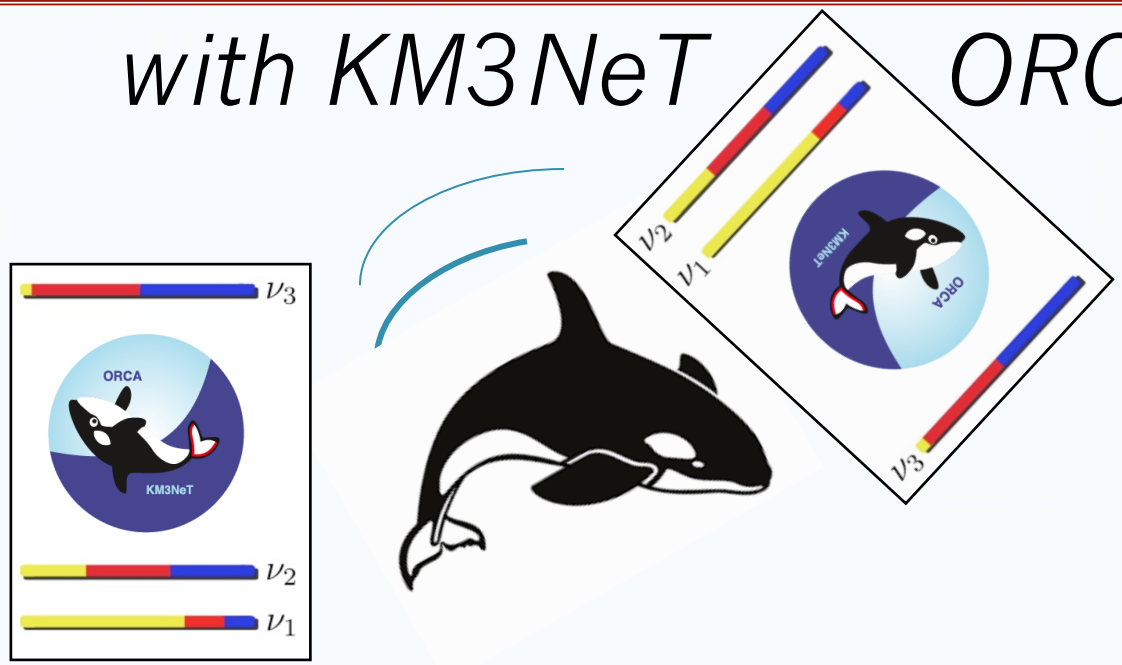
Measuring the neutrino mass ordering with KM3NeT ORCA



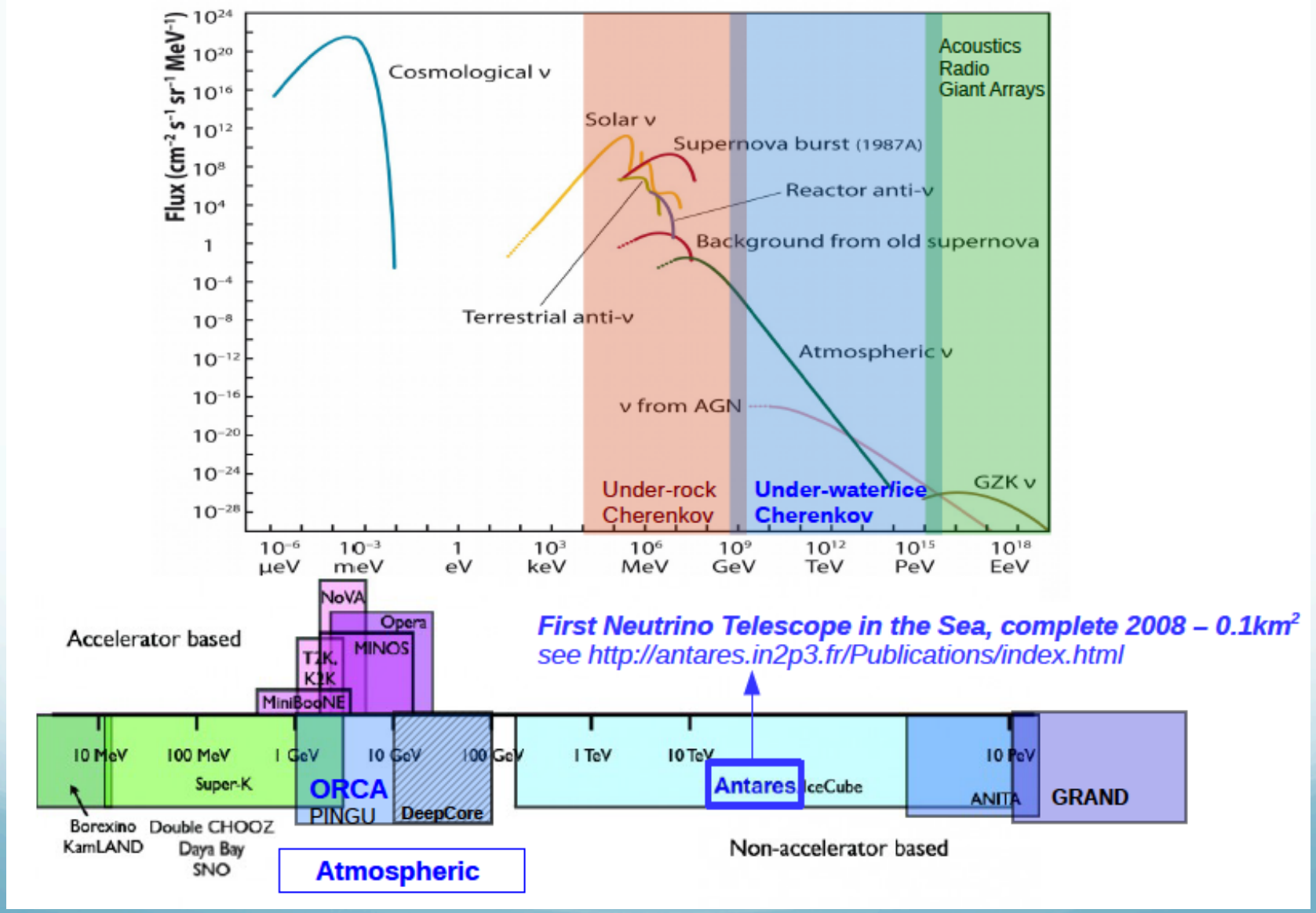
14th International Conference on Topics in Astroparticle and Underground Physics

Antoine Kouchner

University Paris 7 Diderot- AstroParticle and Cosmology

Torino, Italy **September 8, 2015**

Previous expertise in the Deep-Sea



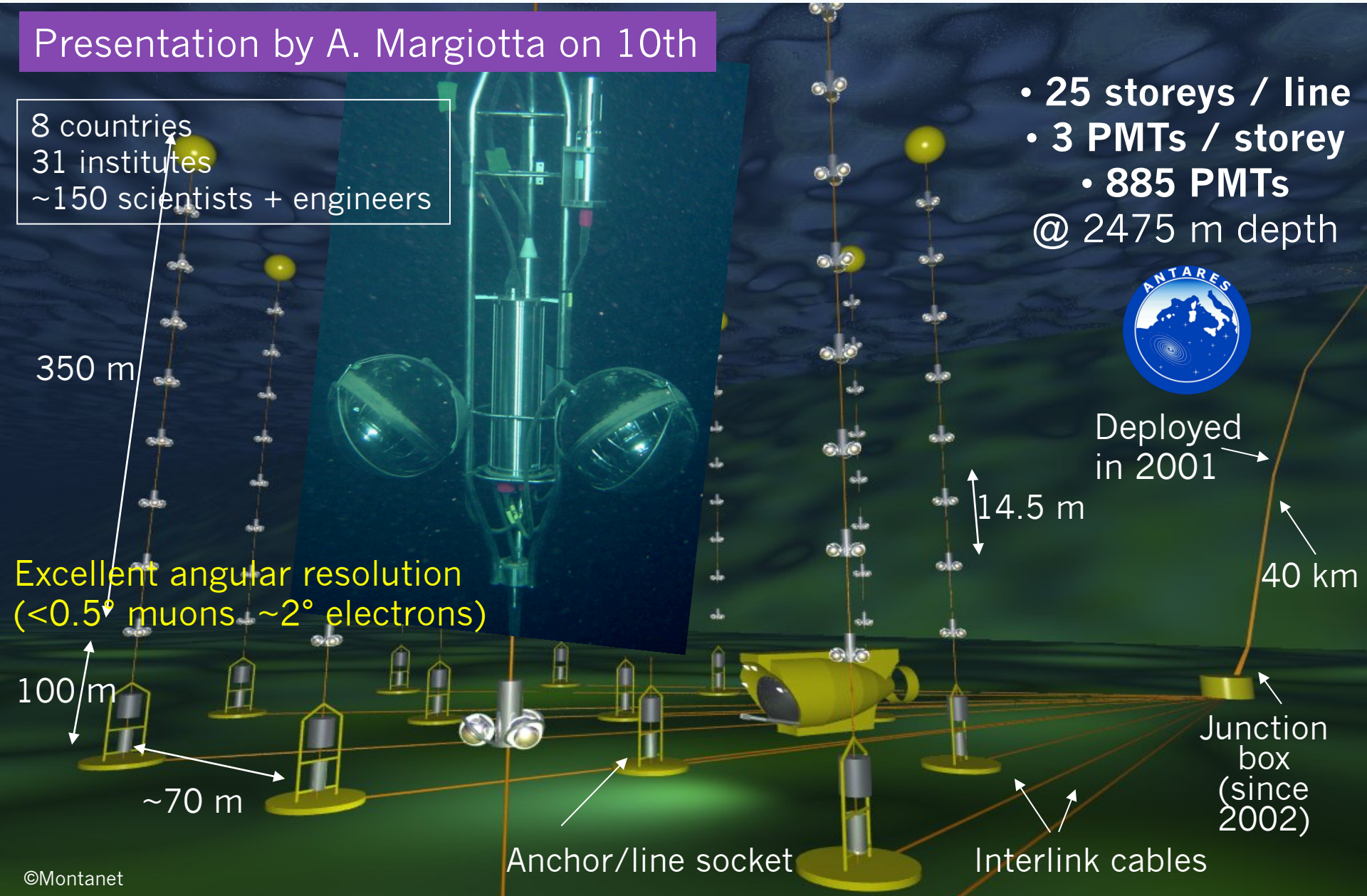
ANTARES: world 1st deep-sea NT

Presentation by A. Margiotta on 10th

8 countries
31 institutes
~150 scientists + engineers

- **25 storeys / line**
- **3 PMTs / storey**
- **885 PMTs**

@ 2475 m depth



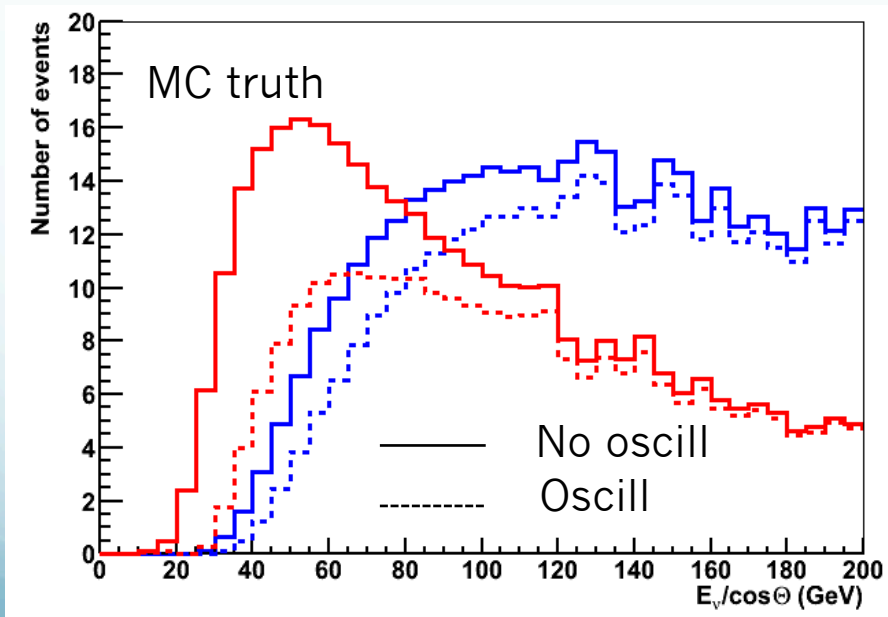
First achievements on neutrino oscillation

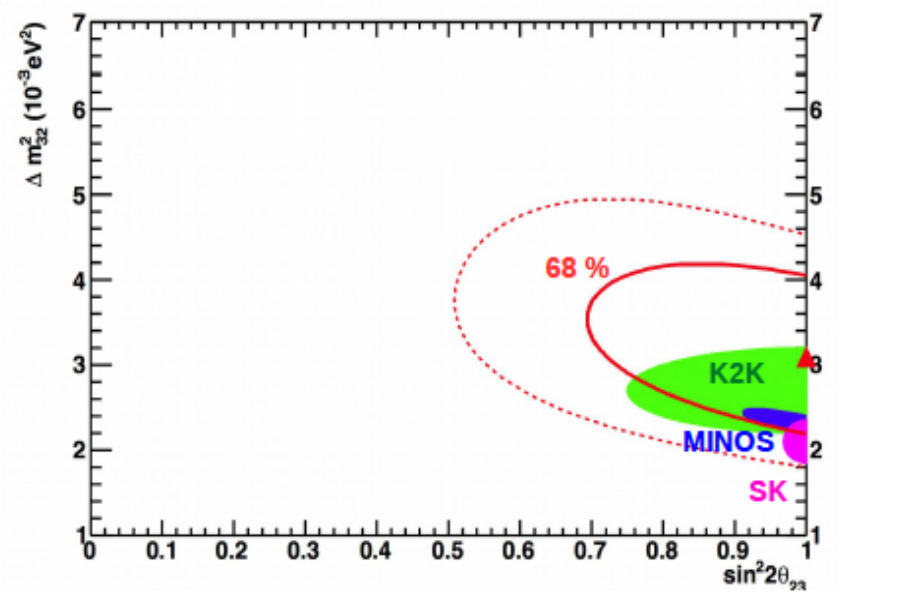
2-flavor approximation analysis with 2008-2010 data

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

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

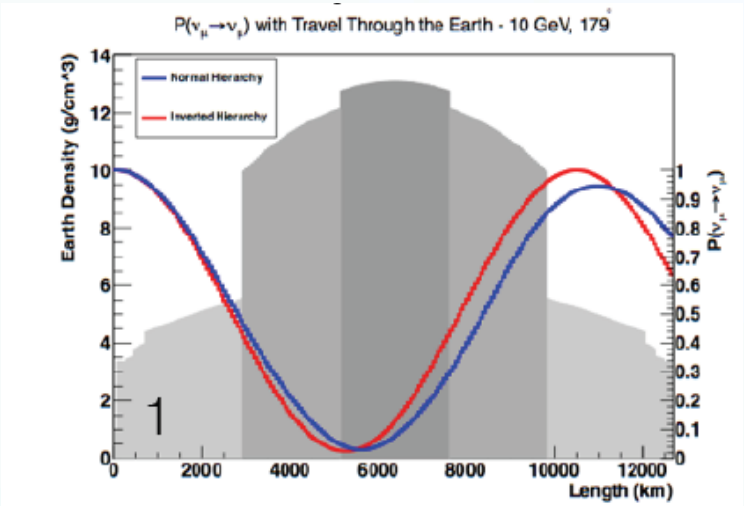
Larger effect on low energy (single lines) than higher energy events (multi-lines)

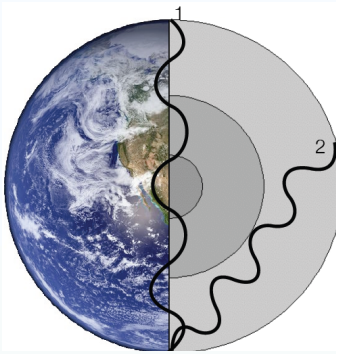




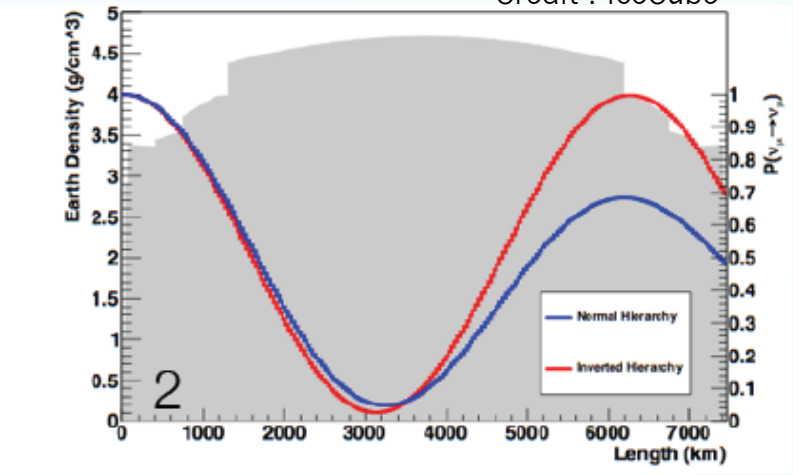
📖 S. Adrian-Martinez et al. Phys. Lett. B 714 (2012) 22.

Matter Effects and Mass Hierarchy



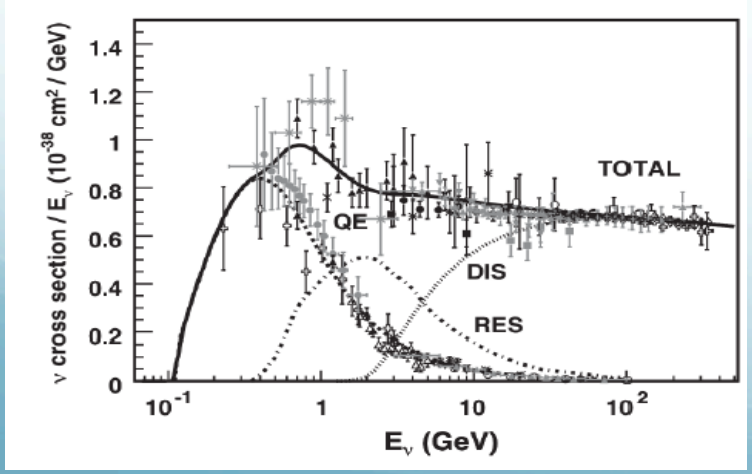


Credit : IceCube

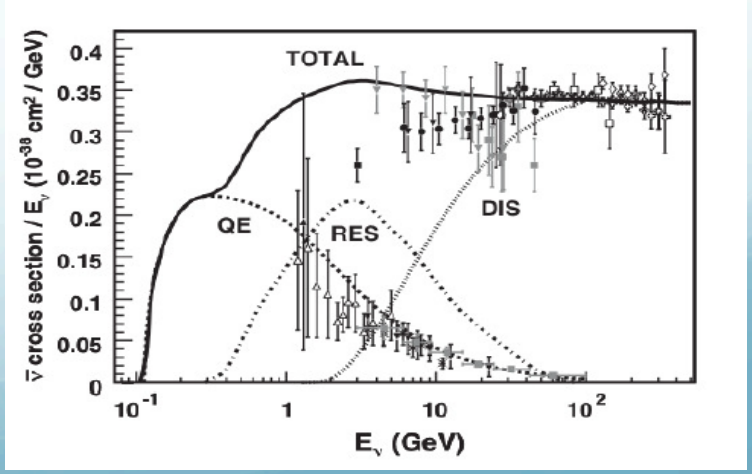


Requirements:

- Δm^2_{13} ~ A matter potential must be significant but not overwhelming
- L large enough – use atmospheric neutrinos !
- Distinction between neutrinos and anti-neutrinos → cross-sections!



$$\sigma(\nu) \approx 2\sigma(\bar{\nu})$$

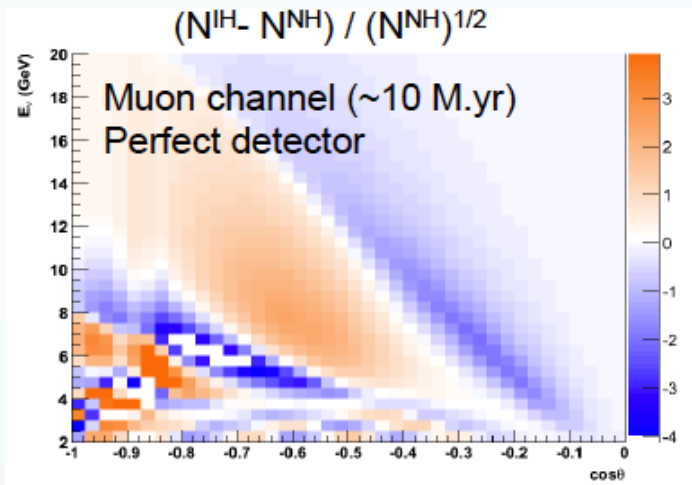


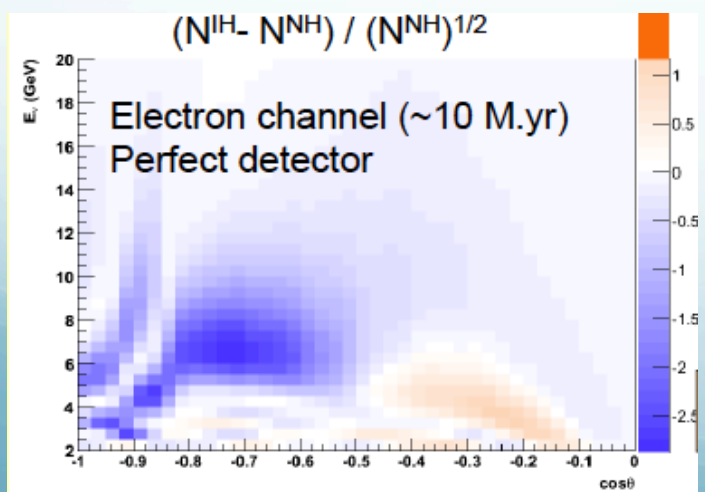
Muon versus Electron channels

Both muon- and electron-channels contribute to net hierarchy asymmetry

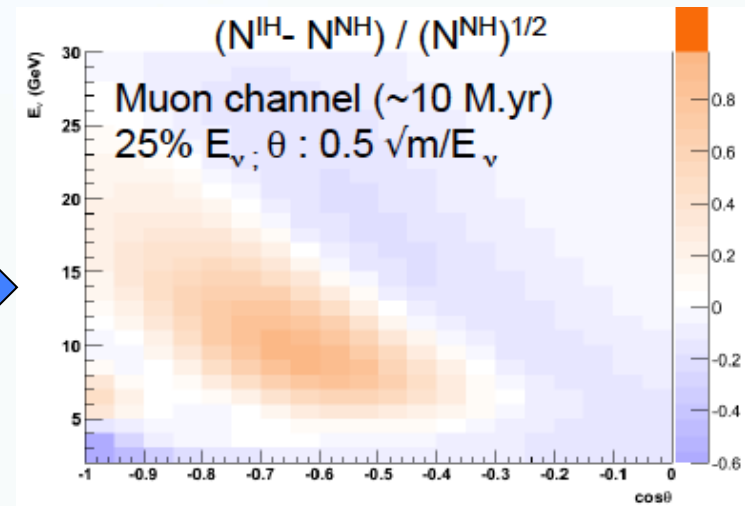
electron channel more robust against detector resolution effects:

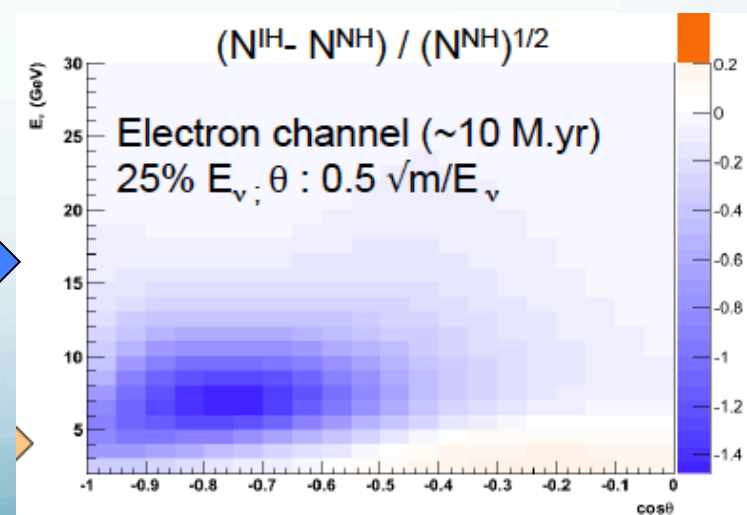
(Significances a la Akhmedov et al. 🕮 JHEP 02 (2013) 082)





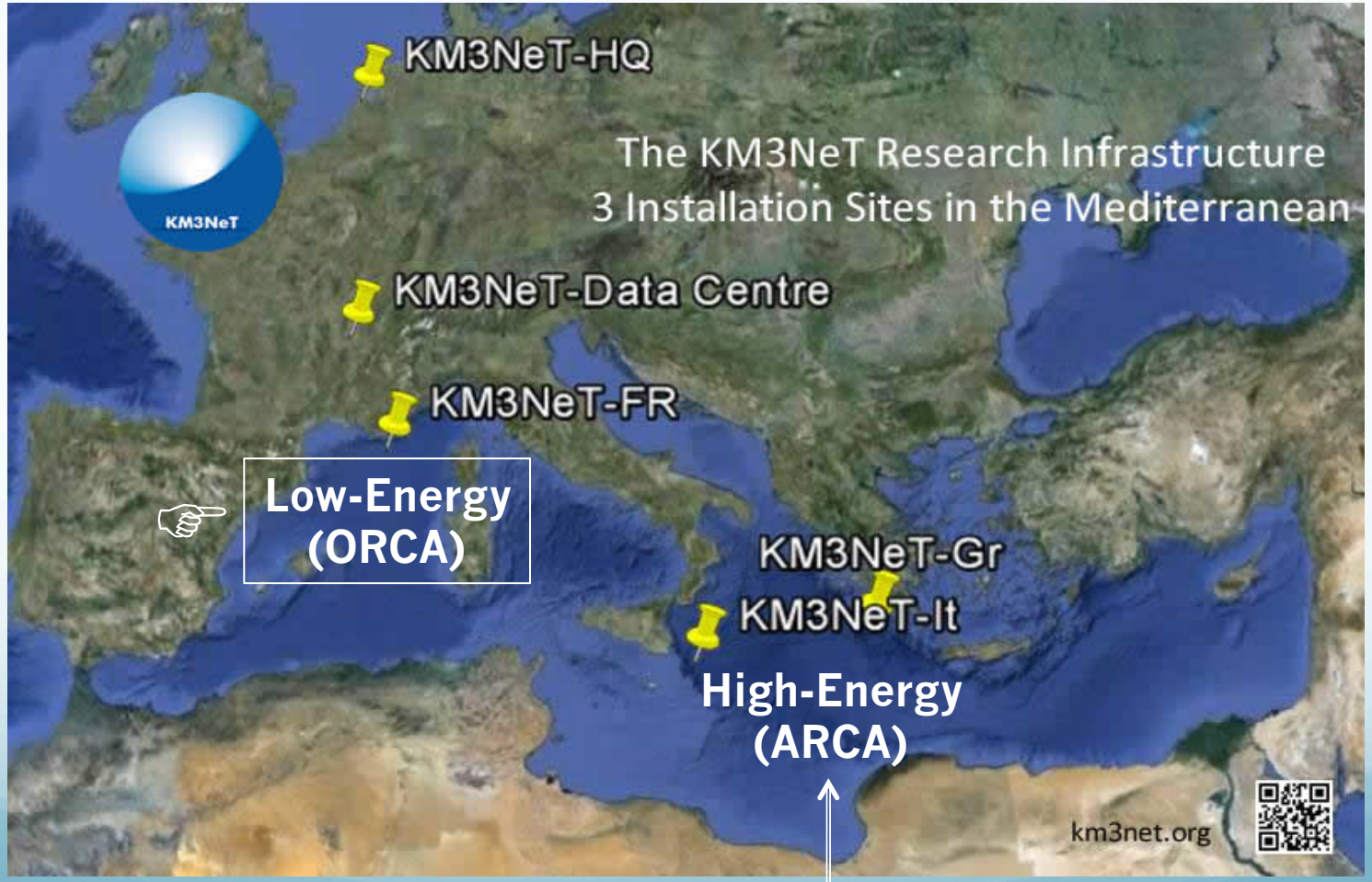
E, θ smearing (kinematics + detector resolution)





KM3NeT: Next generation Med. NT

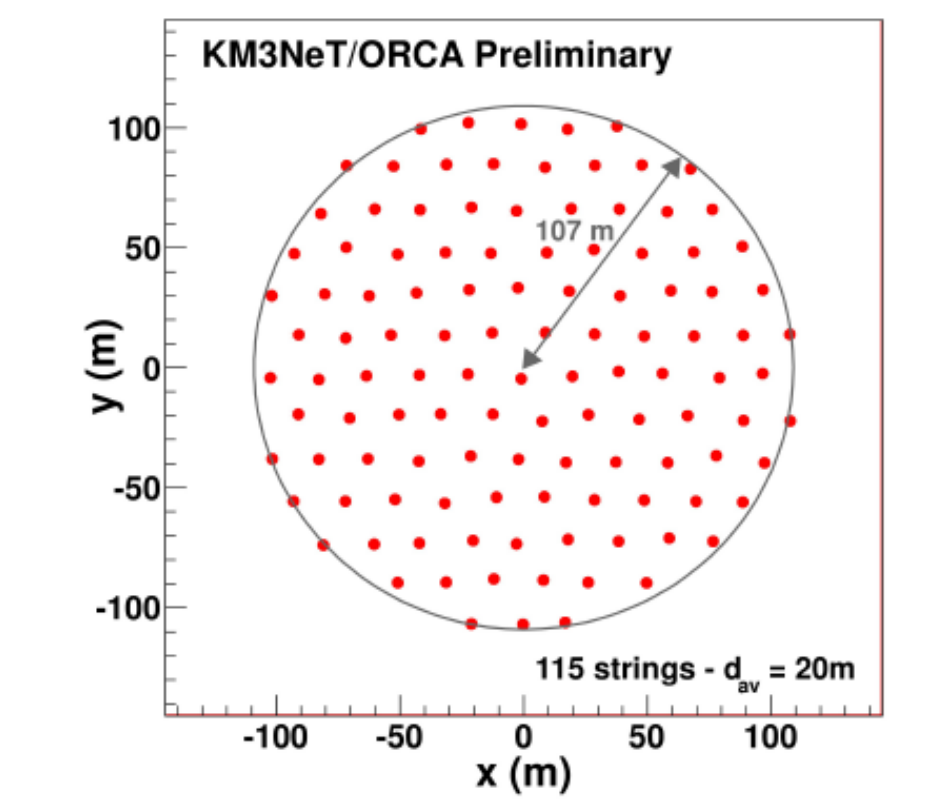
KM3NeT is a distributed research infrastructure with 2 main physics topics:
Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos



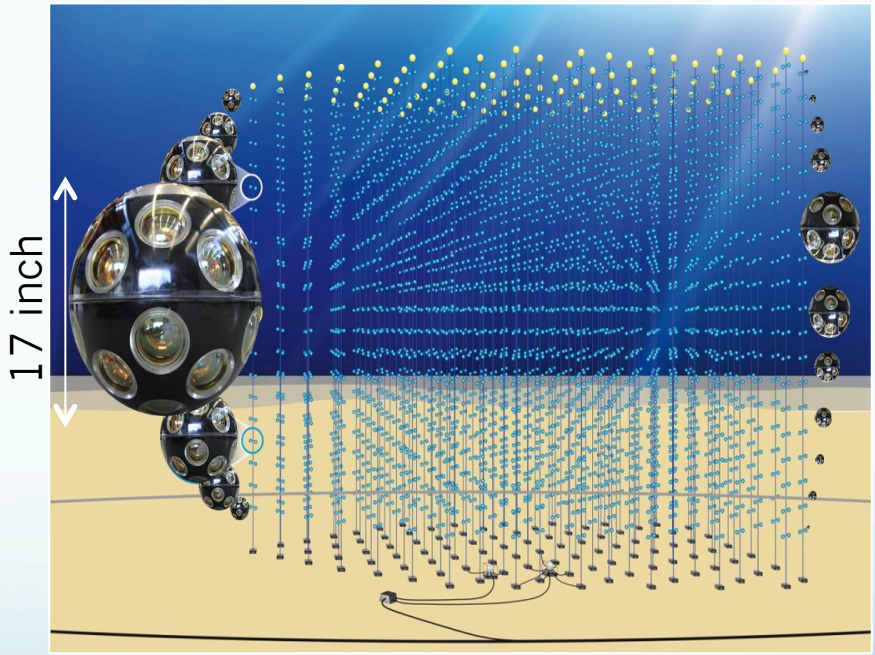
Talk by P. Migliozzi on Thursday

The ORCA benchmark design

115 lines, 20m spaced,
18 DOMs/line 6m spaced



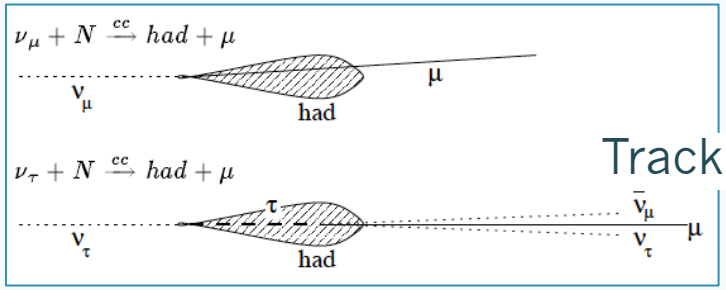
Instrumented volume ~3.8 Mt,
2070 OM
Optical background:
10kHz/PMT & 500Hz coincidence



- 31 3” PMTs
- Digital photon counting
- Directional information

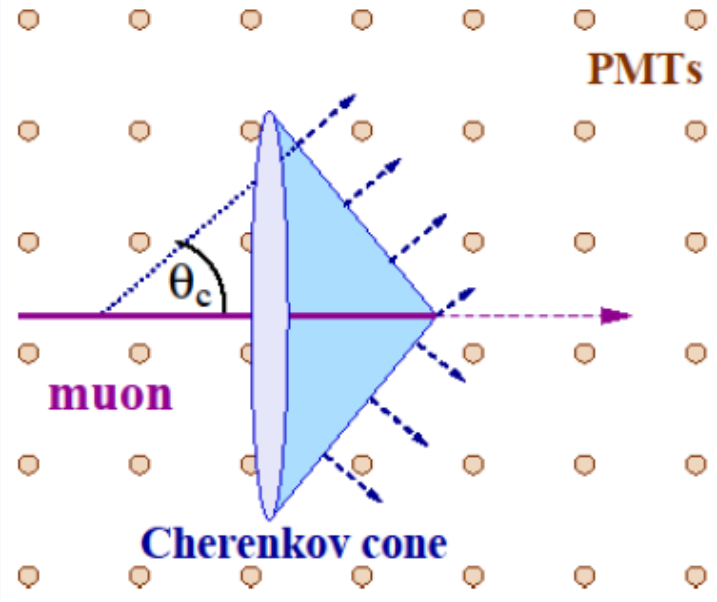
- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction compared to ANTARES

Event topologies

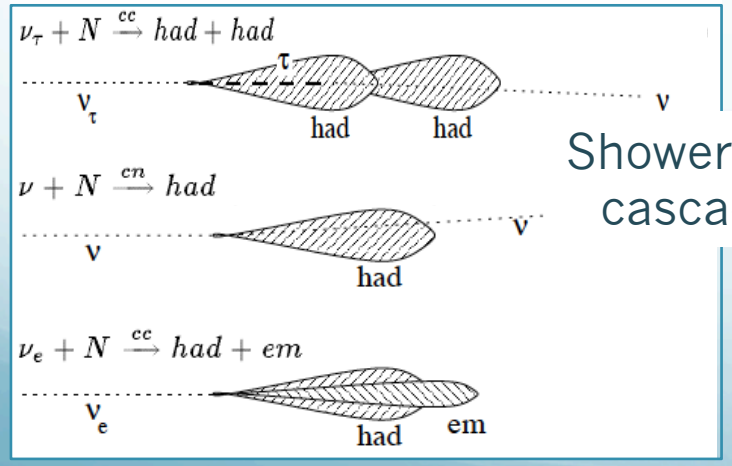


Track-like

Track-like contains both a cascade and one track

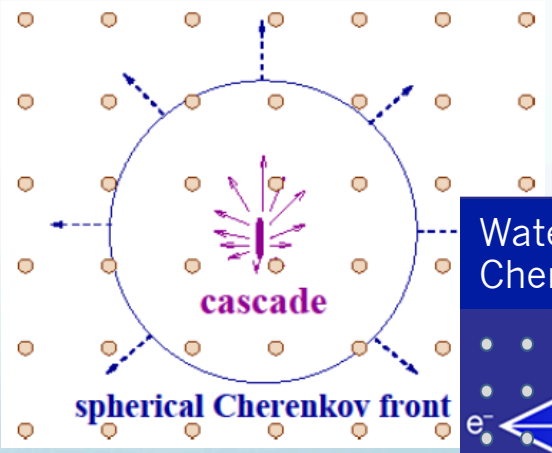


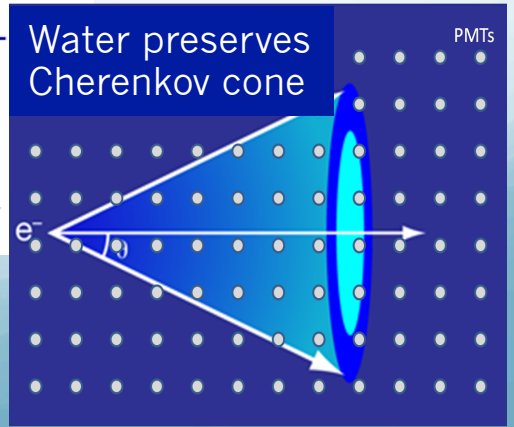
Not to scale



Shower-like cascade

No track is identified





Ingredients for NMH measurement

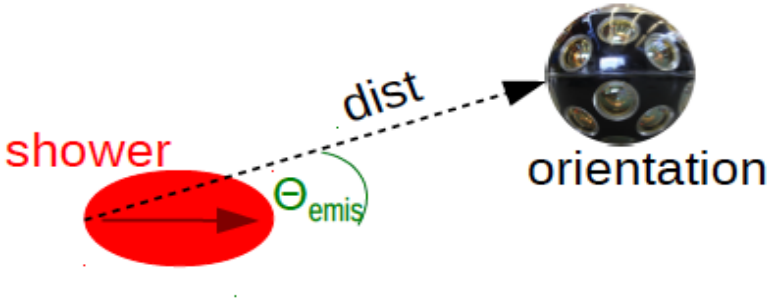
- Efficient and high purity trigger algorithm for neutrino and atmospheric muon events
  - Exploit excellent photon counting of multi-PMT DOMs
  - Use causality of direct photons → water almost scattering free for visible photons
- Reconstruction of cascade and track topologies
  - High efficiency down to relevant energies
  - Good resolution in energy and zenith angle
- Topology Identification (track ←→ cascades)
- Atmospheric muon rejection (no hardware veto)

ORCA shower reconstruction (ν_e)

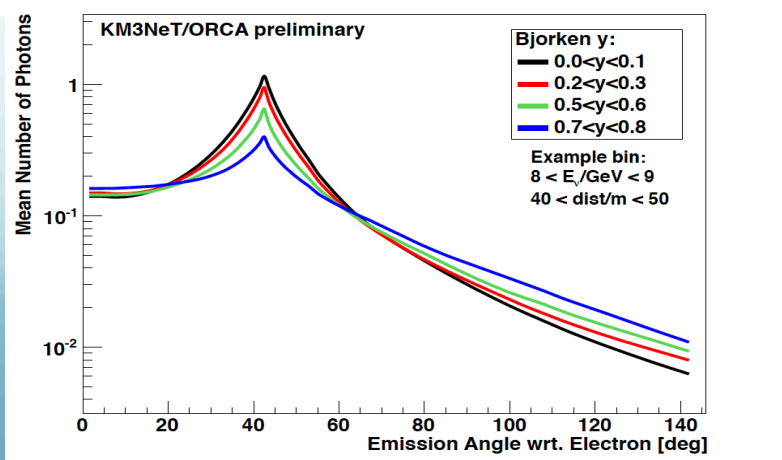
- 1. Vertex fit:
  - maximum likelihood method based on time residuals
  - two fits: first robust prefit then more precise fit

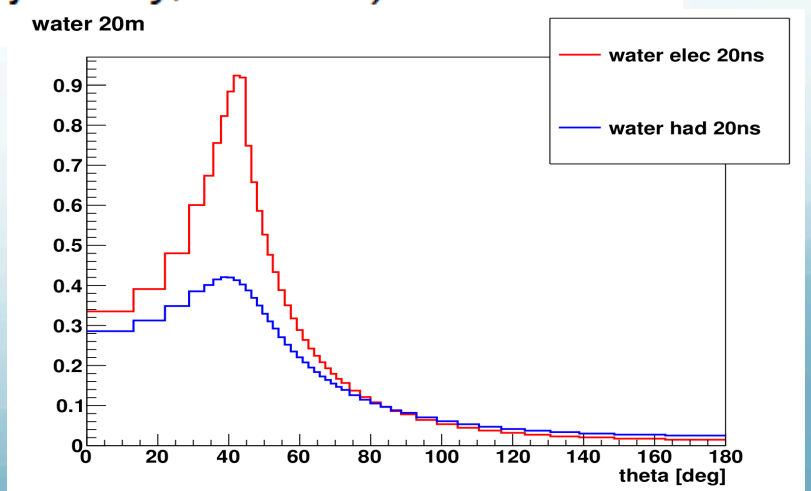
Res. (σ): 0.5-1 m

- 2. Energy + direction fit:
  - PDF for number of expected photons depending on: E_ν , Bjorken y, emission angle, OM orientation, distance(OM,vertex)



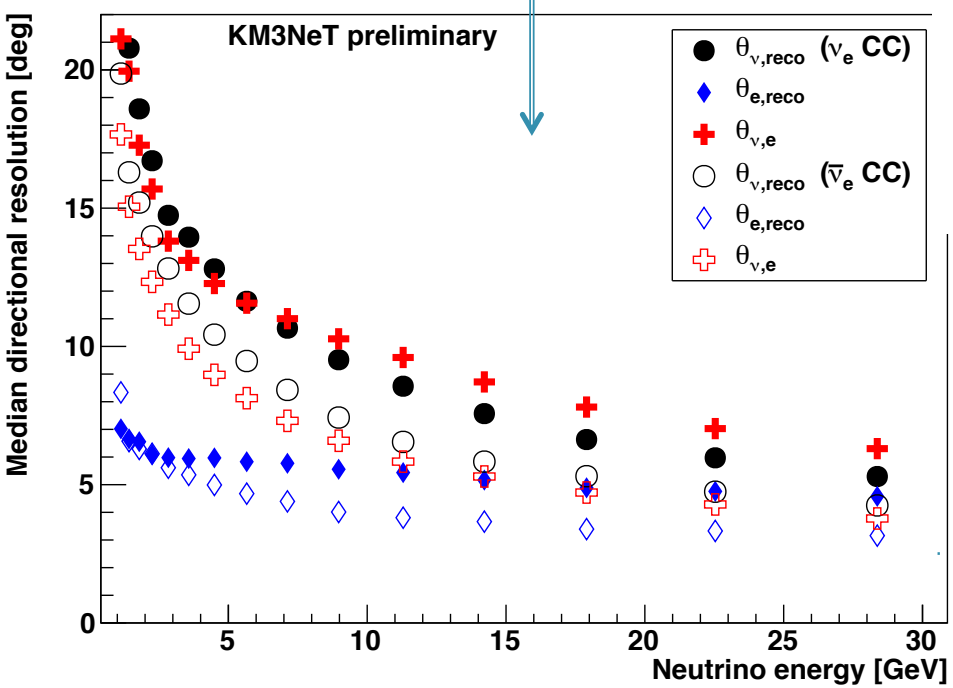
  - maximum likelihood method based probability that hits have been created by certain shower hypothesis (E_ν, Bjorken y, direction)

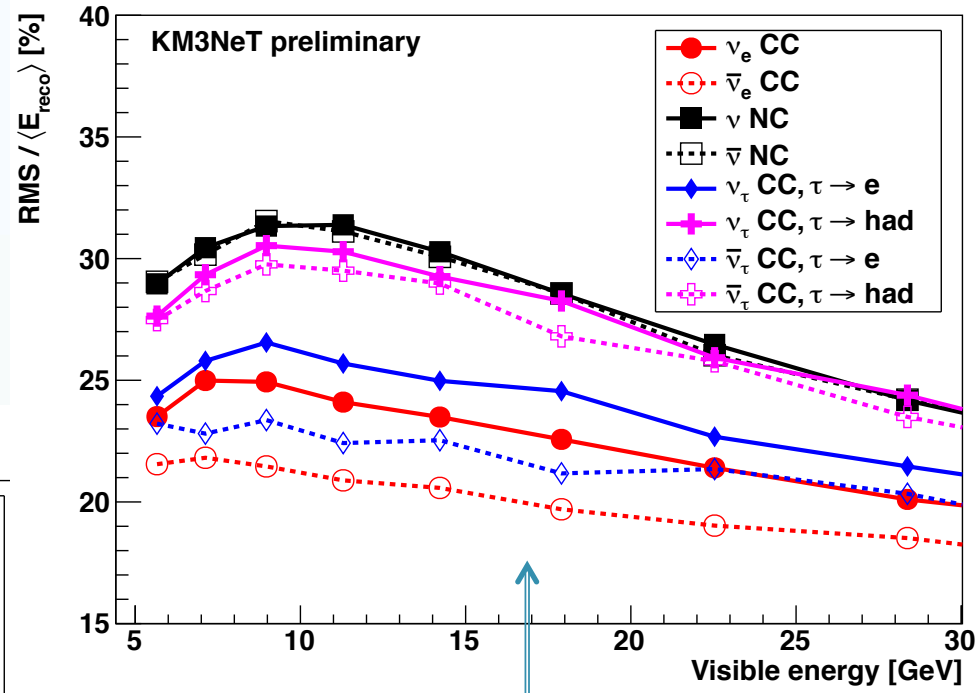




Performances ν_e (cascades)

Excellent angular resolution
Dominated by kinematics

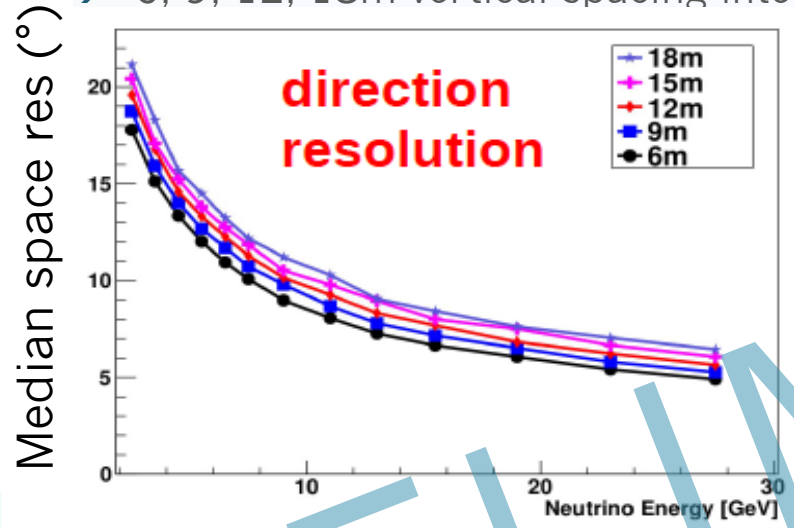


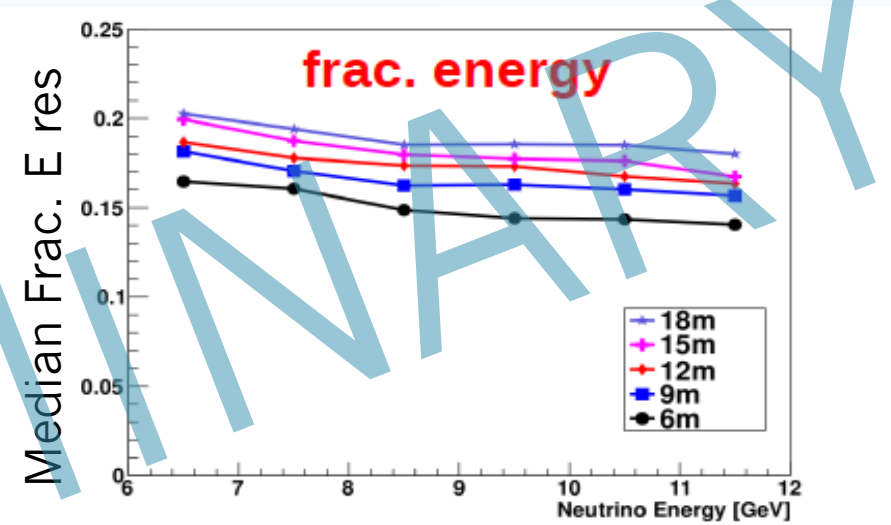


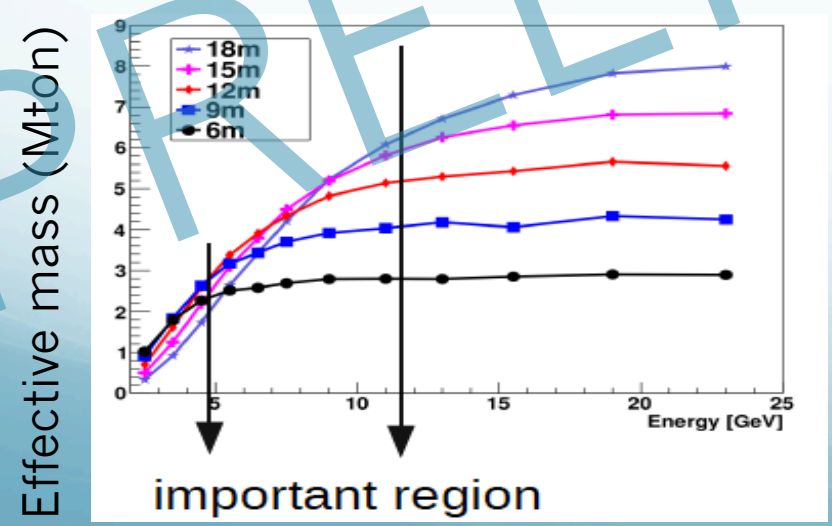
Energy resolution better than 25% in relevant range – close to Gaussian

ORCA Layout Optimization

- Switch off DOMs in proposed 115 line detector
  - → 20 m interline spacing imposed by line deployment (sea operations)
  - → 6, 9, 12, 18m vertical spacing inter-DOM







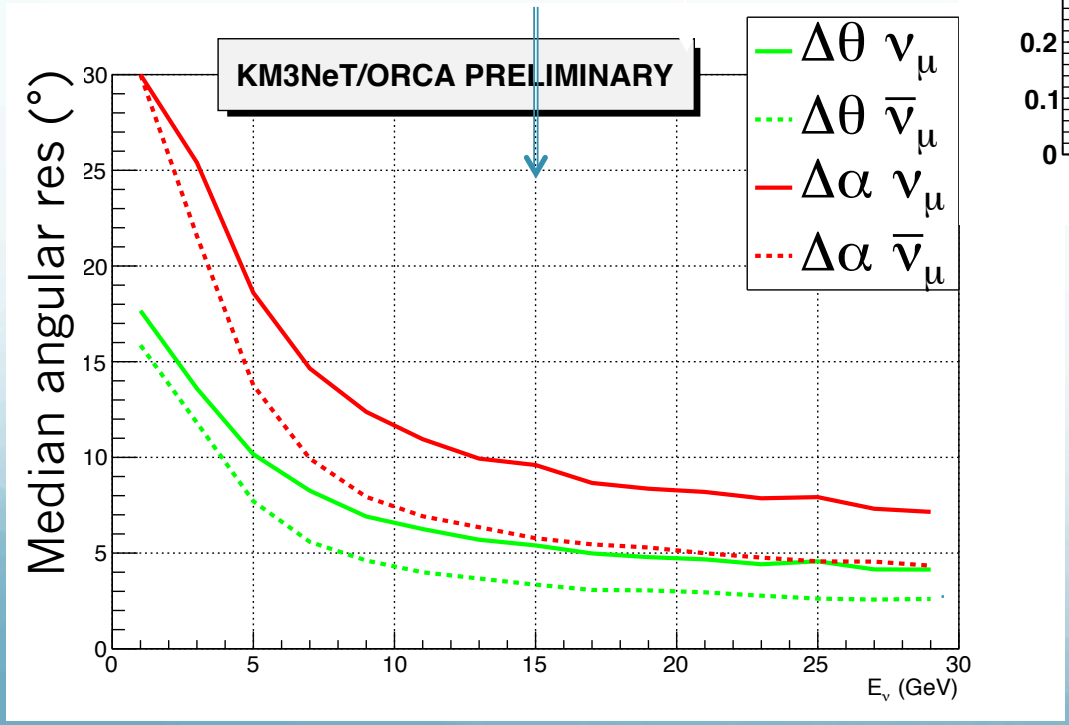
Examples for shower reconstruction

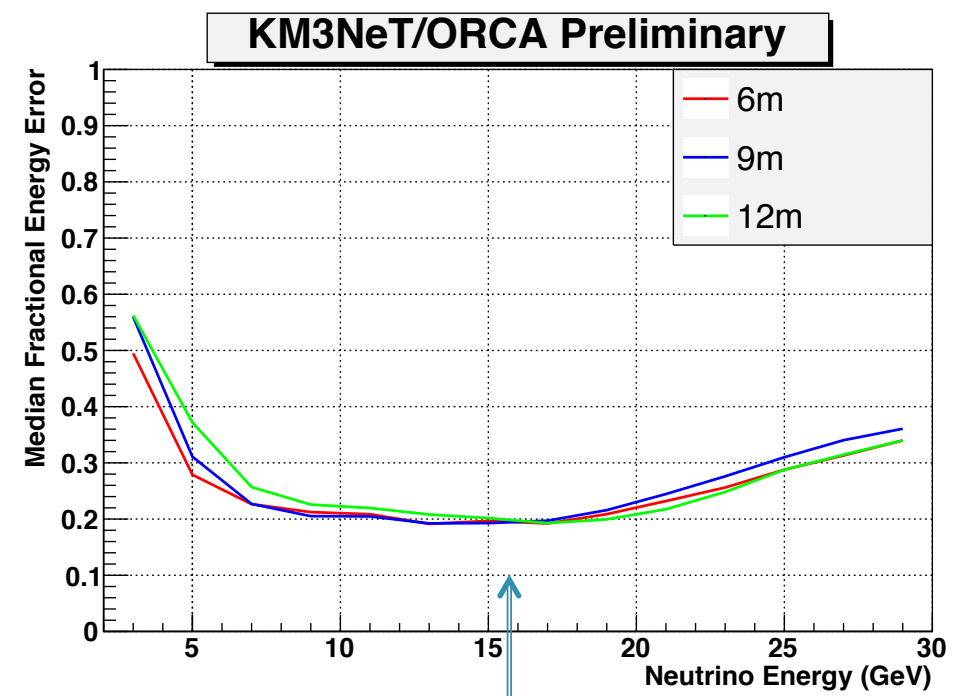
All relevant quantities must be studied in details before adopting an optimum spacing

But substantial improvement possible

Performances ν_μ (tracks)

Excellent angular resolution
Dominated by kinematics

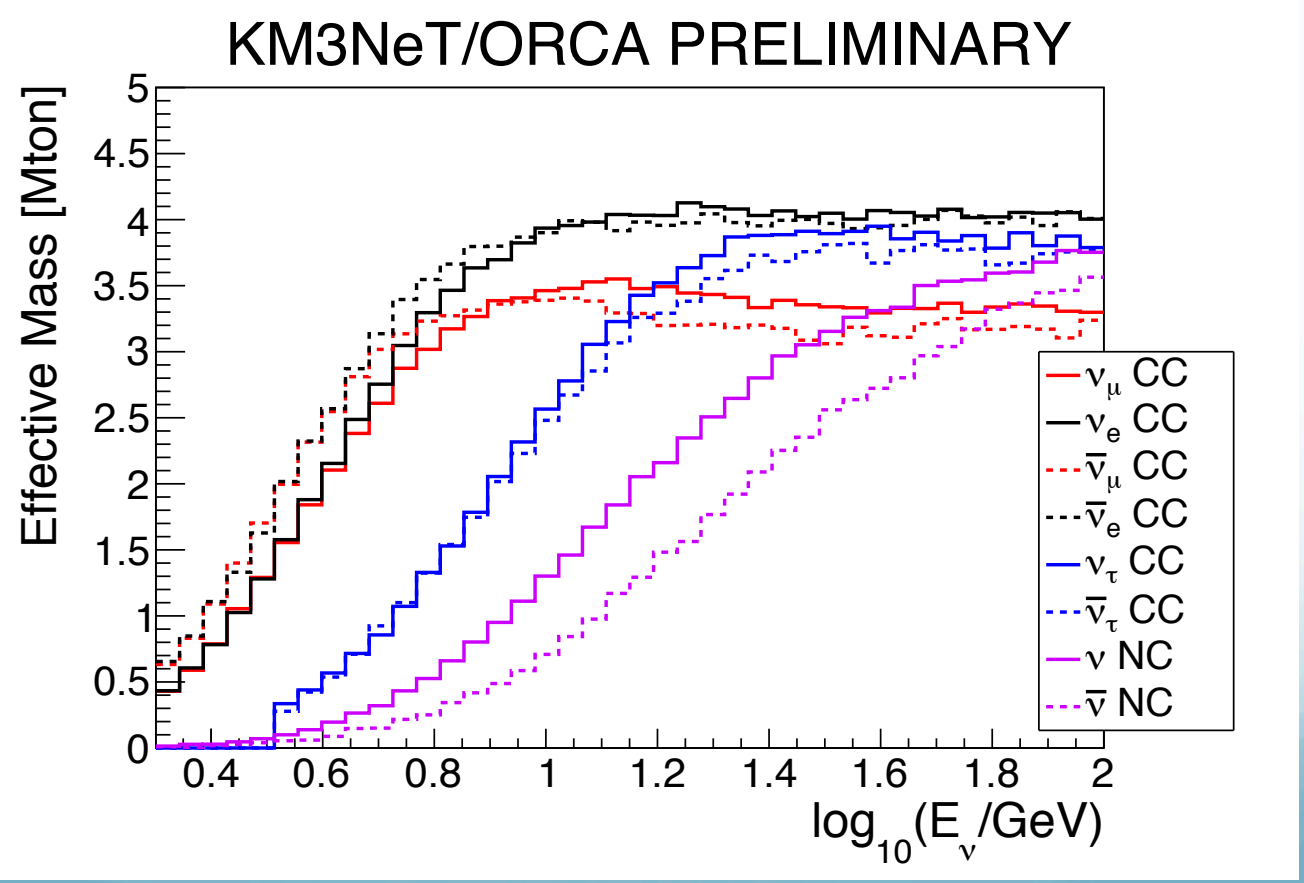




Energy resolution better than 25% in relevant range – close to Gaussian

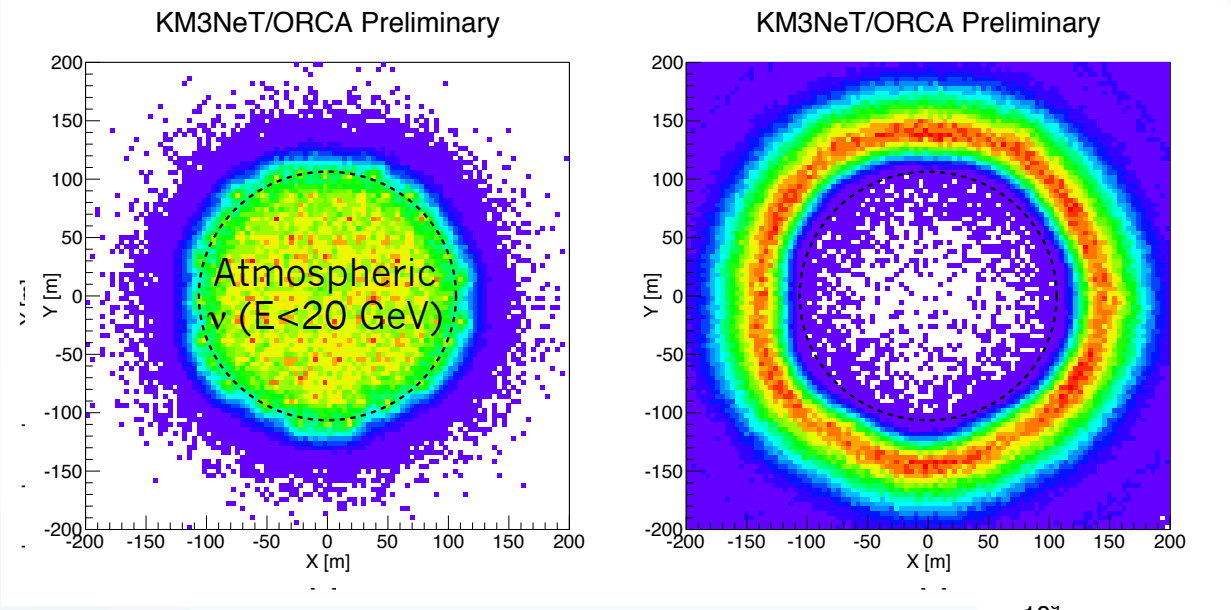
Effective Masses

- Above 10 GeV M_{eff} close to instrumented volume
- Similar for cascades and tracks

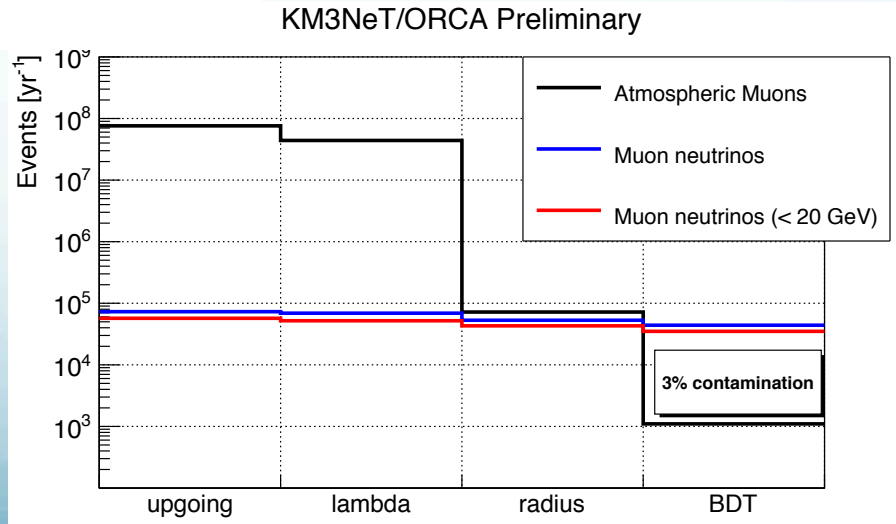


Atmospheric muon rejection

- Simulation based on MUPAGE (📖 Astropart. Phys. 25 (2006) 1) at depth 2475 m
- $\nu\mu$ reconstruction: cut on the reconstructed pseudo-vertex and quality parameters + BDT

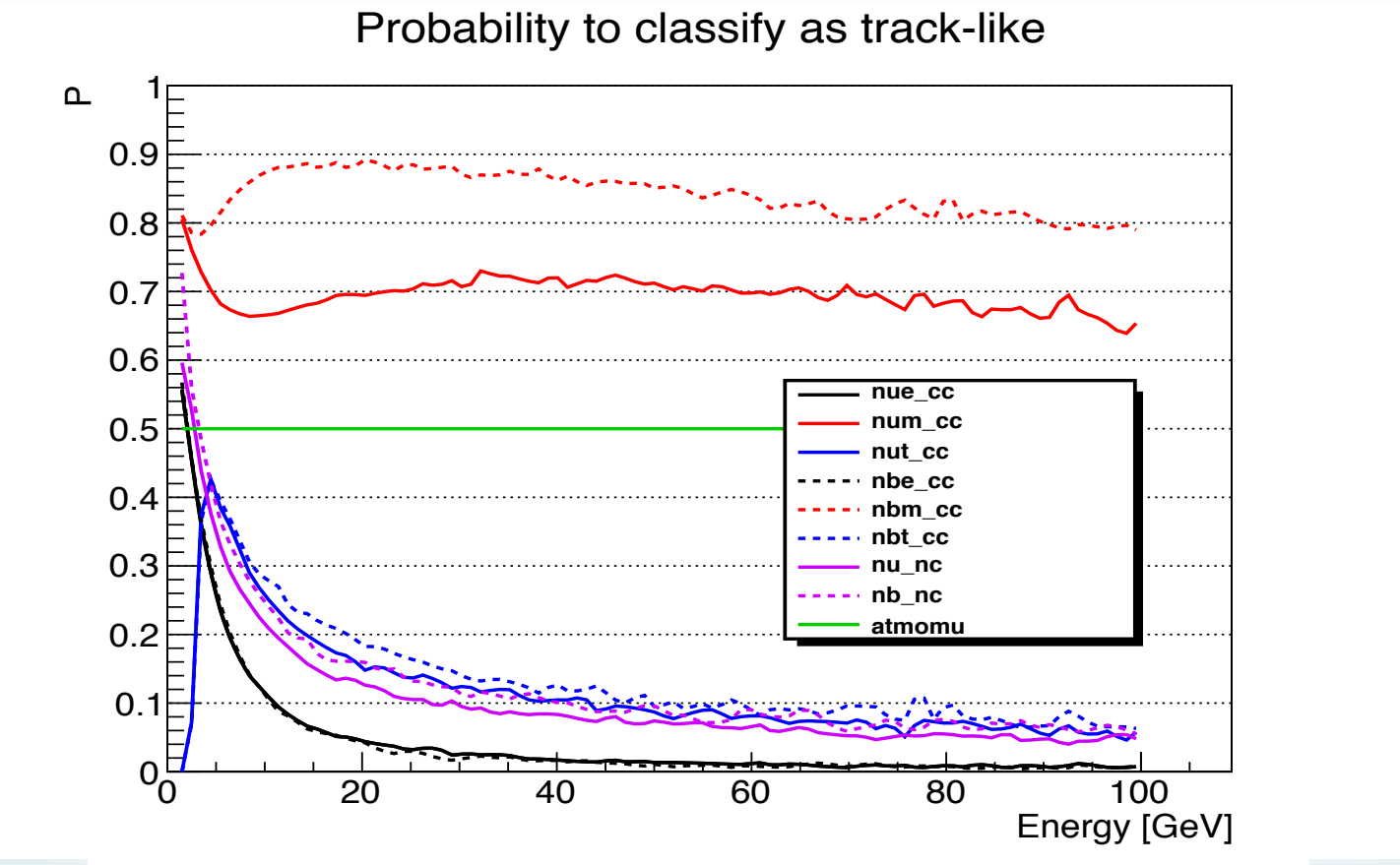


Instrumental veto not mandatory



Tunable few % contamination achievable without too strong signal loss

Flavour (mis)-identification



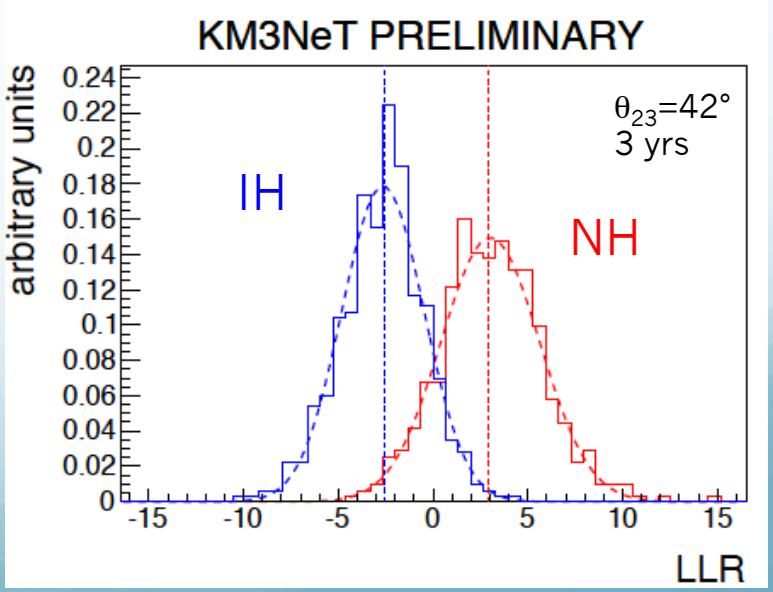
- Discrimination of track-like (ν_μ^{CC}) and cascade-like (ν^{NC}, ν_e^{CC}) events
- Classification uses "Random Decision Forest"
- Better than 80% above 10 GeV for all channels but ν_μ^{CC}

Systematic Effects

- Various systematic effects taking into account
  - Oscillation parameters
    - Δm^2, θ_{12} fixed; θ_{13} fitted within its error
    - ΔM^2, θ_{23}, δ_{CP} → fitted unconstrained
- Flux, cross section, detector related

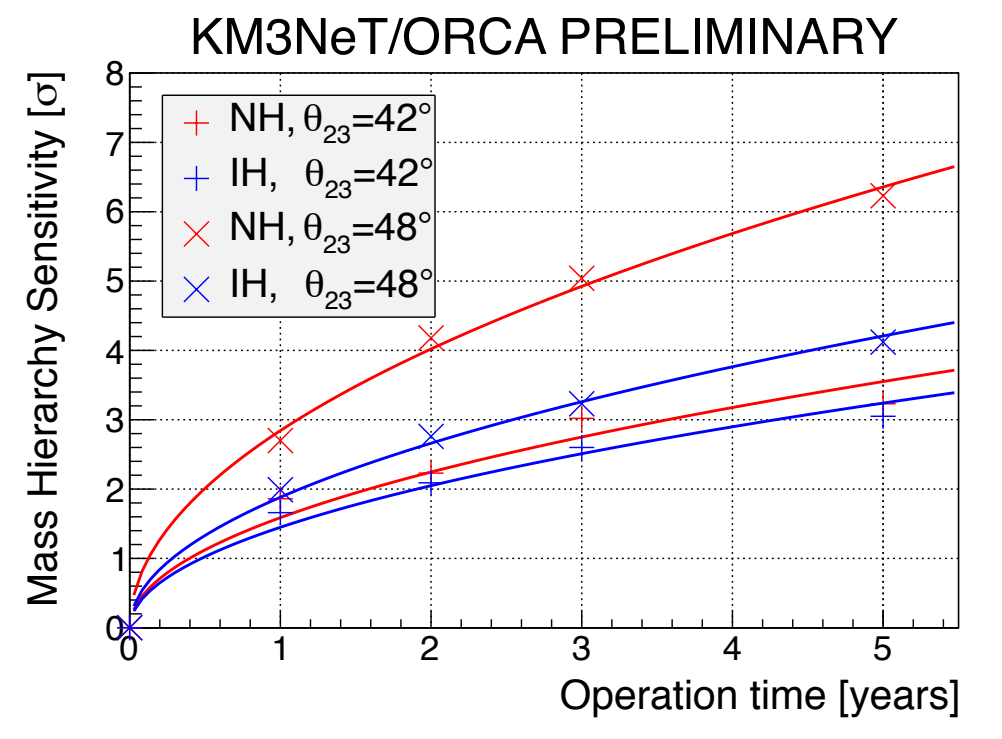
(average fluctuation w.r.t. nominal)

- Overall normalisation (2.0%)
- $\nu / \bar{\nu}$ ratio (4.0%)
- e/μ ratio (1.2%)
- NC scaling (11.0%)
- Energy slope (0.5%)
- →Fitted unconstrained



Sensitivity to Neutrino Mass Hierarchy

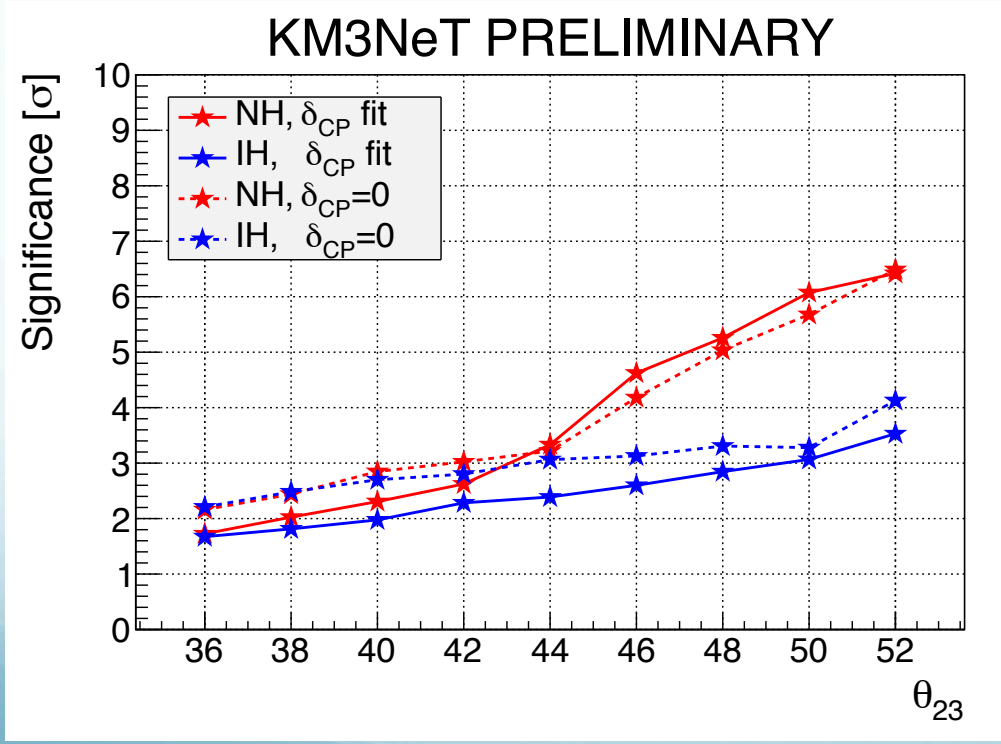
Dependence of sensitivity on time for fixed θ_{23} values
δ_{CP} fixed to zero for easy comparison with other experiments



- ✓ Track vs shower event classification
- ✓ Full MC detector response matrices including misidentified and NC events
- ✓ Atmospheric muon contamination
- ✓ Neutral current event contamination
- ✓ Various Systematic uncertainties

Sensitivity to Neutrino Mass Hierarchy

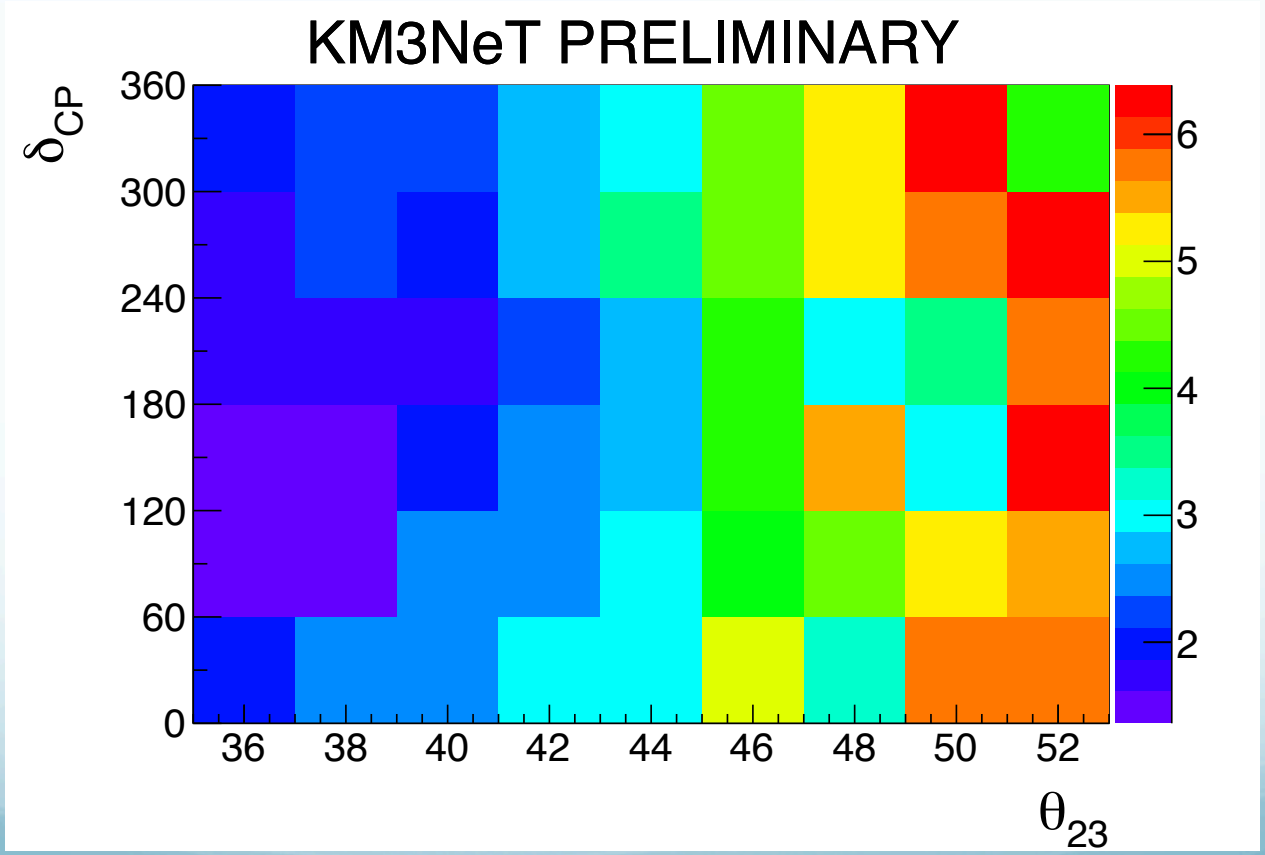
Dependency of sensitivity on θ_{23} for 3 years
NH easier to determine than IH
Second octant easier than first octant
When fixing δ_{CP} to zero sensitivity increases by ~0.5 σ



- ✓ Track vs shower event classification
- ✓ Full MC detector response matrices including misidentified and NC events
- ✓ Atmospheric muon contamination
- ✓ Neutral current event contamination
- ✓ Various Systematic uncertainties

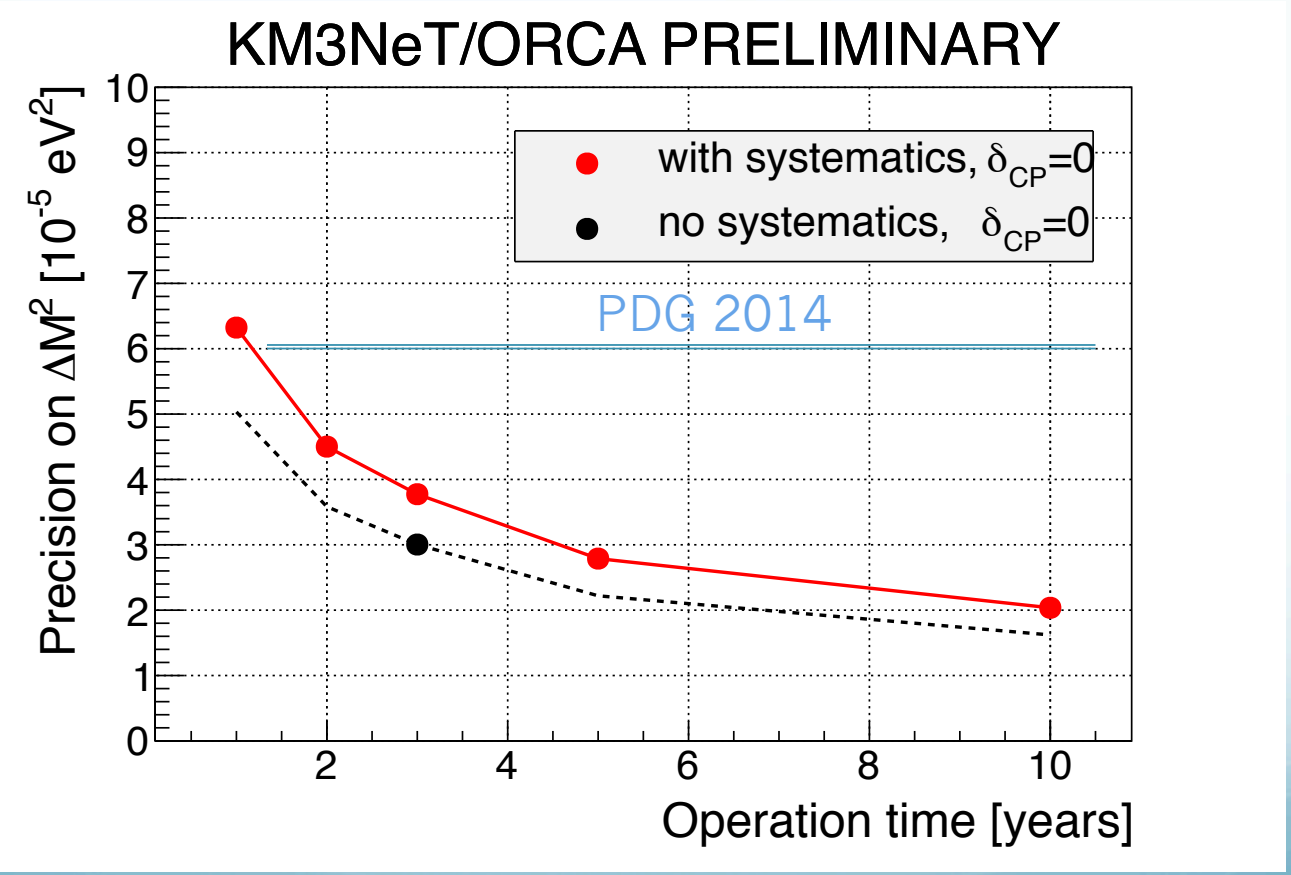
Sensitivity to Neutrino Mass Hierarchy

Dependency of sensitivity on θ_{23} and δ_{CP} for NH and 3 years
Best case : large θ_{23} and δ_{CP} = 0°
Worst case : small θ_{23} and δ_{CP} = 180°



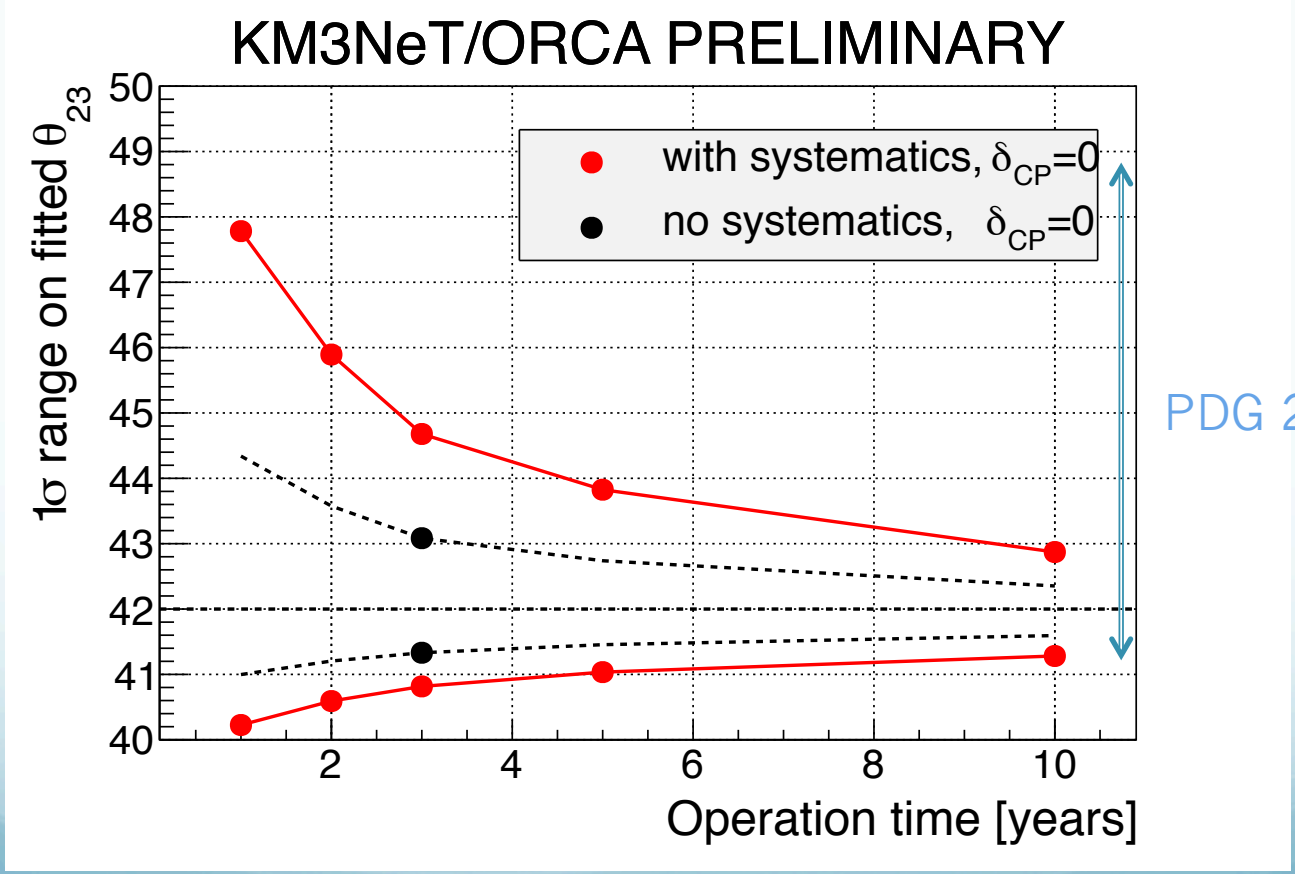
Sensitivity to PMNS parameters

ΔM^2 – unconstrained fit in conjunction to mass hierarchy hypothesis testing
→ Significant improvement of precision achievable



Sensitivity to PMNS parameters

Θ_{23} – unconstrained fit in conjunction to mass hierarchy hypothesis testing
World best measurement after few years of data taking



PDG 2014

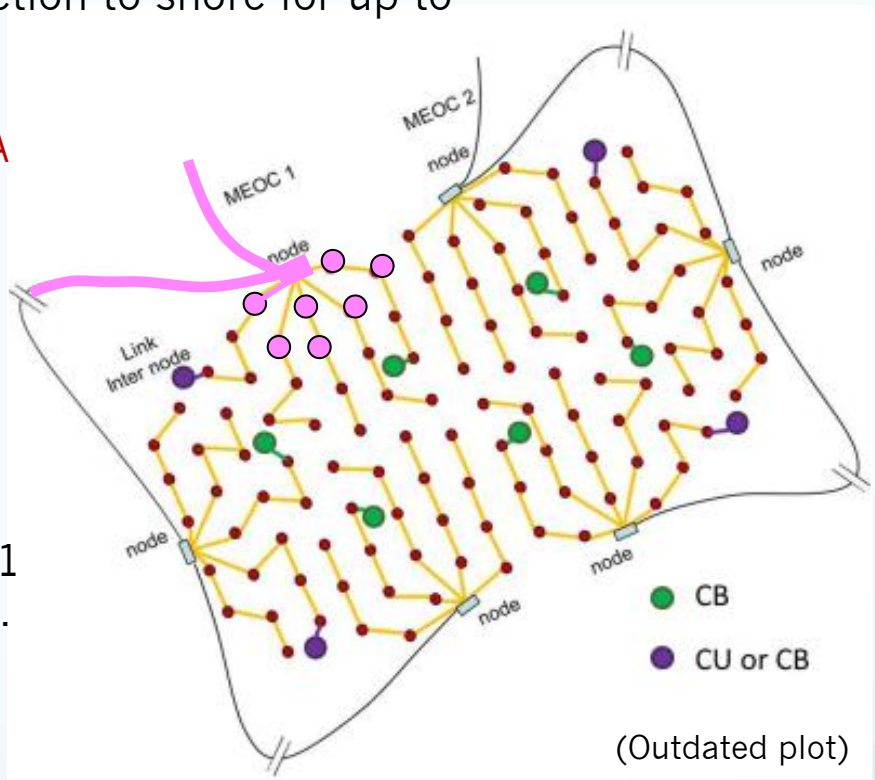
ORCA costs & timeline

Modular ring of up to 6 nodes with double connection to shore for up to 120 detection units + Sea Science instruments

Possibility to redirect the ANTARES cable to ORCA

Phase 1 (funded and spent) : deploy a 6-7 string array in the ORCA configuration to demonstrate detection method in the GeV range.

Phase 2 (~40 M€ wo contingency) : 2017 deploy 1 building block 115 strings in French KM3NeT site. Completion by 2020
Requested funds



(Outdated plot)

Soon available :
ORCA report document
(already ICRC'15 proceedings)

Thank you!

New collaborators are welcome to join the endeavour !

Spare Material

Atmospheric neutrinos measurements

2008-2011 data set

Two different energy estimators:

- dE/dX as evaluated from total collected charge
- Combined likelihood for hit/no-hit for all OMs

$$dE/dX \approx \rho = \frac{\sum^{\text{nHits}} Q_i}{\varepsilon(\vec{x})} \cdot \frac{1}{L_\mu(\vec{x})}$$

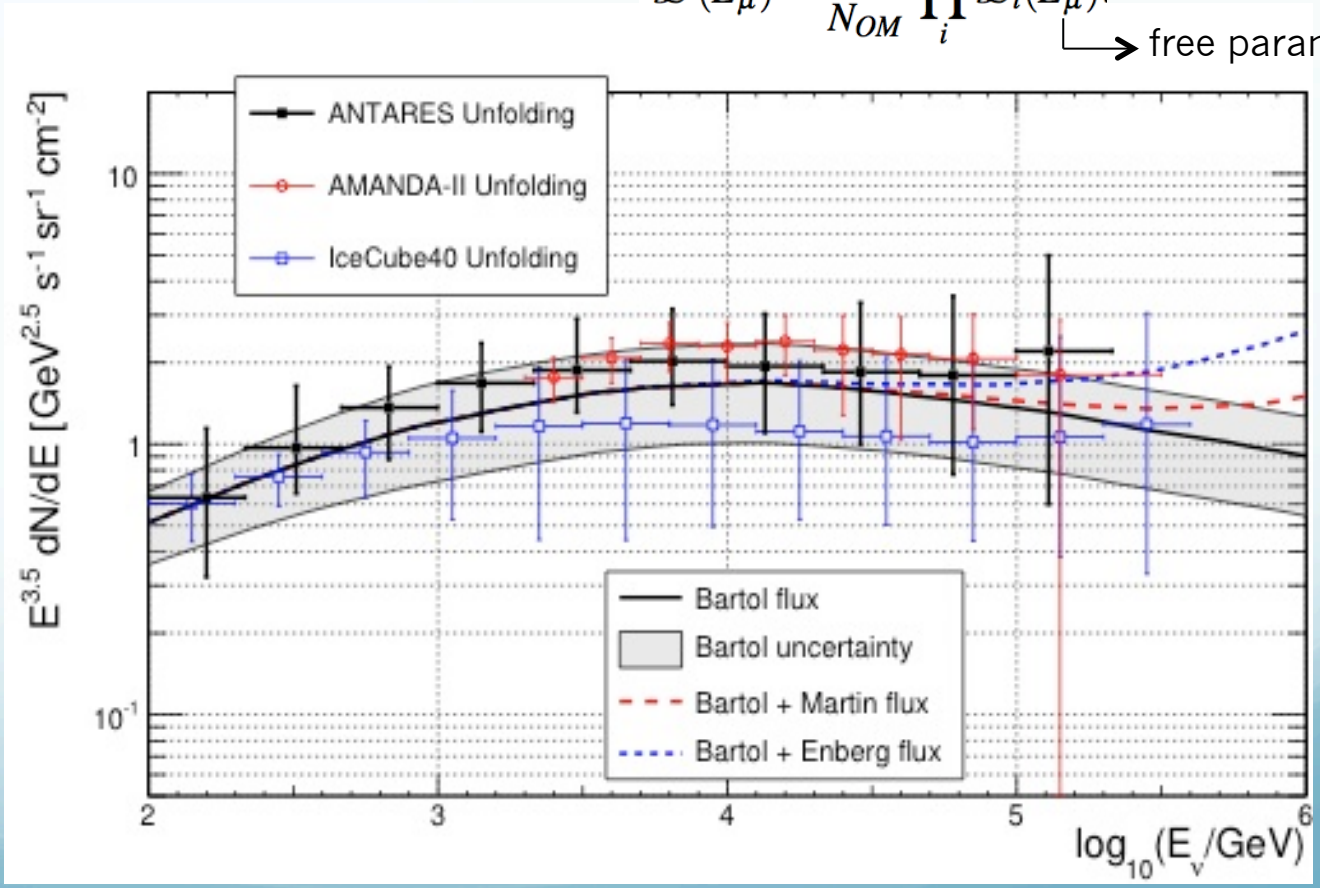
L: length
ε: efficiency

$$\mathscr{L}(E_\mu) = \frac{1}{N_{OM}} \prod_i^{N_{OM}} \mathscr{L}_i(E_\mu).$$

free param

Atmospheric energy spectrum by unfolding measured spectrum averaged in 90°-180° zenith band

Ae = x
A: response matrix
E: true distribution
X: measured distribution

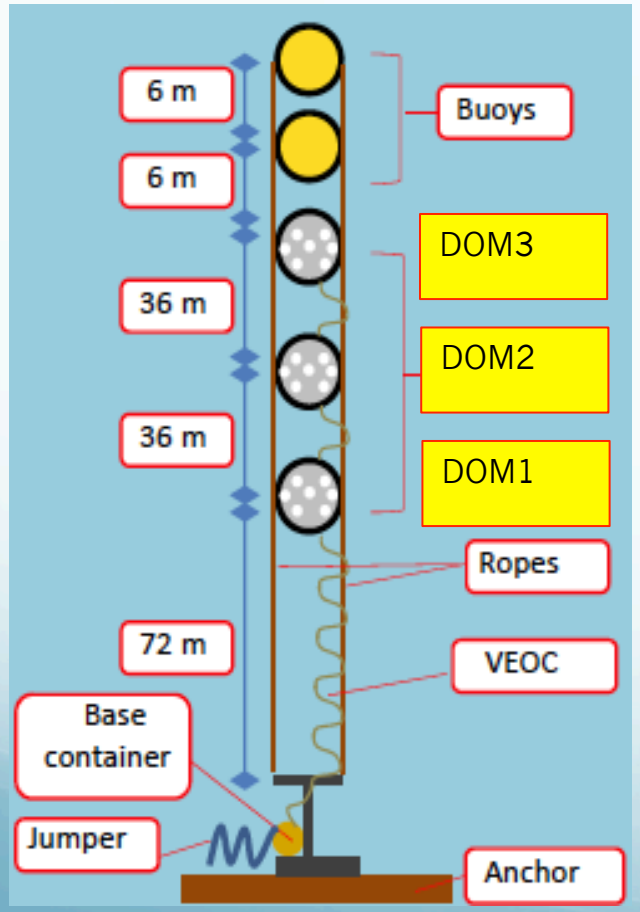


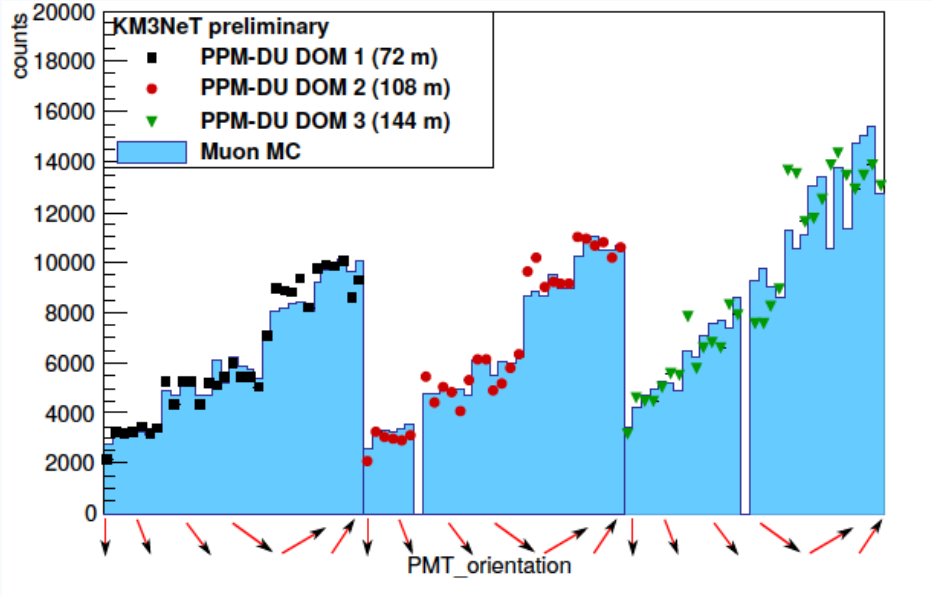
☞Good understanding of the detector

📖 S. Adrian-Martinez et al., Eur. Phys. J.C (2013) 73:2006

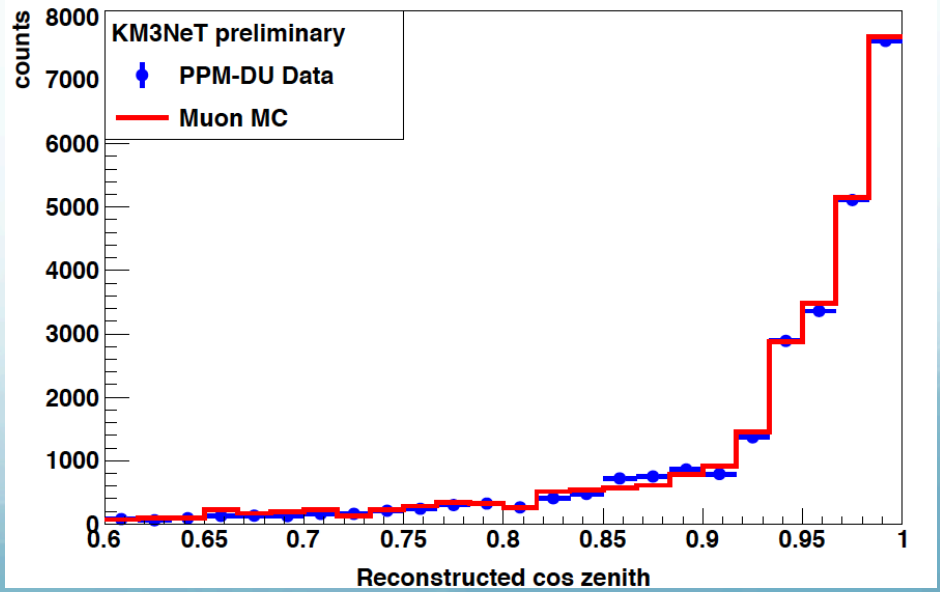
KM3NeT mini-line @ Capo Passero

Smooth operation and data taking since May 2014

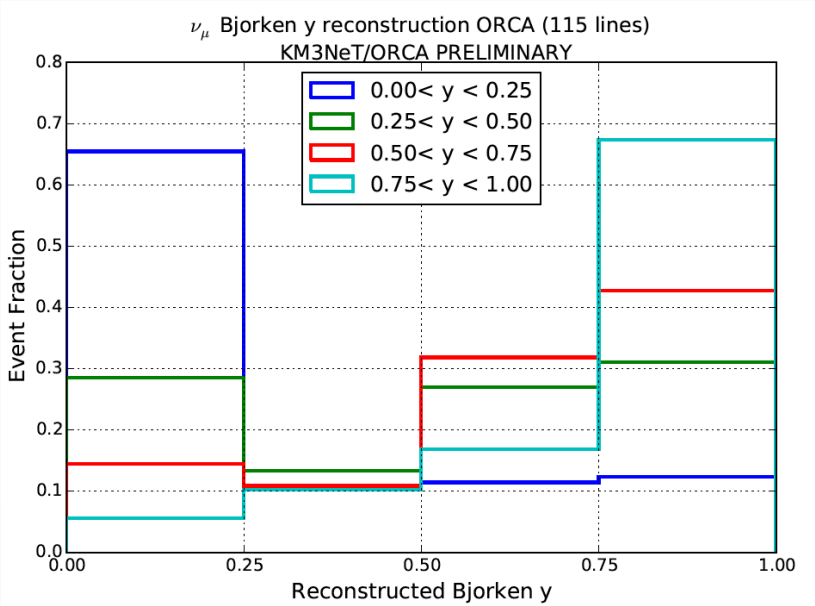




Nice Monte Carlo data agreement



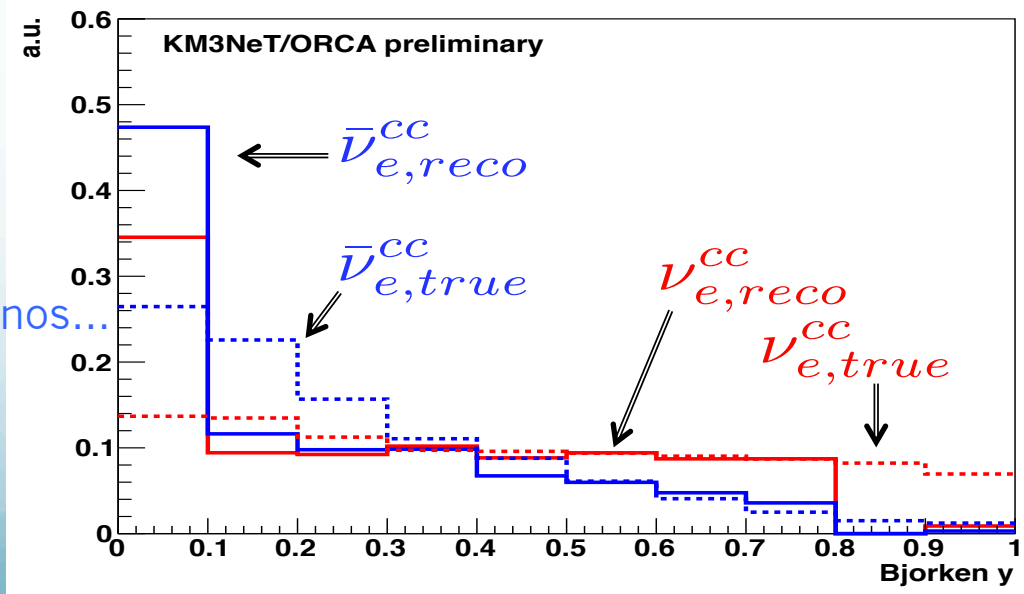
ORCA Sensitivity to Inelasticity



- Use PDFs on the time residuals under the track (low-y) and shower (high-y) hypothesis
- Select y-interval corresponding to highest likelihood

"total significance ... may increase by (20 - 50)%, thus effectively increasing the volume ... by factor 1.5 – 2"
📖 Ribordy & Smirnov PRD, 87. 113007
(**muon channel only**)

Should be further exploited
PID, NC rejection, neutrinos/anti-neutrinos...



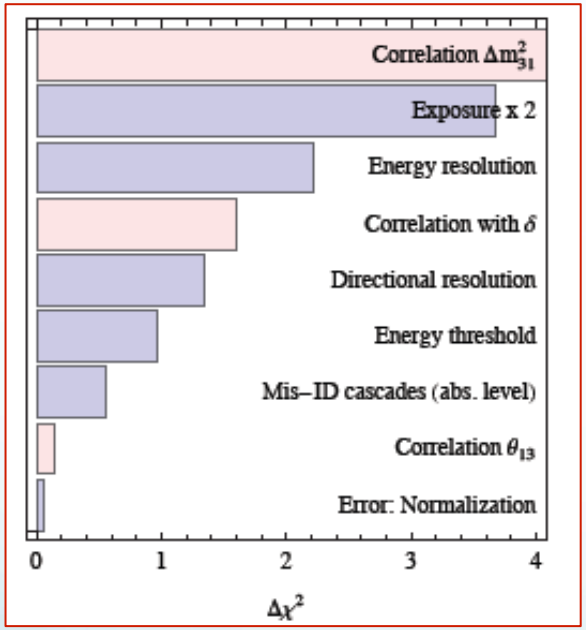
Studies of systematics

Several studies → same conclusions

📖 D. Franco et al, JHEP 04 (2013) 008

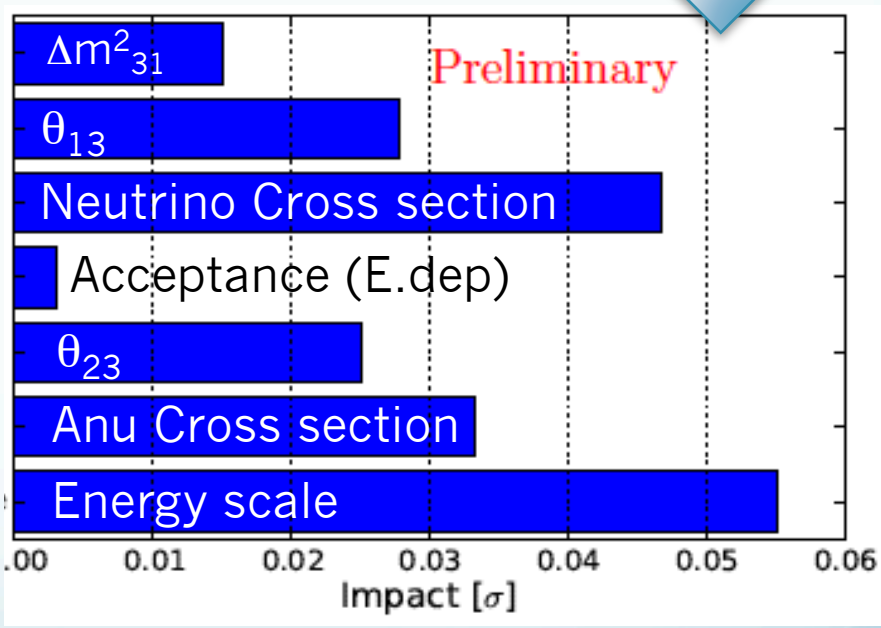
📖 W. Winter, PRD 88 (2013) 013013

(PINGU, 3 yrs)



📖 PINGU LolarXiv1401.2046

Impact (increase) on 1year significance (total 1.75 σ)



📖 Capozzi et al. arXiv1503.01999

Including E, zenith resolution/shape uncertainties +additional uncorrelated uncertainties

Total 5yrs loss in sensitivity from 24% to 40% under very pessimistic assumptions

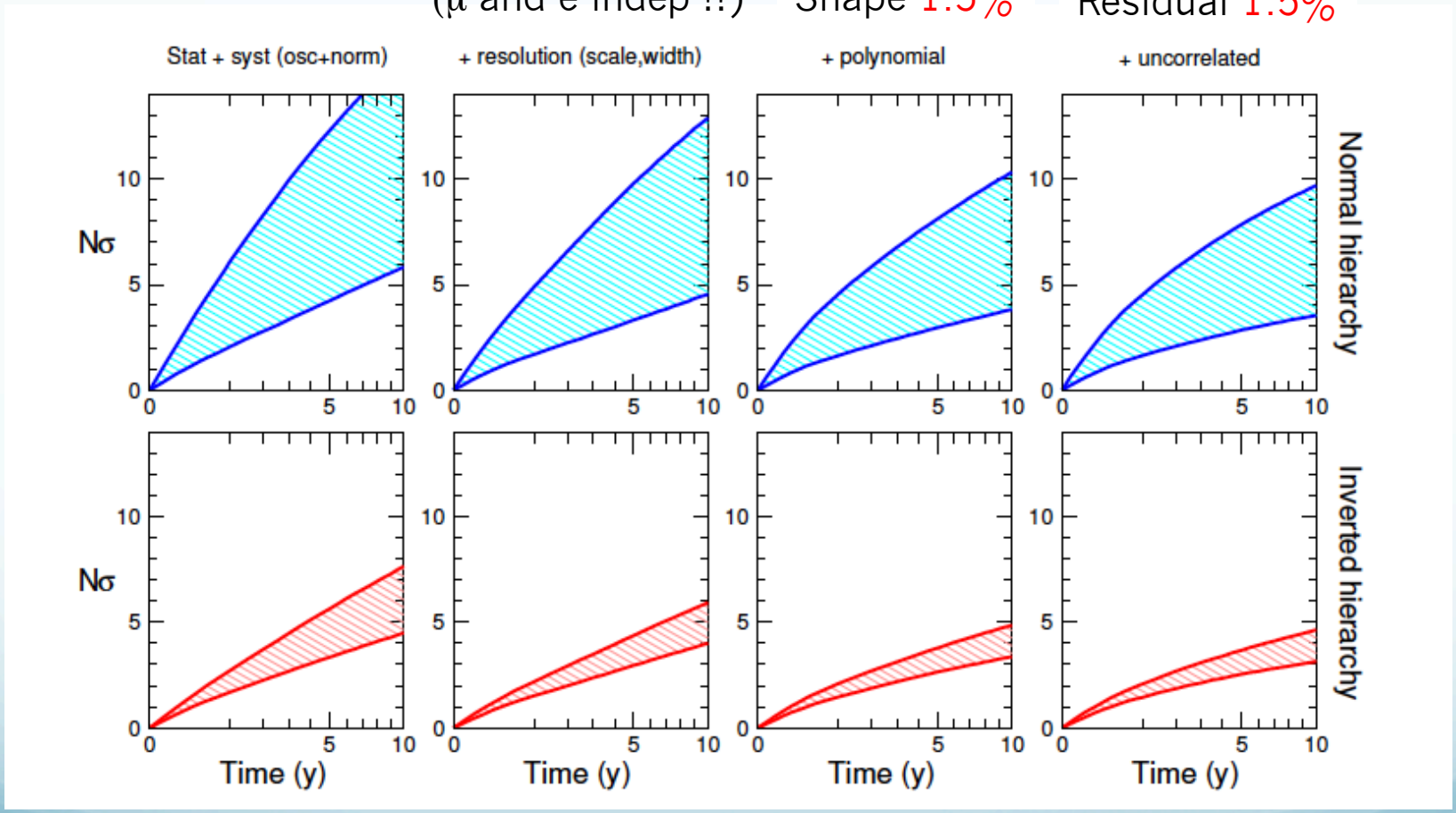
Updates coming up in PINGU, suite of systematics being studied in ORCA

Studies of systematics

$\sin^2 \theta_{23}$ in [0.4; 0.6]

📖 Capozzi et al. arXiv1503.01999
PINGU resolutions and effective masses

(μ and e indep !?) Shape 1.5% Residual 1.5%

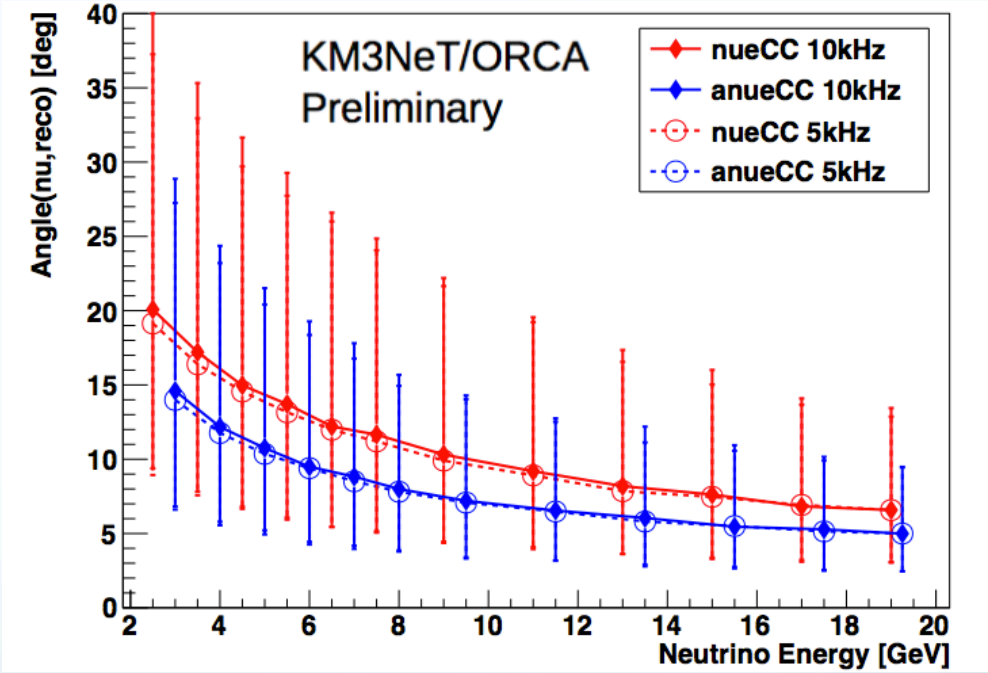


Total 5yrs loss in sensitivity from 24% to 40%

Worst case 3σ in 10 years

ν_e^{CC} : median directional resolution

- error bars: 15% and 85% quantiles
- neutrinos and anti-neutrinos
- negligible differences between 5 and 10 kHz single PMT optical background rates



A phased implementation

PHASE 1:

Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It

31 lines deployed by end 2016 (**3-4 x ANTARES sensitivity**)

Proof of feasibility of network of distributed neutrino telescopes and more?

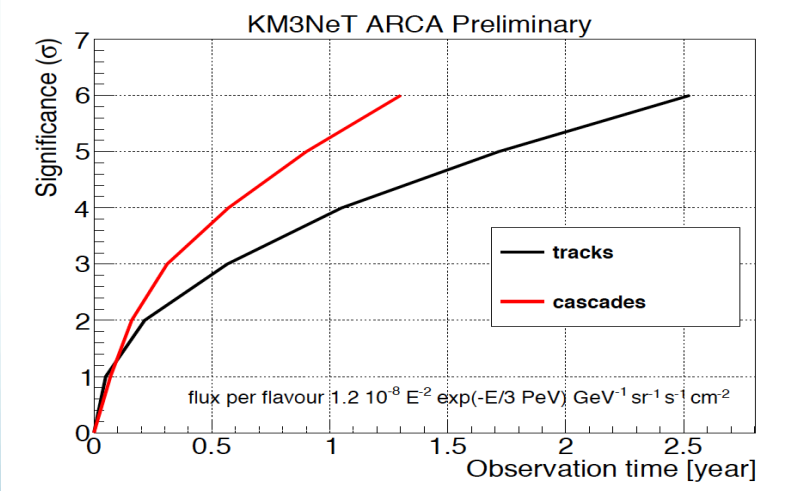
ORCA demonstrator

31 M€ FUNDED ONGOING

2016 PHASE 2: ARCA (+80-90 M€) and ORCA (+40 M€)

230 lines (2 building blocks in Italy) + 115 lines (1 building block) in France

Investigation of IceCube signal *Neutrino Mass Hierarchy*



ARCA and ORCA Letters of Intent in preparation

2020 KM3NeT NEXT: *Neutrino astronomy*

6 building blocks

220-250 M€ ESFRI Roadmap