KM3NeT/ORCA: Status and perspectives

CNNP 2017 Workshop
Catania, October 15-20 2017

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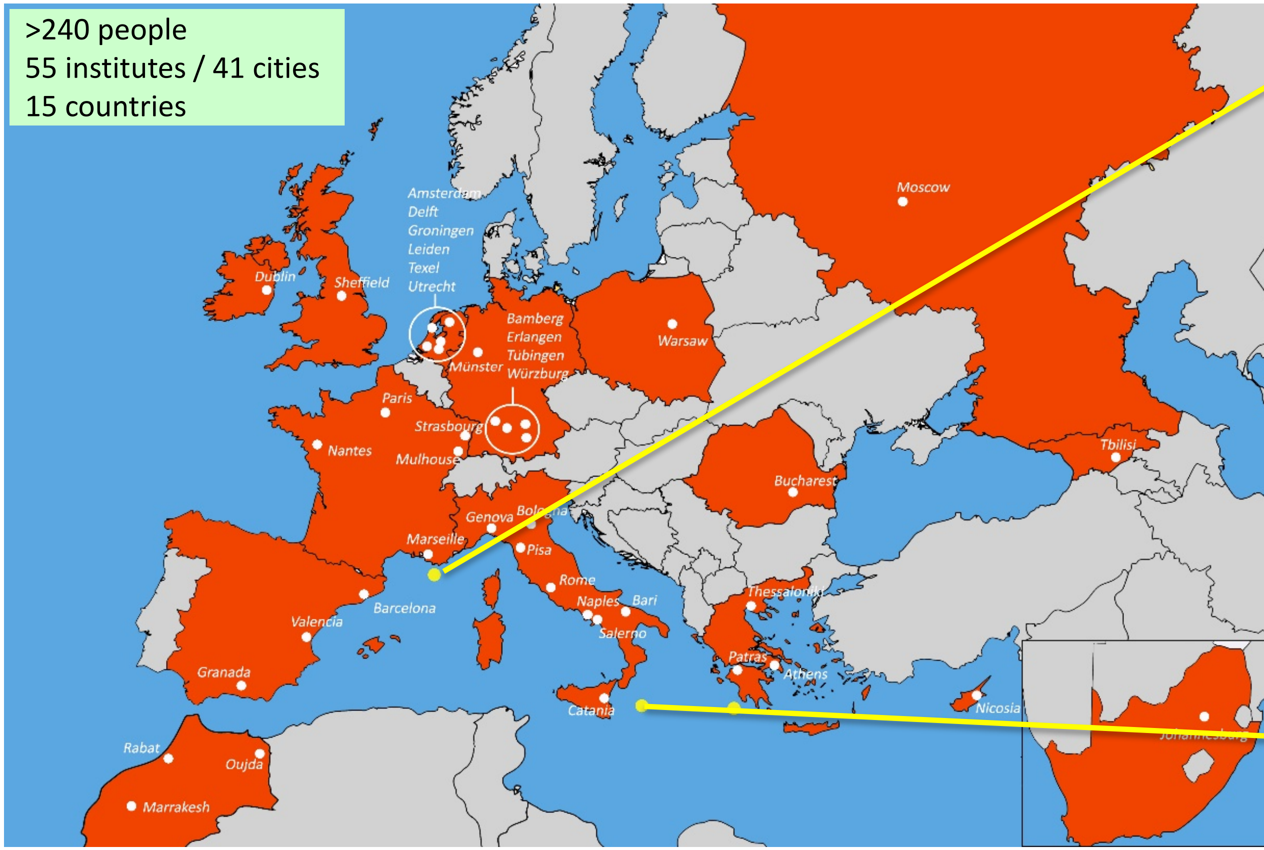
(APC & Université Paris Diderot)

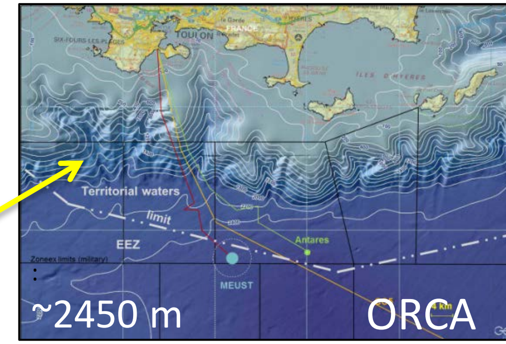
for the KM3NeT Collaboration

KM3NeT: the next-generation neutrino telescope

A distributed research infrastructure

with 2 main physics topics: ORCA & ARCA





Oscillation Research with Cosmics In the Abyss

Low-energy (~GeV) studies of atmospheric neutrinos

Astroparticle Research with Cosmics In the Abyss

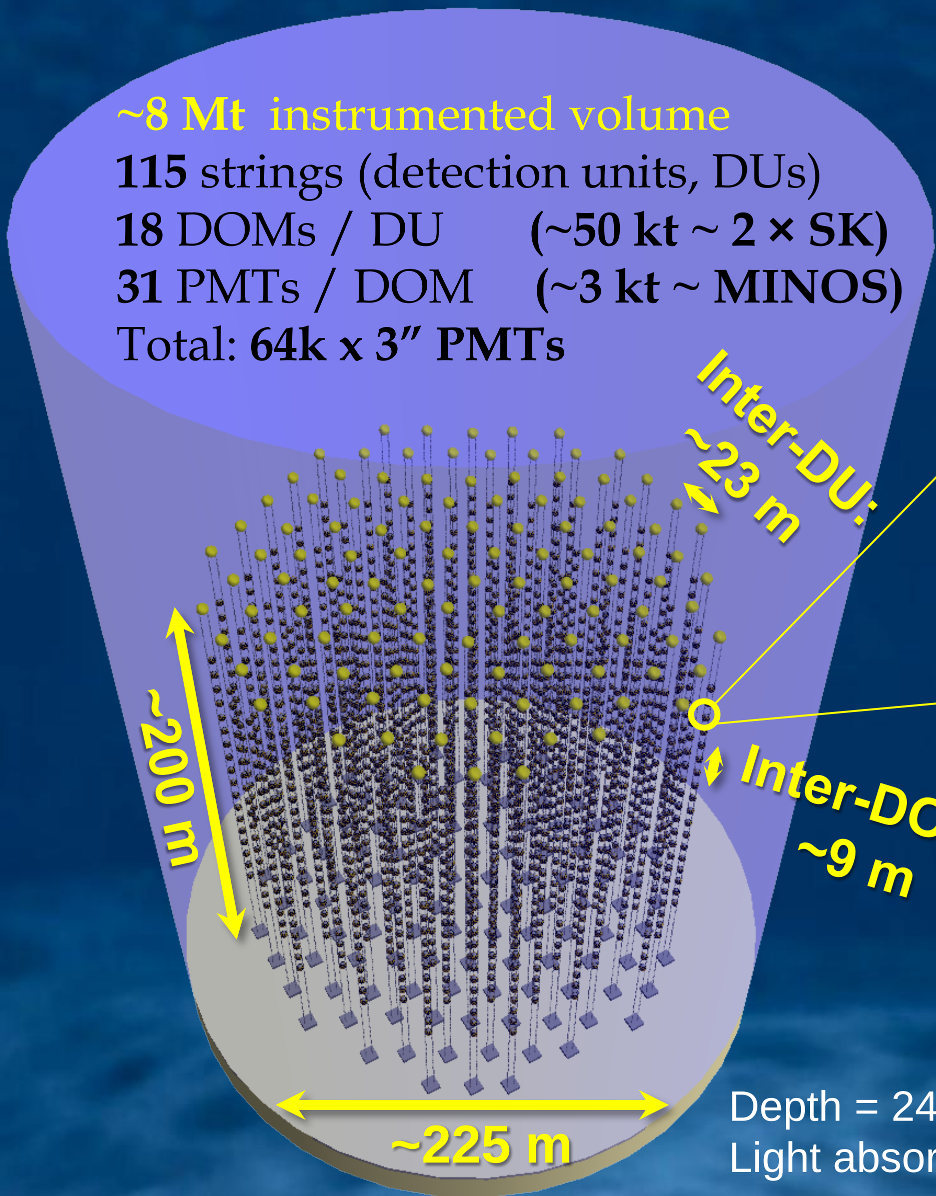
High-energy (TeV-PeV) neutrino astrophysics

- Single collaboration, same technology
- See KM3NeT Letter of Intent:

J. Phys. G 43 (8), 084001, 2016

See poster G. Ferrara

The (new) ORCA detector



Depth = 2435 m
Light absorption length ~ 60 m

Digital Optical Module (DOM)

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

17”

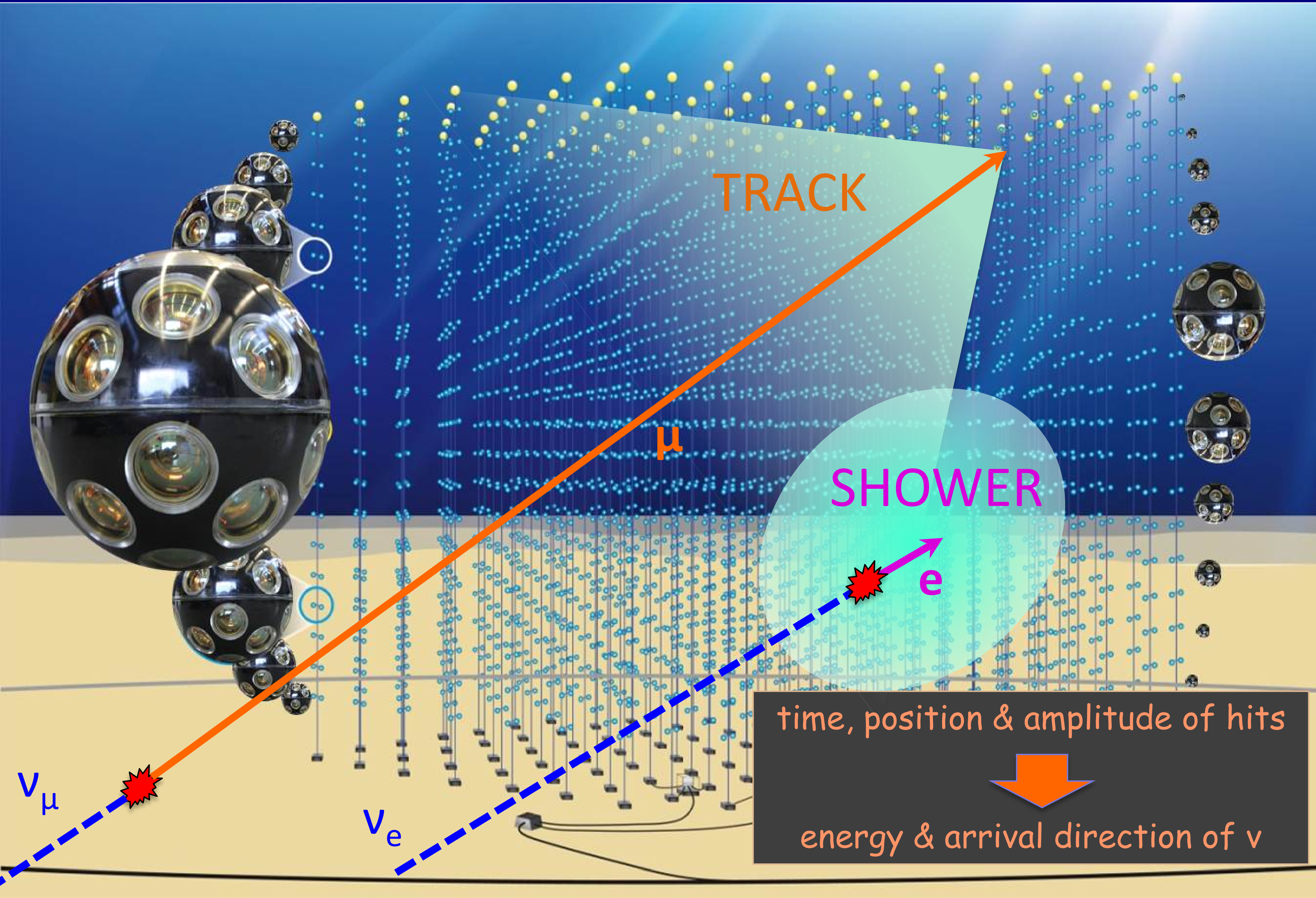
31 x 3” PMTs

Bottom view of a DOM

- Uniform angular coverage
- Directional information
- Digital photon counting
- All data to shore

See talk E. Leonora

Cherenkov telescope: detection principle



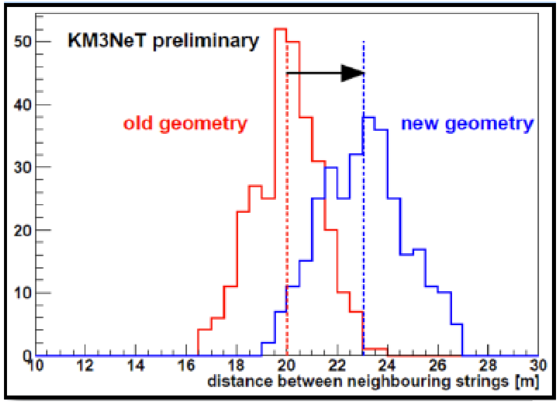
time, position & amplitude of hits

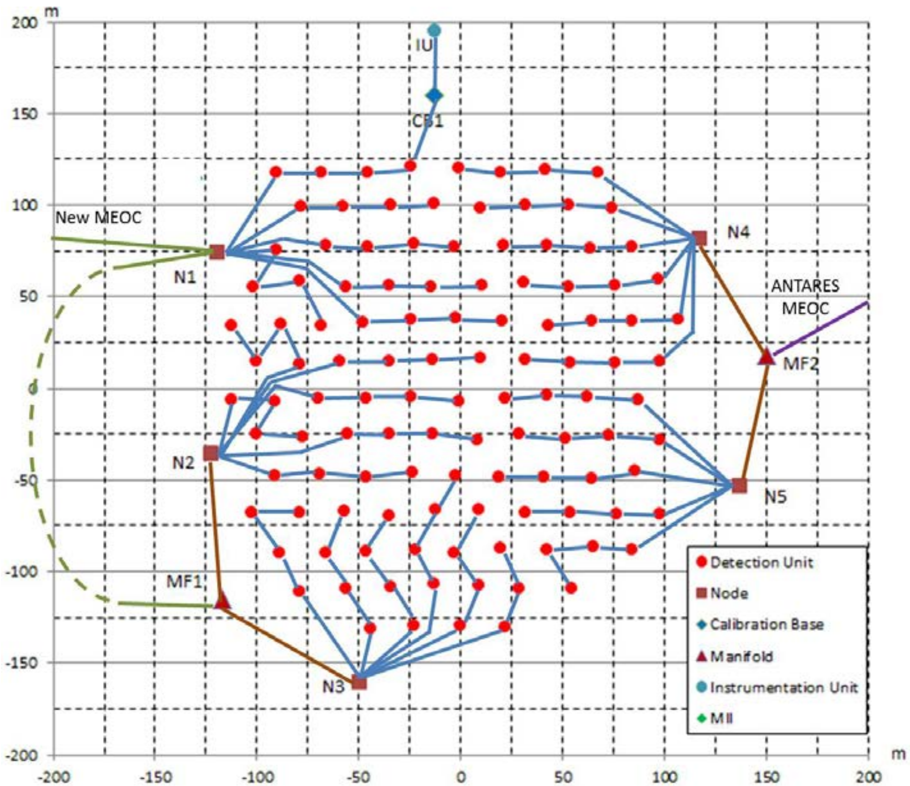
energy & arrival direction of ν

The (new) ORCA detector

Simulations ongoing to study the detector performance with final layout:

Geometry	Vertical spacing (between DOM)	horizontal spacing (between strings)
LoI-based	9 m on average with alternate 6 m and 12 m	20 m
New	realistic (9 m average)	23 m

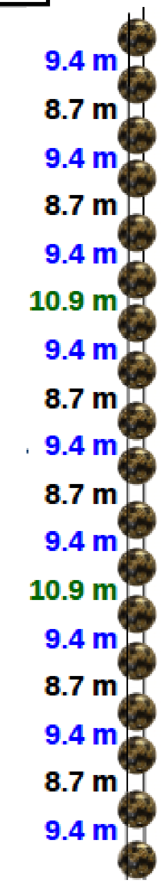




All technical constraints (now) included in simulations

Instrumented volume:
from 5.7 Mton (LoI) to ~8 Mton
(with same number of DOMs)

New set of simulations launched with new geometry, improving in various areas:
Trigger + reconstruction + PID + background rejection



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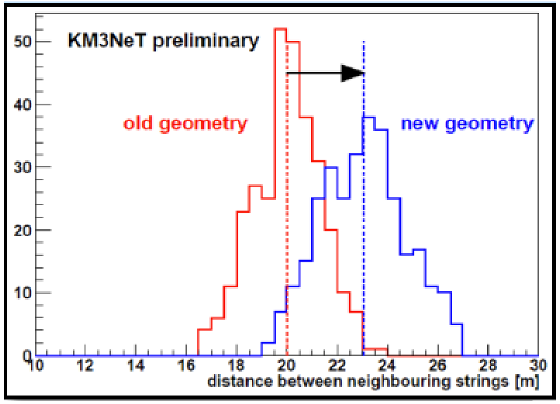

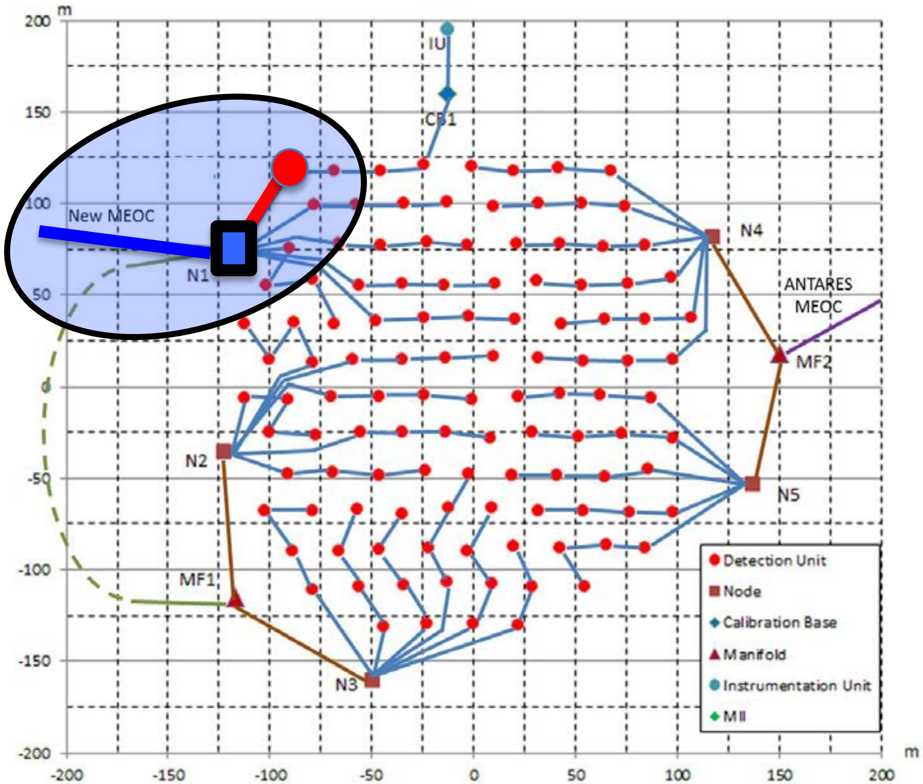

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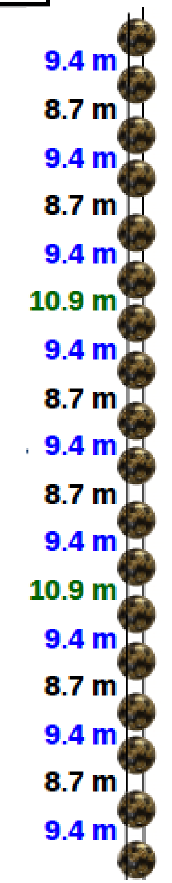

Installed as of today: main electro-optical cable, juction box ...and first ORCA line!

Sept 22d: deployment+connection of first ORCA DU

Deployment of the line coiled in a spherical frame (position accuracy ~1m)

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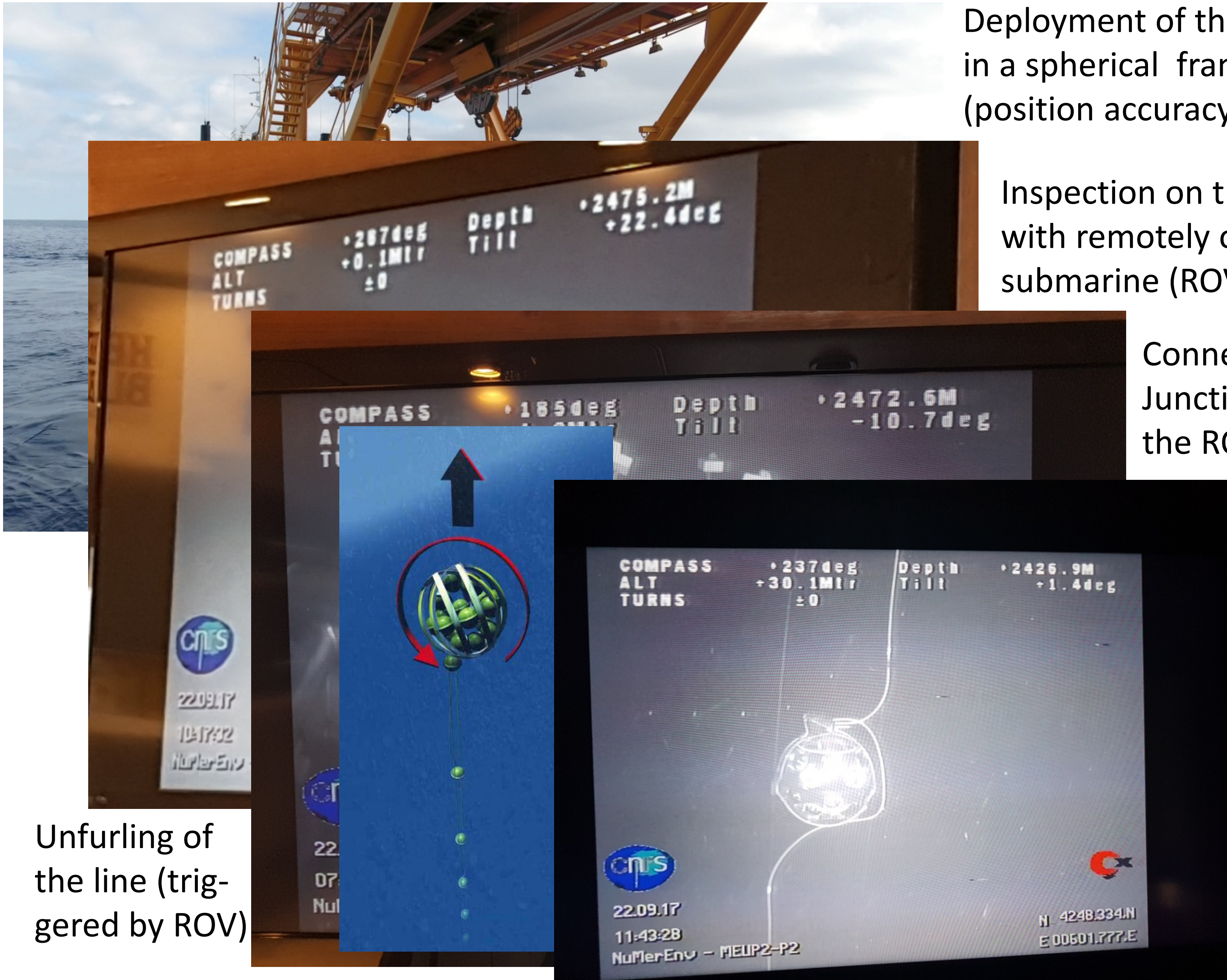

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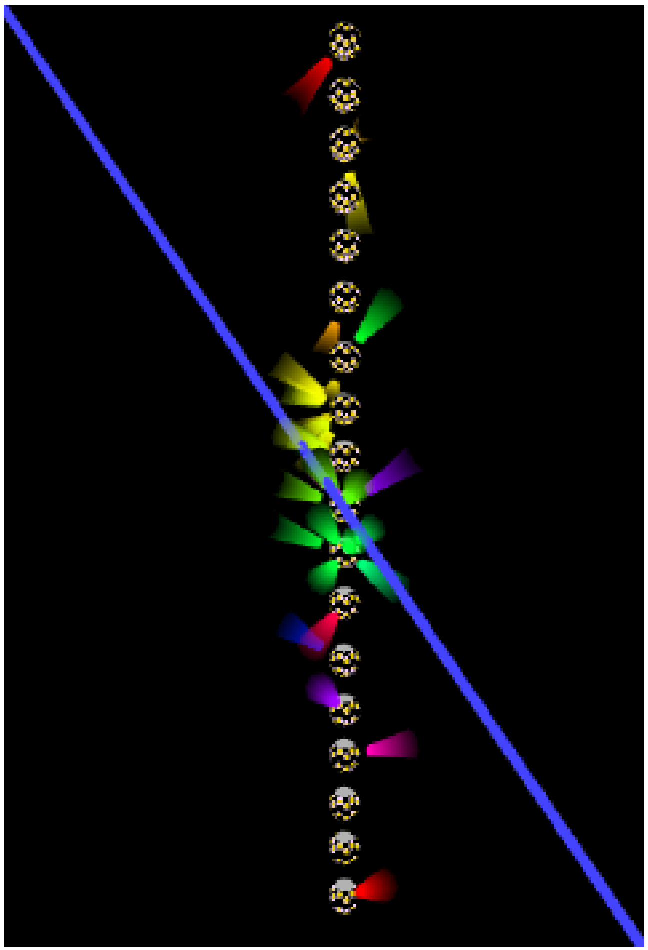
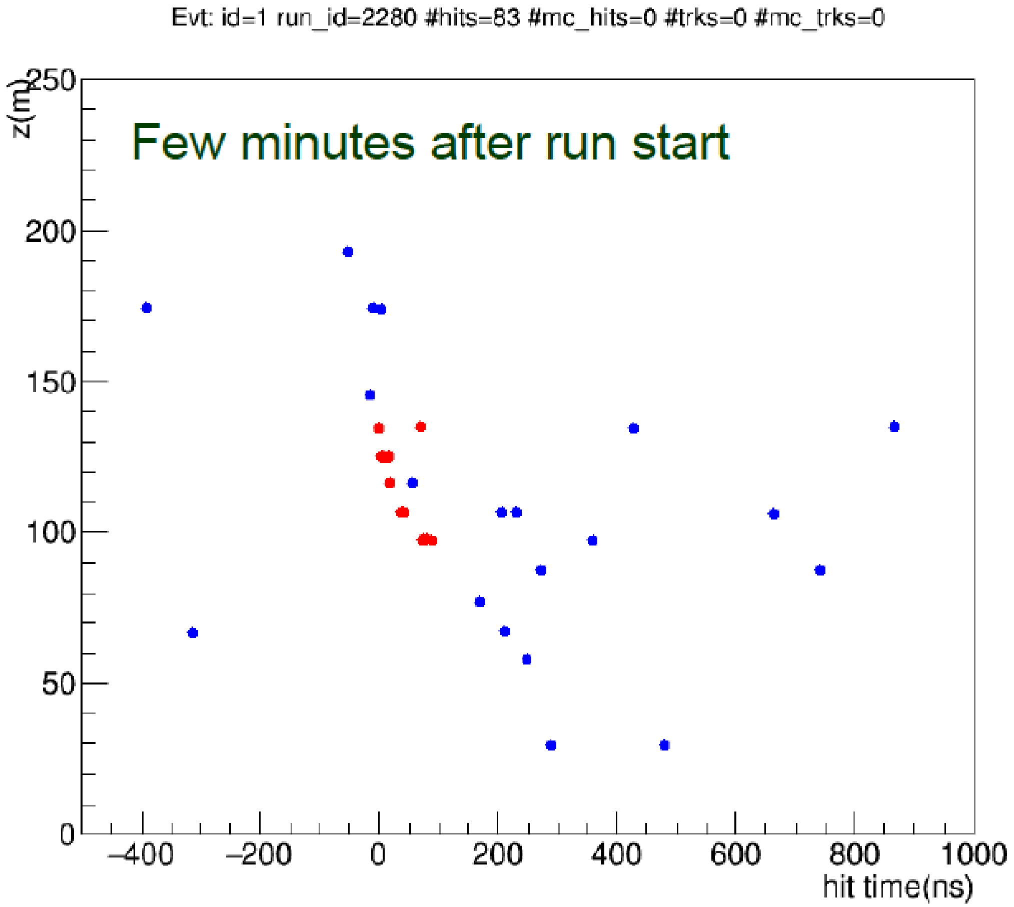
Unfurling of the line (trig-gered by ROV)

Inspection of line by ROV

First ORCA data !

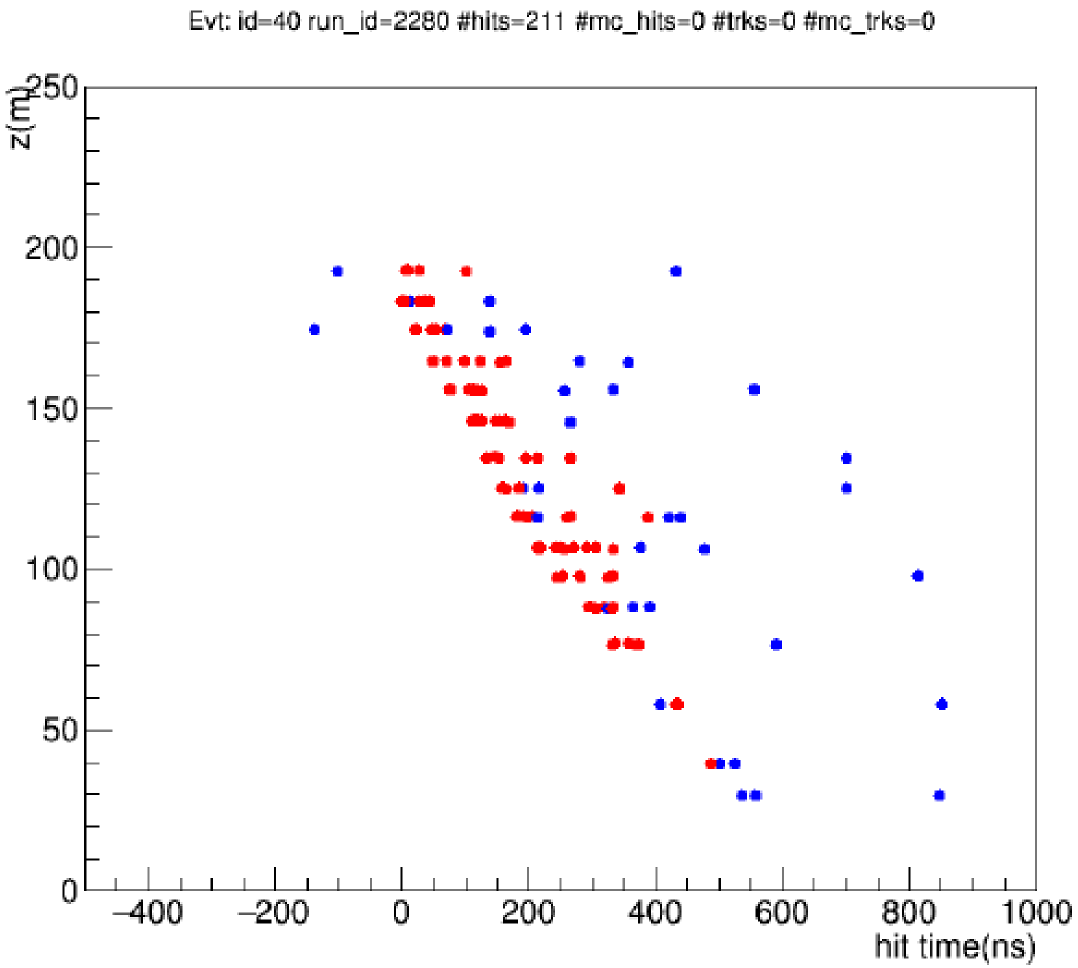
- First event with recorded track reconstructed by ORCA (down-going muon)

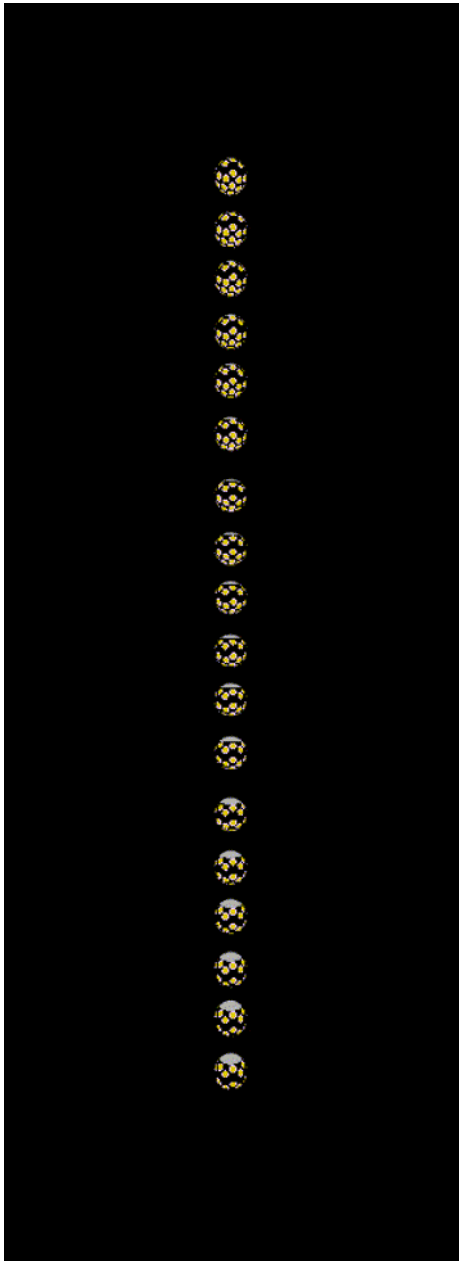




First ORCA data !

- A bright muon bundle

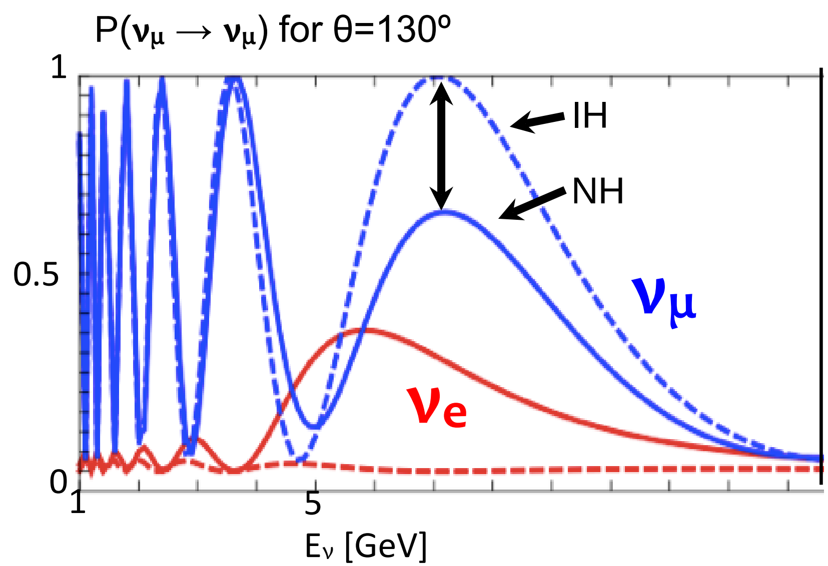


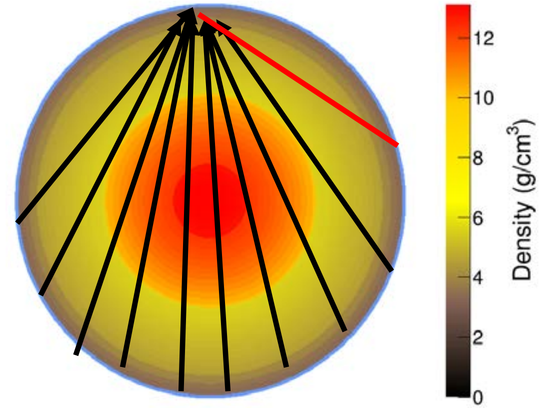


ORCA: measuring the neutrino mass hierarchy

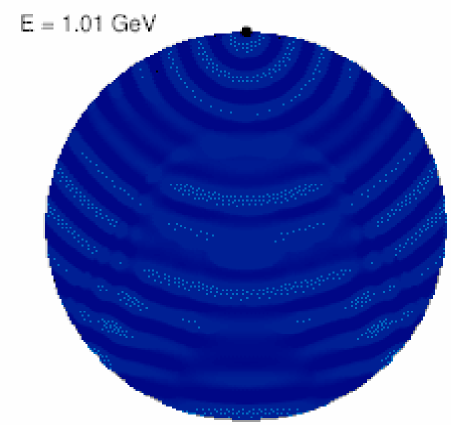
- A ¨free beam¨ of known composition (ν_e, ν_μ)
- Wide range of baselines (←→ zenith) and energies
- Oscillation pattern distorted by Earth matter effects

  maximum difference IH ⇔ NH for resonance in Earth mantle: θ=130° (7645 km) and E_ν = 7 GeV





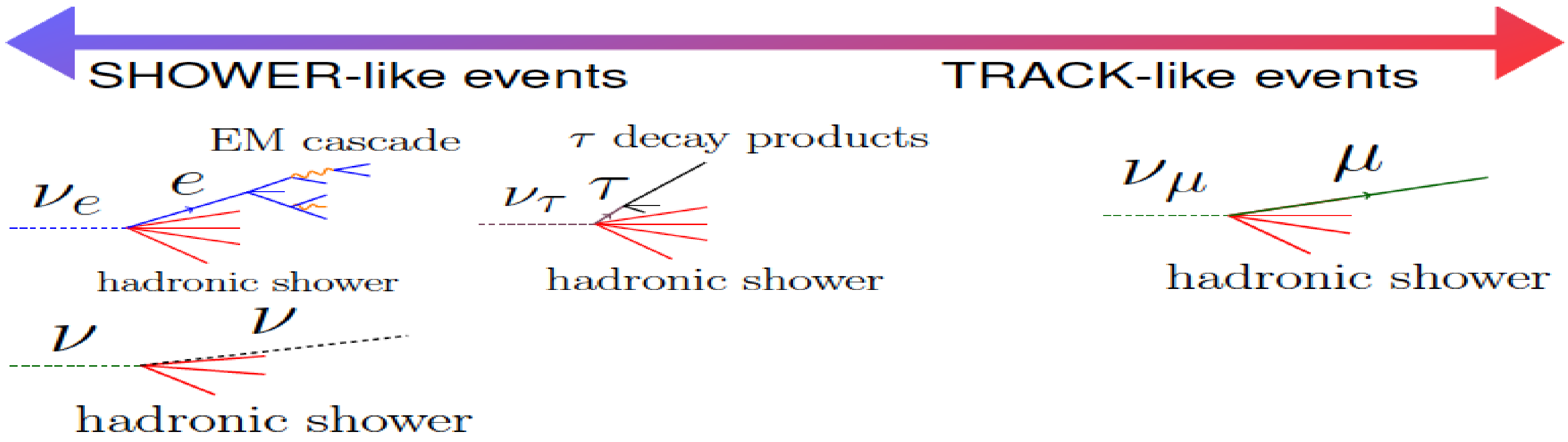
Credits:J. Coelho



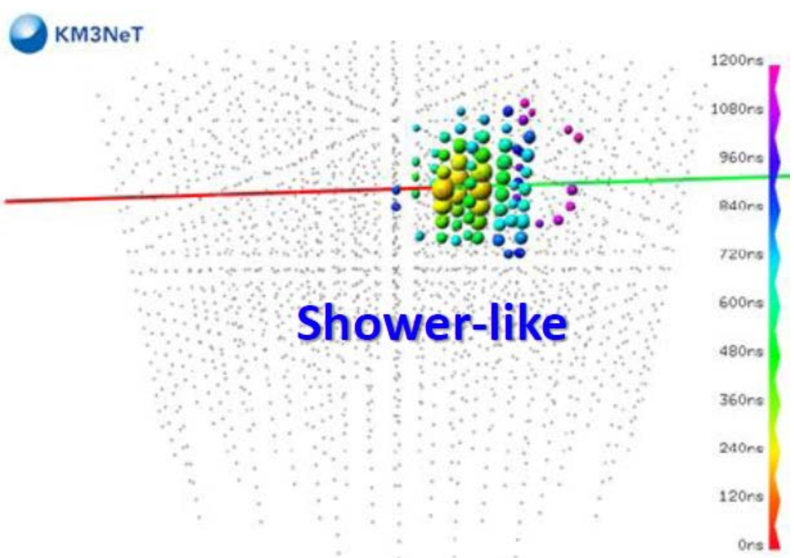
Approach: measure θ, E of upgoing atmospheric GeV-scale neutrinos, identify and count **track** and **shower** channel events

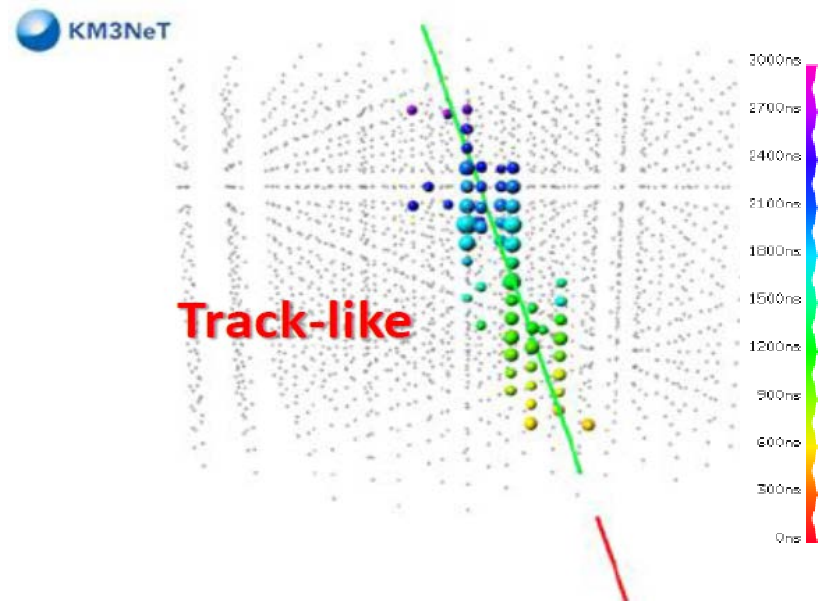
❖ Careful treatment of systematics mandatory

Event topologies



Discrimination of tracks, showers and atmospheric muons (~%) via RDF





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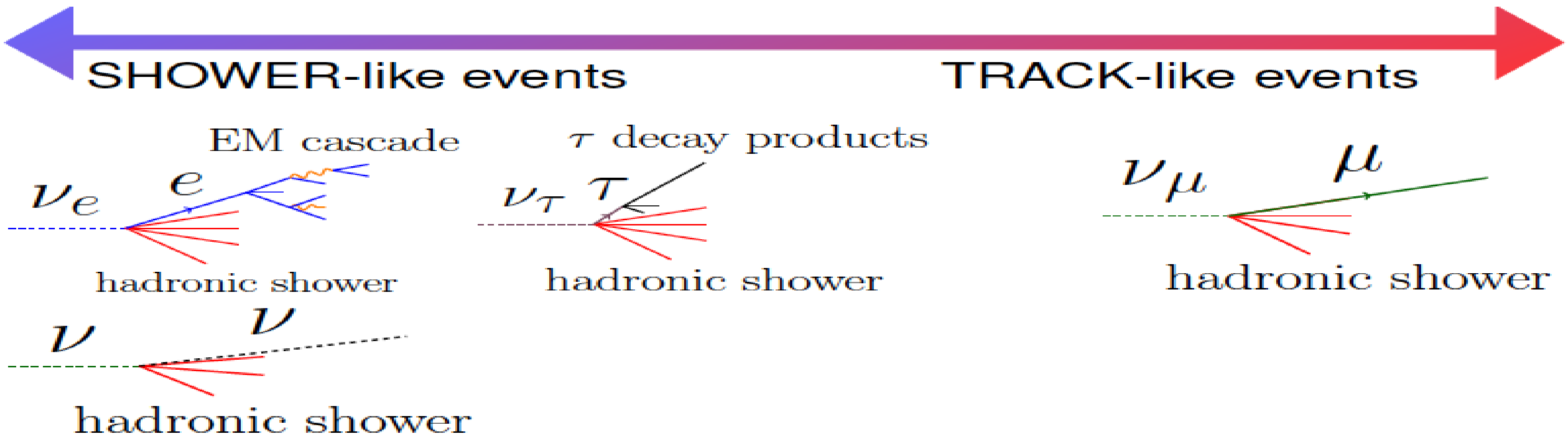
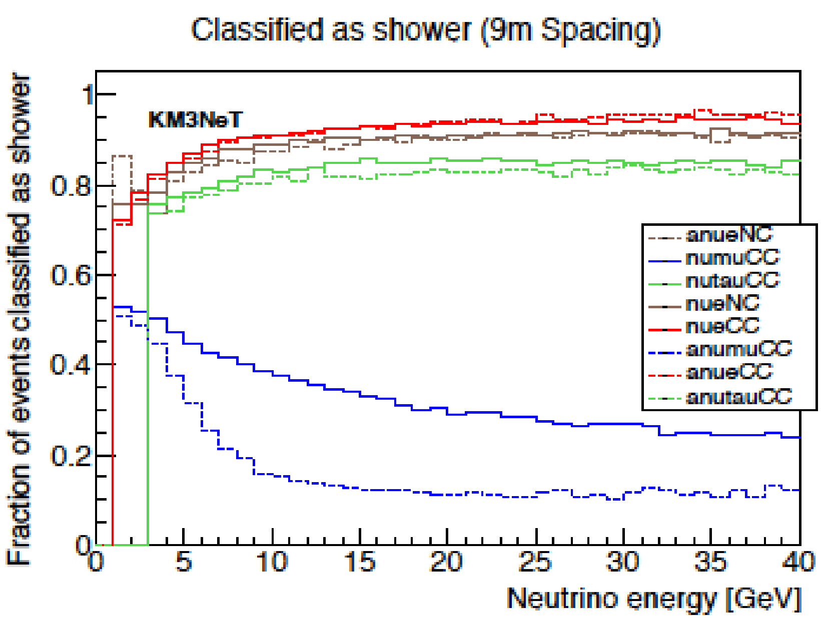
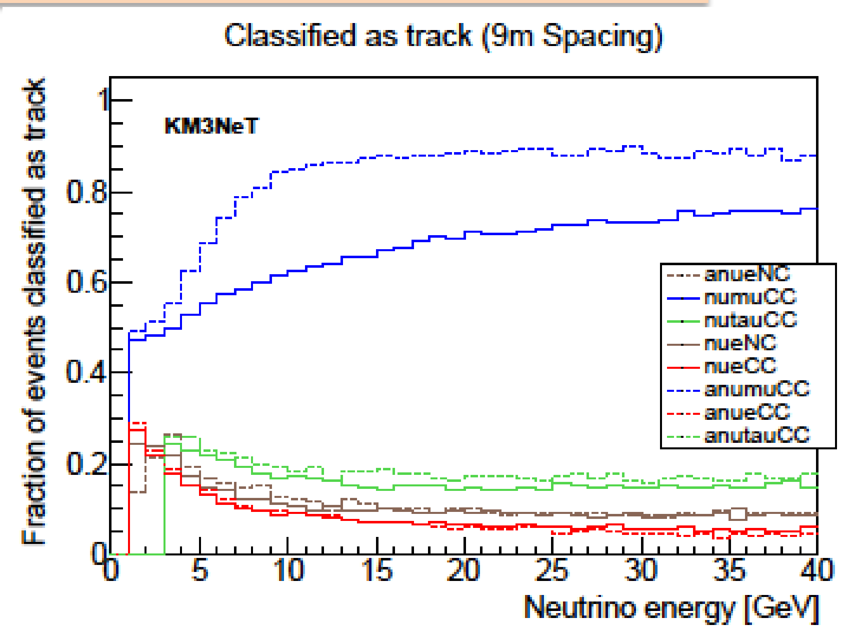


At 10 GeV:

~90% correct ID of ν_e^{CC}

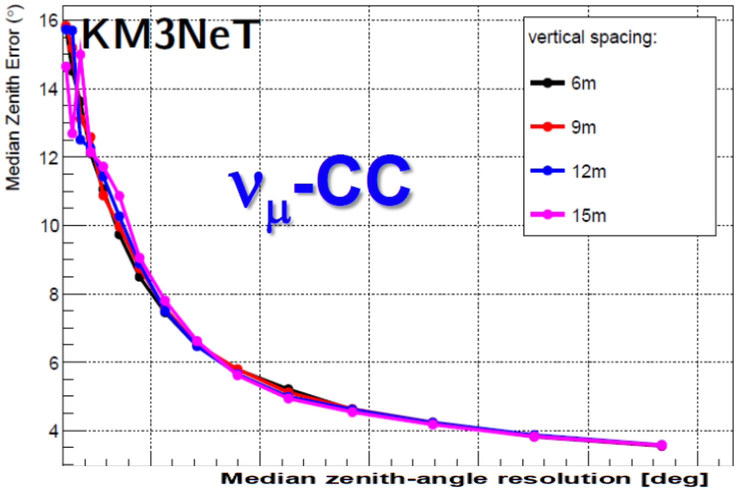
~70% correct ID of ν_μ^{CC}



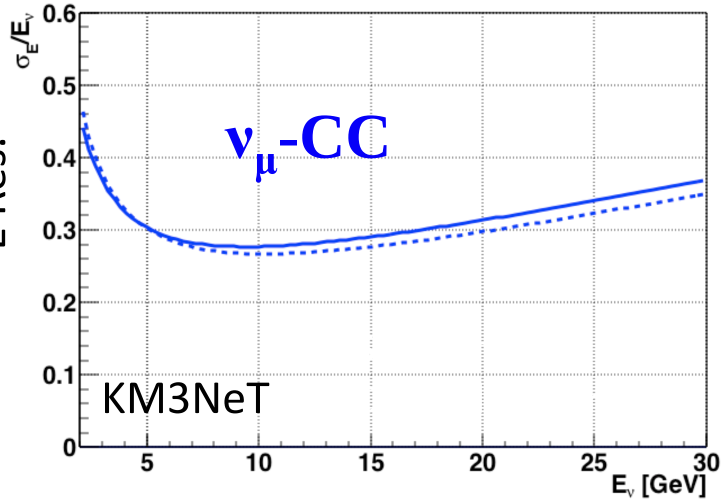


Reconstruction performances (from LoI)

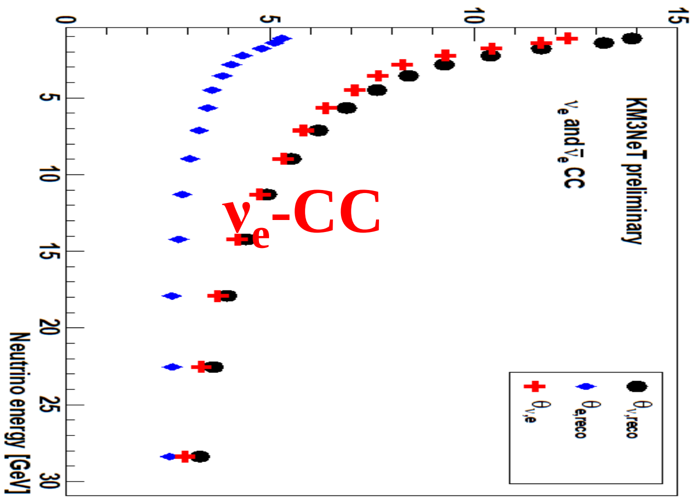
θ Res.



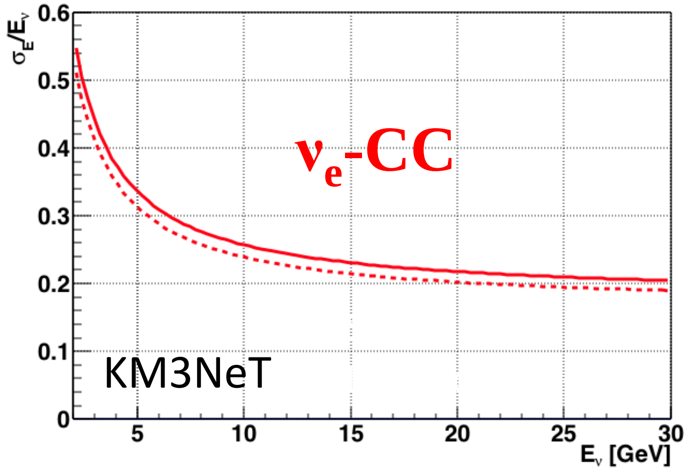
E Res.



θ Res.



E Res.



7°(5°) for 5(10) GeV for both channels
Dominated by kinematic smearing

Energy resolution below 30%
in relevant energy range

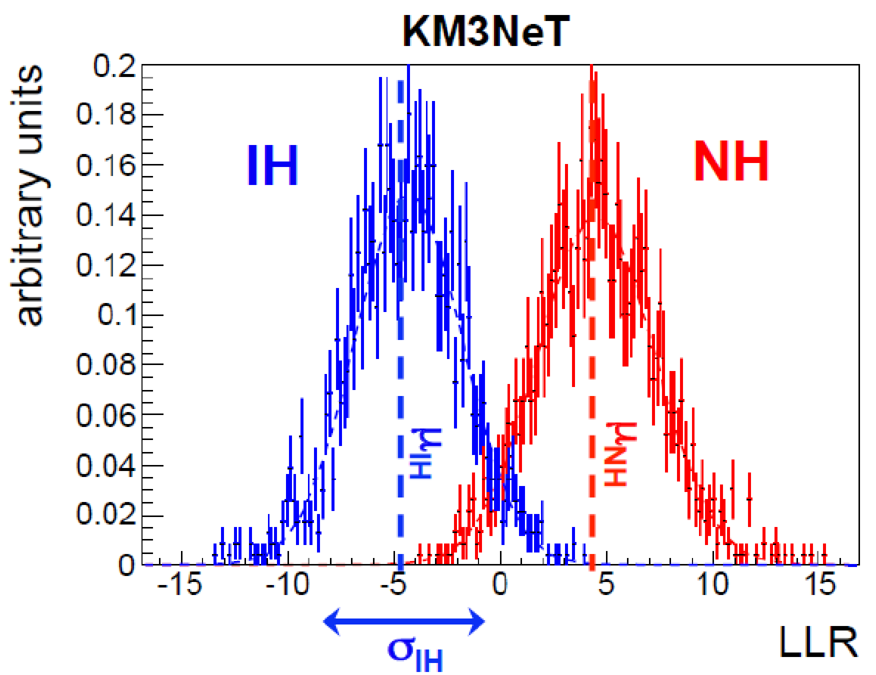
Statistical analysis

parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
θ_{23} [°]	$\{40, 42, \ldots, 50\}$	uniform over $[35, 55]$ †	fitted	no
θ_{13} [°]	8.42	$\mu = 8.42$, $\sigma = 0.26$	fitted	yes
θ_{12} [°]	34	$\mu = 34$, $\sigma = 1$	nuisance	N/A
ΔM^2 [10^{-3} eV^2]	$\mu = 2.4$, $\sigma = 0.05$	$\mu = 2.4$, $\sigma = 0.05$	fitted	no
Δm^2 [10^{-5} eV^2]	7.6	$\mu = 7.6$, $\sigma = 0.2$	nuisance	N/A
δ_{CP} [°]	0	uniform over $[0, 360]$	fitted	no
overall flux factor	1	$\mu = 1$, $\sigma = 0.1$	fitted	yes
NC scaling	1	$\mu = 1$, $\sigma = 0.05$	fitted	yes
$\nu/\bar{\nu}$ skew	0	$\mu = 0$, $\sigma = 0.03$	fitted	yes
μ/e skew	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes
energy slope	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes

- Profile over 4 oscillation & 5 systematic parameters

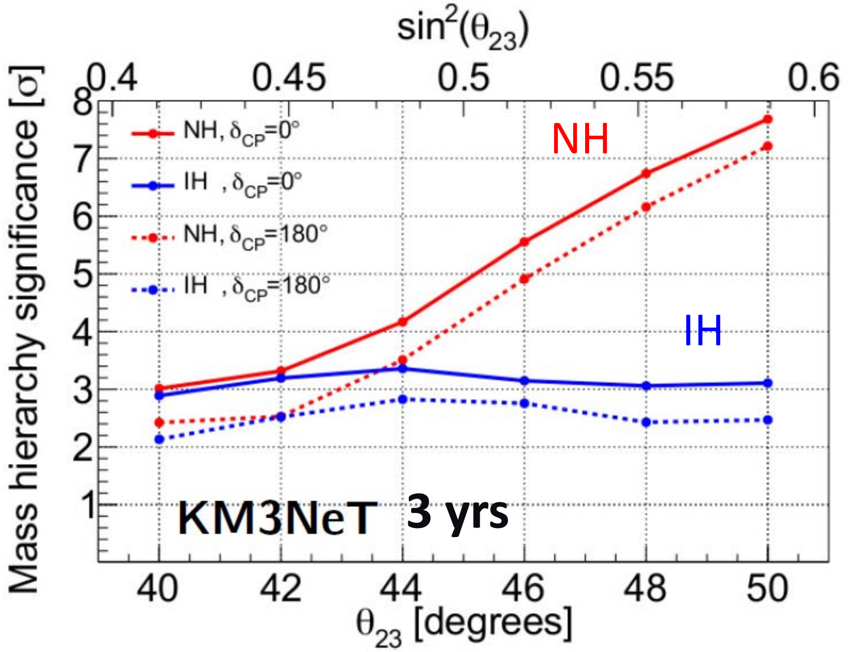
- Generate pseudo-experiments and compute $\mathrm{LLR} = \log\left(\mathcal{L}_{\mathrm{NH}}/\mathcal{L}_{\mathrm{IH}}\right)$
- **Median sensitivity** ⇔ probability of observing median LLR of wrong hierarchy

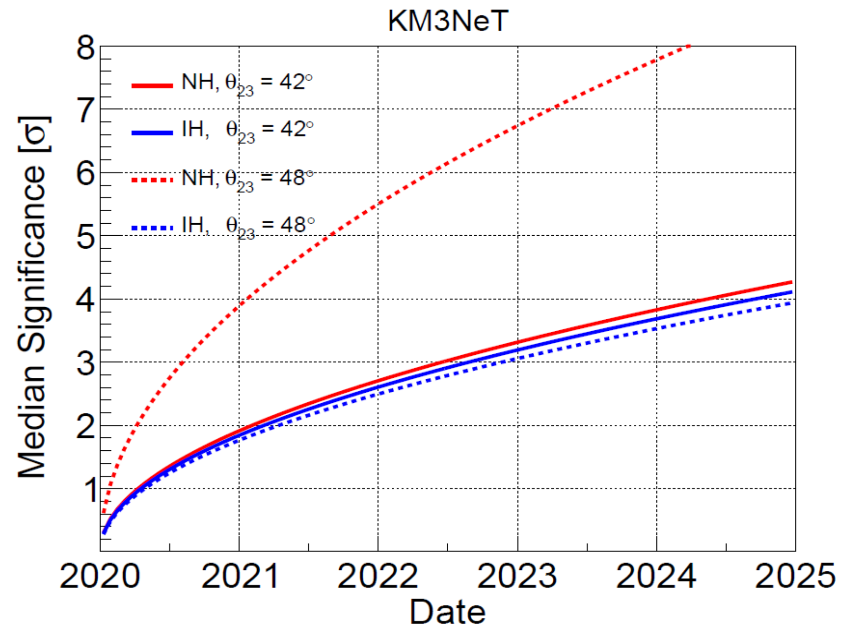
$$\boxed{S_{\mathrm{NH}} = \frac{\mu_{\mathrm{NH}} - \mu_{\mathrm{IH}}}{\sigma_{\mathrm{IH}}}}$$



Sensitivity to NMH (from LoI)

- Worst case: ~3σ sensitivity to NMH in 4 years
- The combination of NH and upper octant of θ_{23} gives significantly improved sensitivity (>5σ in 3 years)
- For IH, sensitivity is essentially independent of θ_{23}
- The value of δ_{cp} has moderate impact on sensitivity (~0.5σ)



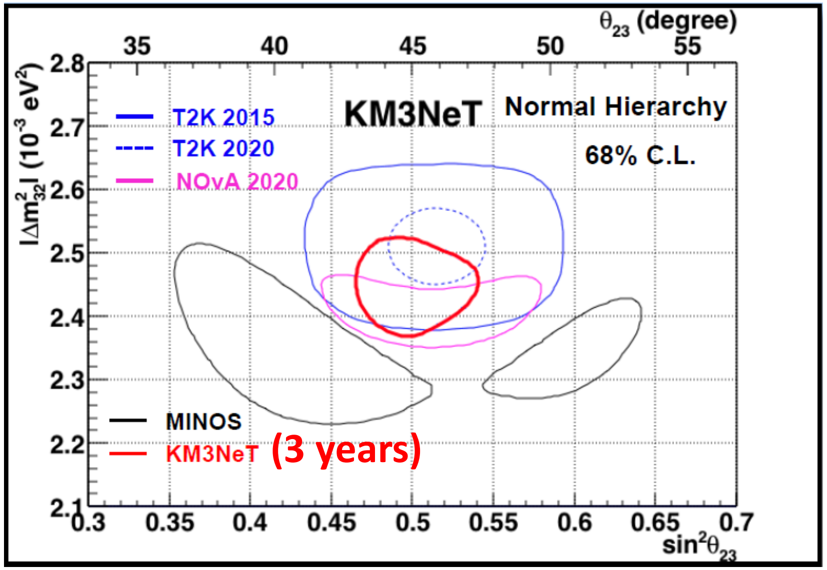


Other measurements

➢ Oscillation parameters

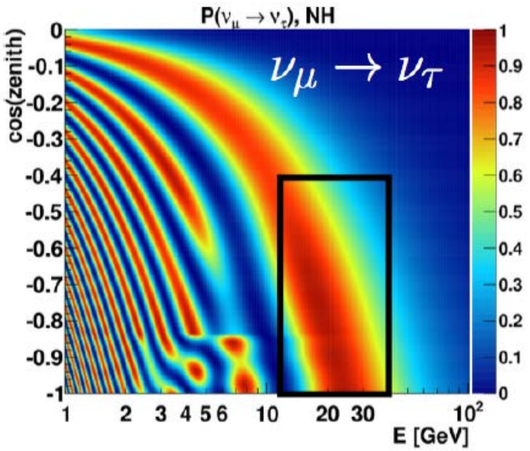
- High statistics and excellent resolution
- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$ (depending on hierarchy)
- Competitive with NOvA and T2K

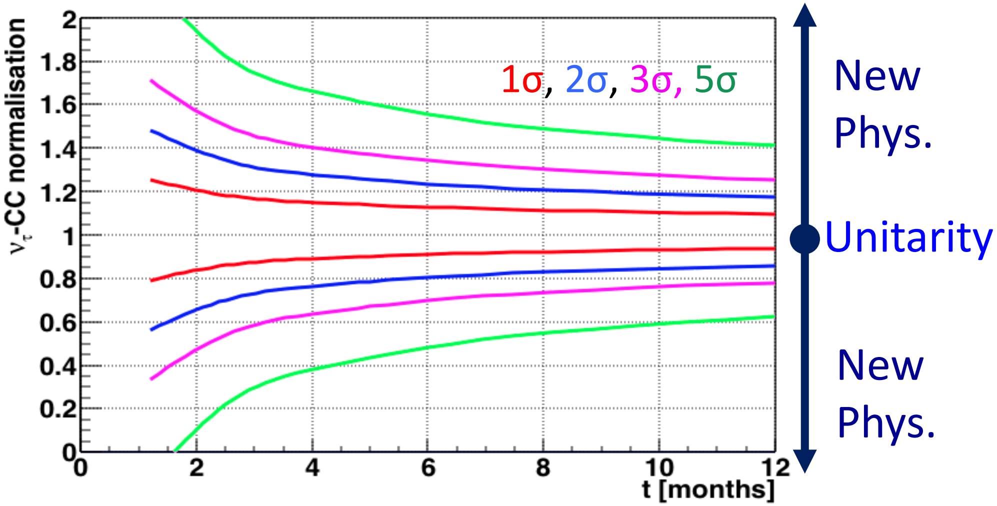
projected sensitivity in 2020



➢ Tau neutrino appearance

- ≈3k ν_τ CC events/year with full ORCA → early physics result!
- Rate constrained within ≈10% in 1 year



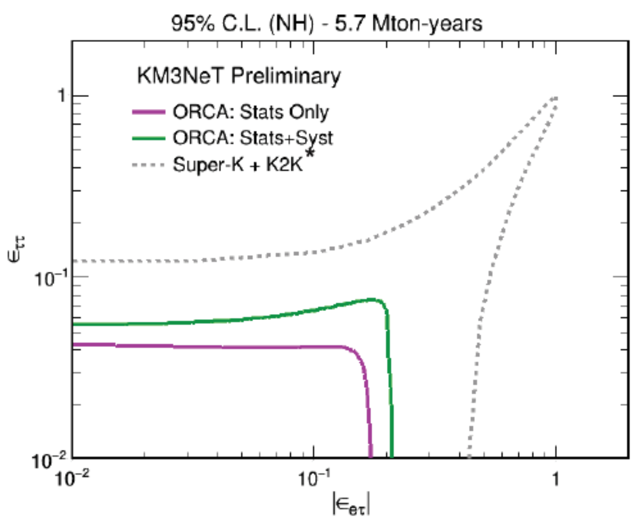


Non-standard interactions

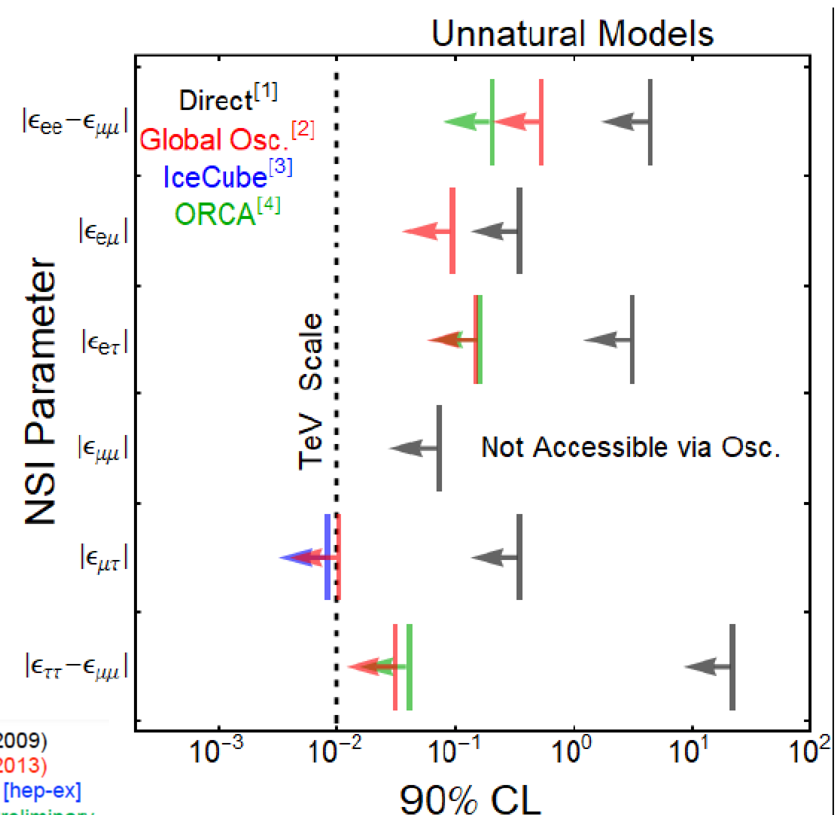
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$

Arbitrary Perturbation

- ORCA sensitive to NSI effects of the order of 10% of Fermi interaction
- for some of the parameters: x10 improvement on direct bounds
- competitive with global limits from oscillation (including solar neutrinos)



*Phys. Rev. D72, 053009 (2005)



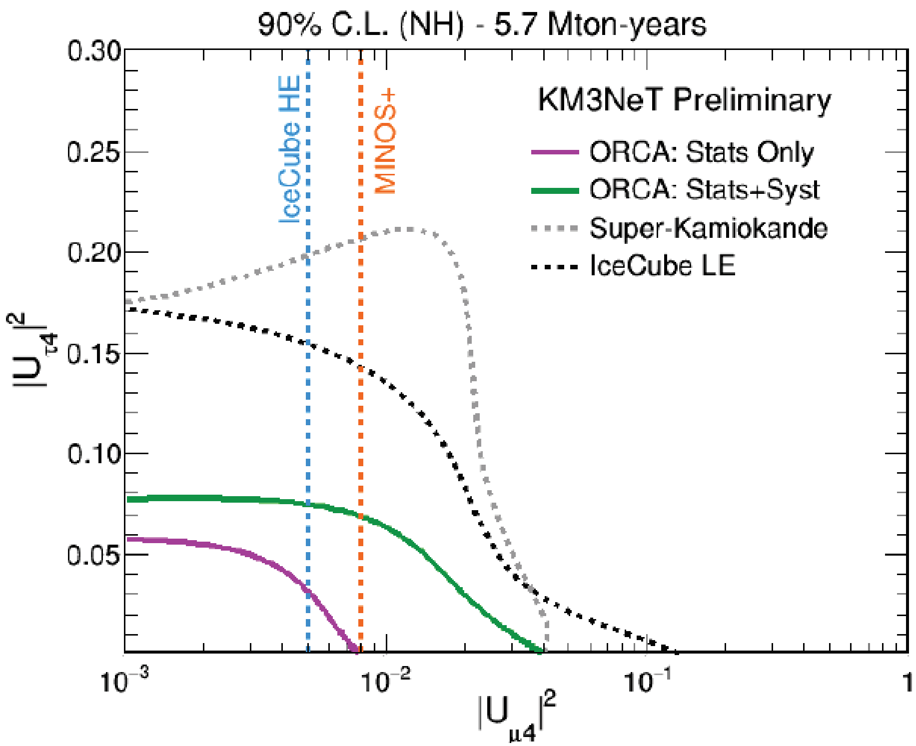
[1] JHEP 0908:090 (2009)
[2] JHEP 1309:152 (2013)
[3] arXiv:1709.07079 [hep-ex]
[4] KM3NeT-ORCA Preliminary

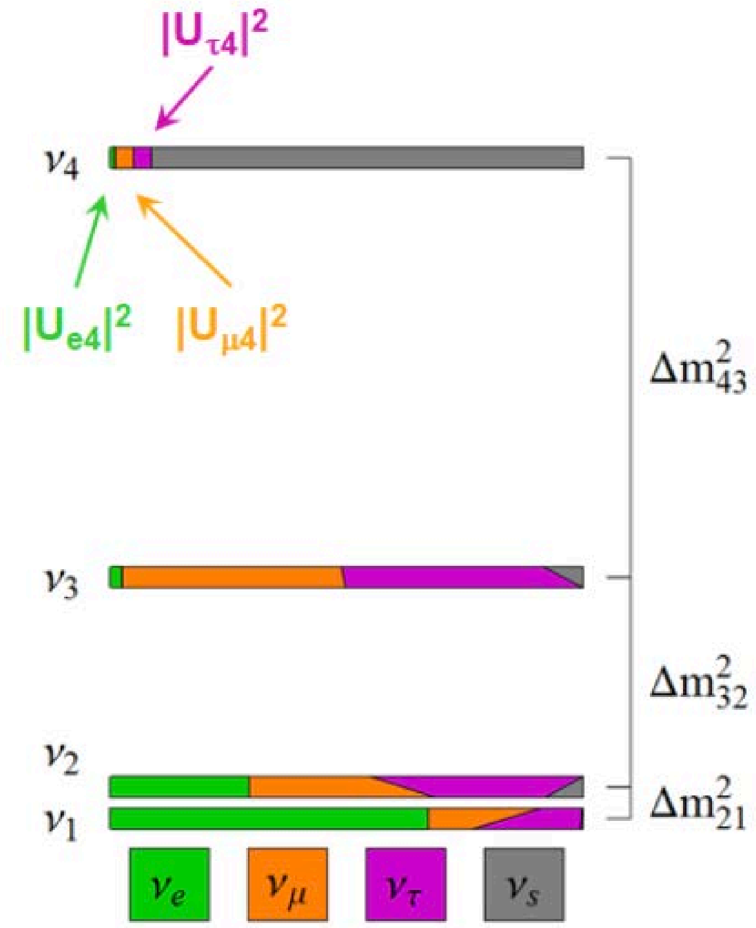
Sterile neutrinos

- Dominant effect of adding an eV-scale sterile neutrino:

suppression of $\nu_\mu \leftarrow \rightarrow \nu_\tau$ oscillation at ~20GeV

- ORCA sensitive to $|U_{\tau 4}|^2$ 2x smaller than current limits set by SuperK & IceCube



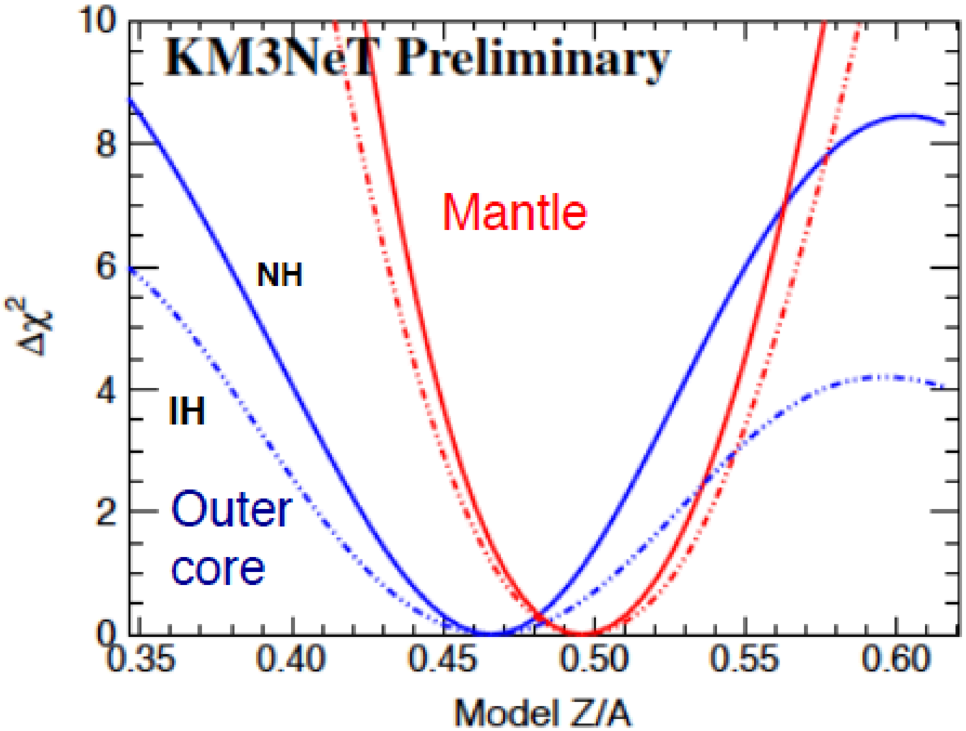


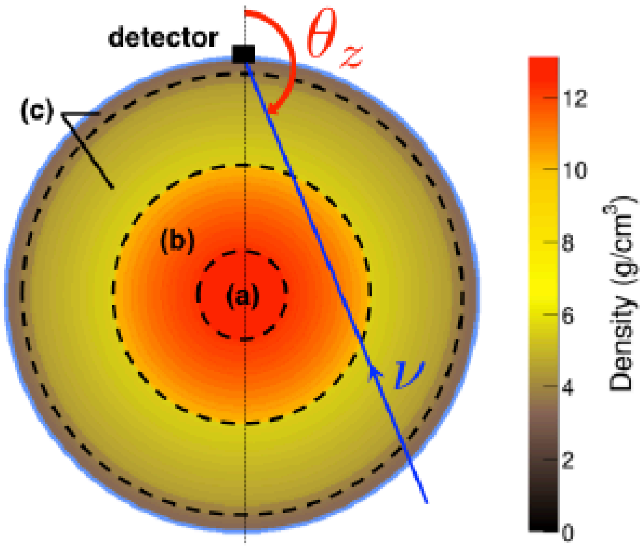
Neutrino oscillation tomography of the Earth

- ORCA is sensitive to the electron density N_e while geophysics measure ρ_m

- 1σ stat.+ syst. uncertainty after 10 years (NH)
  - ~ 5% in the whole mantle (c)
  - ~ 6% in the whole outer core (b)

10 year sensitivity including systematics





$$\frac{N_e}{\rho_m} \propto \sum_i w_i \frac{Z_i}{A_i}$$

- PREM model basis for ρ_m
- uniform Z/A rescaling in layer
- Monte Carlo response & PID
- 4 osc. + 4 syst. param. fitted

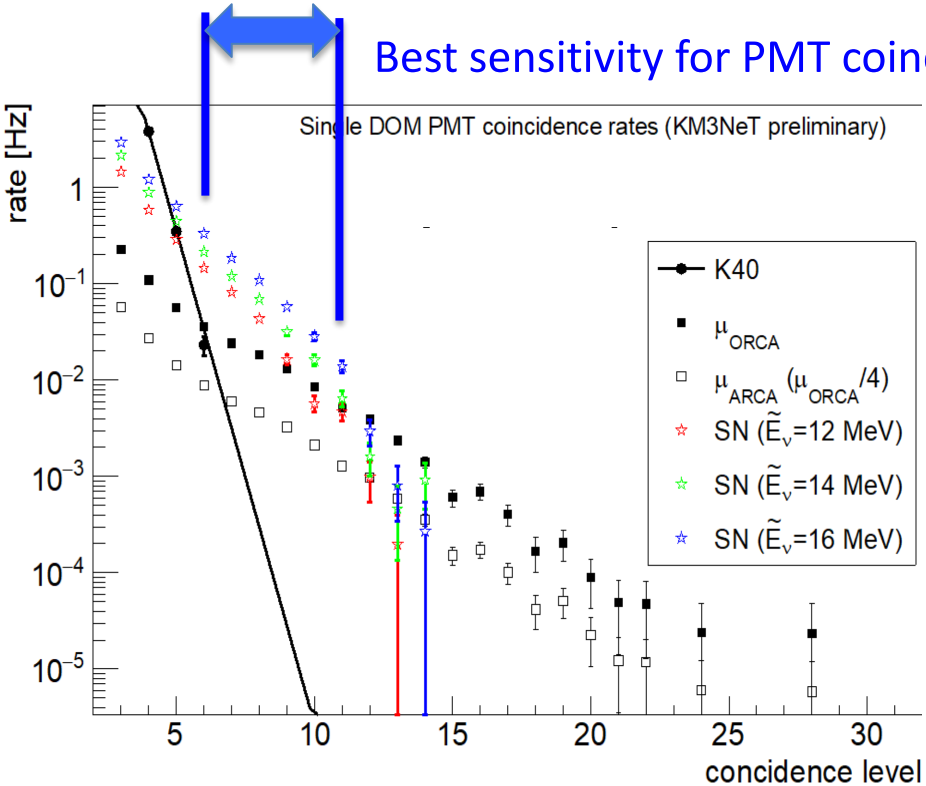
ORCA(/ARCA) sensitivity to supernovae

SN1987A-like simulation: 10 kpc,
3×10^{53} erg
1/6 in $\bar{\nu}_e$
25% in the first 100 ms

Spectra: $$f_\nu^{SN} = \frac{1}{4\pi(10\text{ kpc})^2}\left\{\frac{3\times10^{53}\text{ erg}}{6\ \tilde{E}_\nu}\times\frac{0.25}{100\text{ ms}}\right\}\frac{E_\nu^\alpha \exp(-(\alpha+1)E_\nu/\tilde{E}_\nu)}{\text{Normalization}},\quad \alpha=3$$

$\tilde{E}_{\bar{\nu}_e}$ =12, 14 & 16 MeV

Best sensitivity for PMT coincidence level between 6 and 10



$\tilde{E}_{\bar{\nu}_e}$ MeV	N_{ev} per block	$D_{5\sigma/3\sigma}$ (kpc) ARCA	$D_{5\sigma/3\sigma}$ (kpc) ORCA
12	60	23/30	16/20
14	100	29/37	19/25
16	150	37/47	24/31

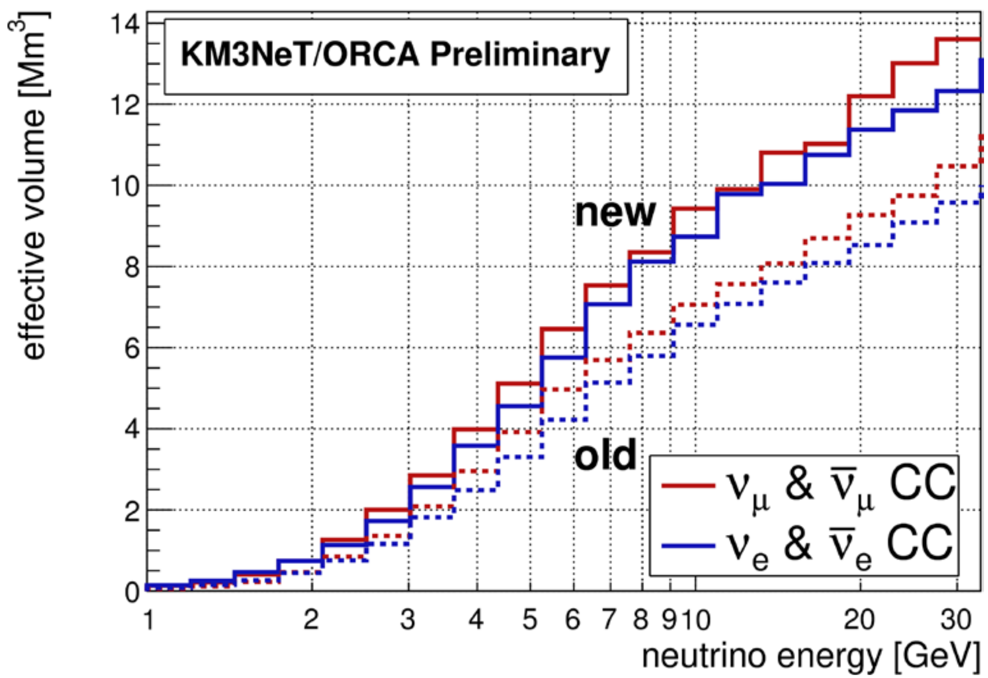
>80% of all Galactic SN with a single building block

Improved performances: trigger

- New trigger: requires only ONE local DOM coincidence (L1)
  + causally-connected hits (L0) on neighbouring DOMs
  (do not have to be coincidences)
  (before: cluster of 3-4 causally connected L1 coincidences)

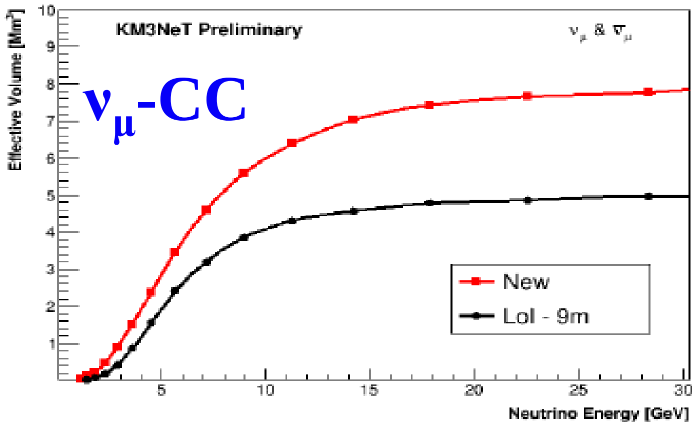
- Keep bandwidth requirements: trigger rate from pure-noise (~20 kHz) smaller than irreducible trigger rate from atmospheric muons (~50 Hz)

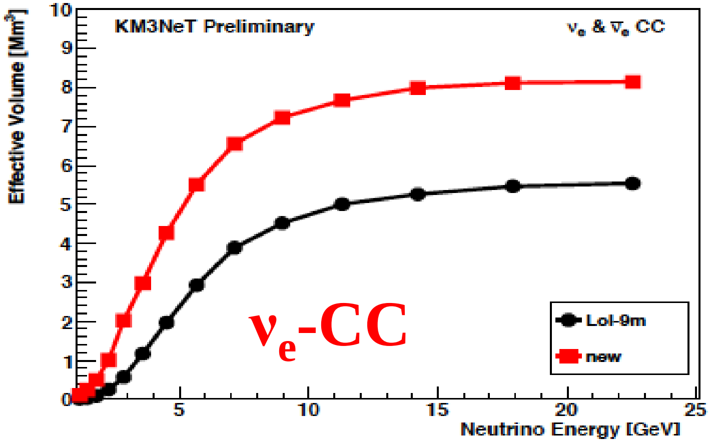
Increase of effective volume at low energies despite sparser detector!

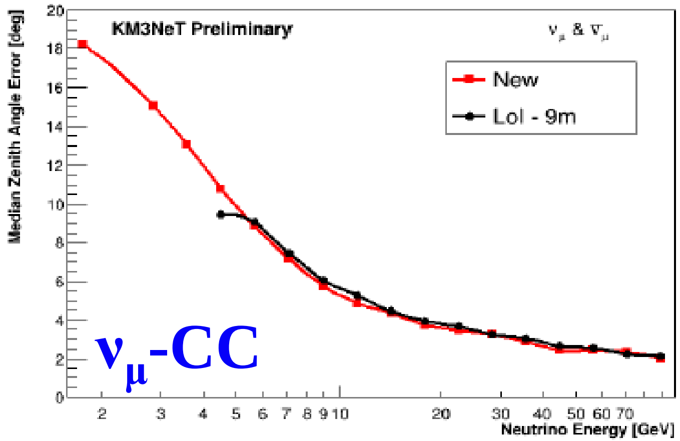


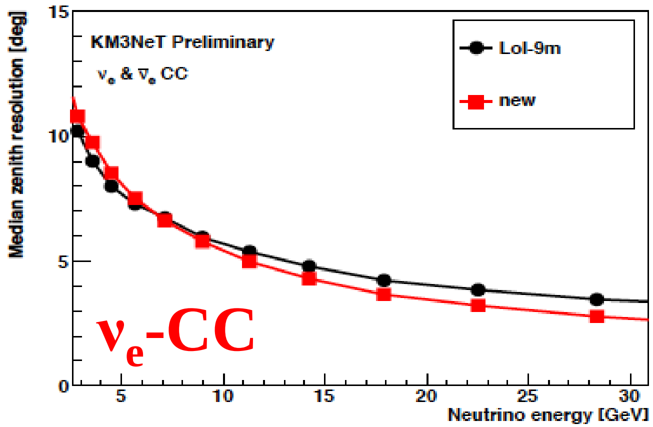
Improved performances: reconstruction

- Reconstruction strategies adjusted for new trigger: allow for fainter events









Efficiency significantly improved - angular resolution unchanged

Expect an increase in sensitivity to NMH and oscillation parameters

(full chain processing ongoing)

Outlook

- New realistic layout simulated accounting for all technical constraints
- Increased detector volume, improved trigger and event reconstruction wrt to LoI

  …working hard to determine the corresponding increase in sensitivity

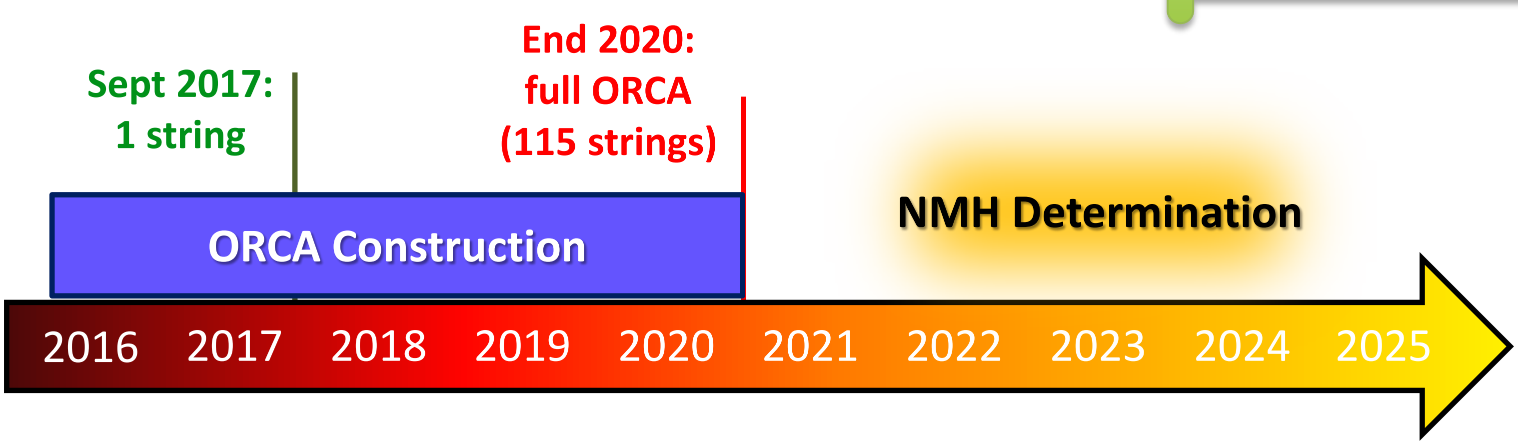
- ORCA 3σ median significance for NMH could be reached in *less than* 3 years (with full detector)

- First detection unit in data taking since last week!

- Plan for completing the construction by 2020

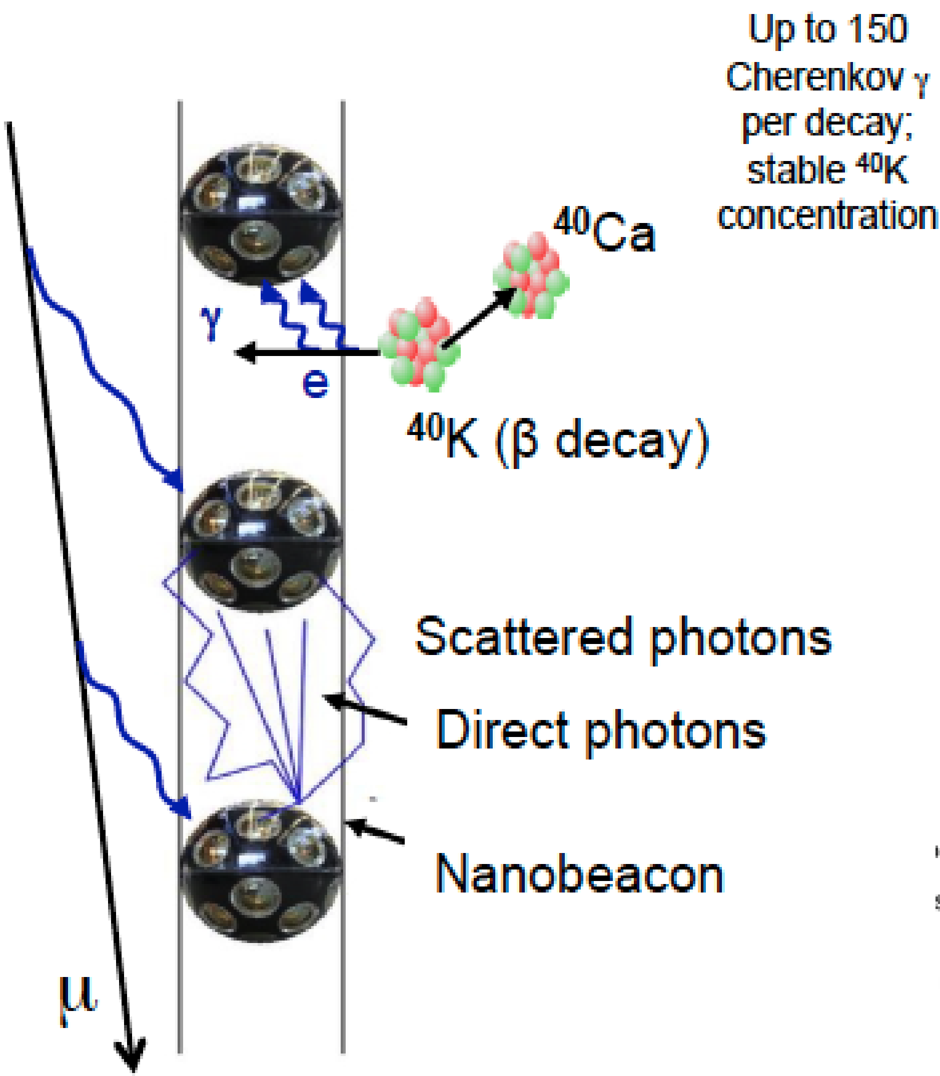
  Process for securing the funds for construction
  of full detector launched

New collaborators very welcome!

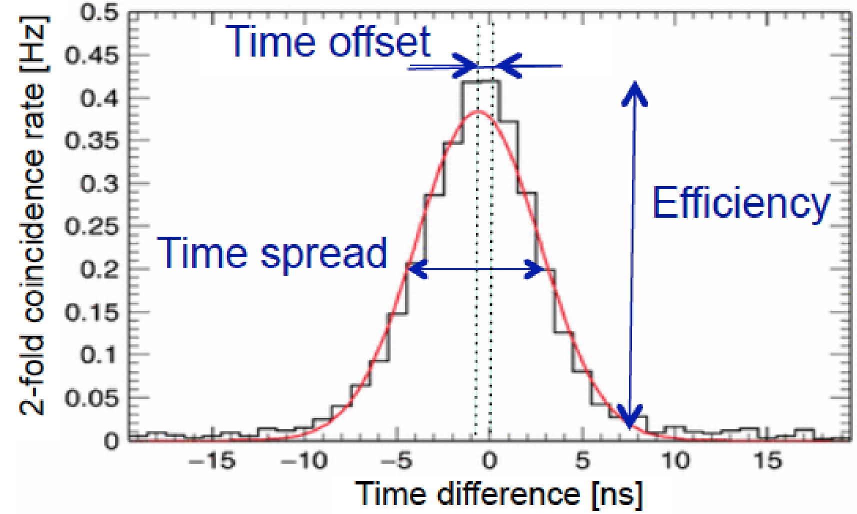


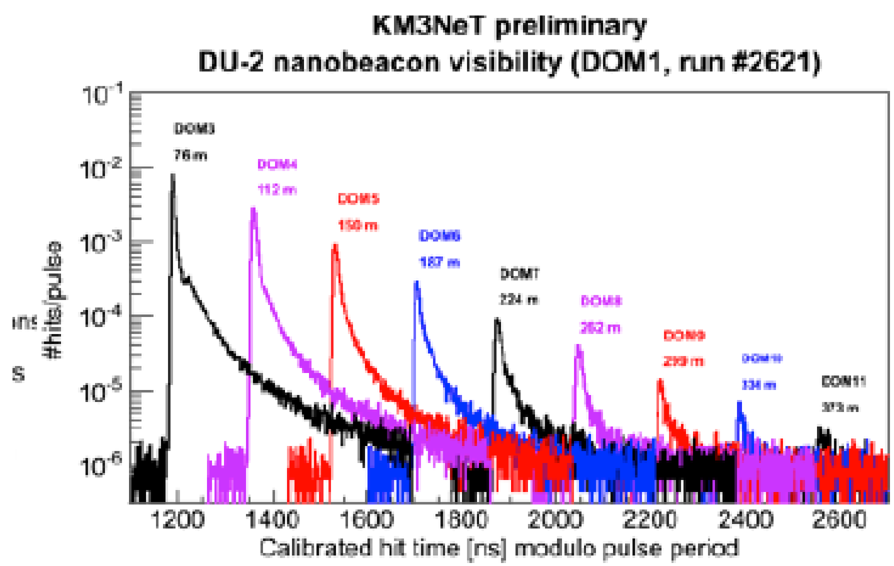
BACKUP

KM3NeT: calibration



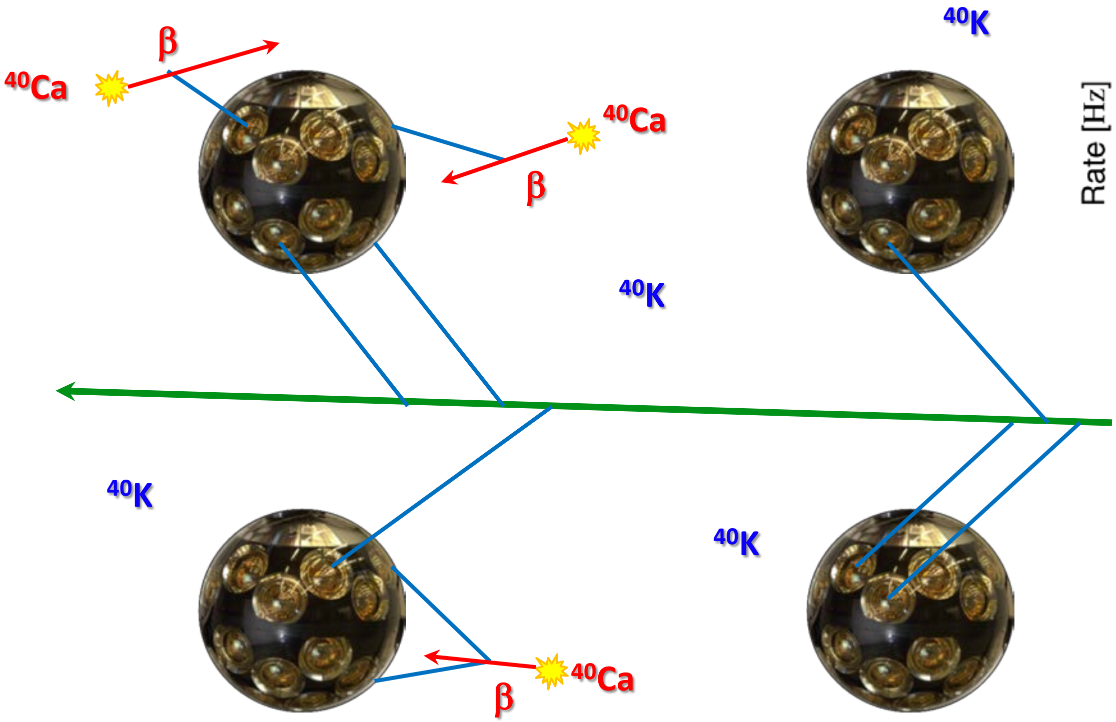
Cross-calibration with muons

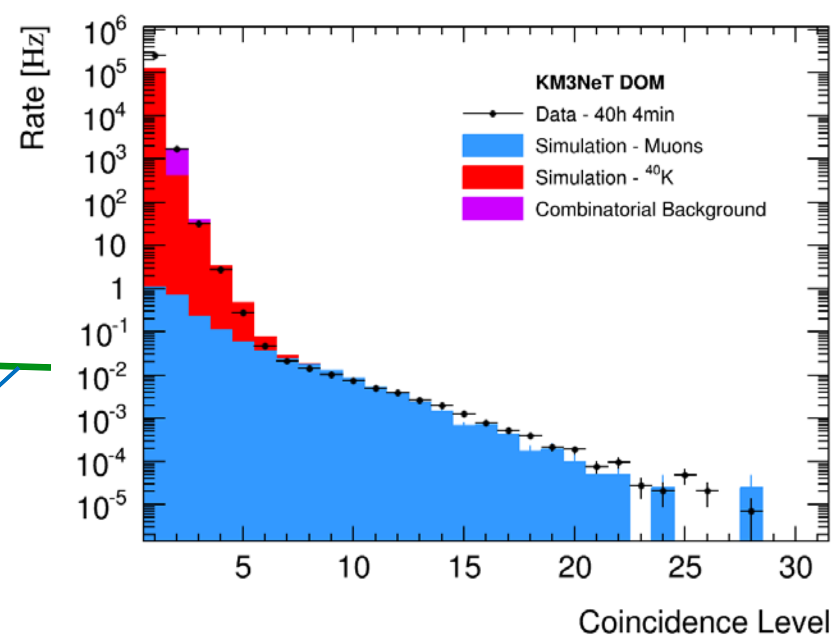




ORCA: trigger

- Optical background mostly from ^{40}K decays in the water
- Measured: **8 kHz** uncorr., **340 Hz** level-two coinc. / PMT **[Eur. Phys. J. C 74, 3056 (2014)]**
- Look for coincidences in time and PMT direction to reduce trigger rate.
- Causality further restricts space and time correlations for extra power.
- Final trigger rate **~59 Hz**, with **70%** of events containing a cosmic ray **muon**.

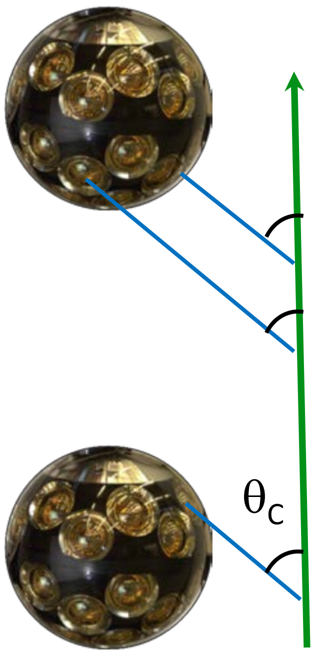




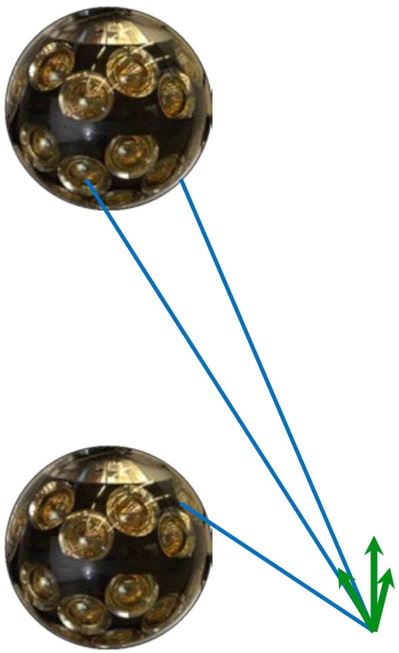
ORCA: reconstruction

1) Start with a track or shower hypothesis
2) Use **causality** to perform a robust **hit selection**
3) Find **vertex** and **direction** that best match hit pattern
4) Estimate track range for computing **track energy** (0.24 GeV / m)
5) Estimate **Shower energy** and direction from hit distribution after initial fit to the vertex position and time

Track Hypothesis



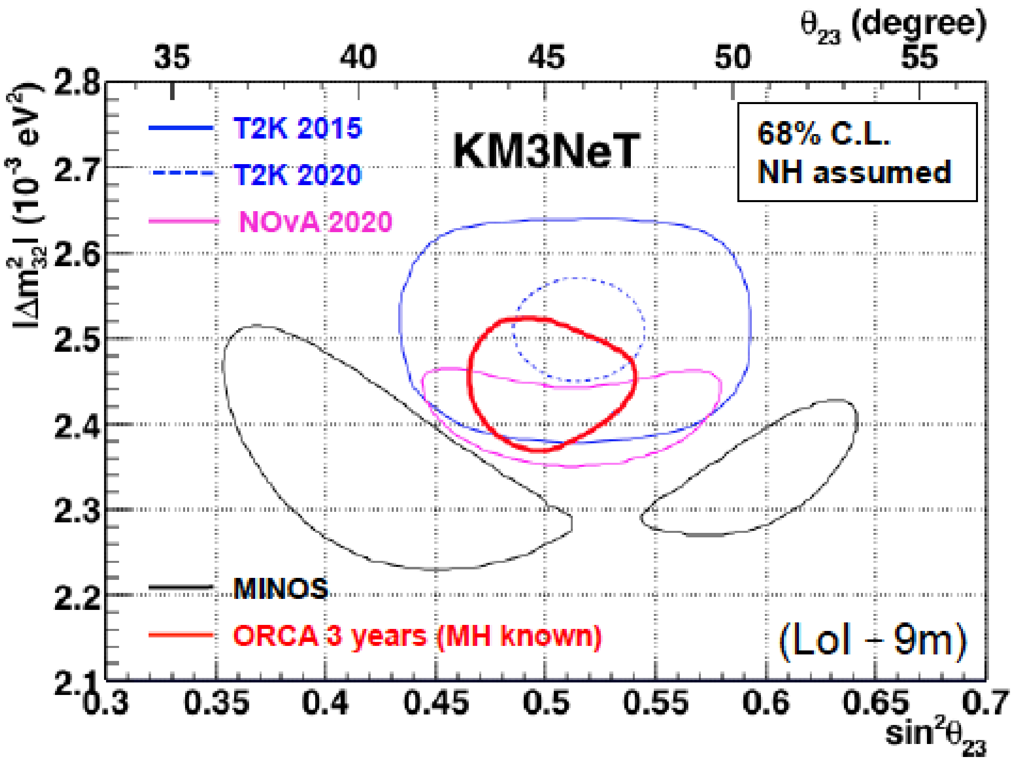
Shower Hypothesis



Oscillation parameters measurement

J. Phys. G 43 (2016) 0840

- Achieve **2-3%** prec. in Δm^2_{32} and **4-10%** in $\sin^2\theta_{23}$ (3 years)
- **Competitive with LBL experiments** projected sensitivity in 2020
- Early determination of the octant of θ_{23} is feasible



NH, $\delta_{CP} = 0$, maximal mixing assumed

- Analysis based on Asimov datasets
- θ_{12}, θ_{13} and δm^2 fixed
- Other param. **unconstrained**
- **Energy scale** uncertainty added (has **no impact** on NMH sens.)

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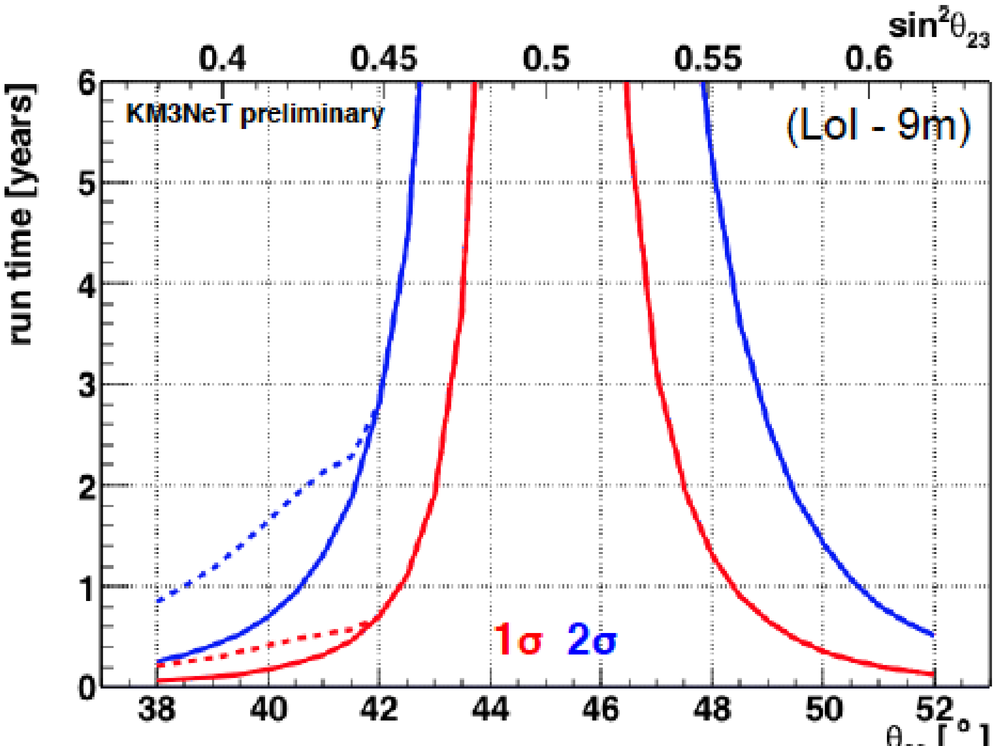

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— **MH known**

--- **MH unknown**

ORCA: non-standard interactions and steriles

Non-Standard Interactions (NSI)

Arbitrary Perturbation

$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{bmatrix}$$

Sterile Neutrinos (3+N Flavours)

$$H_{eff} = U_S \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 & 0 & \cdots \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} & 0 & \cdots \\ 0 & 0 & 0 & \frac{\Delta m_{41}^2}{2E} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} U_S^\dagger + \begin{bmatrix} V_e & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & V_n/2 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

NC Contribution

$$U_S = U_{N-1,N} \cdots U_{34} U_{24}^{(c)} U_{14}^{(c)} U_{23} U_{13}^{(c)} U_{12}$$