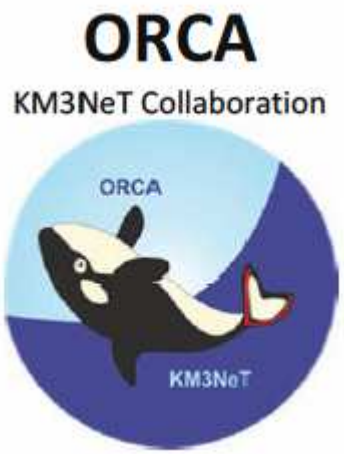
ANTARES/ORCA



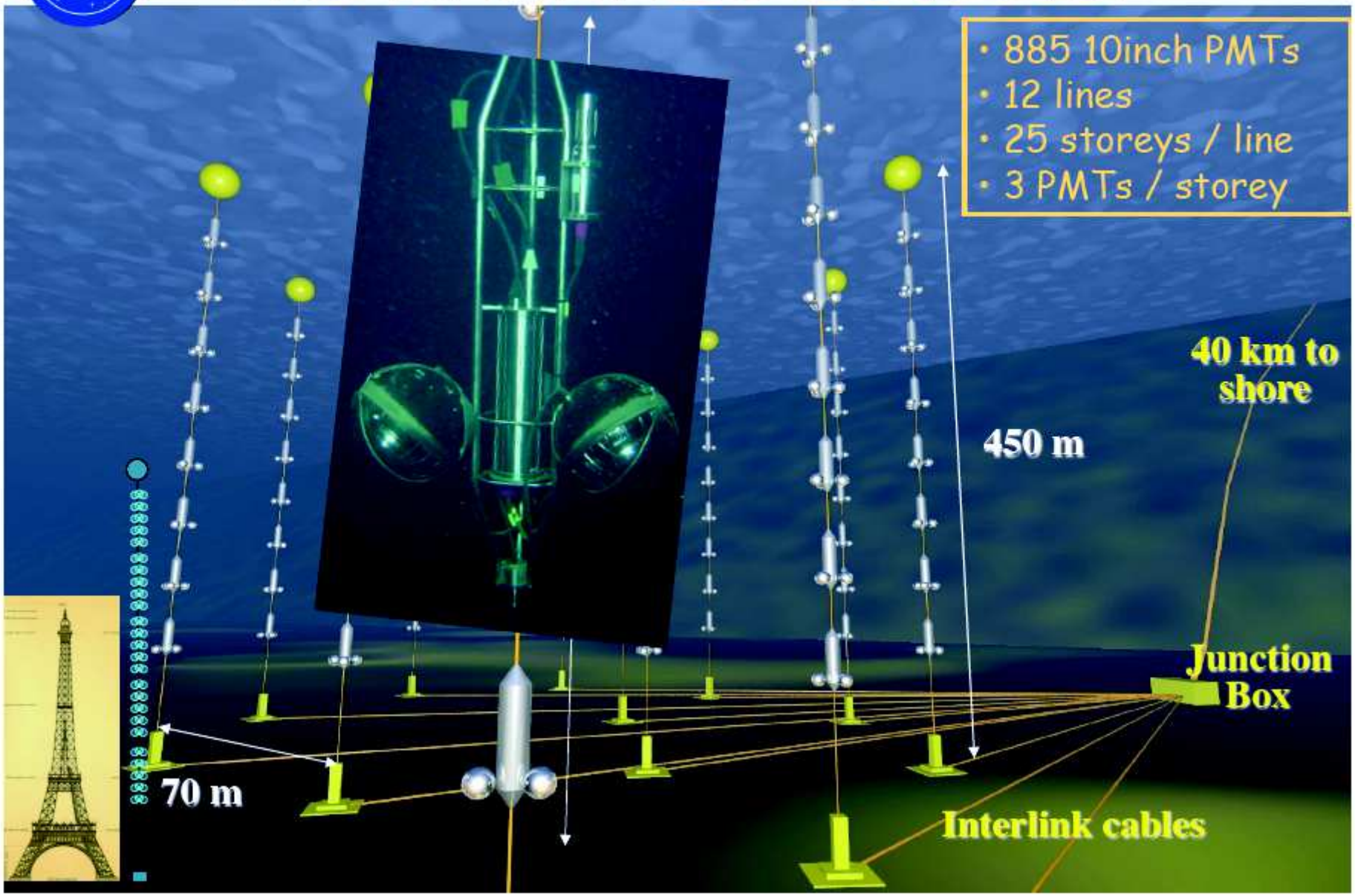
Neutrino Oscillation Measurements in the Deep Sea

Jürgen Brunner, CPPM, Marseille

Outline

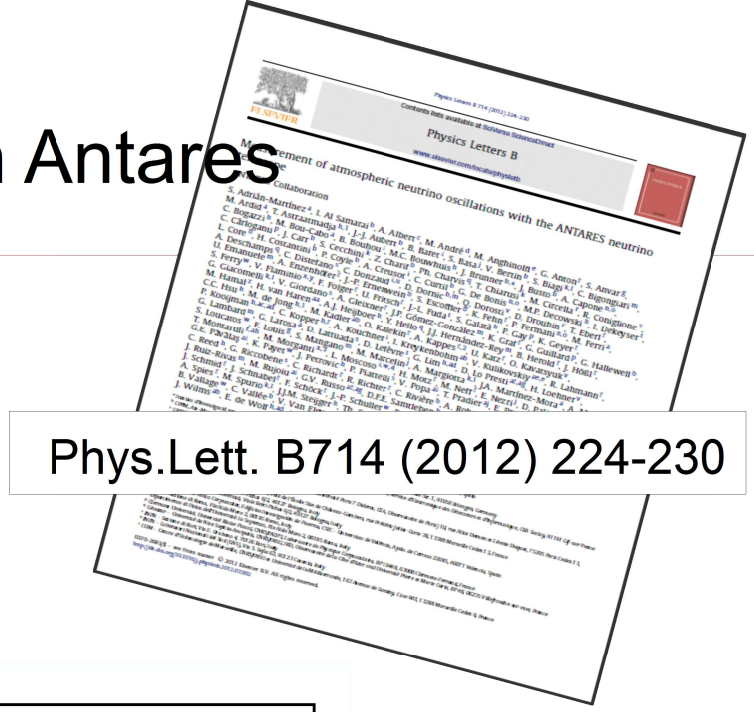
- ANTARES Oscillation study
- KM3Net & ORCA
- Software tools
- Performance parameters
- Sensitivity to Mass Hierarchy

The ANTARES detector

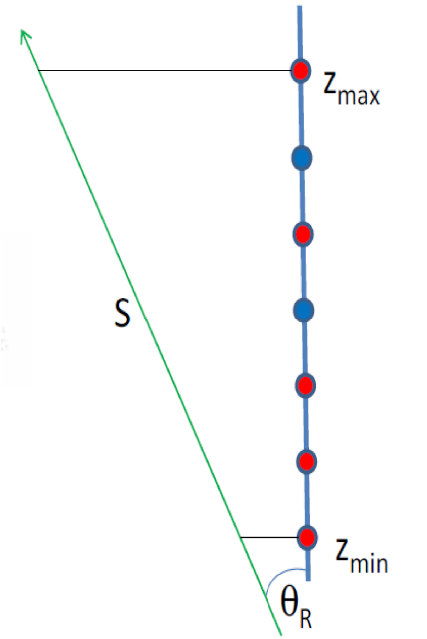


(vacuum) Oscillation physics with Antares

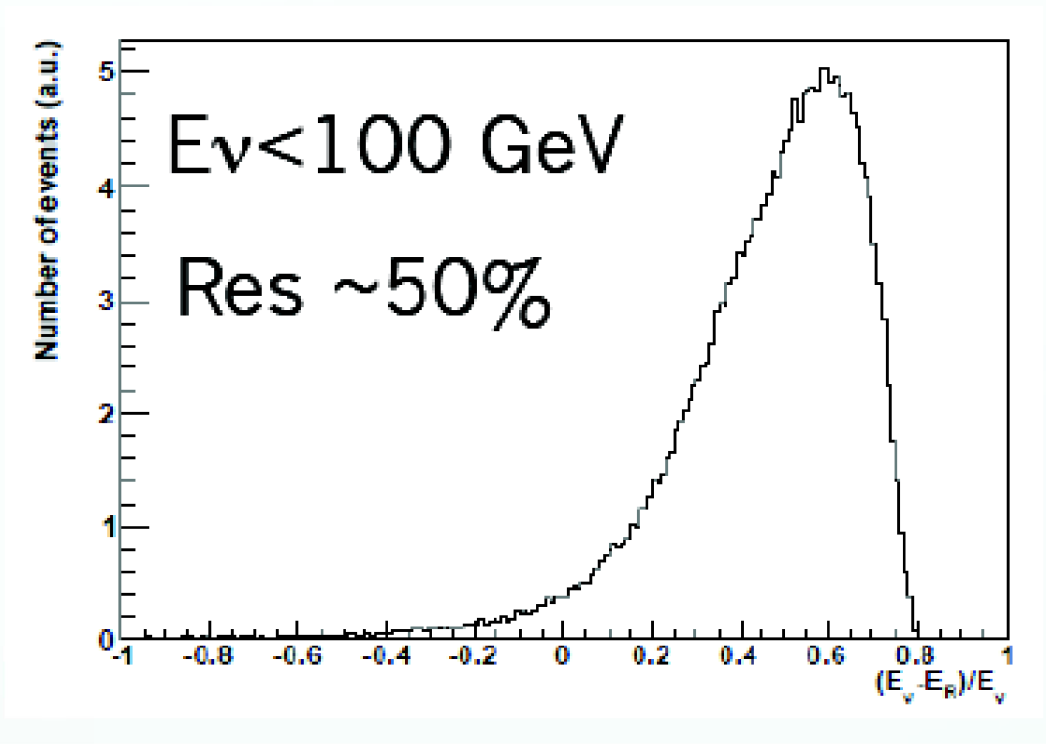
- for Antares: low-energy domain
- 2007 to 2010 : 863 days of active time
- 25 % of events reconstructed on only one line
- energy estimated from muon length



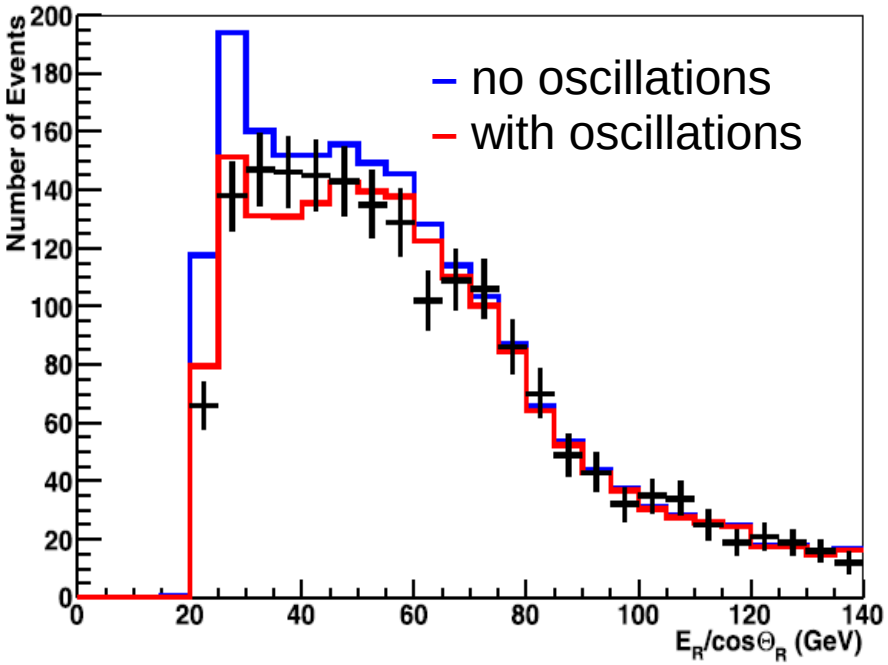
Phys.Lett. B714 (2012) 224-230

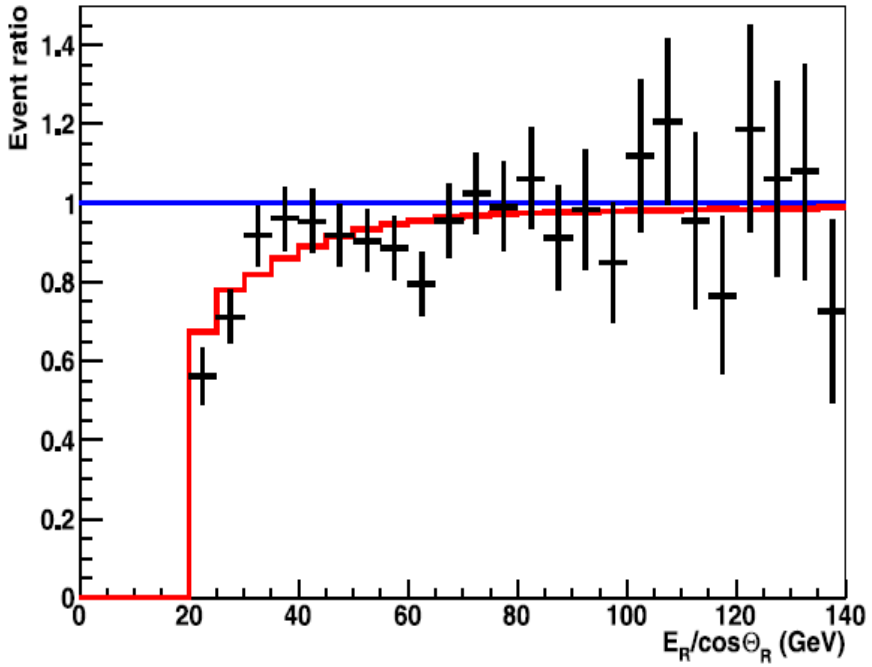


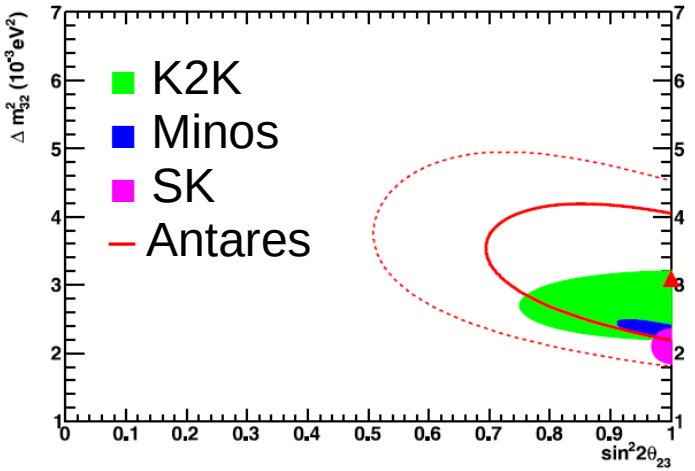
$$E_R = S \cdot 0.2\ \mathrm{GeV/m}.$$



(Vacuum) Oscillation physics with Antares



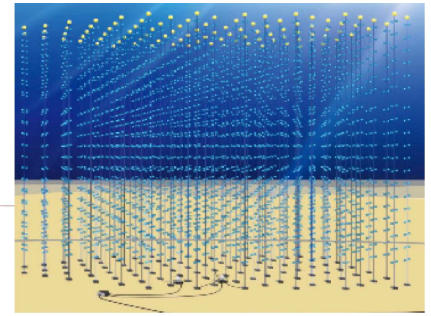


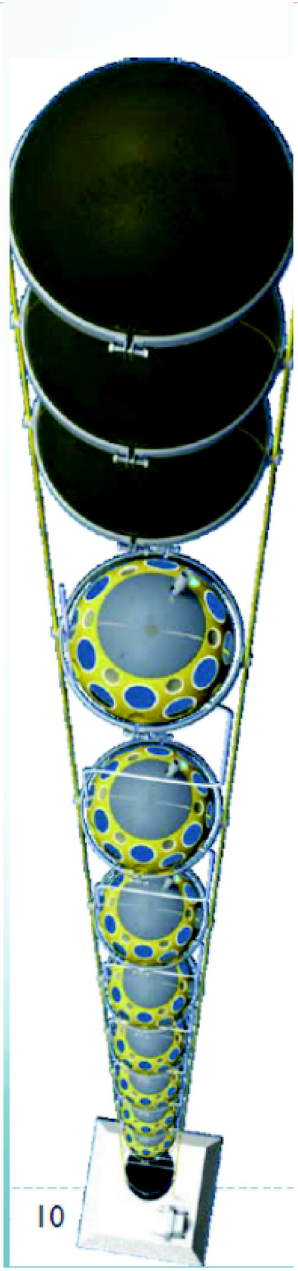


p-value of no-oscillation hypothesis: 2.1%

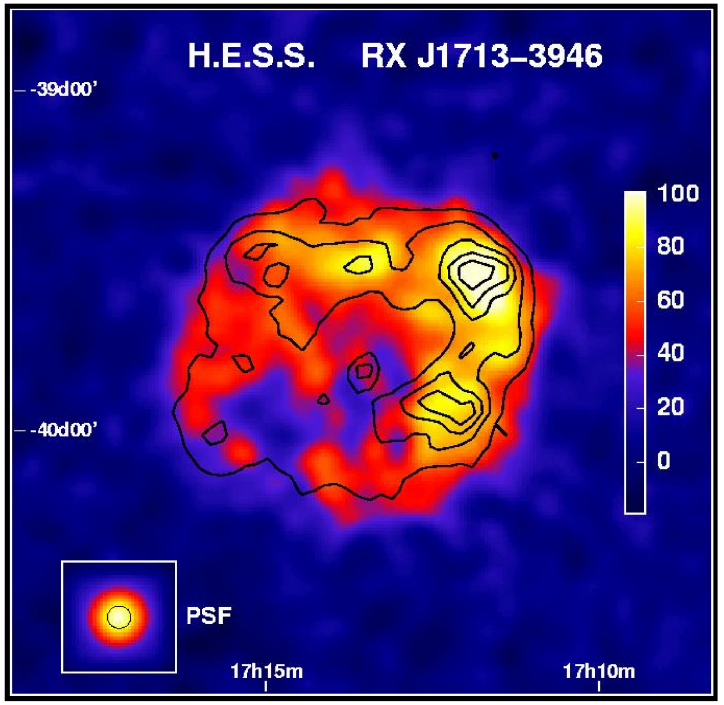
assuming maximal mixing:
$\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}\ eV^2$

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'



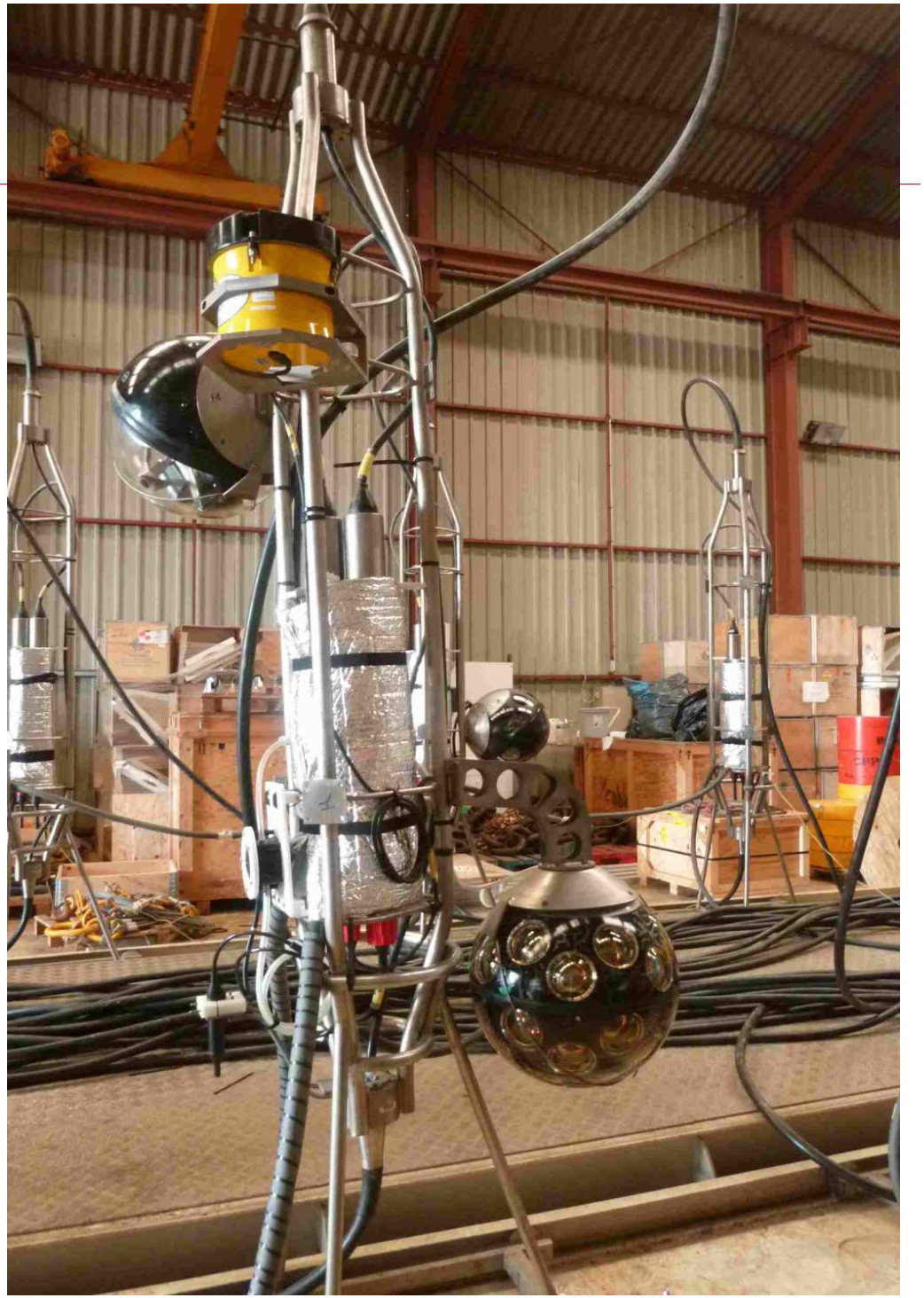
phase-1:

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

The KM3NeT project

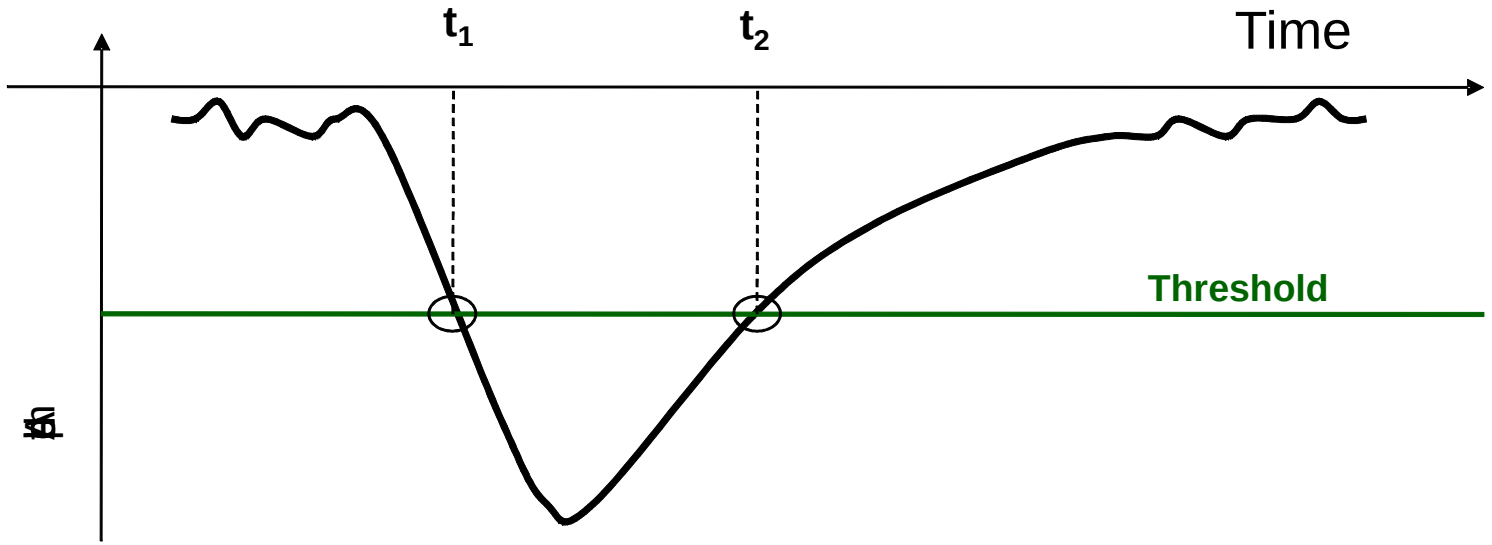
Mutliple small pmt's (helps in photon-counting and background rejection)

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



KM3Net Readout

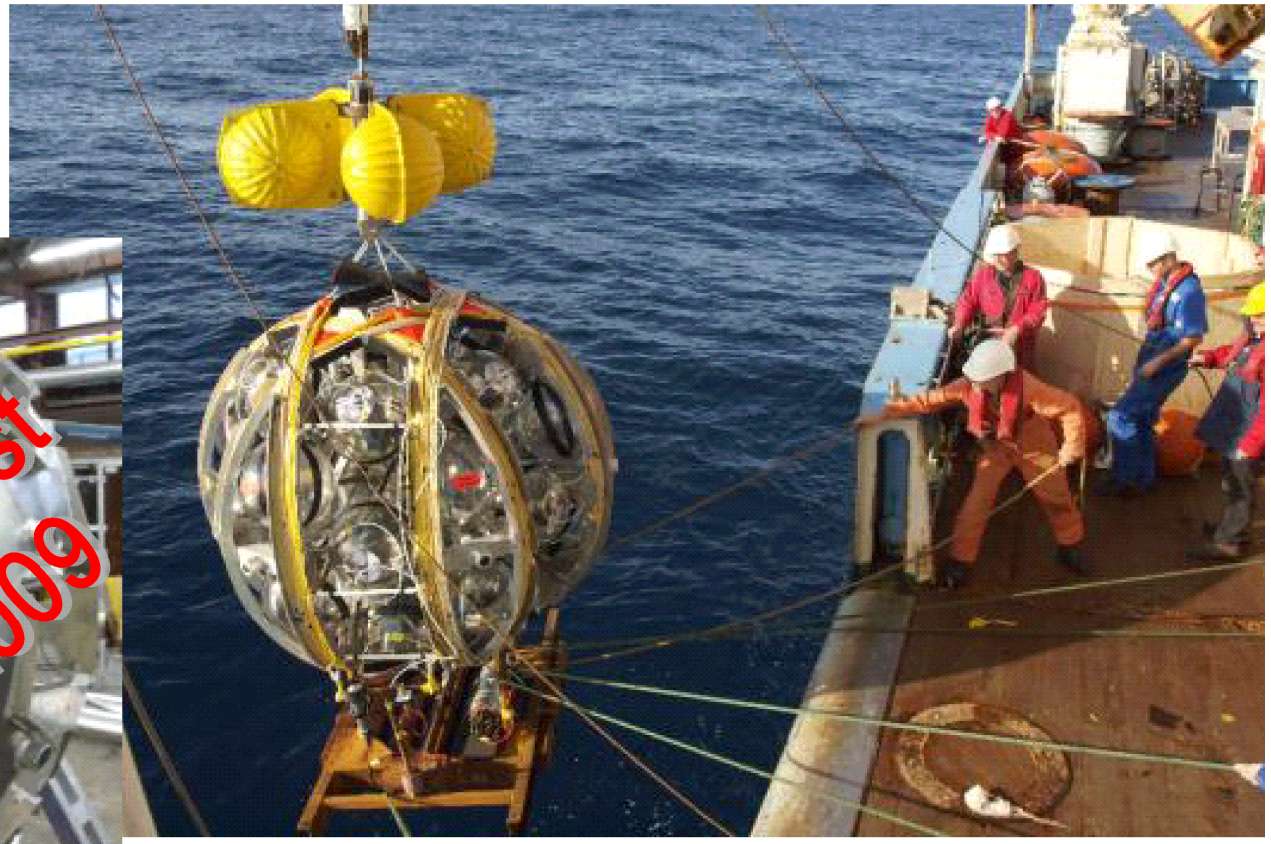
From the analogue signal to time stamped digital data:



- Implemented through FPGA & System on chip contained in optical module
- All data to shore via ethernet link
- Time synchronisation and slow control

Deployment Strategy

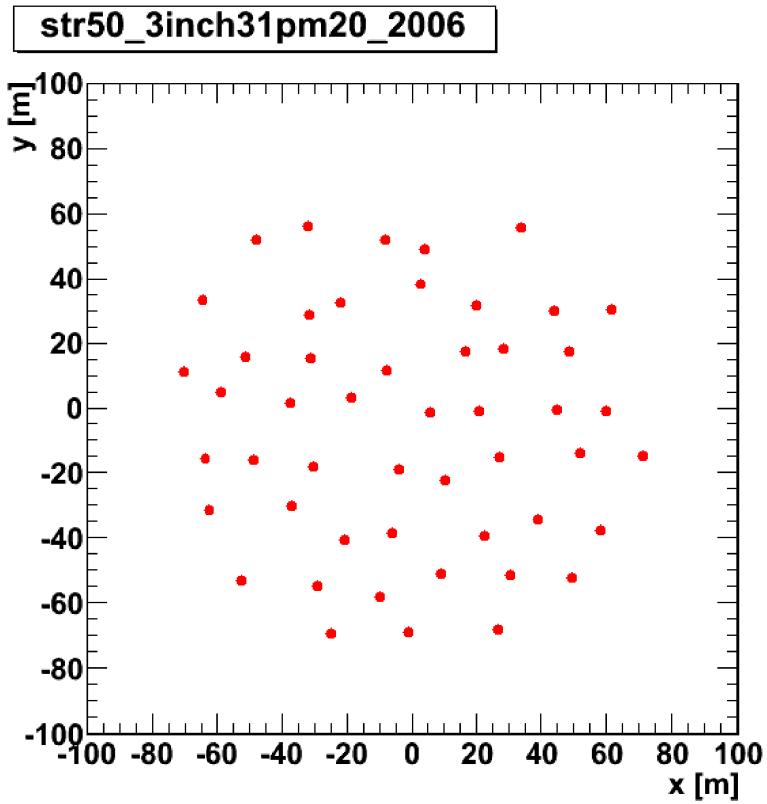
Slender string rolled up for self-unfurling:



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

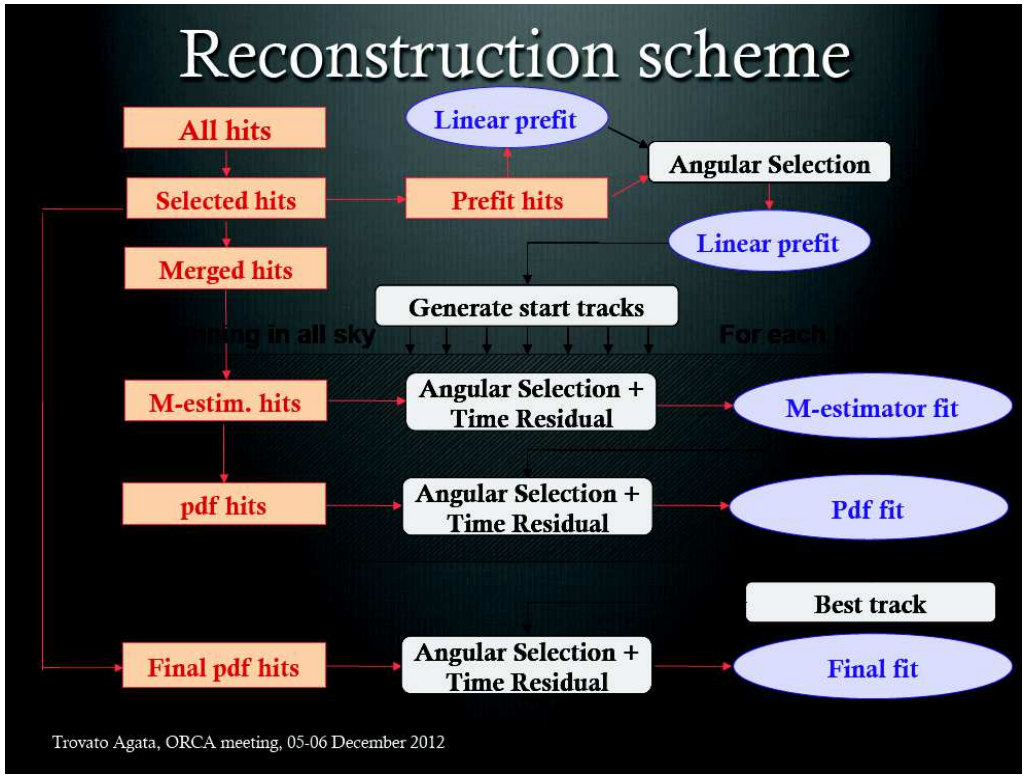
Geasim
(geant3)

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

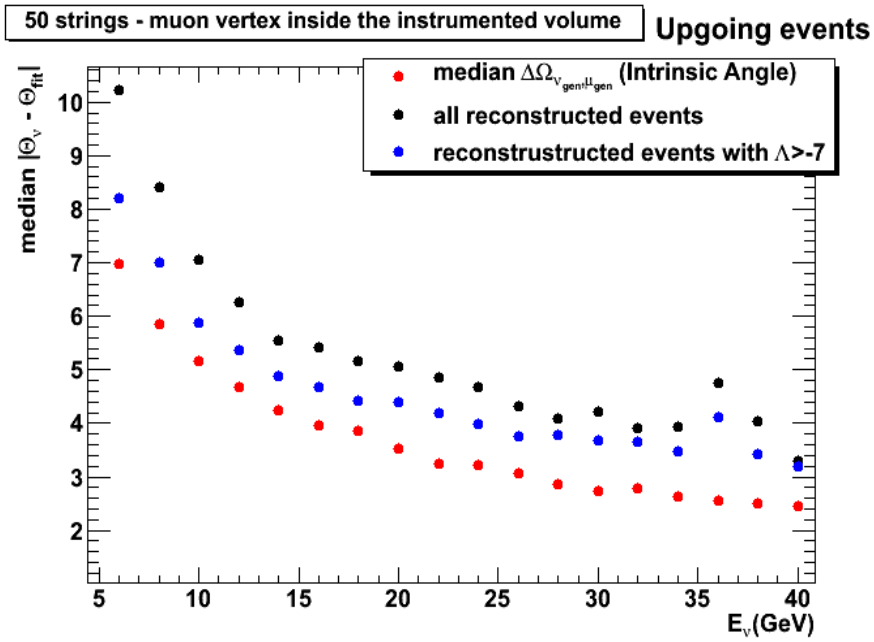
Likelihood fit based on time residual pdfs, several starting points (ANTARES based)

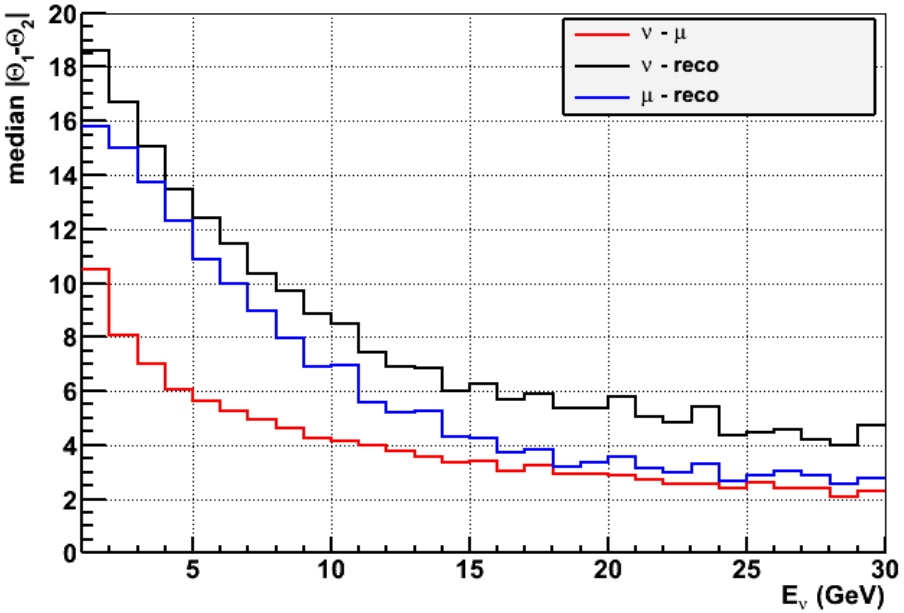
χ^2 fit after strict selection of direct hits (ANTARES based)

Kalman filter (KM3net development)

Angular resolution

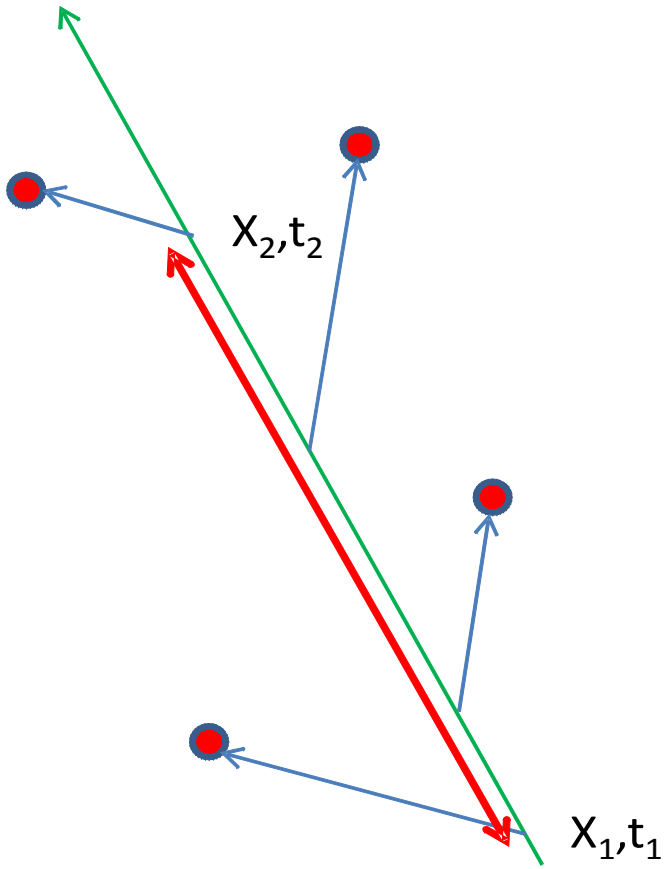
Comparable results for different algorithms
Selection of “direct hits” successful
very good determination of muon direction





Muon energy resolution

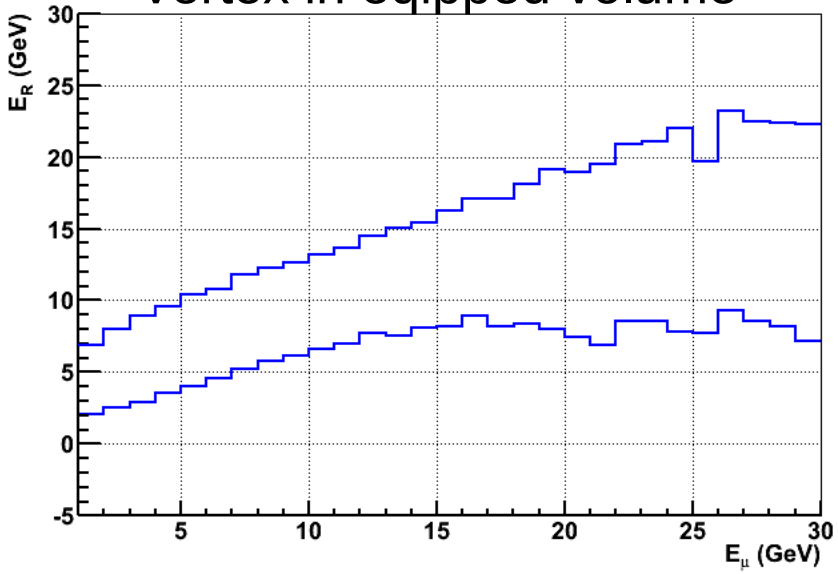
- Use full information
- Starting point
  - Hit selection
  - Track fit
- Muon range overconstrained:
- $E_1/GeV=(x_2-x_1)/5m$
- $E_2/GeV=(t_2-t_1)c/5m$

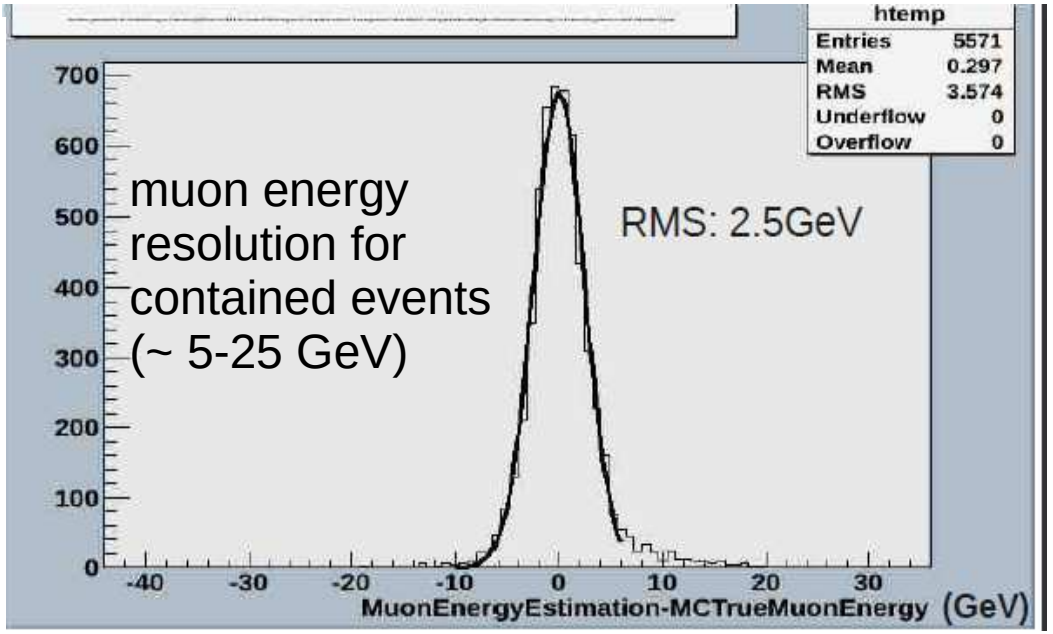


Muon energy resolution

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

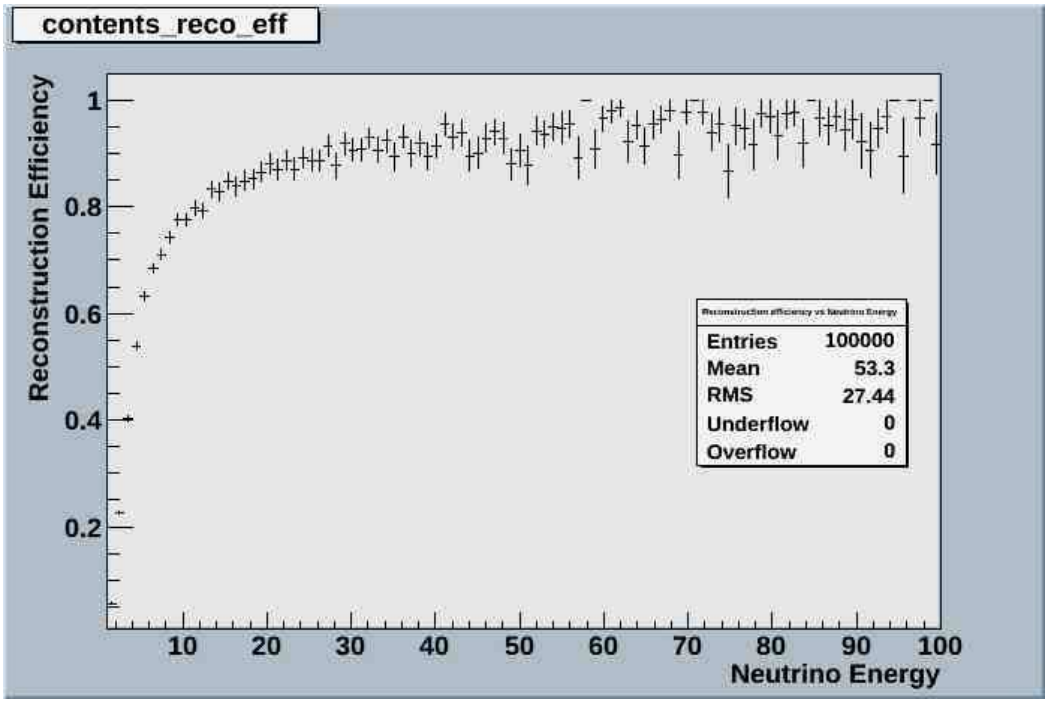
1-Sigma range shown
(Quantiles 16%-84%)
Vertex in eqipped volume



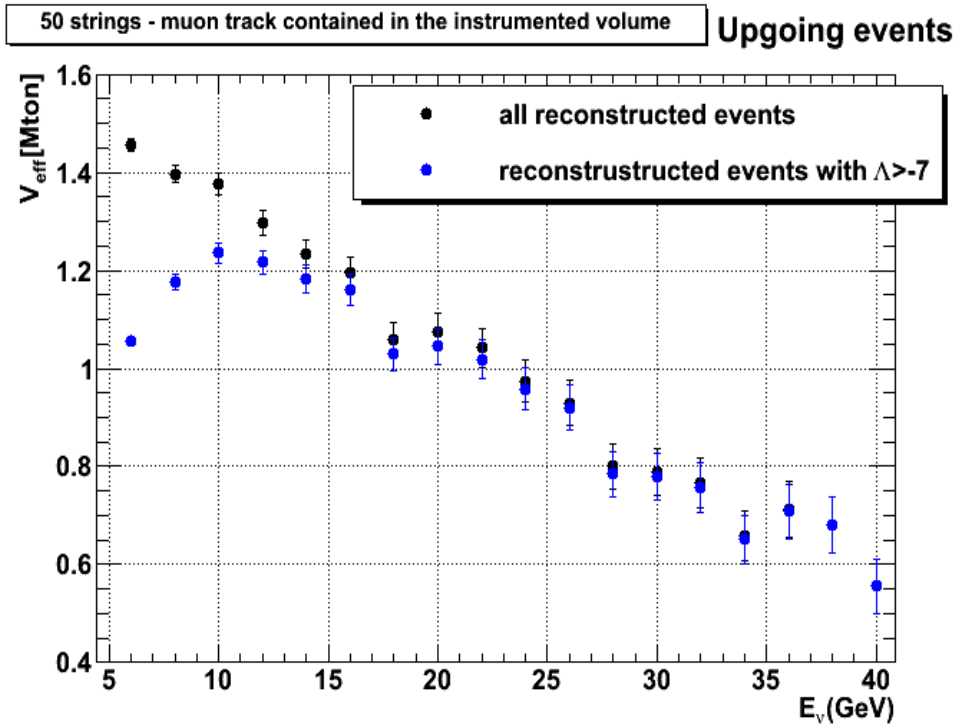


Efficiency – Effective Volume

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



Comparing Oscillation Probabilities

Arxiv:1205.5254

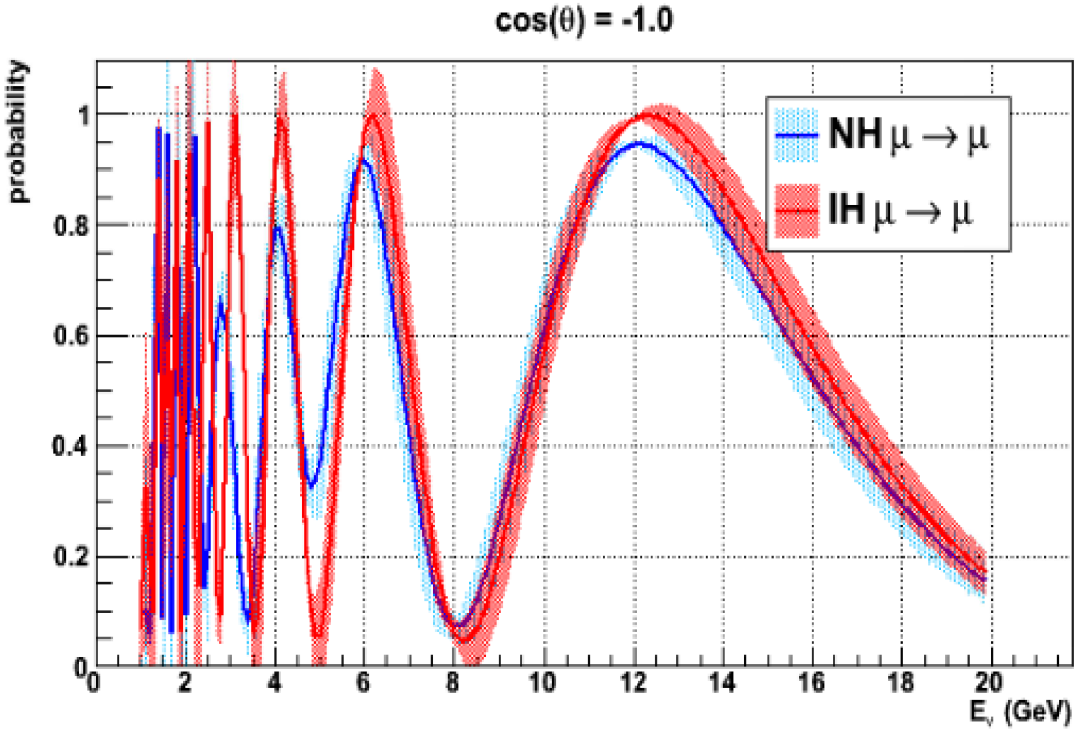
TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

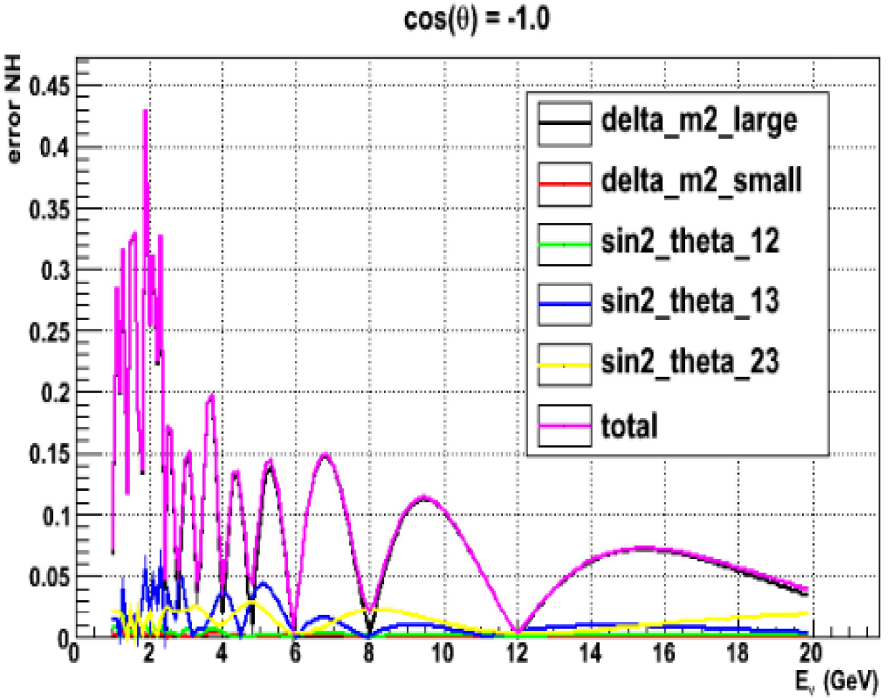
Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (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

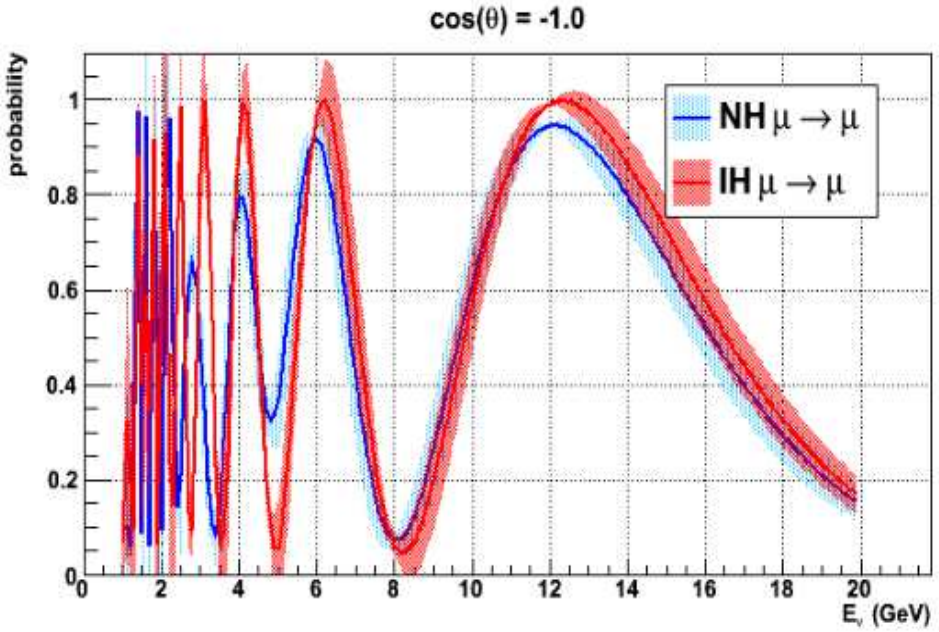
Contribution of individual uncertainty to overall effect

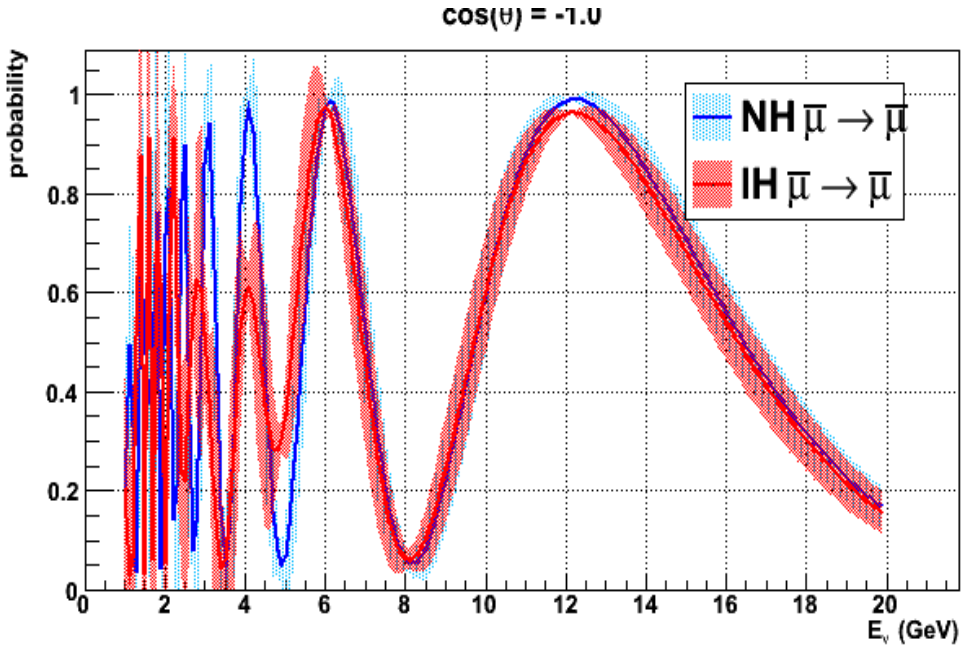
Dominant : Δm^2_{large}

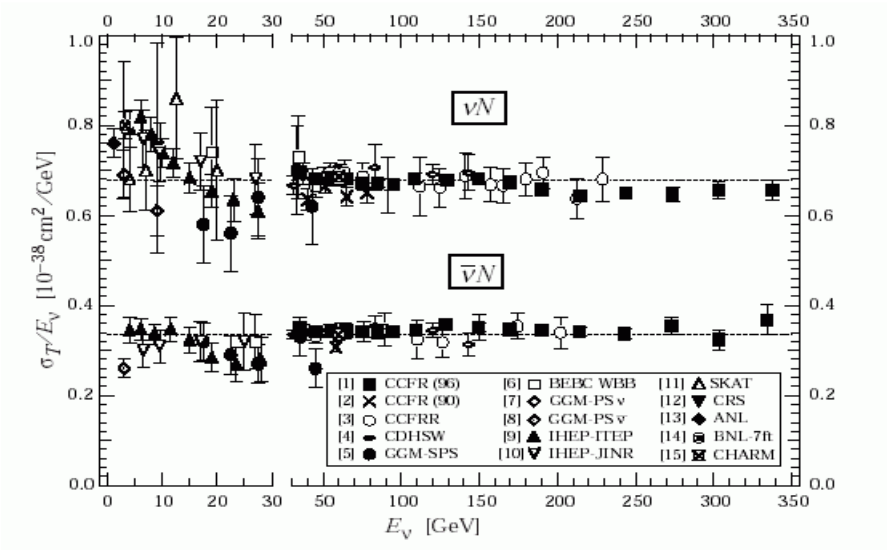
A. Heijboer

Comparing Oscillation Probabilities

with uncertainties







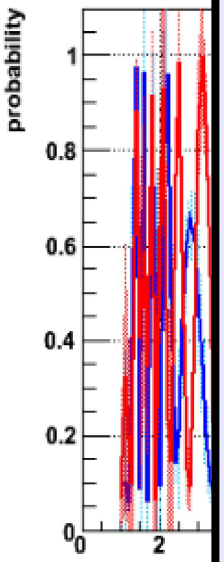
Effect survives because anti-neutrino cross-section is factor ~2 smaller than neutrino cross-section.

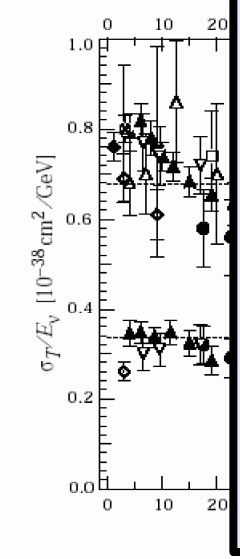
however...

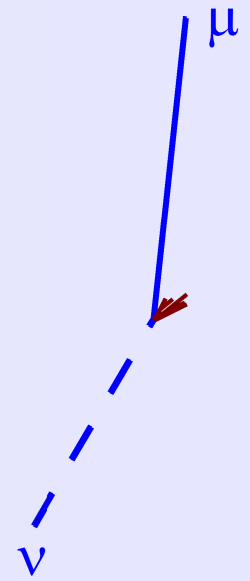
A. Heijboer

Comparing Oscillation Probabilities

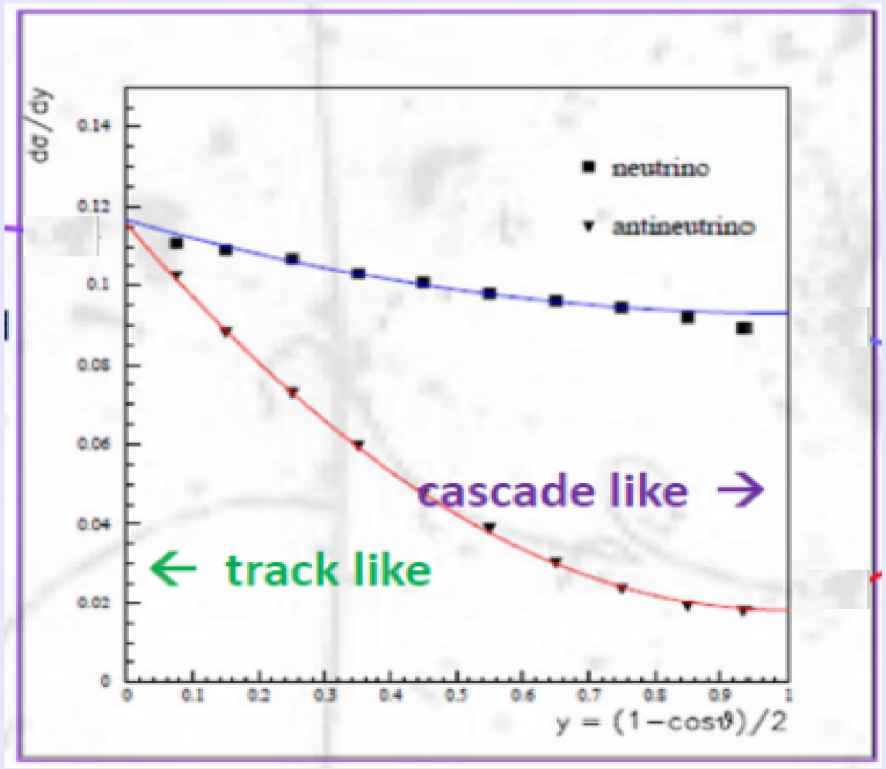
with uncertainties

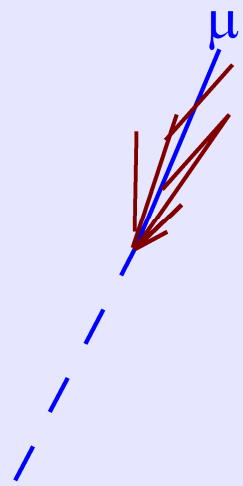






nice events,but
small asymmetry





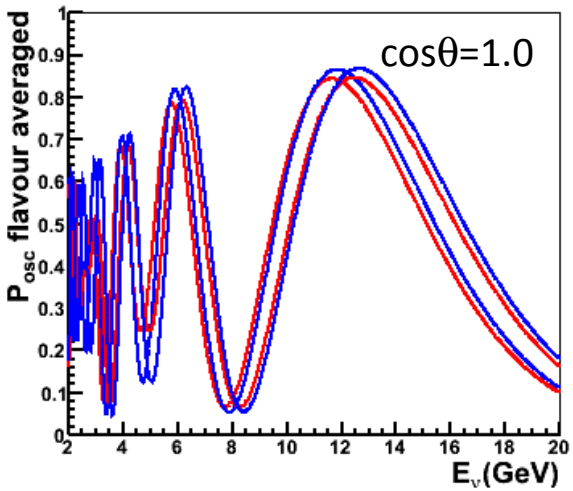
large asymmetry,
but beware of
ν_e ν_τ background
(must tag the μ!)

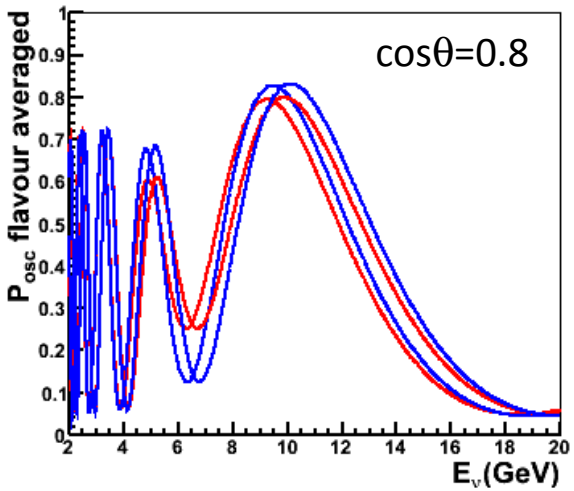
- Different topologies contribute to same E_ν bin
  - systematics of acceptance and energy resolution need to be stringently controlled
  - … but ultimately can put y in the fits

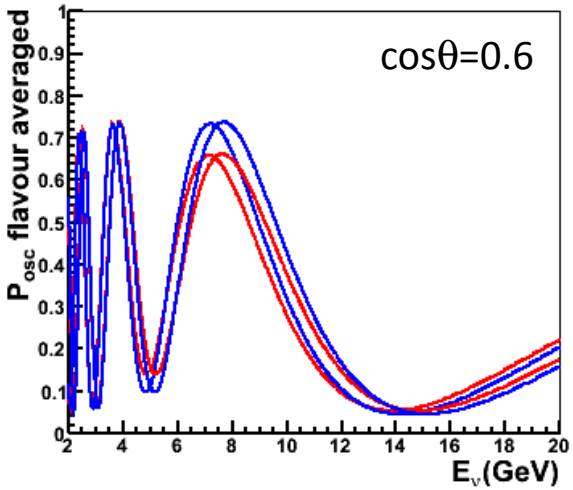
R. Nahnhauer

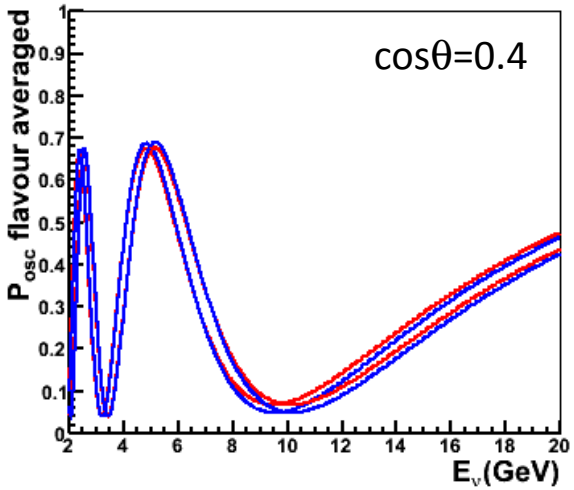
Comparing Oscillation Probabilities

with uncertainties







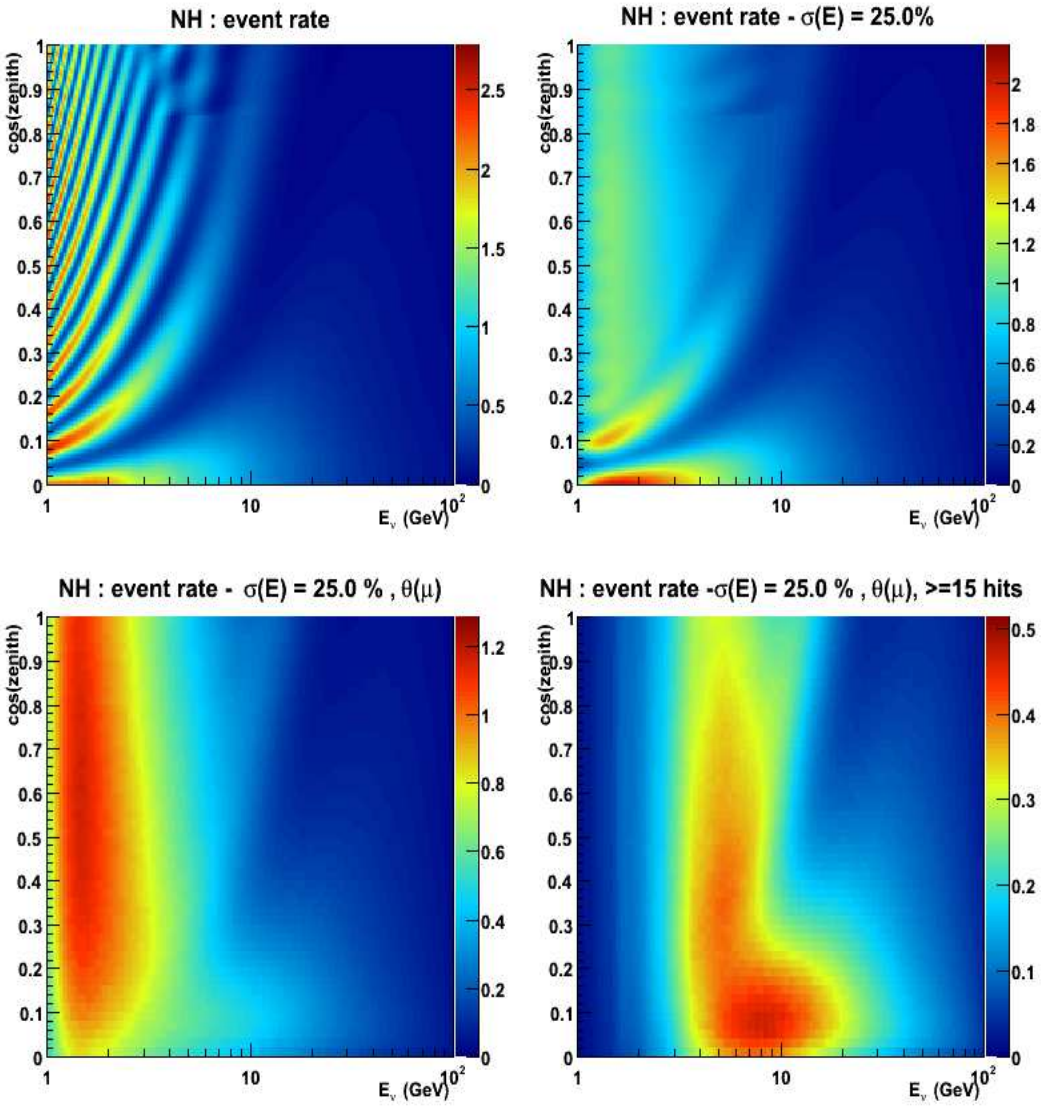


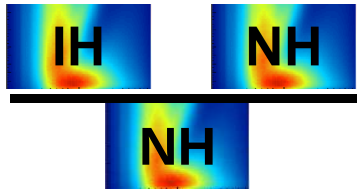
ν_e & ν_μ

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

Band
1σ in Δm^2_{32}
Color:
NH / IH

Toy Analysis – effect of resolutions & acceptance





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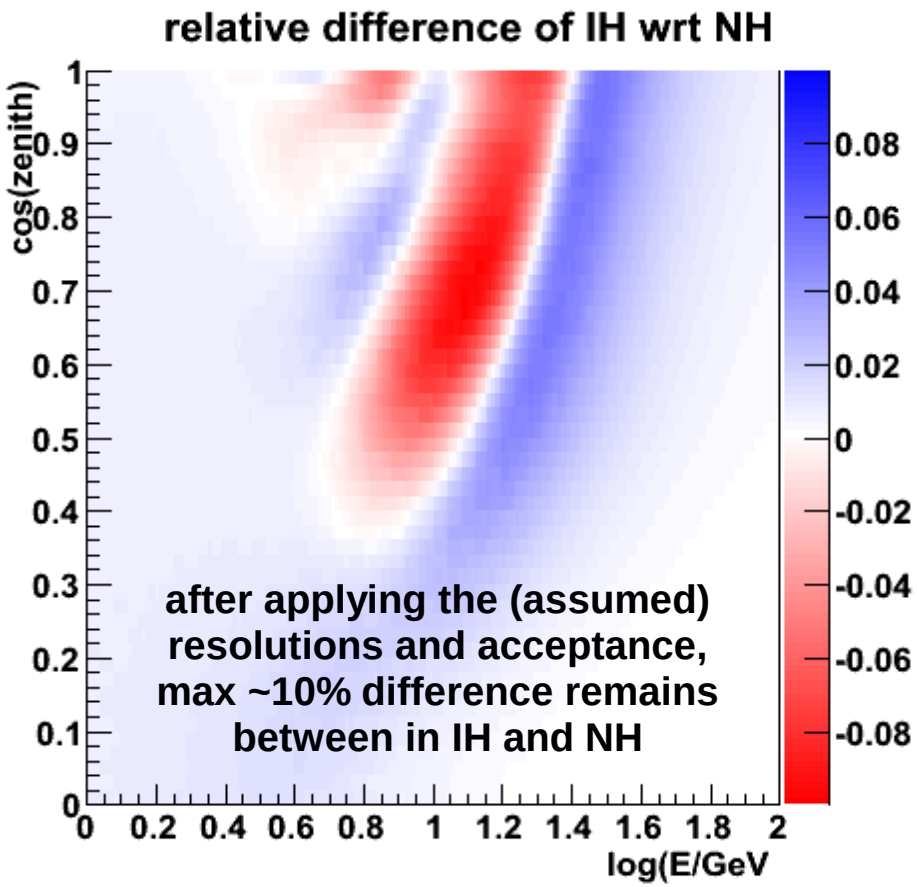
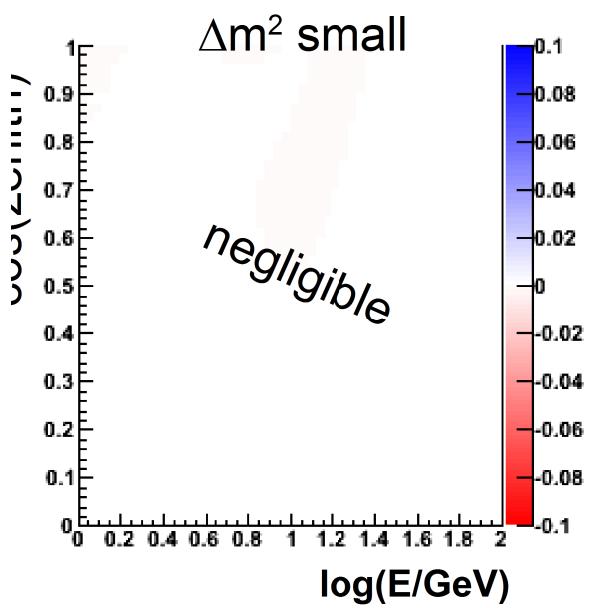
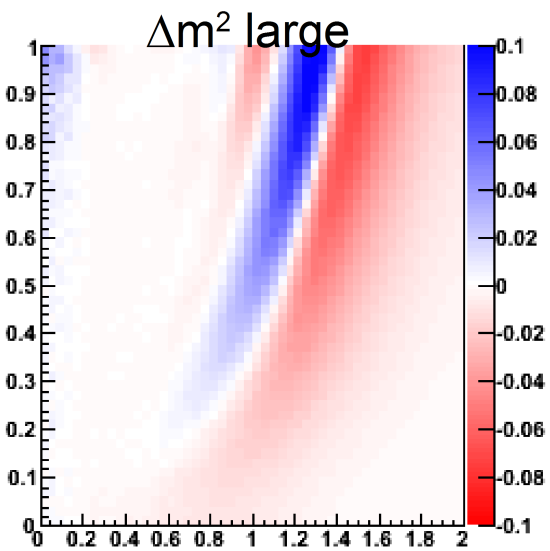
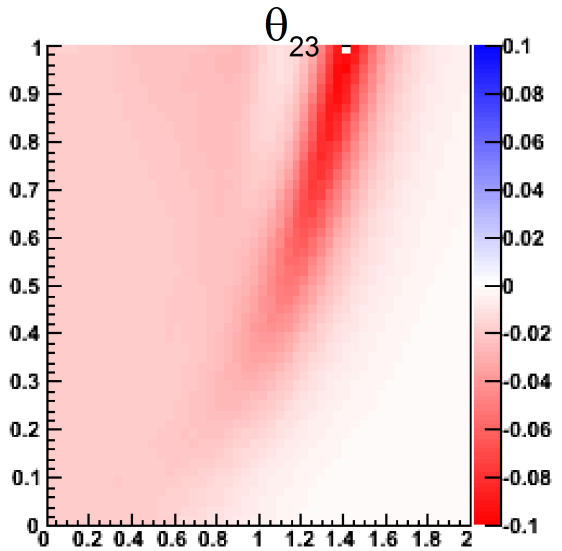


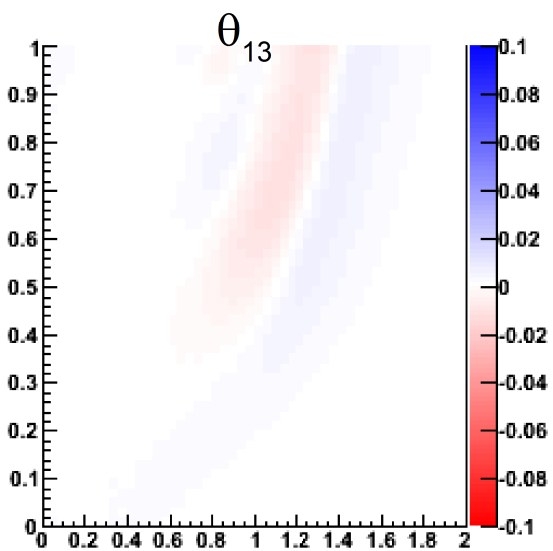
A. Heijboer

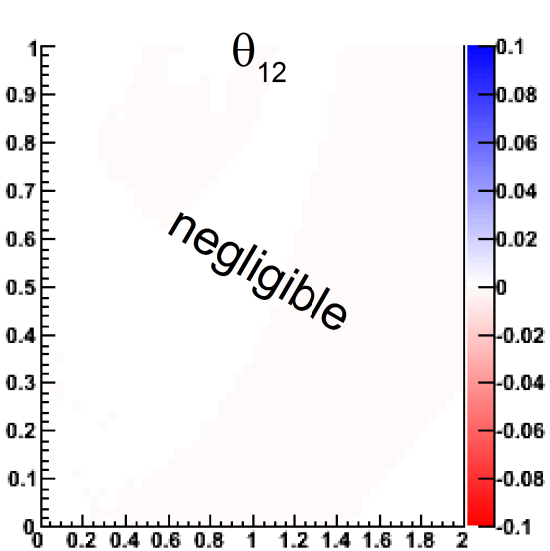
Toy Analysis

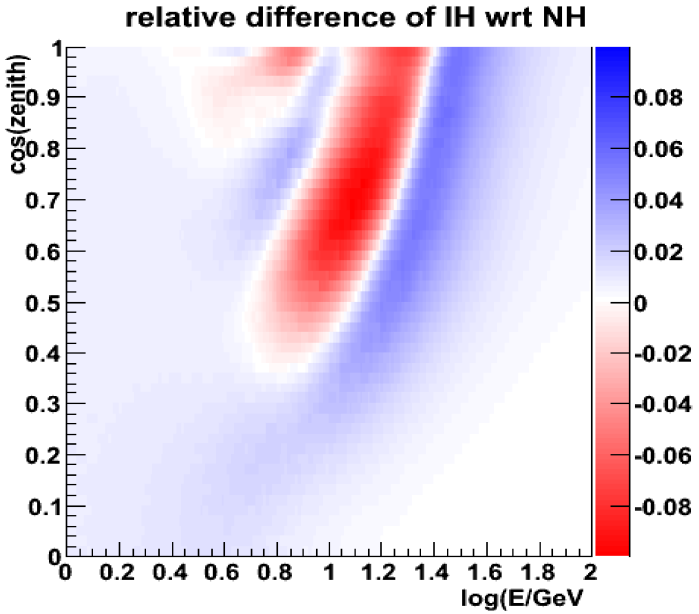




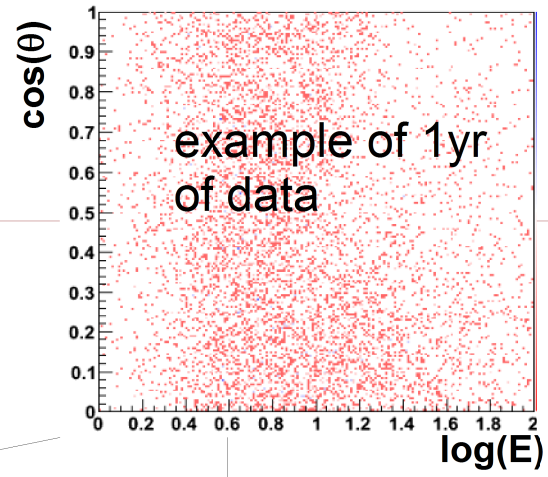








Distinguishing NH and IH

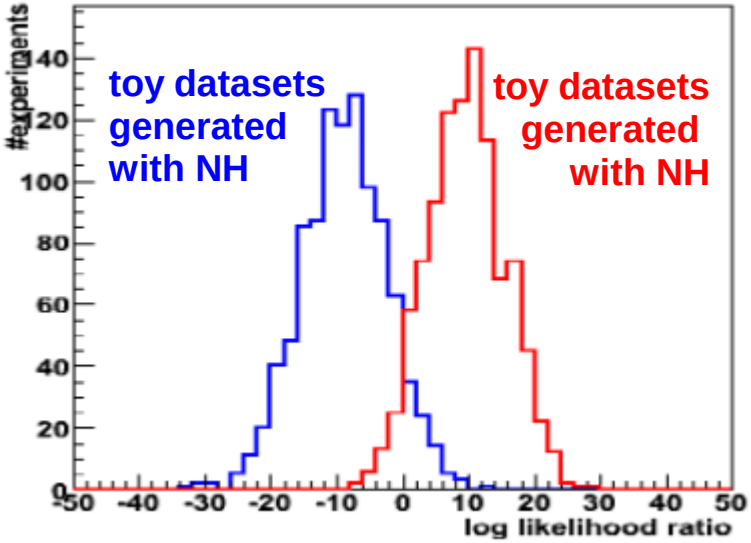


to optimally distinguish between IH and NH:
likelihood ratio test *with nuisance parameters*
→ *in other words: deal with degeneracies by fitting!*

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

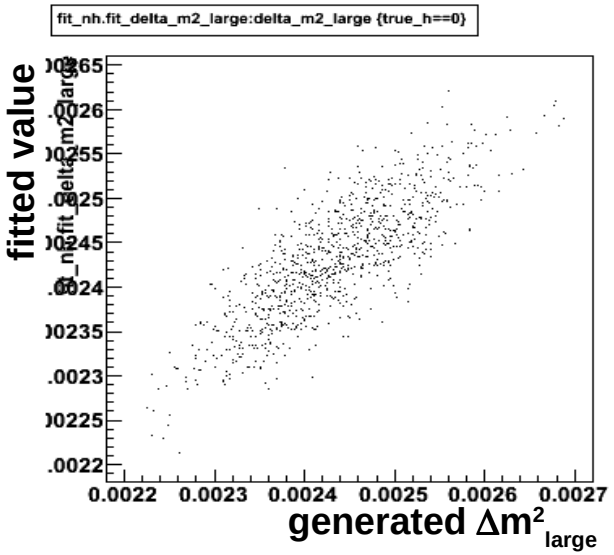
$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

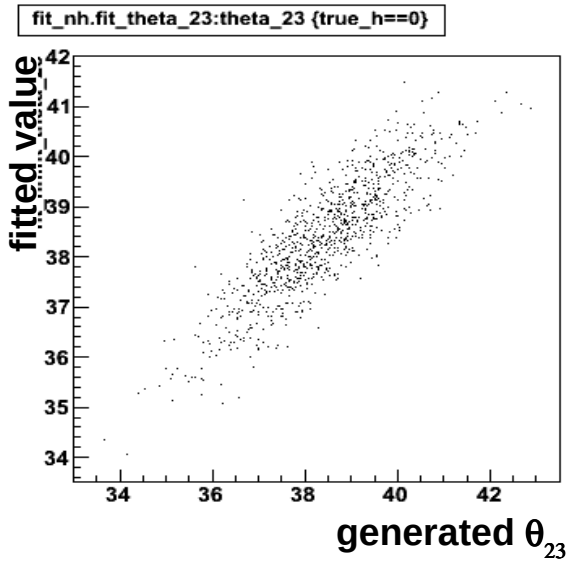
1) fit mixing parameters assuming NH
2) fit mixing parameters assuming IH
3) compute ΔlogL = log(L(NH)/L(IH)

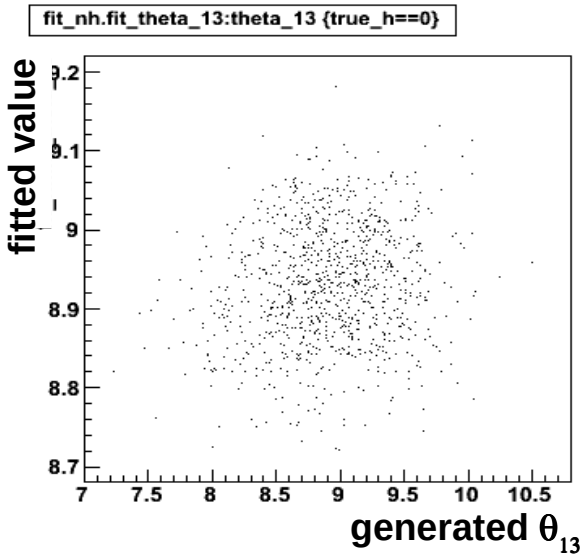


Results of parameter fit

1 Mton*year (NHtrue, NHfit)







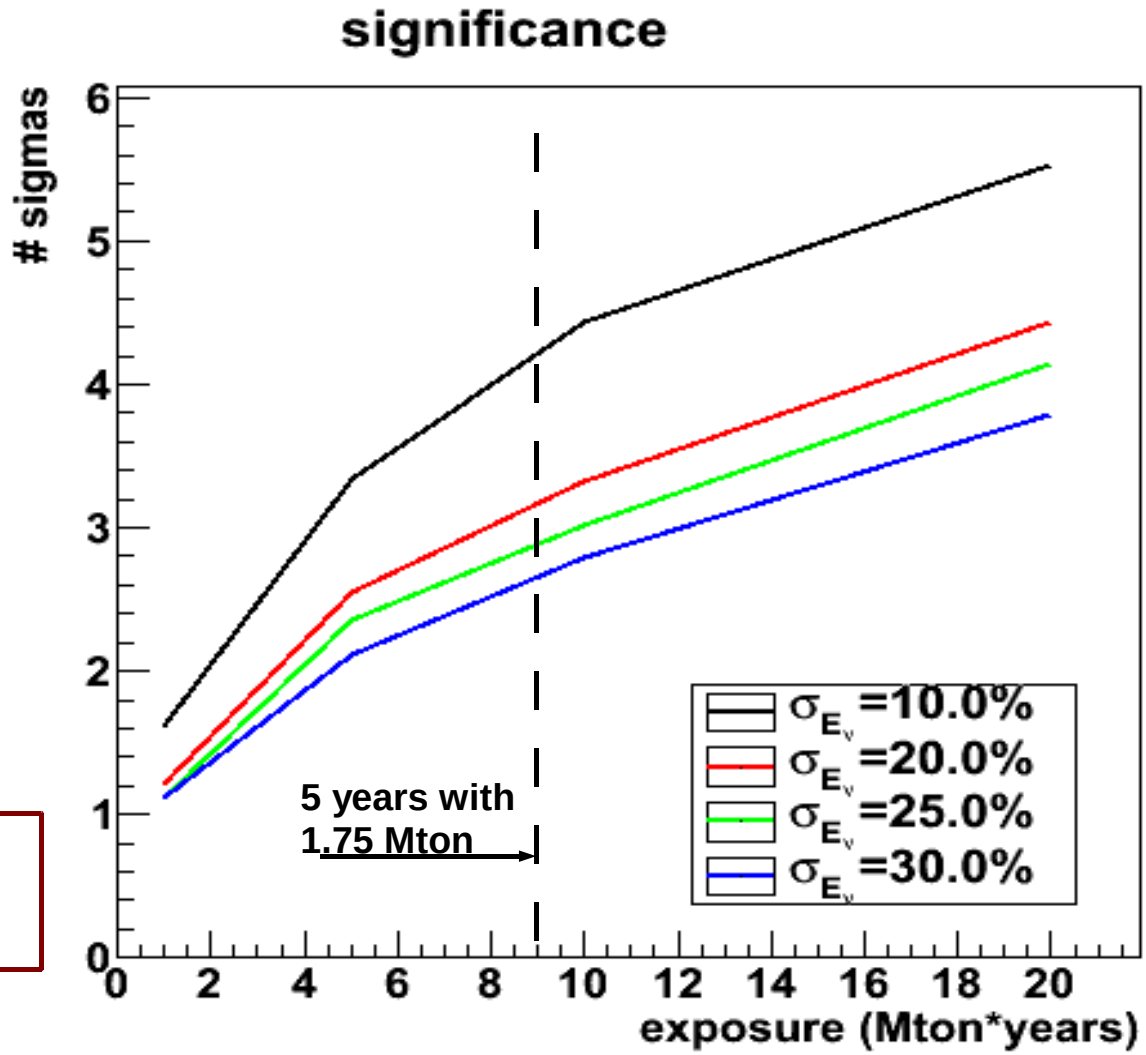
Eres = 25%, 1-100 GeV

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} !

A. Heijboer

Mass hierarchy significance



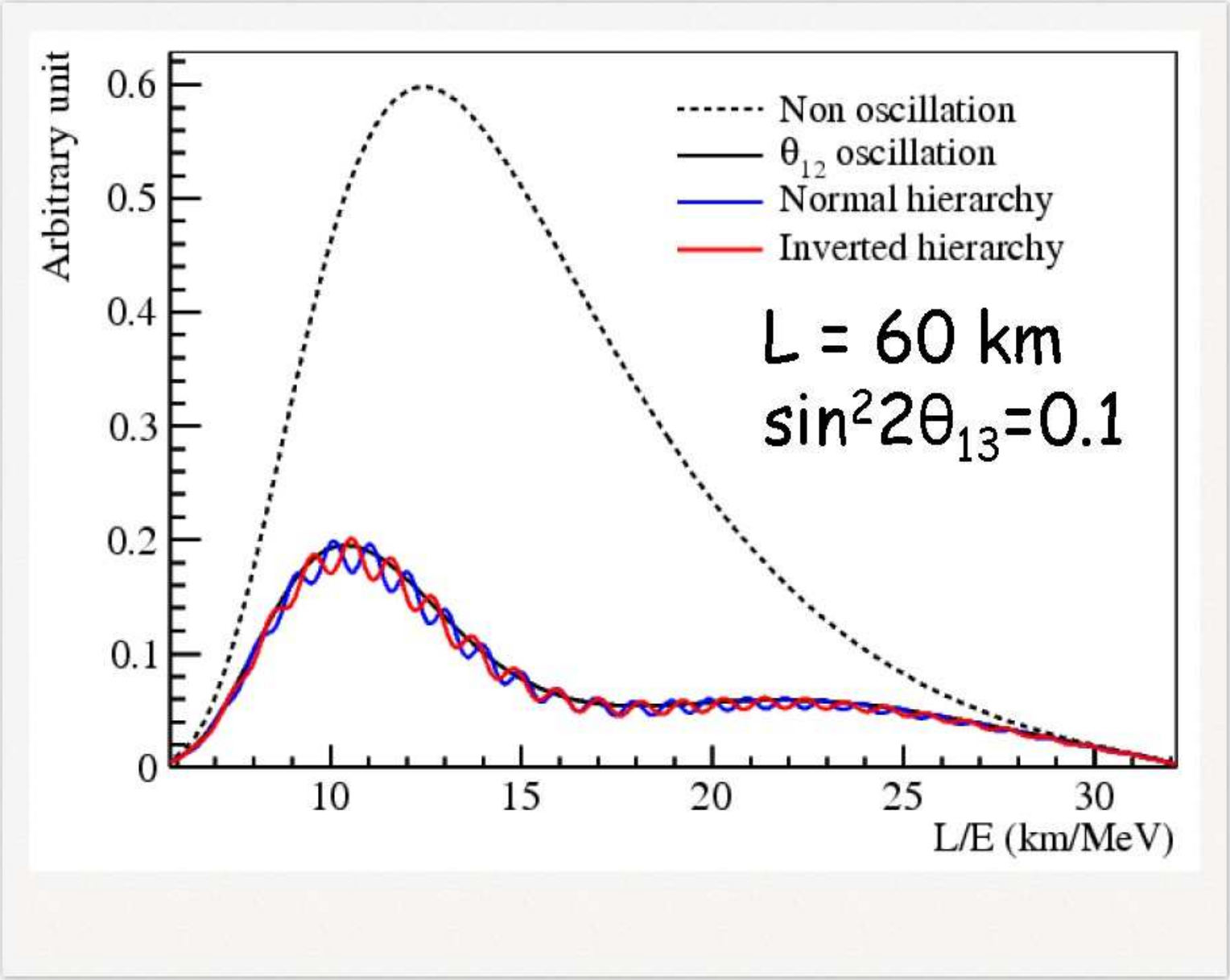
all results are preliminary

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

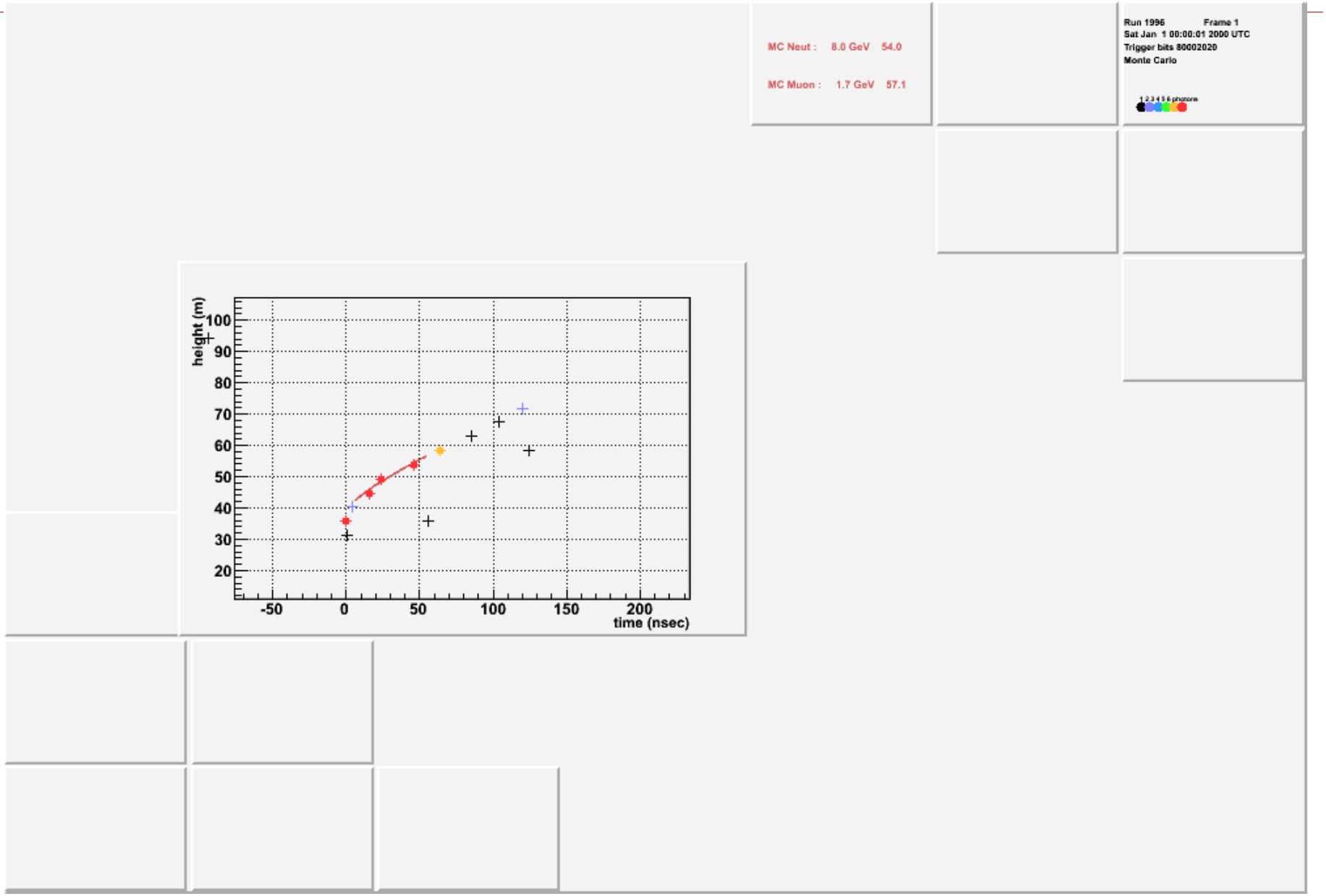
Conclusions

- Antares neutrino telescope taking data for 5 years now
- 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.
- Decision on “Phase 1” for KM3net later in 2013

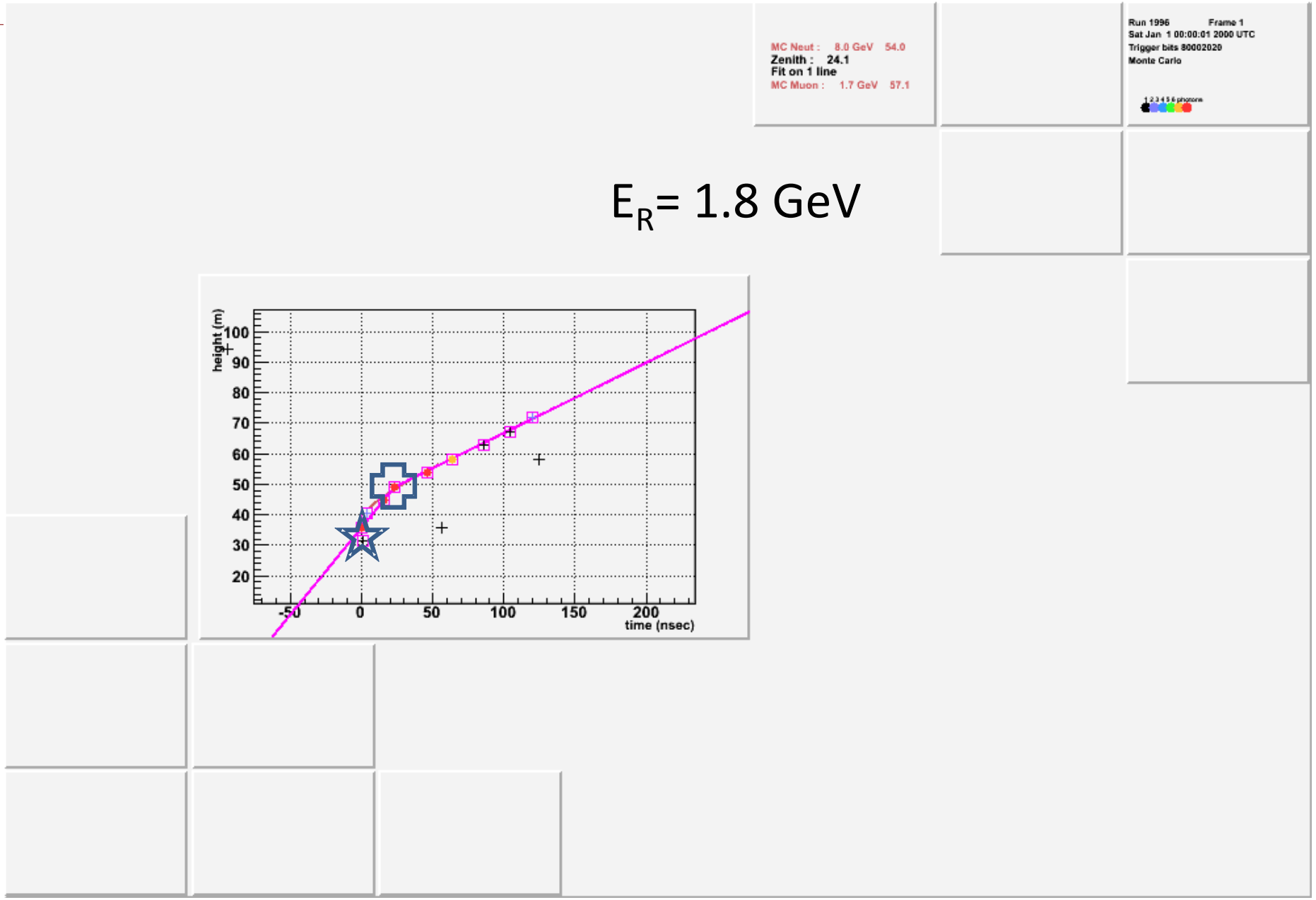
Daya Bay II


Arbitrary unit
0.6
0.5
0.4
0.3
0.2
0.1
0
10
15
20
25
30
L/E (km/MeV)
Non oscillation
θ_{12} oscillation
Normal hierarchy
Inverted hierarchy
L = 60 km
$\sin^2 2\theta_{13}$=0.1

Event Displays – Examples

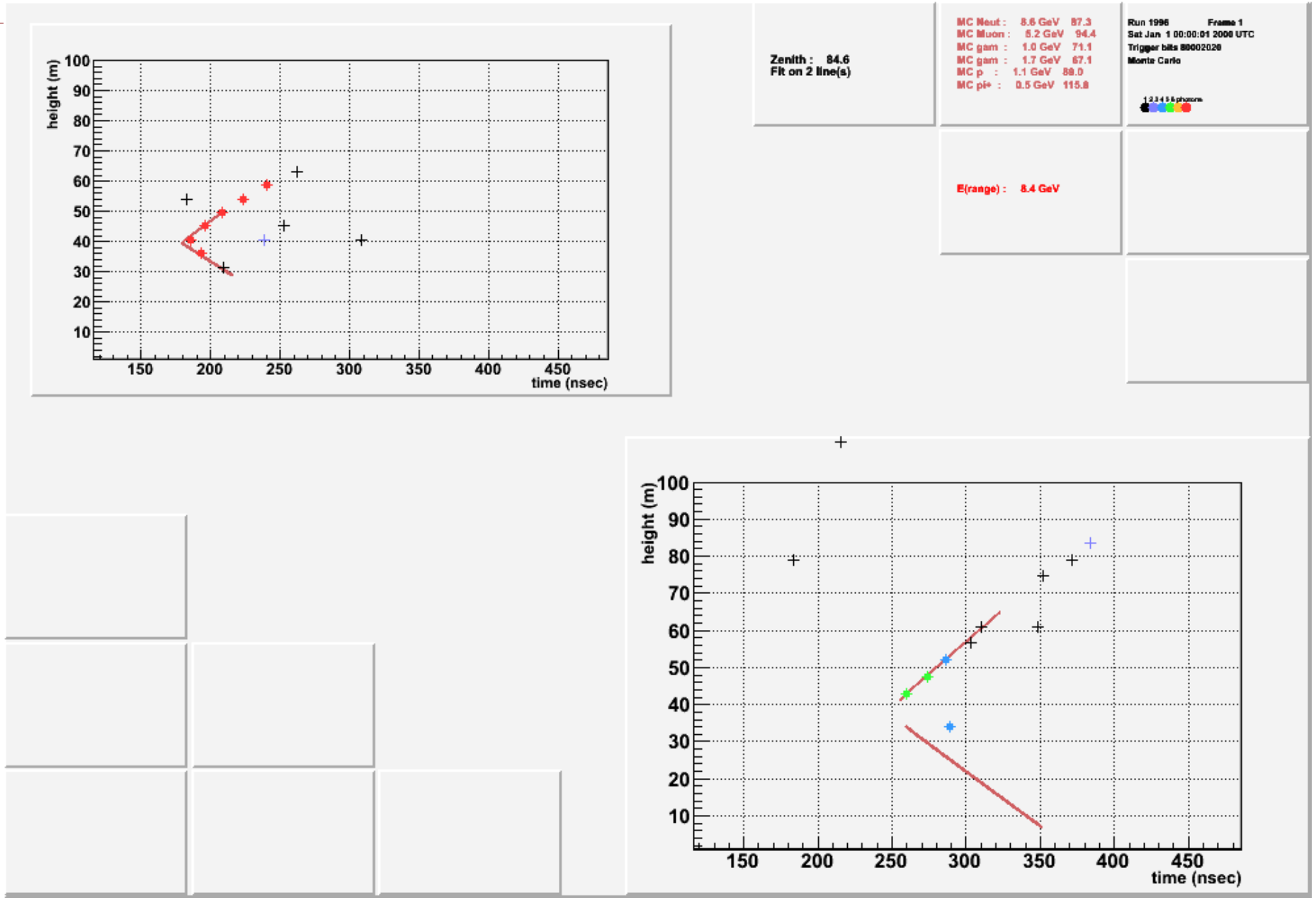


Event Displays – Examples

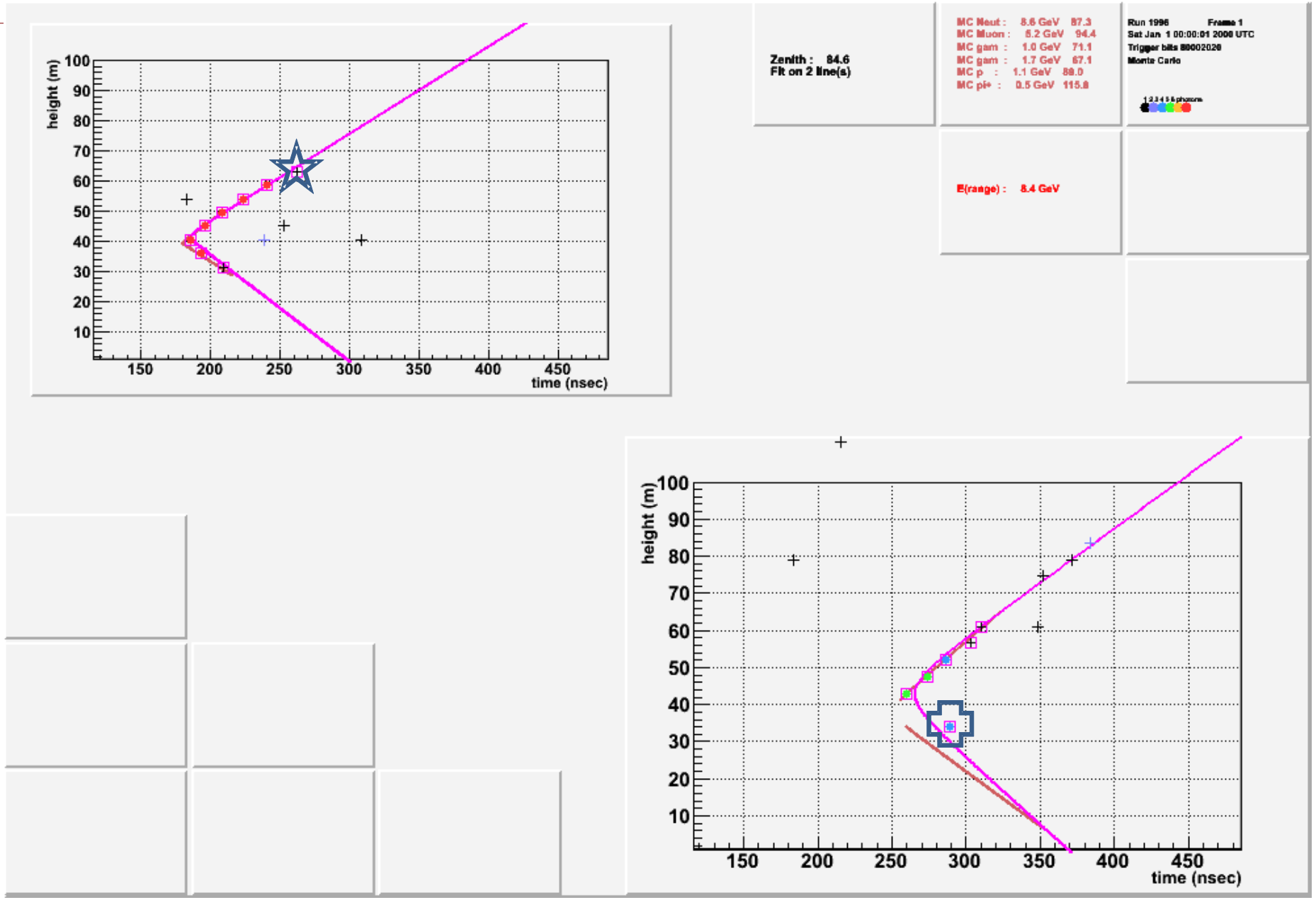


E_R= 1.8 GeV

Event Displays – Examples



Event Displays – Examples



Eres = 10%, 1-100 GeV

Mton x yr	delta_m2_large	theta_23	theta_13
0(now)	8.0e-5	1.3	0.45
1	3.1e-05	0.56	0.44
5	1.5e-05	0.28	0.42
10	1.2e-05	0.2	0.37
20	9.6e-06	0.16	0.32
30	8.5e-06	0.12	0.31

Eres = 25%, 1-100 GeV

Mton x yr	delta_m2_large	theta_23	theta_13
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

Eres = 25%, 1-10 GeV

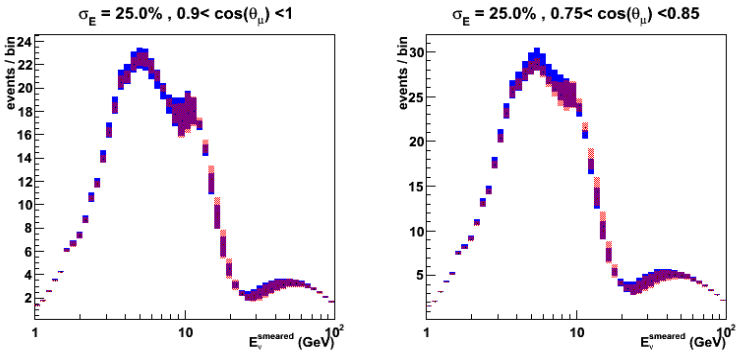
Mton x yr	delta_m2_large	theta_23	theta_13
0(now)	8.0e-5	1.3	0.45
1	6.3e-05	0.72	0.47
5	4.3e-05	0.4	0.43
10	3.3e-05	0.3	0.44
20	2.6e-05	0.22	0.39
30	2.1e-05	0.17	0.4

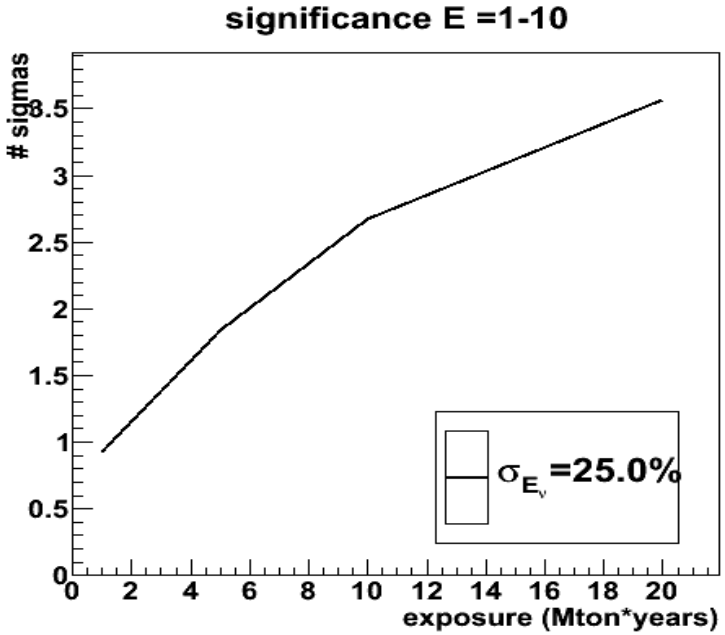
Eres = 25%, 10-100 GeV

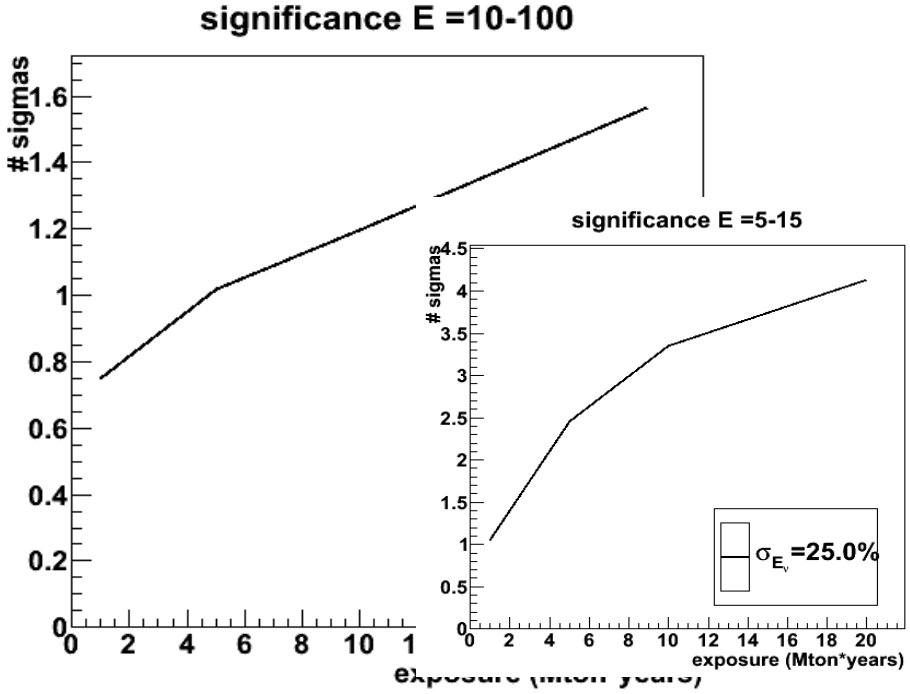
Mton x yr	delta_m2_large	theta_23	theta_13
0(now)	8.0e-5	1.3	0.45
1	4.2e-05	0.87	0.47
5	2.5e-05	0.48	0.43
10	2e-05	0.35	0.45
20	1.6e-05	0.27	0.46
30	1.4e-05	0.22	0.46

Eres = 25%, 5-15 GeV

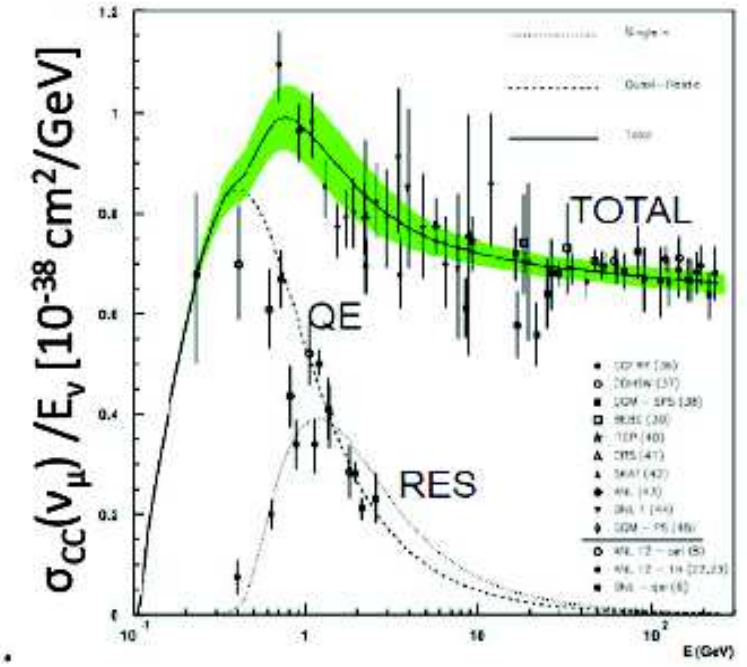
Mton x yr	delta_m2_large	theta_23	theta_13
0(now)	8.0e-5	1.3	0.45
1	5.8e-05	0.82	0.44
5	3.3e-05	0.5	0.45
10	2.6e-05	0.36	0.4
20	1.9e-05	0.25	0.39
30	1.7e-05	0.21	0.37


σE = 25.0% , 0.9< cos(θμ) <1
σE = 25.0% , 0.75< cos(θμ) <0.85
σE = 25.0% , 0.55< cos(θμ) <0.65
σE = 25.0% , 0.35< cos(θμ) <0.45
events / bin
Eνsmeared (GeV)


significance E =1-10
sigmas
exposure (Mton*years)
σEν=25.0%


significance E =10-100
sigmas
significance E =5-15
exposure (Mton*years)
σEν=25.0%

Systematics



Simulation tools

generators

GENHEN

GENIE
+ interface

TOY

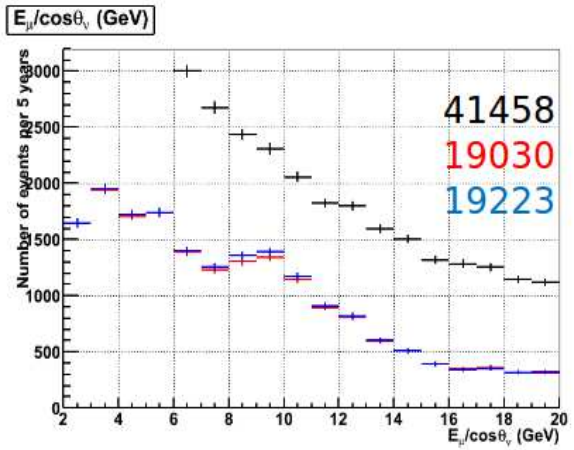
detector simulation

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