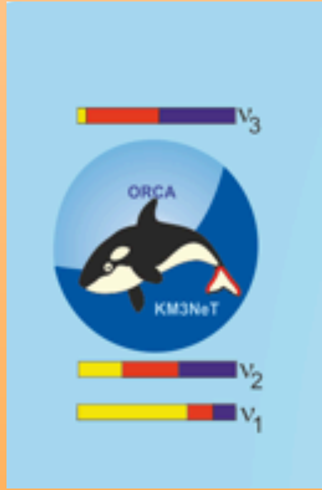
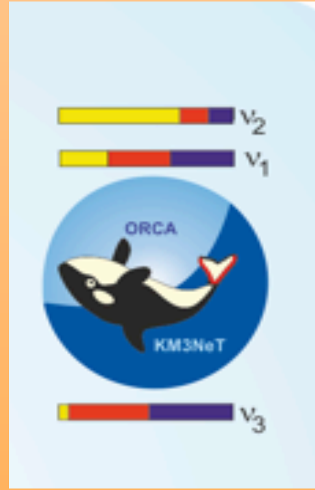




ORCA: Oscillation Research with Cosmics in the Abyss

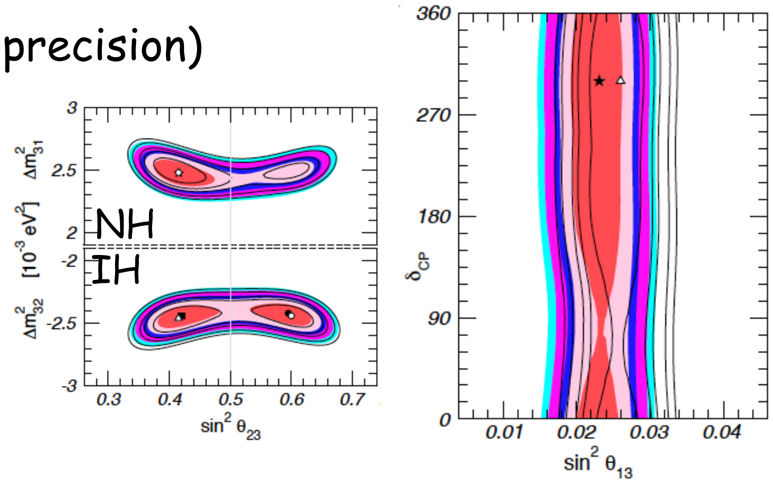
V. Van Elewyck (APC & Université Paris diderot)

Reminder on the motivations

✓ All neutrino mixing parameters known (with fair precision)
✓ θ_{13} is « large » !

❖ Next steps: - δ_{CP} phase
- neutrino mass hierarchy (NMH)

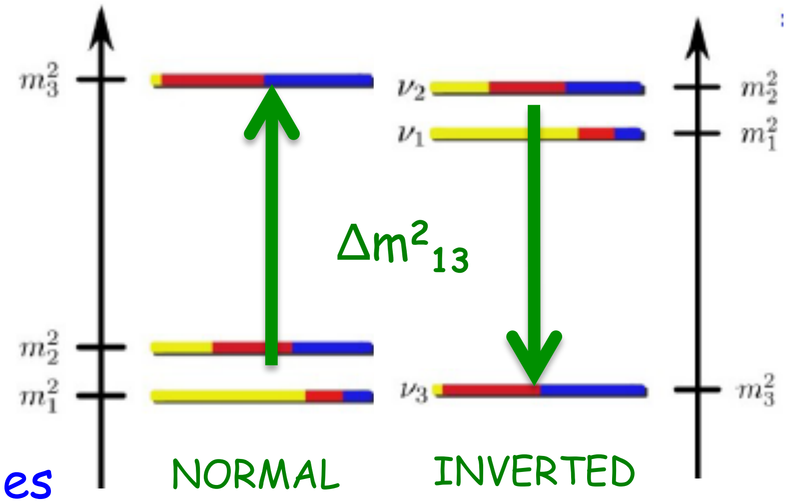
→ neutrino mass pattern, origin of flavour
→ important impact on LBL, $\beta\beta0\nu$ experiments (also for δ_{CP} measurement)



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

Strategy: probe ν_μ ←→ ν_e governed by Δm^2_{13}
+ need matter effects
to resolve the sign of Δm^2_{13}
maximal enhancement at resonant energy

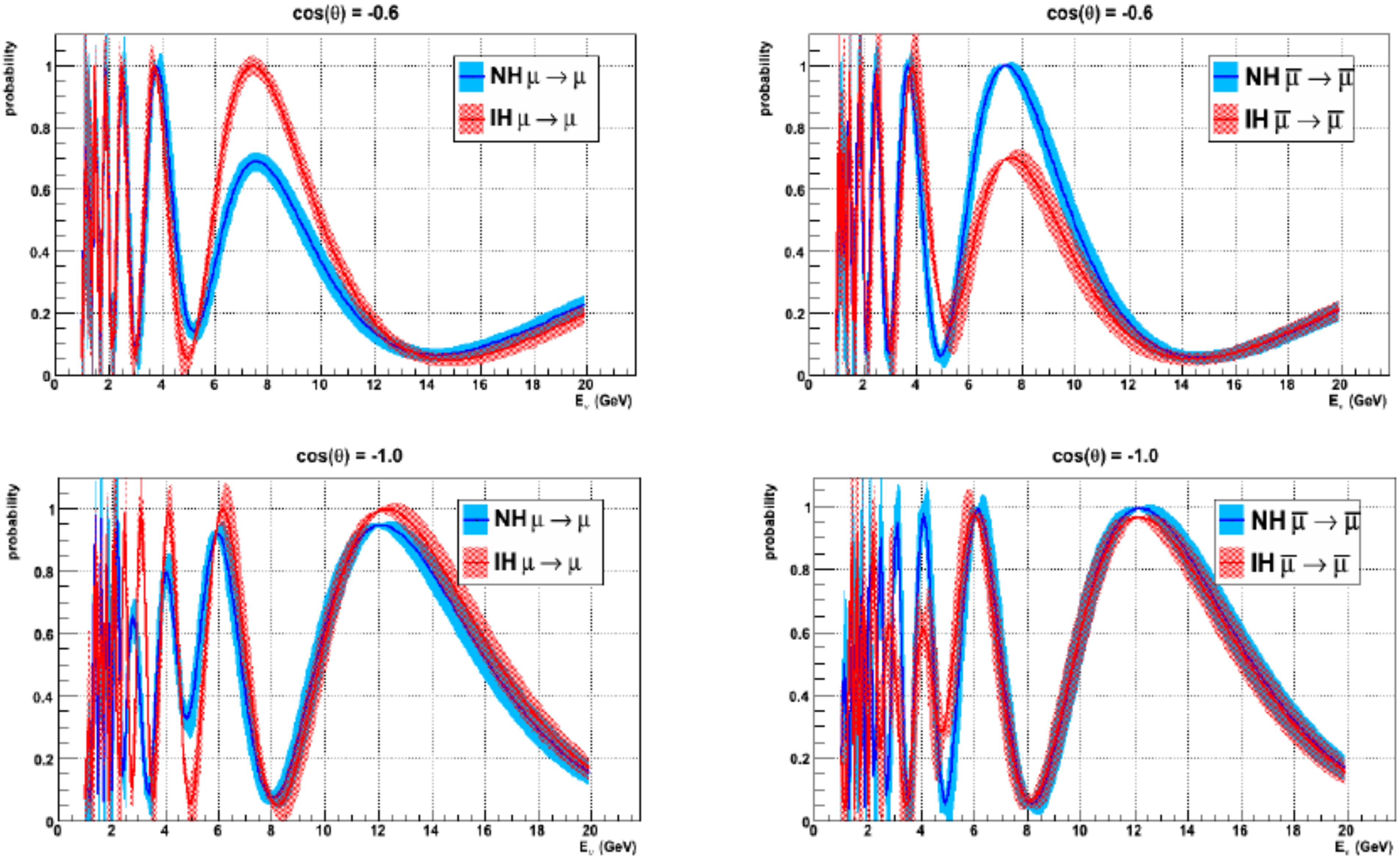
$$E_\nu^{res} = \pm\frac{\Delta m^2_{13}\cos(2\theta_{13})}{2\sqrt{2}G_F N_e}$$ ≈ few GeV for Earth densities



prospects for long-baseline and atmospheric neutrino experiments !

Reminder on the motivations

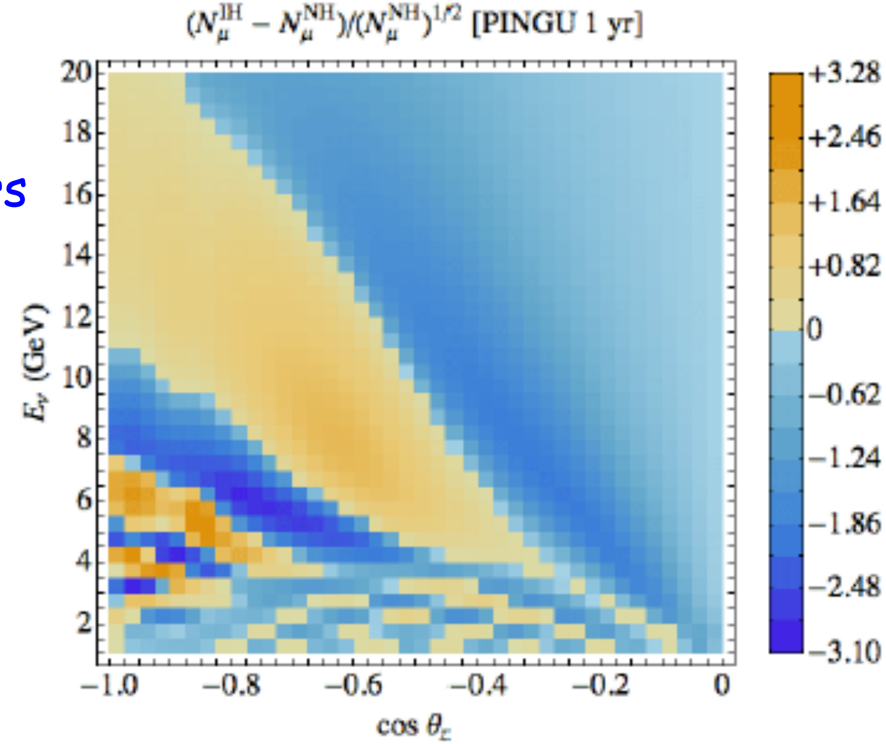
Main target: muon neutrino disappearance (CC channel: muon tagging)



…need matter effects AND difference in cross-sections (& fluxes) for ν and ν̄ !

Reminder on the motivations

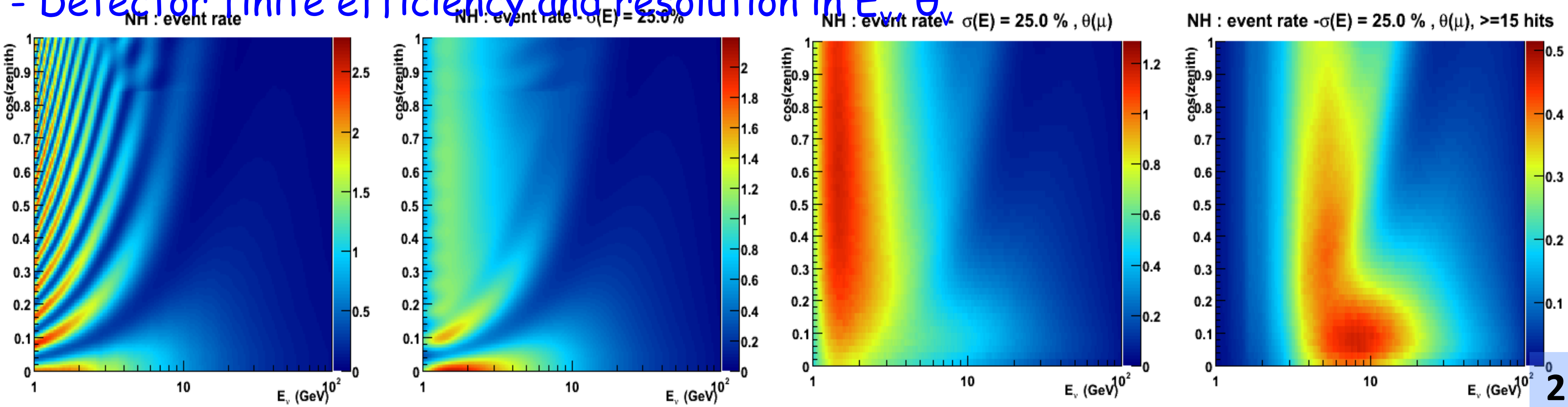
➡ differences in (E_ν, θ_ν) oscillograms make it possible to identify NMH in underwater/ice Cherenkov detectors



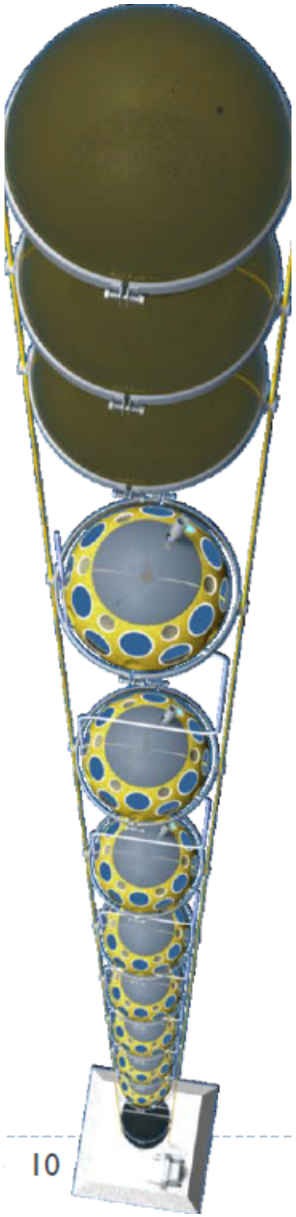
Example with PINGU-like detector:
(perfect resolution, large effective volume)

Akhmedov, et al. JHEP 02 (2013) 082

…BUT
- Uncertainties: atmospheric neutrino fluxes
  oscillation parameters
  Earth matter effects
- Kinematic smearing ν → μ (few degrees)
- Detector finite efficiency and resolution in E_ν, θ_ν



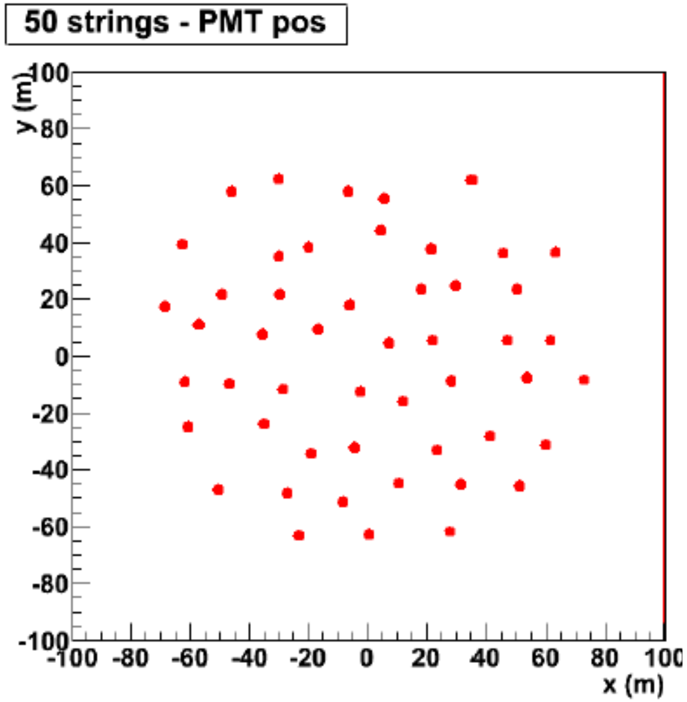
The ORCA detector



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

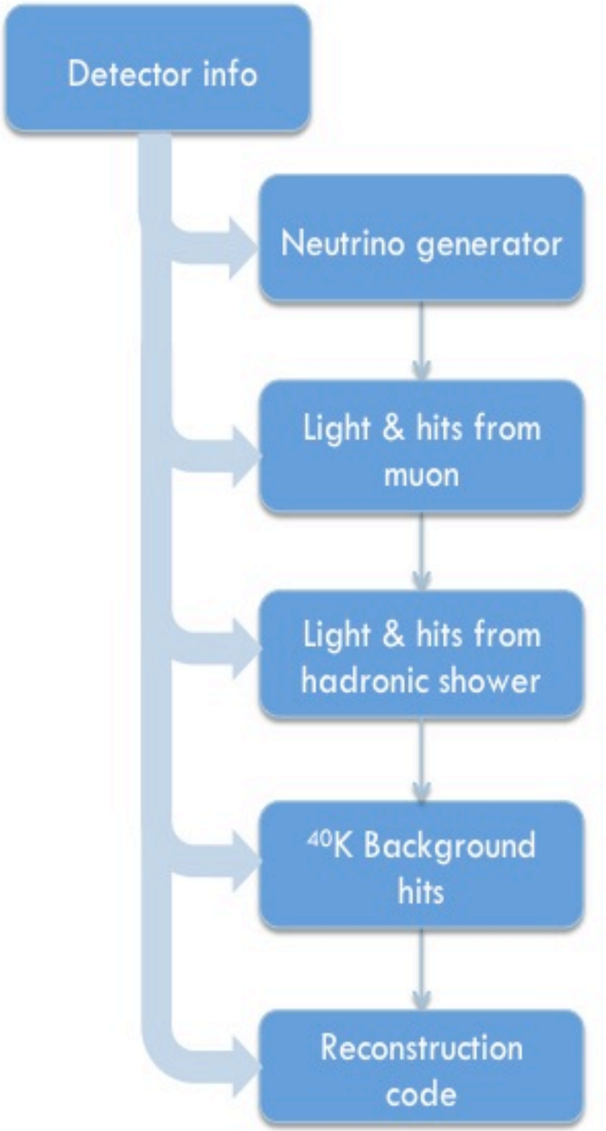
Instrumented volume:

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



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

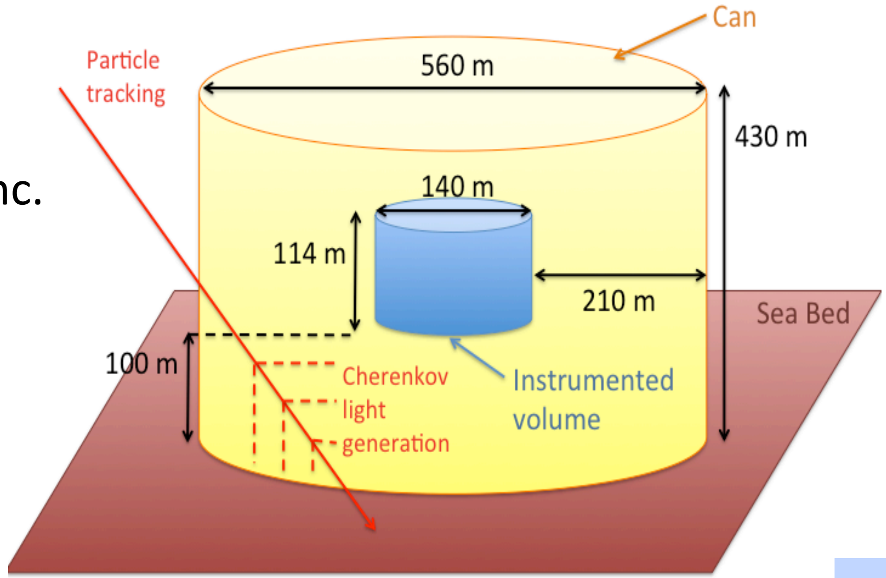
The ORCA detector: simulation chain



atmospheric $\nu_e + \nu_\mu$ (+anti) 1 – 500 GeV (Bartol flux)
neutrino interaction: QE+RES+DIS (GENHEN)

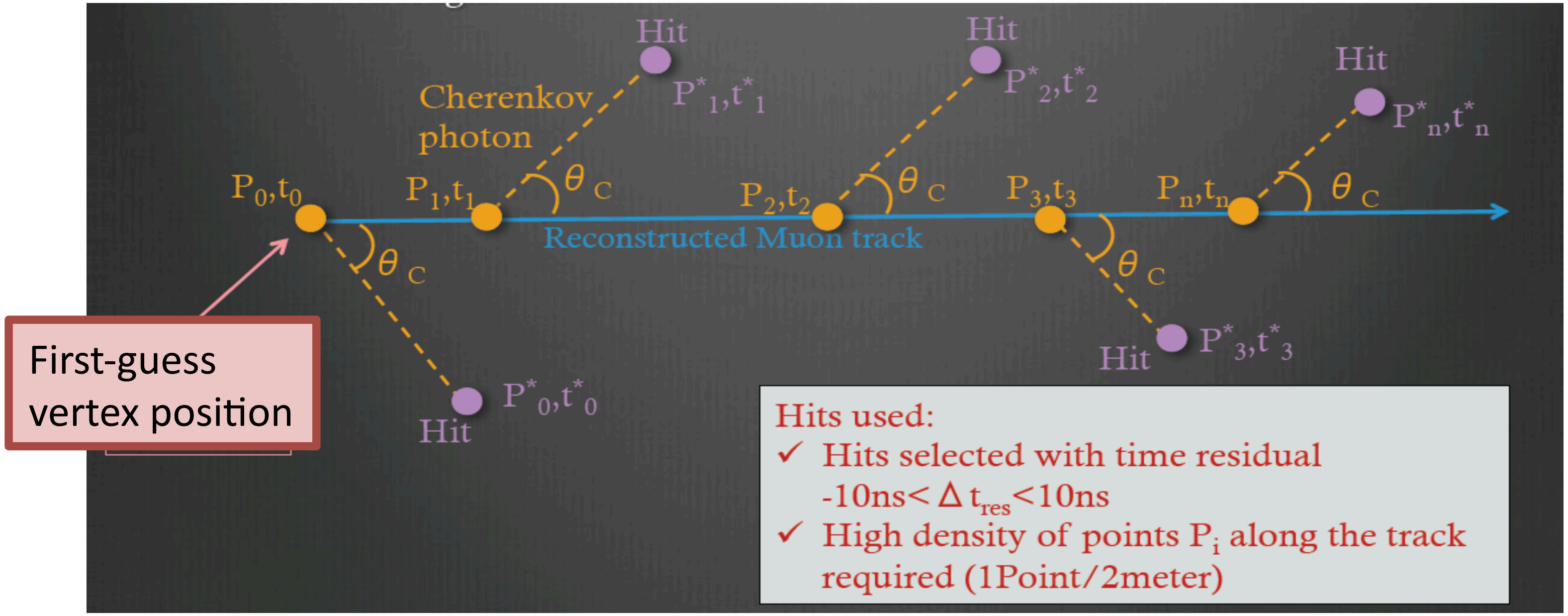
For all particles crossing the can volume:
tracking + Cherenkov light emission
(muons → km3, all others → GEANT3)

Flat noise, 5kHz/PMT
+ 500 Hz in-DOM coinc.
within 20 ns



Reconstruction performances

Good energy/angular resolution required
→ focus on ν_μ CC contained events (track + shower)



1) Muon track reconstruction
+ track length estimation (first/last emission point)

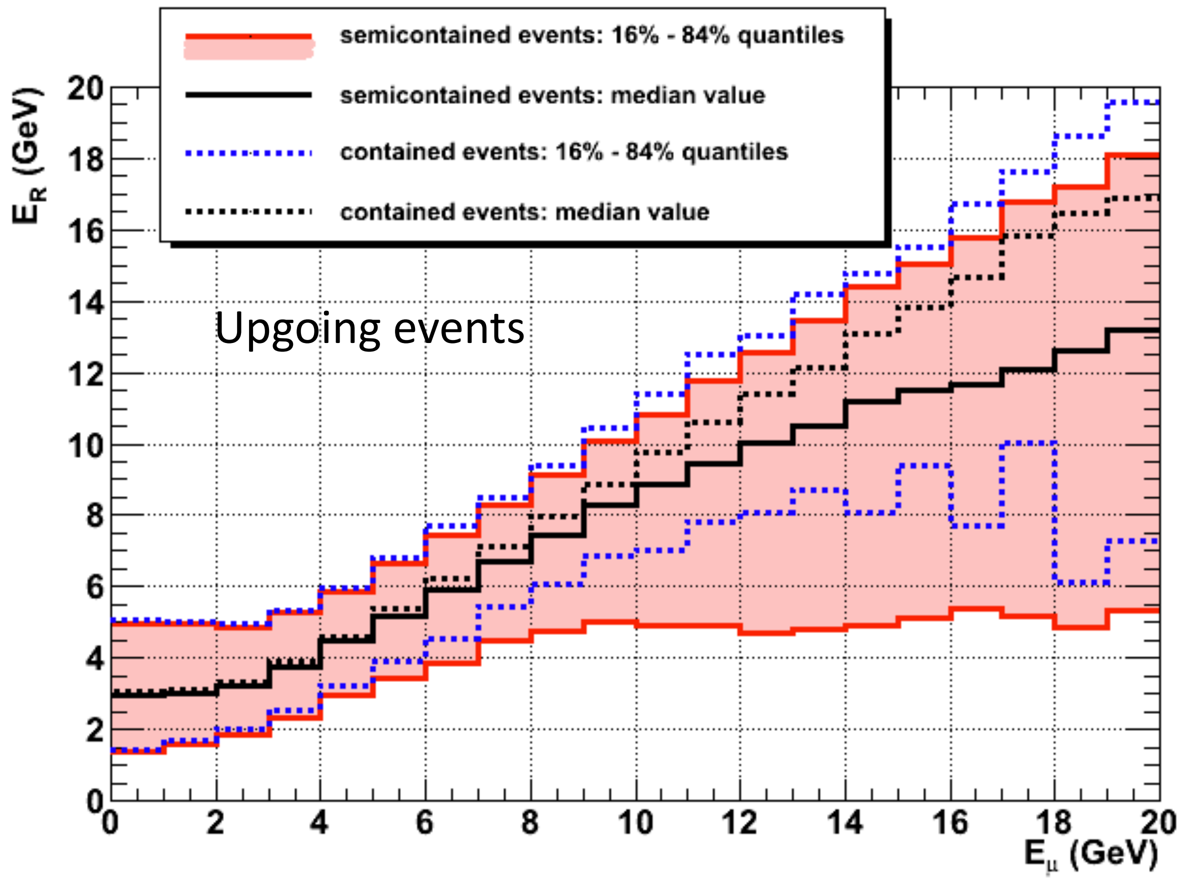
2) Identification of hits belonging to hadronic shower

3) Re-estimation of vertex position (assuming spherically expanding shower)

improved vertex identification
improved track length estimate

Reconstruction performances

Reconstructed energy E_R vs muon energy E_μ



(bands are 1σ range, black lines are median per energy bin)

Muon energy estimate most reliable for fully contained tracks

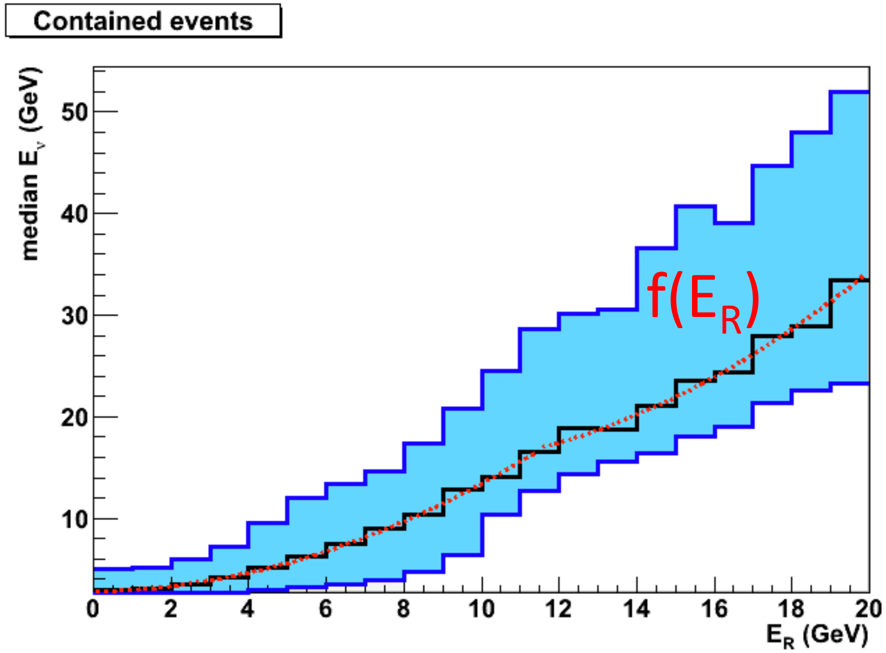
→ need study on containment condition, veto ?

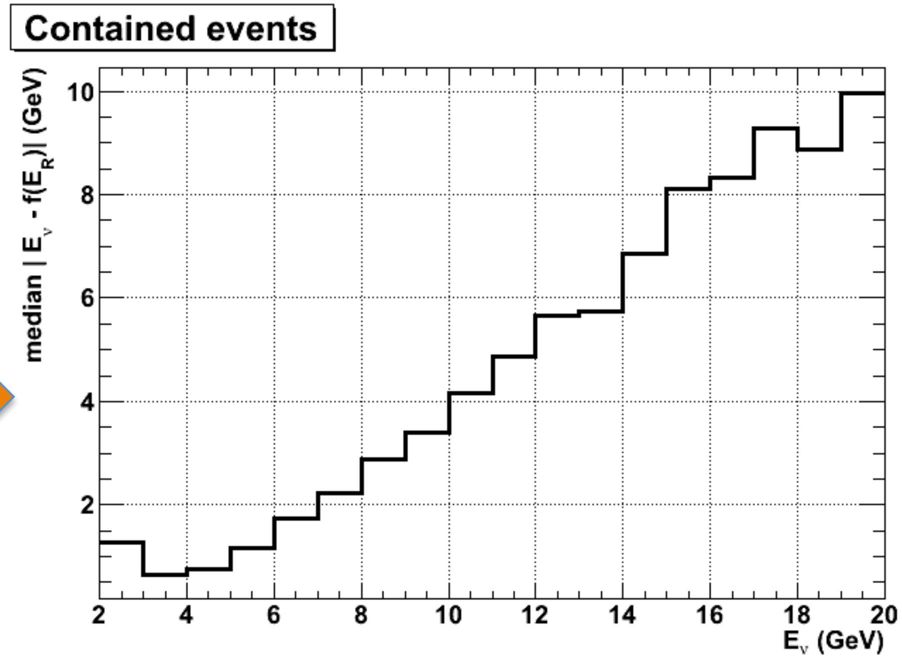
see detector optimisation, background rejection

→ need estimation of shower energy (inelasticity) to obtain neutrino energy

Reconstruction performances

Reconstructed energy E_R vs neutrino energy E_ν



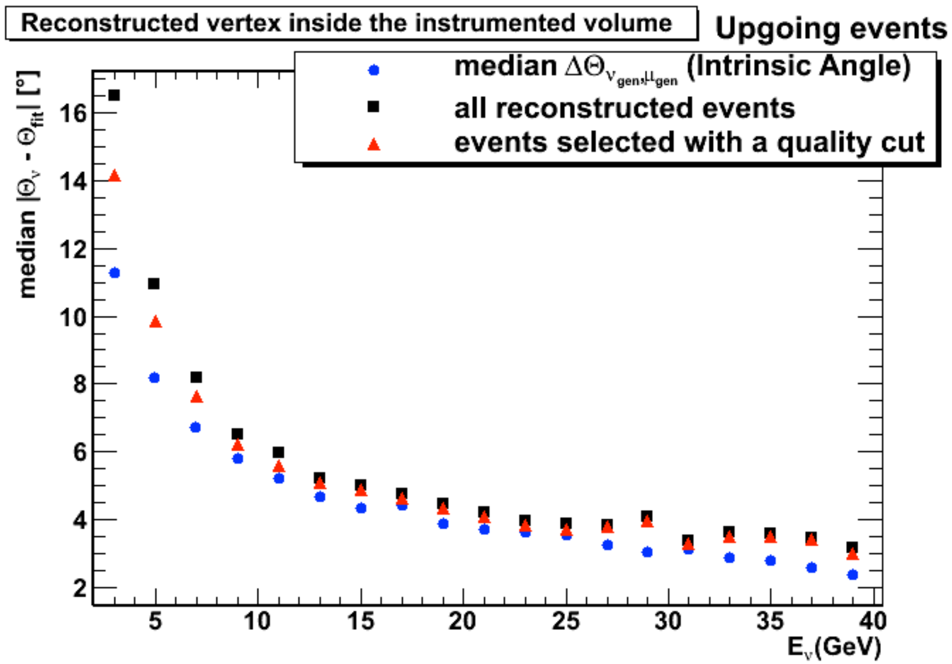


Muon energy estimate most reliable for fully contained tracks

- need study on containment condition, veto ?
  - see detector optimisation, background rejection
- need estimation of shower energy (inelasticity) to obtain neutrino energy

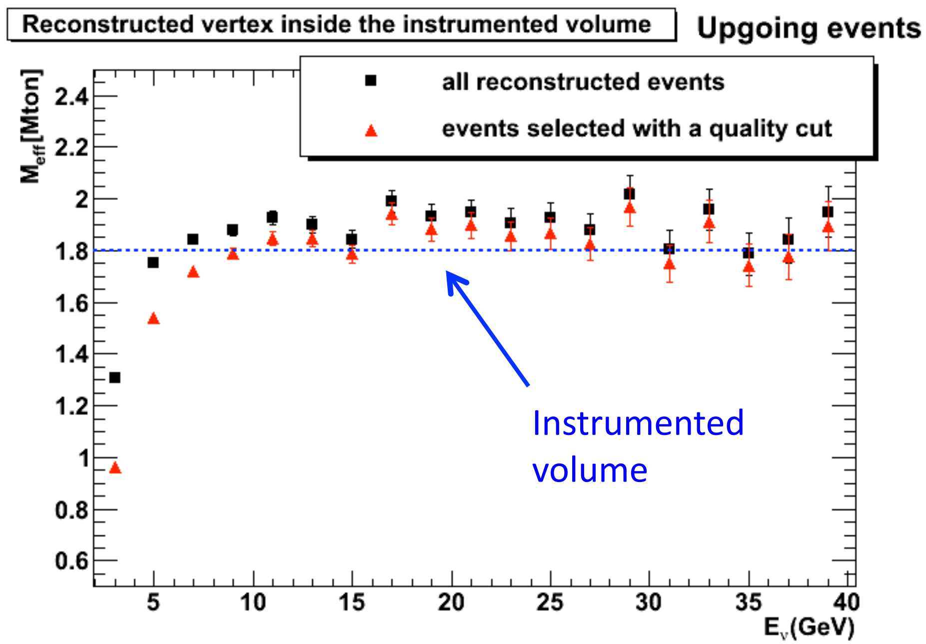
Reconstruction performances

ANGULAR RESOLUTION



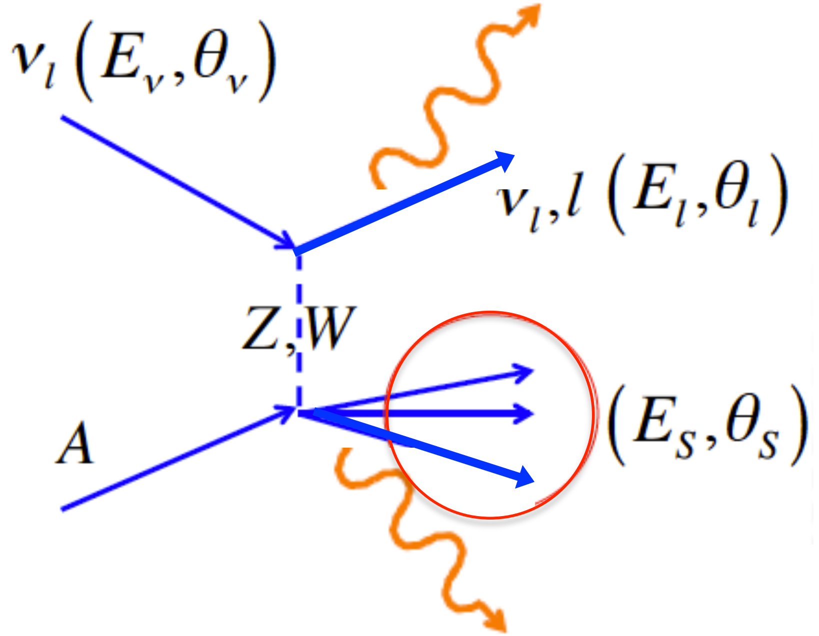
better than 10° for $E_{\nu} \geq 5$ GeV

EFFECTIVE VOLUME



almost flat for $E_{\nu} \geq 8$ GeV

Intrinsic limitations



Physical processes:

-Vertex physics
- particle propagation
- Cherenkov light emission

…accessible
only via the detected photons:
number ~ energy
direct photons ~ direction

Impact of intrinsic limitations (assuming every photon is detected) ?

- Muons (CC): fluctuations in track length (→ energy) and direction

- Showers (NC/CC): particle production at vertex, cascade composition, energy/momentum of recoil nucleus…

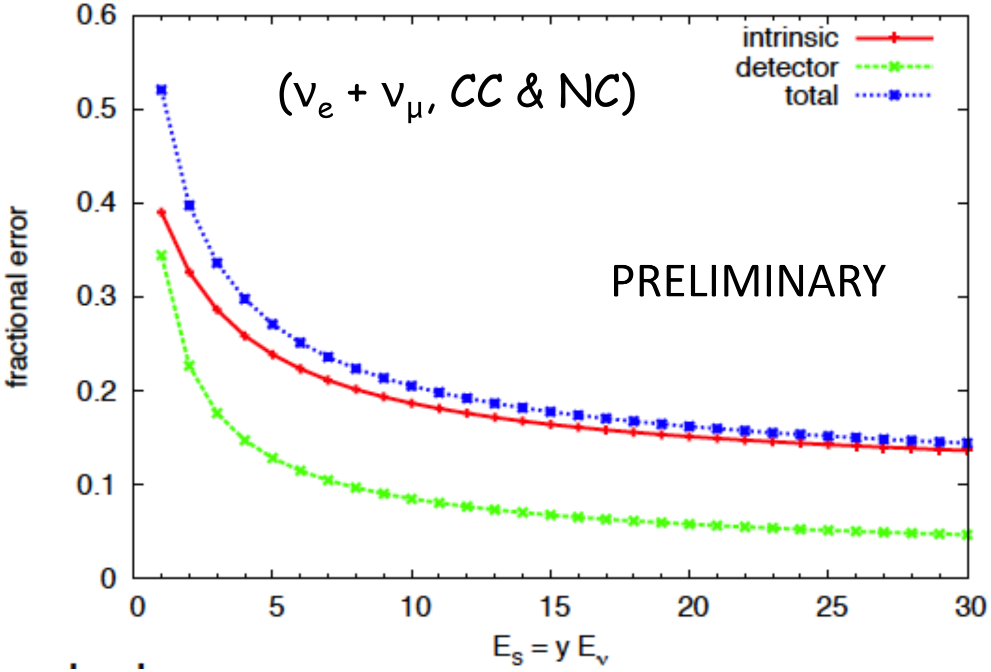
- fluctuations in Cherenkov yield

Intrinsic limitations

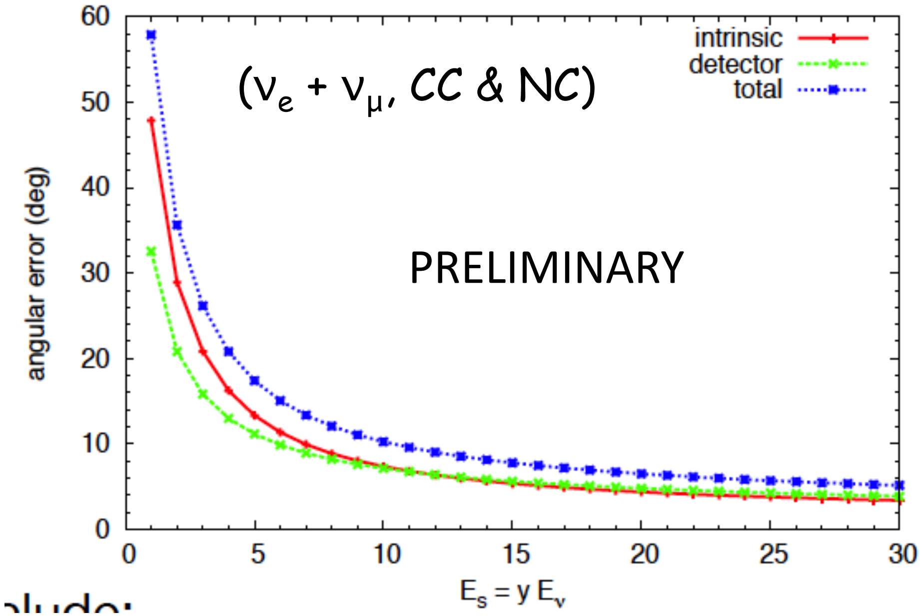
- Muon track length fluctuations (PRELIMINARY):
  - ~ 8% muon energy resolution
  - ~ 4° mean angular deviation at 10 GeV

-Shower-to-shower fluctuations:

Error on the energy reconstruction



Error on the angular reconstruction



Shower energy reconstruction intrinsically limited: ~ 50% at 1 GeV
~ 20% at 10 GeV

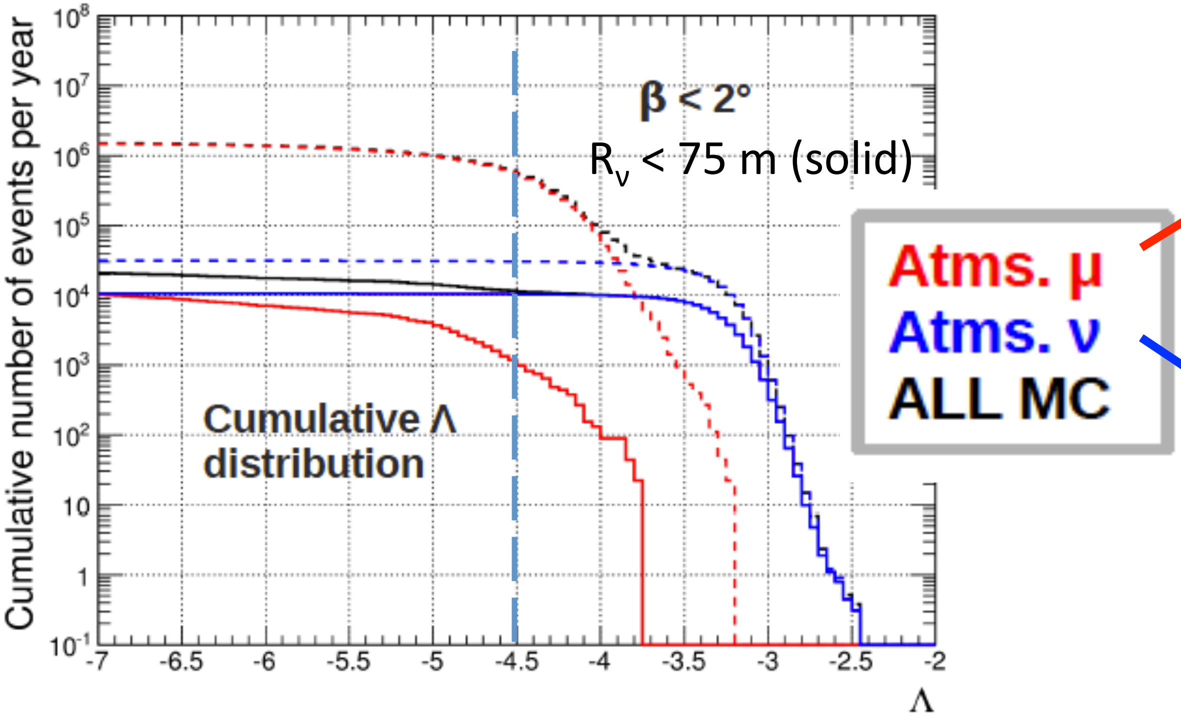
Shower angular reconstruction: detector efficiency also matters !

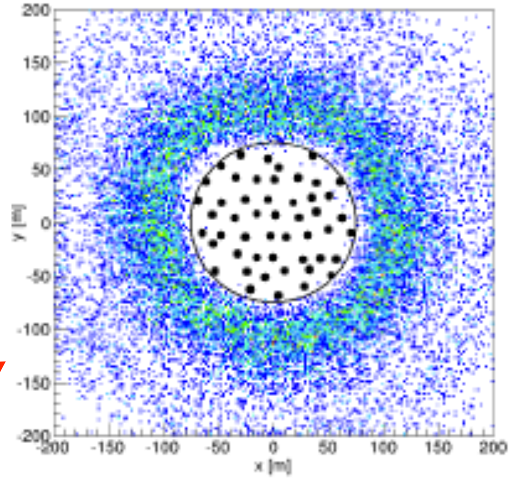
Background rejection

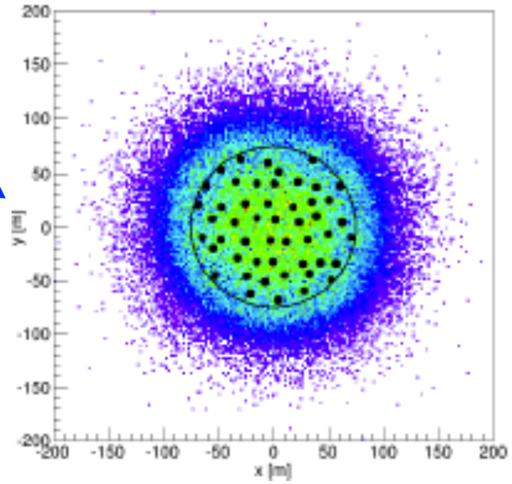
Main backgound: atmospheric muons misreconstructed as upgoing

Efficiently suppressed by cuts on

- angular error estimate: $\beta < 2°$
- track fit quality parameter: $\Lambda > (-4.5)-(-4.8)$
- reconstructed position of vertex: $R_v < 75\text{-}80$ m (from detector centre)







10% muon contamination for $R_v < 75$ m, $\Lambda > -4.5$
(1% for $\Lambda > -4.0$)

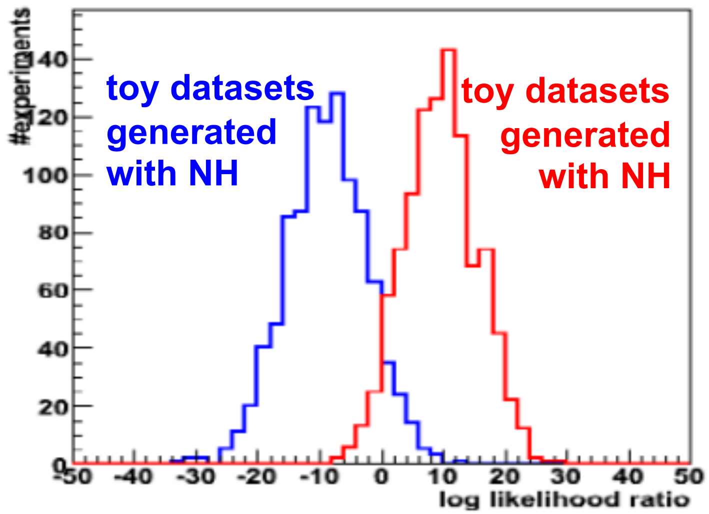
Sensitivity studies

Global fit approach

likelihood ratio test *with nuisance parameters:*

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

$\hat{\theta}^{\text{H}} =$ 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



(example shown is for 10 Mt*yr)

the fitting procedure allows to extract the value of the oscillation parameters !

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

← current knowledge

Good sensitivity to Δm^2_{large} & θ_{23}: x2 improvement with only 1 Mt yr!

7

Sensitivity studies

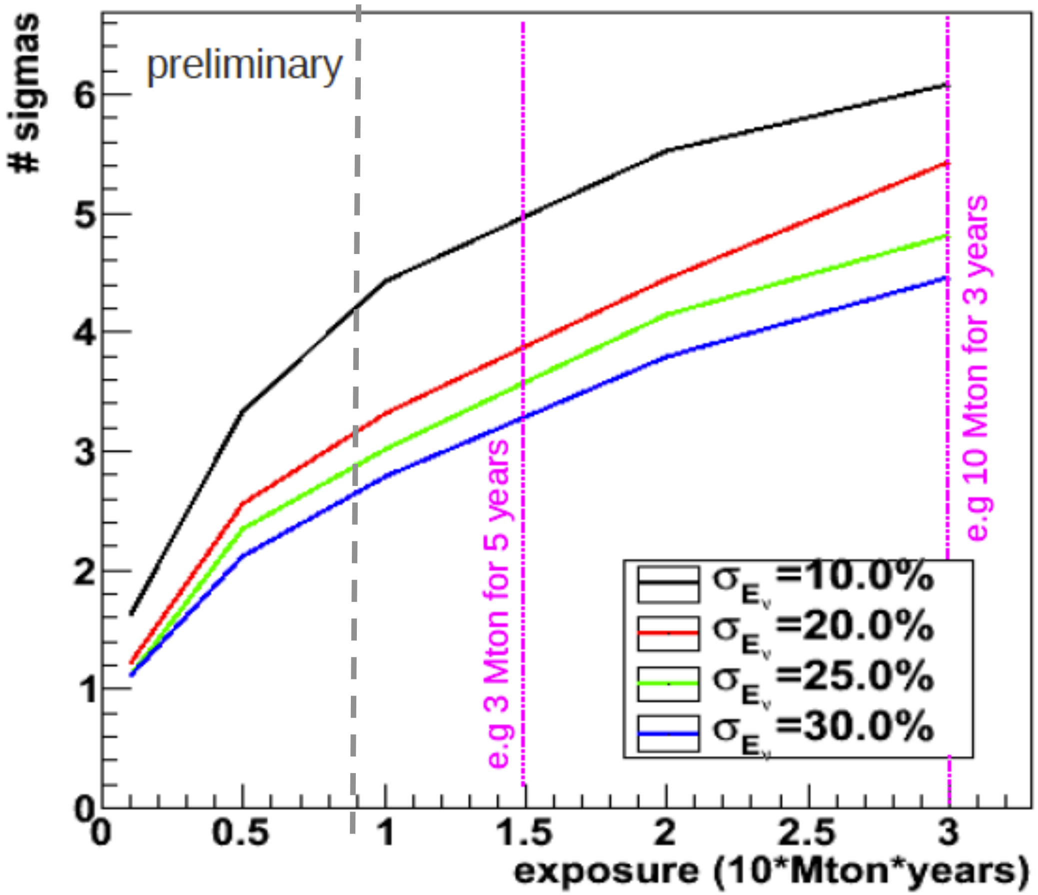
Projected sensitivity:

2.5 → 4σ in 5 yrs with reference detector (depending on reconstruction performances)

> 3σ in 5 years with a 3 Mton detector

With a 10 Mton detector:
3σ after 1 yr
5σ after 3 yrs
(provided 20% energy resolution can be achieved)

significance E =1-100 GeV (50% chance)



Estimate made on basis of educated guesses
-- to be reevaluated with actual detector performances !

Sensitivity studies

Toy Monte Carlo approach

Statistical method:

1) generate pseudo-experiments with a fixed true hypothesis (NH/IH)

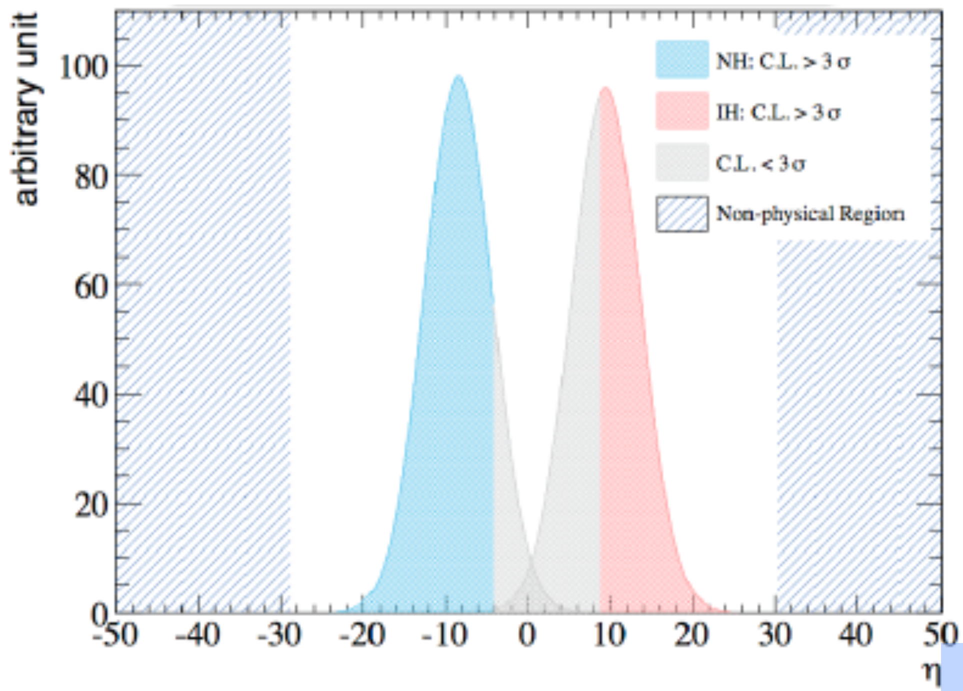
2) For each test model (t=IH,NH) compute extended unbinned likelihood

3) Compute test statistics $\eta = \log(L_{NH}/L_{IH})$

4) p-value for NMH identification at given C.L. α:
fraction of events complying

$$\frac{N_t(\eta)}{N_{\mathrm{NH}}(\eta) + N_{\mathrm{IH}}(\eta)} > \alpha$$

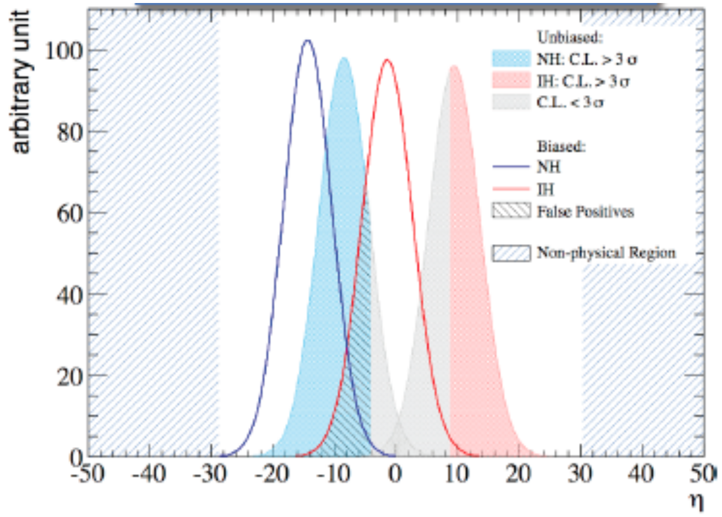
(integrated over all η)



D. Franco et al., JHEP 04 (2013) 008

Sensitivity studies

Toy Monte Carlo approach



Systematics studied by introducing biases in the distributions

If true/model hypotheses have different parameters

→ unphysical results

→ false positives: misidentified hierarchy

IMPACT of…

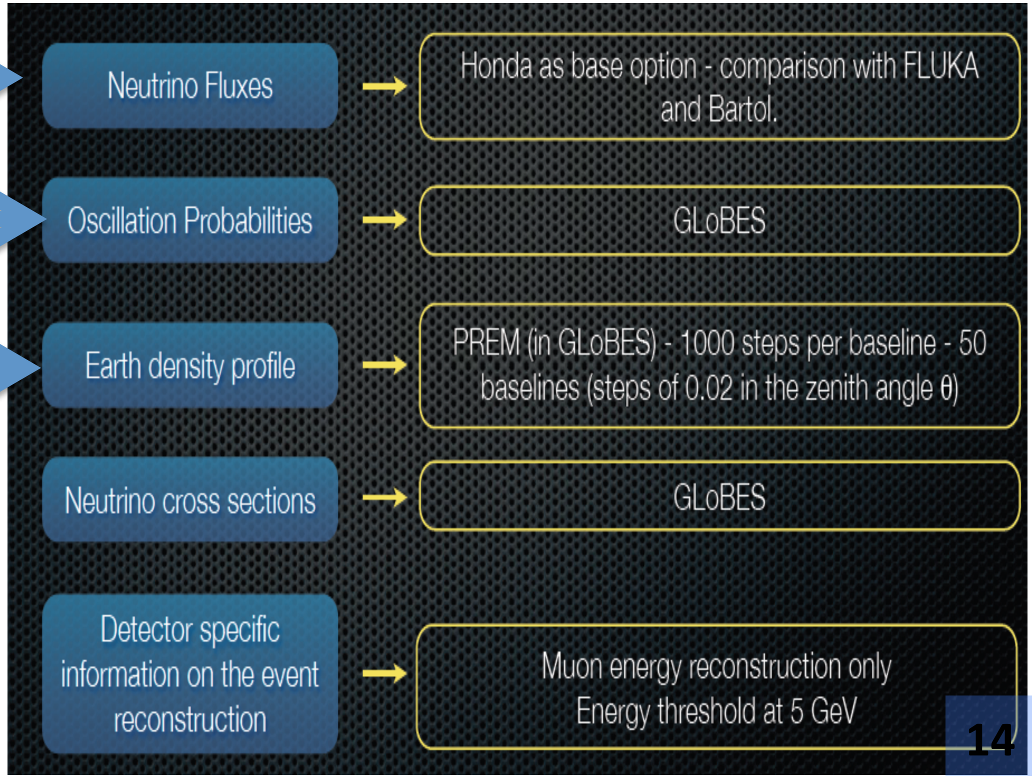
- shape : moderate
- normalization: large (but can be normalized from data)

-Solar (Δm^2_{small}, Θ_{12}), δ_{CP}: weak

-Atmospheric (Δm^2_{large}, Θ_{23}, Θ_{13}): large

almost negligible

(same conclusions shared by many ORCA groups)

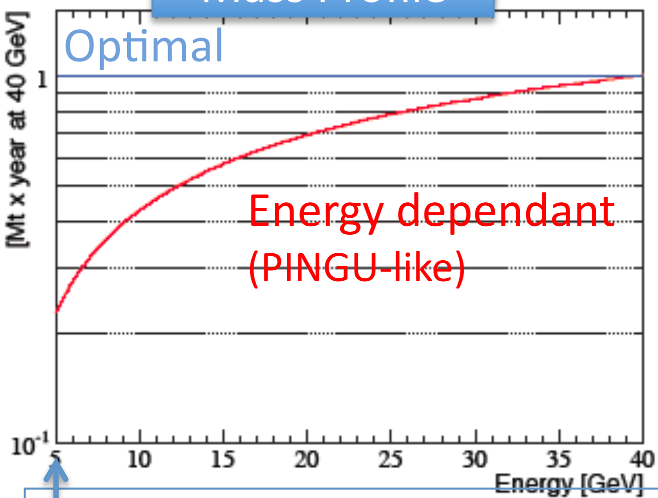


Sensitivity studies

Toy Monte Carlo approach: NMH sensitivity

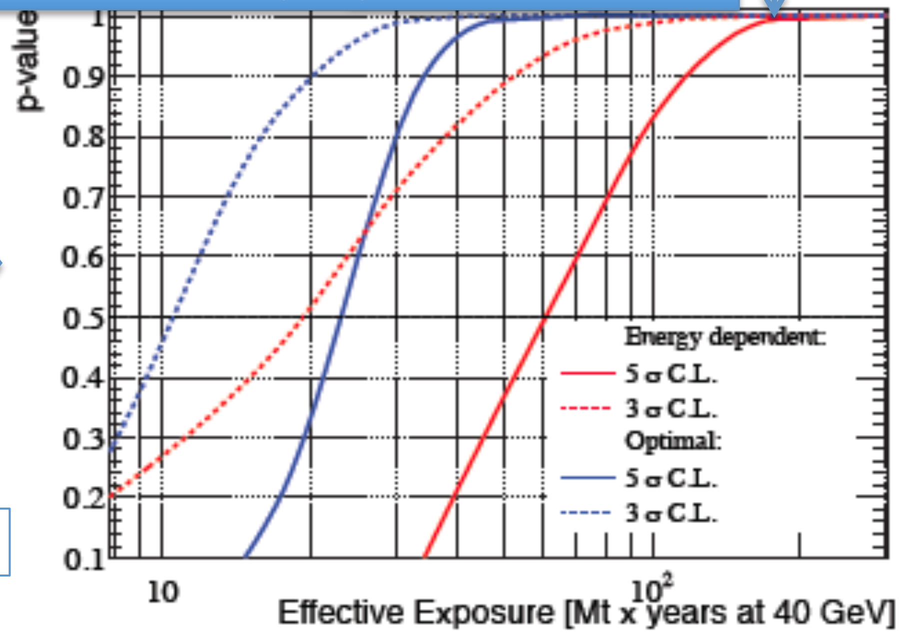
Reference point for further studies p-value~1

Mass Profile

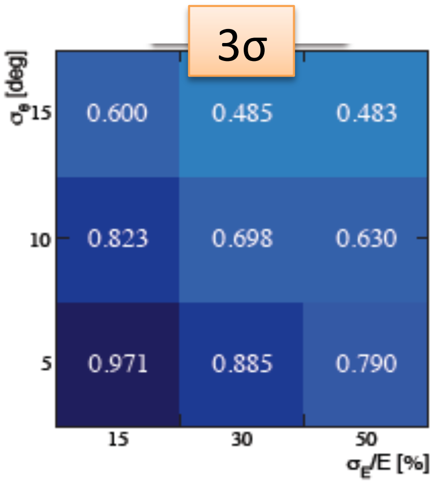


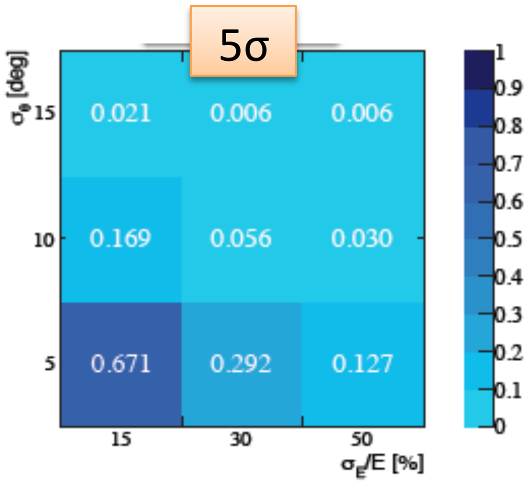
Muon energy reconstruction threshold 5 GeV

Ideal case (no syst, perfect detector)



…BUT degraded by the limited angular/energy resolution of the detector:

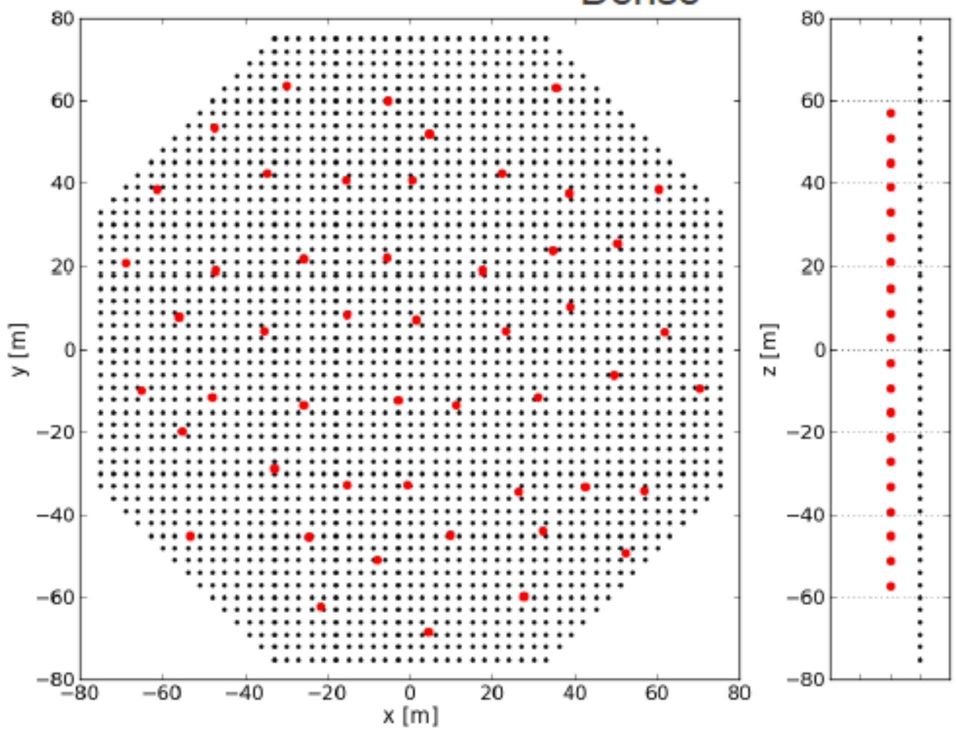




Detector optimisation studies

Full simulation with a dense detector with 3x3x3 m spacing:

2181 strings, 51 DOMs per string
(3.4 x 10^6 PMTs)



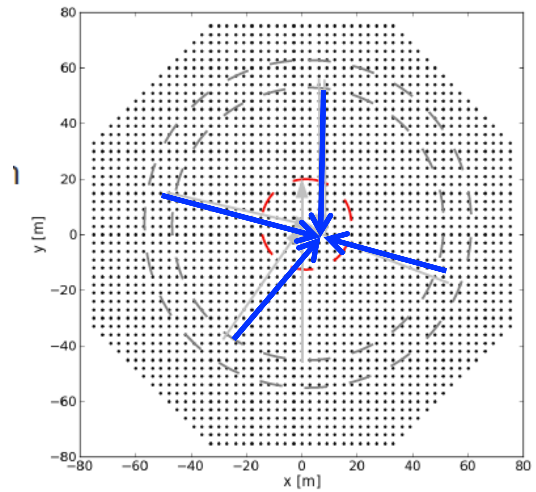
Masking of DOMs to simulate less dense detectors
(shadowing effect ignored in 1st stage)

Full physics simulation:

- Bartol flux 1 – 30 GeV
- GENIE for neutrino interaction
-smaller can to save CPU time
- full GEANT4-based particle & photon tracking

Advantages: - study of various configurations
- (non-)containment/veto studies

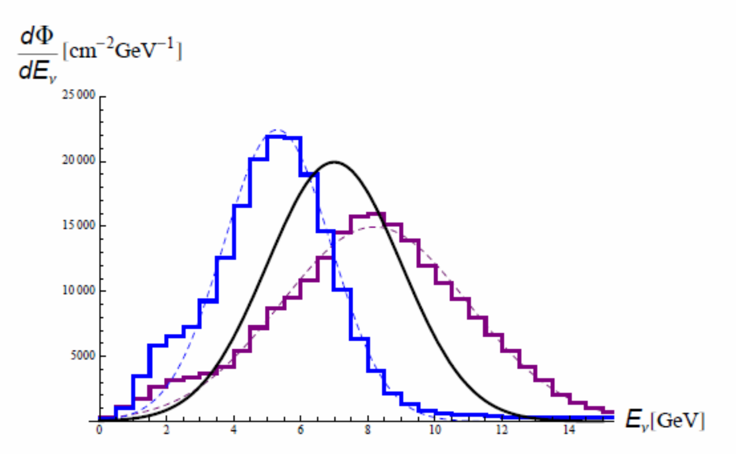
BUT CPU-consumptive !
concentrate on premium events:
most light produced inside the detector



A neutrino beam to ORCA ?

❖ Counting MUONS from a neutrino beam

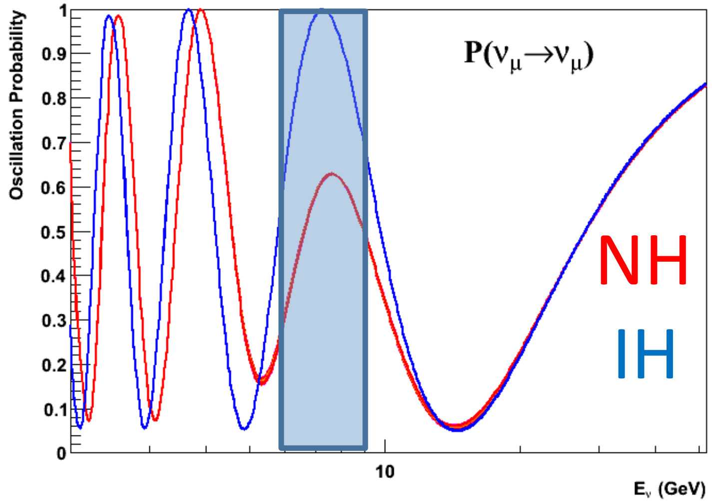
F. Vissani et al., Eur.Phys.J. C73 (2013) 2439



Narrow-band beam 6-9 GeV, 10^{20} pot

Optimal beamline for NH/IH separation: 7000-8000 km

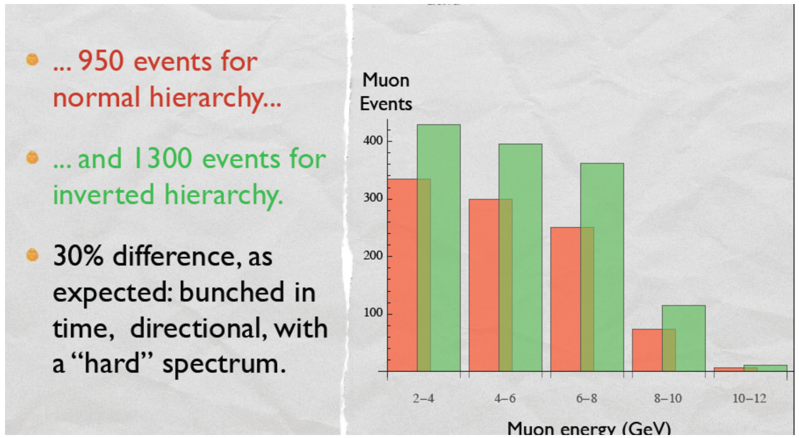
GLOBES cosθ = 0.6, baseline = 7645 km (beam inclination ~37°)



	Fermilab	CERN	J-PARC
South Pole	11600	11800	11400
Sicily	**7800**	1230	9100
Baikal Lake	8700	**6300**	3300

Favoured Option: FermiLab → KM3Net site in Mediterranean Sea

1300 versus 950 events for both mass hierarchy hypotheses in Mton underwater detector (ORCA)



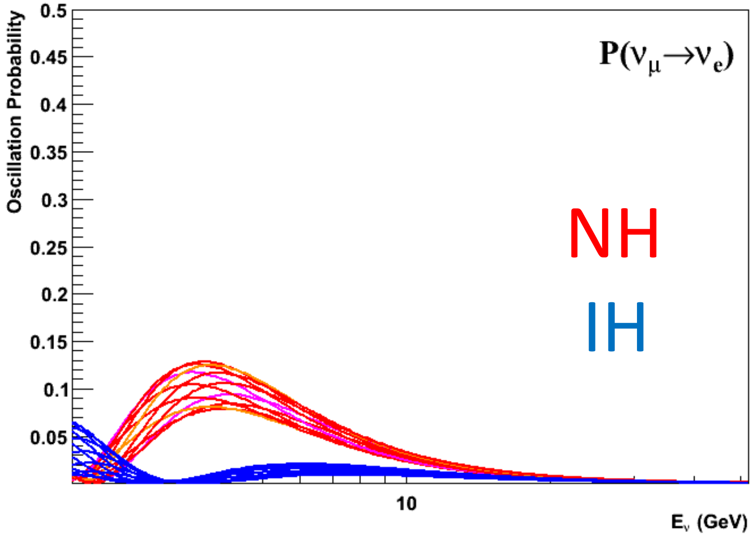
A neutrino beam to ORCA ?

❖ Counting ELECTRONS from a neutrino beam

J. Brunner, arXiv:1304.6230

Optimal beamline for NH/IH separation:
~2600 km (largest difference in event rates)

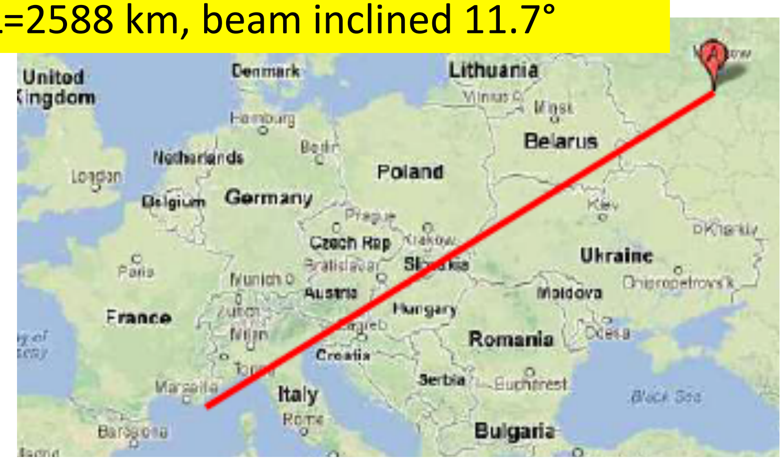
GLOBES $\cos\theta = 0.2$, baseline = 2548 km
(beam inclination ~11,5°)



- moderate inclination
- almost insensitive to δ_{CP}

A possible option: Protvino (Proton Accelerator Complex) → Toulon

L=2588 km, beam inclined 11.7°



need 1.5 10^{21} pot

From preliminary studies:
7σ discrimination in 3 yr from event counting only (3σ with 3-4% systematics)

Summary

❖ Neutrino mass hierarchy measurement with large Cherenkov detectors: probably tougher than originally thought…but possible

need good control of systematics (acceptance, energy/angle measurements, backgrounds, flavour contamination…)

› with 10 Mton detector: 3σ in one year, 5σ in 3 years

› also good sensitivity to oscillation parameters Δm^2_{large} and θ_{23}: x2 improvement on current uncertainty with only 1 Mton yr

❖ ORCA feasibility study ongoing:

- encouraging performances achieved with reference detector (1.75 Mton):
  energy/angular reconstruction (muon tracks)
  atmospheric muon background rejection (→ no need for veto ?)
  flavour discrimination ?
- detector optimization launched

❖ Beam option: complementary to atmospheric measurement
Protvino an option (possible synergy with Modane ? ~4° apart…)

BACKUP

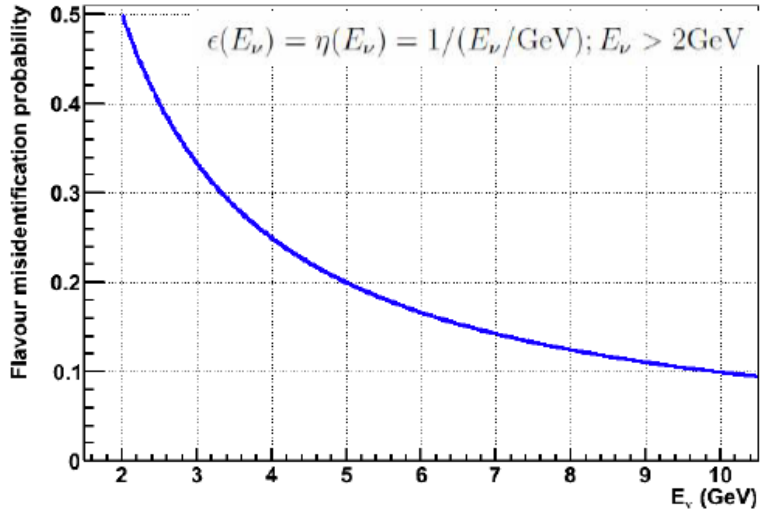
A neutrino beam to ORCA ?

From J. Brunner

- ORCA reference detector, vertex inside instrumented volume

- Same function for all CC interaction
- Same light yield for ν_μ and ν_e
- NC evaluated at E/2

- Flavor misidentification probability based on C2GT project



- Event rates for 10^{21} pot (3 years)

Channel	Tracks NH	Tracks IH	Cascades NH	Cascades IH
No oscil	26315		—	
Signal	8990	8735	1134-1547	350-519
Misreco	232-329	47-79	1326	1280
ν_τ	324-332	351-355	978-998	1057-1068
NC	1092	1092	3640	3640
BG Total	1655-1745	1494-1522	5944-5964	5977-5988
Total	10645-10736	10229-10257	7099-7491	6338-6496

7 σ stat. separation
3 σ with 3-4% sys

No assumption on energy reconstruction

Dark matter

WIMP annihilation in the Sun

Annihilation rate → Fluxes $\frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi d^2} \sum_f BR_f \frac{dN_f}{dE}$

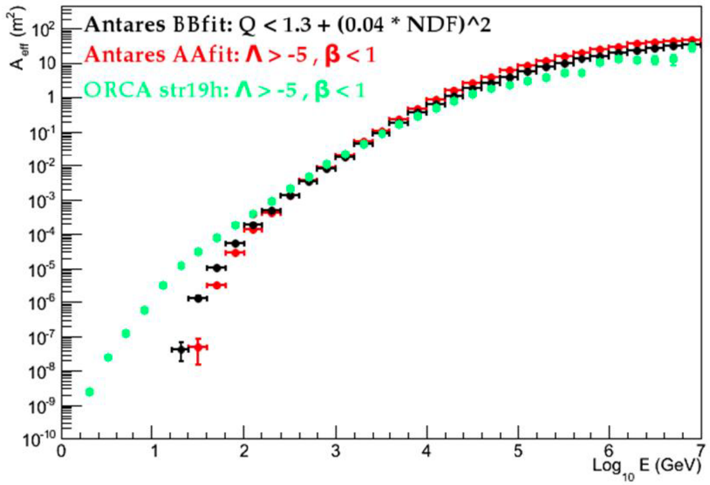
$$\chi\chi \rightarrow \nu\nu, l\bar{l}, q\bar{q}, W^+W^-, ZZ, \text{Higgses, Higgs + gauge}$$

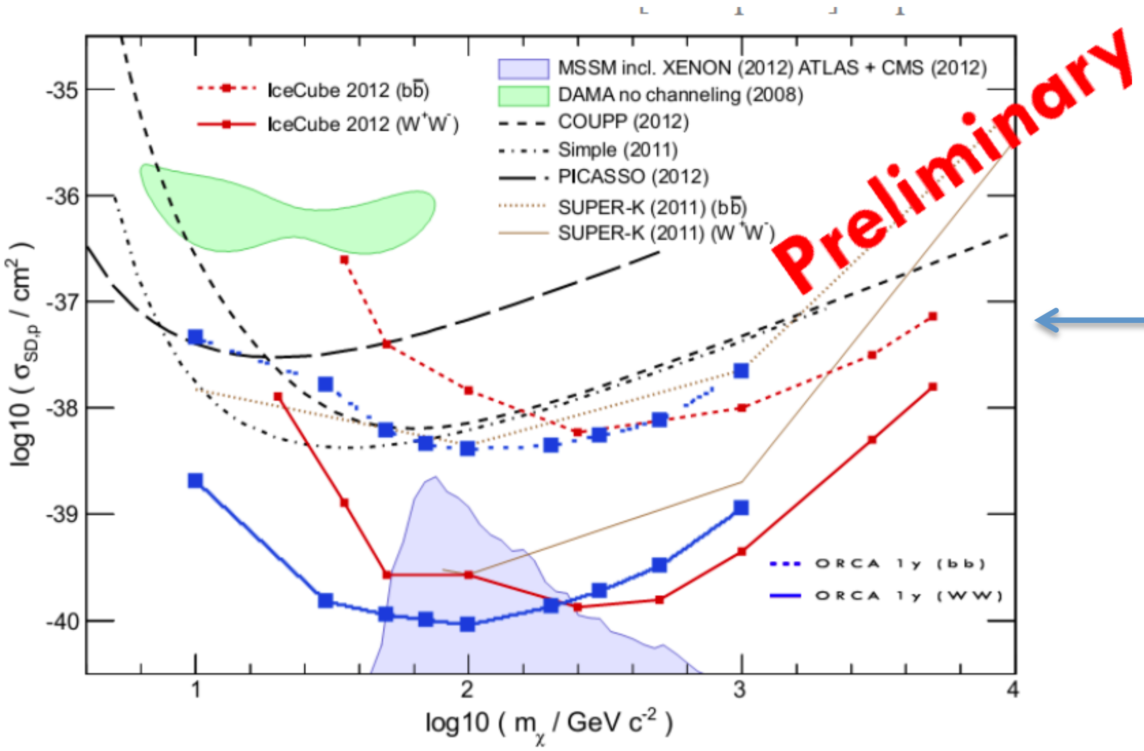
$$\chi\chi \rightarrow b\bar{b} \quad \text{"soft"}$$

$$\chi\chi \rightarrow W^+W^- \quad \text{"hard"}$$

$$\left(\frac{d\varphi_\nu}{d\varepsilon_\nu}\right)_{90} = \frac{< \mu_{90}(b) >}{n_s} \left(\frac{d\phi_\nu}{d\varepsilon_\nu}\right)_{simul}$$

ORCA ref. detector vs ANTARES





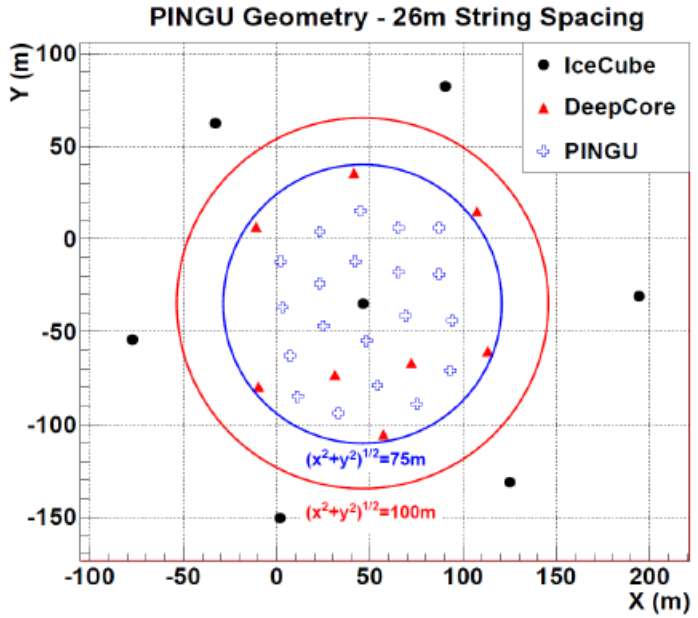
Includes cut to reject atmospheric muons (Bologna sample)

Study by D. Latuada

PINGU

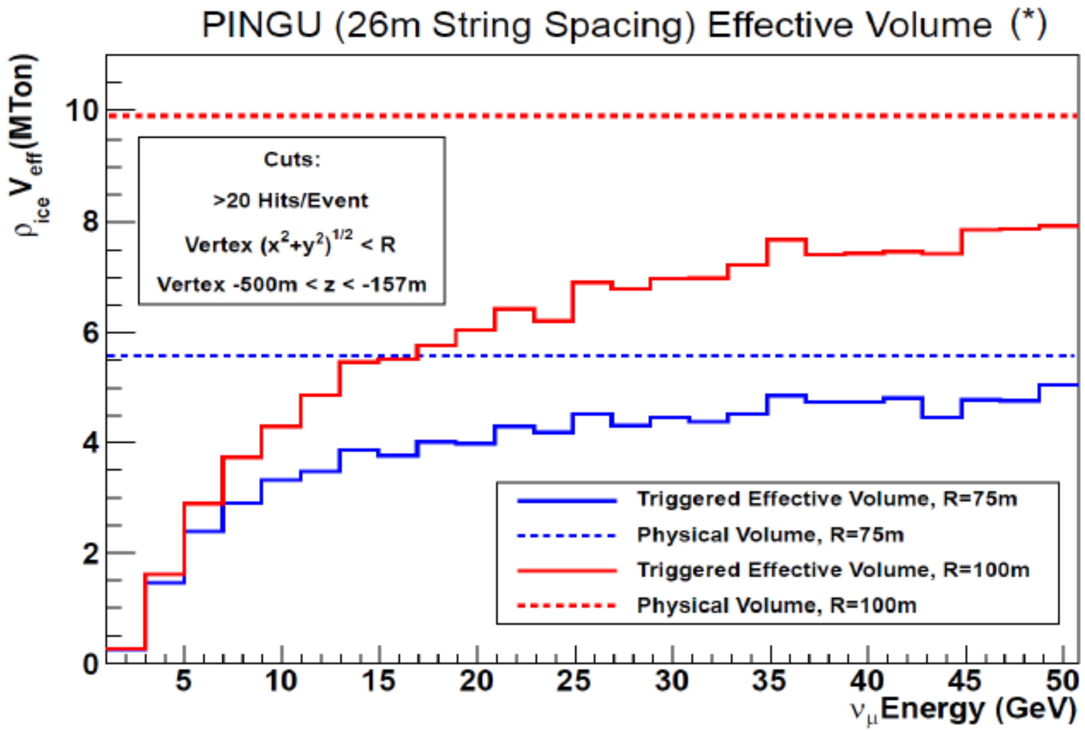
20, 40 string configurations are considered for PINGU.

PINGU string (I/II): 60 / 100 DOMs, spacing: 5 / 3 m



Higher density arrays were also simulated to completely explore the geometry parameter space.

Rezo Shanidze, ORCA meeting, 18/04/2013

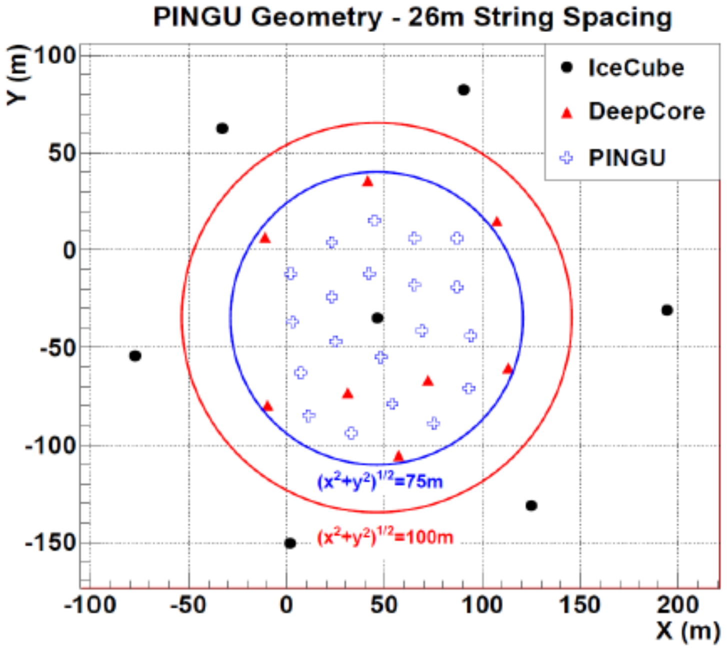


* No reconstruction has been done.
Effective volume will be lower after folding the reconstruction efficiency.

PINGU

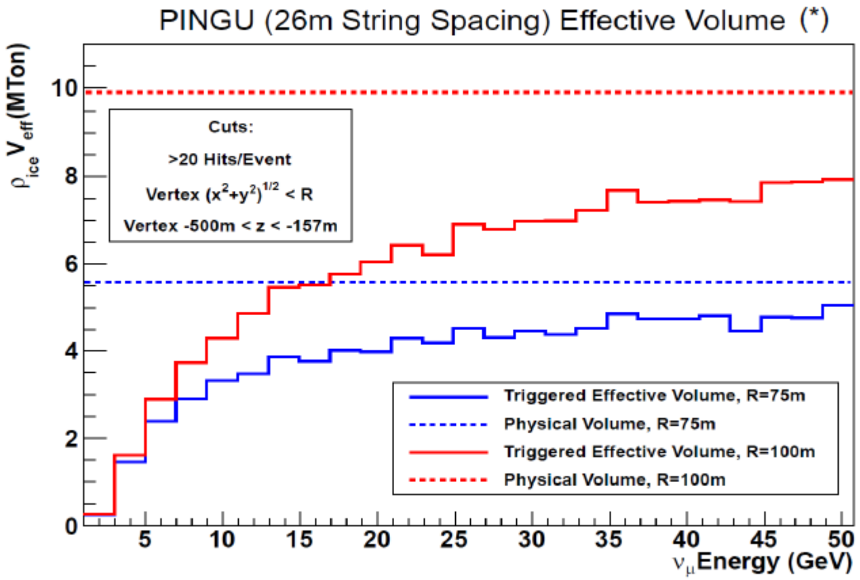
20, 40 string configurations are considered for PINGU.

PINGU string (I/II): 60 / 100 DOMs, spacing: 5 / 3 m

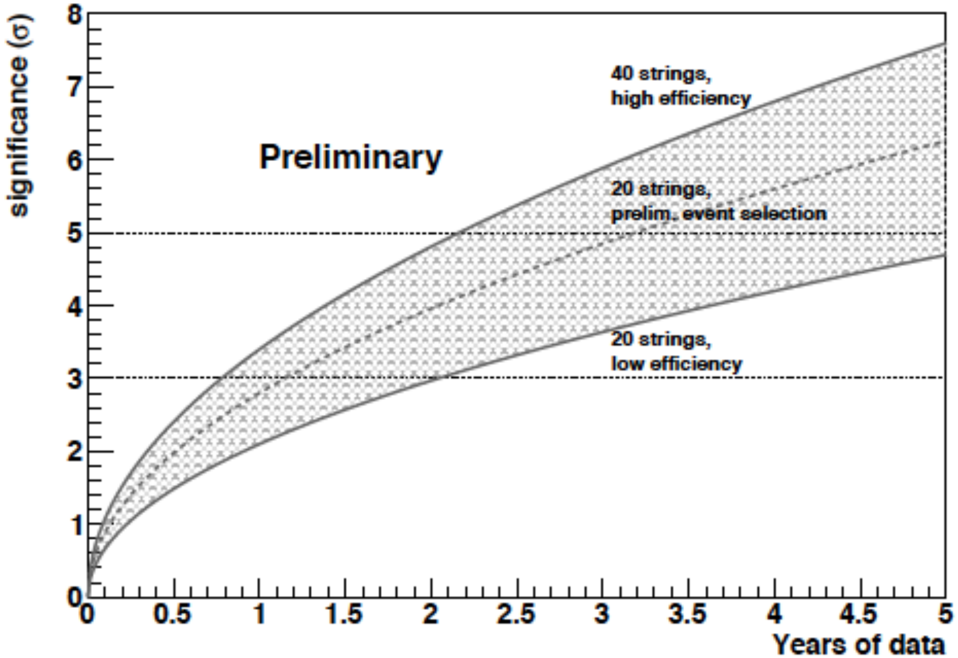


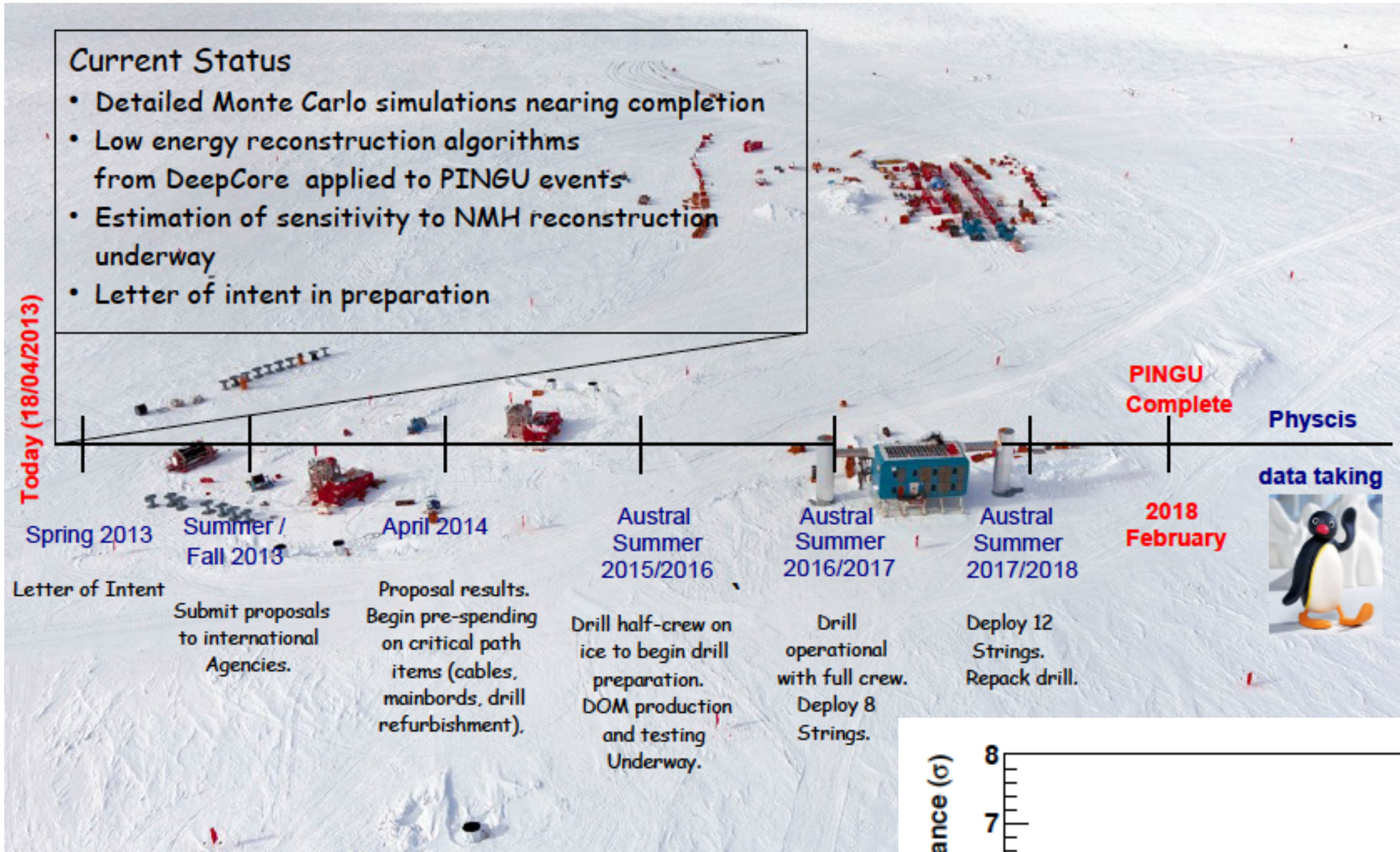
Higher density arrays were also simulated to completely explore the geometry parameter space.

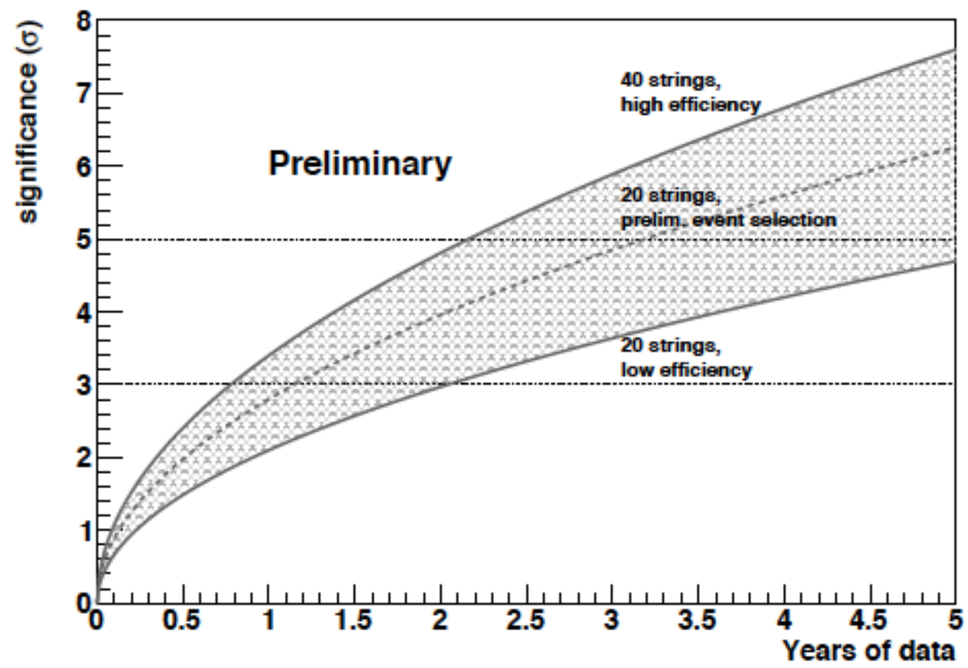
Rezo Shanidze, ORCA meeting, 18/04/2013



* No reconstruction has been done.
Effective volume will be lower after folding the reconstruction efficiency.




Current Status
• Detailed Monte Carlo simulations nearing completion
• Low energy reconstruction algorithms from DeepCore applied to PINGU events
• Estimation of sensitivity to NMH reconstruction underway
• Letter of intent in preparation
Today (18/04/2013)
Spring 2013
Letter of Intent
Summer / Fall 2013
Submit proposals to international Agencies.
April 2014
Proposal results. Begin pre-spending on critical path items (cables, mainbords, drill refurbishment).
Austral Summer 2015/2016
Drill half-crew on ice to begin drill preparation. DOM production and testing Underway.
Austral Summer 2016/2017
Drill operational with full crew. Deploy 8 Strings.
Austral Summer 2017/2018
Deploy 12 Strings. Repack drill.
PINGU Complete
2018 February
Physcis data taking

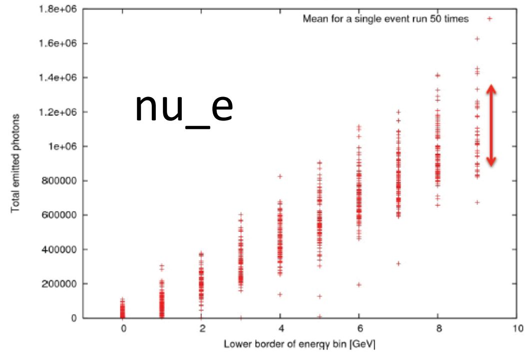

Preliminary
40 strings, high efficiency
20 strings, prelim. event selection
20 strings, low efficiency
significance (σ)
Years of data
0
1
2
3
4
5
6
7
8
0.5
1.5
2.5
3.5
4.5

Detector performance studies

Other ongoing/planned studies

❖ Shower-to-shower fluctuations (both nu_mu and nu_e)

→ intrinsic fluctuations in vertex physics induce 15-20% fluctuations in expected $N_{photons}$ …

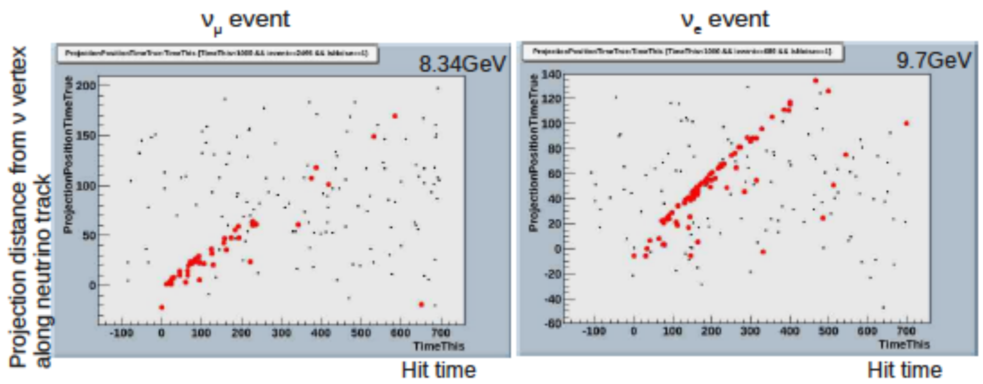


❖ Flavor identification & contamination

impact of nu_e misreconstructed as nu_mu ?

→ evaluate contamination rate

→ evaluate impact on NMH sensitivity (Toy MC Tool)



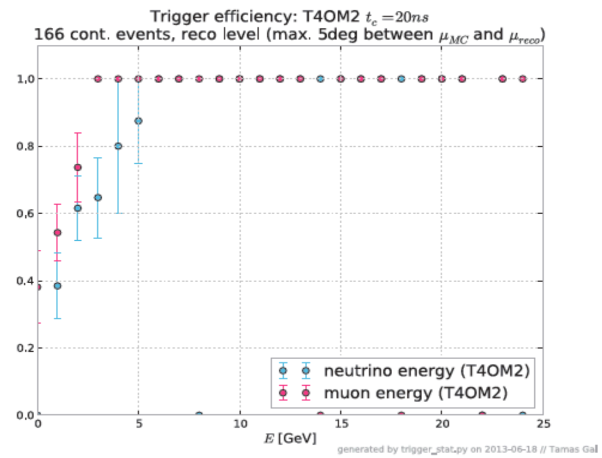
❖ Trigger studies

TnOMm

Trigger condition:

at least '**n**' OMs with '**m**' L0 (> 0.3pe) pulses correlated in **space** (neighbouring or next-to neighbouring PMTs) and **time** (< 20ns).

Example: T4OM2 → good performance for fully contained tracks

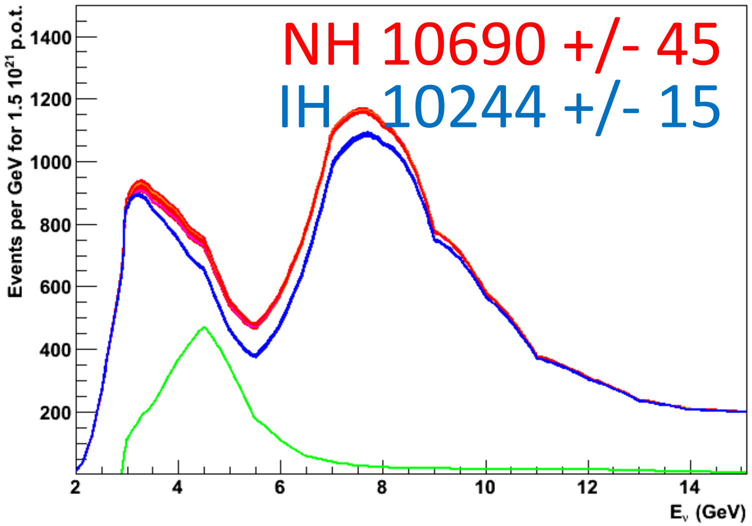


❖ Muon background evaluation: just started

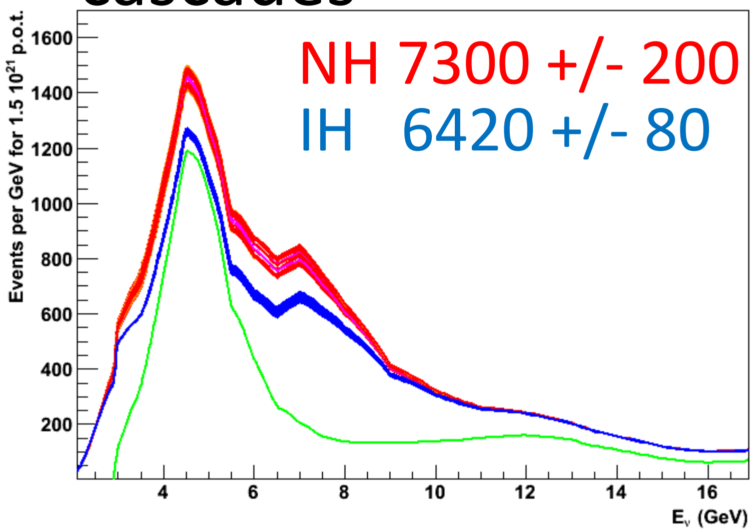
Event rates – All Flavours & Mis-ID

- Event numbers for 1.5 10^{21} pots
- 9-18% difference for NH/IH
- 7 σ statistical separation of MH hypotheses
- Can allow for 3-4 % syst. uncertainty

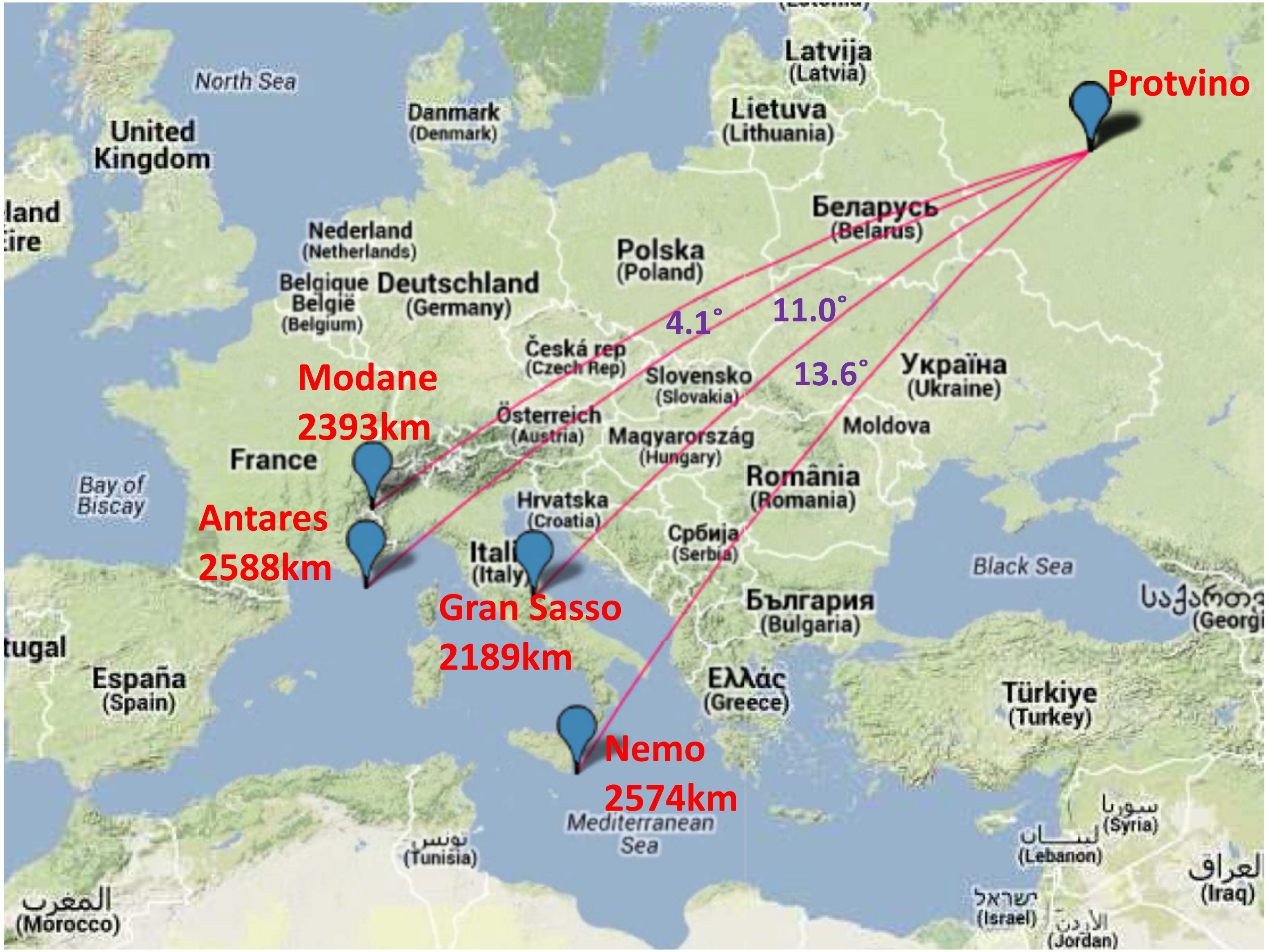
tracks



cascades



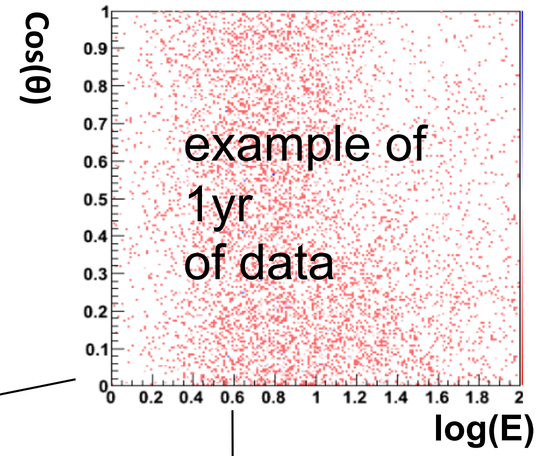
Synergies between potential Sites



Sensitivity studies

Global fit approach

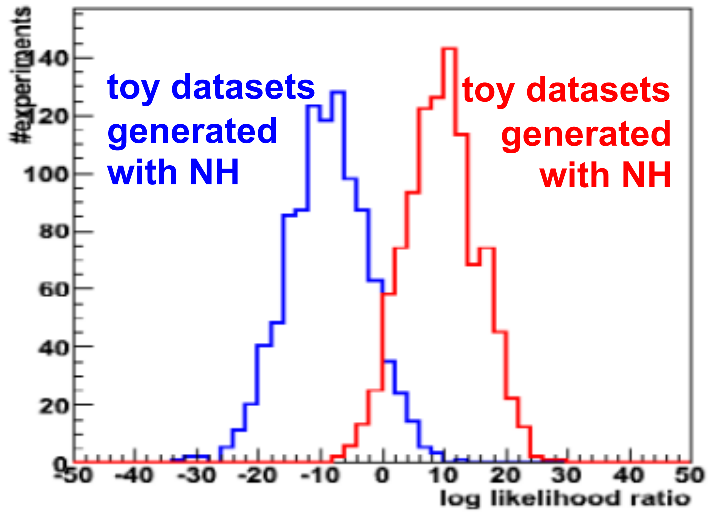
to optimally distinguish between IH and NH:
likelihood ratio test *with nuisance parameters*
(→ deal with degeneracies by fitting)



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

$\hat{\theta}^{\text{H}} =$ 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 DlogL = log(L(NH)/L(IH))



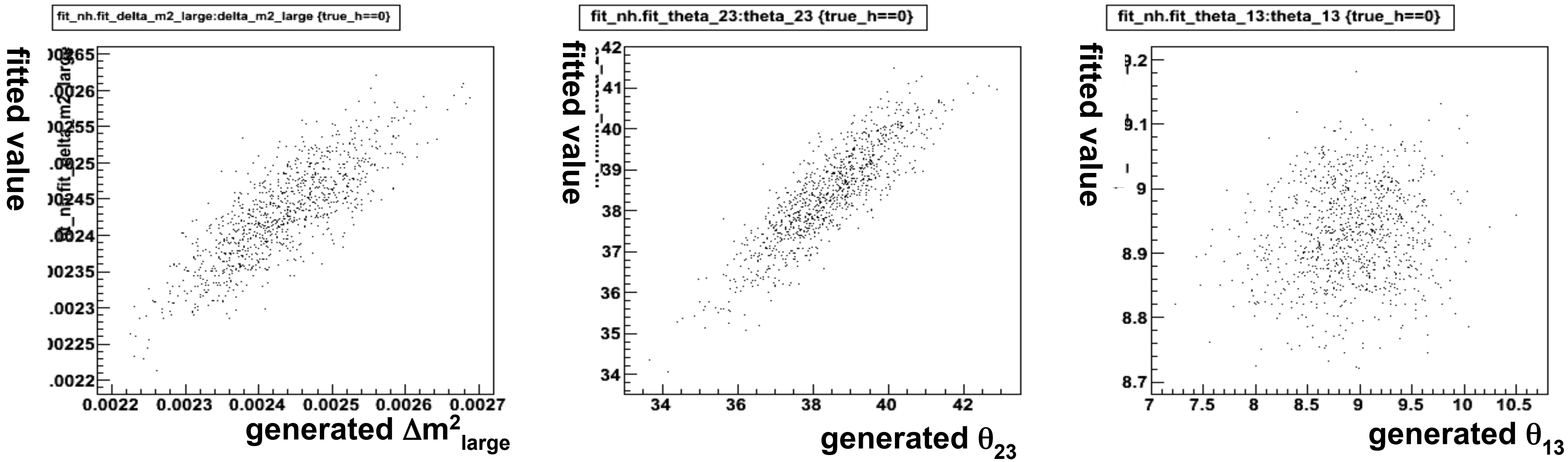
(example shown is for 10 Mt*yr)

Sensitivity studies

Global fit approach

The fitting procedure also allows to extract the value of the oscillation parameters !

1 Mton*year (NH true, NH fit)



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

← current knowledge

Good sensitivity to Δm^2_{large} & θ_{23}

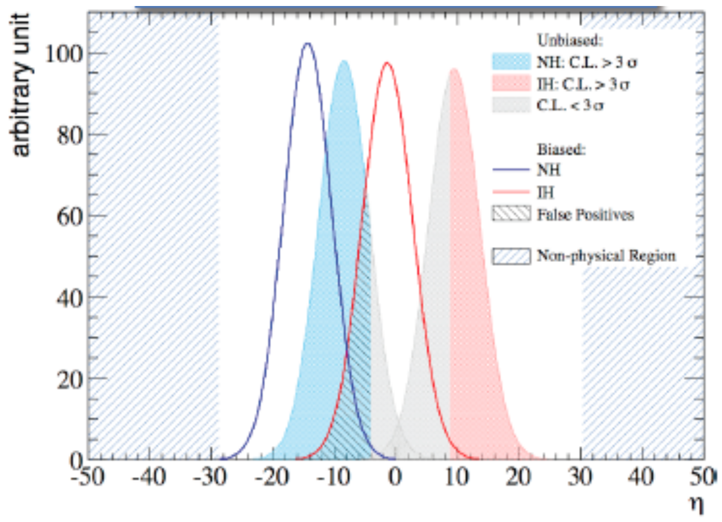
The
the
liste
know
the
show
curr

Sensitivity studies

Toy Monte Carlo approach

Systematics studied by introducing biases in the distributions

If true/model hypotheses have different parameters
→ unphysical results
→ false positives: misidentified hierarchy



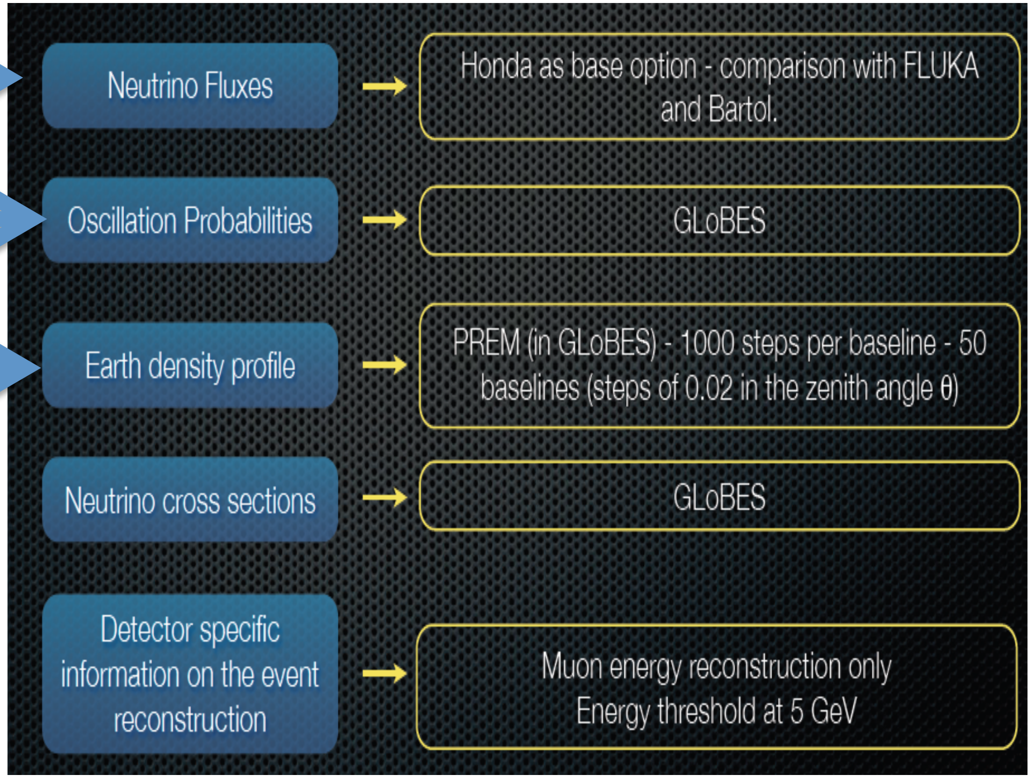
IMPACT of…

- shape : moderate
- normalization: large
(but can be normalized from data)

-Solar (Δm^2_{small}, Θ_{12}), δ_{CP}: weak
-Atmospheric (Δm^2_{large}, Θ_{23}, Θ_{13}): large

almost negligible

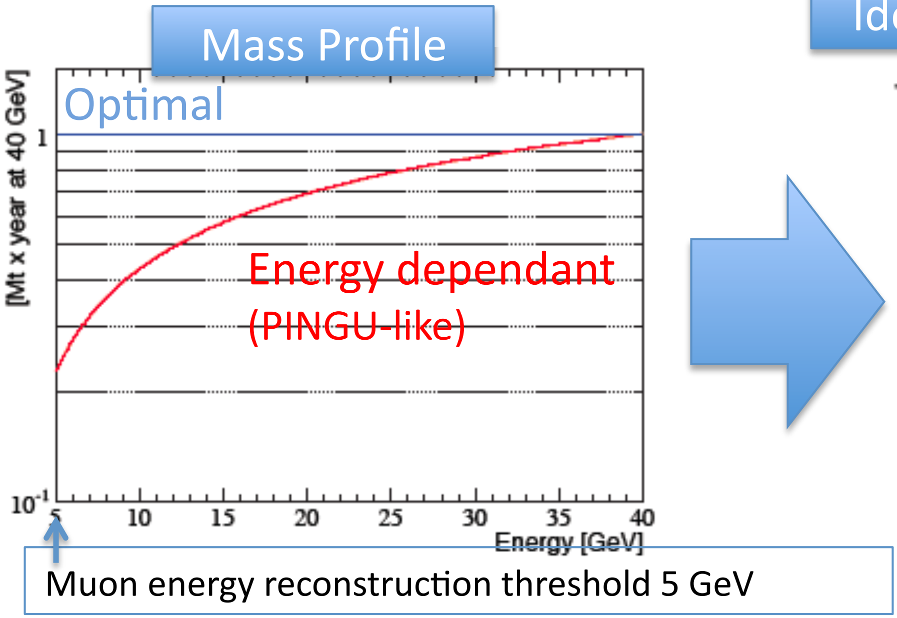
(same conclusions shared by many ORCA groups)

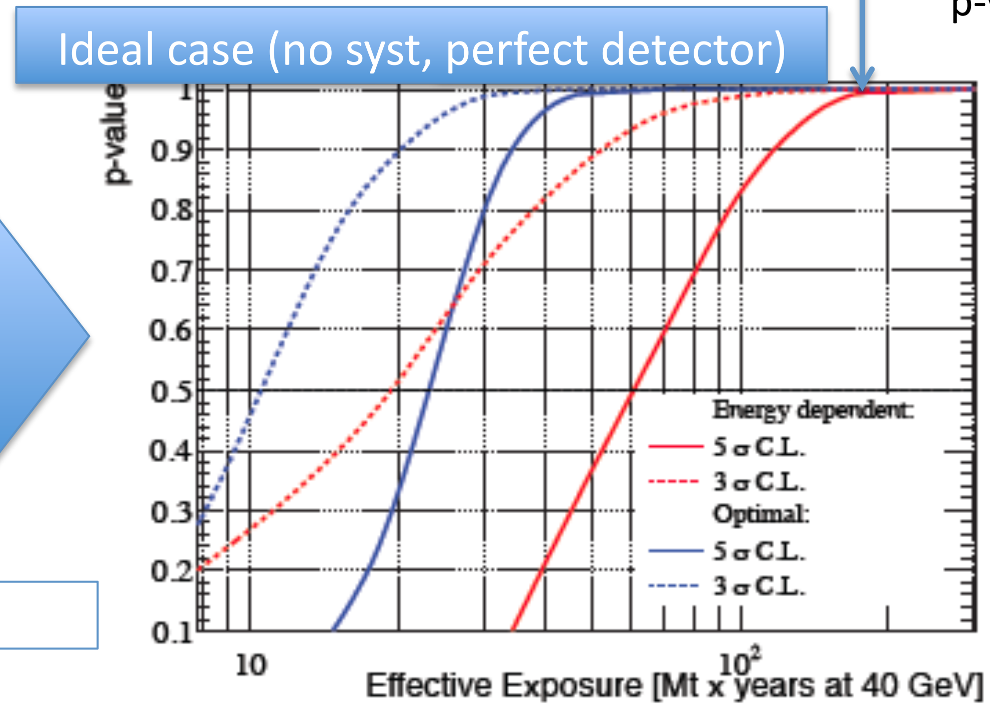


Sensitivity studies

Toy Monte Carlo approach: NMH sensitivity

Reference point for further studies p-value~1





...BUT degraded by the limited angular/energy resolution of the detector: