Physics with KM3NeT/ORCA

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“Prospects of Neutrino Physics“ Workshop,
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KM3NeT

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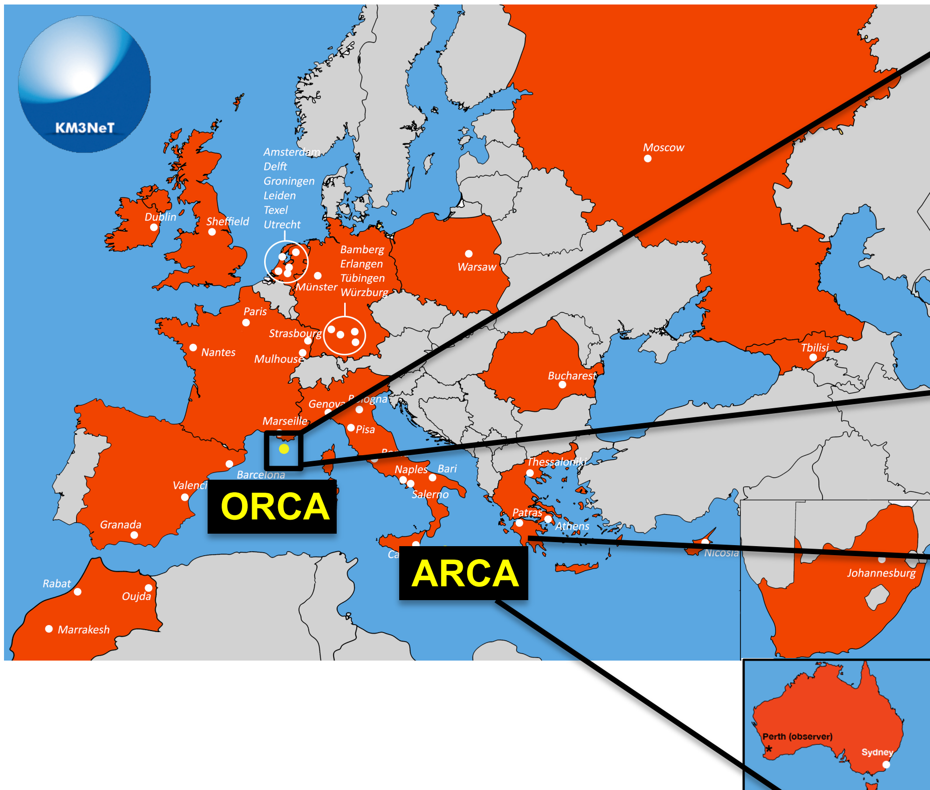
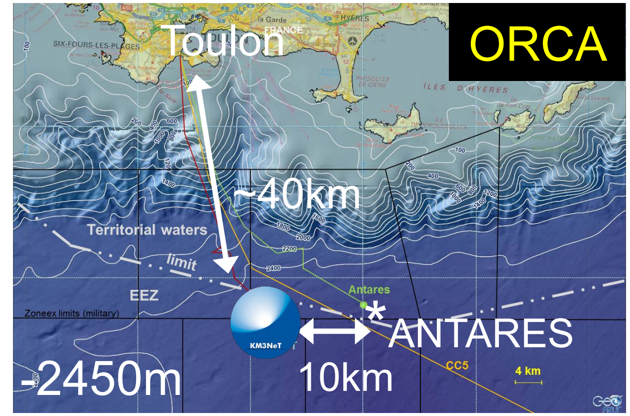
KM3NeT collaboration & ORCA site





ORCA: Oscillation **R**esearch with **C**osmics in the **A**byss

ARCA: Astroparticle **R**esearch with **C**osmics in the **A**byss

KM3NeT: ARCA & ORCA

ARCA → TeV-PeV neutrino astronomy

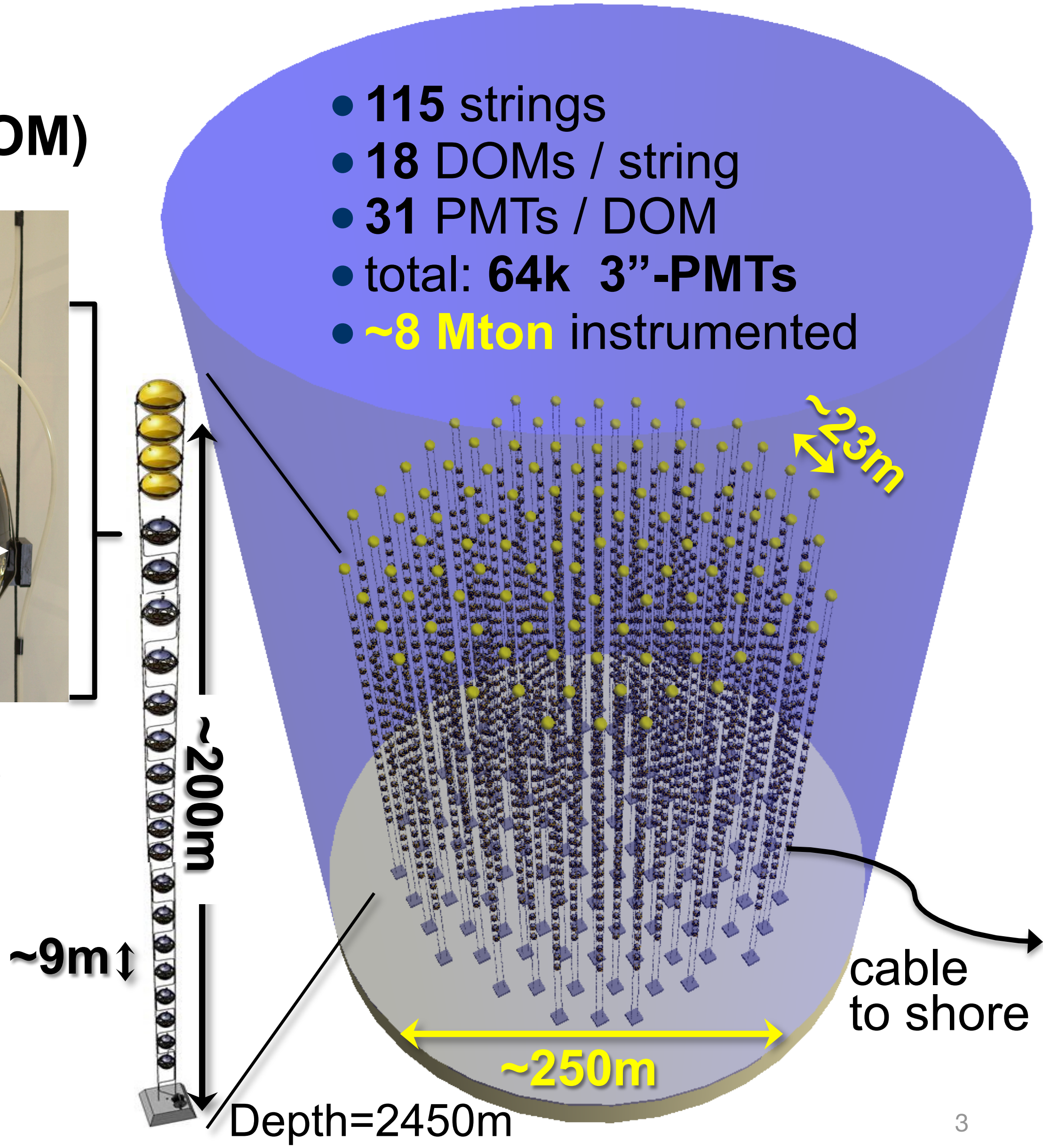
ORCA → neutrino mass hierarchy with few-GeV atmospheric neutrinos

KM3NeT/ORCA detector

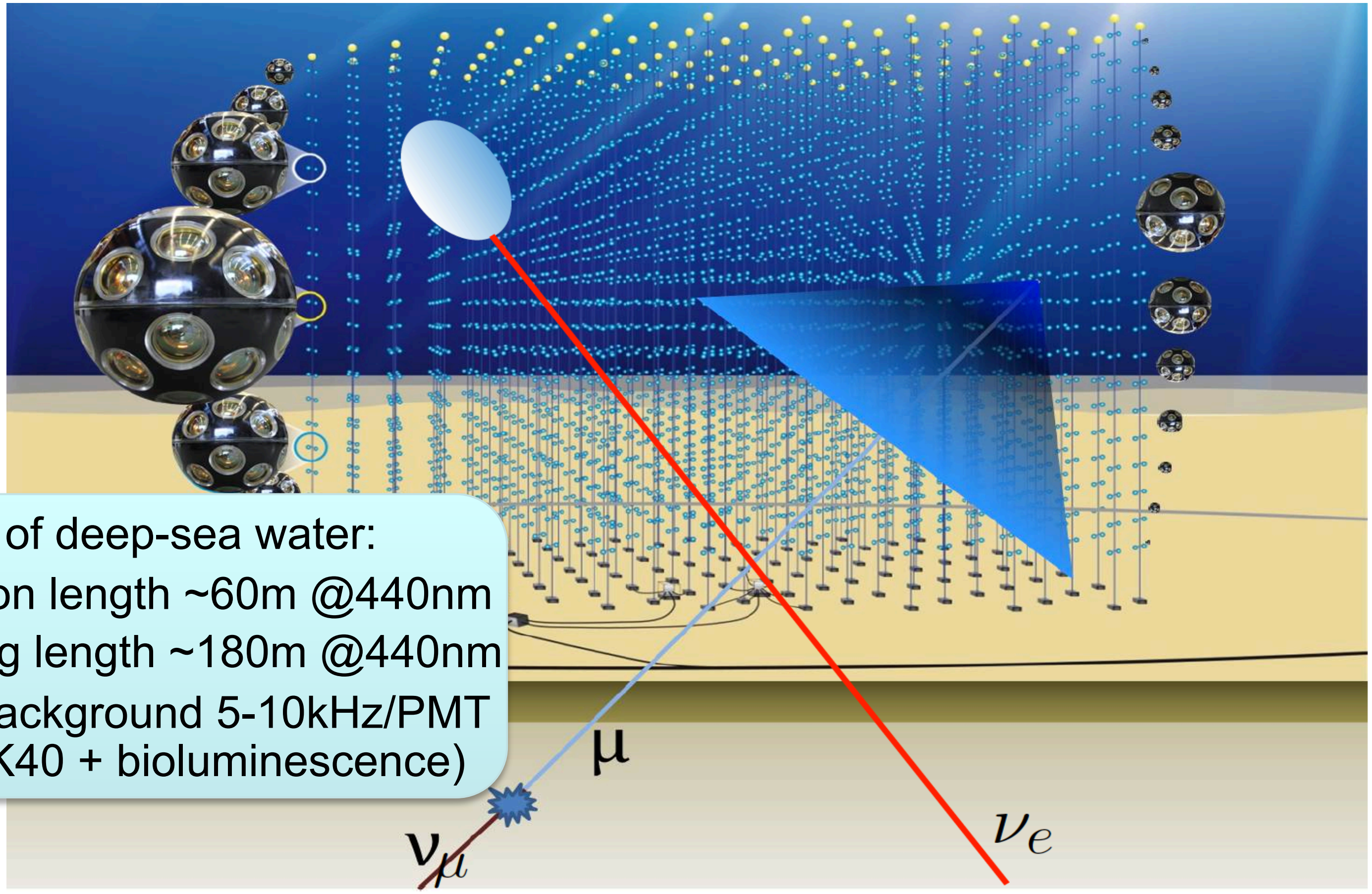
Digital Optical Module (DOM)

31 x 3”-PMTs
(19↓, 12↑)

→ uniform angular coverage
→ directional information
→ single photon counting



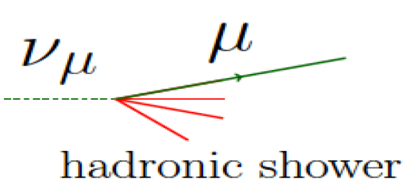
Detection principle and event topologies



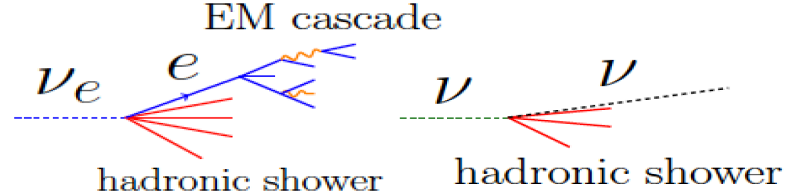
Properties of deep-sea water:

+ absorption length ~60m @440nm
+ scattering length ~180m @440nm
+ optical background 5-10kHz/PMT (K40 + bioluminescence)

Track-like: ν_μ^{CC}, ν_τ^{CC} $(\tau \to \mu)$



Shower-like: ν_e^{CC}, ν^{NC}, ν_τ^{CC} $(\tau \to \cancel{\mu})$



ORCA detector construction status

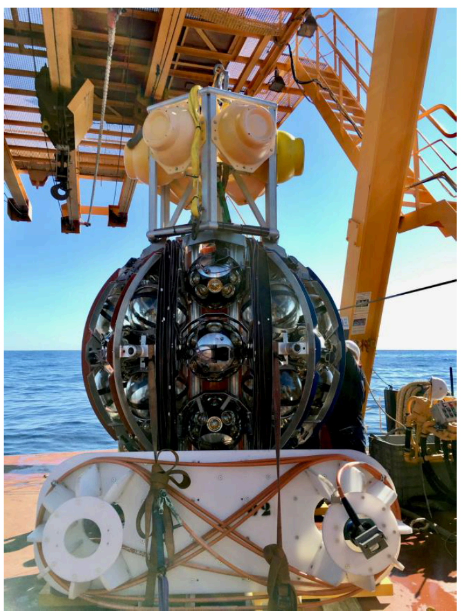
Detector construction status

2018

2019

First ORCA string
22nd Sept. 2017

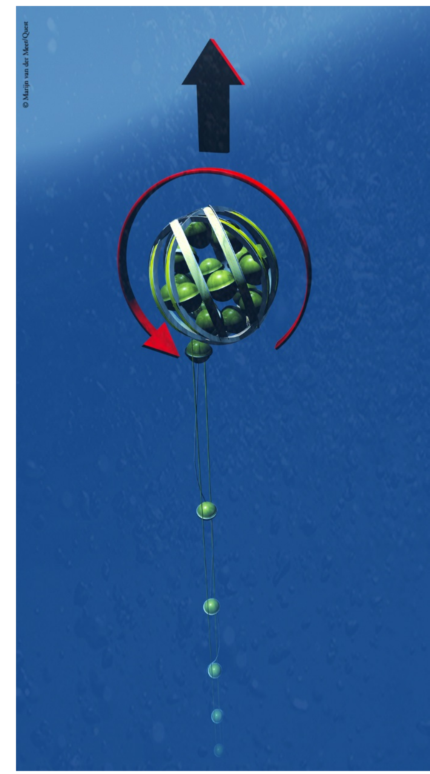
→ Watch: https://youtu.be/omIFkdCkbYk



First string on boat, wound around its spherical launching frame

<u>Deploy process:</u>

- Deploy on sea bed
- Unfurl
- Collect frame at surface
- Connect cables with remotely operated vehicle



Detector construction status

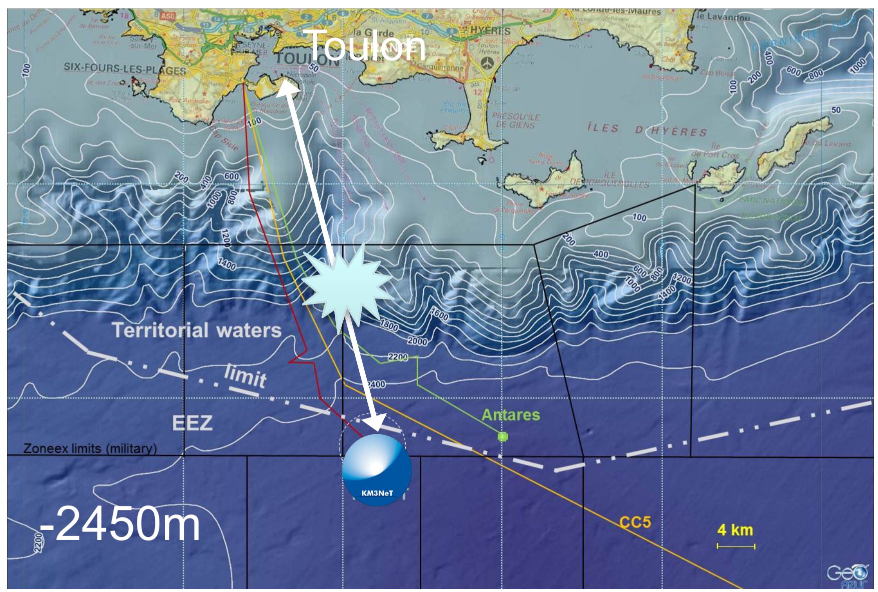
2018

2019

Failure of deep-sea cable, 13rd Dec. 2017

Replacement of deep-sea cable, Oct. 2018

First ORCA string 22nd Sept. 2017



Detector construction status

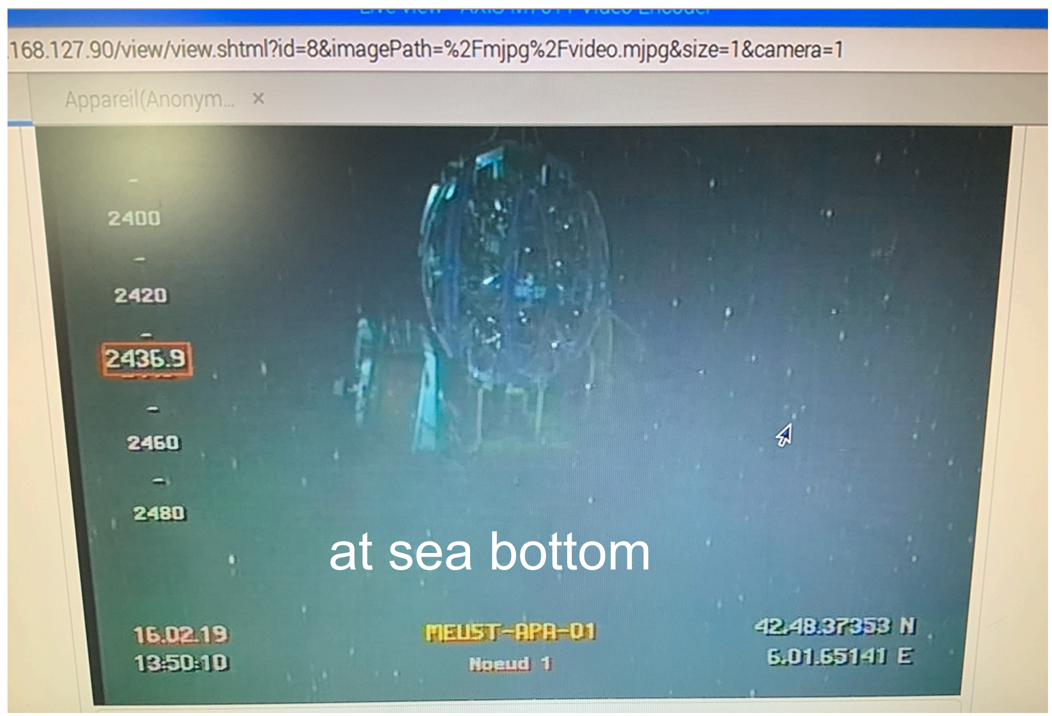
2018

2019

First ORCA string
22nd Sept. 2017

Failure & replacement
deep-sea cable

Re-installation of
one ORCA string,
16th Feb 2019



Detector construction status

2018

2019

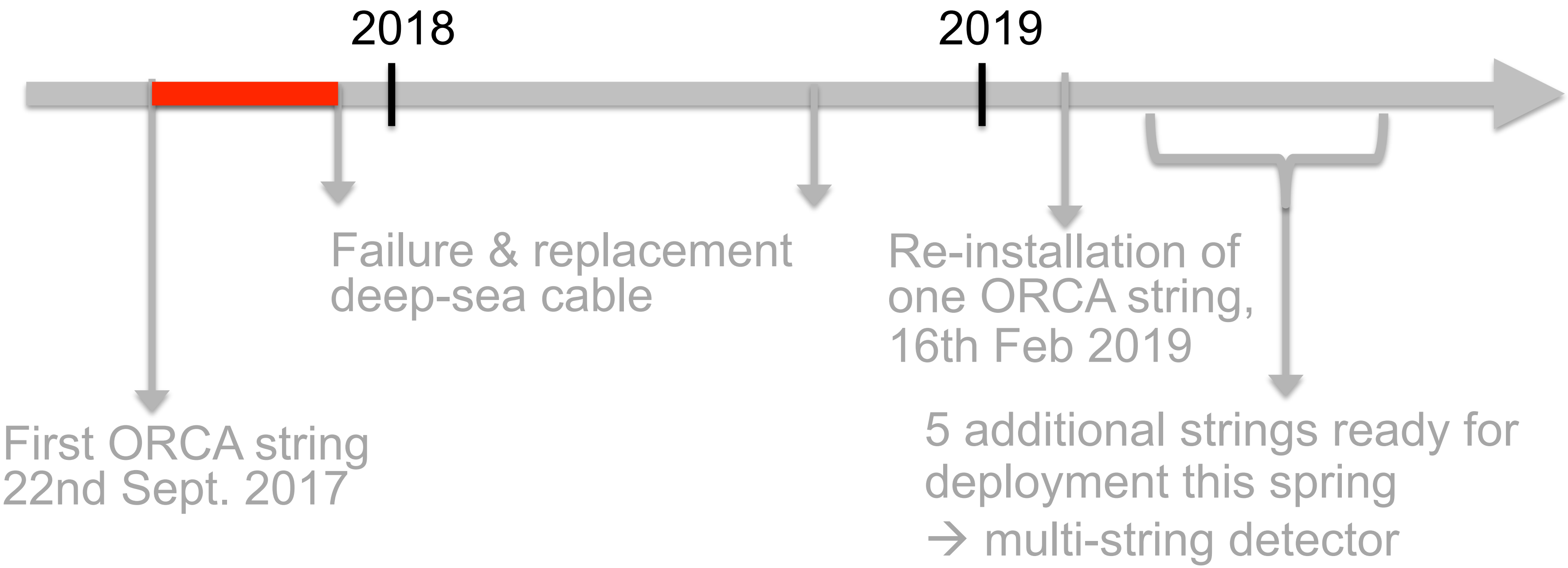
First ORCA string
22nd Sept. 2017

Failure & replacement
deep-sea cable

Re-installation of
one ORCA string,
16th Feb 2019

5 additional strings ready for
deployment this spring
→ multi-string detector

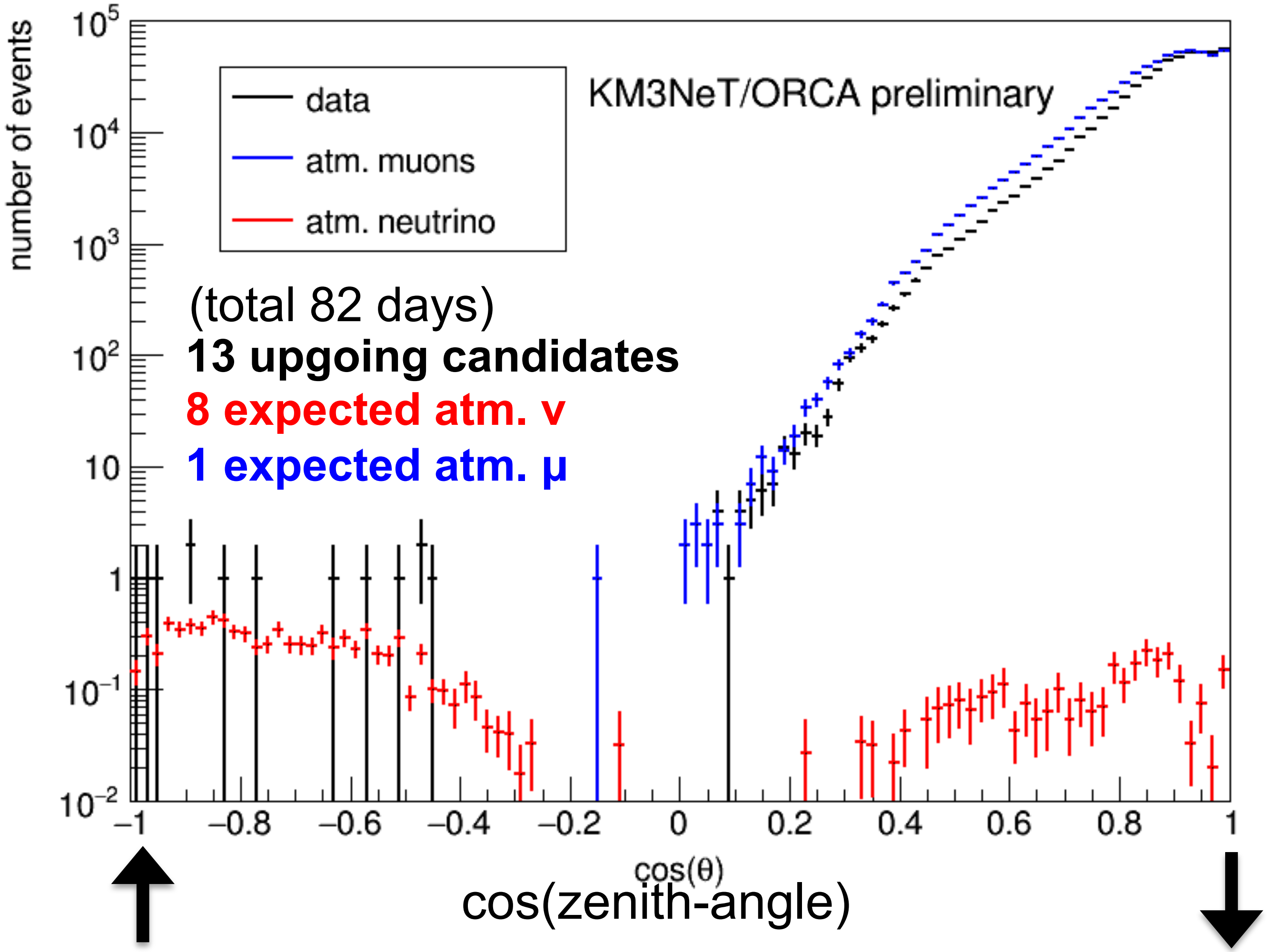
Detector construction status



First data analysis
→ neutrino candidates
→ muon flux measurement

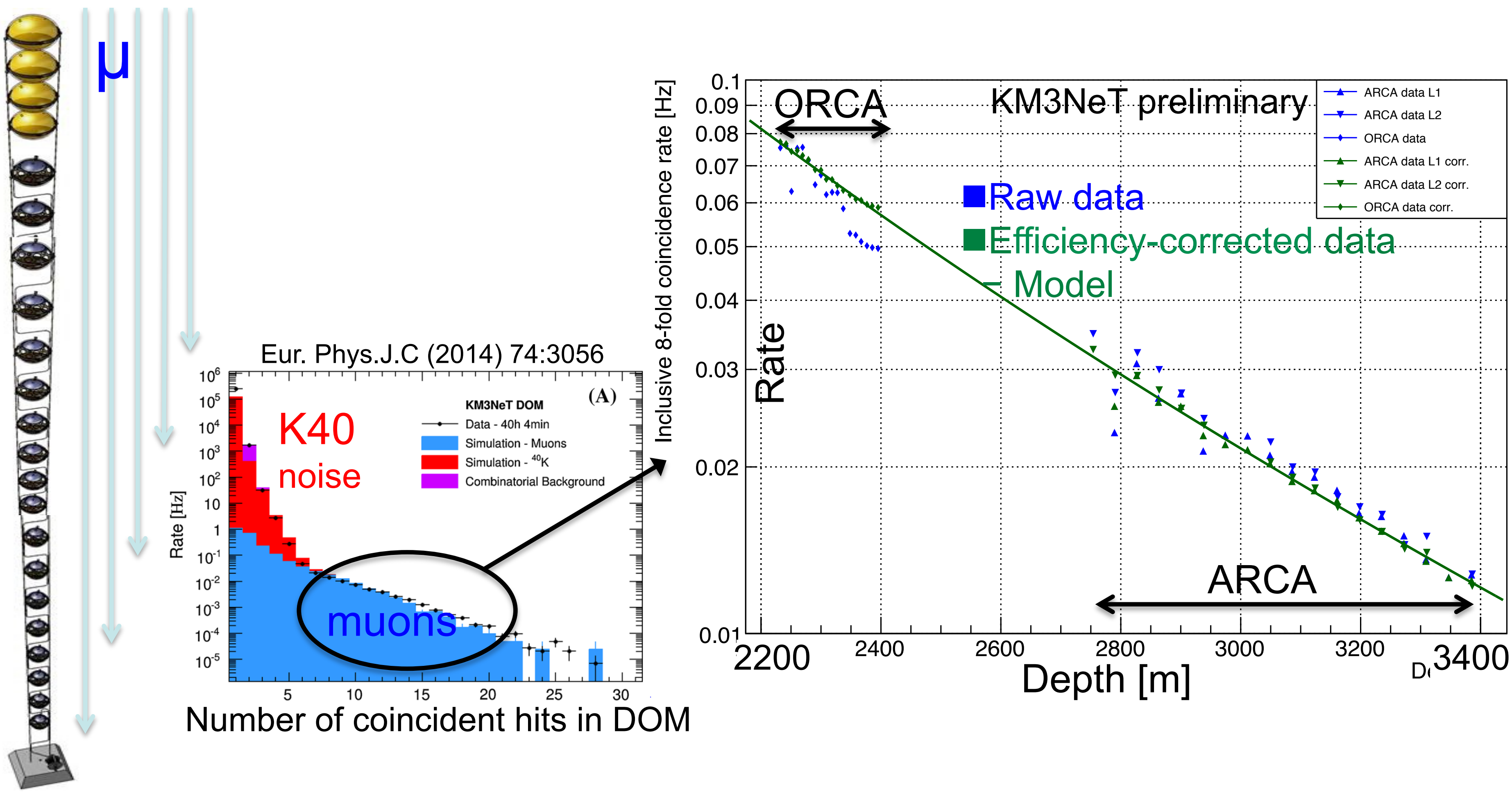
First ORCA data analyses

- First atmospheric neutrino events with data from Sept. – Dez. 2017



Muon depth dependence with ARCA & ORCA

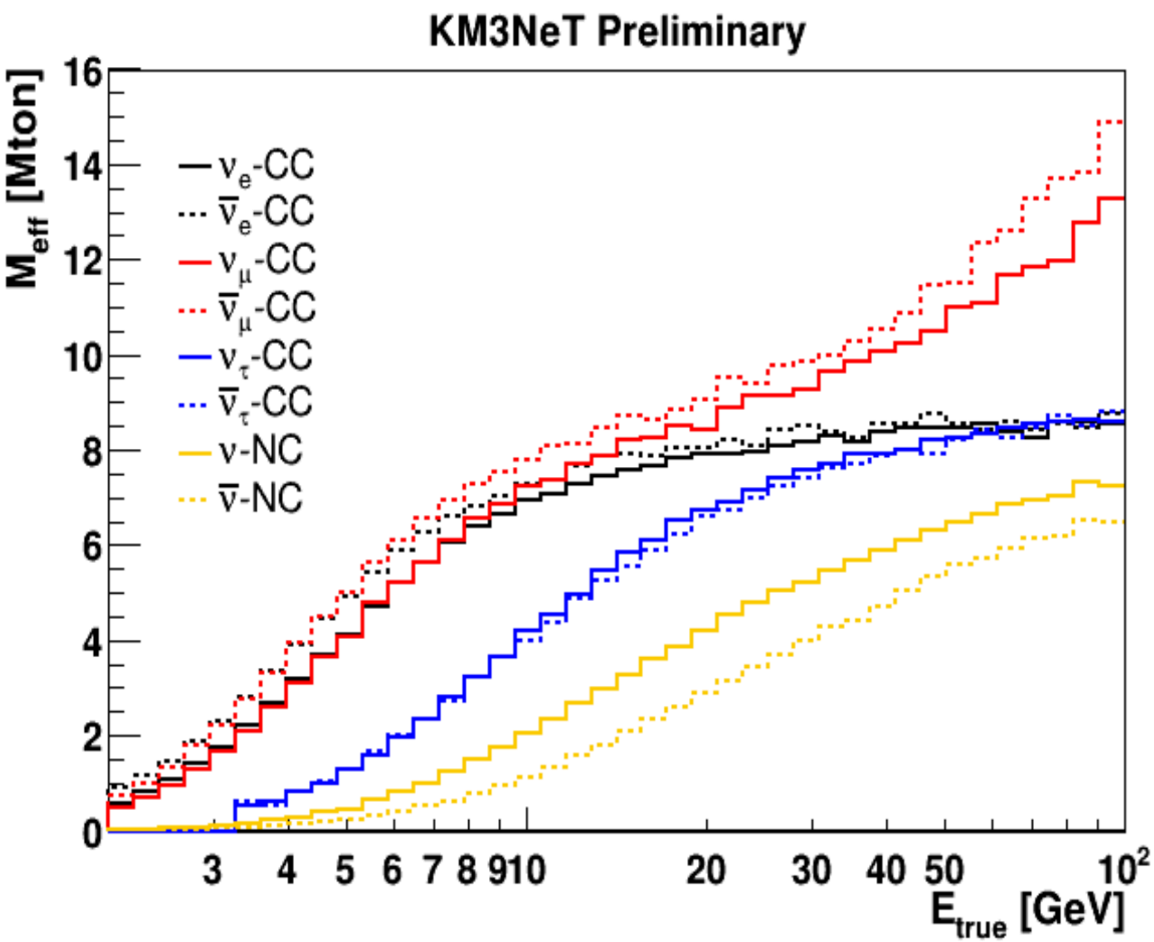
- Muon flux attenuation between 2.2–3.4 km measured with ARCA & ORCA
- Observable: high-multiplicity coincident hits in DOM from close-by muon



Detector performance with full ORCA (115 strings)

ORCA effective mass

- After final event selection cuts



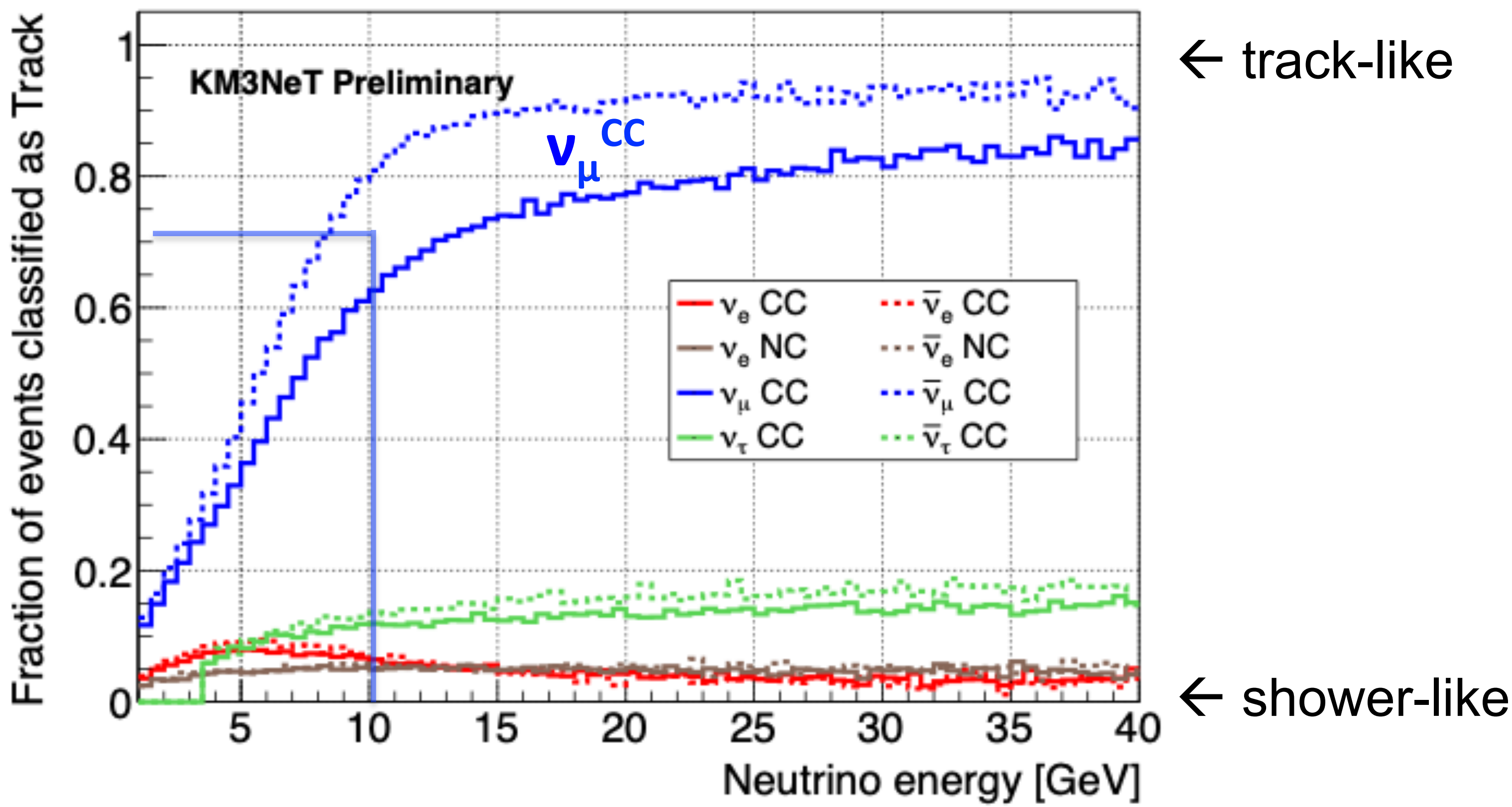
~63k events / year:
ν_eCC: 20.4k
ν_μCC: 31.2k
ν_τCC: 4.2k
NC: 6.8k

For ν_eCC & ν_μCC:

- instrumented mass reached at ~10 GeV
- ~50% efficient at 5GeV

Event topologies classification

- Discrimination of track vs shower events via Random Decision Forest



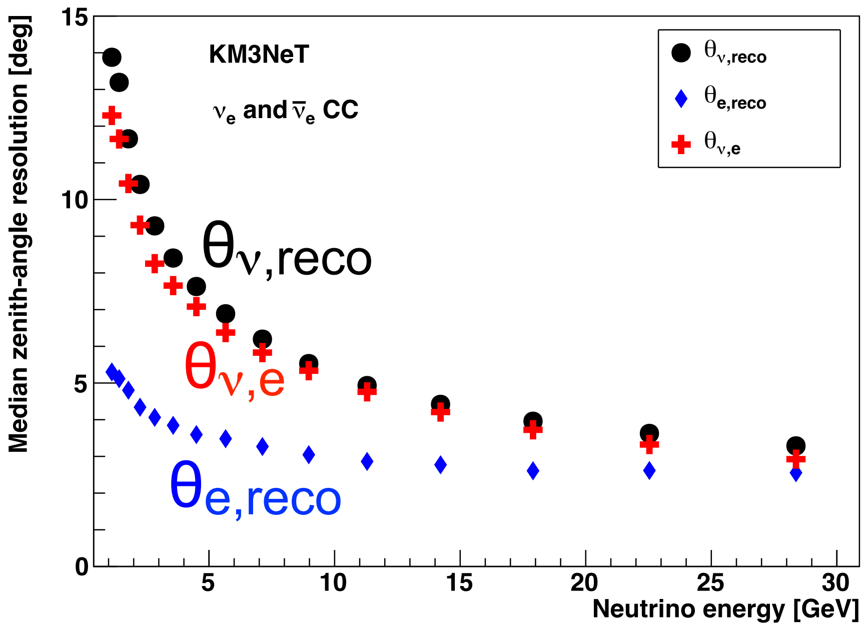
At 10 GeV:

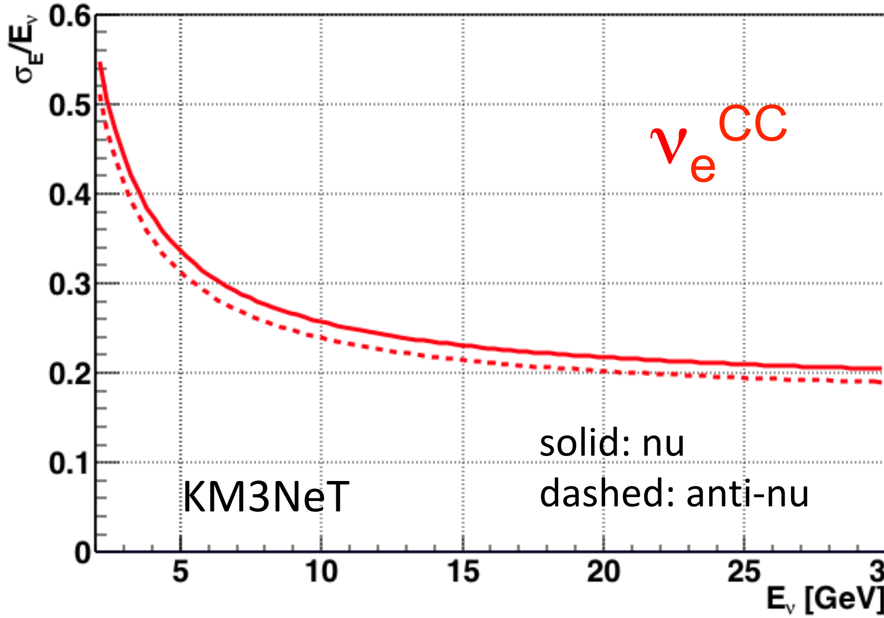
- 70% correct identification of ν_μ^{CC}
- 90% correct identification of ν_e^{CC}

Upcoming improvements:
~20% lower turn-on energy
not yet included in sensitivity study

Zenith and energy resolutions

Illustration plots show shower channel (similar for track channel)





Zenith-angle resolution: 5° @10GeV
(dominated by ν-lepton kinematics)

Energy resolution: 25% @10GeV
(dominated by light yield fluctuations)

Physics potential with full ORCA

Oscillation physics with atmospheric neutrinos

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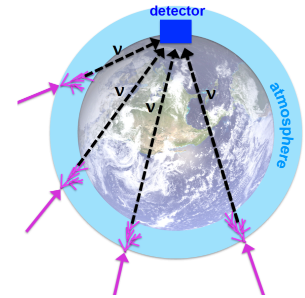
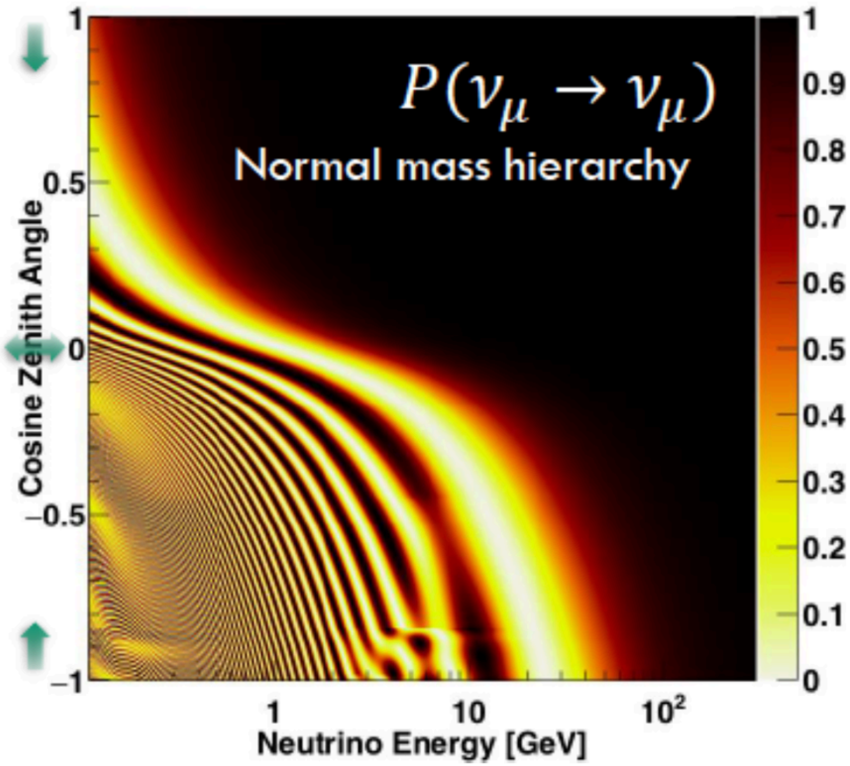
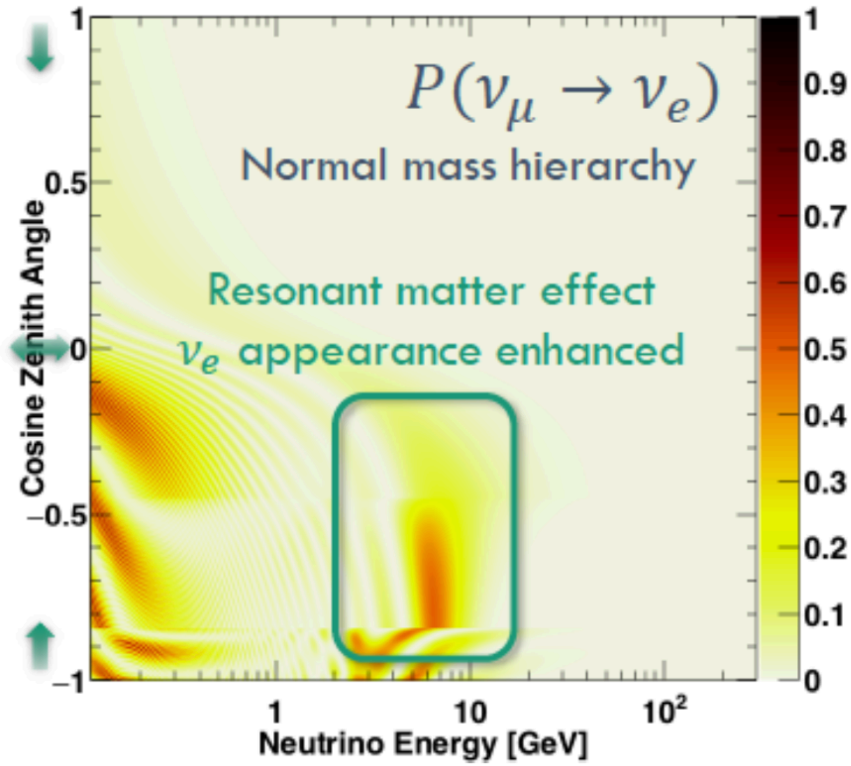
ORCA: Oscillation Research with Cosmics in the Abyss

- Neutrino mass hierarchy (NMH)
- $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$
- ν_τ appearance
- Exotics (sterile ν, NSI, quantum decoherence)



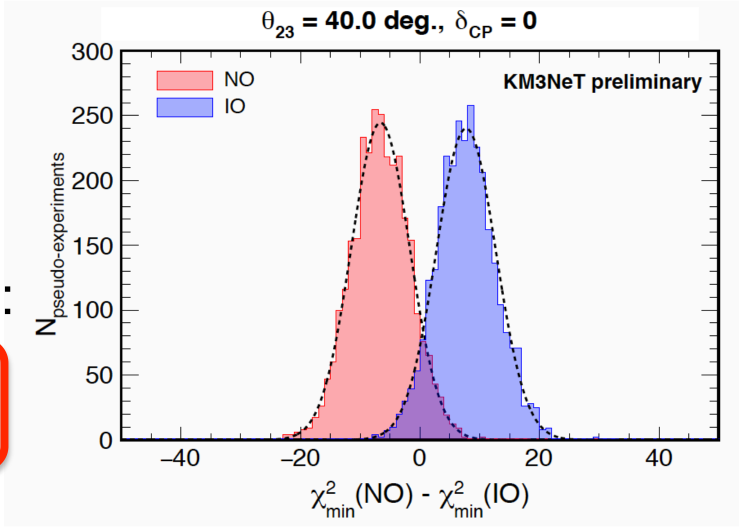




NMH sensitivity analysis method

- Based on pseudo-experiments
- Combined fit of neutrino mass hierarchy, oscillation and other nuisance parameters
- Sensitivity from log-likelihood test statistics:

$$\boxed{TS = -2 \cdot \ln \frac{\max \mathcal{L}_{\mathrm{NO}}}{\max \mathcal{L}_{\mathrm{IO}}} = \chi^2_{\min}(\mathrm{NO}) - \chi^2_{\min}(\mathrm{IO})}$$

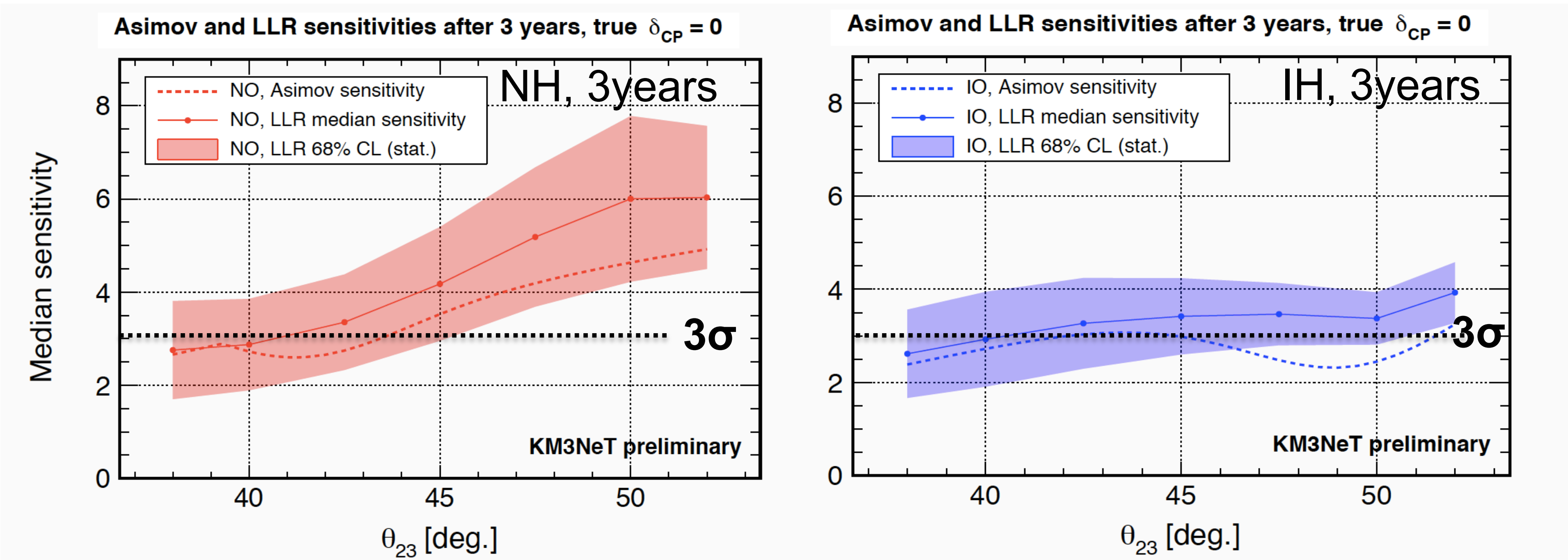


- Systematics:

	parameter	*treatment*	*true value*	*prior*
nu oscillation	$\lvert\Delta M^2\rvert$ (eV^2)	fitted	$2.48\,10^{-3}$	free
	$\Delta m^2{}_{21}$ (eV^2)	fix	$7.53\,10^{-5}$	–
	θ_{13} (°)	fitted	8.42	0.26
	θ_{12} (°)	fix	33.4	–
	θ_{23} (°)	fitted	38 – 52	free
	δ_{CP}	fitted	$0 - 2\pi$	free
experimental and flux	Flux spectral tilt	fitted	0	free
	$\nu/\bar{\nu}$ skew	fitted	0	0.03
	Tracks normalisation	fitted	1	free
	Cascades normalisation	fitted	1	free
	NC events normalisation	fitted	1	0.10

Sensitivity to mass hierarchy

- **2.5σ – 6σ median significance after 3 years**
- Best case (NH, θ_{23} upper octant): 5σ after 3 years



Sensitivity to mass hierarchy

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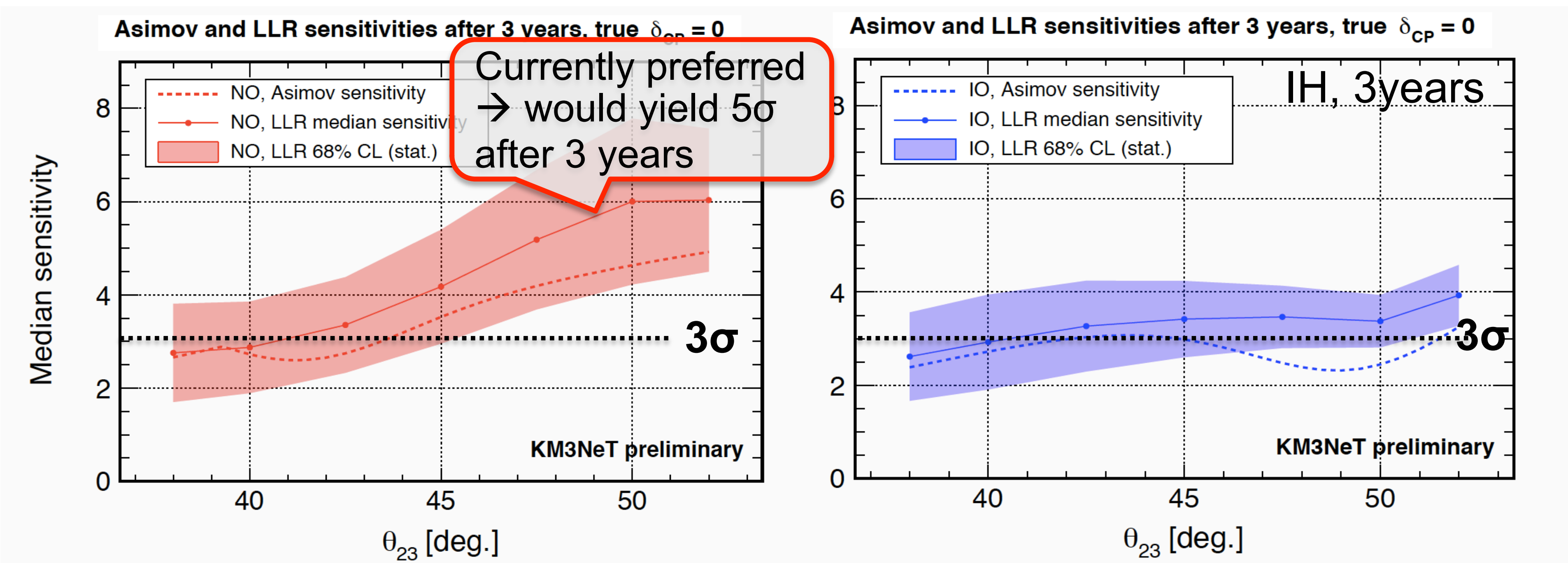
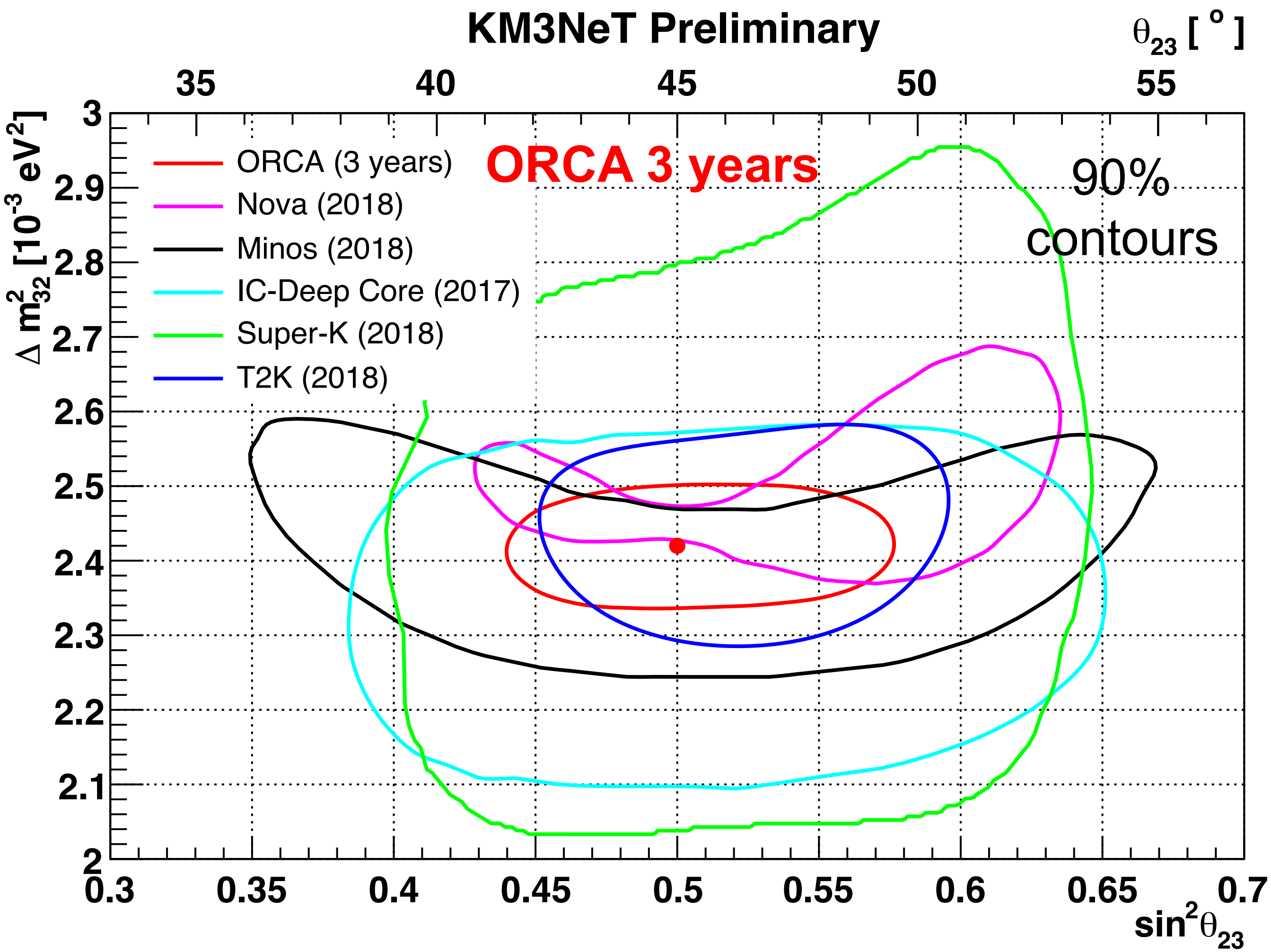


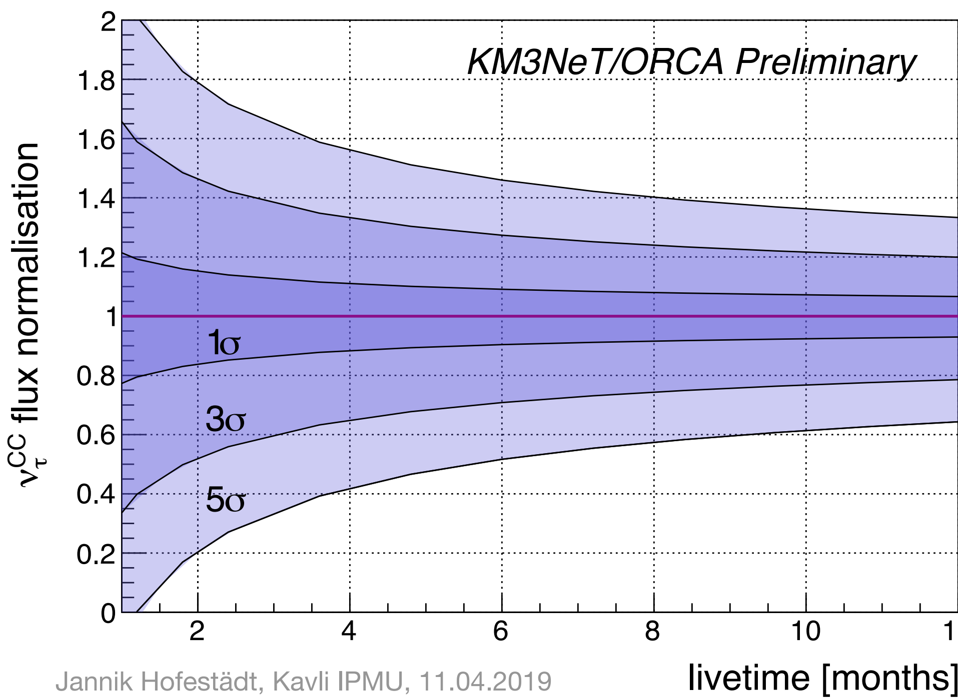
Sensitivity to $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$

- Precision measurement of $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$



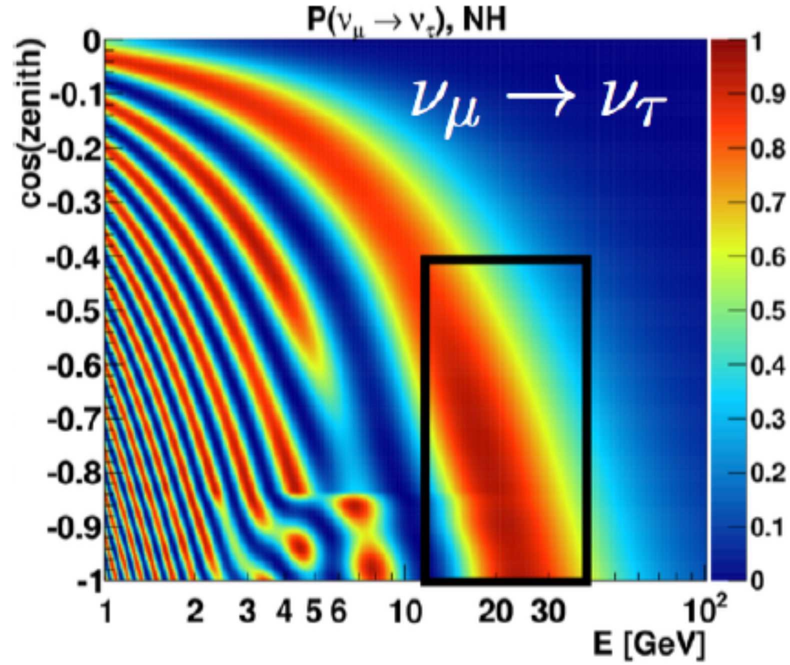
Tau neutrino appearance

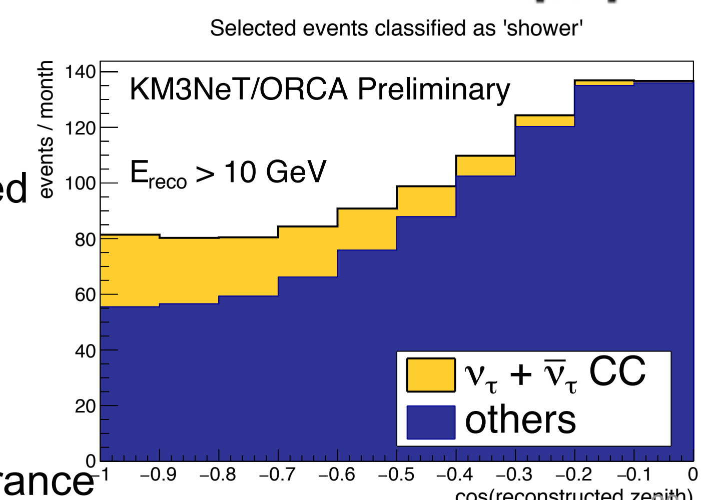
- ν_τ appearance tests unitarity of 3ν-mixing matrix
- ~4k ν_τ^{CC} events / year
- Signature: excess of shower-like events with E_ν ~20GeV & $\cos\theta_\nu$<-0.5
- Deviation from predictions of ν_τ rate constrained to ~10% after 1yr



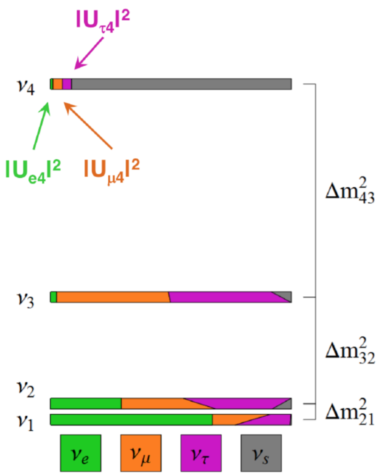
← as expected

← no appearance

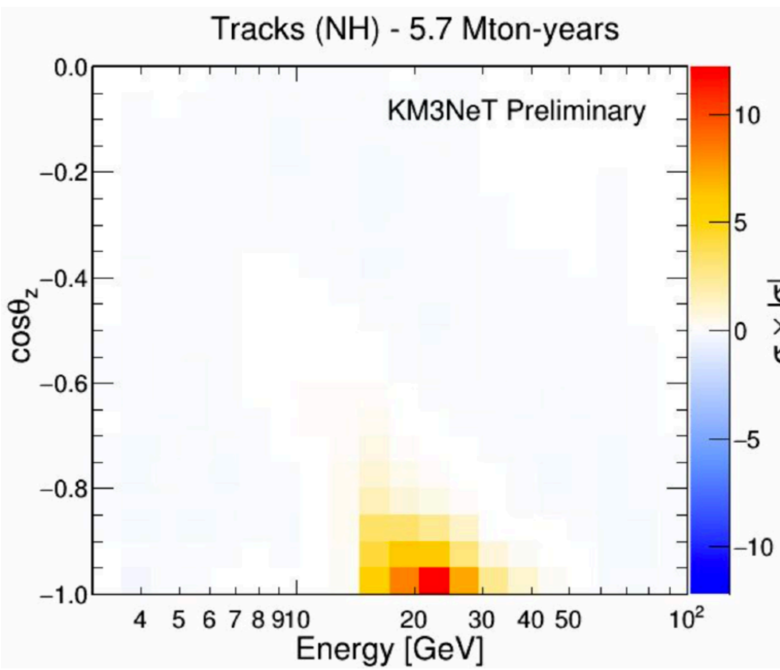


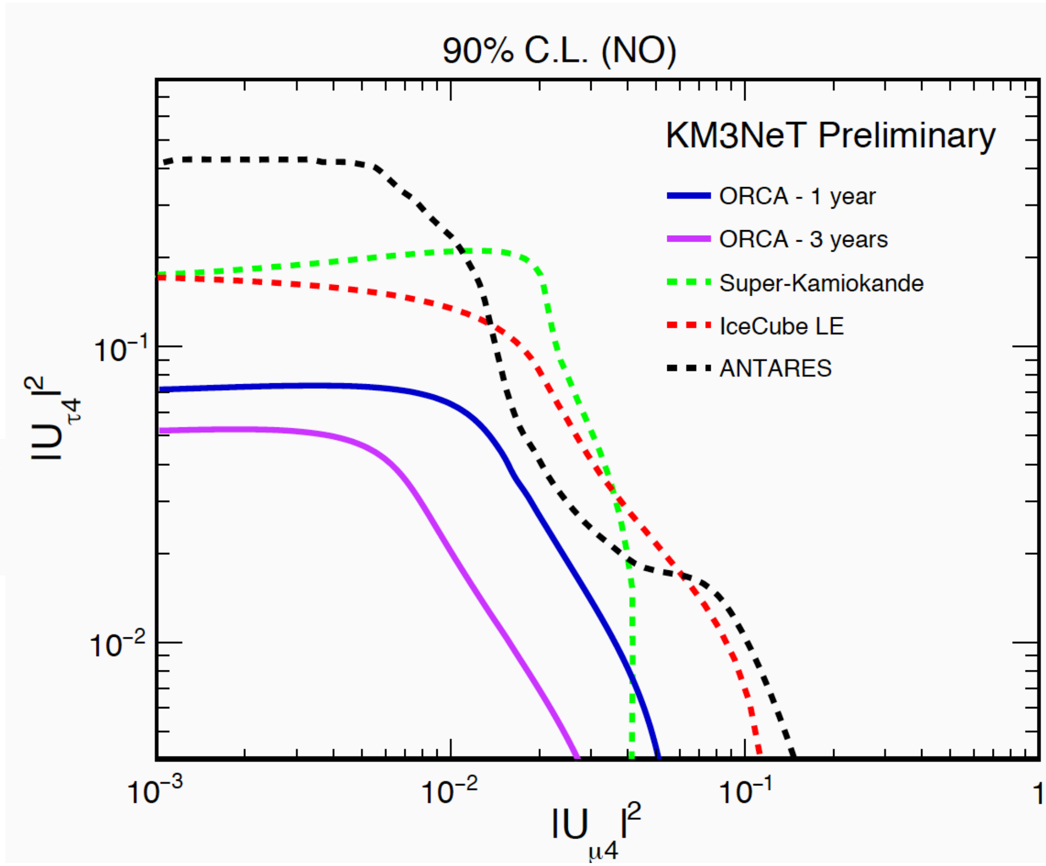


Sterile neutrinos (3+1)



- Atmospheric neutrino oscillations have sensitivity to $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ through $\nu_\mu \leftrightarrow \nu_\tau$ oscillation
- eV-scale sterile ν → excess of upgoing ν_μ at ~20GeV





Additional ORCA science topics

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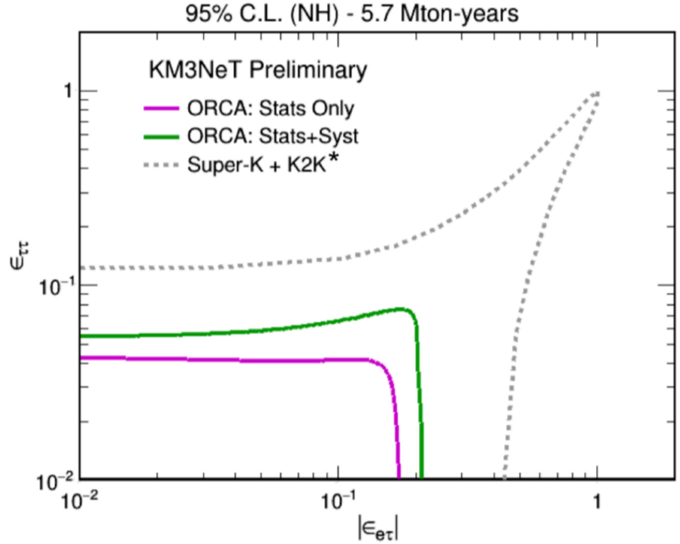
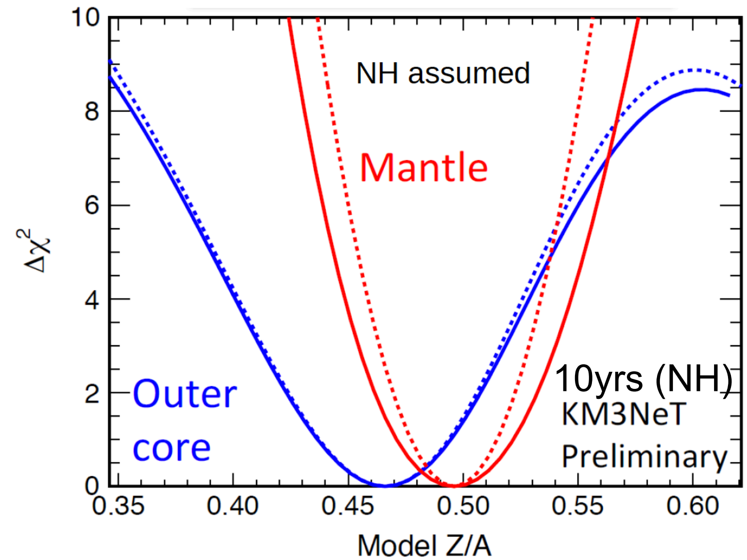
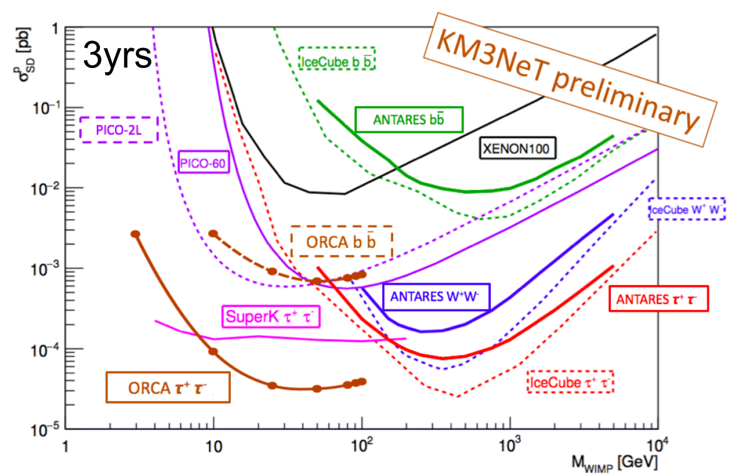
Non-standard interactions (NSI)



Earth tomography and composition



Dark Matter



Additional topics:

- Quantum decoherence
- Supernova monitoring
- GeV-TeV ν-astrophysics
- Earth and Sea science
- …

Possible future option: neutrino beam from Protvino to ORCA (P2O)

Letter of Interest

- Letter of Interest published
- arXiv:1902.06083
- Author list:
  - KM3NeT members
  - Russian institutes

arXiv:1902.06083v1 [physics.ins-det] 16 Feb 2019

Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA

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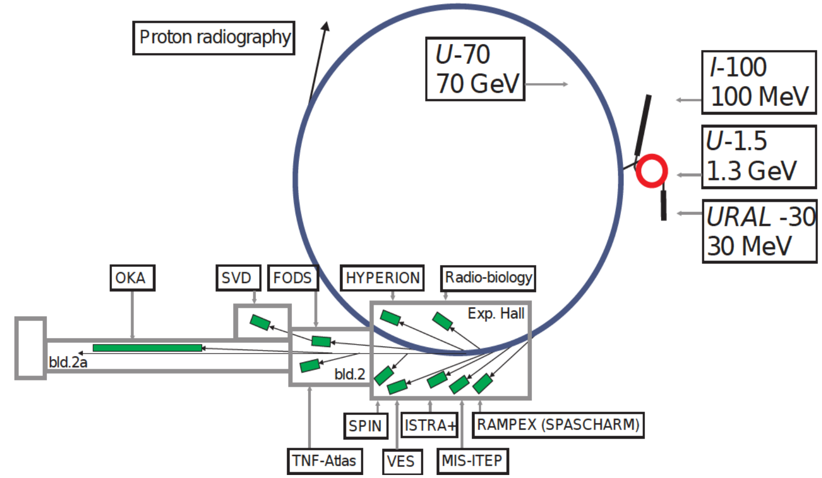
1

P2O: Protvino to ORCA

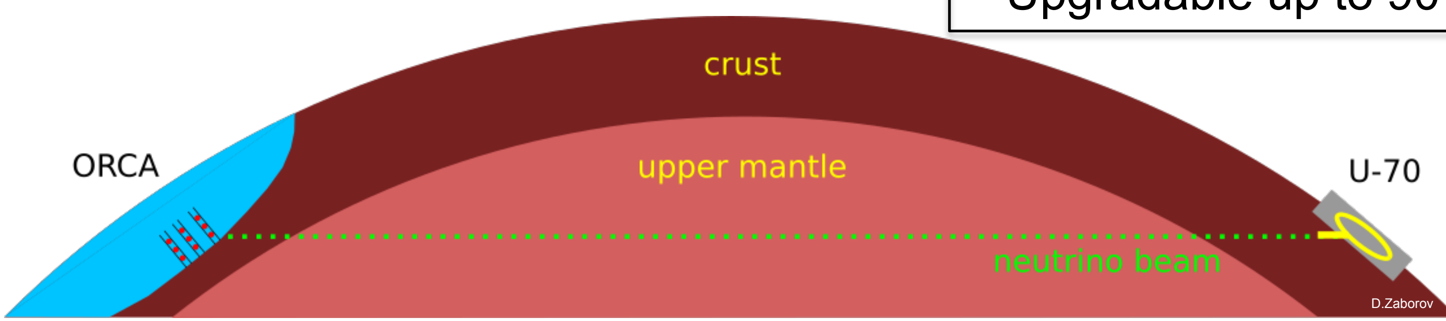
- Baseline L=2595km
- Beam inclination: 11.8° (cosθ=0.2)
- Deepest point 134 km : 3.3 g/cm3

Protvino accelerator complex U-70

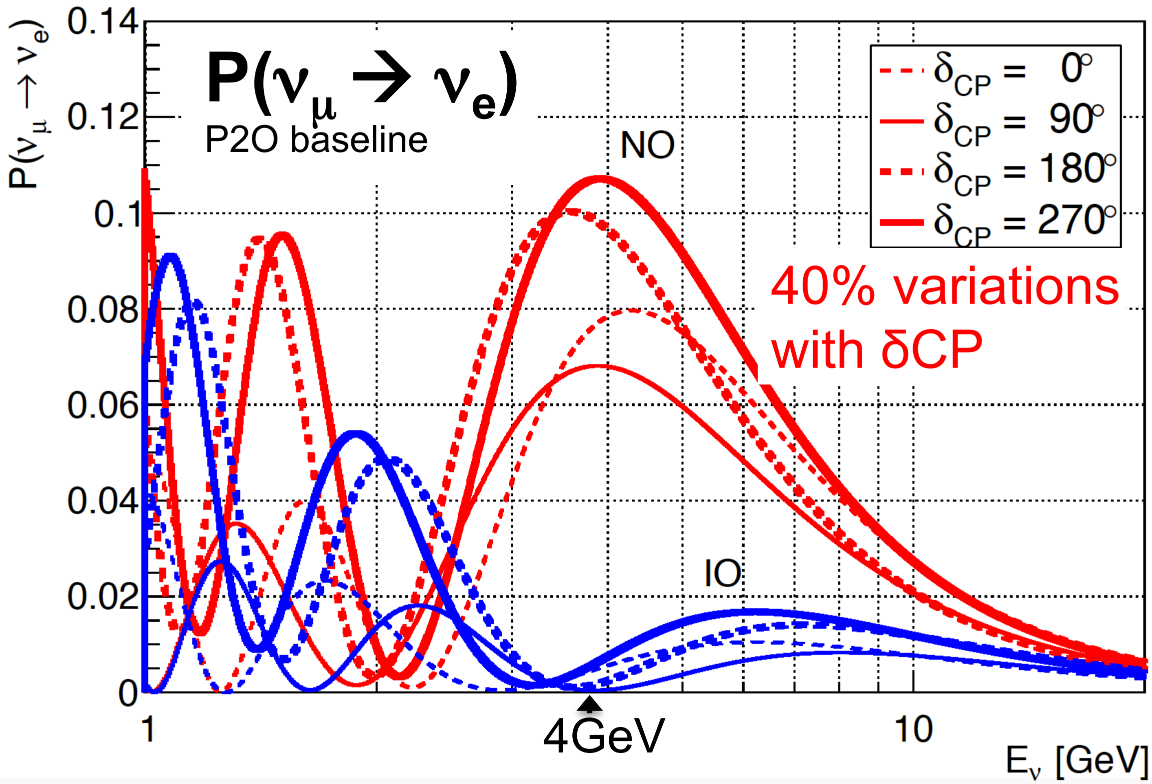


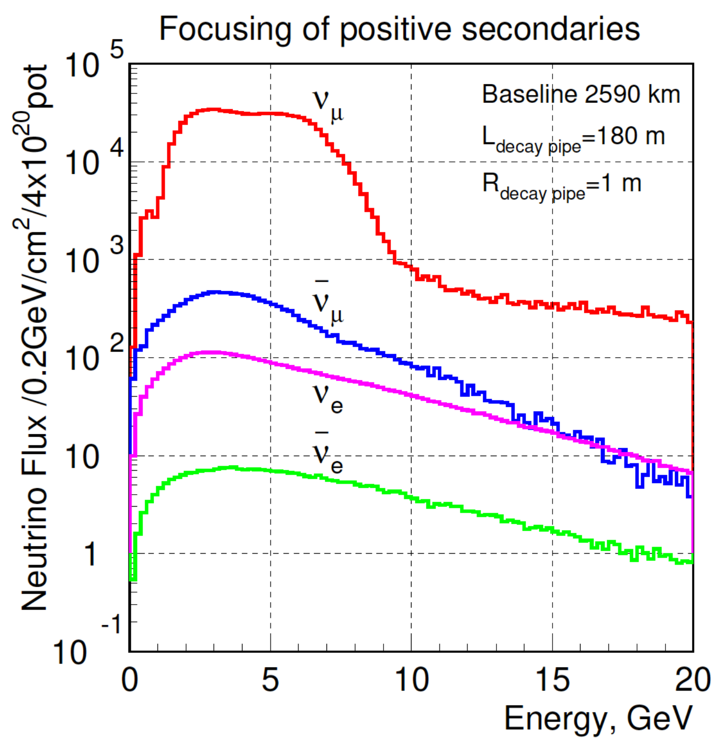
Current operation:
- 70GeV protons
- 5μs spill every 9s
- 15kW beam power

Upgradable up to 90 – 450 kW



P2O: Protvino to ORCA

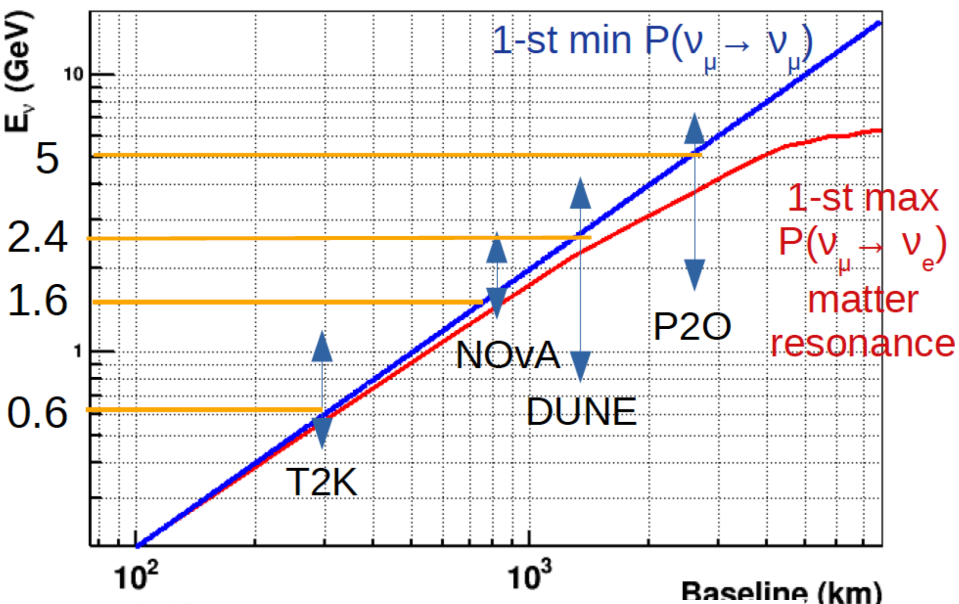


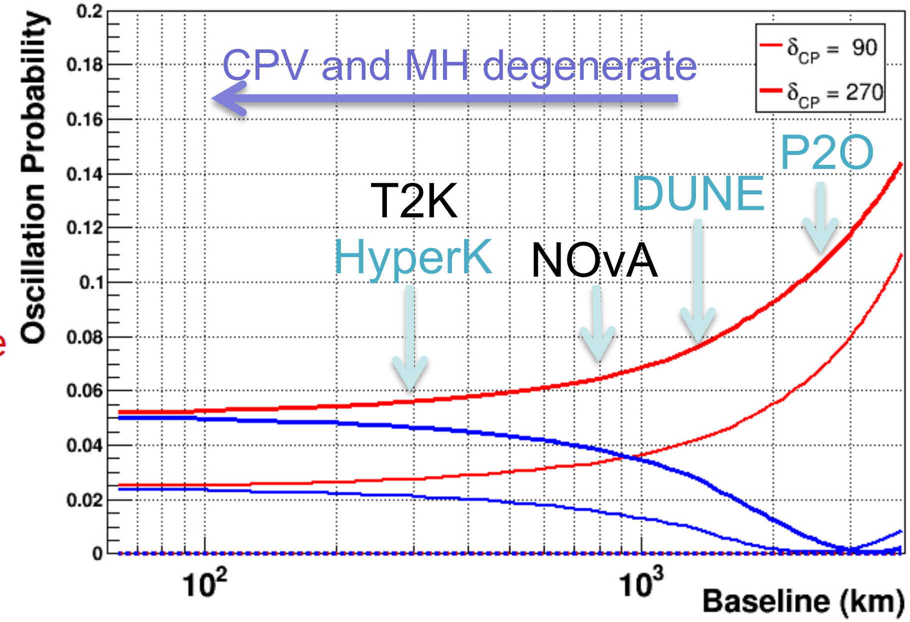


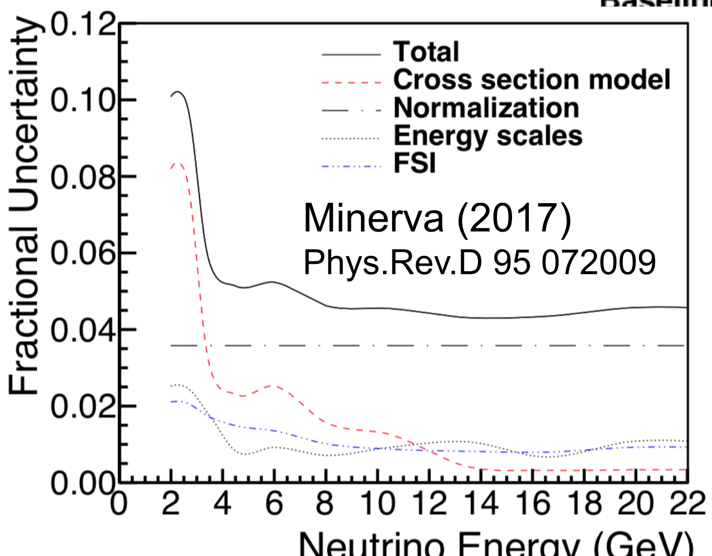
- Oscillation probabilities yield sensitivity to NMH & δCP
- NMH known → chose beam polarity for δCP measurement

- Simulated neutrino beam flux: mainly 1-8GeV ν_μ
- Contamination of wrong flavour below few %

P2O compared to other LBL experiments







- Longest baseline
- Largest matter effects
- Highest energy
- Largest value of $P(\nu_\mu \rightarrow \nu_e)$
- No degeneracy δCP / MH
- Smaller cross section uncertainties

Staged approach

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Stage 1:

- Detector: ‘standard’ ORCA
- Accelerator: 90kW intensity
  - Moderate machine upgrade and beam-line to ORCA
  - 0.8 * 10^{20} protons on target per year

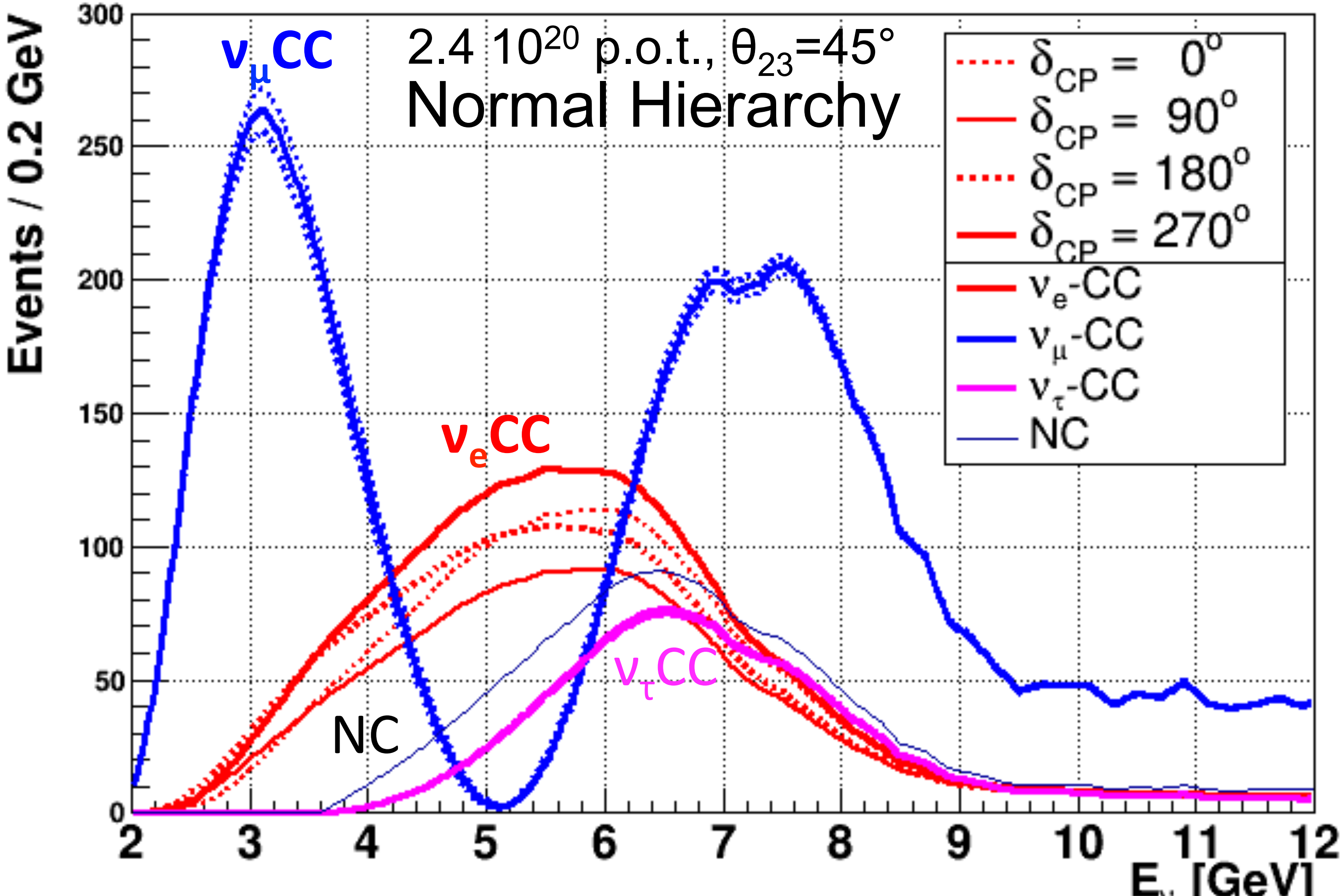
Technical details:
→ arXiv:1902.06083
→ *Zaitsev’s talk @VLVnT2018*

Stage 2:

- Densified ORCA-like detector (‘Super-ORCA’)
  - Example: 10x denser but half as big
  - → lower detection threshold, better resolution and e/μ separation
- Accelerator: 450kW intensity
  - Needs replacement of injector system
  - 4 * 10^{20} protons on target per year

Event numbers

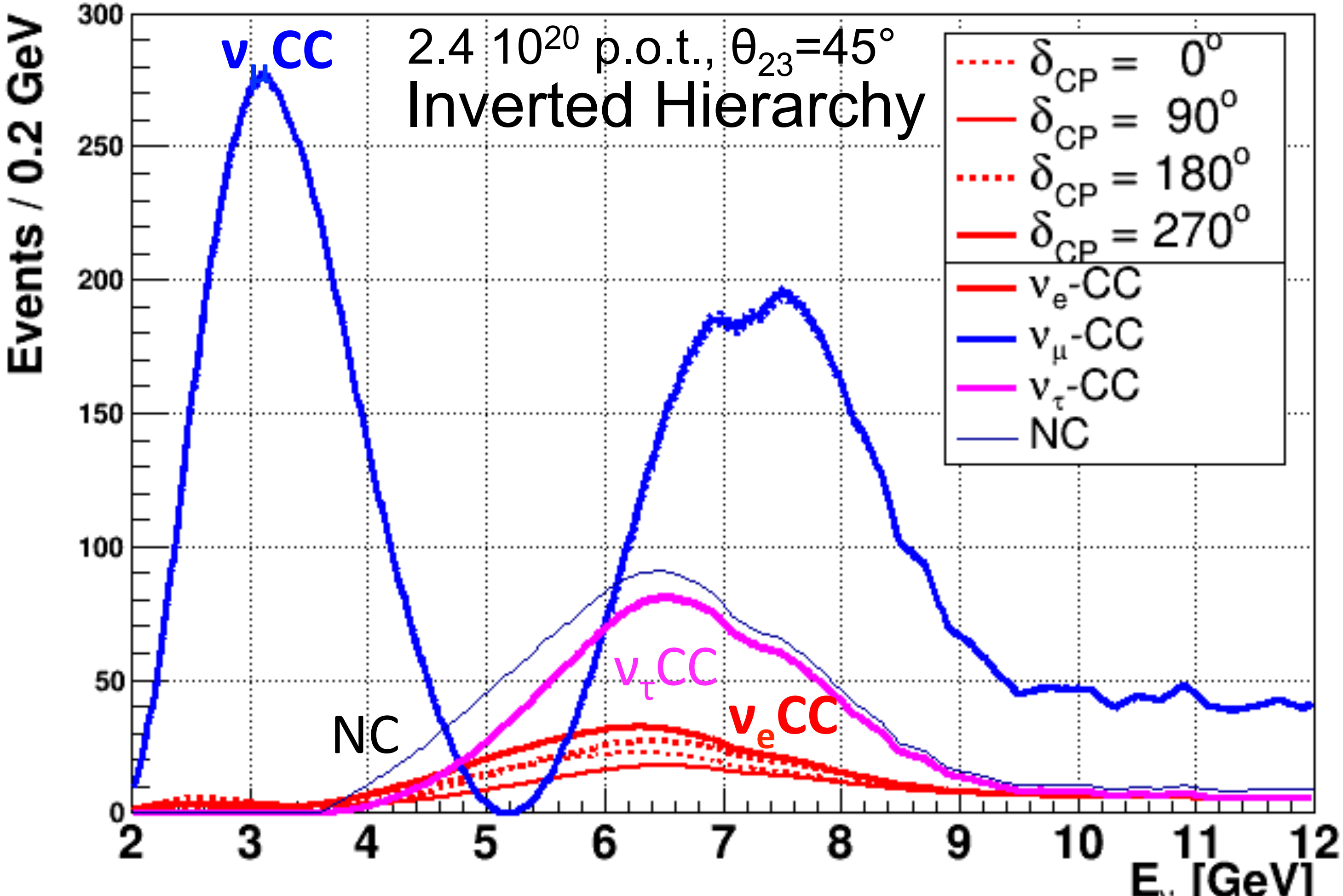
- High statistics long baseline neutrino beam experiment due to large detector mass



Events:
(90kW, 3yrs)
2000 – 2700
7070 ± 20
1340 ± 15
1960

Event numbers

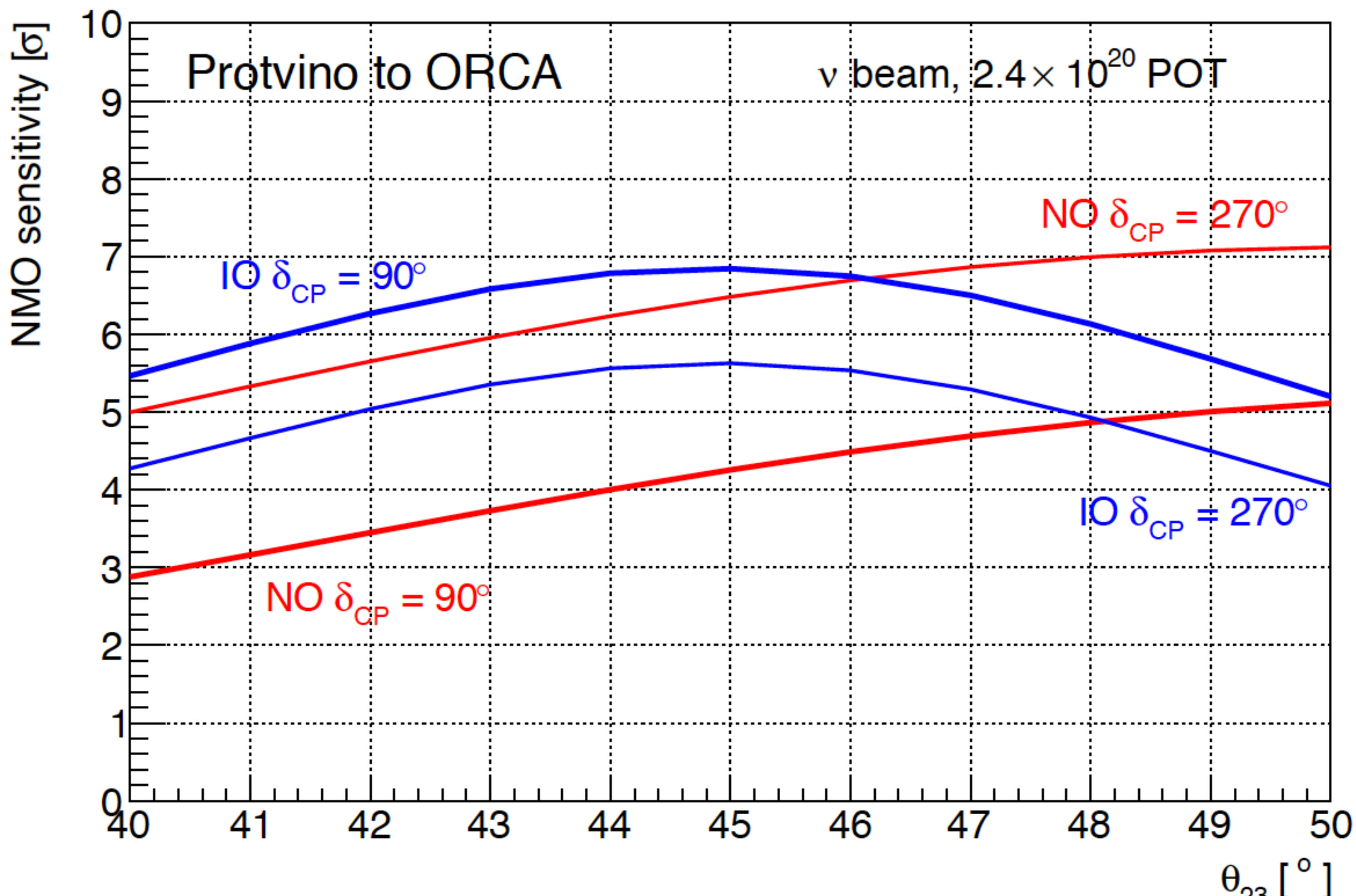
- High statistics long baseline neutrino beam experiment due to large detector mass



Events:
(90kW, 3yrs)
550– 800
6980 ± 40
1420 ± 15
1960

NMH sensitivity

- Neutrino mass hierarchy sensitivity after 3 years with 90kW beam



Staged approach

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Stage 1:

- Detector: ‘standard’ ORCA
- Accelerator: 90kW intensity
  - Moderate machine upgrade and beam line to ORCA
  - 0.8 * 10^{20} protons on target per year

Technical details:
→ arXiv:1902.06083
→ *Zaitsev’s talk @VLVnT2018*

Stage 2:

- Densified ORCA-like detector (‘Super-ORCA’)
  - → lower detection threshold, better resolution and e/μ separation
  - Example: 10x denser but half as big (not optimised yet)
- Accelerator: 450kW intensity
  - Needs replacement of injector system
  - 4 * 10^{20} protons on target per year

Super-ORCA: densified ORCA-like detector

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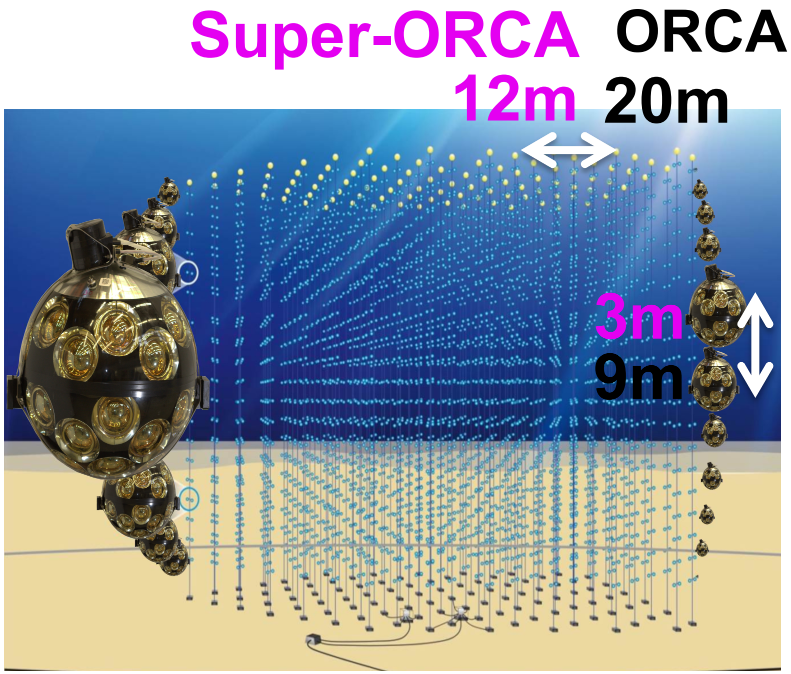
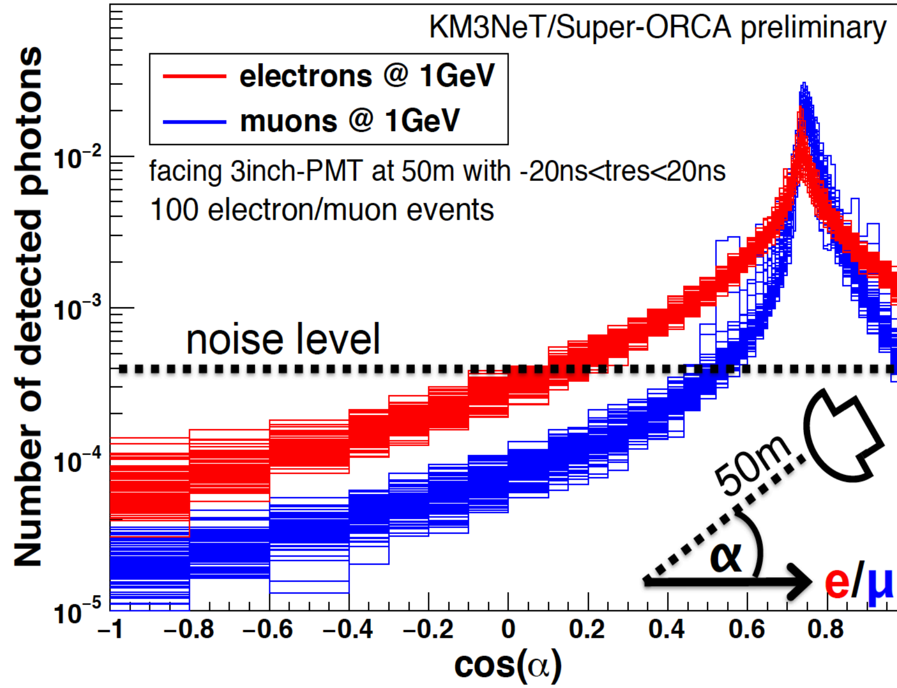
performance → backup slides





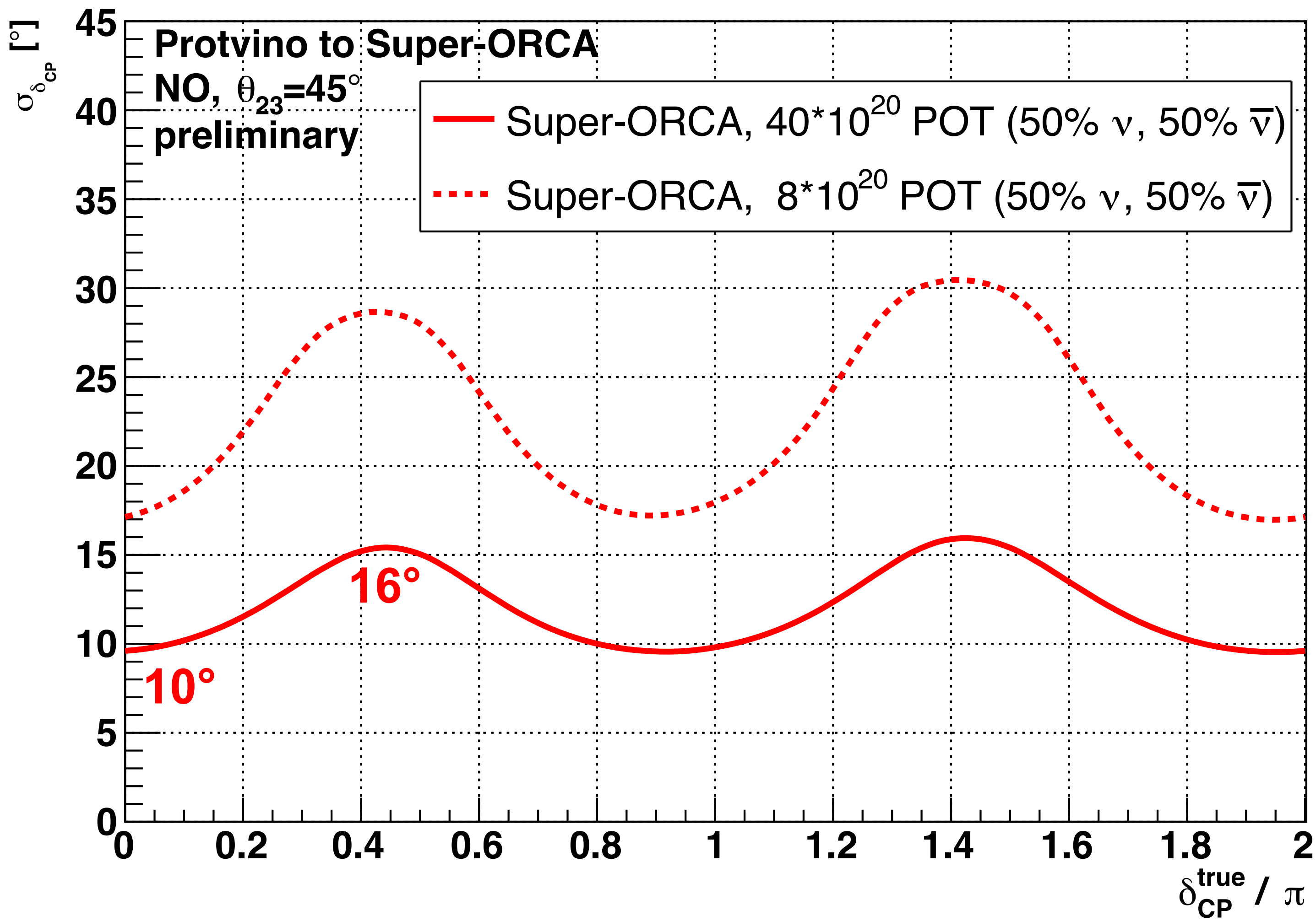
- 10x denser than ORCA
- **100 detected photons per GeV**
- For comparison: ~1% of SK's photo cathode area / detector volume

- e/μ separation via Cherenkov ring fuzziness possible
- Even at 1GeV leading lepton ring well visible at

δ_{CP} resolution

- 1σ-resolution on δCP with 450kW beam & Super-ORCA

Updated plot w.r.t. LoI, including more systematics → backup

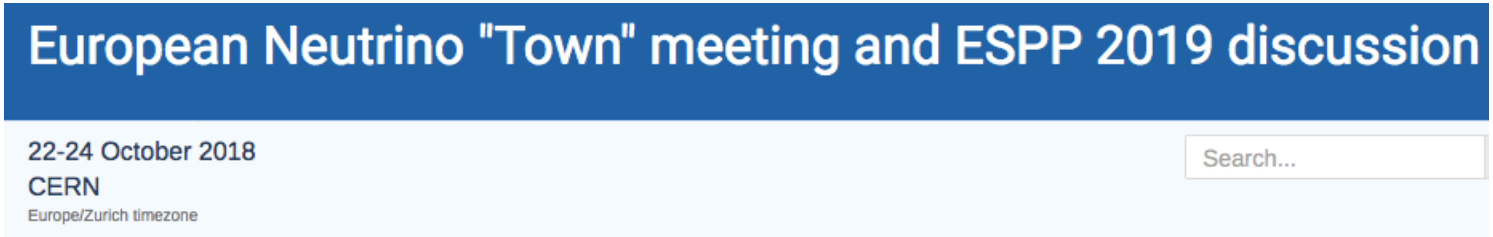


2yr, 450kW (10yr, 90kW)

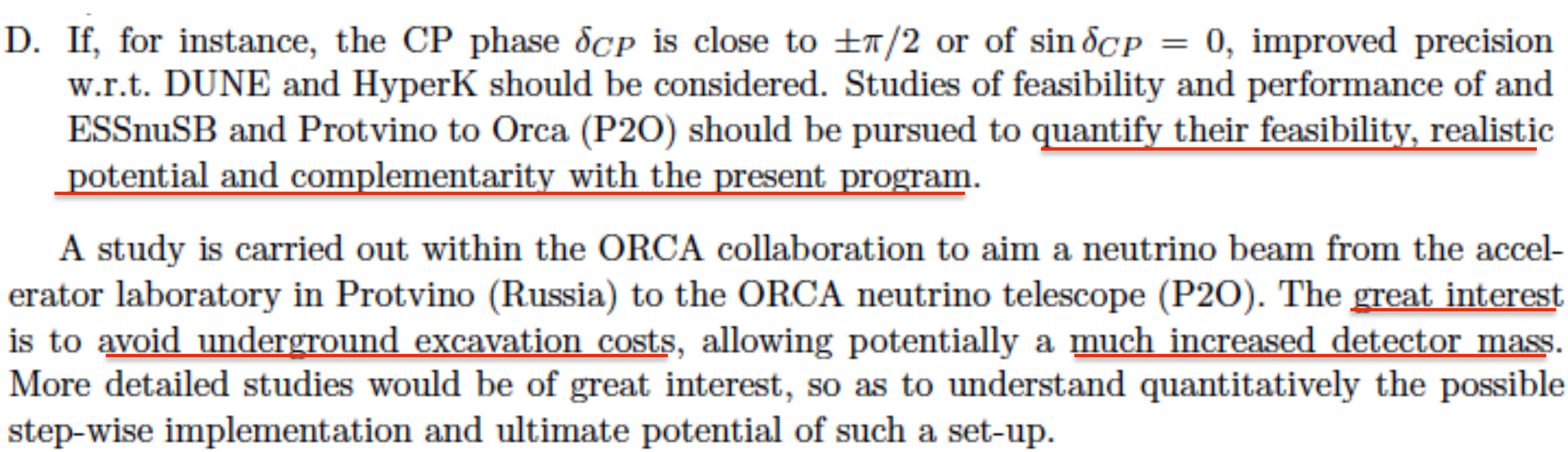
10yr, 450kW

European Strategy for Particle Physics

- P2O is part of 'European Strategy for Particle Physics' discussion



- From CERN 'Town' Meeting summary document **arXiv:1812.06739**


D. If, for instance, the CP phase δ_{CP} is close to $\pm\pi/2$ or of $\sin\delta_{CP} = 0$, improved precision w.r.t. DUNE and HyperK should be considered. Studies of feasibility and performance of and ESSnuSB and Protvino to Orca (P2O) should be pursued to quantify their feasibility, realistic potential and complementarity with the present program.

A study is carried out within the ORCA collaboration to aim a neutrino beam from the accelerator laboratory in Protvino (Russia) to the ORCA neutrino telescope (P2O). The great interest is to avoid underground excavation costs, allowing potentially a much increased detector mass. More detailed studies would be of great interest, so as to understand quantitatively the possible step-wise implementation and ultimate potential of such a set-up.

Summary and outlook

- **ORCA: O**scillation **R**esearch with **C**osmics in the **A**byss

→ main goal: determination of neutrino mass hierarchy, ~3σ after 3y

→ lots of other physics potential as well

- Current construction status:

→ one operating string

→ deployment of multiple strings in spring 2019

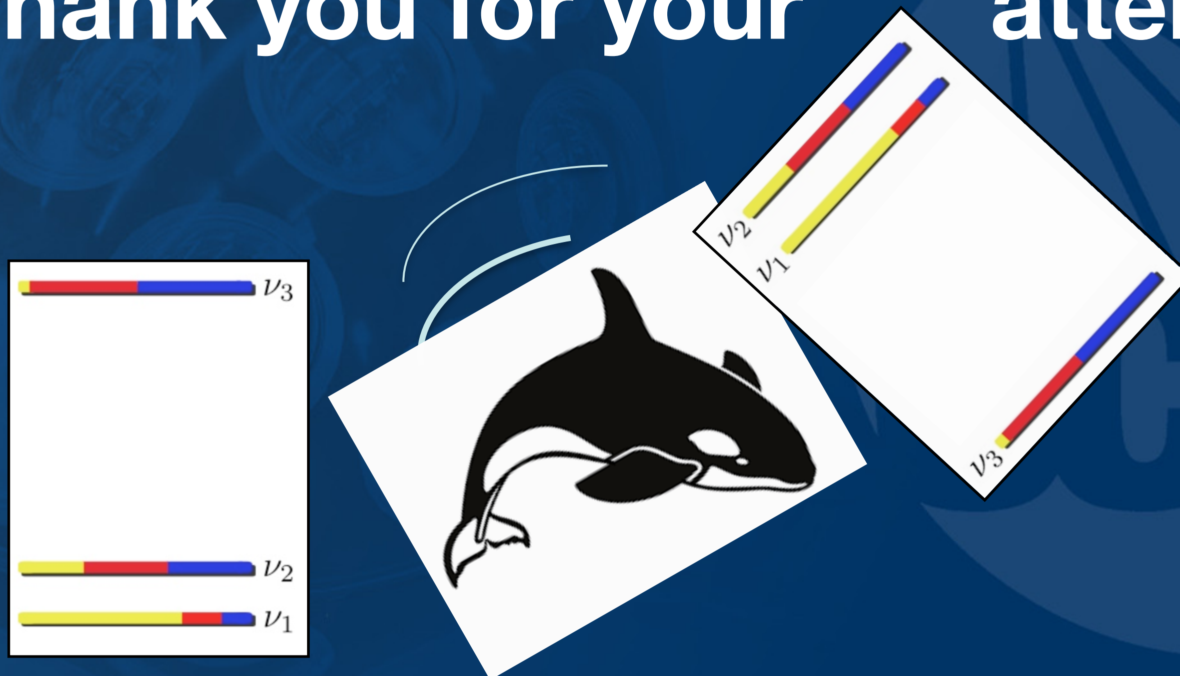
- Future option: neutrino beam from Protvino to ORCA (P2O)

→ high statistics long baseline neutrino experiment

→ competitive & complementary δCP measurement

Letter of Interest
arXiv:1902.06083

Thank you for your attention !



DFG Deutsche Forschungsgemeinschaft

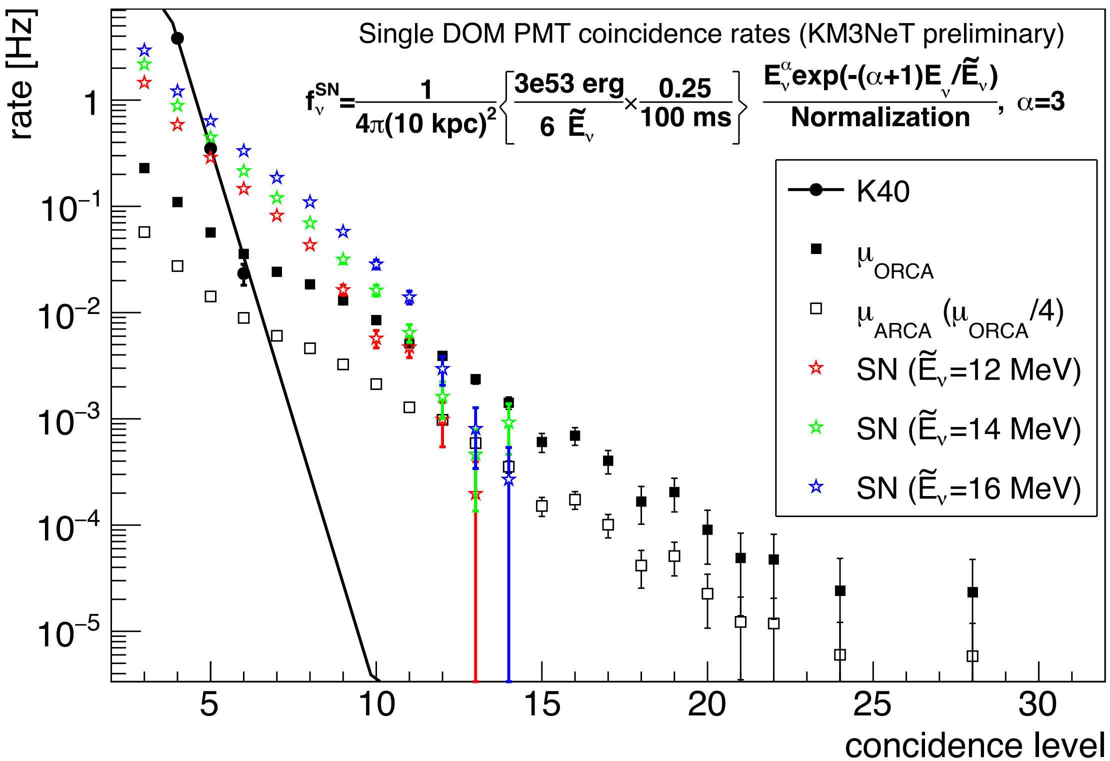
Horizon 2020
European Union Funding
for Research & Innovation

FAU FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

Backup

Supernova monitoring

- Count coincidence signals on individual Optical Modules
- Excess of DOMs where 6-10 PMTs fire together
- 10 MeV anti-nu e from core-collapse SN
- >80% of all Galactic SN with single building block



CP violation sensitivity

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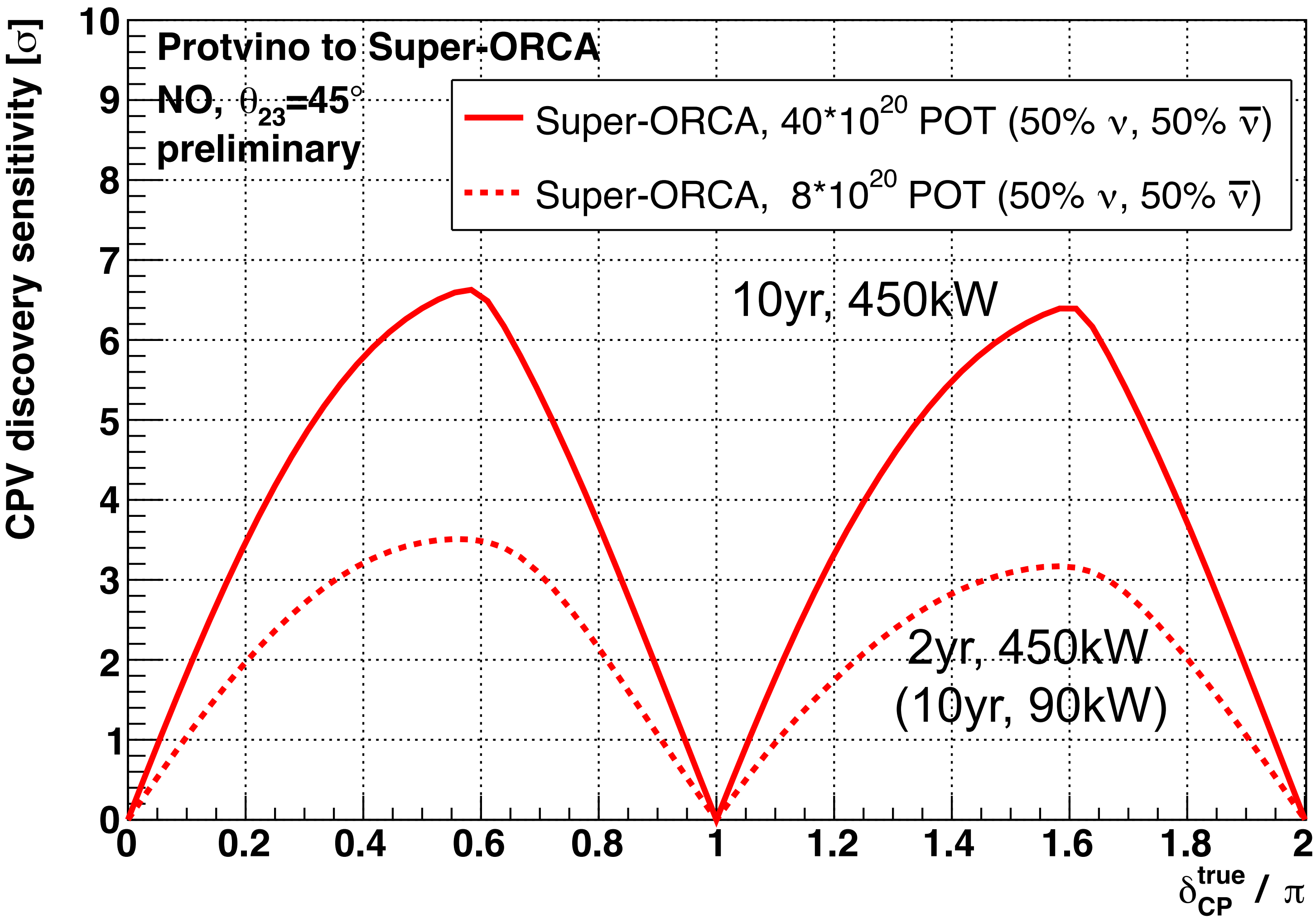
- CPV sensitivity with 450kW beam & Super-ORCA

Updated plot w.r.t. LoI, including more systematics → backup



Systematics for P2SO

- Combined fit of nuisance and oscillation parameters
- Choice of nuisance parameters and priors inspired by LBNO study

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}	45°	2.0°	41° & 49°
ΔM^2 [eV^2]	$2.5\ 10^{-3}$	0.05	$2.5\ 10^{-3}$
δ_{CP}	many	no	many

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

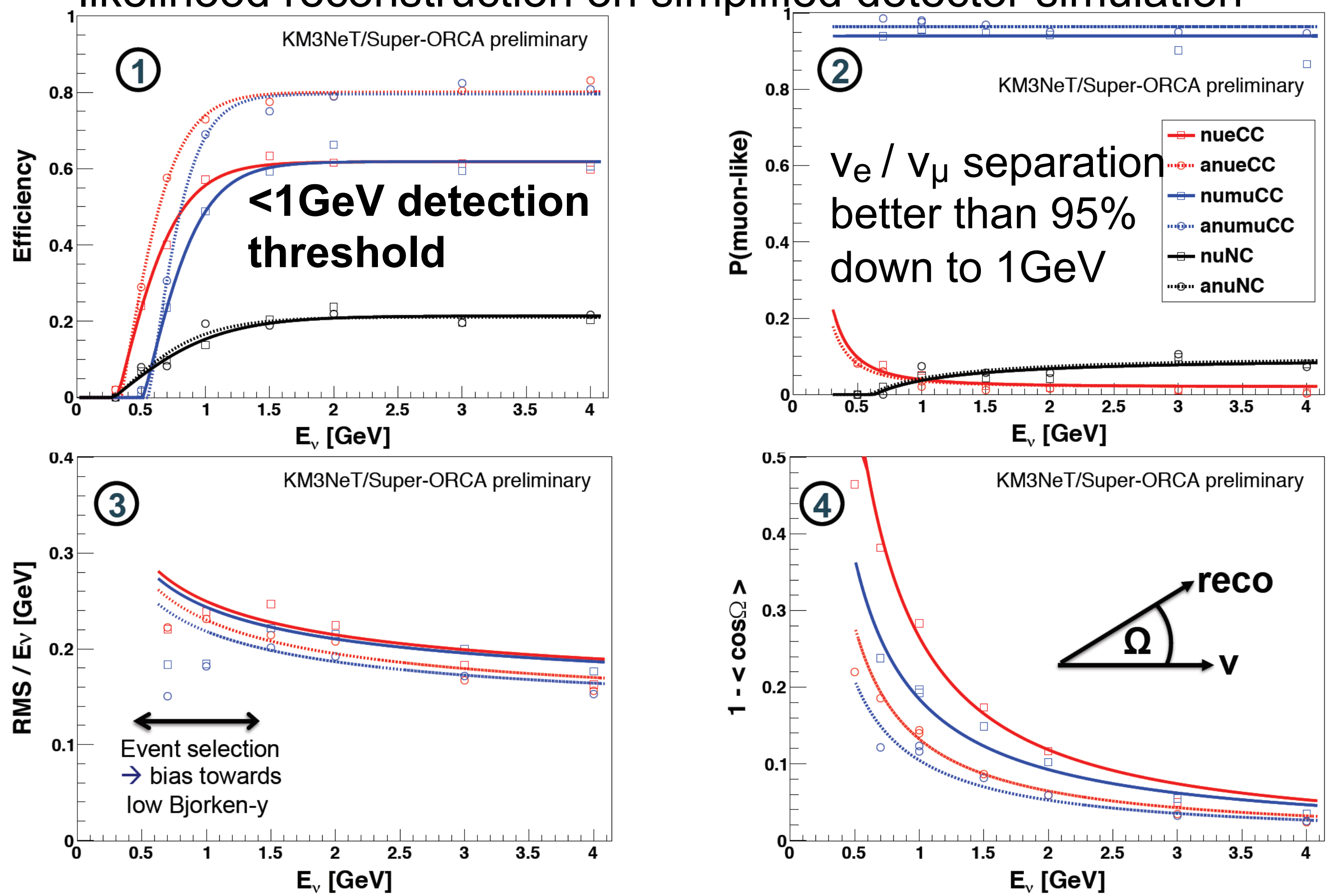
*For each beam polarity ($\nu/\bar{\nu}$)

Parameter	True value	Prior	Start value
Escale ν_e CC	1	0.03	1
Escale ν_μ CC	1	0.03	1

Added for plots of this talk, but not yet included in Letter of Interest arXiv:1902.06083

Super-ORCA detector performance

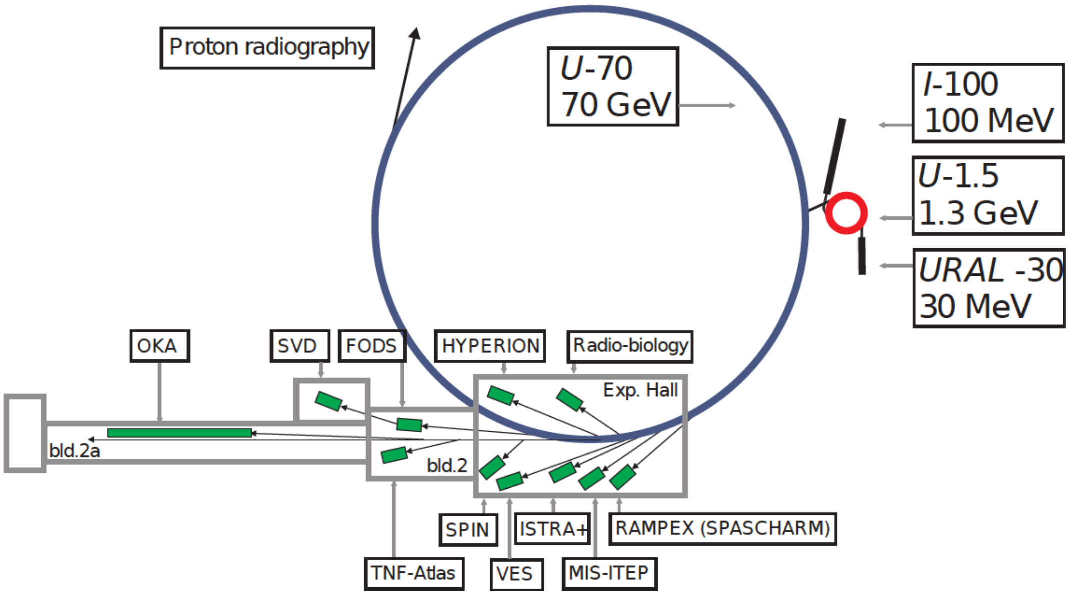
Detector performance based on performing maximum likelihood reconstruction on simplified detector simulation

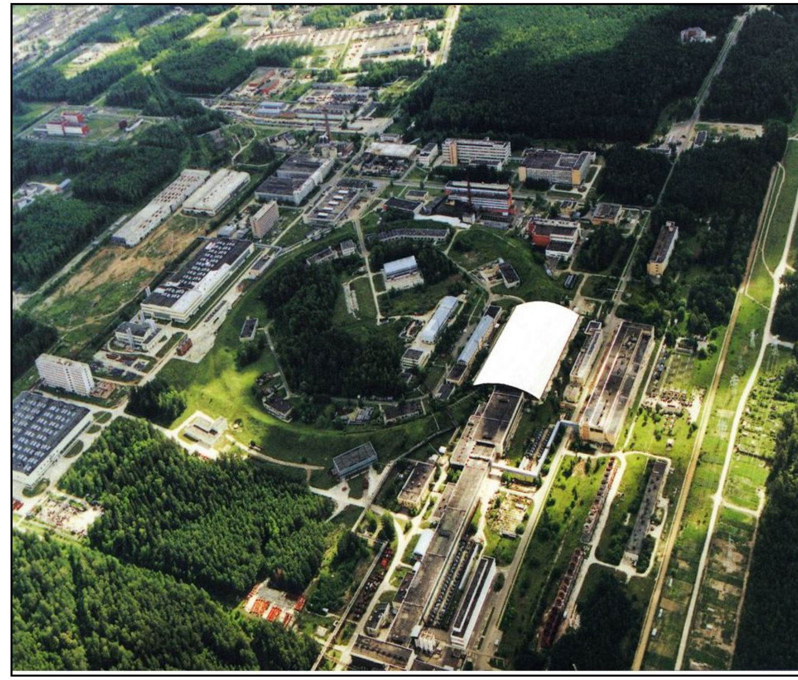


10.5281/zenodo.1292936

1 Event selection efficiency: ~0.8/0.6/0.2 for $\bar{\nu}$CC / νCC / NC events
2 Event classification purity : ~95%
3 Neutrino energy resolution: ~20% (dominated by intrinsic light yield fluctuations)
4 Neutrino direction resolution dominated by intrinsic ν-lepton scattering angle

Protvino accelerator complex





Accelerator	Length, m	Energy
Linear accelerator Ural-30	25.3	30 MeV
Linear accelerator I-100	79.4	100 MeV
Synchrotron U-1.5	99.16	1.32 GeV
Synchrotron U-70	1483.7	50-70 GeV

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

The OMEGA project proposal

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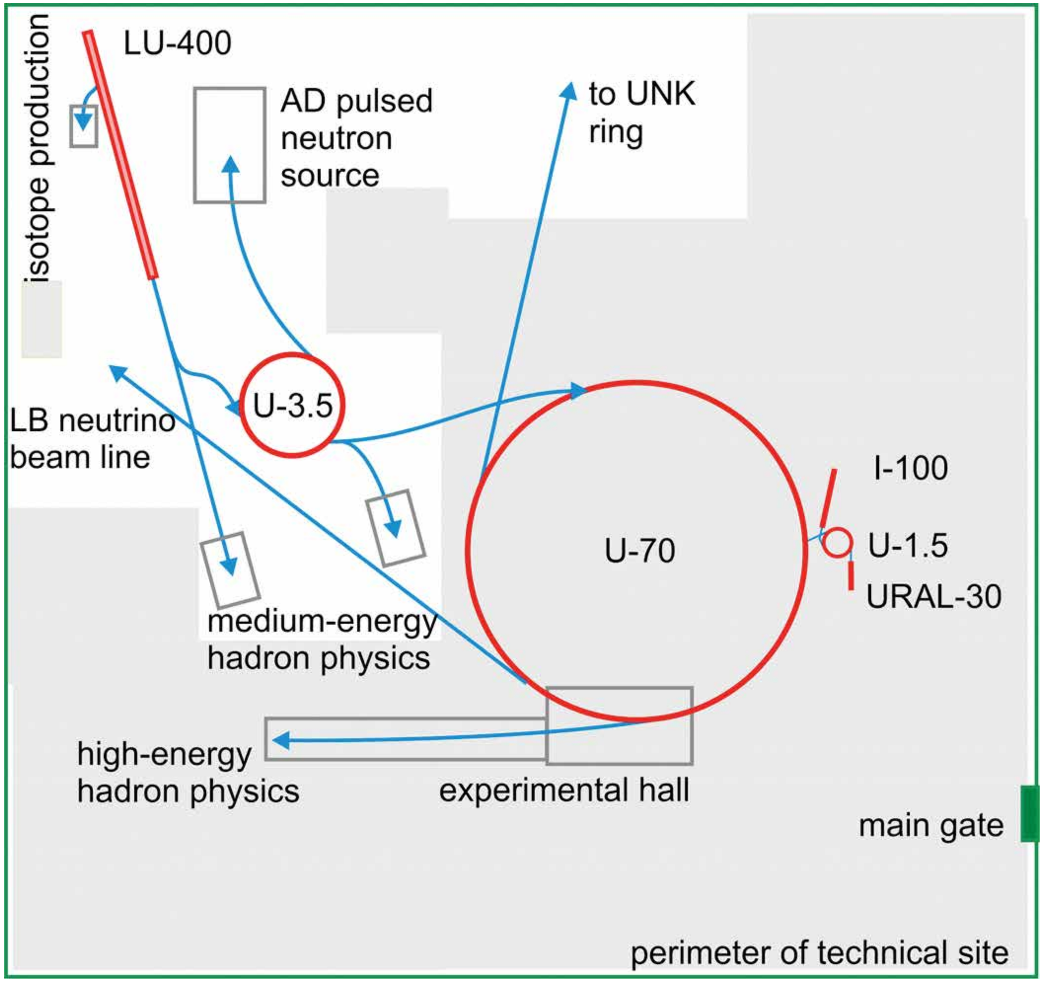
- New high intensity linac and booster synchrotron (3.5 GeV)
- 1.1 MW proton beam
- High-intensity spallation neutron source
- 450 kW power at 70 GeV using existing U-70 synchrotron
- A long baseline neutrino beam



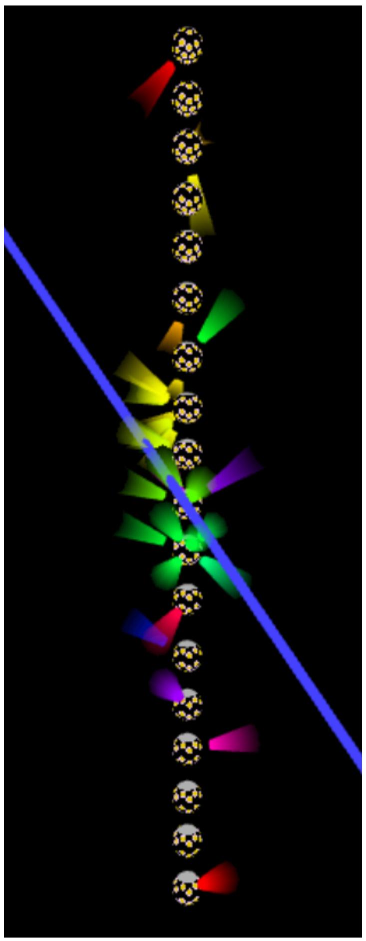
Construction estimate 8 yr

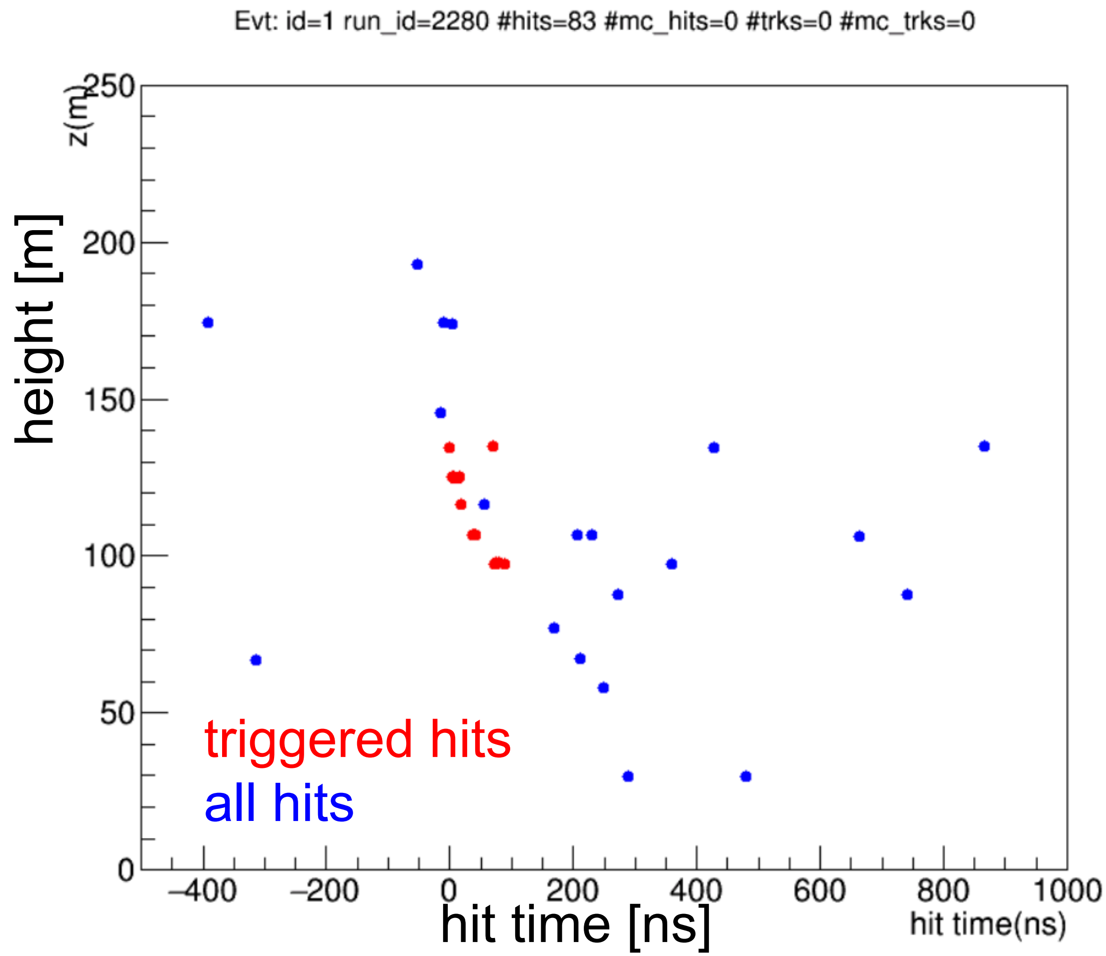
N.E. Tyurin et al, Facility for intense hadron beams (Letter of Intent), News and Problems of Fundamental Physics 2 (9), 2010, http://ihep.ru/files/IHEP-2-10.pdf

Event displays

- First event with reconstructed track recorded by ORCA

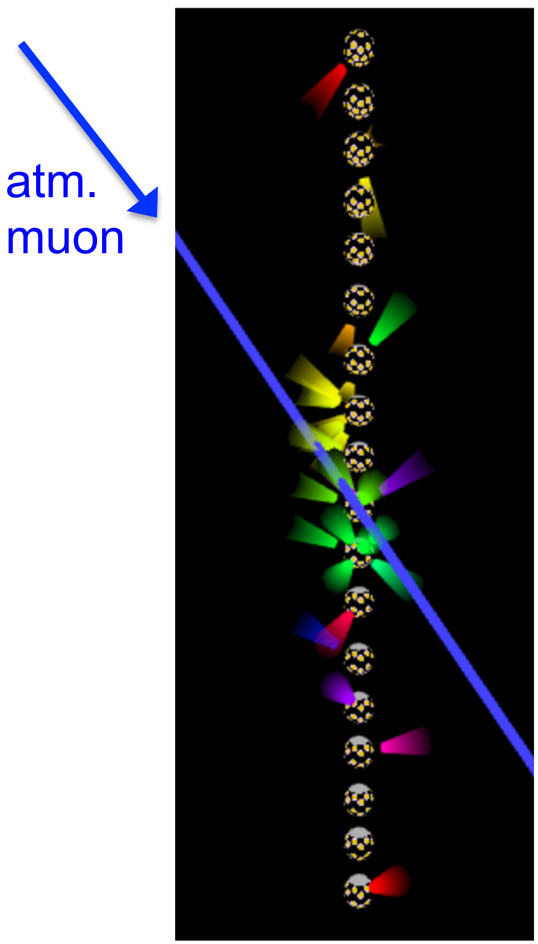
atm.
muon

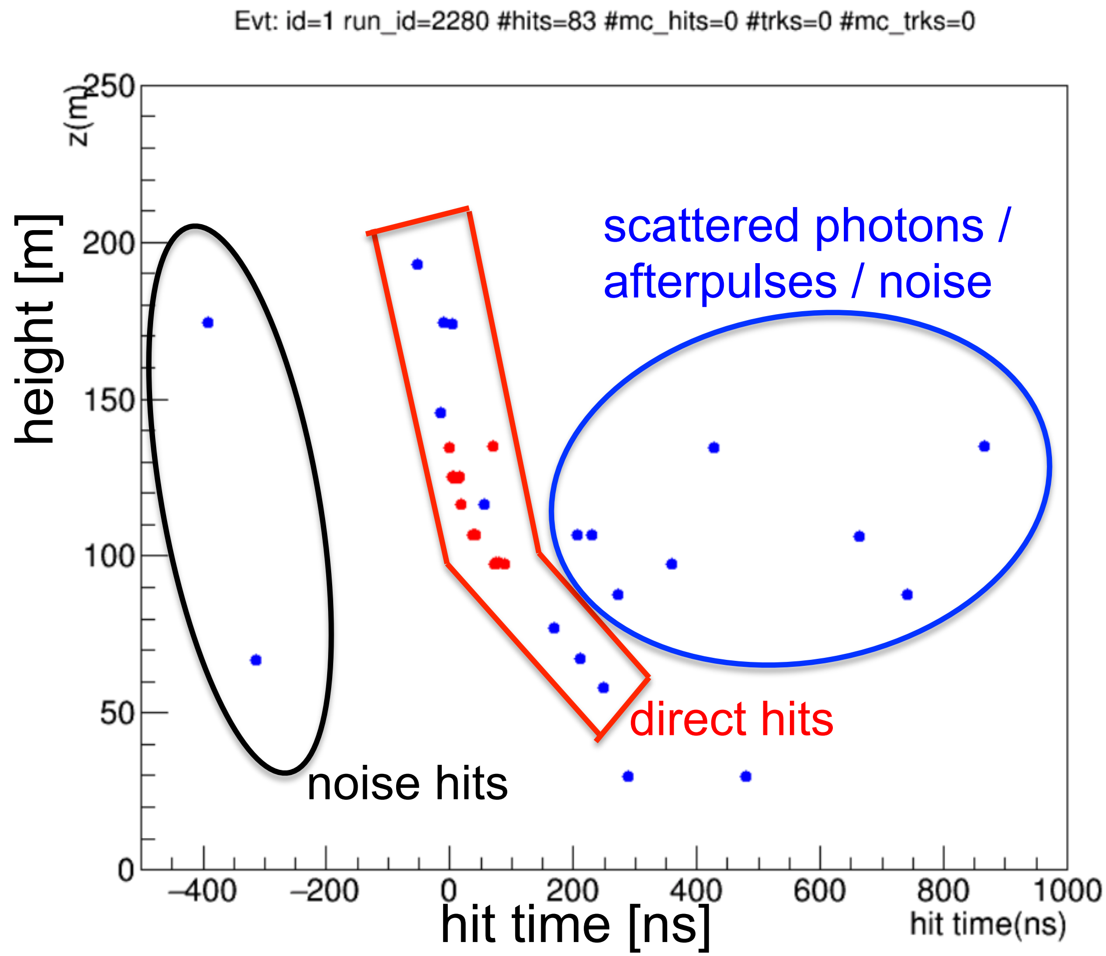




Event displays

- First event with reconstructed track recorded by ORCA

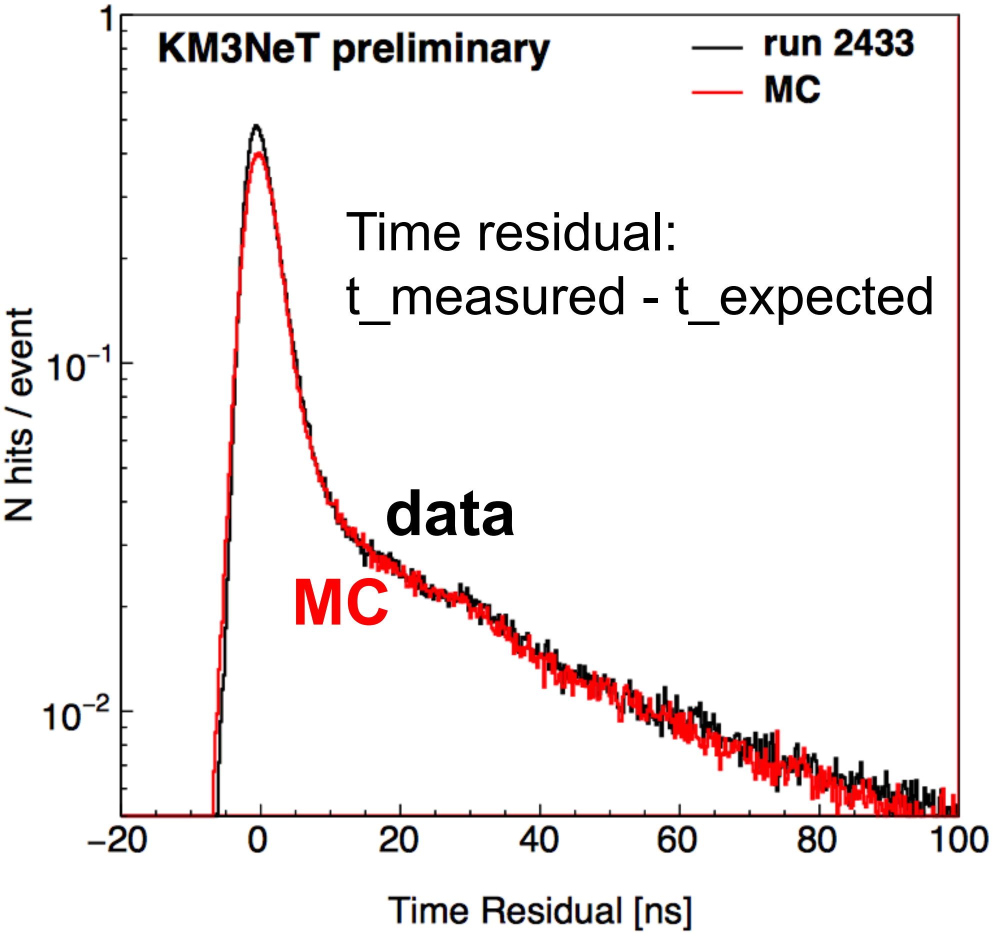




Data / MC comparison

- Dedicated single-string track reconstruction
- Good data/MC agreement

Time residual distribution



Reconstructed zenith angle