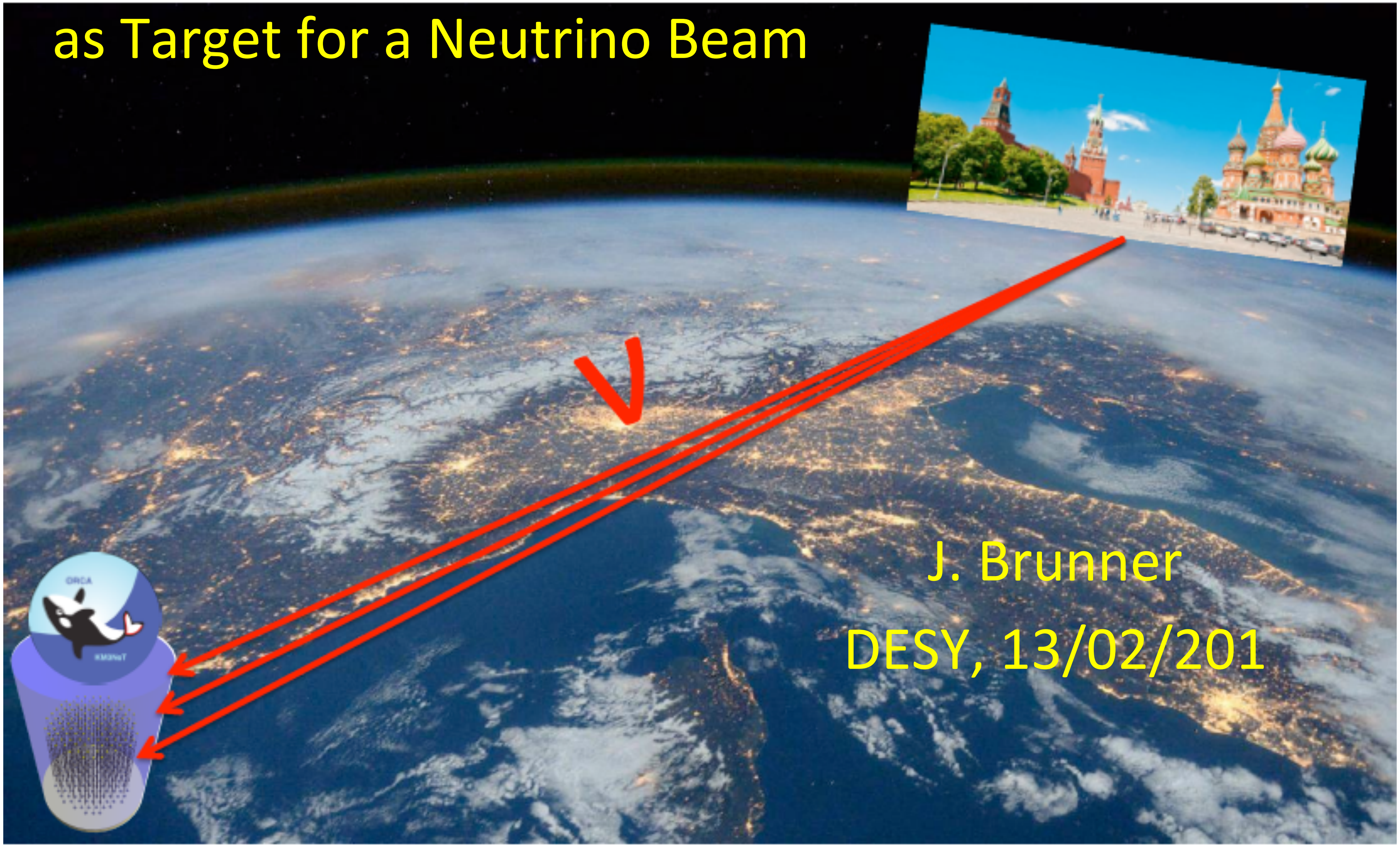
A Neutrino Detector in the Mediterranean Sea as Target for a Neutrino Beam



J. Brunner

DESY, 13/02/201

A Neutrino Detector in the Mediterranean Sea as Target for a Neutrino Beam

- Neutrino Oscillations
- The KM3NeT/ORCA Project
- Recent ORCA News
- Long-baseline Landscape
- P2O Project

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Neutrino Oscillations

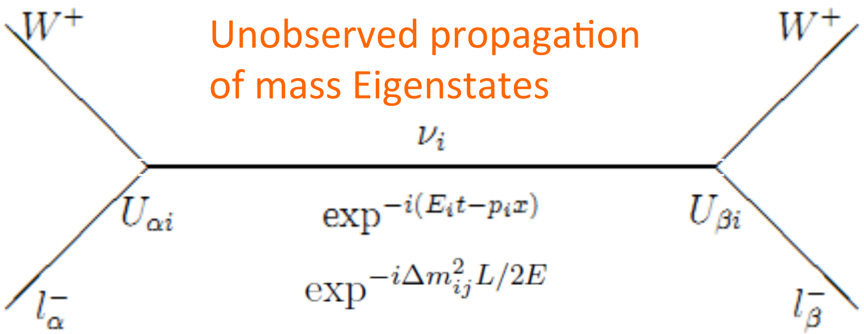
- Weak Eigenstates are superposition of mass Eigenstates

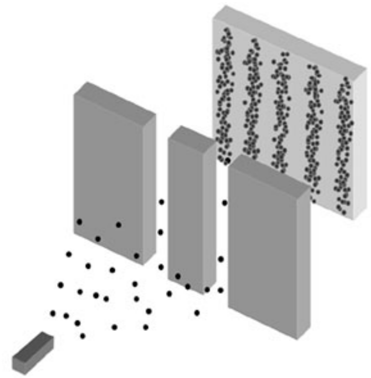
$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Neutrino production via CC interaction

Neutrino detection via CC interaction

Equivalence to double slit experience





Neutrino flavour defined via charged leptons

Coherent sum

$$P(\alpha \to \beta) = |\sum_i U_{\beta i} \, \exp^{-i(E_i t - \vec{p_i}\vec{x})} \, U^*_{\alpha i}|^2.$$

Classic: incoherent sum

$$P(\alpha \to \beta) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Neutrino mixing and oscillations

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

$$\underset{\text{weak eigenstates}}{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\underset{\text{mass eigenstates}}{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}$$

3 mixing angles + 1 phase

$$(c_{ij} \equiv \cos\theta_{ij}, \qquad s_{ij} \equiv \sin\theta_{ij})$$

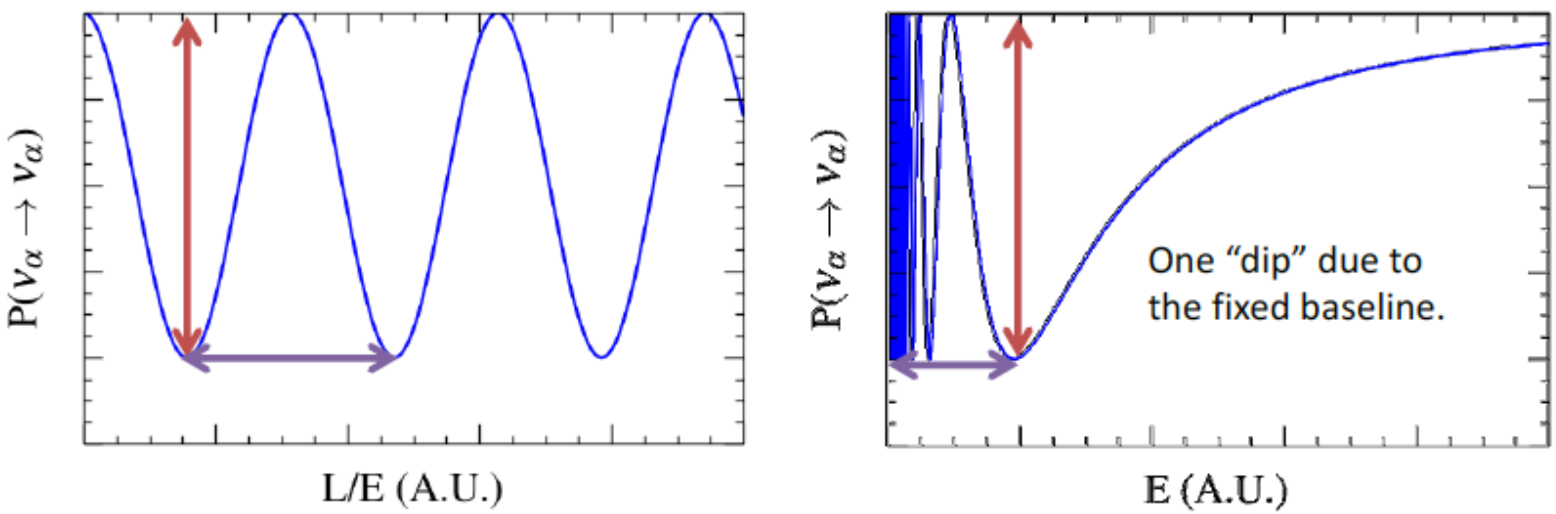
$$U = \underset{\text{Solar}}{\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}}\underset{\text{Atmospheric Reactor}}{\begin{pmatrix} c_{13} & & s_{13}\cdot e^{i\delta}\\ & 1 & \\ -s_{13}\cdot e^{i\delta} & & c_{13}\end{pmatrix}}\underset{\text{Atmospheric}}{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}}\underset{\text{Majorana Phases}}{\begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta}\end{pmatrix}}$$

Oscillation experiments

- Disappearance

Sub-dominant term due to small θ_{13}

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \boxed{\sin^2(2\theta_{23})} \right) \sin^2\left(\frac{\boxed{\Delta m^2} L}{4E} \right)$$



Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

Oscillation experiments

- Appearance

$$P\left(\nu_\mu \to \nu_e\right) \approx \left|\sqrt{P_{\text{atm}}} e^{-e(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}}\right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}}\,(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP})$$

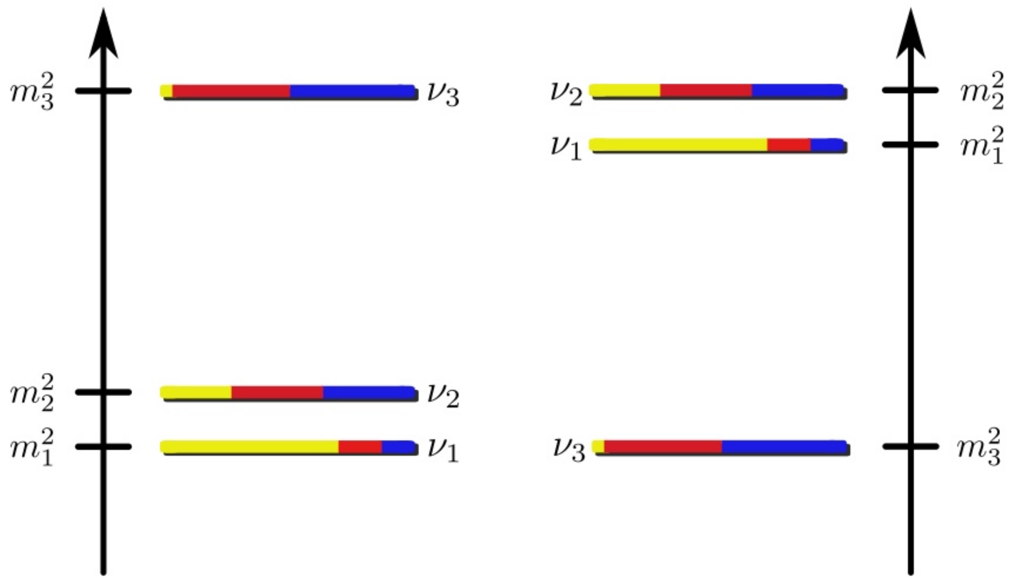
$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

- $\nu_\mu \to \nu_e$ depends on:
  - CP phase: δ_{CP}
  - Mass hierarchy and matter effects
  - Atmospheric parameters: $\sin^2(\theta_{23})$, $\Delta m^2{}_{32}$
  - The smallest mixing angle: θ_{13}

Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

Possible mass pattern

- Naming/Color convention
  - Index 1, 2, 3 : increasing contribution of electron state
  - Electron Muon Tau
- Matter effect in sun fixes $m_2 > m_1$
- No matter effects to measure Δm_{31}^2 → sign unconstraint
- 2 schemes survive



Current Status

NuFIT 3.1 (2017)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.50$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$ 4%	$0.272 \to 0.347$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.347$	$0.272 \to 0.347$
$\theta_{12}/^\circ$	$33.63^{+0.78}_{-0.75}$ 2%	$31.44 \to 36.07$	$33.63^{+0.78}_{-0.75}$	$31.44 \to 36.07$	$31.44 \to 36.07$
$\sin^2\theta_{23}$	$0.565^{+0.025}_{-0.120}$ 21%	$0.401 \to 0.628$	$0.572^{+0.021}_{-0.028}$	$0.419 \to 0.628$	$0.401 \to 0.628$
$\theta_{23}/^\circ$	$48.7^{+1.4}_{-6.9}$ 14%	$39.3 \to 52.4$	$49.1^{+1.2}_{-1.6}$	$40.3 \to 52.4$	$39.3 \to 52.4$
$\sin^2\theta_{13}$	$0.02195^{+0.00075}_{-0.00074}$ 3.4%	$0.01971 \to 0.02434$	$0.02212^{+0.00074}_{-0.00073}$	$0.01990 \to 0.02437$	$0.01971 \to 0.02434$
$\theta_{13}/^\circ$	$8.52^{+0.15}_{-0.15}$ 1.7%	$8.07 \to 8.98$	$8.55^{+0.14}_{-0.14}$	$8.11 \to 8.98$	$8.07 \to 8.98$
$\delta_{CP}/^\circ$	228^{+51}_{-33}	$128 \to 390$	281^{+30}_{-33}	$182 \to 367$	$128 \to 390$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$ 3%	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.035}_{-0.035}$ 1.4%	$+2.408 \to +2.621$	$-2.483^{+0.034}_{-0.035}$	$-2.589 \to -2.379$	$\begin{bmatrix} +2.408 \to +2.621 \\ -2.580 \to -2.389 \end{bmatrix}$

Open Questions

- Neutrino Oscillation Experiments
  - Is CP violated in the lepton sector : δ_{CP} ?
  - Normal / inverted mass hierarchy ?
  - Is θ_{23} maximal ? If not : which octant ?
- Double Beta Decays
  - Neutrinos : Dirac / Majorana particles ?
- Beta Decays / Cosmology
  - Absolute Neutrino mass scale ?

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- Neutrino Oscillations
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KM3NeT

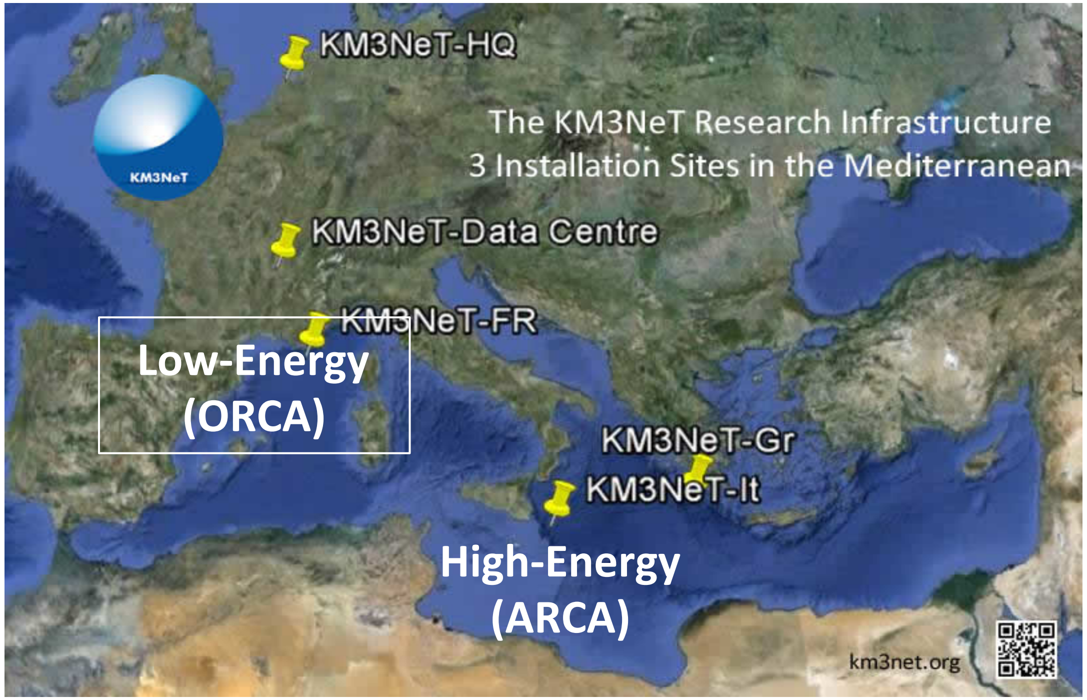
KM3NeT is a research infrastructure with 2 main physics topics:

- The origin of cosmic neutrinos (high energy)
- Measurement of fundamental neutrino properties (low energy)
- Deep Sea Observatory (Oceanography, bioacoustics, bioluminescence, seismology)

Single Collaboration

Single Technology

Single Management

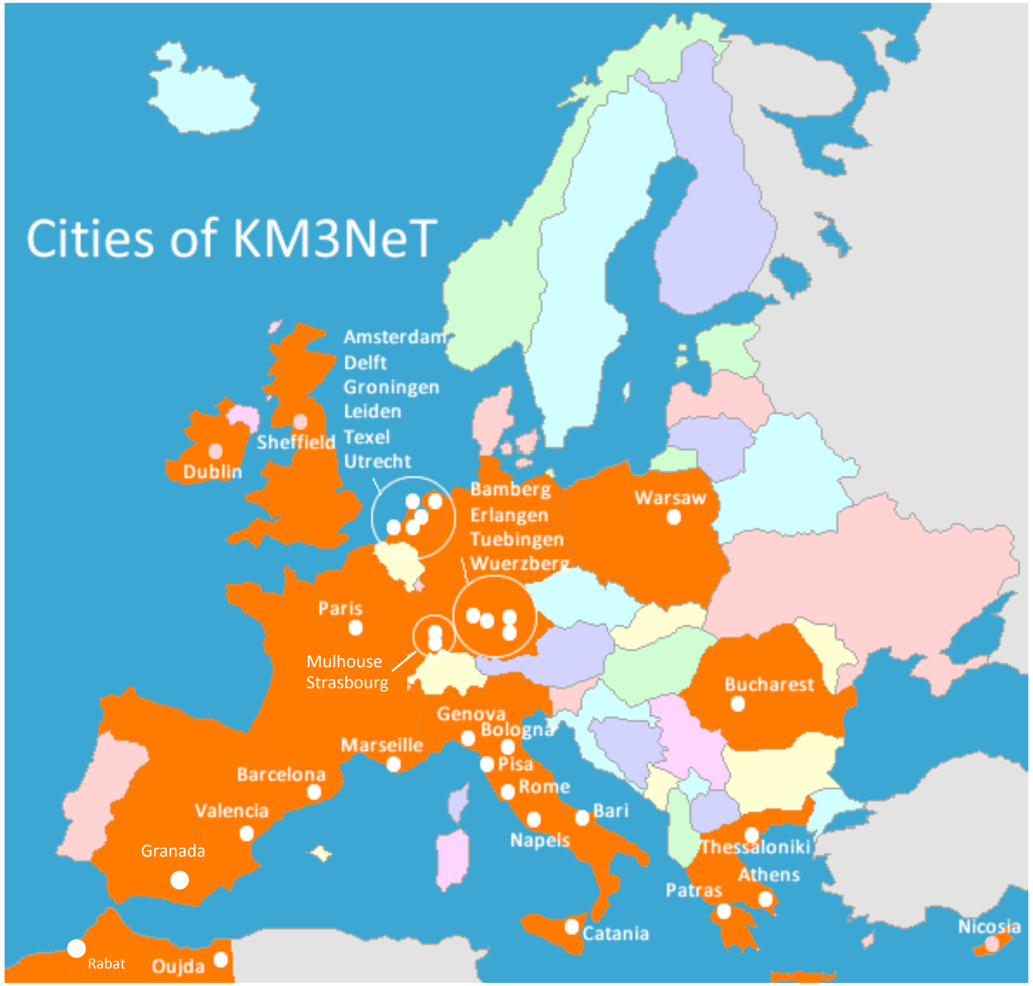


ARCA- Astroparticle Research with Cosmics in the Abyss

ORCA- Oscillation Research with Cosmics in the Abyss

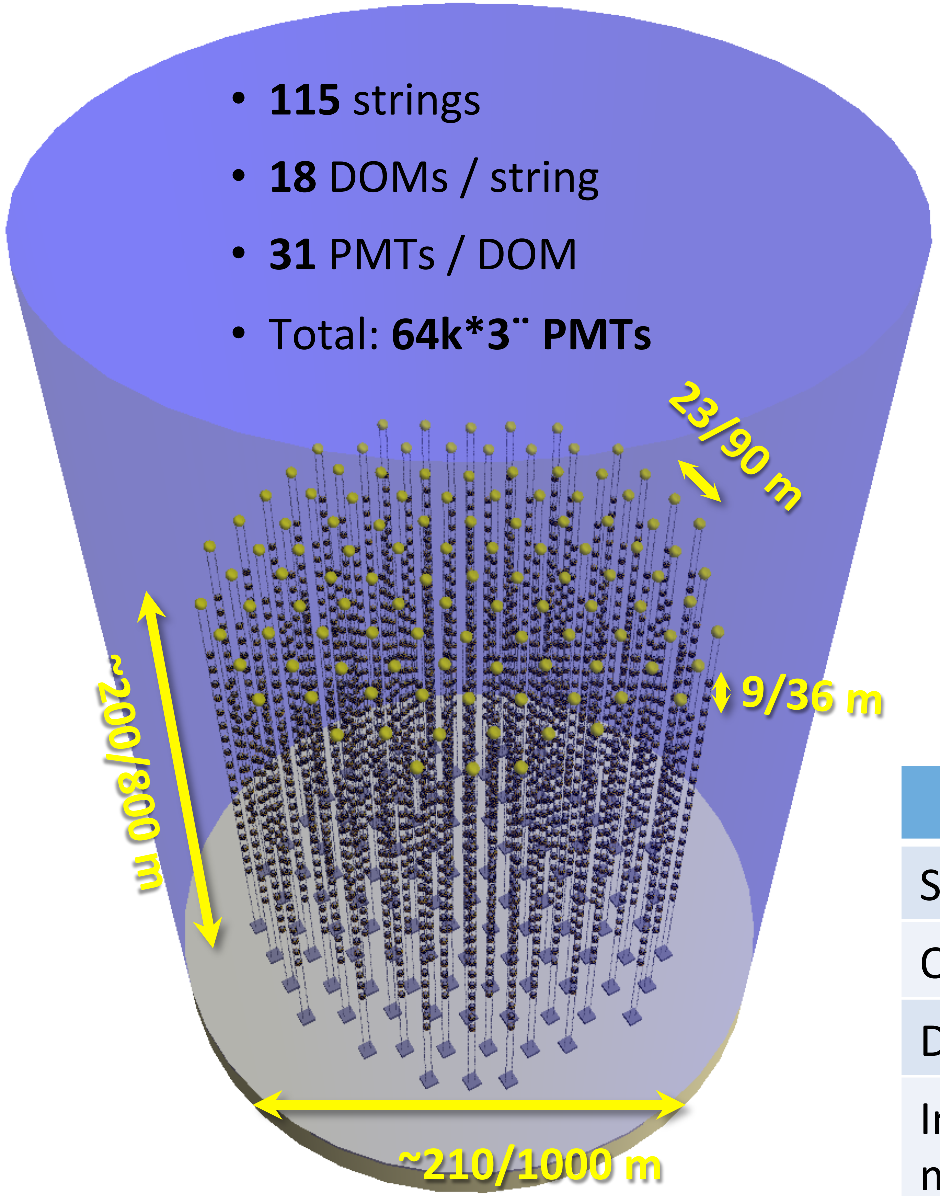
KM3NeT Collaboration

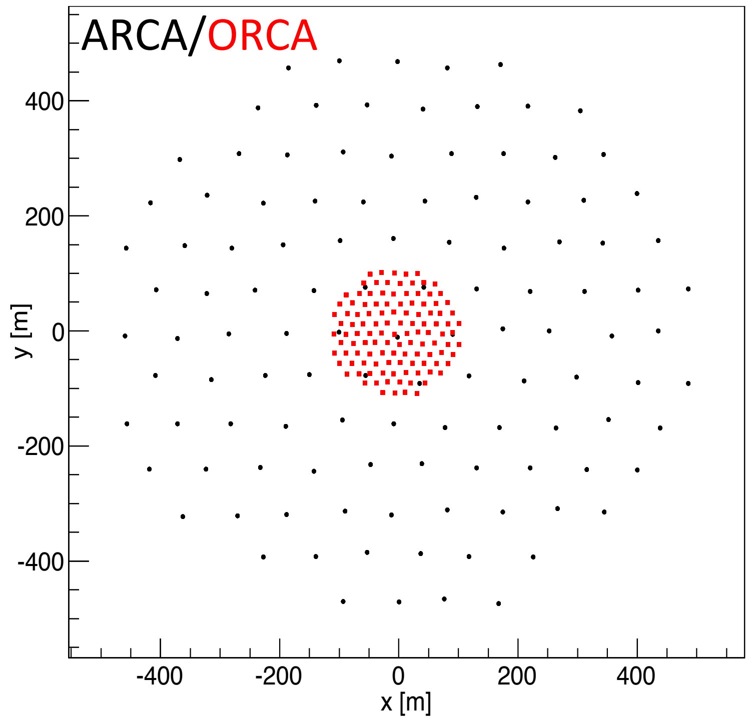
12 Countries
>40 Institutes
>220 Scientists



KM3NeT LoI , arXiv:1601.07459 [astro-ph.IM]
Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016

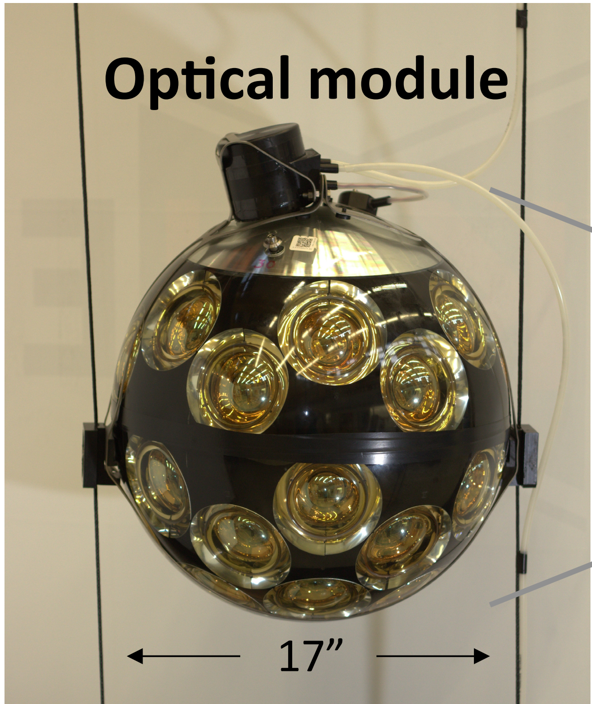
KM3NeT Building Block



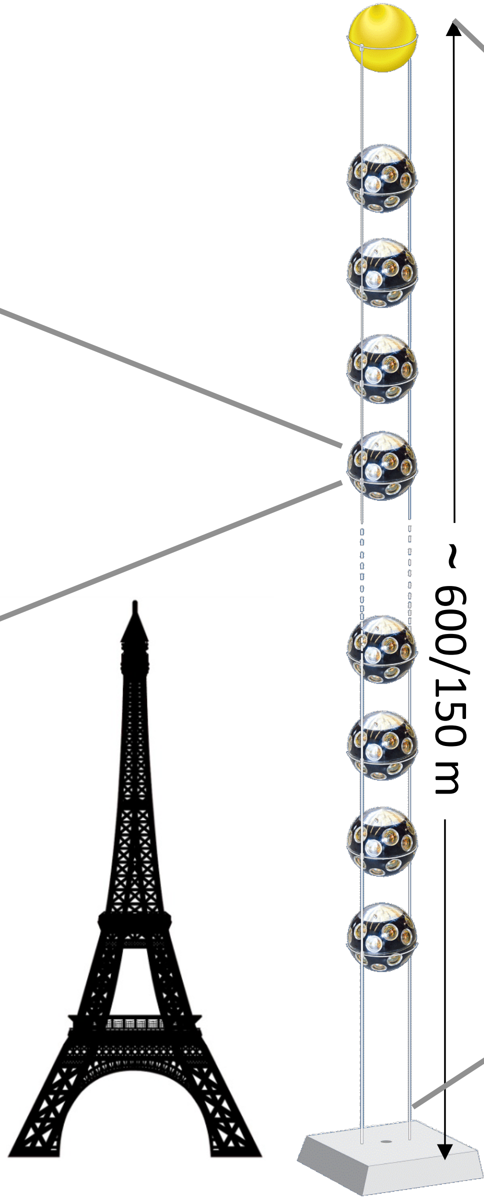


	ORCA	ARCA
String spacing	23 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	8 Mton	0.6*2 Gton

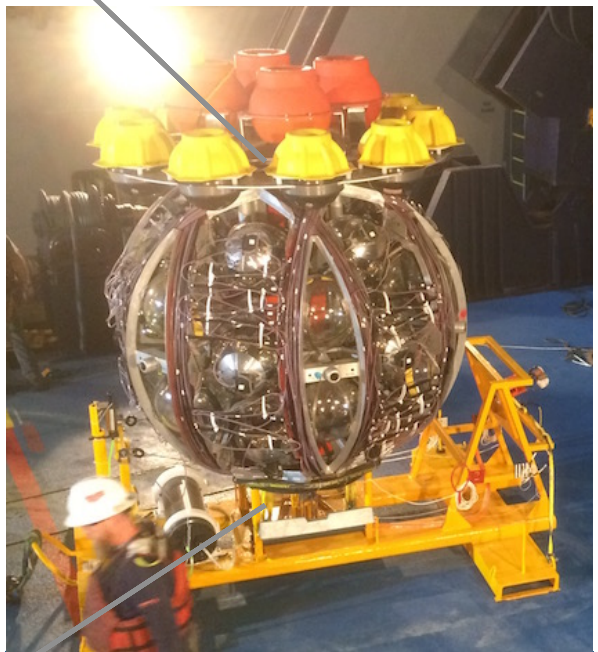
KM3NeT Technology



31 x 3” PMTs
PMT HV
LED & piezo inside
FPGA readout
Photon counting
Directional information



Launcher vehicle

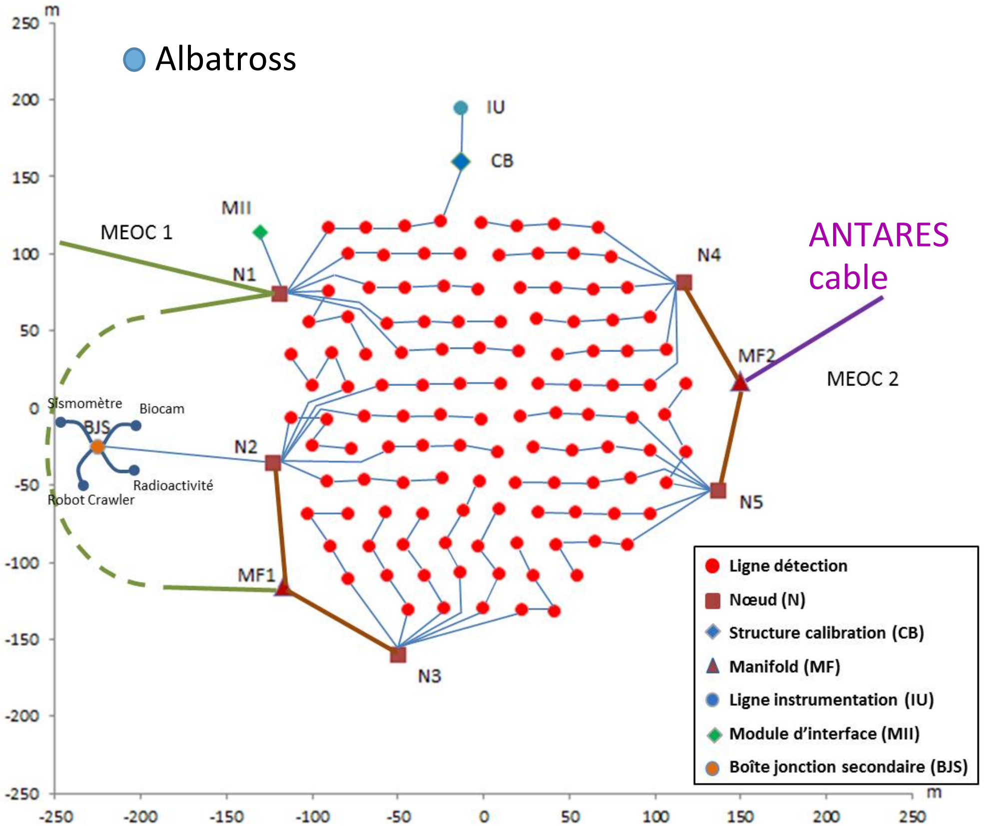


rapid deployment
autonomous unfurling
recoverable

ORCA Status

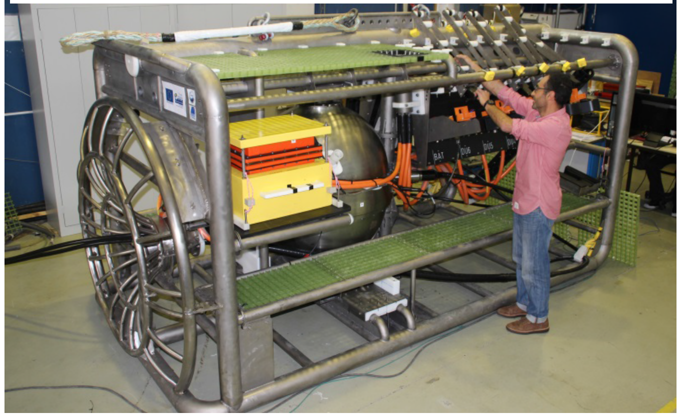
Phase 1: 7 string array at KM3NeT-France site to demonstrate technology/detection methods in the GeV range

Phase 2: Deploy 1 building block (115 strings)

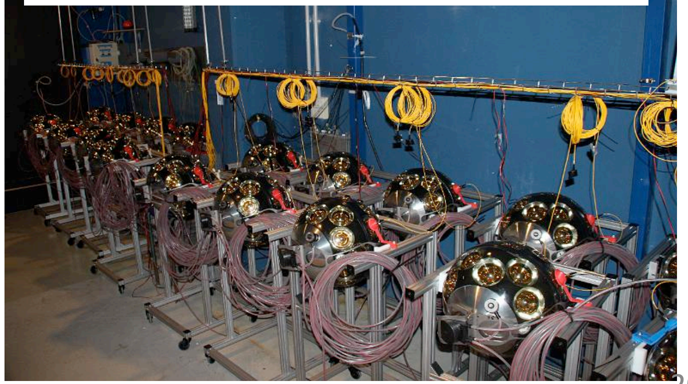


Main Cable, 2015

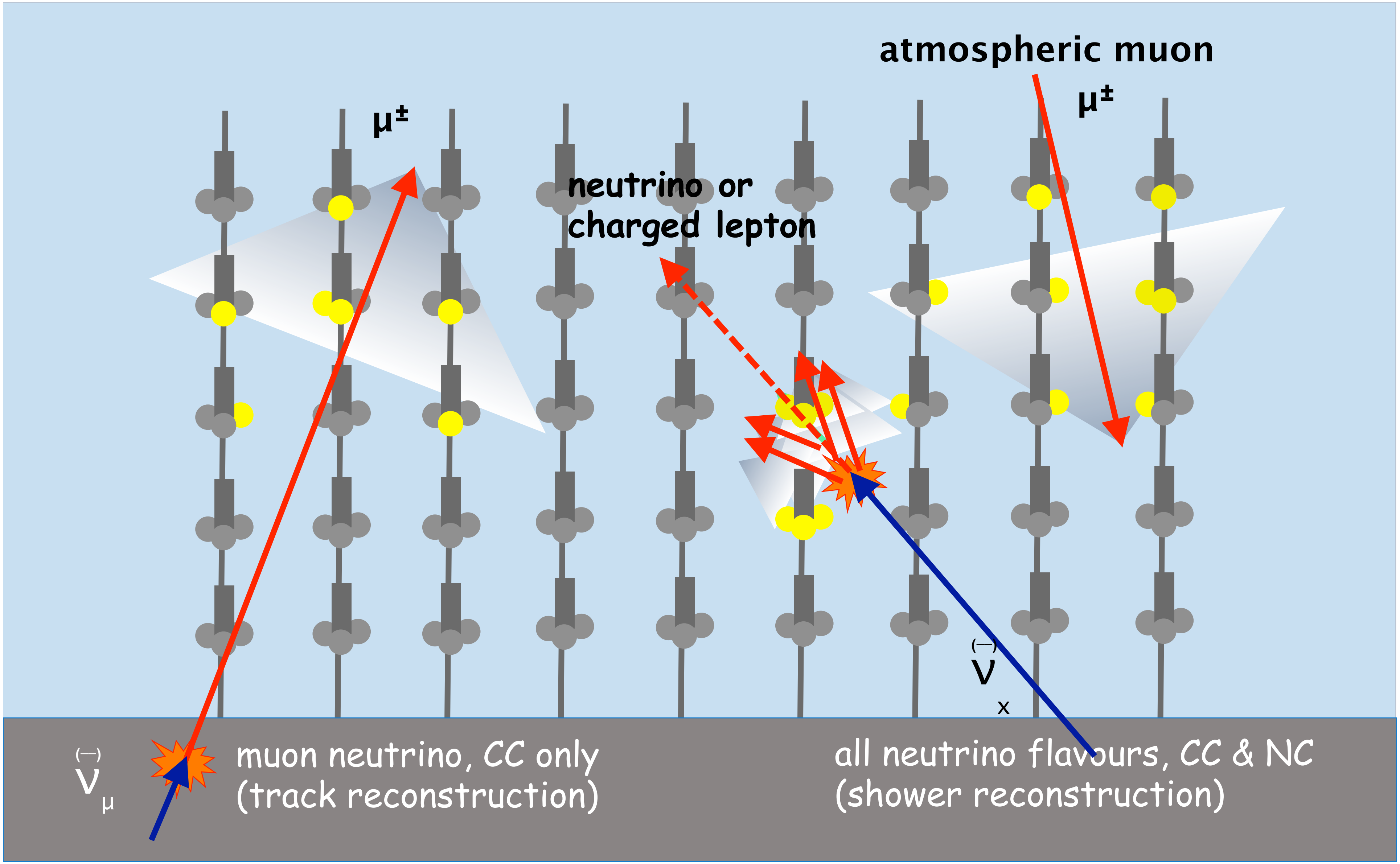
Junction Box, Sept 2016



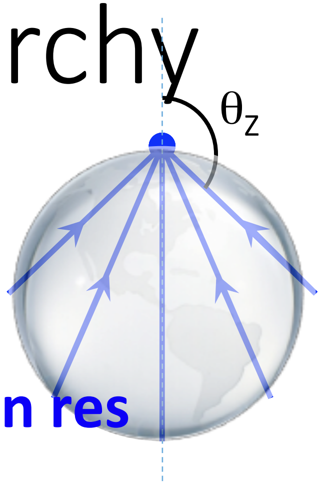
First ORCA string: Sep 2017



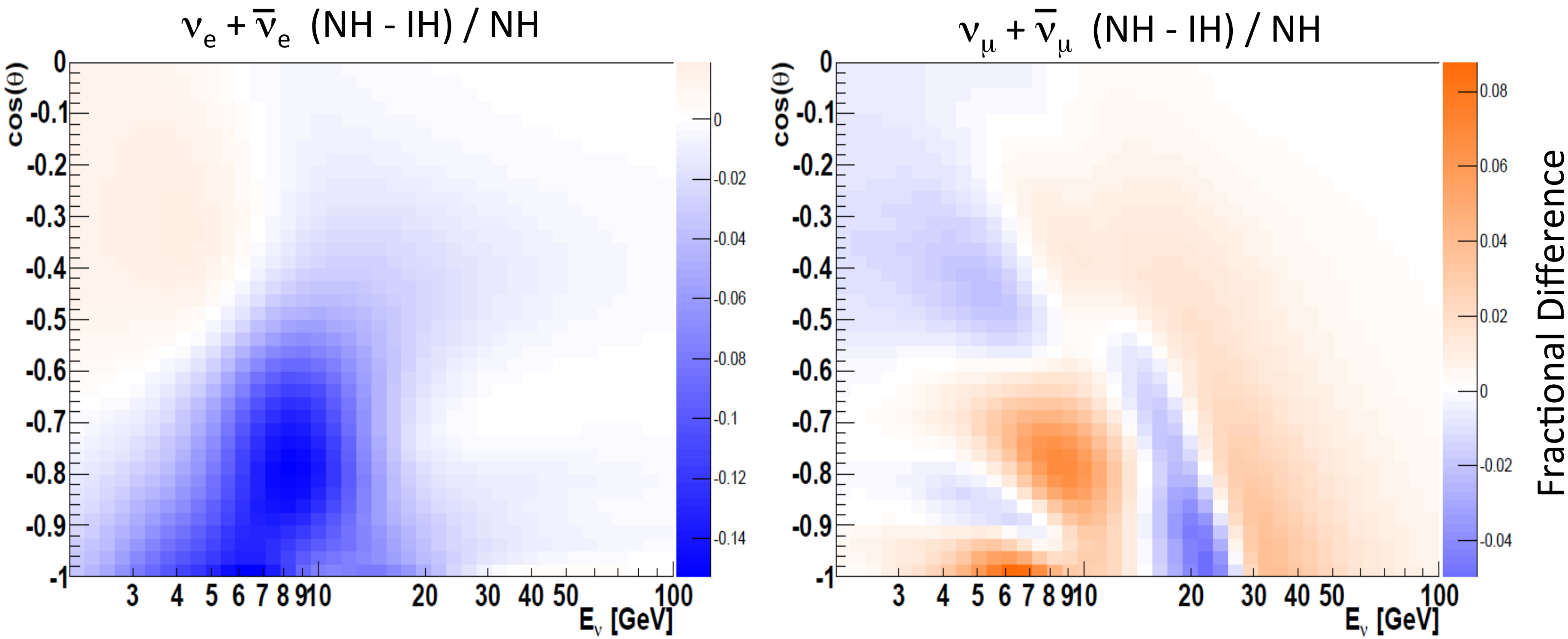
Neutrino Signatures



Measuring NeutrinoMassHierarchy

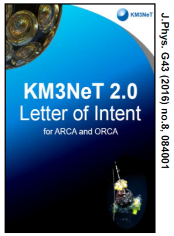


- Measure neutrino direction and energy
- Search for **oscillation patterns** from **matter effects**
- Requires **large statistics** and good **energy and direction res**



E_{resol} = 25% $\theta_{resol} = (m_p/E)^{1/2}$

LoI: ORCA Oscillations

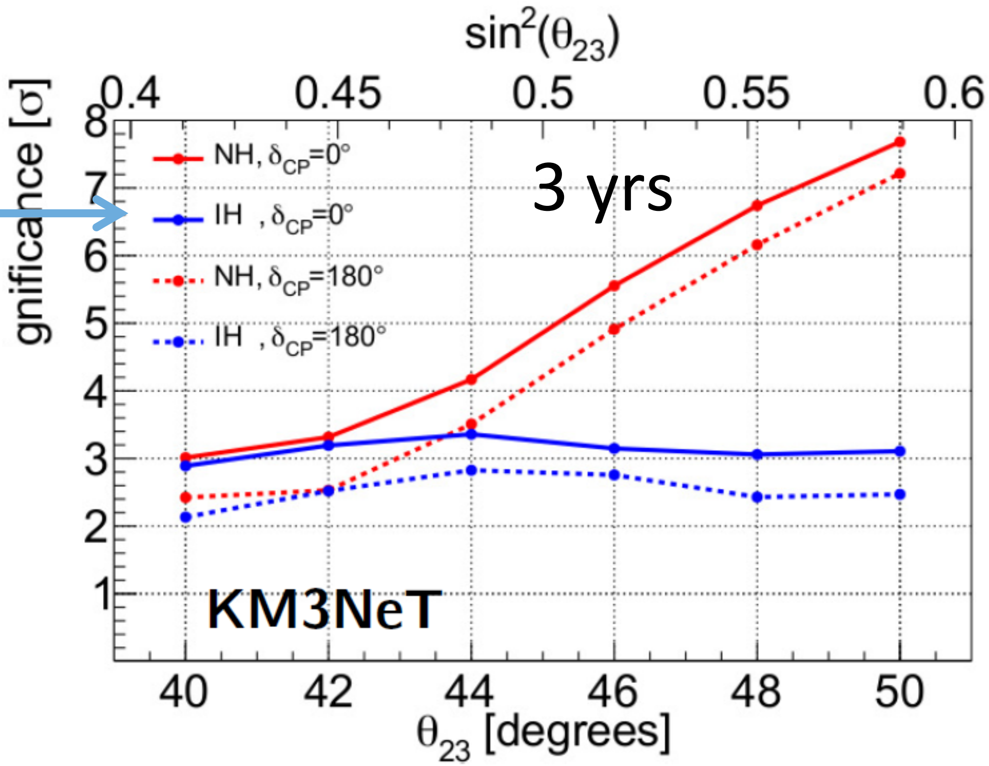


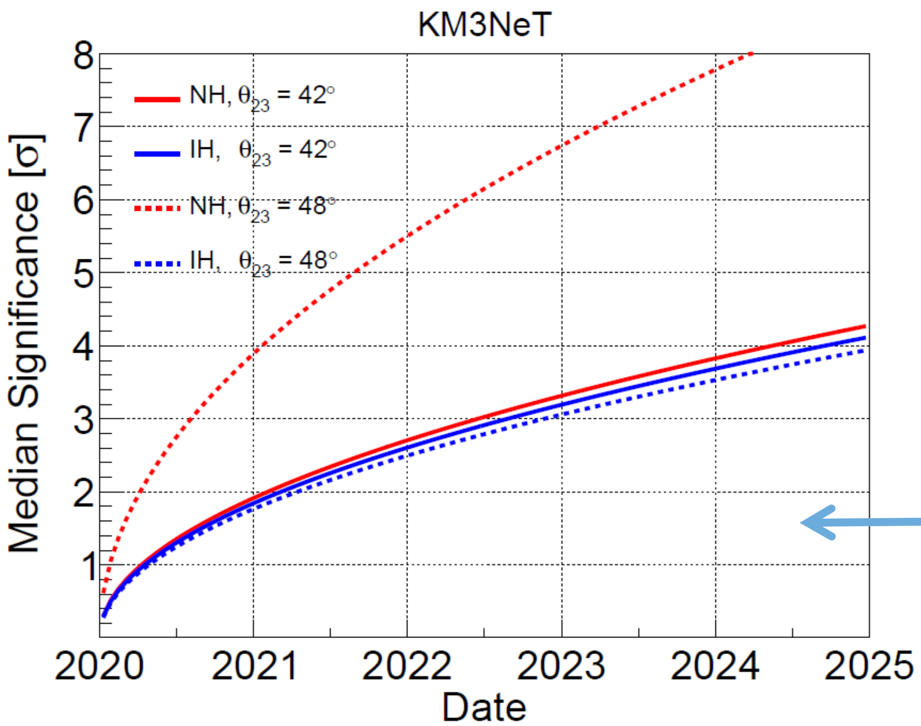
[KM3NeT 2.0: Letter of Intent](http://dx.doi.org/10.1088/0954-3899/43/8/084001)

http://dx.doi.org/10.1088/0954-3899/43/8/084001

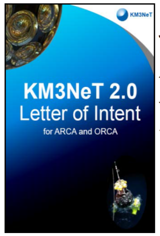
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Sensitivity to measure Neutrino Mass Hierarchy





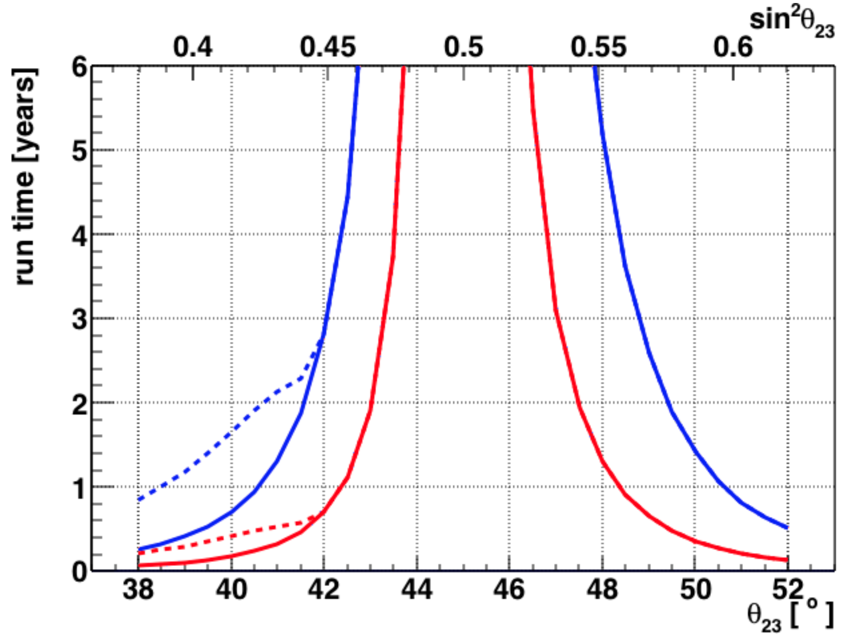
Time evolution of this sensitivity

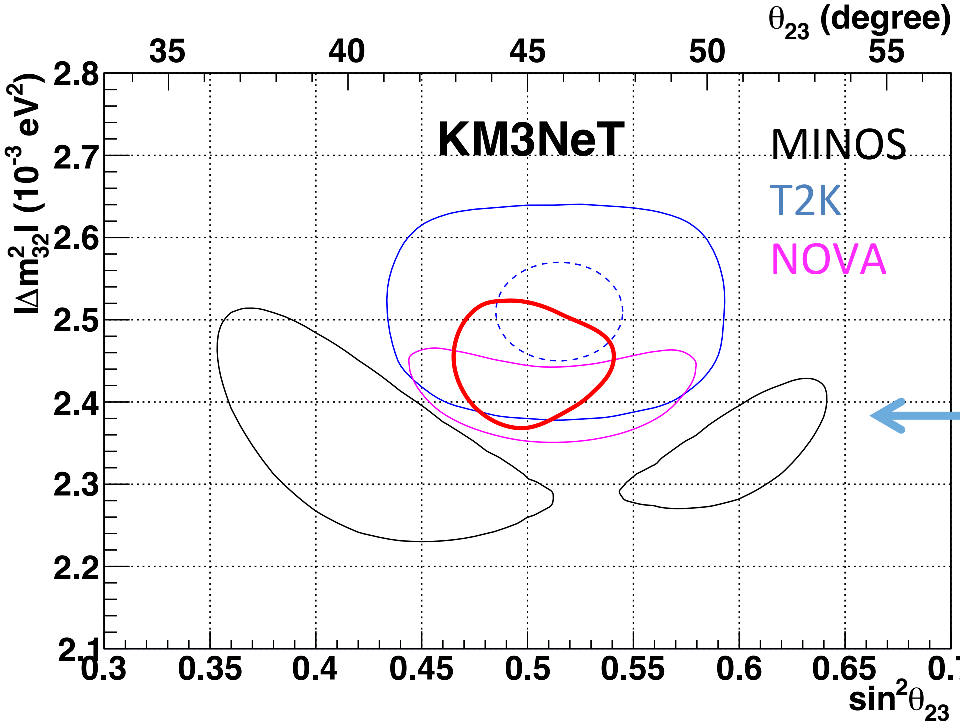


LOI: ORCA Oscillations

KM3NeT 2.0: Letter of Intent
http://dx.doi.org/10.1088/0954-3899/43/8/084001
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Time to measure octant with 1σ or 2σ

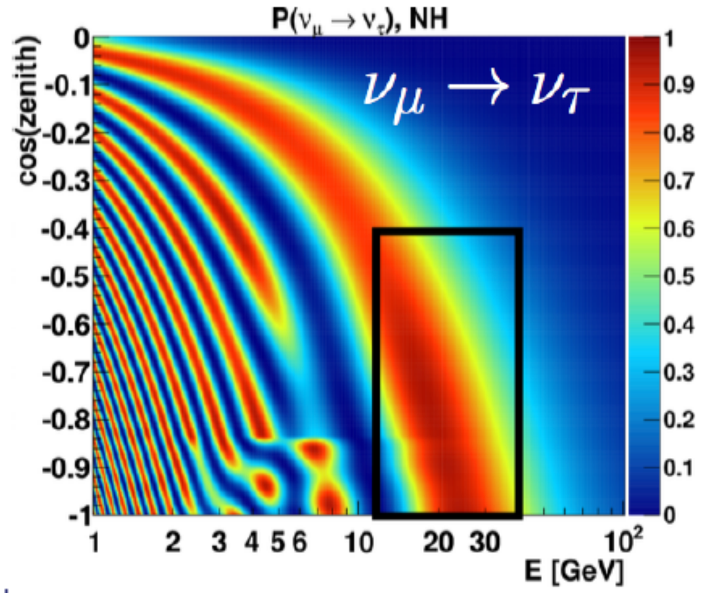


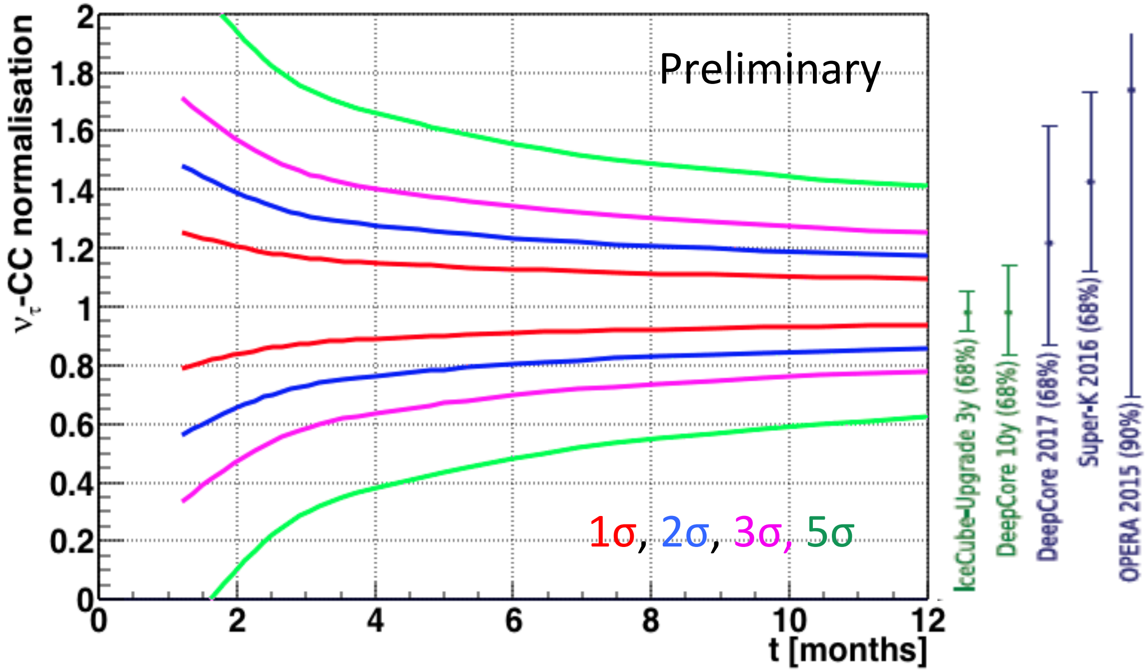


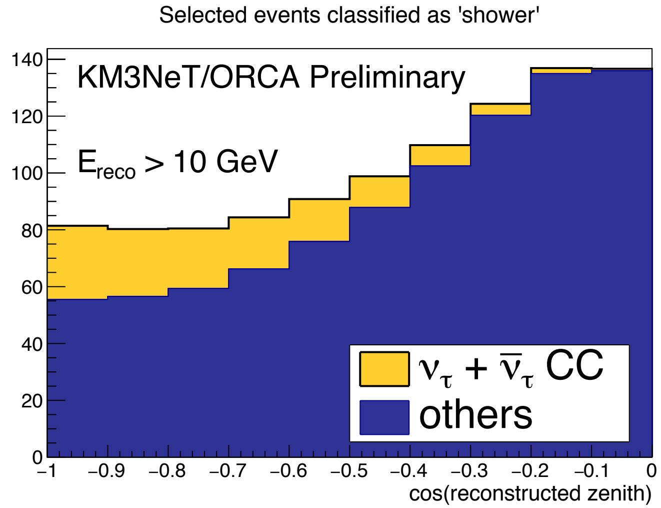
68% measurement contours for Δm^2_{32} and $\sin^2\theta_{23}$

ORCA Post LoI - Tau Appearance

- ν_τ appearance tests PMNS unitarity and BSM theories
- 30% deviations allowed by world data
- ≈3k ν_τ CC events/year with full ORCA
- Rate constrained within ≈10% in 1 year







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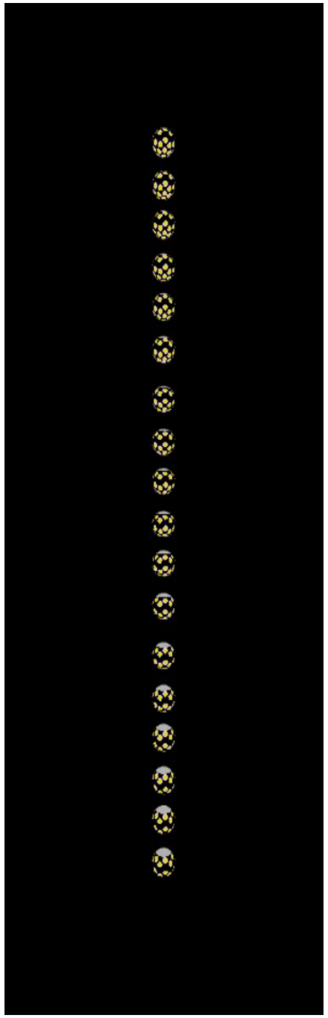
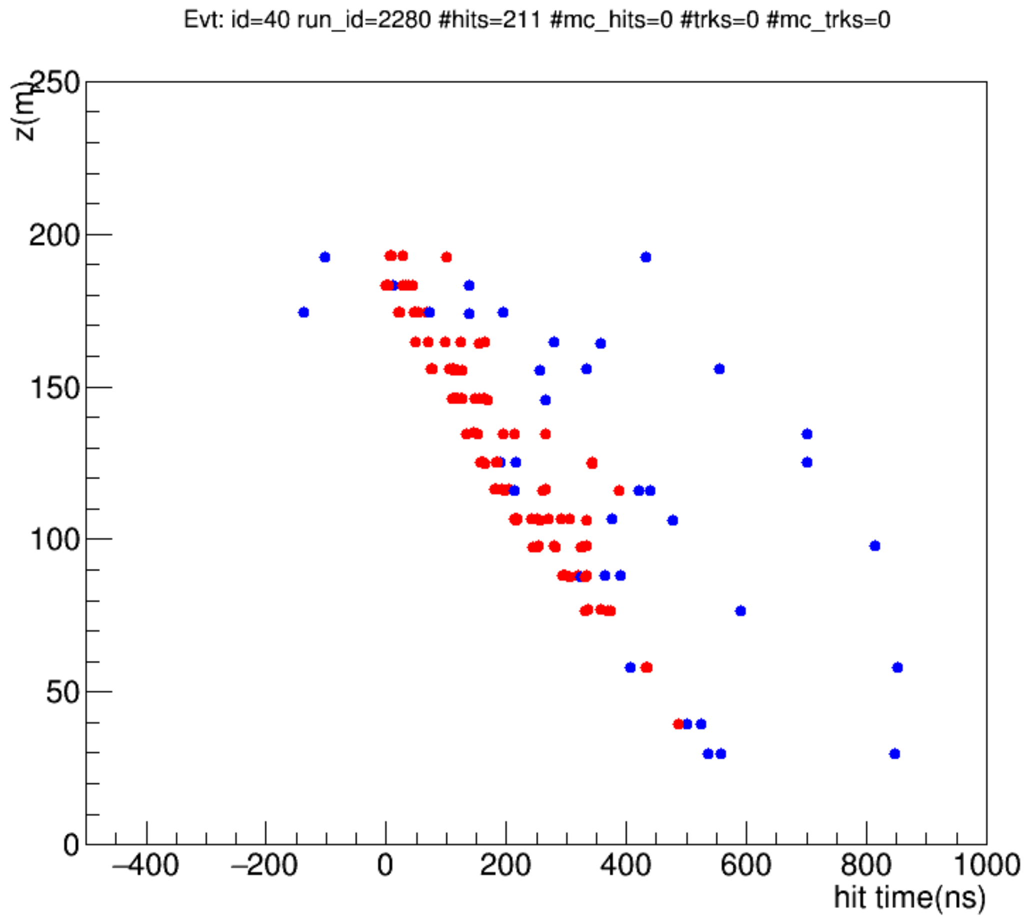
Deployment First Line 22/09/2017

https://www.youtube.com/watch?v=omlFkdCkbYk

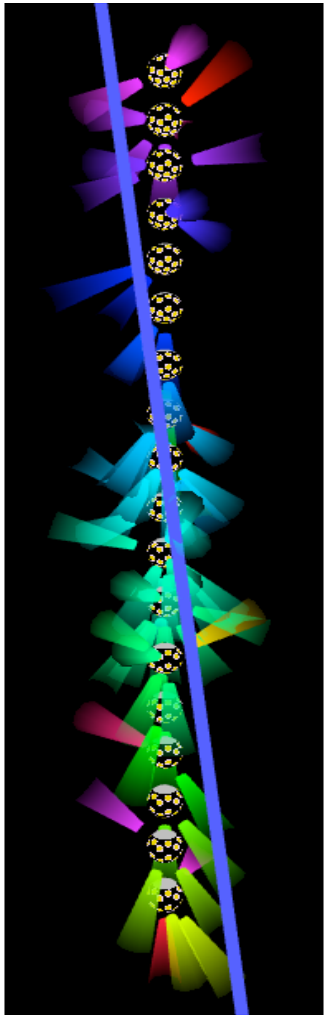
Early Muon bundle

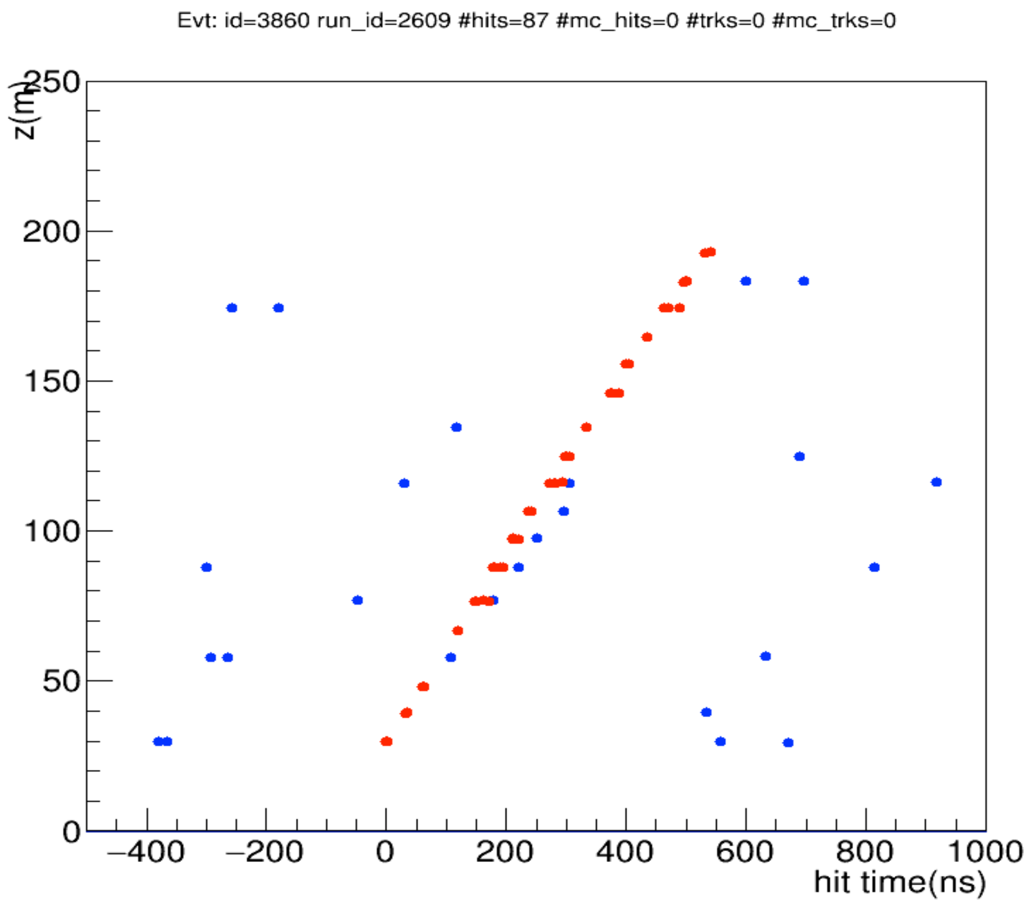




First Neutrino Analysis

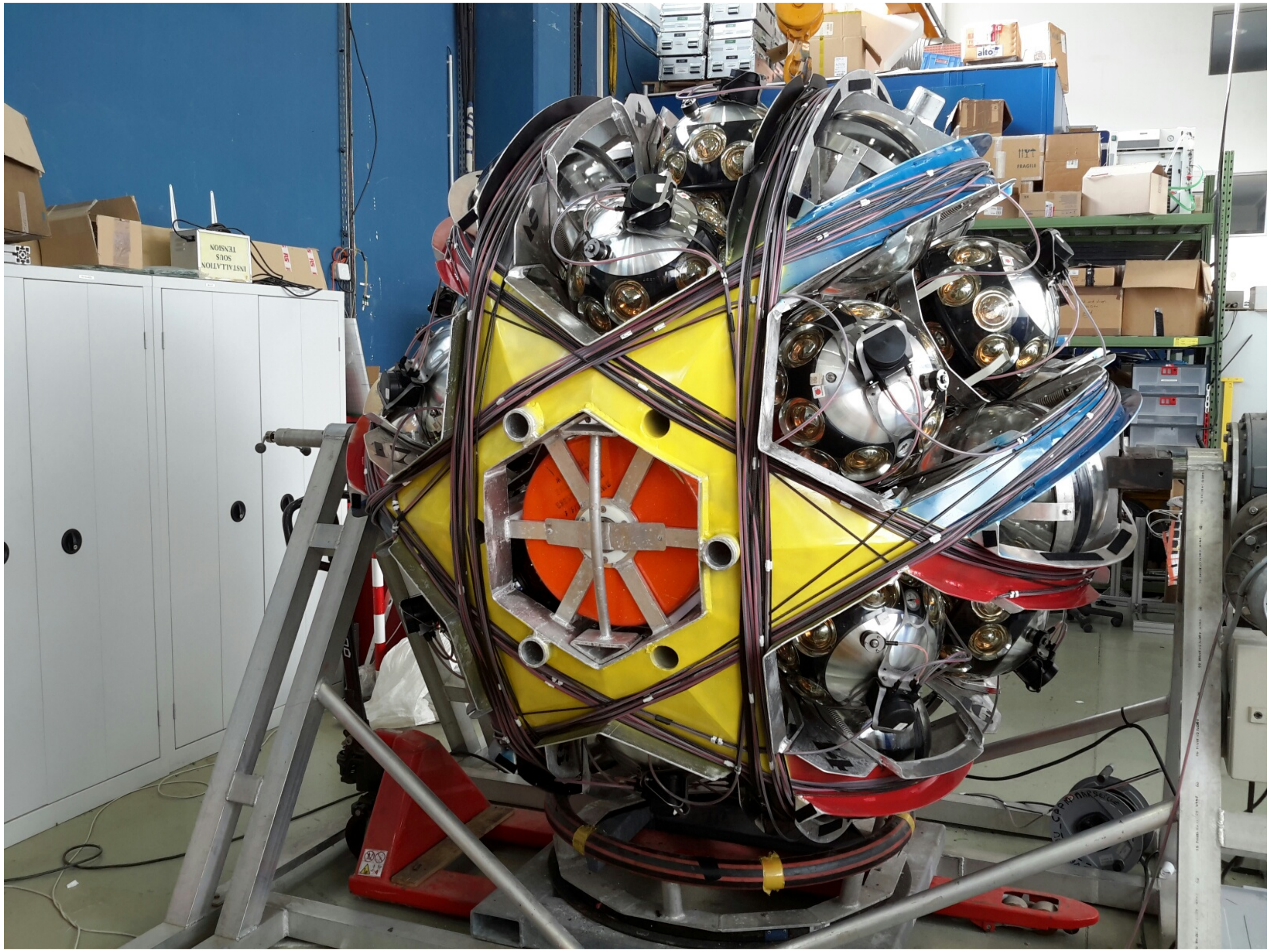
1 month of data analysed
MC : (6 ν_{μ} + 1 atm. muon)
Data : 7





2nd Line ready for deployment

Deployment of 4 lines planned around summer 2018 in a single sea operation



KM3NeT/ORCA as Target for a Neutrino Beam

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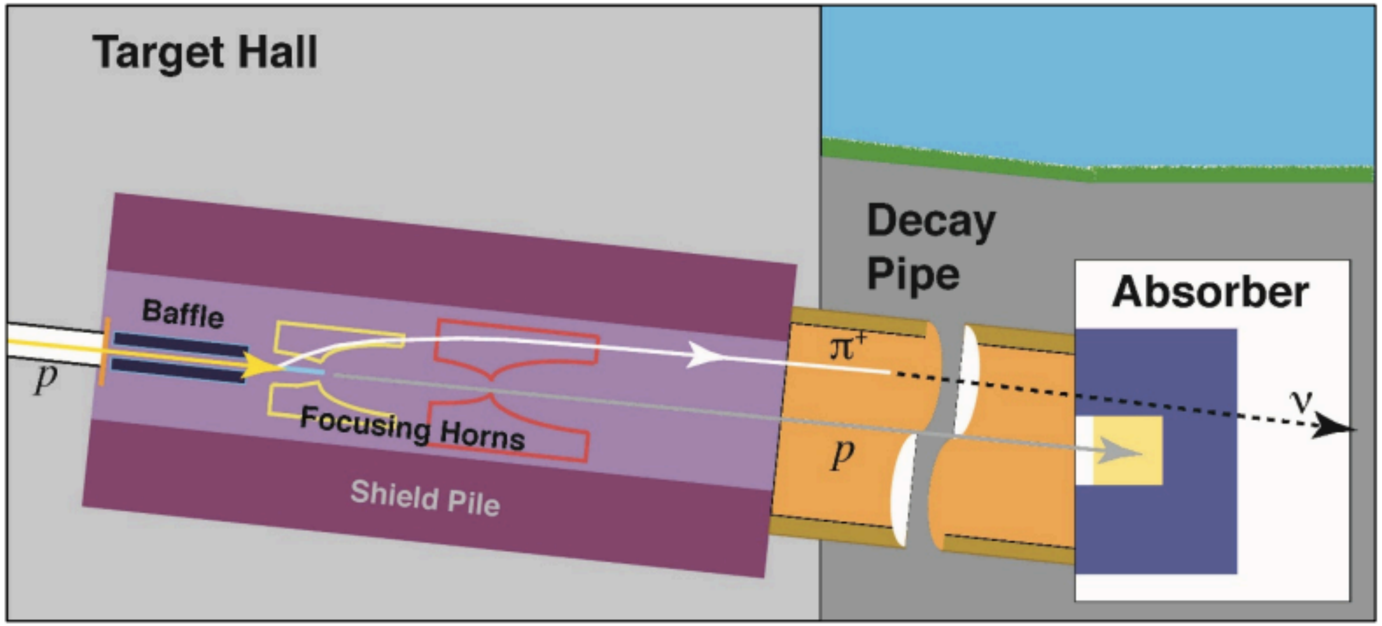
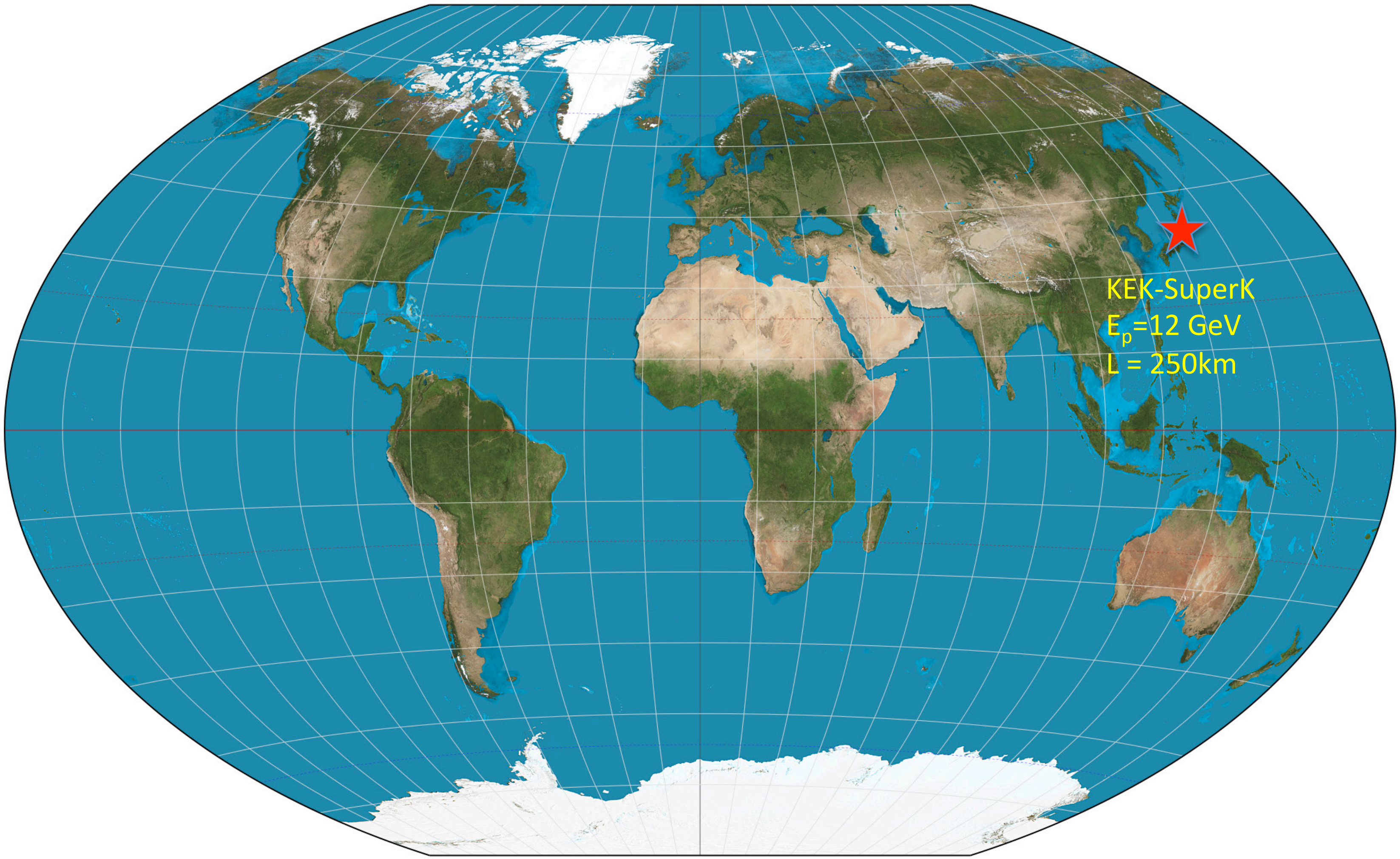
Neutrino Beams

1. accelerate protons
2. Shoot them on a "thin" target
3. Focus positive/negative secondaries (pions, Kaons)
4. Send them into a decay tunnel ($\pi \rightarrow \mu\nu$, $K \rightarrow \mu\nu$)

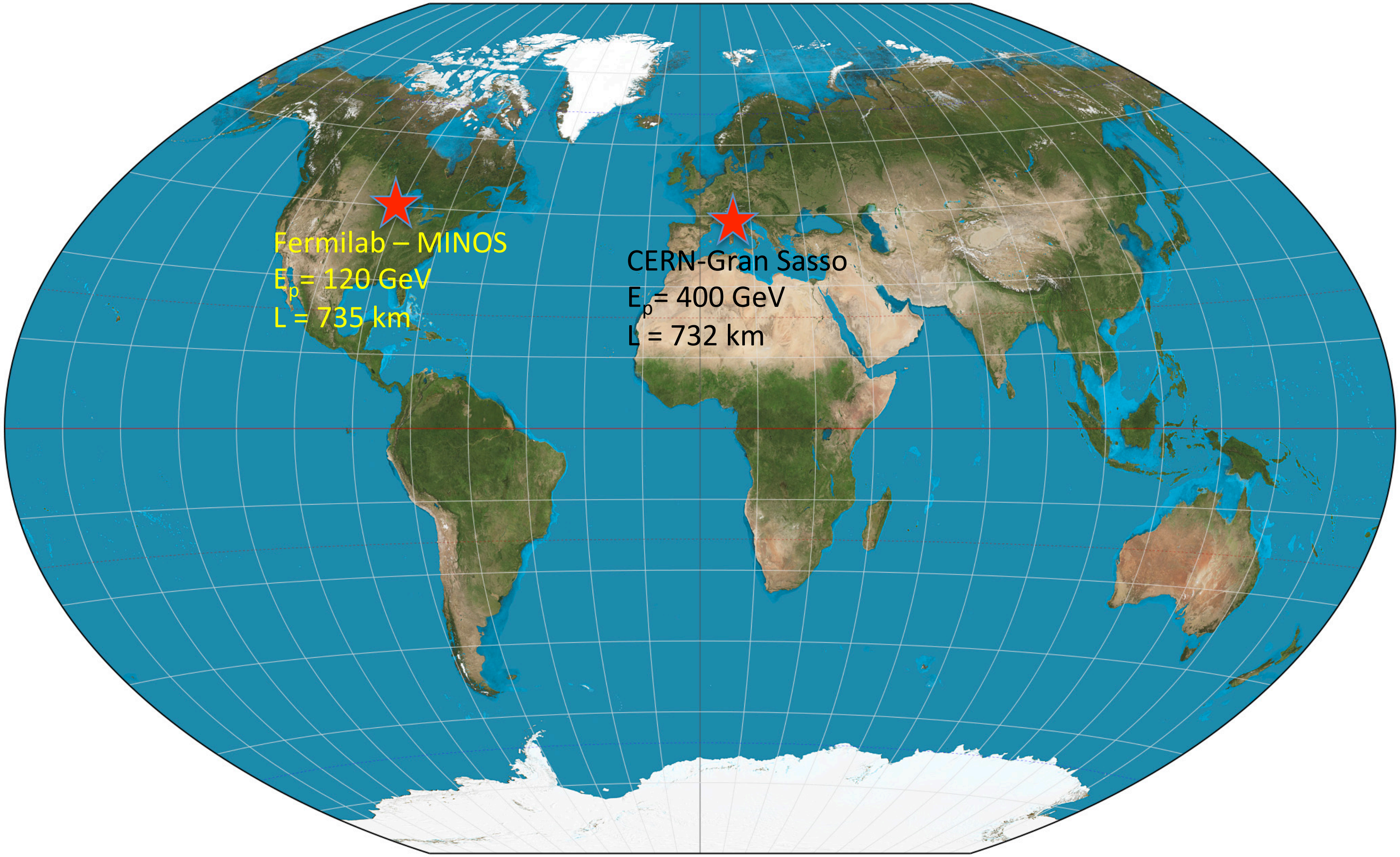


DUNE CDR, arXiv:1606.09550

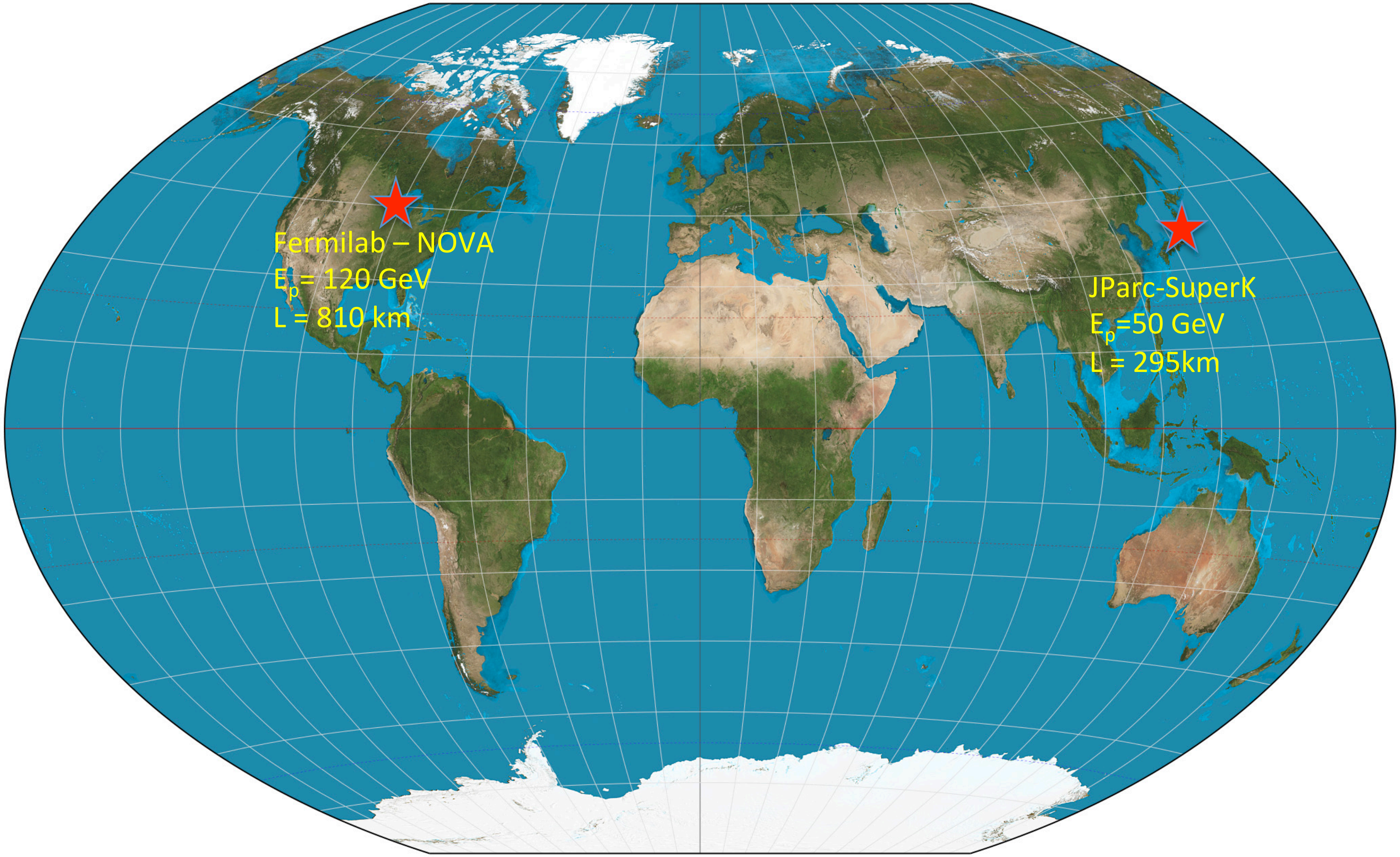
Longbaseline Projects 2000



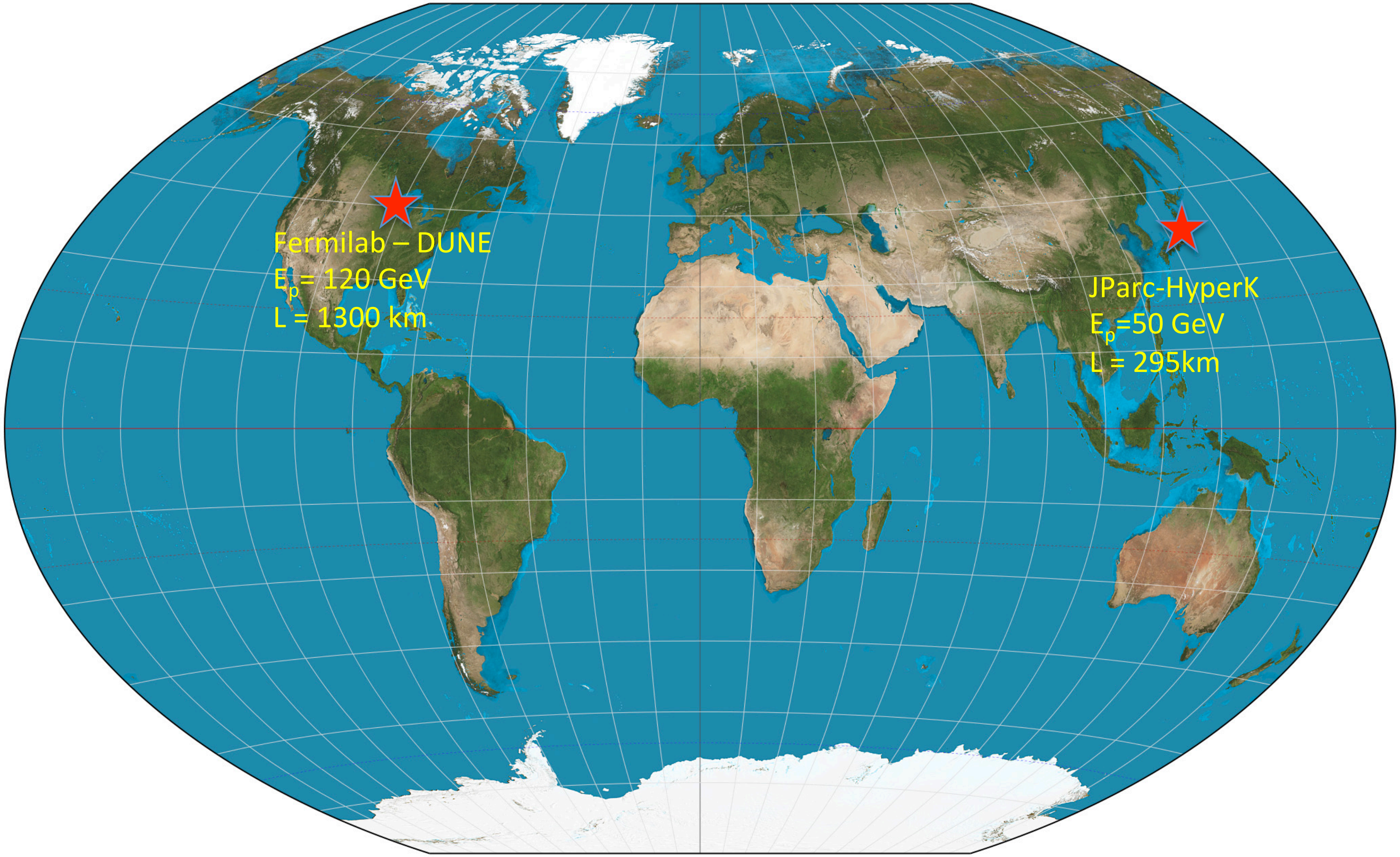
Longbaseline Projects 2010



Longbaseline Projects 2017



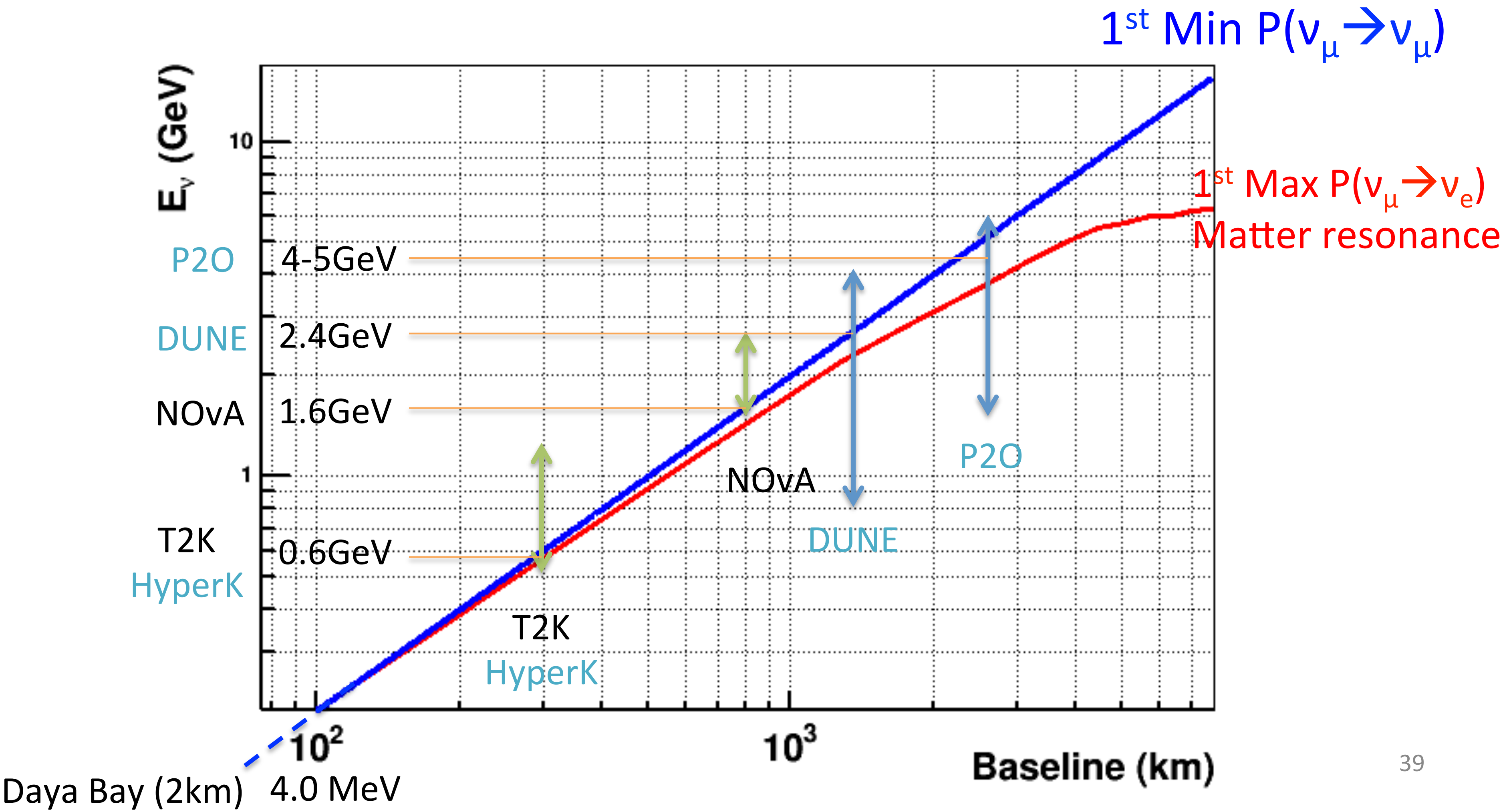
Longbaseline Projects 2030



No supported LBL project in Europe after end of LBNO

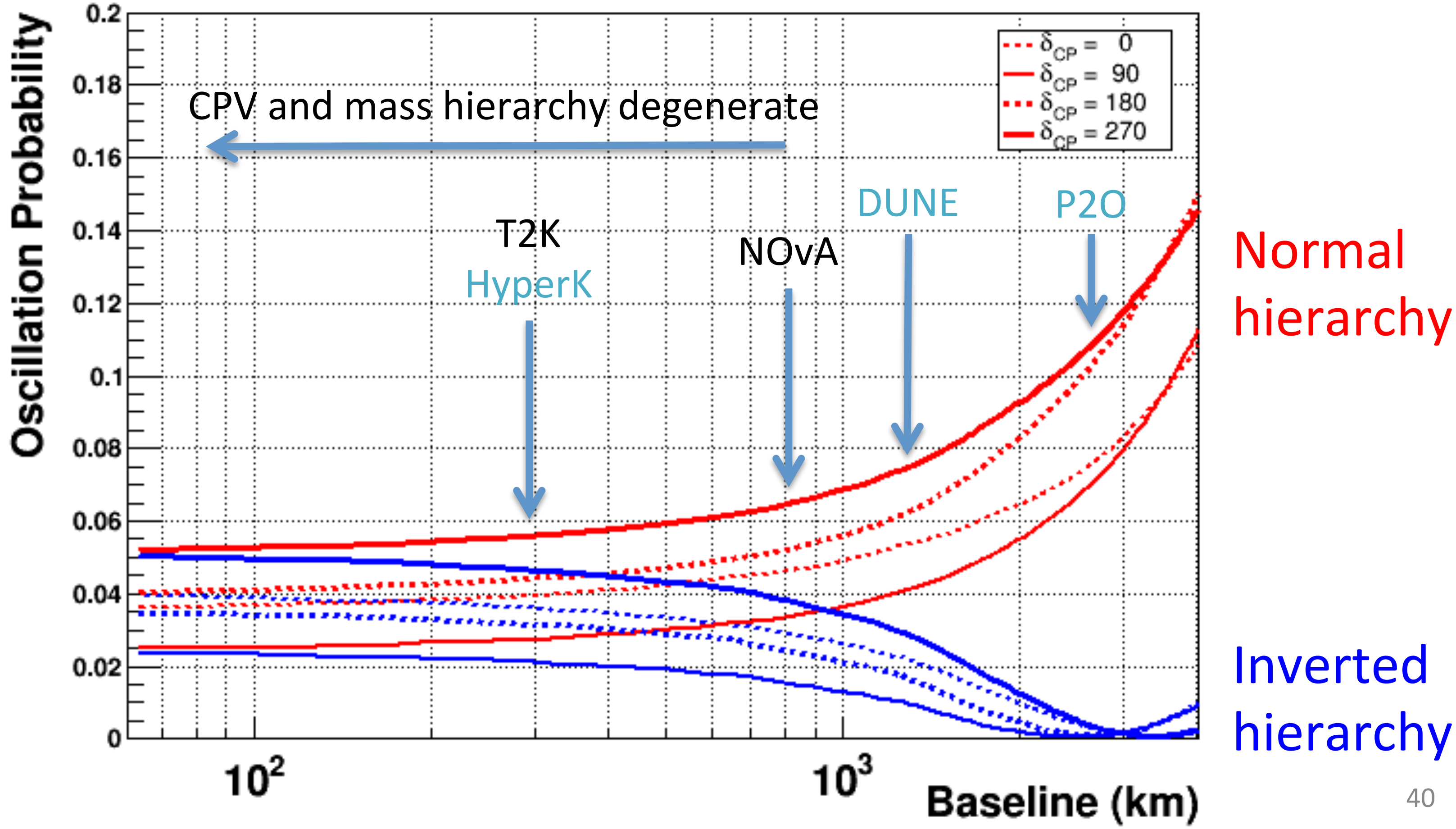
Comparison of LBL Projects

- Energy versus baseline



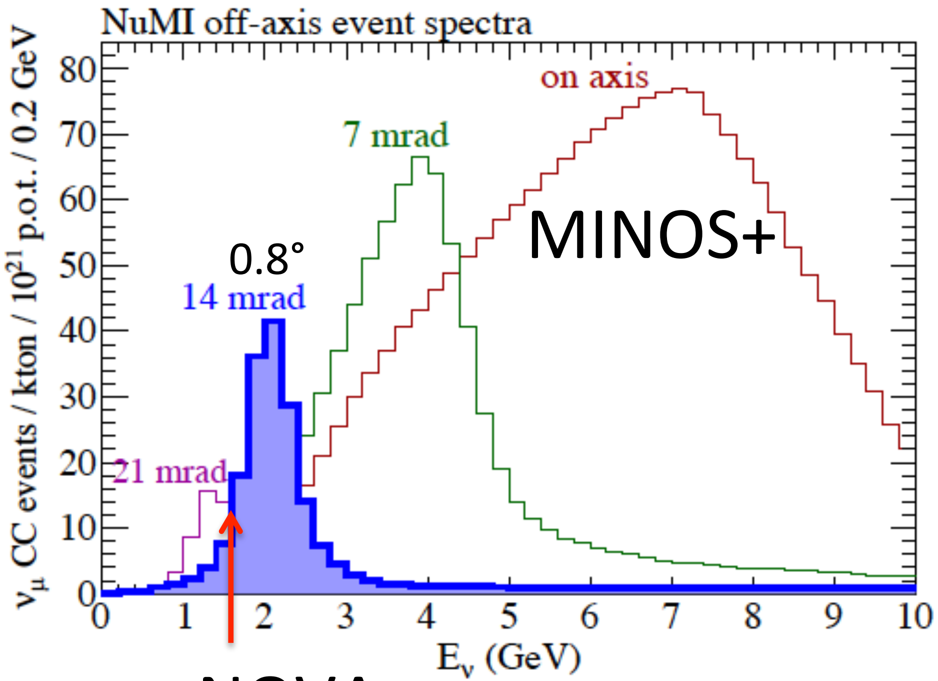
Comparison of LBL Projects

- Main Signal : Appearance of ν_e : $P(\nu_\mu \rightarrow \nu_e)$

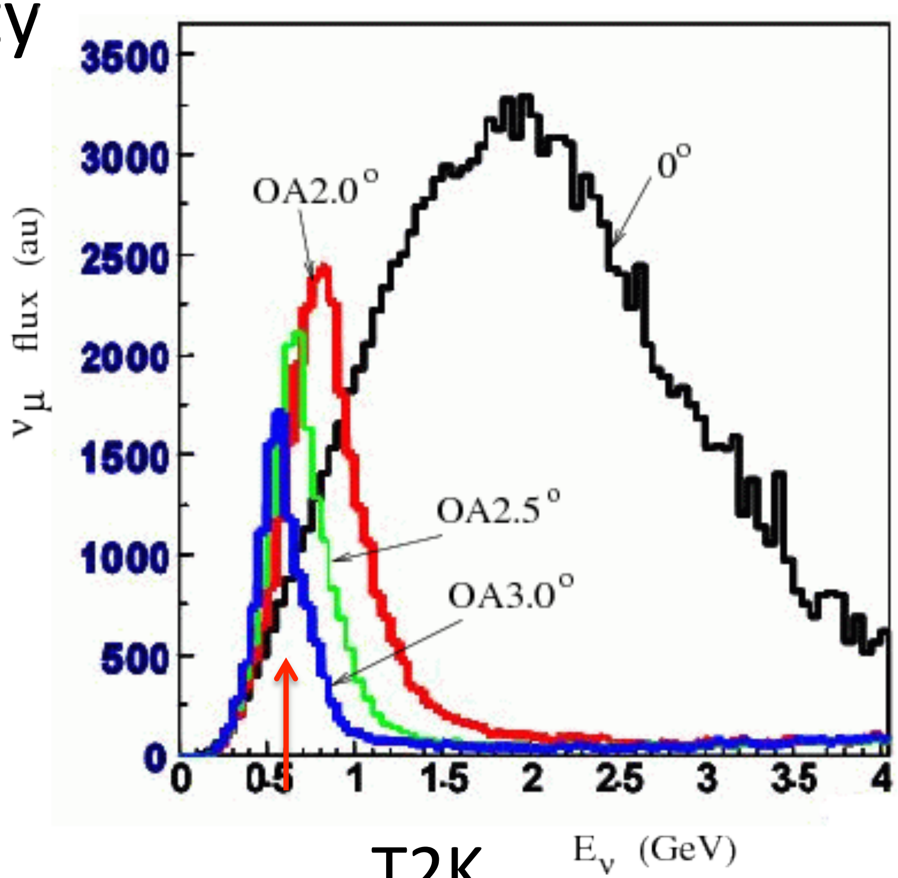


Match L and E_p

- Off-axis trick : narrow-band low energy
- Waste of beam intensity



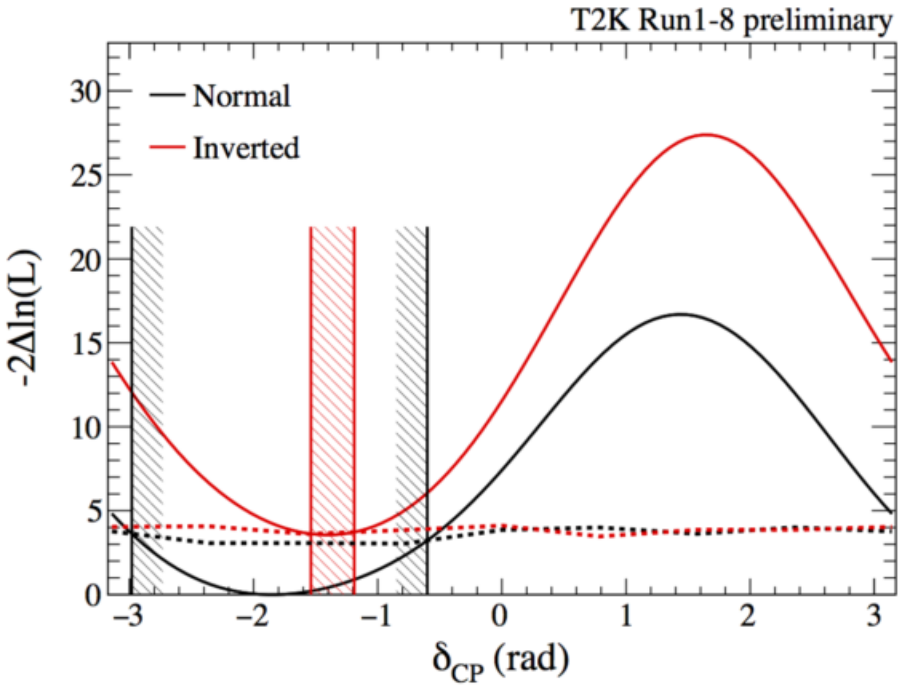
NOVA



T2K

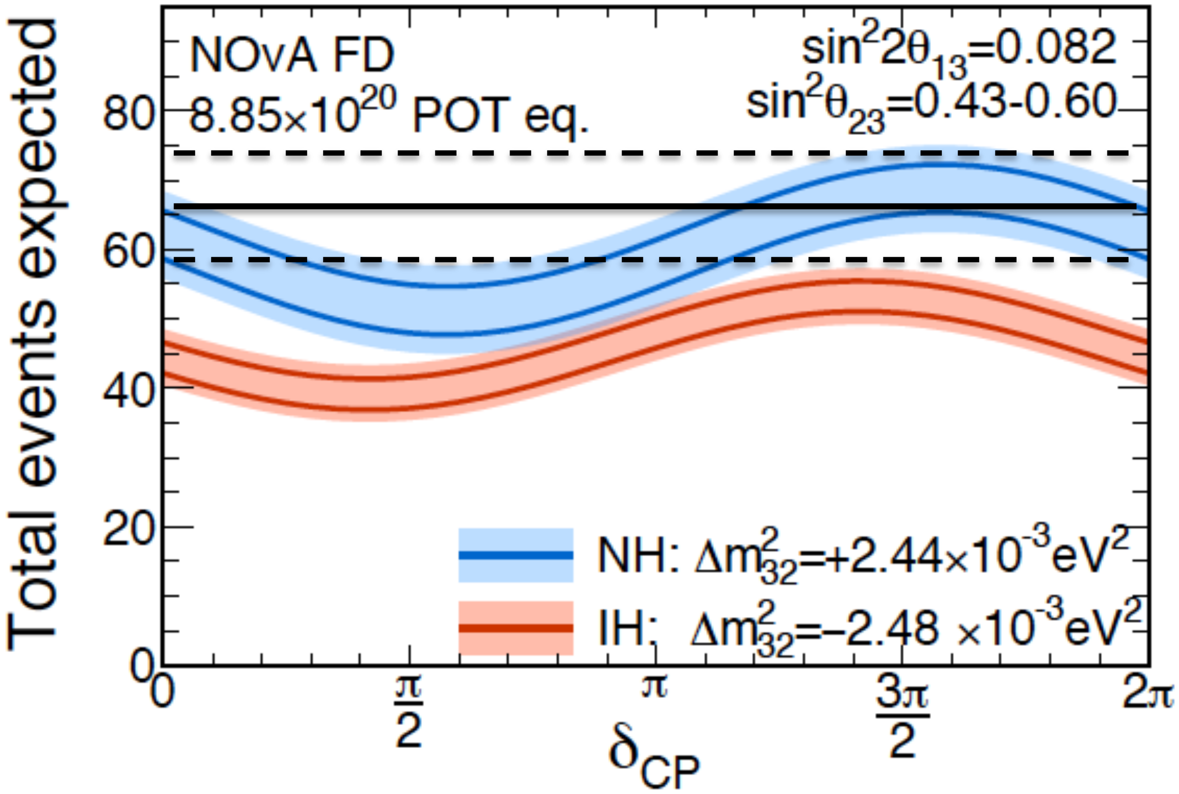
T2K recent result

- Based on 28% of 7.8 10^{21} p.o.t. (2021)
- 89 ν_e-CC events + 7 $\bar{\nu}_e$-CC (22kt)
- Extension planned 20 10^{21} p.o.t. (2026)
  - 1000 ν_e-CC events + 70 ν_e-CC



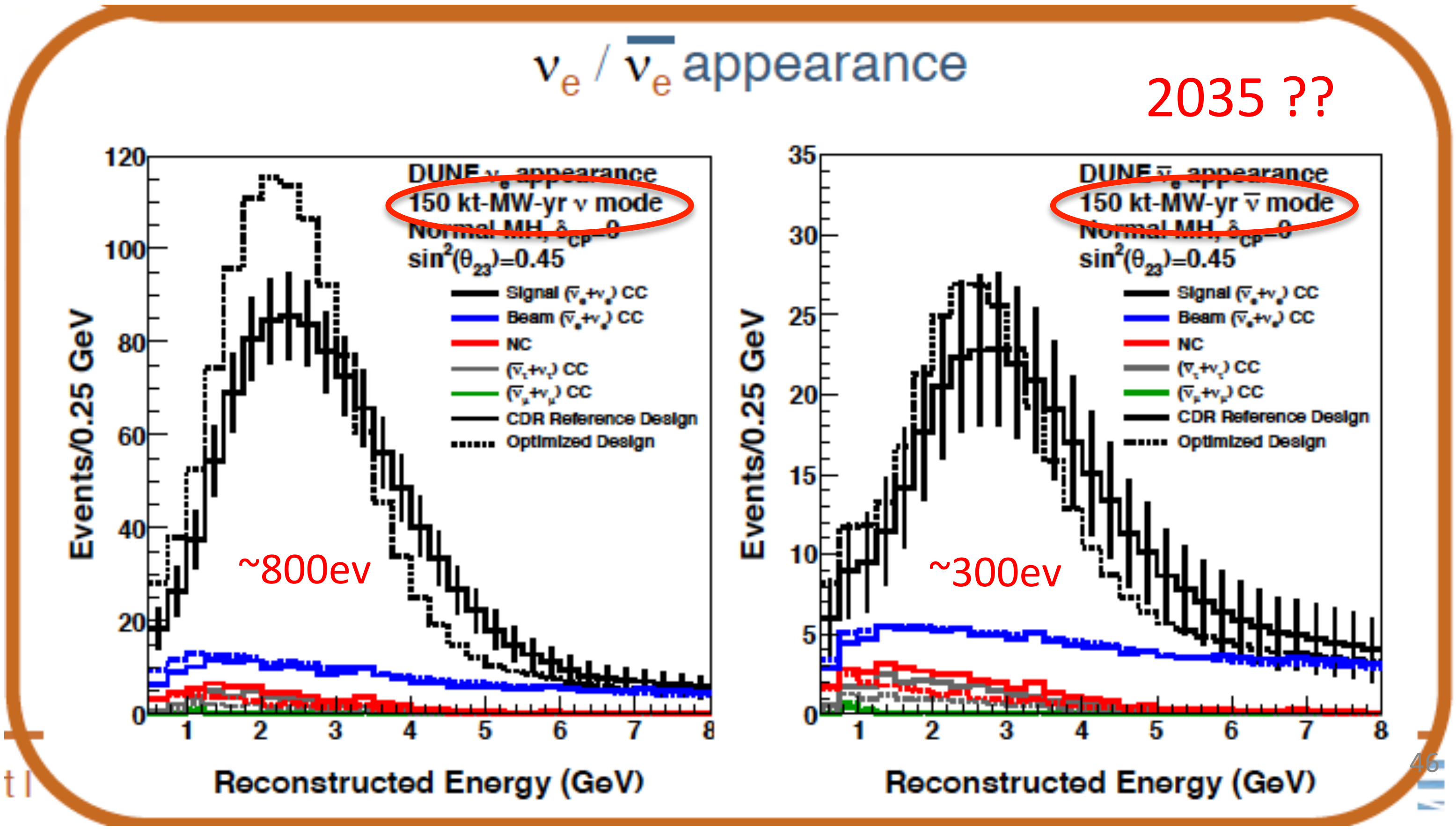
NOVA 2018 result

- Based on 8.85 10^{20} p.o.t. (2018 – 1/2 of design)
- 35 ν_e-CC signal events (66 – 21 bckg) (14kt)
- Currently running in $\bar{\nu}$ mode (shutdown 2024)



DUNE

- On-Axis, 40kt LAr TPC + 1.2 MW beam
- First data 2024-2028 (?)(10 – 20 – 30 – 40 kt)

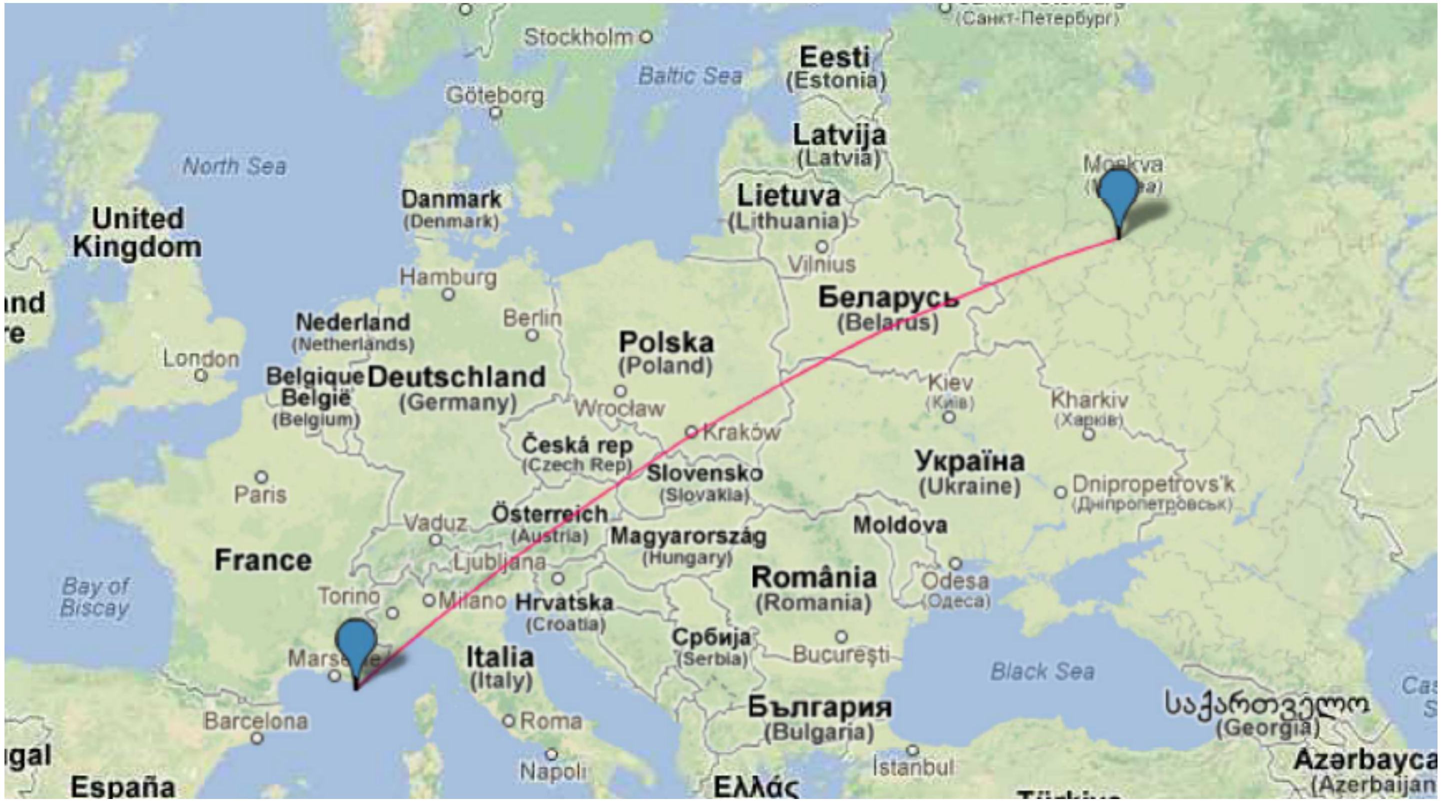


KM3NeT/ORCA as Target for a Neutrino Beam

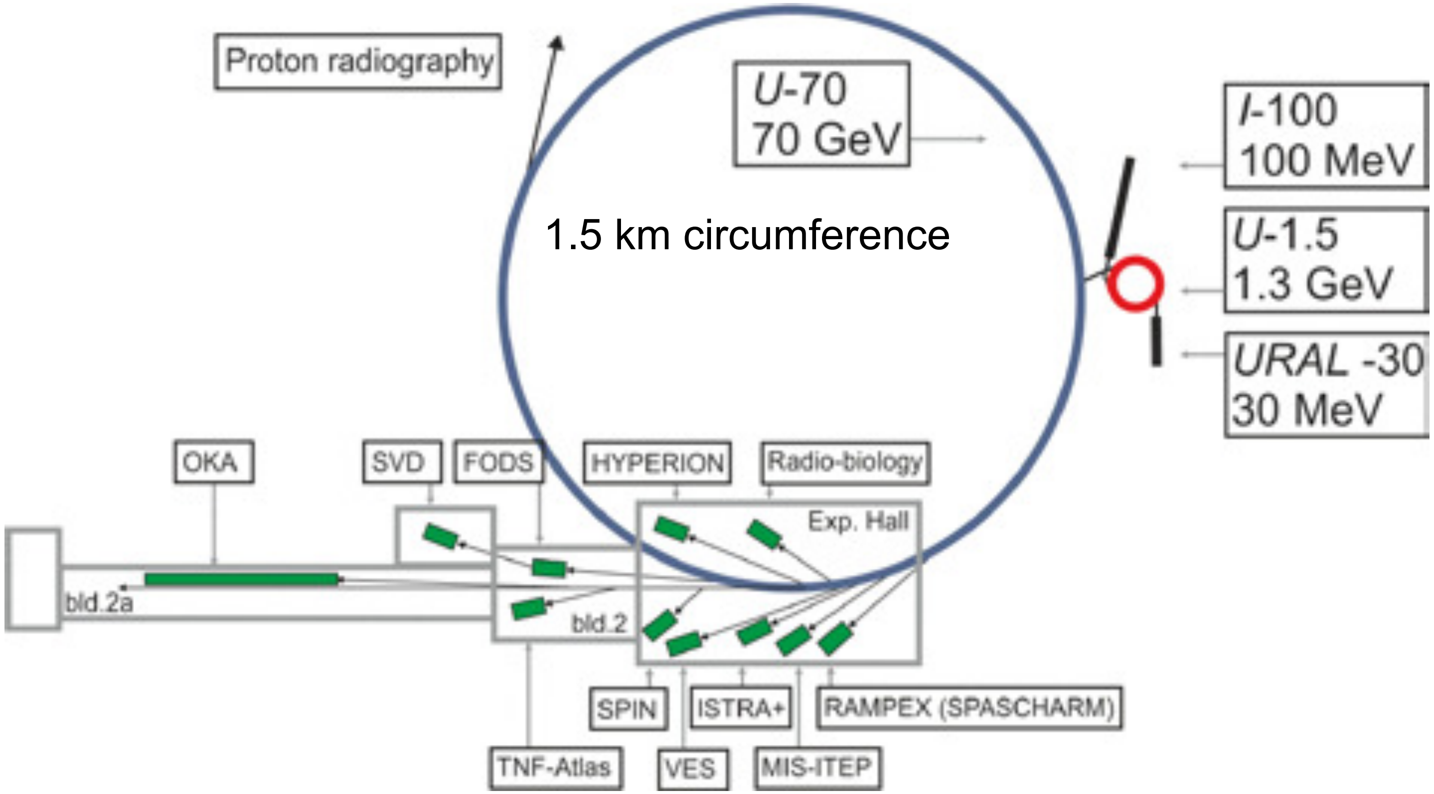
- The KM3NeT/ORCA Project
- Recent ORCA News
- Long-baseline Landscape
- P2O Project

P2O : Protvino to ORCA

- Baseline 2588km ; beam inclination : 11.7˚ ($\cos\theta = 0.2$)
- ORCA position : 42° 48' 16.28" N , 06° 01' 53.06" E
- Deepest point 134km : 3.3 g/cm^3
- First oscillation maximum 5.1 GeV, matter maximum 3.8 GeV



Protvino accelerator complex
(100 km South of Moscow)

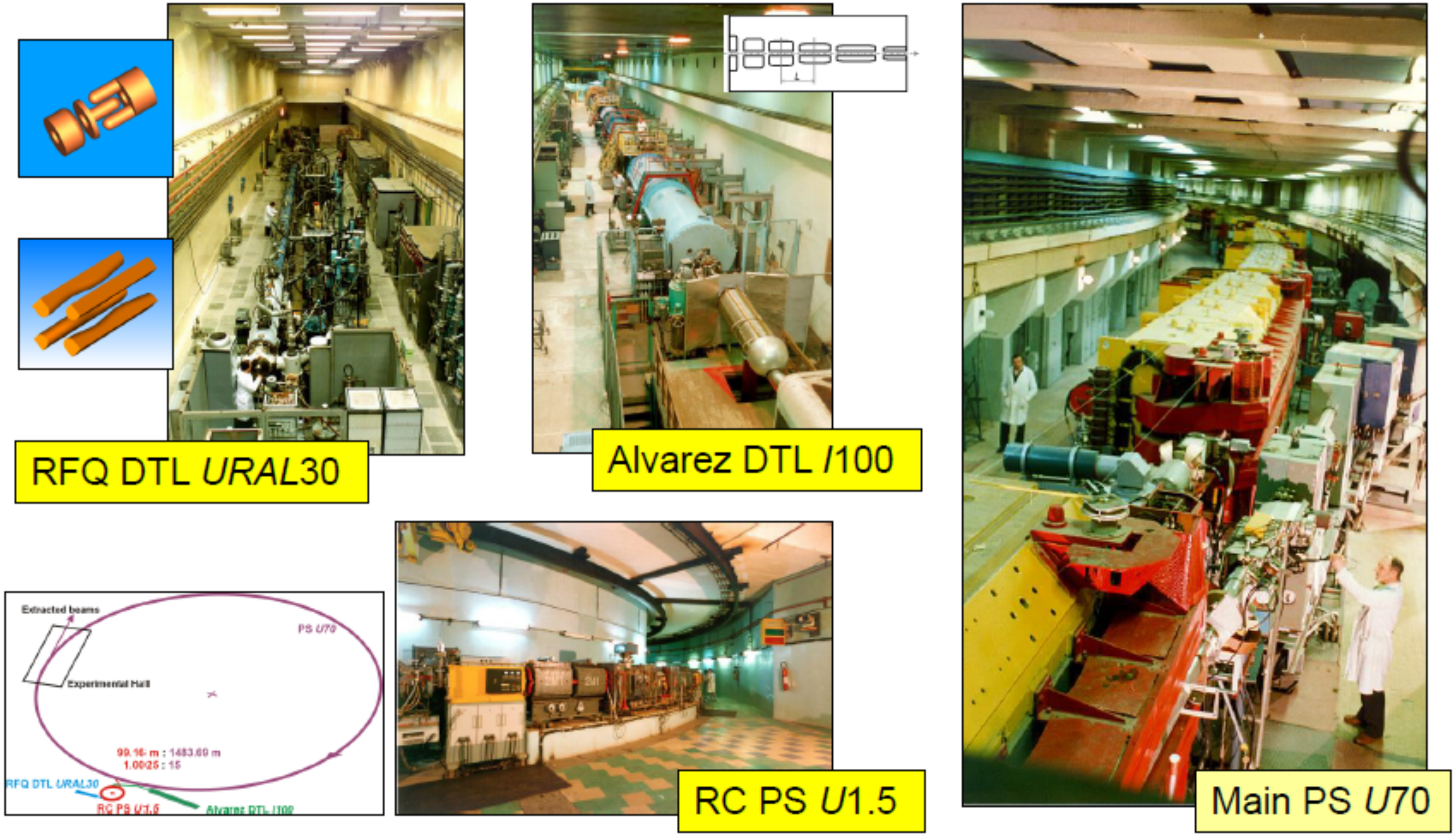


1-turn fast extraction:
5 μs spill every 9 s

U-70 accelerator constructed in 1967
Now operates at 8 - 15 kW for ~ 60 days / yr

Operated by NRC «Kurchatov Institute» – Institute for High Energy Physics (IHEP), Protvino

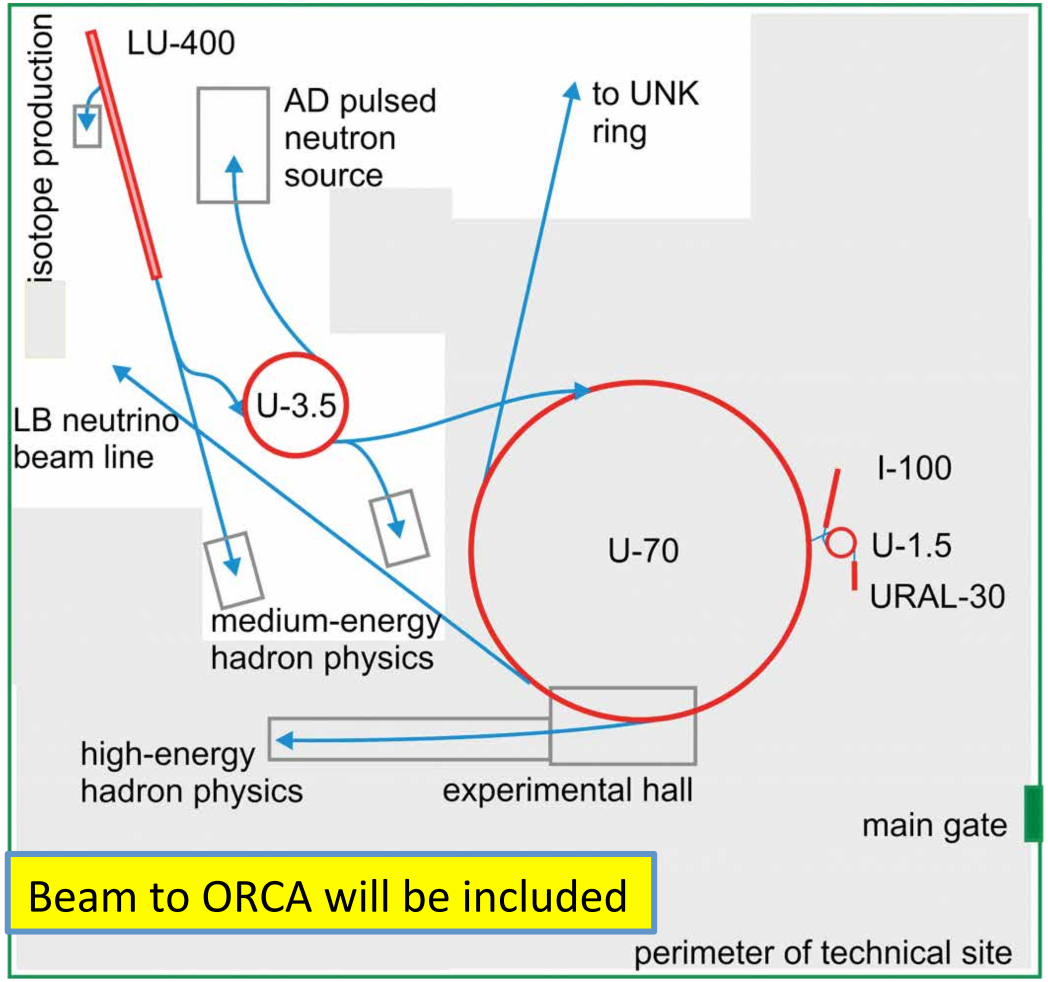
Proton Accelerator Complex Protvino



Presentation S. Ivanov (IHEP) on 22/11/2012 @ CERN

The OMEGA project proposal

- New high intensity linac and booster synchrotron (3.5 GeV)
- 1.1 MW proton beam
- High-intensity spallation neutron source
- 450 kW power at 70 GeV using existing U-70 synchrotron
- A long baseline neutrino beam



Construction over 8 yr (not yet approved)

N.E. Tyurin et al, Facility for intense hadron beams (letter of intent), News and Problems of Fundamental Physics 2 (9), 2010, http://exwww.ihep.su/ihep/journal/IHEP-2-2010.pdf

Cost estimates

Table extracted from the OMEGA project LoI

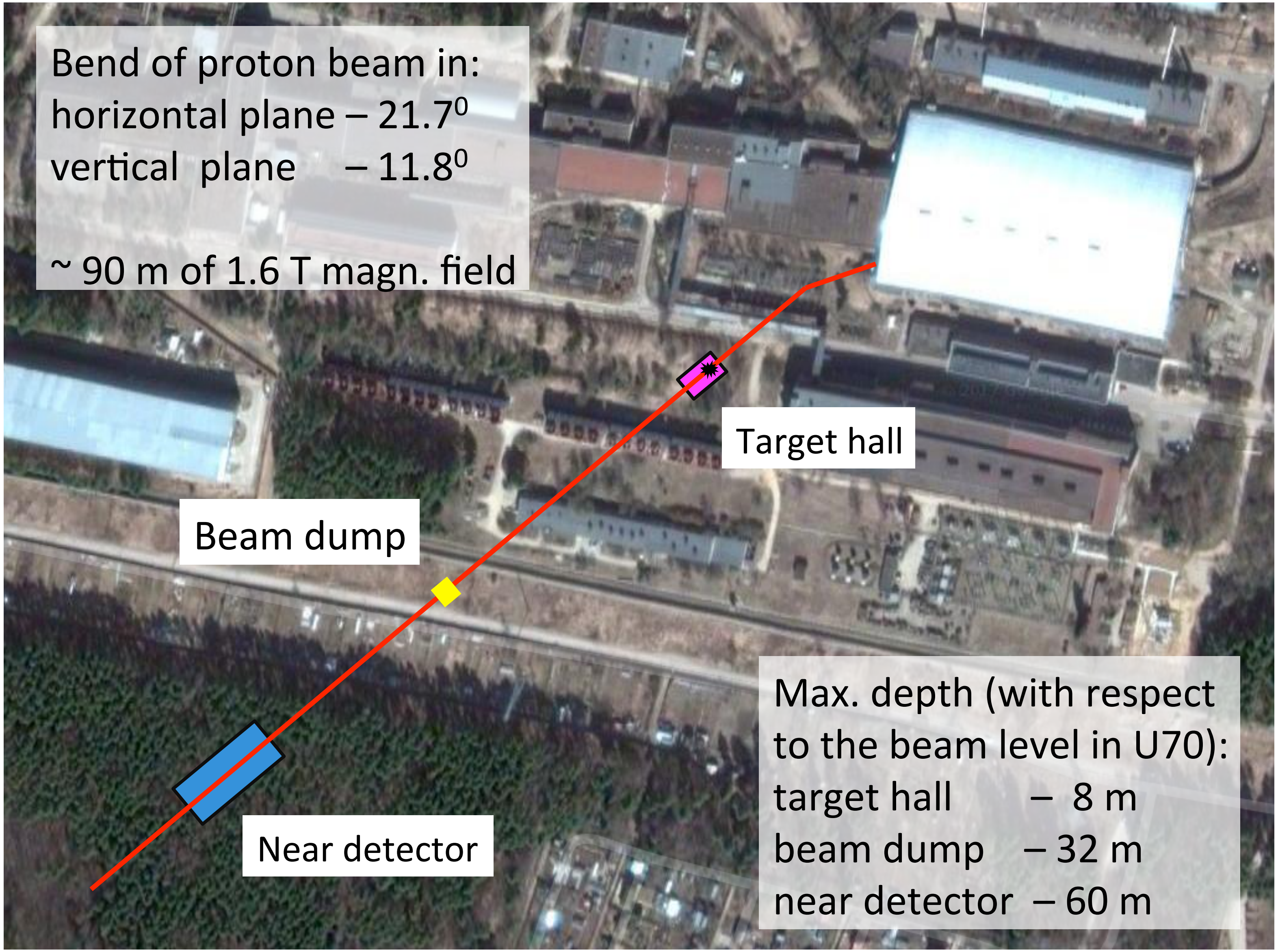
№	Object	Cost (million rubles)	**M €** (approx)
1	Linac LU-400	7 200	**180**
2	RC PS U-3.5	10 100	**250**
3	Neutrino channel	1 500	**40**
4	Near Neutrino Detector	1 000	25
5	Neutron source (target station T1)	8 400	210
6	Neutron research set-ups	1 500	40
7	Injection from U-3.5 to U-70	800	**20**
8	Target stations T2 and T3	800	20
9	Infrastructure	700	17
10	Total	32 000	**800**

Using 2013 exchange rate 40:1

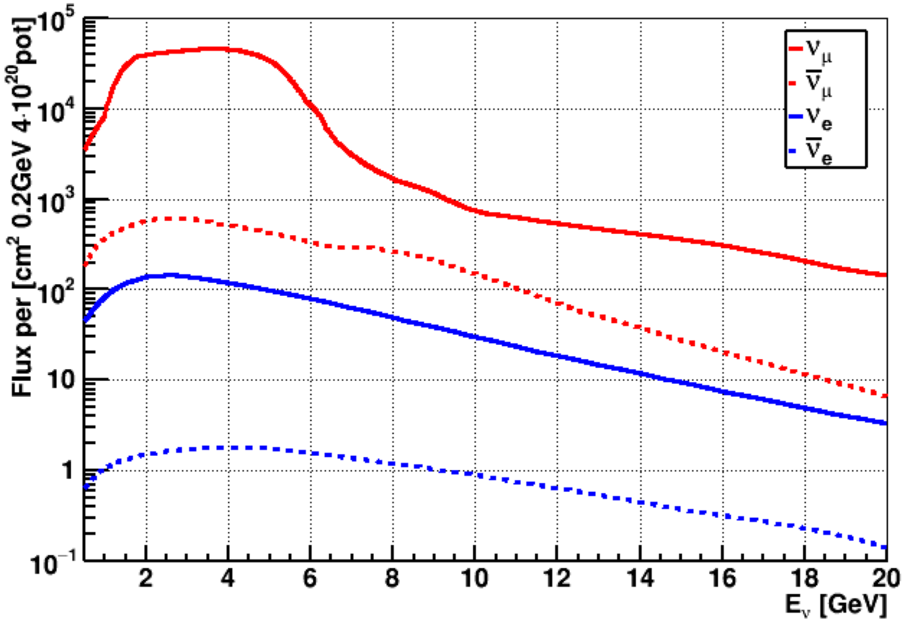
Staged Approach possible

- Stage 1
  - Neutrino beam line to ORCA
  - New ion injection scheme (H^-) : x3
  - Double cycling frequency : 9s → 4.5s : x2
  - Intensity : 90kW cost : 100kEuro
- Stage 2
  - New Linac LU-400
  - New booster 3.5 GeV
  - Intensity : 450kW   cost : 500kEuro

Possible location of the near beam detector



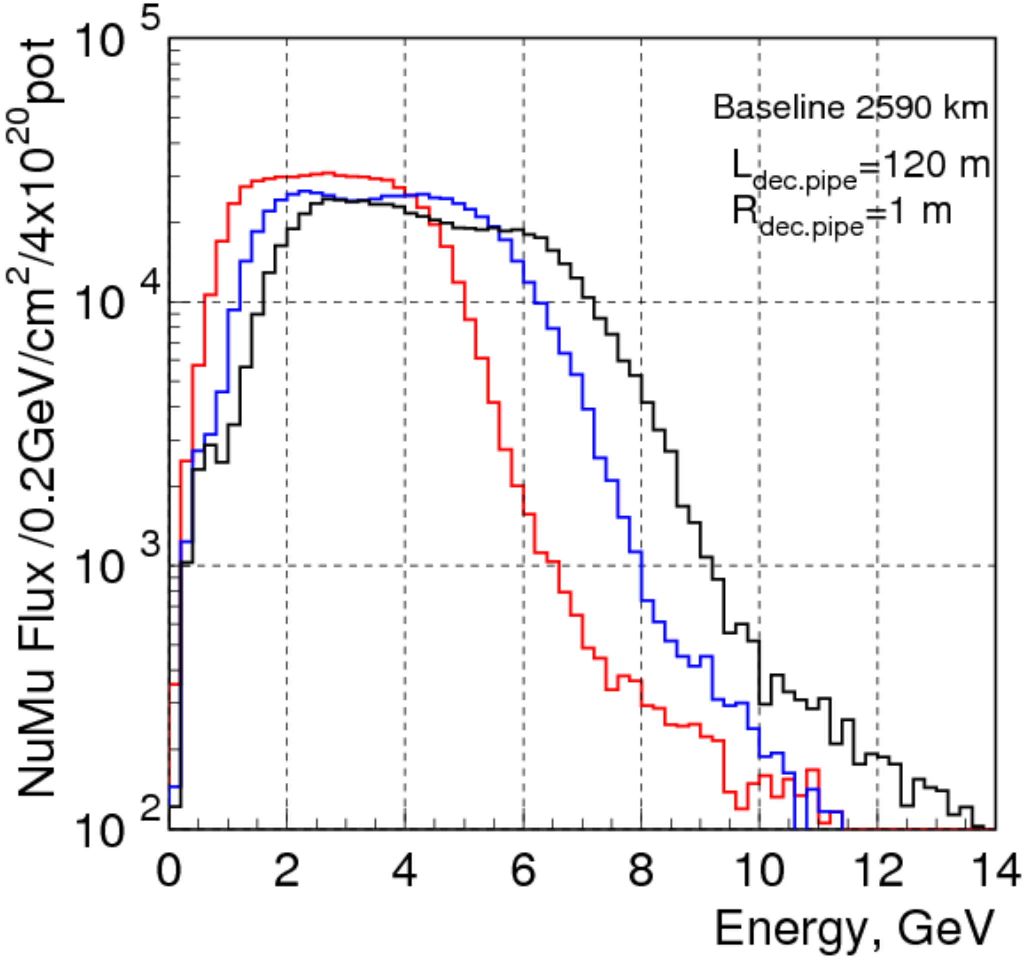
Neutrino Flux



Focus π^+ (Neutrino beam)

- Used for current study : IHEP Protvino internal note 2015-5
- Designed for Beam to Gran Sasso (2200km)
- Beam power 450kW → $4 \bullet 10^{20}$ p.o.t. per year
- Fermilab-Nova : 700kW → $6 \bullet 10^{20}$ p.o.t. per year

Beam optimization (work in progress)

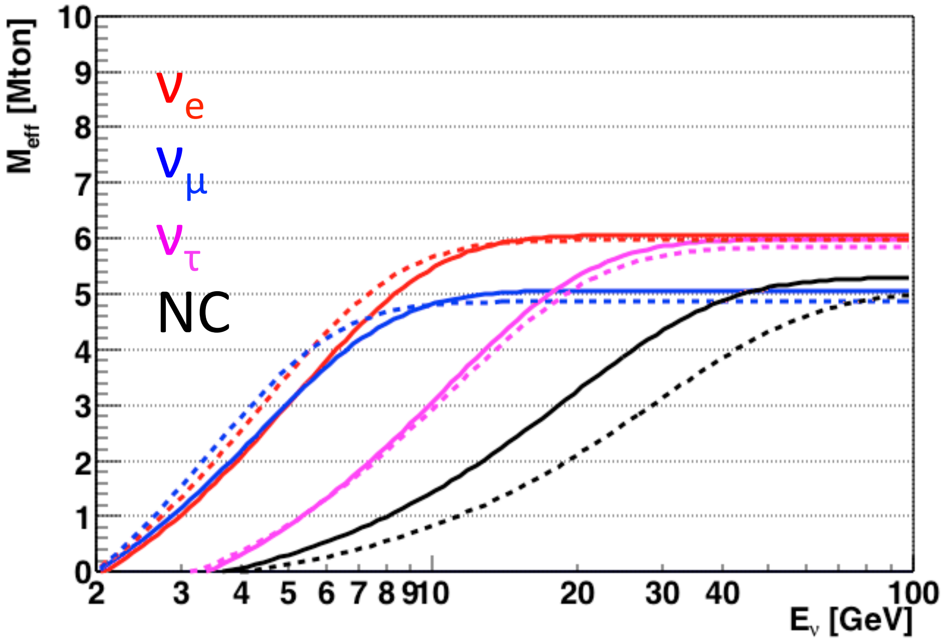


- Red: two 3 m horns as in arXiv: 1412.0804
- Blue: target shifted towards the beam
- Black: target shifted towards the beam + horns moved further away from each other

Idea: choose the beam option which gives best sensitivity to CP violation

Effective Mass

After triggering, atmospheric muon rejection and containment cuts:

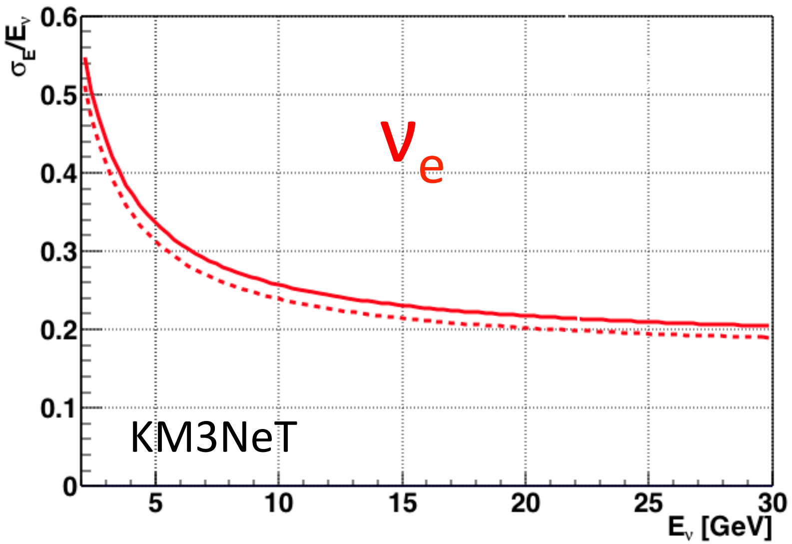


Events/yr (atm):
ν_eCC: 17,300
ν_μCC: 24,800
ν_τCC: 3,100
NC: 5,300

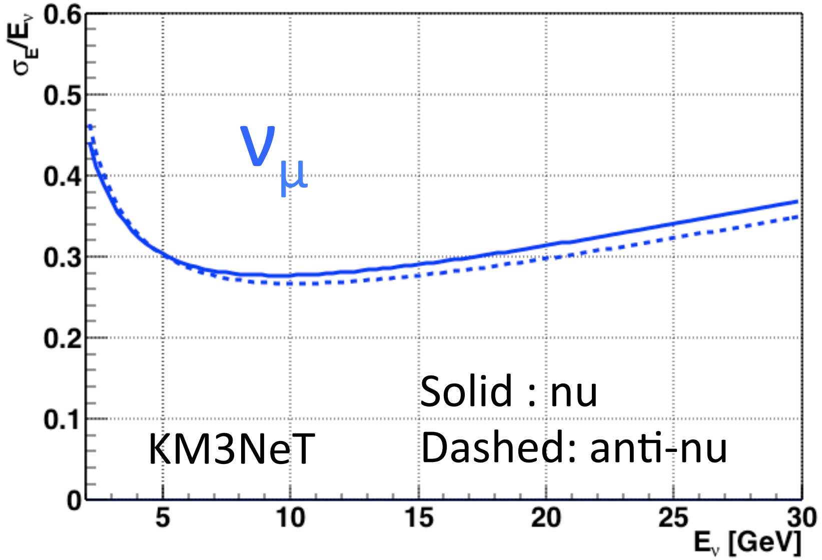
- Energy threshold determined by DOM spacing
- 6 Mton@10 GeV
- 50% Efficiency at 5 GeV

Energy Resolutions

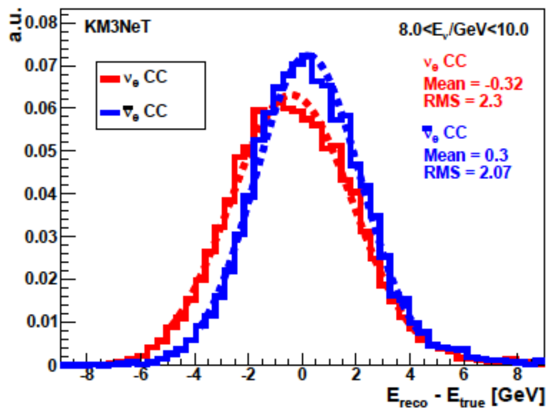
Shower



Track

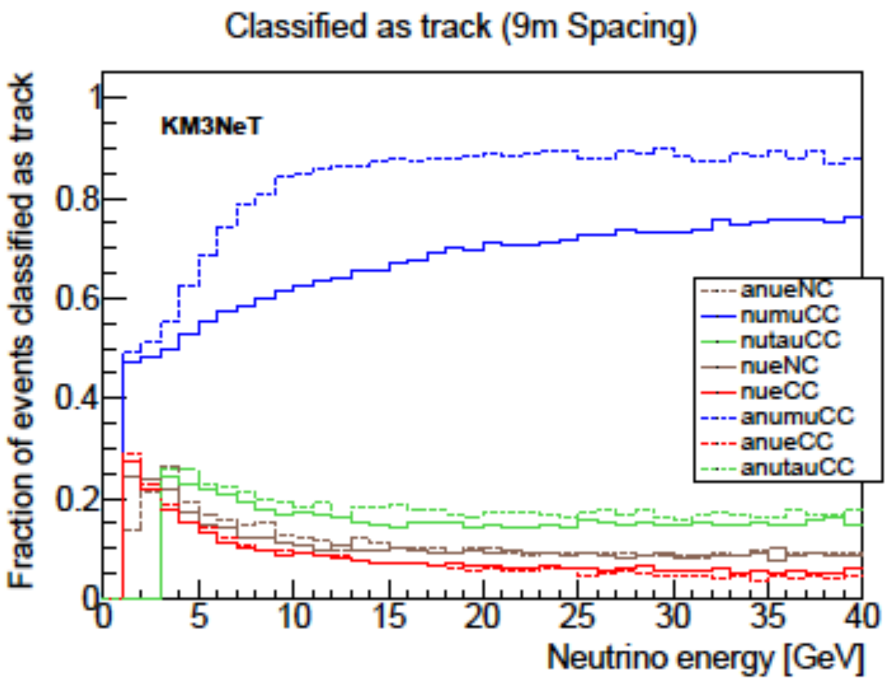


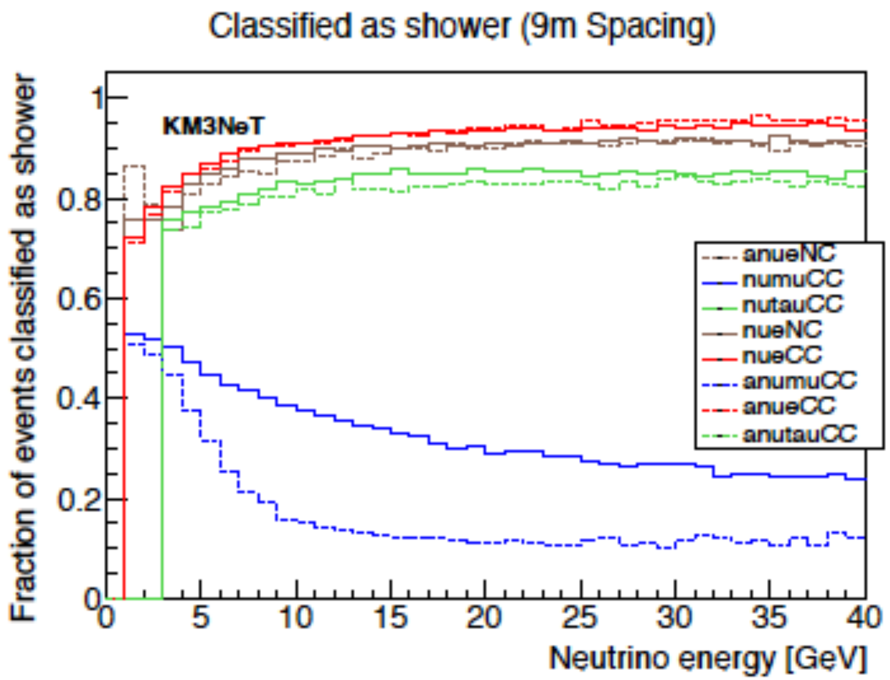
- Energy resolution better than 30% in relevant range
- Close to Gaussian



Shower/Track Identification

Discrimination of track-like and shower-like events via Random Decision Forest

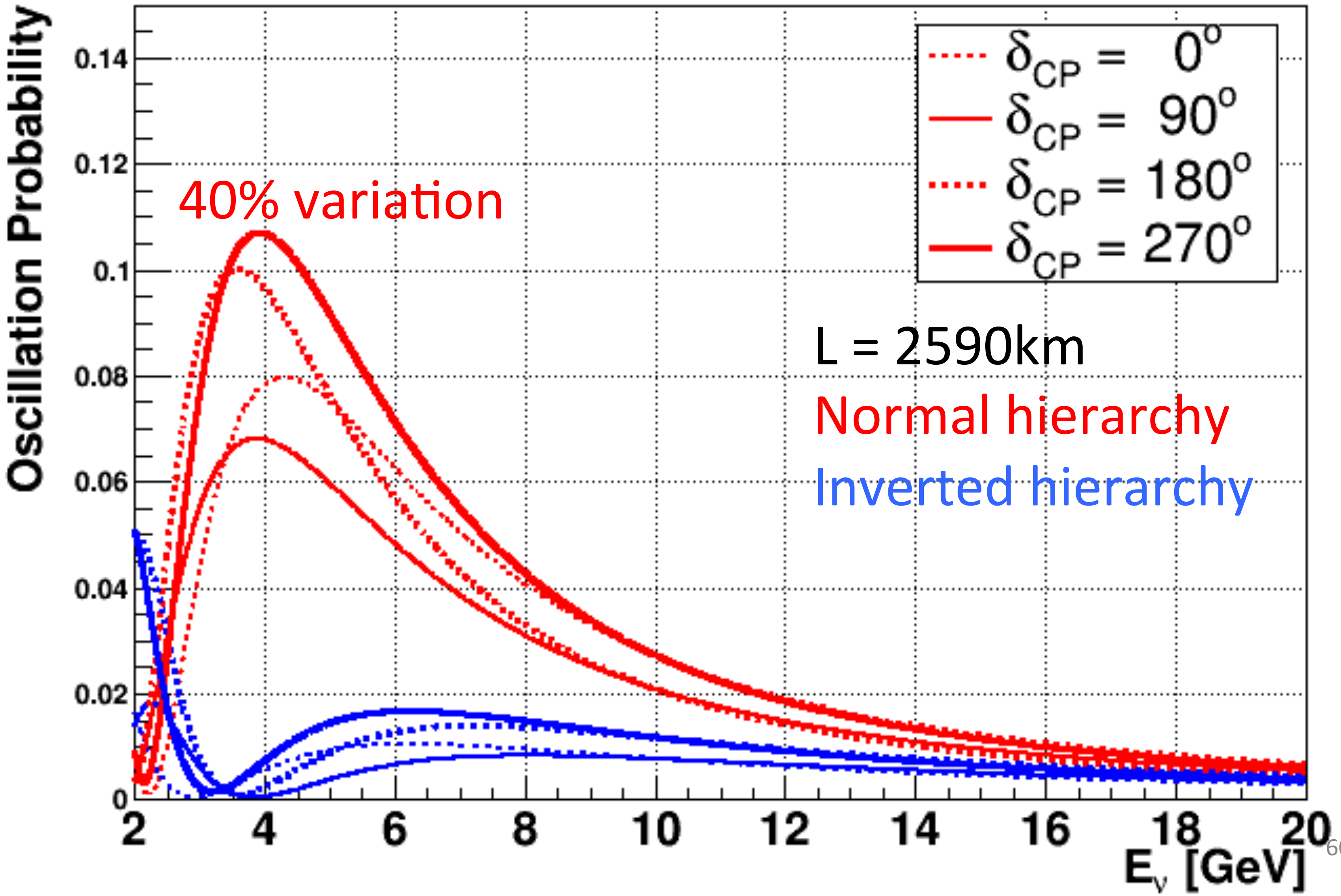




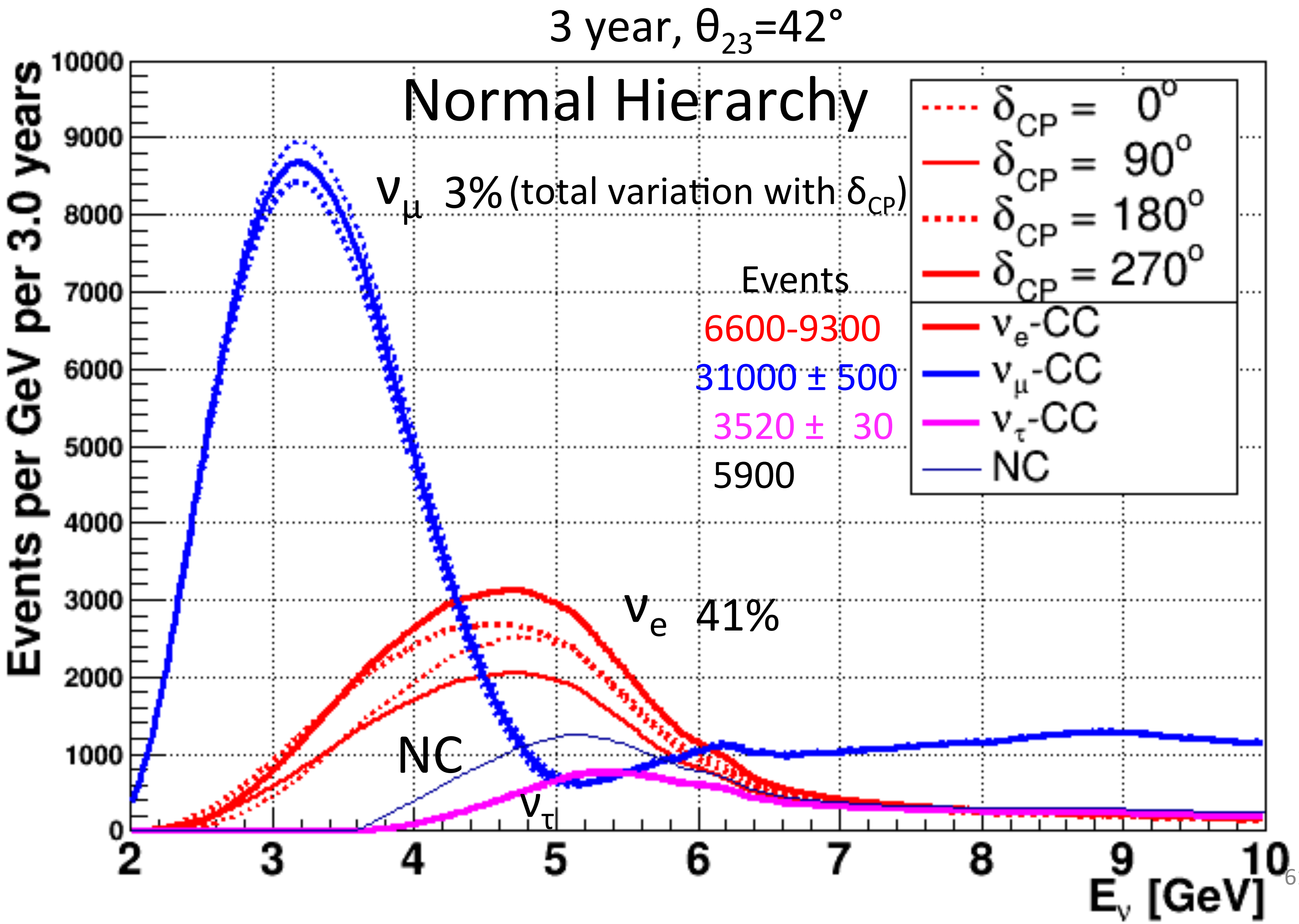
At 10 GeV:

- 90% correct identification of ν_e^{CC}
- 70% correct identification of ν_μ^{CC}

Oscillation Probabilities $P(\nu_\mu \rightarrow \nu_e)$

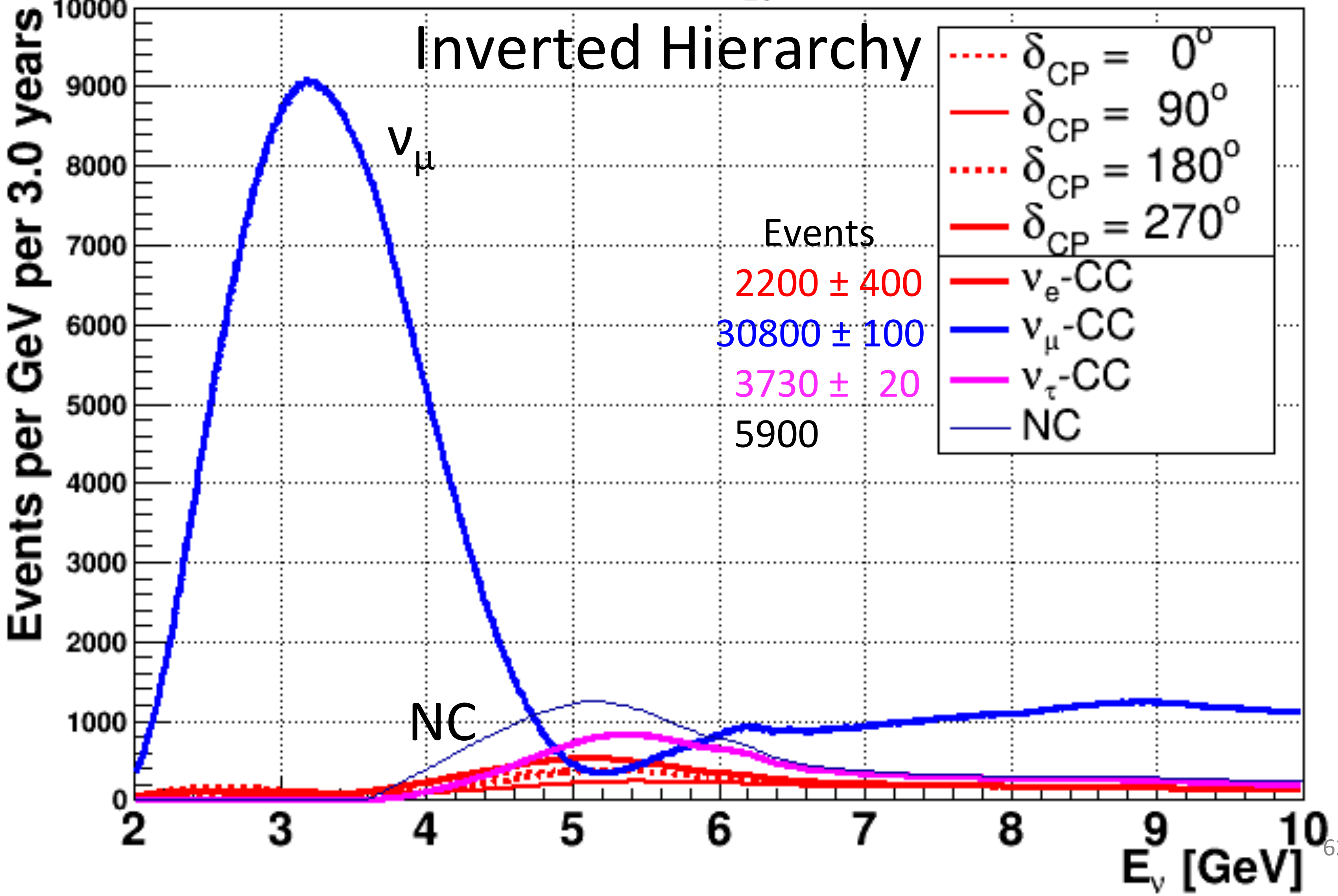


Event numbers – Neutrino Beam



Event numbers – Neutrino Beam

3 year, θ_{23}=42°



Modified Multi-Parameter fit

- Combined fit of nuisance and oscillation parameters
- Choice of nuisance parameters and priors inspired by LBNO study
- No neutrino/anti-neutrino skew
- No spectral index skew
- No energy scale shift

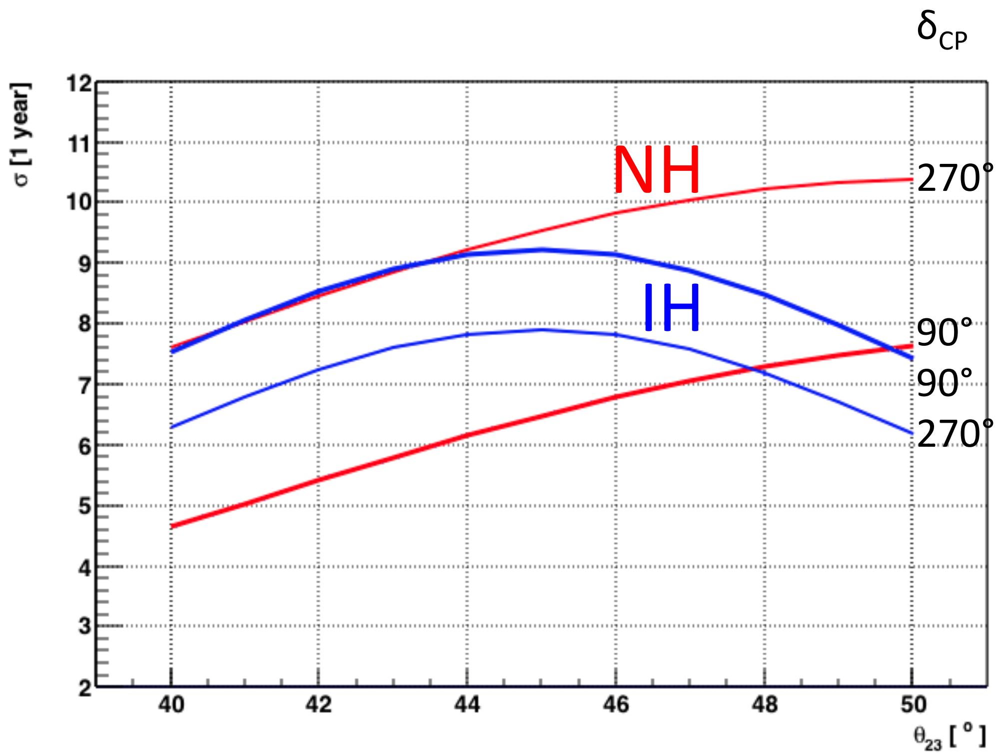
Parameter	True value	Prior	Start value
θ_{12}	33.4°	fix	fix
Δm^2 [eV^2]	7.53 10^{-5}	fix	fix
θ_{13}	8.42°	0.15°	8.42°
θ_{23}	41.5°	1.3°	41.5°
ΔM^2 [eV^2]	2.44 10^{-3}	0.06	2.44 10^{-3}
δ_{CP}	many	no	many

Only used for CP fits, not for NMH

Parameter	True value	Prior	Start value
Norm ν_e CC	from ν_μ CC	fix	fix
Norm ν_μ CC	1	0.05	1
Norm ν_τ CC	1	0.10	1
Norm NC	1	0.05	1
PID	1	0.10	1

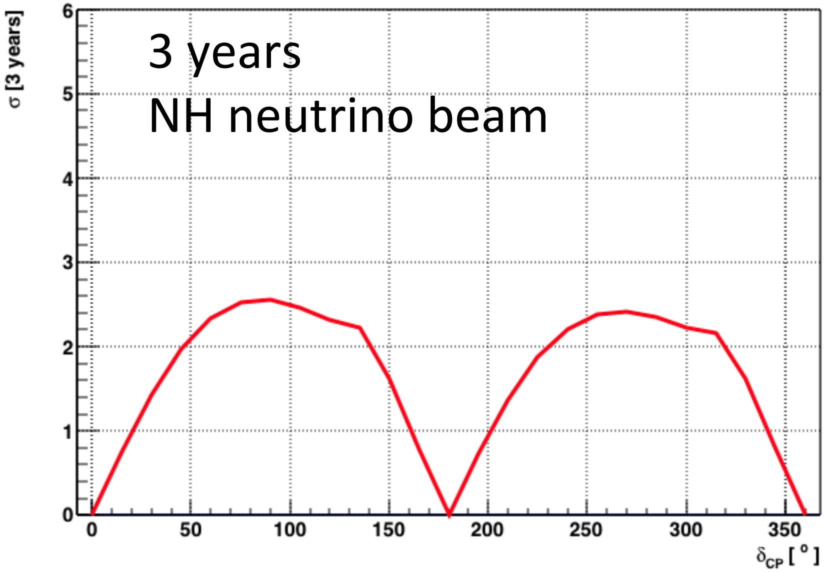
NMH determination

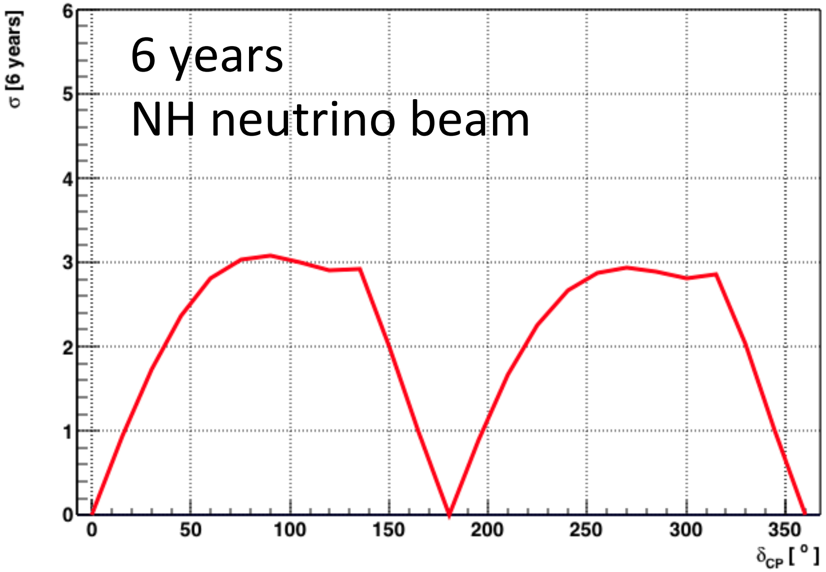
- ORCA detector, 1 year neutrino beam
- Better than 5σ for all combination of parameters



Sensitivity to δ_{CP}

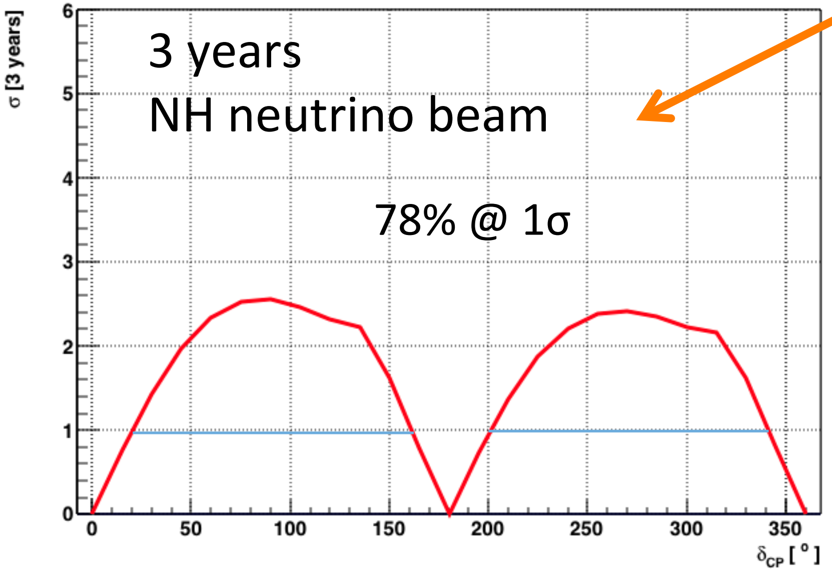
- Sensitivity of measuring non-zero CP-violation, i.e. δ_{CP} different from 0° AND 180°
- After 6 years non CP-violation excluded for 35% of δ_{CP} values at about 3σ

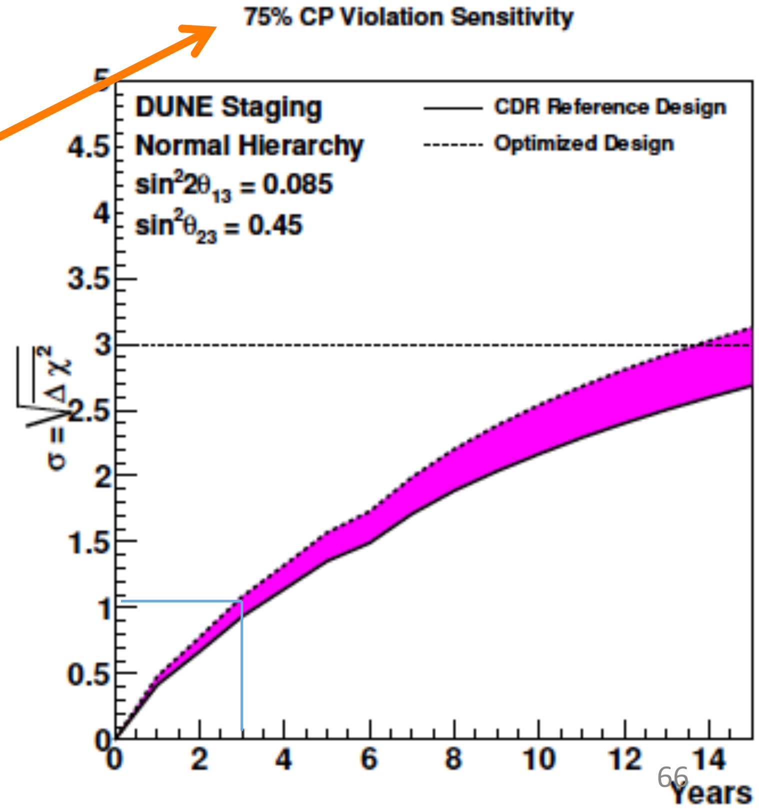




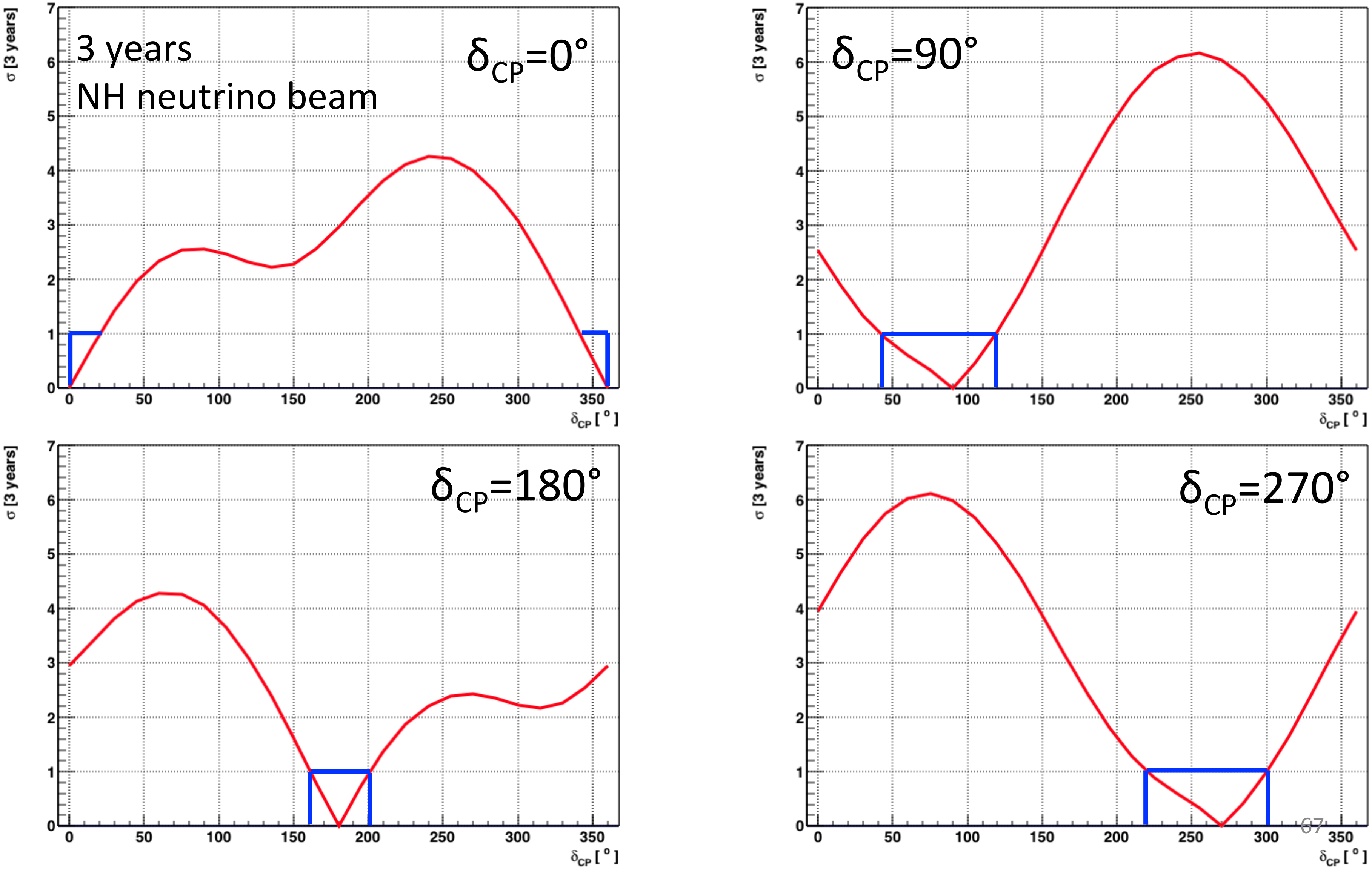
Comparison to DUNE CDR

- https://arxiv.org/abs/1601.05471
- CP violation after 3 years → ORCA comparable



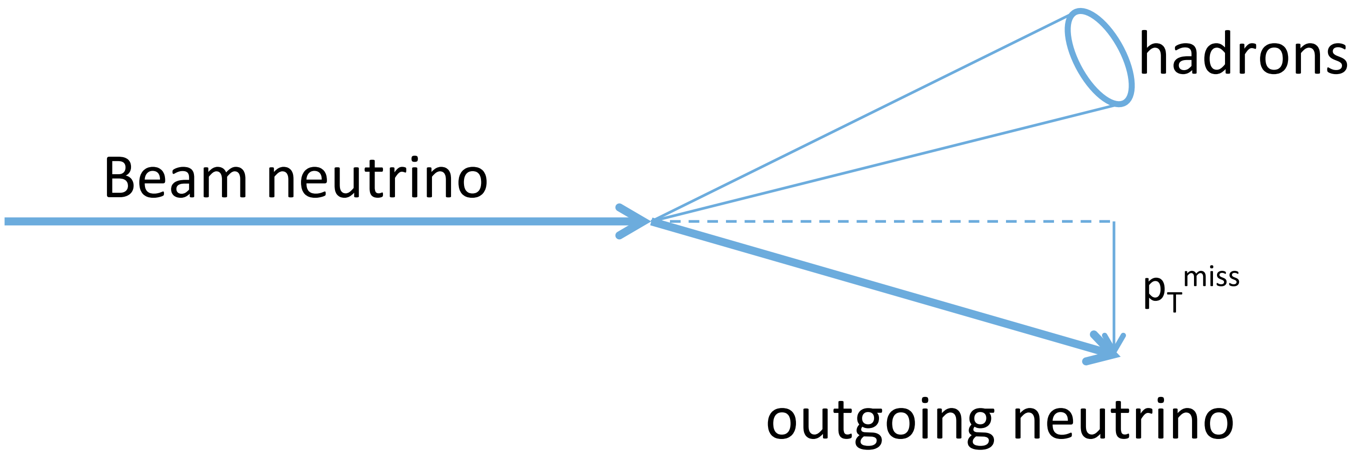


Measurement of δ_{CP}



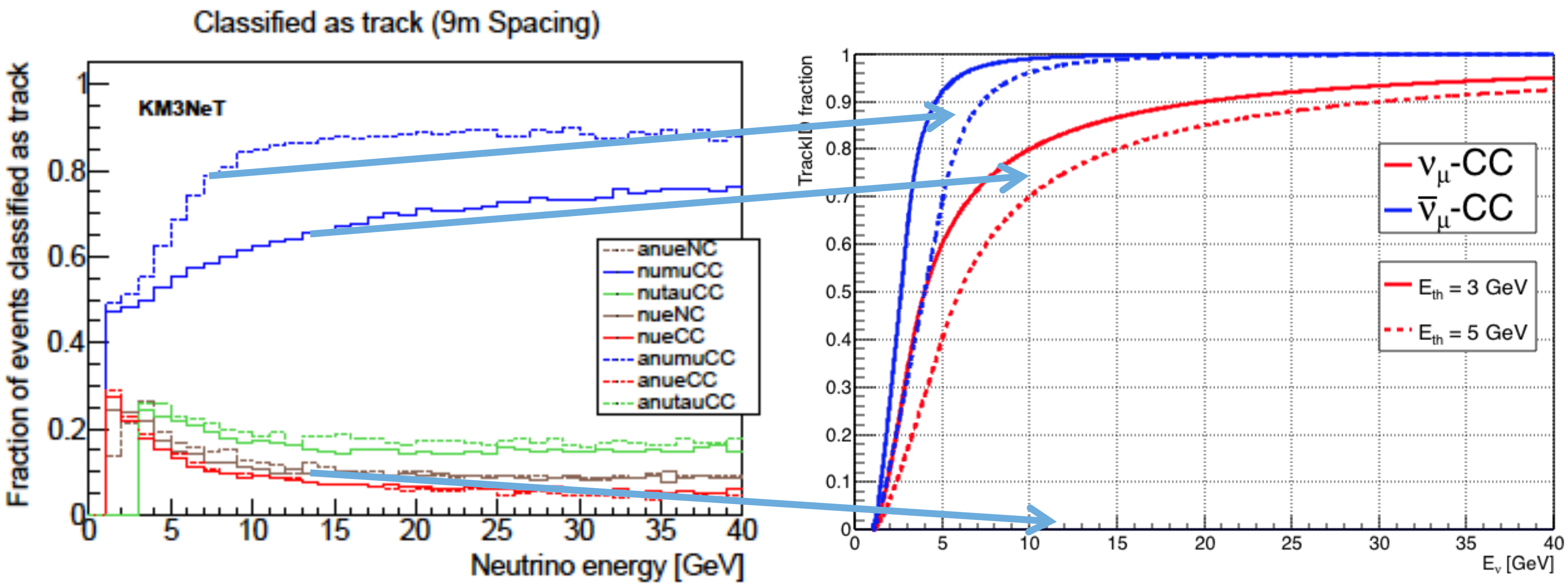
Where to go from here ?

- beam neutrinos ←→ atmospheric neutrinos
  - Arrival direction known
  - Background free due to short beam spill
- → new analysis chain to be developed
- Example : identify NC by "missing p_T"



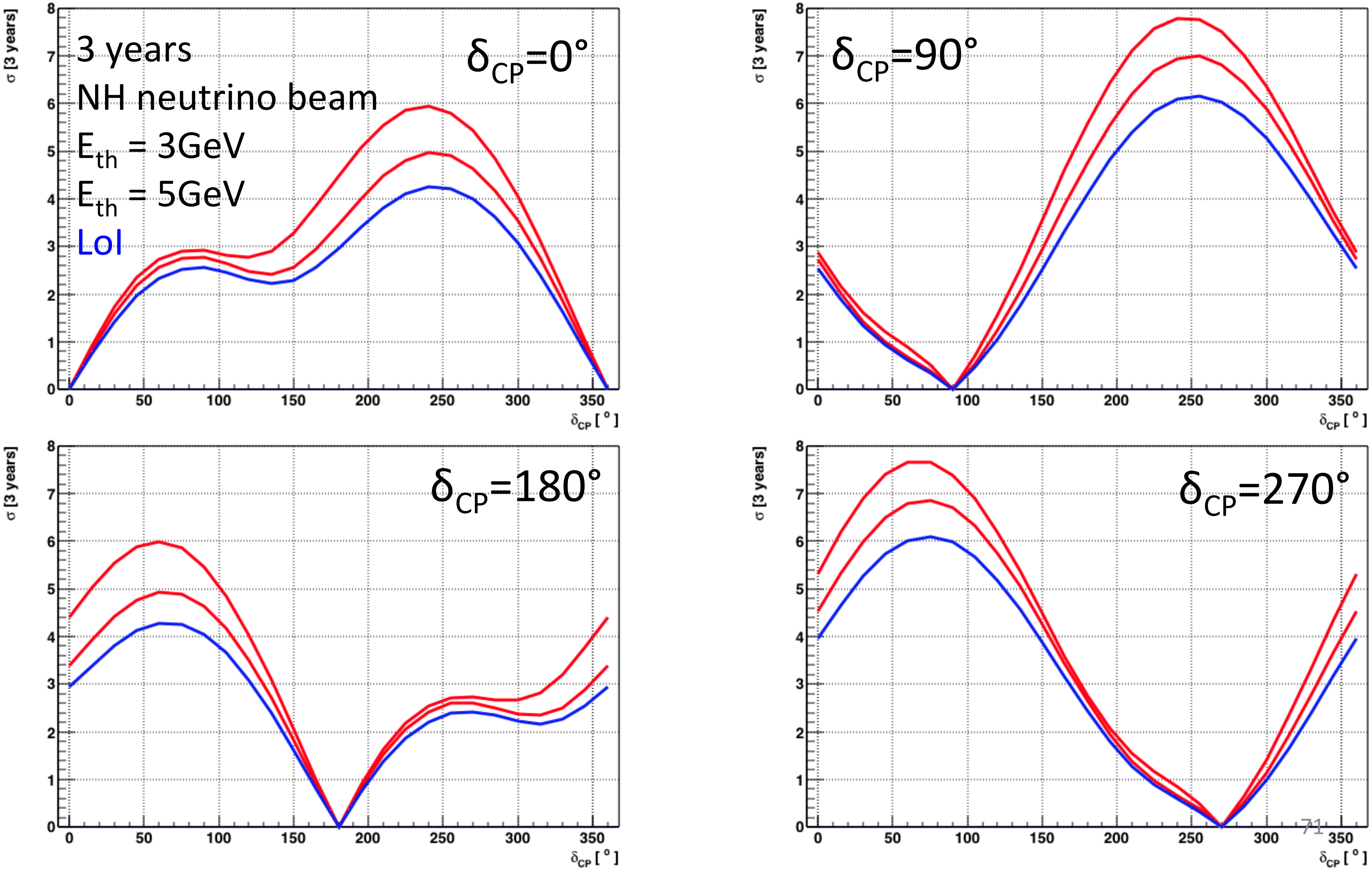
Track Identification improvement

Assume that muons can be identified 100% above E_{th}
Linear decrease of performance below E_{th}



Different behaviour of neutrino and anti-neutrino due to difference in momentum transfer to hadronic system (Bjorken-y)

Improvement in δ_{CP} determination



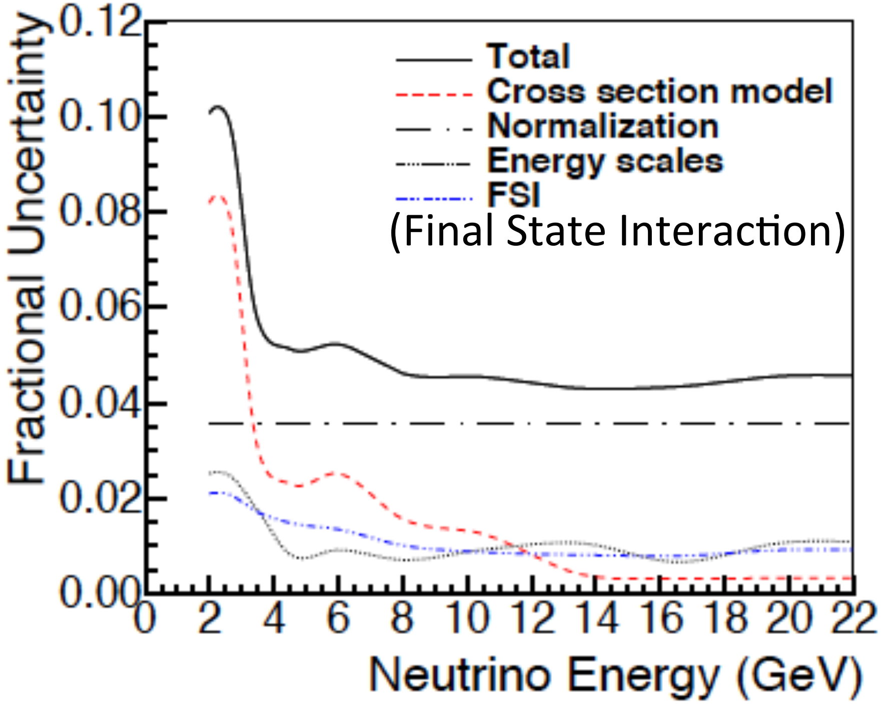
Comparison of Future projects

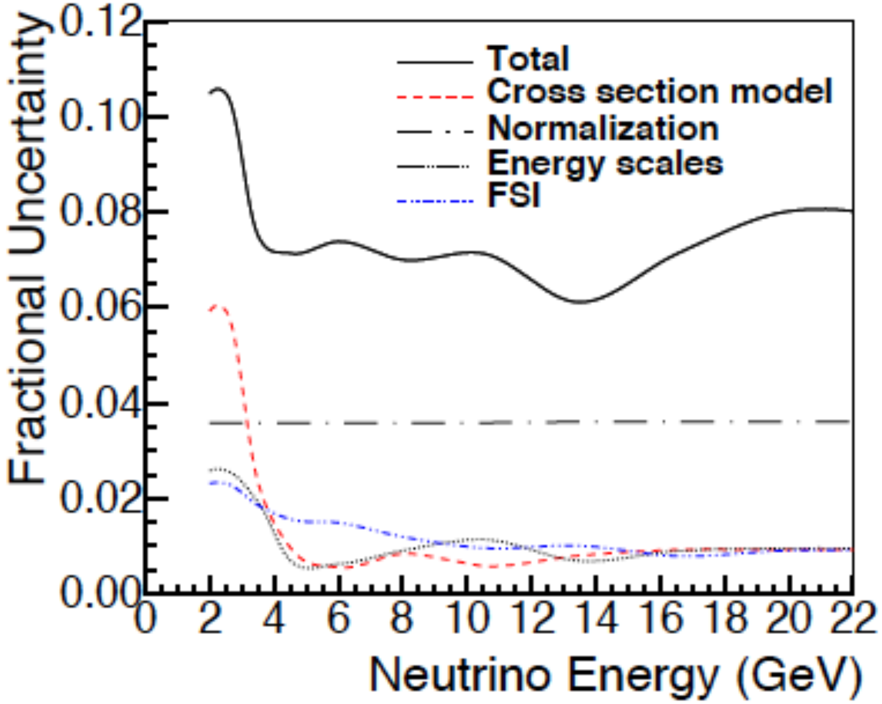
- Advantages / challenges are complementary

Experiment	Baseline Energy	Detector	Advantages	Challenges
Dune	1300km 2.4 GeV	Liquid Ar 40 kton	Resolution Particle ID	Technology Scalability
HyperK	295 km 0.6 GeV	Pure Water 0.3 Mton	Proven concept	Cavern, phototube production
P2O	2600km 5 GeV	Sea Water 8 Mton	Low cost High statistics	Particle ID

Cross section

- Below 3 GeV uncertainty explodes





Minerva arXiv:1701.04857

Roadmap for the international, accelerator-based neutrino programme

The ICFA Neutrino Panel

arXiv:1704.08181

4.3. Detector Development

4.3.7 Deep sea multi-Megaton detectors

[106] C. Vallee, "Pacific Neutrinos: Towards a High Precision Measurement of CP Violation ?," 2016. http://inspirehep.net/record/1494807/files/arXiv:1610.08655.pdf.

[107] J. Brunner, "Counting Electrons to Probe the Neutrino Mass Hierarchy," arXiv:1304.6230 [hep-ex].

[108] KM3Net Collaboration, S. Adrian-Martinez et al., "Letter of intent for KM3NeT 2.0," J. Phys. **G43** no. 8, (2016) 084001, arXiv:1601.07459 [astro-ph.IM].

Physics goals

The concept for a detector that exploits a large volume of sea water to produce a multi-megaton-scale detector illuminated by a powerful neutrino beam has been described in [106]. The KM3NeT collaboration is currently validating second generation, compact, modular instrumentation that is suited for the detection in sea water of neutrinos with energies of a few GeV [107, 108]. This technology would allow volumes of order tens of Megatons to be instrumented. Such a large detector located at a sufficiently long baseline (≥ 2500 km to yield a first oscillation maximum above ~ 5 GeV) would have the potential to measure oscillation parameters with high precision.

Opportunities for such programs would rely on the feasibility of a neutrino beam from, for example, Fermilab to the existing infrastructures NEPTUNE and OOI offshore of British Columbia, which have been established as deep-sea observatories; this project is referred to as the "Pacific Neutrinos" project [106]. Alternatively, a beam might be sent to the KM3NeT/ORCA detector that is being developed offshore of Toulon (see 6.1.4). To assess the potential of such configurations, quantitative studies must be performed with an optimised detector configuration. An in-situ validation of the technology with the ORCA detector should be carried out, prototypes should be deployed in NEPTUNE/OOI and an investigation of the characteristics of the deep-sea candidate sites should be carried out.

Conclusion

- Running ORCA in a neutrino beam is promising
- First high statistics long baseline experiment

- NMH determination better than 5σ after 1 year
- Neutrino/anti-neutrino mode decided rom NMH
- No need to run both polarities !

- CP phase well measured after 3 years

What next ?

- Project in transition phase : Crazy dream → real project

- Fruitful collaboration with IHEP Protvino established
- → Strong interest from Russian site

- Various funding requests for detailed performance studies launched for 2018
  - ANR / DFG
  - Marie Curie fellowship
  - ERC
- Final goal : Letter of Intent within ~2years

P2O ←→KM3NeT

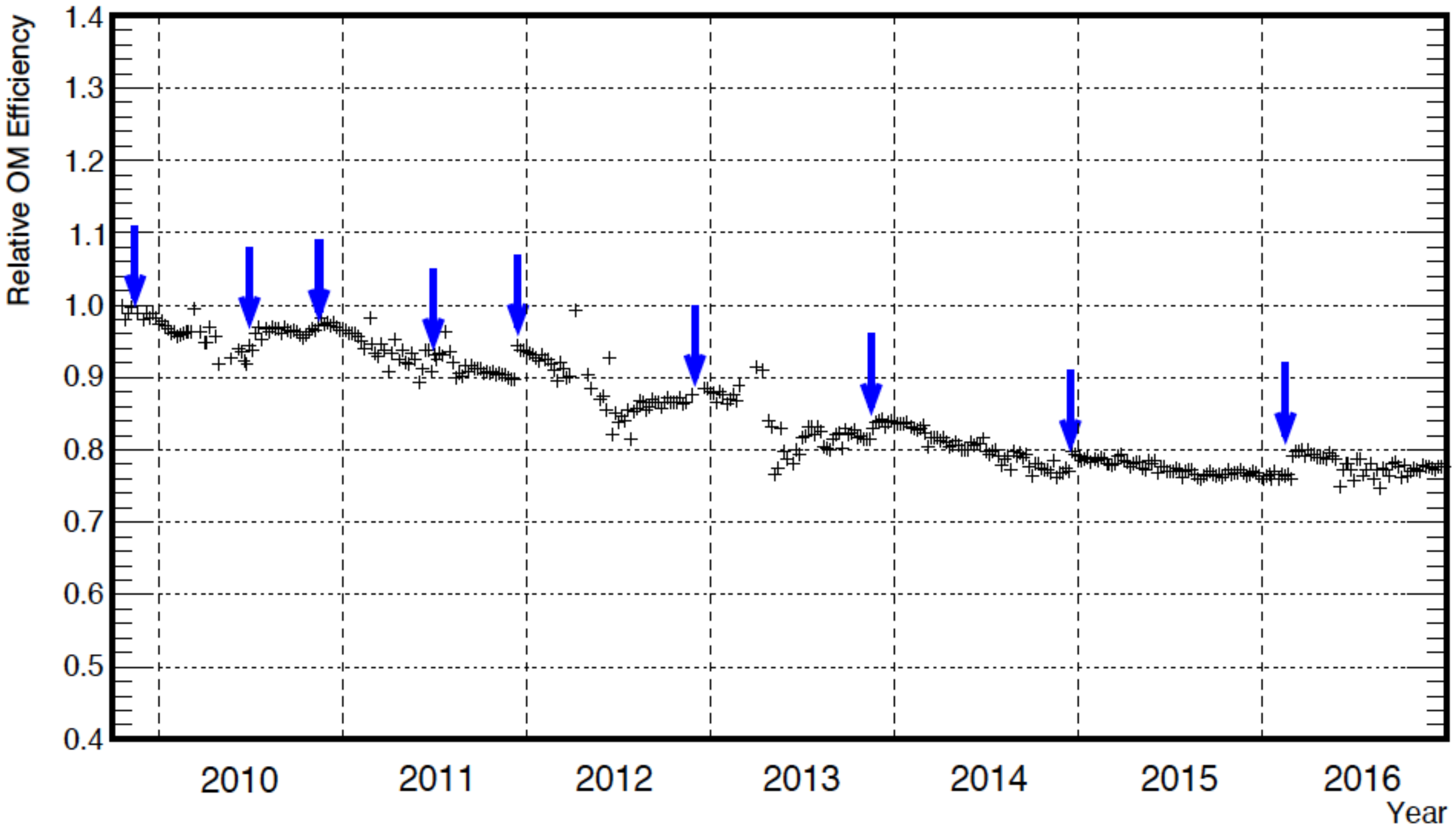
- Relation to be defined
- P2O supported in KM3Net by various groups
  - CPPM (FR), APC (FR), NIKHEF (NL), ECAP (Dt)
- Might become an independent collaboration
  - See Superk ←→T2K

- Seeking new collaborators
  - even groups which do NOT want to join KM3NeT (!)
- Possible to make significant contributions
  - Near detectors
  - Beam monitoring
  - Intensity upgrade beam
  - Super-ORCA
  - independent analysis chain

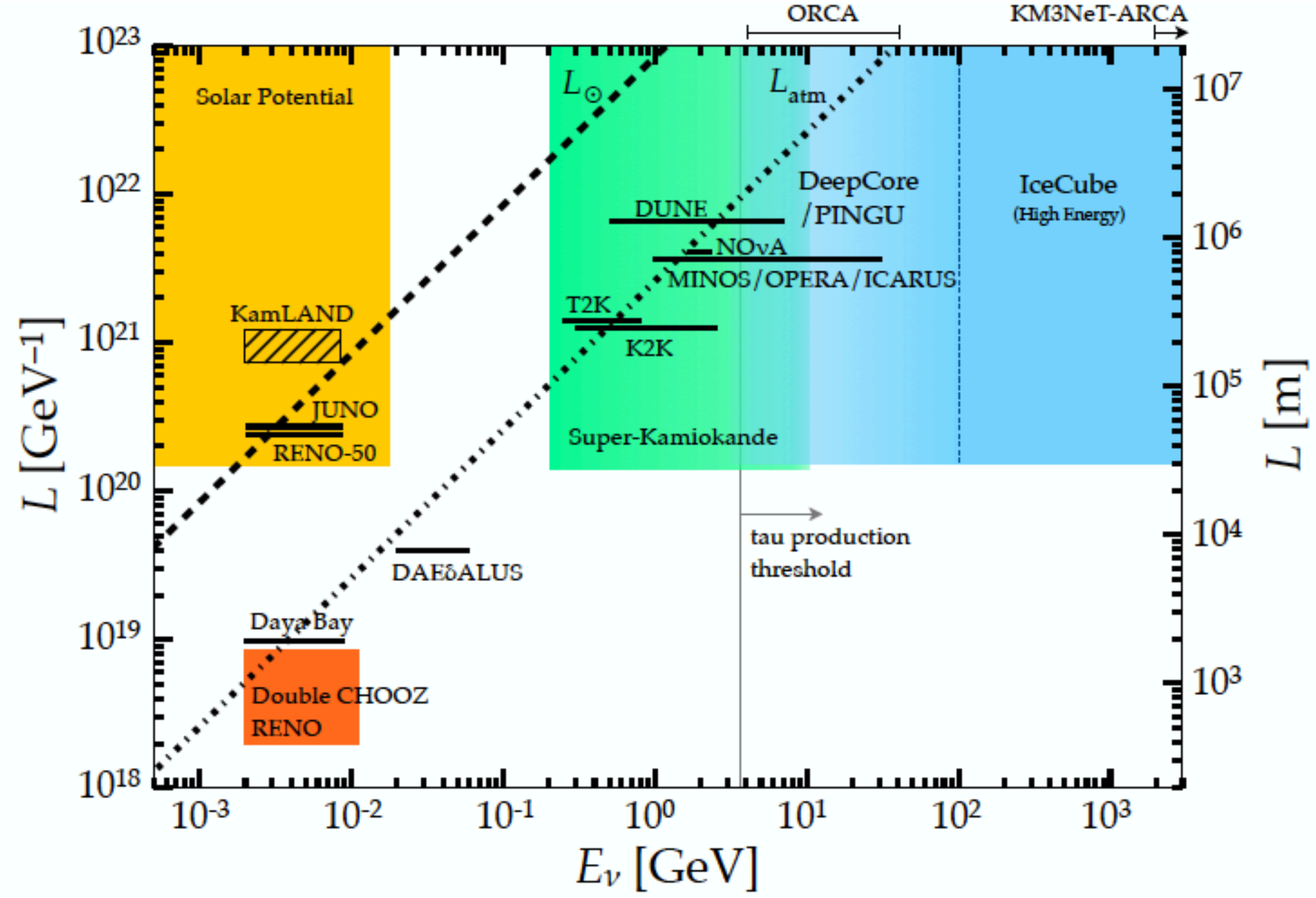
Backup

Antares Optical Module Efficiencies

- After 7 years, 20% drop (blue : HV tuning)
- Long-term operation in deep sea possible



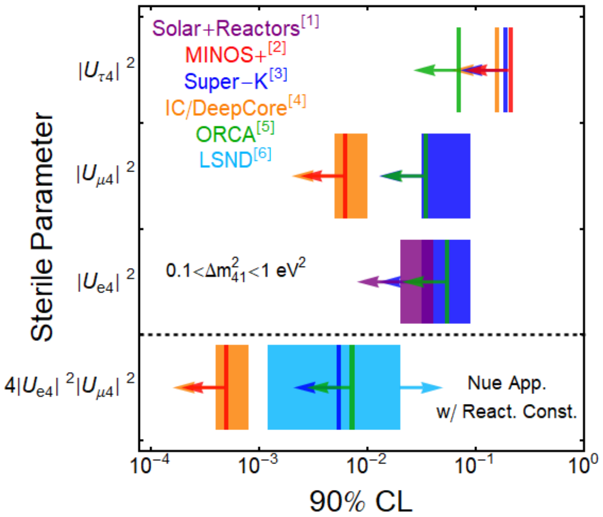
ORCA: Oscillation Physics



Baselines and energies inaccessible to LBL or reactor neutrino experiments
Very different systematics
Above tau production threshold

ORCA Post LoI: Sterile, NSI, Tomography

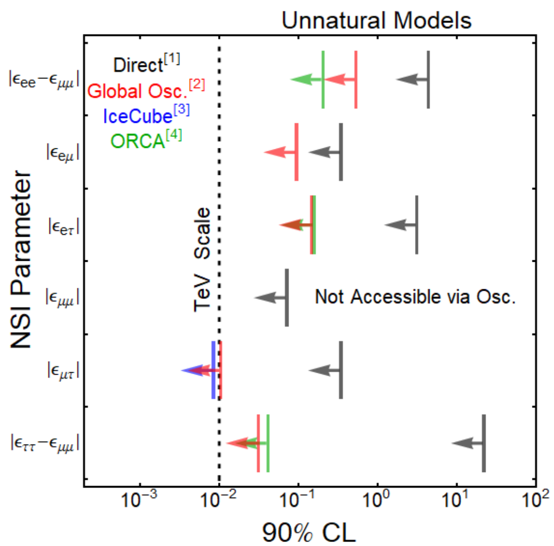
Sterile Neutrinos



Good sensitivity in $U_{\tau 4}$ mixing

Factor of two better sensitivity cf current limits from SK and IC after only 1 year of data taking

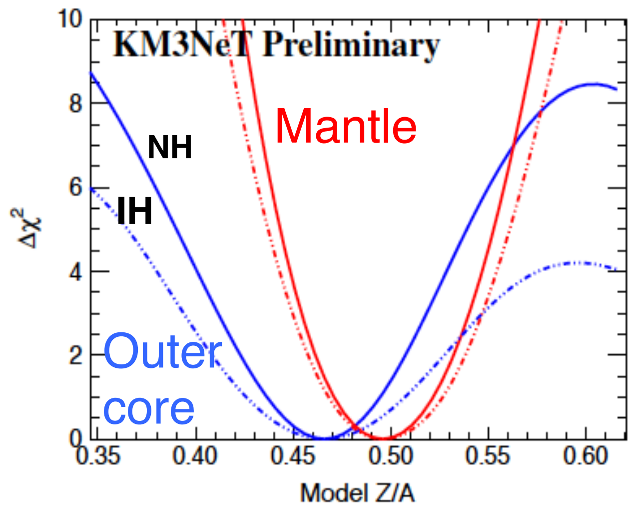
Non-Standard Interactions



ORCA sensitive to NSI effects ≈10% of the Fermi int.
Direct bounds are more than 10x larger in some cases
ORCA improves over current atmospheric scale bounds

Earth Tomography

10 year sensitivity (w systematics)



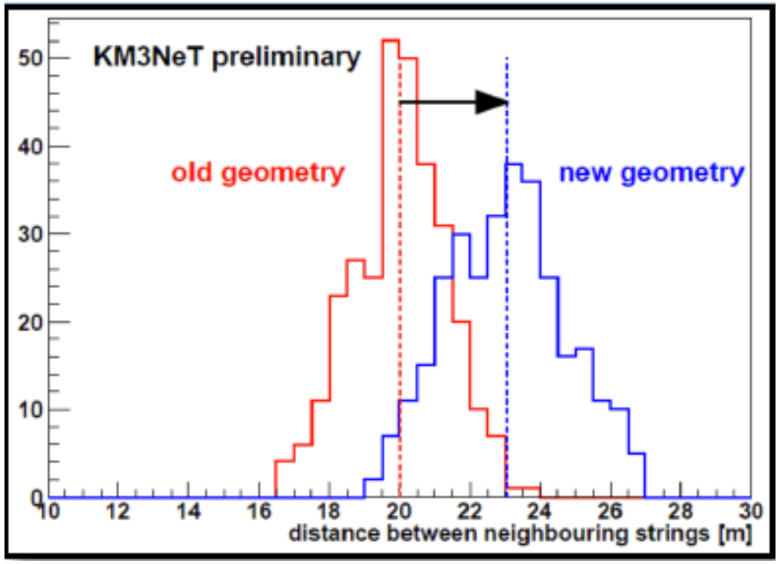
ORCA is sensitive to N_e geophysics measure ρ_m

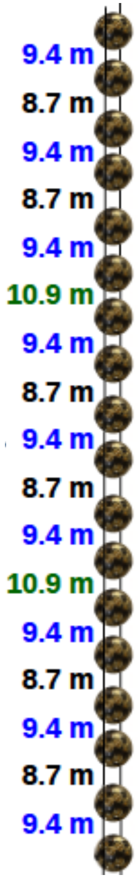
1σ stat.+ syst. Uncertainty:
5% in the whole mantle
6% in the whole outer core

ORCA Improvements: Geometry+Trigger

Geometry:

Geometry	Vertical spacing (between DOM)	horizontal spacing (between strings)
LoI-based [3]	9 m on average with alternate 6 m and 12 m	20 m
New	9 m	23 m



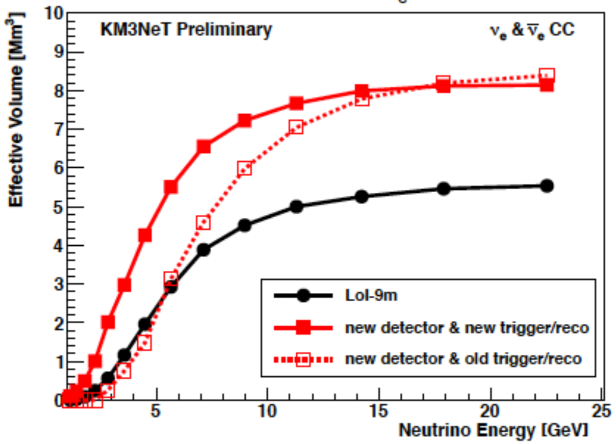


New “MX” trigger:

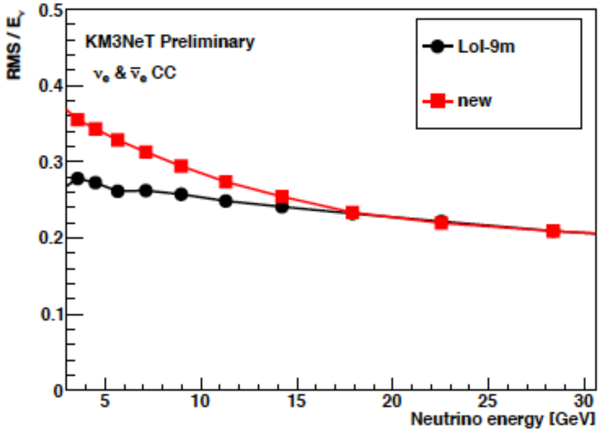
require one local coincidence (L1) + causally connected L0 hits on adjacent DOMs
trigger rate from pure noise remains marginal

ORCA Improvements: Effect on Reconstruction

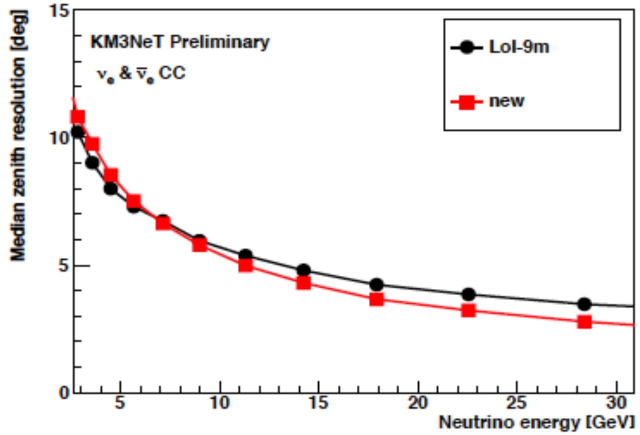
Effective volume – ν_e channel



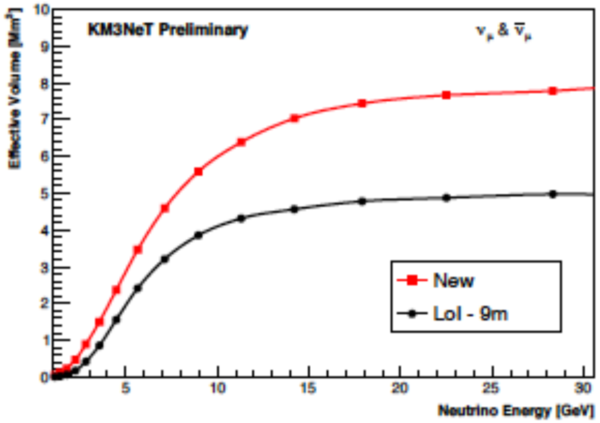
Relative energy spread



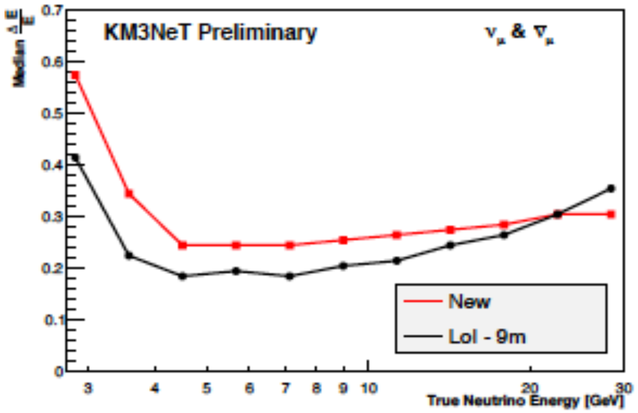
Median zenith error



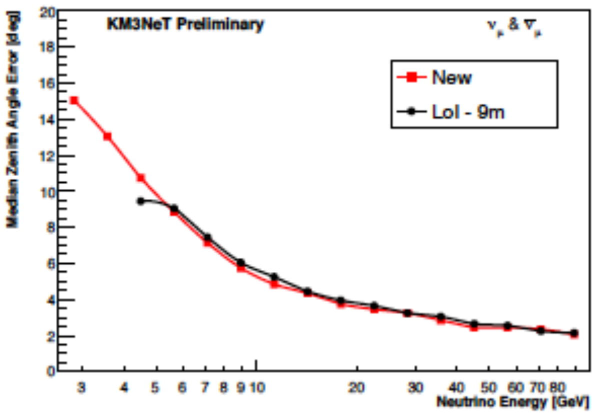
Effective volume – muon channel



Median energy error

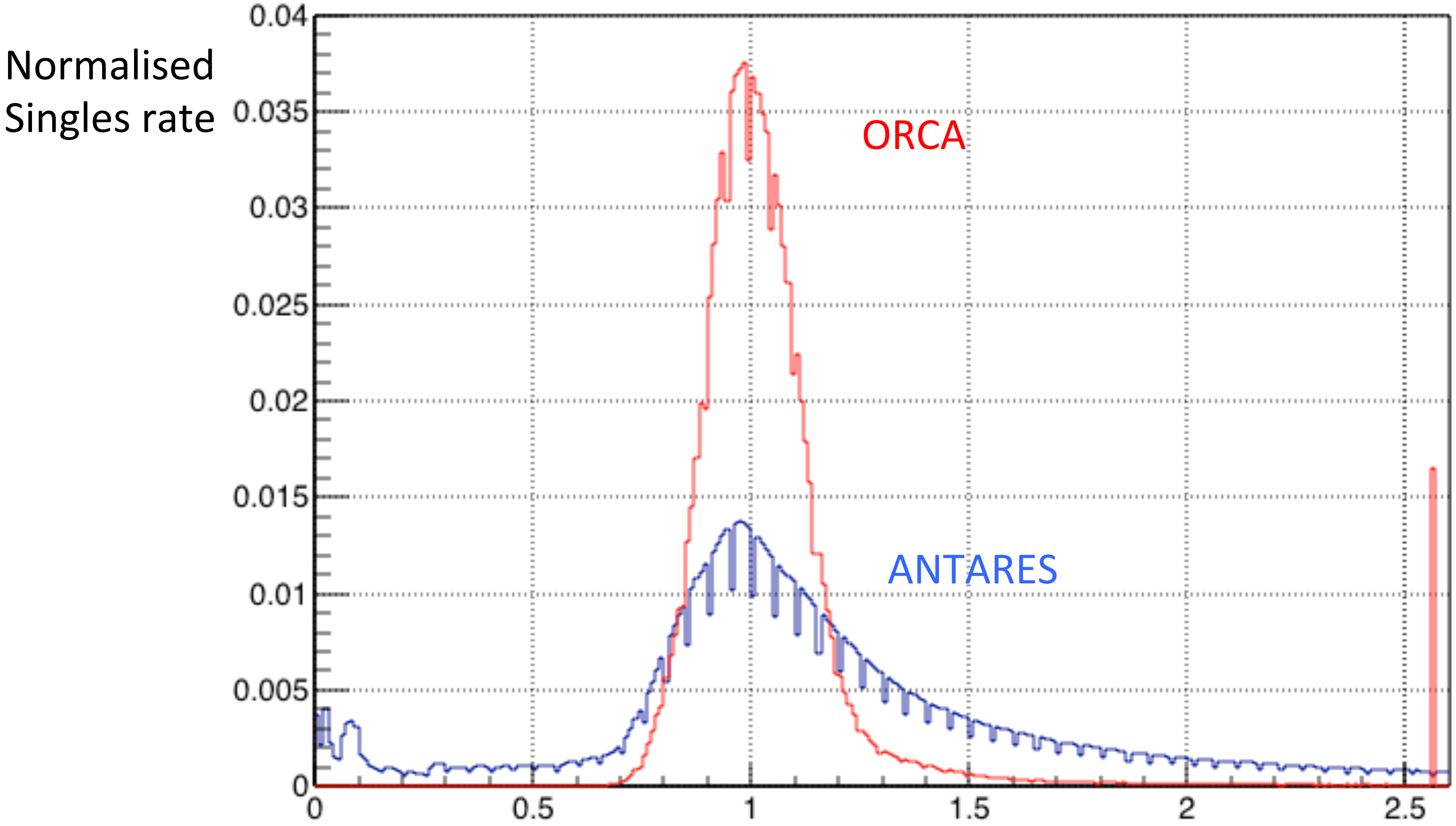


Median zenith error



Pending steps to evaluate new sensitivity :
Particle ID & atmospheric muon background MC

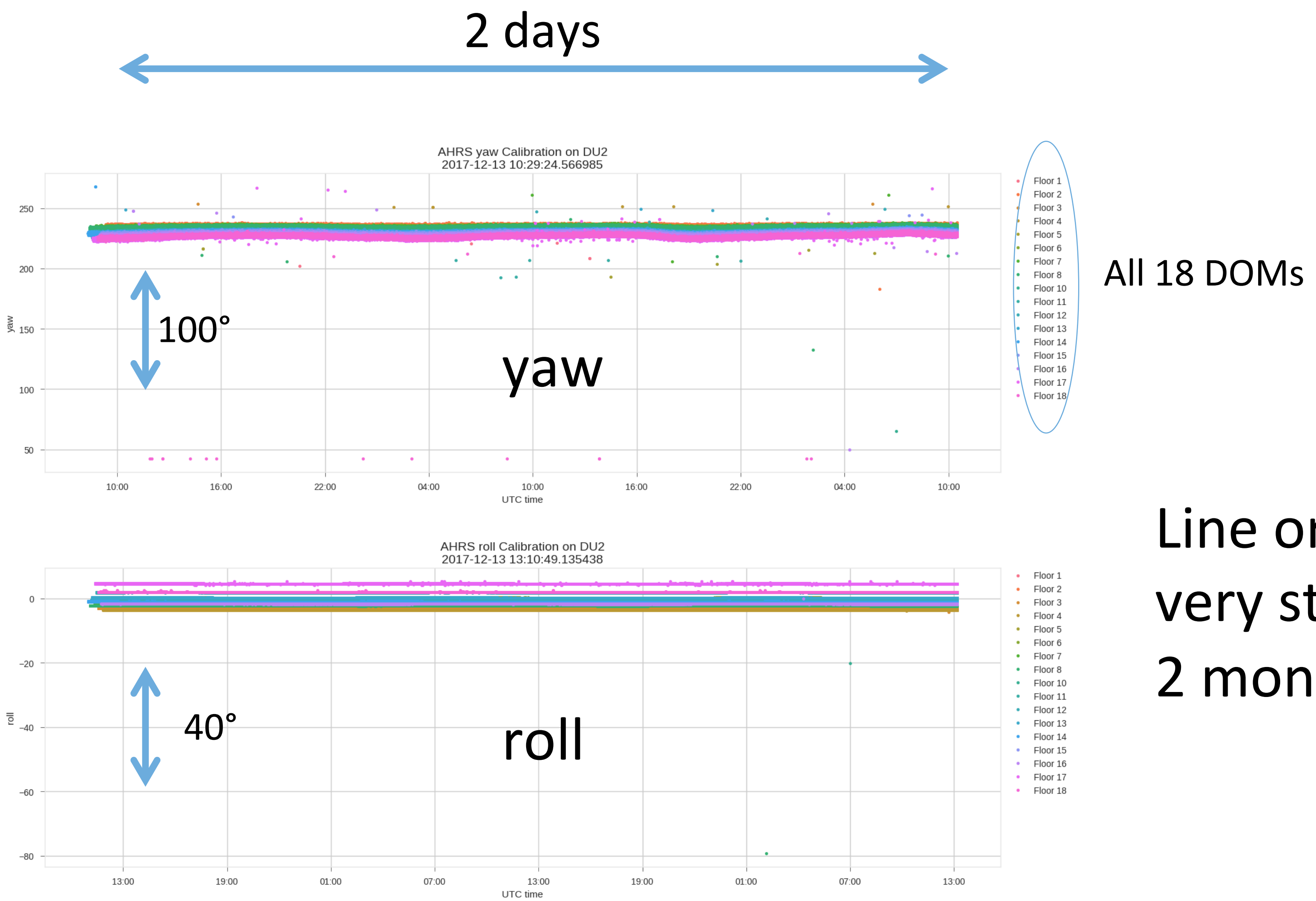
Singles rates: ORCA1 vs ANTARES



For same sea current ➔ less bioluminescence in ORCA cf ANTARES

85

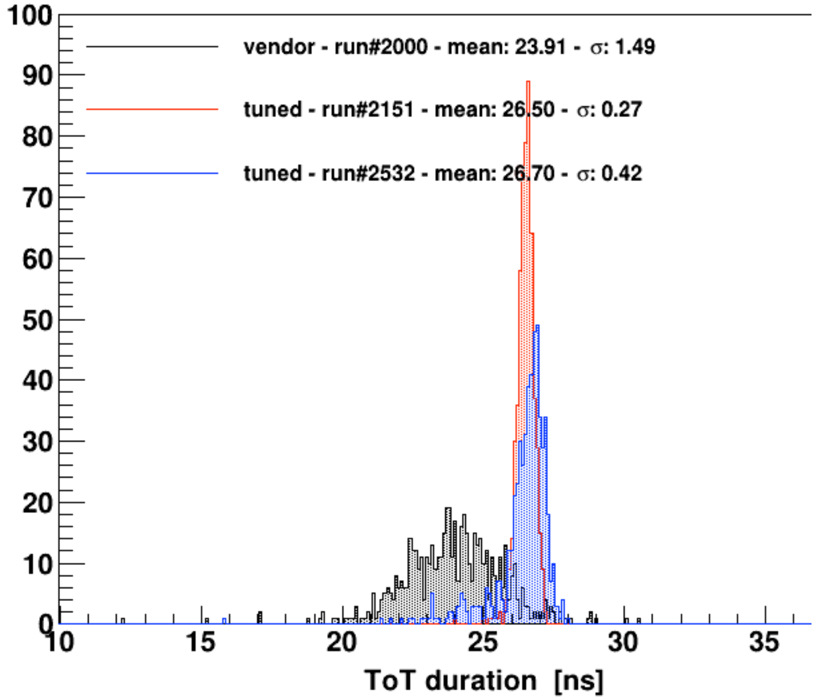
Compass Data

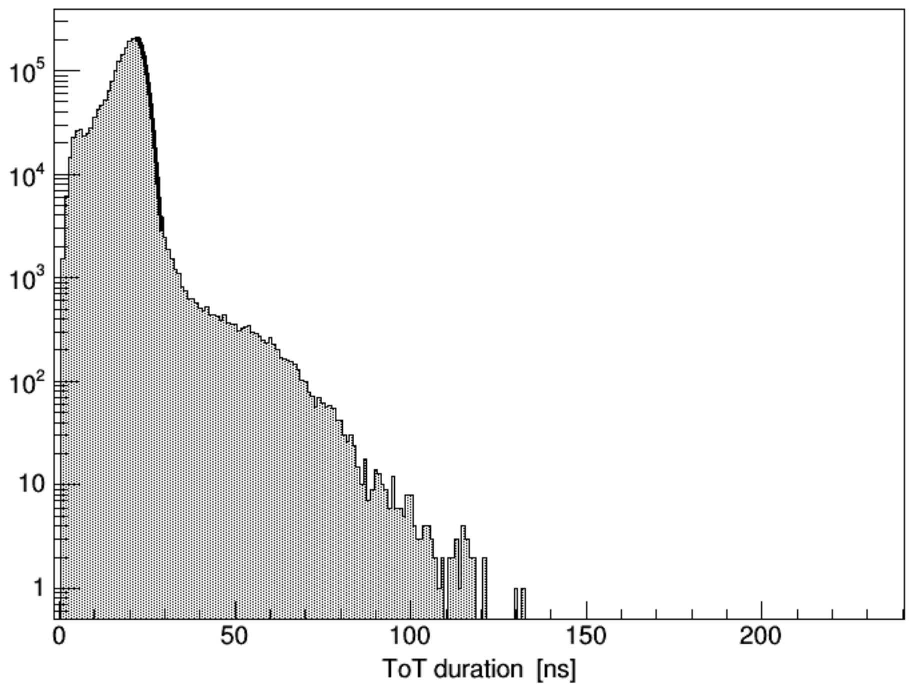


Line orientation very stable over 2 months

HV Tuning

Adjust individual PMT HV to obtain predefined ToT value (27nsec)

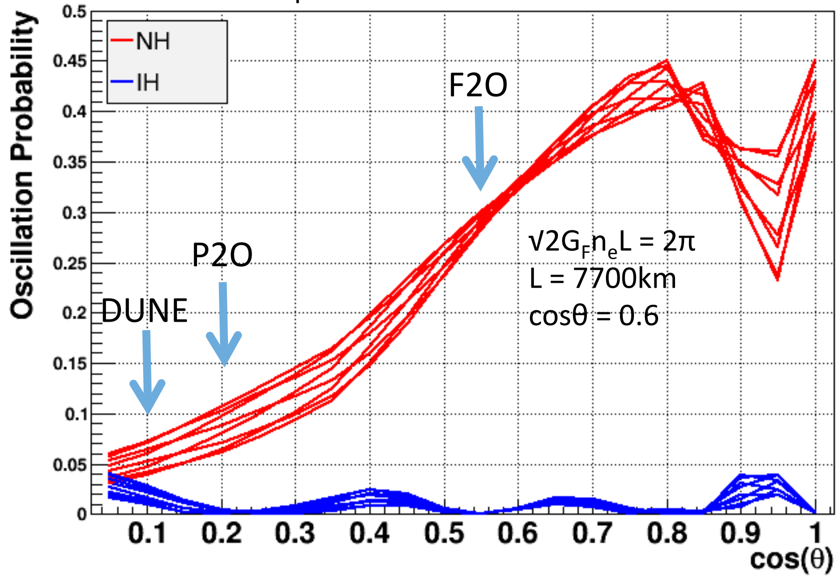


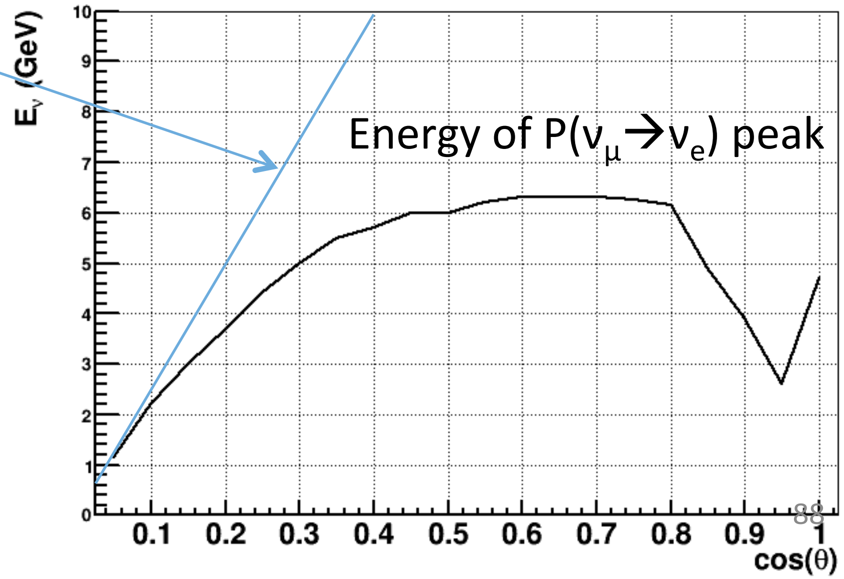


Which Baseline to measure δ_{CP} ?

- Optimal baselines to measure δ_{CP} between 1000 km and 4000 km
- Peak energy follows initially first oscillation maximum at
  $(1.27\ \Delta m_{32}^2\ E/L) = \pi/2$
  $E = 25\ \text{GeV} * \cos\theta$
- levels off at mantle resonance energy

$P(\nu_\mu \rightarrow \nu_e)$ at peak energy

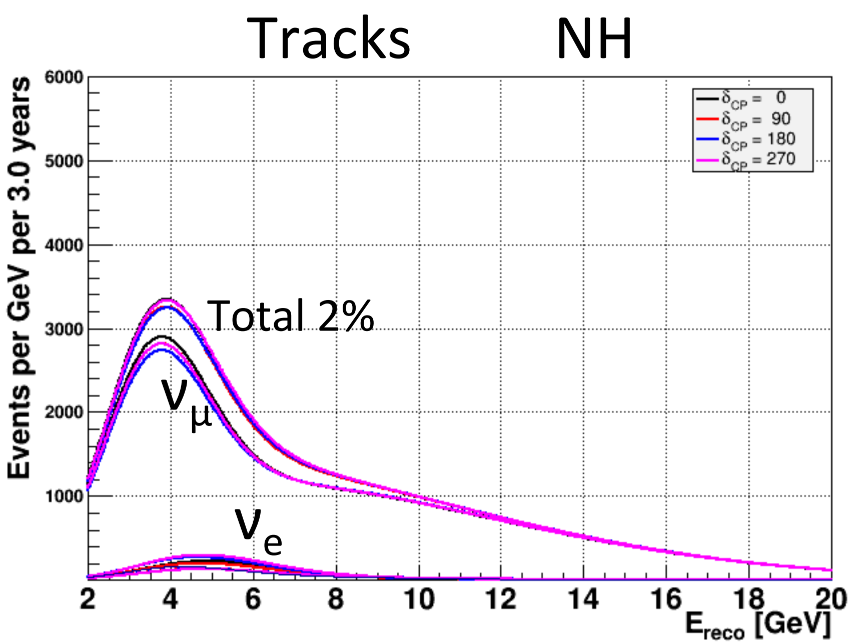


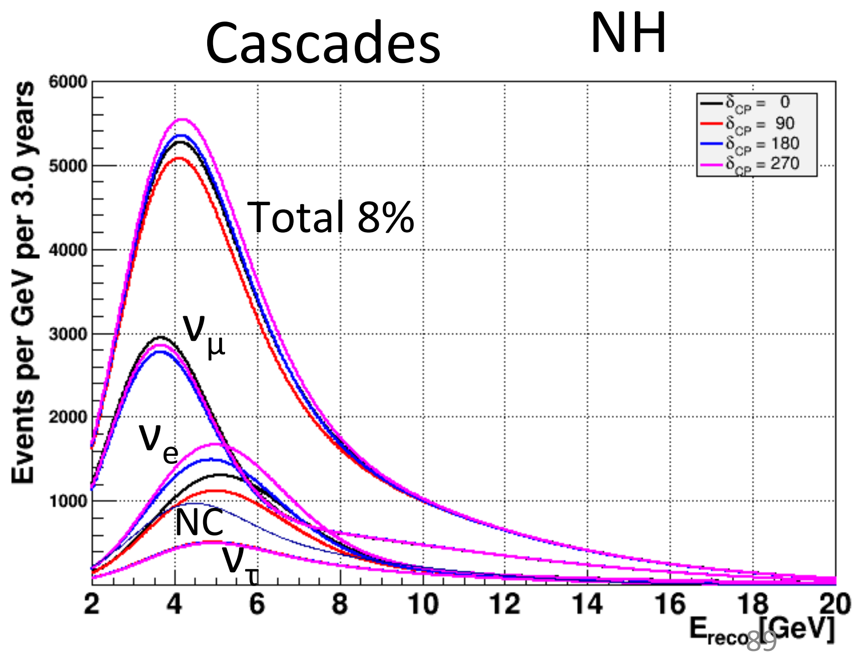


Events after PID

δ_{CP}	0°	90°	180°	270°
tot	20386	20065	20121	20432
ν_e	1021	904	1178	1294
ν_μ	17929	17717	17506	17709
ν_τ	677	685	679	671
NC	758	758	758	758

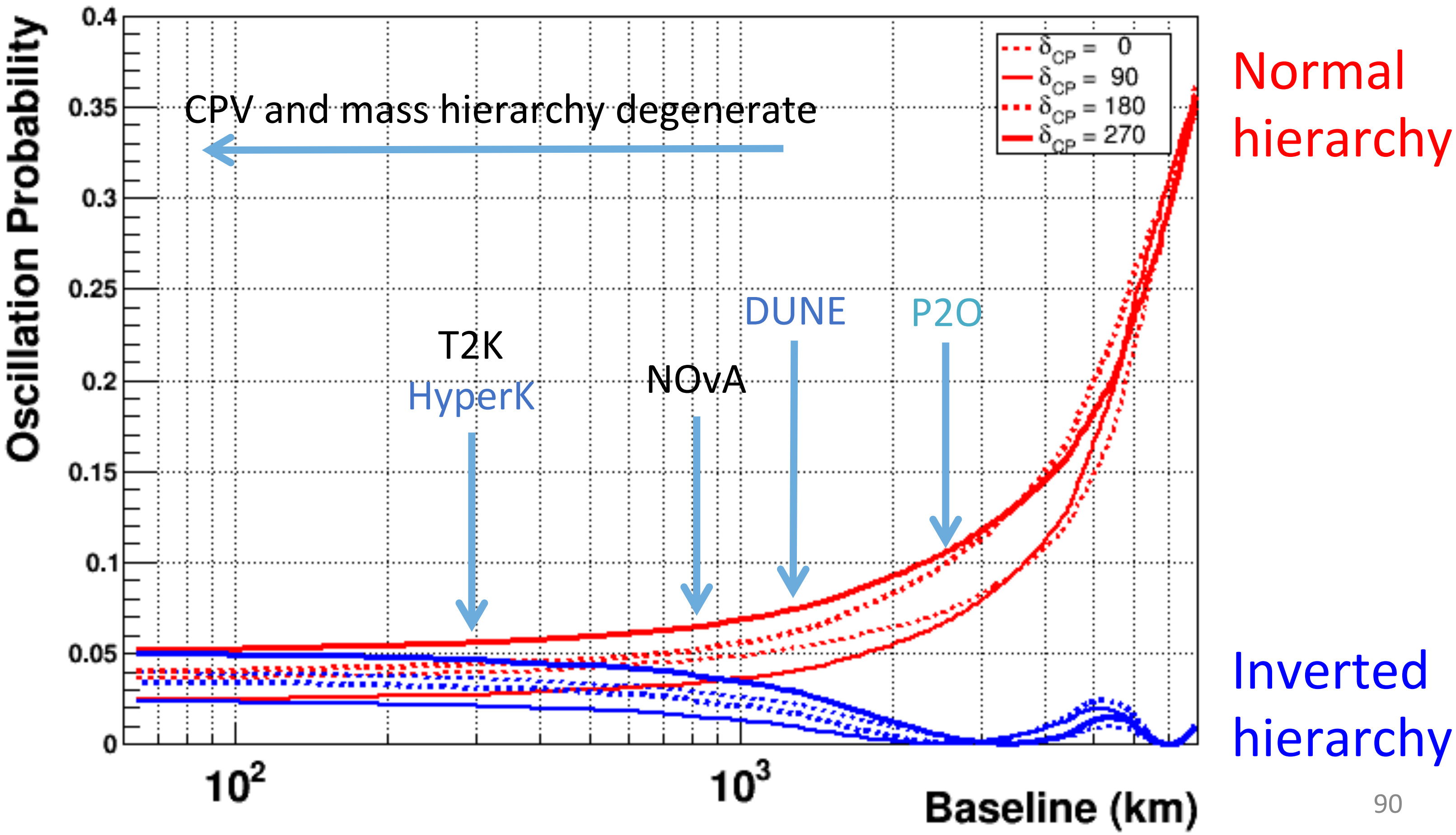
δ_{CP}	0°	90°	180°	270°
tot	28084	27016	28188	29246
ν_e	6570	5710	7142	8001
ν_μ	13509	13270	13034	13263
ν_τ	2842	2873	2848	2818
NC	5164	5164	5164	5164





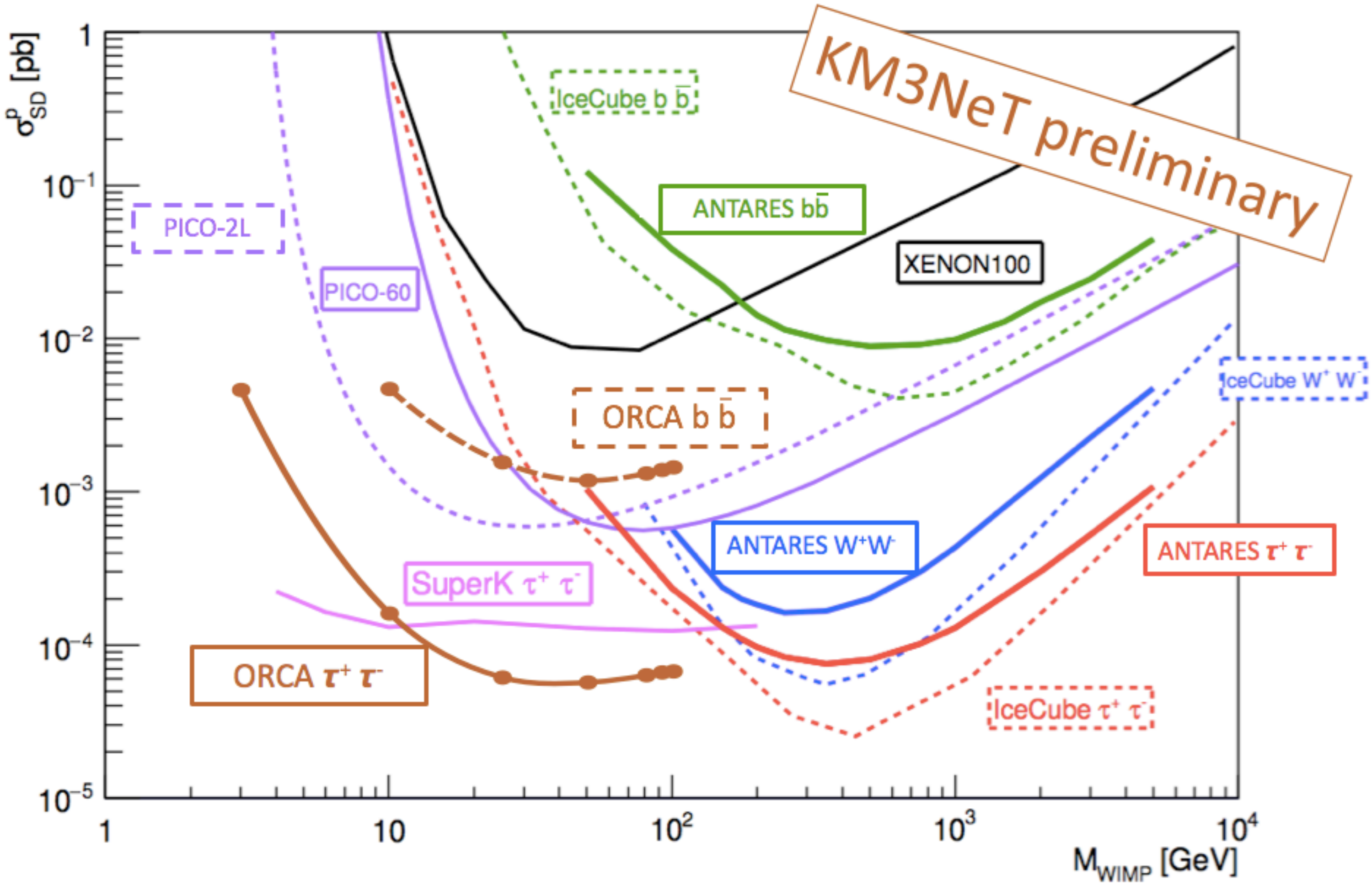
Comparison of LBL Projects

- Main Signal : Appearance of ν_e : $P(\nu_\mu \rightarrow \nu_e)$



ORCA Post LoI – Dark Matter

ORCA 3 years, track+showers
Competitive for Spin Dependent coupling



Neutrino Oscillations

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

Global fit – Normal hierarchy

$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5}\mathrm{eV}^2$

$\Delta m^2_{31} = 2.457^{+0.047}_{-0.047} \times 10^{-3}\mathrm{eV}^2$

$\theta_{12} = 33.48^{+0.78}_{-0.75}(^\circ)$

$\theta_{23} = 42.3^{+3.0}_{-1.6}(^\circ)$

$\theta_{13} = 8.50^{+0.20}_{-0.21}(^\circ)$

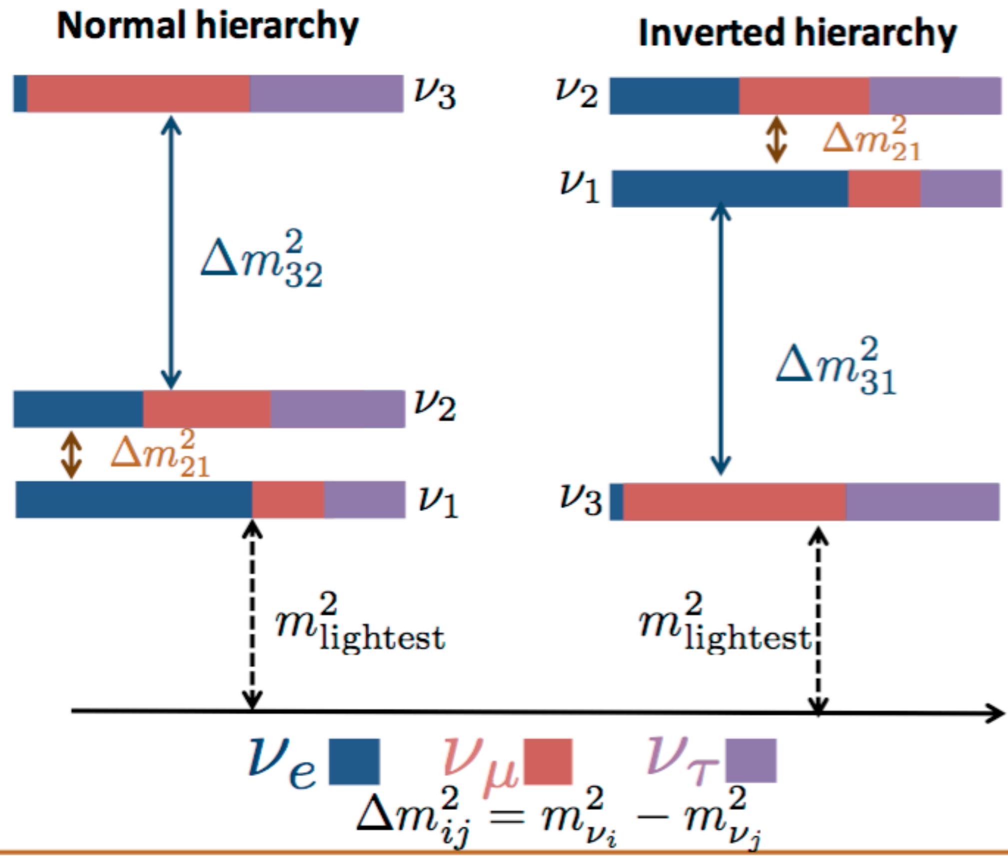
$\mathrm{sign}(\Delta m^2_{32}) = ?$

θ_{23} is maximal ?

$\delta_{CP} = ?$

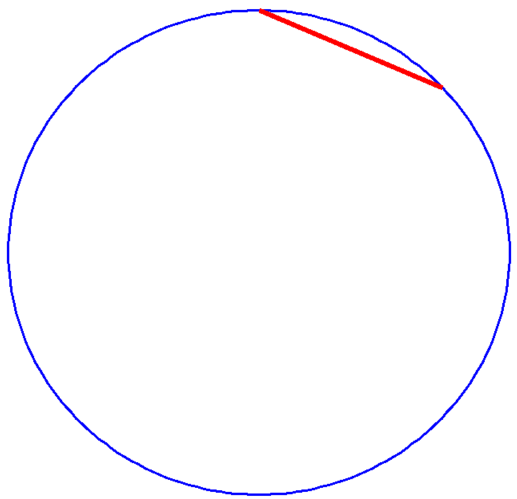
$m_{\mathrm{lightest}} = ?$

Gonzalez-Garcia *et al.*, arXiv:1512.06856



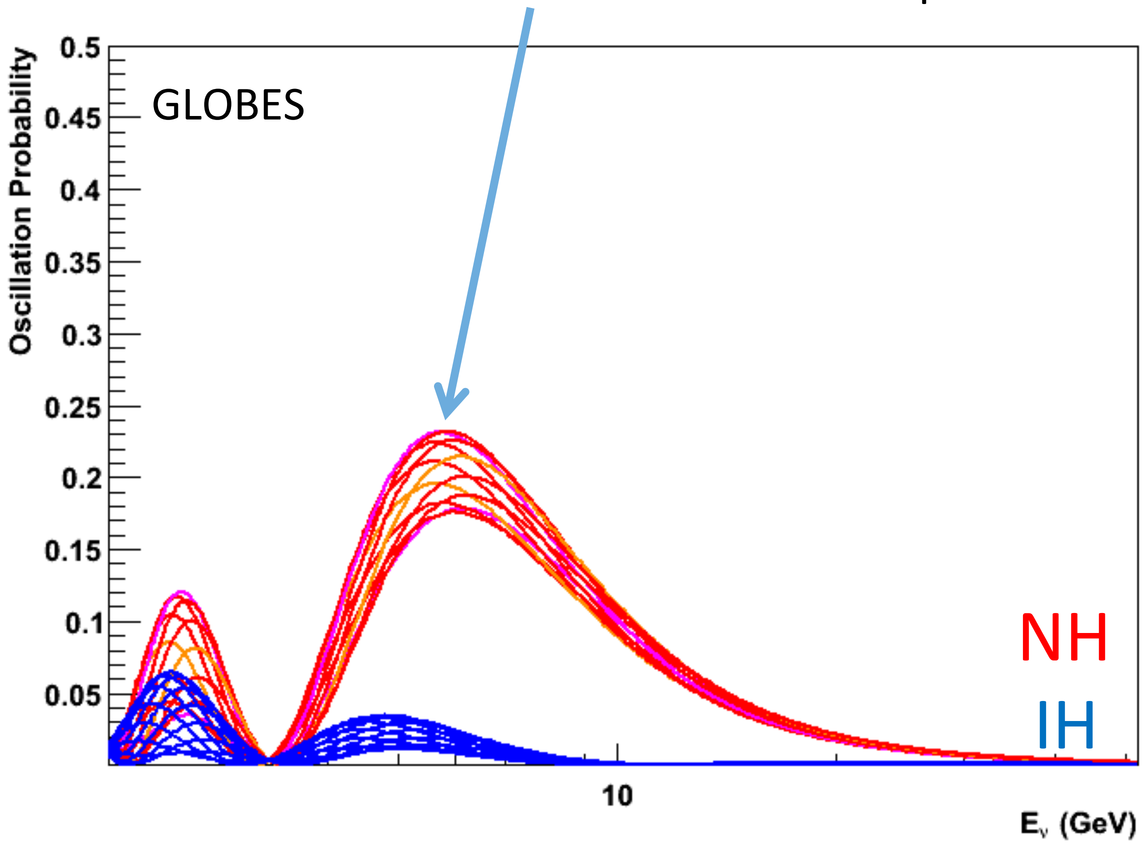
S. Cao, PASCOS 2016

Which Baseline to measure δ_{CP} ?



$\cos\theta = 0.4$
Baseline = 5097 km
Inclination = 23.6˚

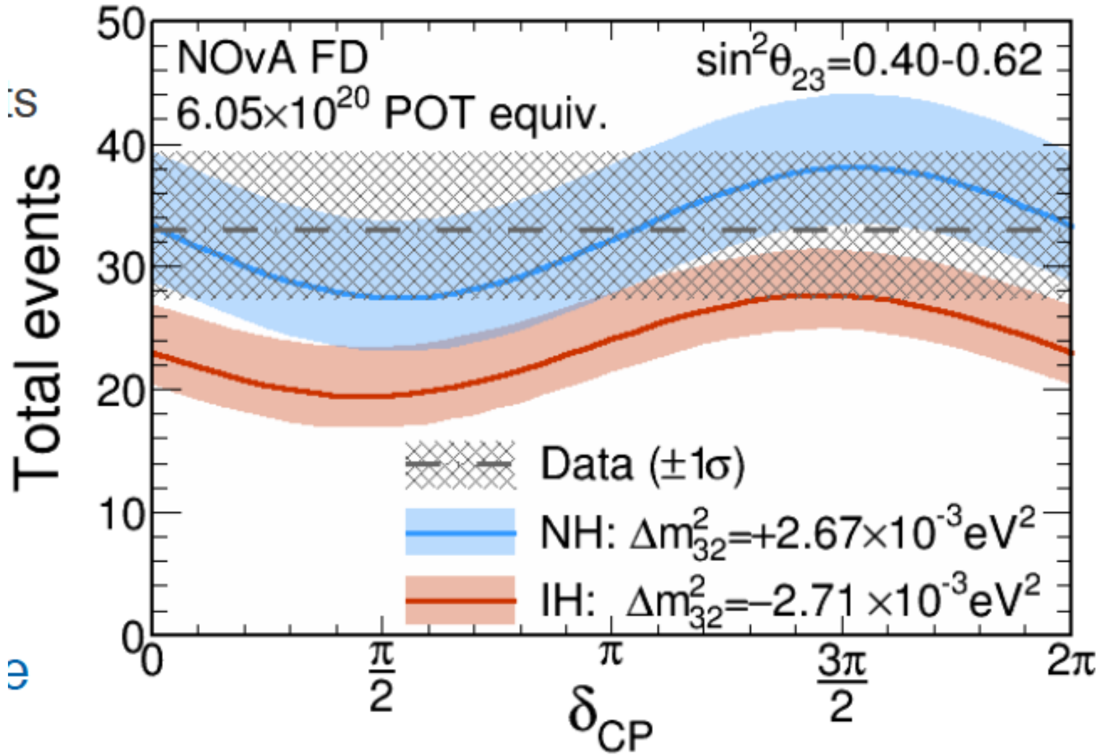
- Consider peak energy of $P(\nu_\mu \rightarrow \nu_e)$



Approximation : $P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27\, \Delta m_{32}^2\, E/L)$

NOVA 2016 result

- Based on 6.05 10^{20} p.o.t. (2016 - 1/3 of design)
- 25 ν_e-CC signal events (33 - 8 bckg) (14kt)
- Currently running in ν mode (shutdown 2024)



DUNE

- On-Axis, 40kt LAr TPC + 1.2 MW beam
- Measuring 2nd oscillation maximum at 0.8 GeV ?