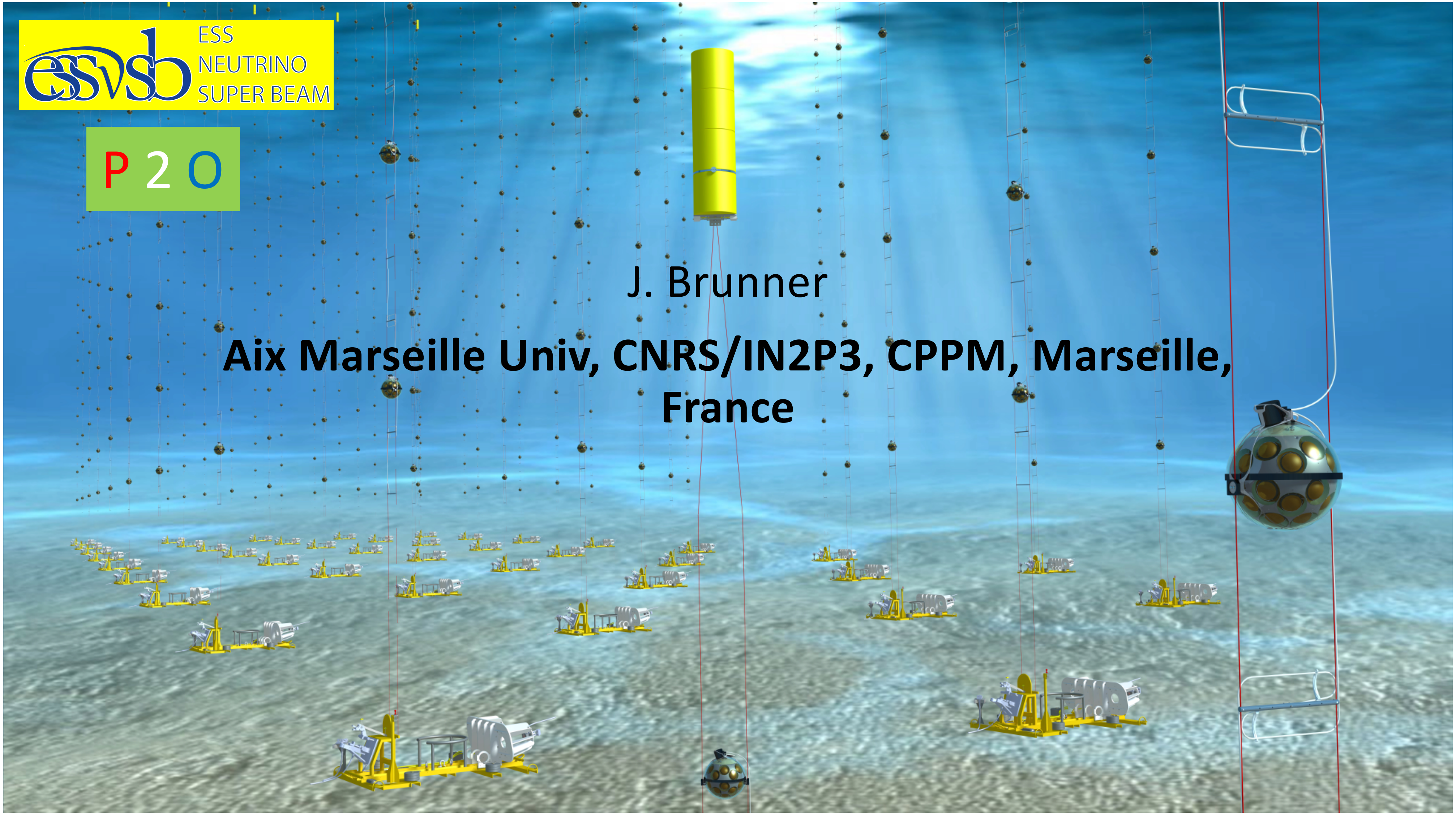
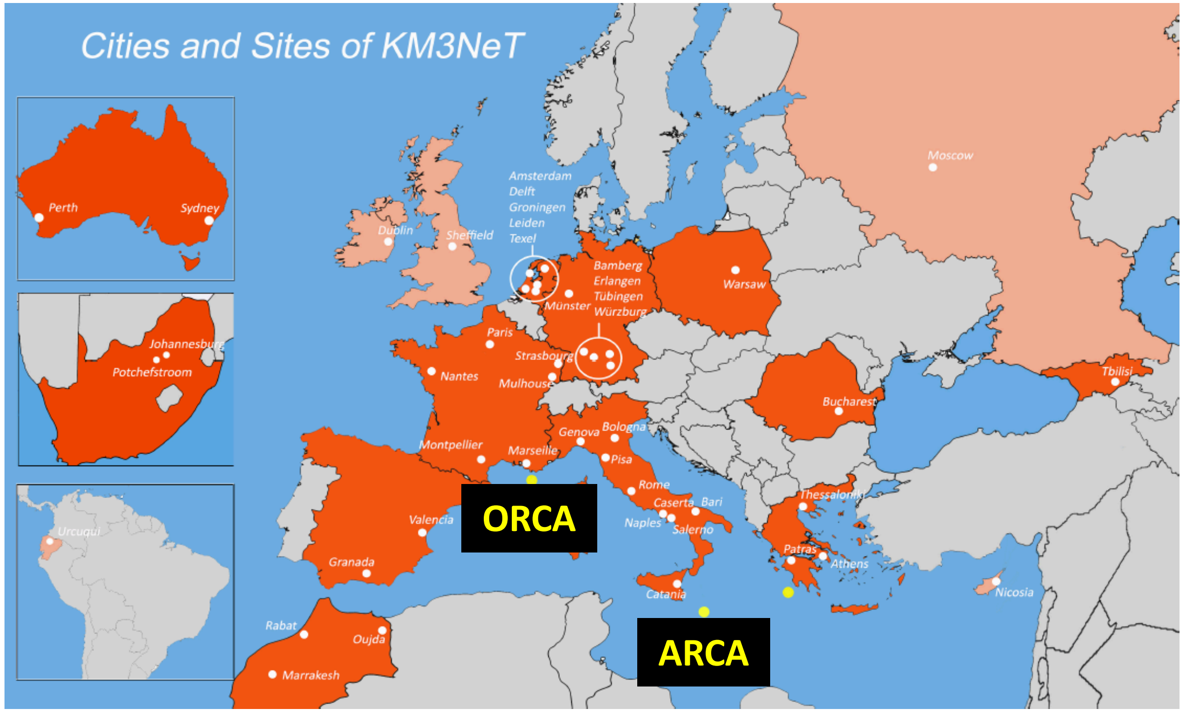
Neutrino Physics in Europe (atmospheric & accelerator)

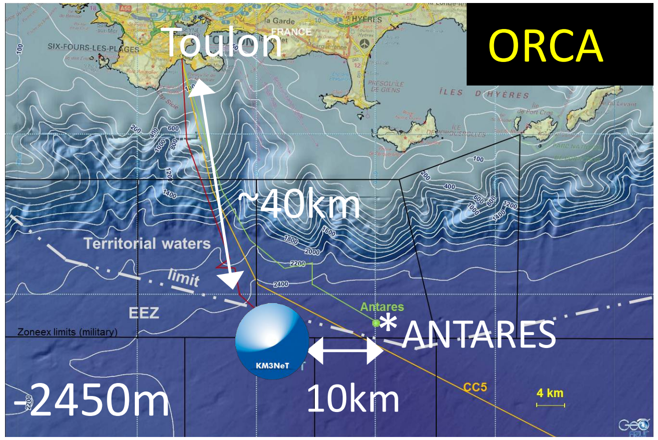


J. Brunner

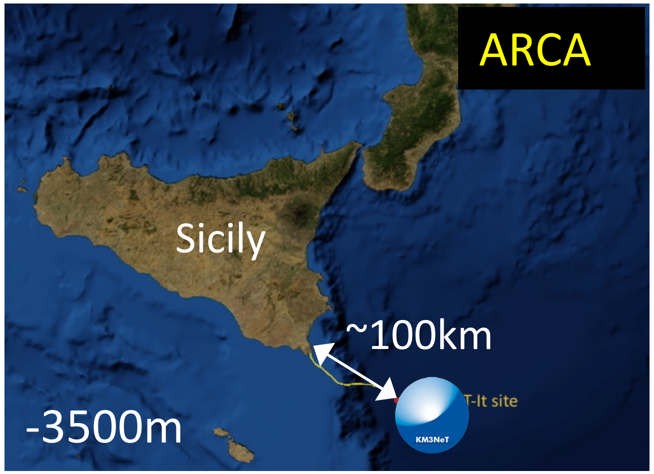
Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

KM3NeT Collaboration: ARCA & ORCA





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

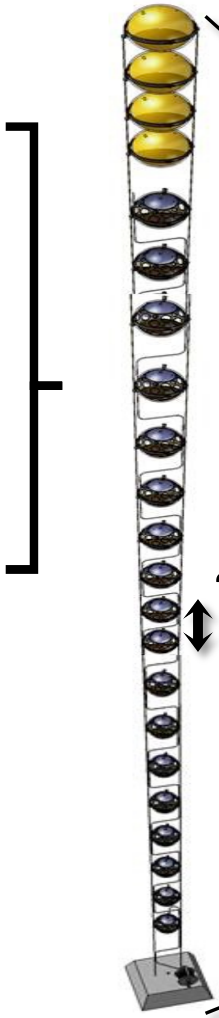
ORCA → neutrino mass ordering with few-GeV atmospheric neutrinos

ARCA & ORCA detectors

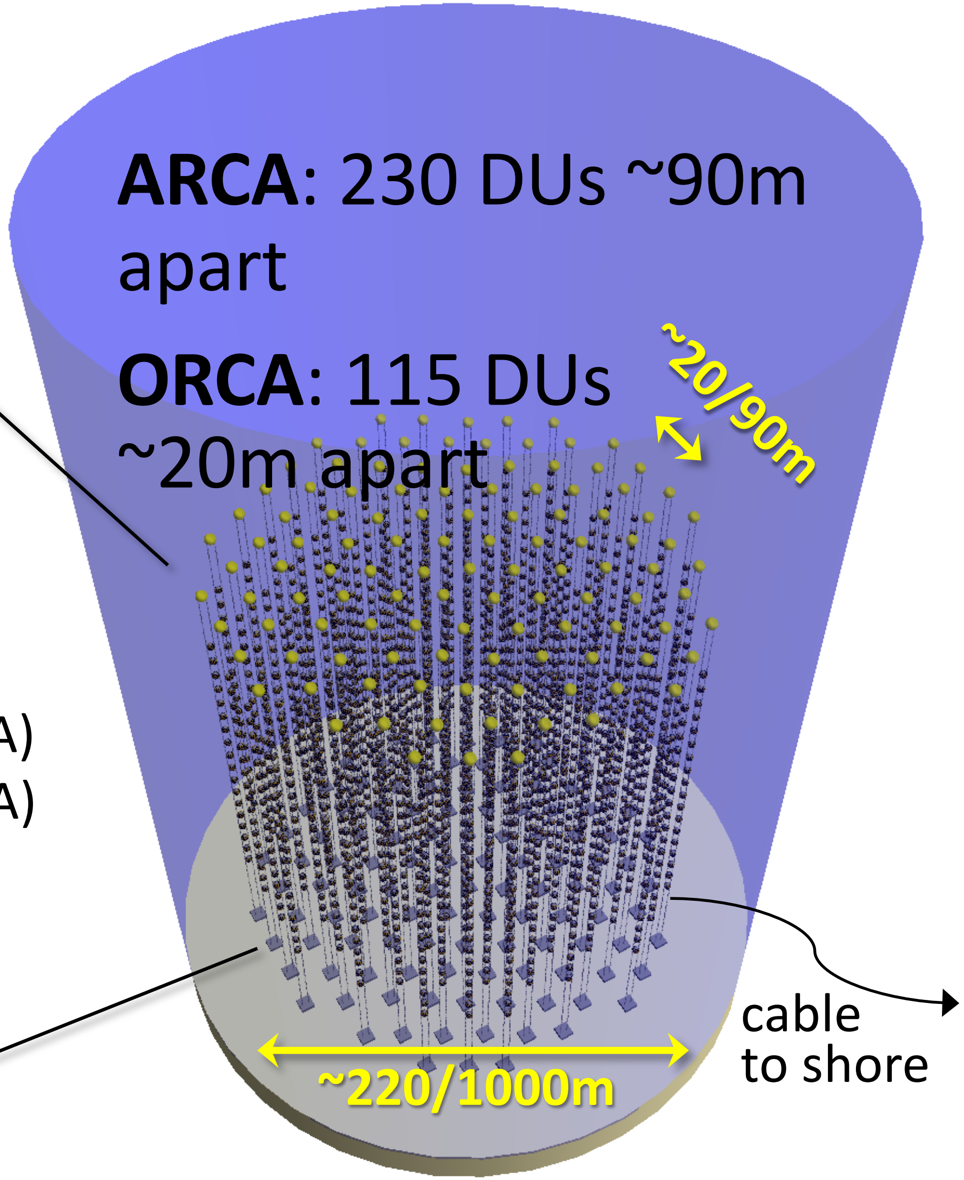
Digital Optical Module (DOM)

31 x 3”-PMTs
(19↓, 12↑)

Detection Unit (DU)

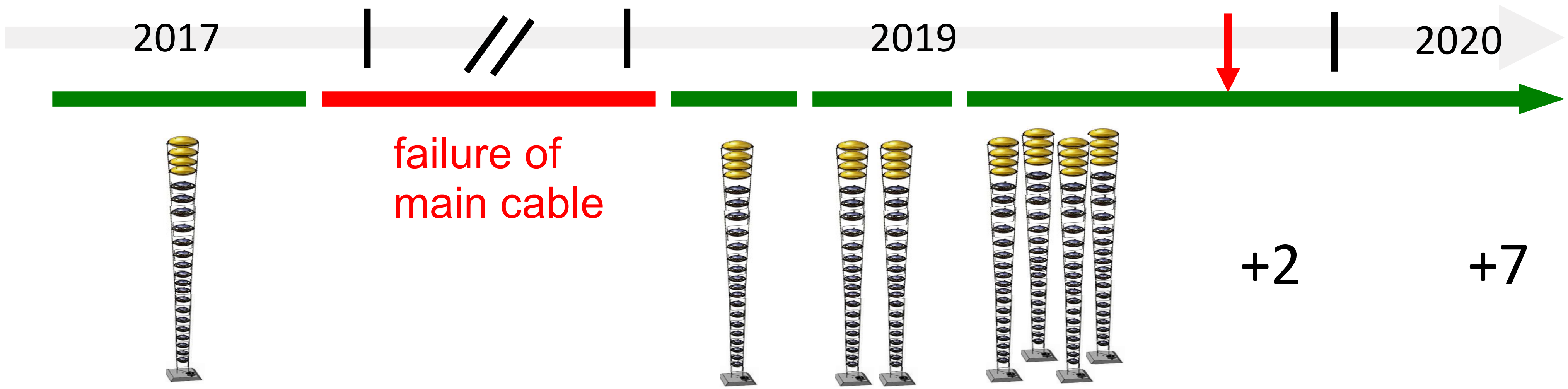


~36m (ARCA)
~9m (ORCA)



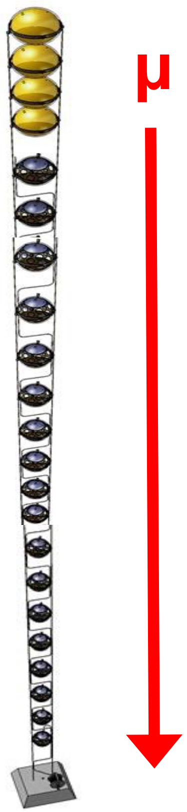
Detector construction status ORCA

- Main cable repair in October 2018
- Three successful deployments in 2019
- 9 months continued data taking with 1 DU
- 4 months continued data taking with 4 DUs
- One more deployment planned in Nov 2019 (+2 DUs)
- Double number of DUs planned in 2020

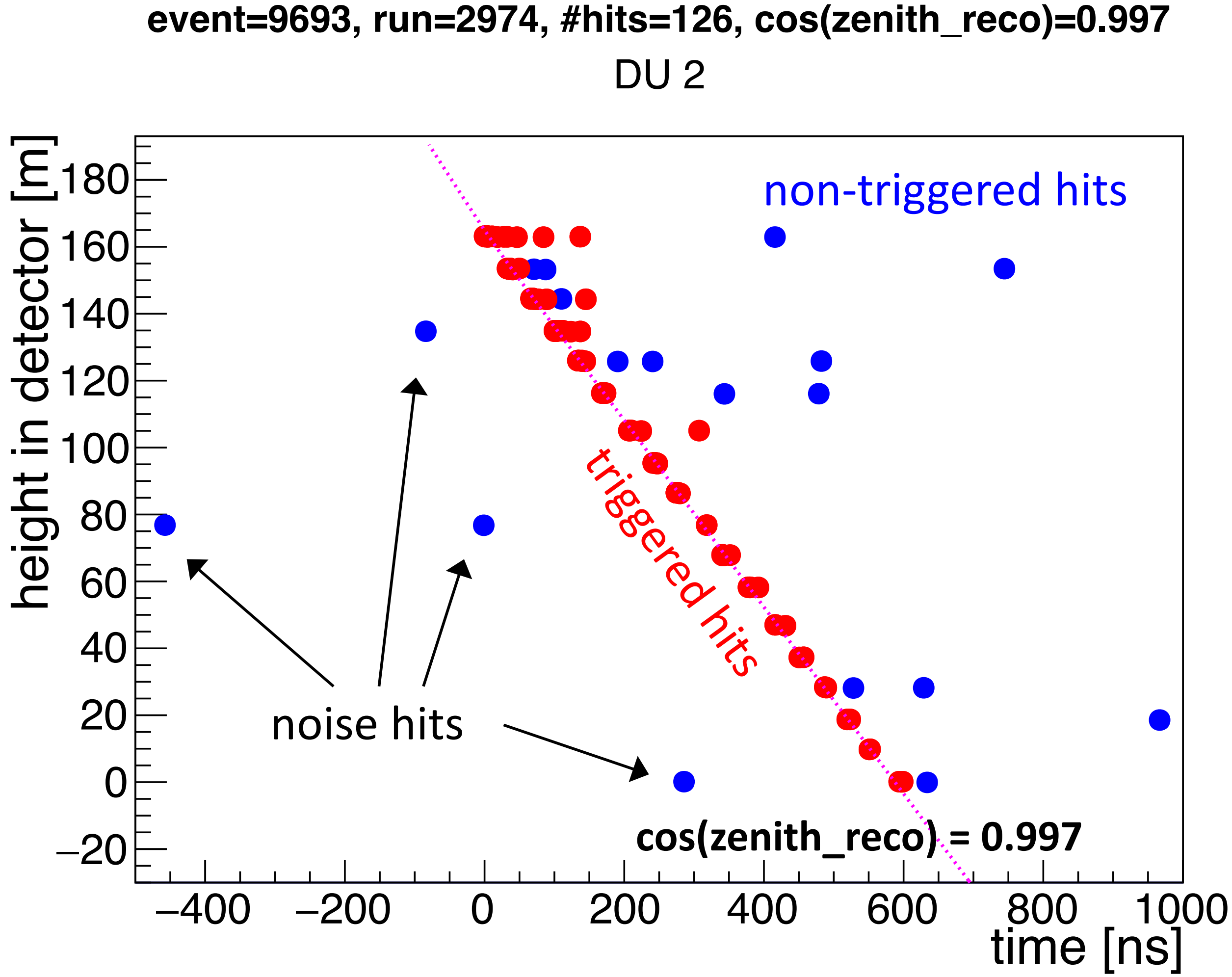


Real data – atmospheric muon

- Example**: down-going atmospheric muon** passing close to DU



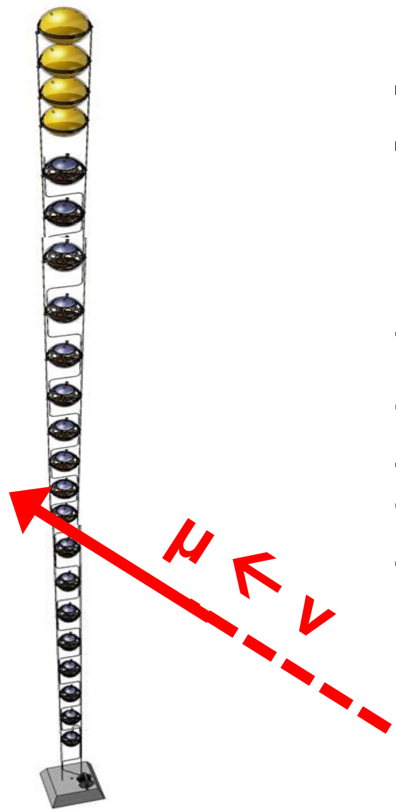
ORCA1



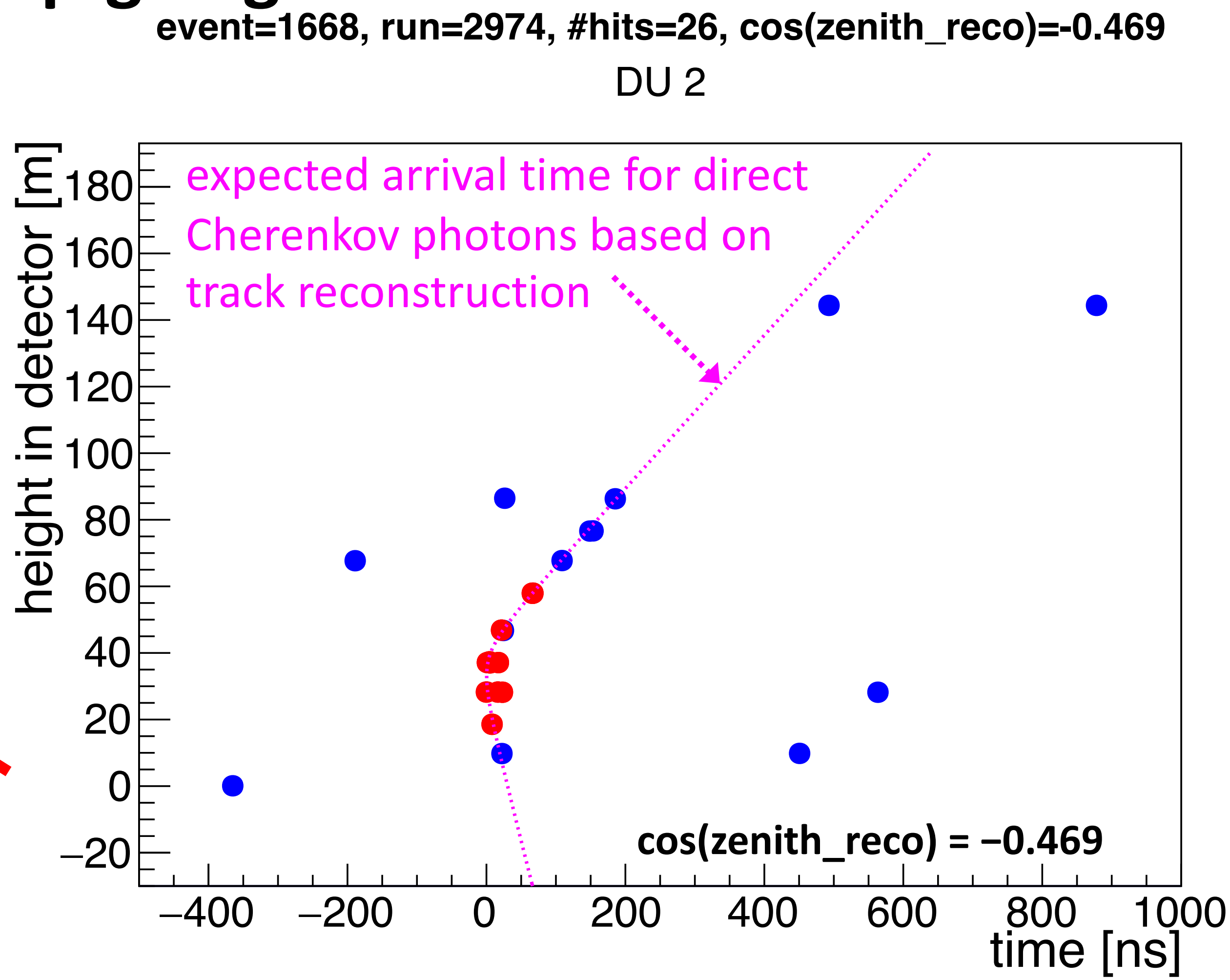
- Most detected photons arrive 'on-time' due to the large scattering length in deep-sea water

Real data – neutrino candidates

- Example: **up-going neutrino candidate**



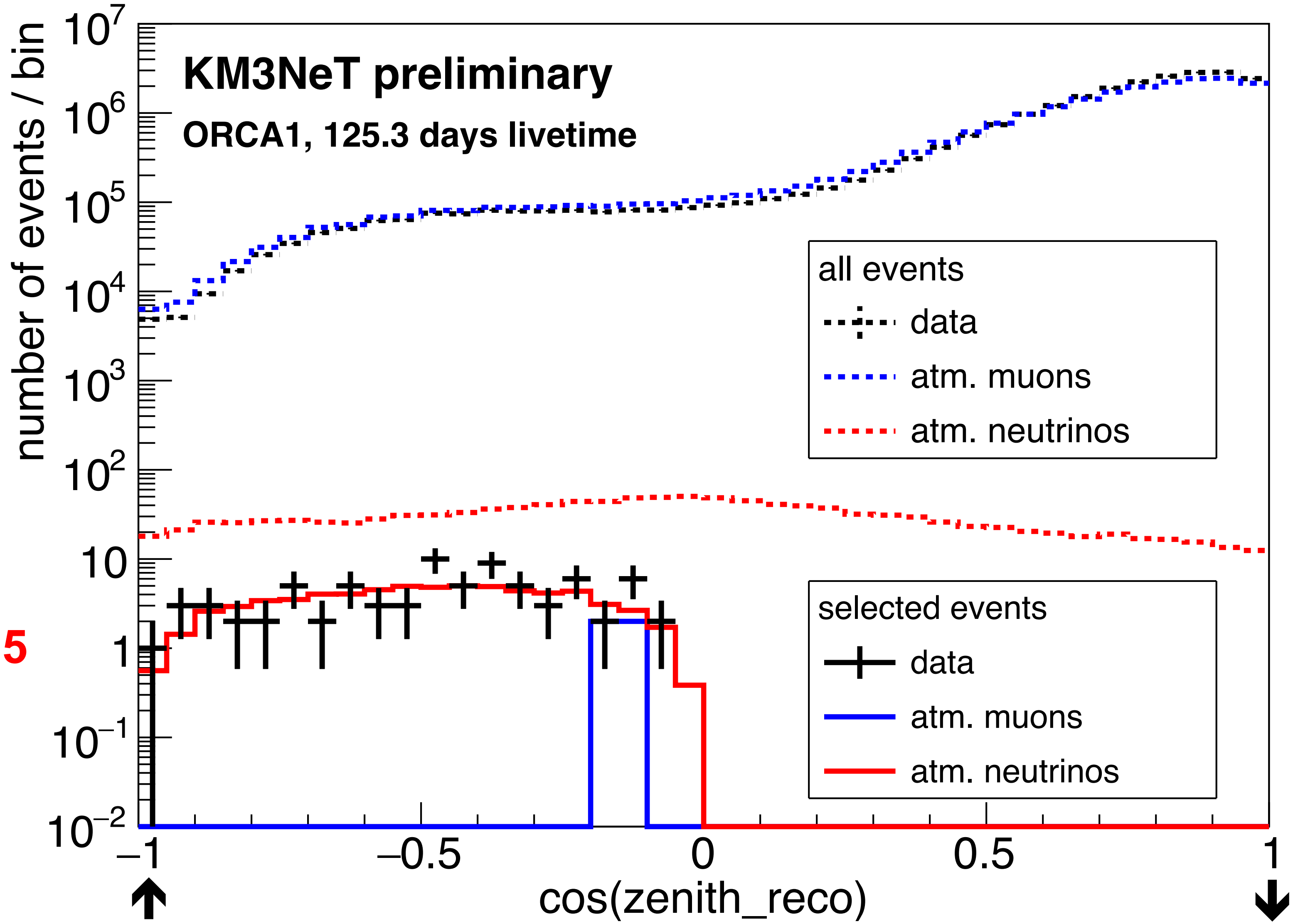
ORCA1



- Most detected photons arrive 'on-time' due to the large scattering length in deep-sea water

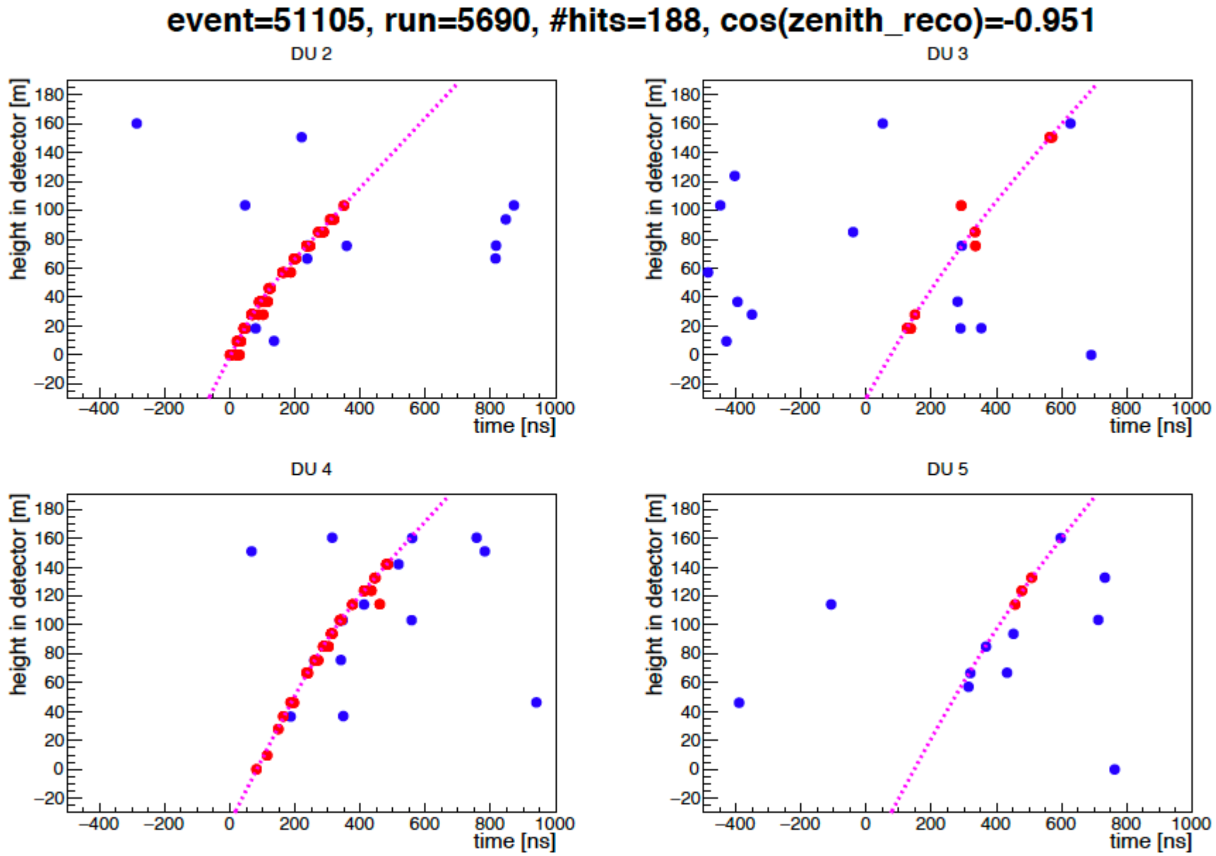
Real data – selected neutrino sample

Data: 77
ν MC: 67.5
μ MC: 4



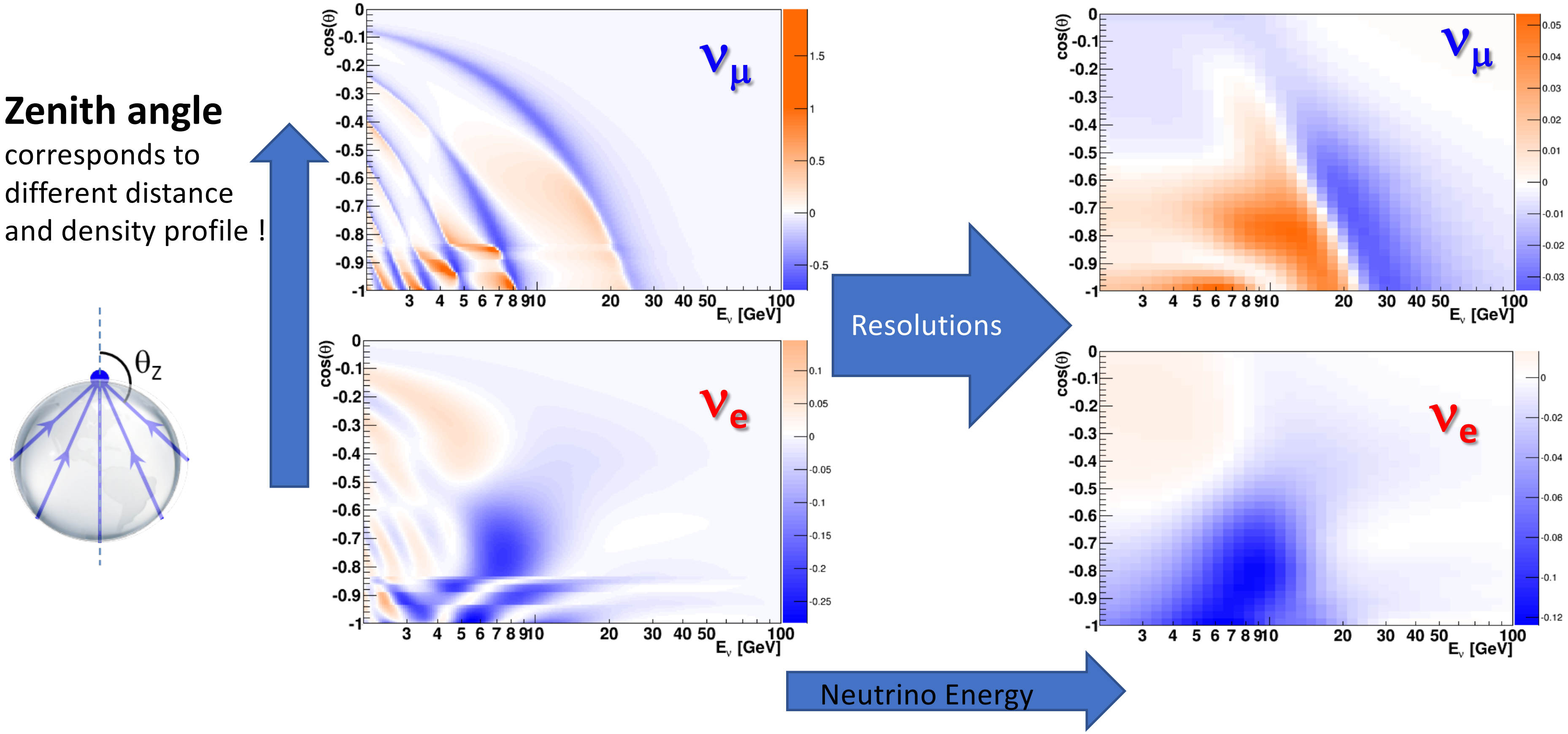
Real data – neutrino candidate with 4 DUs

- July 2019, seen on all 4 DUs
- estimated energy 30-40 GeV



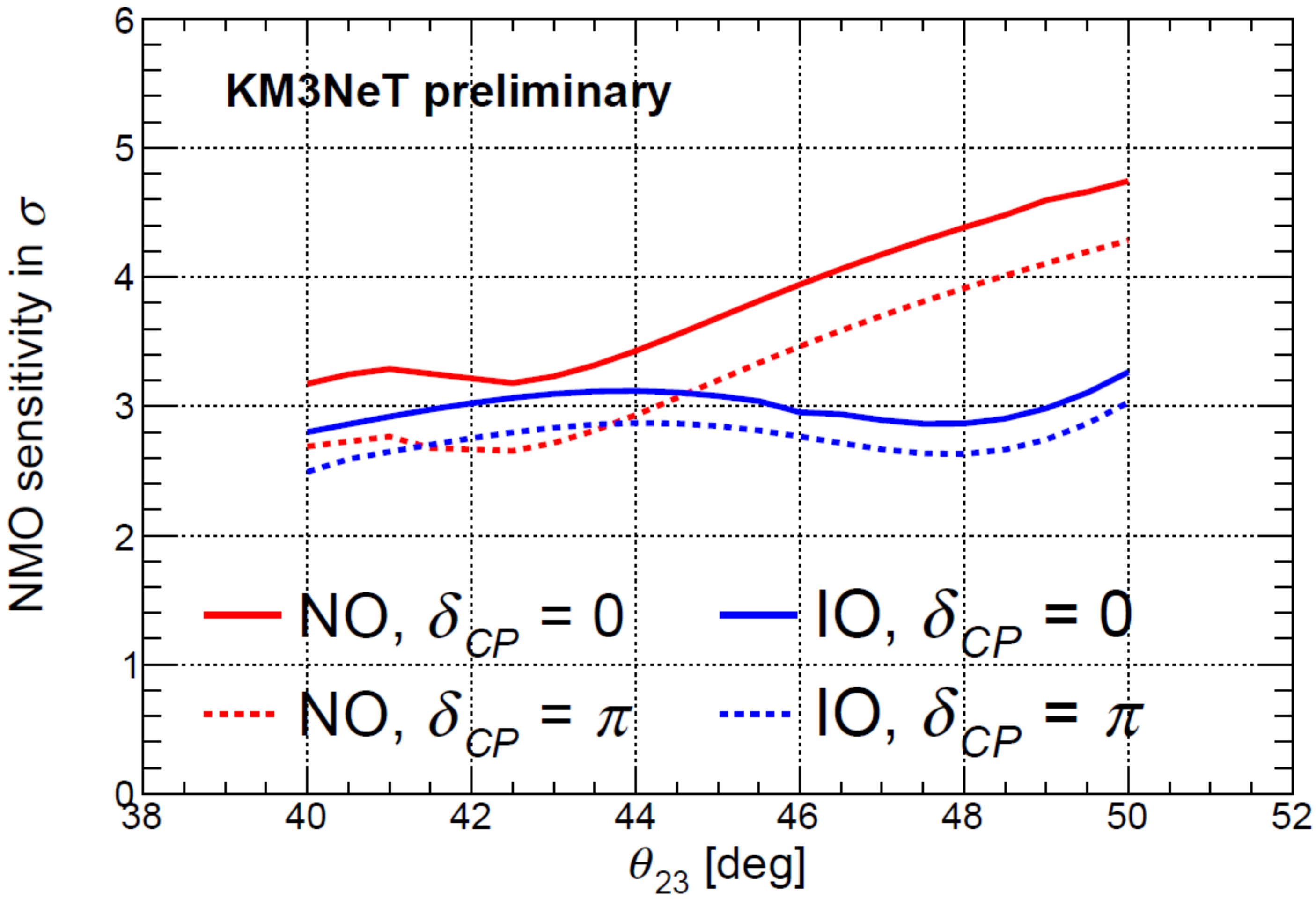
Determining the NMH with atmospheric $\boldsymbol{\upsilon}$´s

Relative difference in event numbers between normal and inverted hierarchy $(N_{IH}-N_{NH})/N_{NH}$



Sensitivity for Neutrino mass ordering

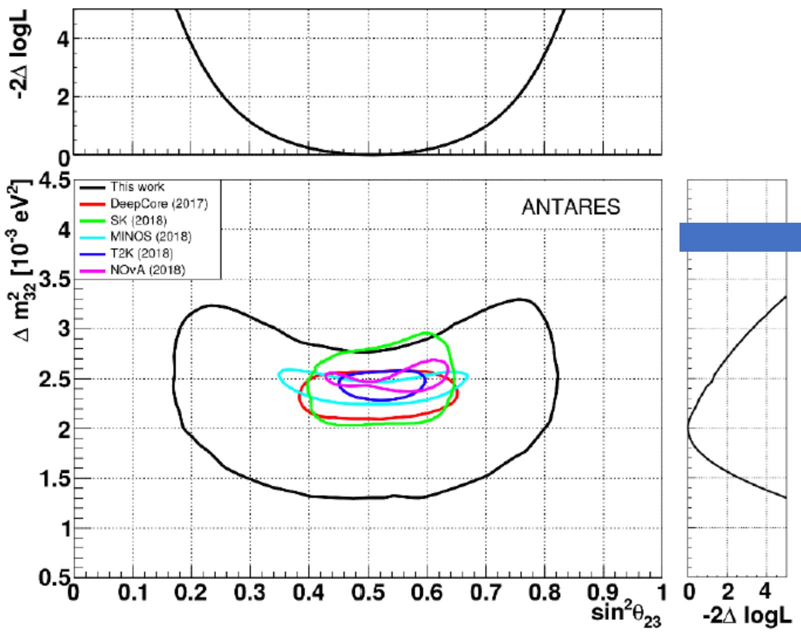
Sensitivity to distinguish between normal and inverted hierarchy:
~3 σ in 3 years (median sensitivity)

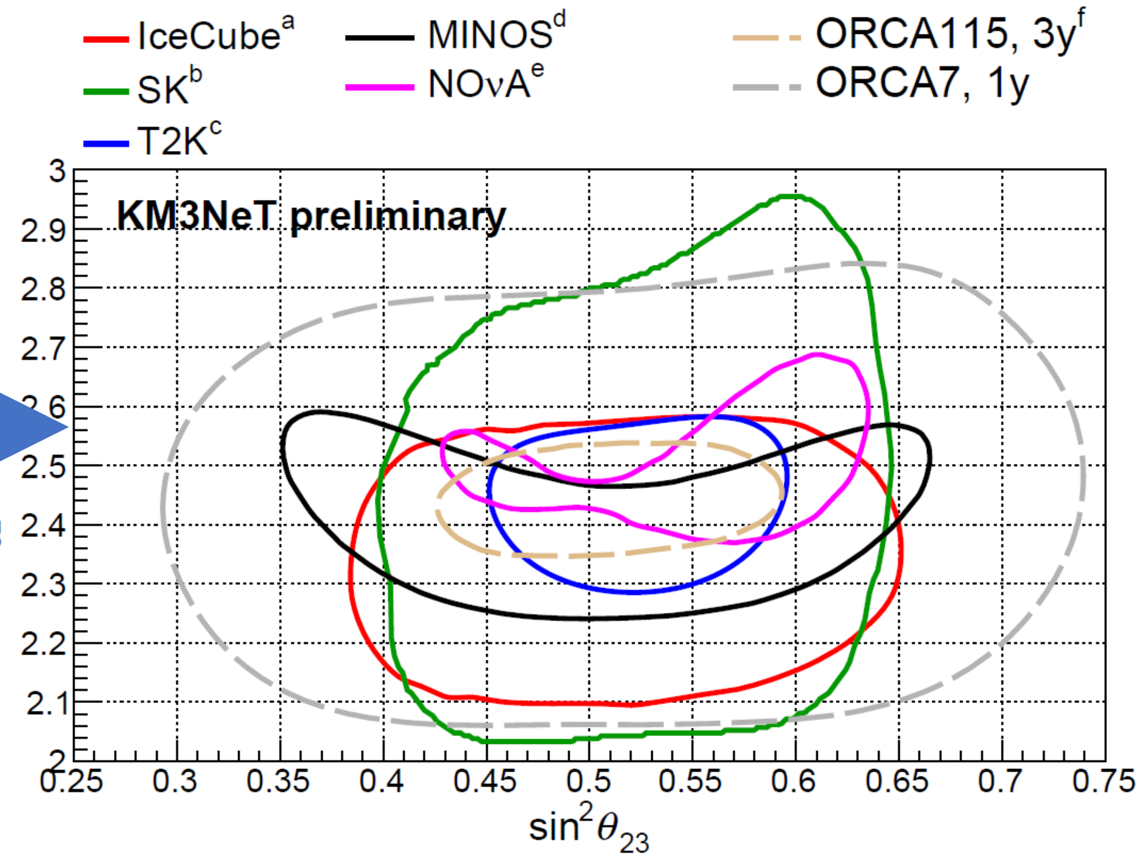


$Measurement\ of\ \Delta m^2_{32}$ and $sin^2\theta_{23}$

Competitive measurements of Δm^2_{32} (2-3%) and $sin^2\theta_{23}$ (4-10 %)
Interesting results already with few lines after 1 year

ANTARES
J. High Energ. Phys. (2019) 2019: 113

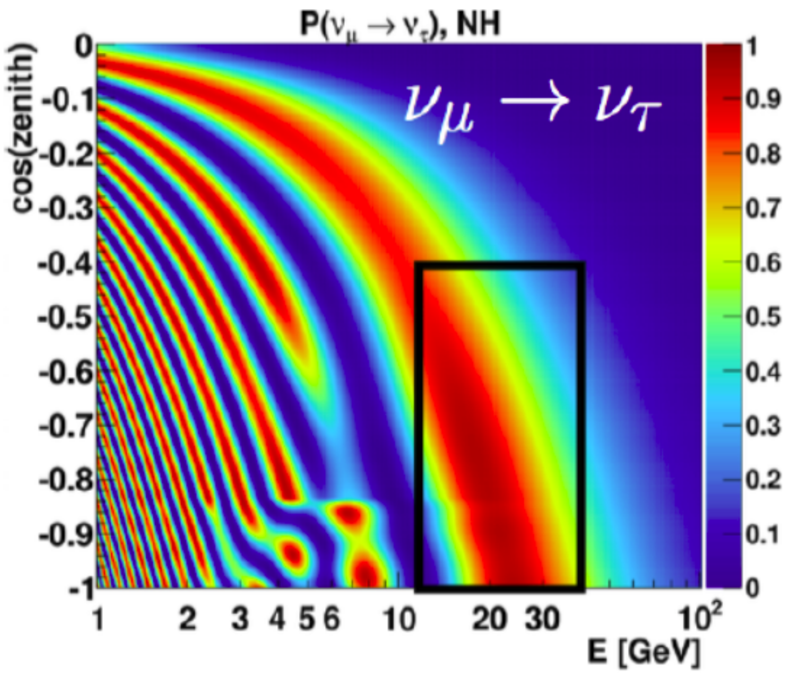


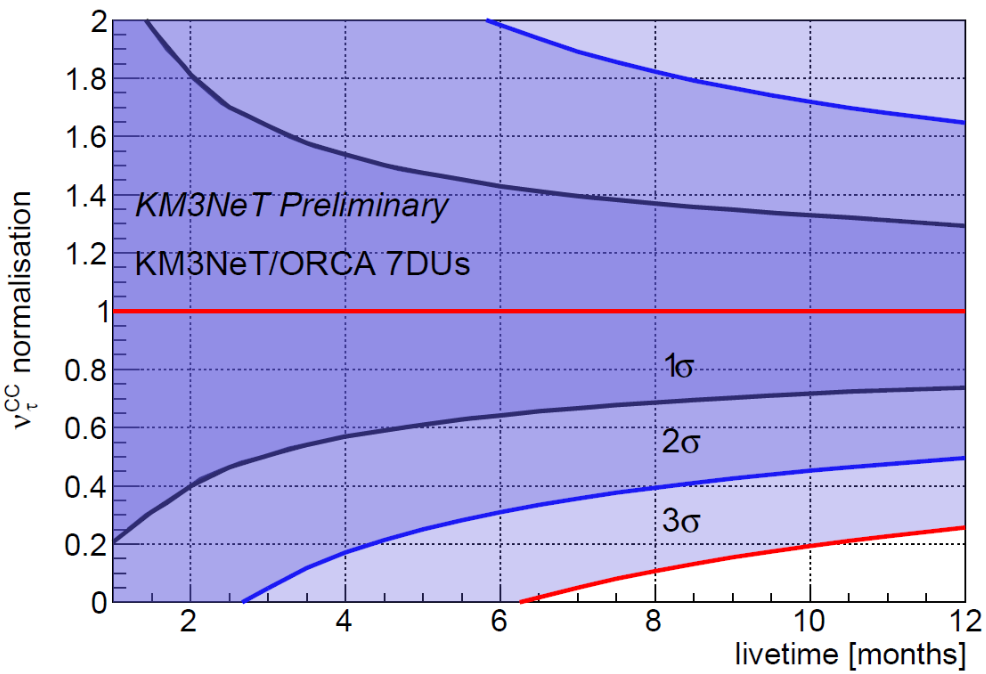


Unitarity check : τ appearance

Early physics result
3k tau events/year (full detector)
Rate constrained to 10% in one year (full detector)

KM3NeT Preliminary



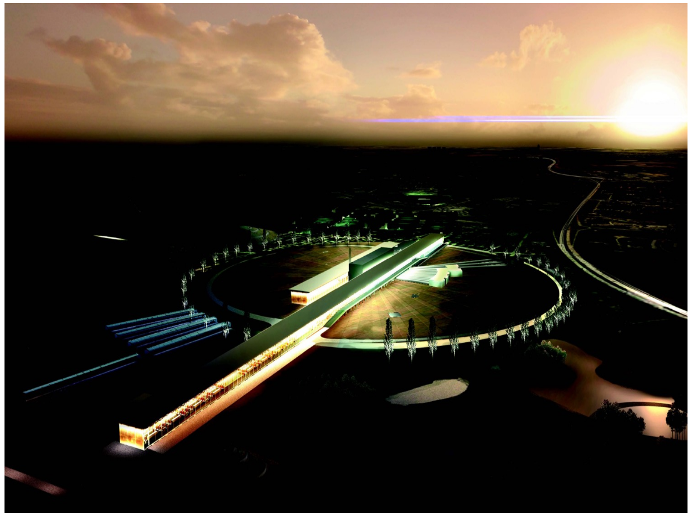


7 Detection Units!

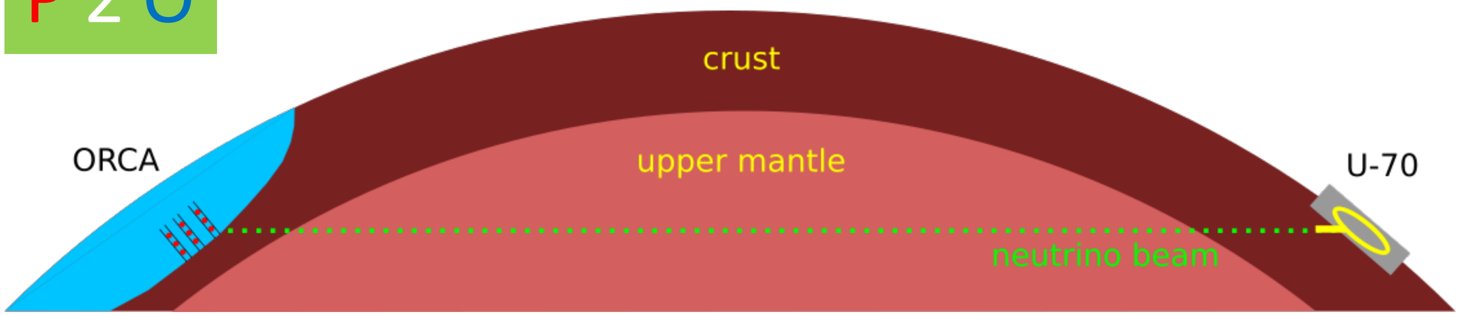
Long baseline ideas in Europe

- After shutdown of LBNO some years of reflection
- Two projects emerged

essνsb ESS NEUTRINO SUPER BEAM



P 2 O



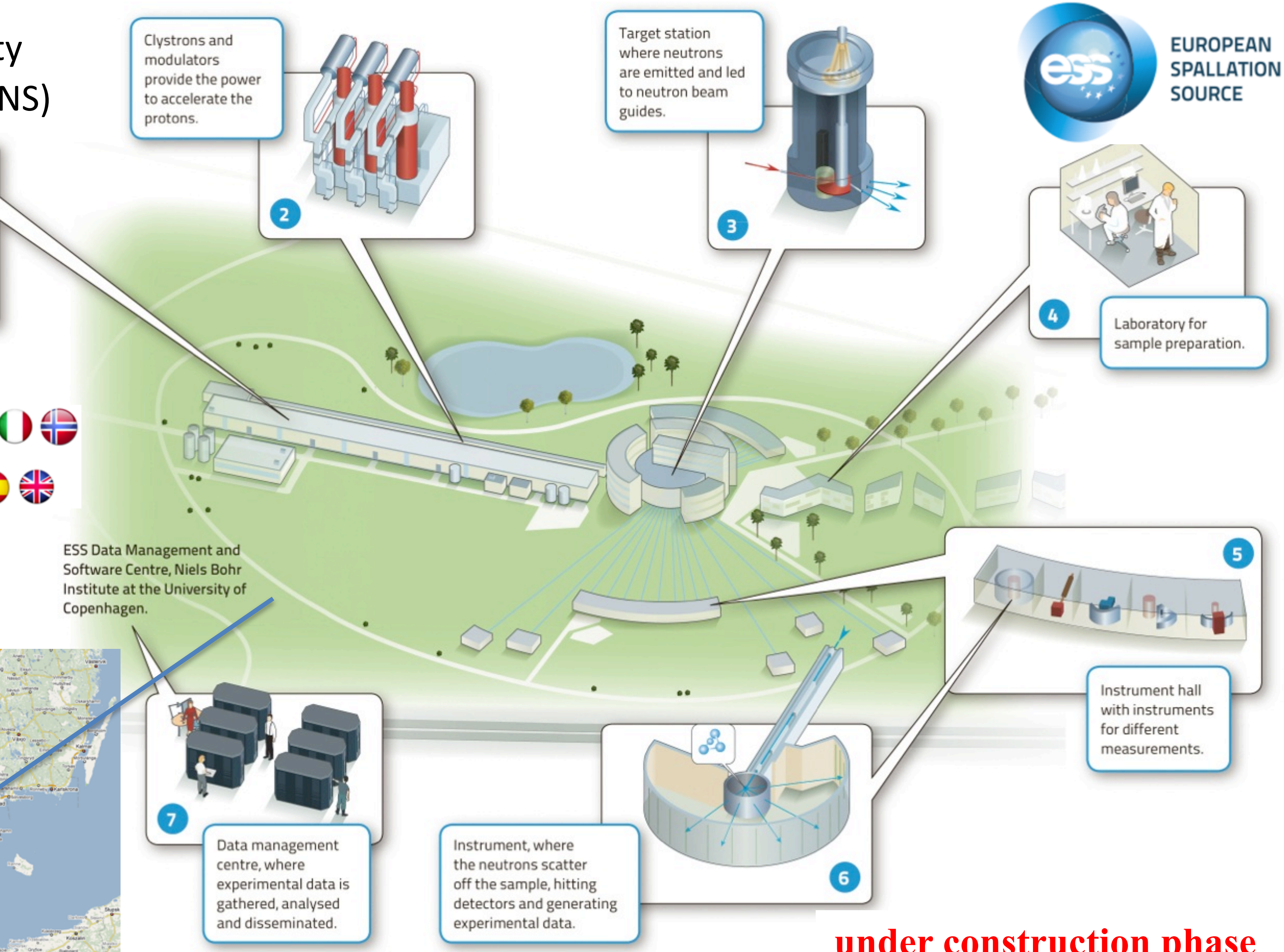
ESS NEUTRINO SUPER BEAM

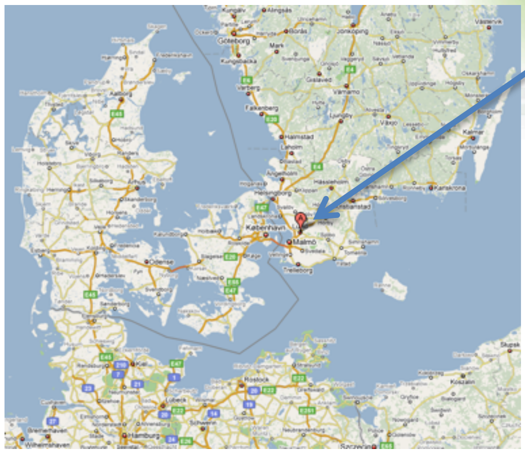
European Spallation Source

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

EUROPEAN SPALLATION SOURCE

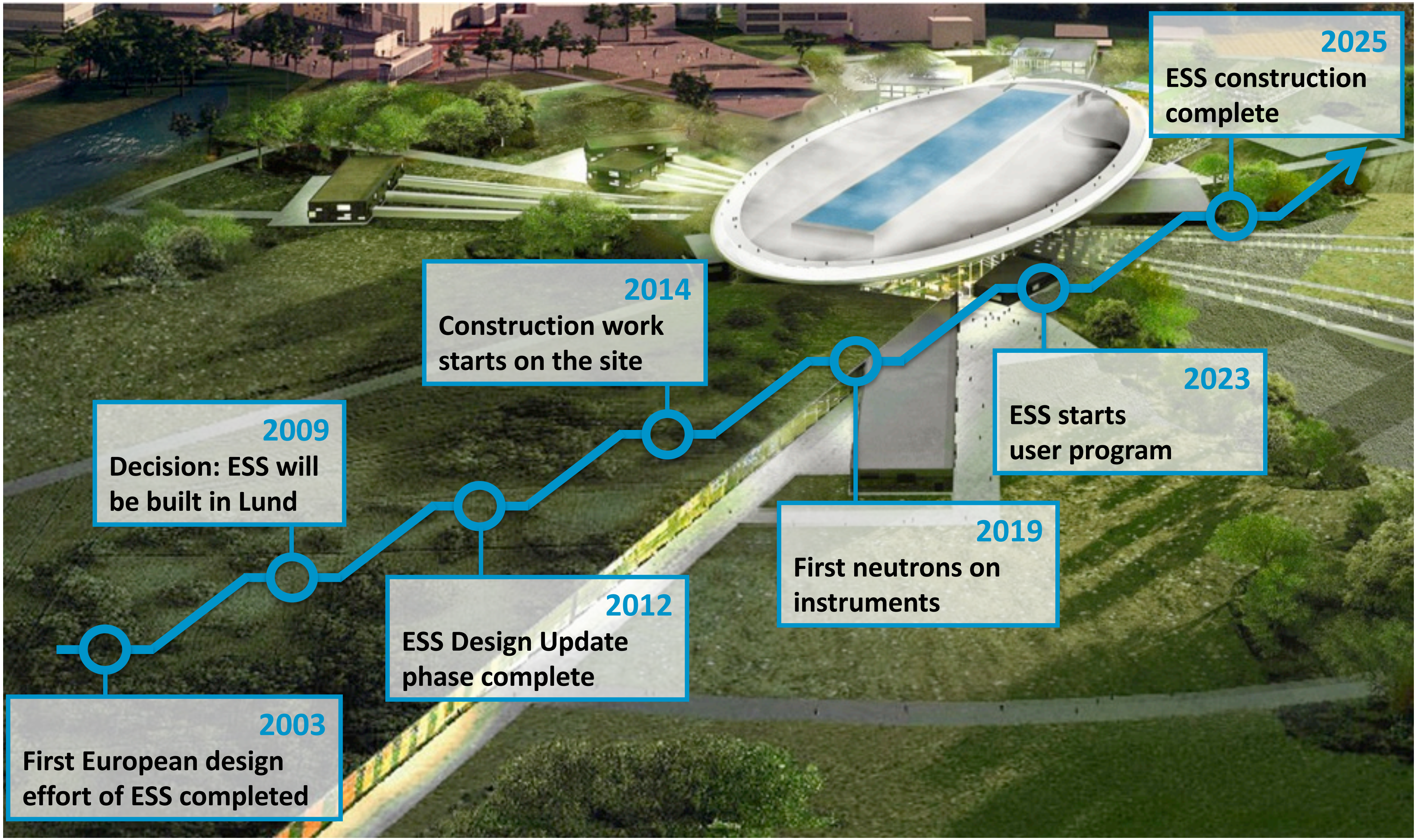
Neutron facility
(equivalent to SNS)





under construction phase
(~1.85 B€ facility)

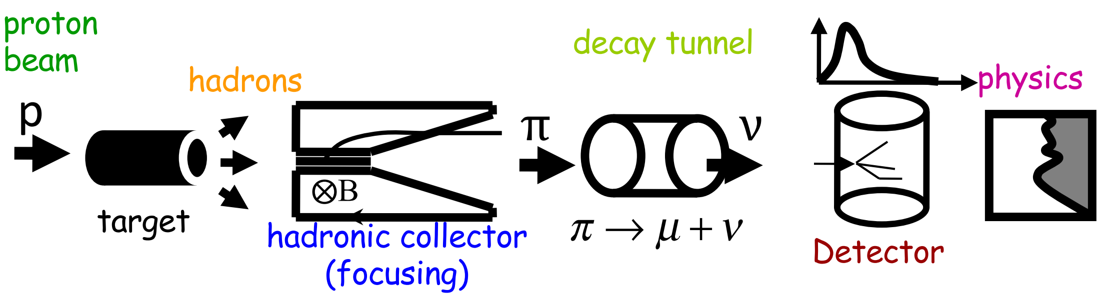
ESS schedule



Having access to a powerful proton beam…

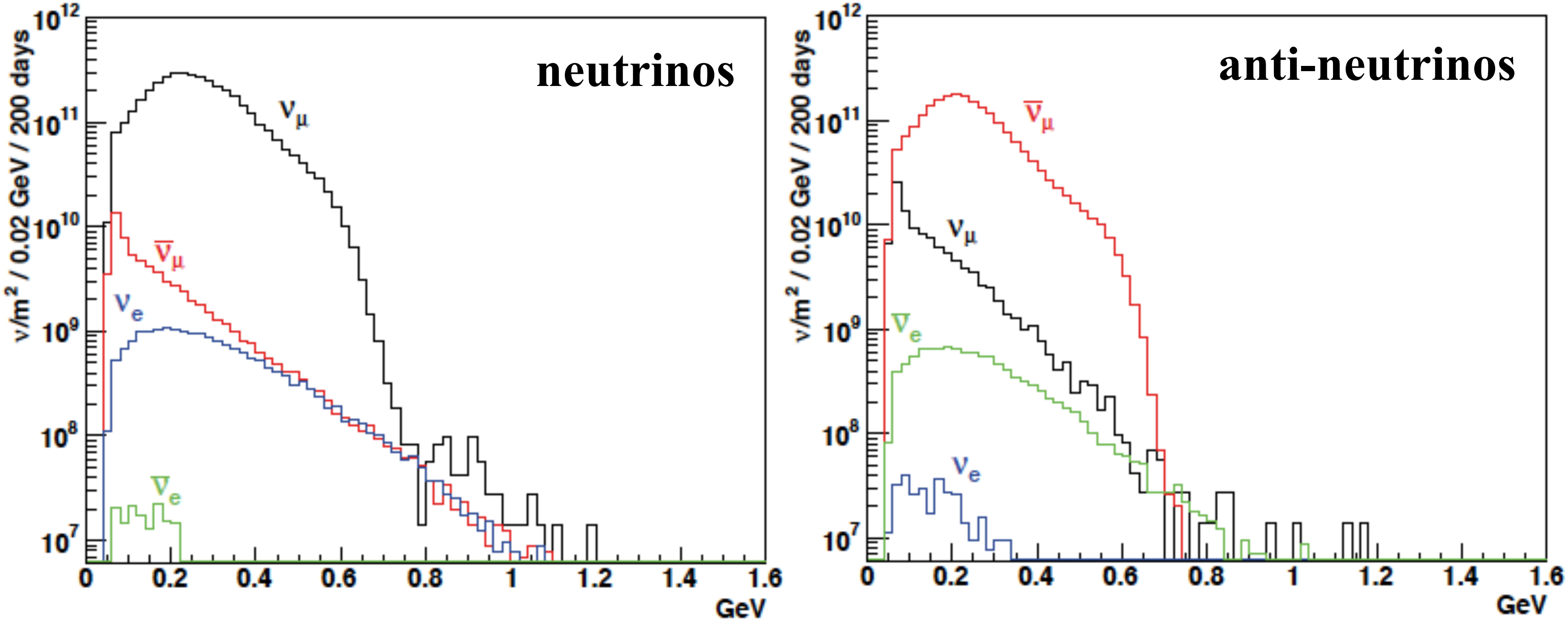
What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7\times10^{23}$ protons/year



conventional neutrino (super) beam

ESSνSB ν energy distribution



	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

at 100 km from the target, per year (in absence of oscillations)

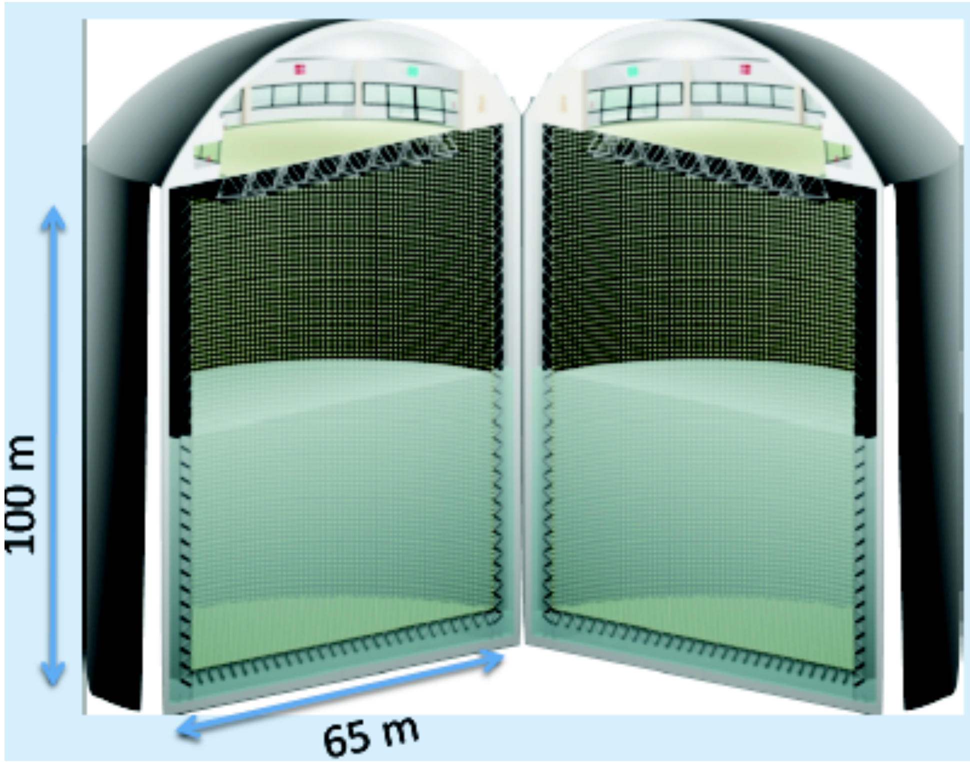
(Nucl. Phys. B 885 (2014) 127)

Far detector @ 400-500km
2^{nd} oscillation maximum

MEMPHYS like Cherenkov detector
(MEgaton Mass PHYSics studied by LAGUNA)

- 500 kt fiducial volume (~2xHyperK, 1/16 ORCA)
- Readout: ~240k 8” PMTs
- 30% optical coverage

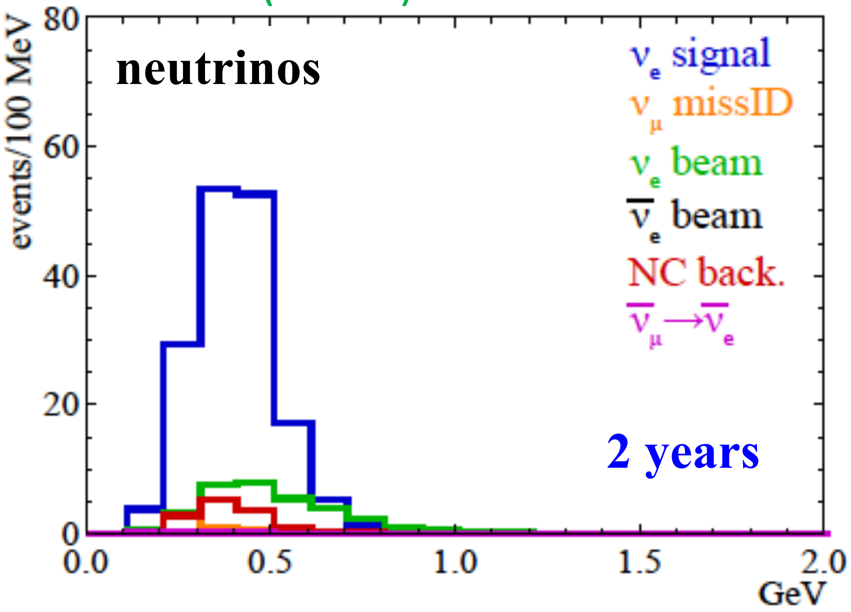
(arXiv: hep-ex/0607026)

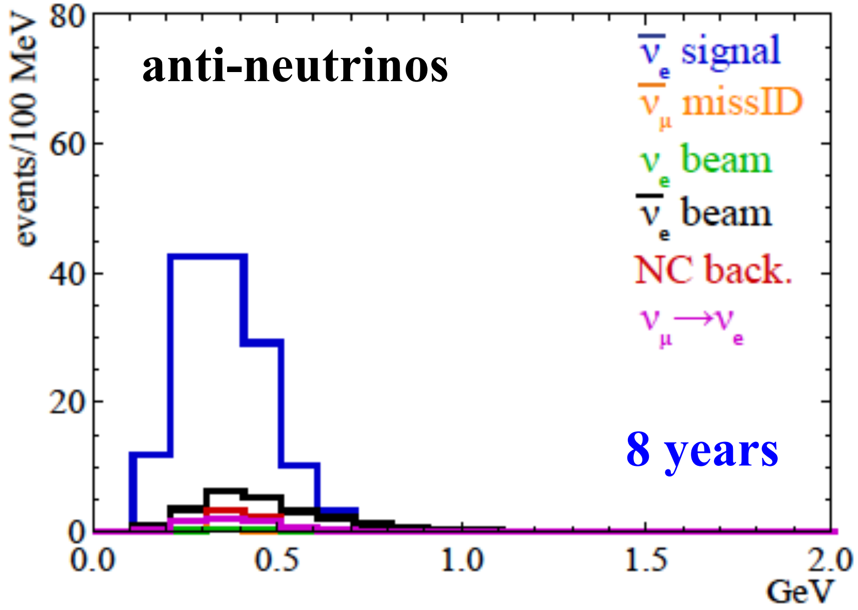


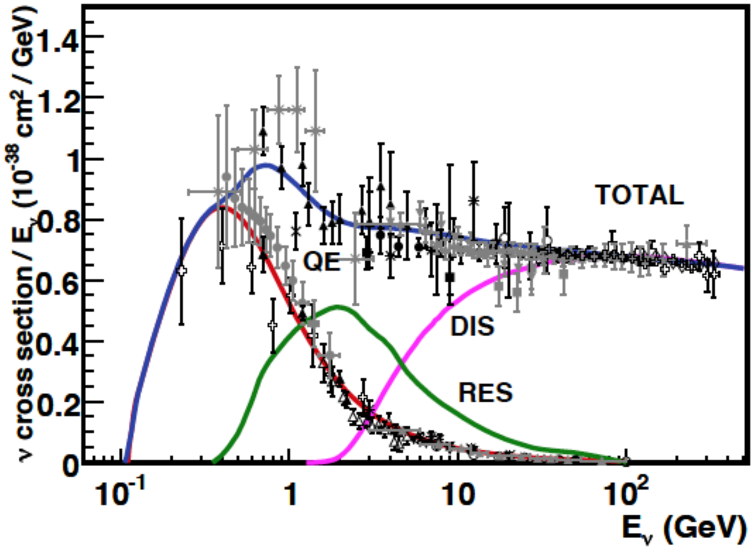
ν_e in the far detector

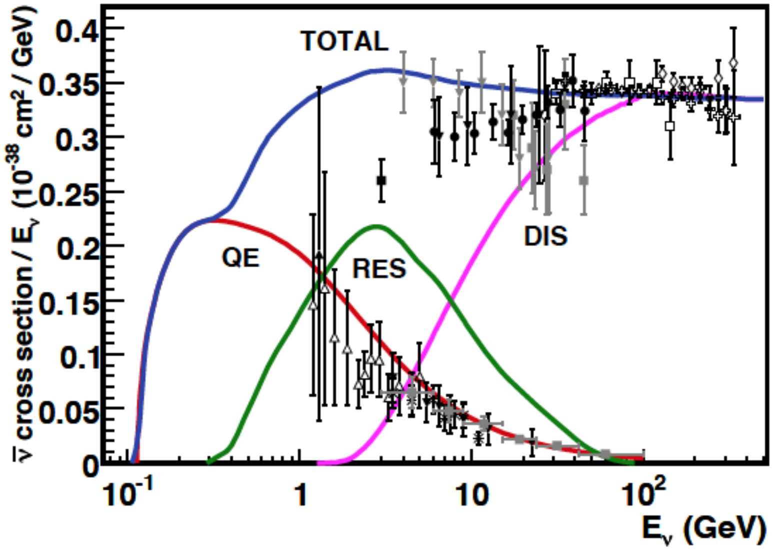
540 km (2 GeV)

$\delta_{CP}=0$



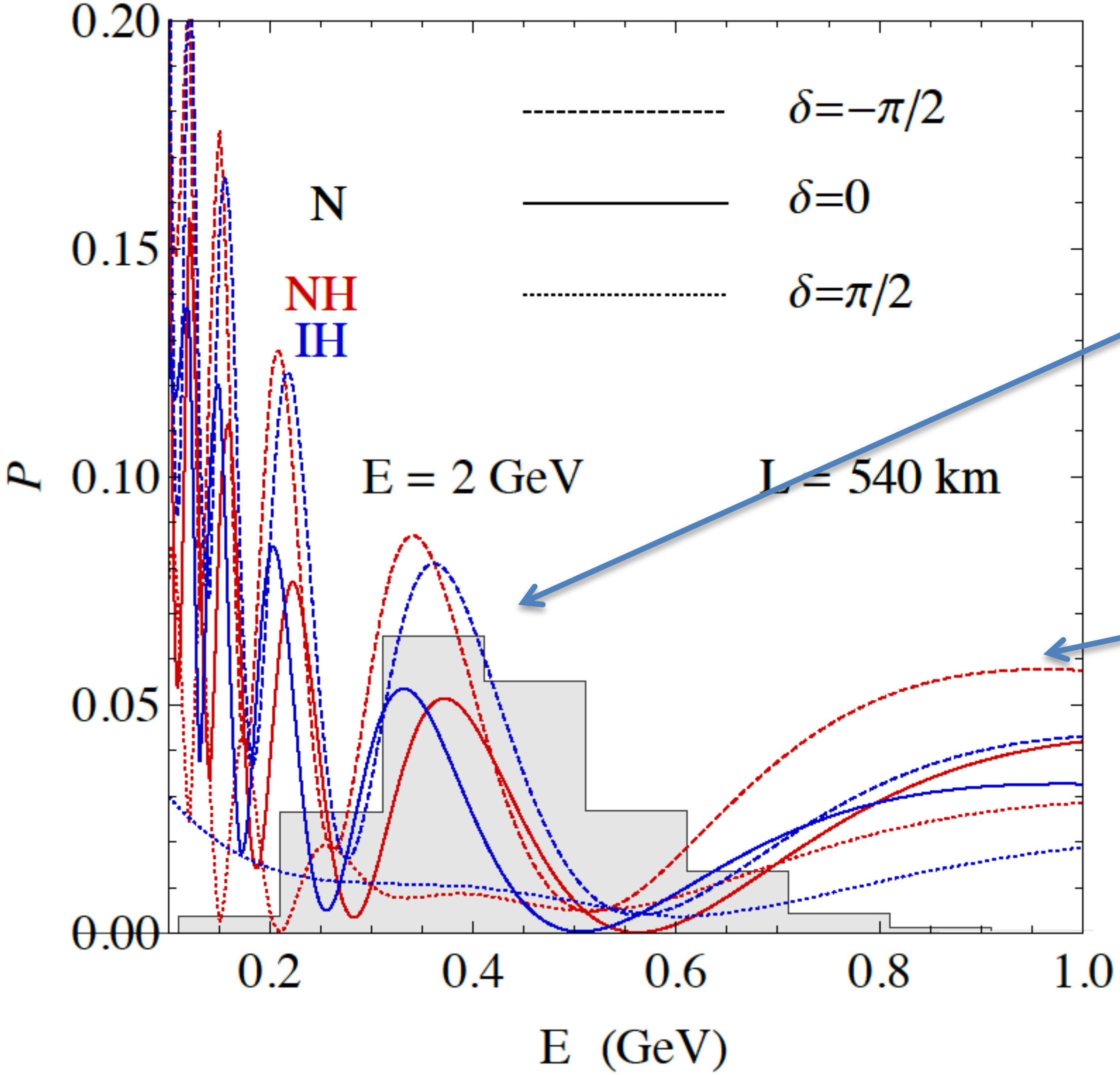






Below ν_τ production, almost only QE events, not suffering too much by π^0 background.

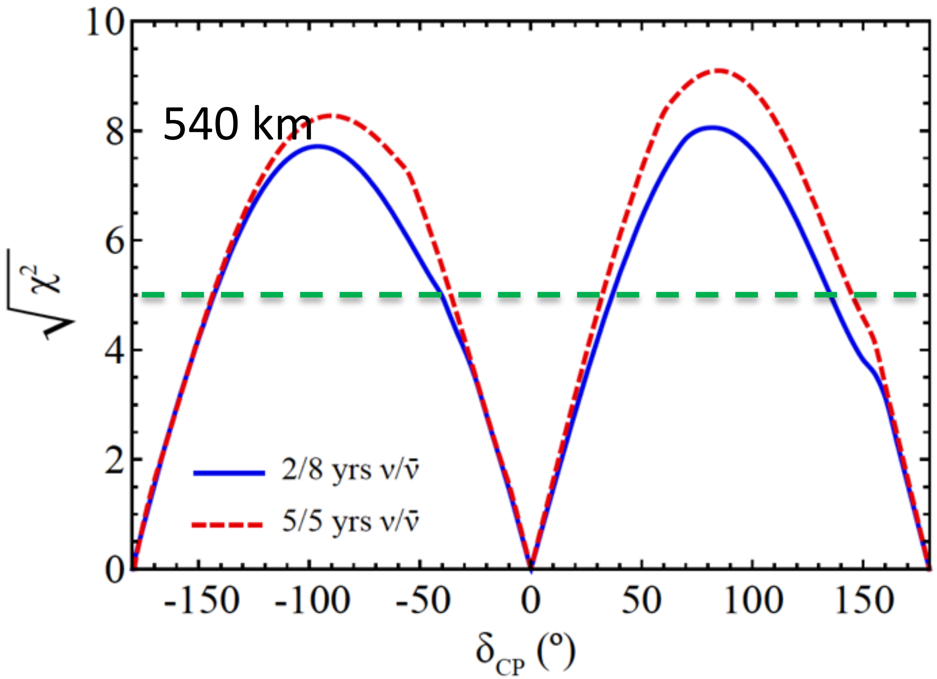
2nd Oscillation max. coverage

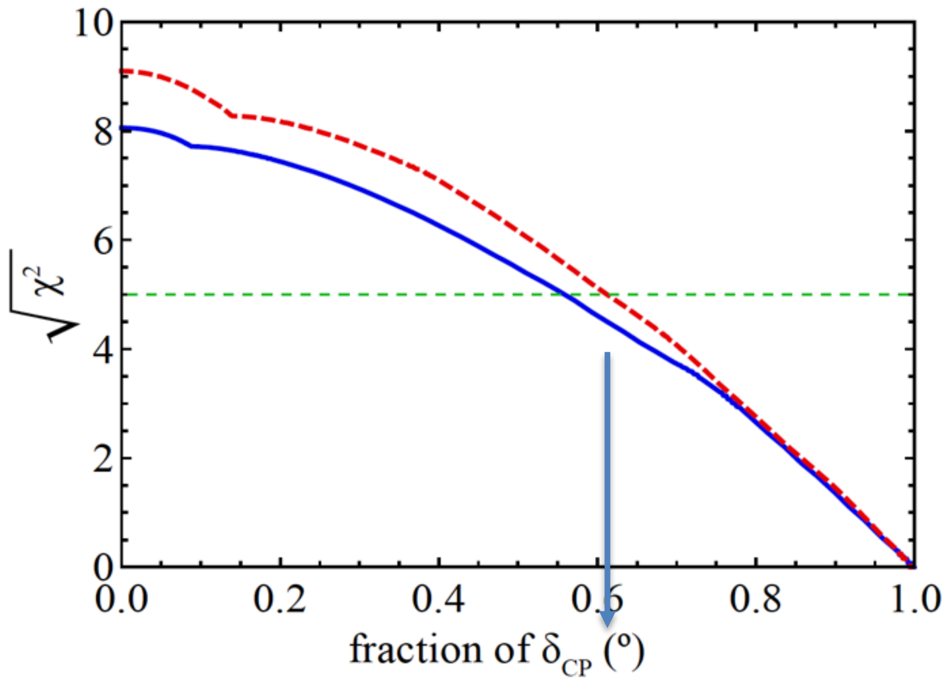


2nd oscillation max. well covered by the ESS neutrino spectrum

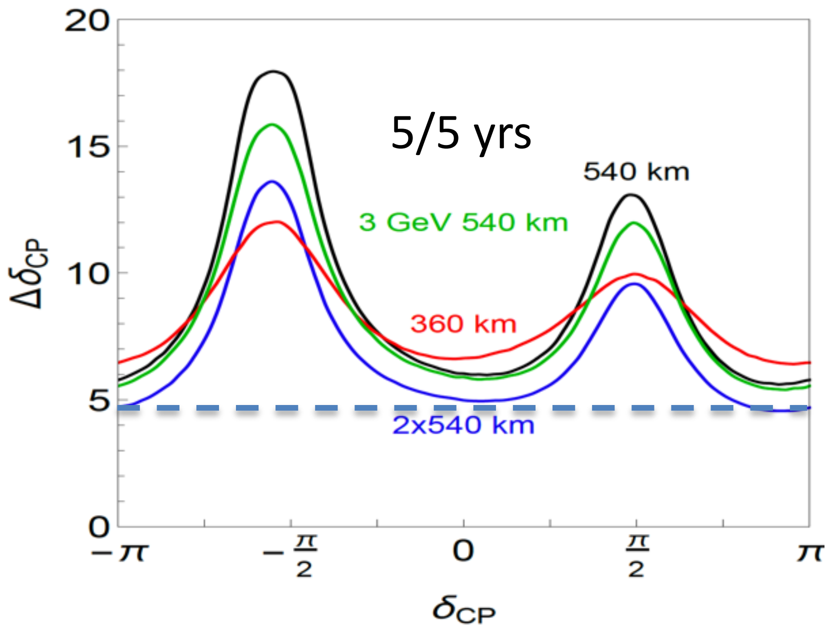
1st oscillation max.

Physics Performance



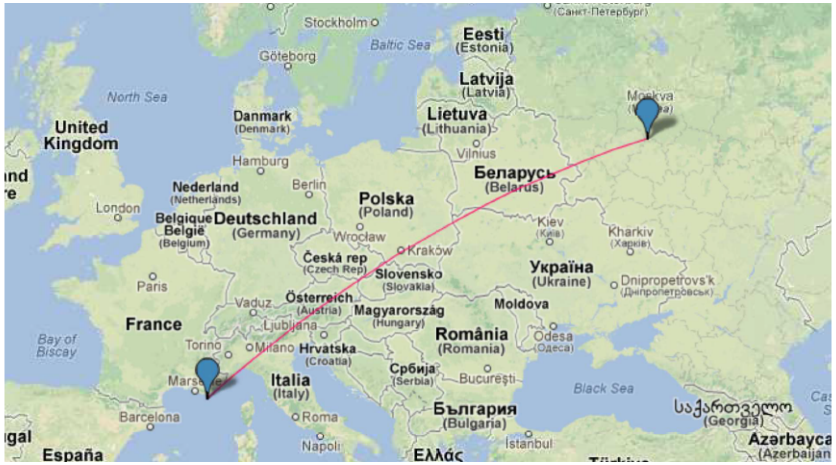


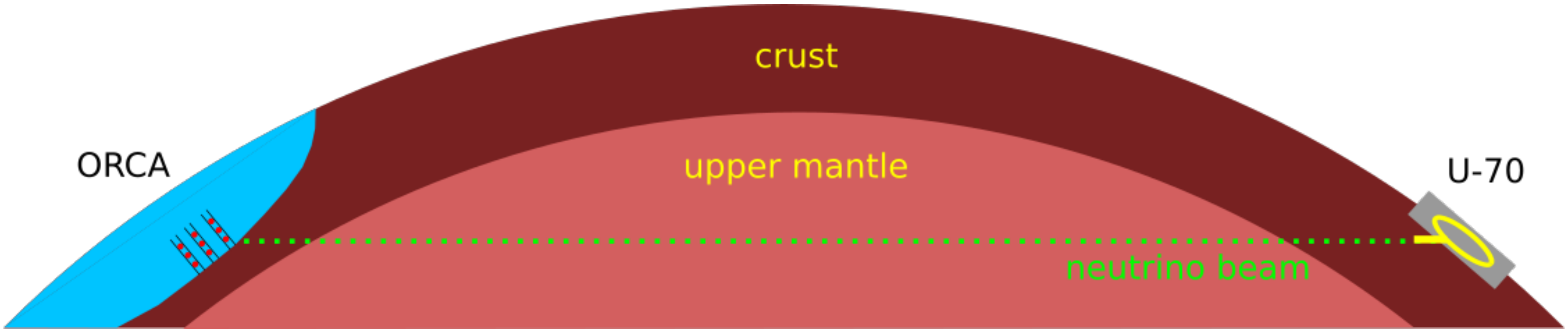
- little dependence on mass hierarchy,
- δ_{CP} coverage at 5 σ C.L. up to **60%**,
- δ_{CP} accuracy down to **6°** at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility,
- 5/10% systematic errors on signal/background.



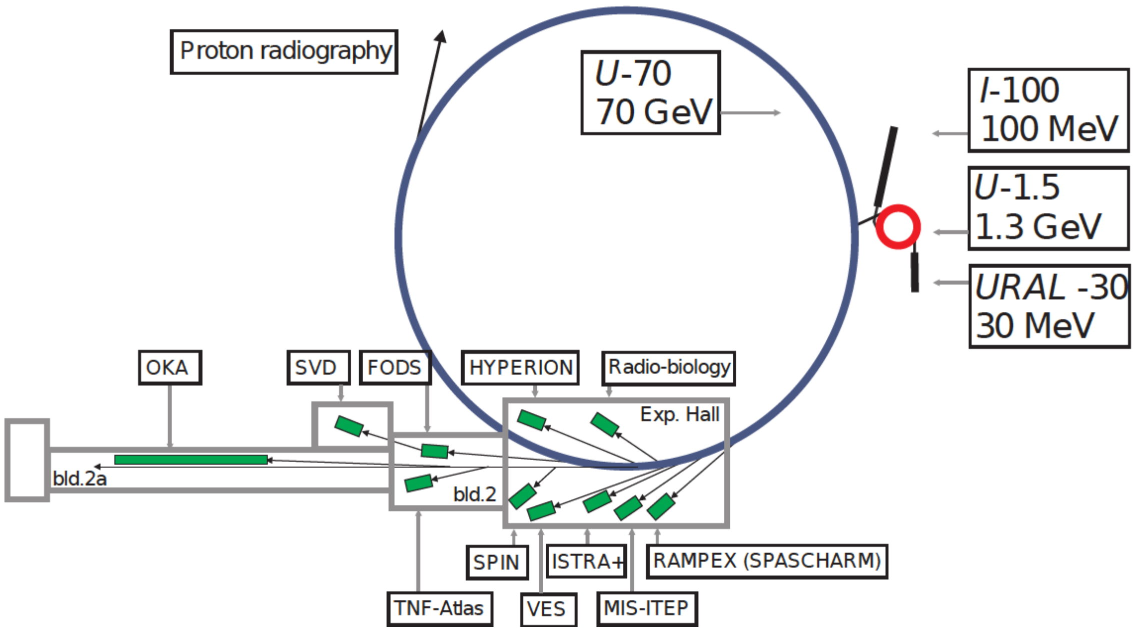
Protvino to ORCA – key numbers

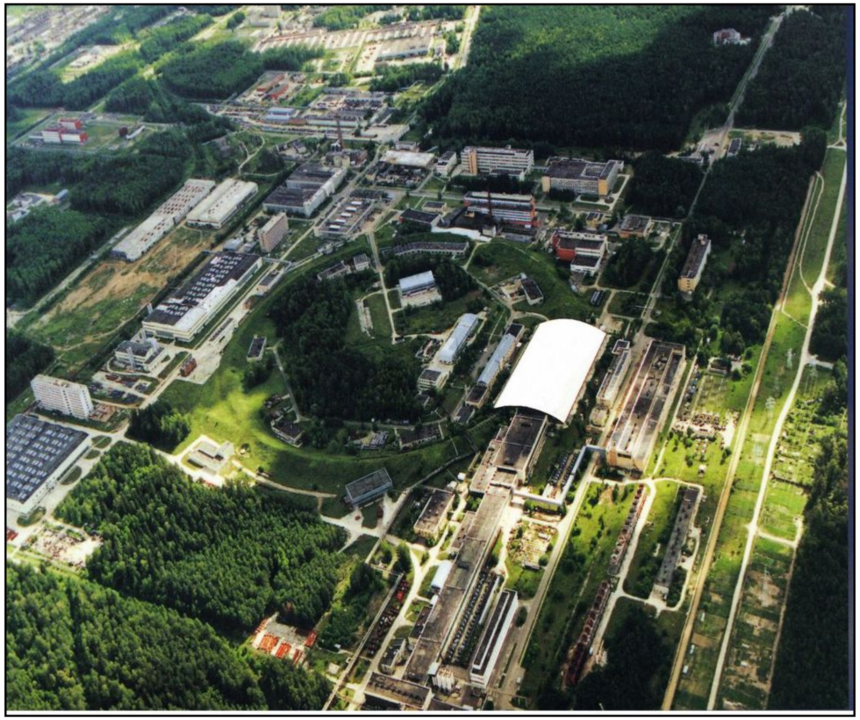
• Baseline	2590 km
• First oscillation maximum	5.1 GeV
• Matter resonance	3.8 GeV
• Beam inclination	11.7°





Protvino accelerator complex

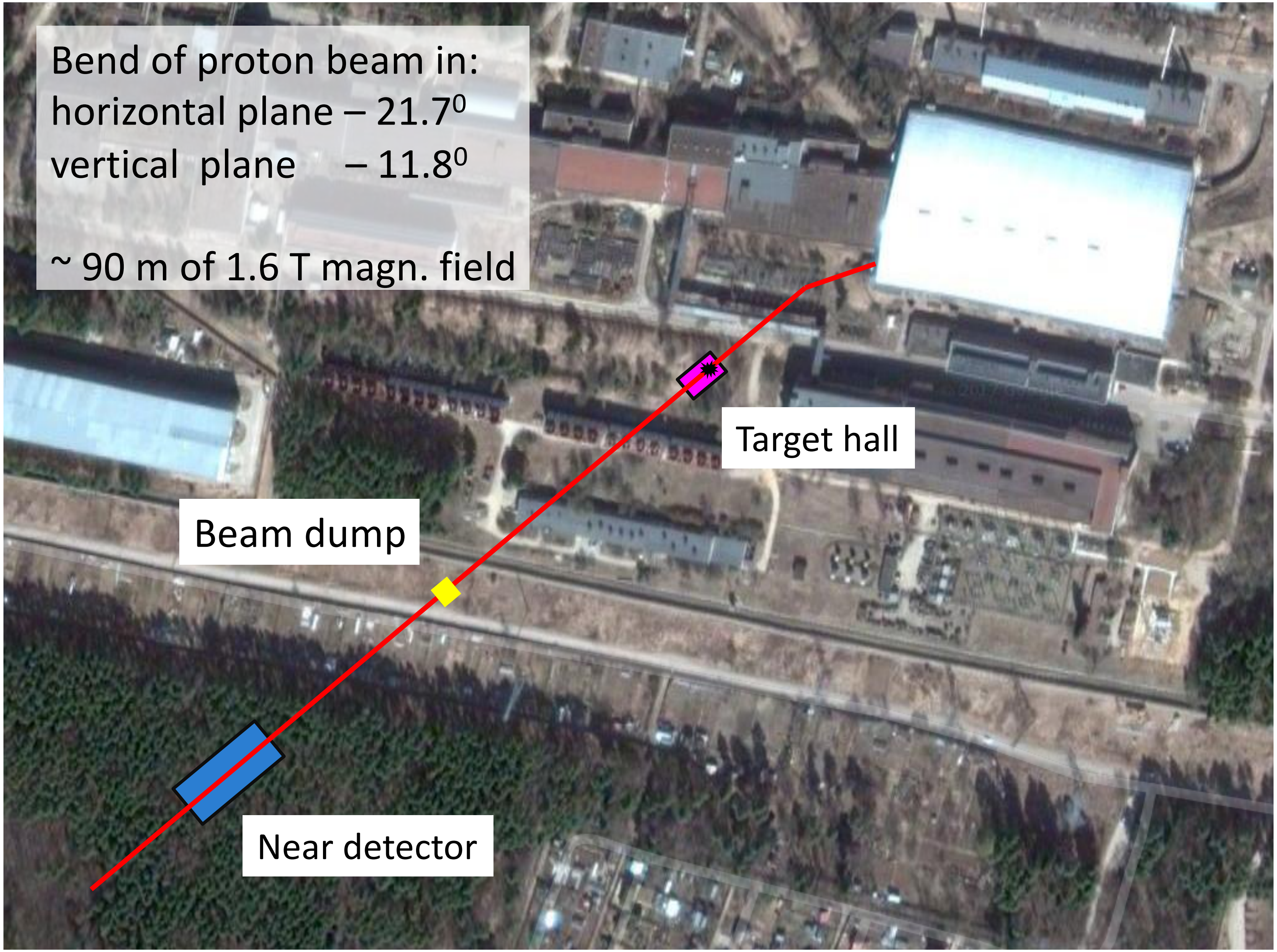




Accelerator	Length, m	Energy
Linear accelerator Ural-30	25.3	30 MeV
Linear accelerator I-100	79.4	100 MeV
Synchrotron U-1.5	99.16	1.32 GeV
Synchrotron U-70	1483.7	50-70 GeV

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

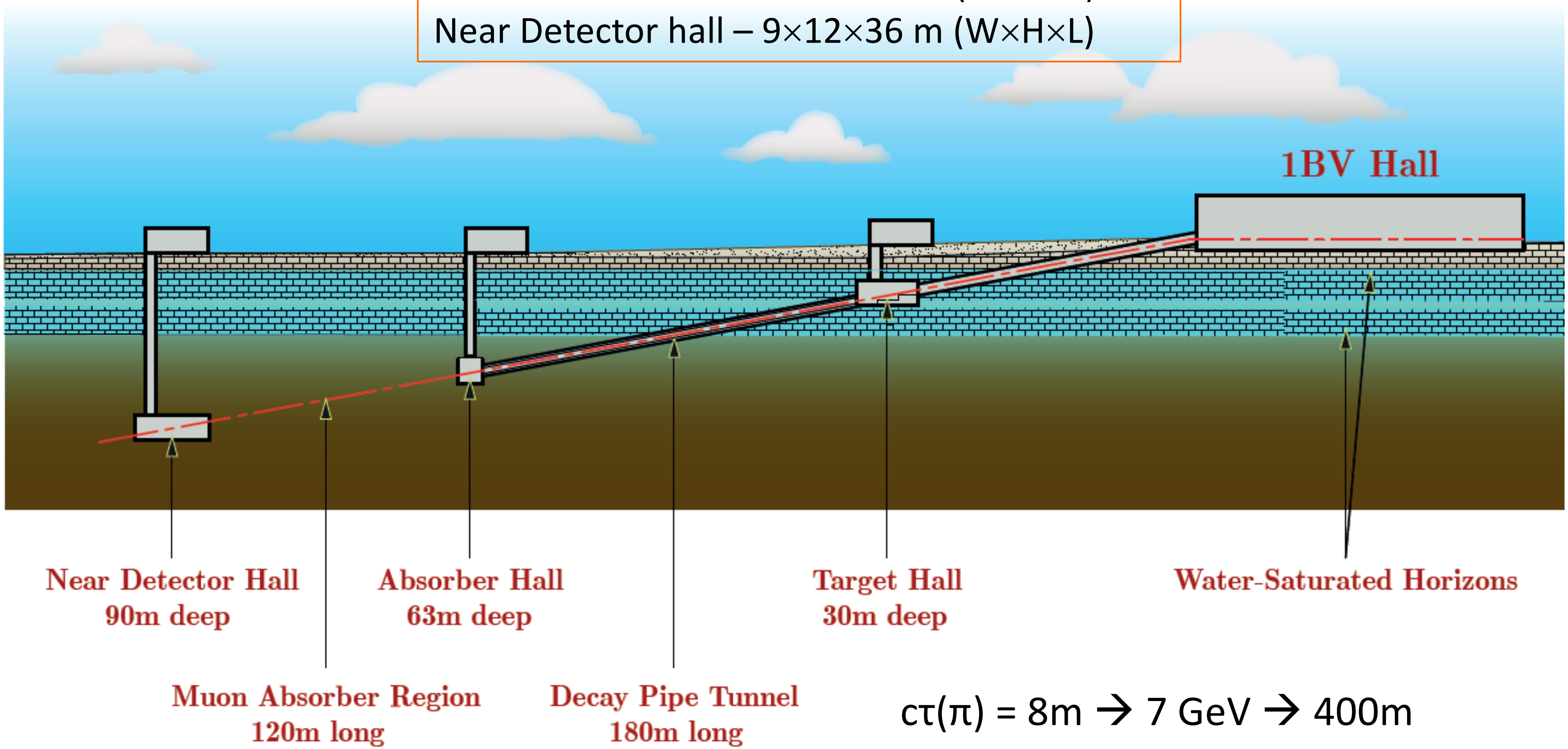
Possible Beam Layout



Possible Beam layout

- Depth profile of beam and various underground halls

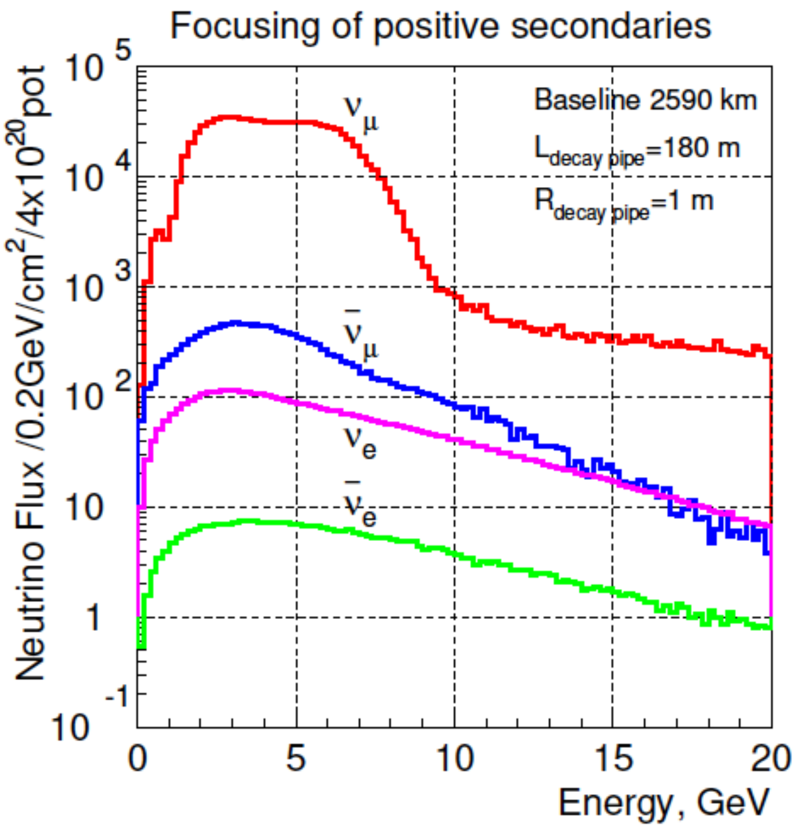
Target hall – 9×12×24 m (W×H×L)
Absorber hall – 6×12×12 m (W×H×L)
Near Detector hall – 9×12×36 m (W×H×L)

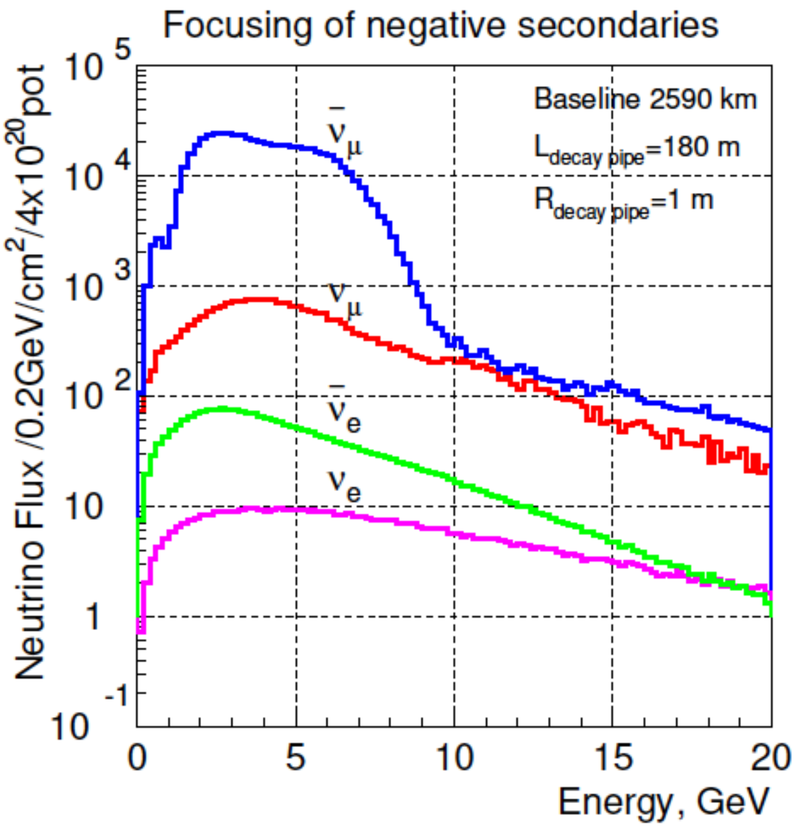


$c\tau(\pi) = 8\text{m} \rightarrow 7\ \text{GeV} \rightarrow 400\text{m}$

Neutrino Flux

- Very clean beam in leading flavour
- 1% (3%) (anti-)neutrino contamination
- Sub-percent ν_e contamination





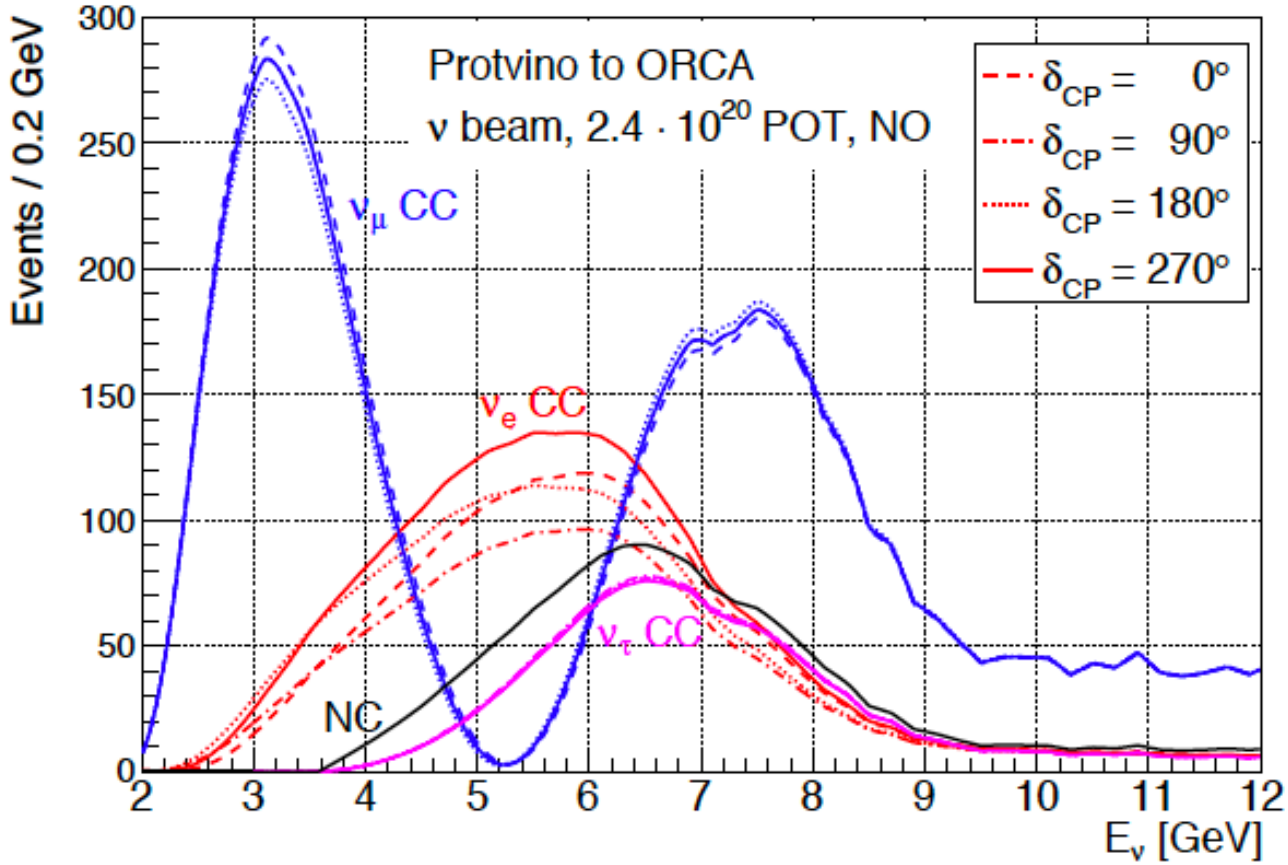
Phased approach – Phase 1

- ORCA : 1 building block
  - 115 detection units, performance as in LoI
- Accelerator : moderate intensity upgrade
  - Neutrino beam line to ORCA
  - 2 10^{13} protons per pulse
  - New ion injection scheme (H^-) : x3
  - Double cycling frequency : 9s → 4.5s : x2
  - 8 months per year operation
  - 8 10^{19} protons on target per year
  - Intensity : 90kW cost : 100 MEuro

Event numbers – Neutrino Beam

2.4 10^{20} p.o.t (3years @ 90kW)

Normal Hierarchy (θ_{23}=45°)



Events

ν_e 2000 – 2700

ν_μ 7000 ± 20

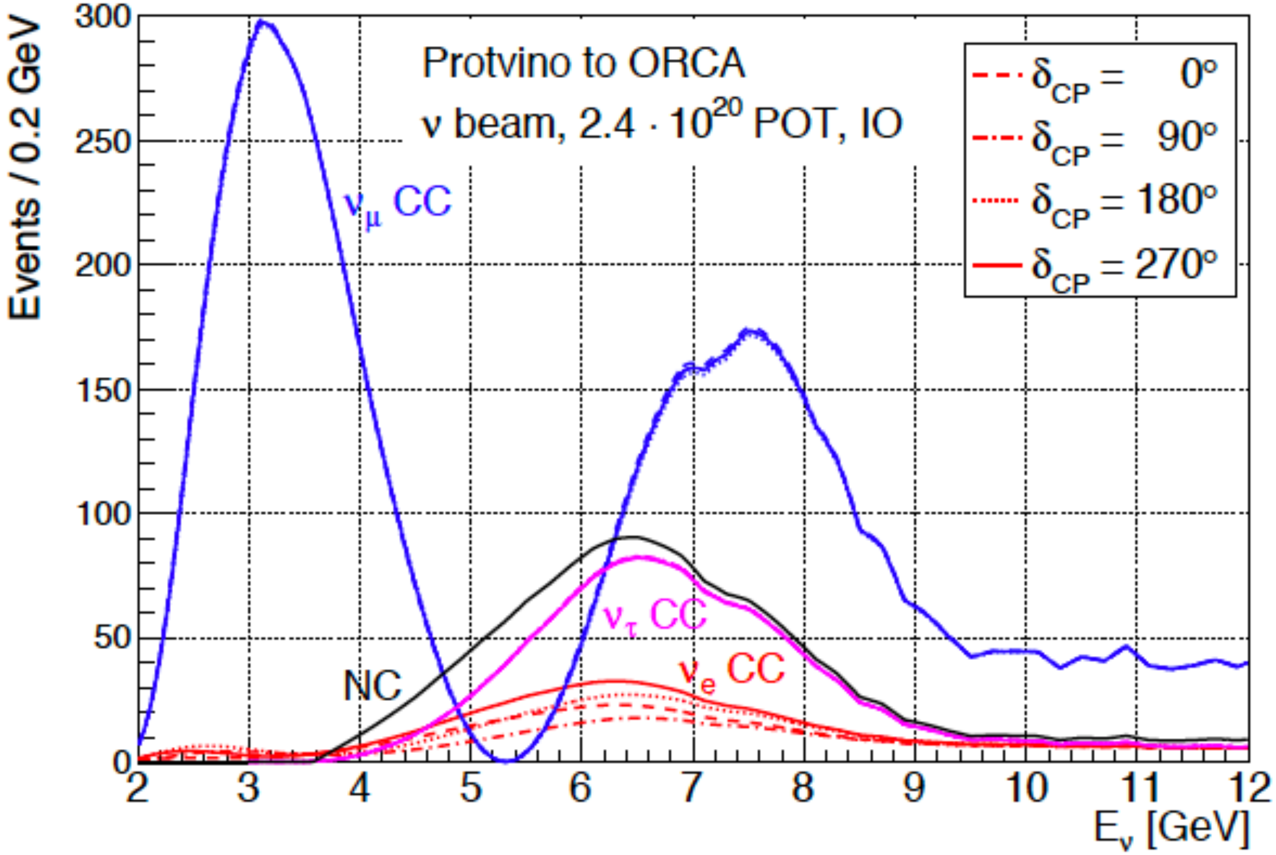
ν_τ 1340 ± 15

NC 1960

Event numbers – Neutrino Beam

2.4 10^{20} p.o.t. (3years @ 90kW)

Inverted Hierarchy (θ_{23}=45°)



Events

ν_e 550 – 800

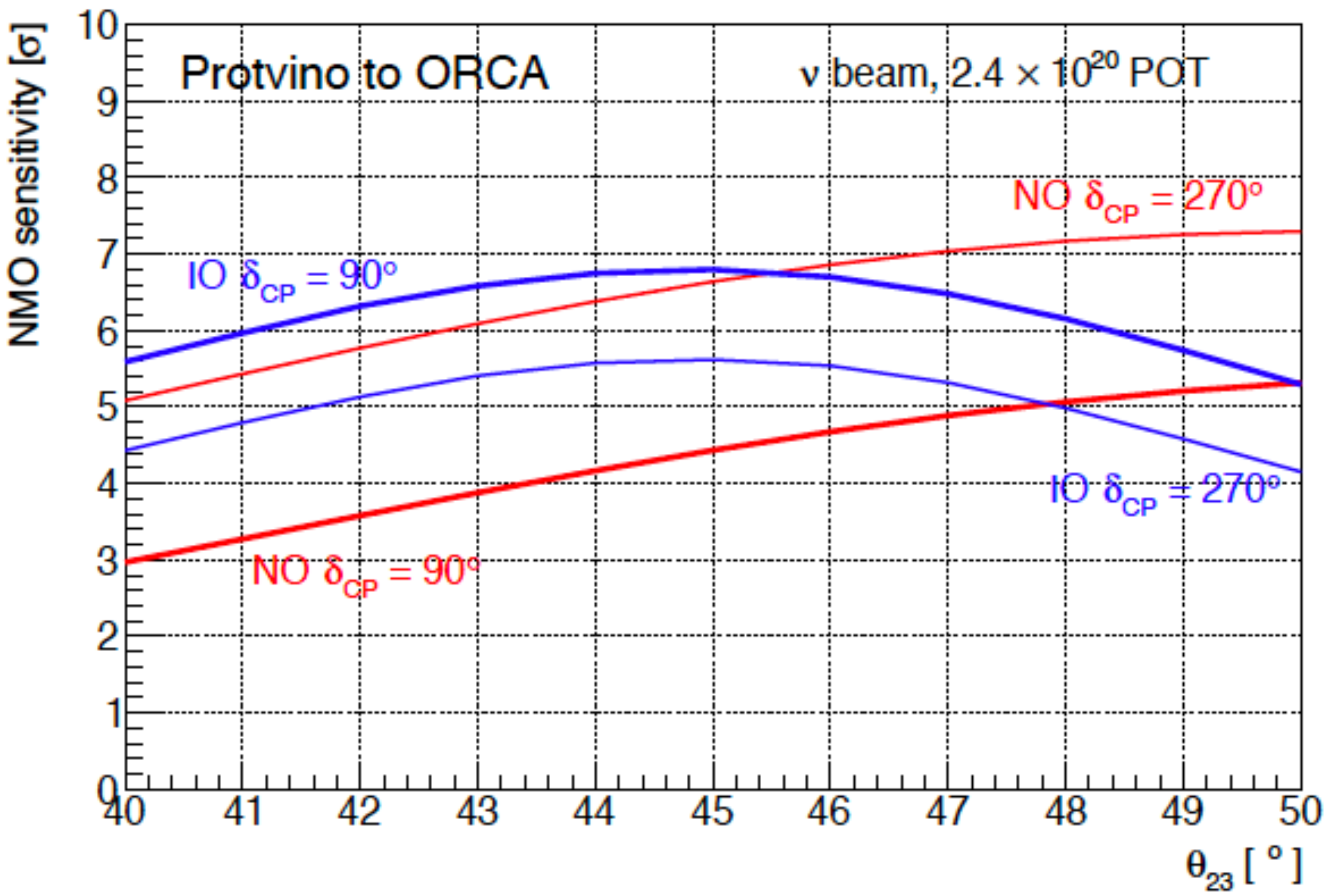
ν_μ 7000 ± 40

ν_τ 1420 ± 10

NC 1960

NMH determination

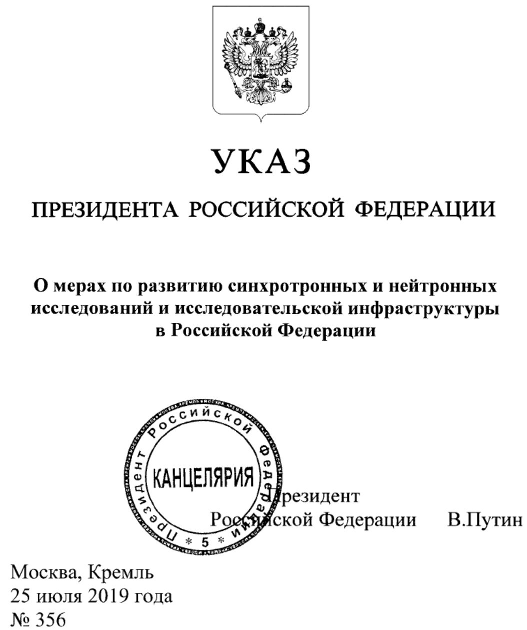
- ORCA detector, 3 year with 90kW neutrino beam



Phased approach – Phase II

- Densified ORCA (~5x more photocathode area)
  - Example : 10x denser but half as big
  - Particle ID via Cherenkov ring fuzziness becomes possible
  - Particle ID improves as shorter muon tracks can be seen
  - More low energy events as detection threshold decreases
  - Better energy resolution
- Accelerator : 450 kW
  - 4 10^{20} protons on target per year
  - 10^{14} protons per pulse
  - Repetition cycle 5 sec
  - 8 months per year operation
- Needs replacement of injector system

Decree from Russian President



УКАЗ

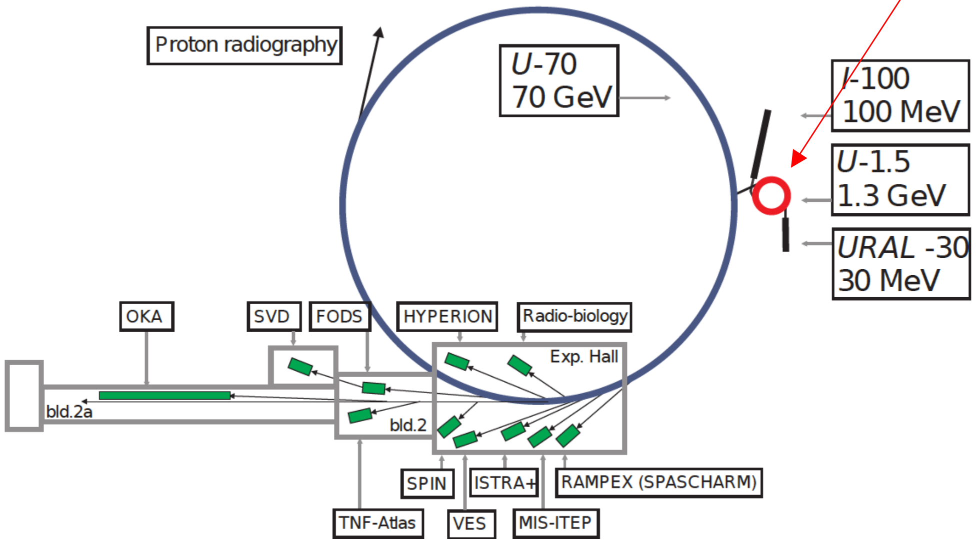
ПРЕЗИДЕНТА РОССИЙСКОЙ ФЕДЕРАЦИИ

О мерах по развитию синхротронных и нейтронных исследований и исследовательской инфраструктуры в Российской Федерации

Президент Российской Федерации В.Путин

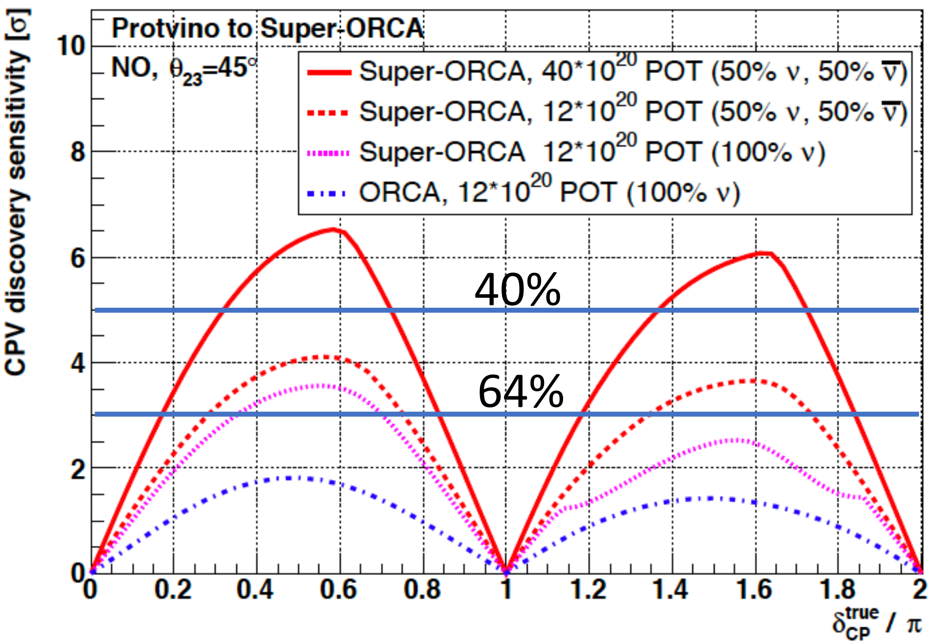
Москва, Кремль
25 июля 2019 года
№ 356

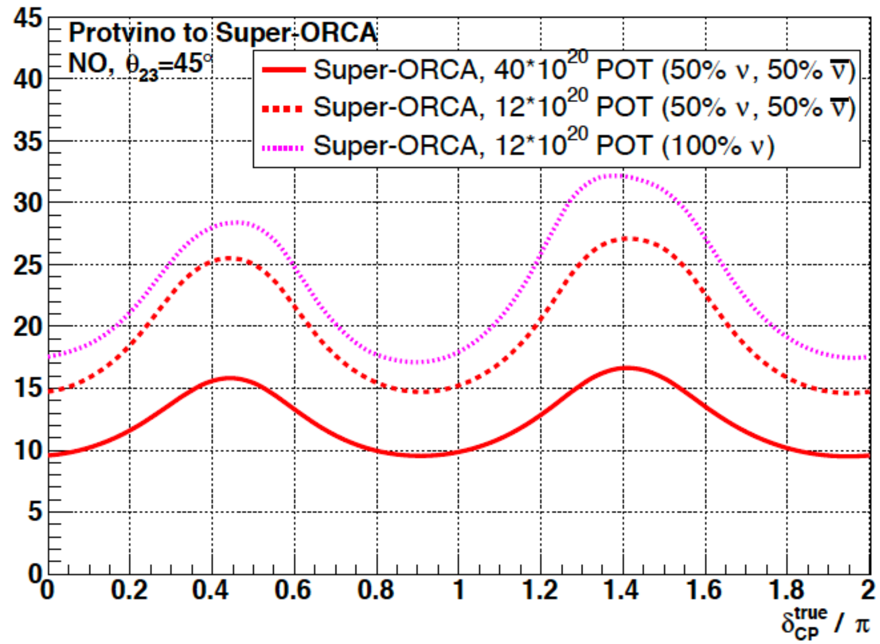
- **Issued 25/07/2019**
- Reactor PIC at S.Petersburg
  - commissioning
- Synchrotron source at Novosibirsk
  - construction
- Synchrotron source at Kurchatov Institute, Moscow
  - upgrade
- **Neutron spallation source at IHEP, Protvino**
  - **Prototype & 1.5GeV booster**
- Synchrotron source at Far East
  - R&D



CP measurement – precision

- 450 kW, 3 / 10 years, 10x denser ORCA but 2x smaller
- High precision measurement possible



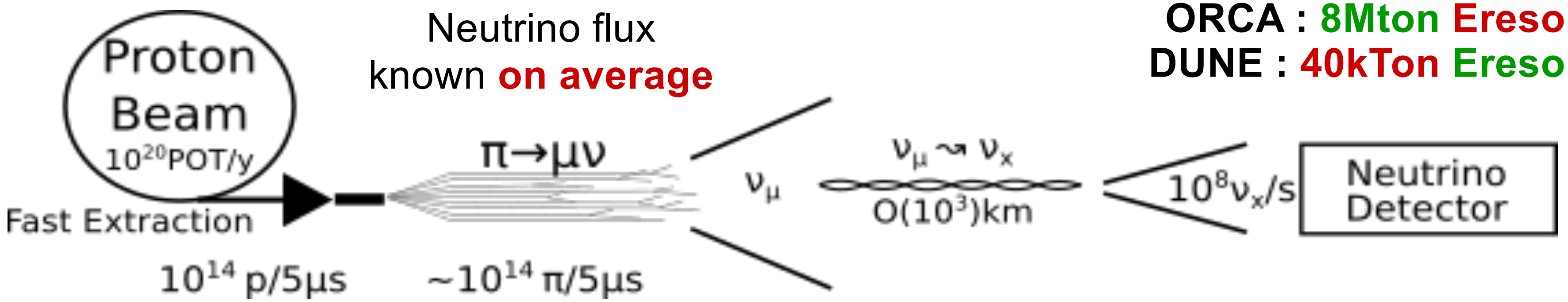


Tagged Neutrino Beam Experiment (ANR Mathieu Perrin-Terrin CPPM)

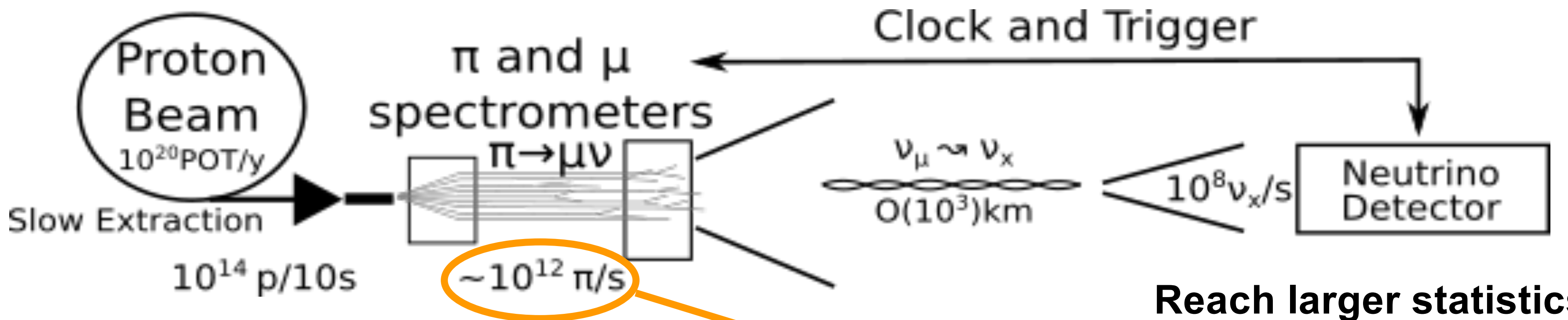
- **Standard Long Base Line (LBL) Experiment**

ν statistics VS performances
ORCA : 8Mton Ereso 30 %
DUNE : 40kTon Ereso 10 %

Neutrino flux known **on average**



- **Tagged LBL, the Next Generation of Experiment?**



Each ν is reconstructed:
Flavour known w/o ambiguity
Energy resolution < 1 %

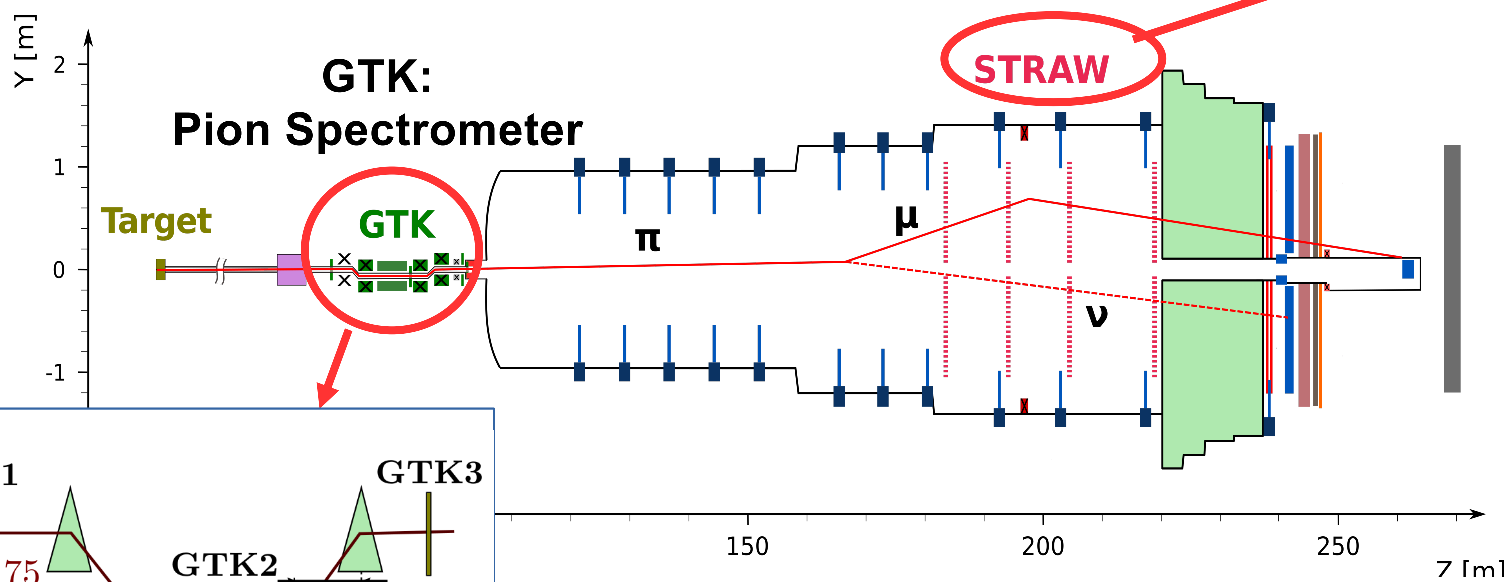
Very challenging tracking capability

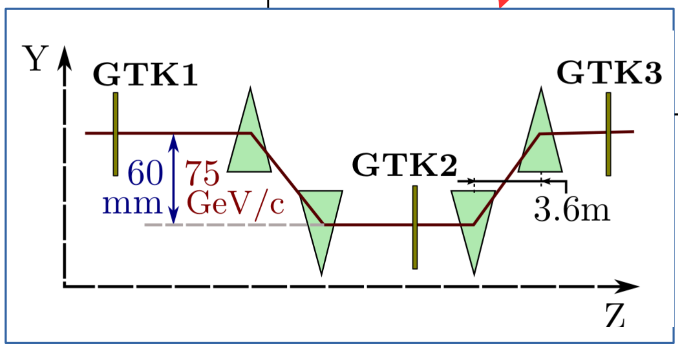
Reach larger statistics as performances are less demanding (E,θ known)

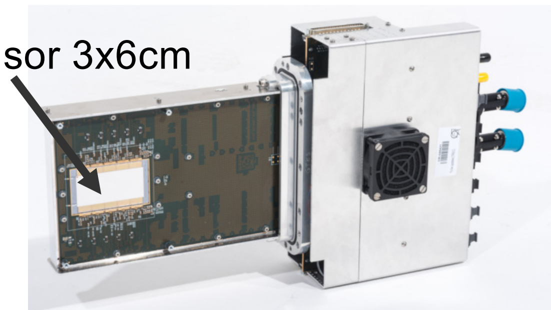
TagP2O: 8Mton Ereso 1 %

How to make a Neutrino Tagger (ANR Mathieu Perrin-Terrin CPPM)

- **A miniature is already running: NA62!**





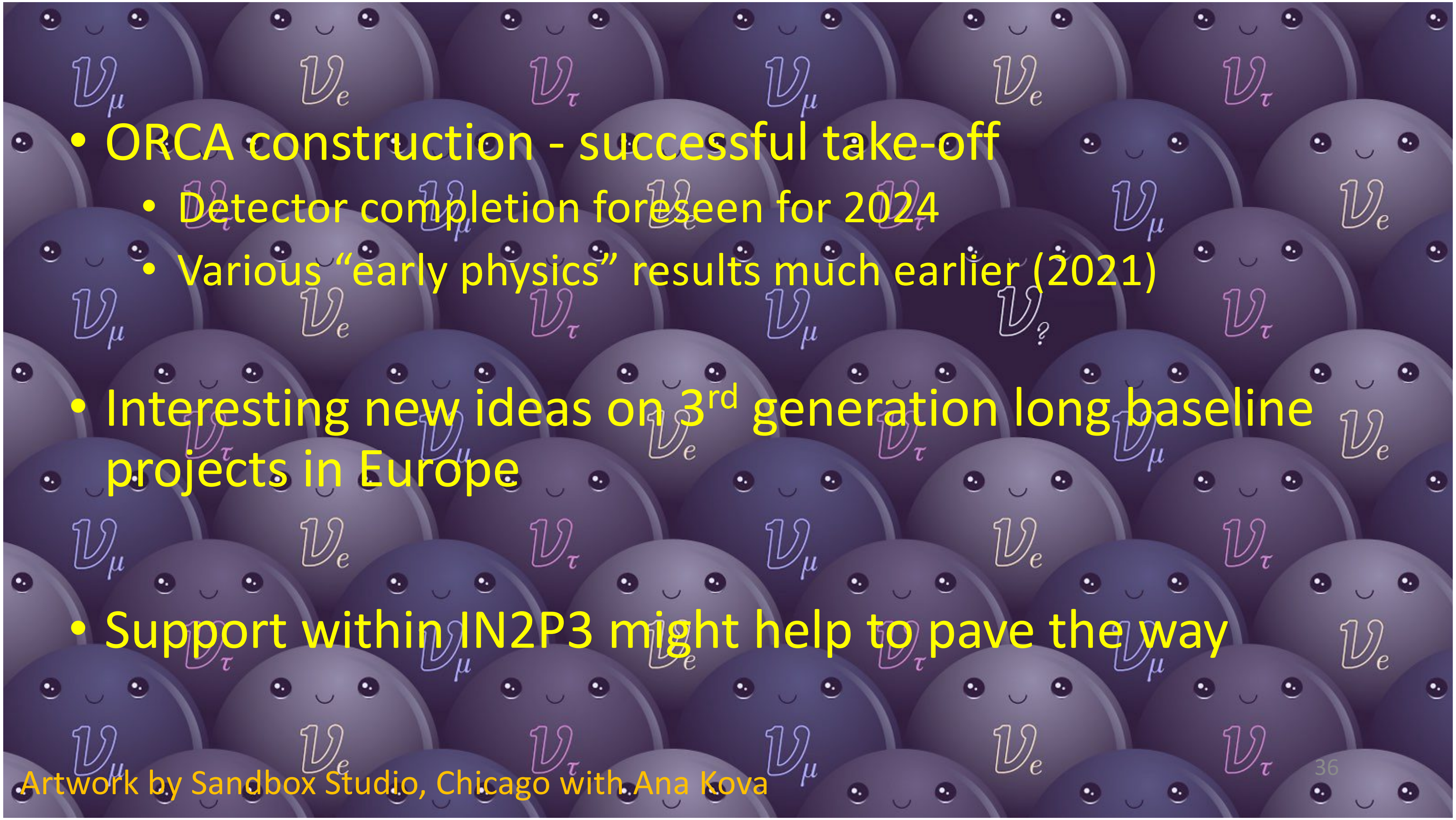


GTK : 10^9 part/sec
1. sensor: 3x6cm
2. 300um x 300um pixels
3. pixel time reso 130 ps
4. 3 stations
5. fluence (10^{14} $n_{eq}/cm^2/y$)

NuTag for P2O : 10^{12} part/sec
1. larger sensor [>x10]
2. smaller pixels (30x30um) [x100]
3. better pixel time reso (30 ps)
4. >3 stations
5. fluence (10^{16} $n_{eq}/cm^2/y$)

Individually 2,3,5 are doable but all **together is challenging!**

Conclusion

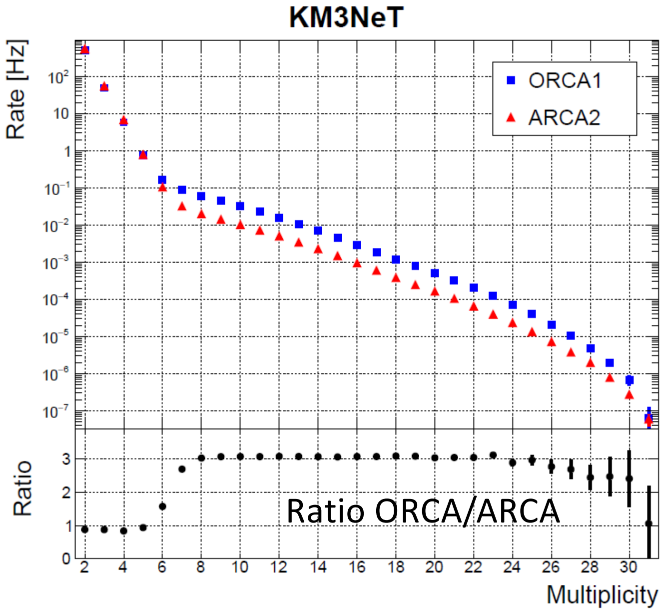


- ORCA construction - successful take-off
  - Detector completion foreseen for 2024
  - Various “early physics” results much earlier (2021)
- Interesting new ideas on 3rd generation long baseline projects in Europe
- Support within IN2P3 might help to pave the way

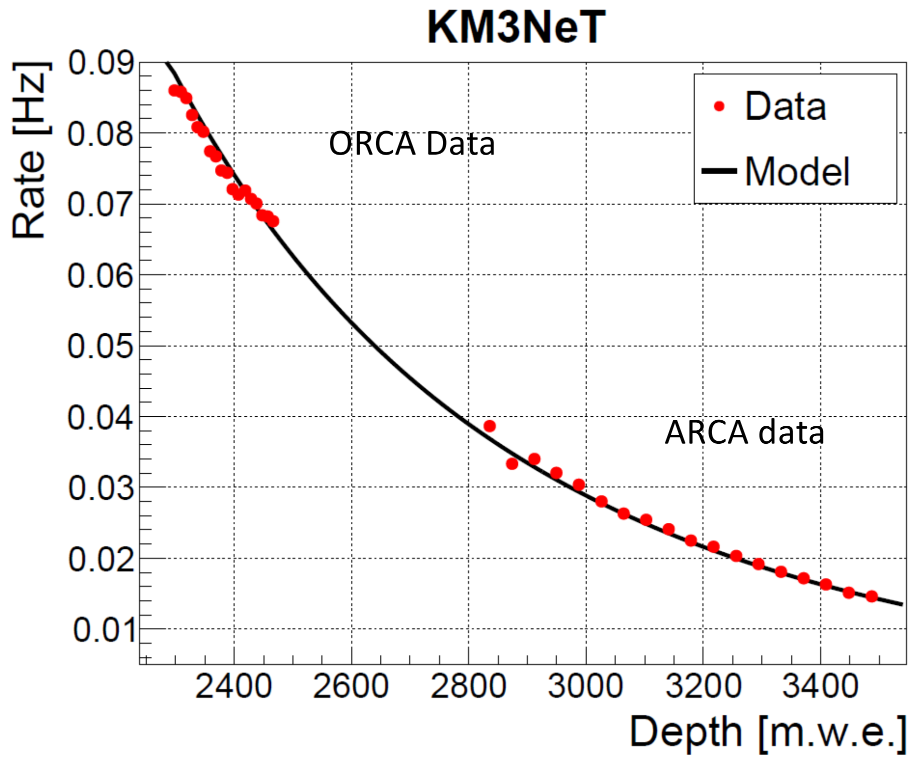
Artwork by Sandbox Studio, Chicago with Ana Kova

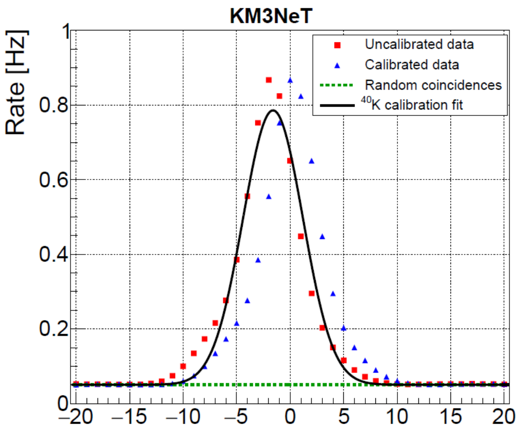
backup

Real data - Muon Depth Dependence



Above a multiplicity of 8 PMTs, rate is dominated by atmospheric muons



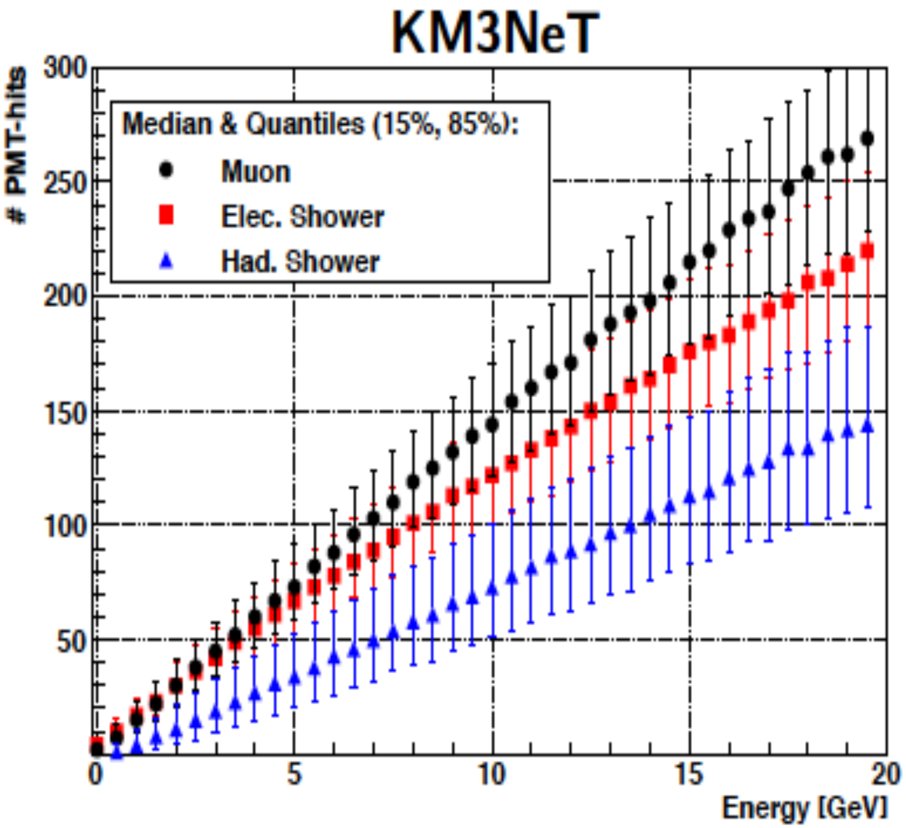


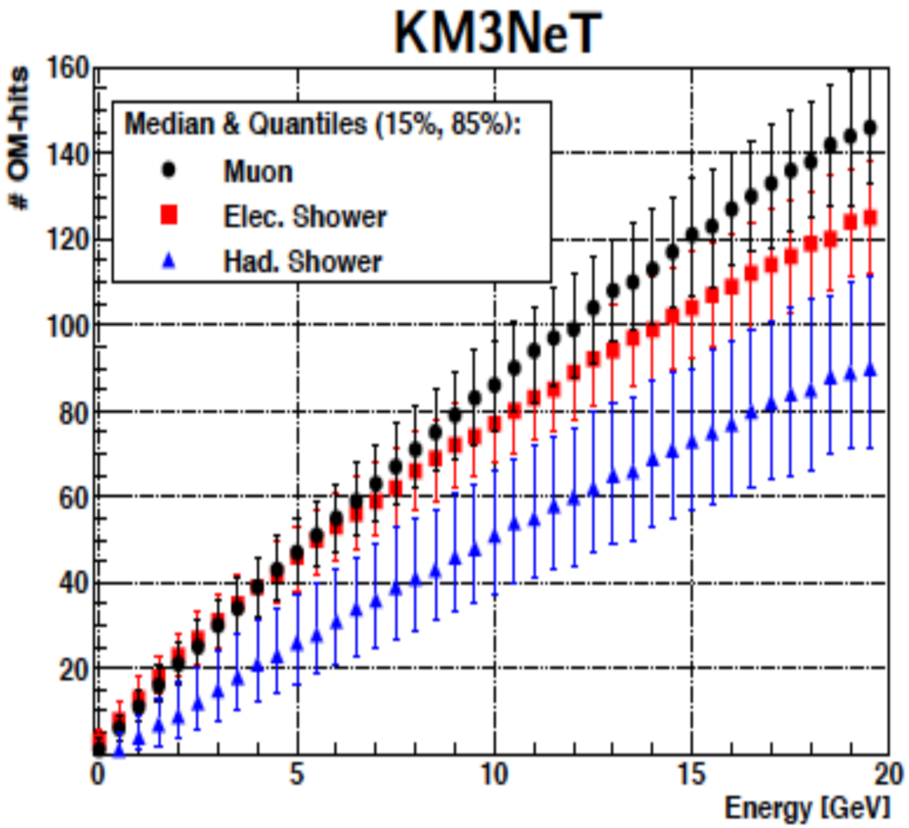
Coincidences between PMTs on a DOM allow time, efficiency and transit time spread calibration

Muon depth dependence (multiplicity >8)
Efficiency corrected

Photon detection in (Super) ORCA

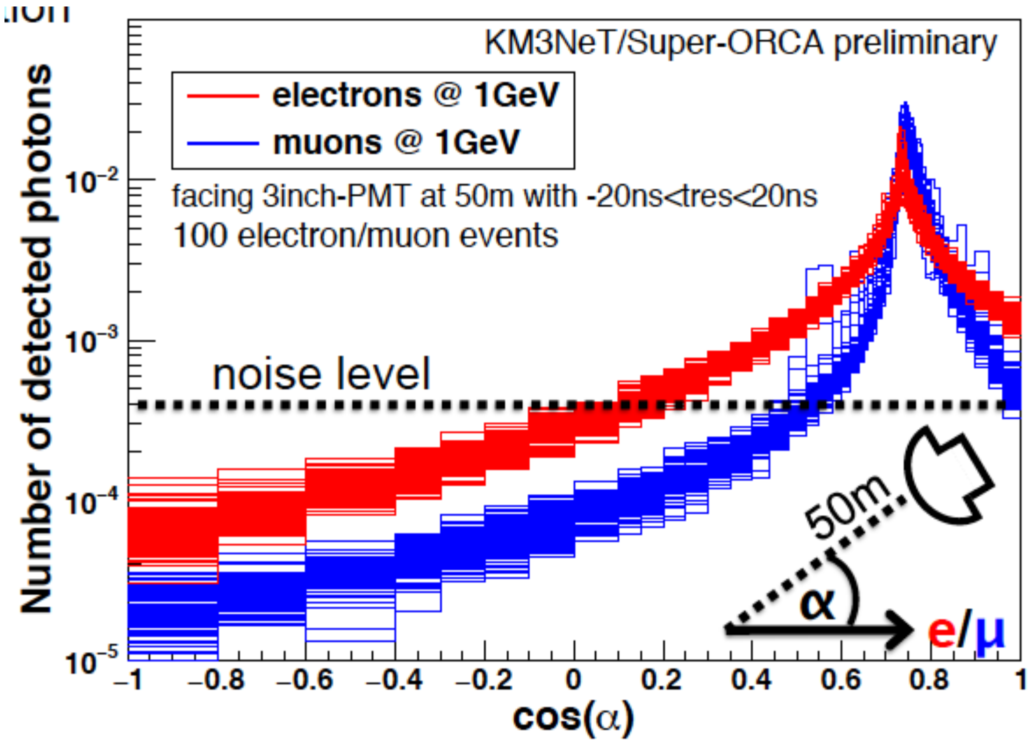
- 150 (muon), 130 (e/m), 70 (hadron) PMTs hit per GeV
- 90 (muon), 80 (e/m), 50 (hadron) Optical modules hit per GeV

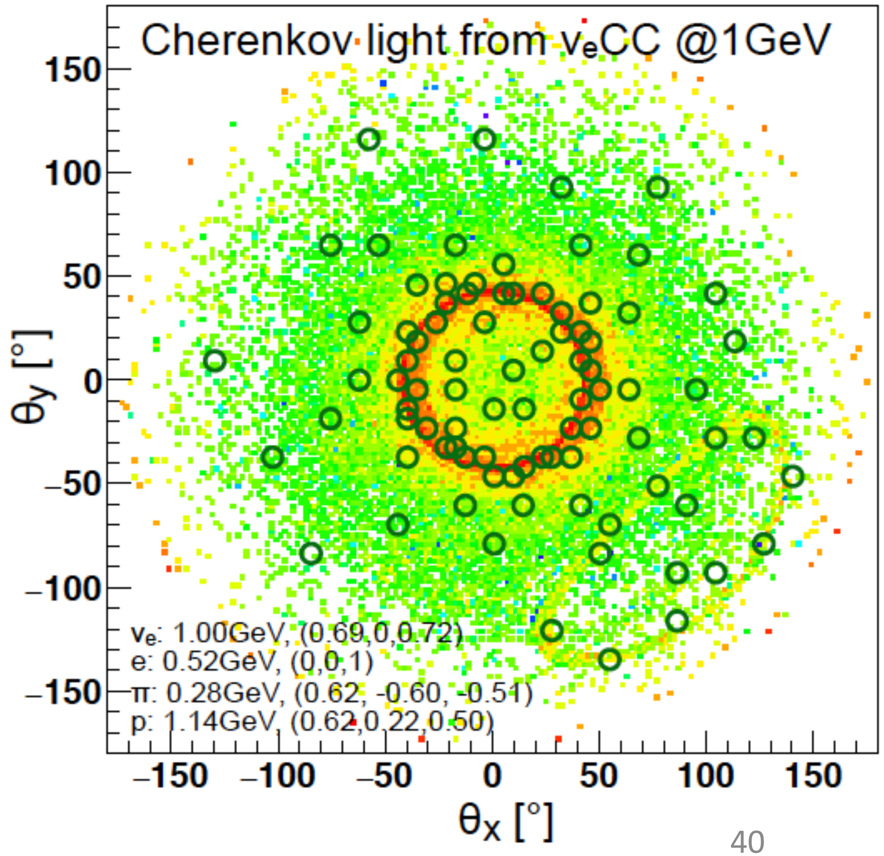




Super ORCA performance

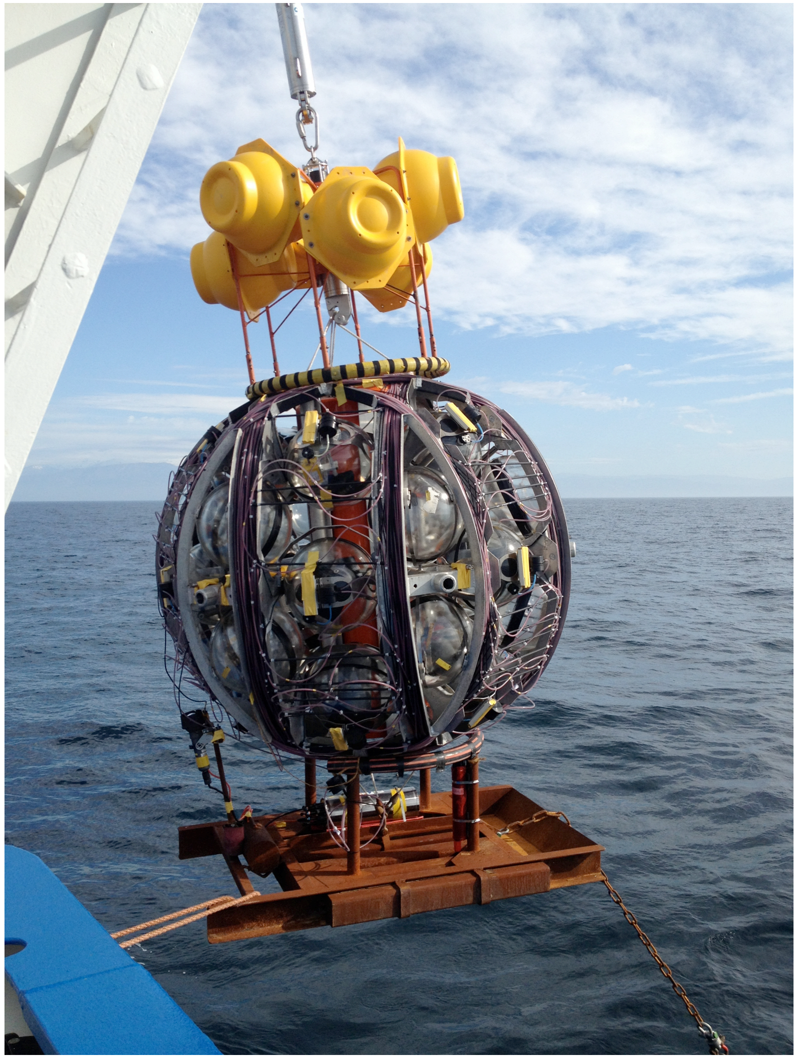
- Exploit fuzziness of Cherenkov rings
- Even at 1 GeV leading lepton ring well visible





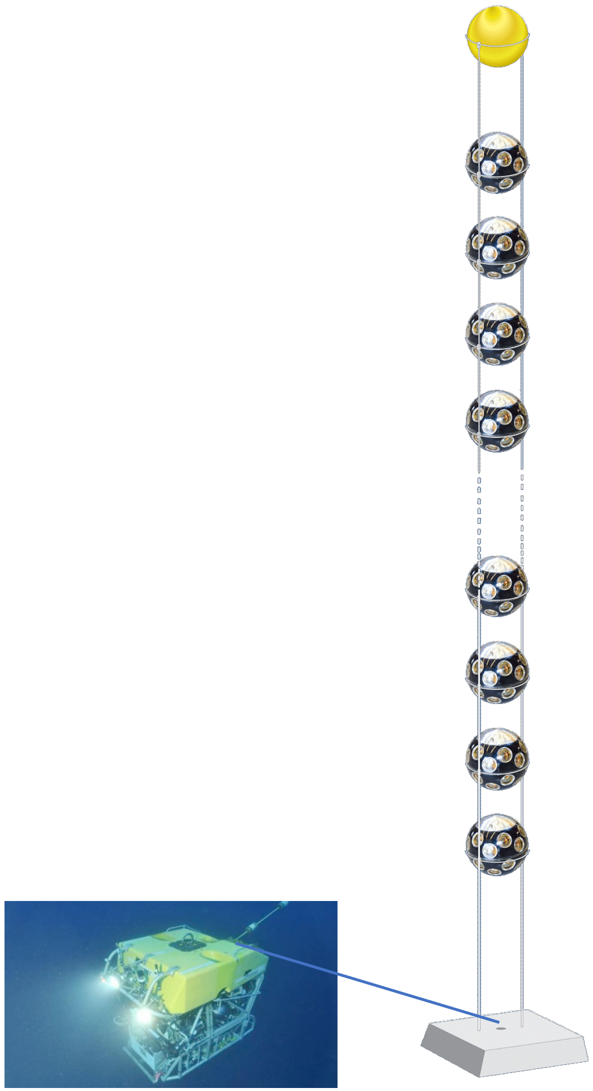
How to make ORCA 10x denser ?

- One example :
- Vertical spacing 9m → 3m
- New LOM design ?
- Different structure ?



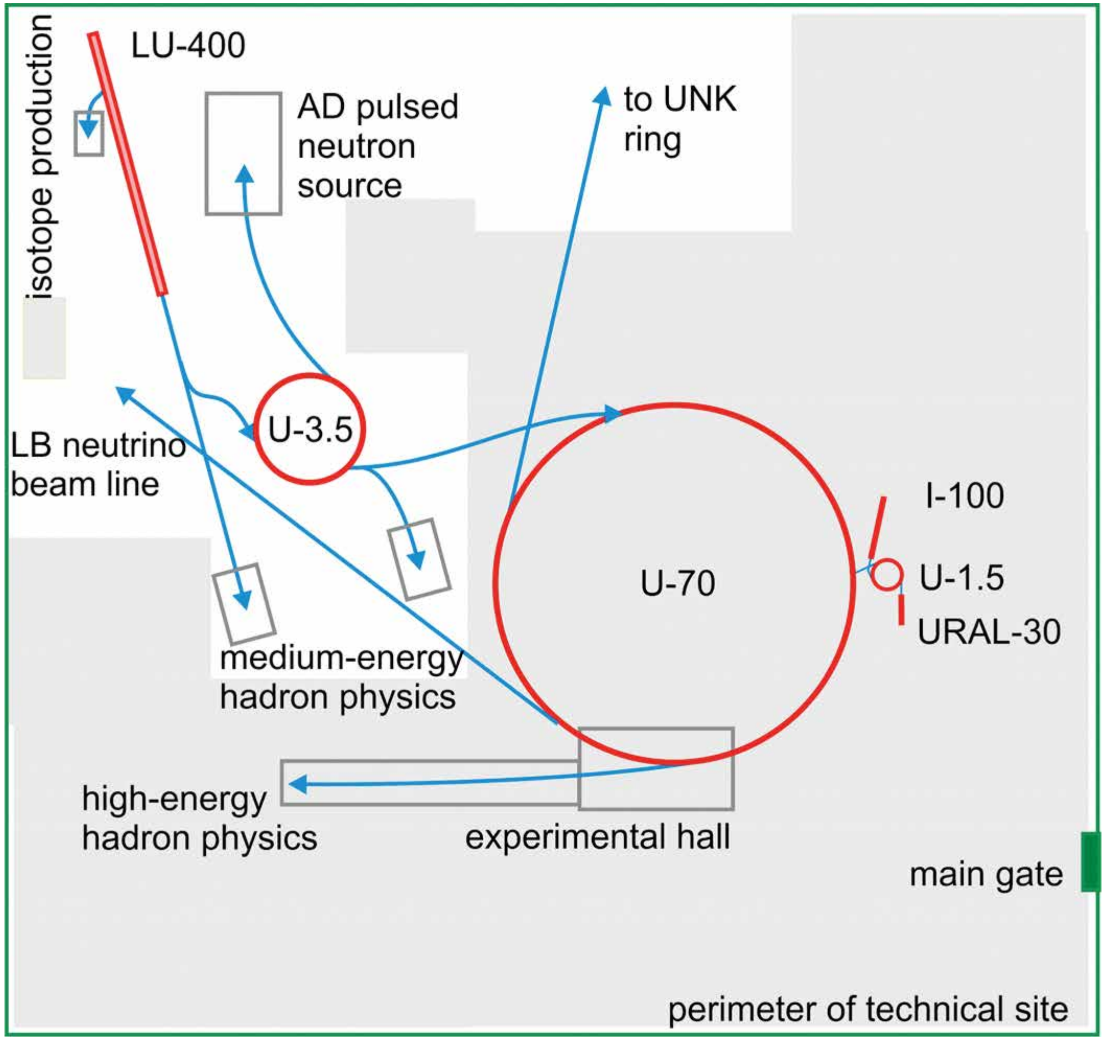
How to make ORCA 10x denser ?

- Horizontal spacing 23m → 13m
- Deployment security
- Drag lines with ROV
- More complex structure than vertical lines ?
- OM curtain ?



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 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://exwww.ihep.su/ihep/journal/IHEP-2-2010.pdf

Cost estimates

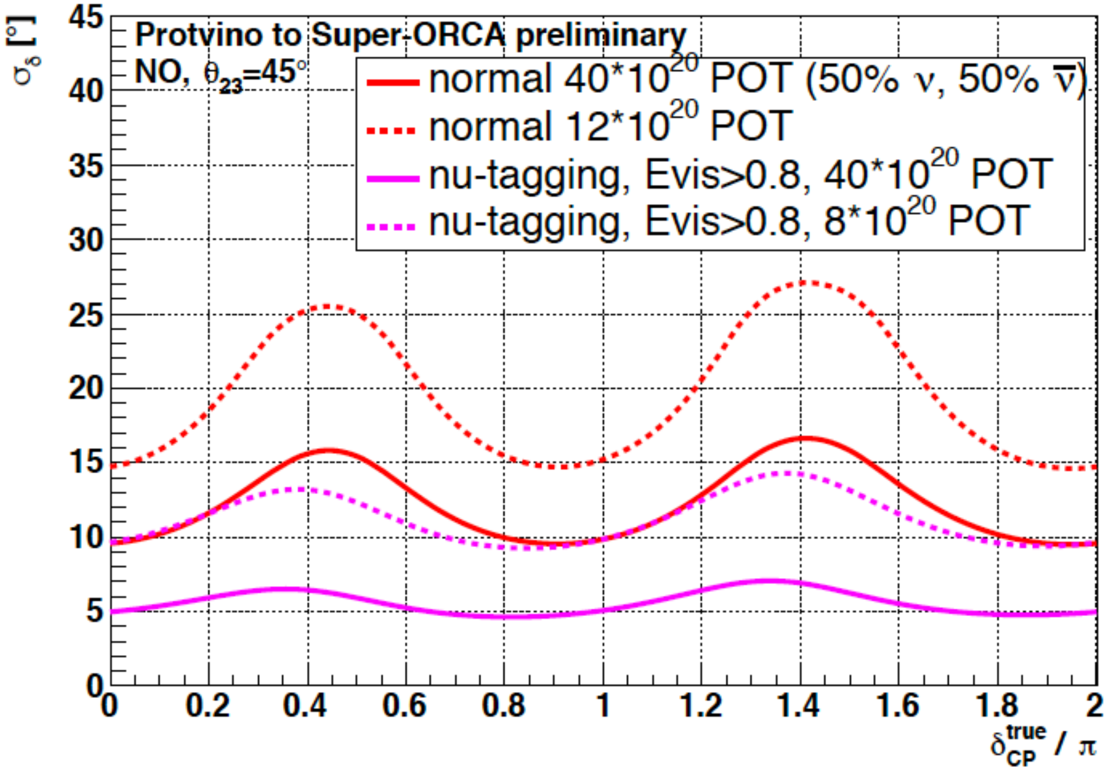
Table extracted from the OMEGA project LoI

№	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

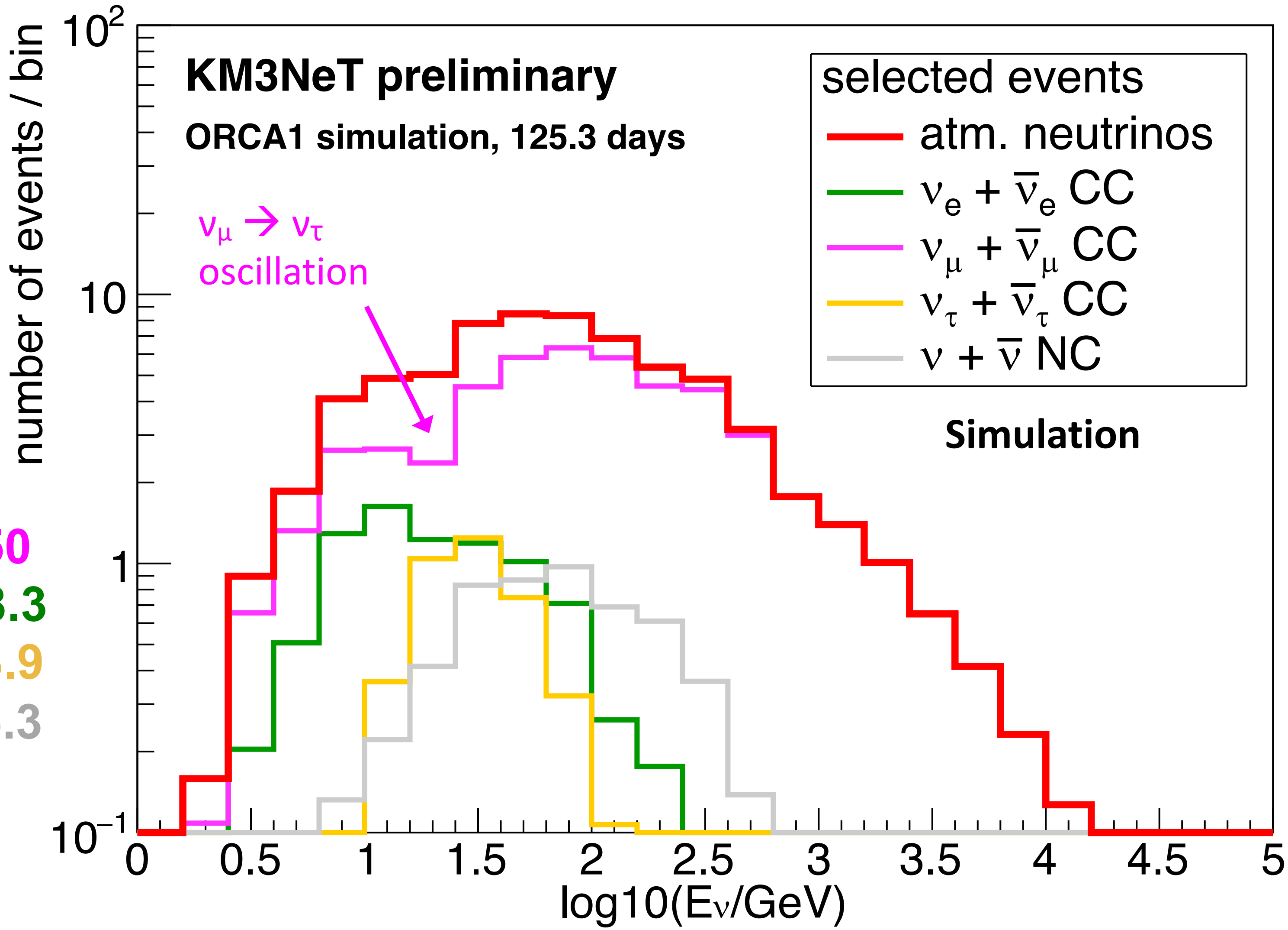
Measurement precision

- 1% energy resolution and negligible systematic energy shape uncertainty due to tagging
- Ultimate precision for large CP violation



ORCA1: True neutrino energy

- Detection threshold: ~few GeV



ν_μ CC: 50

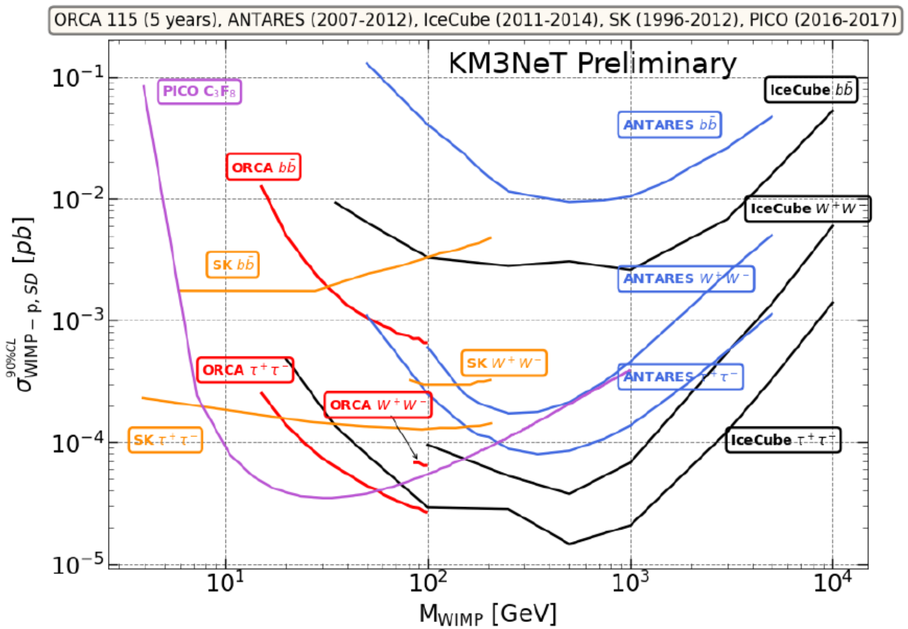
ν_e CC: 8.3

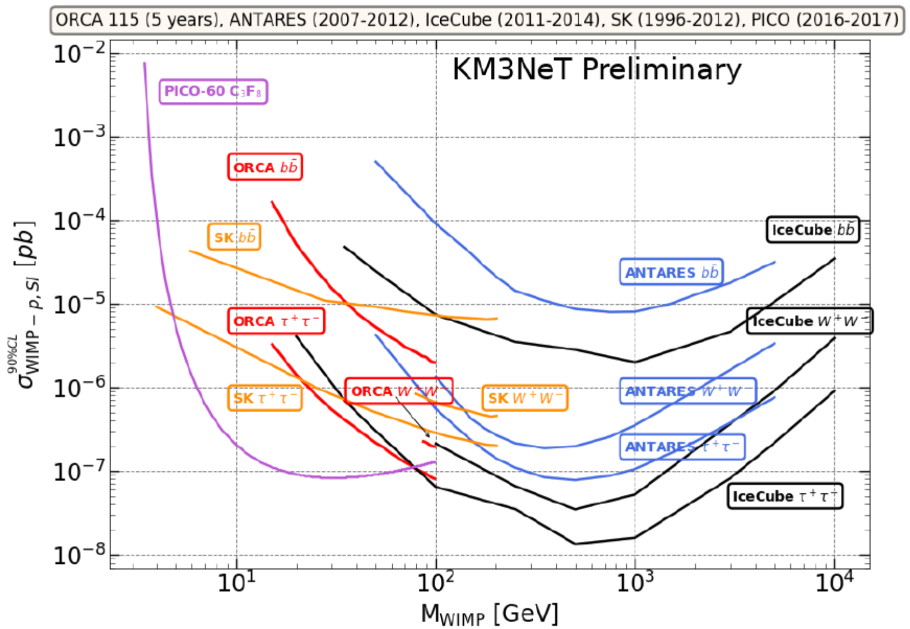
ν_τ CC: 3.9

NC: 5.3

Indirect Dark Matter detection

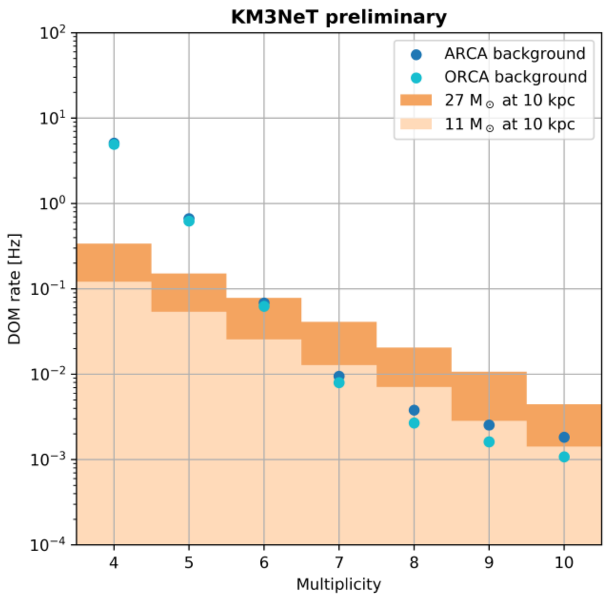
Gravitationally trapped relic WIMPs (Sun) annihilate and resulting products are measured.



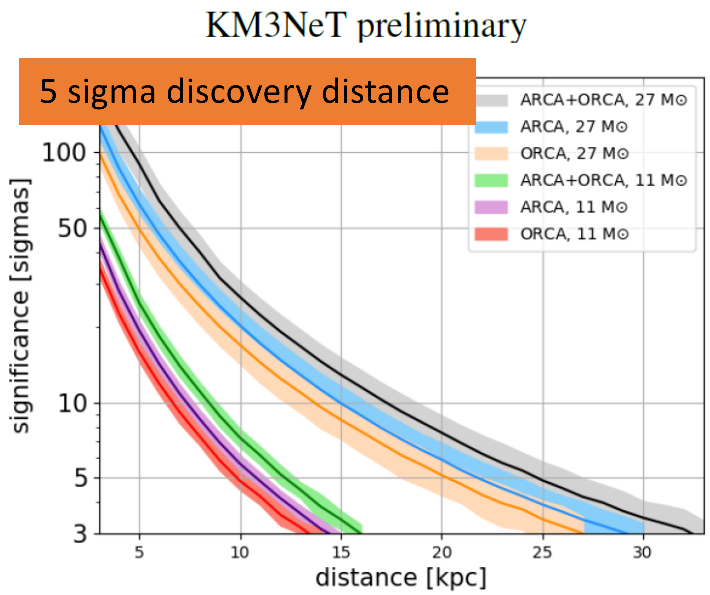


Supernova detection

~10 MeV supernova neutrinos cannot be resolved individually
Detection of Galactic supernovae by enhanced coincidence rates



Number of coincident (~10 ns) PMTs on DOM

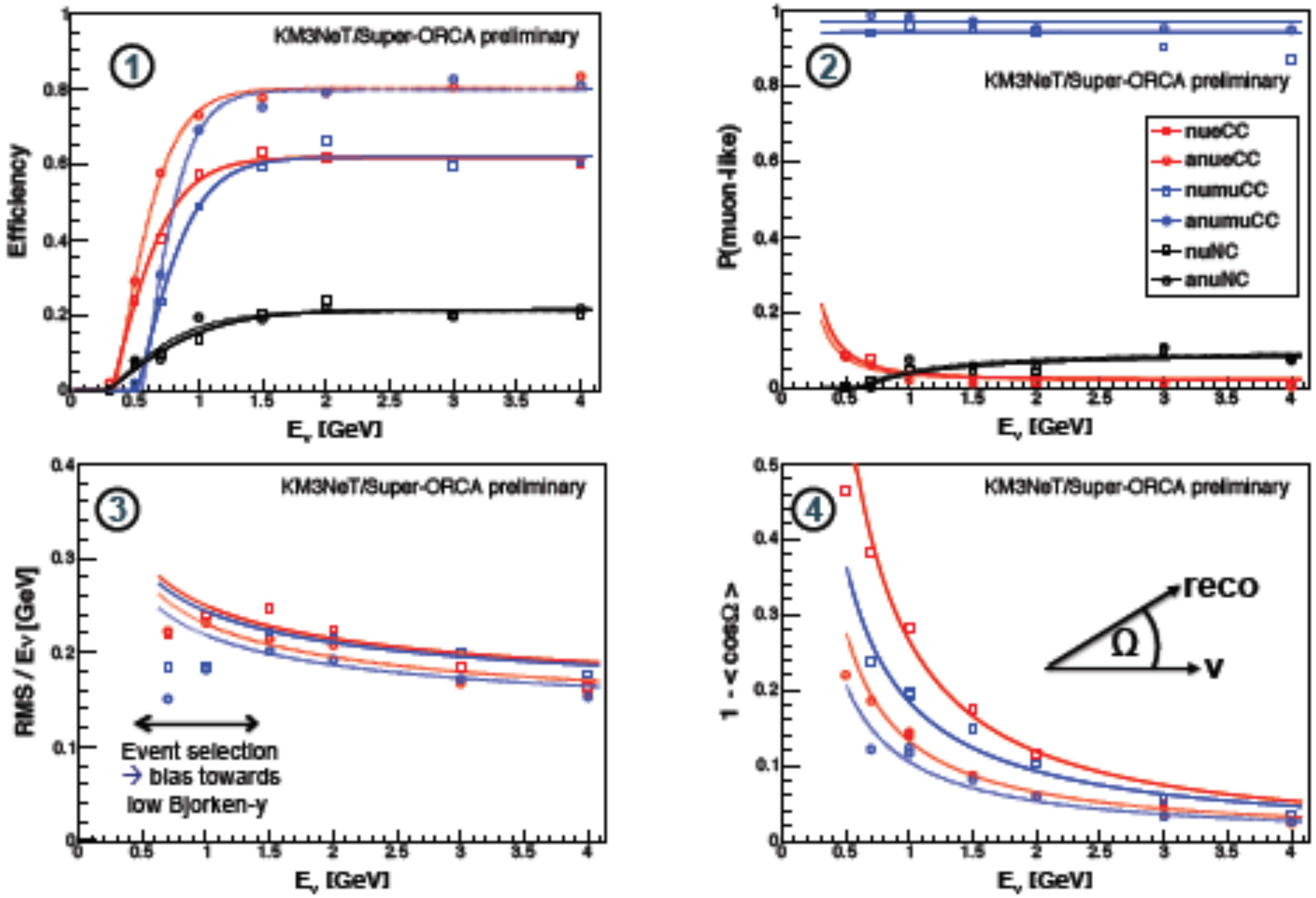


At >= 6 coincidences per DOM, SN signal exceeds background.

Neutrino energy can be resolved
Time resolution allows sensitivity to SASI
SNEWs and real-time alerts

Super ORCA performance

- Flat acceptance down to ~1 GeV
- Particle ID better than 95% down to 1 GeV



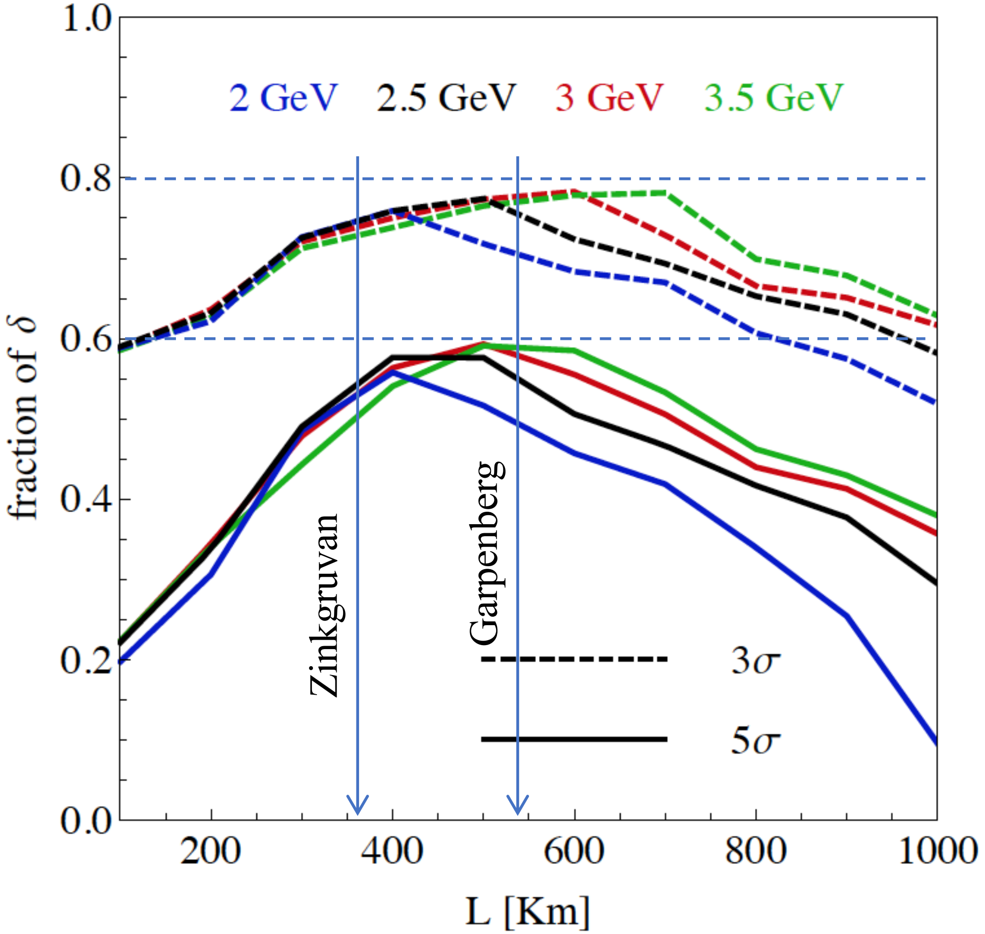
Systematic Uncertainties

- P2SO

Parameter	prior
N_μ	1 ± 0.05
N_e	N_μ
N_τ	1 ± 0.10
N_{NC}	1 ± 0.05
θ_{13}	$(8.51 \pm 0.15)^\circ$
θ_{23}	$(45.0 \pm 2.0)^\circ$
Δm^2_{32} [10^{-3} eV^2]	2.5 ± 0.05
ParticleID skew	1 ± 0.10
E_{scale} overall	1 ± 0.03
E_{scale} e/μ skew	1 ± 0.03
E_{scale} had/e skew	1 ± 0.03

Which baseline?

CPV (*Nucl. Phys. B 885 (2014) 127*)



Candidate active mines

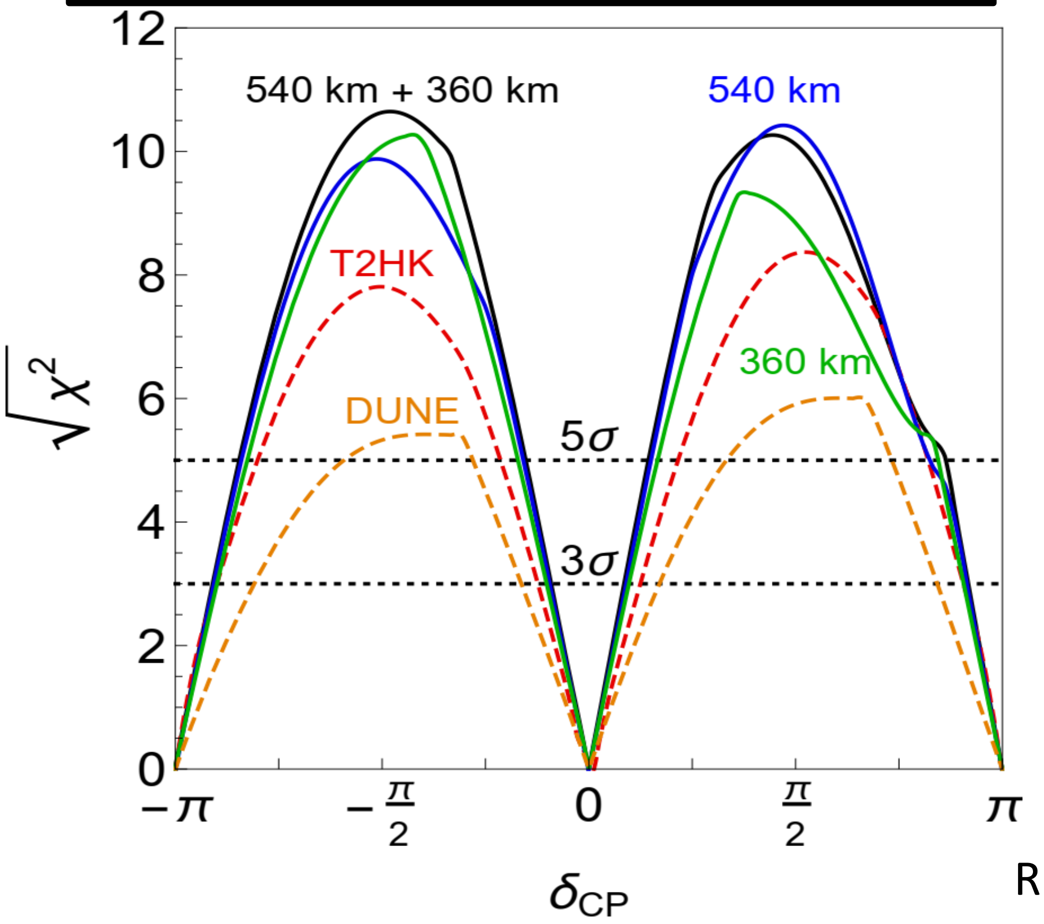
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

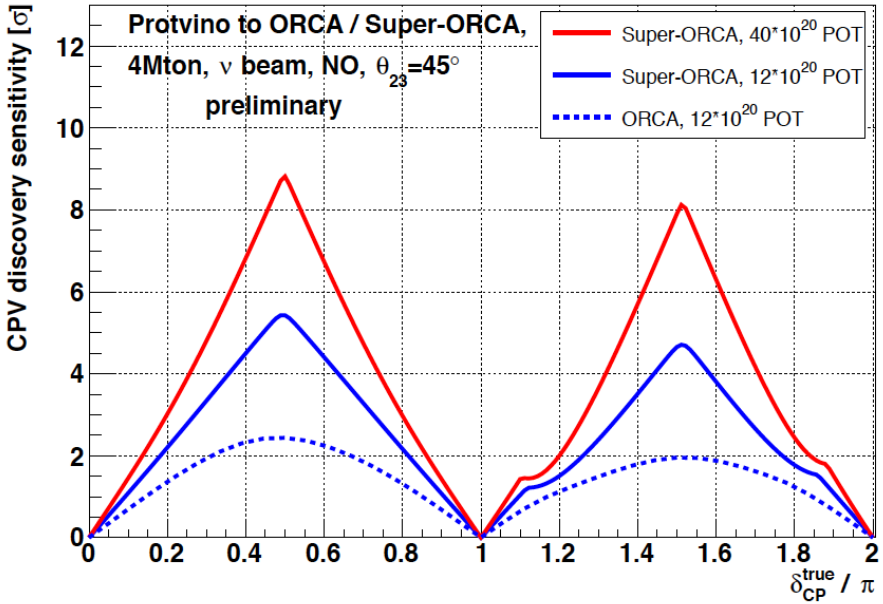
$\sin^2 2\vartheta = 0.1$; $\vartheta_{23} = \pi/4$; 10 years of running

ESSνSB 500 kt tank at 540 km.

ESSνSB 500 kt tank at 360 km.

ESSνSB 250 kt tank at 540 km
and 250 kt tank at 360 km.





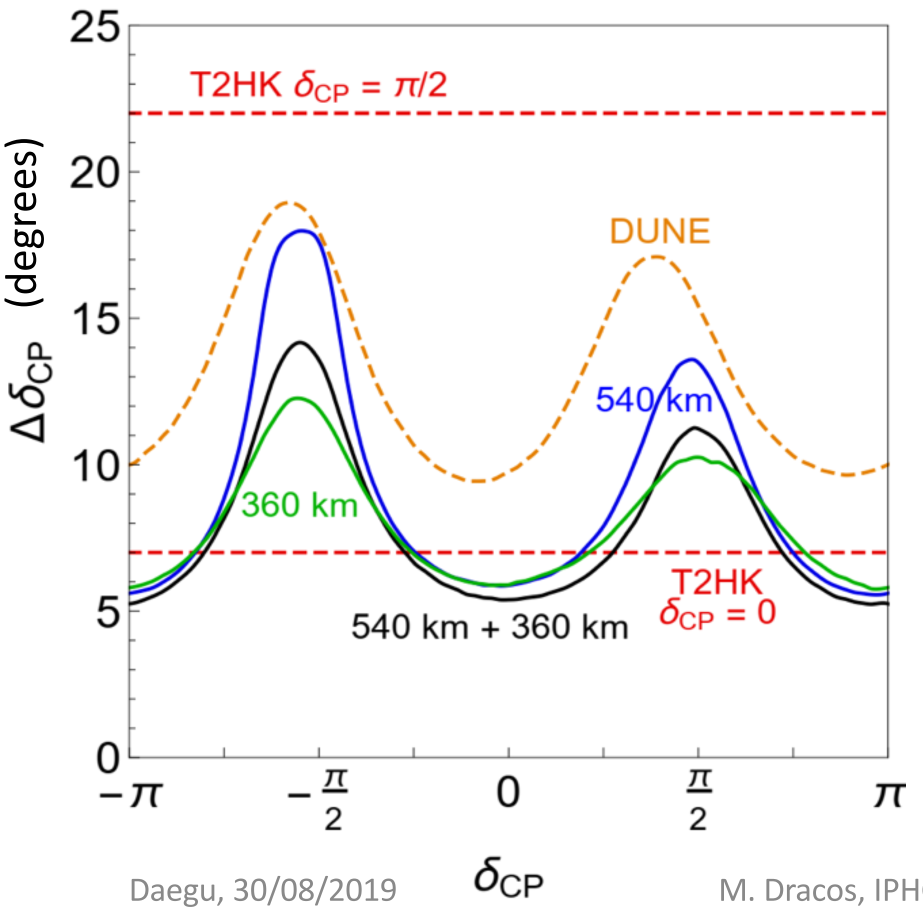
Enrique Fernandez Martinez
private communication

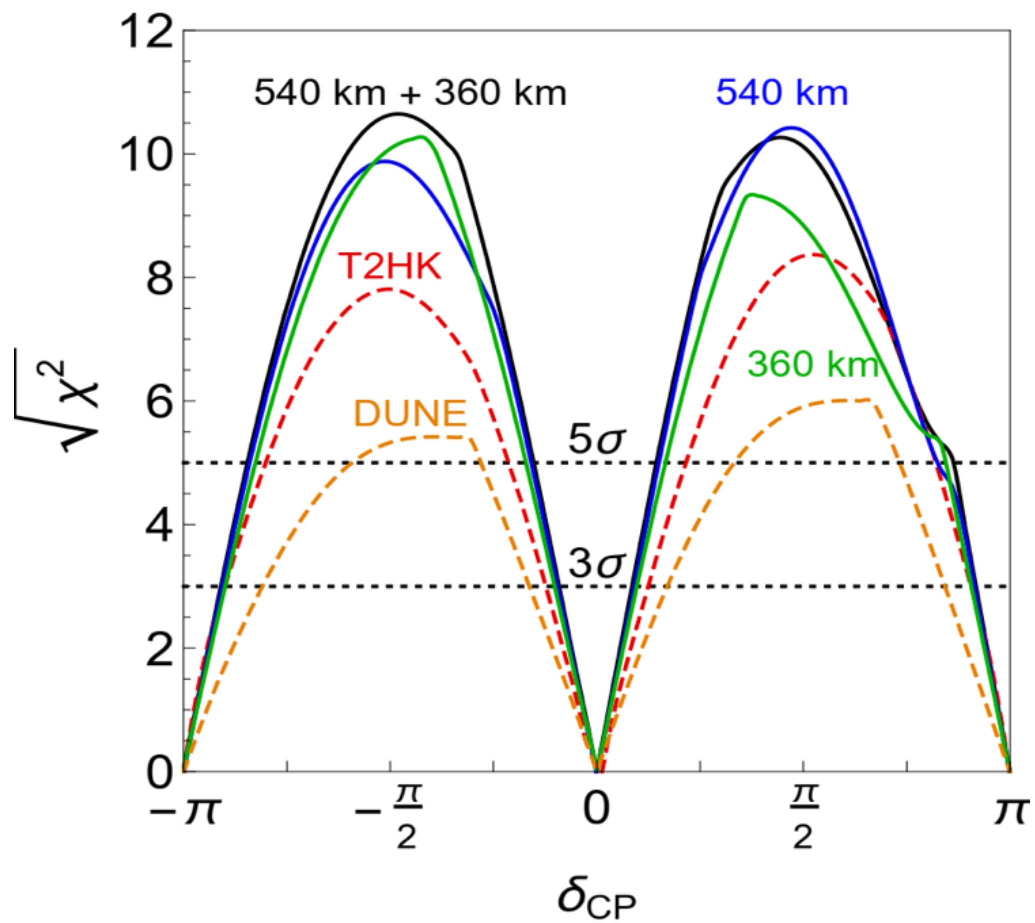
R. Tsenov, https://indico.cern.ch/event/740296

CPV performance comparison between ESSnuSB, DUNE and Hyper-K assuming 3% systematic errors for ESSnuSB in line with the other two.

ESSνSB 500 kt tank at 540 km.

ESSνSB 500 kt tank at 360 km.

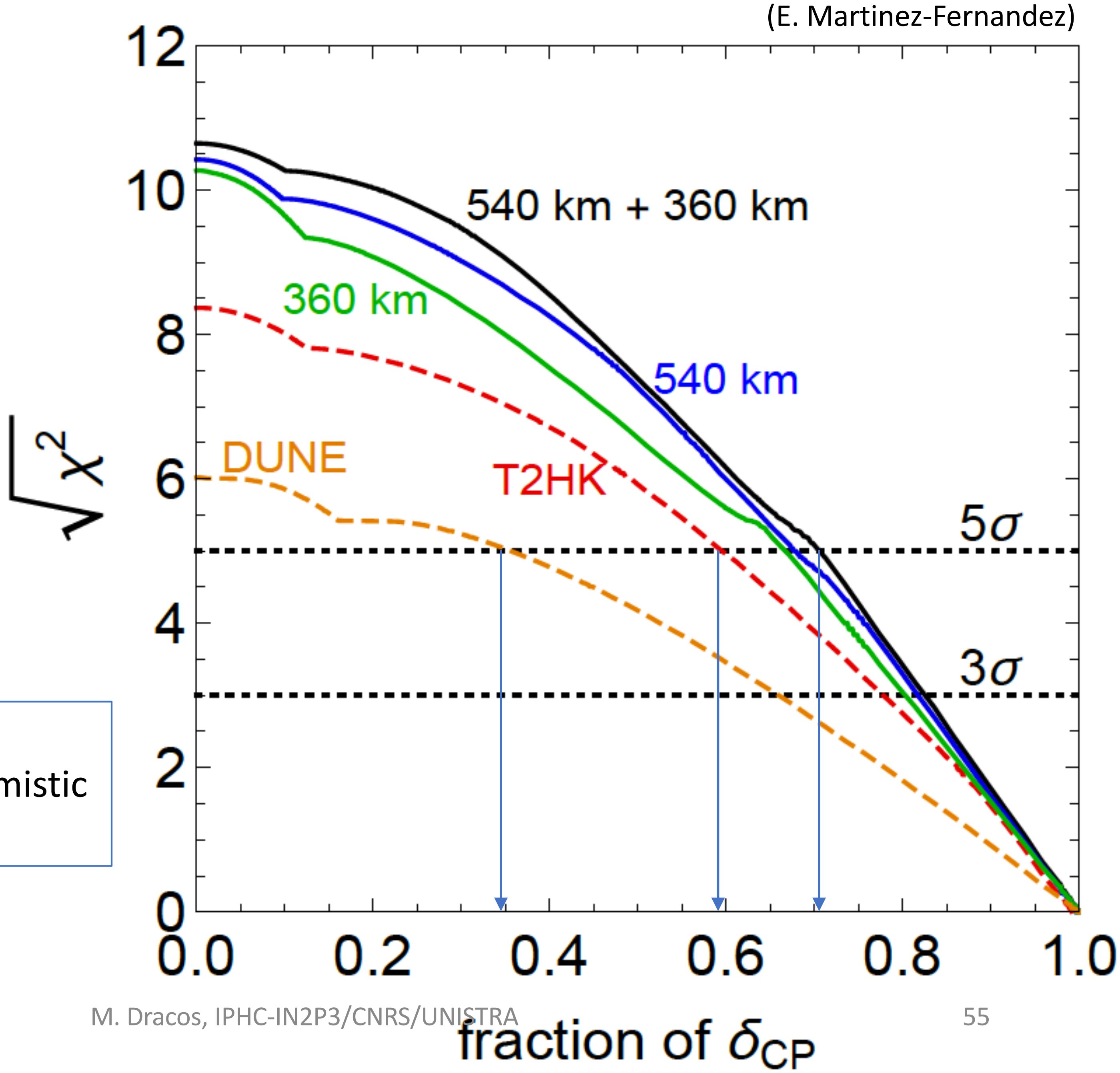




ESSνSB 250 kt tank at 540 km and 250 kt tank at 360 km.

Fraction of δ_{CP}

2 active mines aligned…



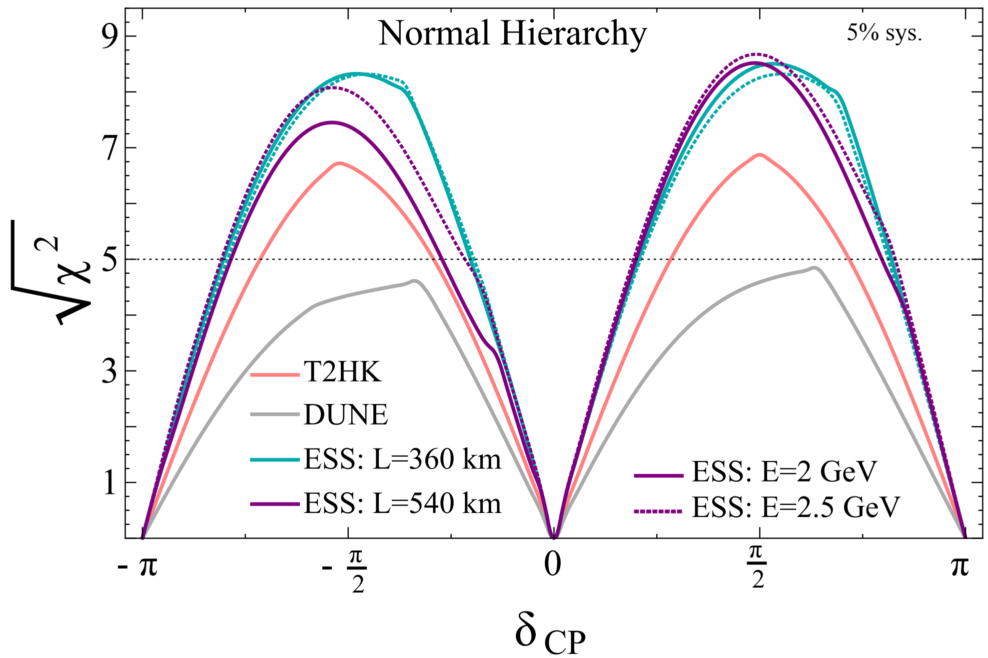
My personal opinion:
these scenarios are too optimistic for all facilities

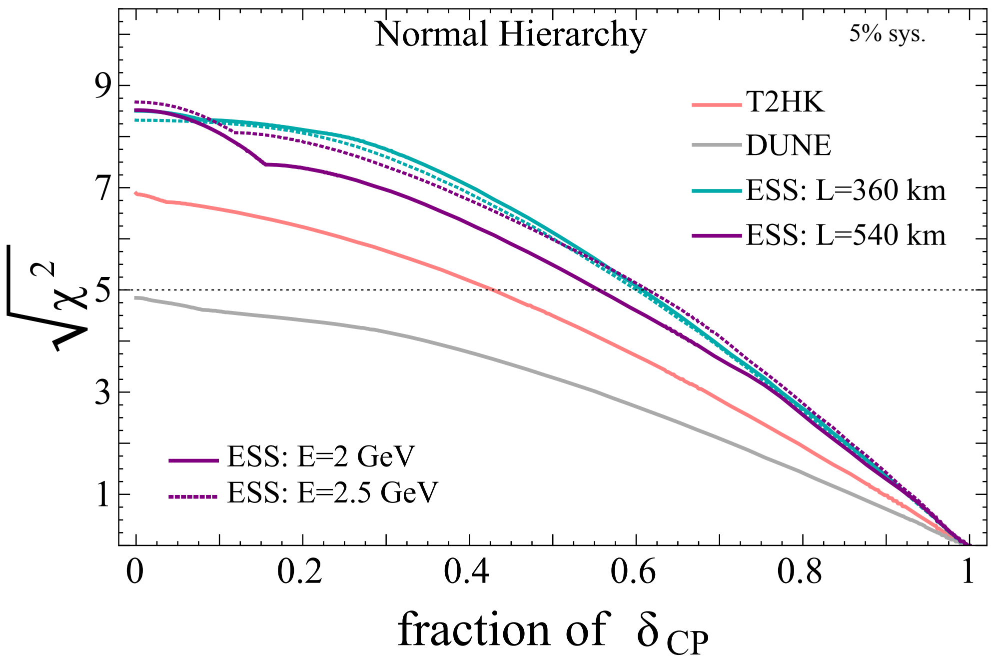
Systematic errors

Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
(incl. near-far extrap.)									
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs $\times$ eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

Comparisons

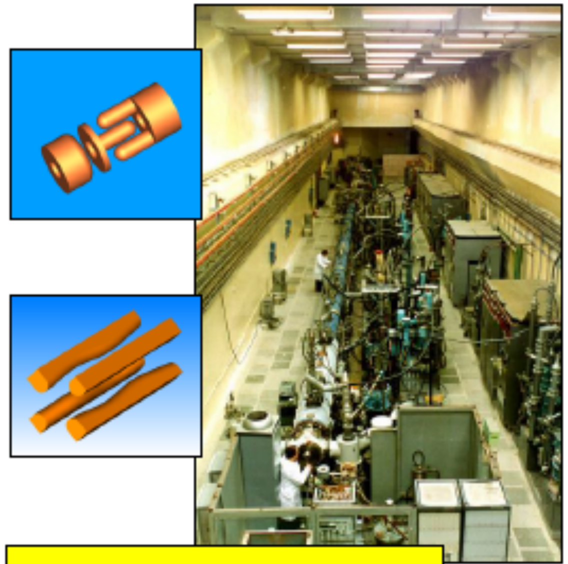




Comparison using the same systematic errors

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

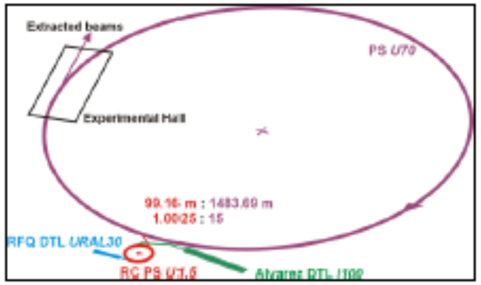
Proton Accelerator Complex Protvino



RFQ DTL *URAL*30

Alvarez DTL *I*100

Main PS *U*70



RC PS *U*1.5

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