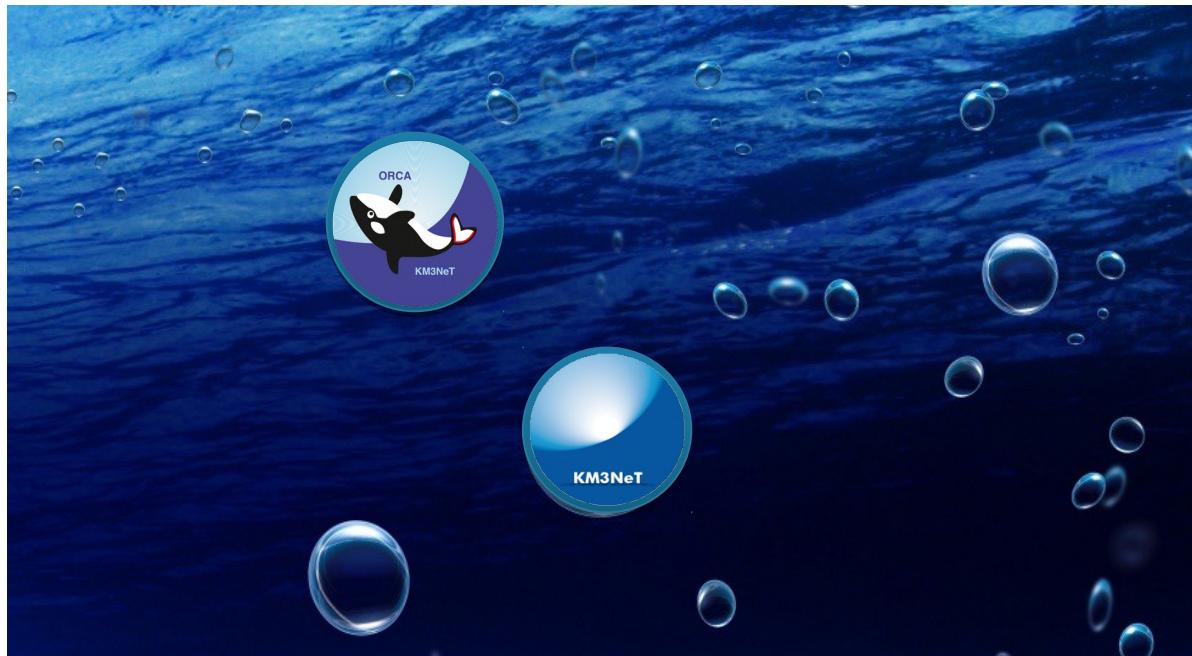


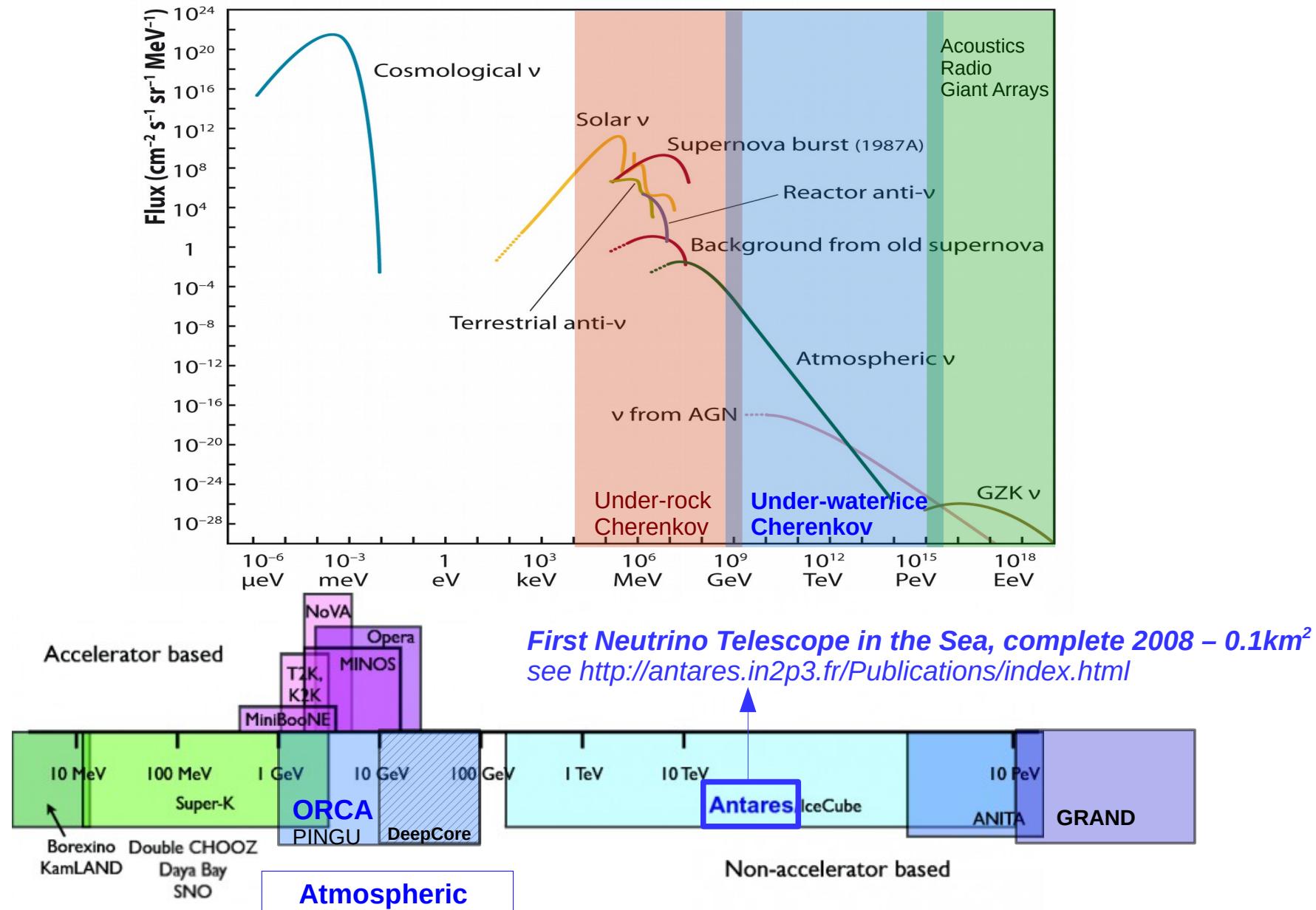
KM3NeT/ORCA : measuring the Neutrino Mass Hierarchy with a deep-sea telescope

Thierry PRADIER – pradier@in2p3.fr

University of Strasbourg & IPHC/DRS for the KM3NeT Collaboration



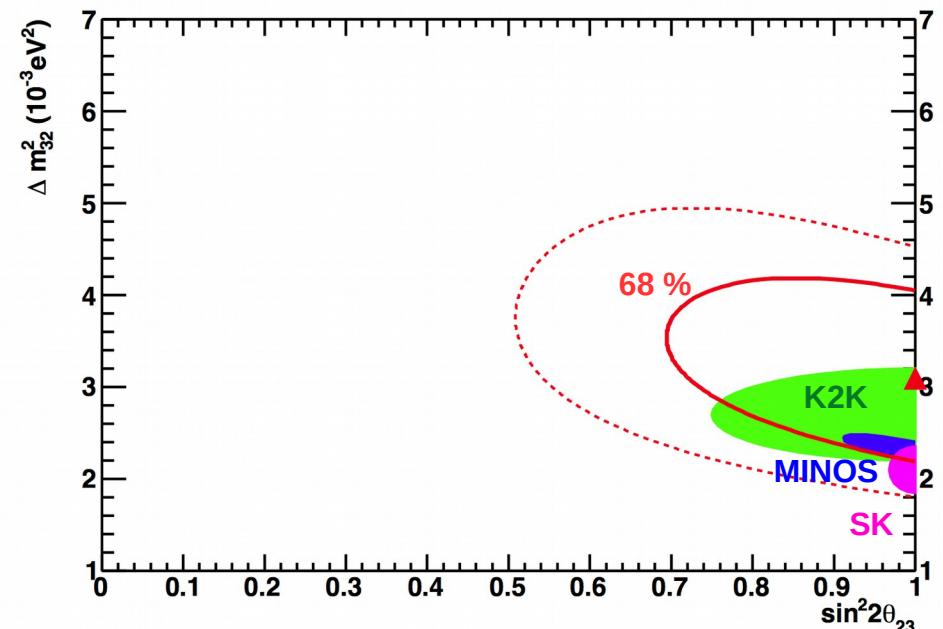
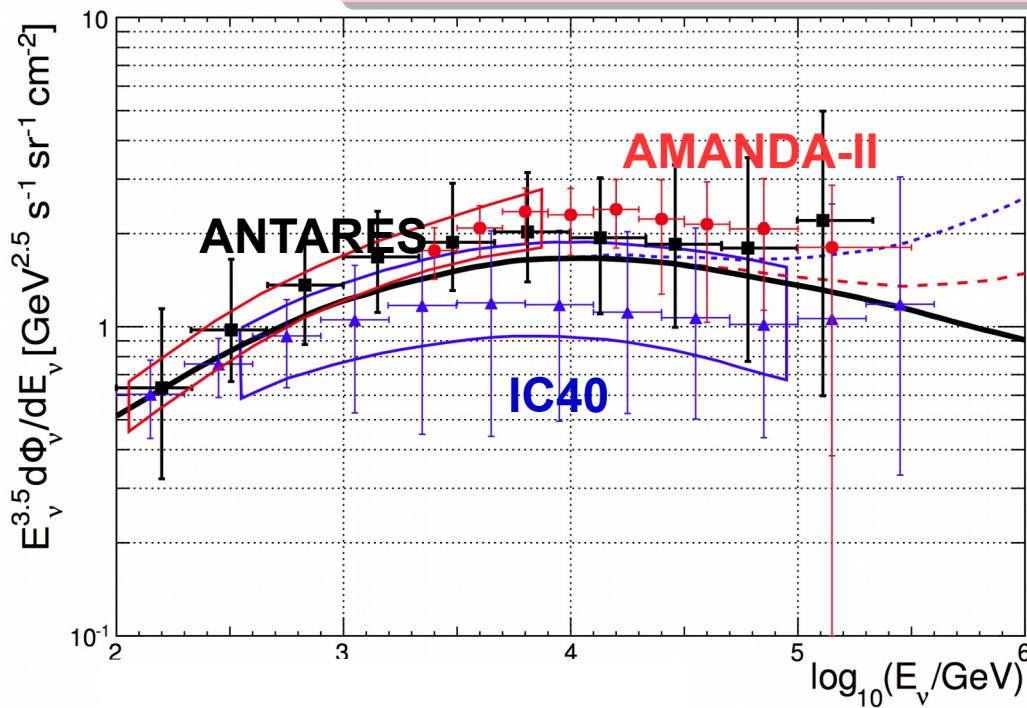
Neutrino detectors : ANTARES and ORCA/PINGU



Neutrino detectors : ANTARES

ANTARES – optimized for cosmic TeV neutrinos, was able to :

- measure the spectrum of atmospheric neutrinos (>100 GeV)
- Independent confirmation of oscillation parameters



[34] of antares.in2p3.fr/publications/index.html

[27] of antares.in2p3.fr/publications/index.html

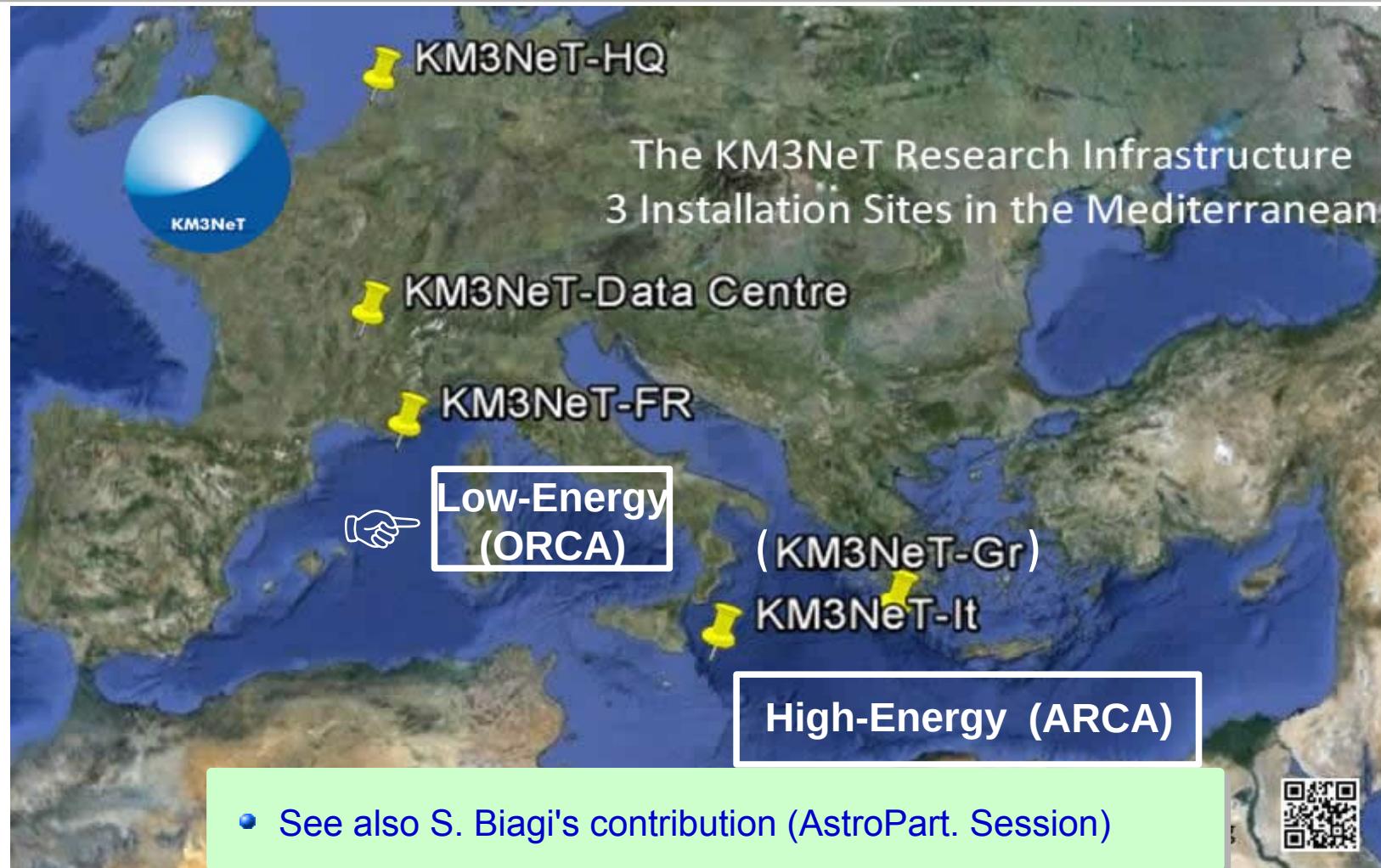
- See also S. Biagi's contribution (AstroPart. Session)

KM3NeT: Next Generation Neutrino Telescopes in the Sea

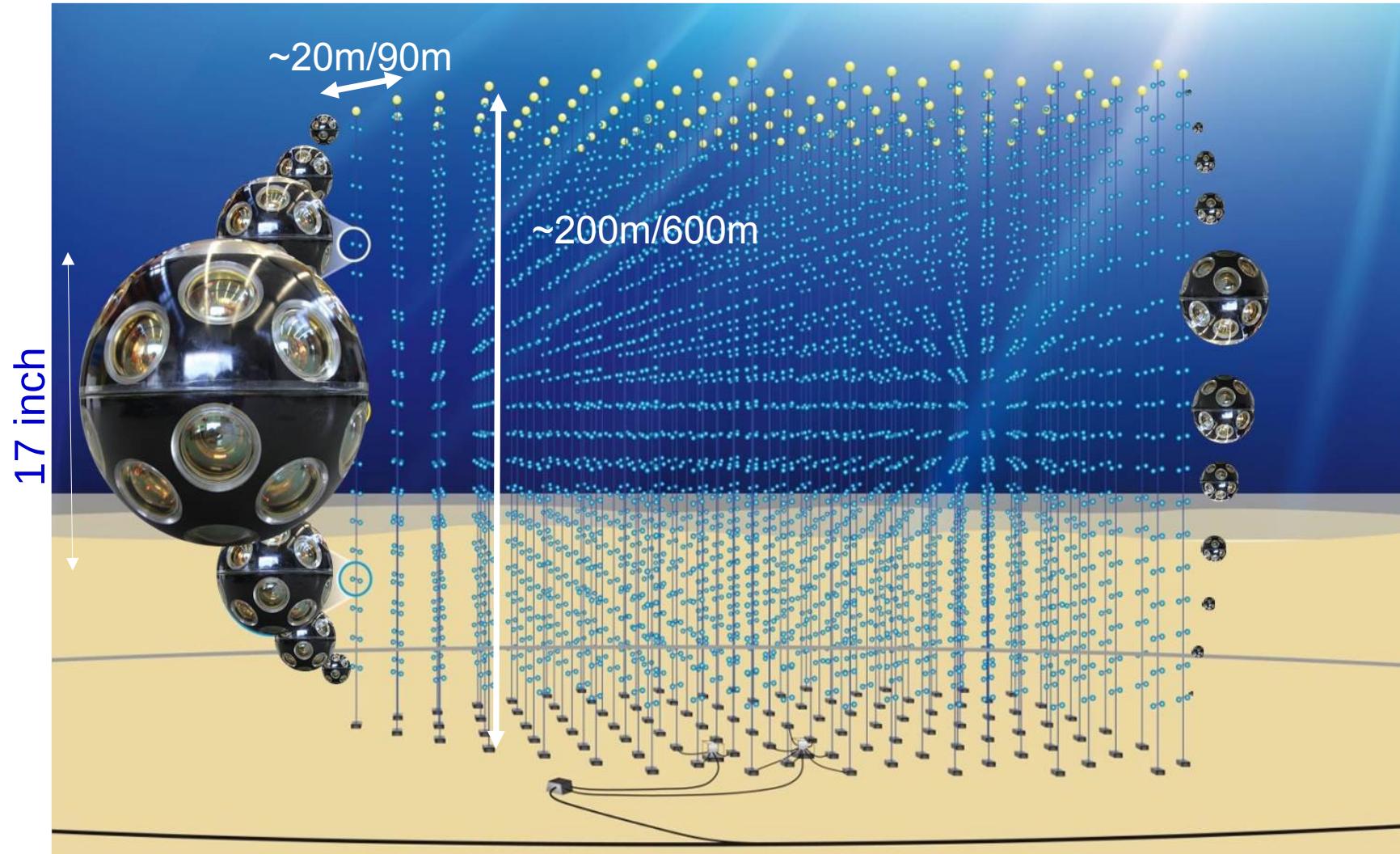
KM3NeT is a distributed research infrastructure with 2 main physics topics:

ORCA = Oscillation Research with Cosmics in the Abyss

ARCA = Astroparticle Research with Cosmics in the Abyss



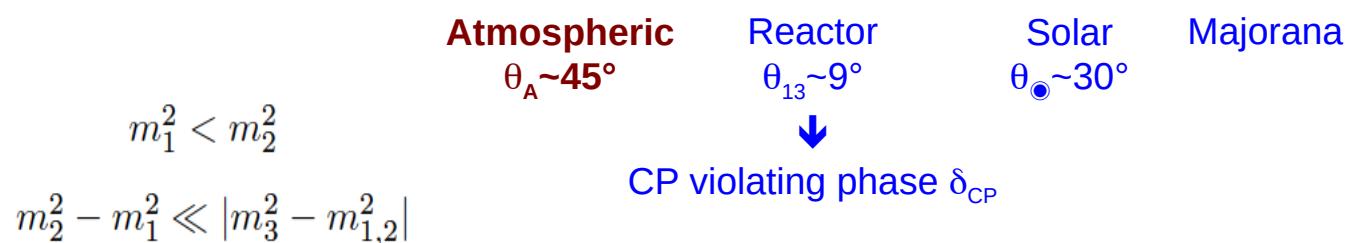
KM3NeT: Detector technology – Digital Optical Modules



- 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction wrt ANTARES

Oscillations of Massive Neutrinos

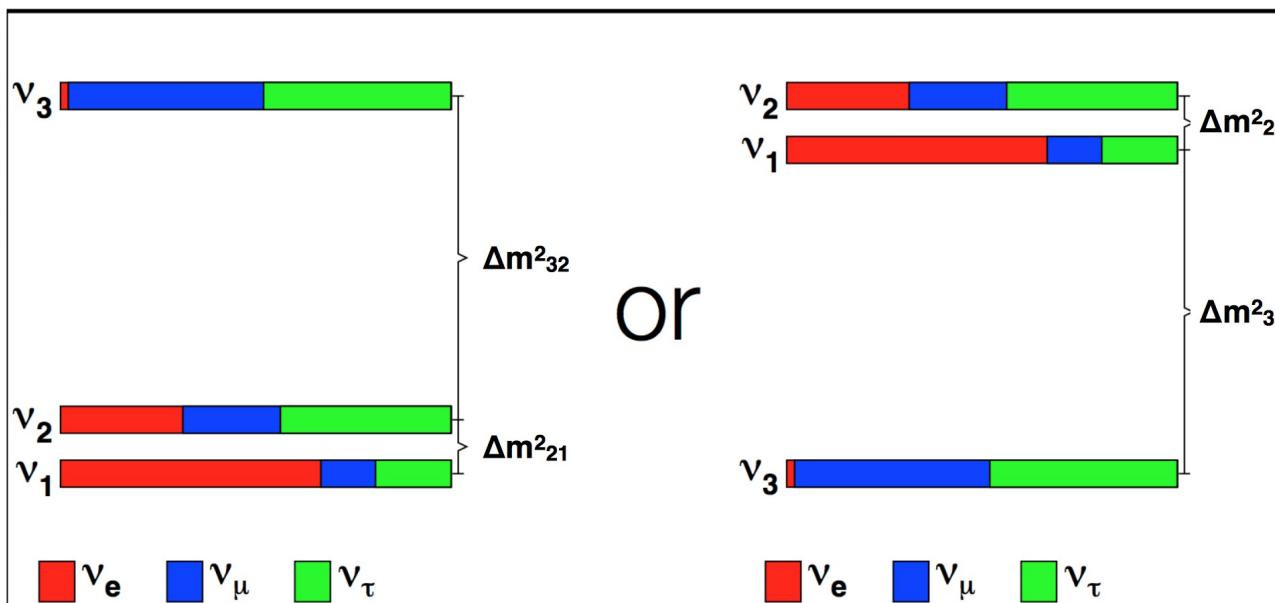
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Parameter	best-fit ($\pm 1\sigma$)	3σ
$\Delta m_{\odot}^2 [10^{-5} \text{ eV}^2]$	$7.58^{+0.22}_{-0.26}$	$6.99 - 8.18$
$ \Delta m_A^2 [10^{-3} \text{ eV}^2]$	$2.35^{+0.12}_{-0.09}$	$2.06 - 2.67$
$\sin^2 \theta_{12}$	$0.306 (0.312)^{+0.018}_{-0.015}$	$0.259 (0.265) - 0.359 (0.364)$
$\sin^2 \theta_{23}$	$0.42^{+0.08}_{-0.03}$	$0.34 - 0.64$
$\sin^2 \theta_{13}$ [140]	$0.021 (0.025)^{+0.007}_{-0.008}$	$0.001 (0.005) - 0.044 (0.050)$
$\sin^2 \theta_{13}$ [142]	0.0251 ± 0.0034	$0.015 - 0.036$

All parameters measured to fair precision except:

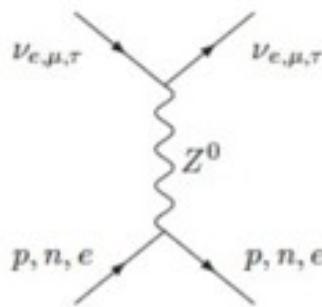
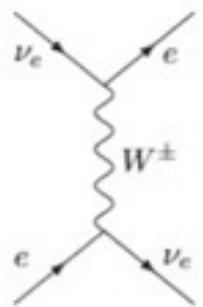
- **Mass Hierarchy (MH)**
- octant of θ_{23}
- CP phase
- Nature Dirac/Majorana



ORCA & matter effects in Long BaseLine experiments

« Standard approach » - probe $\nu_\mu \leftrightarrow \nu_e$ governed by Δm_{31}^2 :

$$P_{3\nu} (\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} P_{2\nu} = \sin^2 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 \left(\frac{\Delta^m m_{31}^2 L}{4E_\nu} \right)$$



$$\sin^2 2\theta_{13}^m \equiv \sin^2 2\theta_{13} \left(\frac{\Delta m_{31}^2}{\Delta^m m_{31}^2} \right)^2$$

$$\Delta^m m_{31}^2 \equiv \sqrt{(\Delta m_{31}^2 \cos 2\theta_{31} - 2E_\nu A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$$

$$E_{\text{res}} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7 \text{ GeV} \left(\frac{4.5 \text{ g.cm}^{-3}}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta_{13}$$

Matter resonance: $A \rightarrow \Delta_{13} \cos 2\theta_{13}$
 - Effective mixing maximal
 - Effective osc. frequency minimal

Resonance energy Earth:
 - Mantle $E_{\text{res}} \sim 7 \text{ GeV}$
 - Core $E_{\text{res}} \sim 3 \text{ GeV}$

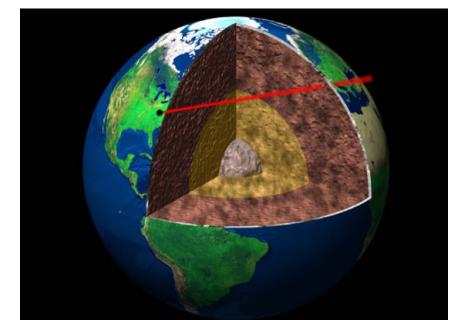
Only electron neutrinos interact through CC with electrons
 → Additional potential A in the Hamiltonian

$$A \equiv \pm \sqrt{2} G_F N_e$$

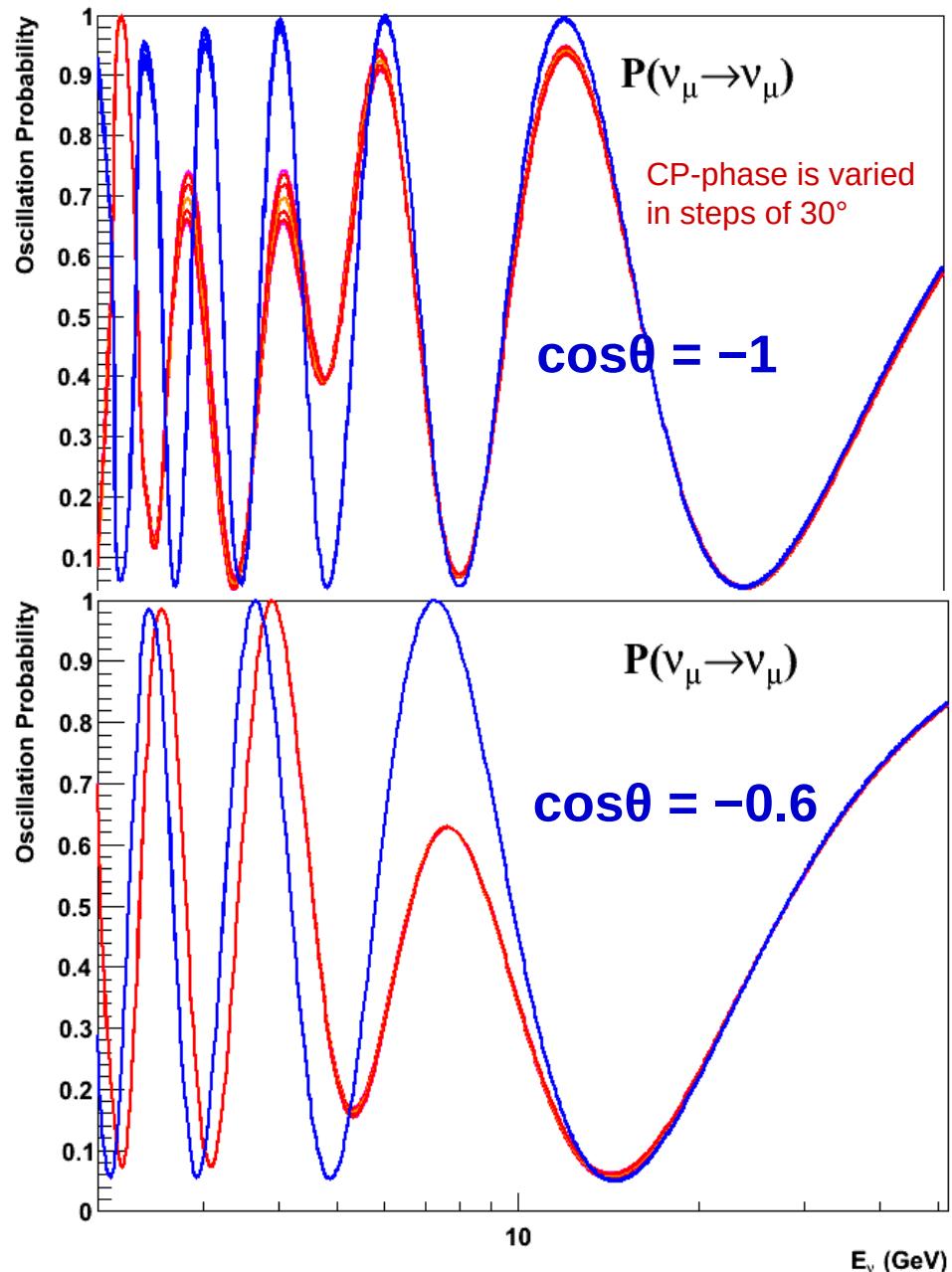
→ **Modify Phase/Amplitude of Oscillation Probability**

$\Theta_{13} \sim 10^\circ \rightarrow \text{Possible with atmospheric !}$

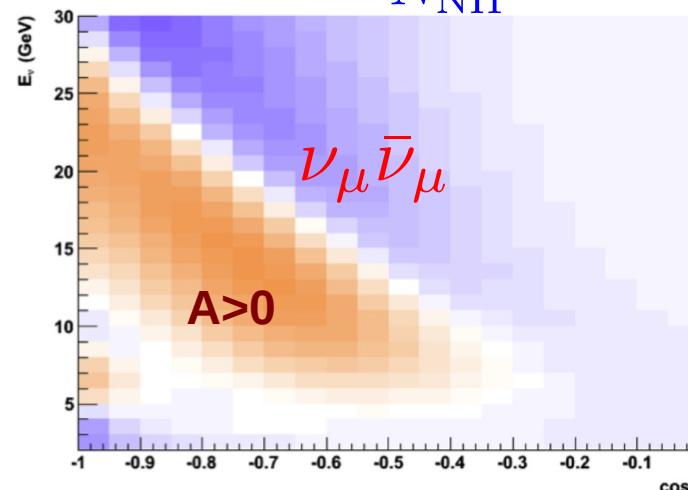
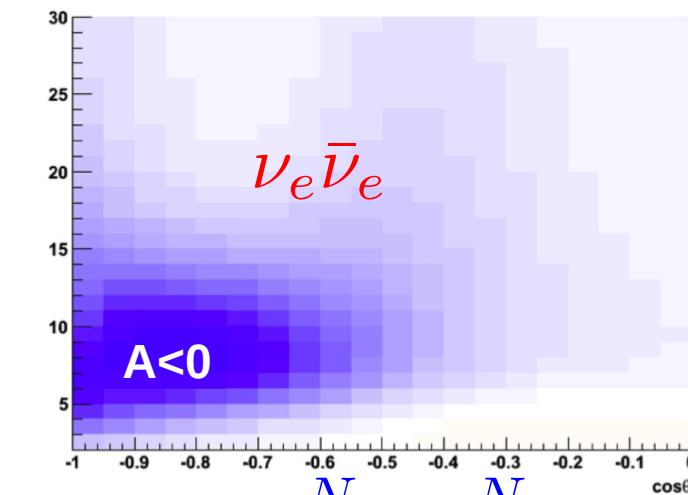
Akhmedov, Razzaque & Smirnov
JHEP 02 (2013) 082



ORCA : Phenomenological Summary

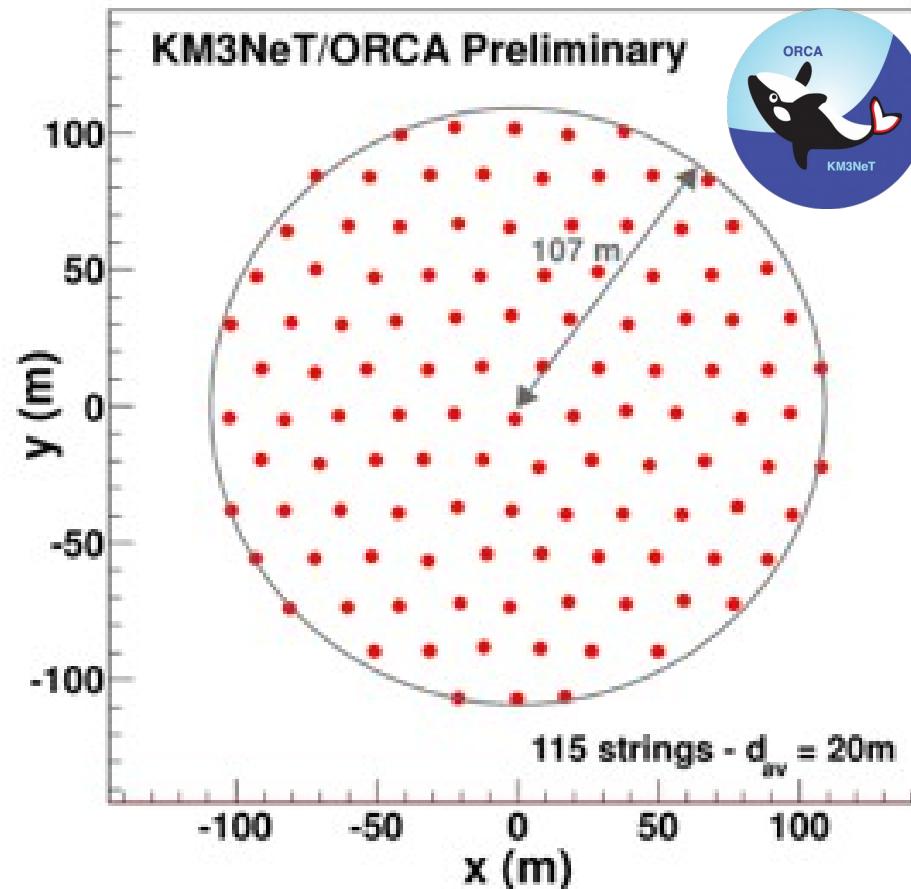


- Inverted Hierarchy
- Normal Hierarchy
- Hierarchy differences disappear at around 15 GeV
- E/θ resolution is paramount !



25% smearing on E
 $(m_p/E_\nu)^{1/2}$ on θ

Proposed Low Energy Telescopes : ORCA



115 lines, 20m spaced,
18 OM/line 6m spaced
Instrumented volume ~3.8 Mt, 2070 OM
3/2 more photocathode area than PINGU

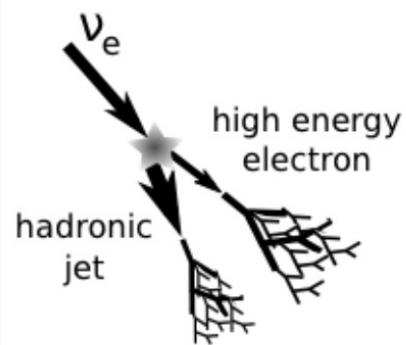
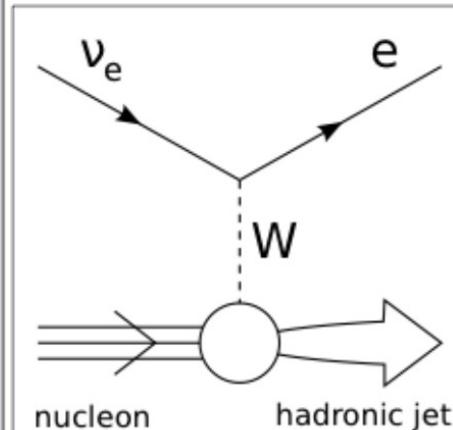
Optical background: 5kHz single rate / PMT & 500 Hz coincidence rate

Optimised layouts still under study

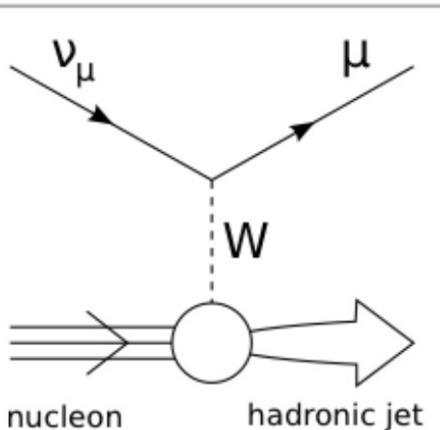
ORCA : Event Topologies

credit: J. Tiffenberg, NUSKY11

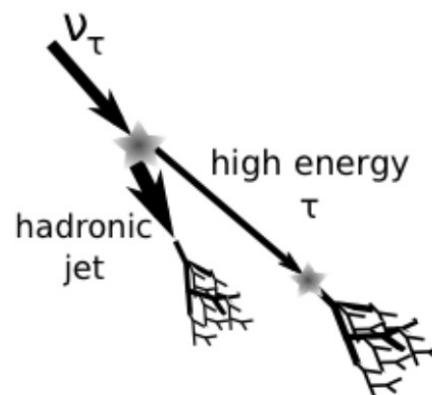
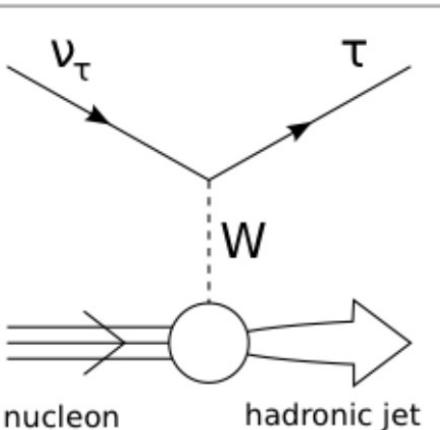
Charged Current



shower-like

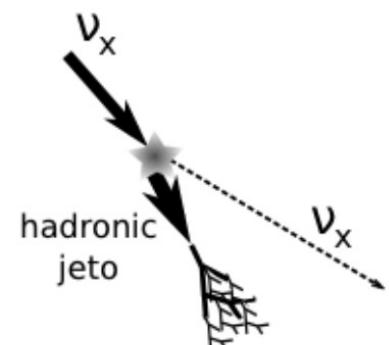
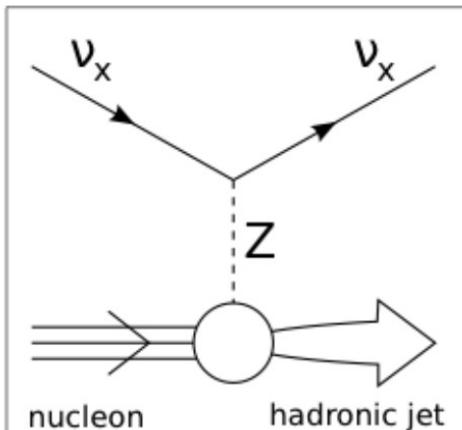


track-like



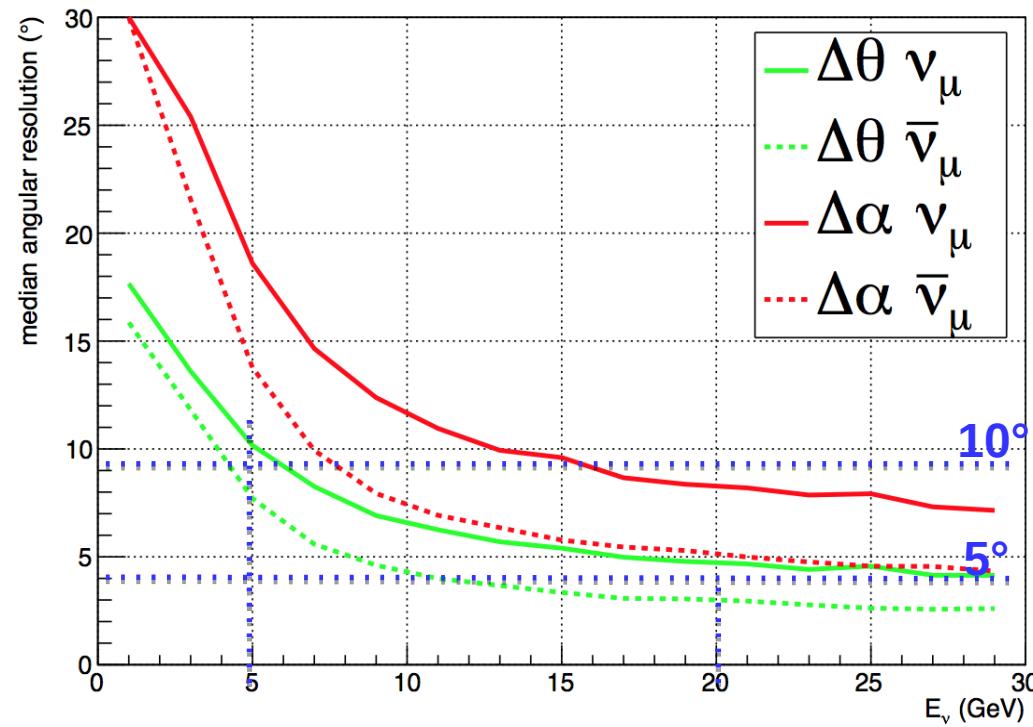
shower-like

Neutral Current

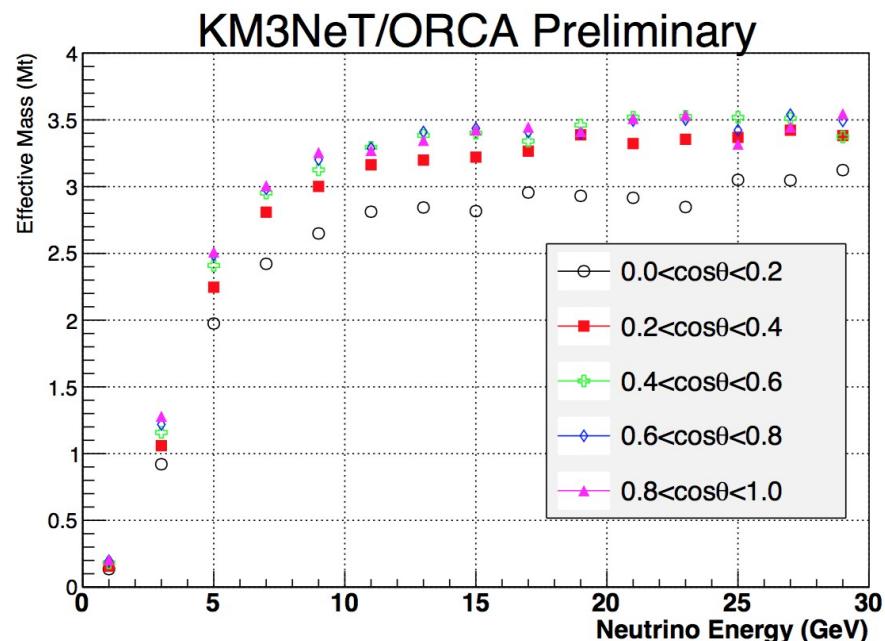
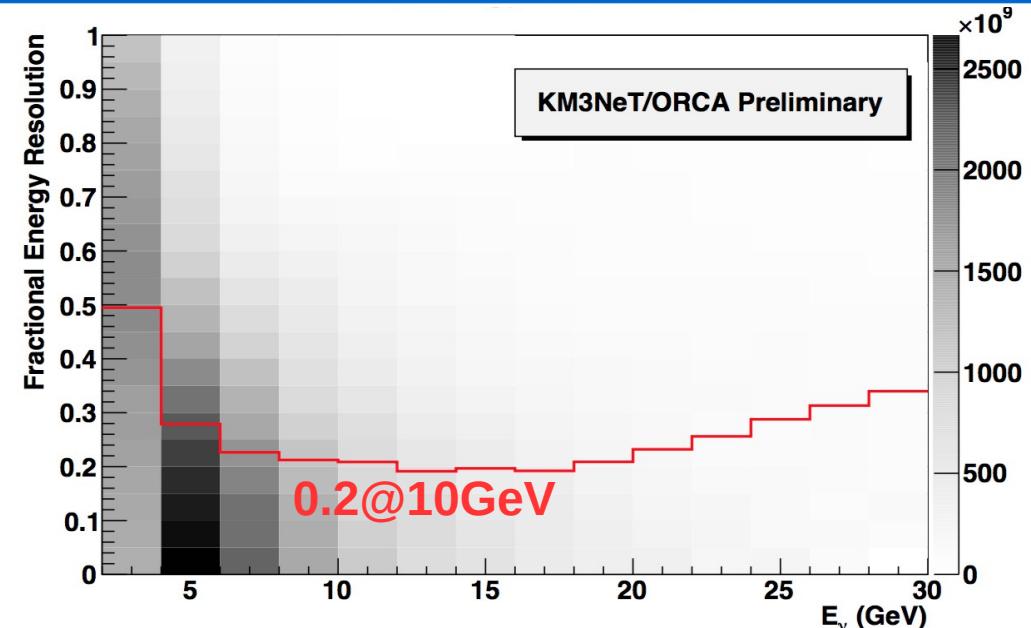


shower-like

ORCA : Preliminary performances (ν_μ CC - tracks)

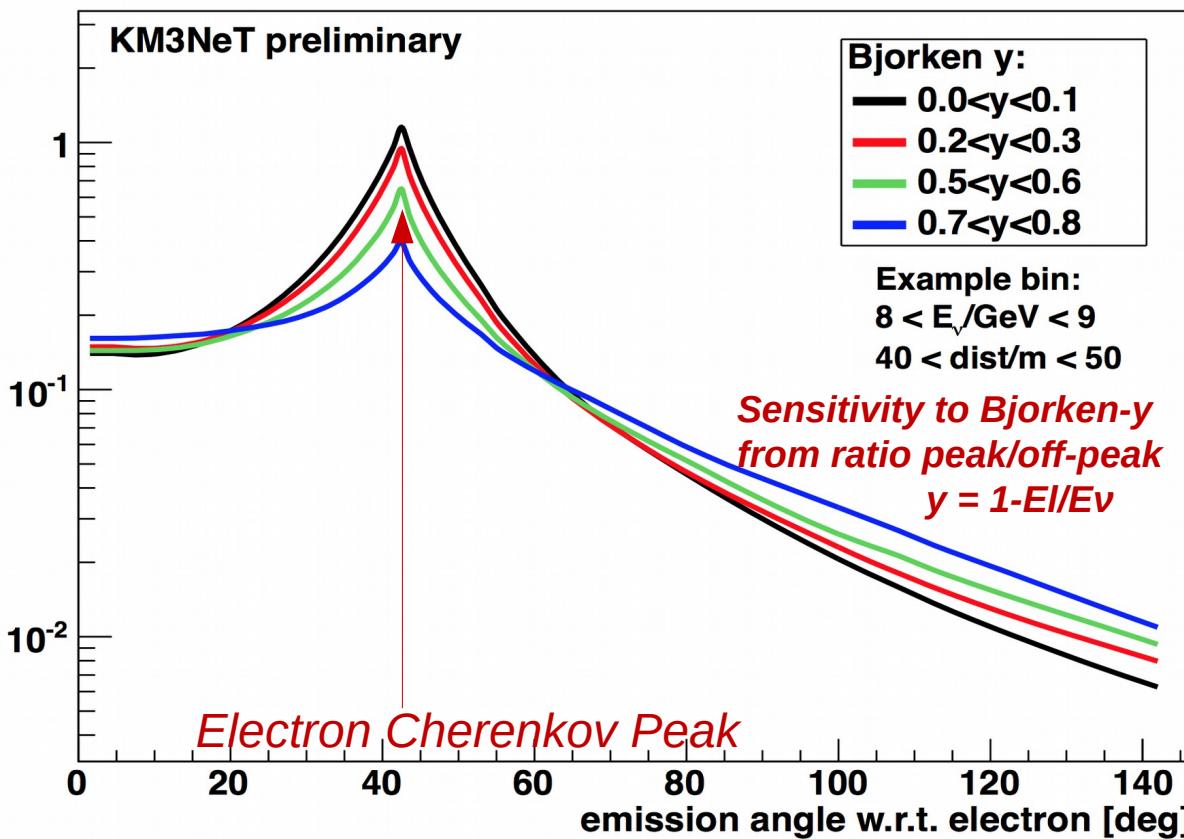


Water = excellent tracker !



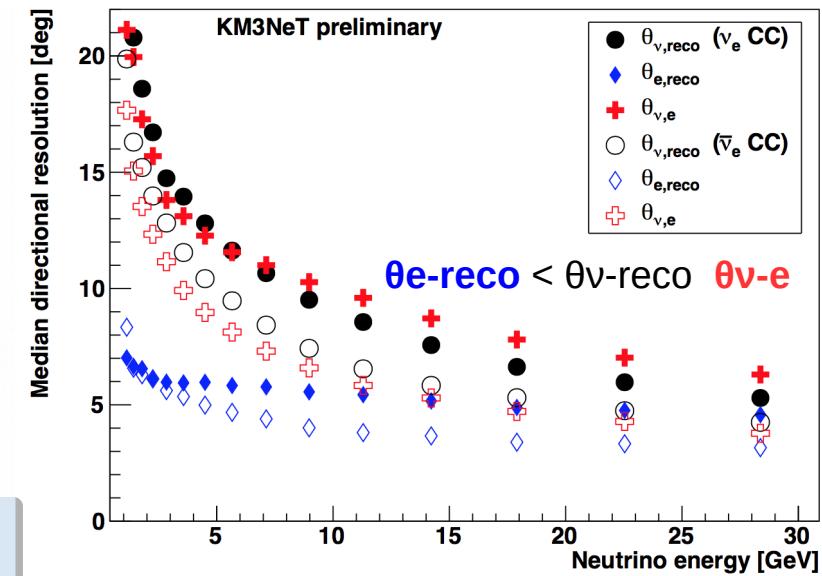
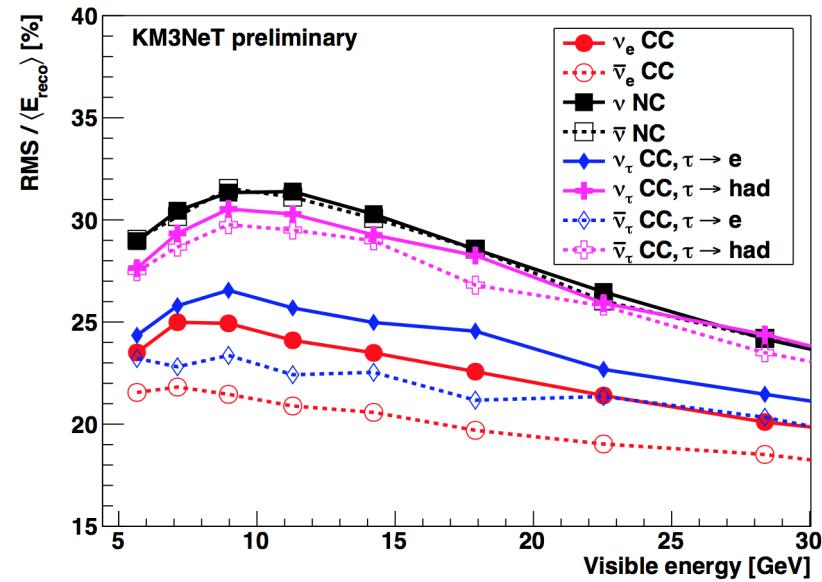
ORCA : Shower reconstruction (ν_e)

mean number of photons per DOM



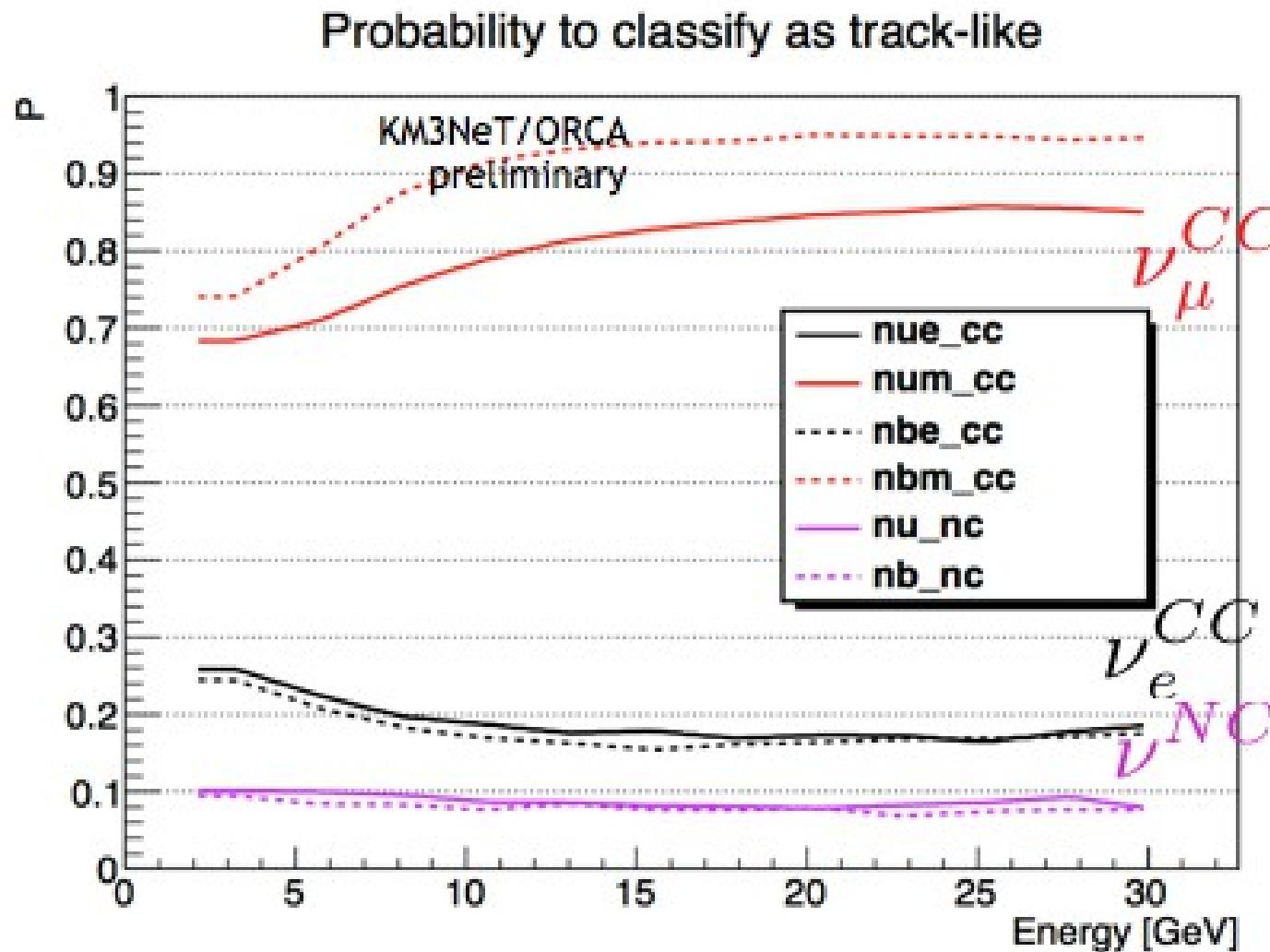
Sensitivity to Bjorken-y in water helps for:

- Shower reconstruction
- Separation $\nu\text{CC}/\text{anti-}\nu\text{CC}/\nu\text{NC}$



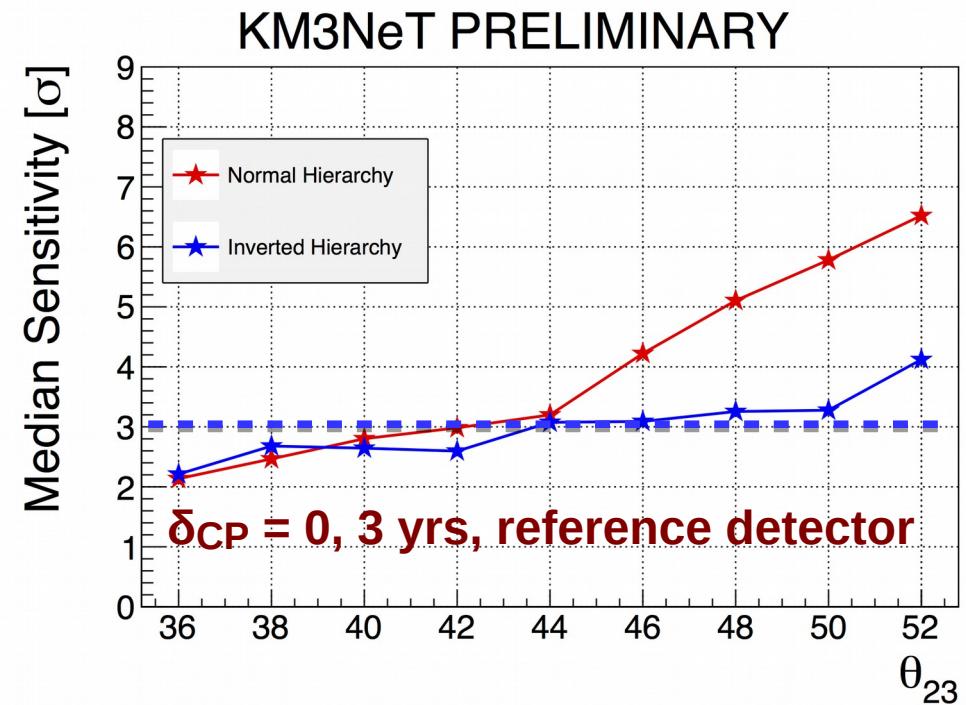
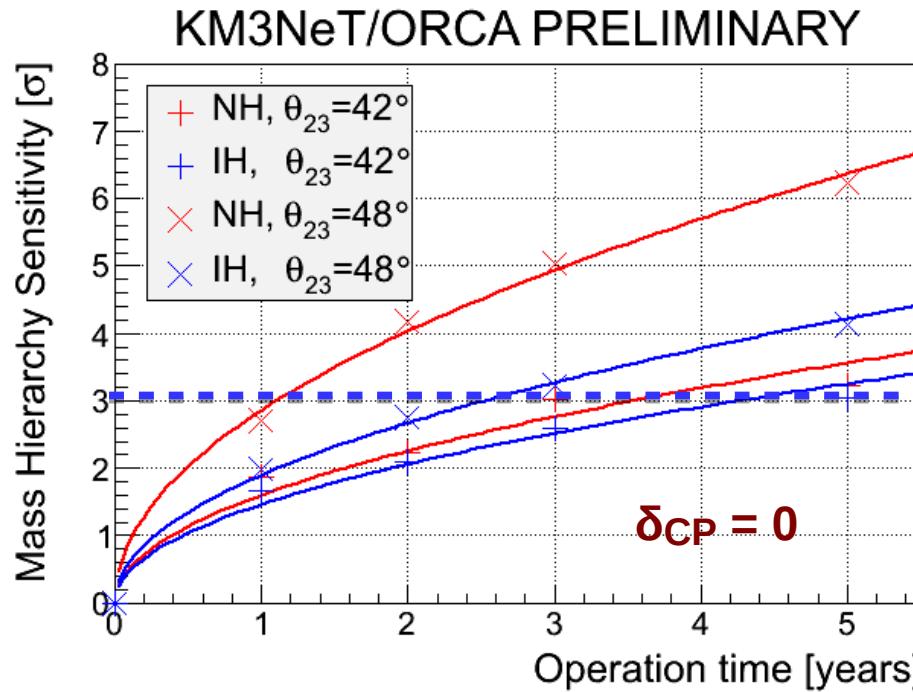
Reco. finds electron in ν_e CC events

Particle IDentification



Goal = Discriminate Track-Like and !Track-Like

Latest Sensitivities vs time / parameters



- MH test using Log-Likelihood Ratio – fitting of ΔM^2 , θ_{23}
- Including Latest track vs shower classification, tracks and shower resolutions, muon contamination in track channel
- Taking into account systematics :
 - scaling of atmospheric spectrum (Fréjus), detector efficiency, $\bar{\nu}N$ cross-section (GENIE) ;
 - $\bar{\nu}/\nu$ events ratio ;
 - ν_μ/ν_e ratio ;
 - energy slope of atmospheric neutrino spectrum ;
 - Neutral Current contamination

Without Geometry optimisation (inter-line/storey spacing) - under way

Improving ORCA's Sensitivity

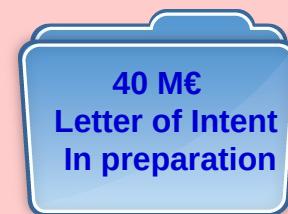
Expected improvements

- Full correlations of osc. parameters
☞ *uncertainties will reduce in future*
- Improvement in the muon channel for energy
- Statistical separation of neutrinos (shower-like $y \sim 1$) from anti-neutrinos (track-like $y \sim 0$)
- Neutral Current event contamination
- Atm. muons contamination (back-up slides)
- Multi-particle reconstruction (back-up slides)
- Add reconstructed inelasticity (y)
- Geometry optimisation **underway**

Summary and perspectives

ORCA Letter of Intent in preparation

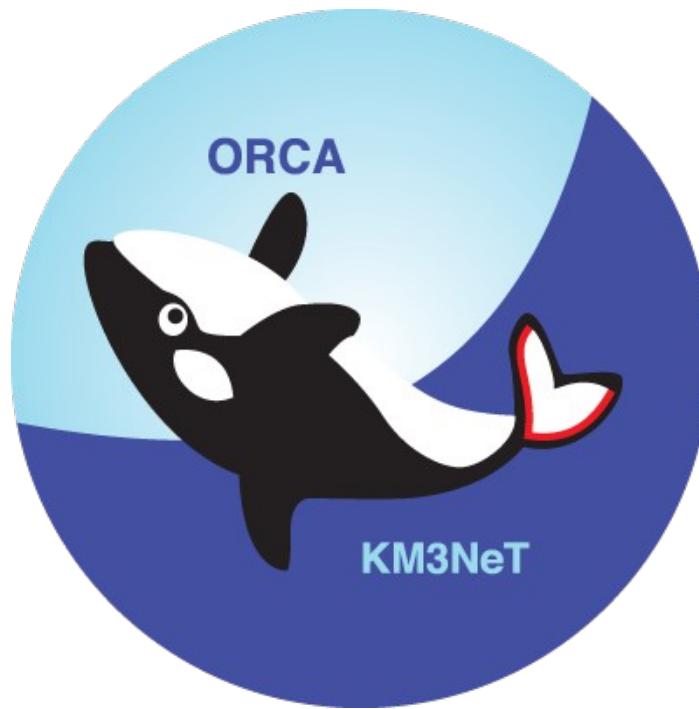
- Measurement of the NMH in a **faster** and **cheaper** way than other alternatives...
- Milestones :**
 - End 2014** : Shore cable installation to KM3NeT-Fr site
 - End 2015** : integration of first ORCA line
 - End 2016** : ORCA 6-line demonstrator in 2016 (Fr)
- Phase 1.5 : 115 lines** → Operational by 2019-2020 ?



Stay tuned ! More details at ICRC
(The Hague, from July 30th)



WE WANT YOU



ORCA

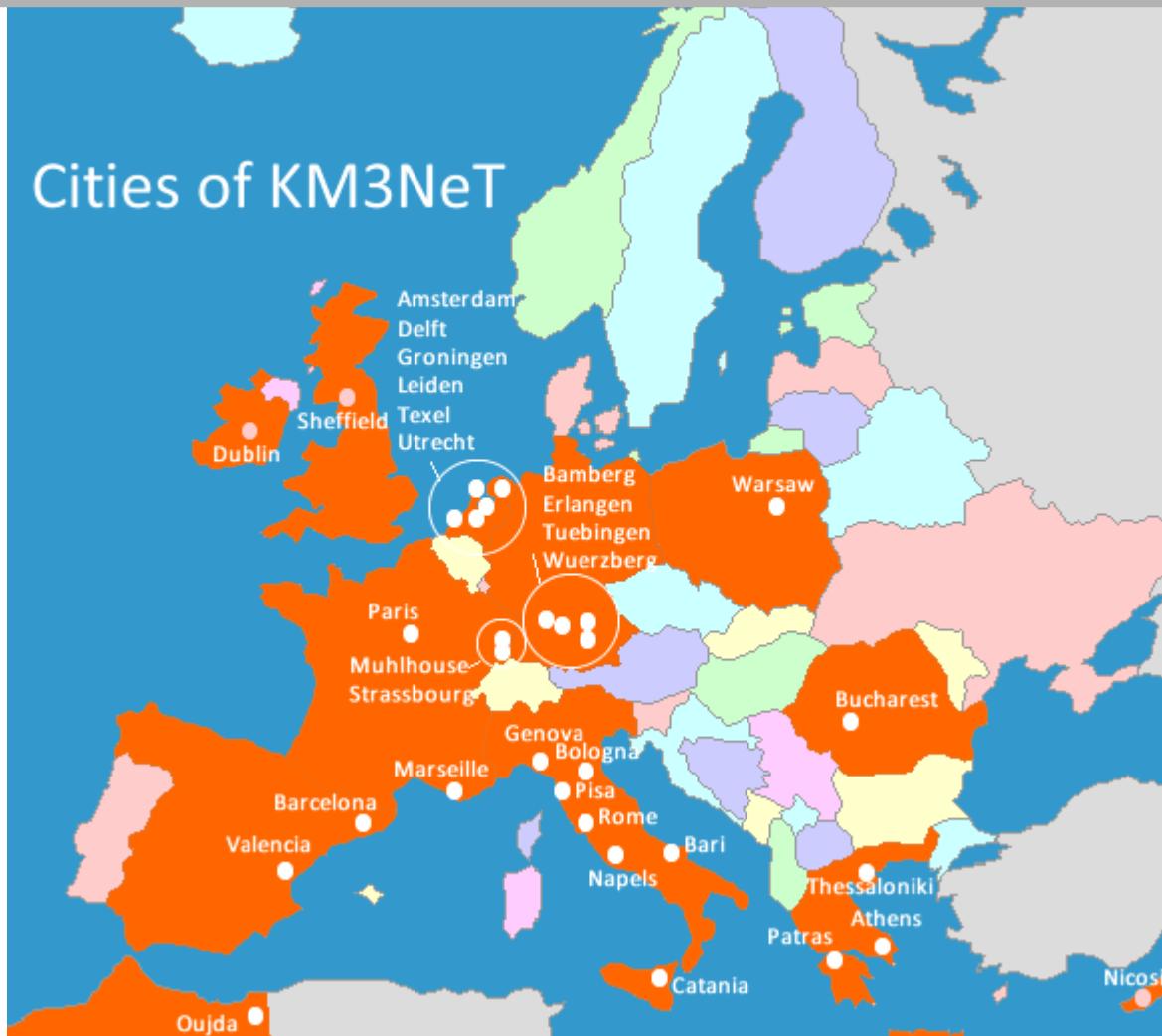
KM3NeT

Back-up : KM3NeT Collaboration

KM3NeT is a distributed research infrastructure with 2 main physics topics:

ORCA = Oscillation Research with Cosmics in the Abyss

ARCA = Astroparticle Research with Cosmics in the Abyss



Back-up : KM3NeT : A phased implementation

Parallel to ORCA (+40M€)

PHASE 1:

Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It
31 lines deployed by end 2016 (3-4 x ANTARES sensitivity)

31 M€
FUNDED
ONGOING

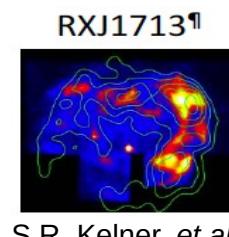
Proof of feasibility of network of distributed neutrino telescopes and more?

2016 PHASE 1.5:

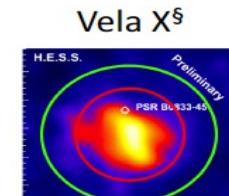
230 lines (2 building blocks)

Investigation of IceCube signal

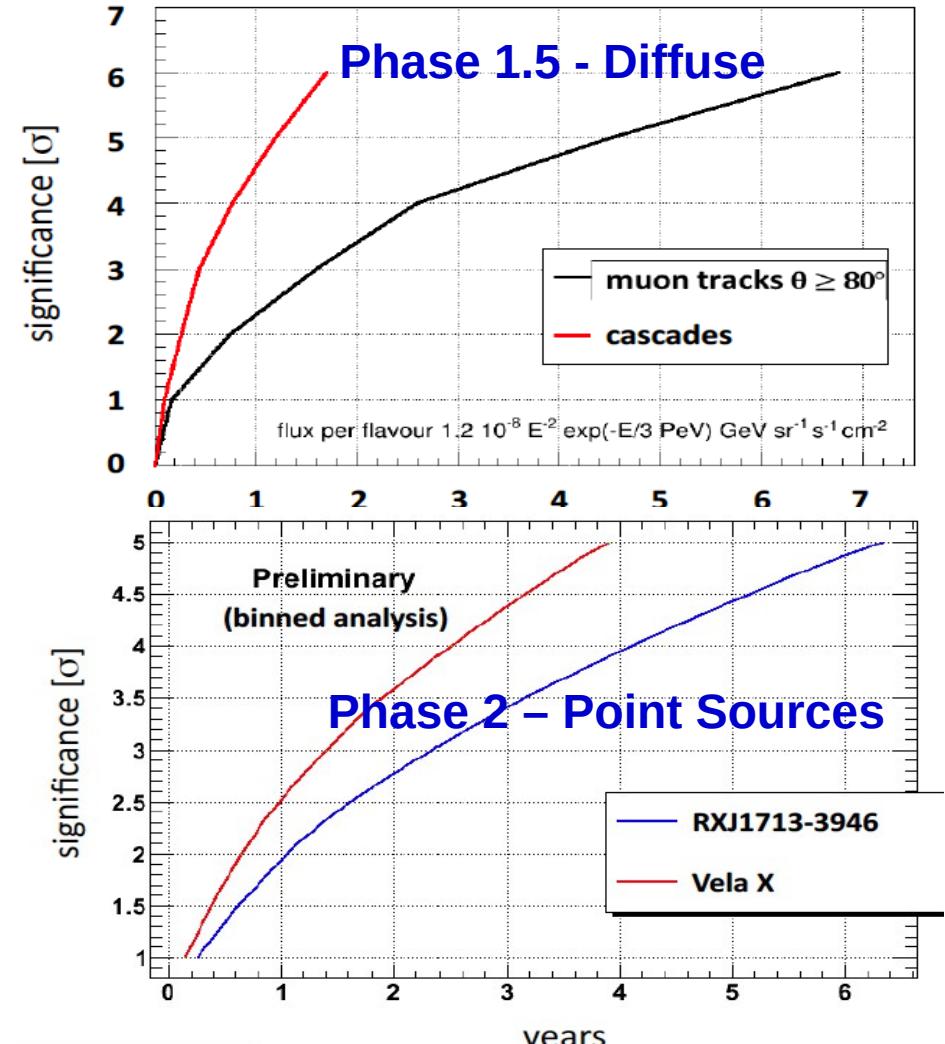
80-90 M€
Letter of Intent
In preparation



RXJ1713[¶]
S.R. Kelner, et al



Vela X[§]
H.E.S.S.
Preliminary
PSR B1933+45
Villante & Vissani

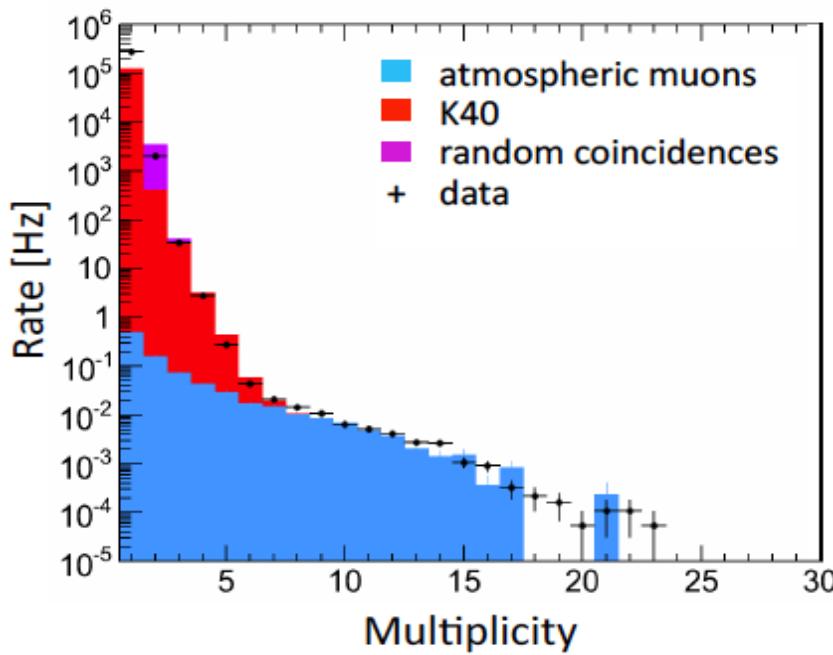


2020 PHASE 2:
6 building blocks
Neutrino astronomy

220-250 M€
ESFRI* Roadmap

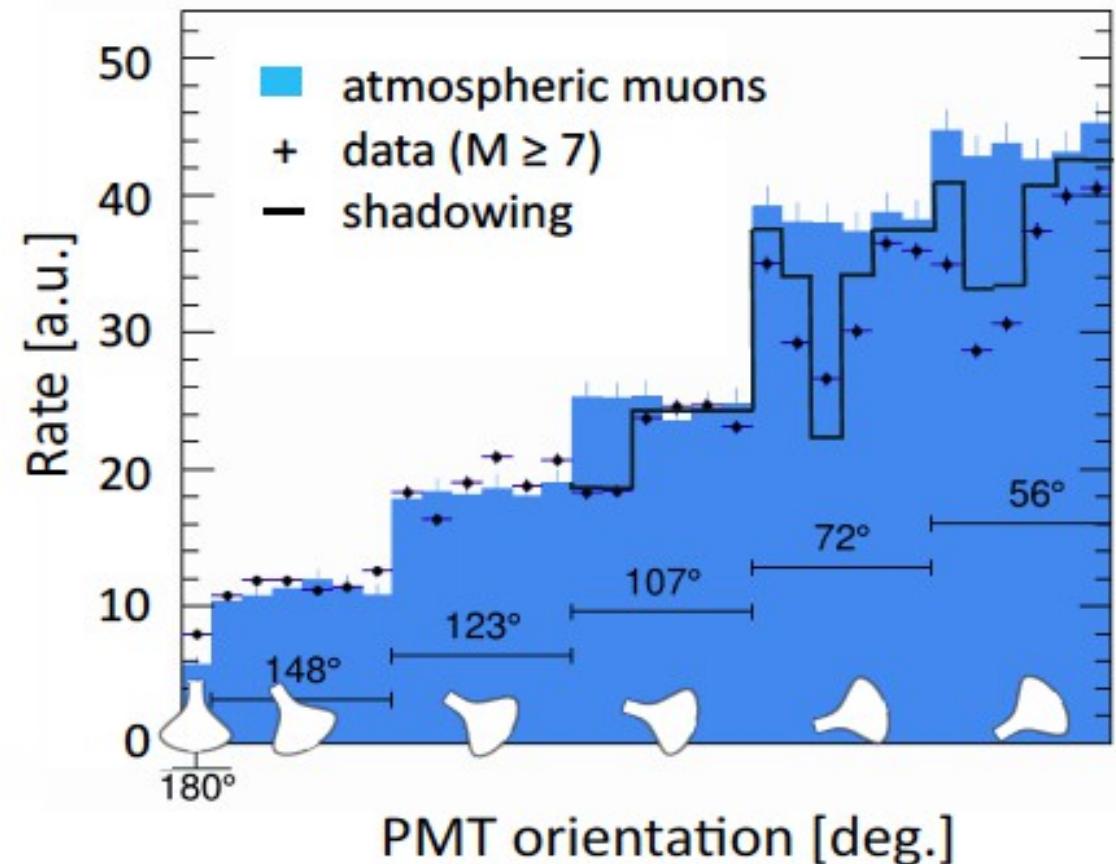
*European Strategy Forum on Research Infrastructures

Back-up : 1st prototype @ ANTARES Site



April 2013: First DOM installed on instrumented line

Validates photon counting & directionality



Eur. Phys. J. C (2014) 74:3056

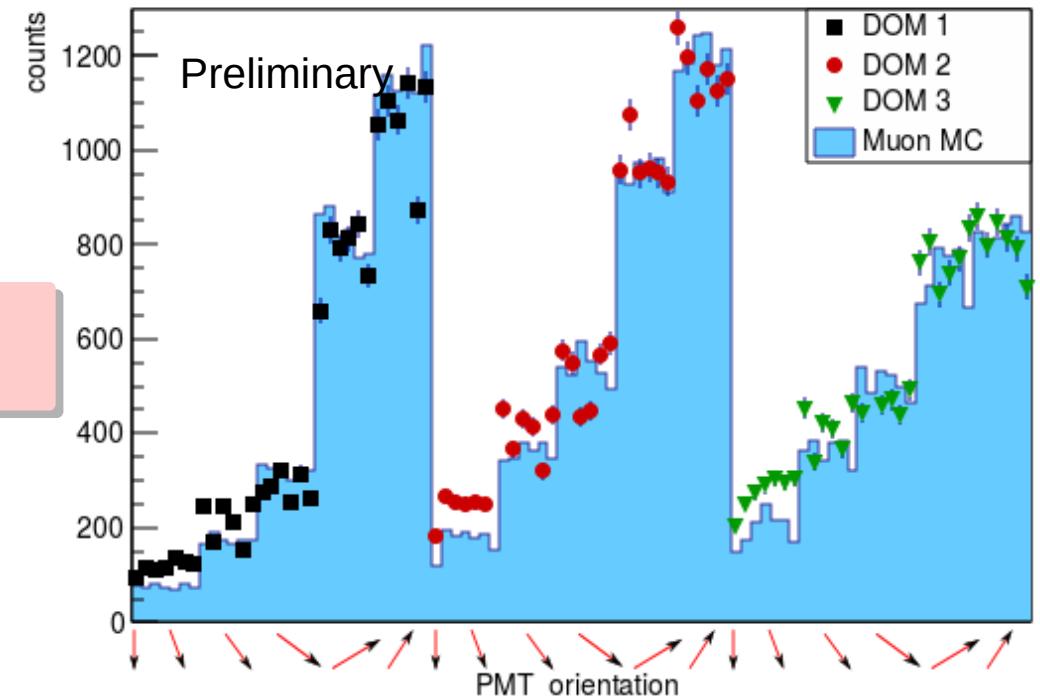
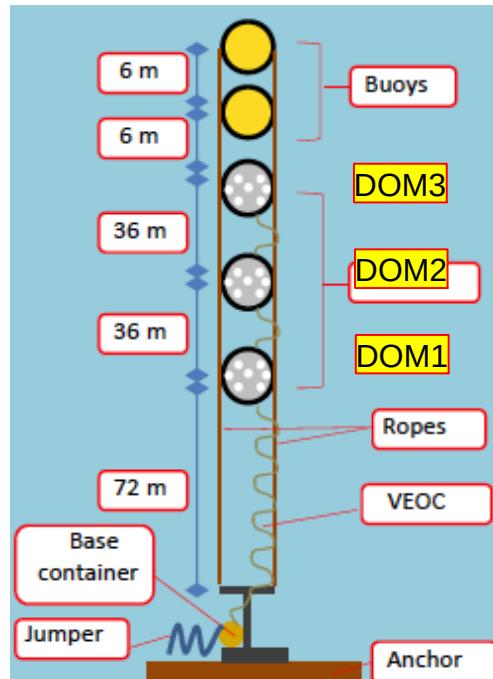
Back-up : KM3NeT mini-line @ Capo Passero (KM3NeT-It)



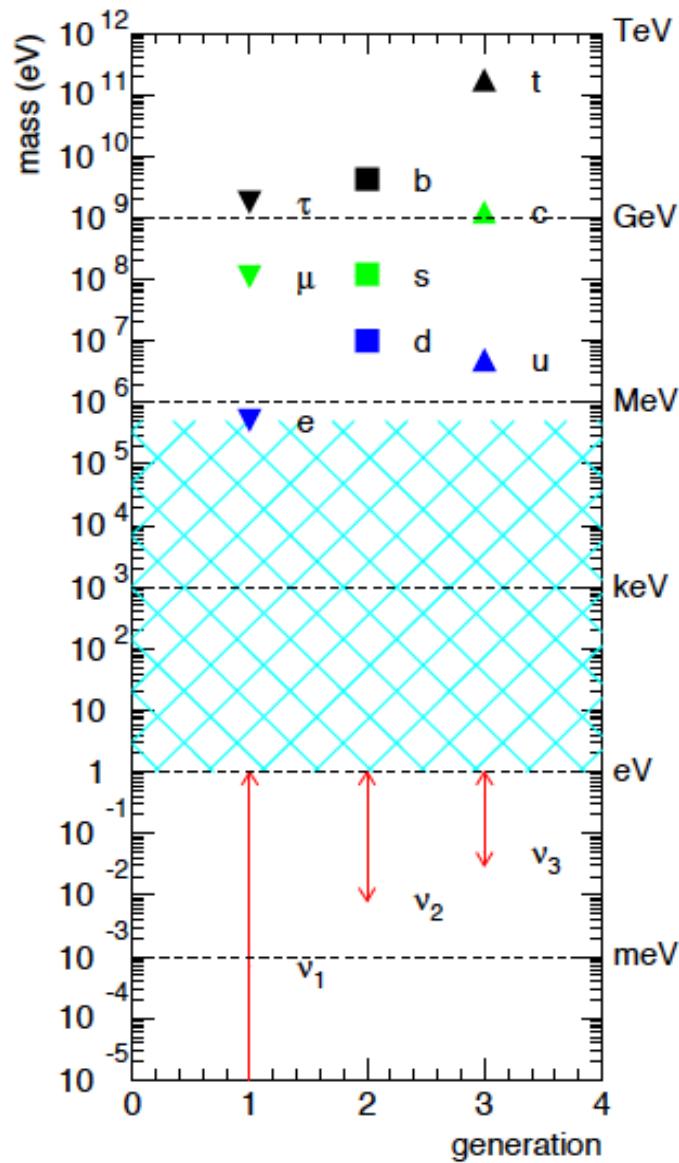
Integration
Nikhef & CPPM



Deployment KM3NeT-It
May 2014

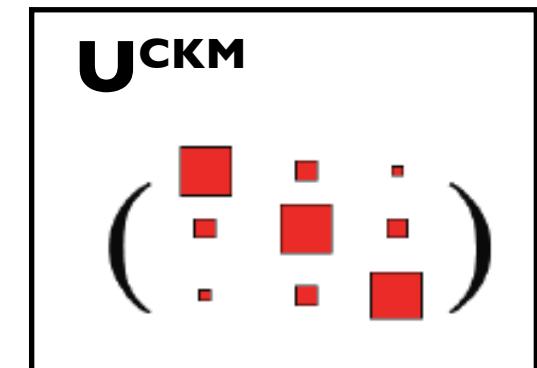
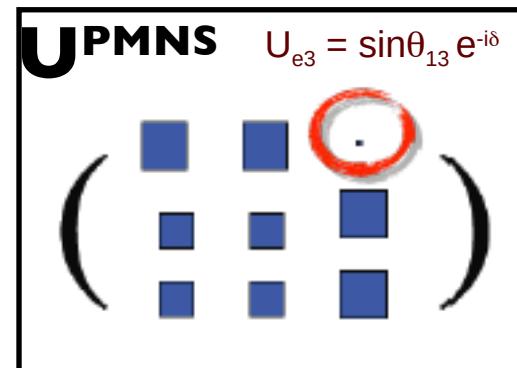


Back-up : Massive neutrinos



- Neutrinos have distinct masses → why so light?
- Often considered as first evidence of physics beyond the Standard Model. Are neutrinos fundamentally different from other particles?
- Neutrinos mix like quarks → why so similar/different?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Back-up : Atmospheric neutrinos in ANTARES

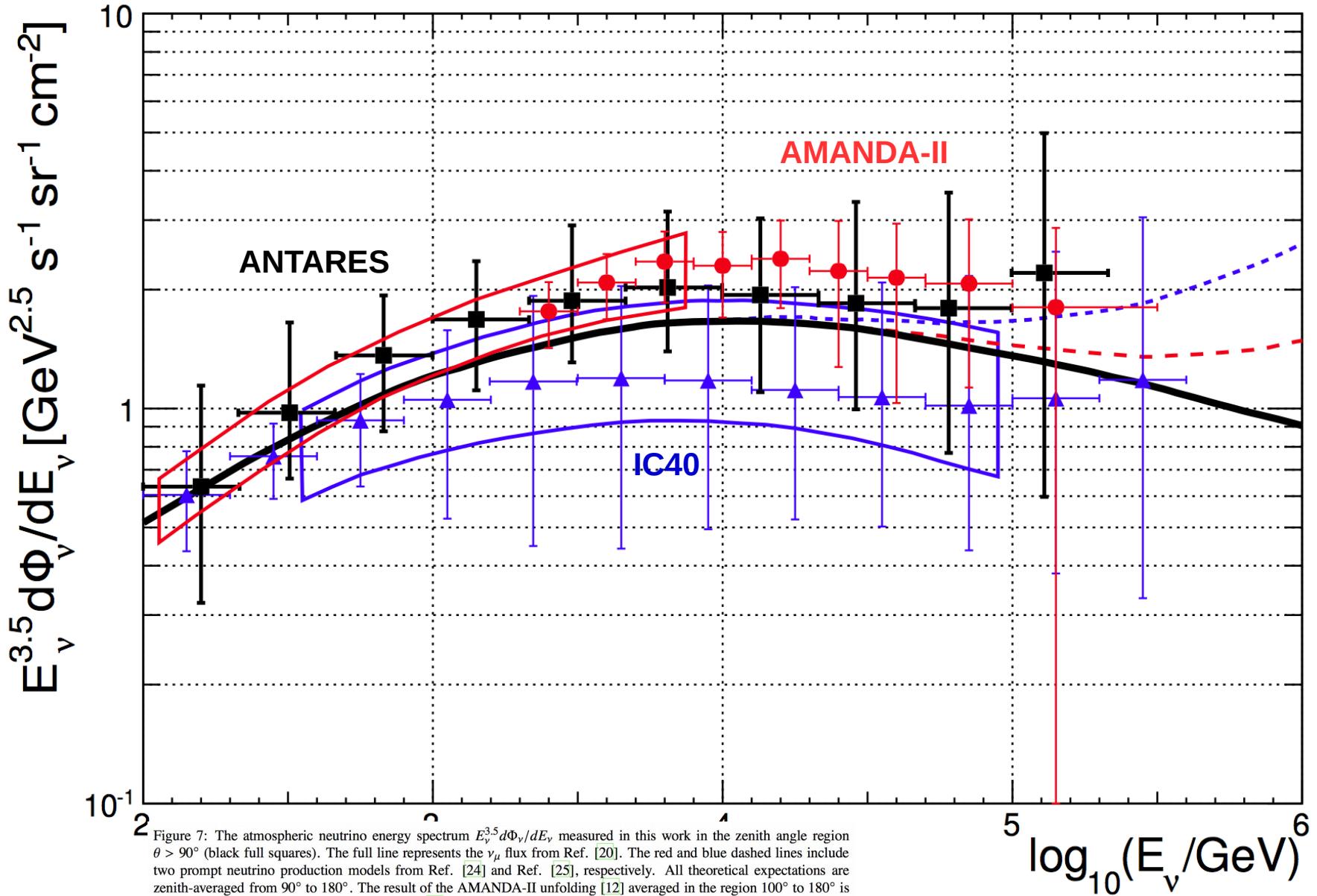


Figure 7: The atmospheric neutrino energy spectrum $E_\nu^{3.5} d\Phi_\nu/dE_\nu$ measured in this work in the zenith angle region $\theta > 90^\circ$ (black full squares). The full line represents the ν_μ flux from Ref. [20]. The red and blue dashed lines include two prompt neutrino production models from Ref. [24] and Ref. [25], respectively. All theoretical expectations are zenith-averaged from 90° to 180° . The result of the AMANDA-II unfolding [12] averaged in the region 100° to 180° is shown with red circles and that of IceCube40 [13] zenith-averaged from 97° to 180° is shown with blue triangles. The red region corresponds to the ν_μ measurement from Ref. [11], and the blue one the IC40 update from Ref. [49].

Back-up: Oscillations with ANTARES

2007-2010 - 863 days → 2000 events

arXiv:1206.0645

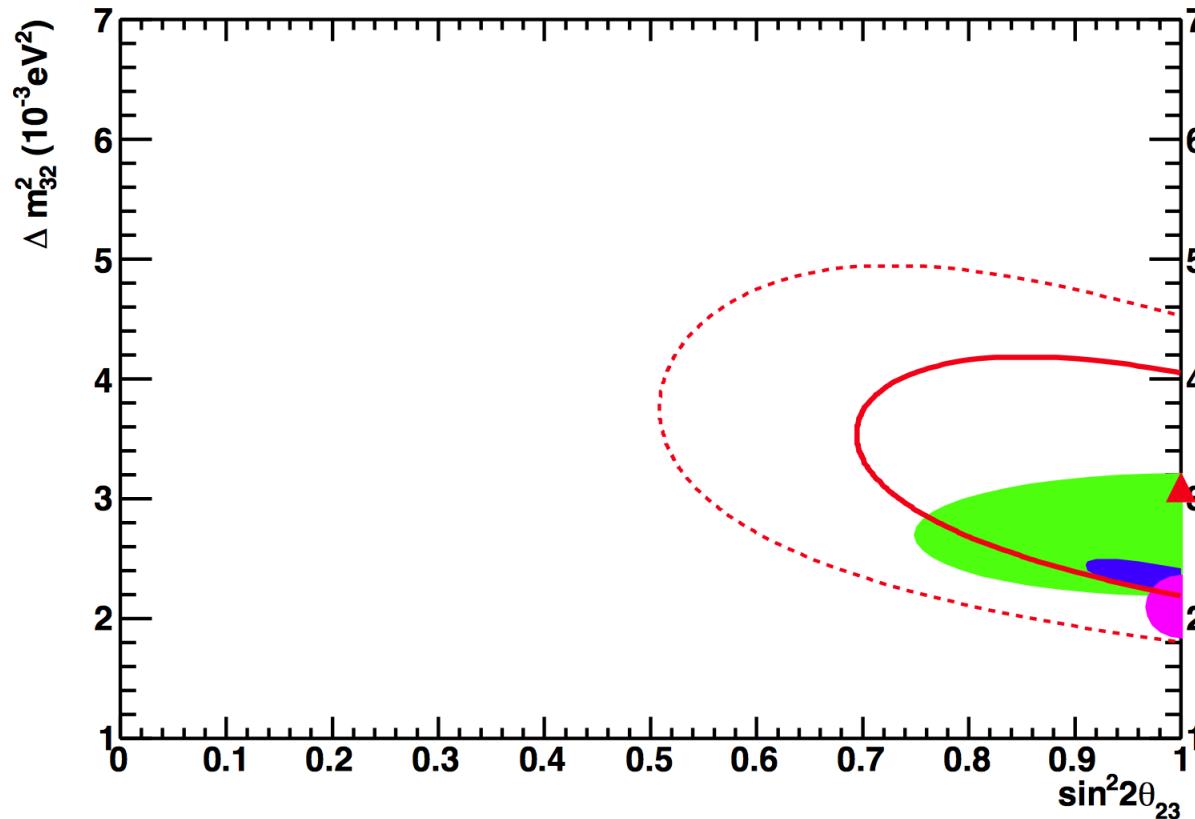


Figure 5: 68% and 90% C.L. contours (solid and dashed red lines) of the neutrino oscillation parameters as derived from the fit of the $E_R / \cos \Theta_R$ distribution. The best fit point is indicated by the triangle. The solid filled regions show results at 68% C.L. from K2K [20] (green), MINOS [21] (blue) and Super-Kamiokande [22] (magenta) for comparison.

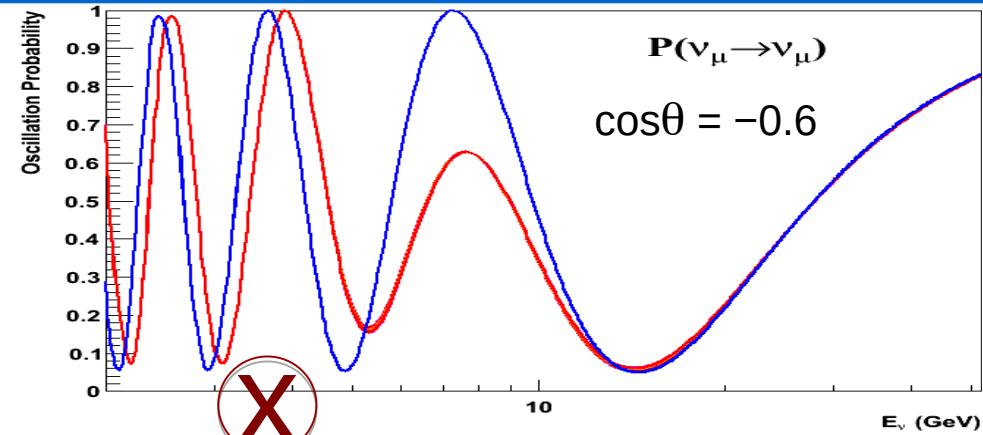
Back-up : Fluxes and cross sections

Cosmic Ray + A_{air} $\rightarrow \pi^+ + \dots$
 $\pi^+ \rightarrow \mu^+ + \nu_\mu$
 $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- Produce neutrinos (+30%) and anti-neutrinos
- Broad energy range: Steeply falling spectrum
 - Requires good energy resolution
- Broad path-length range
 - Requires good direction resolution
- Different cross sections for ν and $\bar{\nu}$!

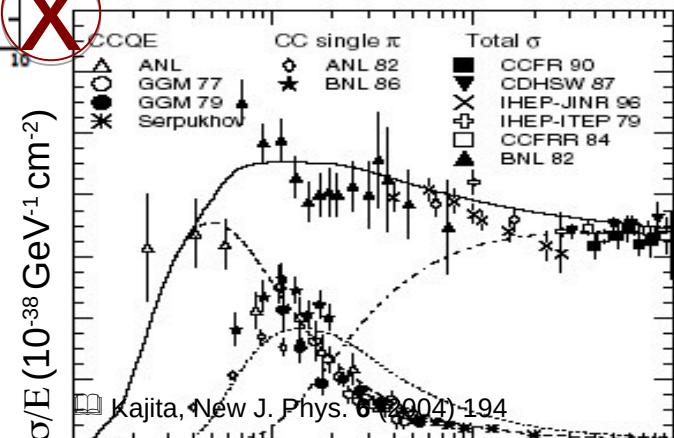
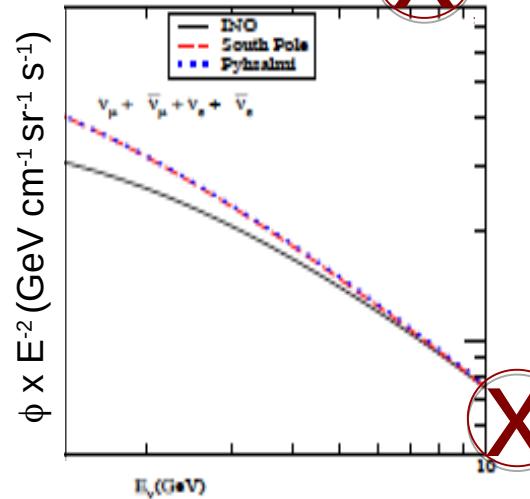
$$\sigma(\nu) \approx 2\sigma(\bar{\nu})$$
- Three main contributions:
 - Quasi-elastic, Resonant, DIS

Use external measurements and regions without oscillations



M.S. Athar et al.
arXiv:1210.5154

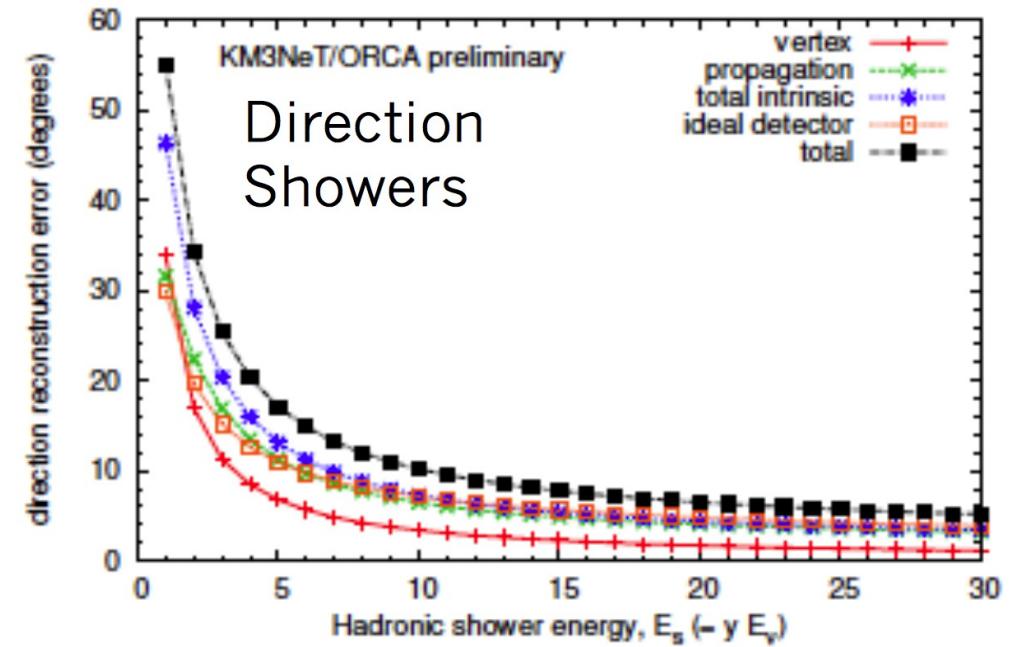
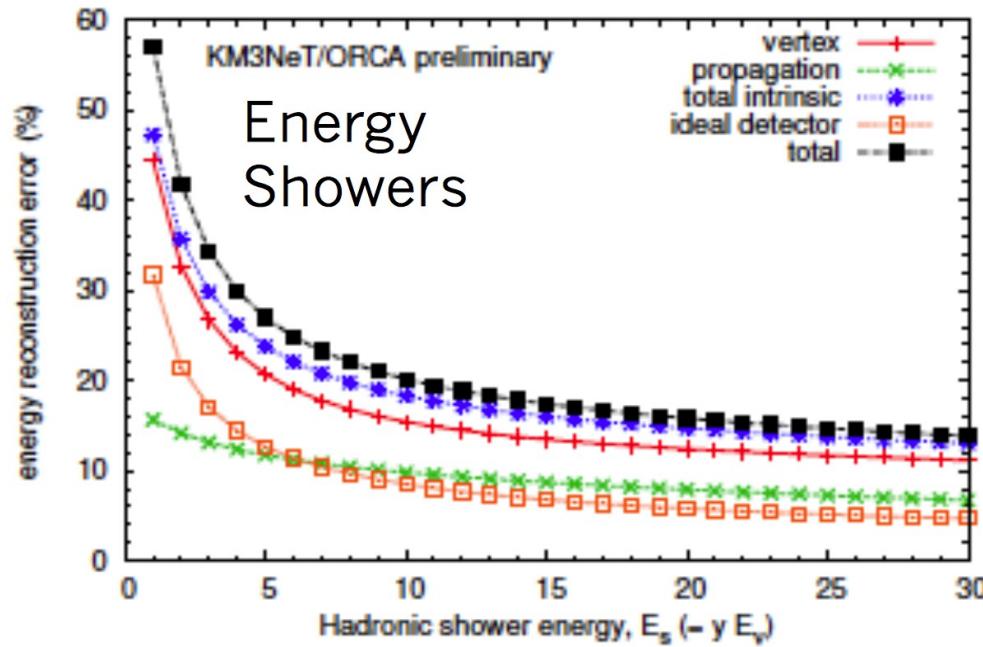
Calculations now made as
a function of the position
on Earth and the time in
year



Back-up : Additional ORCA physics topics

- Indirect Search for Dark Matter
 - ❑ Gonzales-Garcia et al., Phys. Rev. Lett. 100:061802, 2008,
 - ❑ Agarwalla et al., arXiv:1212.2238v1
- Earth tomography and composition
- Test Non-Standard Interactions and other exotic physics
 - ❑ Ohlsson et al, Phys. Rev. D 88 (2013) 013001
 - ❑ Gonzales-Garcia et al., Phys. Rev. D71 (2005) 093010
- Sensitivity to CP phase (Threshold <1GeV, MH known)
 - ❑ Razzaque & Smirnov, arXiv:1406.1407
- Supernovae monitoring (takes advantage of new DOM features)
 - MeV neutrinos – **dense configuration ?**
- Low Energy Neutrino Astrophysics
 - Gamma-ray bursts, Colliding Wind Binaries
 - ❑ J. Becker Tjus, arXiv:1405.0471 ...
- A Neutrino beam from to ORCA (NMH and CP phase)
 - ❑ Lujan-Peschard et al, Eur. Phys. J. C (2013) 73:2439
 - ❑ Tang & Winter, JHEP 1202 (2012) 028
 - ❑ J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538.

Back-up : Intrinsic physical limits - showers and μ



- Fluctuations of muon track length :

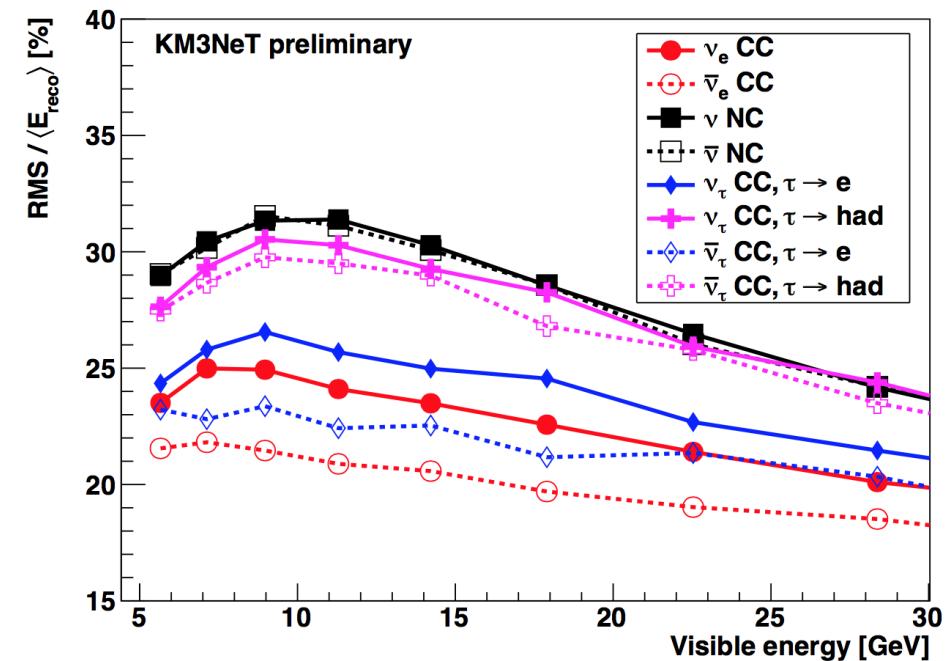
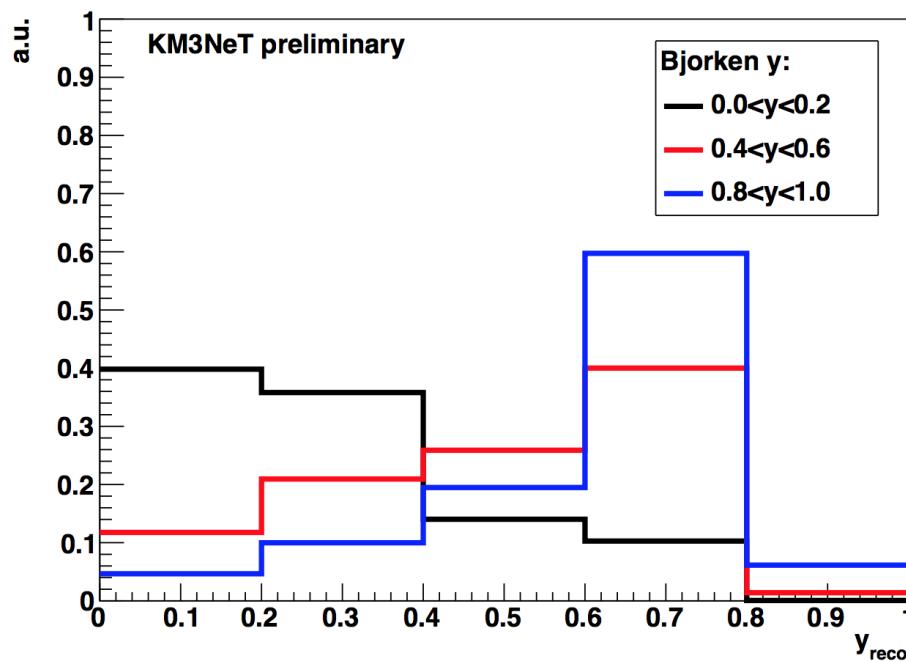
$$\sigma_{E_\mu} = \sqrt{(0.06E_\mu)^2 + (0.3GeV)^2}$$

Energy (Direction) of cascade@ 5 GeV
25 %/16°
Energy/Direction of muon @ 5GeV
0.5 GeV/0.2°

Useful results to guide the optimization of the detector design and to set upper bounds on the sensitivity to the NMH

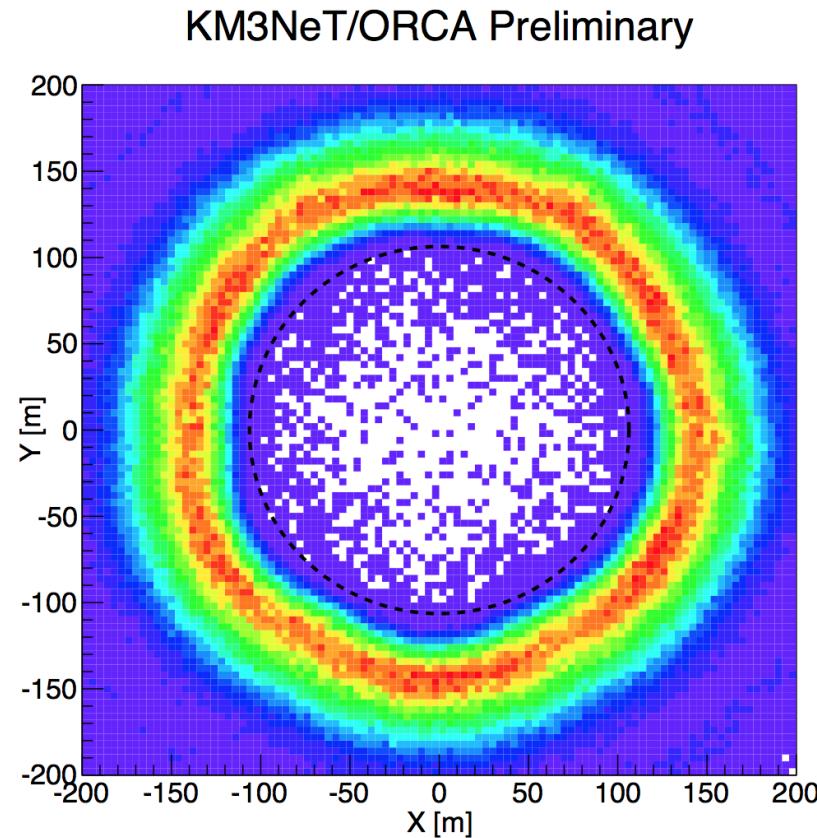
Back-up : Sensitivity to inelasticity - Preliminary

Shower reconstruction applied to electron ν has some sensitivity to Bjorken y

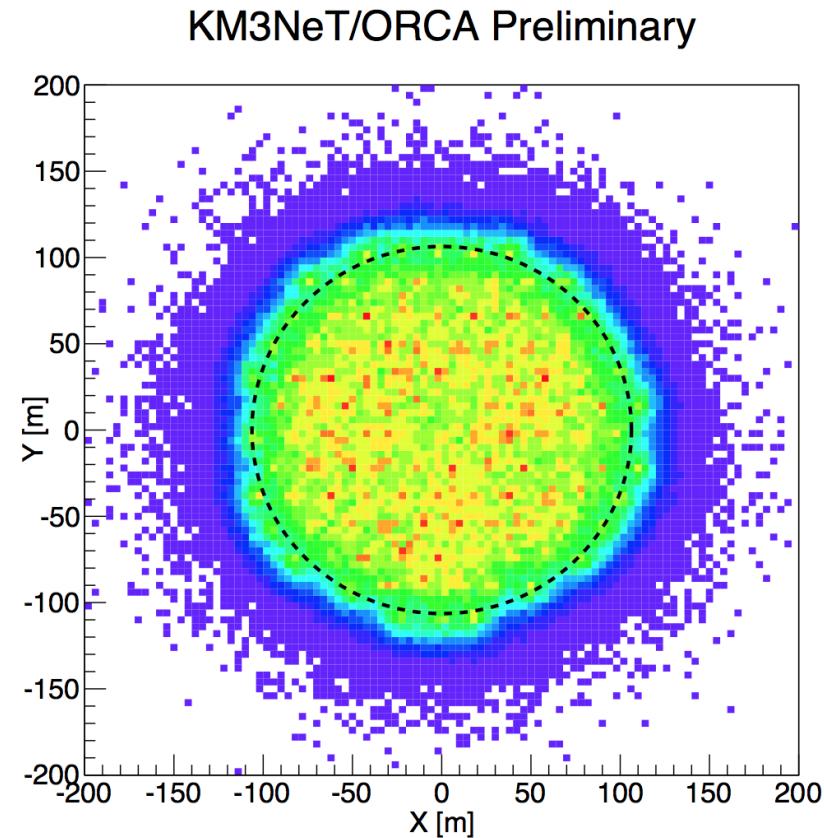


Back-up : atmospheric muon rejection

- Simulation based on MUPAGE - [Astropart. Phys. 25 \(2006\) 1](#)
- ORCA depth 2475 m, 40K 5kHz, 500 Hz coincidence
- Cut on the reconstructed pseudo-vertex and quality parameters



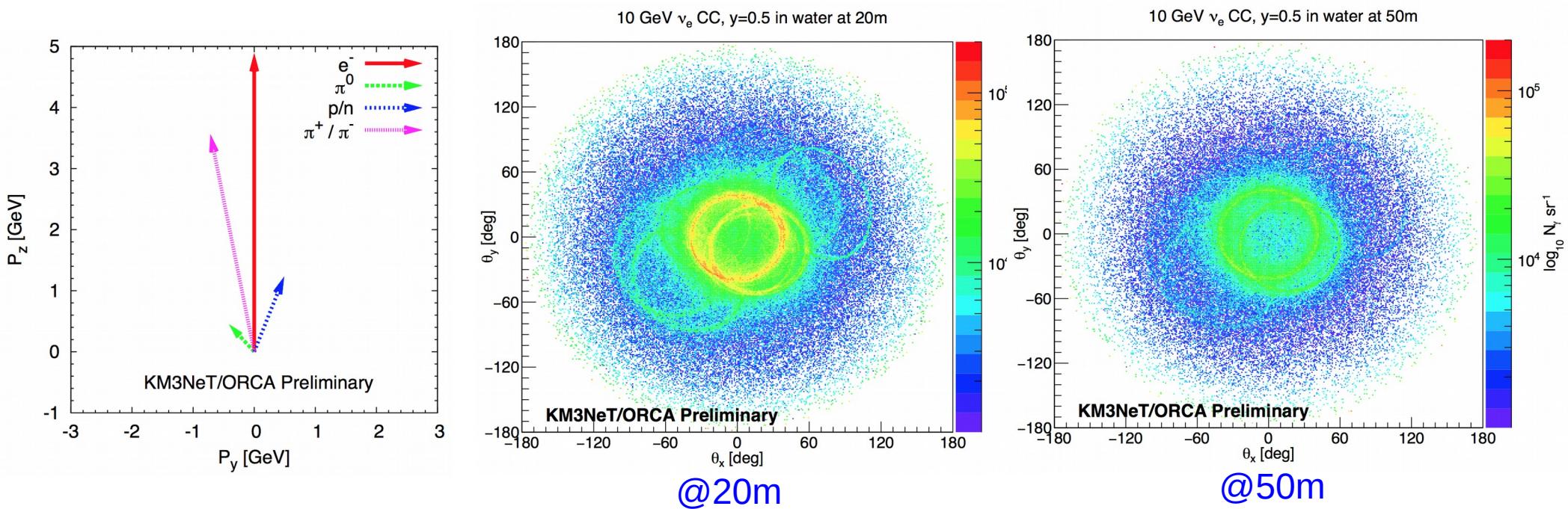
Atmospheric muons



Atmospheric neutrinos < 20 GeV

Back-up : a multi-particle reconstruction is possible

PRELIMINARY



« Neutrino interaction spectroscopy » in Water ?
(if detector « dense enough »)

Back-up : Sensitivity : Global Fit Approach

Global Fit approach

Performance of ORCA for the determination of the NMH is assessed by means of a likelihood ratio test:

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

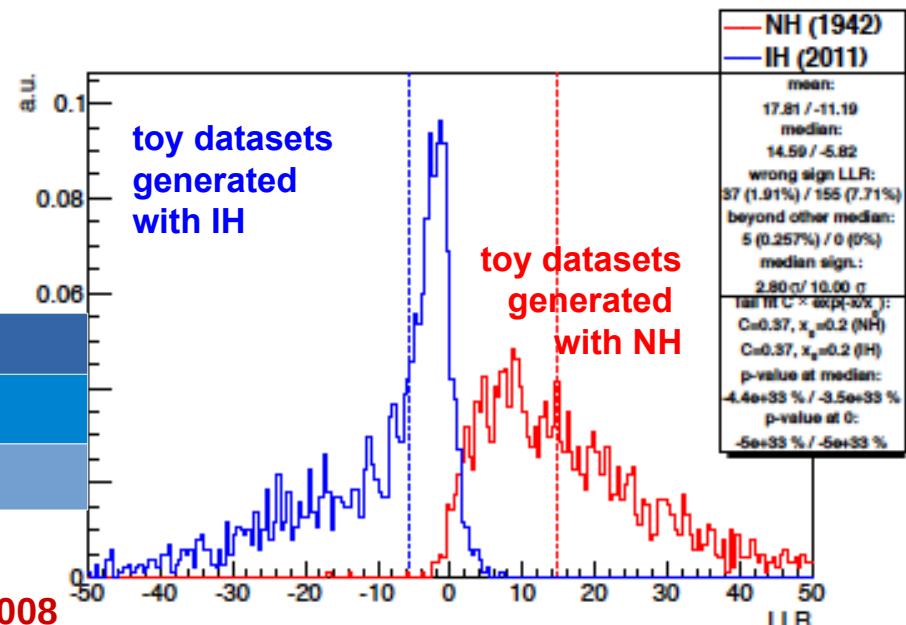
$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2 's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

θ_{23} conservatively restricted to first octant

- Fit mixing parameters assuming NH
- Fit mixing parameters assuming IH
- Compute $\Delta \log L = \log(L(\text{NH})/L(\text{IH}))$

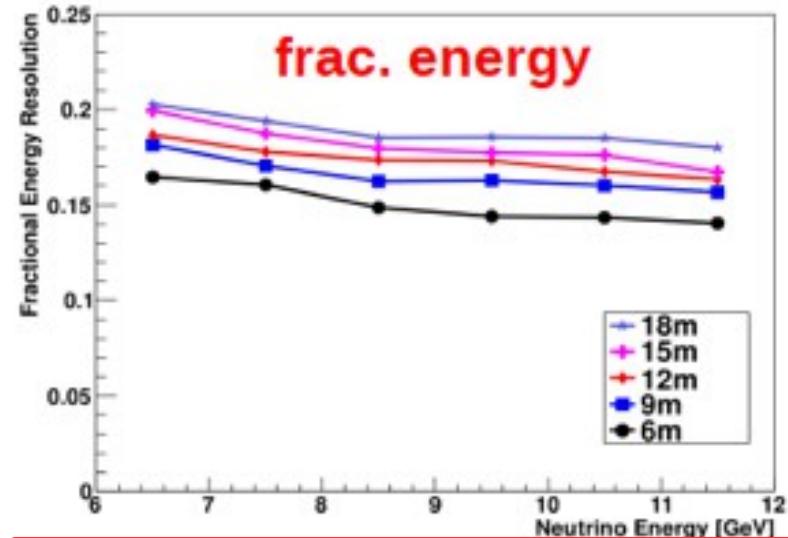
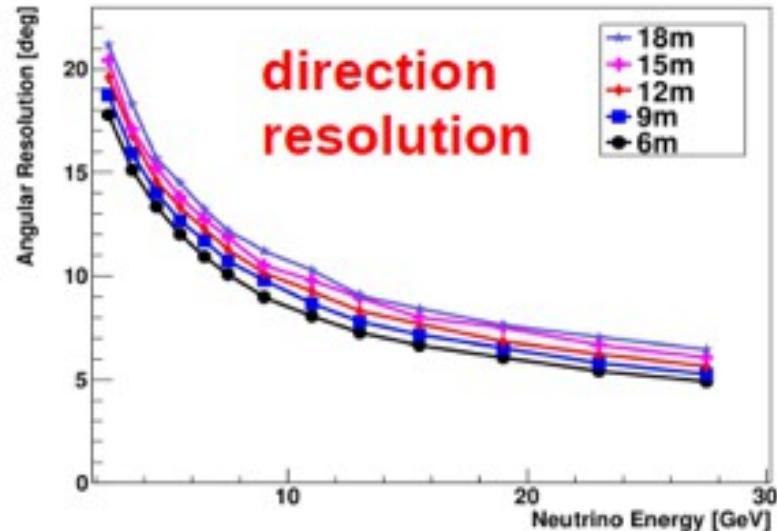
With proposed detector (3.75 MT)

Error on	current	1.5yr	2.5yr	5yr
$\Theta_{23} [\text{deg}]$	1.6°	0.6°	0.4°	0.3°
$\Delta m^2 [10^{-5} \text{ eV}^2]$	8	7.2	5.8	4.3

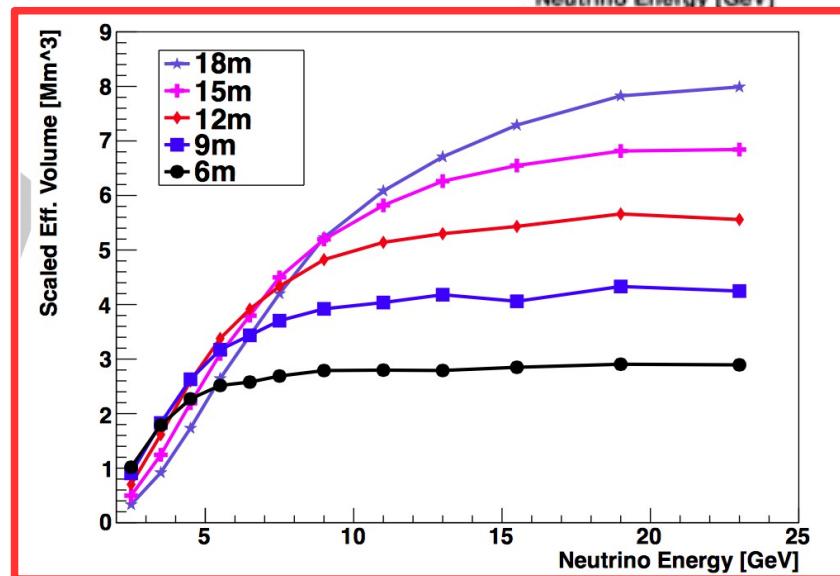


First Sensitivity estimates : D. Franco et al, JHEP 04 (2013) 008

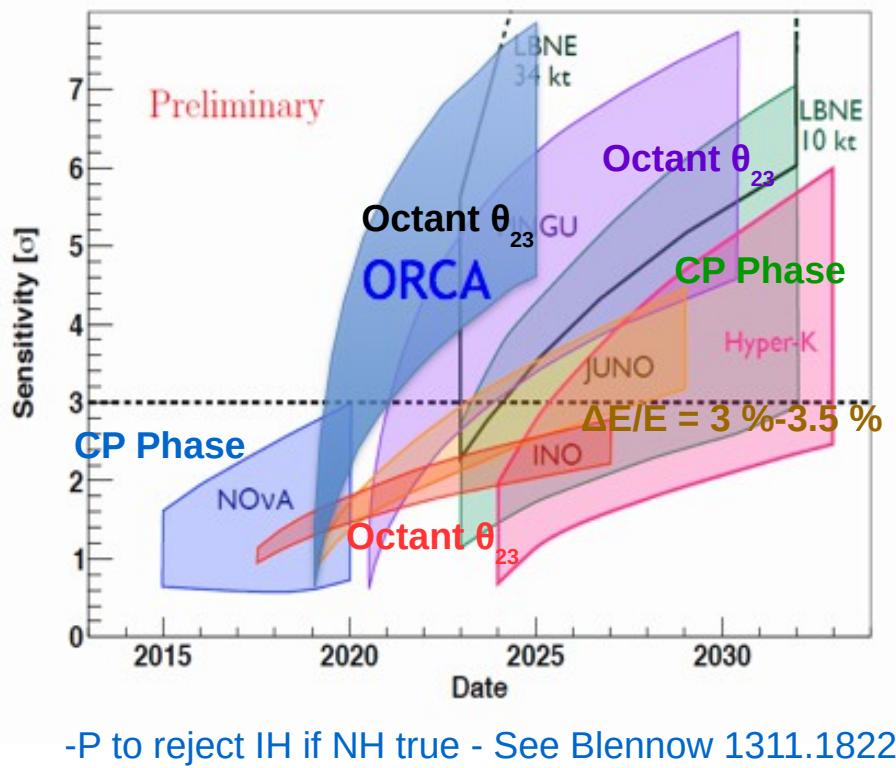
Back-up : Improving ORCA - Layout Optimisation



- Optimization of inter-storey spacing :
 - Improvement with > 6m ?
- Inter-line spacing underway



Back-up : Illustrative plot for comparing sensitivities



Effect	Nuisance Parameter	Default	Constraint
Normalisation	R_{Norm}	1	none
Mass difference	ΔM^2	$2.43 \cdot 10^{-3}$ eV	none
Mixing angle	θ_{13}	9°	1°
Mixing angle	θ_{23}	39°	none
CP phase	δ_{CP}	0	none
Energy slope	ϵ_E	0	3%
Energy scale	Δ_E	0	0.3 GeV
Angular slope	$\epsilon_{\cos \vartheta}$	0	1%
Angular scale	$\Delta_{\cos \vartheta}$	0	0.01
Asymmetry $\nu/\bar{\nu}$	$\epsilon(\nu/\bar{\nu})$	0	0.03
Asymmetry μ/e	$\epsilon(\mu/e)$	0	0.05
track/shower	$\epsilon(tr/sh)$	0	0.05
NC scale	ϵ_{NC}	0	0.05
ν_τ scale	ϵ_{ν_τ}	0	0.05
$\sigma(E)$ scale	$\epsilon_{\sigma(E)}$	0	0.05
$\sigma(\cos \vartheta)$ scale	$\epsilon_{\sigma(\cos \vartheta)}$	0	0.05

For illustration