KM3NeT/ORCA

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Tokyo

Overview

Does Ronald talk about statistical methods?

- Introduction
  - KM3NeT & neutrino detection
  - Main science goal: Neutrino mass hierarchy

NO

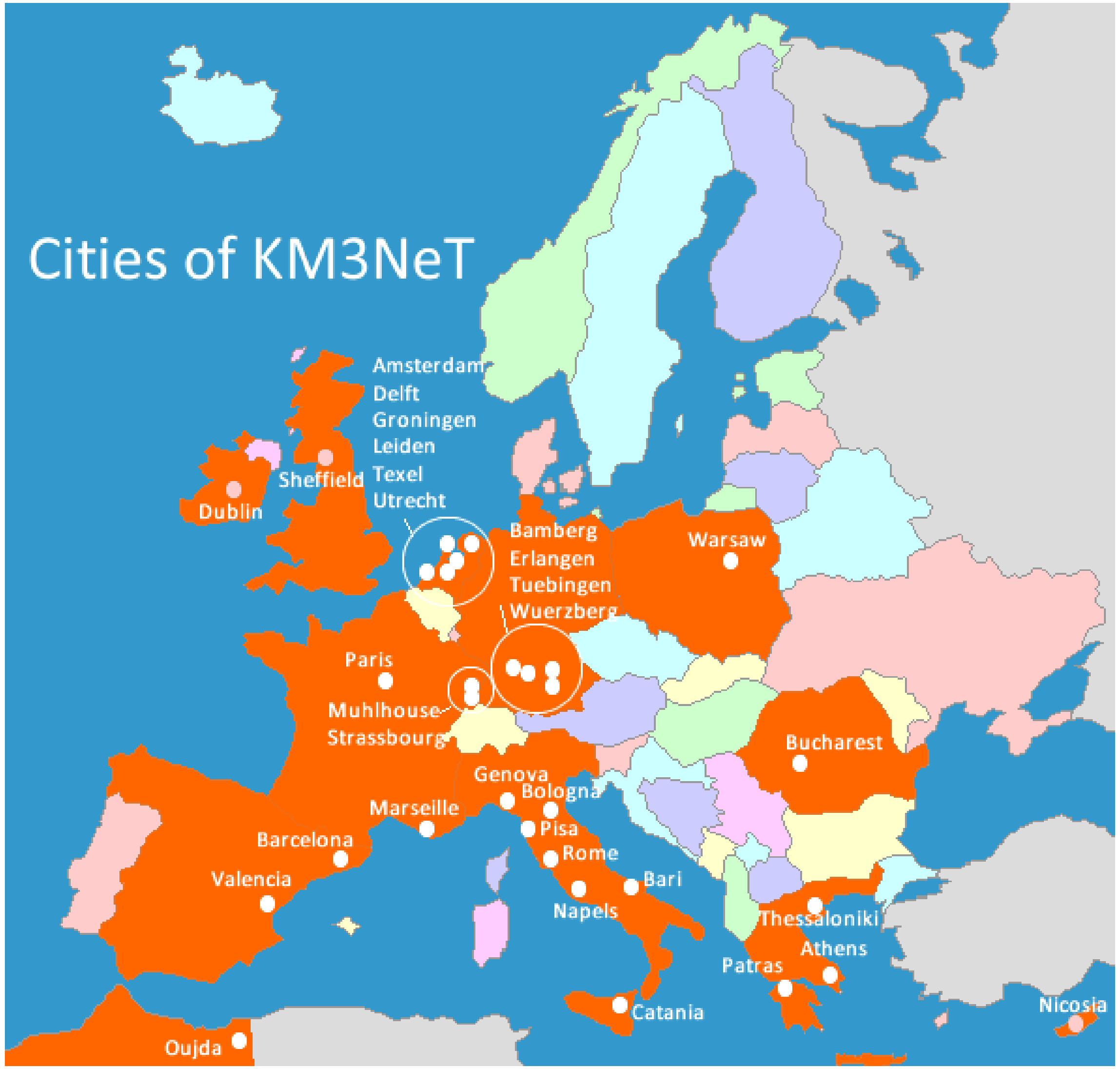
- ORCA sensitivity study & detector optimization
  - ORCA sensitivity study
    - General scheme
    - Pseudo-experiment log-likelihood ratio based
    - Simplified method
    - Results

YES!

KM3NeT Collaboration

KM3NeT
Opens a new window on our universe

12 Countries
42 Institutes
225 Scientists



Special credits for the sensitivity study:
M. Jongen (Nikhef, Amsterdam),
J. Brunner (CPPM, Marseille)

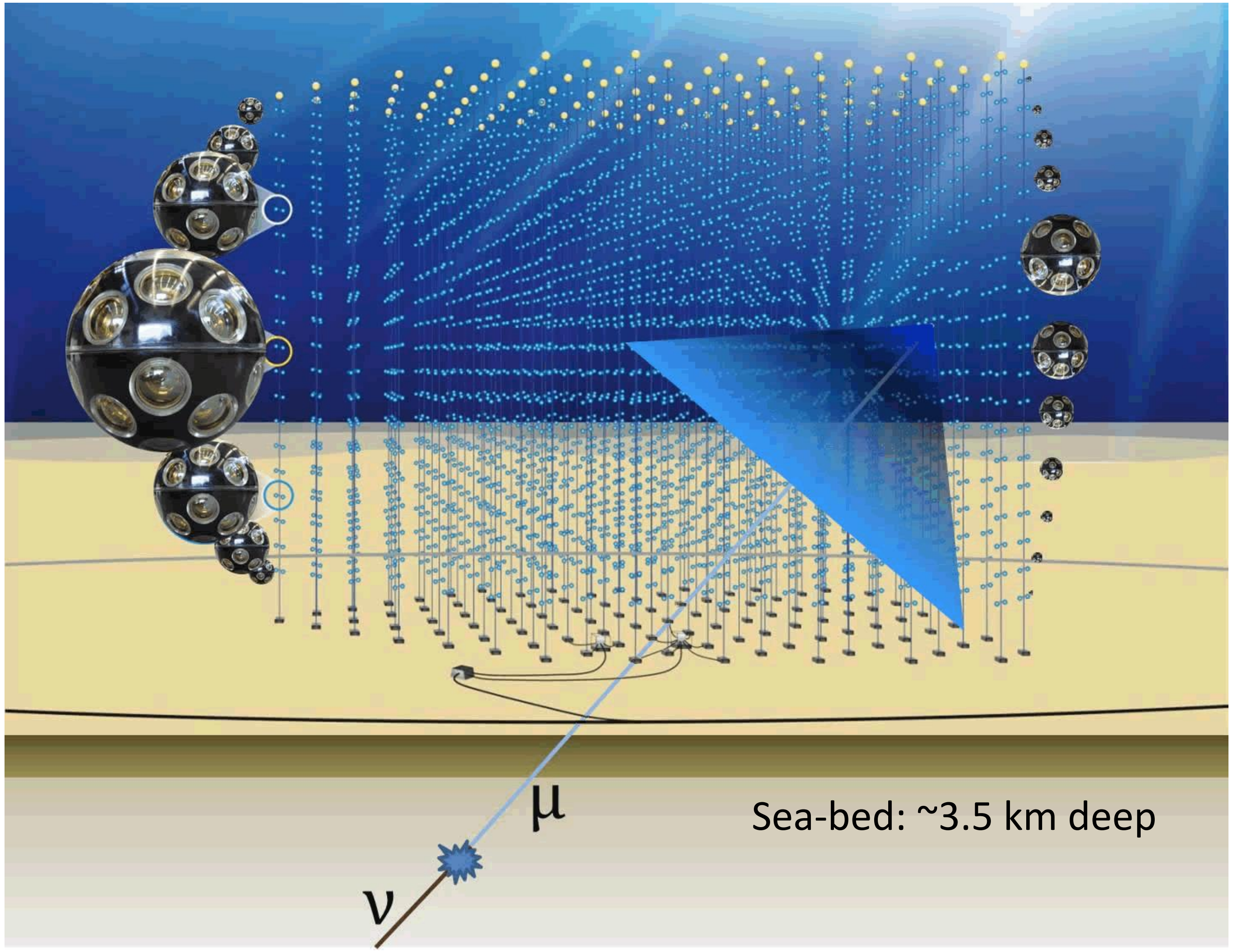
Large Volume Neutrino Telescopes

Cherenkov light from the charged products of neutrino interactions in sea-water are detected by a sparse array of photo-multiplier tubes

Two *general* event types:

Tracks - Charged current (CC) υ_μ interaction

Showers - Neutral current υ interaction
- υ_e CC electromagnetic shower
- Vertex of CC interaction
- τ decay shower



153m or 612 m instrumented

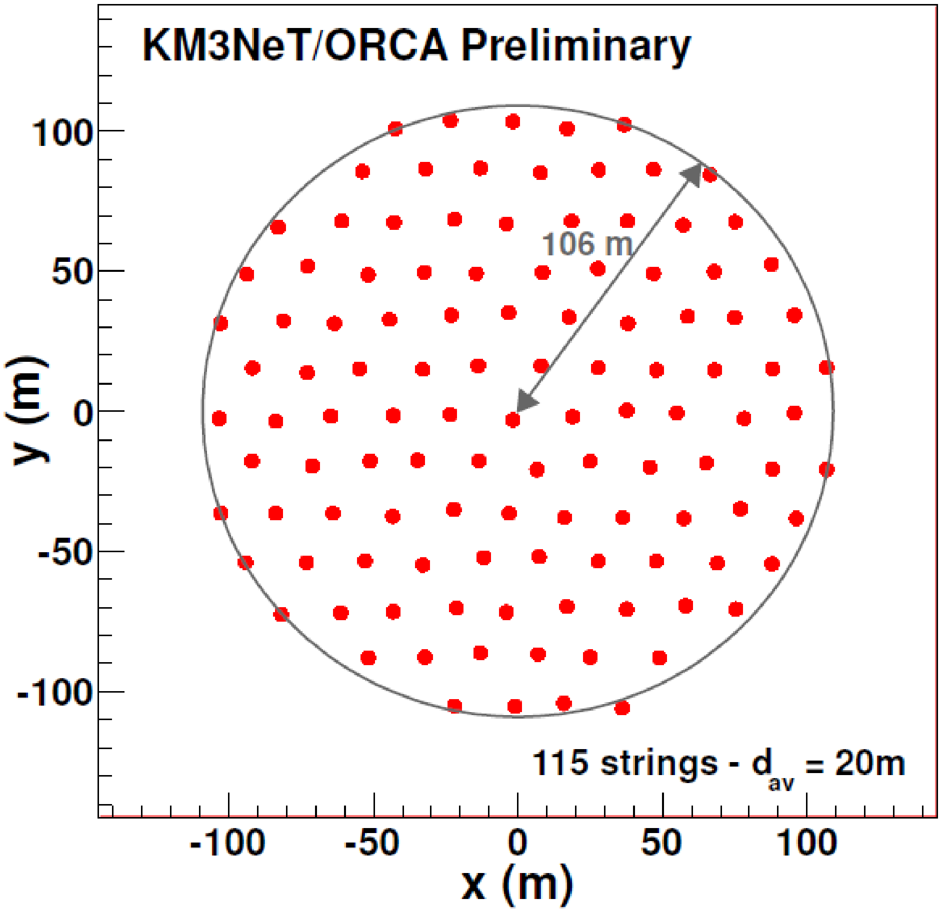
KM3NeT Design

Detection Units:

18 optical modules per vertical string
~36m or 9m between optical modules
Lowest optical module ~100m or 40m above seabed
Two Dyneema® ropes
Backbone: 2 copper conductors; 18 fibres (+spares)
Break out of cable at each optical module
Base module with DWDM at anchor
Cable for connection to seafloor network
<u>Cost saving design</u>

Infrastructure:

Building blocks of 115 strings
Sea-bed infrastructure
(facility for long term high-bandwidth connection for sea-science, biology etc.)
Optical data transmission
All-data-to-shore
Filtering/Trigger on-shore in computer farm



(´ORCA´ layout)

KM3NeT Digital Optical Module (DOM)

Segmented cathode area: 31 x 3" PMTs

➢ Directional Sensitivity

➢ Photon Counting

Light concentrator ring

Cathode area: ~ 3 x 10-inch PMT

➢ Less overhead

Custom low-power HV bases

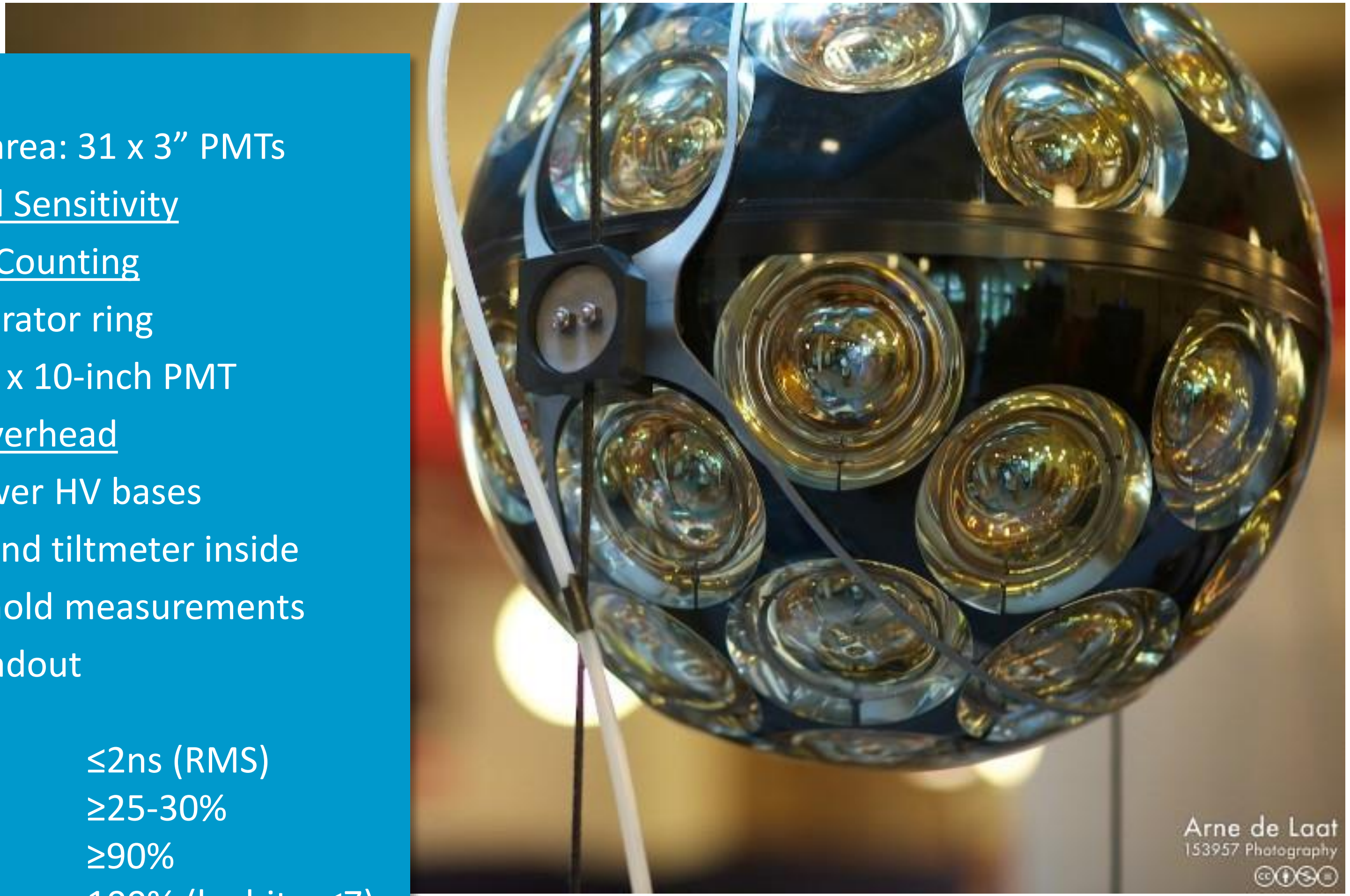
LED, piezo, compass and tiltmeter inside

PMT Time-over-Threshold measurements

FPGA readout

PMT Features:

➢Timing	≤2ns (RMS)
➢QE	≥25-30%
➢Collection efficiency	≥90%
➢Photon counting purity	100% (by hits, ≤7)
➢Price/cm2	≤10" PMT



ARCA & ORCA

High Energy Neutrino Astronomy:

ARCA: Astroparticle Research with Cosmics in the Abyss

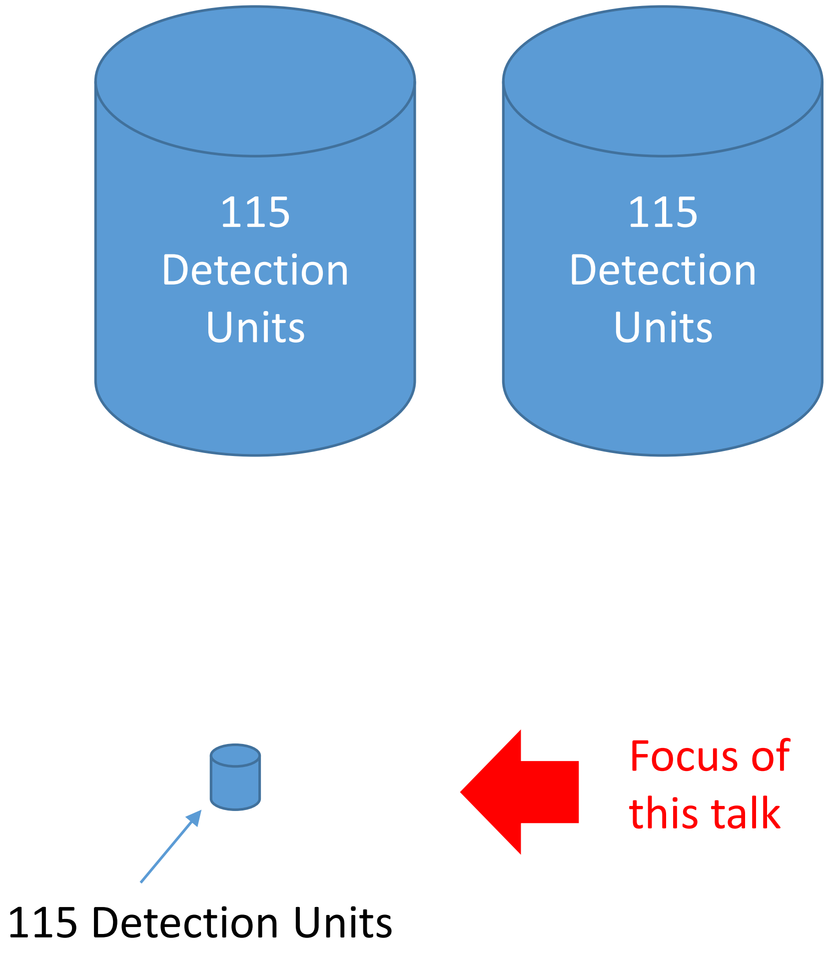
Large Detector: ~1 km^3 total
Sparse: 36 m vertical spacing, 100 m horizontal
TeV-PeV Energies
Astrophysical Neutrinos

Same technology & layout, dimensions scaled

Neutrino Physics:

ORCA: Oscillations Research with Cosmics in the Abyss

´Smaller´ detector: 5.7 Mton
Dense : 9m vertical spacing, 20m horizontal
GeV energies
Atmospheric neutrinos



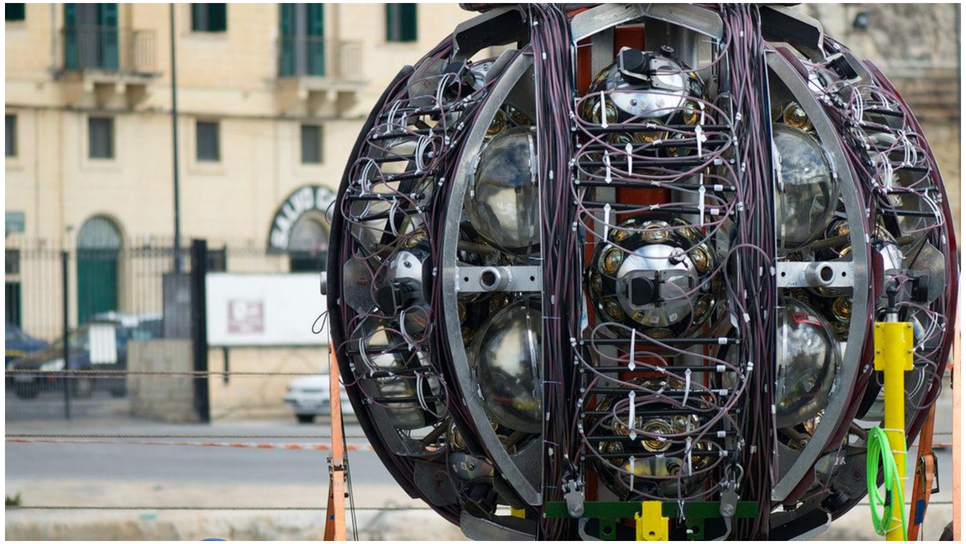
Current Status & Future

- KM3NeT Phase-1:
  - Fully funded
  - 24 ARCA Detection Units
  - 6 ORCA Detection Units
  - Under Construction

- KM3NeT 2.0 :
  - ARCA: 2 x 115 Detection Units
  - ORCA : 115 Detection Units
  - ESFRI Roadmap

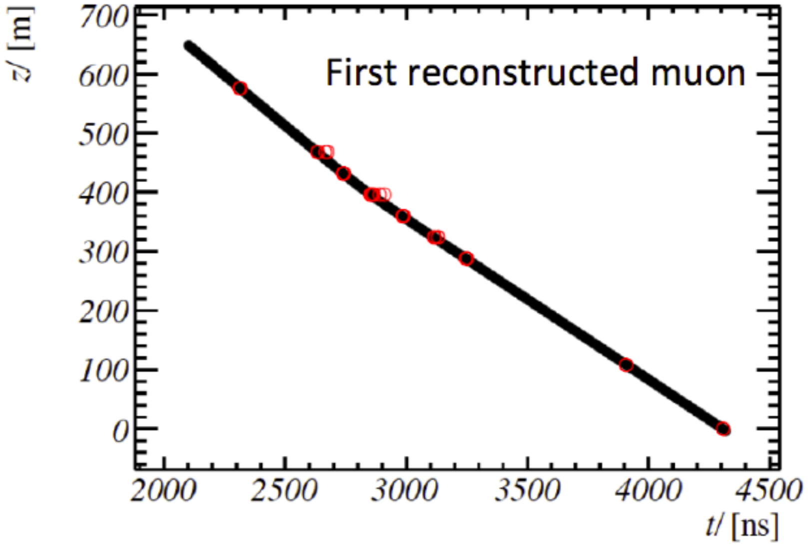
KM3NeT 2.0 Letter of Intent !
https://arxiv.org/abs/1601.07459
(Accepted for publication in
Journal of Physics G)

Current Status



December 2015:
ARCA-DU1 : fully operational

May 2016:
ARCA-DU2 & 3: testing and commissioning phase



ORCA Goal: Neutrino Mass Hierachy

Neutrinos can change flavour during propagation as the mass eigenstates are not their flavour eigenstates

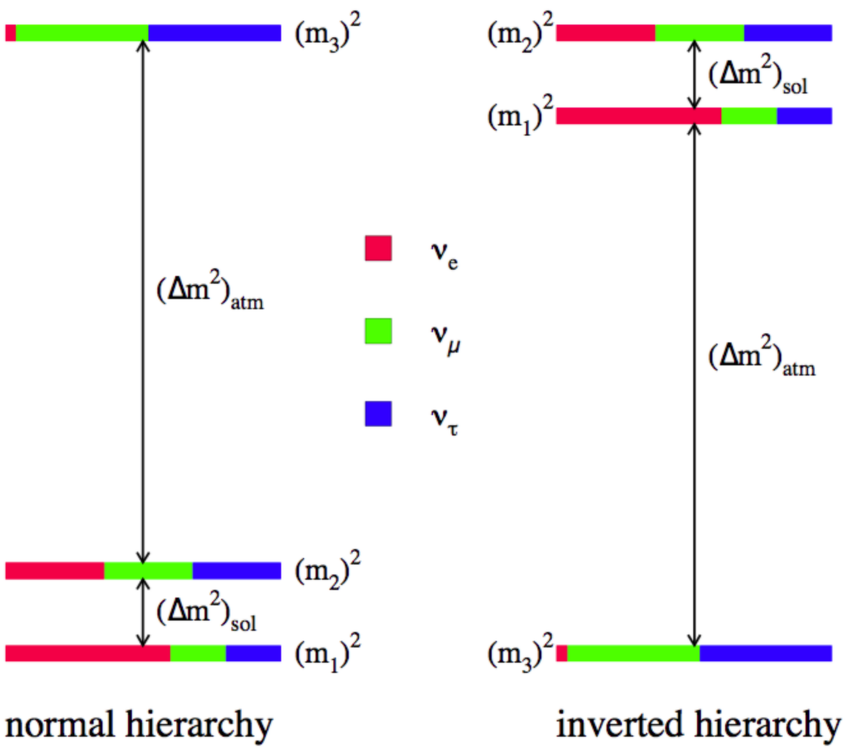
Neutrino flavour oscillations are described by the PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and two mass squared differences

Only the size of the large mass squared difference ΔM^2 is known. This allows for two orderings of the neutrino mass eigenstates

Neutrino Mass Hierarchy (NMH)



Also: CP violating phase δ_{CP} unknown and octant of θ_{23}

Determining the NMH with atmospheric υ´s

In vacuum, neutrino oscillations are unaffected by the mass ordering. E.g:

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

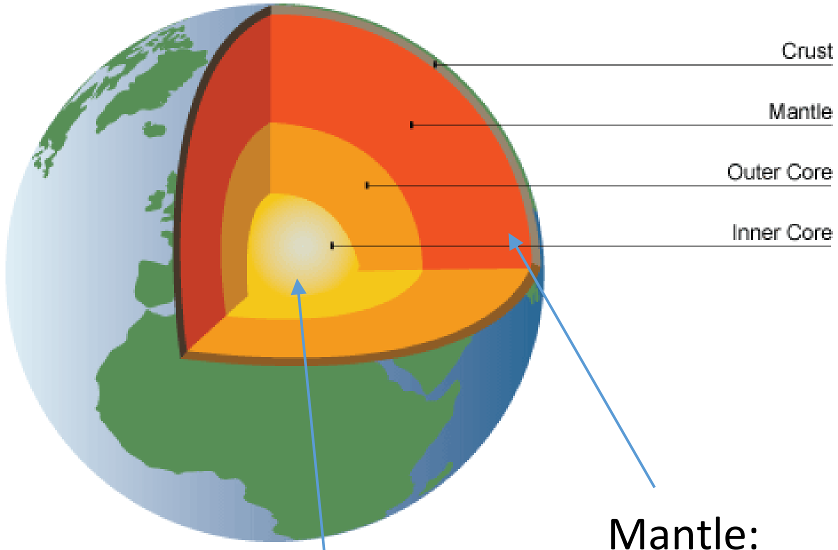
$$P_{3\nu}(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\,\sin^2\theta_{23}\,(1-\cos^2\theta_{13}\,\sin^2\theta_{23})\,\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$

In matter $\nu_e(\,\overline{\nu}_e)$acquires effective potential $A = \pm\sqrt{2}G_f N_e$ through charged current elastic interactions with electrons. And oscillations probabilities are modified.

This affects phase and amplitude of oscillations and is strongest at resonance energy:

$$E_{\rm res} \equiv \frac{\Delta m_{31}^2\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,\mathrm{GeV}\left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right)\left(\frac{\Delta m_{31}^2}{2.4\times10^{-3}\,\mathrm{eV}^2}\right)\cos 2\theta_{13}$$

Density profile of the path through the Earth depends on zenith angle



Mantle:

$E_{res} \approx 7GeV$

Core:

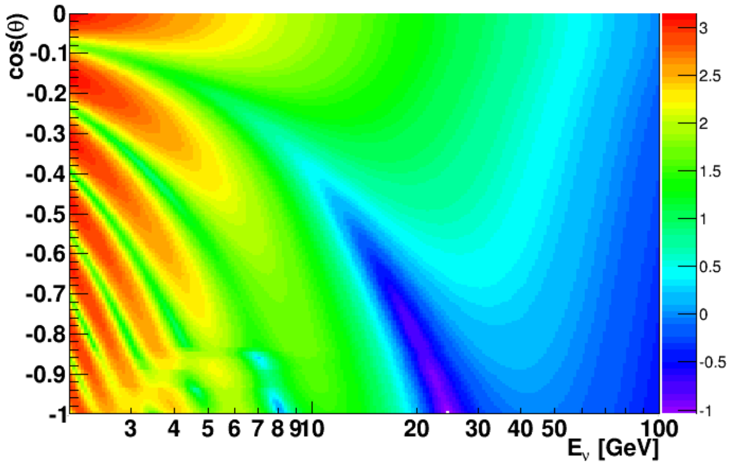
$E_{res} \approx 3GeV$

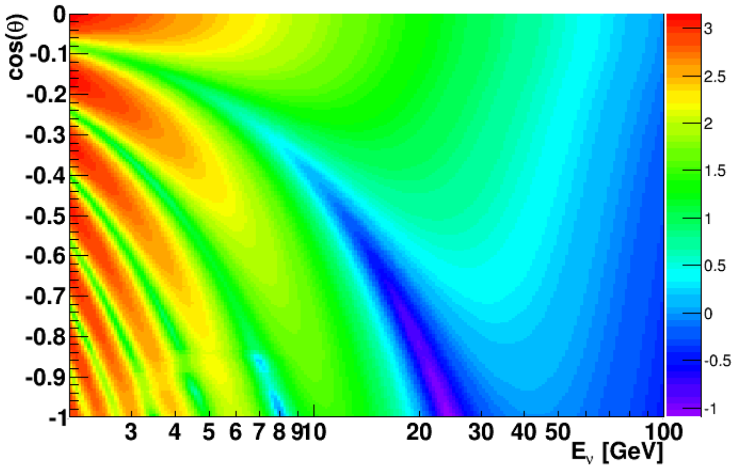
Measure atmospheric neutrino flux as function of energy and zenith angle!

Determining the NMH with atmospheric υ´s

Problem: Decide between the Normal Hierarchy (NH) and Inverted Hierarchy (IH) hypotheses from a measurement of the zenith angle and energy dependent atmospheric neutrino flux

Without detector effects (angle & energy resolutions, event classification, detection efficiency) the ´oscillograms´ look like this:





One needs to take into account:

Physics uncertainties (flux, cross-sections)
Oscillation parameter uncertainties
Detector effects and uncertainties
Degeneracies

Sensitivity study/Detector optimization

- An extensive study was done to:
  - Quantify the performance of ORCA
    - Neutrino mass hierarchy sensitivity
    - Sensitivity to other oscillation parameters
  - Optimize the detector geometry for mass hierarchy measurement
  - This included development and optimization of diverse algorithms
    - Muon track reconstruction
    - Shower reconstruction
    - Particle identification
    - Background suppression (atmospheric muons)
- This study is summarized in the KM3NeT 2.0 LOI (see slide 8)

Sensitivity study/Detector optimization

So: Compare measured rate vs. zenith and angle between different hypotheses:

Ingredients:

Detector independent (interaction rates)
Physics inputs

Atmospheric neutrino flux per flavor (E, theta)
Oscillation probabilities per flavor (E, theta)
Neutrino interaction cross-sections

Detector dependent (detector response, reconstruction,…)
Derived from Monte-Carlo simulations

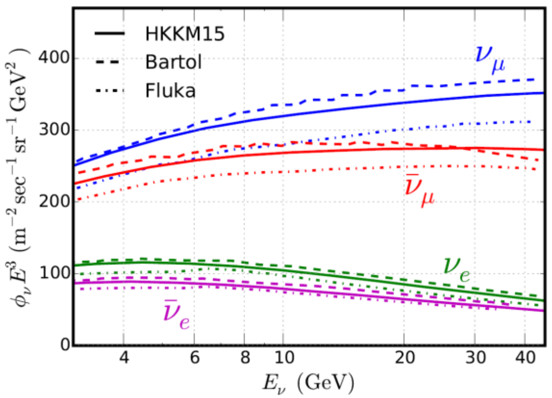
Misreconstructed background added
Event classification (16 event classes!)
Direction and energy resolutions (for each class)

Sensitivity Calculation

Pseudo-experiment based log-likelihood ratio
Simplified (Asimov sets)

Neutrino physics/Event rates

Fluxes (Bartol)



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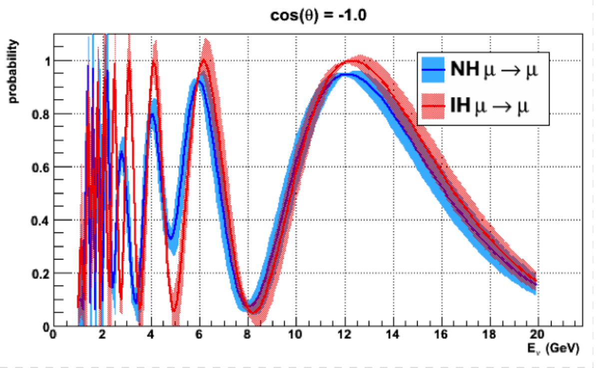
Oscillation probabilities



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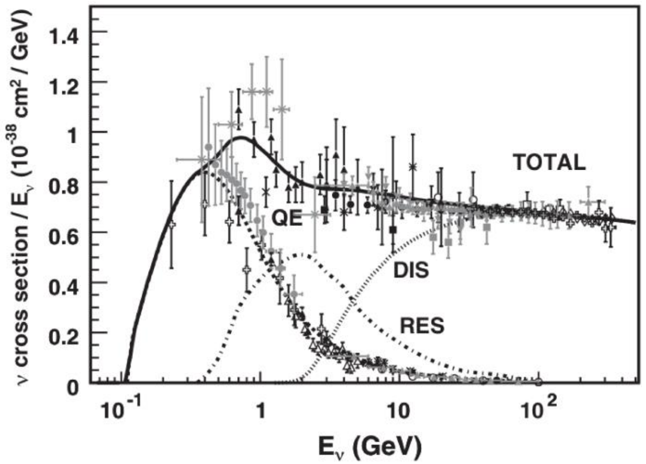
Cross-sections (GENIE)



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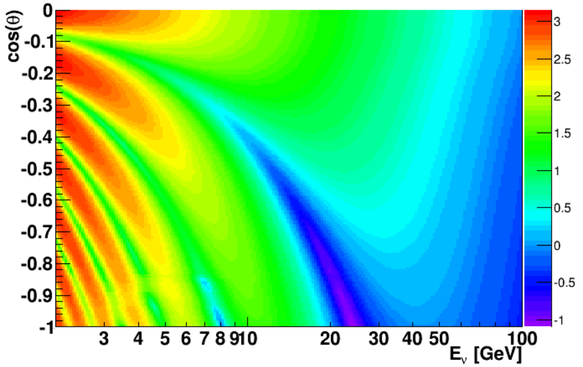
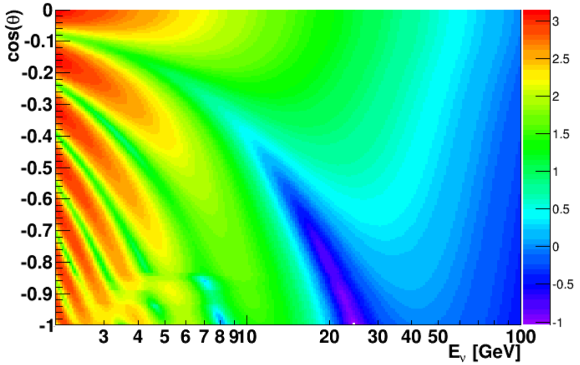
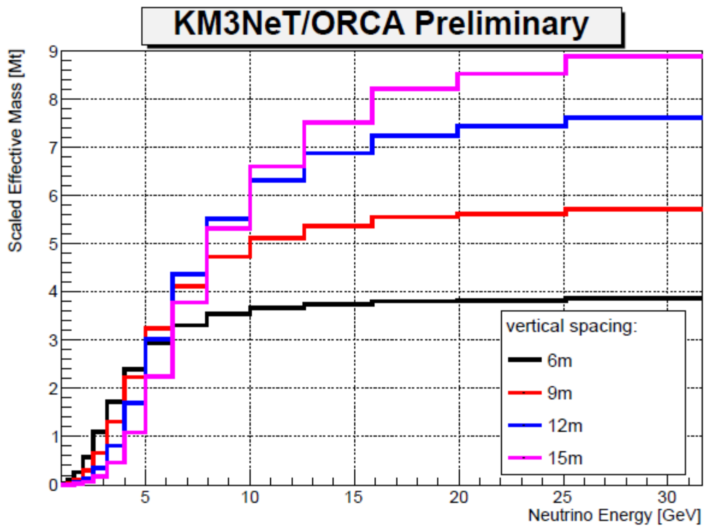
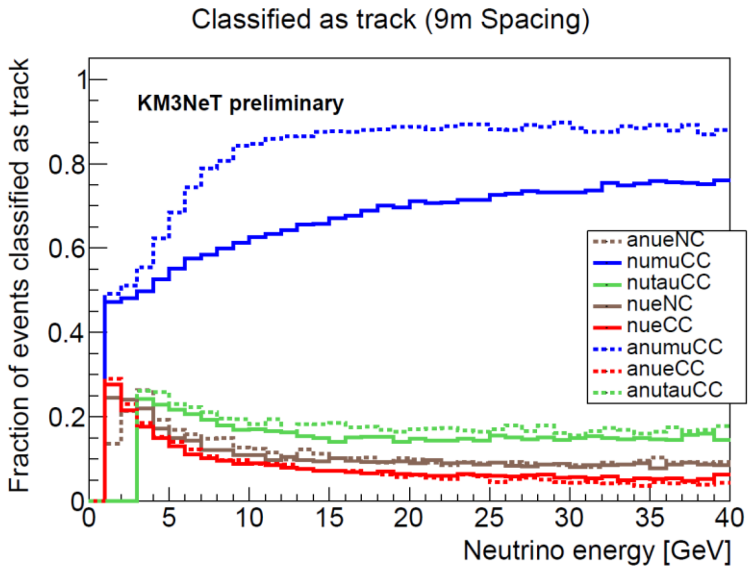
Predicted event rates

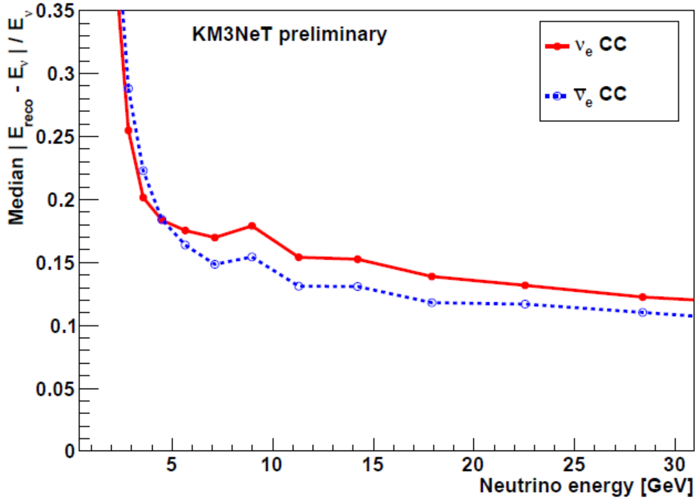




Detector response







Calculate event rates as function of zenith and energy from fluxes using effective masses for different neutrino types (shown ν_μ)

Add misreconstructed atmospheric muons

Determine as what type of events are reconstructed
(How many of each class)
e.g.

- ν_μ interaction identified as track
- $\bar{\nu}_e$ interaction identified as shower
- ν_e misidentified as track
- … (16 types)

Apply type dependent zenith angle and energy smearing with response matrices (dependent on type, so, 16x)
This results in 2 histograms :
Showers
Tracks

Sensitivity calculation

The procedure to calculate the sensitivity summarised:

1. Pick a set of *true* parameters
   - Oscillation parameters, *including hierarchy (normal or inverted)*
   - Systematics
2. Calculate the expected number of detected events (vs. zenith and energy)
   - See previous slides
   - 2 histograms
3. Generate pseudo-data by drawing from a Poissonian distribution with means given in step 2 or each bin of the rate histograms
4. Perform two maximum likelihood fits, imposing normal hierarchy and inverted hierarchy
   - Obtain LNH and LIH, the maximum likelihood values for both assumptions
5. Calculate the log-likelihood ratio of these values
   - This is the discriminating value

Sensitivity calculation: Likelihood

The likelihood is given by $\mathcal{L} = \prod_{i \in bins} \mathcal{P}(N_i|\mu_i)$ where the product is over all bins (zenith, angle) of the pseudo-data

where a Poisson probability is assigned to each bin $\mathcal{P}(n|\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$

The discriminating quantity, the log-likelihood ratio (LLR) is the log of the ratio of the best fit likelihoods imposing normal hierarchy and inverted hierarchy

$$LLR \coloneqq log\left(\frac{\mathcal{L}^{bestfit,NH}}{\mathcal{L}^{bestfit,IH}}\right)$$

This is done for every pseudo-experiment, thus creating a distribution for each hierarchy (two, thus).

Fit & Parameters

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

- Oscillation parameters
- Hierarchy (NH or IH) assigned

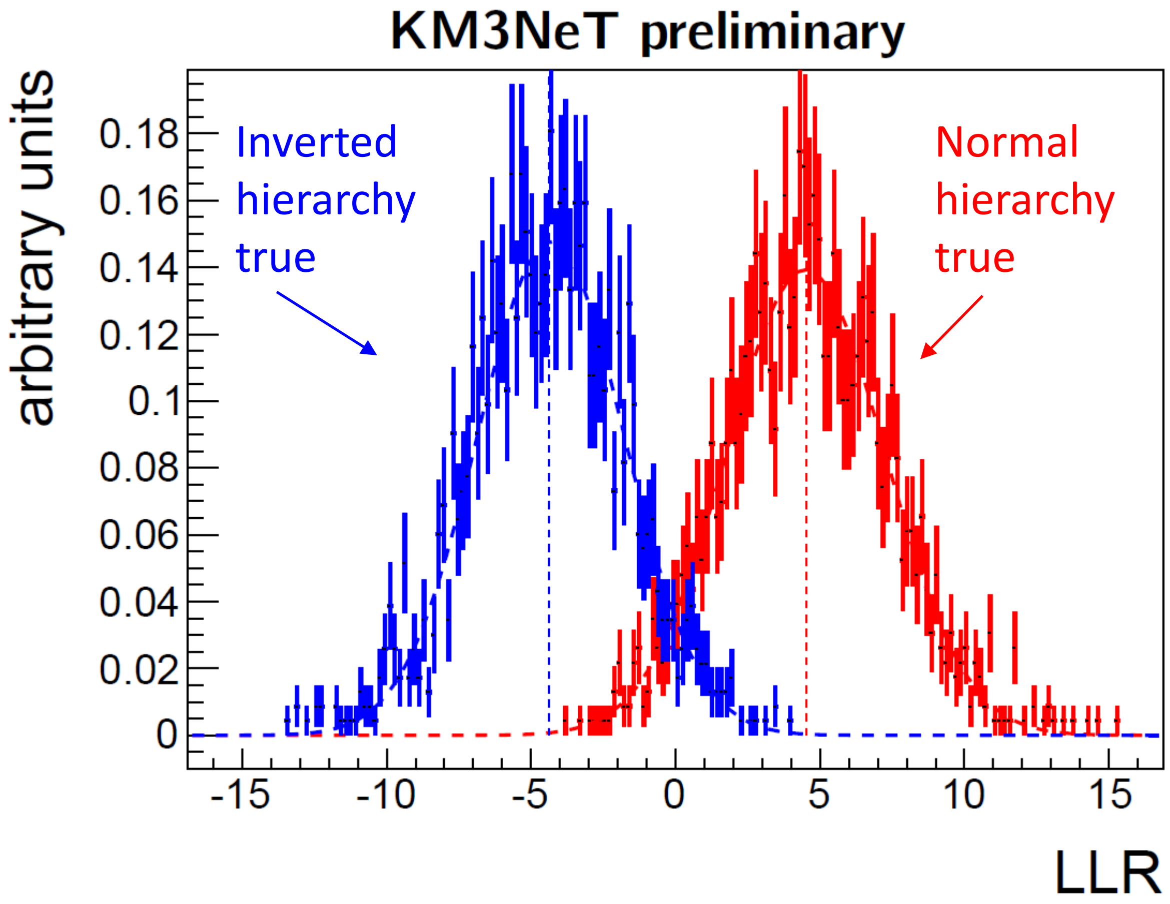
Systematics fitted with priors

Nuisance parameters:
Constrained by external measurements
Randomly assigned a ‘ best-fit’ value to each pseudo-experiment

Priors
Multiply likelihood with Gaussian probability

Θ_{23} octant uncertainty:
Start the fit multiple times with different values, spread over octants and take best likelihood

Figure of Merit



Log-Likelihood ratio distributions from pseudo-experiments

Median significance

`The significance with which the wrong hierarchy can be excluded at the median of the true hierarchy`

$$S := \frac{\mu_{NH} - \mu_{IH}}{\sigma_{IH}}$$

LLR distributions are very well described by Gaussians (mean μ, width σ)

Alternative hypotheses

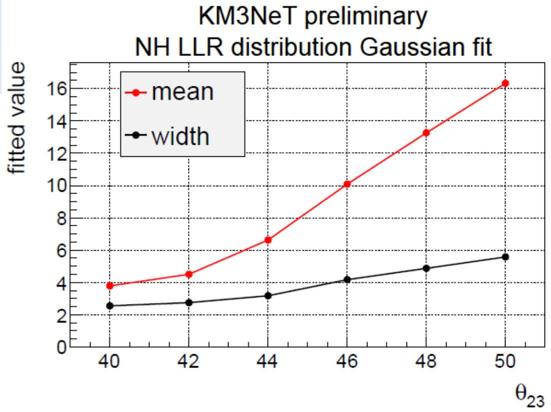
NH and IH pseudo-experiments are generated from same true parameters
This is ok for most parameters

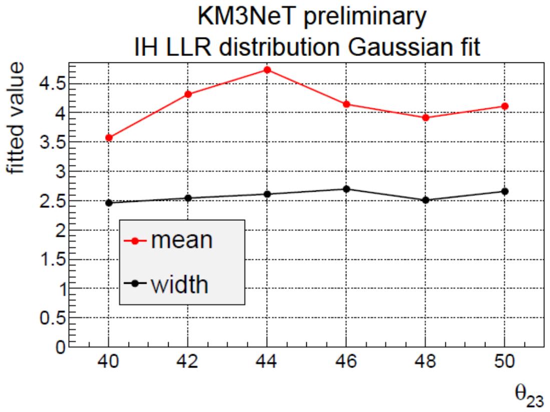
However, the best fit value Θ_{23} depends strongly on hierarchy

NH and IH hypotheses with different Θ_{23} and LLR distributions need to be distinguished

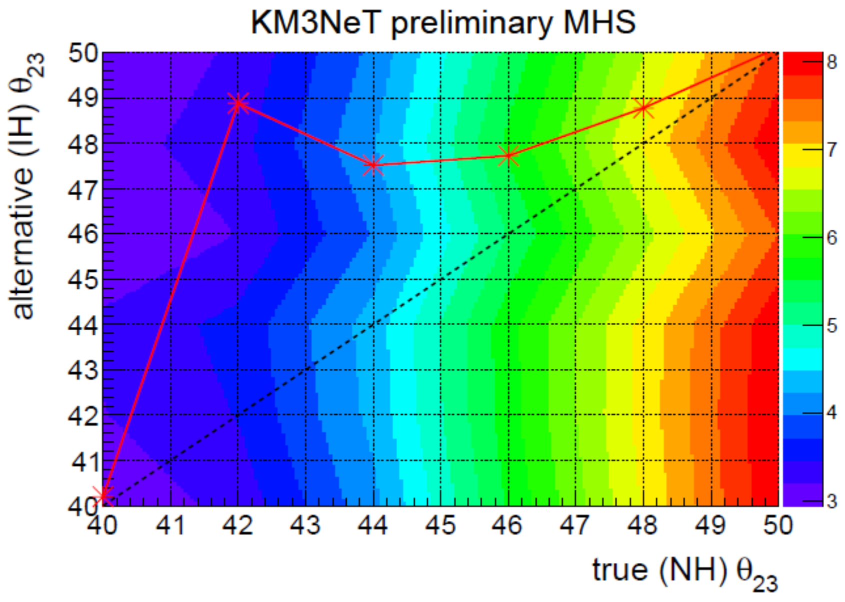
Approach :

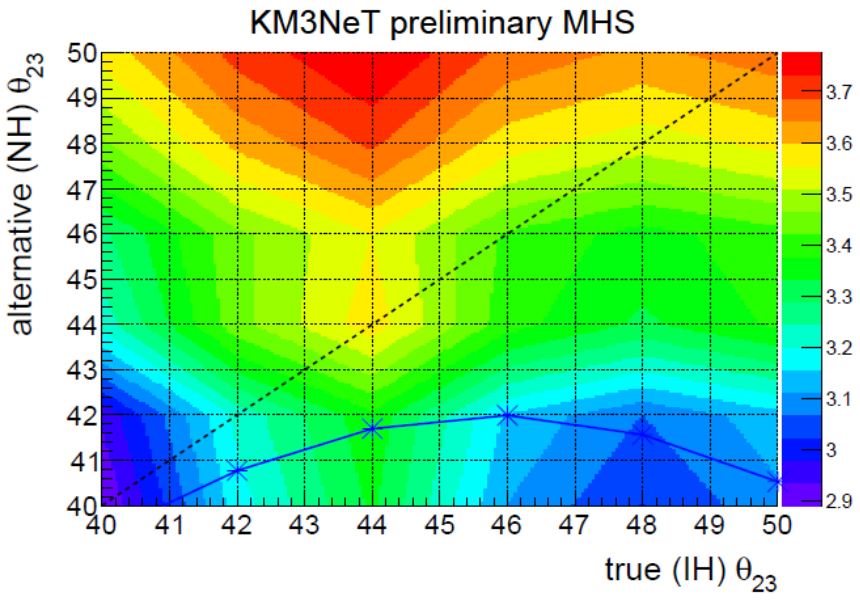
- Parameterize the Gaussian LLR distributions
- Determine for each true hierarchy Θ_{23} the most likely 'wrong' hierarchy Θ_{23}
- Use these to calculate significance





Alternative hypotheses





Colour:
Exclusion significance
(in standard deviations)

Diagonal line: $\Theta_{23}^{true} = \Theta_{23}^{alternative}$

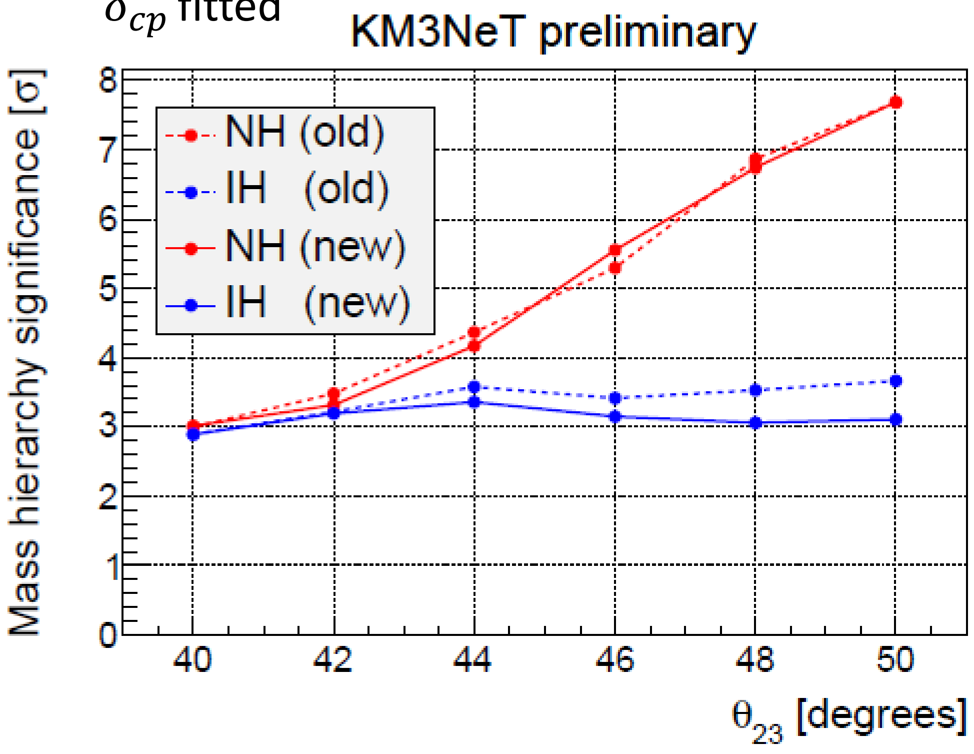
Coloured line: Most likely alternative Θ_{23} *for given true* Θ_{23}

Median significance : $$S := \frac{|\mu_{true} - \mu_{alt}|}{\sigma_{alt}}$$

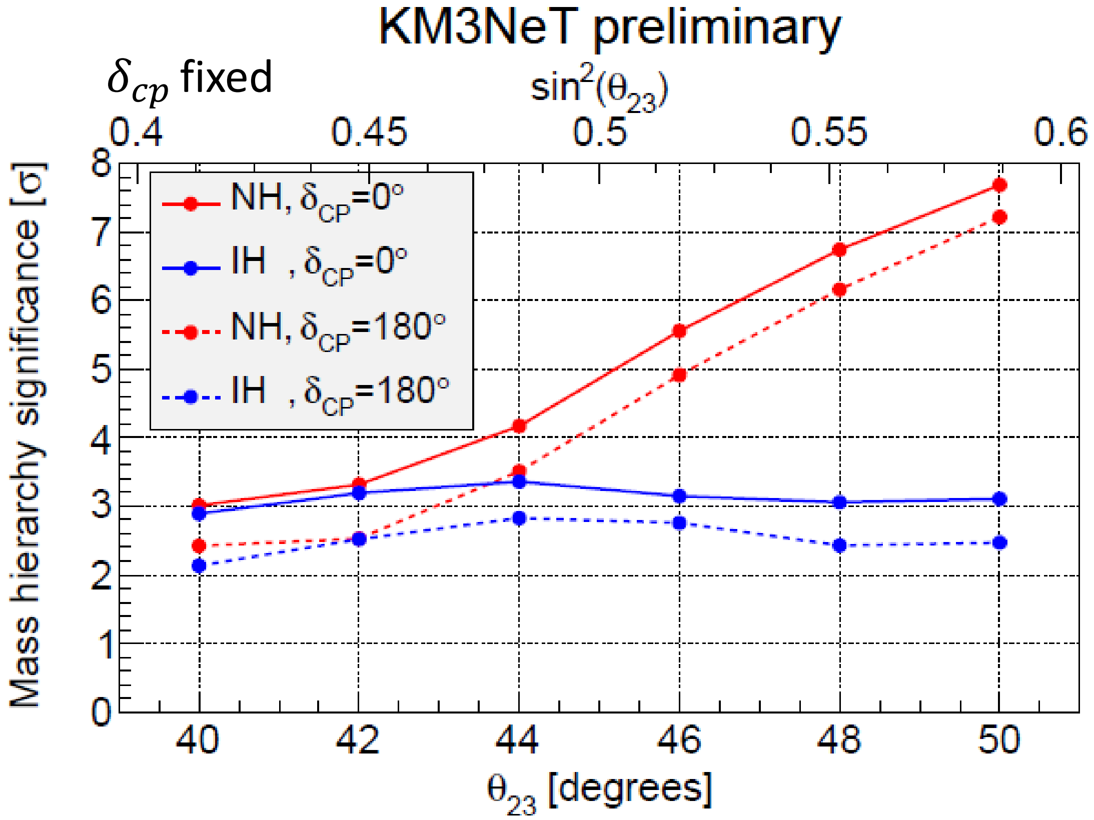
Results

Sensitivity after 3 years, 9m vertical spacing

δ_{cp} fitted



δ_{cp} fixed



Dashed: old treatment of alternative hypothesis
Solid: new treatment of alternative hypothesis

Simplified approach

The pseudo-experiment+LLR method is most detailed, but for detector optimization and specific questions, a quicker method is used.

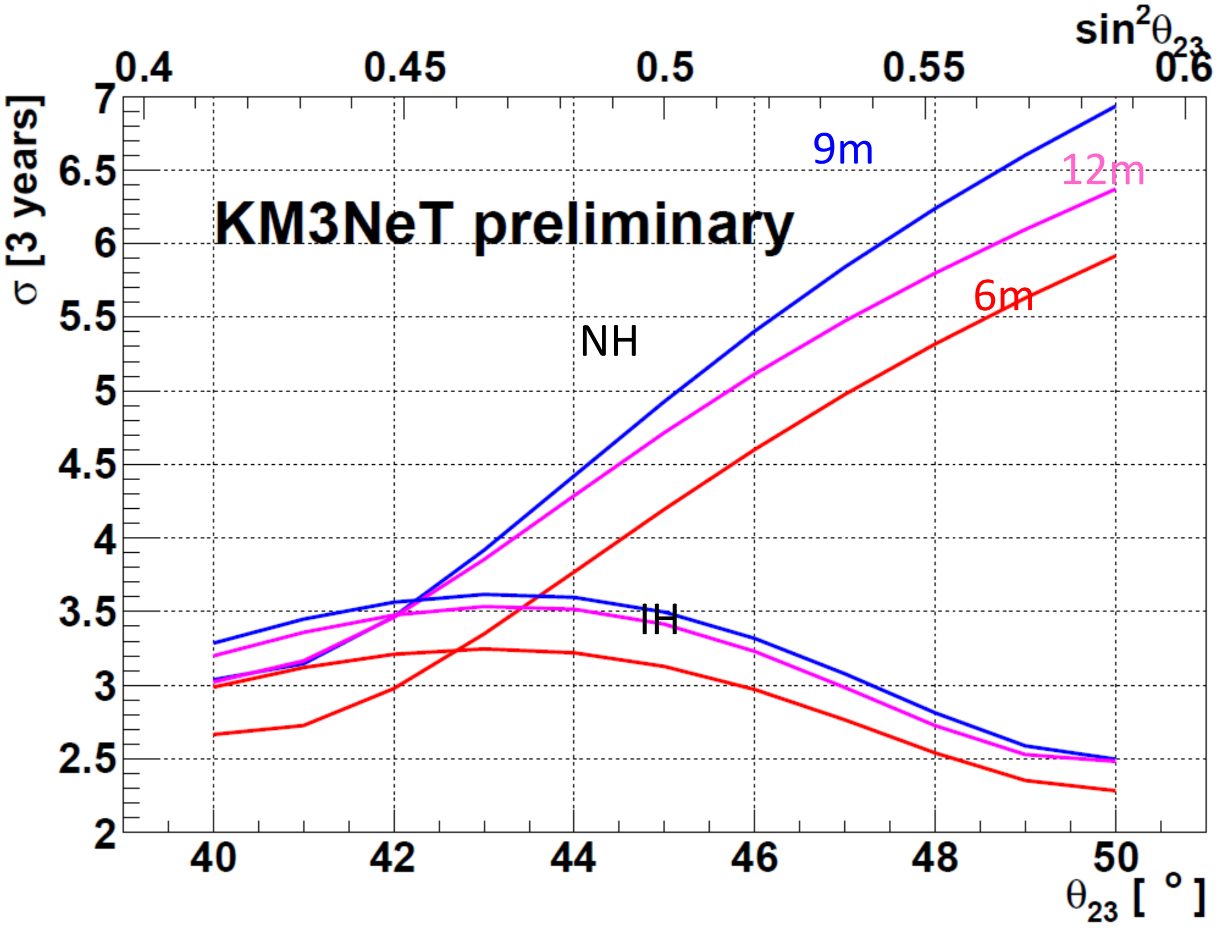
<u>Simplified approach</u> *'Asimov sets'* :

- Generate two sets of histograms (track and showers) for chosen true (TH) hierarchy
- Perform χ^2 minimization with 'wrong' hierarchy (WR)
  - $\chi^2_{min} = \sum_i \frac{\left(\mu_i^{TH} - \mu_i^{WH\,Fit}\right)^2}{\mu_i^{TH}}$
  - Same parameters as before, but:
    - Θ_{12}, Θ_{13} and Δm^2 fixed to true values
    - All other (8) parameters fitted <u>unconstrained</u> (no priors)
- Significance can be expressed as $\sigma = \sqrt{\chi^2_{min}}$

Results of this method are close to full LLR method

Scatter of parameters that have prior in LLR treatment agrees.

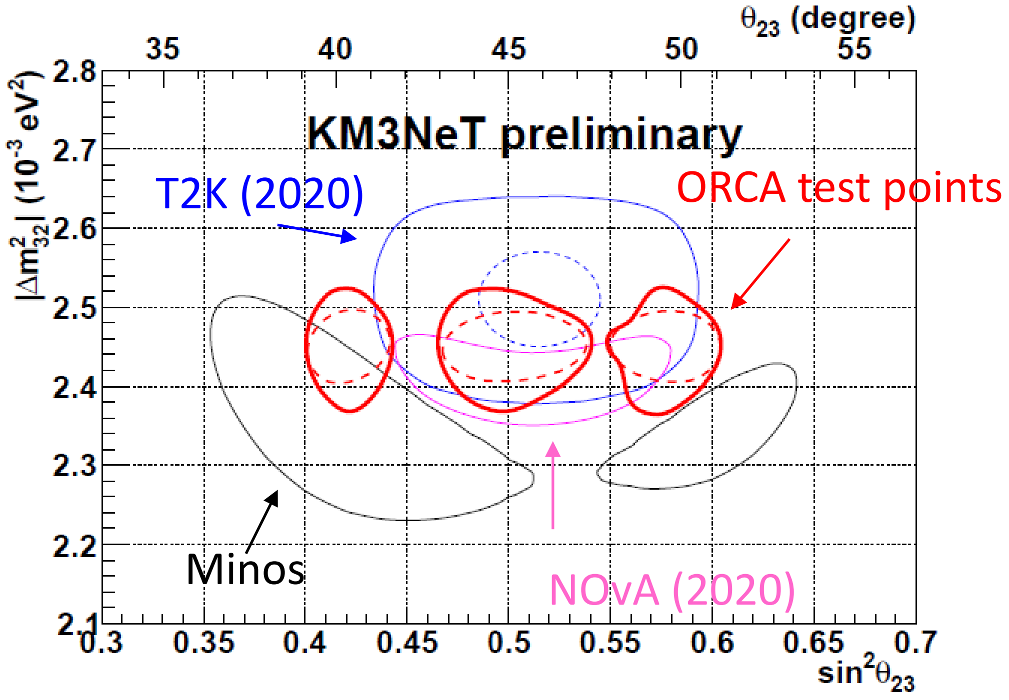
Simplified method – Detector geometry



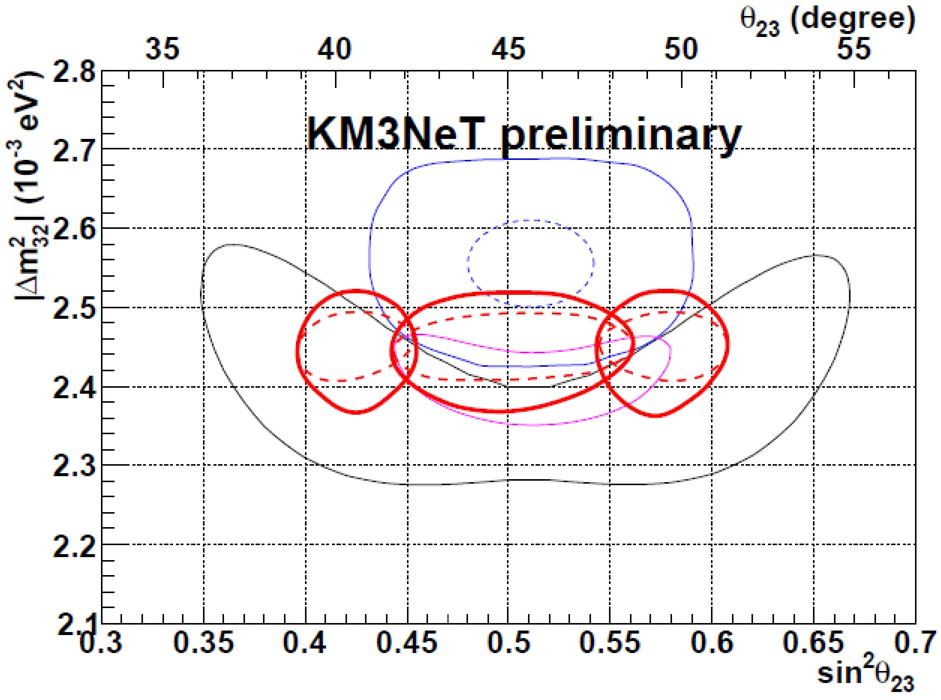
Mass hierarchy significance after 3 years
for different vertical spacings

Simplified method - $|\Delta m^2_{23}|$ and $\sin^2(\Theta_{23})$

Normal Hierarchy



Inverted Hierarchy



3 years, 1 sigma contours

Summary

- KM3NeT ORCA aims at determining the neutrino mass hierarchy
- The detector is under construction
- Extensive sensitivity study has been performed
  - Pseudo-experiment based Log-likelihood ratio
  - Strong correlation between Θ_{23} and mass hierarchy
  - Simplified Asimov set based method yields similar results
  - Including detector geometry optimization
- Promising prospects for mass hierarchy determination