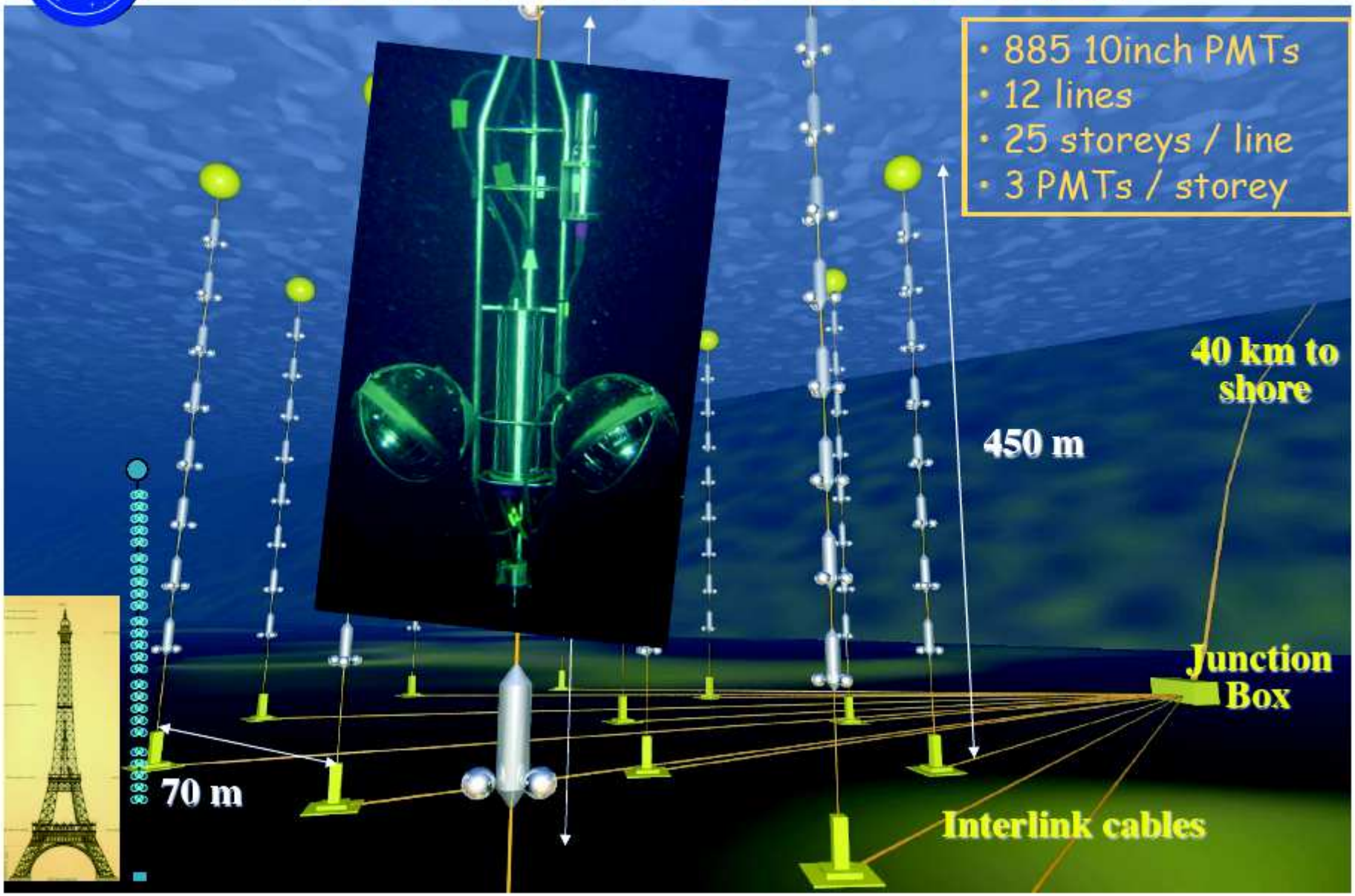
ORCA

Oscillation Research with Cosmics in the Abyss

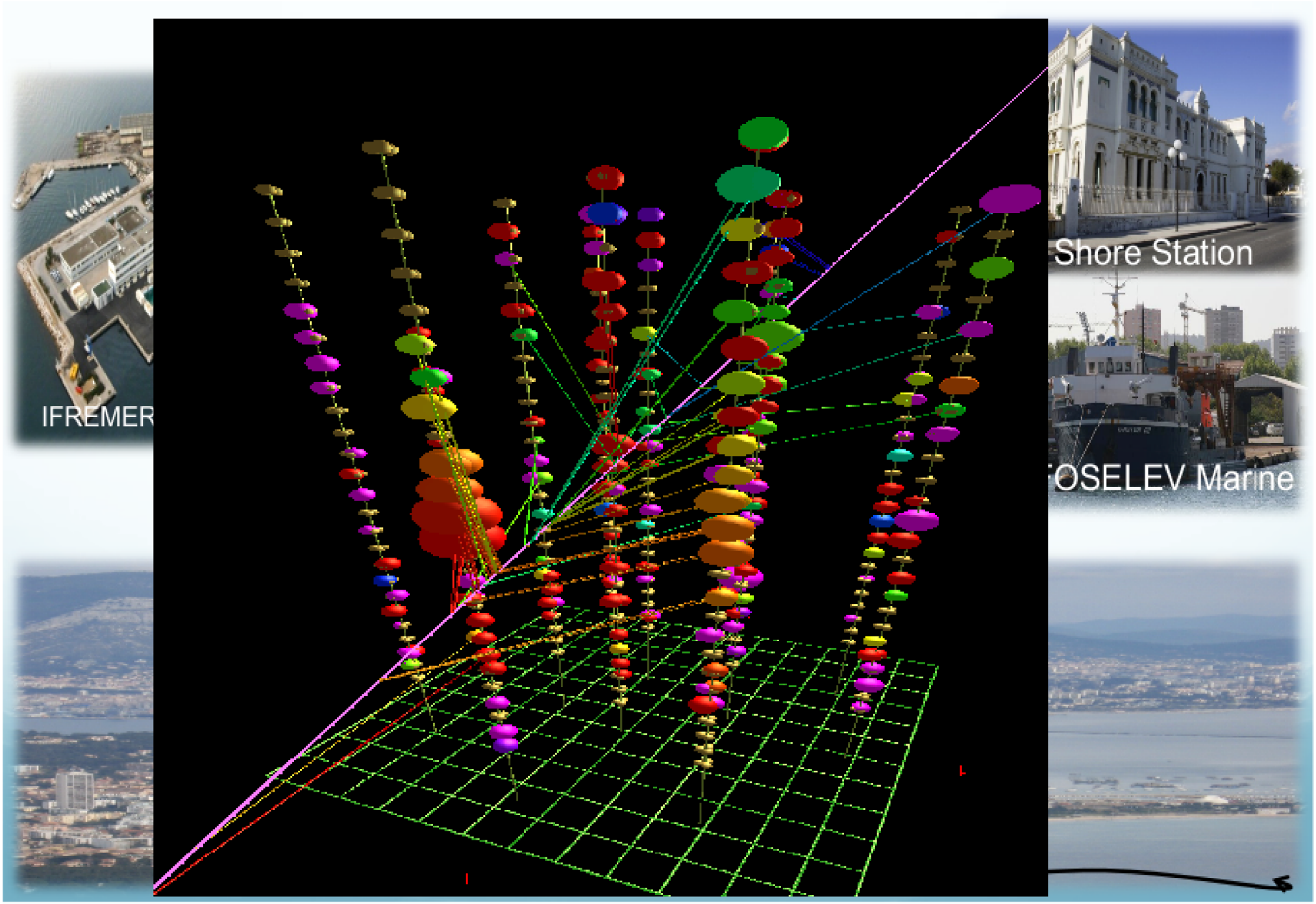
Measuring the neutrino mass hierarchy in the Mediterranean Sea

Jürgen Brunner, CPPM, Marseille

The ANTARES detector

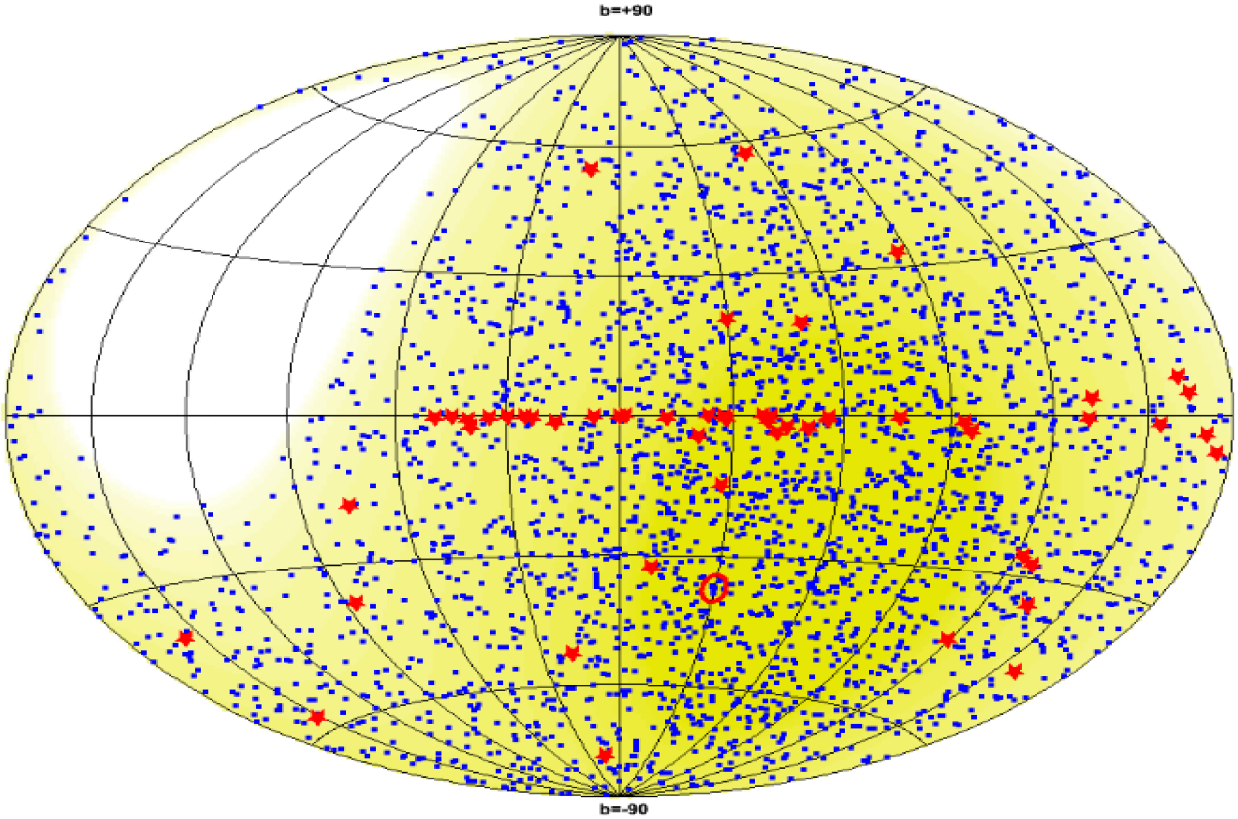


The Antares detector



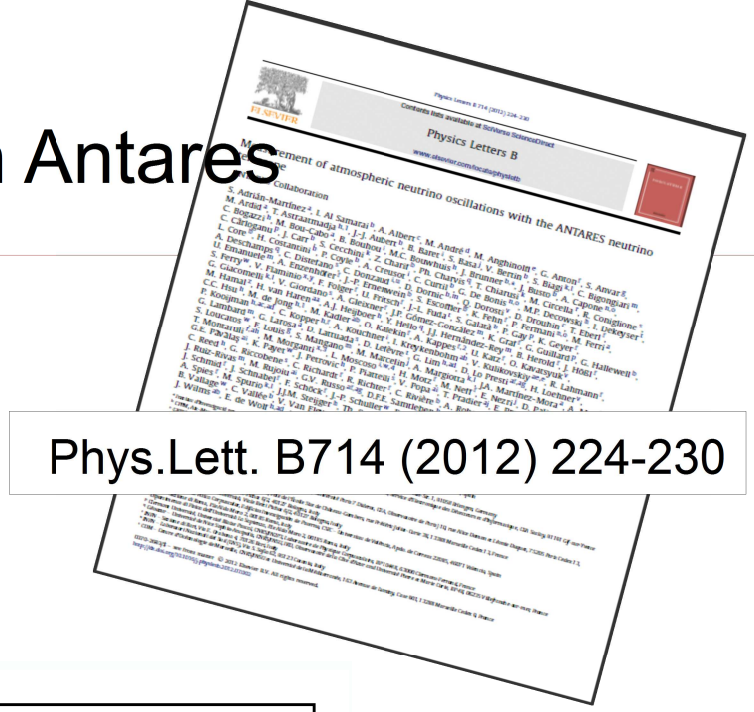
Antares:

- ***Exploring southern neutrino sky 2007-now***
- ***O(5000) neutrinos (atmospheric) collected***
- ***unfortunately no cosmic sources seen yet***

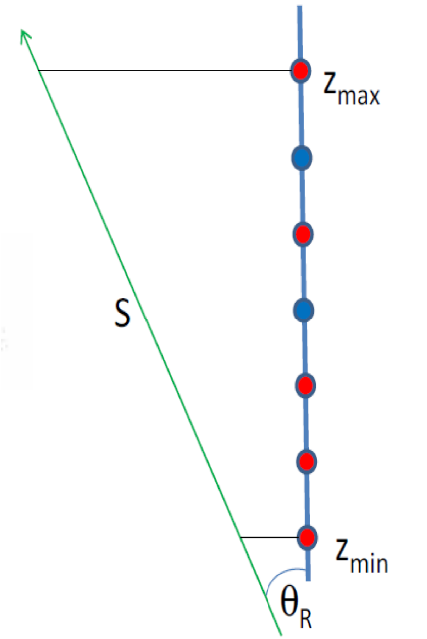


(vacuum) Oscillation physics with Antares

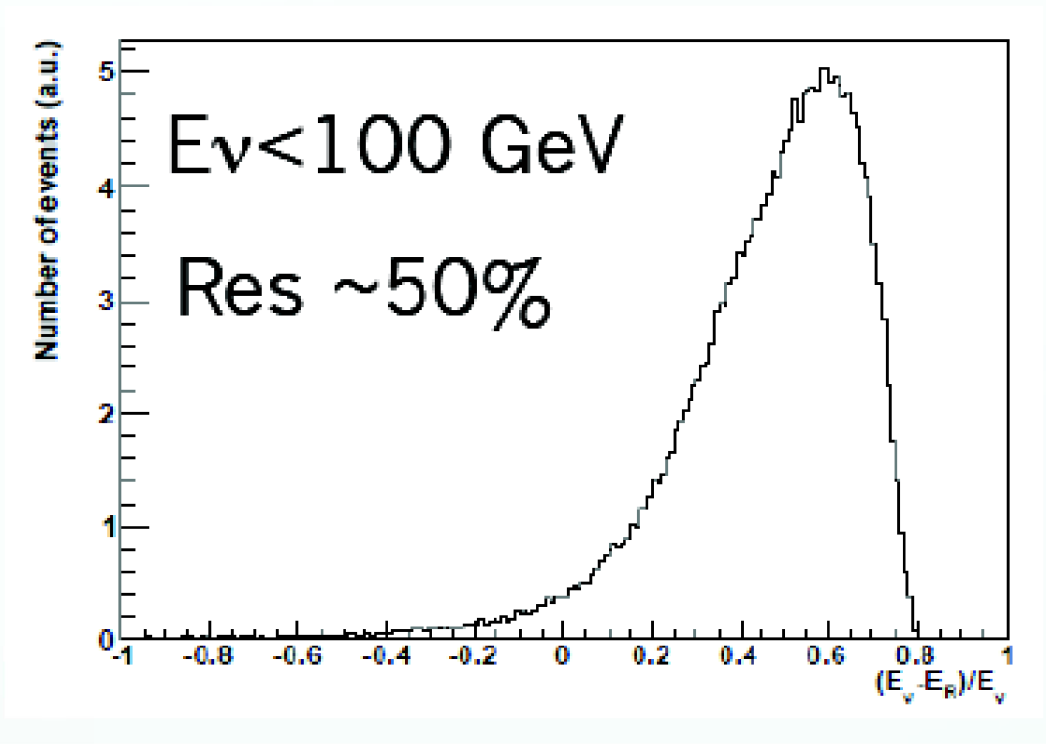
- for Antares: low-energy domain
- 2007 to 2010 : 863 days of active time
- 25 % of events reconstructed on only one line
- energy estimated from muon length



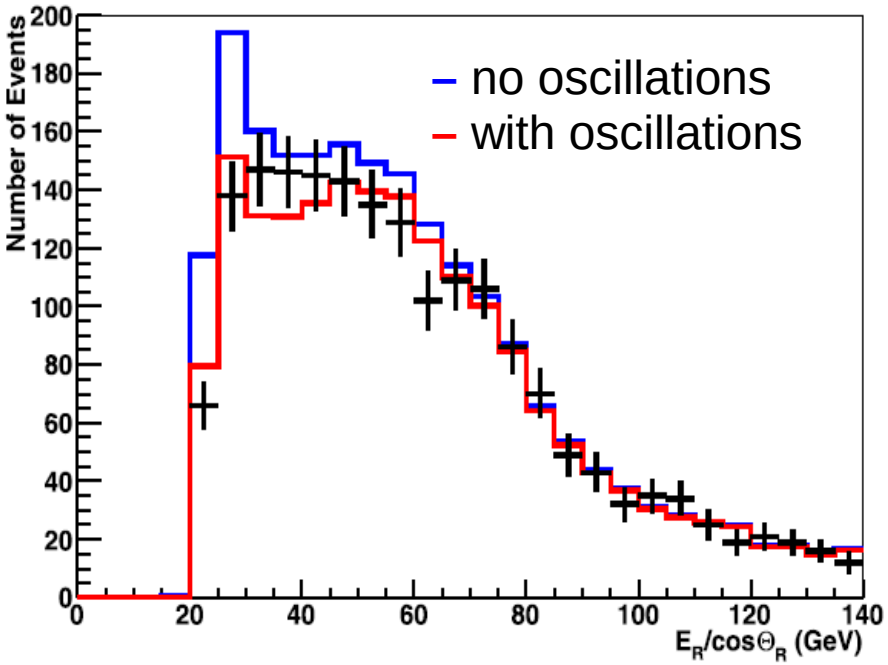
Phys.Lett. B714 (2012) 224-230

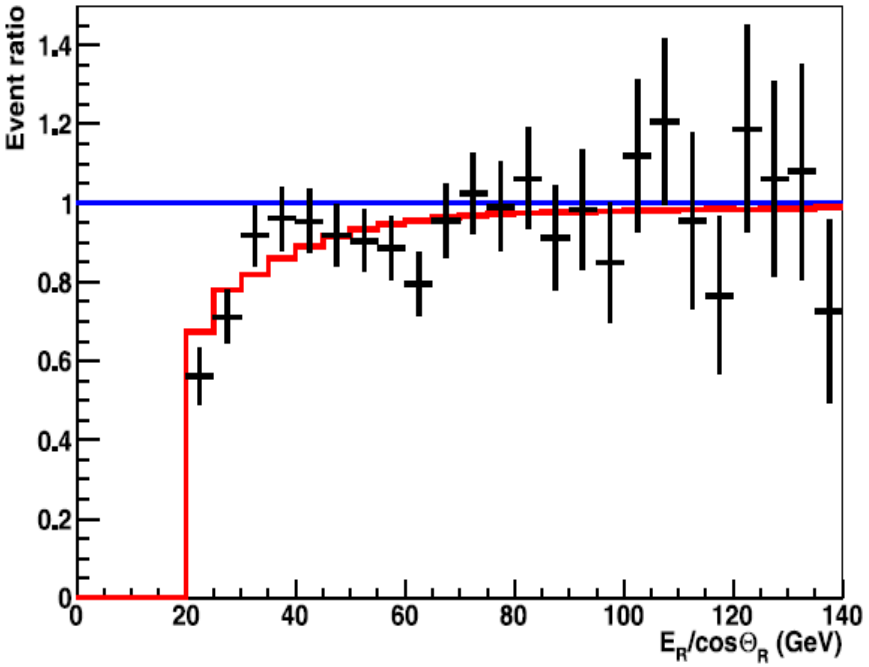


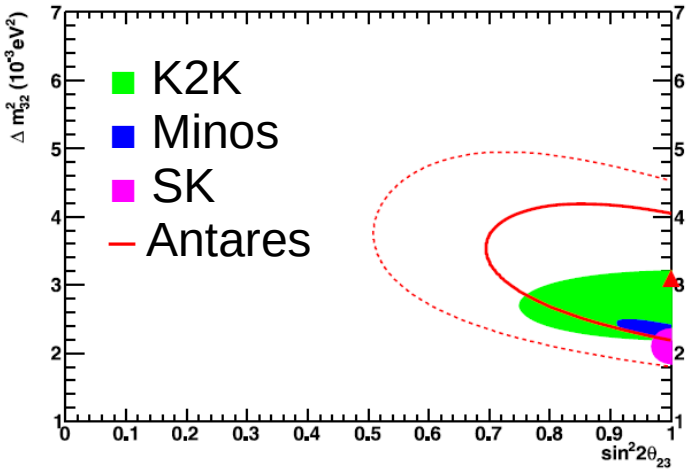
$$E_R = S \cdot 0.2\ \mathrm{GeV/m}.$$



(vacuum) Oscillation physics with Antares



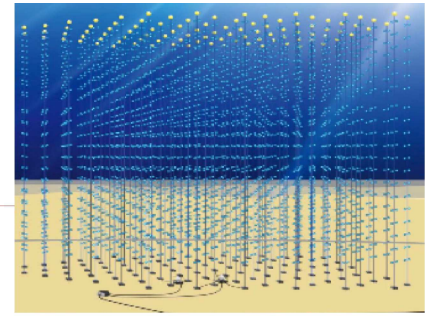


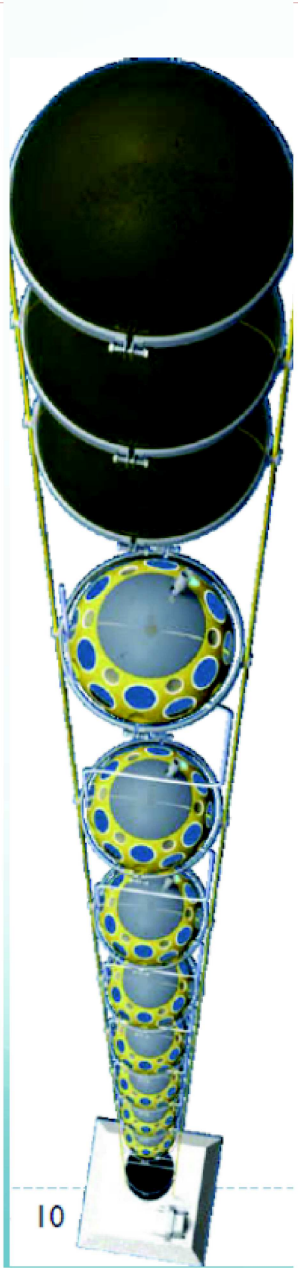


p-value of no-oscillation hypothesis: 2.1%

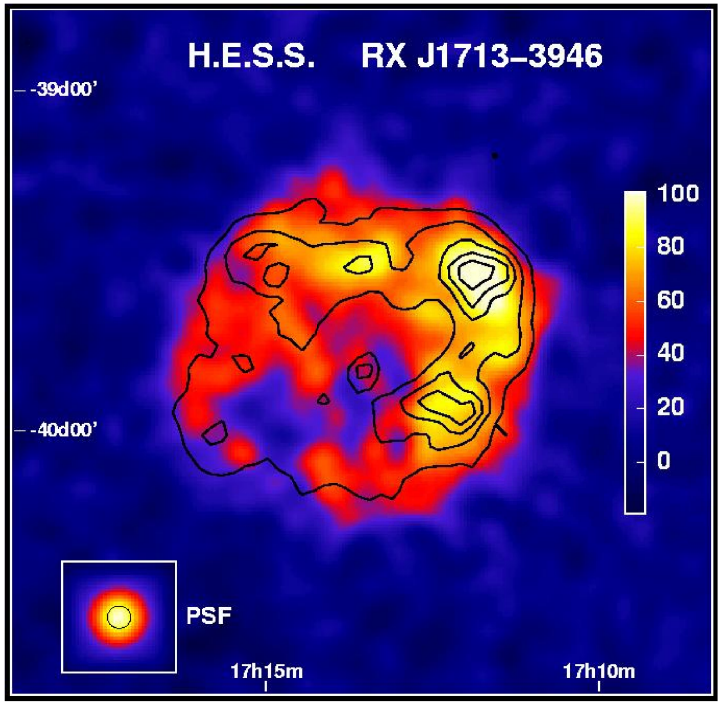
assuming maximal mixing:
$\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}\ eV^2$

The KM3NeT project





- Next generation (multi-km^3) neutrino telescope in Mediterranean
- Main goal: detection of ν from galactic sources (SNR)
- recent milestones
  - multi-pmt Optical Module design agreed & prototyped
  - string configuration
  - partial funding obtained
    - ~1/5 of total wishes (~50 strings)
    - must be spent soon → 'phase 1'



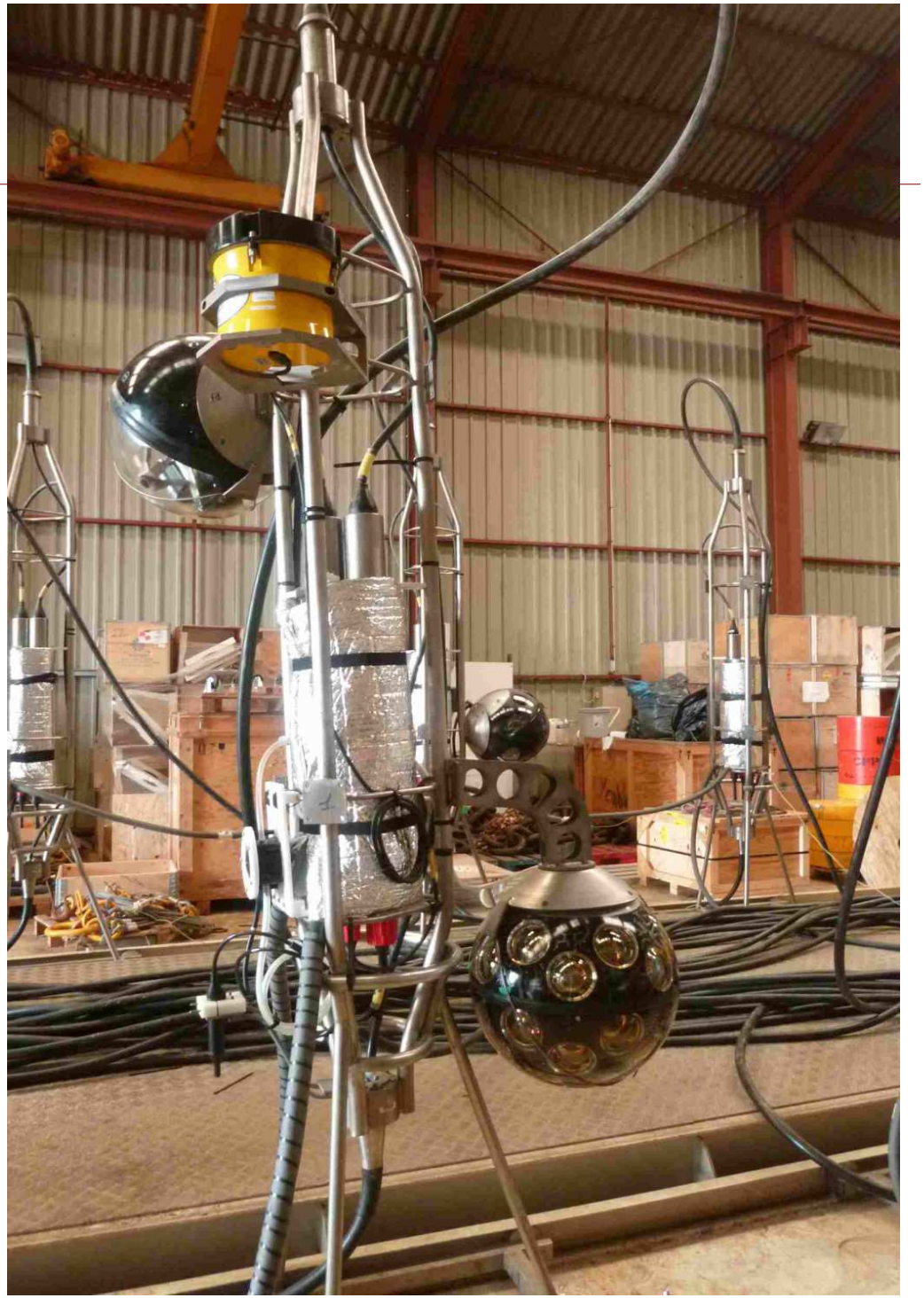
phase-1:

- baseline plan: start construction of HE telescope with available funds
- alternative : devote 'phase-1' to Low Energy neutrinos → ORCA

The KM3NeT project

Mutliple small pmt's (helps in photon-counting and background rejection)

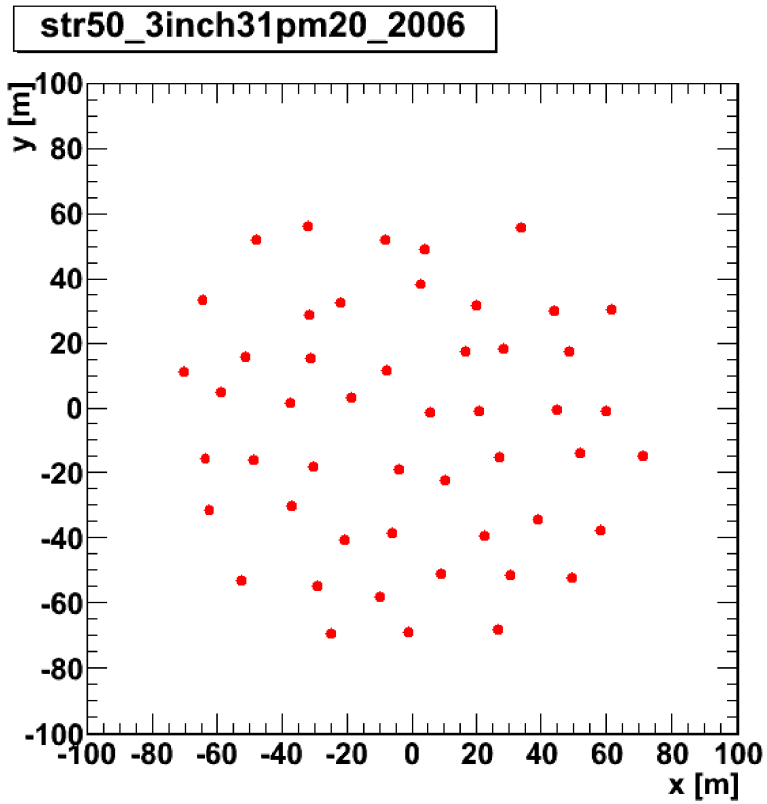
KM3NeT Optical Module integrated in Antares instrumentation line.
(To be deployed soon)



ORCA Detector layout

Instrumented volume = 1.75 Mt

- ✓ 50 Strings
- ✓ OM=31 3”PMTs
- ✓ 20 OM in each string
- ✓ 6 m vertical distance between OM
- ✓ 20 m average distance between strings



String number can be scaled according to financial situation
Other parameters determined by deployment constaints

Simulation algorithms

event generation

GENHEN
(ok > ~2 GeV)

Genie
(gSeaGen)

Quasi-elastic, resonant and DIS

detector simulation

KM3

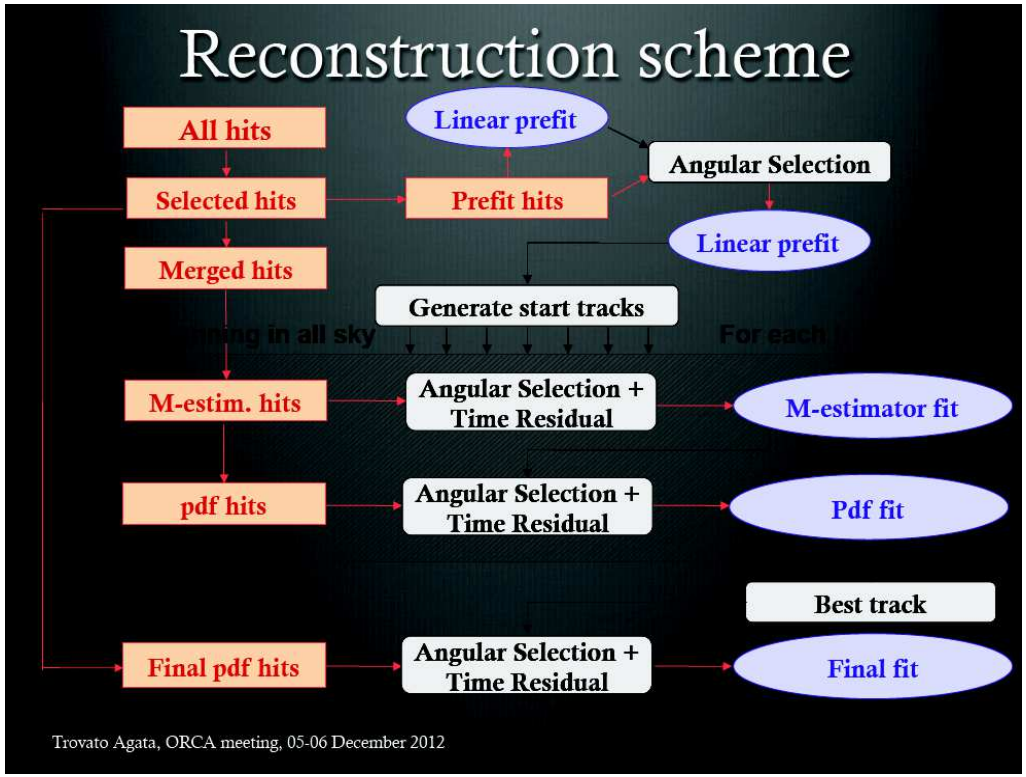
Geasim
(geant3)

several Geant4 codes with
(gpu) full photon tracking

Light diffusion in water tables
Full hadronic shower without
light diffusion

New codes on testing level

Reconstruction algorithms



Different track fits have been tried

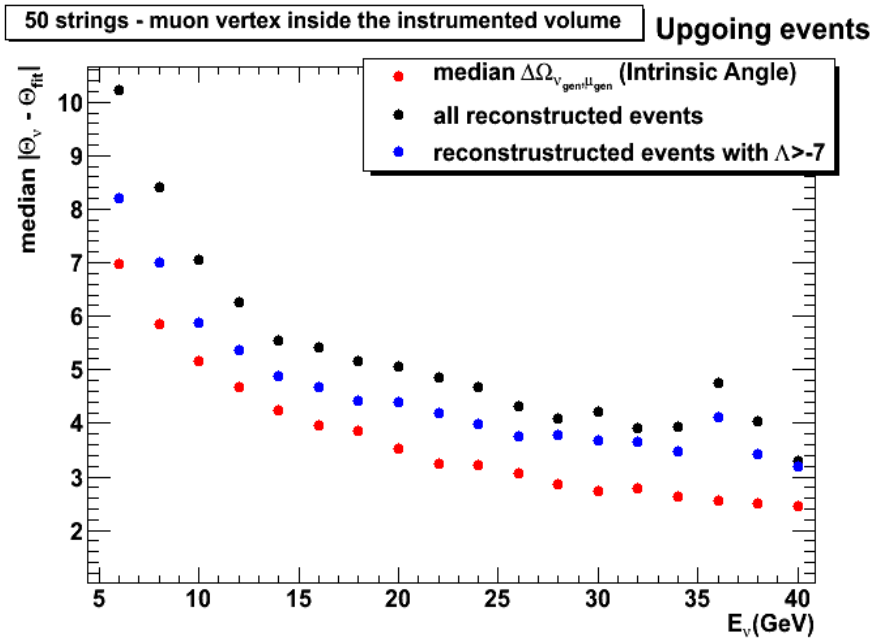
Likelihood fit based on time residual pdfs, several starting points (ANTARES based)

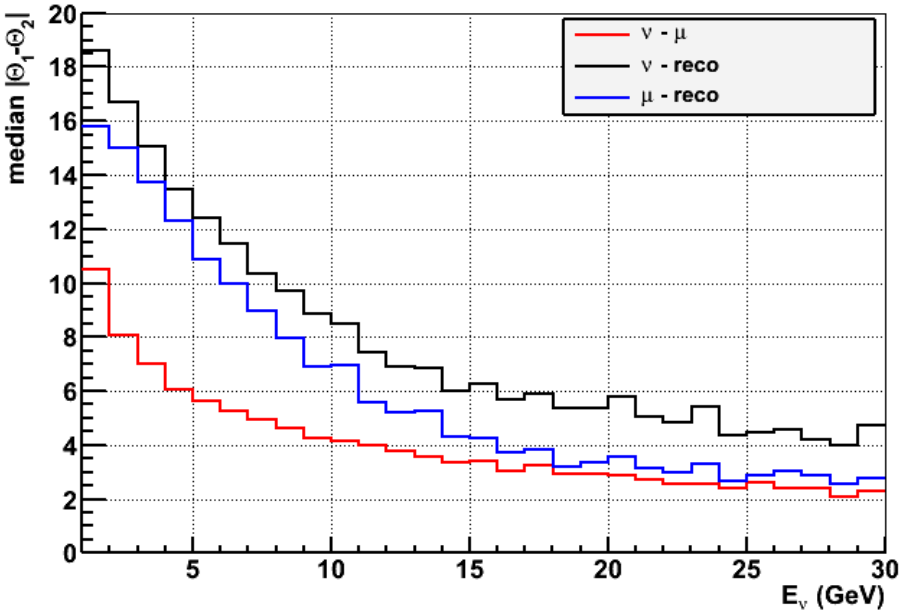
χ^2 fit after strict selection of direct hits (ANTARES based)

Kalman filter (KM3net development)

Angular resolution

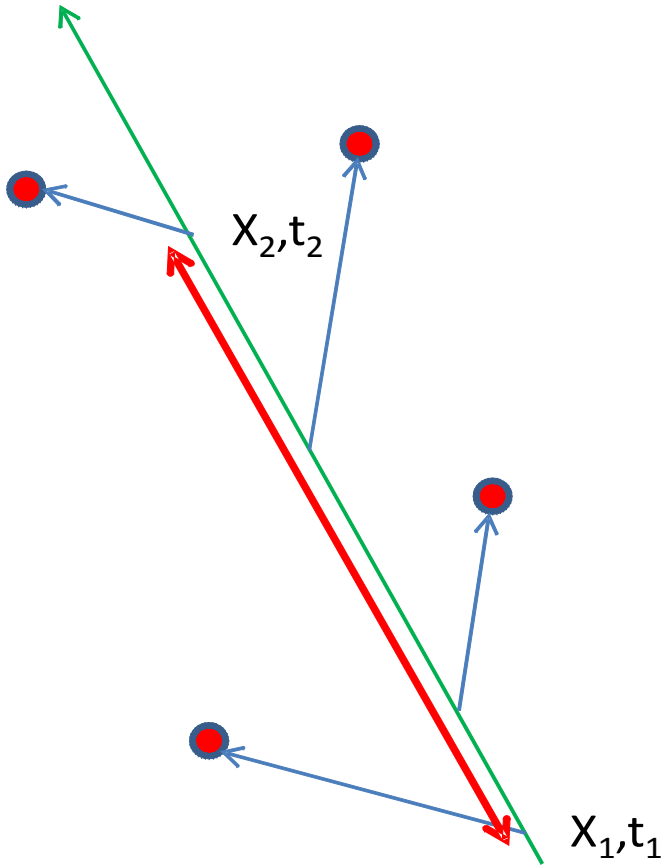
Comparable results for different algorithms
Selection of “direct hits” successful
very good determination of muon direction





Muon energy resolution

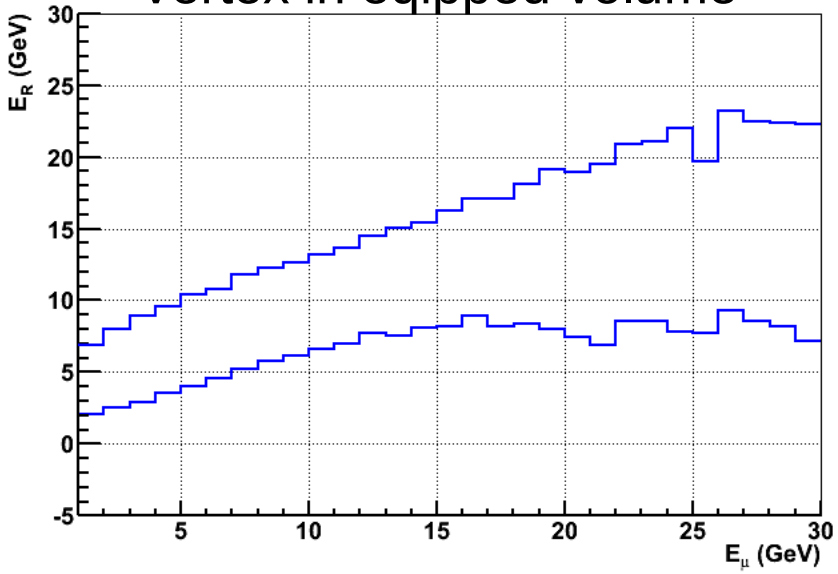
- Use full information
- Starting point
  - Hit selection
  - Track fit
- Muon range overconstrained:
- $E_1/GeV=(x_2-x_1)/5m$
- $E_2/GeV=(t_2-t_1)c/5m$

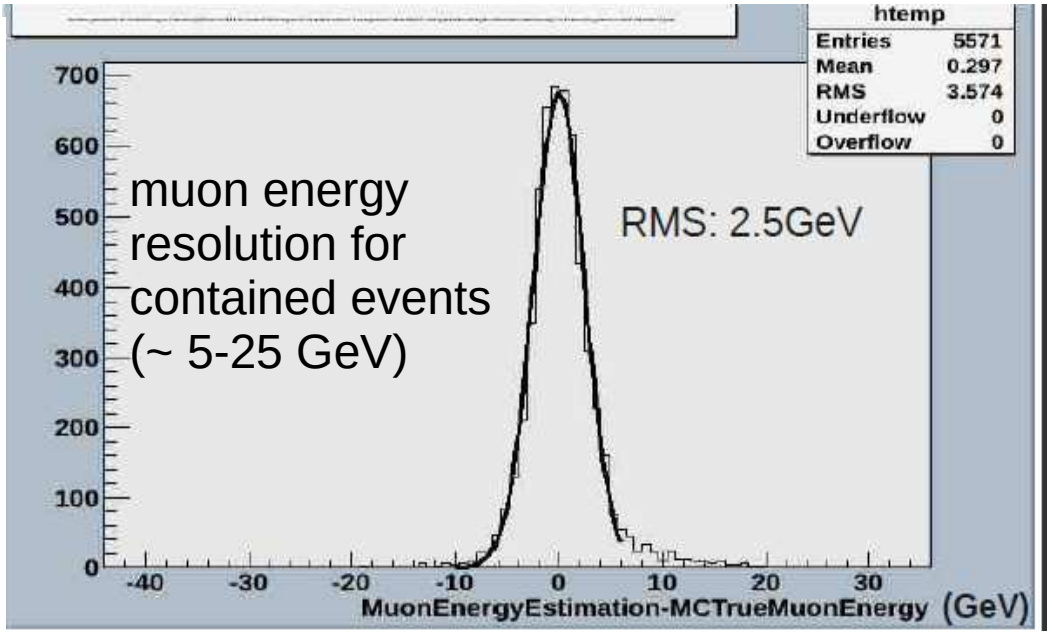


Muon energy resolution

Good correlation between measured and true muon energy found below 15 GeV
Resolution about 30%
Confirmed in combination with different track reconstruciton methods

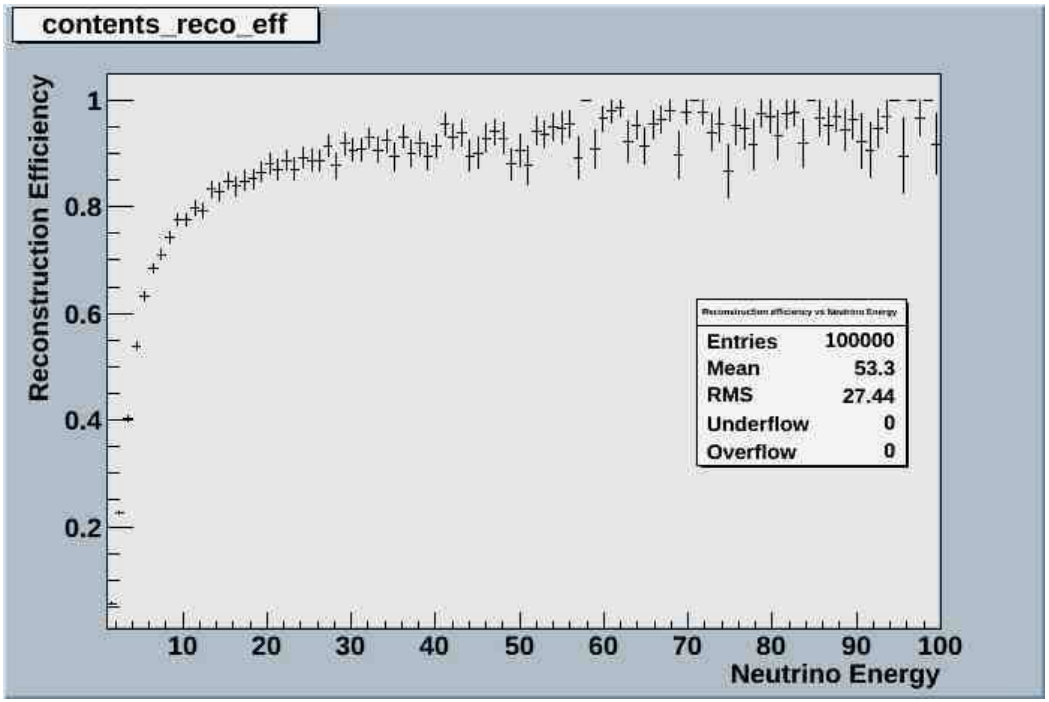
1-Sigma range shown
(Quantiles 16%-84%)
Vertex in eqipped volume



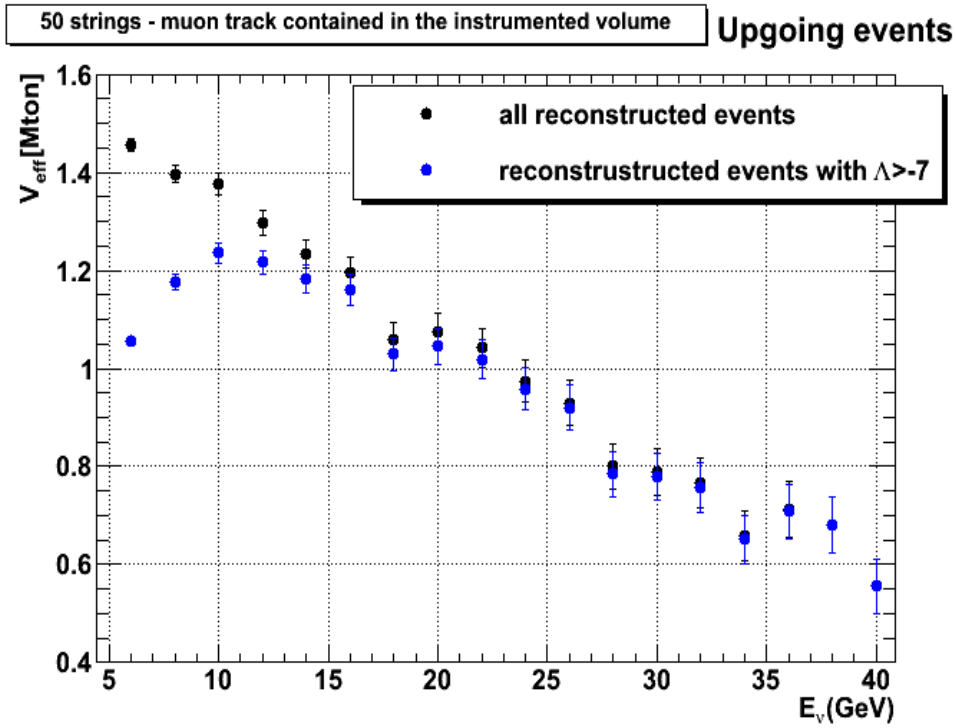


Efficiency – Effective Volume

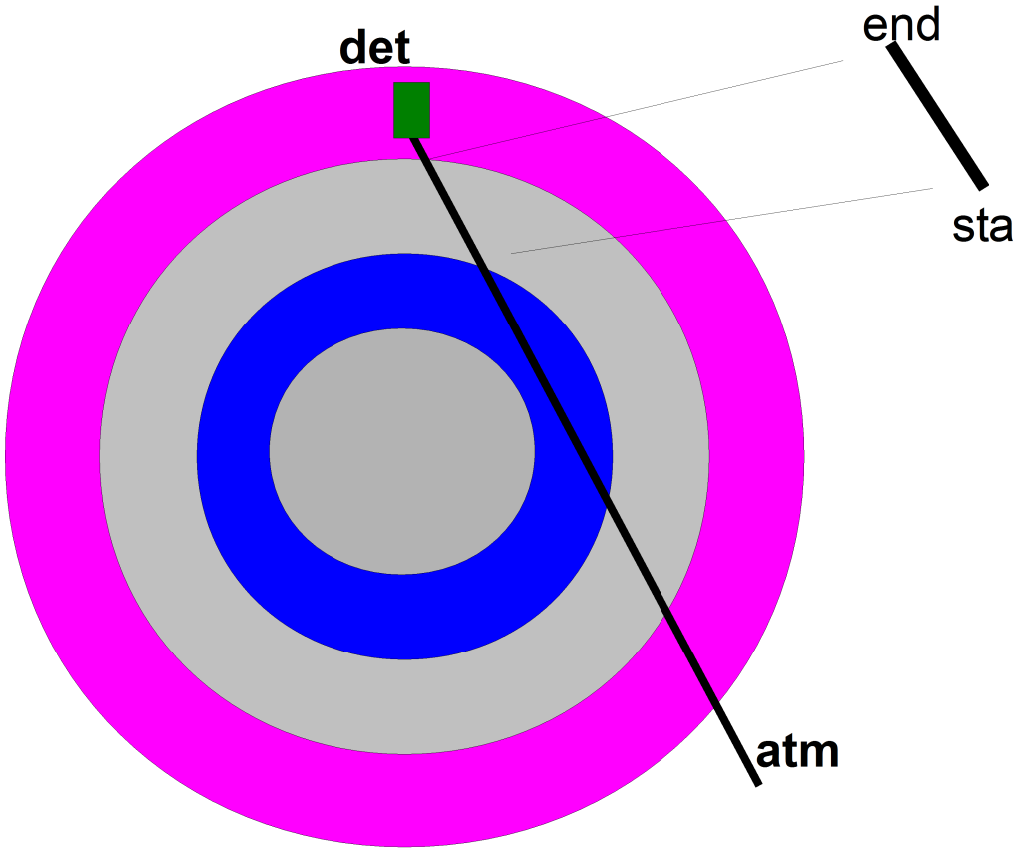
Efficiency w.r.t. Events with vertex in equipped volume
Can be scaled to large volumes



Effective volume for fully contained muon tracks
→ decrease for long tracks



Computing Oscillation Probabilities (numerically)



for one piece of constant matter density:

$$i\frac{\partial}{\partial t}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = \mathcal{H}_m(\rho)\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$\mathcal{H}_m(\rho) = \begin{bmatrix}E_1 & & \\ & E_2 & \\ & & E_3\end{bmatrix} + \mathbf{U}^{\mathbf{T}}\begin{bmatrix}A(\rho) & & \\ & 0 & \\ & & 0\end{bmatrix}\mathbf{U}$$

$$\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}_{\text{end}} \equiv \mathbf{T}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = e^{-i\mathcal{H}_m L}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}_{\text{start}}$$

for traversing the full Earth:

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}_{\text{det}} = \mathbf{U}\,\mathbf{T}_n\,\mathbf{T}_{n-1}\,\ldots\,\mathbf{T}_1\,\mathbf{U}^{\mathbf{T}}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}_{\text{atm}}$$

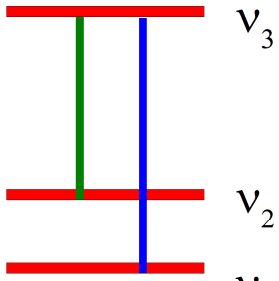
square to get probability

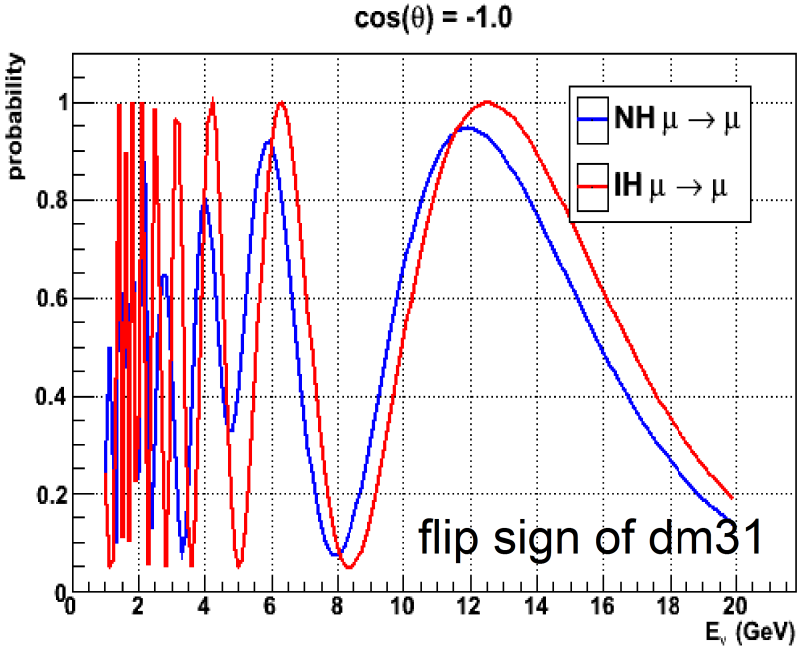
Transition matrix T involves exponent of complex 3x3 matrix
(diagonalize, power series, Cayleigh Hamilton..)

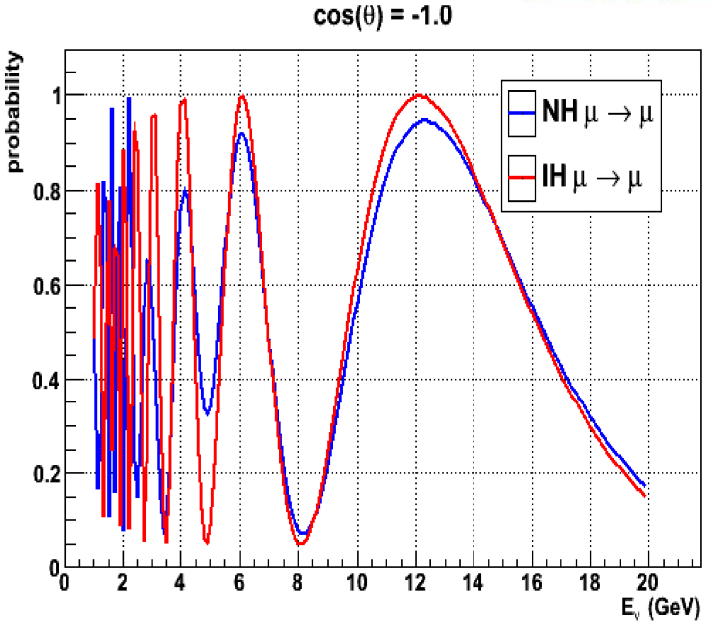
and include parameter uncertainties.

Comparing Oscillation Probabilities

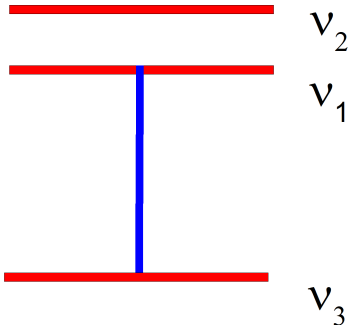
NH



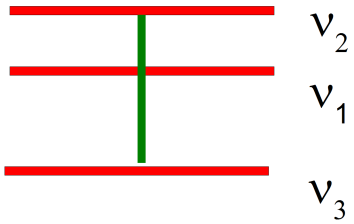




IH flip sign of Δm^2_{31}



IH : flip sign of Δm^2_{32}



want to 'plot probabilities for NH and IH, keeping oscillation parameters the same'

Depending on how one has parameterized the problem, simply flipping the sign of a Δm^2 may result in a IH model that is disfavored (~1σ) in the global fits.

Comparing Oscillation Probabilities

Arxiv:1205.5254

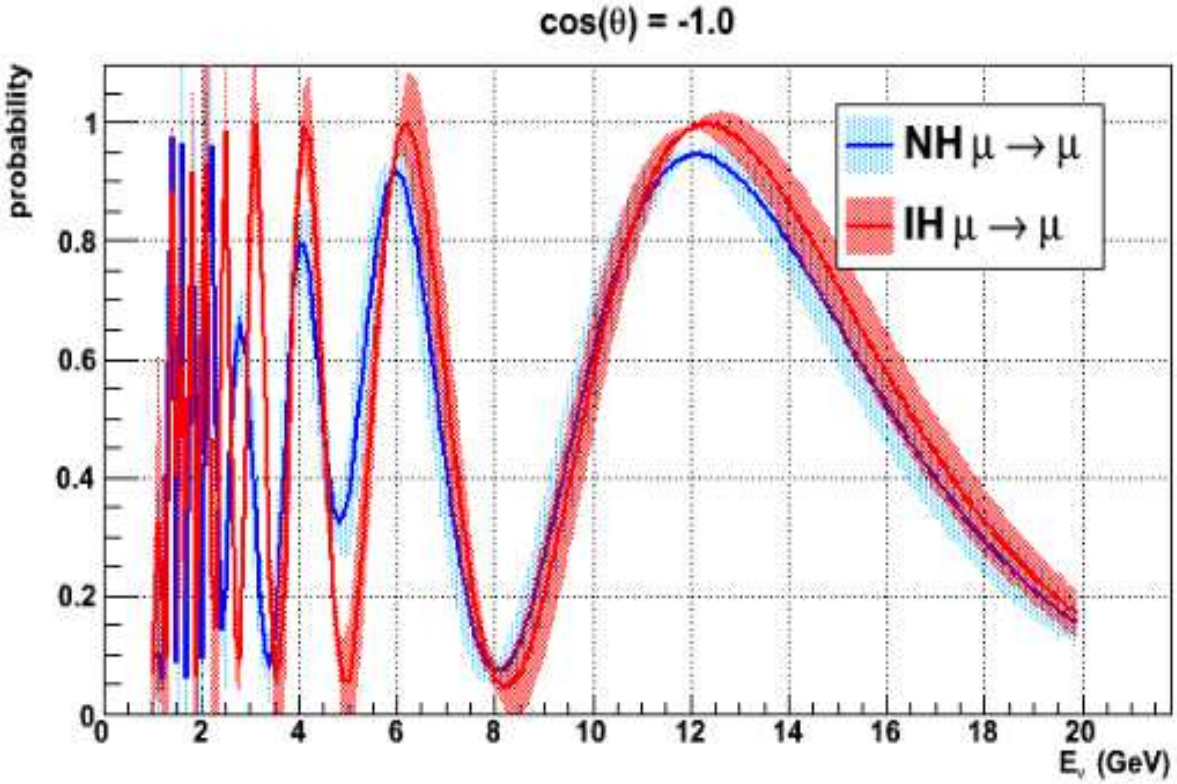
TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

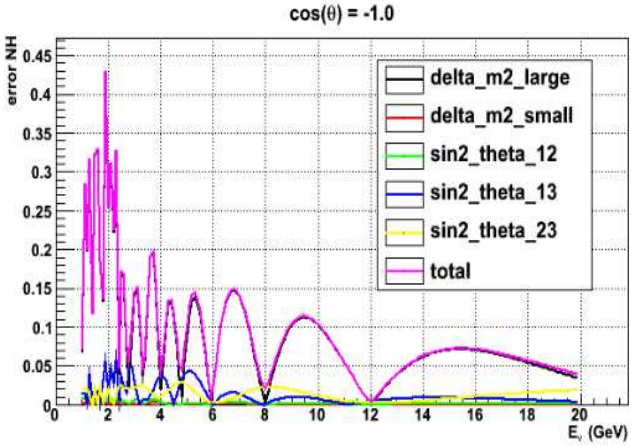
Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

Used in the following, but so far we set δ=0

Comparing Oscillation Probabilities

with uncertainties

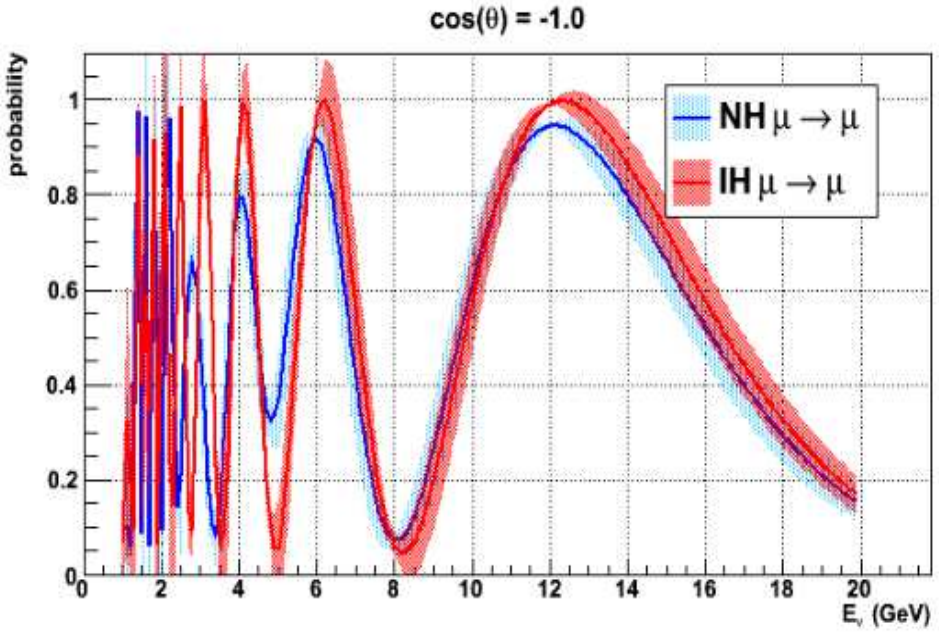


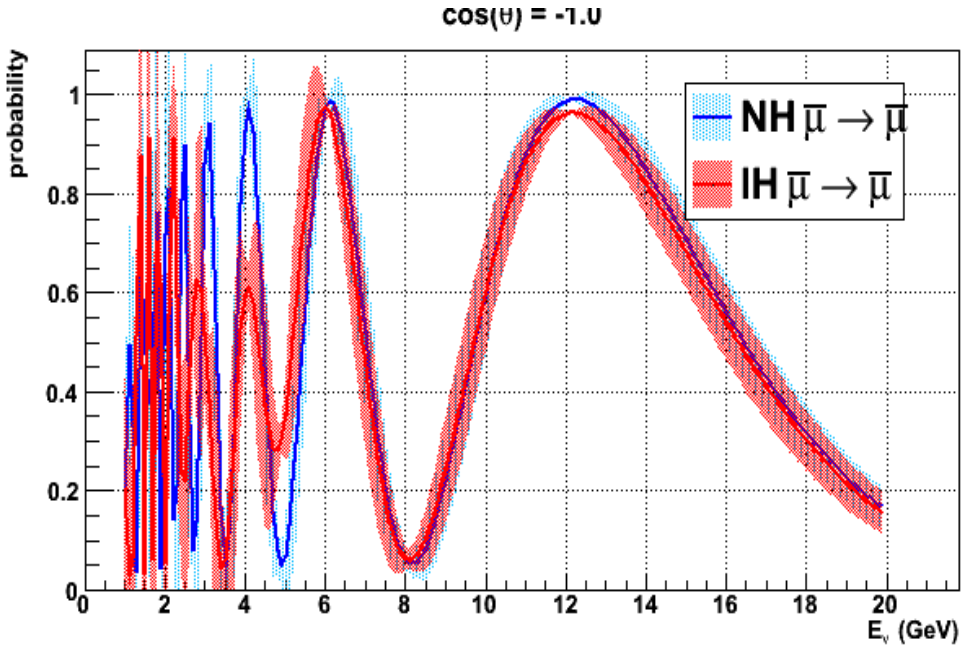


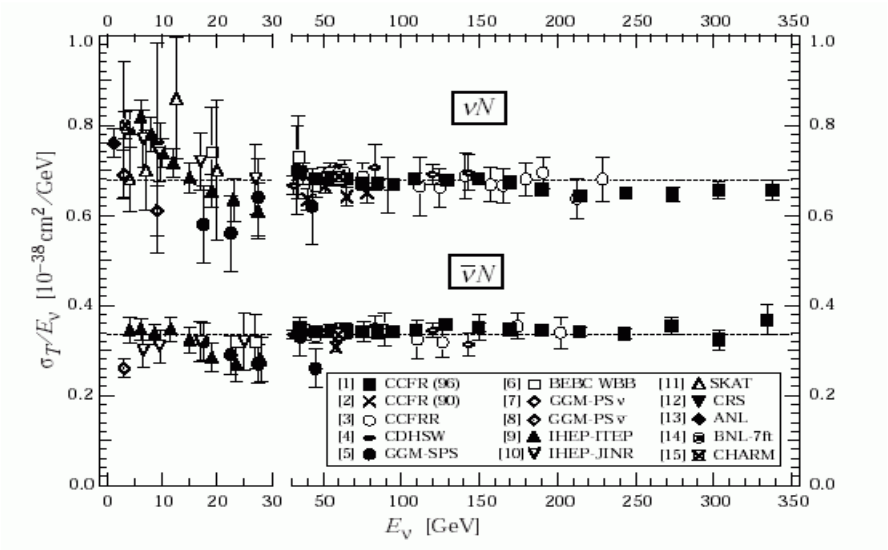
- NH/IH difference above ~13 GeV is degenerate with Δm^2_{large}
- → can use data to constrain this parameter?
- regions around 5 GeV where genuine NH/IH difference remains

Comparing Oscillation Probabilities

with uncertainties





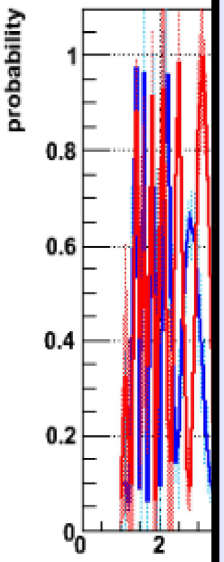


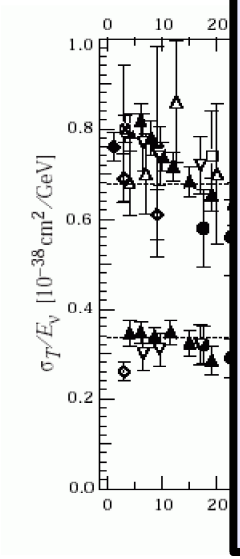
Effect survives because anti-neutrino cross-section is factor ~2 smaller than neutrino cross-section.

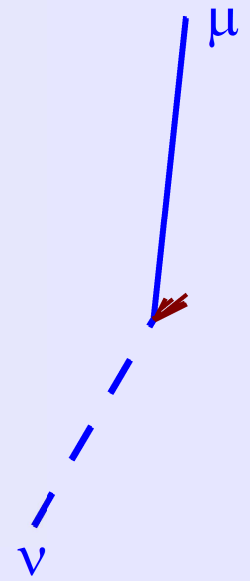
however...

Comparing Oscillation Probabilities

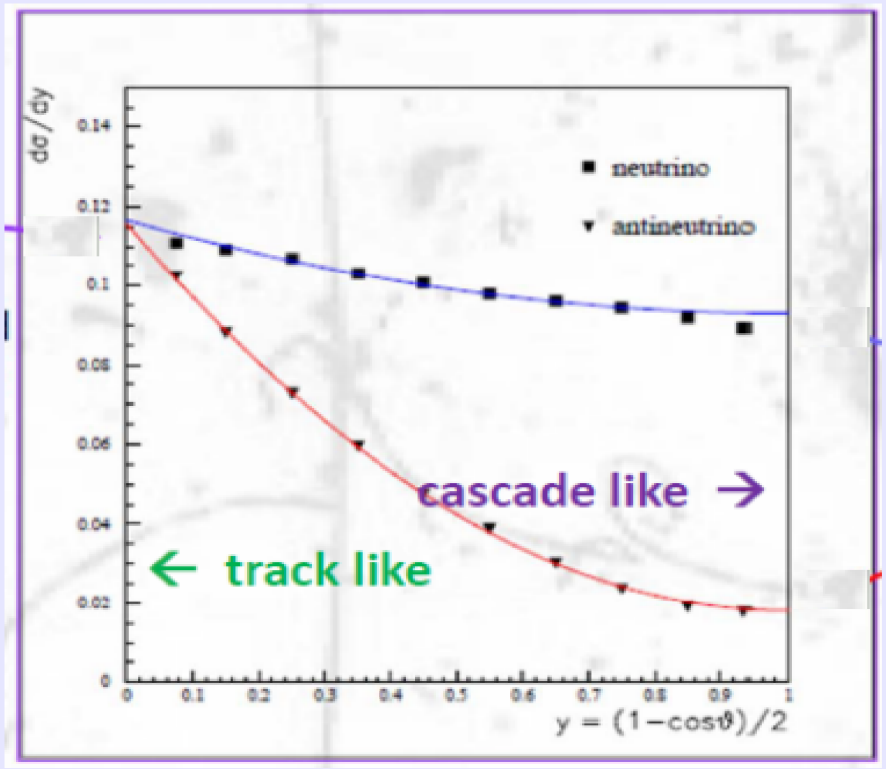
with uncertainties

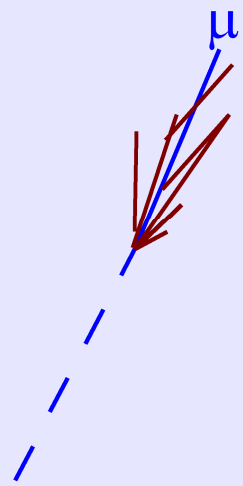






nice events,but
small asymmetry



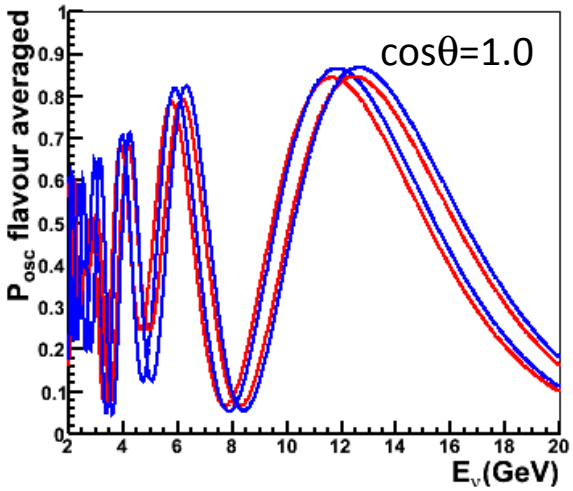


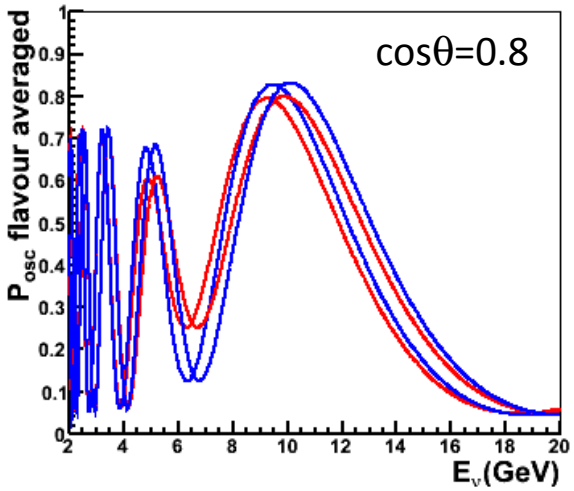
large asymmetry,
but beware of
ν_e ν_τ background
(must tag the μ!)

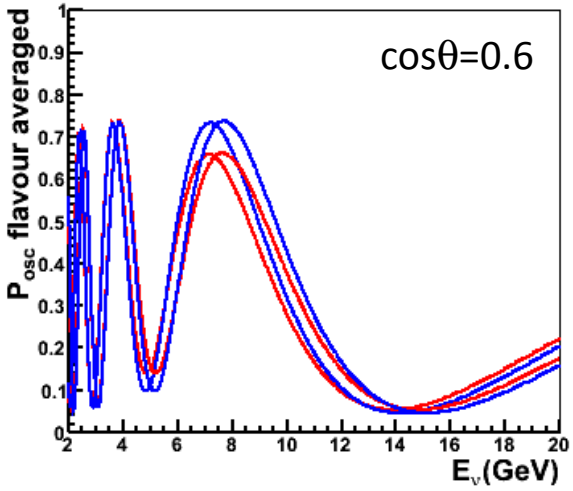
- Different topologies contribute to same E_ν bin
  - systematics of acceptance and energy resolution need to be stringently controlled
  - … but ultimately can put y in the fits

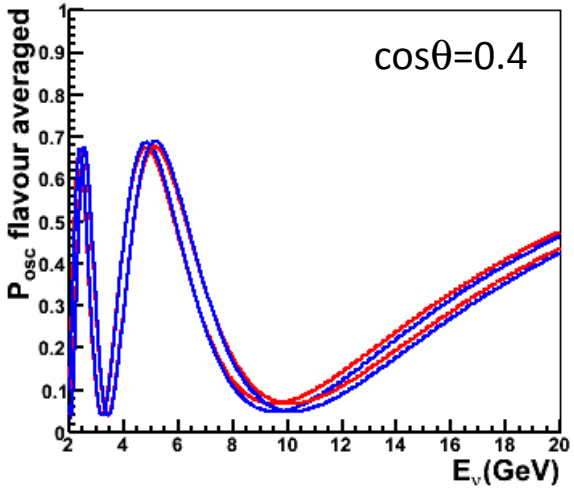
Comparing Oscillation Probabilities

with uncertainties









ν_e & ν_μ

$\overline{\nu}/\nu$ = 0.5

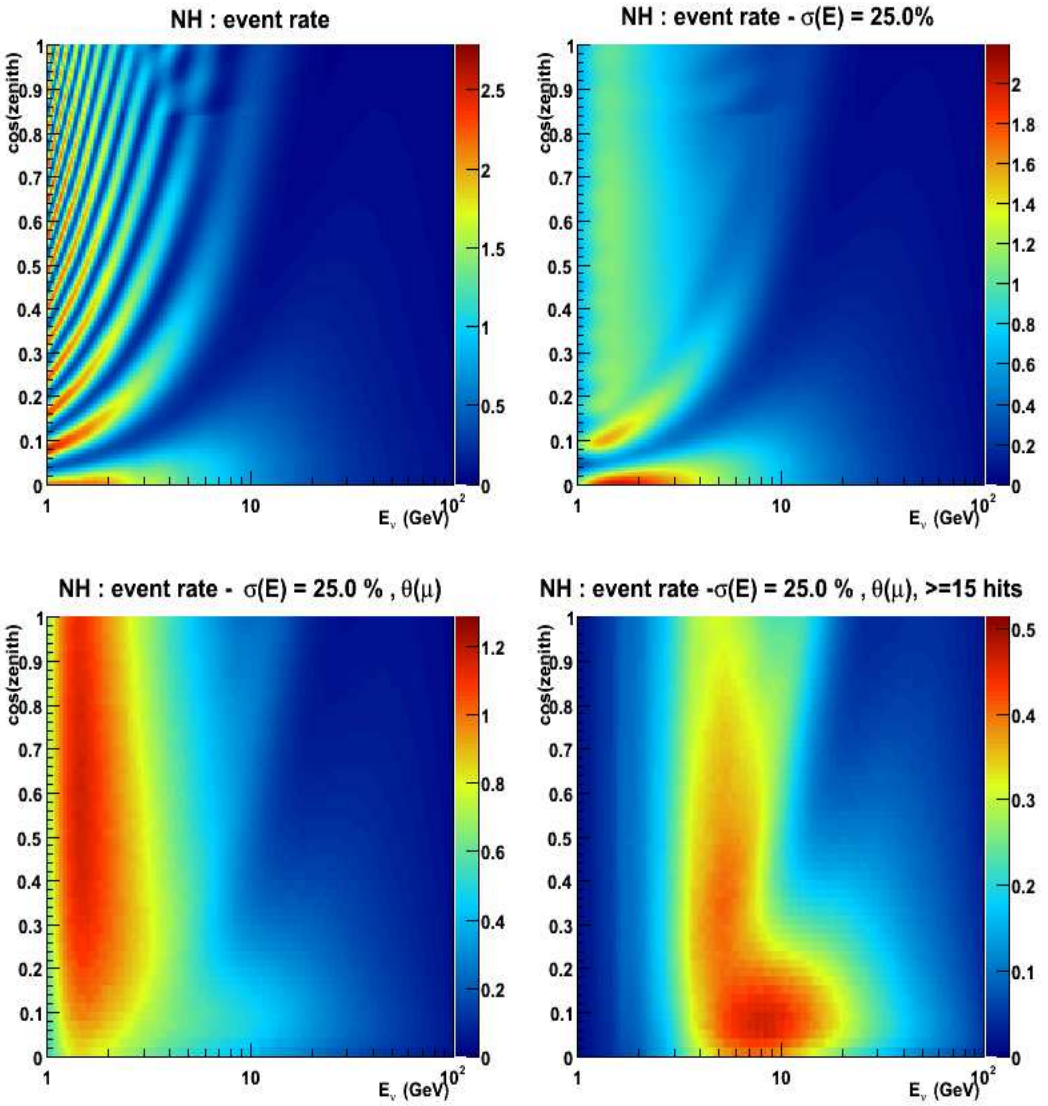
Band

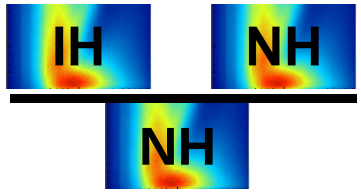
1σ in Δm^2_{32}

Color:

NH / IH

Toy Analysis – effect of resolutions & acceptance





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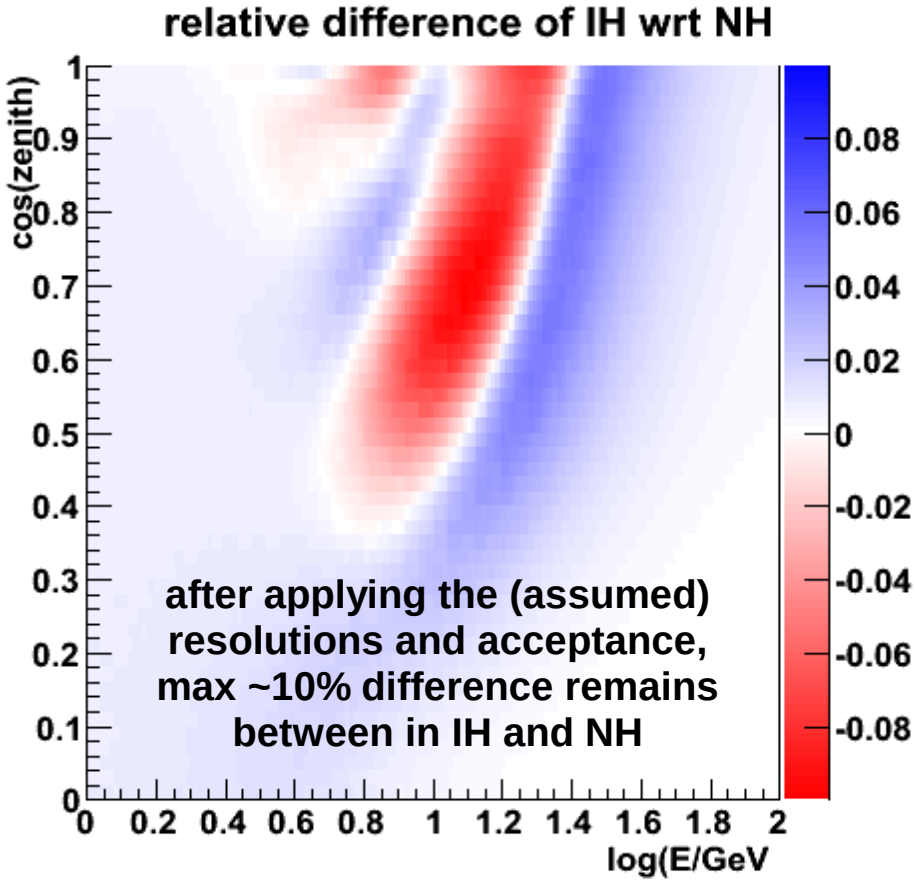
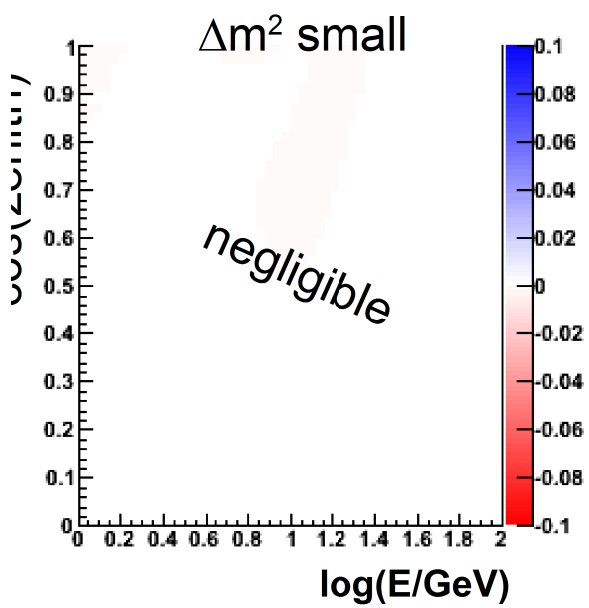
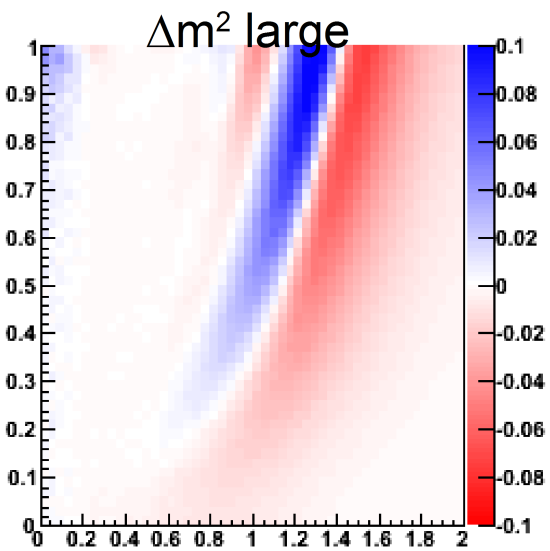
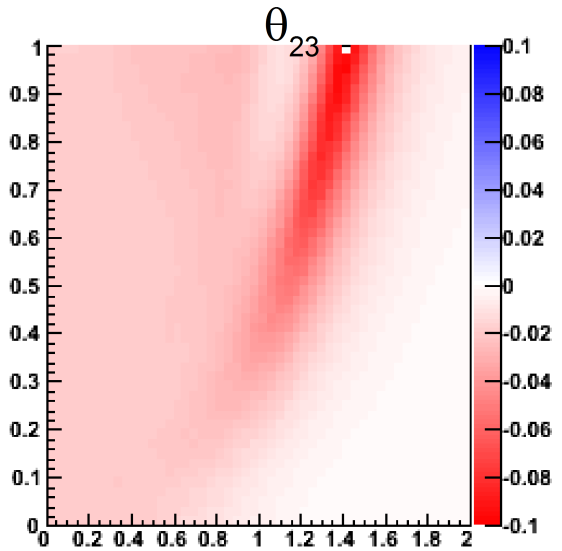
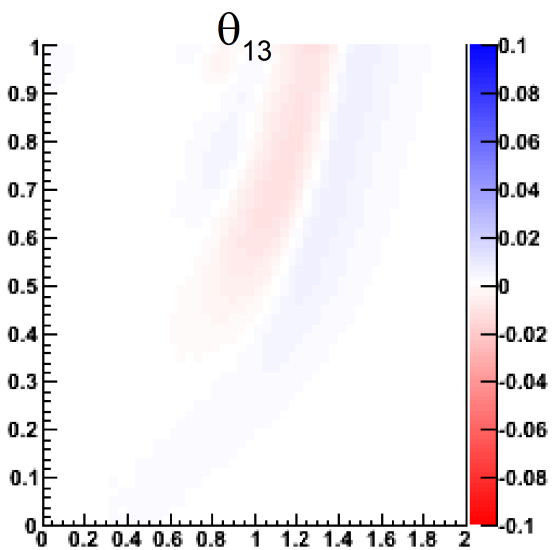


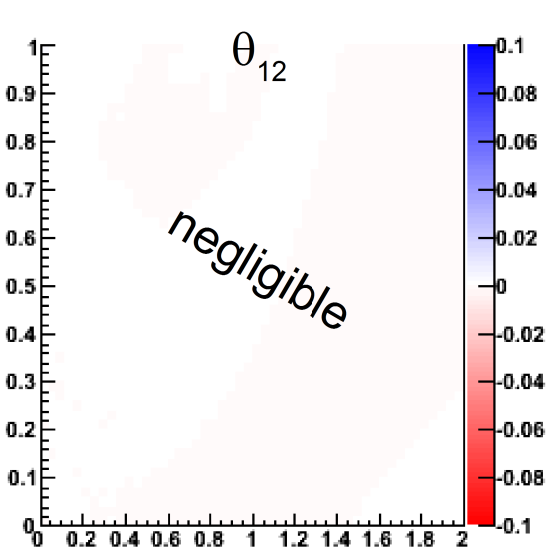
Toy Analysis

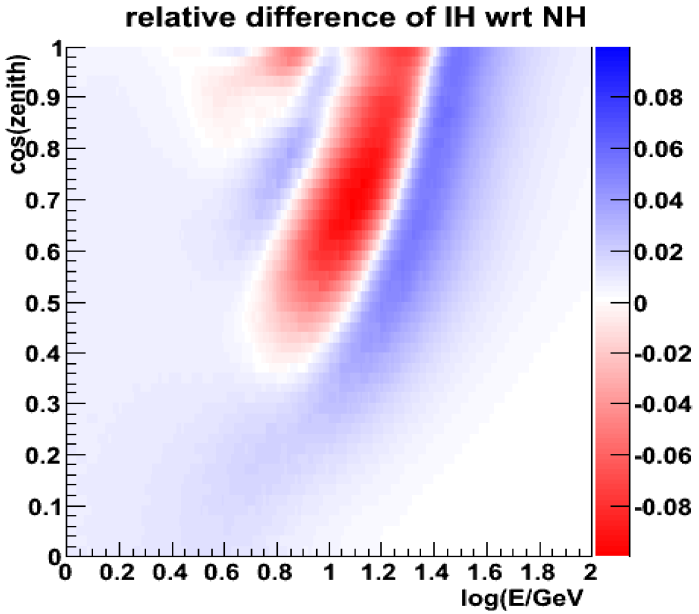




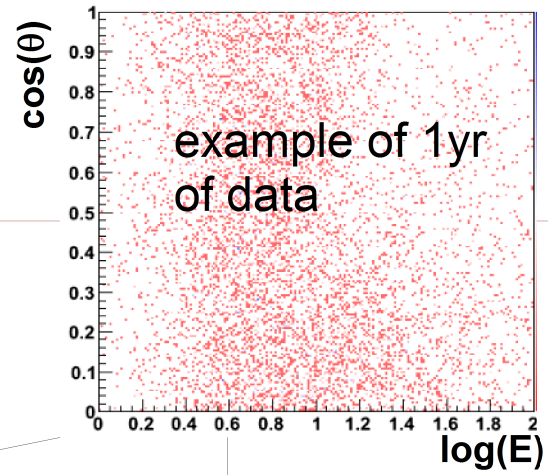








Distinguishing NH and IH

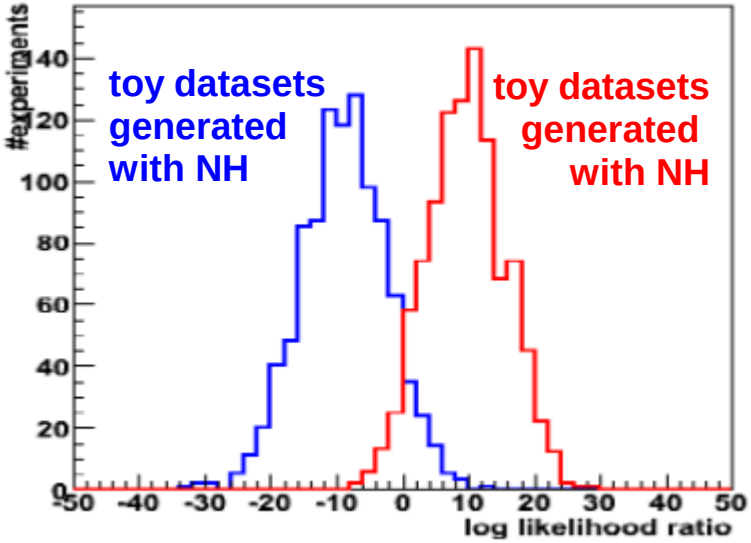


to optimally distinguish between IH and NH:
likelihood ratio test *with nuisance parameters*
→ *in other words: deal with degeneracies by fitting!*

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

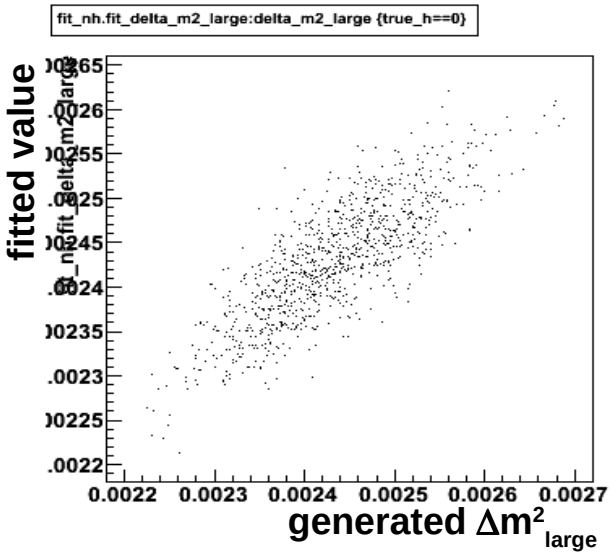
$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

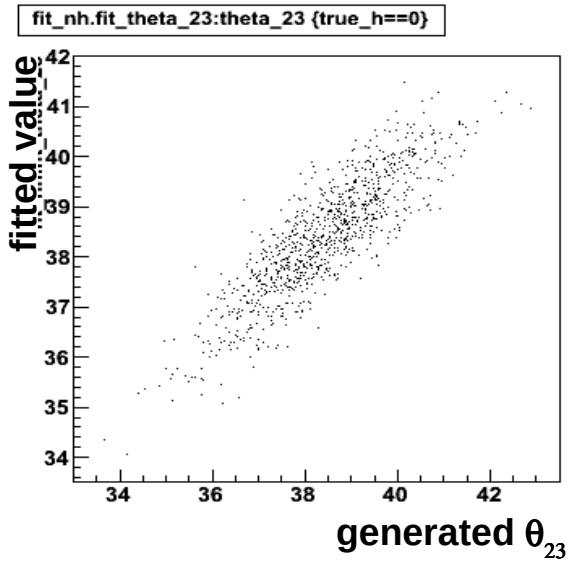
1) fit mixing parameters assuming NH
2) fit mixing parameters assuming IH
3) compute ΔlogL = log(L(NH)/L(IH)

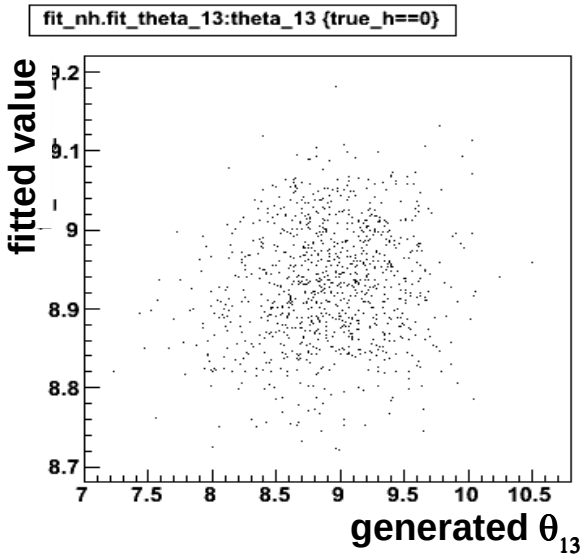


Results of parameter fit

1 Mton*year (NHtrue, NHfit)





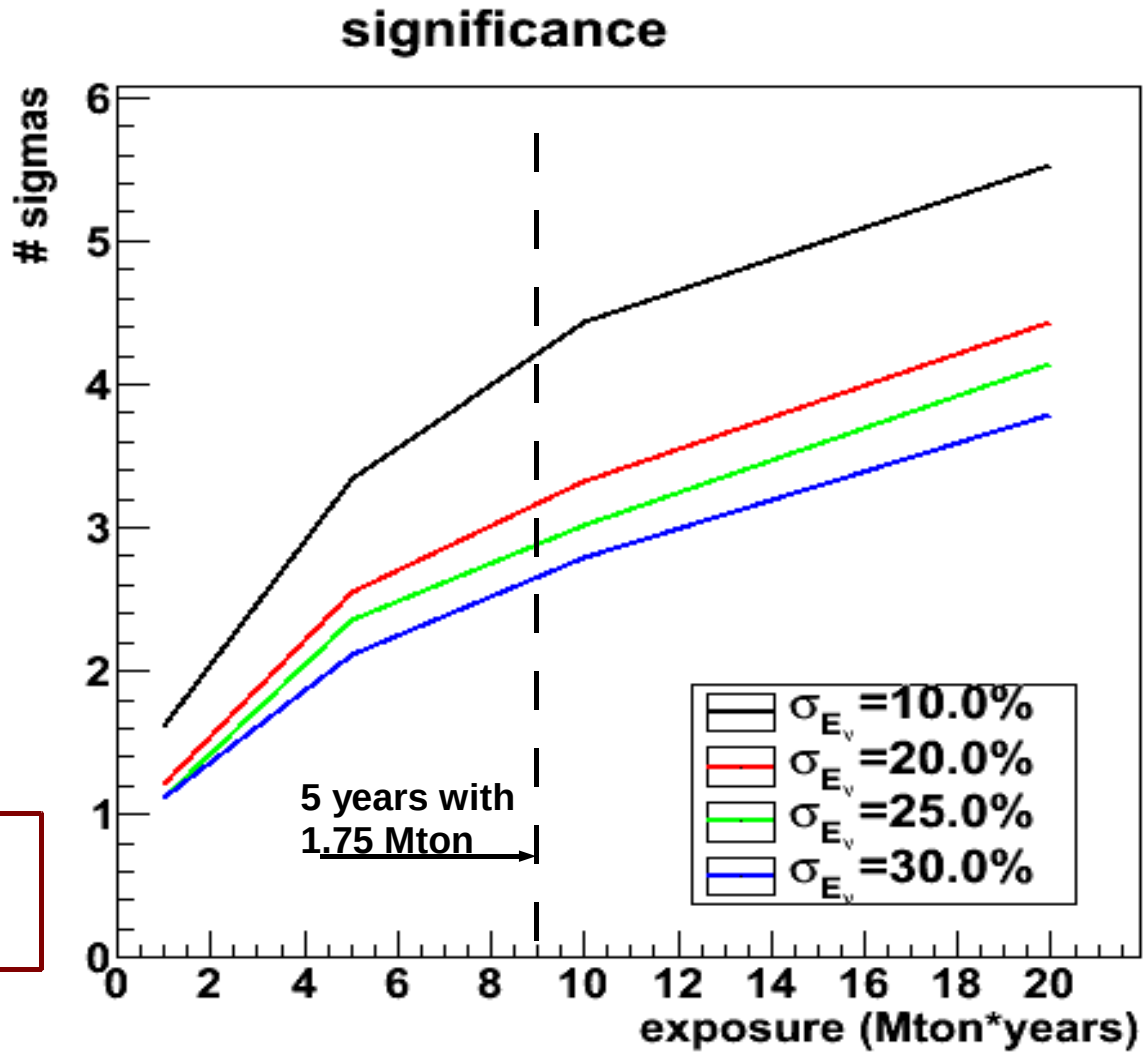


Eres = 25%, 1-100 GeV

Mton x yr	$\sigma(\Delta m^2_{large})$ (eV^2)	$\sigma(\theta_{23})$ (deg)	$\sigma(\theta_{13})$ (deg)
0(now)	8.0e-5	1.3	0.45
1	4.3e-05	0.61	0.42
5	2.3e-05	0.32	0.44
10	1.8e-05	0.22	0.39
20	1.4e-05	0.16	0.39
30	1.2e-05	0.13	0.37

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

Mass hierarchy significance

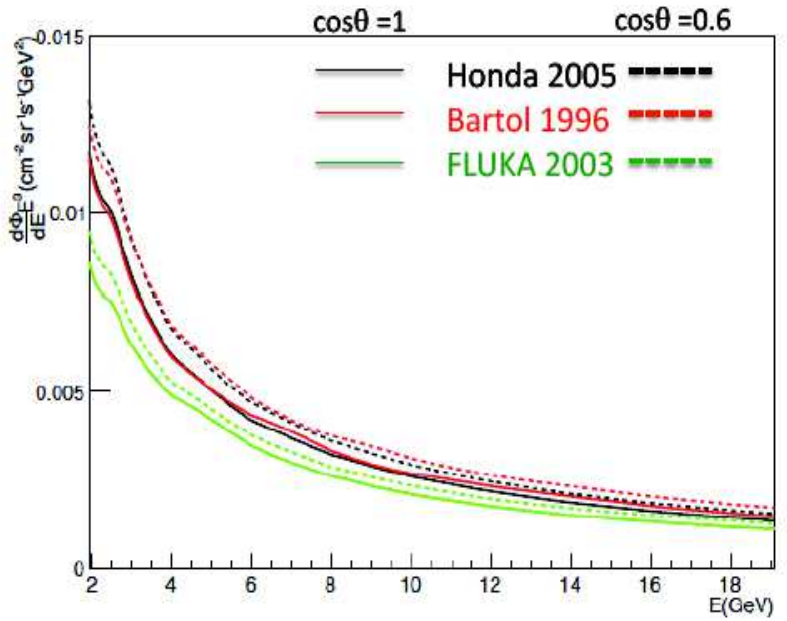


all results are preliminary

with current assumptions (which may be wrong) : non-trivial measurement.

Status / Todo list

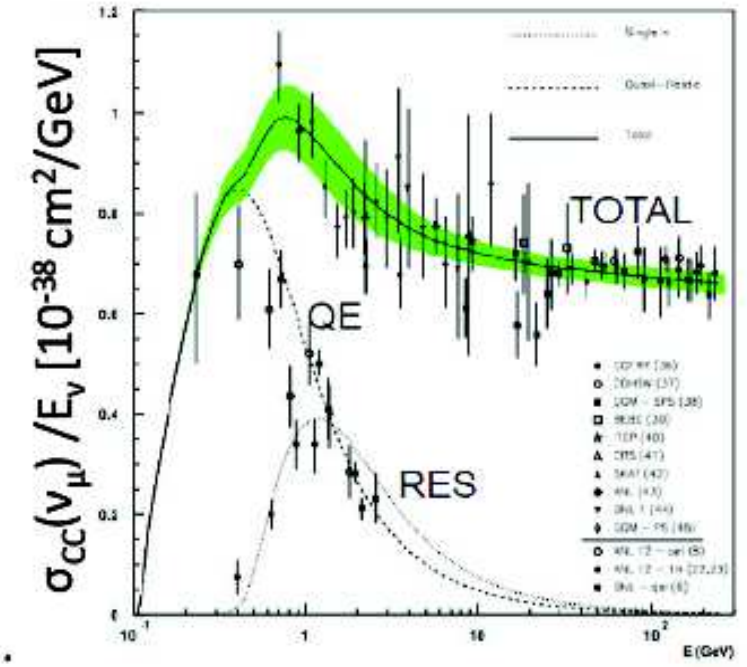
- Posc computations
  - solved already many times
- Event Simulation:
  - mostly fine: have genhen, genie, several geant3/4 codes
- Reconstruction:
  - Working well for muon (lots of progress already), but that is not enough
    need accurate energy measurement of full event (including shower)
- Background rejection (and ν flavour tagging)
  - Still to be started!
    (different problem for ORCA compared to Pingu)
- Fit of data and likelihood ratio
  - under control
- Detector optimization
  - needs all af the above
- Systematics
  - started in some area's (fluxes, earth model)



Conclusions

- Antares neutrino telescope taking data for 5 years now
  And KM3NeT making good progress towards deploying first part of detector.
- Exciting possibility to measure the mass hierarchy, but challenging.
- New energy regime (for us) and stronger requirements on accuracy and resolution.
- Good sensitivity to Δm^2_{large} and θ_{23} before we can measure the MH.
- Studies into reconstruction etc progressing well; nevertheless critical items remain.
- Next review (by funding agencies) this summer; we will know more by then.

Systematics



Simulation tools

generators

GENHEN

GENIE
+ interface

TOY

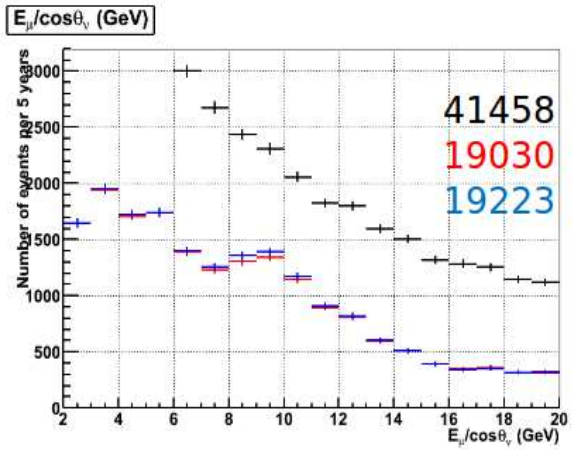
detector simulation

KM3

Geant3 (geasi

Step 2

- Muon energy and Neutrino zenith are measured
- Perfect measurement of Eμ and cosθν
- χ^2= 19.2/19 ; p-value 0.44 ; σ = 0.14



5 years of data
bins of 1 GeV

No oscillations
Normal hierarchy
Inverted hierarchy

Without νe CC