Oscillation Research with Cosmics in the Abyss

NEUTRINO HIERARCHY MEASUREMENT WITH UNDERWATER DETECTOR

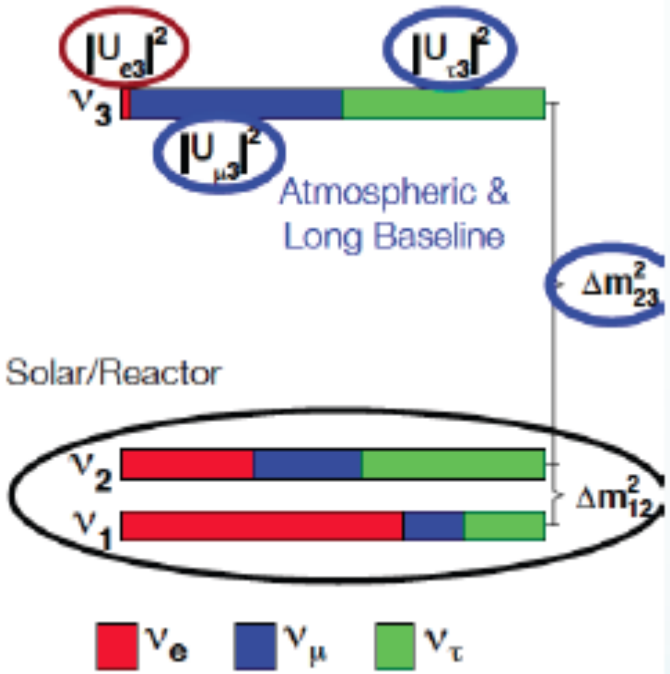
Summary of ORCA simulation results presented at the ORCA meeting 5-6 December Catania

Slides from A. Kouchner, A. Heijboer, A. Trovato, A. Tsirigotis, Sirin Odowky

Agenda in https://agenda.infn.it/conferenceOtherViews.py?view=cdsagenda&confId=5510

Neutrino mixing

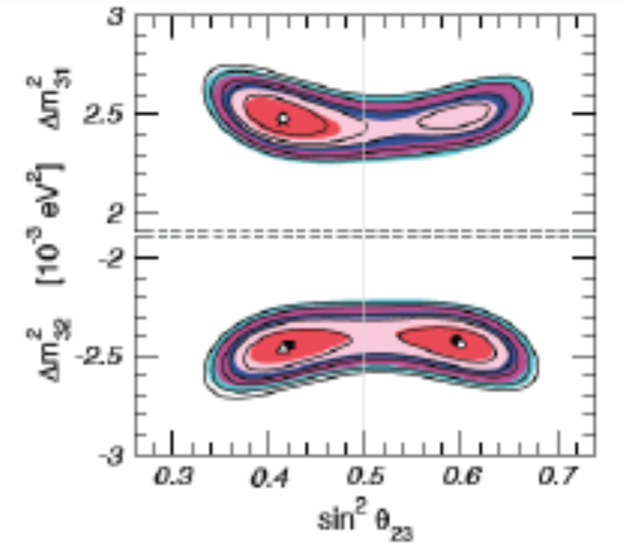
Experiment type	Oscillation Channel
Solar & Reactor	$(\nu_e \to \nu_\mu)$
Short Baseline (SBL) & Off-Axis	$(\nu_e \to \nu_e)$ $(\nu_\mu \to \nu_e)$
Atmospheric & Long Baseline	$(\nu_\mu \to \nu_\mu)$ $(\nu_\mu \to \nu_\tau)$

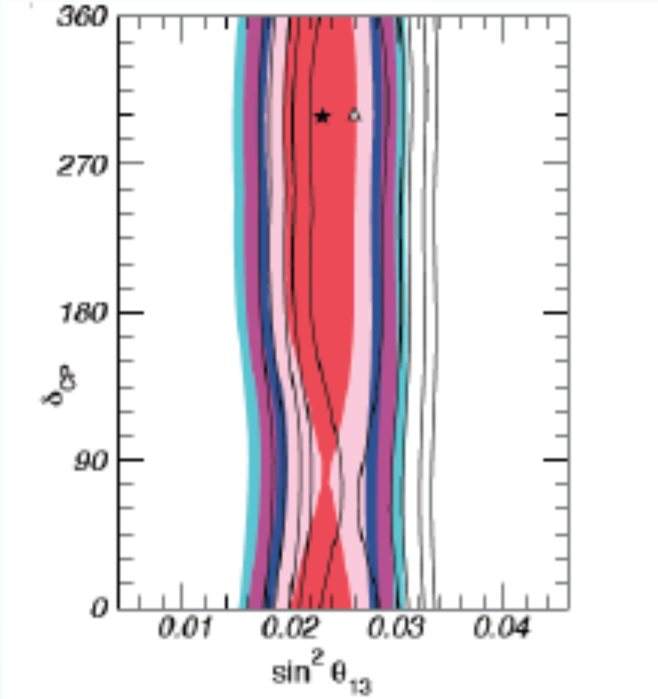


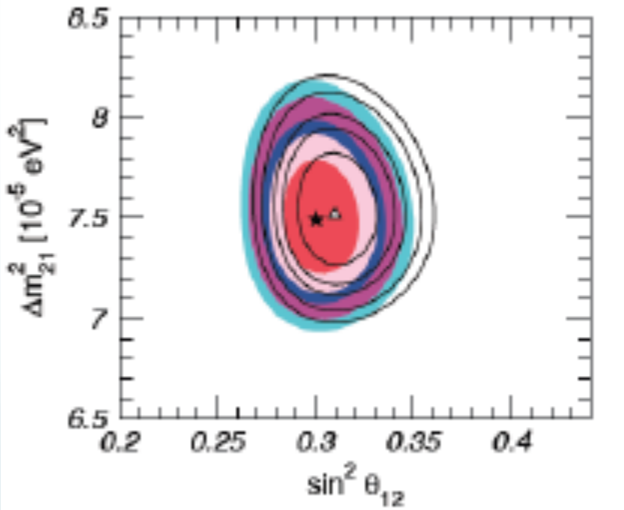
$U_{e3} = \sin\theta_{13}\, e^{-i\delta}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Status



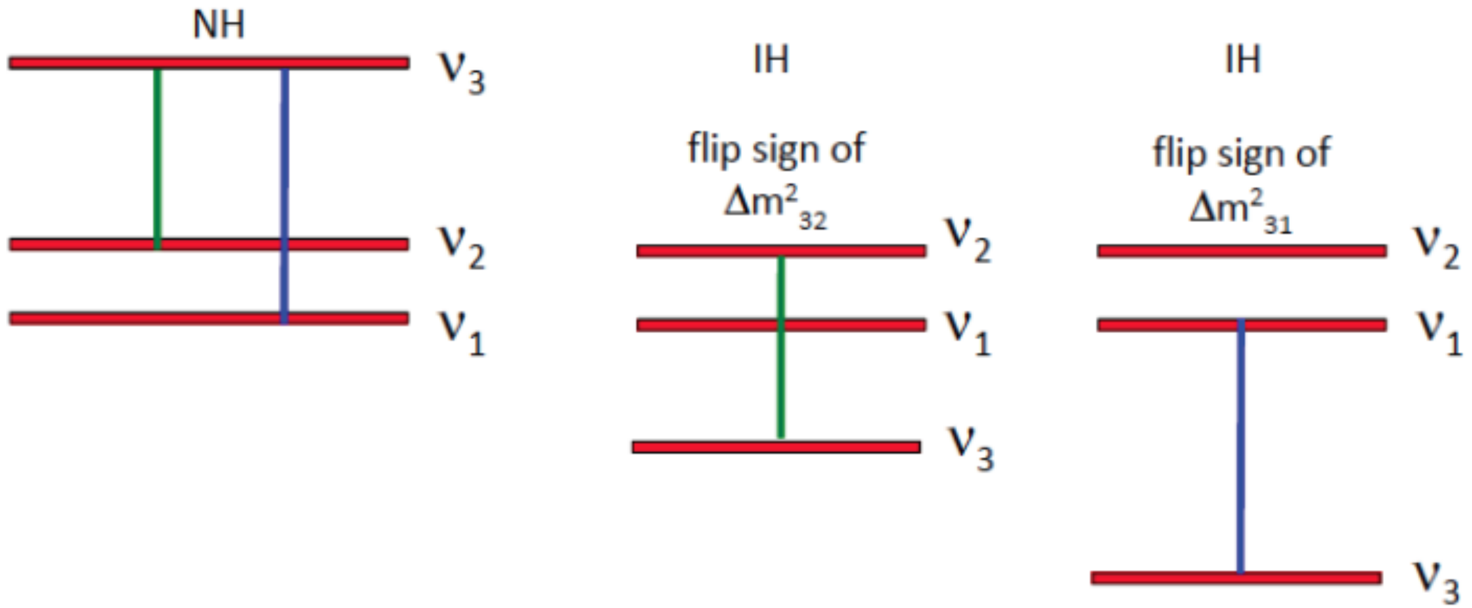




- All parameters are measured to good precision except for the mass hierarchy and the CP phase.

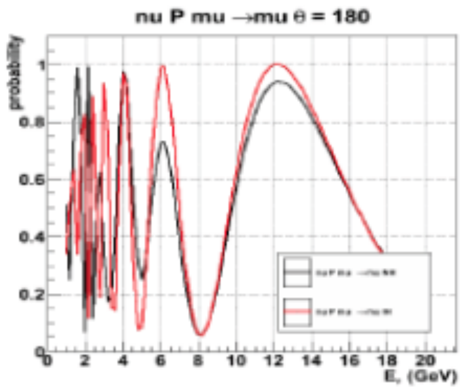
M. C. Gonzalez-Garcia et al., 1209.3023

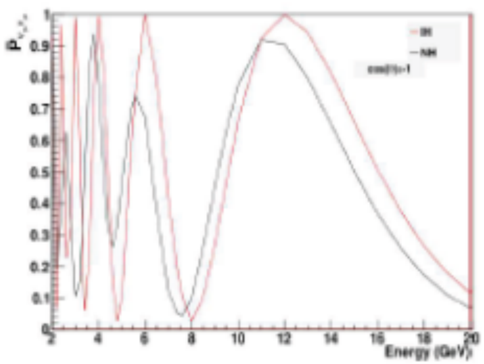
Definition of Inverted Hierarchy



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

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





Mass hierarchy measurements – When?

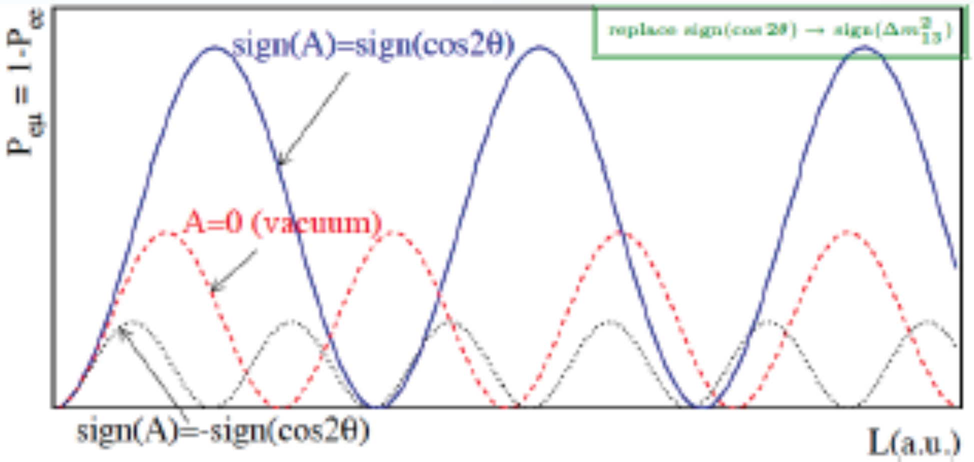
Project	Neutrino source	Detector	Goal	Problem
NOvA	LBL 810 km	14 kt tracking calorimeter	2σ for some values of δ ; 2020	Parameter degeneracy
Daya Bay II Reno II	Reactor 60 km	50 kt liquid scintillator	3σ in 2023	E_ν resolution & absolute scale
PINGU / ORCA	Atmosphere	1-10 Mt	3-5σ in ?	E_ν resolution 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

(Constant density) Matter effects

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

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

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



$A \equiv \pm\sqrt{2}G_F N_e$: Is the matter potential. $\begin{cases} >0 \text{ for neutrinos} \\ <0 \text{ for anti-neutrinos} \end{cases}$

Requirements:

Δ ~ A matter potential must be significant not overwhelming

L large enough – matter effects are absent near the origin

Matter resonance: A ➔ Δcos2θ

In this case:

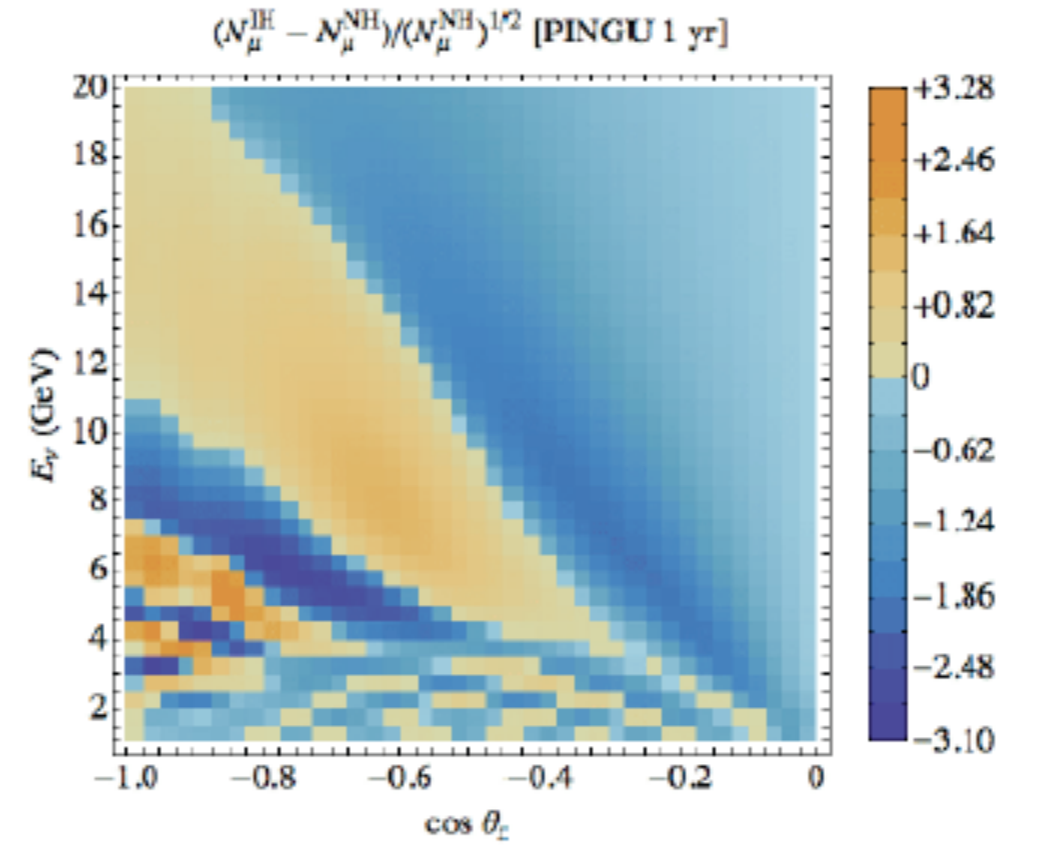
- Effective mixing maximal
- Effective osc. frequency minimal

Resonance energy:

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

ARS: Inverted vs Normal

Akhmedov-Razzaque-Smirnov paper



Perfect resolution

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

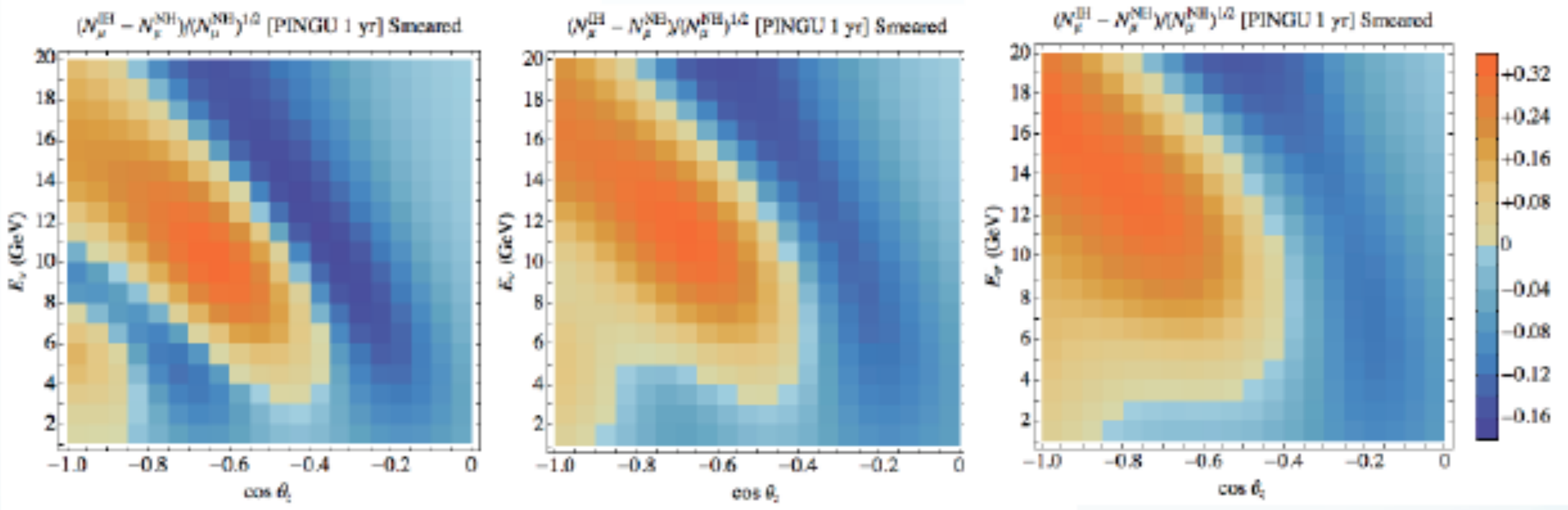
$$\sigma_{ij}^2 = N_{ij}^{NH} + (f N_{ij}^{NH})^2$$

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%)

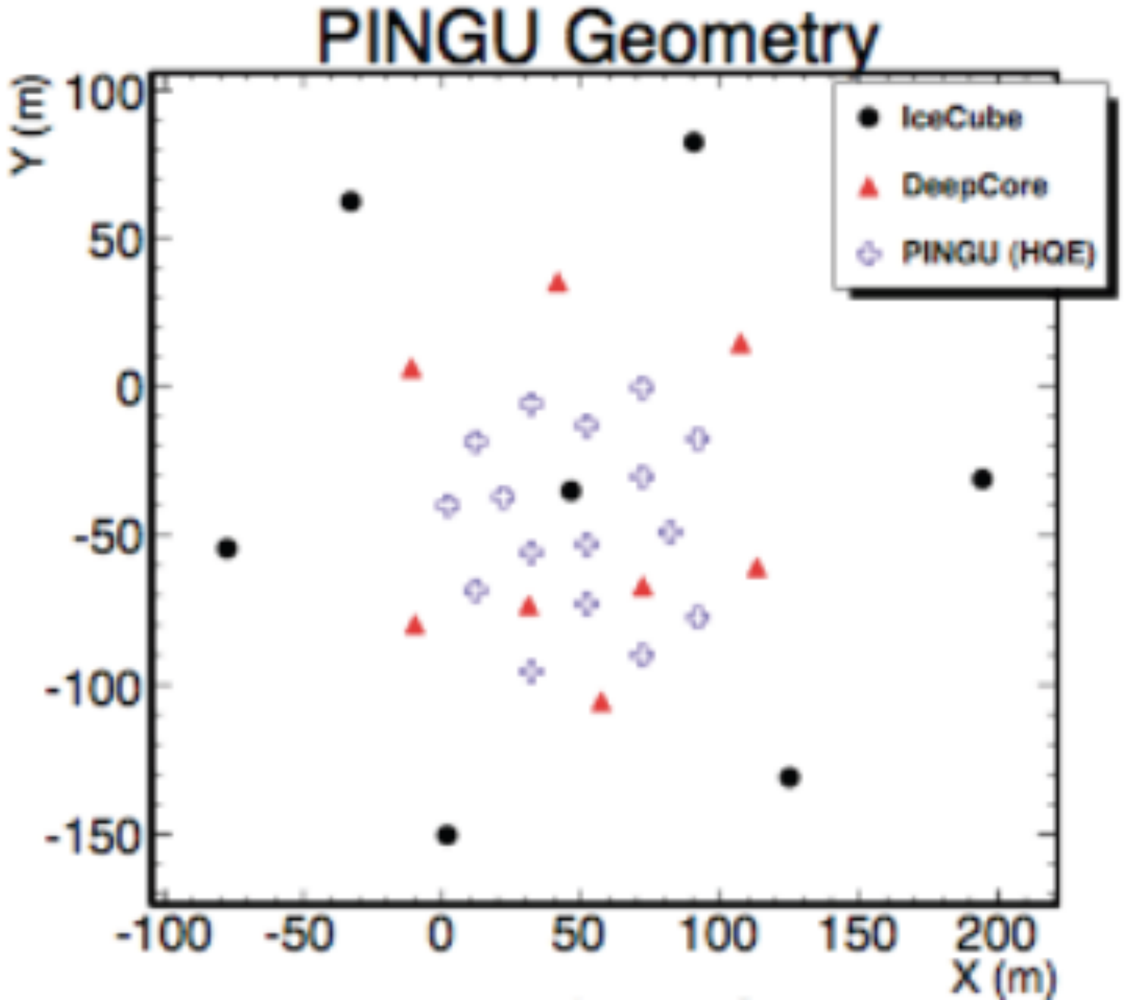
σE=4 GeV, σθ= 22.5°

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

5 years

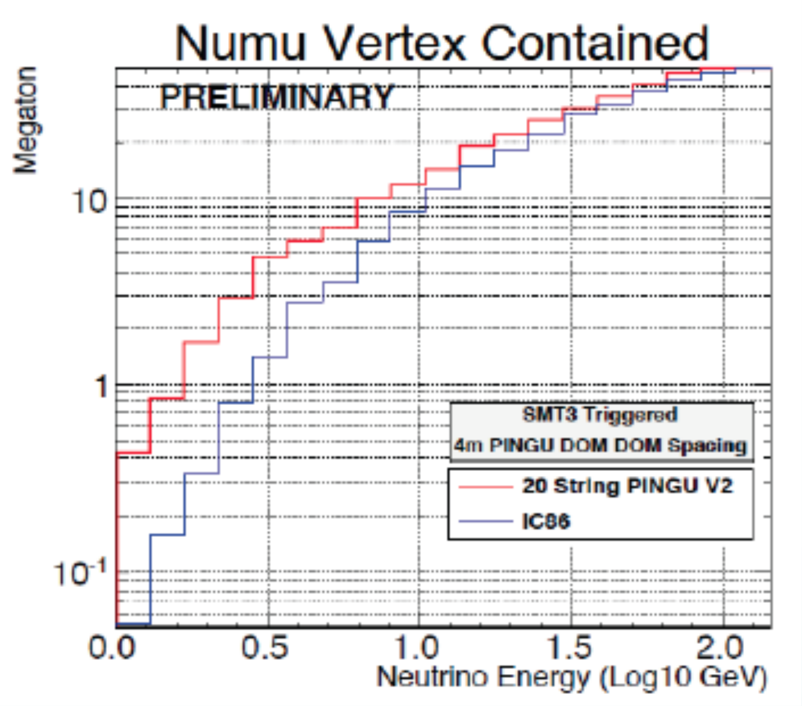
The PINGU fact sheet

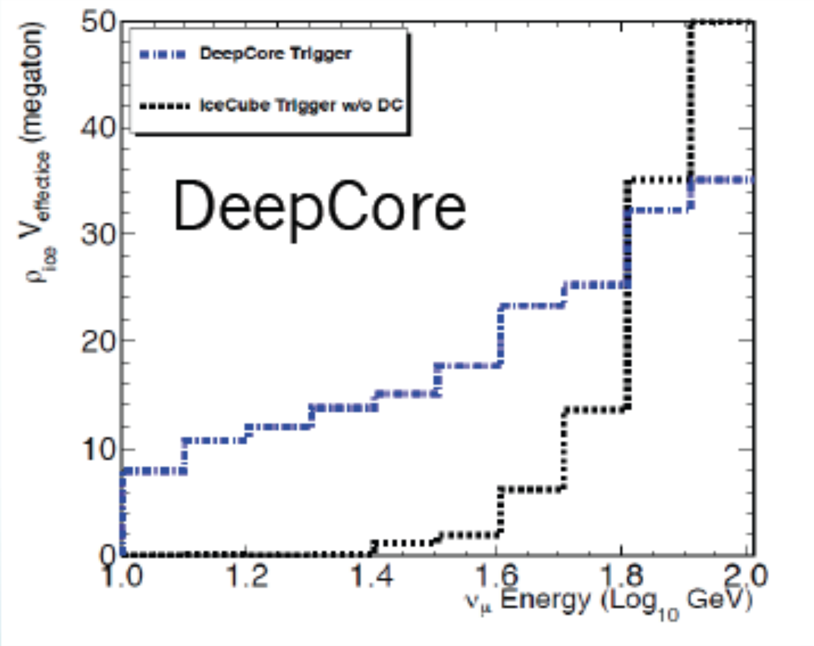
- Phased IceCube Next-Generation Upgrade
- Add 20 strings in Deep Core region
- Vertical distance between OM~5m
- Expected energy threshold at 1 GeV



PINGU effective volume

- Beware: at the trigger level SMT3
- Include Deep Core (non contained PINGU events)





$$\rho V_{\rm eff}(E_\nu) = 14.6 \times [\log(E_\nu/{\rm GeV})]^{1.8}\ {\rm Mt.}$$

Definition of Inverted Hierarchy

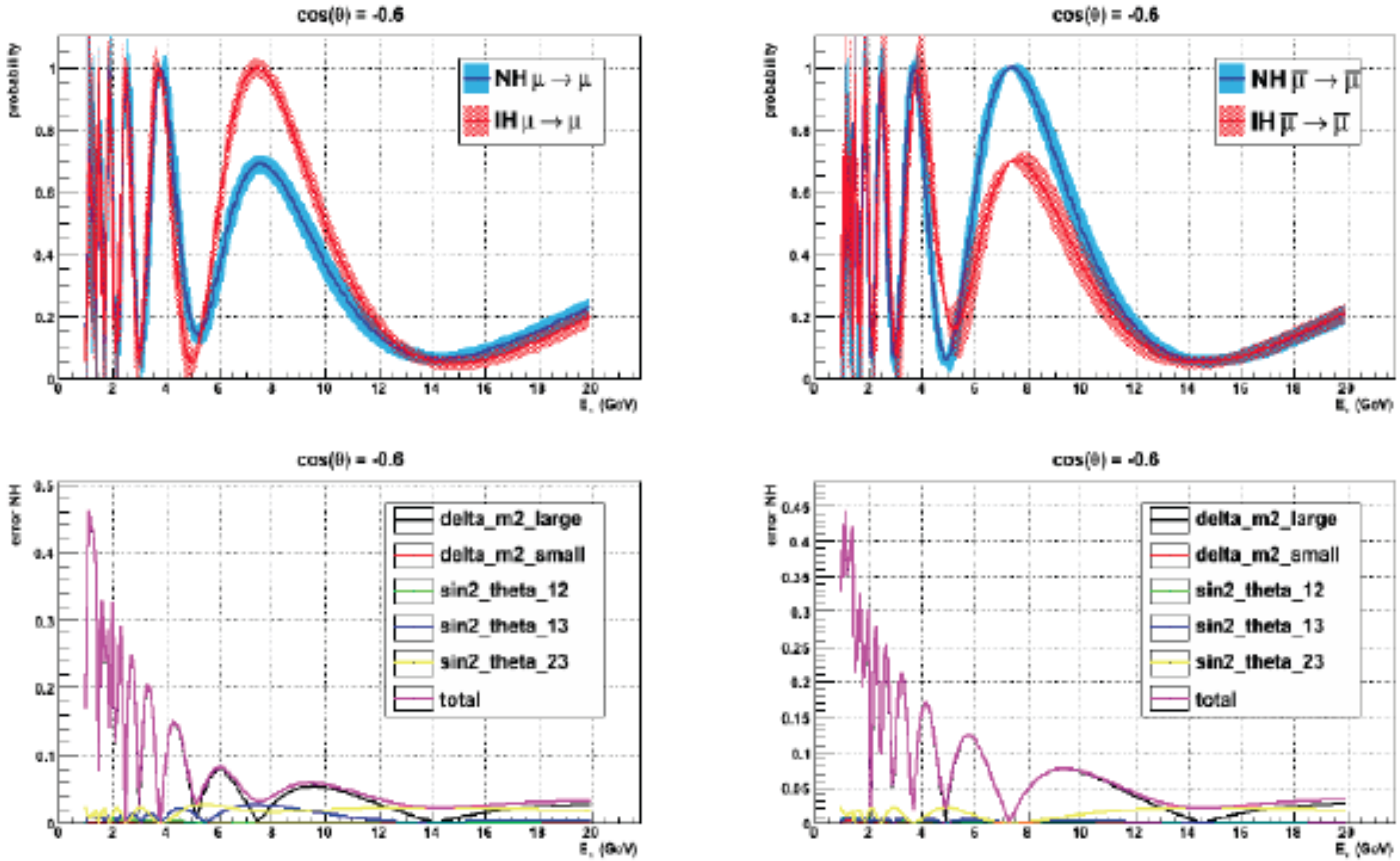
- A most reasonable choice:

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

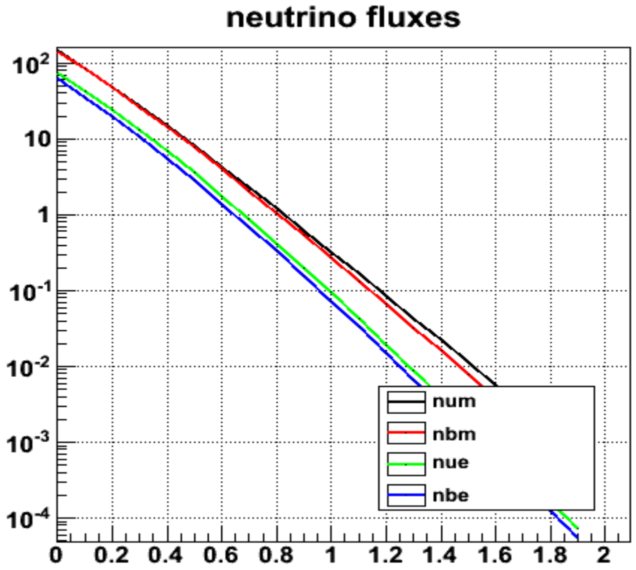
Parameter	Central value	1σ allowed range
$\delta m^2/10^{-5}$eV (NH or IH)	7.54	7.32-7.8
$\sin^2\theta_{12}/10^{-1}$(NH or IH)	3.07	2.91-3-25
$\Delta m^2/10^{-3}$eV (NH)	2.43	2.33-2.49
$\Delta m^2/10^{-3}$eV (IH)	2.42	2.31-2.49
$\sin^2\theta_{13}/10^{-2}$(NH)	2.41	2.16-2.66
$\sin^2\theta_{13}/10^{-2}$(IH)	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

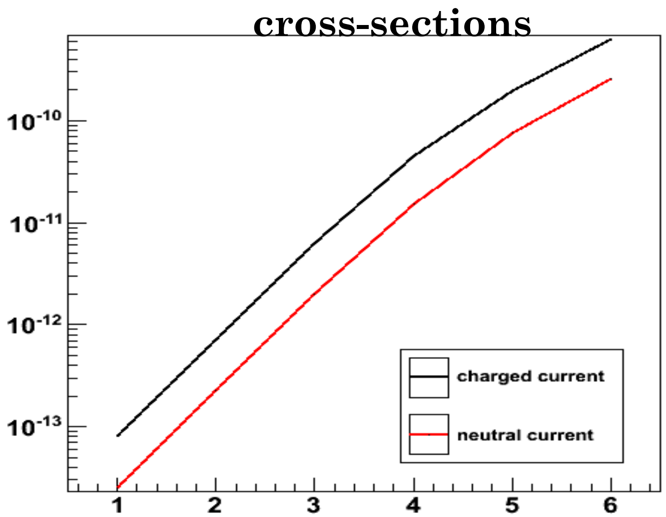


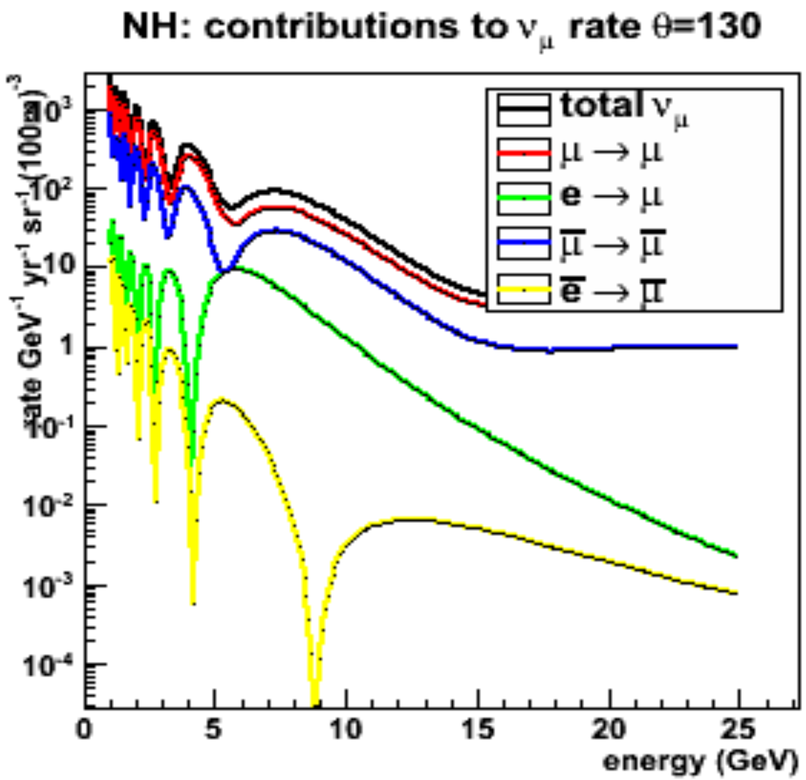
Interaction rates : ingredients



- neutrino fluxes (Bartol), include ν_e
- cross-sections from integrating DIS formula

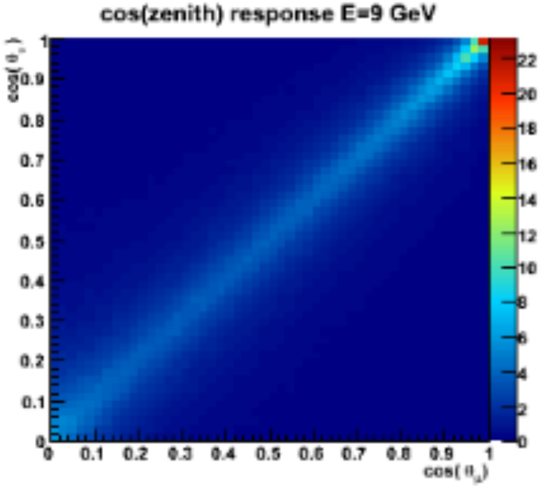
(approximates to ~20% genie and measurements)





Adding detector effects

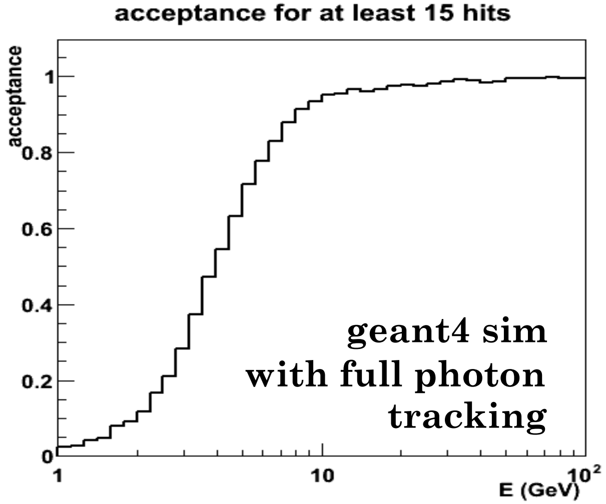
- This is where the guess-work starts; all results depend crucially on these assumptions

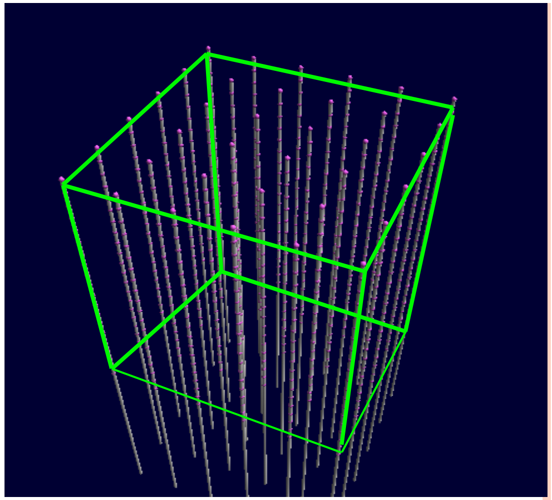


- assume zenith angle **muon** is measured **perfectly.**
  resolution comes for angle between ν and μ

- Neutrino energy resolution: assume **25%**
  requires reconstruction of muon and hadronic shower

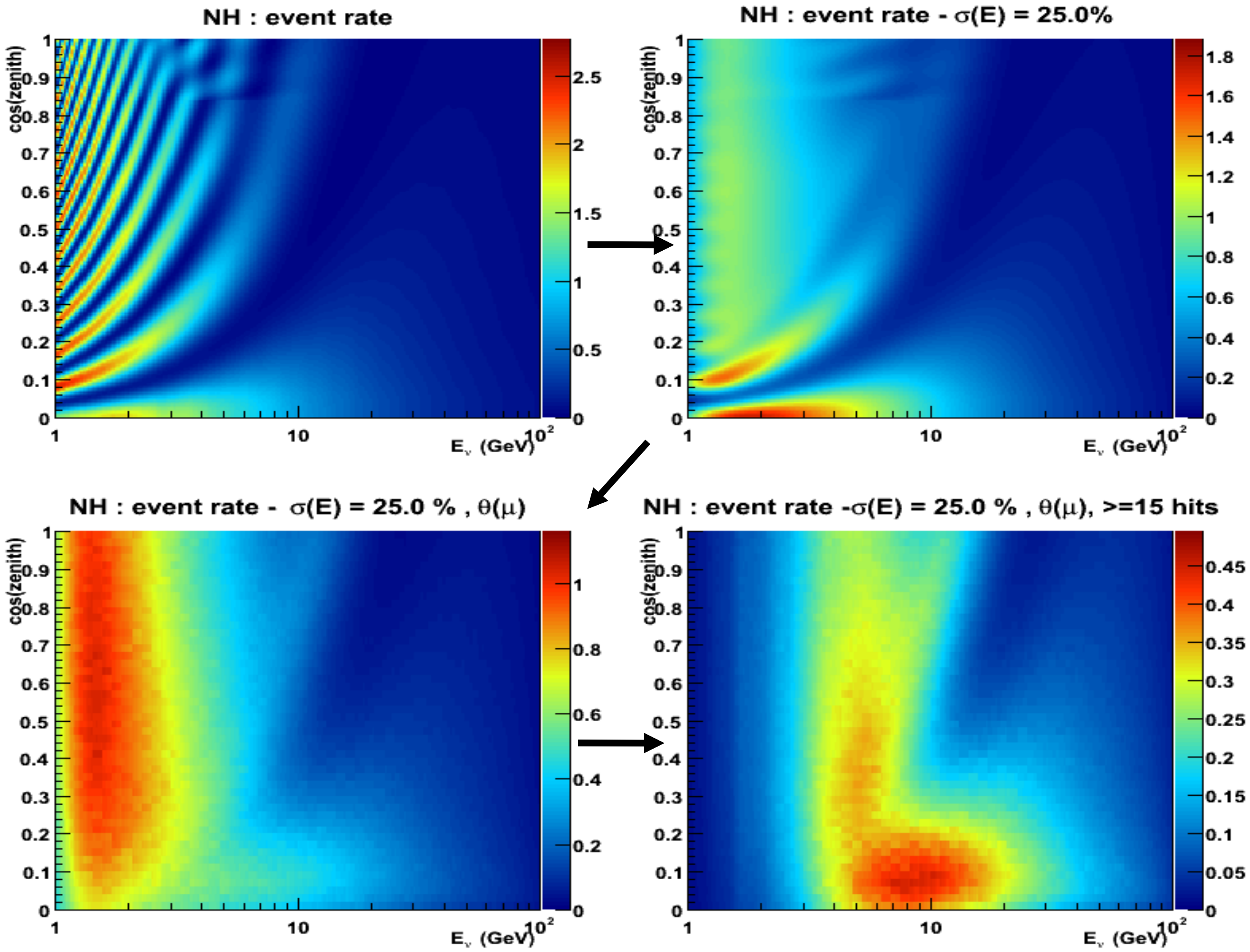
- Acceptance:
  - neutrino vertex inside instrumented volume
  - require **15 hits**
    (educated guess: need direction, E-resolution, rejection of atm. muons.).



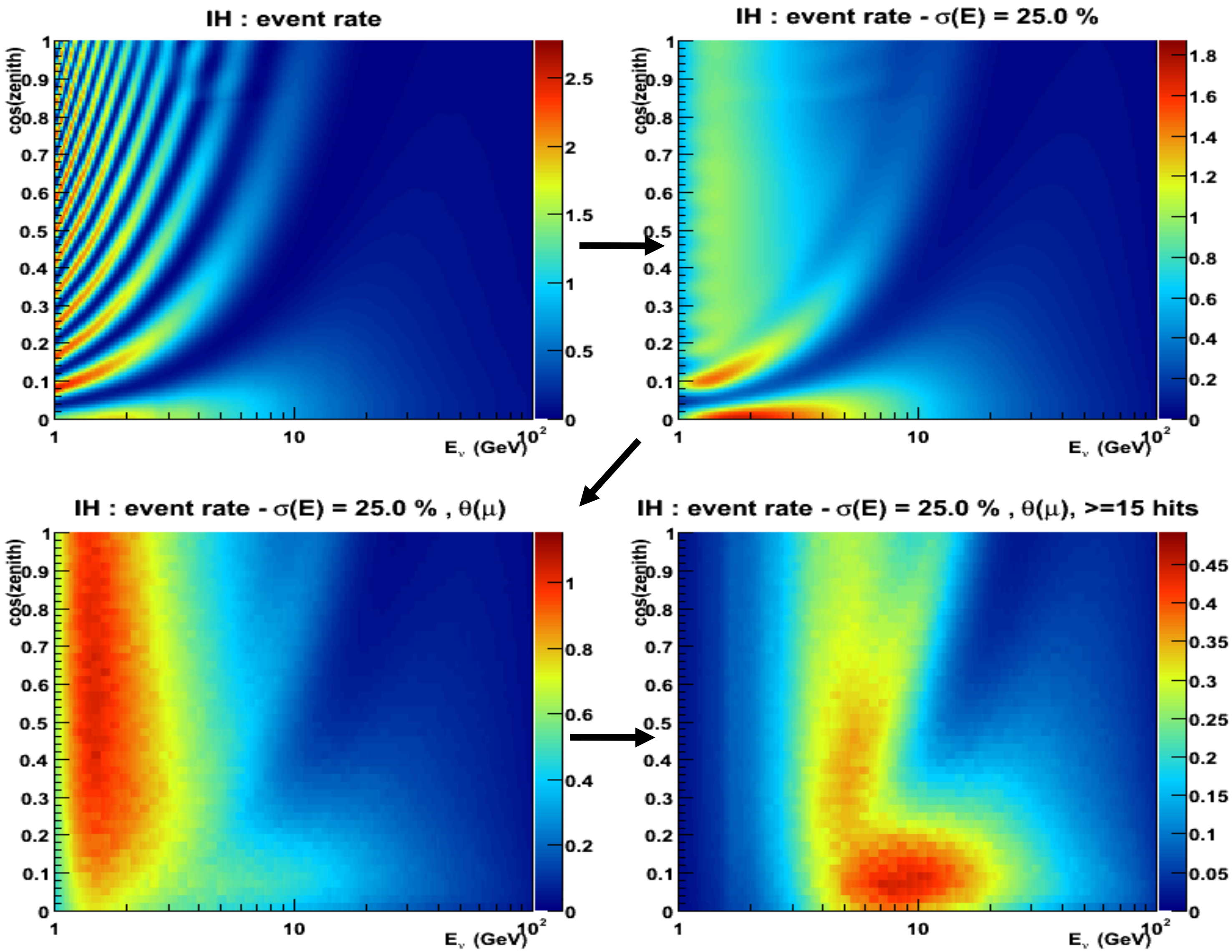


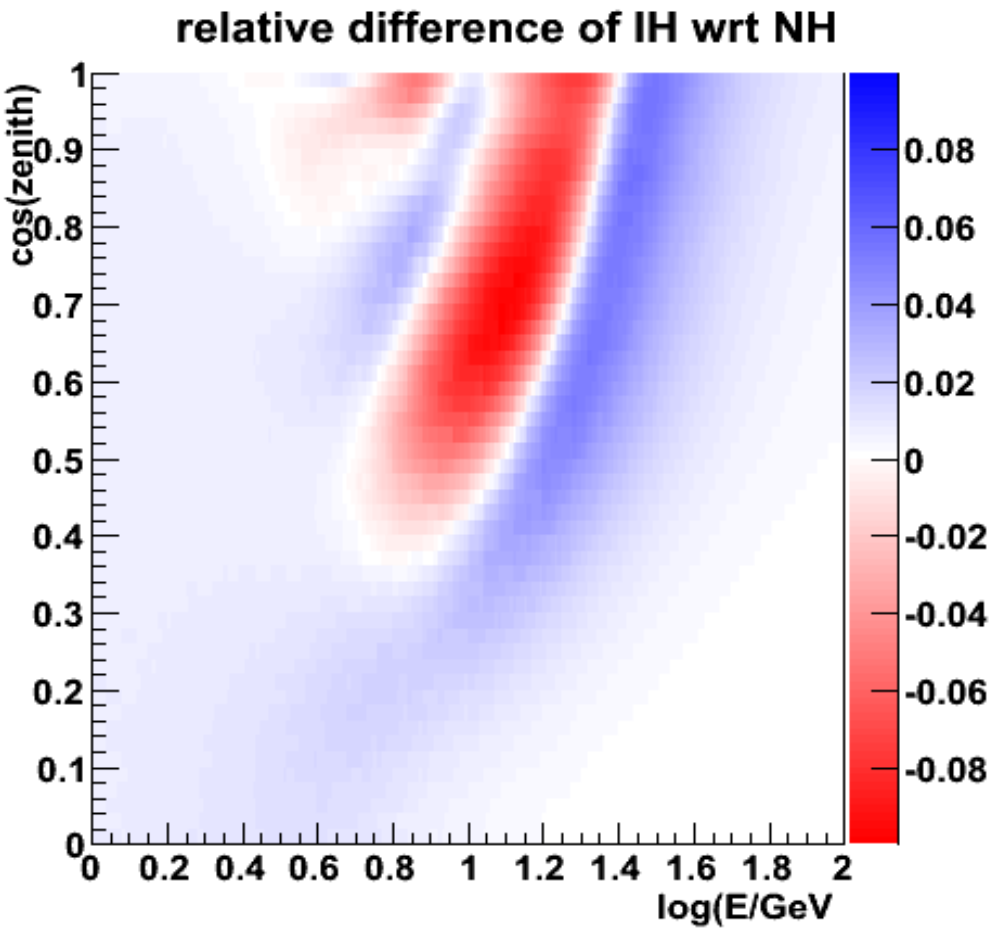
assumed detector:
$(100\text{m})^3$ =1Mton
6x6 strings
20 oms/string

Effect of detector on oscillogram: NH



Effect of detector on oscillogram: IH





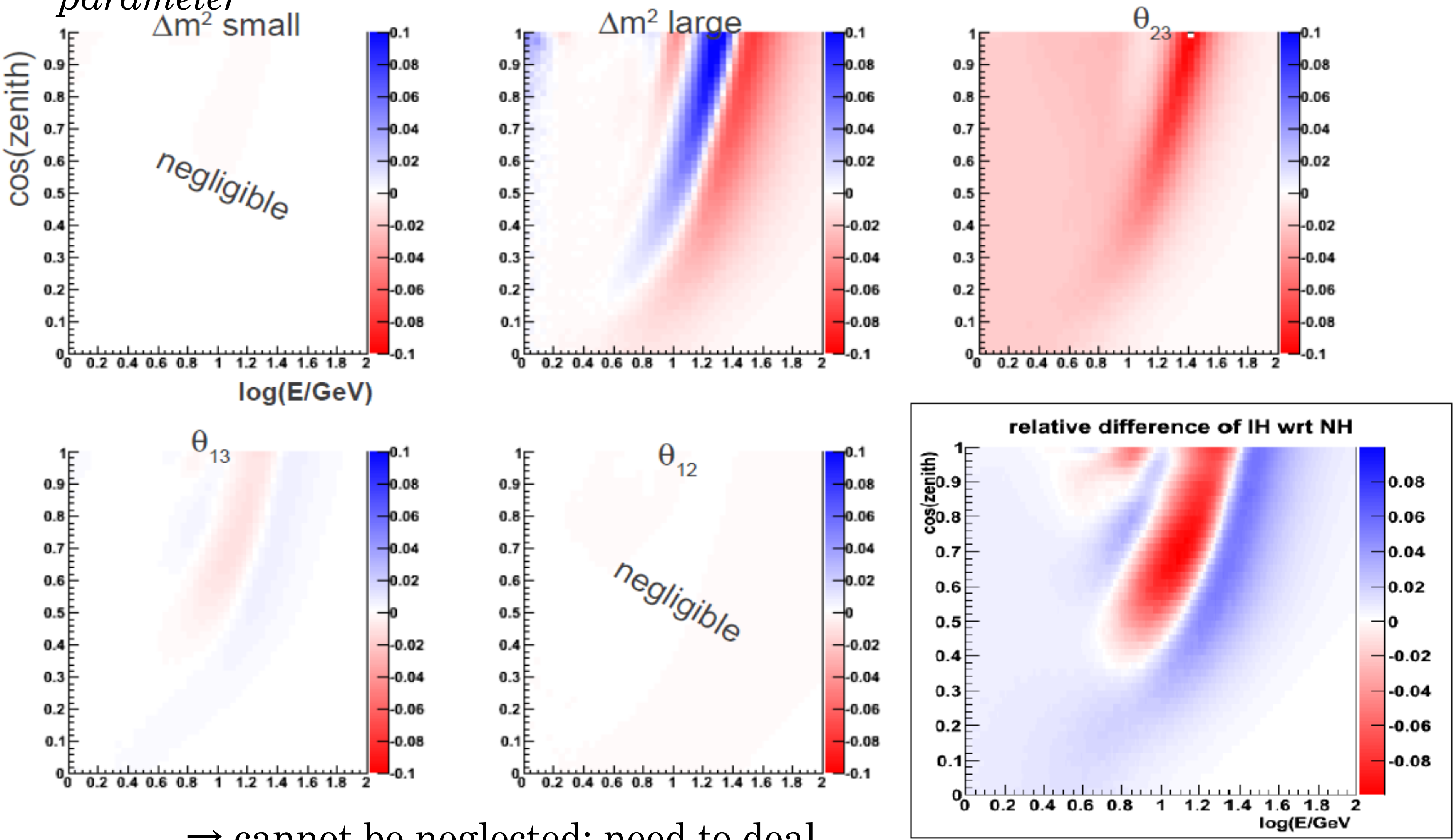
difference between NH(central values from global fit) and IH (central values from global fit)

- after accounting for assumed detector resolutions:
- maximum rate difference between NH and IH ~10%

- to be compared to other uncertainties (e.g. on mixing angles and masses → next slide).

effect of parameter uncertainties : NH

each plot compares central values with +1 sigma variation in each parameter



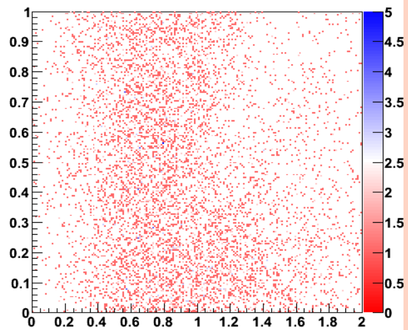
→ cannot be neglected: need to deal with these (nuisance) parameters

(Optimal) analysis to distinguish NH and IH

- Optimal observable to distinguish between NH and IH hypotheses = Maximum likelihood ratio

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

$\hat{\theta}^{\text{H}} =$ 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, for each pseudo-experiment (data):

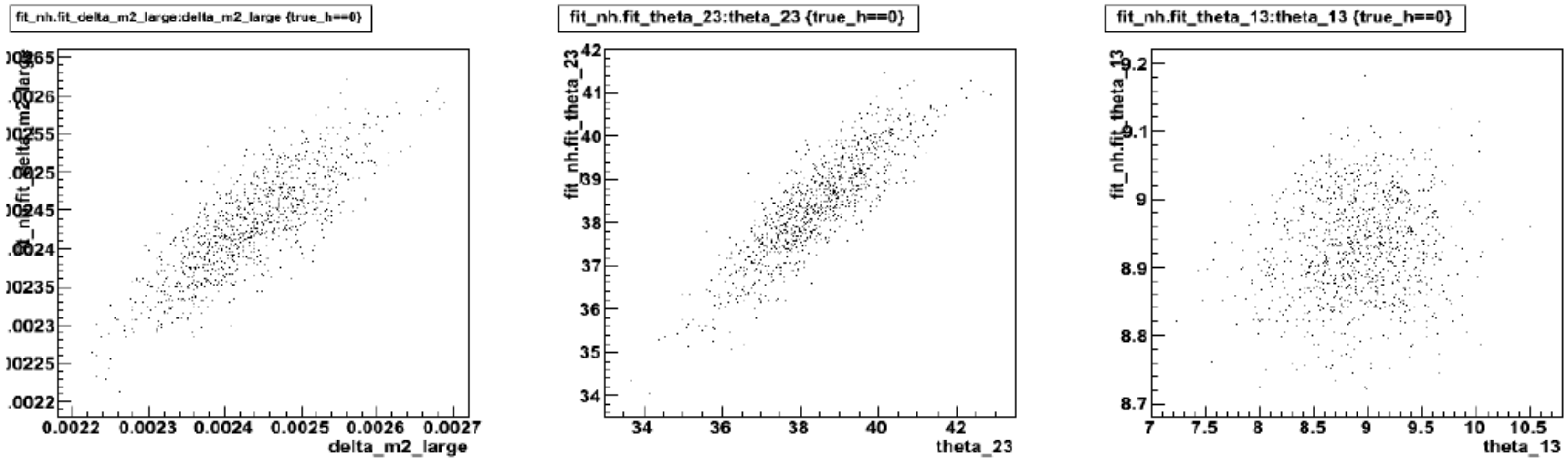
1. assume NH and find $\hat{\theta}^{\text{NH}}$ by maximizing $P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH})$
   (this involves computing many smeared-oscillograms for NH
2. do the same for IH
3. compute $\Delta \log(L^{\max})$

- The likehood contains a gaussian constraint representing the current knowledge from the global fit
- Δm^2_{21} and ϑ_{21} are fixed in the fit to gain speed

Results of parameter fit on (NH) peudo-experiments

1 Mton*year (NHtrue, NHfit)

fitted value



true value drawn
from global-fit-

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

- ORCA can improve the current uncertainty for Δm^2_{large} & ϑ_{23} already with 1 year of data
- $\sigma(\vartheta_{13})$ still dominated by other dat

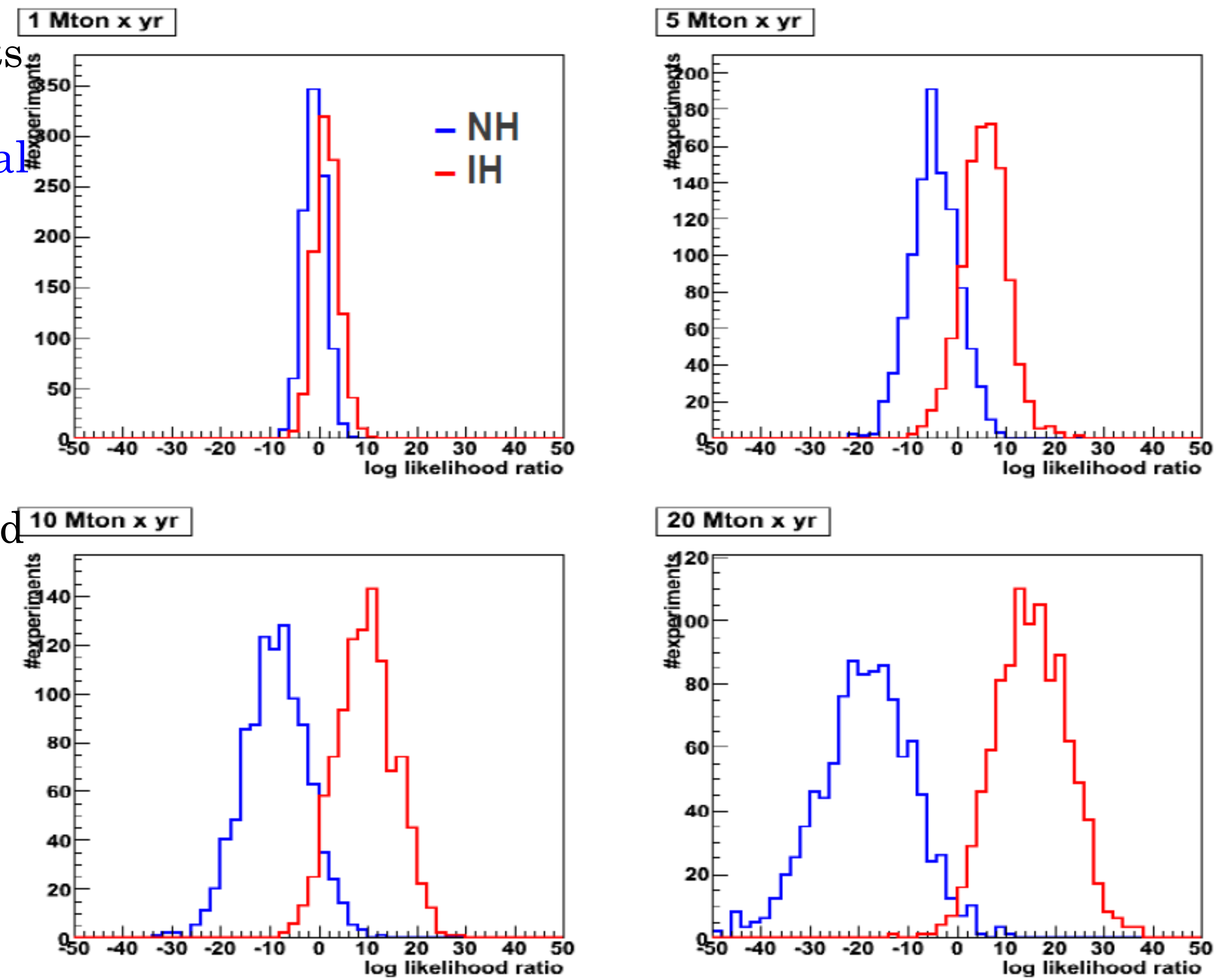
(via Gaussian constraint in the likelihood)

after 10 Mtonyr → ORCA not very sensitive to it.

likelihood ratio distribution

for toy experiments in which the true hierarchy is normal or inverted.

remember: results depend crucially on assumptions on resolution and detector layour and acceptance

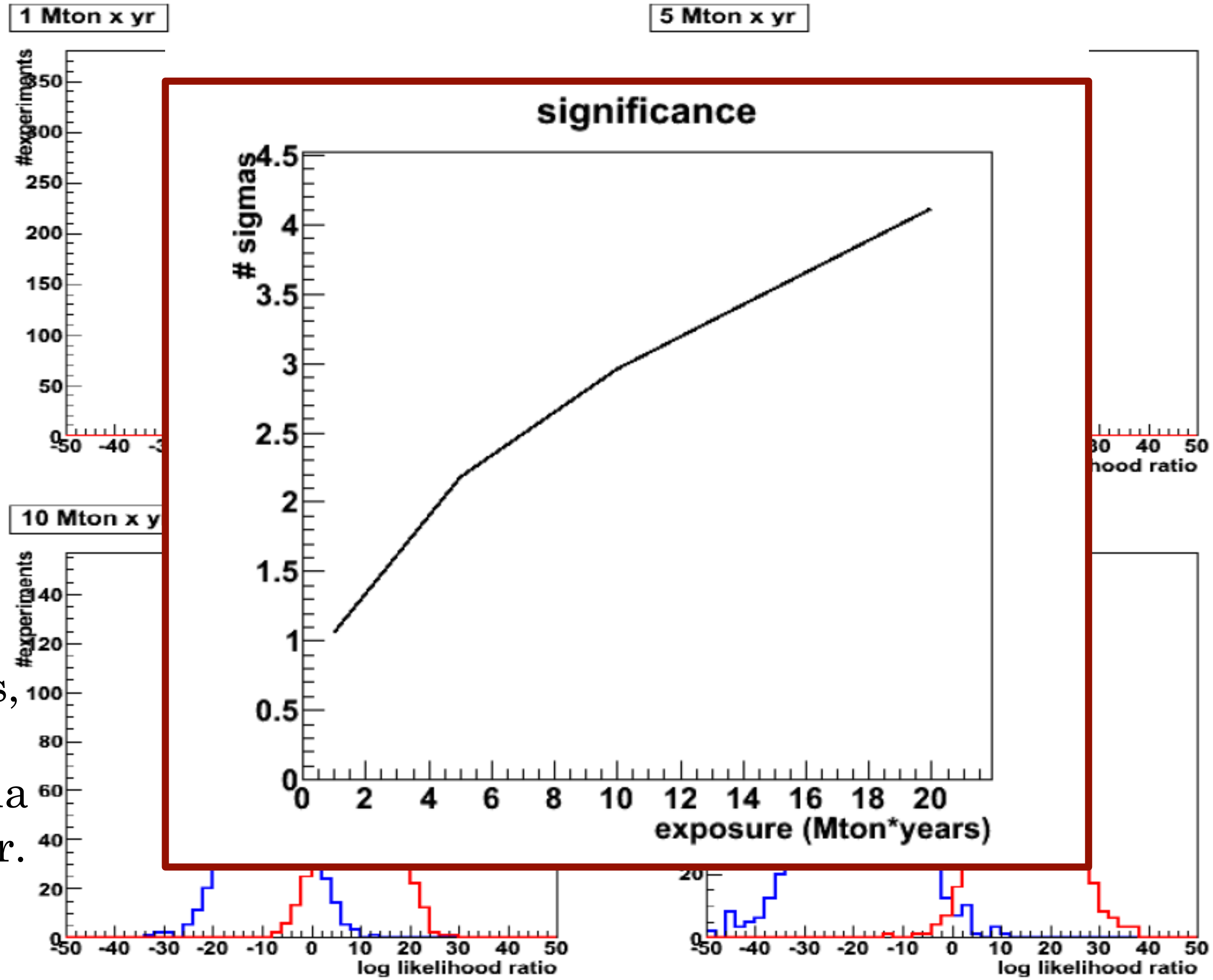


likelihood ratio distribution

for toy experiments in which the true hierarchy is normal or inverted.

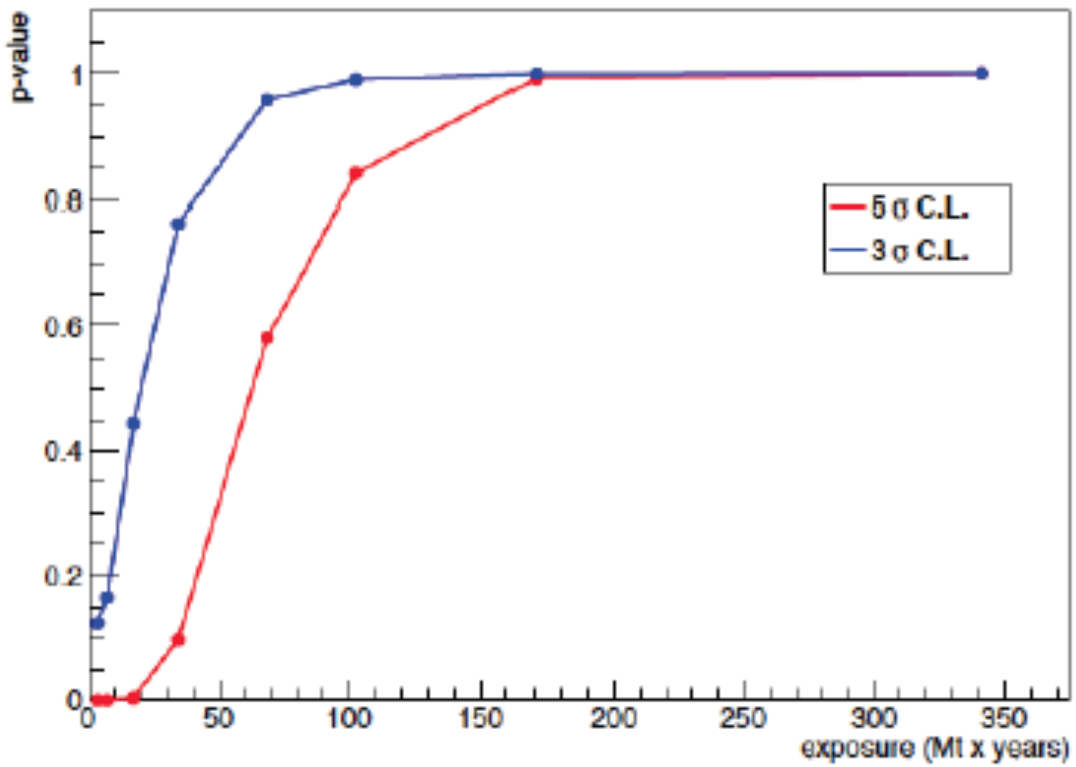
remember: results depend crucially on assumptions on resolution and detector layour and acceptance.

expressed in sigma's, separation between NH and IH = 3 sigma with 10 Mton x year.



Similar results from Veronique Van Elewyck

Preliminary results:
kinematics smearing included,
detector with perfect resolution in E, θ



Preliminary results: effect of the detector resolution

from Veronique Van Elewyck

Add smearing in E, θ

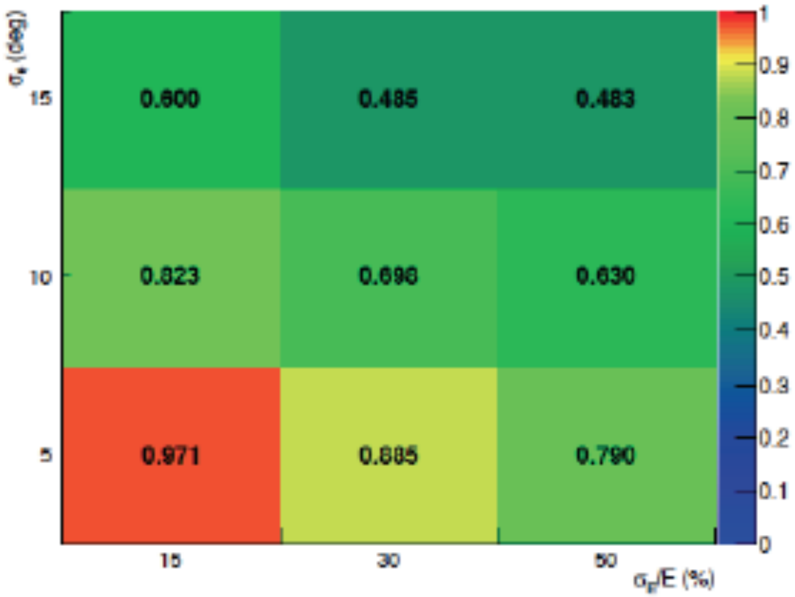
$\sigma(\theta)$ = 5°, 10°, 15°

$\sigma(E)/E$ = 15%, 30%, 50%

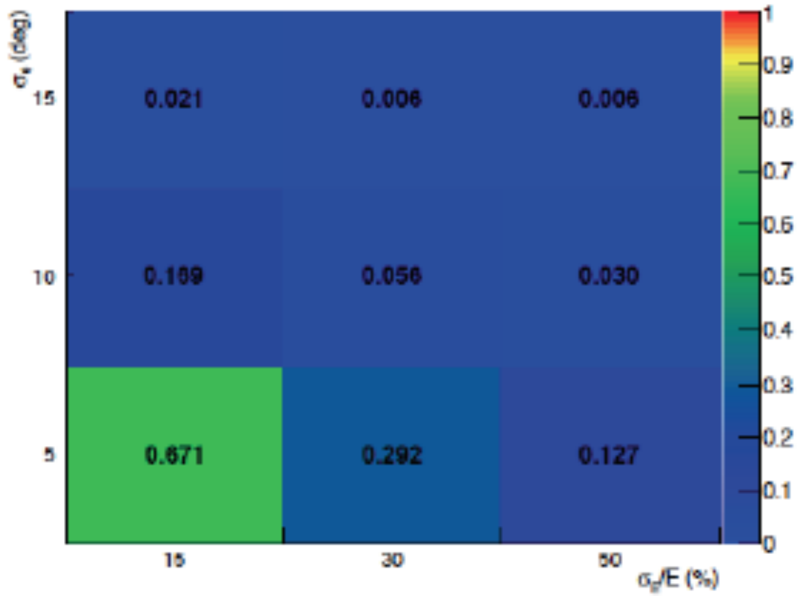
Kinematics smearing included

Exposure 170 Mton year (p-value =1 for perfect detector)

3σ discrimination



5σ discrimination



Conclusions / thoughts

Aart Hiejboer

- This is not an easy measurement
  - if assumptions are correct, need 10 Mton x year for 3 sigma
  - assumptions could be pessimistic, of course
  - Still several sources of systematic to be accounted for

  (earth density, rate normalization, cross-sections,....)

- Determining the mass hierarchy with this type of detector requires Large instrumented volume (1 Mton is not enough)
  - When we have full simulation and reconstruction, we should investigate sparse (or variable-density) detectors

    (But demand on (energy) reconstruction quality are very high and likely require dense detector in the full volume & fully contained events)
  - Investigate the effect of event topology

Effective volume and energy reconstruction

Simulation chain

gSeaGen
Neutrino generator

Genhen (v6r10 seawiet)
Neutrino generator

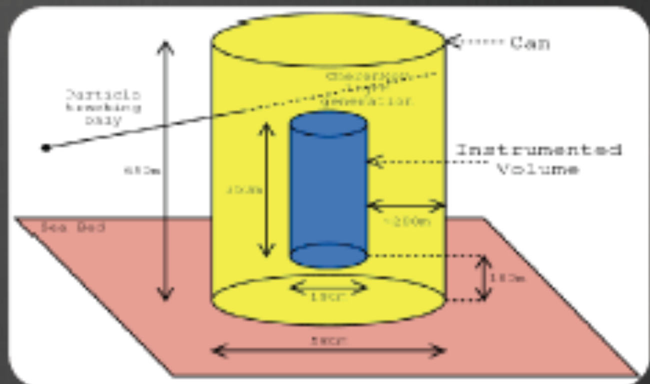
KM3 (v4r4)
Light & hits

GENDET
geometry

GEASIM
(v4r13seawiet)
Light & hits

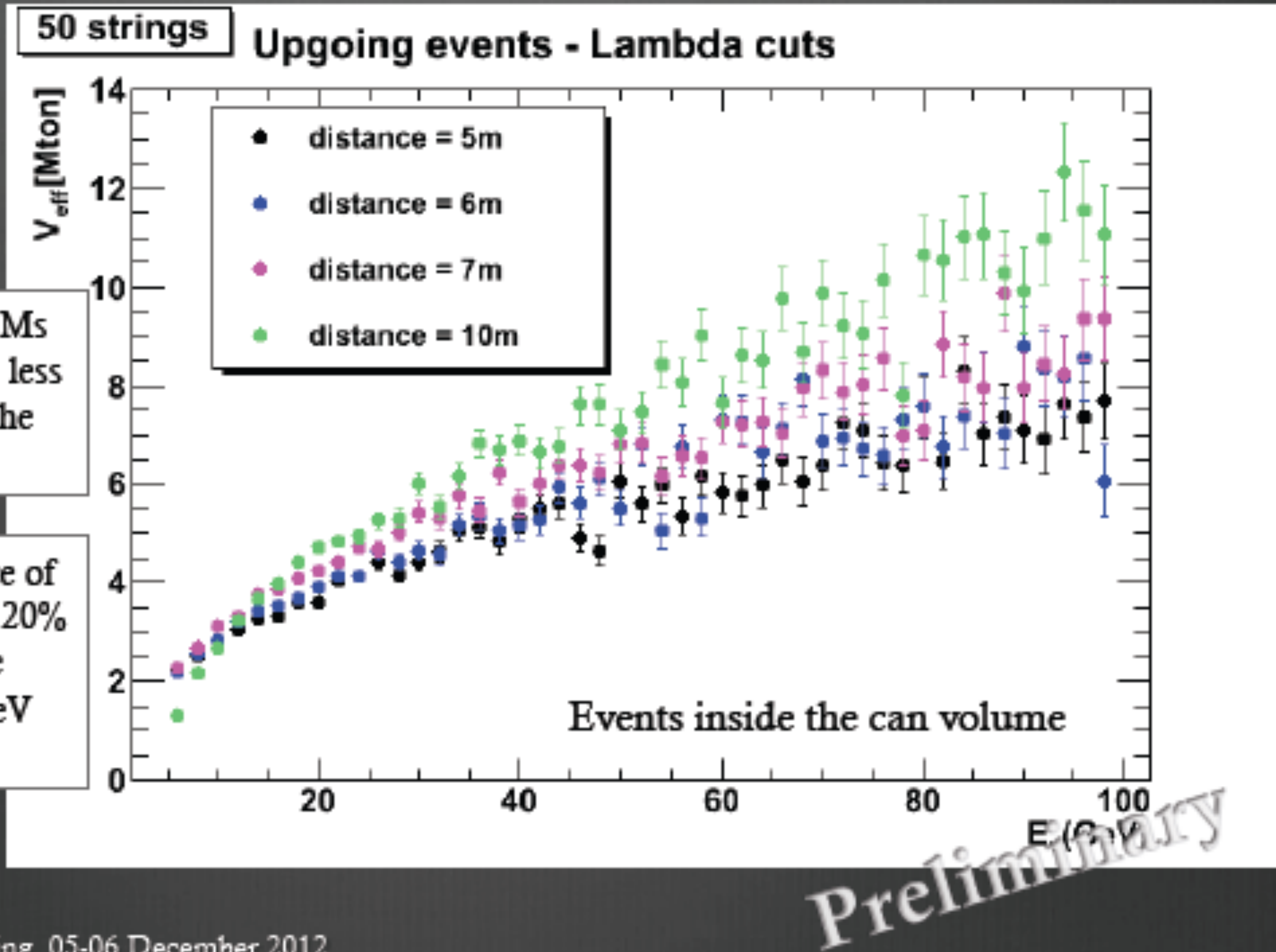
MODK40
(v4r13seawiet)
40K Background hits

RECO
Reconstruction code
(see next slide)



Detector optimization: distance between OM

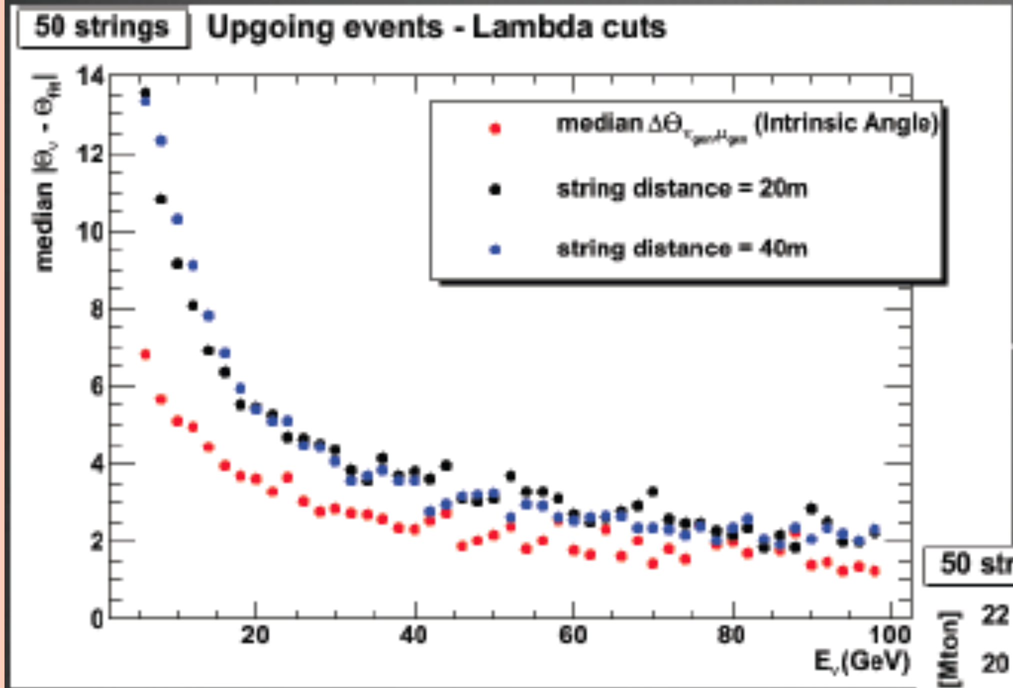
Quality cuts applied to get, for each distance, nearly the same median of $\Delta\,\theta$ at low energy



Differences of 1 m in the OMs distance lead to a variation less then 7-8% at E<50GeV in the effective volume

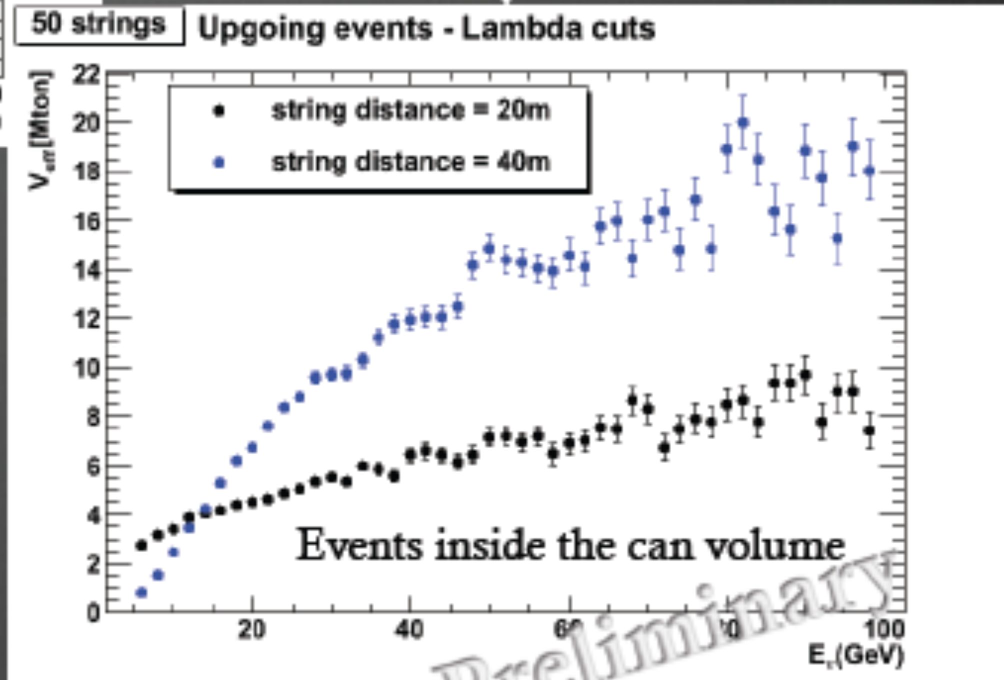
Increasing the OMs distance of 5 m lead to a gain of about 20% at 15GeV<E<50GeV in the effective volume, but at 5GeV the loss is about 18%

Detector optimization: string distance



Quality cuts applied to get, for each distance, the same median of $\Delta\Theta$

Spriral footprint

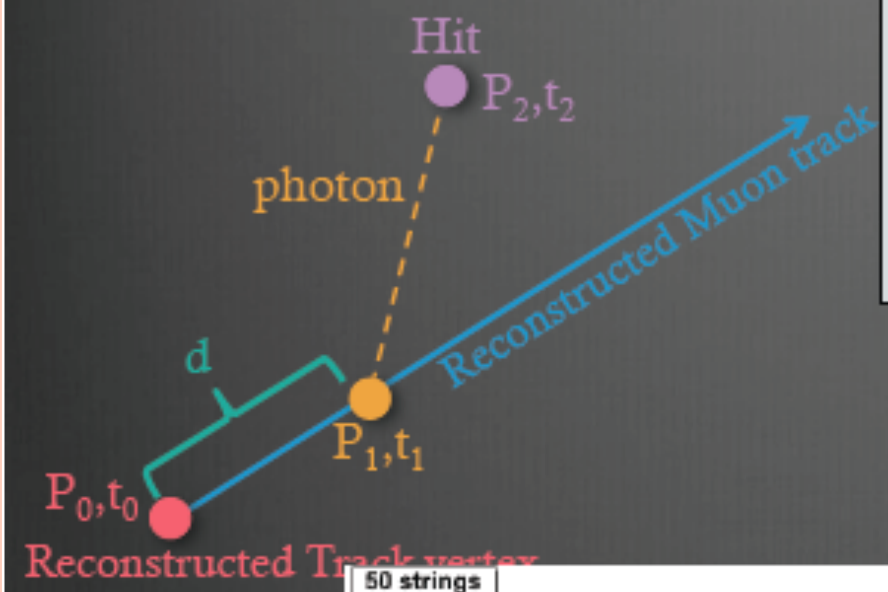


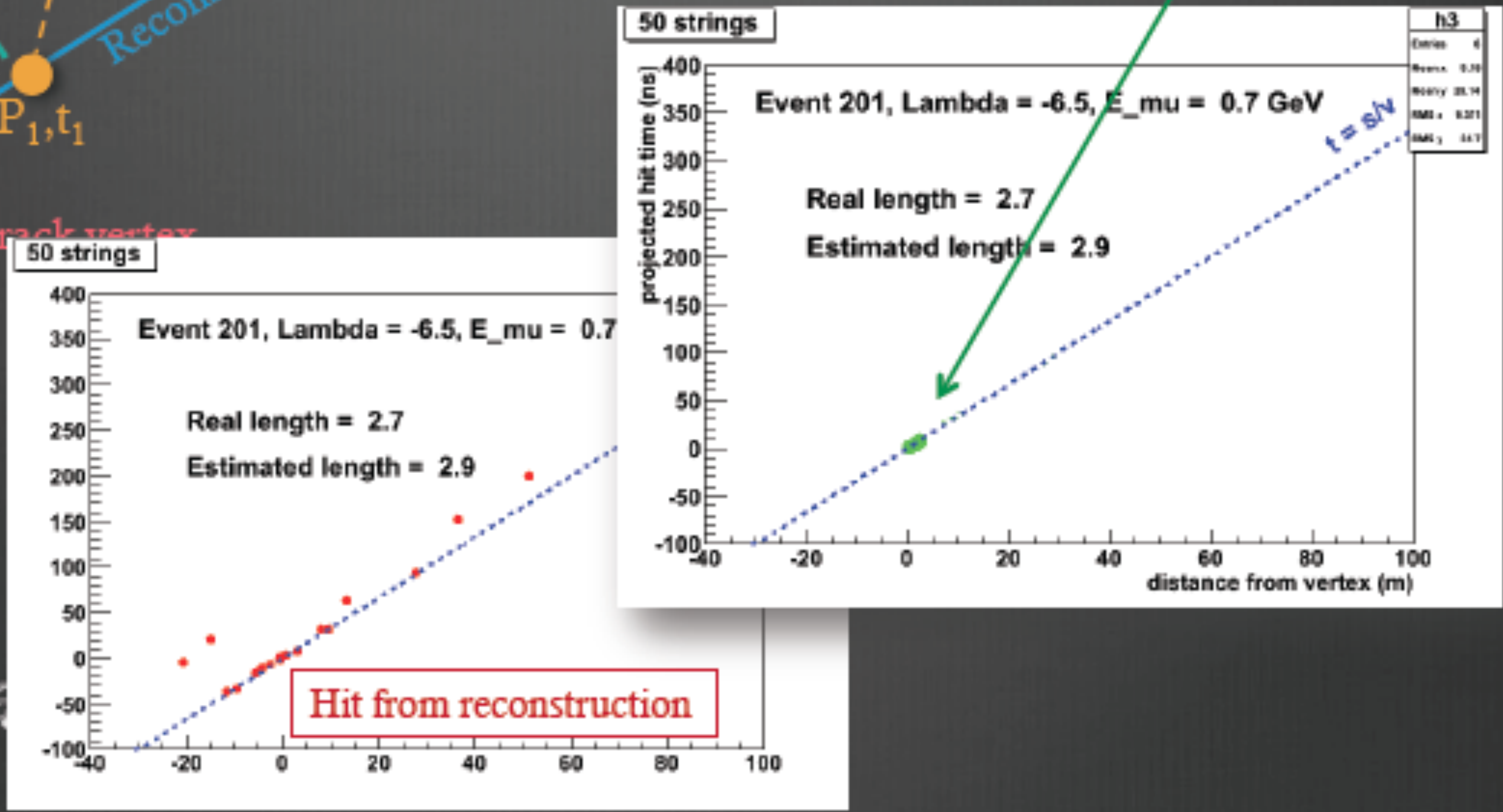
Optimal string distance depends on the energy range of interest.

Muon Track length estimate

Hit used:

- ✓ Hit selected with the condition $d/t_1=c$
- ✓ High density of points P_1 along the track required
- ✓ $t>0$

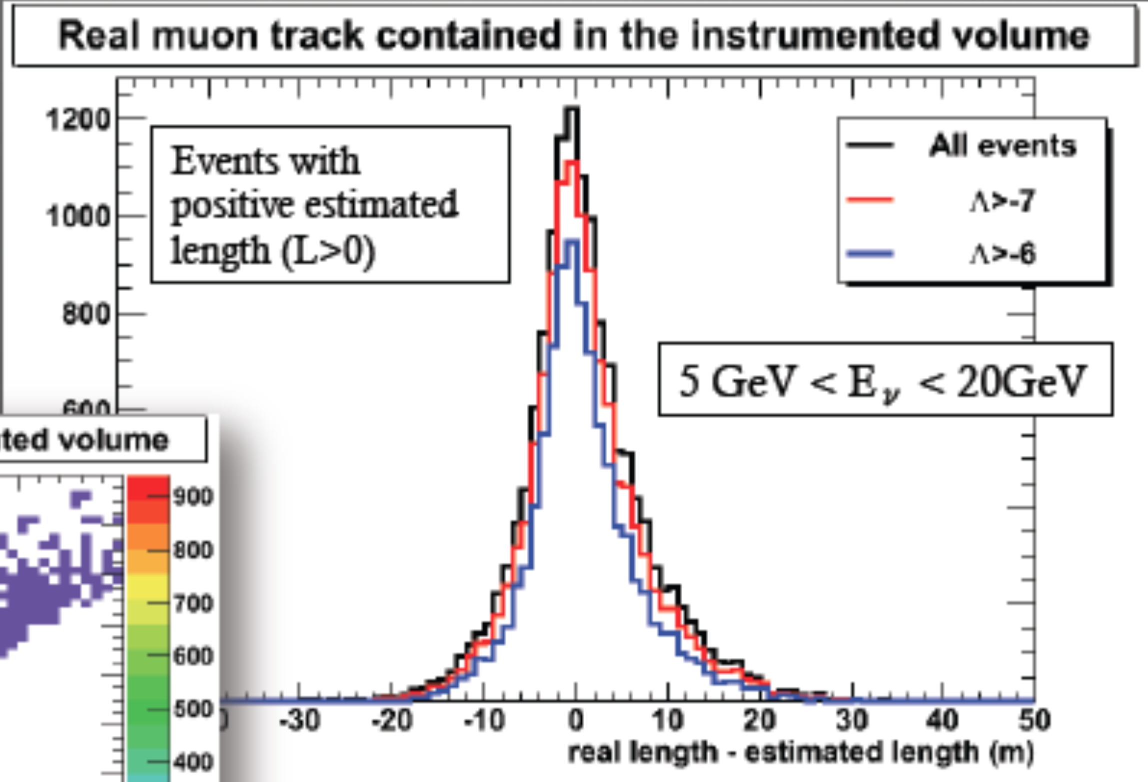


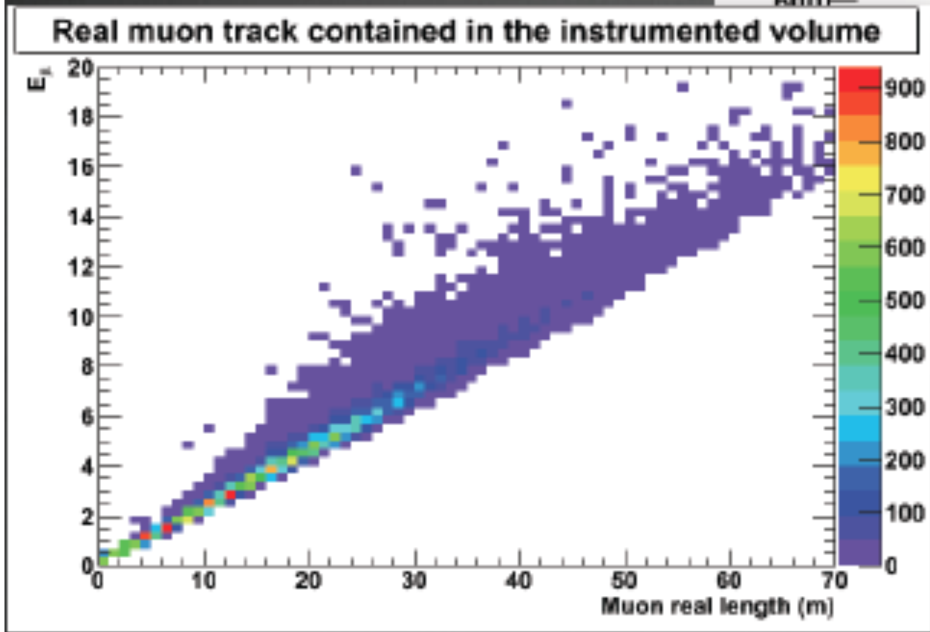


Prelimina

Muon Track length estimate

Case I - Only events with E_ν<20GeV and the muon track fully contained in the instrumented volume (1.75 Mton)





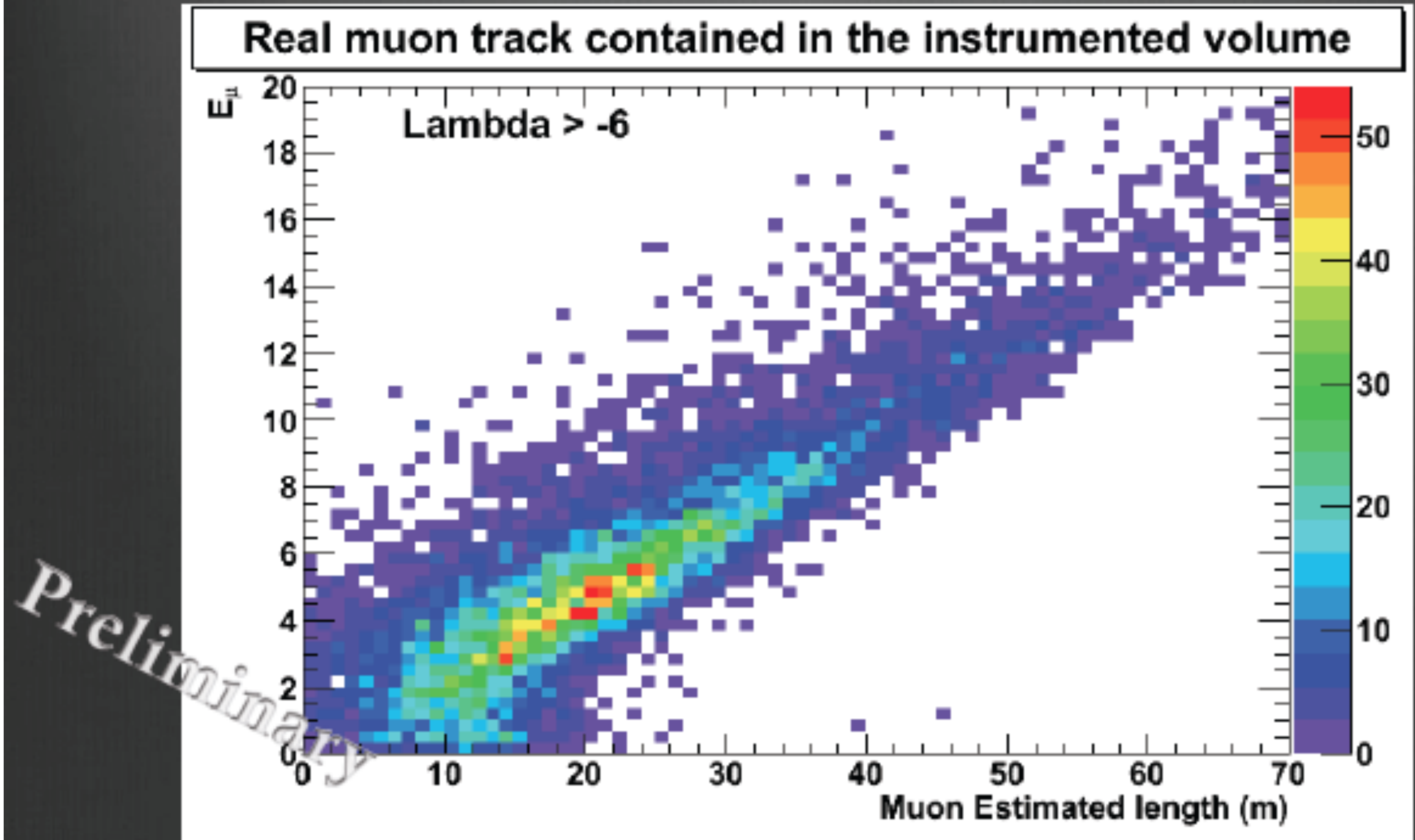
Only reconstructed events

	events	% w.r.t. contained
Contained	15397	100%
L>0	14064	91%
L>0 && Λ>-7	12215	79%
L>0 && Λ>-6	9513	62%

Preliminary

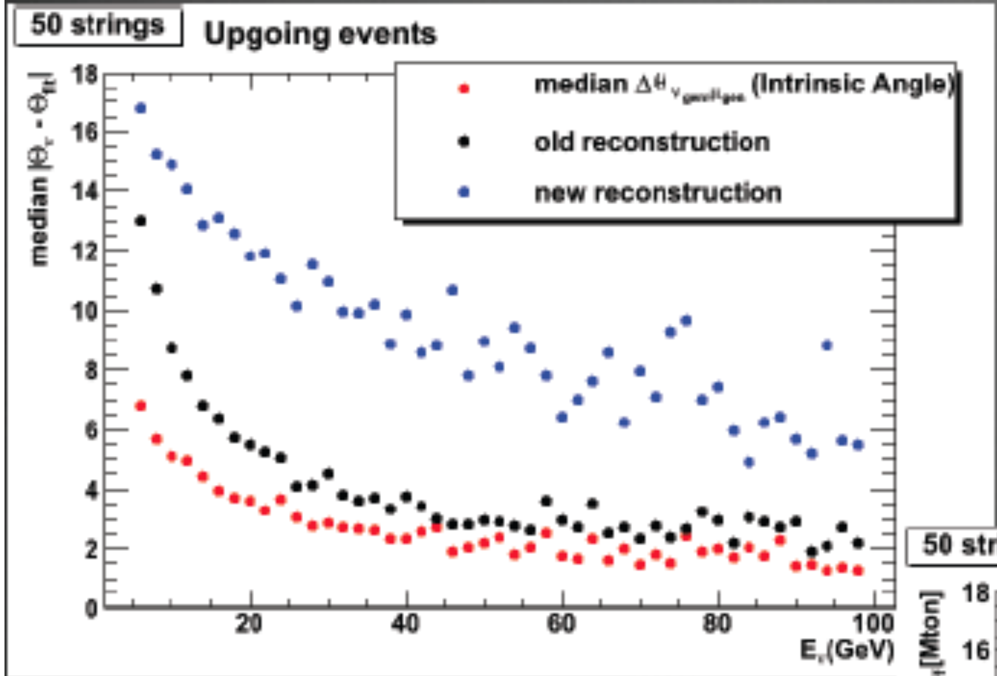
Muon Track length estimate

Case I - Only events with E_ν<20GeV and the muon track fully contained in the instrumented volume (1.75 Mton)

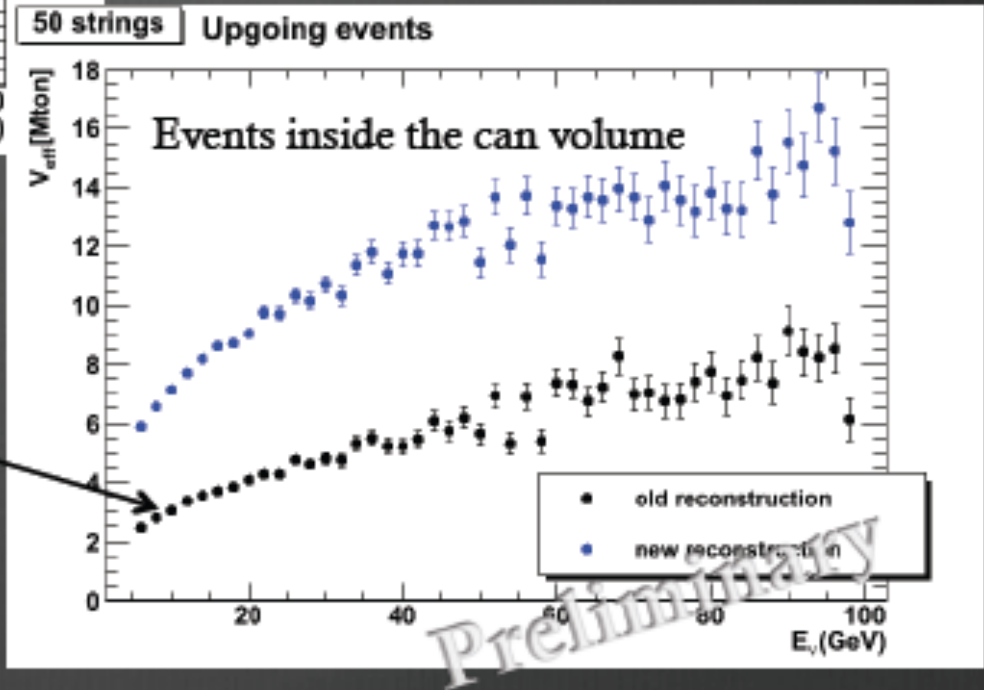


Trovato Agata, ORCA meeting, 05-06 December 2012

New Reconstruction results

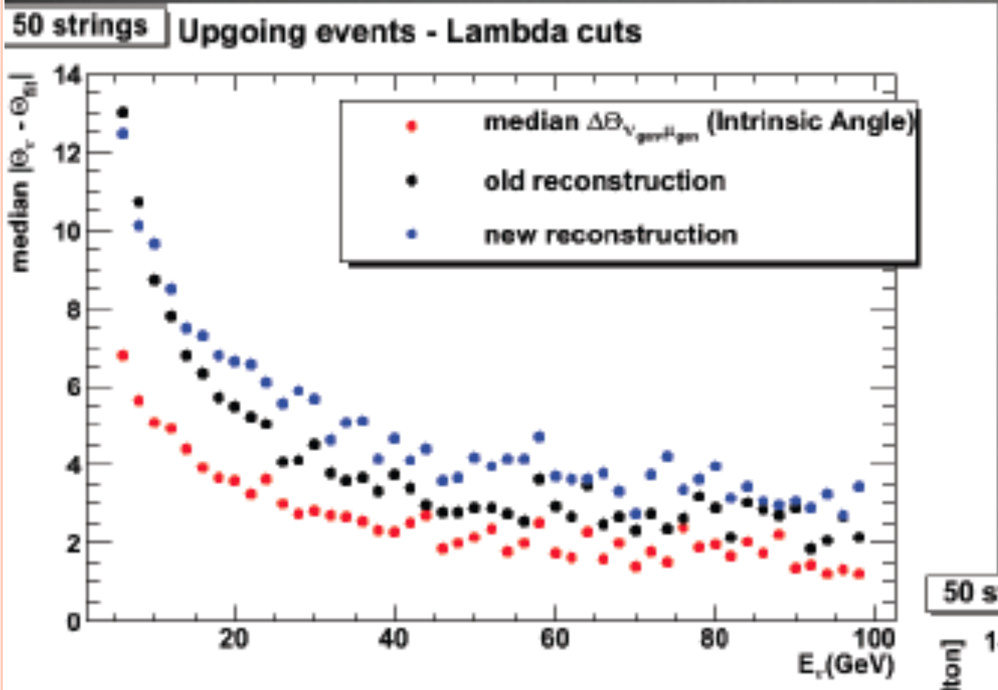


Both the effective volume and the angular error increase but…

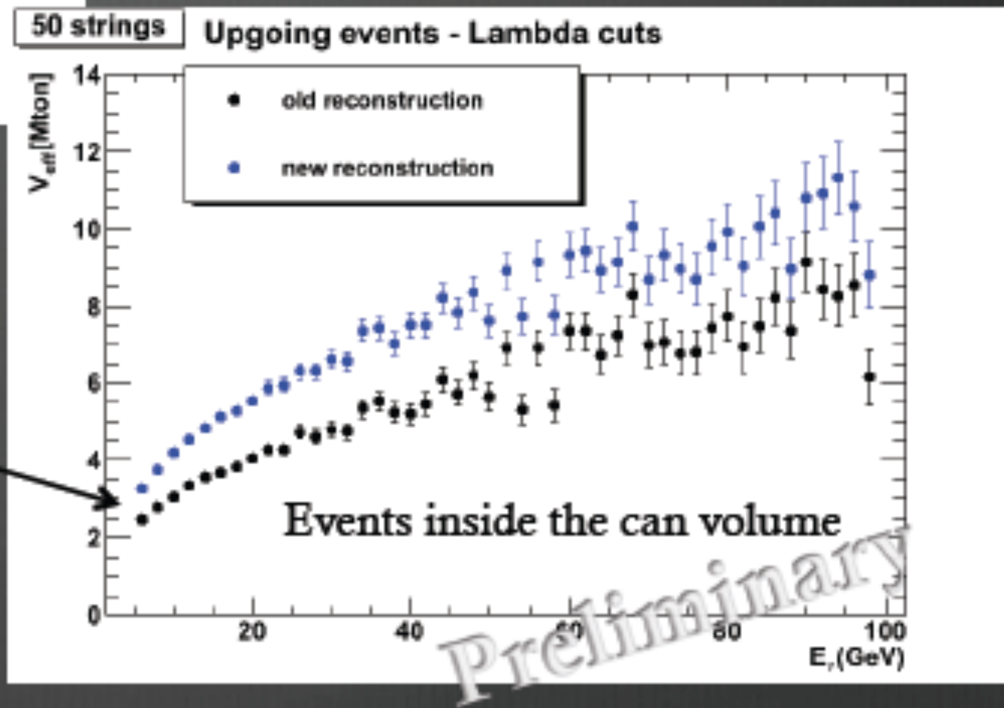


This reconstruction was used in the detector optimization

New Reconstruction results



Quality cuts applied to get the same angular resolution at low energy



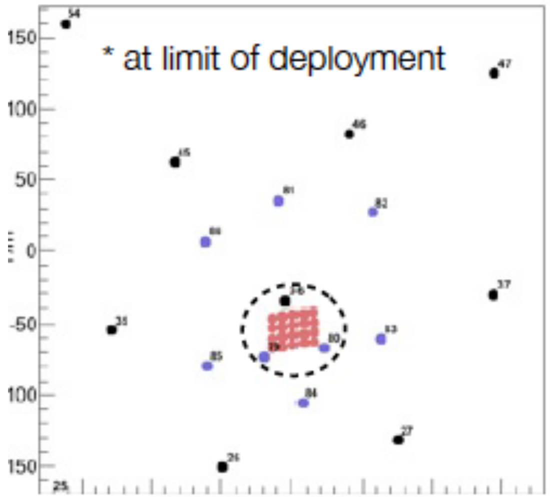
Effective volumes increase of about 25%-30% at E_ν<50 GeV

A Range of Geometries

PINGU effective volume

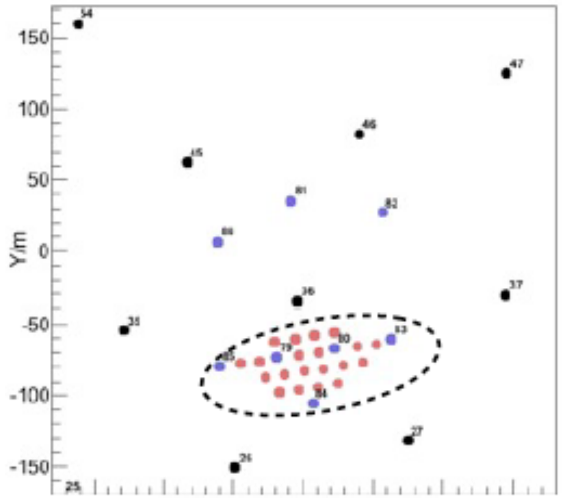
Dal talk di Sirin Odrowki

PINGU v3 - Top View

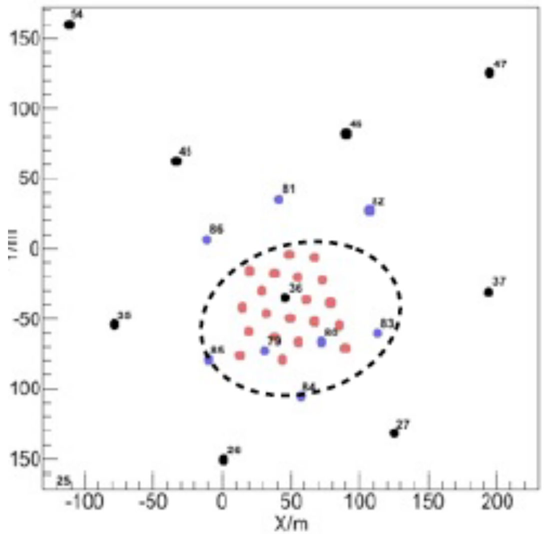


string spacing	DOM spacing	version
7m	3m	v3
14m	5m	v5
18m	5m	v8
22m	5m	v7
26m	5m	v6

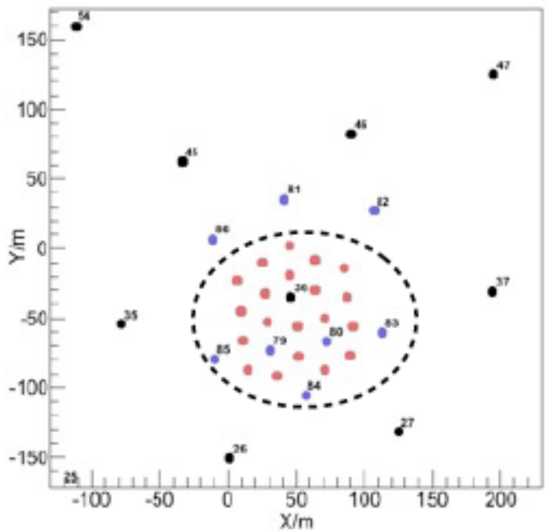
PINGU v5 - Top View



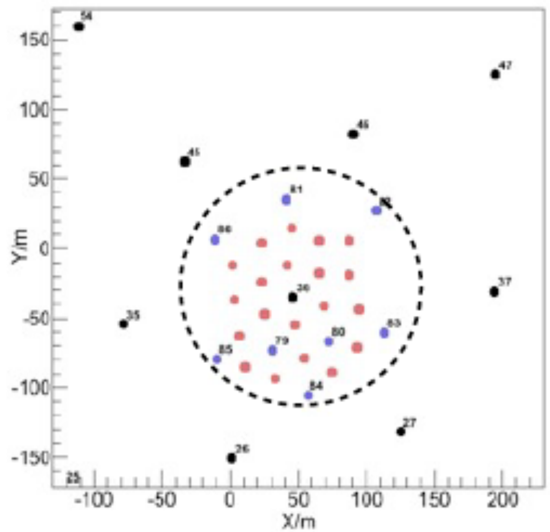
PINGU v8 - Top View



PINGU v7 - Top View

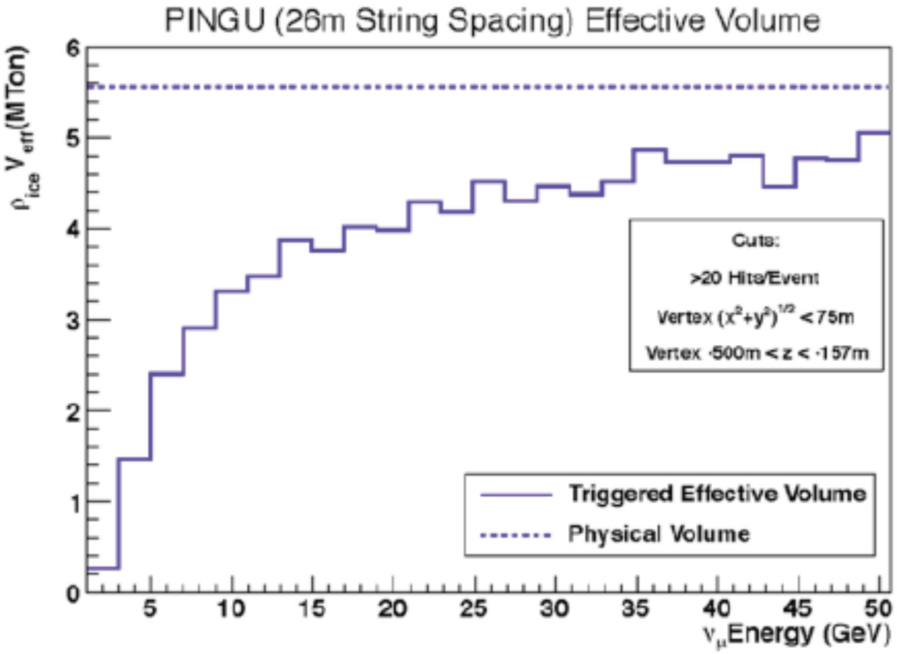


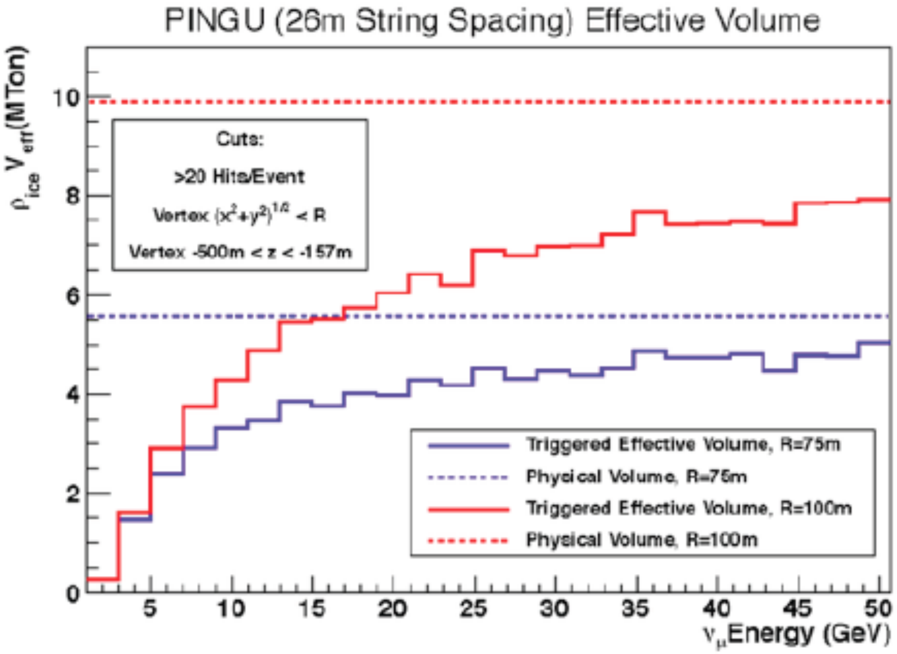
PINGU v6 - Top View



PINGU effective volume

Dal talk di Sirin Odrowki





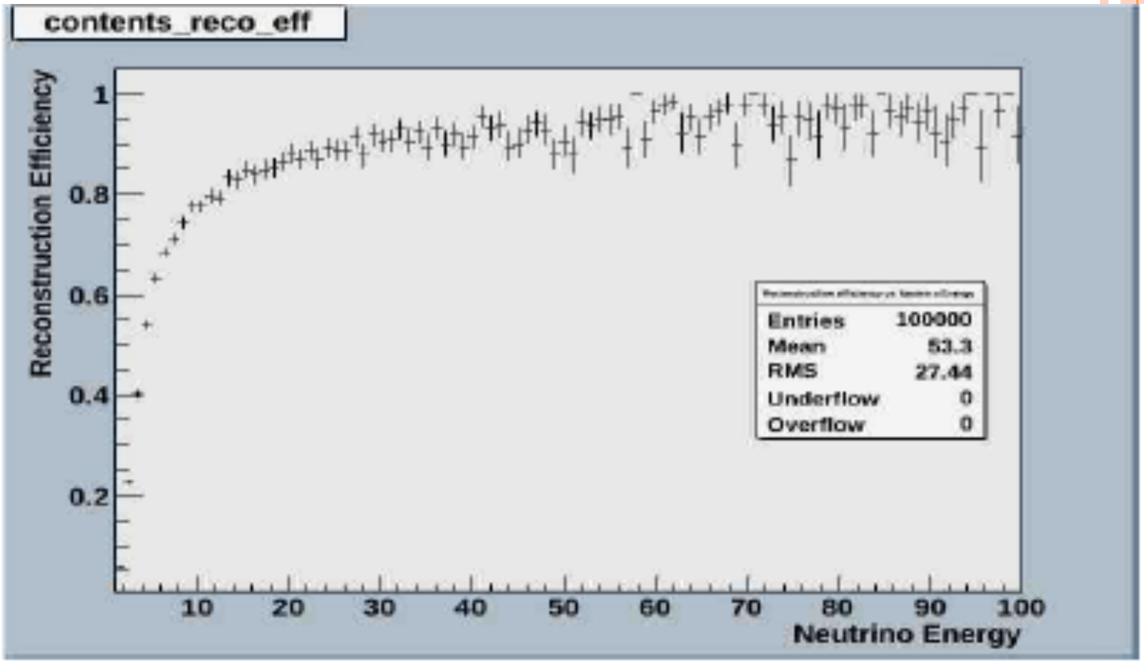
Muon Track reconstruction
(infinite track)

Apostolos Tsirigotis

First results

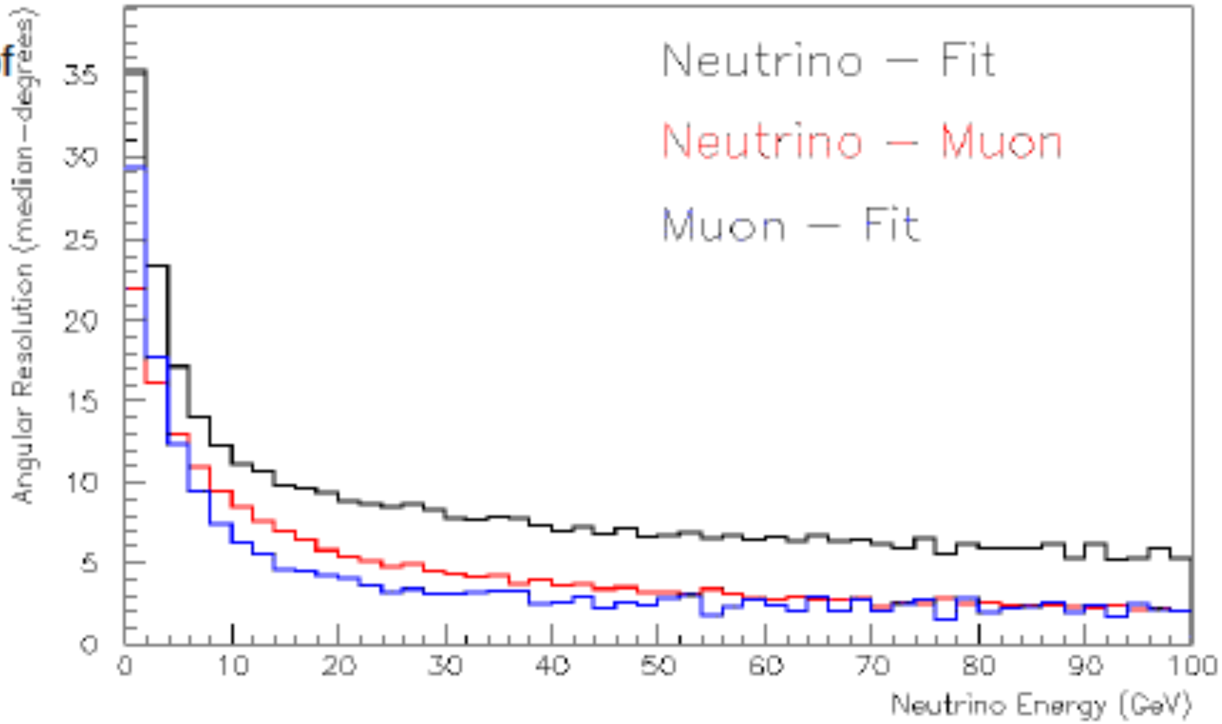
Reconstruction efficiency as a function of neutrino energy

- Events originating from inside the instrumented volume (semi – contained events)
- Events with at least 4 signal L1s
- No quality cuts after reconstruction.
- At 6 GeV an effective volume of 70% of the instrumented volume is achieved



Angular resolution as a function of neutrino energy for semi-contained events.

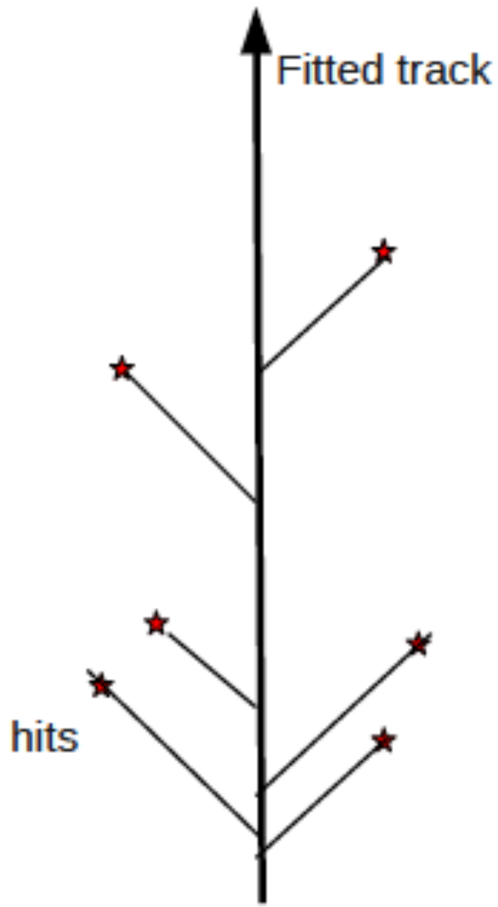
- Median angular resolution (black line) is below 15° for energies above 6 GeV.

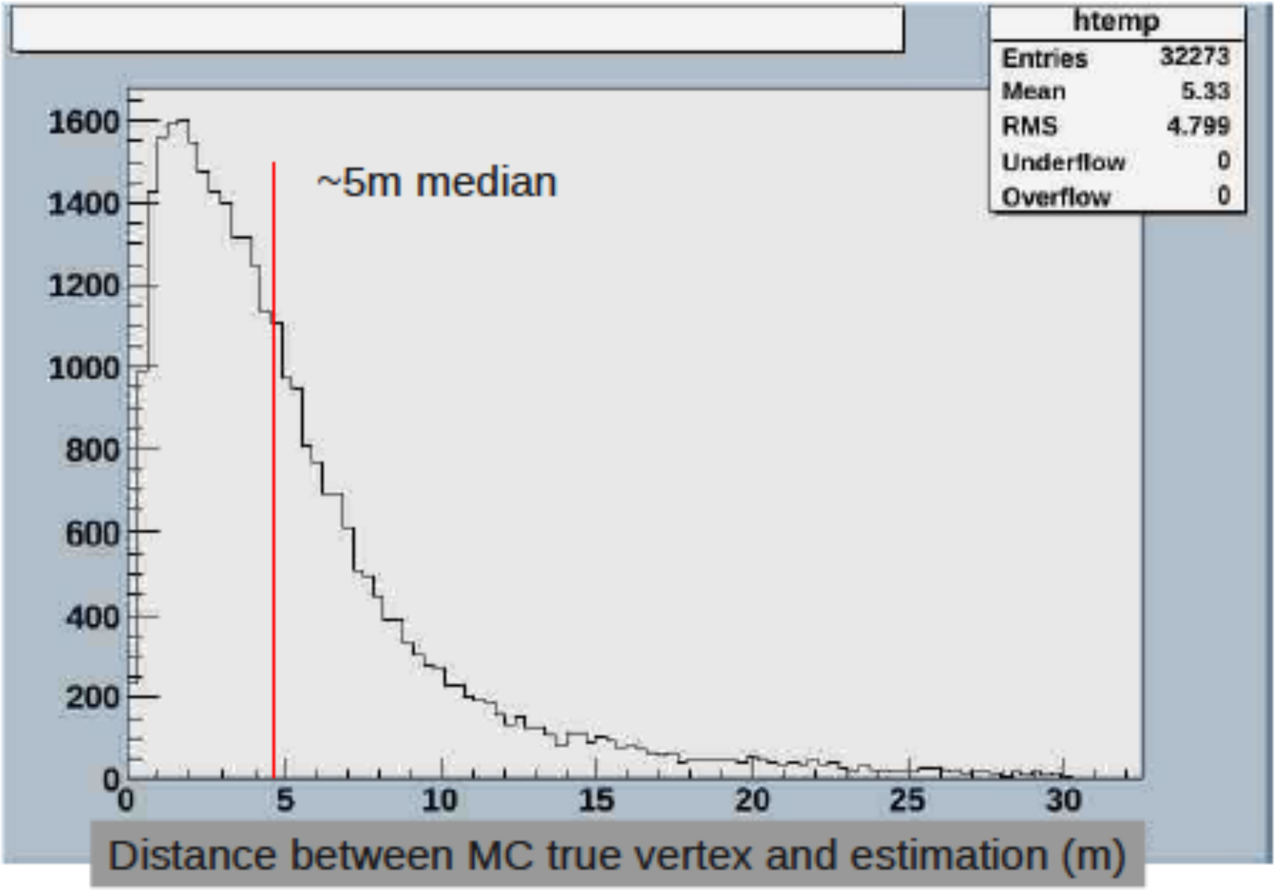


Muon track length estimation and energy reconstruction

Estimation of the neutrino interaction vertex

- Projections (with the Cherenkov angle) of the hit positions on the fitted track
- Accept only hits with residual<10ns and distance<40m from fitted track, reducing the ^{40}K noise contribution to a few per event (from an initial of ~200)
- From the first hits projection estimate the neutrino vertex
- The last hit define the track end

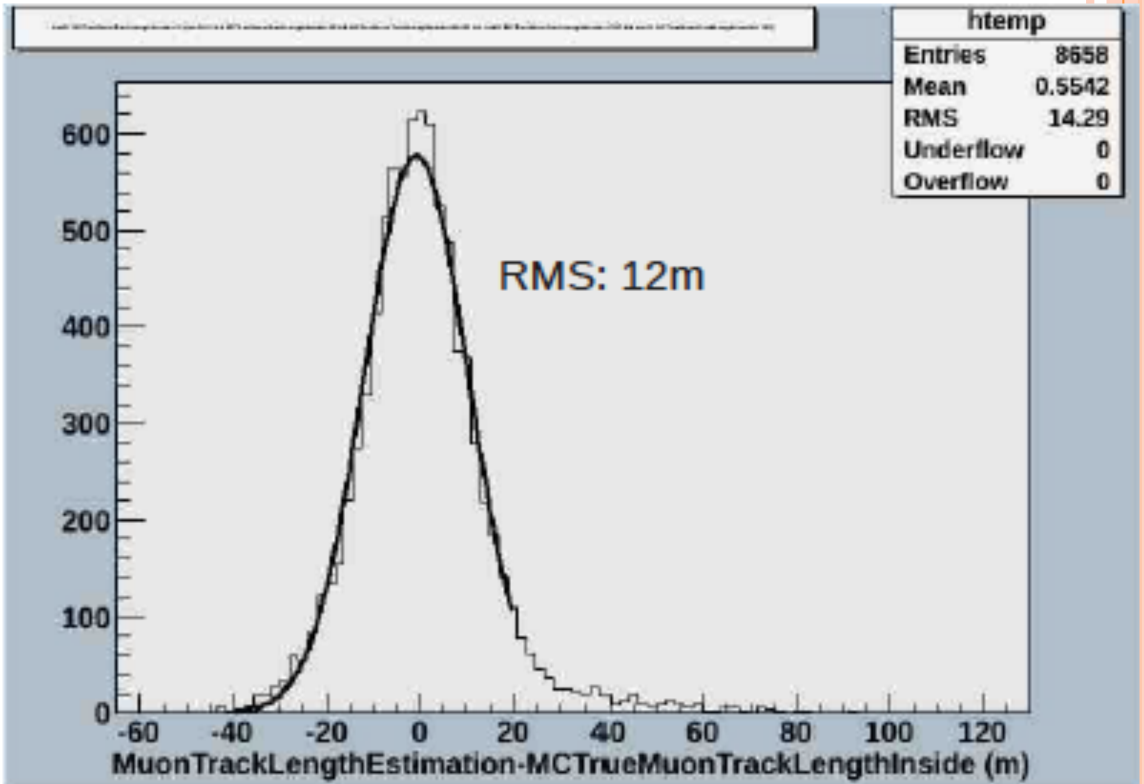




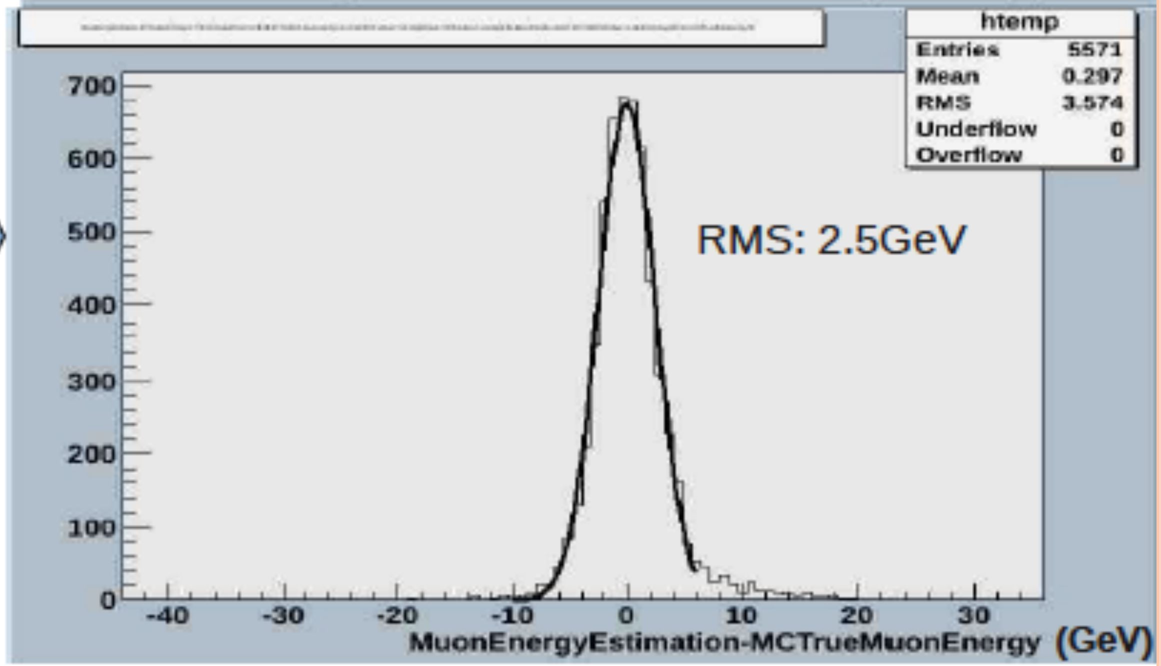
Muon track length estimation and energy reconstruction

Contained events with MC true
muon track length>20m
(~5GeV muon energy)

Muon track length resolution
For fully contained events



Muon energy estimation resolution
for fully contained events



work
under
progress

Neutrino energy reconstruction
(global fit)

To do List

- Valutazione della influenza della wave form analysis nella risposta in carica dei PMT
- Scorporare la parte di trigger dalla parte di ricostruzione
- Ricostruzione ottimizzate per le basse energia
- Ricostruzione in energia o definizione di parametri sensibili all'energia
- Ricostruzione di sciami elettromagnetici per la rivelazione di ν_e
- ……

- Codici modificati per apparati "misti": es. Stringhe con multi-PMT + torri con PMT grandi

ORCA To do list

- 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!

Kouchner

- Probabilità di oscillazione (Vissani....)
  - Errori sistematici da conoscenza delle proprietà neutrini
  - Errori sistematici da Earth model
- Simulazione di muoni atmosferici - stima del livello di contaminazione (Bologna)
- Normalizzazione flusso atmosferici
- Contaminazione da νe (Carla??....)
  - Indeterminazione sul flusso neutrini elettronici atmosferici
  - Ricostruzione di sciami elettromagnetici per la rivelazione di ν_e
- Ricostruzione in direzione ed energia ν_μ (Agata....)
- Ricostruzione energia di sciami adronici
- Trigger & Veto (neutrini atmosferici mal ricostruiti come contenuti, muoni atmosferici, μ_{atm}, ν_e.....)
- Ottimizzazione geometria
- Apparati misti (tower10" PMT & string DOM)