European Neutrino "Town" meeting and ESPP 2019 discussion, CERN, 24.10.2018

Beyond DUNE, JUNO, HyperK:
ESSνSB, P2O and Neutrino factory

Roumen Tsenov
Department of Atomic Physics, University of Sofia

CP Violating Observables ($\nu_\mu \to \nu_e$)

$$P_{\nu_\mu\to\nu_e(\bar\nu_\mu\to\bar\nu_e)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde B_\mp}\right)^2 \sin^2\left(\frac{\tilde B_\mp L}{2}\right)$$ atmospheric

$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ solar

Non-CP terms

$$+\tilde J \frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde B_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde B_\mp L}{2}\right)\cos\left(\pm\delta_{CP} - \frac{\Delta_{13}L}{2}\right)$$ interference

CP violating

$$\tilde J \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde B_\mp \equiv \left|A \mp \Delta_{13}\right|,\ A = \sqrt{2}G_F N_e$$

matter effect

⇒ accessibility to mass hierarchy

⇒ very long baseline

(small in our case)

$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar\nu_\mu\to\bar\nu_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar\nu_\mu\to\bar\nu_e}}$$

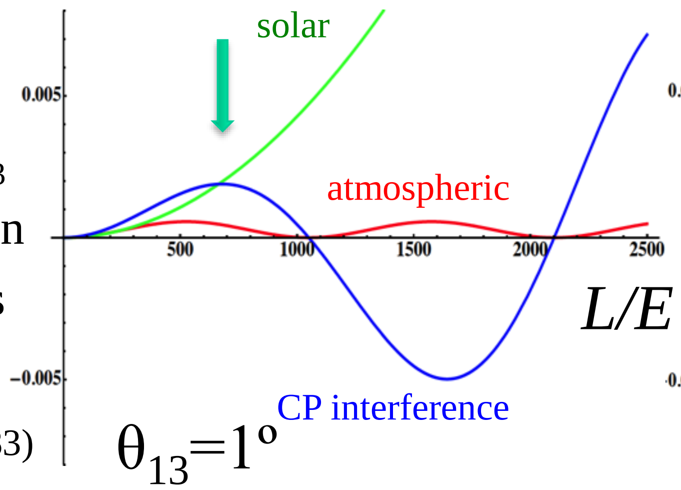
$\neq 0 \Rightarrow$ CP violation.

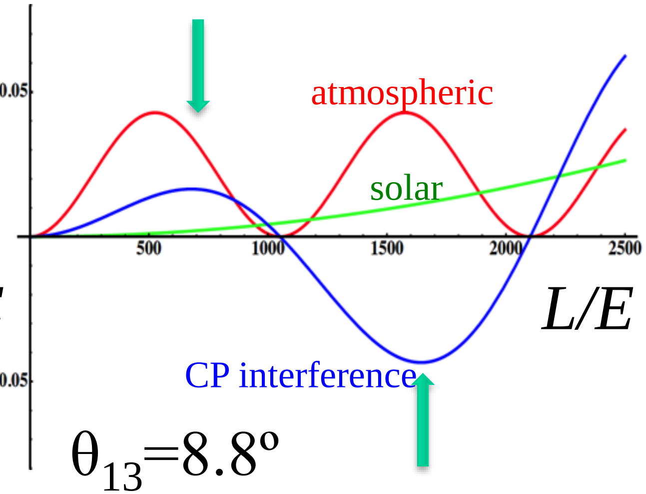
But matter effects also create asymmetry.

Neutrino Oscillations with "large" θ_{13}

for small θ_{13} 1st oscillation maximum is better

(arXiv:1110.4583)



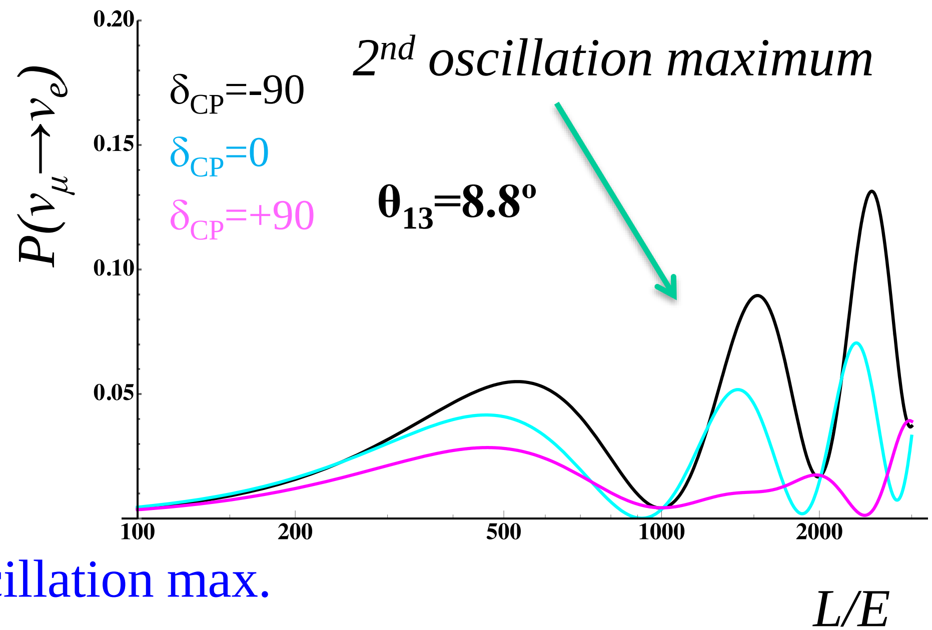


for "large" θ_{13} 1st osc. max. is dominated by the atm. term

1st oscillation max.: $\mathcal{A}=0.3\sin\delta_{CP}$

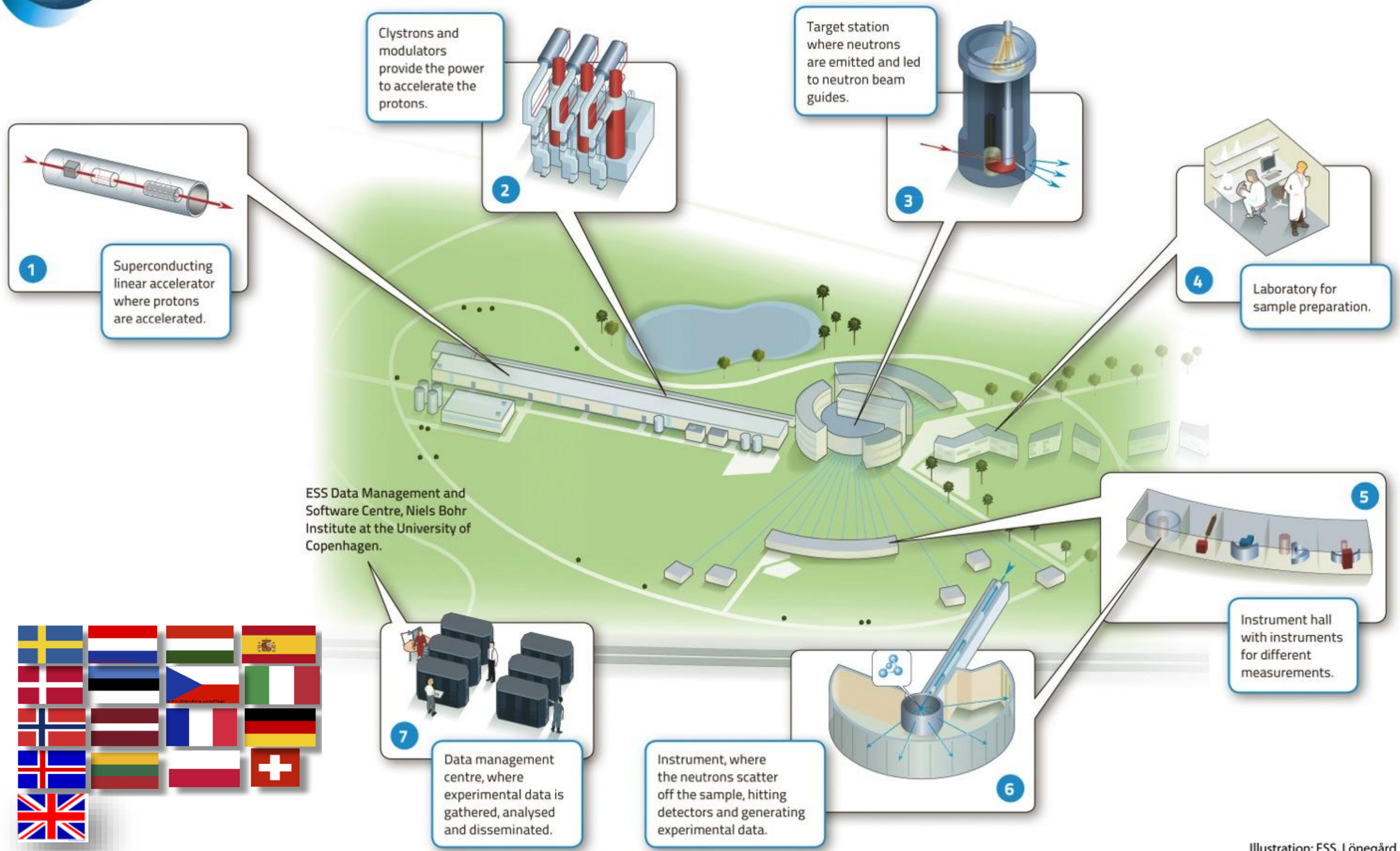
2nd oscillation max.: $\mathcal{A}=0.75\sin\delta_{CP}$

(see arXiv:1310.5992 and arXiv:0710.0554)



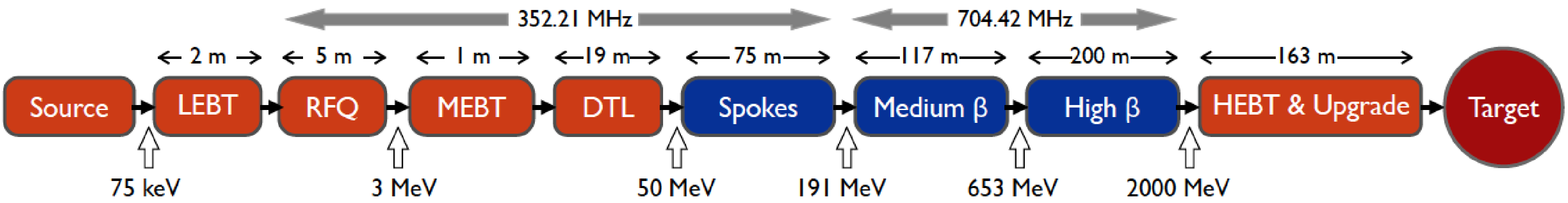
better sensitivity at the 2nd oscillation max.

European Spallation Source

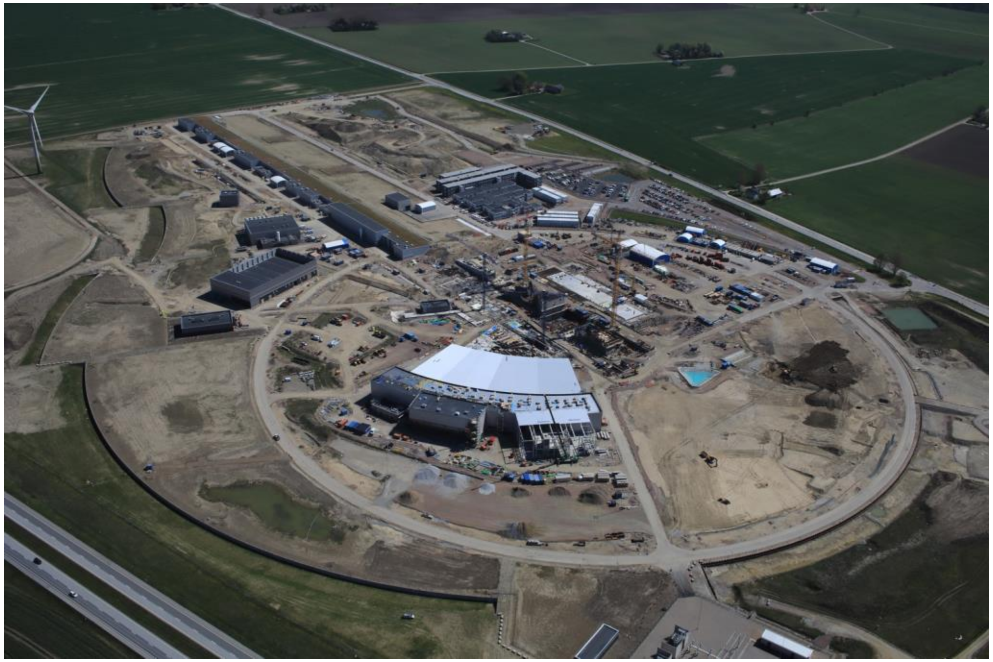


under construction since 2014 (~1.85 B€ facility)

ESS proton linac



- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons, up to 3.5 GeV possible with linac upgrades
- **>2.7x10^{23} p.o.t/year.**



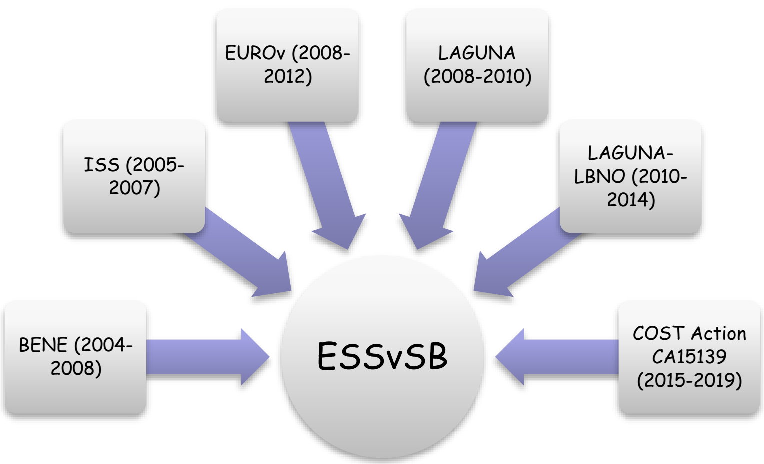
Linac ready by 2023 (full power)

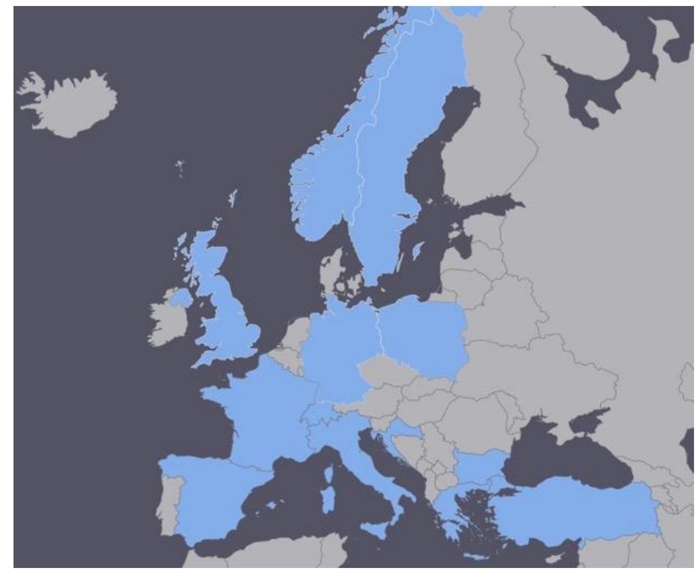
How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, that would be affordable by the magnetic horn (350 kA, power consumption, Joule effect). Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutrinos produced at the neutron target
- H^- source (instead of protons), solves space charge problems at injection. (up to here: 250 M€)
- **~300 MeV neutrinos.**
- **Target station (studied in EUROν).**
- **Underground Far detector (studied in LAGUNA).**
- **Near detector.**

ESSvSB at European level

COST Action CA15139 (2016-2019) EuroNuNet : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* (**http://www.cost.eu/COST_Actions/ca/CA15139**).





H2020 Design Study (2018-2012): *Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator.*

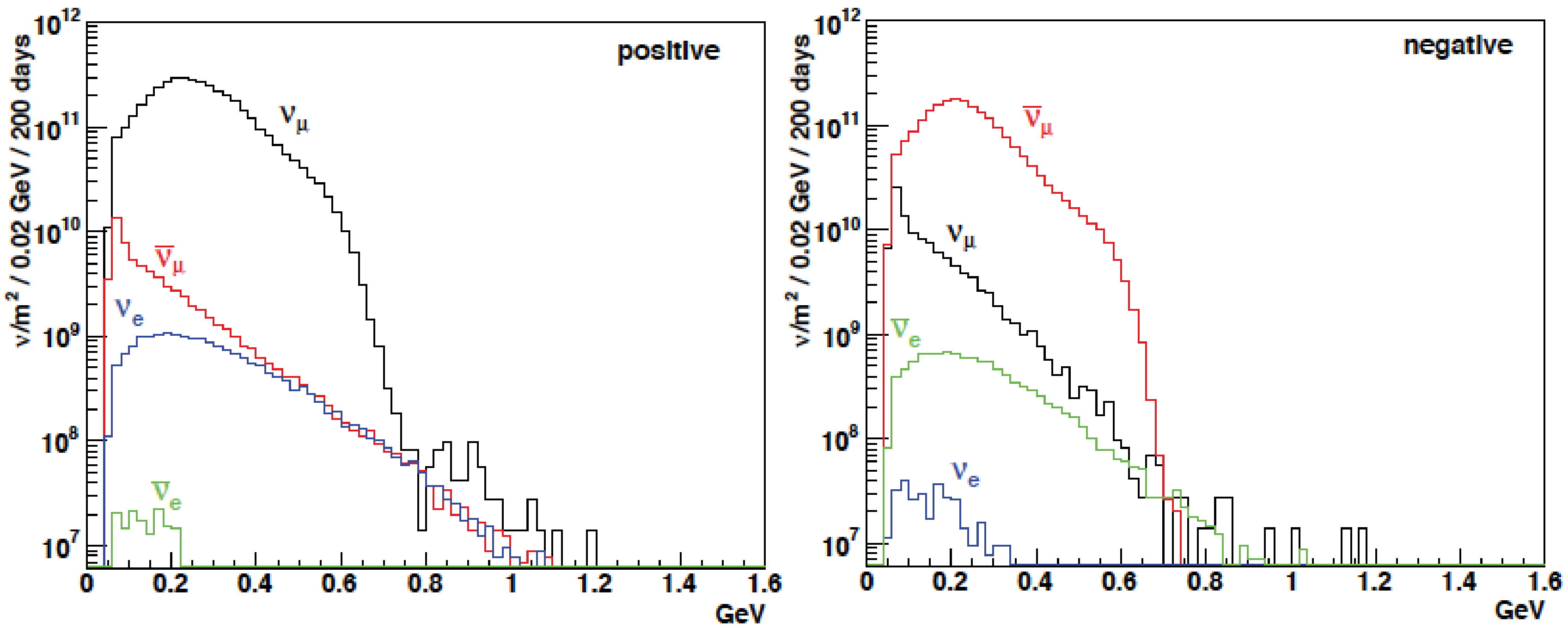
Total cost: 4.7 M€, H2020 budget: 3 M€, 15 participating institutes from 11 European countries, CERN and ESS, 6 WP (*the Grant Agreement is being signed*).

ESS neutrino energy distribution

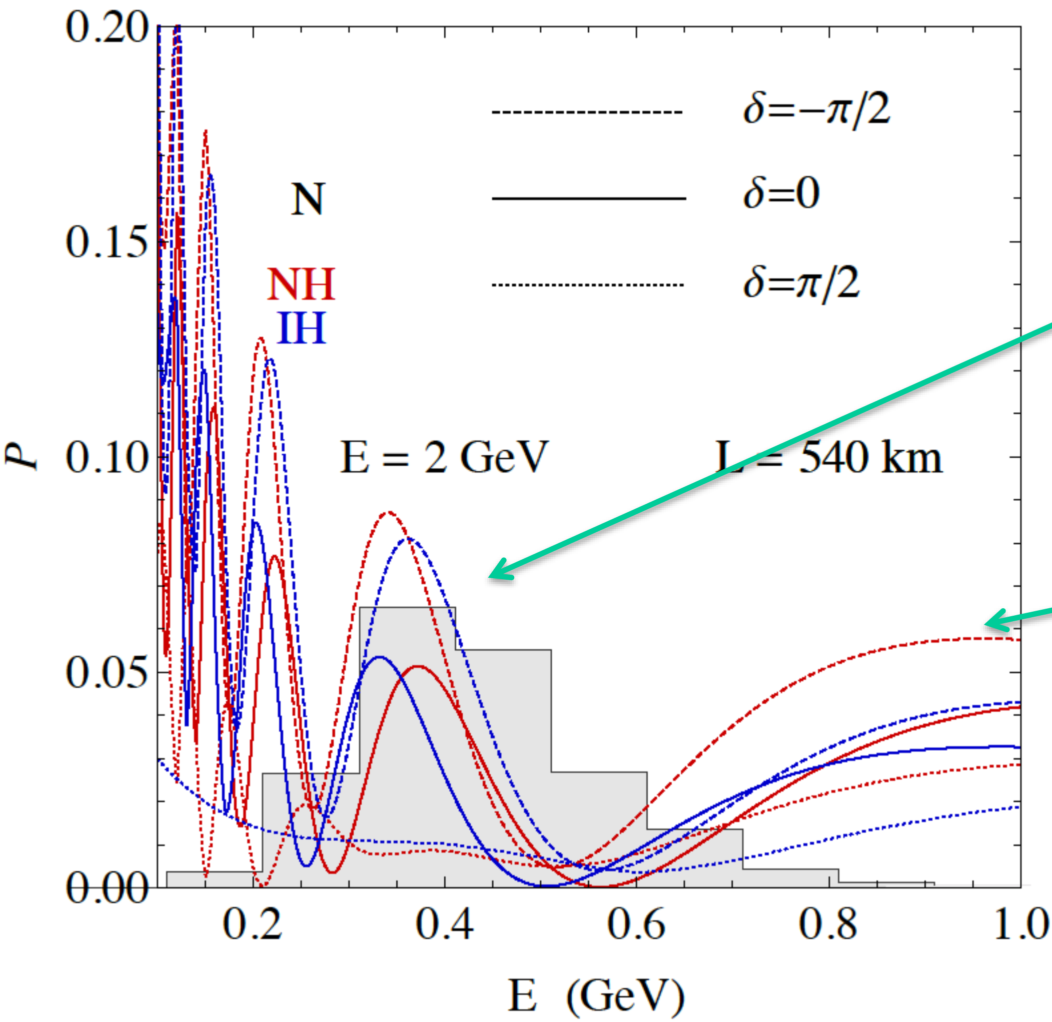
- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in the near detector

	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 and per year (10^7 s)



2nd oscillation maximum coverage

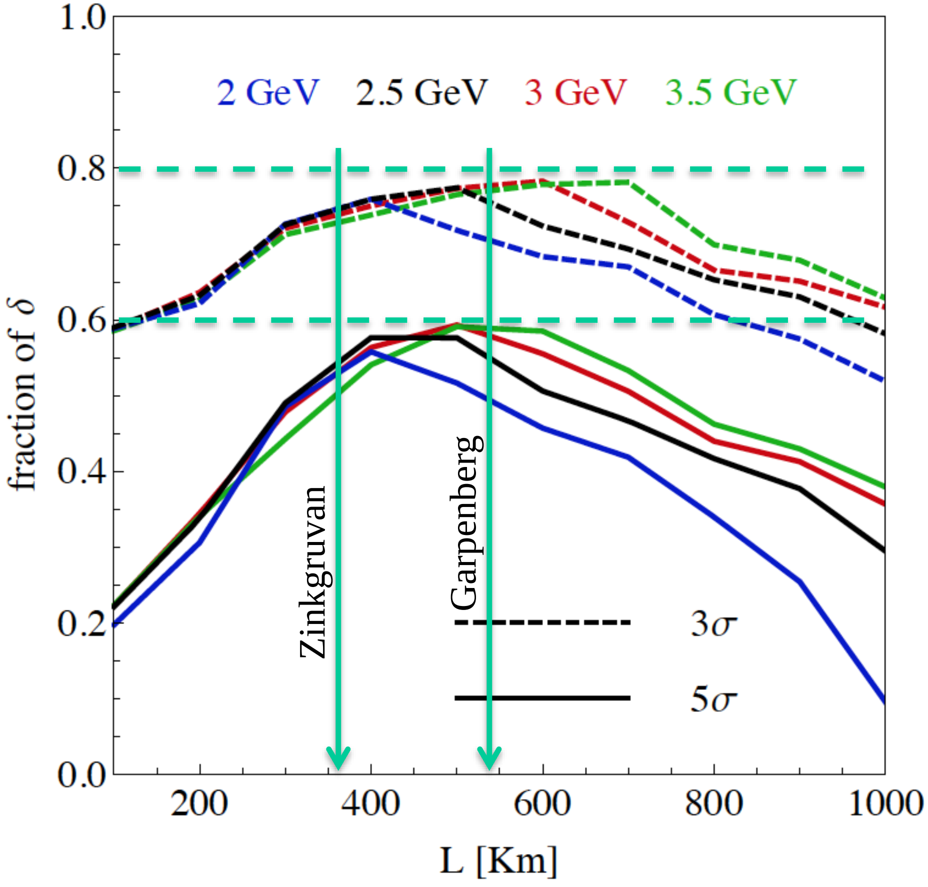


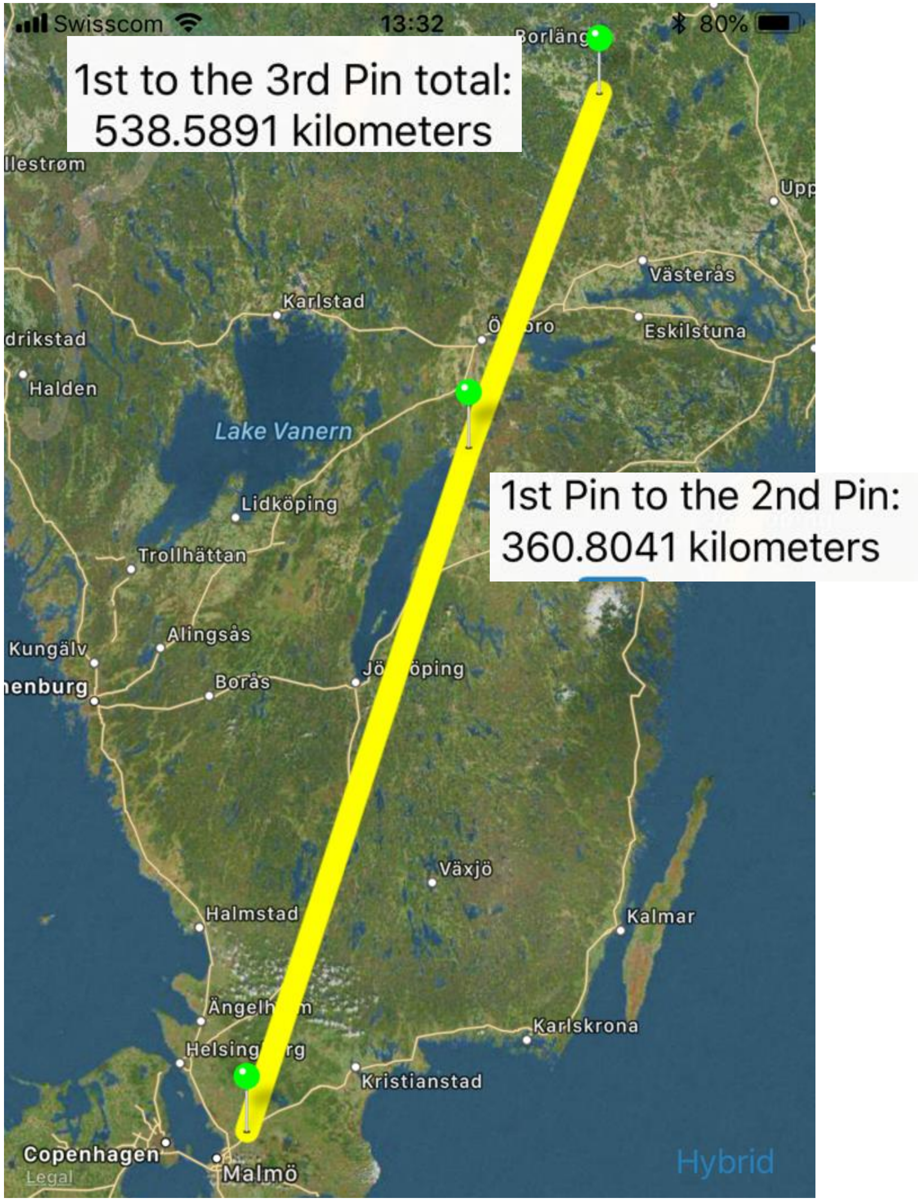
2nd oscillation max.
Well covered by the ESS neutrino spectrum (grey histo)

1st oscillation max.

Baseline

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

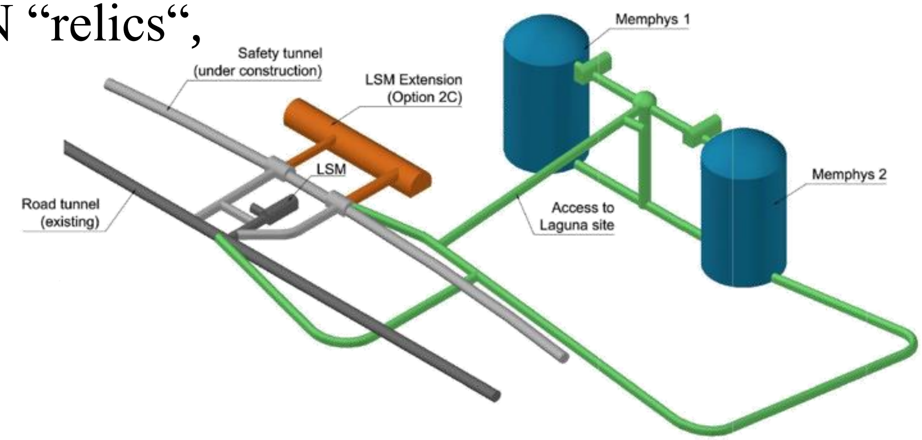




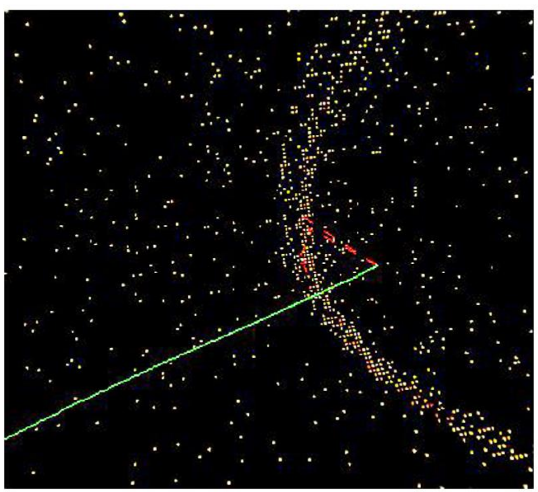
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/background)**

MEMPHYS (MEgaton Mass PHYSics) Water Cherenkov Detector

- **Neutrino oscillations (Super Beam)**
- **Proton decay**
- **Astroparticle physics:** galactic SN ν, SN “relics“, solar and atmospheric neutrinos

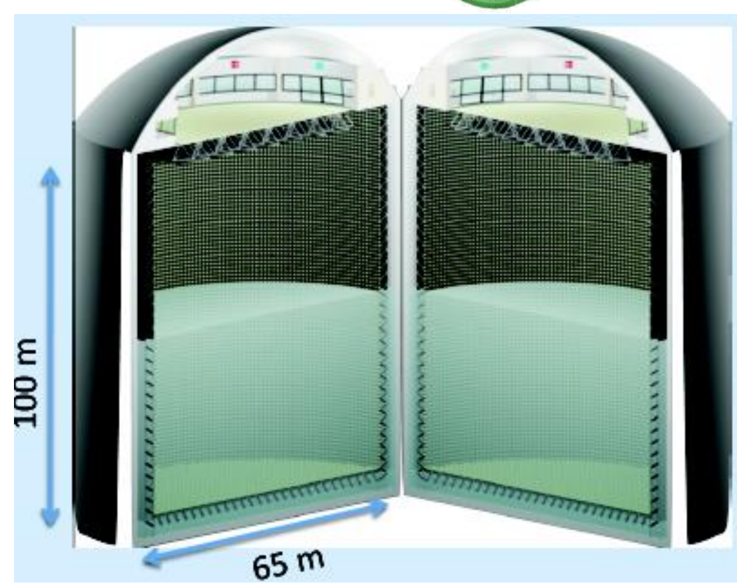


- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage



(arXiv: hep-ex/0607026)

FIG. 4. Pattern of hit PMTs after the interaction of a 500 MeV muon with the full MEMPHYS simulation. The green line is the muon track, the red dashed lines are gammas from muon capture, each white dot represents one hit PMT.



Processes to be measured

QE with a muon in the final state:

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\tilde{\nu}_\mu + p \rightarrow \mu^+ + n$$

QE with an electron/positron in the final state:

$$\nu_e + n \rightarrow e^- + p$$

$$\tilde{\nu}_e + p \rightarrow e^+ + n$$

Small admixture (< 5% ?) of single pion production:

$$\nu_\mu + p \rightarrow \mu^- + p + \pi^+ \quad E_{th}=277 \text{ MeV}$$

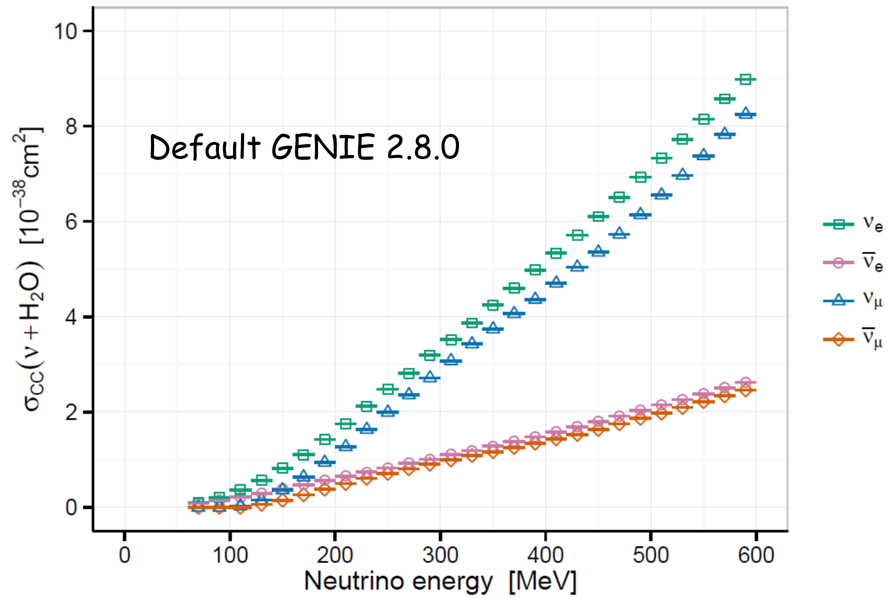
$$\nu_\mu + p \rightarrow \mu^- + \Delta^{++}(1232)$$

E_{th}=953 MeV

Important (not known) background in the Far detector (difficult to measure):

$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$$

E_{th}=145 MeV

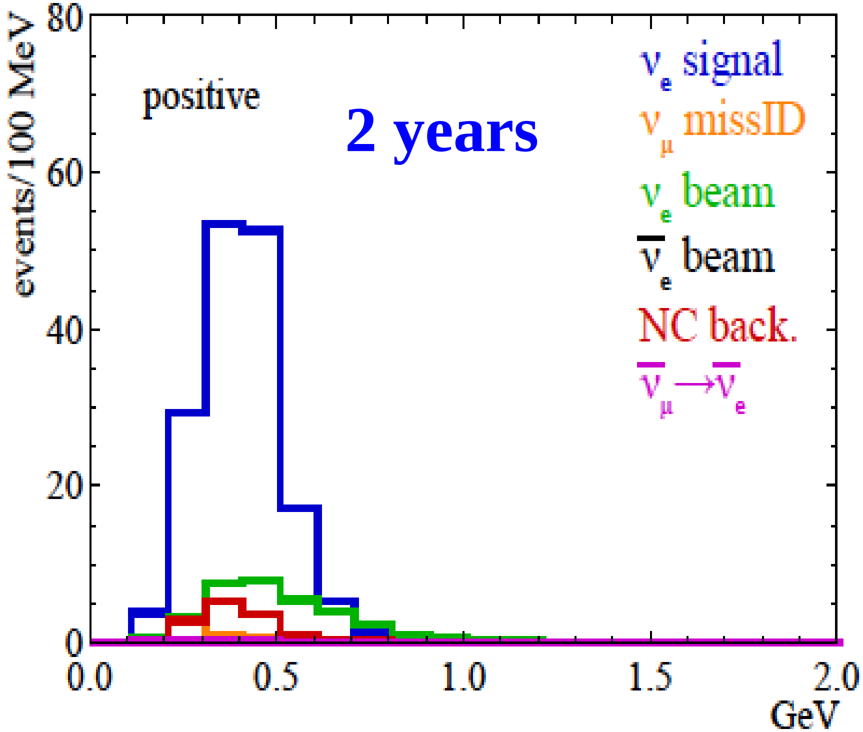


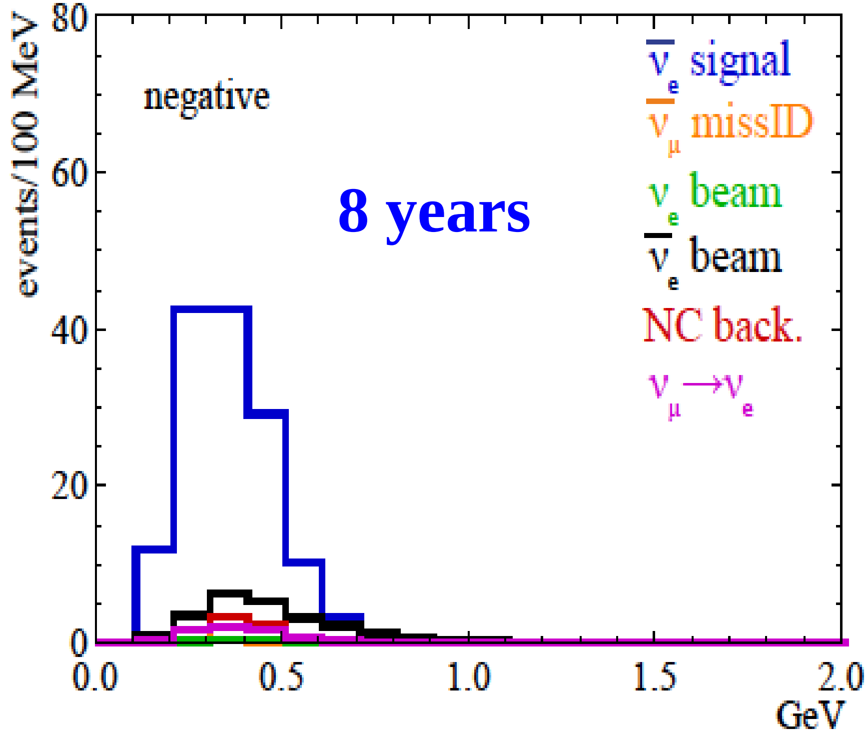
Number of events in the Far detector

540 km (2 GeV), 2+8 years of data taking

neutrinos **anti-neutrinos**

$\delta_{CP}=0$



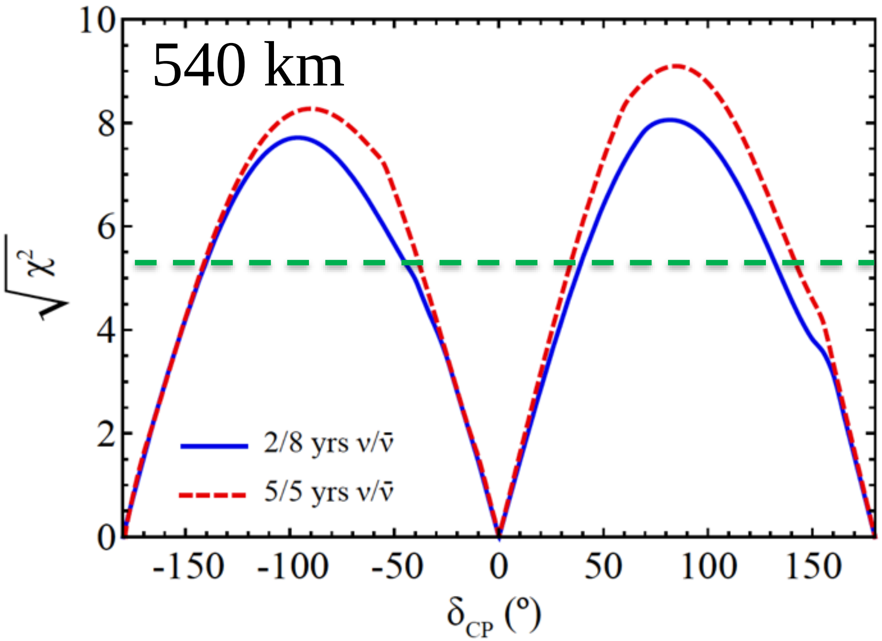


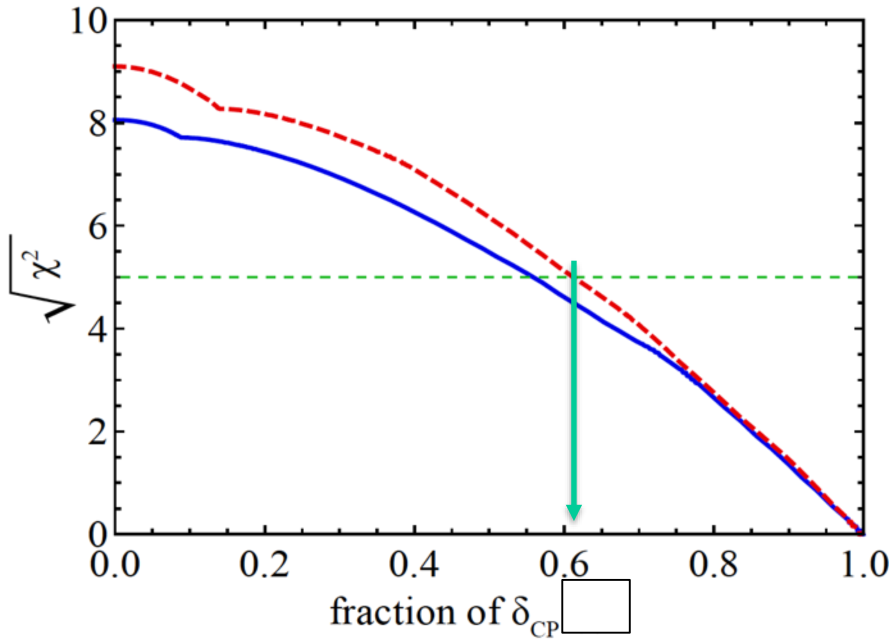
Systematic errors

	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
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 × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × 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%

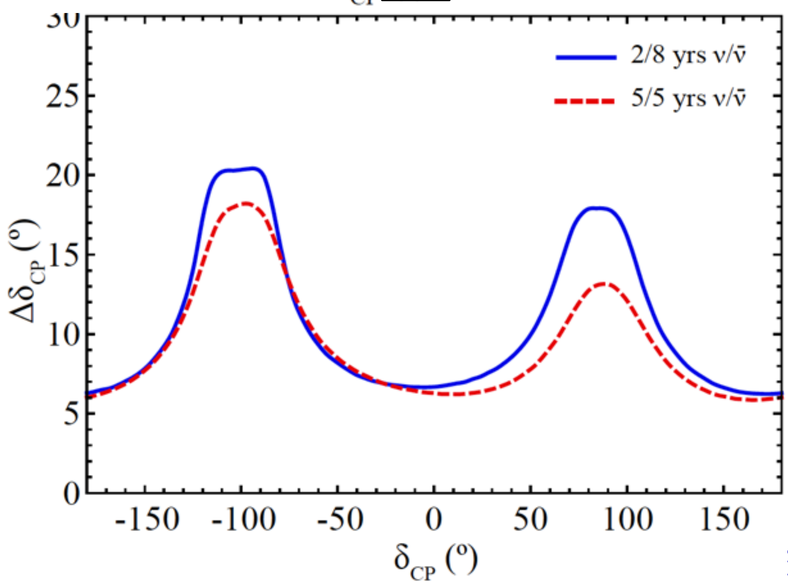
Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

δ_{CP} performance



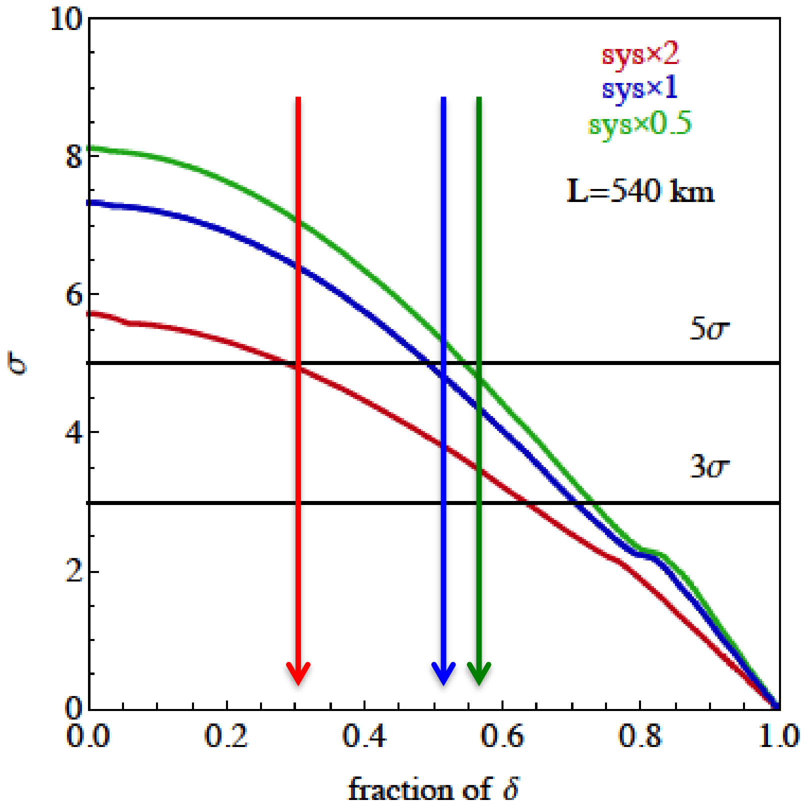


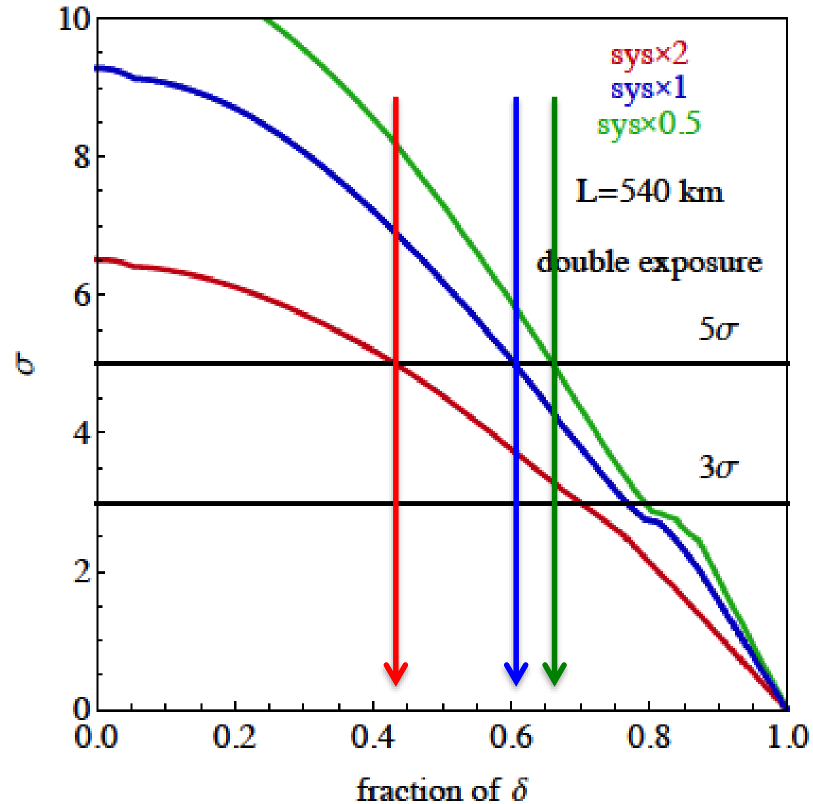
- little dependence on mass hierarchy,
- δ_{CP} coverage at 5 σ C.L. up to **60%**,
- δ_{CP} accuracy down to **6°** at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility,
- **5/10%** systematic errors on signal/background.



Effects of the systematics and statistics

CPV (2 GeV protons)





Exposure 10 years

With 2 times more statistics

Systematic errors (nominal values): 5%/10% for signal/background

more than 50% δ_{CP} coverage using reasonable assumptions on systematic errors

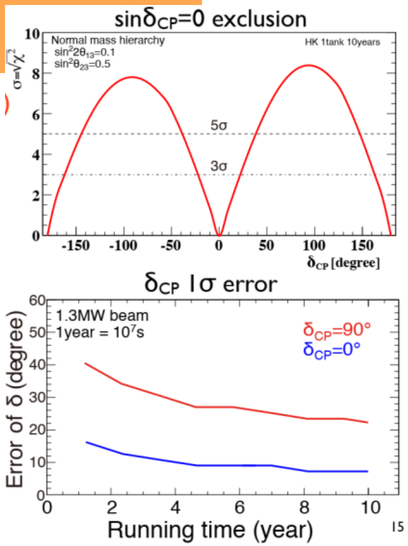
Comparison ESSνSB/T2HK/DUNE on equal footing

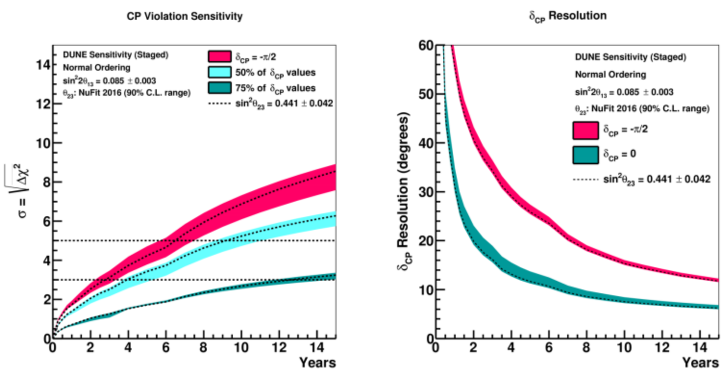
$\sin^2 2\theta = 0.1;\ \theta_{23} = \pi/2;$ 10 years of running

T2HK: Sensitivity curves shown yesterday and at Neutrino 2018.

DUNE: Public GloBES file released by the DUNE collaboration with the CDR, but 10 instead of 7 years running.

ESSnuSB: An overall 3% systematic error in the different channels (signal and background).

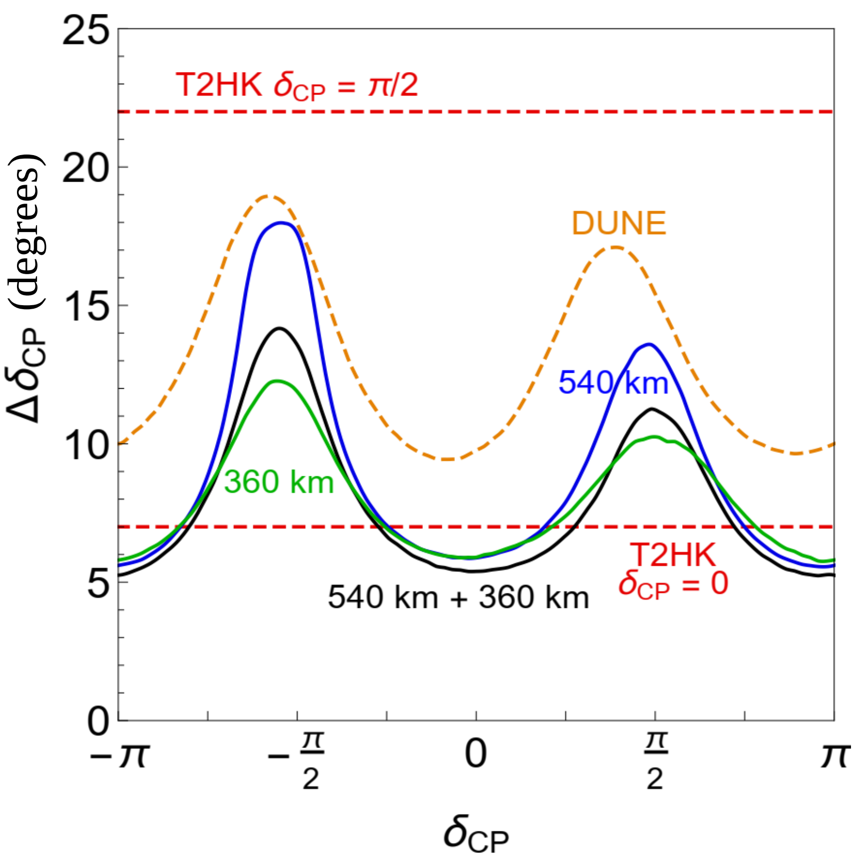


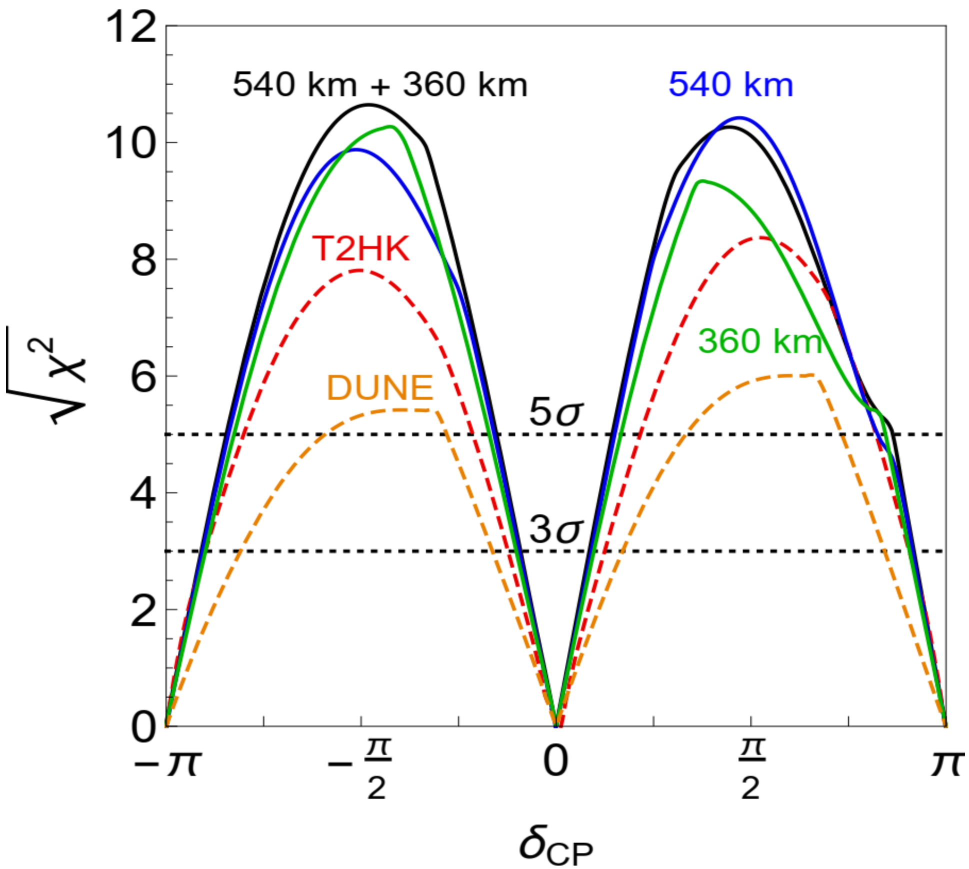


Enrique Fernandez Martinez
private communication

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.

ESSνSB schedule

ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESFRI

2012: inception of the project

2016-2019: beginning of COST Action EuroNuNet

2018: beginning of ESSνSB Design Study (EU-H2020)

2021: End of ESSνSB Design Study, CDR and preliminary costing

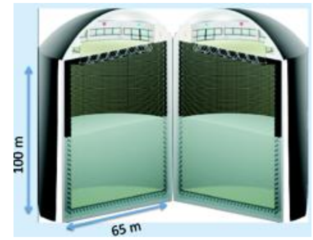
2022-2024: Preparatory Phase, TDR

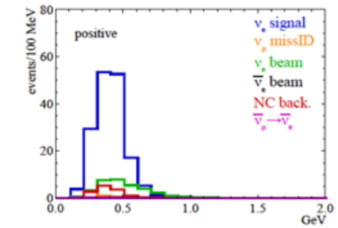
2025-2026: Preconstruction Phase, International Agreement

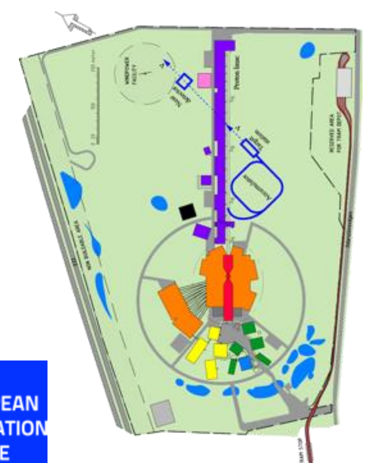
2027-2035: Construction of the facility and detectors, including commissioning

2036-: Data taking

Nucl. Phys. B 885 (2014) 127

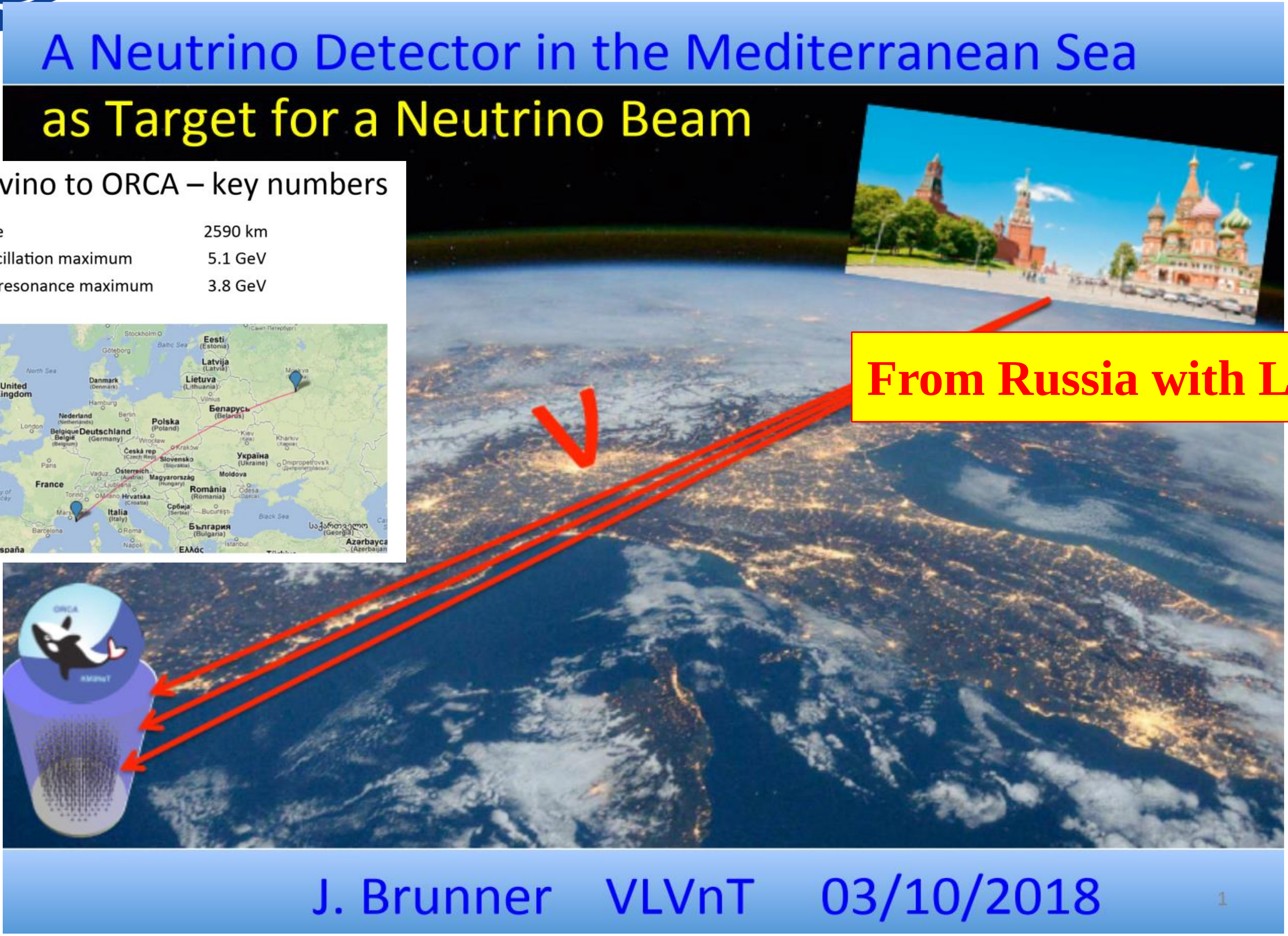






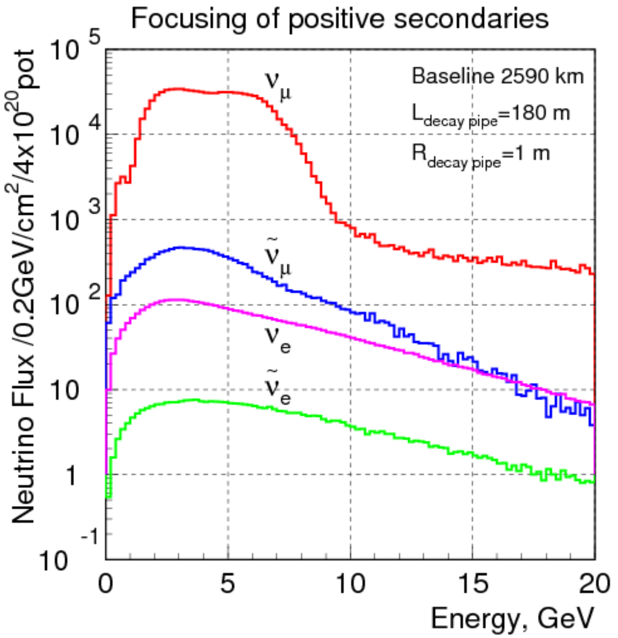
EUROPEAN SPALLATION SOURCE

The idea P20


A Neutrino Detector in the Mediterranean Sea
as Target for a Neutrino Beam
Protvino to ORCA – key numbers
• Baseline 2590 km
• First oscillation maximum 5.1 GeV
• Matter resonance maximum 3.8 GeV
From Russia with Love
ν
J. Brunner VLVnT 03/10/2018
1

Phased approach – Phase 1

- ORCA : 1 building block
- 115 detection units, performance as in LoI
- Accelerator : moderate intensity upgrade
- 15 kW → 90kW
- 2 10^{13} protons per pulse
- Repetition cycle 5 sec
- 8 months per year operation
- 8 10^{19} protons on target per year

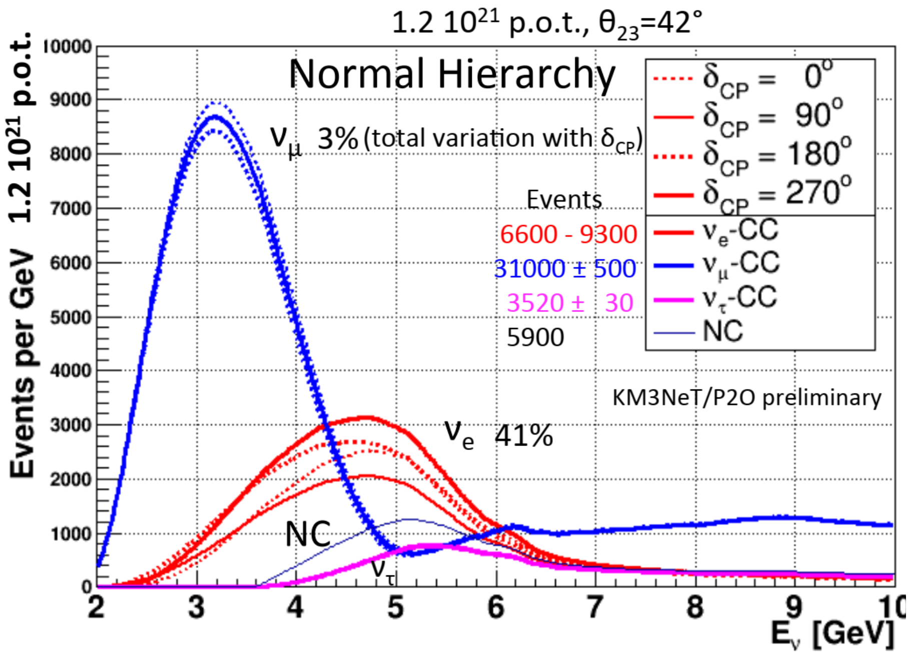


Higher Intensity

- Plots for 1.2 10^{21} proton on target
  - Either through intensity increase 90 kW → 450kW
  - Or through 5x longer run time
- 450 kW parameters
  - 10^{14} protons per pulse
  - Repetition cycle 5 sec
  - 8 months per year operation
  - 4 10^{20} protons on target per year

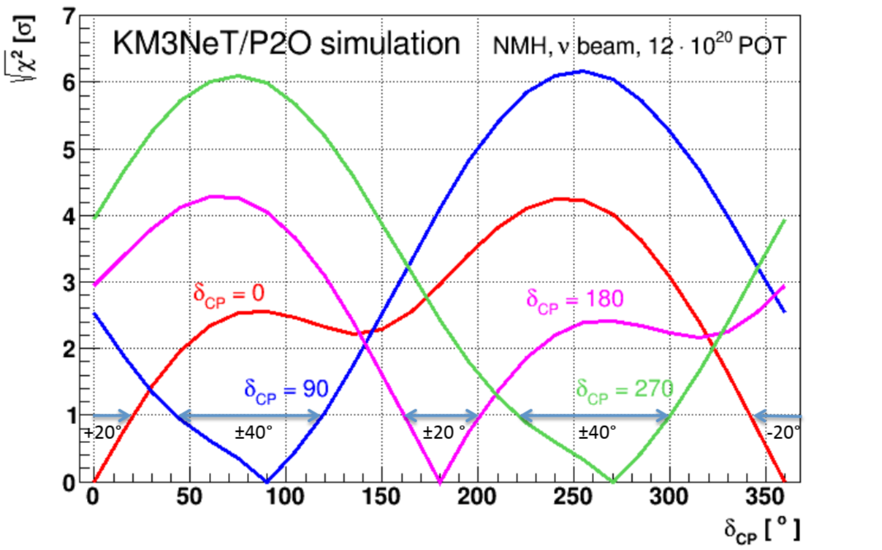
P20 idea

Event numbers – Neutrino Beam

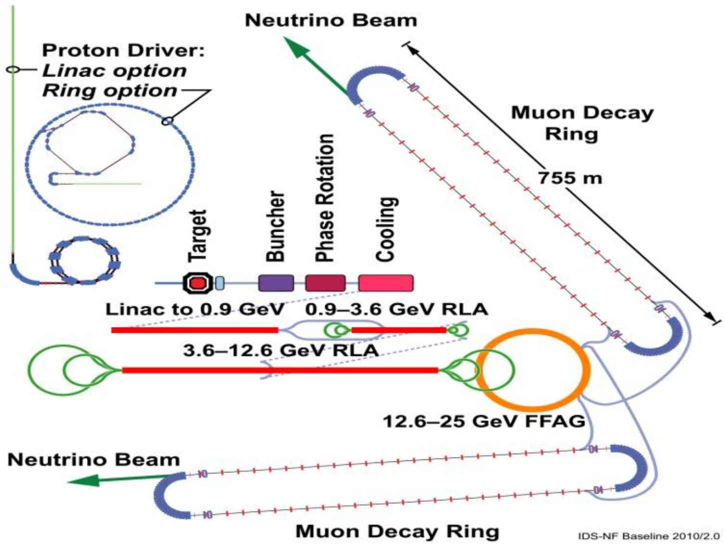


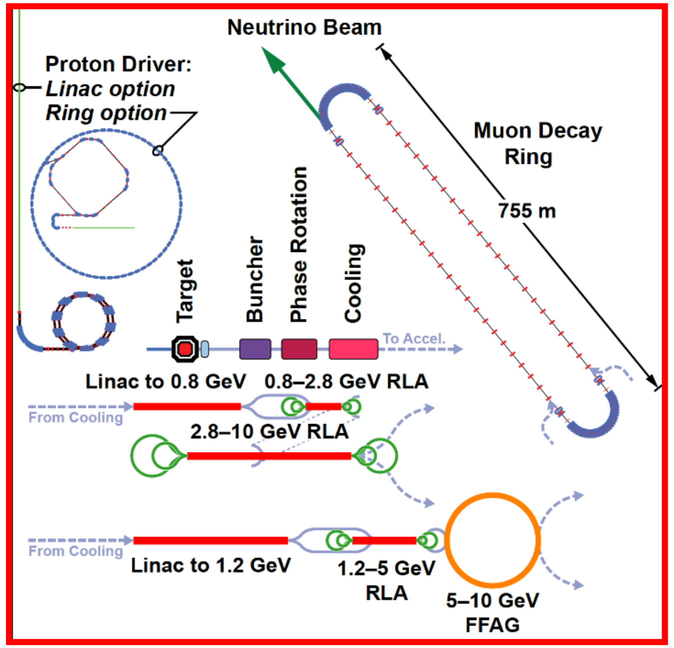
Measurement of to δ_{CP}

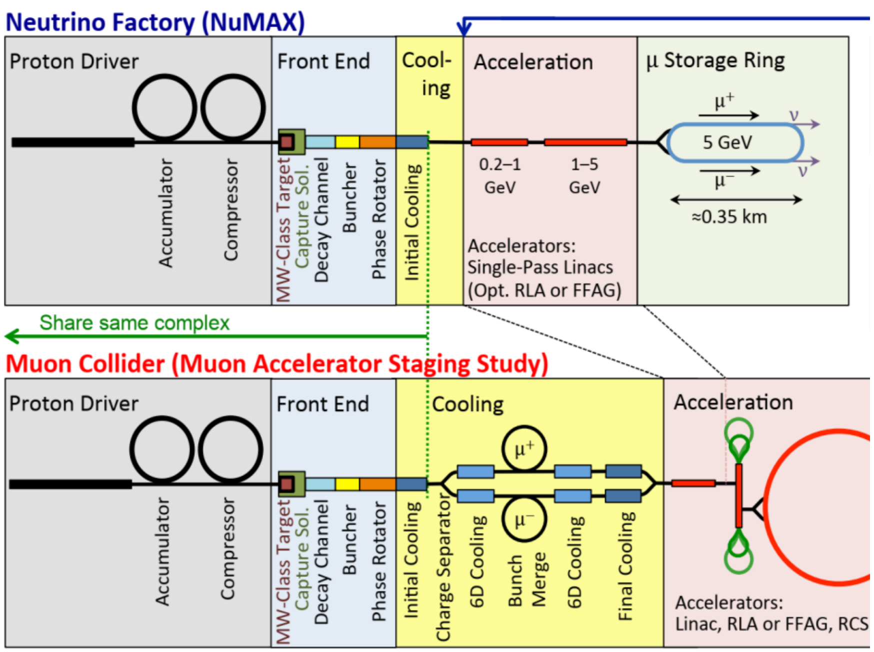
- Reachable precision : 20° (40°) after 3 years (~DUNE)

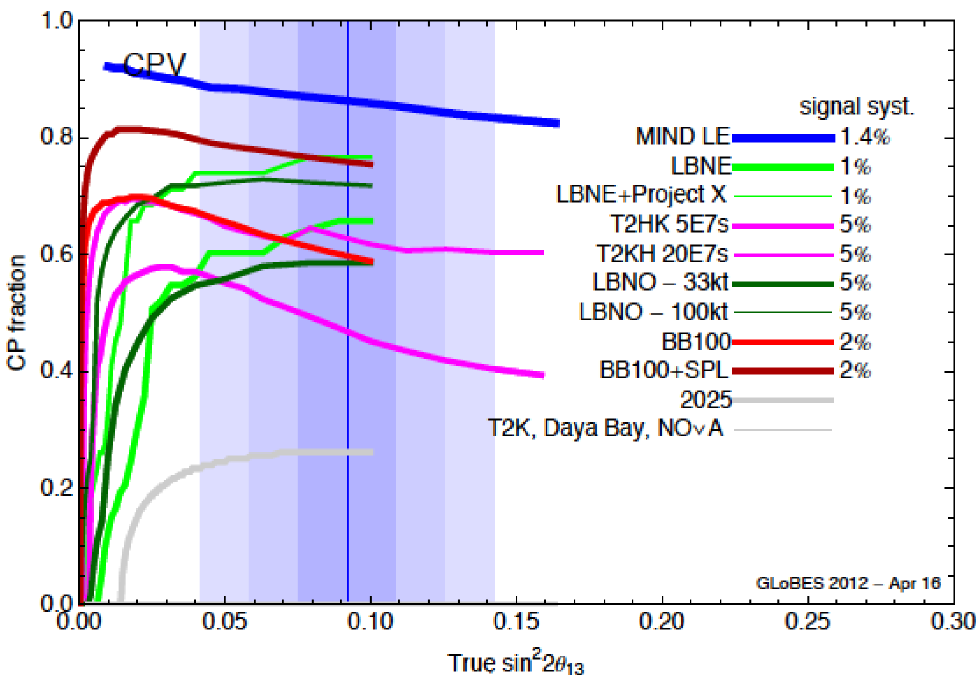


Neutrino factory



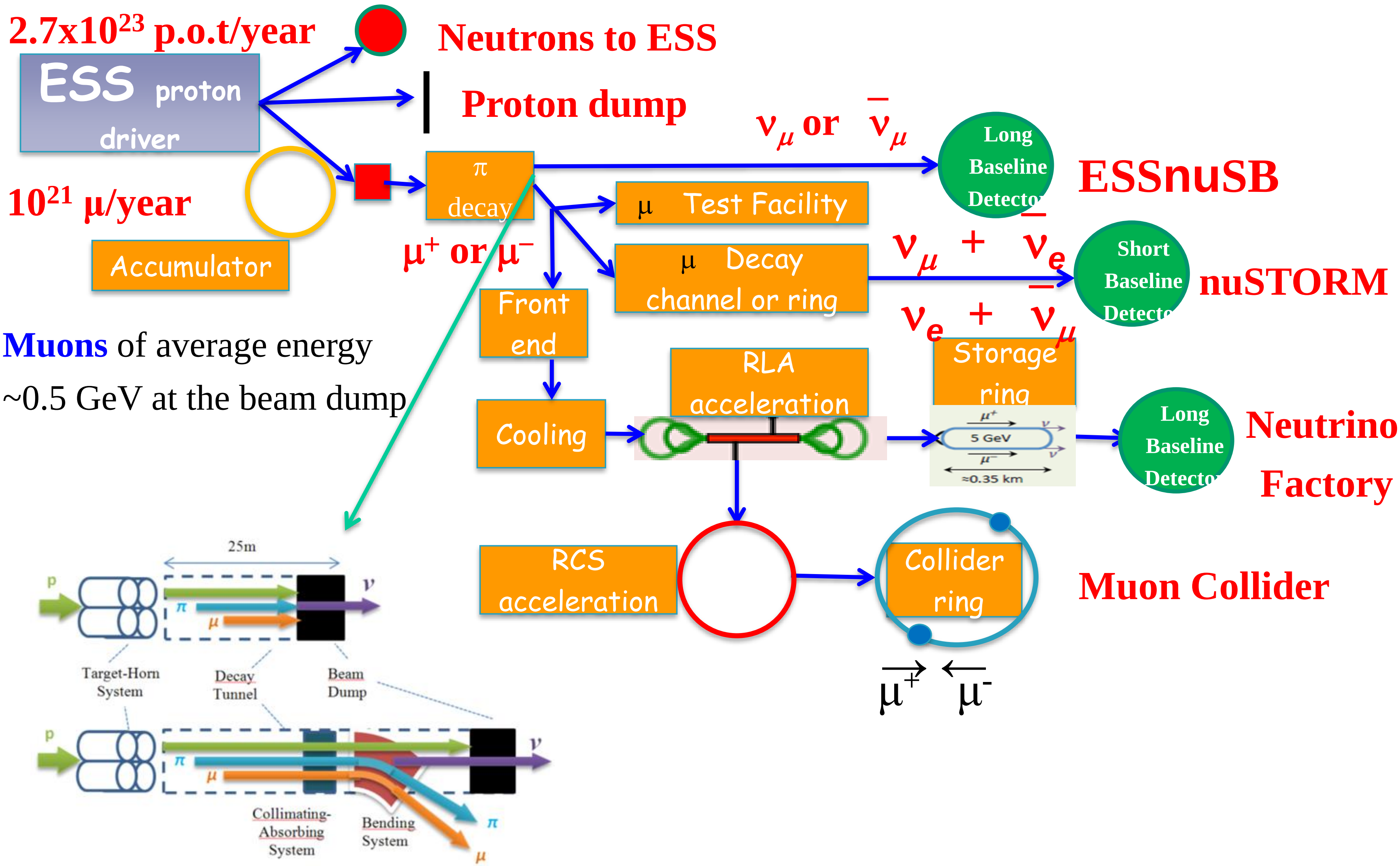






Roumen Tsenov

ESS neutrino and muon facility



In lieu of conclusion (a personal opinion)

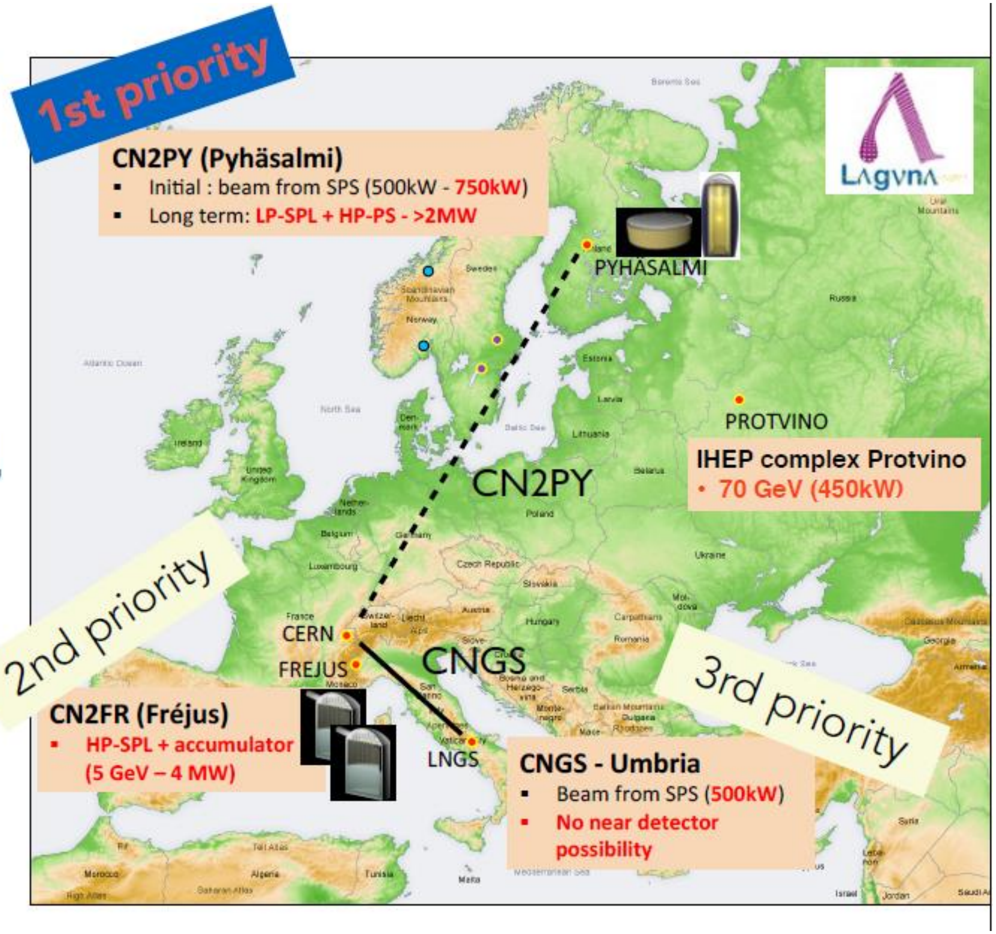
- T2HK (start of operation 2026) and DUNE (start of operation 2024-6), if successful, in 10 years of data taking will determine the **mass hierarchy** (+JUNO) and measure $\boldsymbol{\delta_{CP}}$ with O(10°) precision.
- For further precise measurements the **ESSνSB** project (start of data taking, if pursued, around 2035) is the only viable option **(that will bring *ν's* back in Europe!).**
- The ultimate neutrino facility is the Neutrino Factory and Muon collider (sharing common first stages).

The physics case for the Neutrino Factory + Muon Collider is much more clear and rich than those for ILC, FCC, CEPC, *etc*.

Back - up

LAGUNA Design Study

- **Pyhäsalmi mine** (privately owned), 4000 m.w.e overburden, excellent infrastructure for deep underground access
- **Fréjus**, nearby road tunnel, 4800 m.w.e. overburden, horizontal access
- **Umbria** (LNGS extension), green site with horizontal access, 2000 m.w.e., CNGS off-axis beam



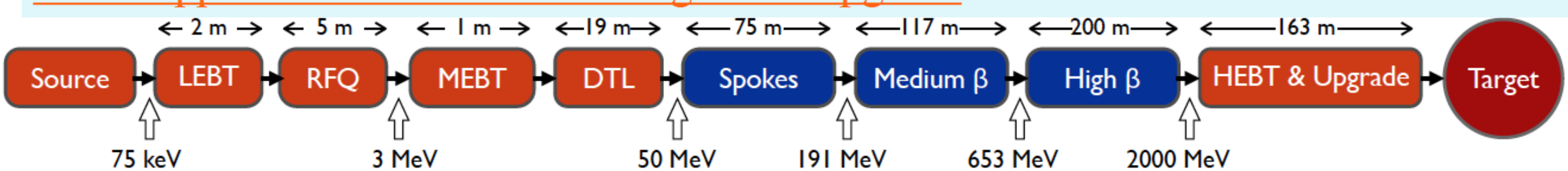
Required modifications of the ESS accelerator architecture for ESSνSB

F. Gerigk and E. Montesinos
CERN, Geneva, Switzerland

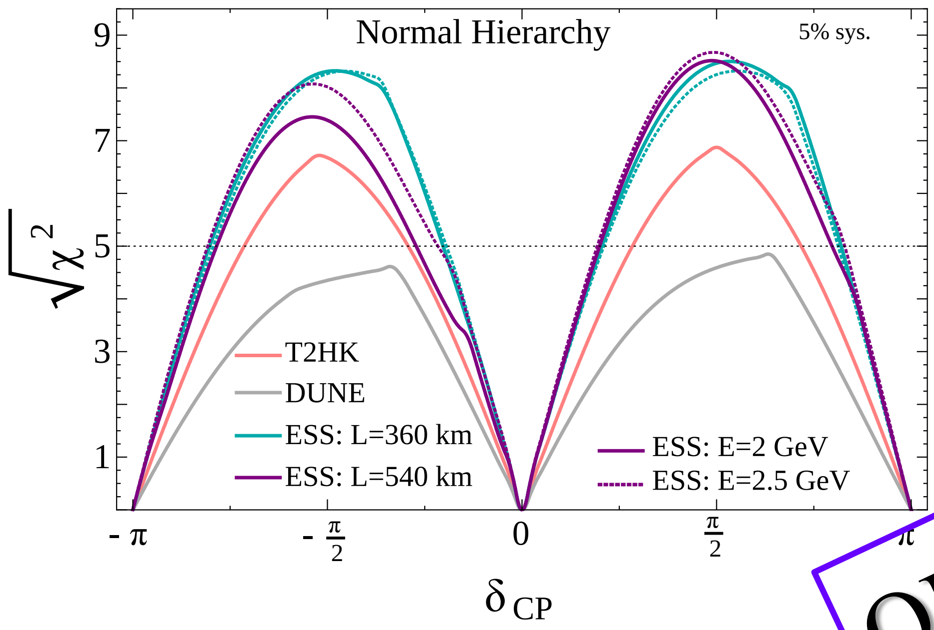
CERN-ACC-NOTE-2016-0050 8 July 2016

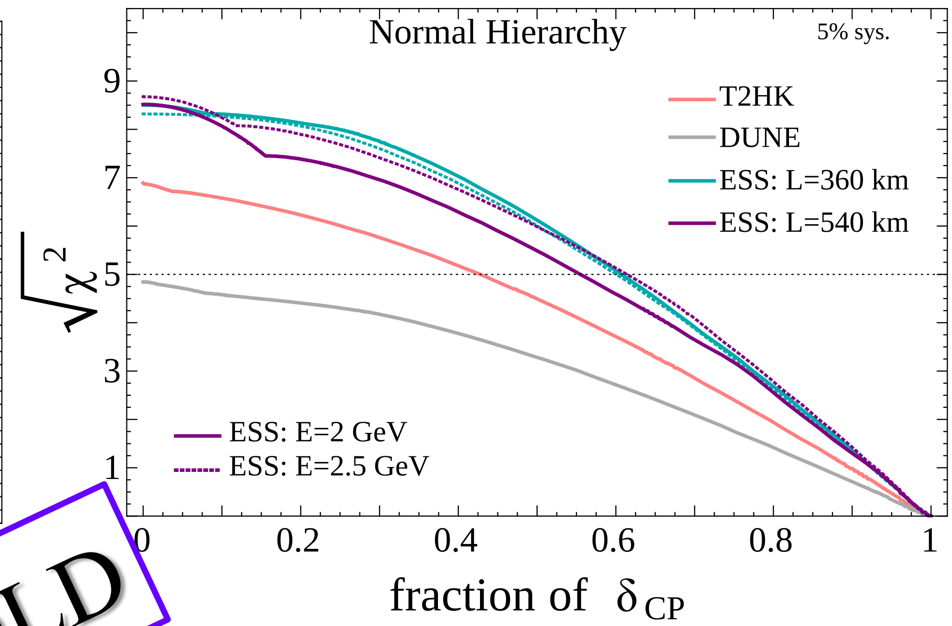
Contents

Quotation from "Executive Summary:
"No show stoppers have been identified for a possible future addition of the capability of a 5 MW H- beam to the 5 MW H+ beam of the ESS linac built as presently foreseen. Its additional cost is roughly estimated at 250 MEuros."



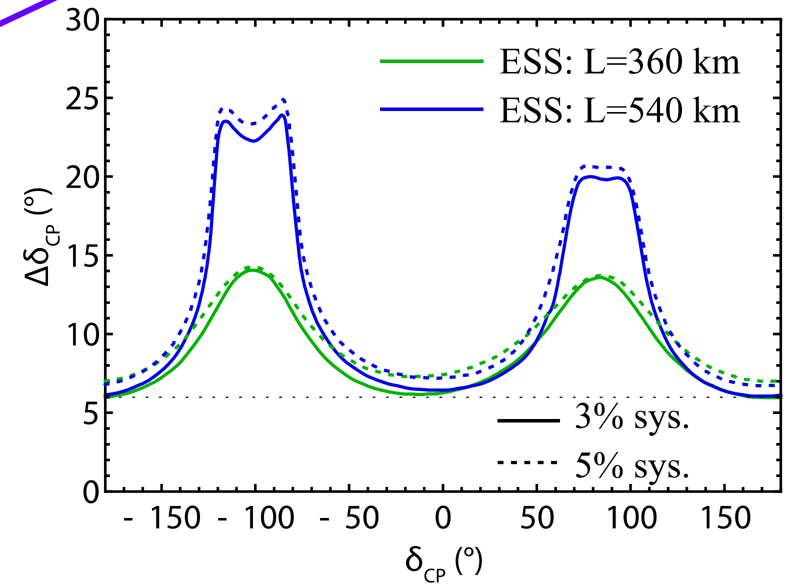
Physics Performance



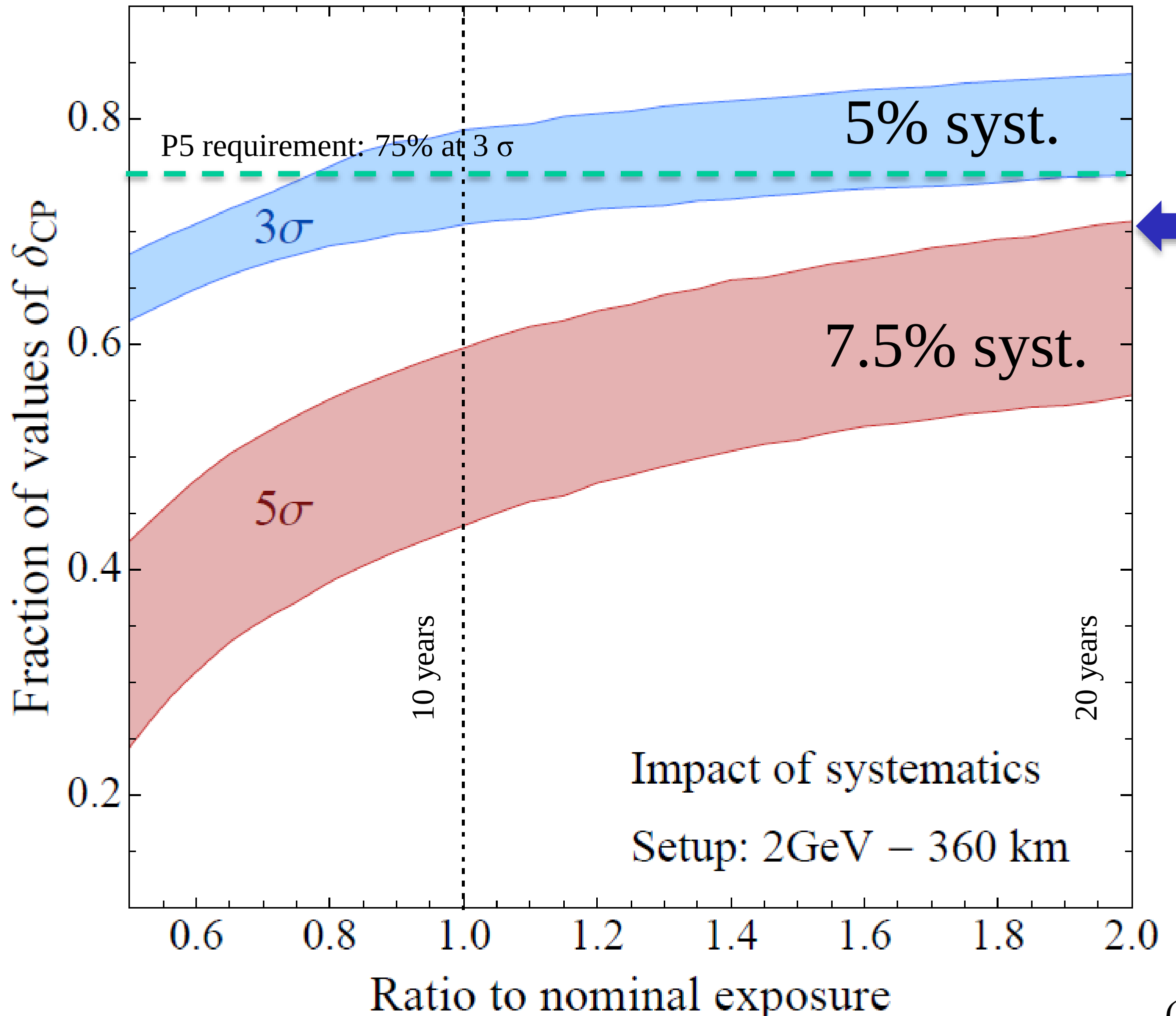


OLD

- little dependence on mass hierarchy (not so long baseline),
- 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.



Systematic errors and exposure



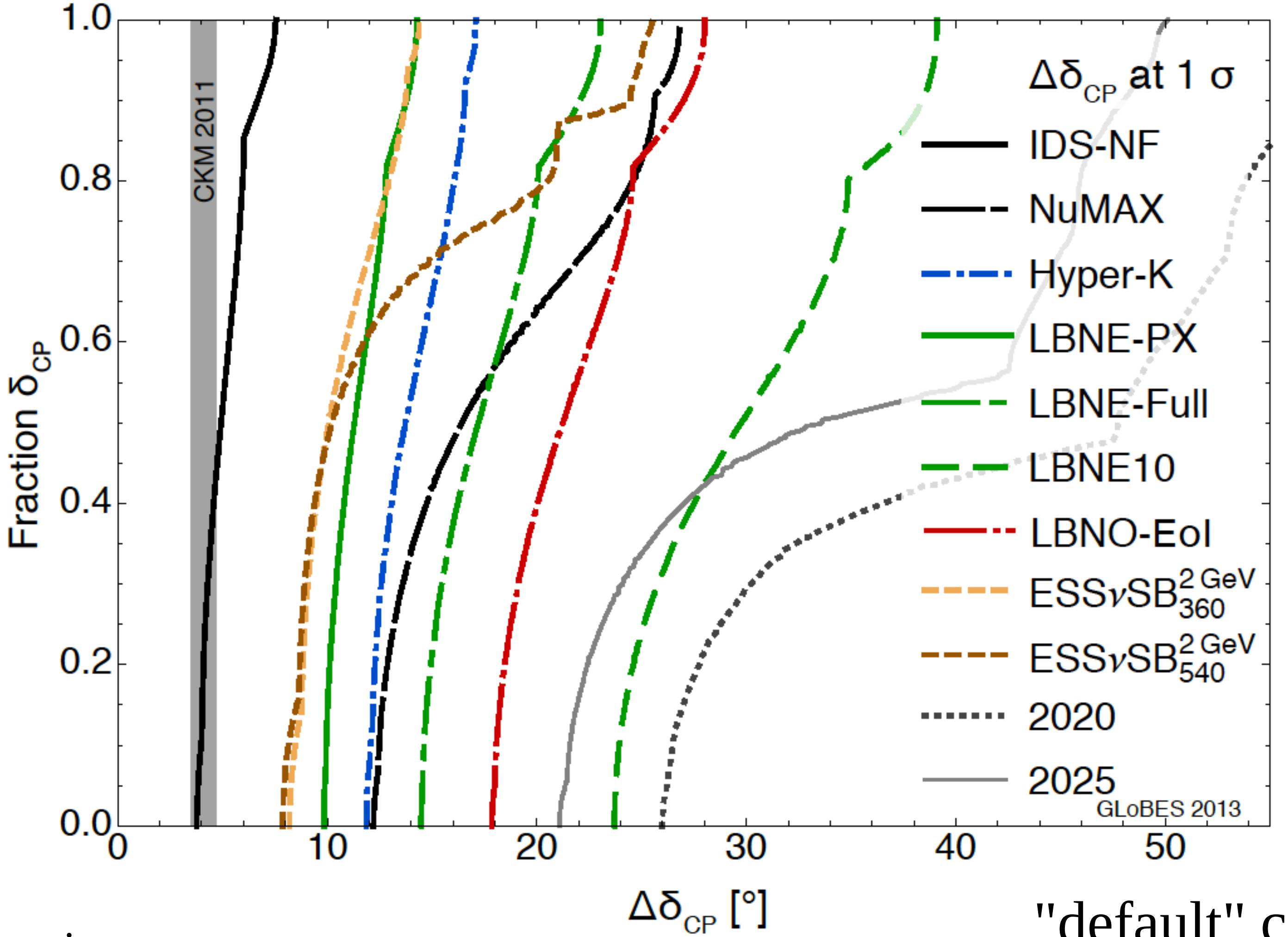
High potentiality

Lower band boundary - "default" case, upper boundary "optimistic" case.

(courtesy P. Coloma)

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)



for systematic errors see:

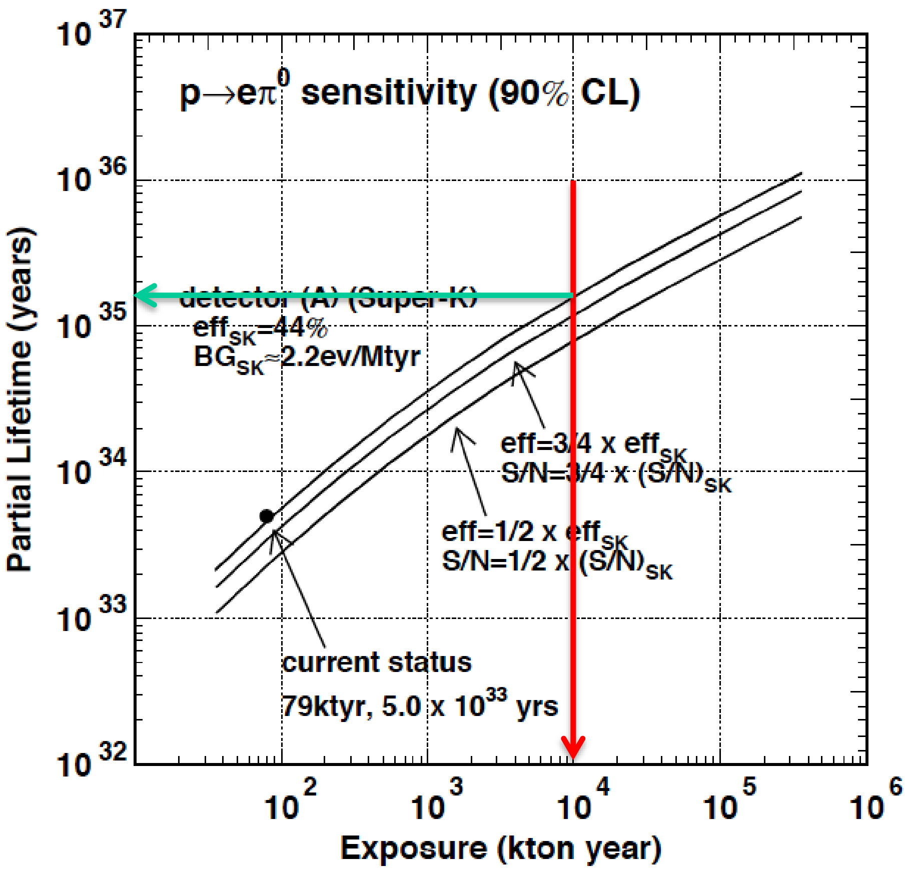
Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

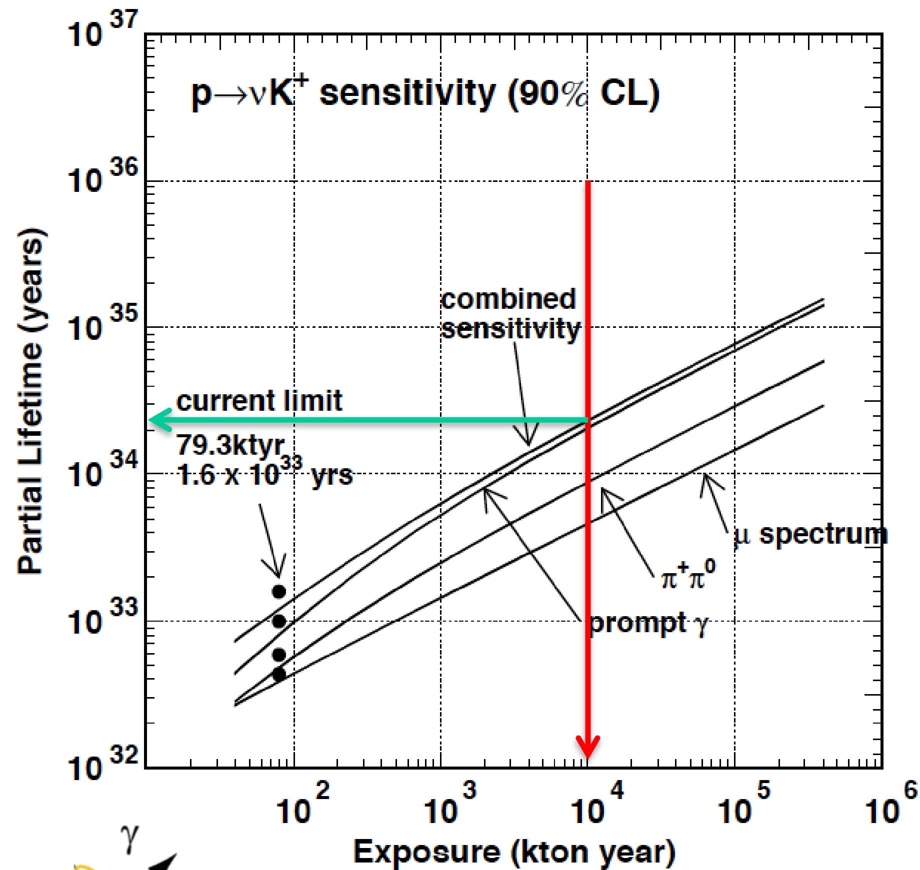
"default" column:

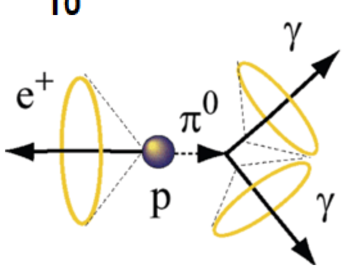
7.5%/15% for

ESSnuSB

The MEMPHYS Detector
(Proton decay)

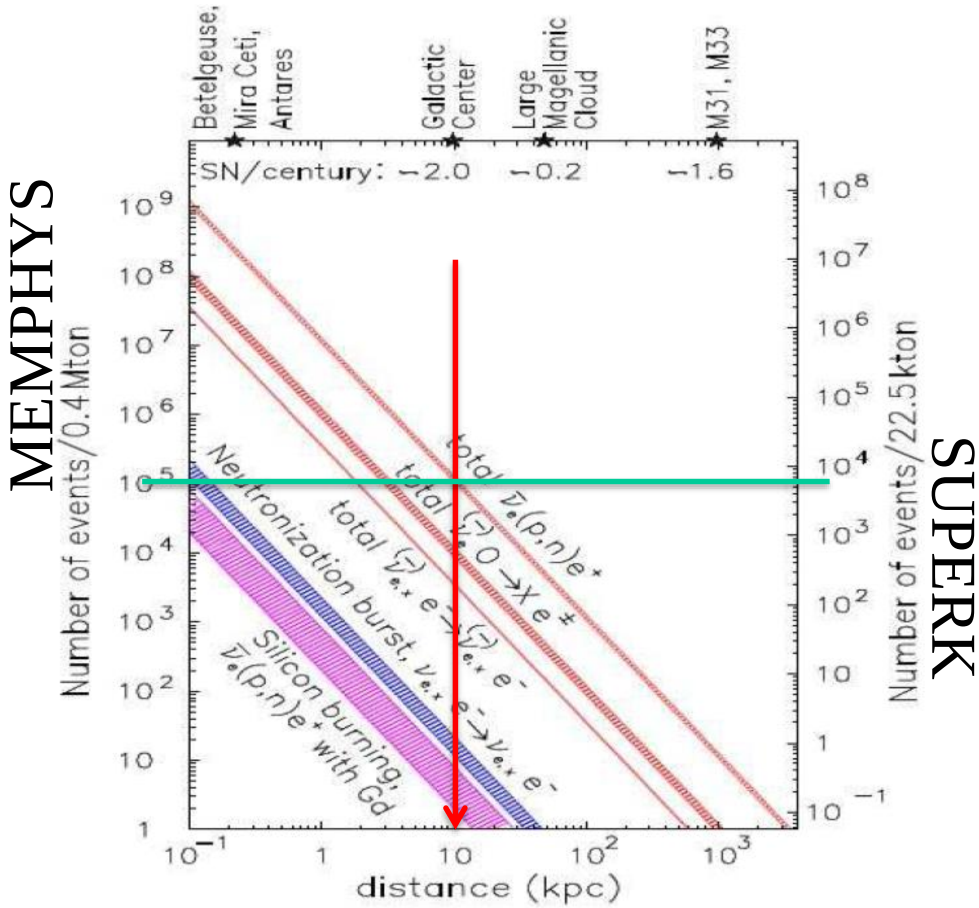


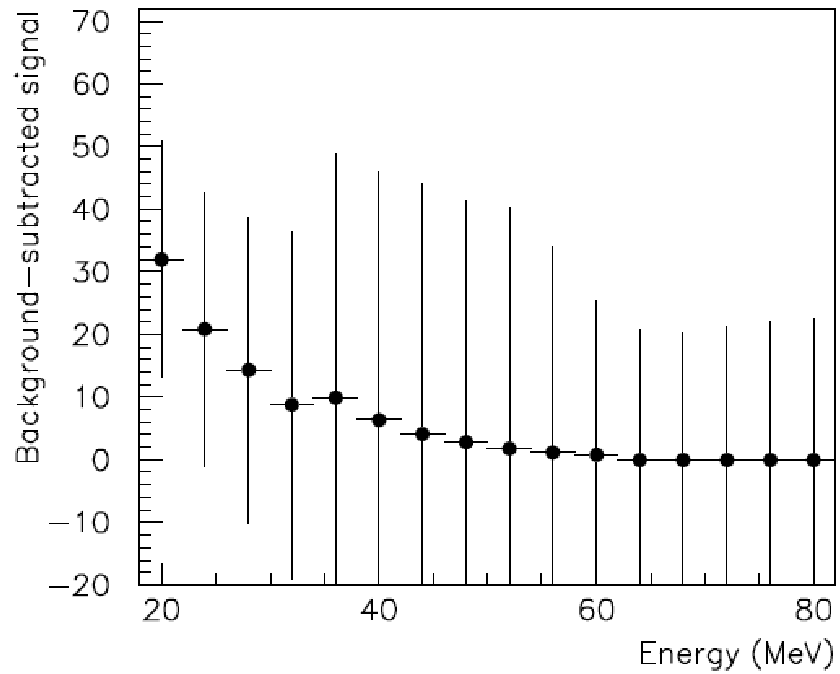




(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Supernova explosion)





For 10 kpc: ~10^5 events

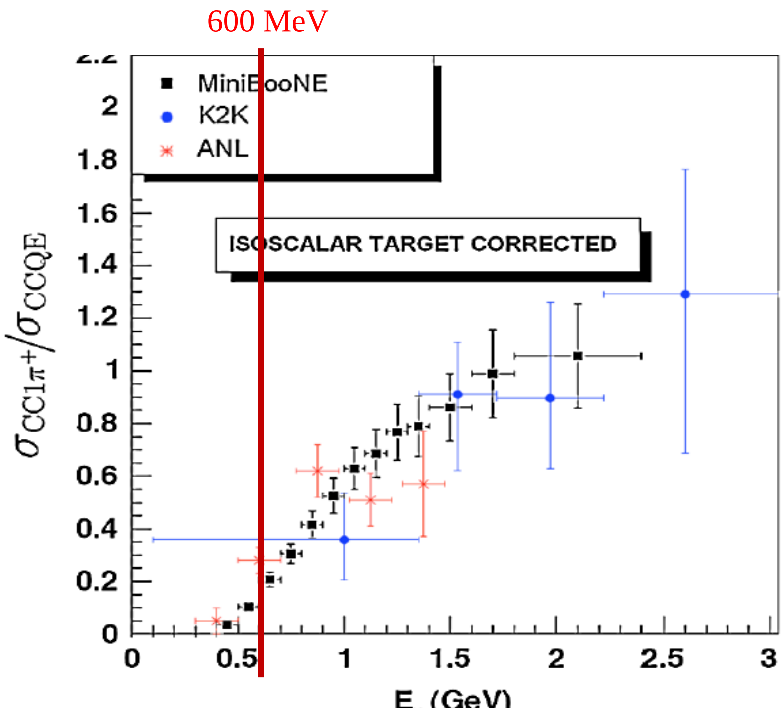
Diffuse Supernova Neutrinos
(10 years, 440 kt)

Near detector

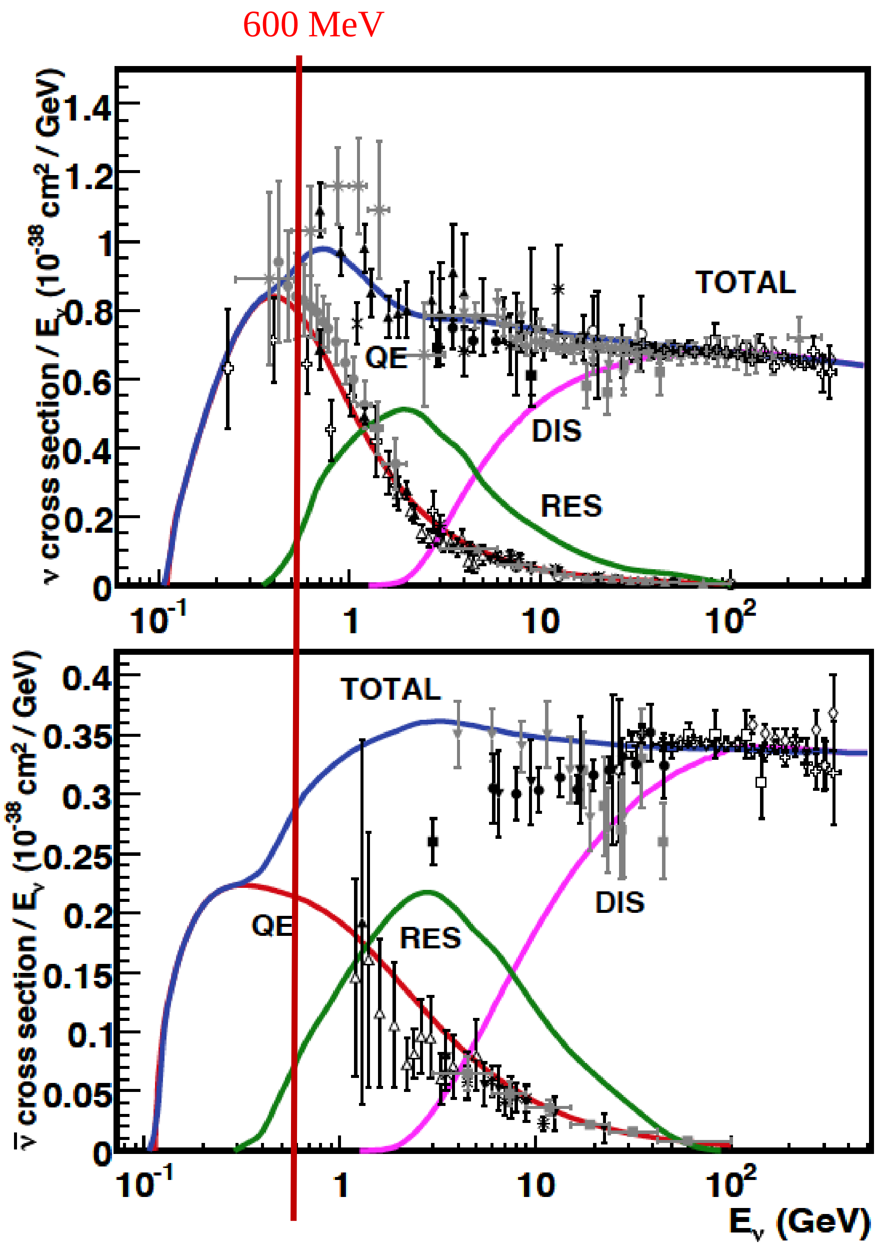
- Flux monitoring
- Event rates/cross-section measurements
- Low energy neutrino physics ?

ν cross sections in this energy range

- Poorly measured for muon neutrinos (BooNE, T2K, Minerνa, ArgoNeuT)
- **Not** measured for electron neutrinos



Single pion production



Detector requirements

They depend strongly on what we want:

- For flux monitoring and event rate/cross-section measurements one needs large statistics, i.e. large fiducial volume.
- For precise physics measurements a general purpose detector with good tracking/energy/PID capabilities is needed

A muon event in MEMPHYS

PhysRevSTAB.16.061001

Range of a 600 MeV muon in water is ~2.5 m. Water rad. length is ~38 cm. Thus, we will contain almost all muon and electron events in a detector with dimensions $\Phi 8 \times 20 m^3$.

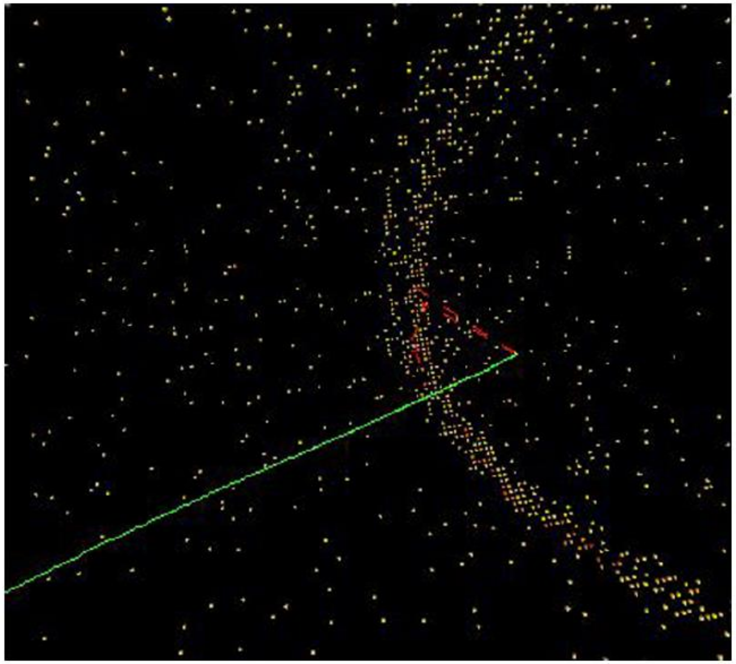


FIG. 4. Pattern of hit PMTs after the interaction of a 500 MeV muon with the full MEMPHYS simulation. The green line is the muon track, the red dashed lines are gammas from muon capture, each white dot represents one hit PMT.

Event rates

at 100 m from the source

	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 and per year (10^7 s)

'On back of the envelope' estimation:

Beam divergence (from kinematics) ~40 mrad.

Beam spot at **100 m** ~50 m^2 . At this distance the numbers in table would correspond to a flux per **mm^2** if the illumination is uniform.

Thus, at ~100 m from the source one would have had

~5x10^7 ν_e crossed a surface of ~50 m^2 per year.

Event rate for **ν_e** CC interactions in **1 kt** water Cherenkov detector per year:

$(1.9 \times 10^{10} \times 100) \times ((1/18) \times 6 \times 10^{23} \times 10^9) \times (2 \times 10^{-38}) \times (0.5_{eff})$

$\approx$ **6x10^5 events.**

Thus, the event rate is not a problem.

Fine grained tracker

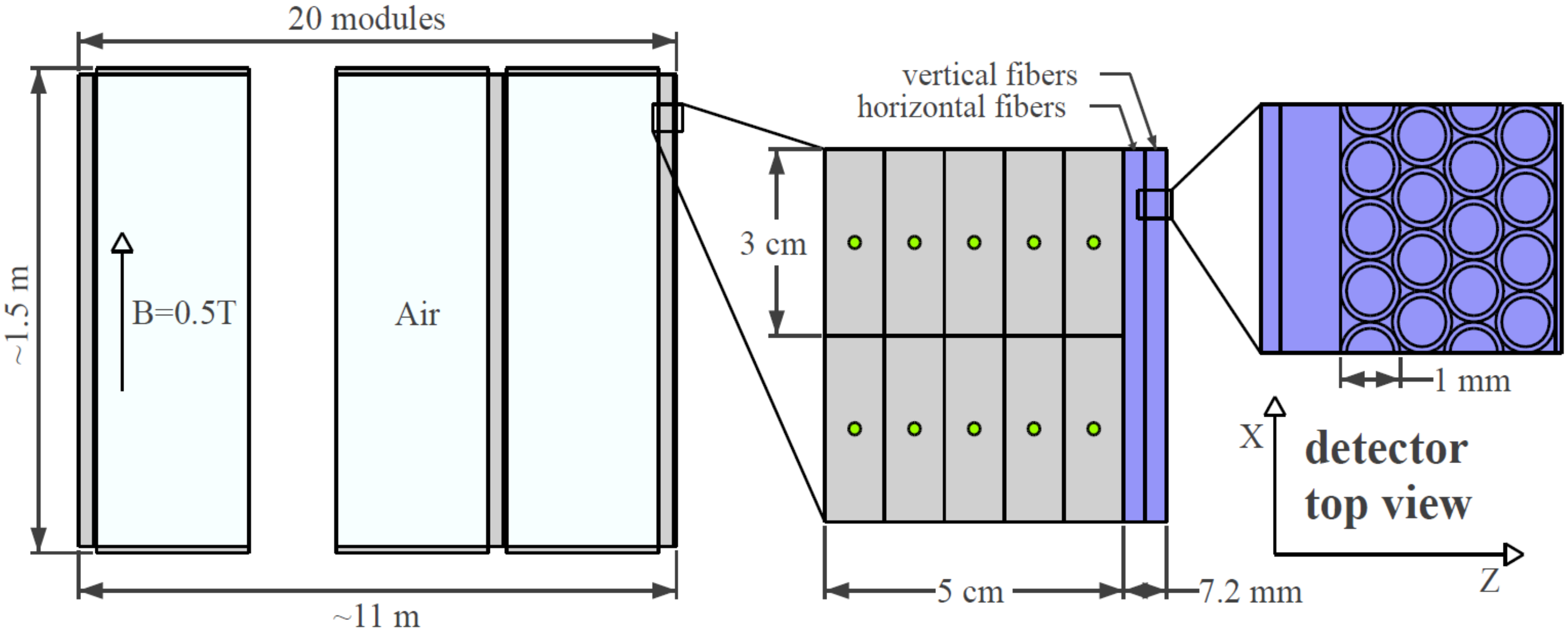
A fine grained tracker in magnetic field would be needed in front of the Water Cherenkov in order to measure precisely enough the neutrino cross sections.

Options (among many others):

- Scintillating fiber tracker (developed within the EUROnu project)
- Super fine cubic tracker being developed for the T2K ND280 upgrade

Scintillating fiber tracker for Neutrino Factory

FP7 EUROν Design Study (2008-2012)

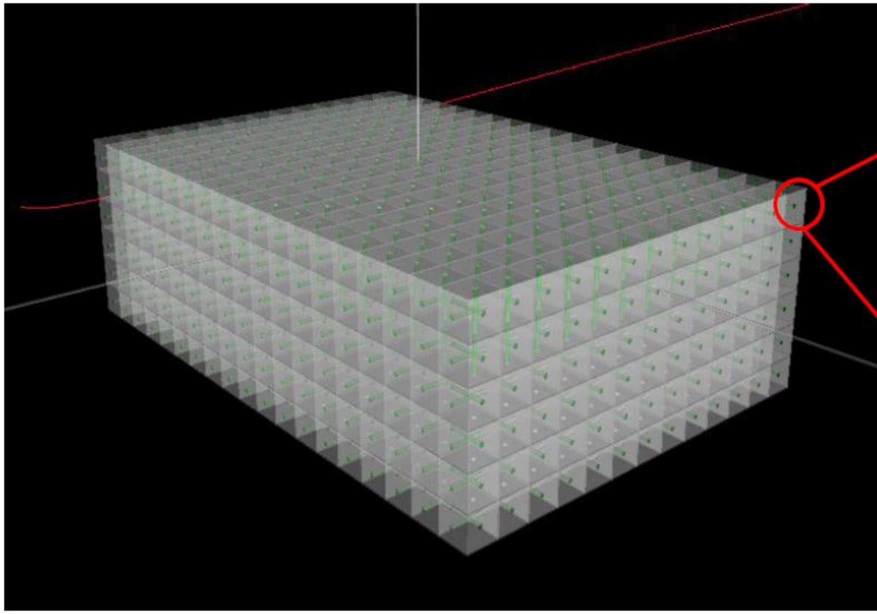


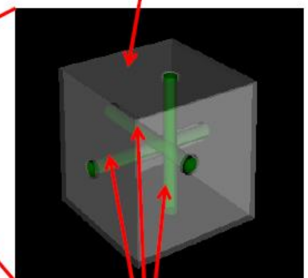
- 20 tracker stations, each consists of 4 X and 4 Y layers of 1 mm diameter scintillating fibres shifted with respect to each other; 12 000 fibres per station (240k in total);
- 5 cm thick active absorber (target), divided into 5 slabs to allow for more precise measurement of recoil energy near the event vertex;
- Air gaps are closed by a layer of scintillating bars;
- Overall detector dimensions: 1.5 x 1.5 x 11 m^3 (2.7 tons);

SuperFGD

arXiv:1707.01785

D. Sgalaberna, A. Blondel, F. Cadoux, S. Fedotov, A. Korzenev, Y. Kudenko, A. Longhin, O. Mineev, E. Noah, N. Yershov, *University of Geneva, INR RAS, NFN Padova, MIPhT,, MEPhI*





Cubes: 10x10x10 mm³
Material: extruded polystyrene + p-terphenyl
White chemical reflector: thickness ~ 50 mkm
3 holes: each of 1.5 mm diameter
WLS fibers: Kuraray Y11,

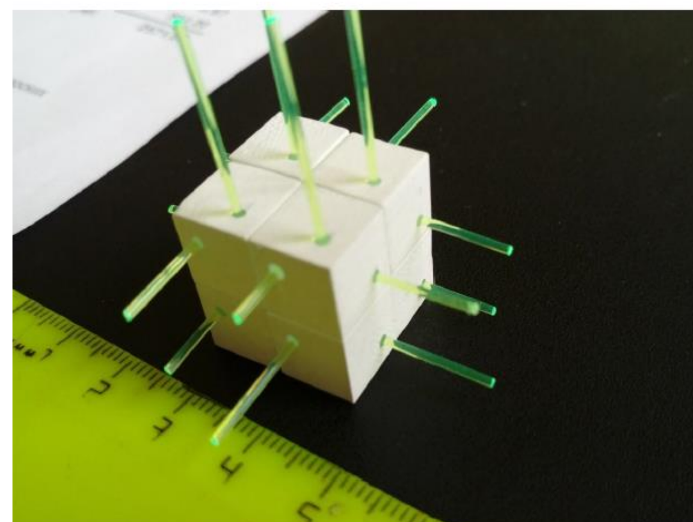
Yuri Kudenko

5th Workshop on Near Neutrino Detectors based on gas TPC
Tokai, Japan, 8 October 2017

Main parameters of the proposed detector of the size of $1.8 \times 0.6 \times 2.0$ m^3.

Parameter	Cube edge: 1 cm	Cube edge: 2 cm
# of cubes	2.16M	270k
# of channels	58.8k	14.7k

T2K ND280 upgrade (2.2 t)



Produced by Uniplast, Vladimir

Thoughts

- A near detector with ~kton mass would help in:
  - monitoring the neutrino flux,
  - having better control over systematics in δ_{CP} by measurement of the $\nu_e N$ and anti-$\nu_e N$ cross sections in the respective energy range.
- For ~500 km baseline the detector would be practically at the surface and the background conditions would be heavy (cosmic ray muons, atmospheric neutrinos).
- Detailed MC study is needed for further evaluation of the near detector impact on the ESSνSB project:
  - What is the influence of flux knowledge on the δ_{CP} measurement (appearance experiment; do we need precise knowledge of the flux)?
  - What precision is needed in the (unmeasured so far) $\nu_e N$ and anti-$\nu_e N$ cross sections/event rates in water?
- Do we want to do a general study of neutrino interactions in this energy region? The physics is not very rich…