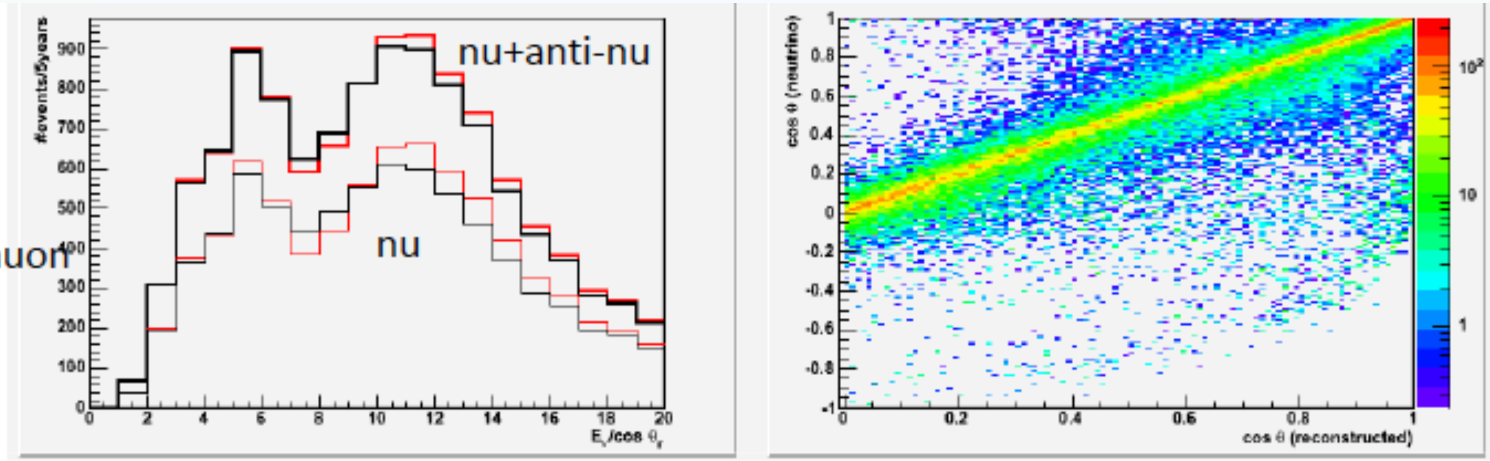
Some reconstruction ideas

- Select events with little hadronic activity
  - Enhances anti-neutrino sample
  - Enhances QE and RES contributions
  - Muons aligned to neutrinos (kinematics)

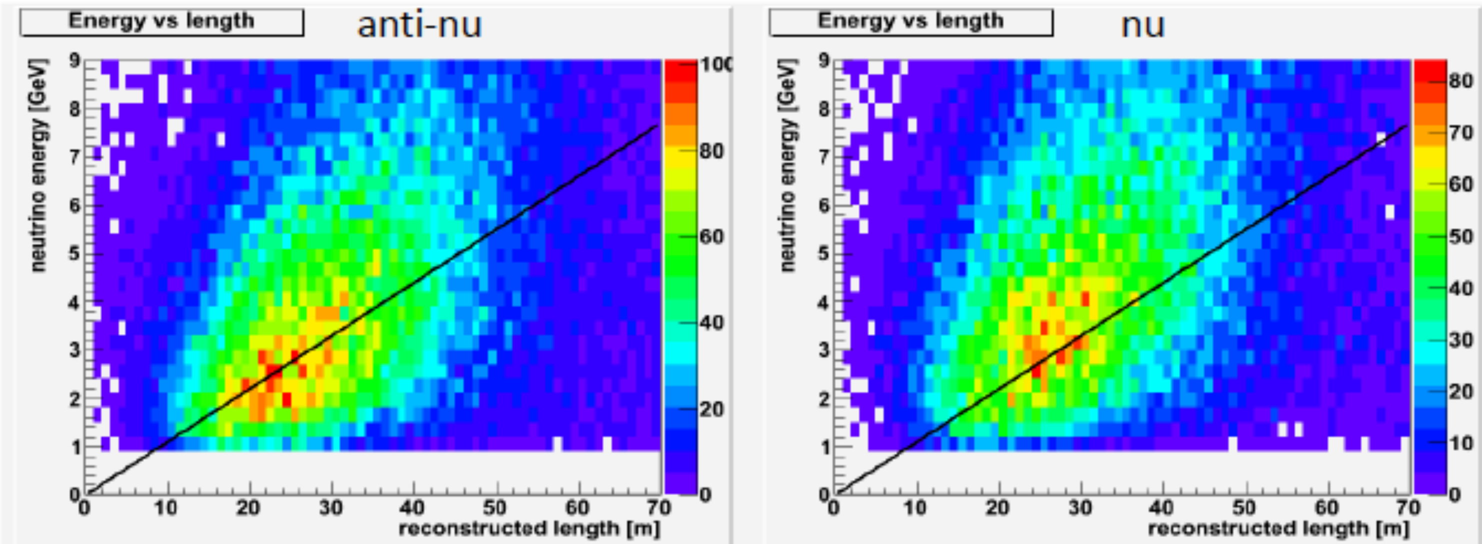


First look with GRIDFIT

True Enu
Recons θmuon



See
anti-nu
give more
energy
to muon



Global fit strategy

Dealing with oscillation parameter uncertainties

- For determining the MH, the angles and mass differences are nuisance parameters. → use ratio of ***maximum*** likelihoods

$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

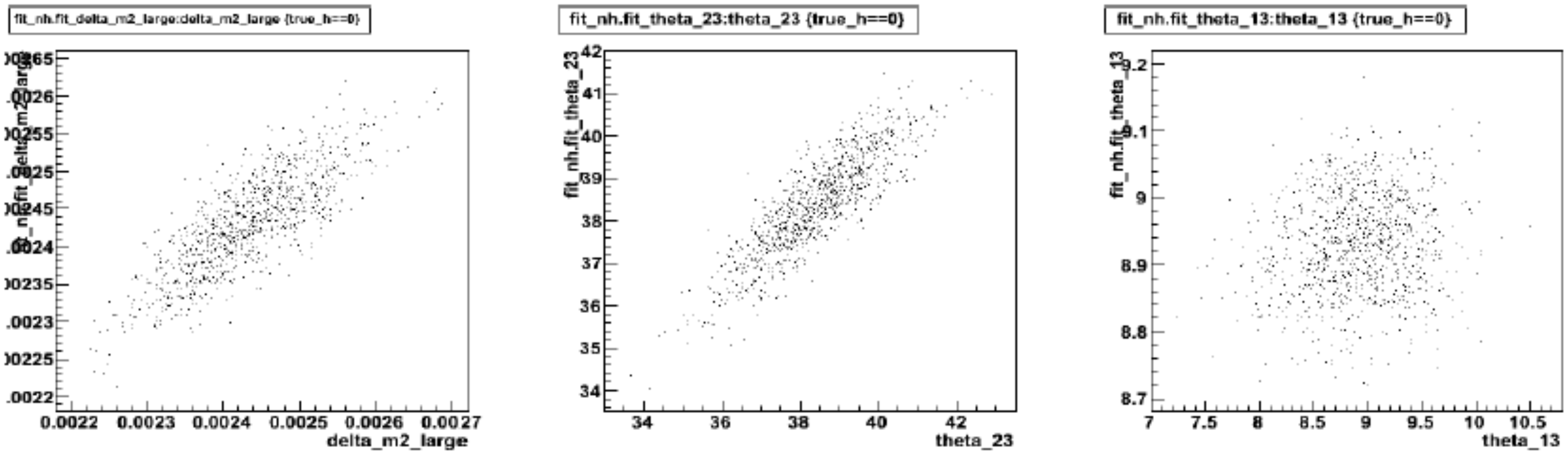
So this means fitting the mixing parameters to the data, twice, before computing the test-statistic.

Δm_{21} and θ_{21} fixed to central values. Others are fitted.
Zenith angle resolution : true muon direction
Energy resolution 25%
No background - No other flavours – No other syst.

- pick a true hierarchy Htrue
- vary model parameters within allowed range(Htrue) (assuming no correlations, since they are not published(?)) and generate toy experiment
- constraint fit of 3 non-fixed model parameters to experiment assuming both NH and IH → two sets of parameters $\hat{\theta}^{\text{NH}}$ and $\hat{\theta}^{\text{IH}}$
- likelihood ratio

Fit sensitivity

1 Mton*year (NHtrue, NHfit)



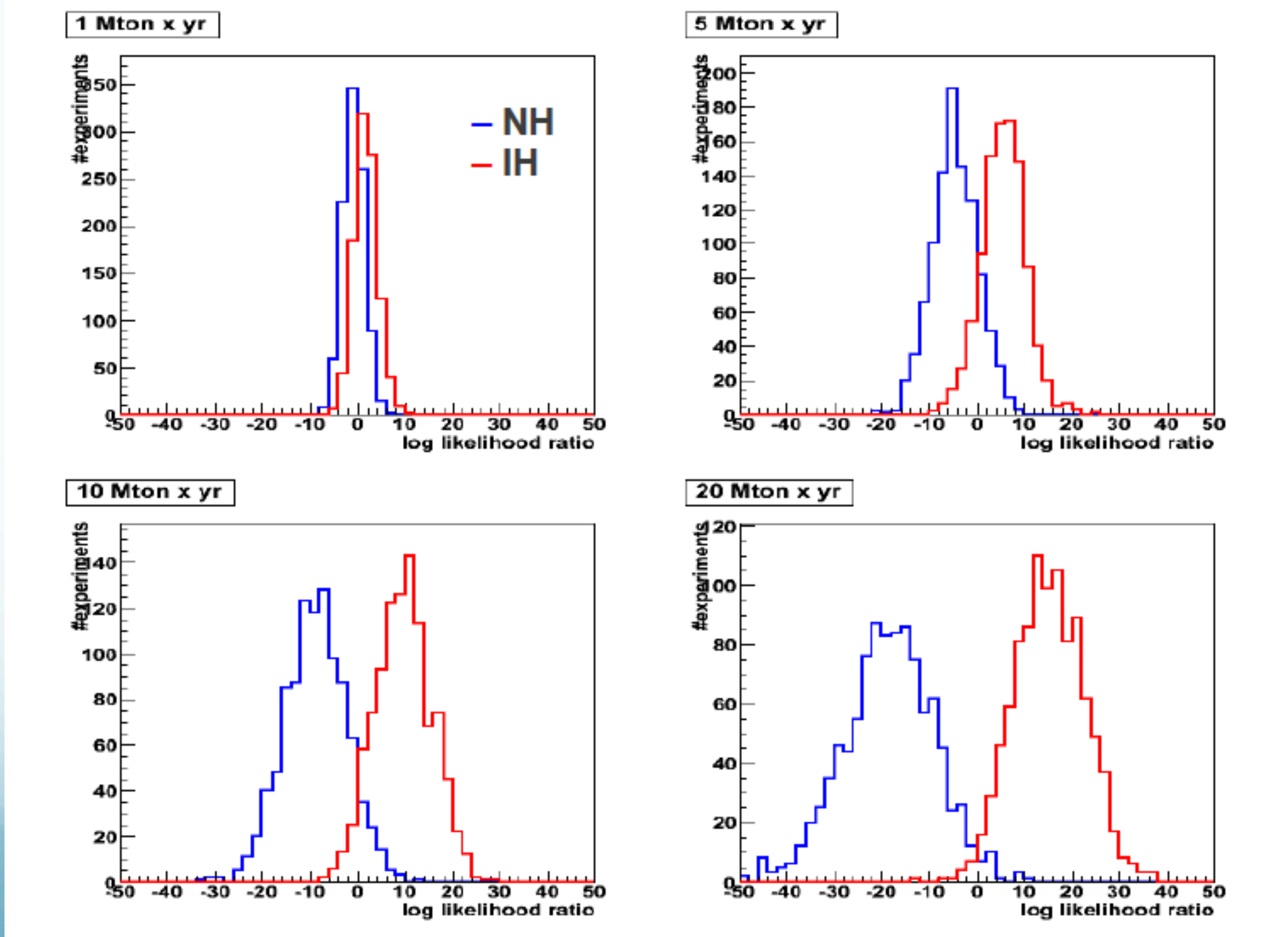
Fit working well.
Good sensitivity to Δm^2_{large} & θ_{23} !

parameter name	central now	sigma now	sigma 1 Mtonyr	sigma 10 Mtonyr
delta_m2_large	2.43e-3	8.0e-5	4.3e-5	1.8e-5
theta23 (deg)	38.4103	1.3	0.66	0.23
theta13 (deg)	8.93082	0.45	0.45	0.41

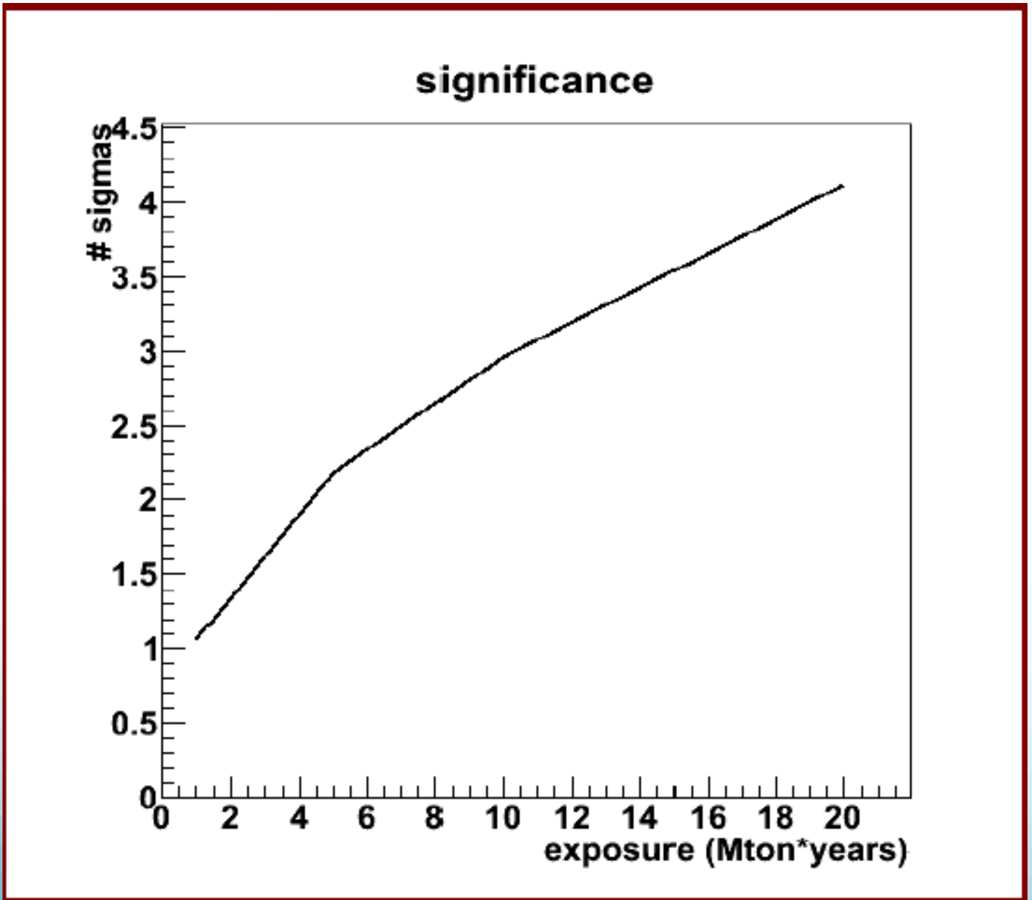
nb: paramter fit is for one assumed MH

Decreasing the current errors is already an important achievement !

Current results



Median expected significance



- 25 % energy resolution on ν
- direction from perfect measurement of muon direction
- fully efficient for fiducial events with 15 or more hits
- no background from atm. mu or mis-id'ed showers
- no systematics at all

Conclusions & outlook

- Fruitful exchange of ideas with PINGU
  - Agreement to cross check each others significance calculation
- Full simulation & reconstruction chain being put into place
- Modifications in simulations planned
- Challenges in Event Reconstruction and Energy Resolution
- Large effort to prove feasibility of mass hierarchy measurement with neutrino telescopes just started.
- ORCA could reduce current uncertainties on oscillations parameters. But too early to draw conclusions on the mass hierarchy discrimination.
- Need ~ one more year
  - Finalize systematic studies (started)
  - Improved reconstruction (started)
  - Optimize geometry (just started)
  - Background rejection (consider veto?) (just started)
  - Study other flavours (not started)
  - ...
- Welcome if you want to join our efforts!