ESSNUSB AND THE PRECISE MEASUREMENT OF LEPTONIC CP VIOLATION AT THE SECOND NEUTRINO OSCILLATION MAXIMUM

ALESSIO GIARNETTI, ON BEHALF OF THE ESSNUSB+ PROJECT

ESS neutrino Super Beam plus

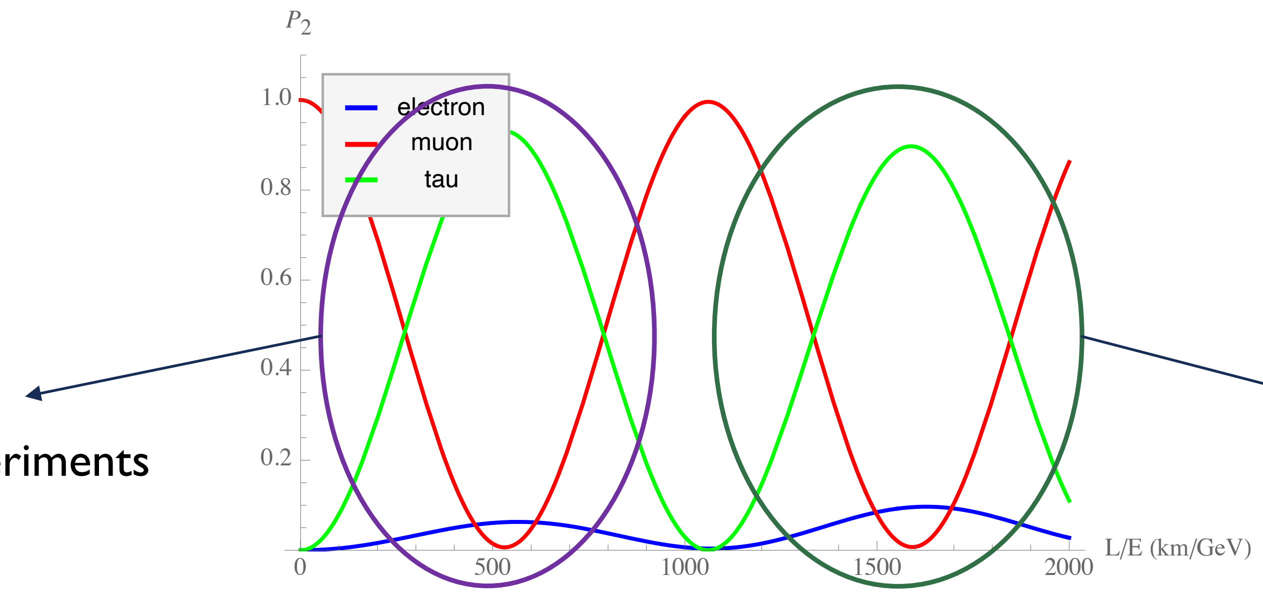
Co-funded by the European Union

FPCP, BANGKOK, 30/05/2024

ROMA TRE UNIVERSITÀ DEGLI STUDI

ESSNUSB: NEUTRINO OSCILLATION AT SECOND MAXIMUM

ESSnuSB is a design study for a next-to-next generation neutrino oscillation experiment which aims at the precise measurement of the CP violation in the leptonic sector looking at neutrino oscillation at the second atmospheric oscillation maximum.



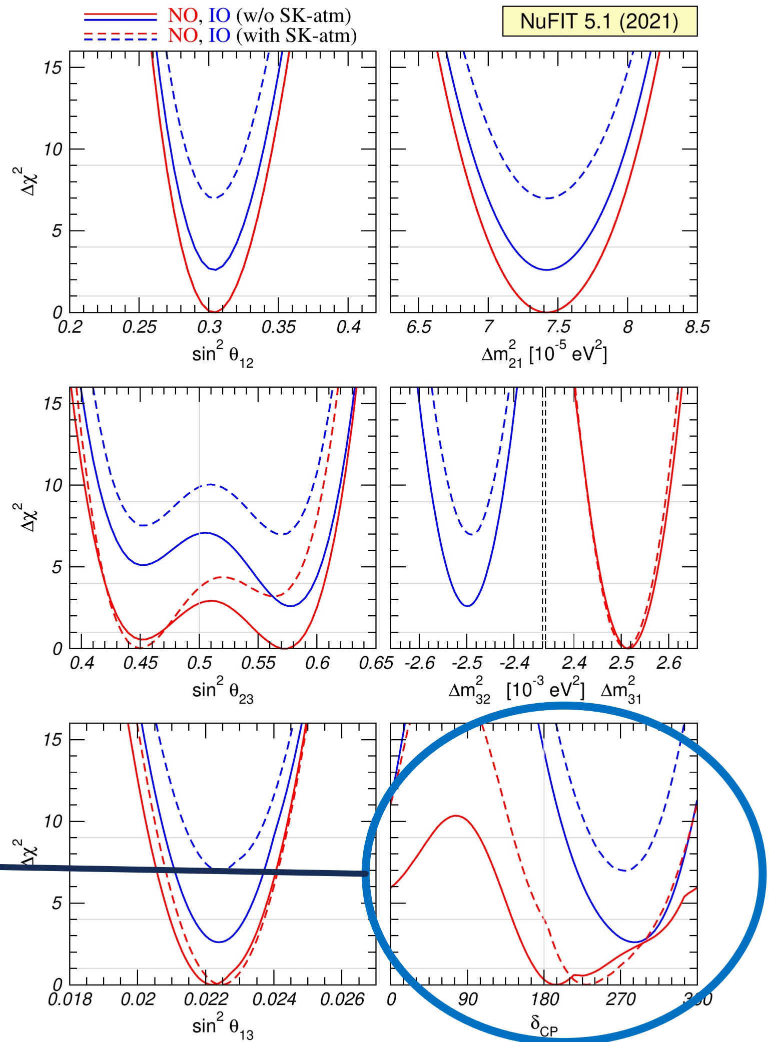
LBL experiments

ESSnuSB

OSCILLATION PHYSICS AT THE SECOND MAXIMUM

In the precision era for the oscillation parameters measurements, we still do not know the amount of CP violation in the leptonic sector.

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$



Most of the possible values for the mixing matrix phase are allowed by current measurements, especially in Normal Ordering

OSCILLATION PHYSICS AT THE SECOND MAXIMUM

How to measure the phase?

$\bar{J} \equiv cos\theta_{13}sin2\theta_{12}sin2\theta_{23}sin2\theta_{13}$

Electron neutrino appearance

$$P(\nu_\mu \to \nu_e) = \underbrace{sin^2\theta_{23}sin^2 2\theta_{13}sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)}_{\text{Atmospheric oscillations, leading term}} + \underbrace{cos^2\theta_{23}sin^2 2\theta_{12}sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)}_{\text{Solar subleading term}} + \underbrace{\bar{J}cos\left(\delta_{CP} - \frac{\Delta m^2_{31}L}{4E}\right)sin\left(\frac{\Delta m^2_{21}L}{4E}\right)sin\left(\frac{\Delta m^2_{31}L}{4E}\right)}_{\text{Interference term, depends on the phase!}}$$

Atmospheric oscillations, leading term

Solar subleading term

Interference term, depends on the phase!

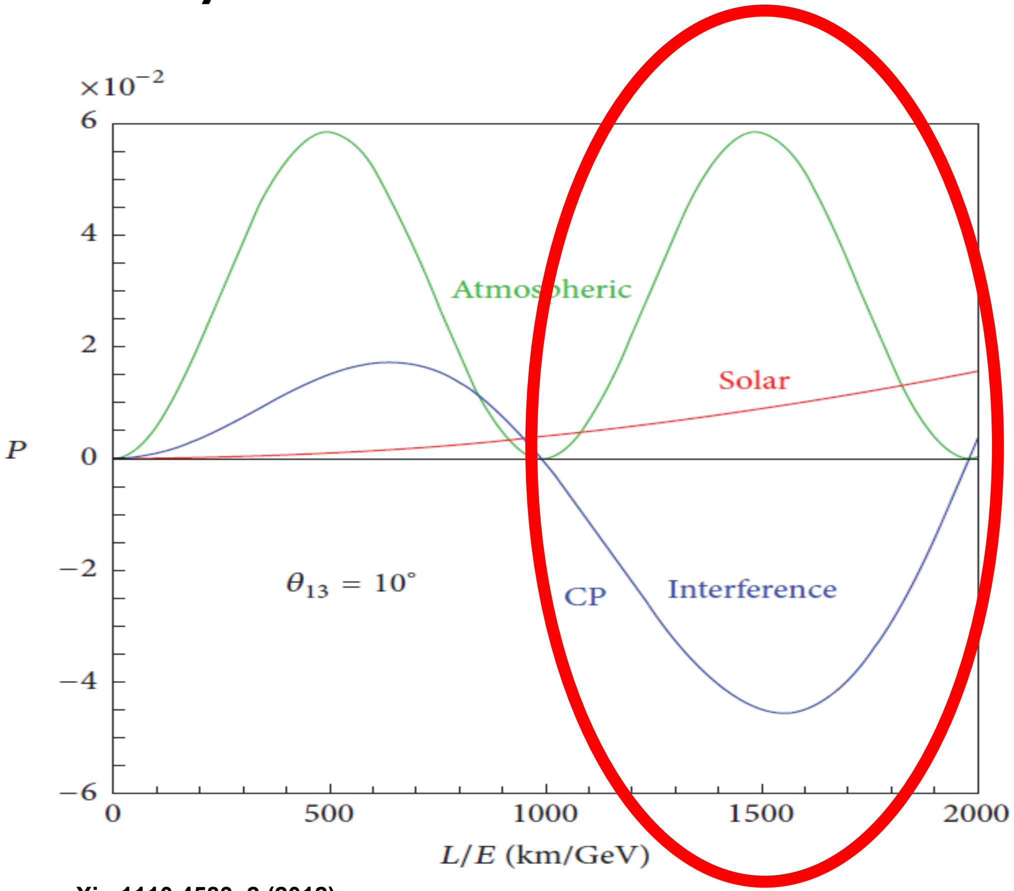
CP VIOLATION → $P_{\nu_\mu \to \nu_e} \neq P_{\overline{\nu}_\mu \to \overline{\nu}_e}$ $(\delta \to -\delta)$

We want to look at both electron neutrino and antineutrino appearance starting with two different fluxes:

Muon neutrinos and Muon antineutrinos

OSCILLATION PHYSICS AT THE SECOND MAXIMUM

Why 2nd maximum?



arXiv:1110.4583v2 (2012)

$$\mathcal{A}_{\mathrm{CP}}^{\alpha\to\beta} = P_{\nu_\alpha\to\nu_\beta} - P_{\bar{\nu}_\alpha\to\bar{\nu}_\beta}$$

At the second oscillation maximum the interference term is large!

$$\frac{\mathcal{A}_{\mathrm{CP}}^{\mu\to e}\left(x_{\max}^{(2)}\right)}{\mathcal{A}_{\mathrm{CP}}^{\mu\to e}\left(x_{\max}^{(1)}\right)} \approx 2.7$$

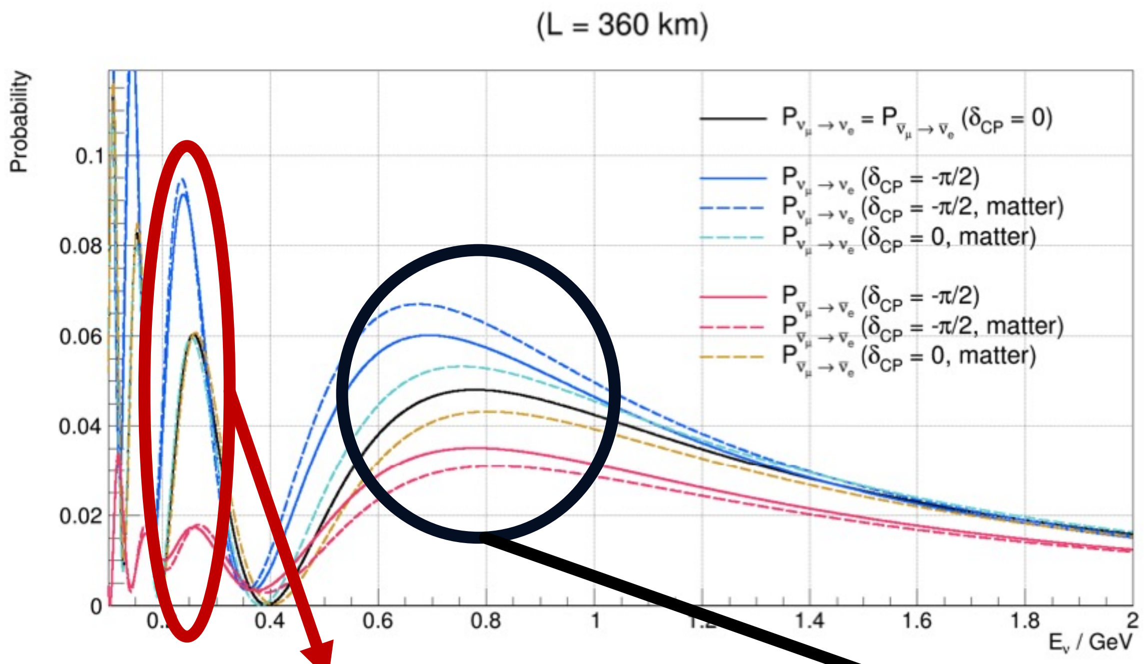
OSCILLATION PHYSICS AT THE SECOND MAXIMUM

What about matter effects?

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E_\nu}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A_{CC}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Change sign for antineutrinos,
like the CP-violating phase

FAKE CP VIOLATION

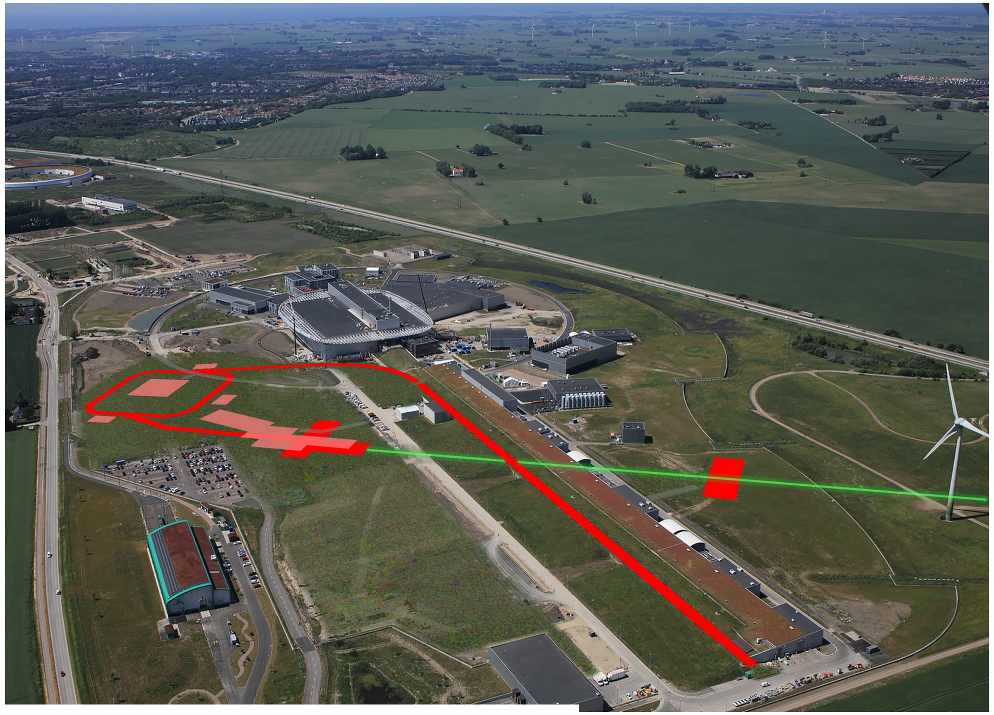


Second maximum, the matter effects are not important, pure phase determination

First maximum, matter and CP phase have the same effect

THE ESSNUSB PROJECT (2017-2022)

ESS PROTON ACCELERATOR



EUROPEAN SPALLATION SOURCE

First beam on target expected in 2026.

Under construction in Lund, Sweden

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

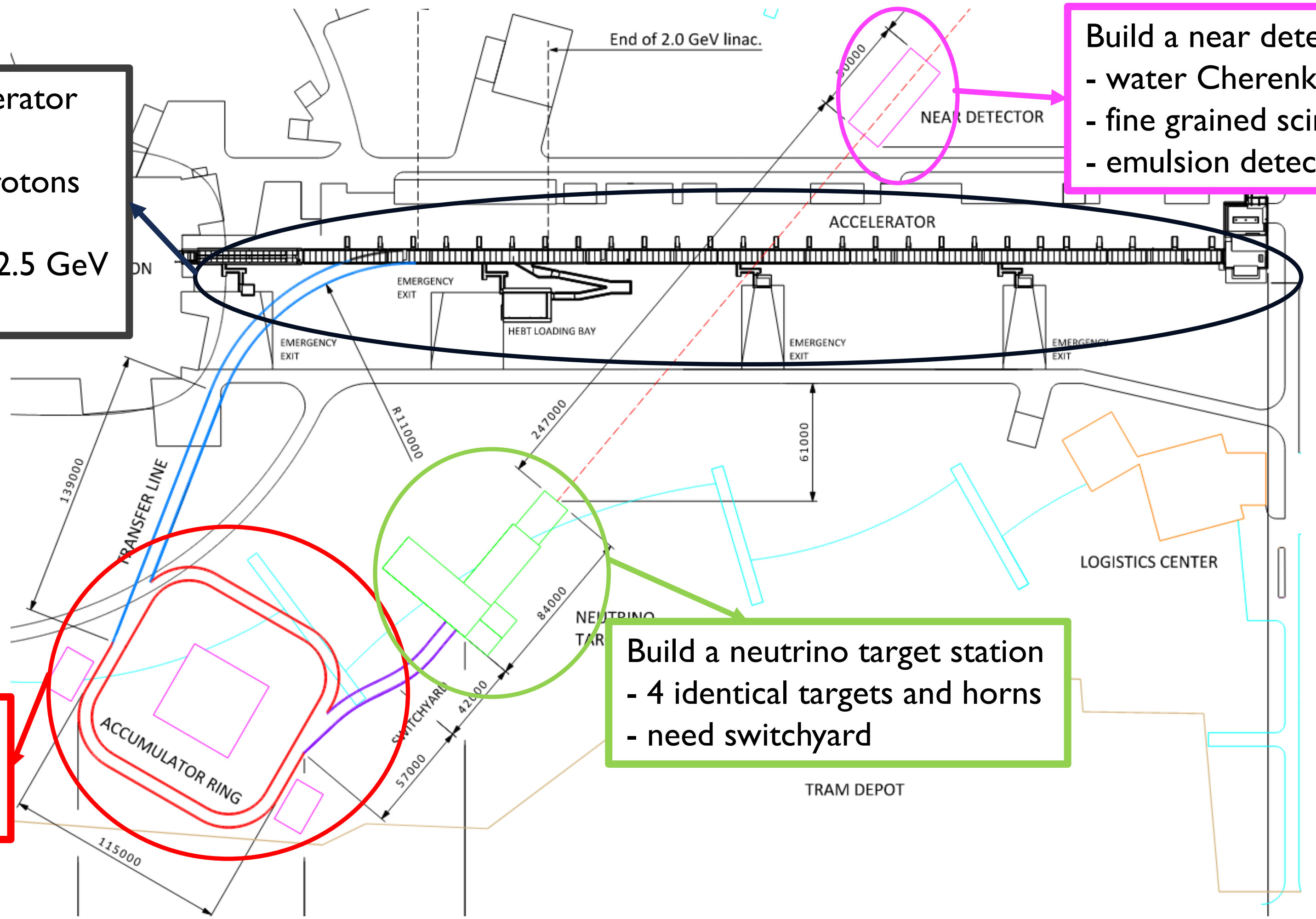
From such a powerful accelerator, we can produce an intense neutrino beam!

The European Spallation Source neutrino Super Beam (ESSνSB)

UPGRADE OF THE ESS SITE

Upgrade of the accelerator
- 14 Hz to 28 Hz
- use H^- instead of protons in ESSnuSB cycles
- increase energy to 2.5 GeV kinetic

Build a near detector site
- water Cherenkov detector
- fine grained scintillator
- emulsion detector



Build a neutrino target station
- 4 identical targets and horns
- need switchyard

Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 μs

NEUTRINO PRODUCTION: TARGET STATION

Hot Cell
- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

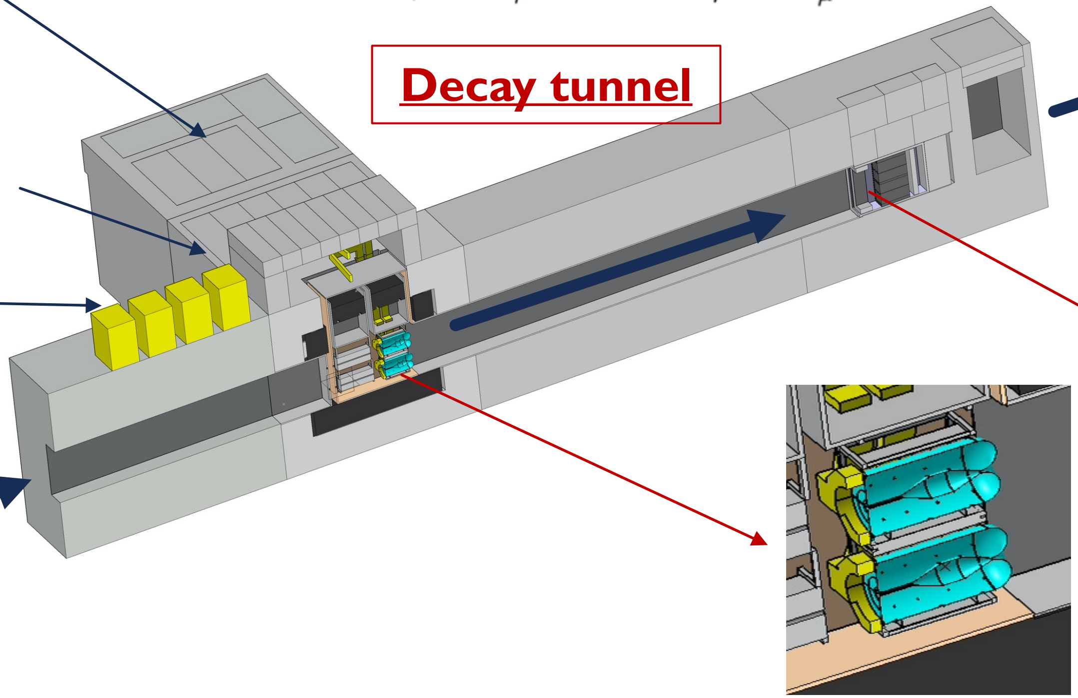
Power Supply Unit
- 16 modules (350 kA, 1.3 μs)
- Located above the switchyard
- Outside of radioactive part of Facility

Morgue
To Store radioactive wastes

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\qquad$ $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$

Decay tunnel

Neutrino beam

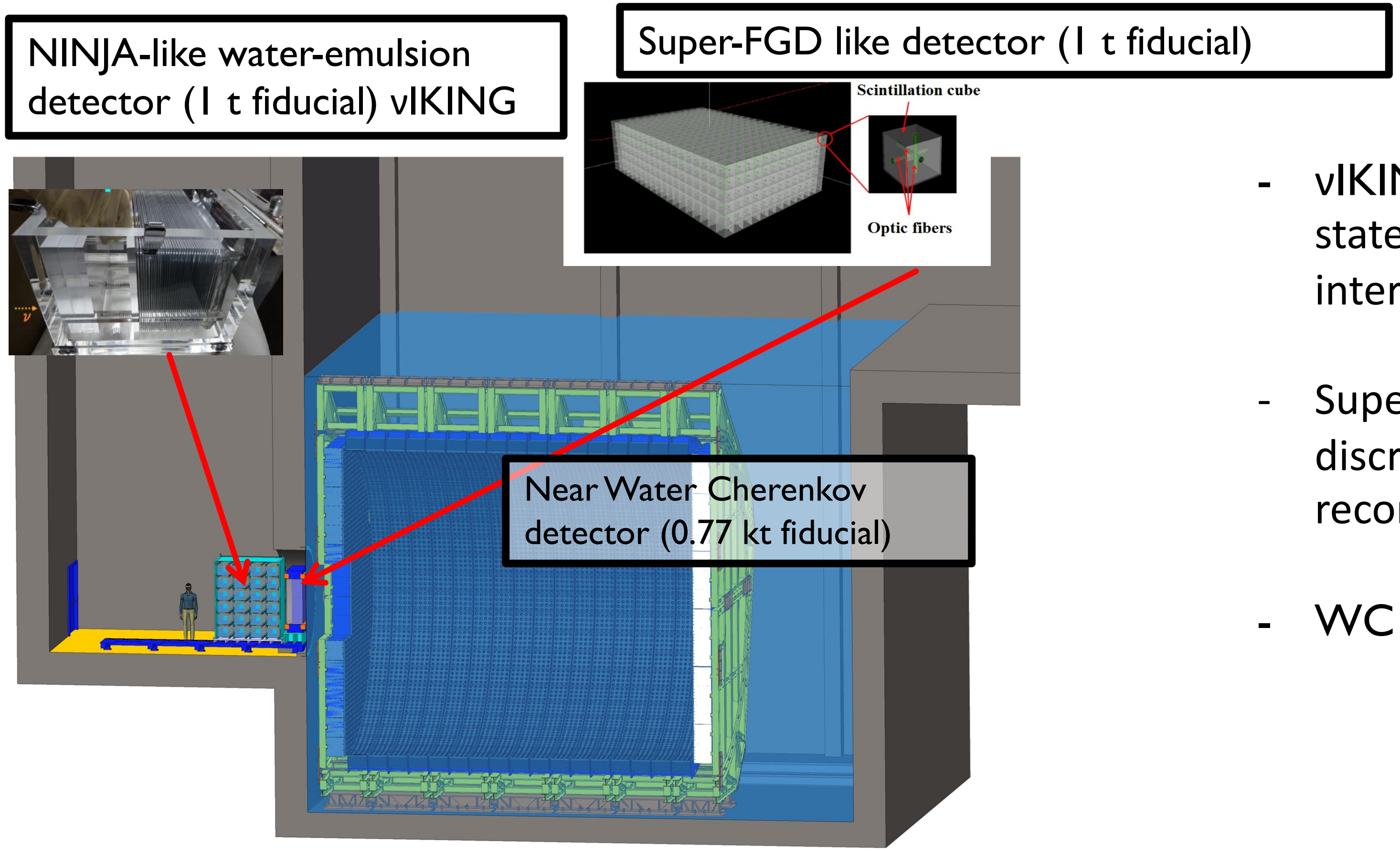


Proton Beam
(Ep=2.5 GeV, 14 Hz)
4 x 1.25 MW

Beam dump

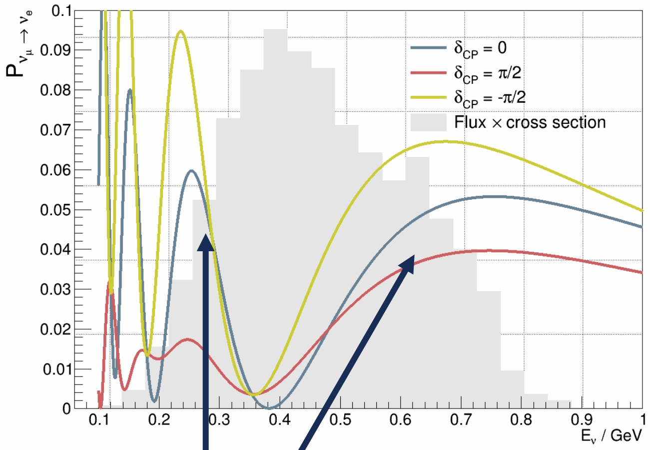
Hadronic Collector: Target + Horns

NEAR DETECTOR SITE

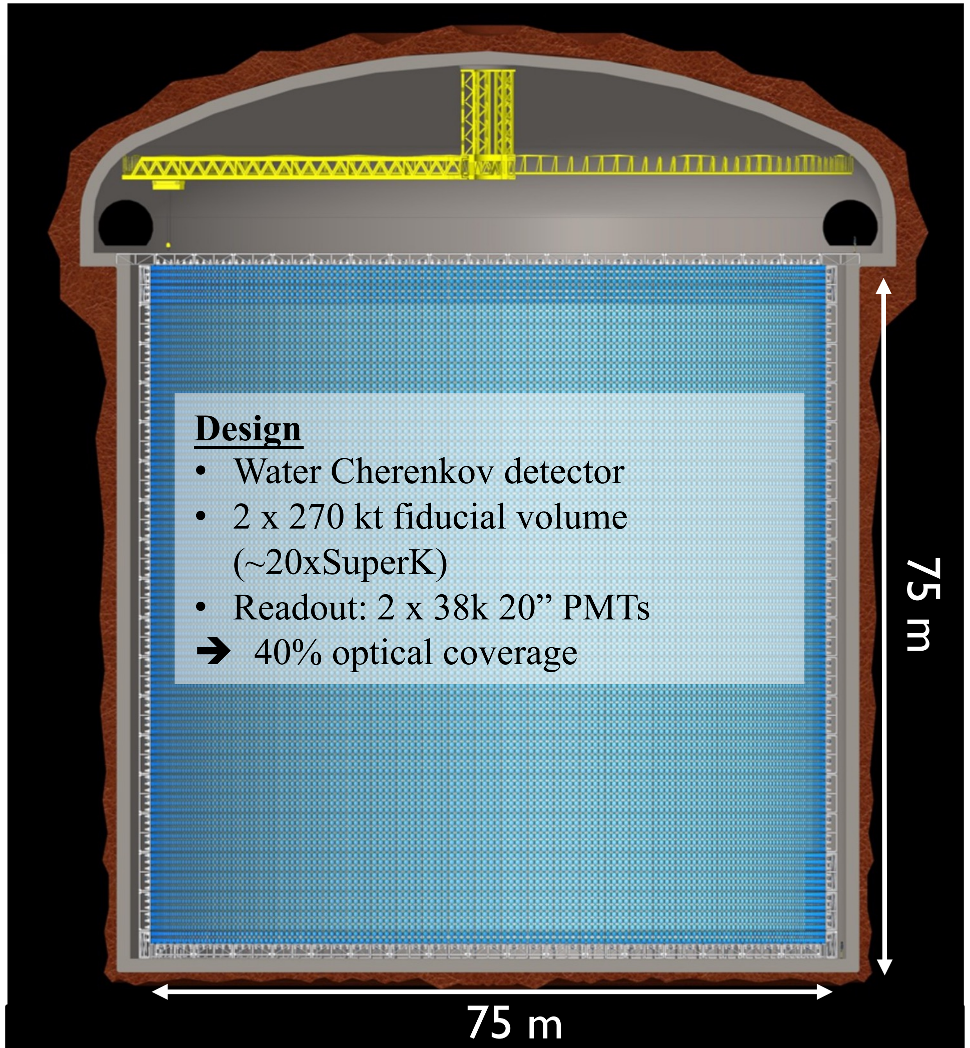


- νIKING: precise measurement of the final state topology of the neutrino–water interactions
- Super-FGD: magnetized, charge discrimination and neutrino energy reconstruction for the ND detectors
- WC detector: flux determination

THE FAR DETECTOR



First and second oscillation maxima covered at 365 km baseline!



Design

- Water Cherenkov detector
- 2 x 270 kt fiducial volume (~20xSuperK)
- Readout: 2 x 38k 20" PMTs

➔ 40% optical coverage

THE EVENT SPECTRA AT 360 KM

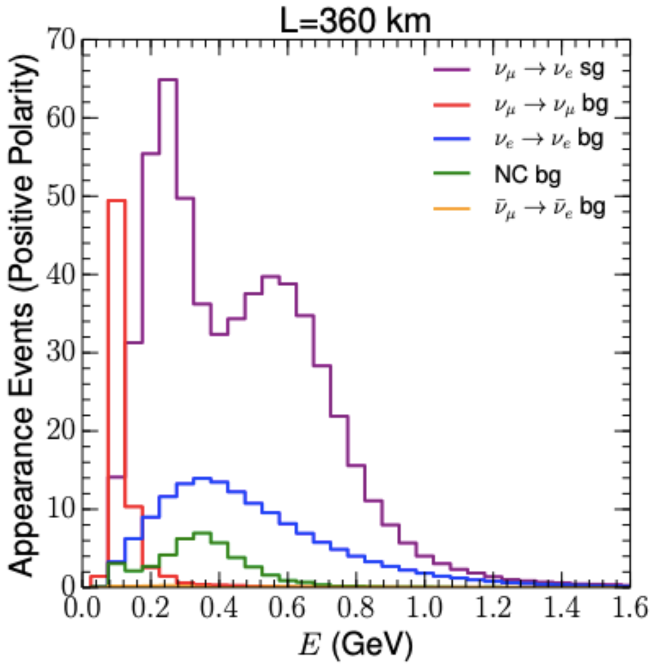
Table 29 Number of expected neutrino interactions in the detector per running year, per flavour and interaction type, and per each horn polarity

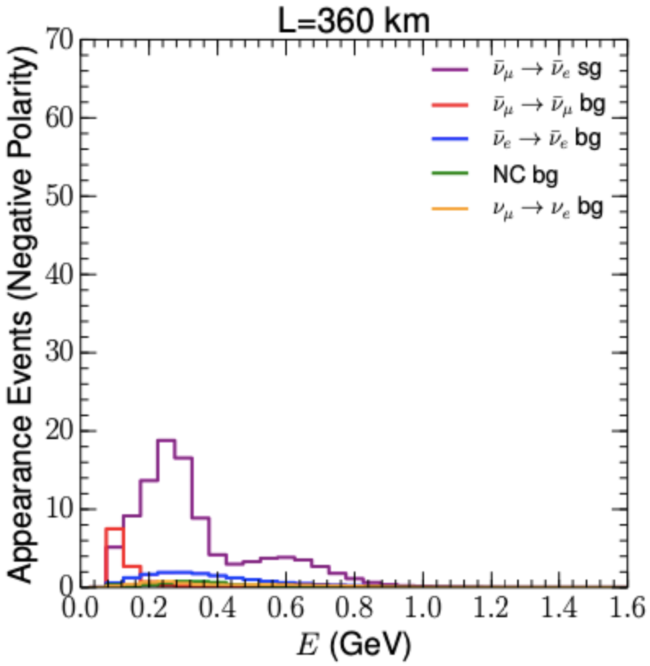
All interactions

	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC	ν_μ NC	ν_e NC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ NC
Positive polarity	5.20×10^7	1.07×10^6	9.25×10^4	1.11×10^3	4.42×10^7	6.11×10^5	3.36×10^5	8.72×10^2
Negative polarity	1.06×10^6	8.90×10^3	9.74×10^6	1.89×10^5	8.81×10^5	1.11×10^4	9.65×10^6	1.36×10^5

Initial flux

At FD w oscillation



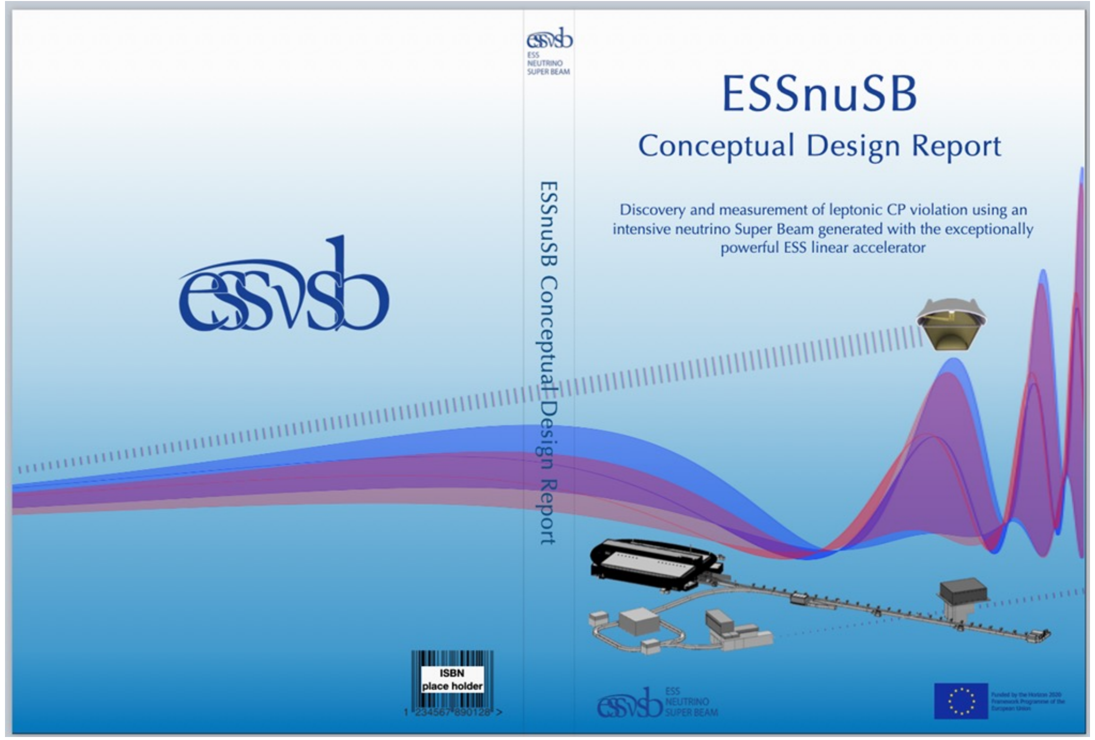


- Almost pure ν_μ beam
- Small ν_e contamination -> ν_e cross-sections at the ND

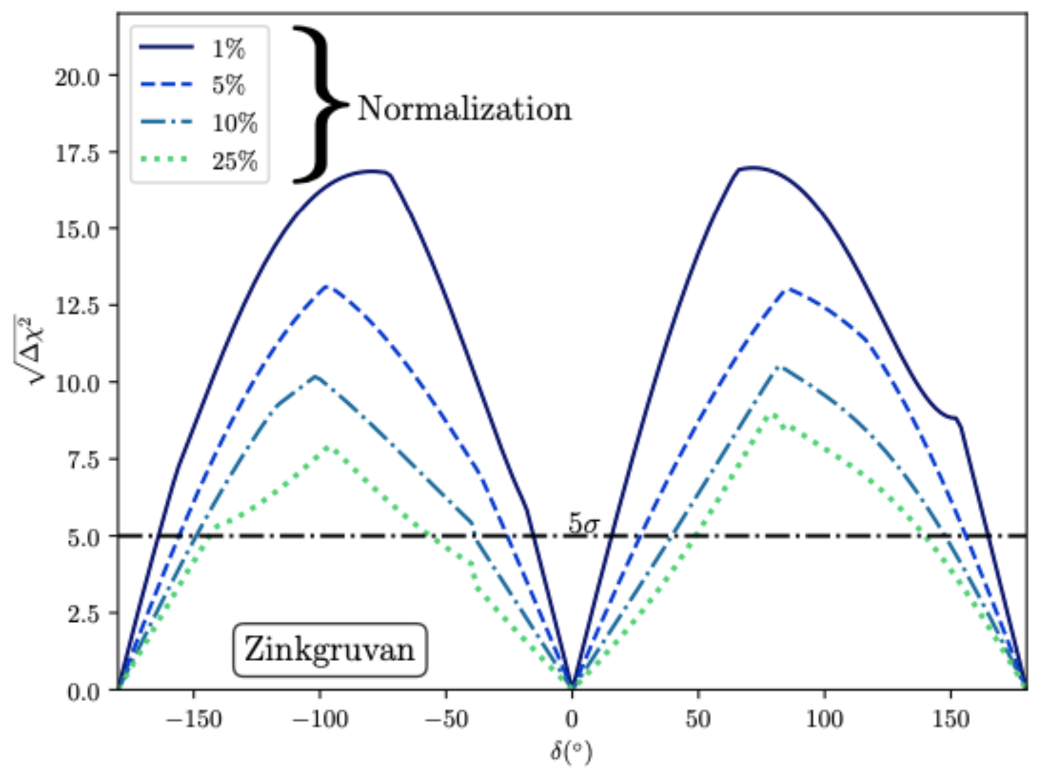
THE PHYSICS AT ESSNUSB

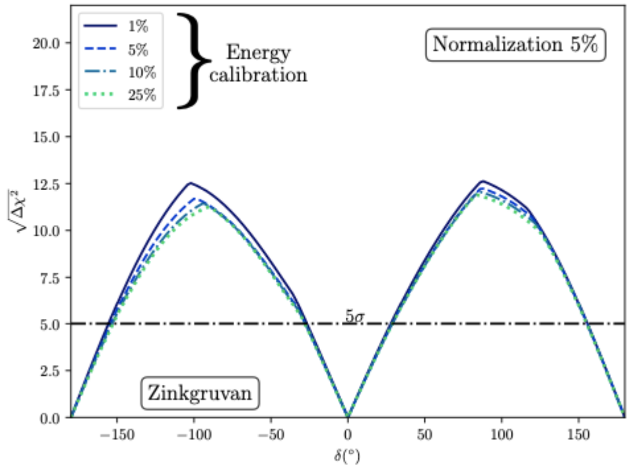
THE CDR (2022)

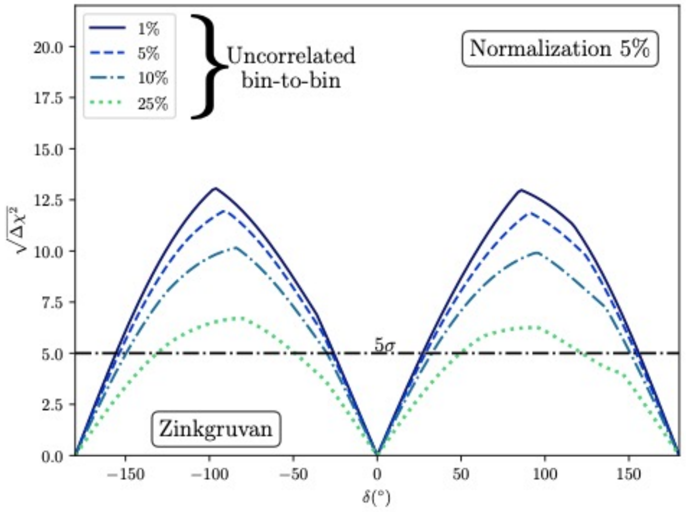
Conceptual Design Report Eur. Phys. J. ST. 231 (21), (2022) 3779



CP VIOLATION SENSITIVITY: EFFECT OF SYSTEMATICS



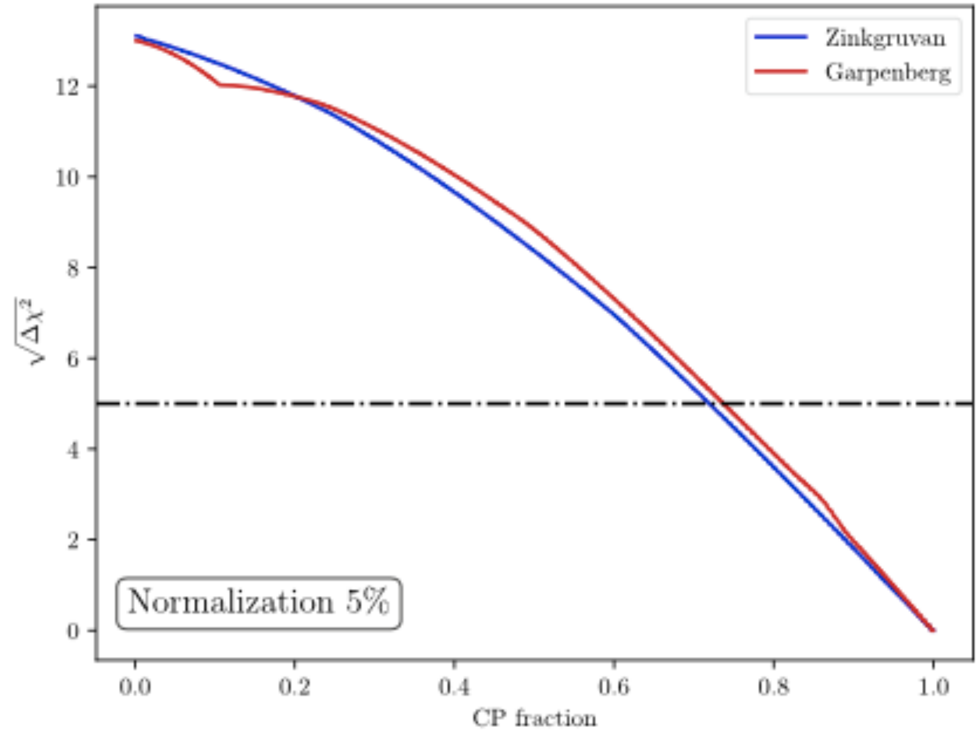


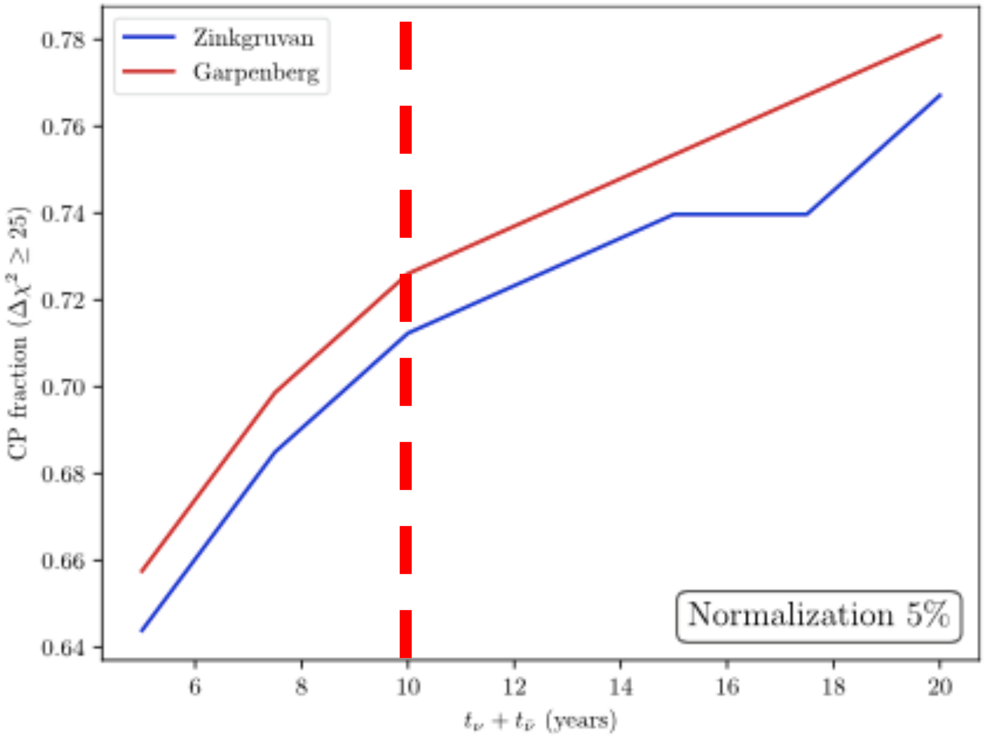


With 5% systematic uncertainty, up to 12.5 σ for maximum CPV!

CP VIOLATION COVERAGE

Nominal 5+5 yrs



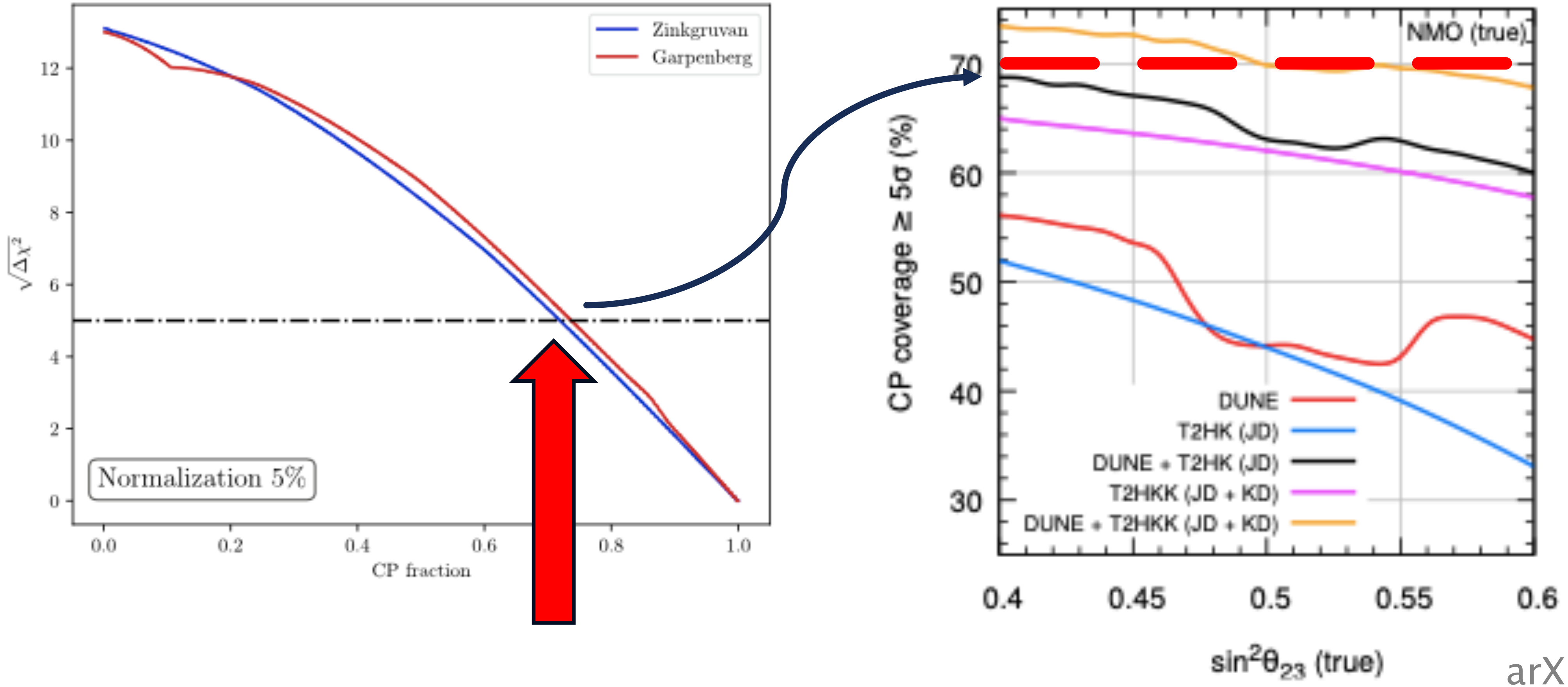


70% CP coverage at 5 σ

Results gets better with more running time

$\sin^2 2\theta_{23}$ 0.9898 ± 0.0077

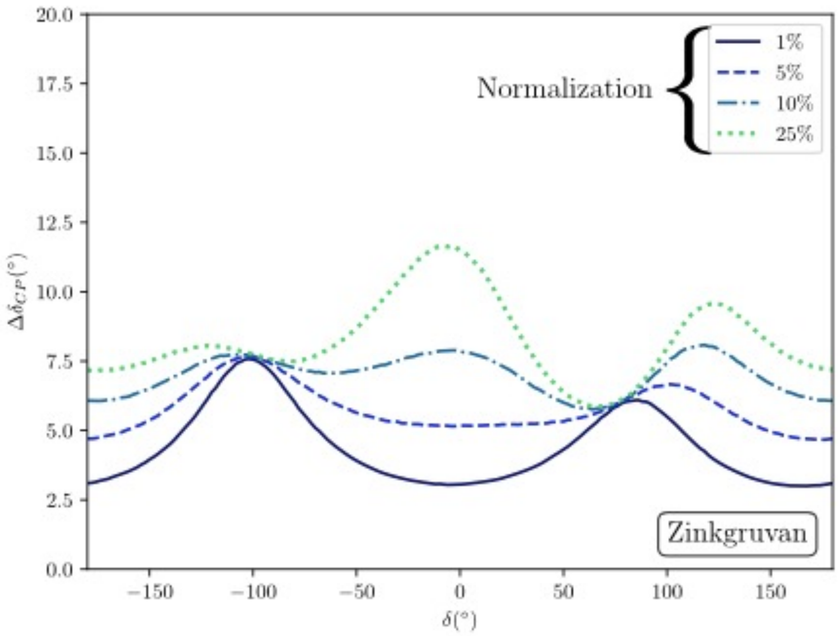
COMPARISON WITH NEXT-GEN LBL



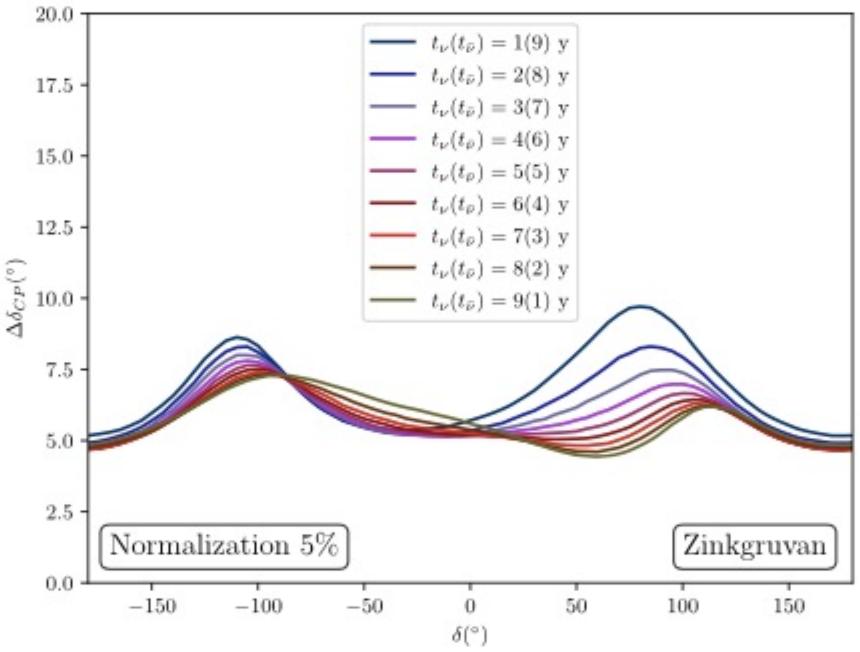
The same coverage might be reached only by DUNE+T2HKK (also, next-to-next gen proposed upgrade of T2HK) for LO values of th23

arXiv:2211.10620

UNCERTAINTY ON CP VIOLATING PHASE



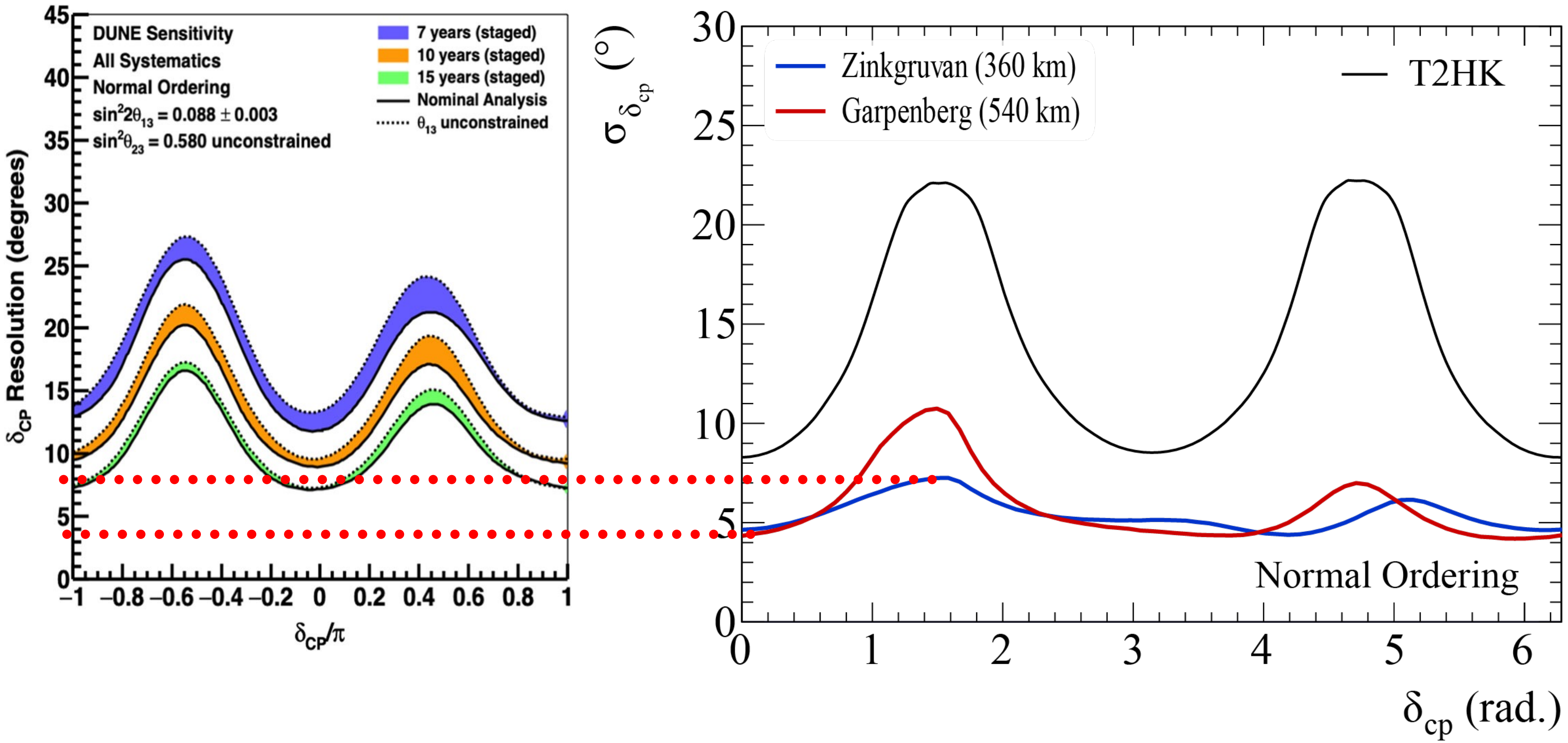
CP precision always under 7.5° for 5% sys



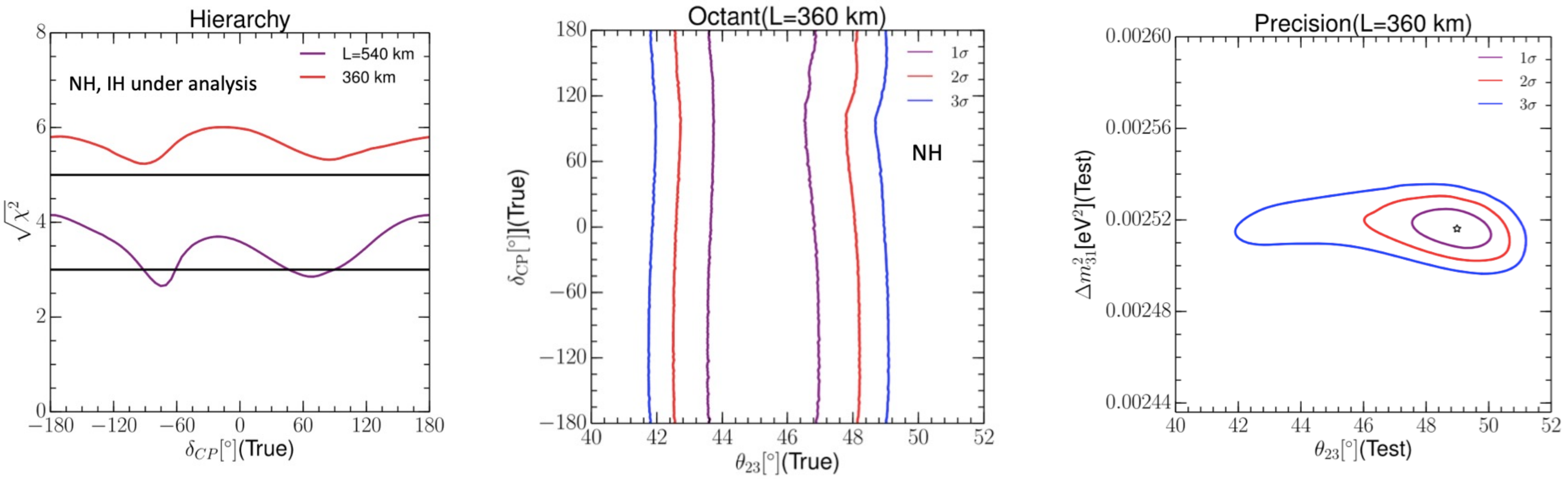
Precision optimized in a balanced run (5+5 yrs)

COMPARISON WITH NEXT-GEN LBL

Great improvement with respect to DUNE and T2HK!!



OSCILLATION BEYOND CPV

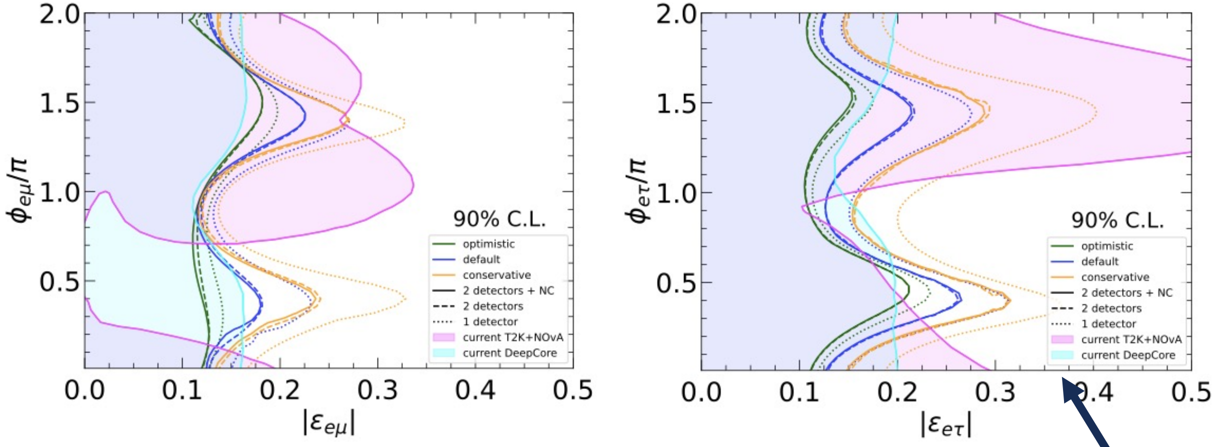


From: DOI:10.1140/epjc/s10052-021-09845-8, arXiv:2107.07585

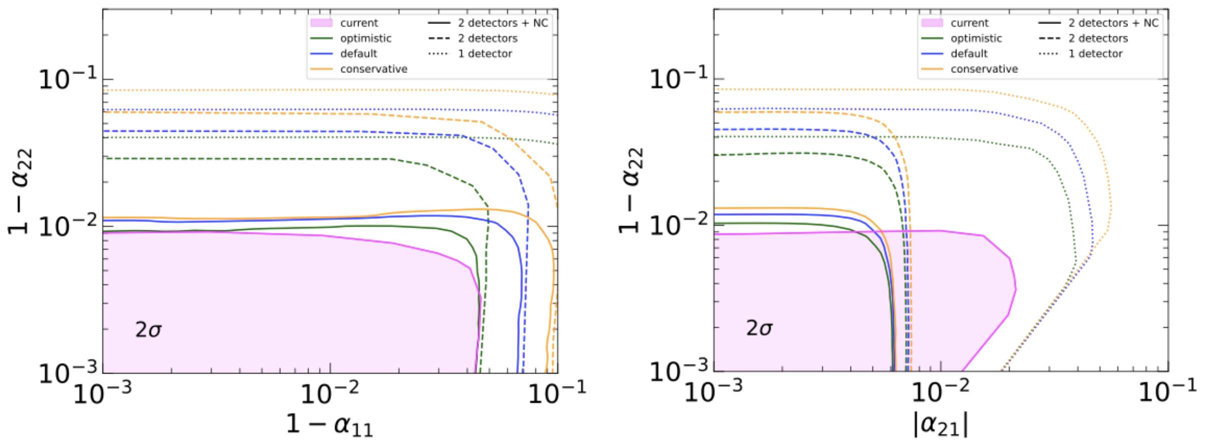
WHAT ABOUT BSM?

https://doi.org/10.1007/JHEP04(2023)130

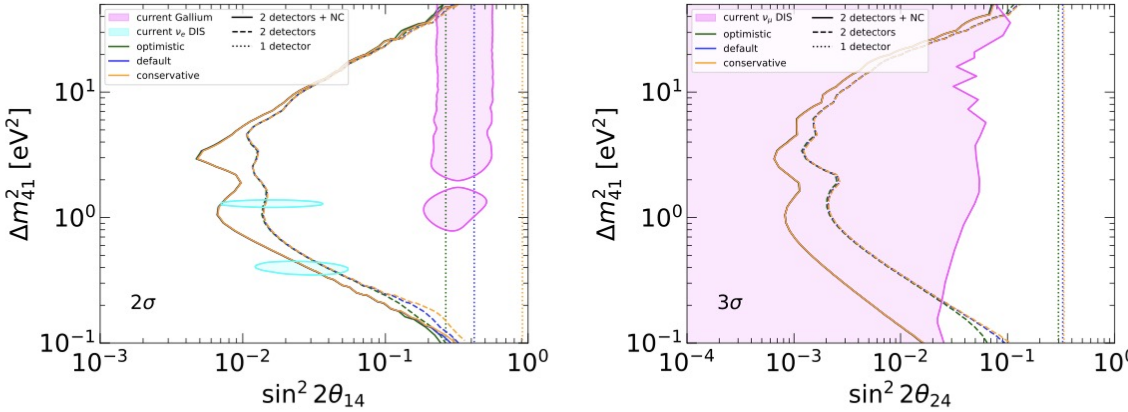
Non-Standard Interactions



Non-Unitarity of PMNS matrix



Steriles

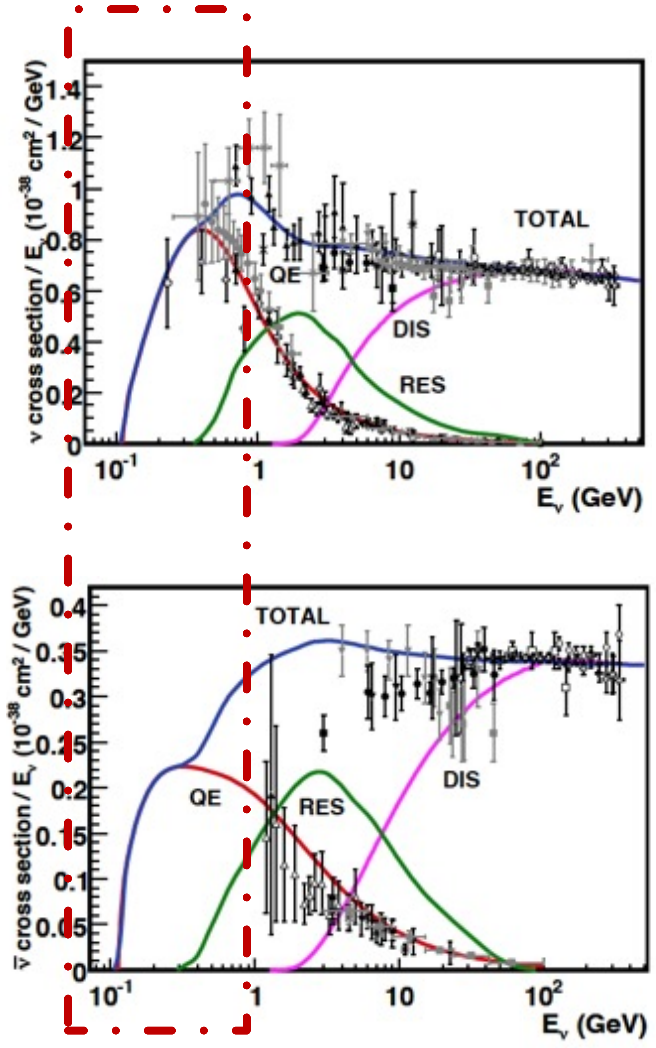


Possible new sources of CPV: Great sensitivity!

See also:
- https://doi.org/10.1007/JHEP03(2020)026
- https://doi.org/10.1007/JHEP05(2021)133
- https://doi.org/10.48550/arXiv.2305.16234
- https://doi.org/10.1103/PhysRevD.106.075016
- https://doi.org/10.1103/PhysRevD.107.075023
- ....

THE FUTURE: ESSNUSB+

THE LOW ENERGY NEUTRINO CROSS SECTION



Lack of neutrino cross section measurements in the low energy region fundamental for ESSnuSB!

<u>Even though the effect of systematics for the CP violation measurement is much less in ESSnuSB is crucial to obtain new precise results in this direction</u>

From eV to EeV: Neutrino cross sections across energy scales, *Rev. Mod. Phys. 84, 1307 – Published 24 September 2012*

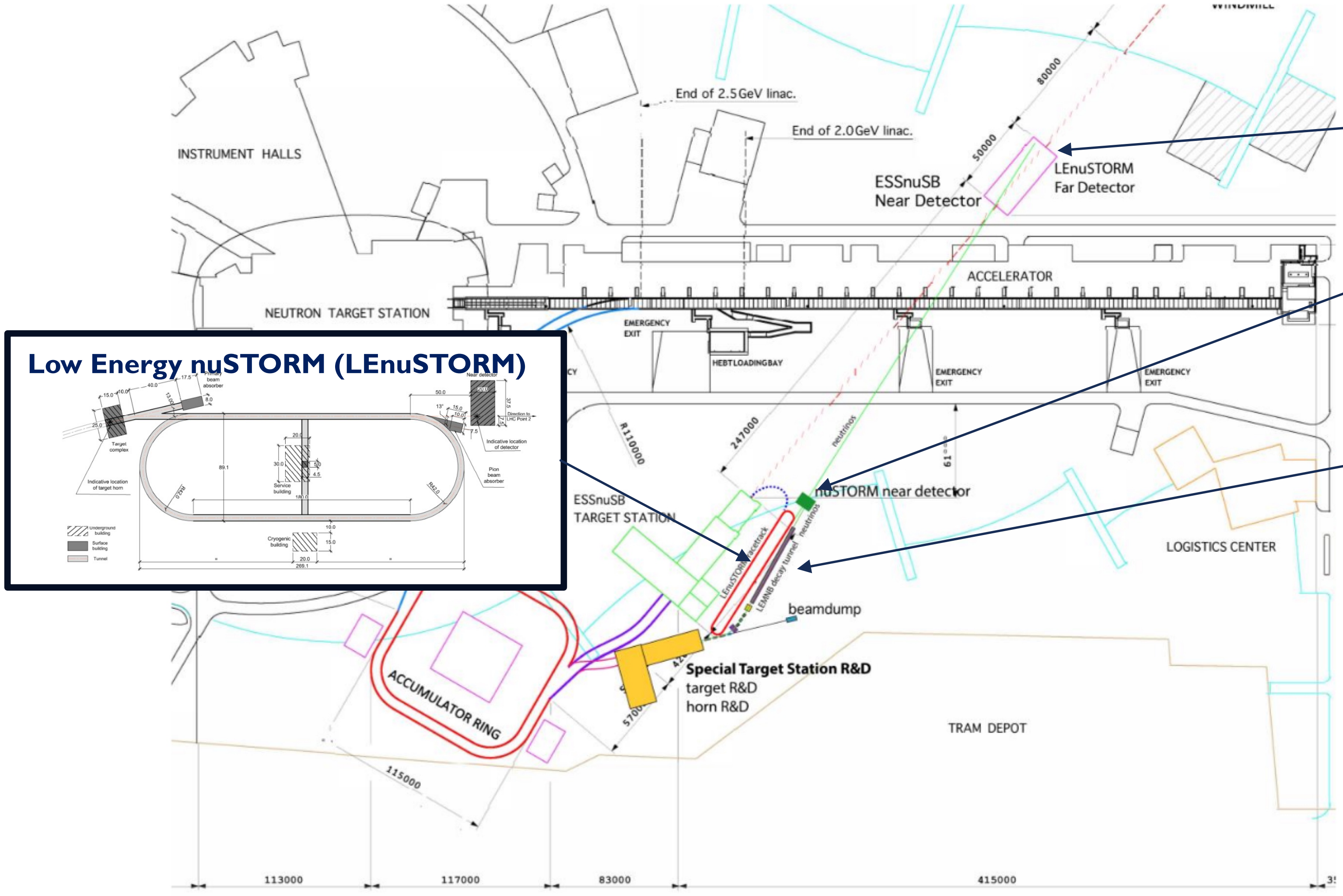
POSSIBLE STUDIES FOR THE CROSS SECTION MEASUREMENTS

1. Design a **transfer line** from the ESSνSB accumulator ring to the target
2. Design a **special target facility** that depends on one horn-target system
3. Design a pion **extraction and deflection system**
4. Design an **injection scheme** for the extracted pions to the racetrack storage ring, where the pions will decay to muons
5. Design a **storage ring** for the low energy nuSTROM (for cross section measurements and sterile neutrino searches)
6. Design a **Monitored Neutrino Beam** (low energy ENUBET for cross section measurements)
7. **Optimize the performance** of the ESSνSB detectors

Cross-section measurements with:

- Low Energy nuSTORM: $\pi \longrightarrow \mu \longrightarrow e + \nu_\mu + \nu_e$
- Low Energy ENUBET: $\pi \longrightarrow \mu + \nu_\mu$

ESSNUSB+



Gd doping for WC detectors

New Near Detector

Monitored Beam (LEMNB)

ESSNUSB+

Research and Innovation actions

Design Study

HORIZON-INFRA-2022-DEV-01

Title of Proposal:

Study of the use of the ESS facility to accurately measure the neutrino cross-sections for ESSνSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics.

Acronym of Proposal: ESSνSB+

Marcos DRACOS
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
RUE MICHEL ANGE 3
75794 PARIS
FRANCE

Subject: Horizon Europe (HORIZON)
Call: HORIZON-INFRA-2022-DEV-01
Project: 101094628 — ESSnuSBplus
GAP invitation letter

Dear Applicant,

I am writing in connection with your proposal for the above-mentioned call.

Having completed the evaluation, we are pleased to inform you that your proposal has passed this phase and that we would now like to start grant preparation.

Please find enclosed the evaluation summary report (ESR) for your proposal.

Invitation to grant preparation

Approved! 26/07/2022

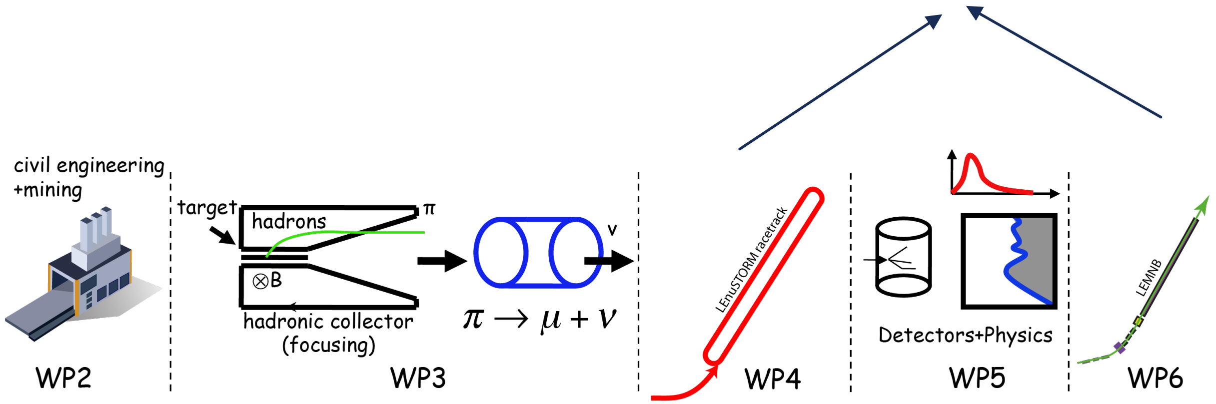
3 M €, 4 YEARS

ESSNUSB+

20 participant institutes

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Centre National de la Recherche Scientifique	CNRS	France
2	Université de Strasbourg	UNISTRA[1]	France
3	Rudjer Boskovic Institute	RBI	Croatia
4	Tokai National Higher Education and Research System, National University Corporation	NU[2]	Japan
5	Uppsala Universitet	UU	Sweden
6	Lunds Universitet	ULUND	Sweden
7	European Spallation Source ERIC	ESS	Sweden
8	Kungliga Tekniska Hoegskolan	KTH	Sweden
9	Universitaet Hamburg	UHH	Germany
10	University of Cukurova	CU	Turkey
11	National Center for Scientific Research "Demokritos"	NCSRD	Greece
12	Aristotelio Panepistimio Thessalonikis	AUTH[1]	Greece
13	Sofia University St. Kliment Ohridski	UniSofia	Bulgaria
14	Lulea Tekniska Universitet	LTU	Sweden
15	European Organisation for Nuclear Research	CERN	IEIO[3]
16	Universita degli Studi Roma Tre	UNIROMA3	Italy
17	Universita degli Istudi di Milano-Bicocca	UNIMIB	Italy
18	Istituto Nazionale di Fisica Nucleare	INFN	Italy
19	Universita degli Istudi di Padova	UNIPD[1]	Italy
20	Consorcio para la construccion, equipamiento y explotacion de la sede espanola de la fuente Europea de neutrones por espalacion	ESSB	Spain

Cross-sections and steriles



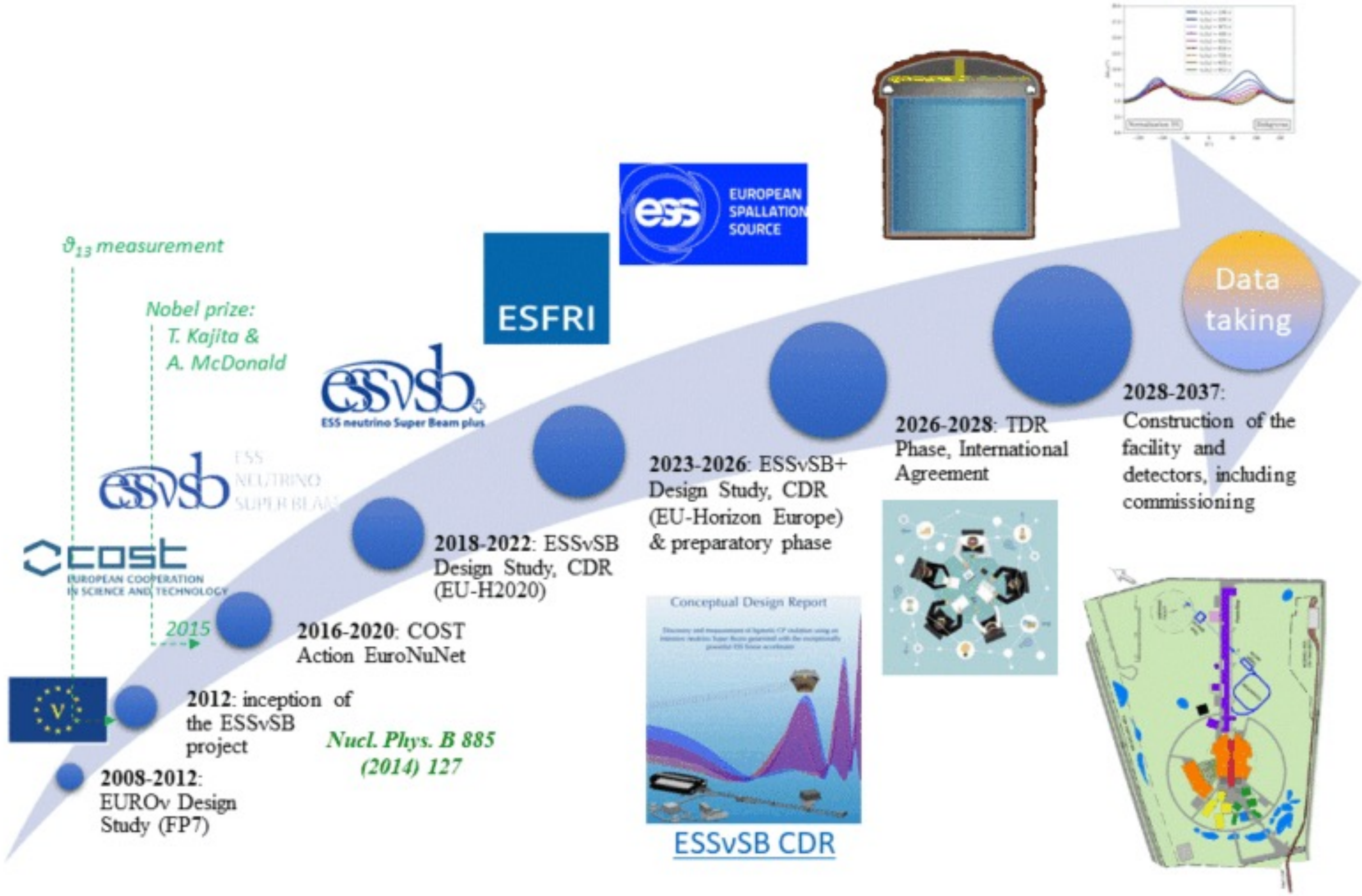
Non Beam physics:

-Atmospheric

-Supernovae

-…

TIMELINE



ϑ_{13} measurement
Nobel prize:
T. Kajita &
A. McDonald
2015
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
ESS neutrino Super Beam plus
ESFRI
EUROPEAN SPALLATION SOURCE
2008-2012: EUROv Design Study (FP7)
2012: inception of the ESSvSB project
Nucl. Phys. B 885 (2014) 127
2016-2020: COST Action EuroNuNet
2018-2022: ESSvSB Design Study, CDR (EU-H2020)
2023-2026: ESSvSB+ Design Study, CDR (EU-Horizon Europe) & preparatory phase
Conceptual Design Report
ESSvSB CDR
2026-2028: TDR Phase, International Agreement
2028-2037: Construction of the facility and detectors, including commissioning
Data taking

CONCLUSIONS

•ESSnuSB is a next-to-next generation neutrino oscillation experiment which aims to precisely measure CP violation looking at neutrino oscillations at the 2nd oscillation maximum

• This baseline choice allows to have a measurement less affected by systematic errors and matter effects

• We predict that in 10 years of data taking ESSnuSB will be able to reach a 70% coverage for the CP violating phase and a precision of less than 8°

•The accelerator complex will be based at the ESS linac, the most powerful proton accelerator in the world

•The large far detectors can also be used for rich astroparticle physics programme

•The ESSnuSB Design Study has been supported by EU-Horizon 2020 during the period 2018-2022 and the ESSnuSB+ Project which started this year has further enriched the great physics program of the experiment

ESSνSB+
ESS neutrino Super Beam plus

Co-funded by
the European Union

ΔΗΜΟΚΡΙΤΟΣ
СВ. КЛИМЕНТ ОХРИДСКИ
ÇUKUROVA UNIVERSITY 1973
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CERN
LULEÅ UNIVERSITY OF TECHNOLOGY
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ROMA TRE UNIVERSITÀ DEGLI STUDI
UNIVERSITÀ DEGLI STUDI DI PADOVA
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KTH VETENSKAP OCH KONST
名古屋大学 NAGOYA UNIVERSITY
cnrs
AGH
UNIVERSITEIT GENT
ESS bilbao
UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG
Université de Strasbourg
ARISTOTLE UNIVERSITY OF THESSALONIKI
UPPSALA UNIVERSITET
HELLENIC OPEN UNIVERSITY
RB
INFN Istituto Nazionale di Fisica Nucleare
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

THANK YOU FOR YOUR ATTENTION

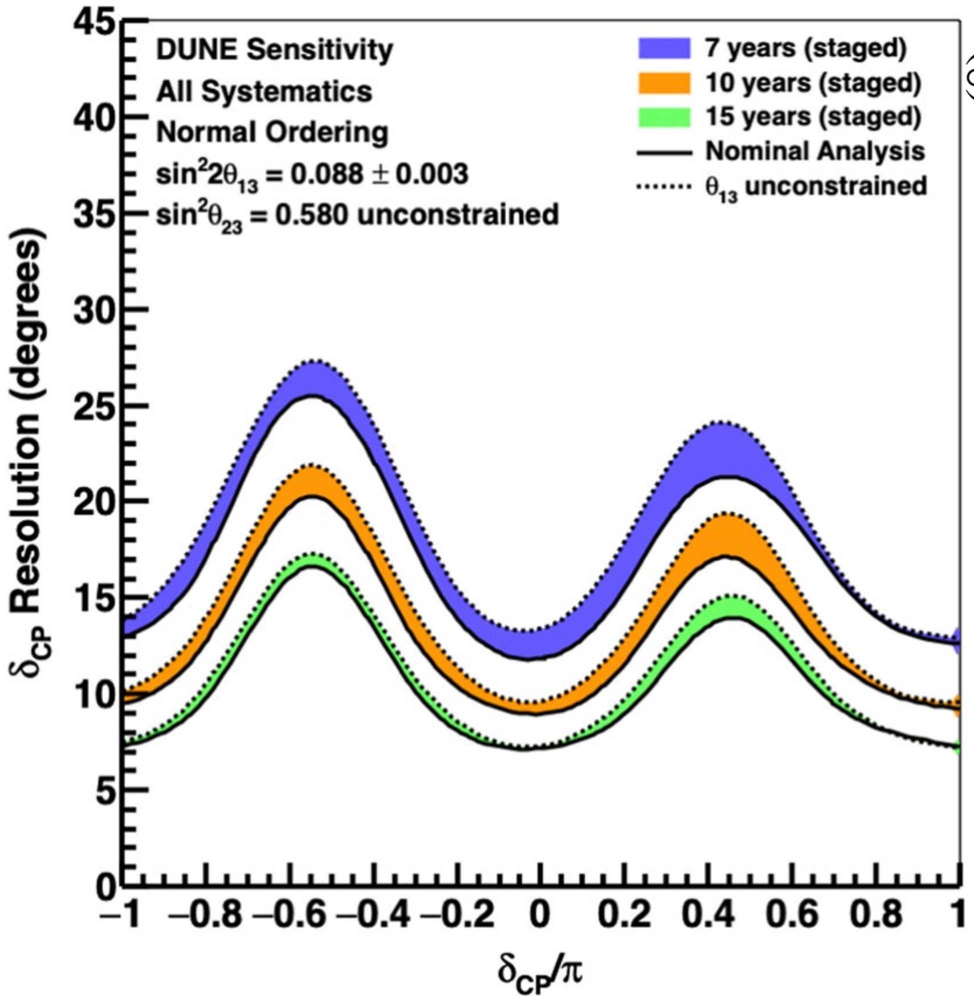
BACKUP

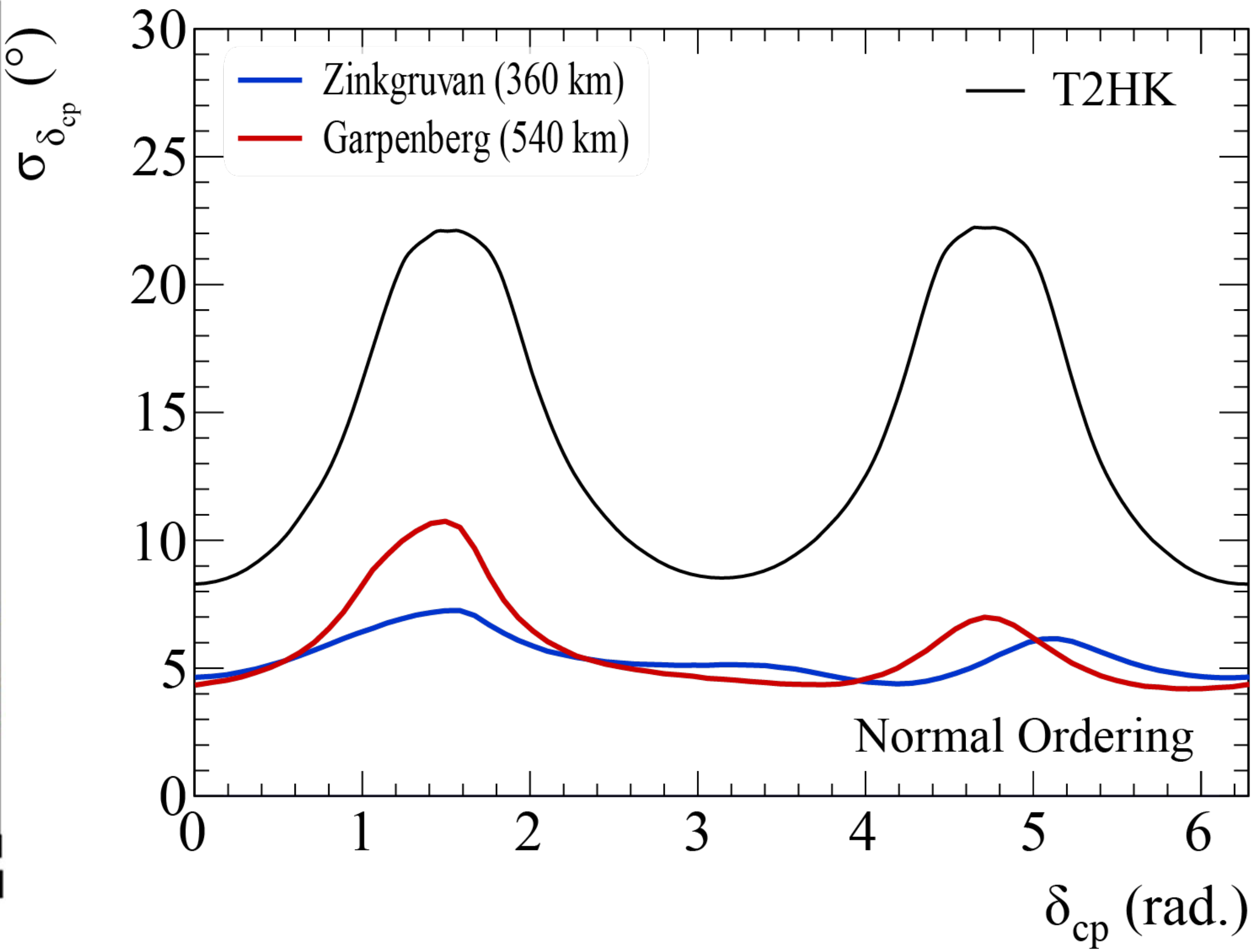
SYSTEMATICS

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 (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 $\times$ 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%

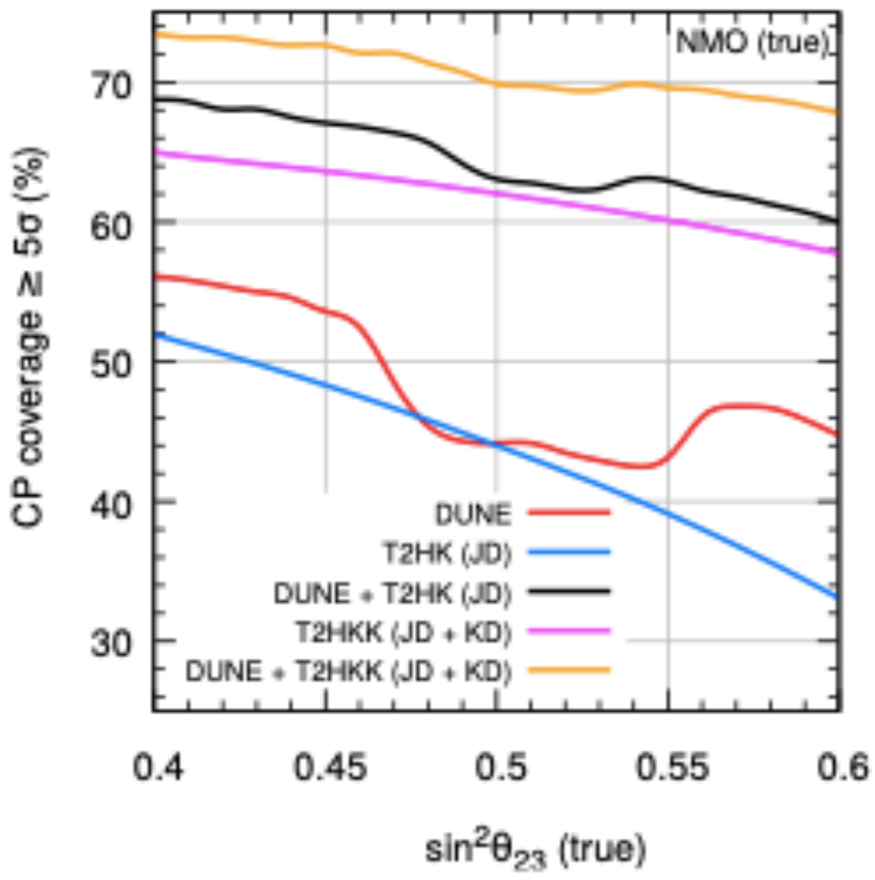
Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

COMPARISON WITH LBL





COMPARISON WITH LBL



arXiv:2211.10620

EVENTS

Table 5.13: Expected number of neutrino interactions in 538 kt FD fiducial volume at a distance of 360 km (Zinkgruvan mine) in 200 days (one effective year). Shown for positive (negative) horn polarity.

	Channel	Non oscillated	Oscillated $\delta_{CP}=0$	Oscillated $\delta_{CP}=\pi/2$	Oscillated $\delta_{CP}=-\pi/2$
CC	$\nu_\mu \to \nu_\mu$	22 630.4 (231.0)	10 508.7 (101.6)	10 430.6 (5.8)	10 430.6 (100.9)
	$\nu_\mu \to \nu_e$	0 (0)	768.3 (8.6)	543.8 (5.8)	1 159.9 (12.8)
	$\nu_e \to \nu_e$	190.2 (1.2)	177.9 (1.1)	177.9 (1.1)	177.9 (1.1)
	$\nu_e \to \nu_\mu$	0 (0)	5.3 (3.3×10^{-2})	7.3 (4.5×10^{-2})	3.9 (2.4×10^{-2})
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	62.4 (3 640.3)	26.0 (1 896.8)	26.0 (1 898.9)	26.0 (1 898.9)
	$\bar{\nu}_\mu \to \bar{\nu}_e$	0 (0)	2.6 (116.1)	3.5 (164.0)	1.4 (56.8)
	$\bar{\nu}_e \to \bar{\nu}_e$	1.3×10^{-1} (18.5)	1.3×10^{-1} (17.5)	1.3×10^{-1} (17.5)	1.2×10^{-1} (17.5)
	$\bar{\nu}_e \to \bar{\nu}_\mu$	0 (0)	3.0×10^{-3} (4.0×10^{-1})	1.5×10^{-3} (2.1×10^{-1})	4.1×10^{-3} (5.6×10^{-1})
NC	ν_μ	16 015.1 (179.3)			
	ν_e	103.7 (0.7)			
	$\bar{\nu}_\mu$	55.2 (3 265.5)			
	$\bar{\nu}_e$	1×10^{-1} (13.6)			

EVENTS

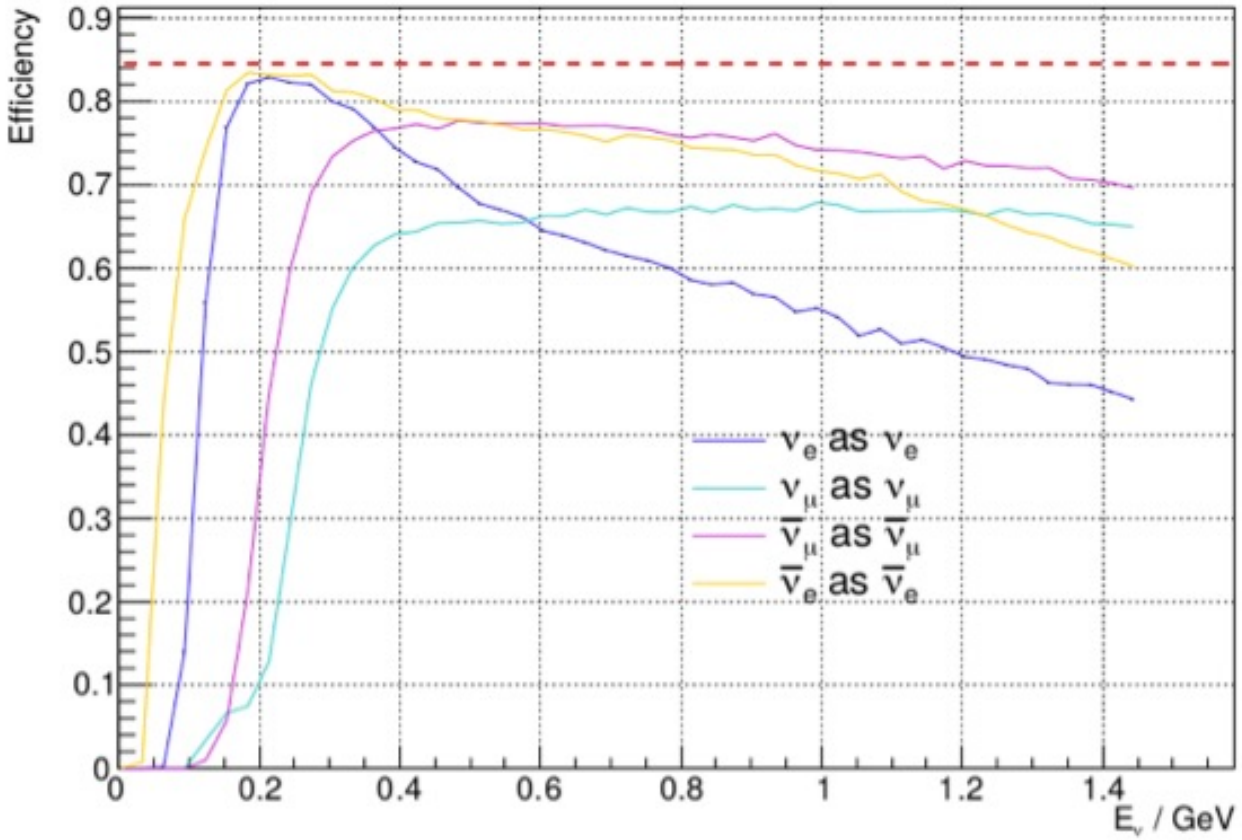
	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	272.22 (63.75)	578.62 (101.18)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	31.01 (3.73)	67.23 (11.51)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	67.49 (7.31)	151.12 (16.66)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	18.57 (2.10)	41.78 (4.73)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	1.08 (3.08)	1.94 (6.47)

Table 1: Signal and major background events for the appearance channel corresponding to positive (negative) polarity per year for $\delta_{CP} = 0°$.

	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	4419.69 (733.31)	7619.16 (1602.02)
Background	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	7.77 (0.02)	17.08 (0.05)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	69.23 (8.24)	155.77 (18.54)
	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	14.68 (0.06)	61.30 (0.17)
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ ($\nu_\mu \to \nu_\mu$)	12.35 (41.00)	21.39 (72.59)

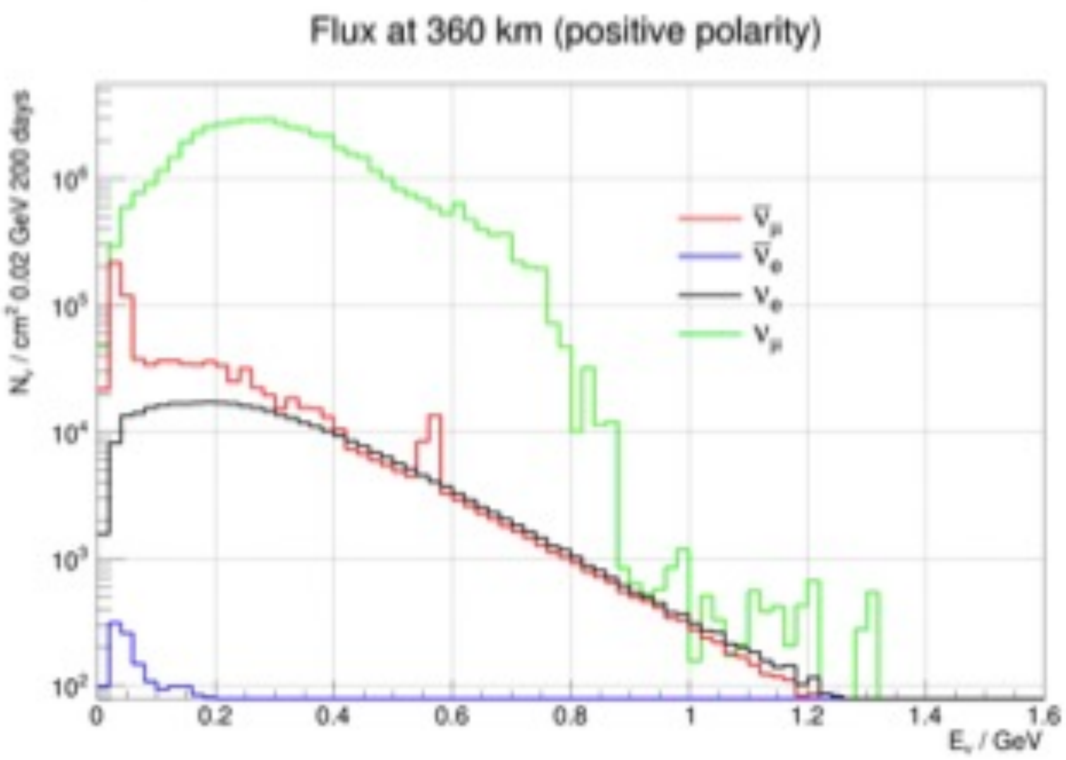
Table 2: Signal and major background events for the disappearance channel corresponding to positive (negative) polarity per year for $\delta_{CP} = 0°$.

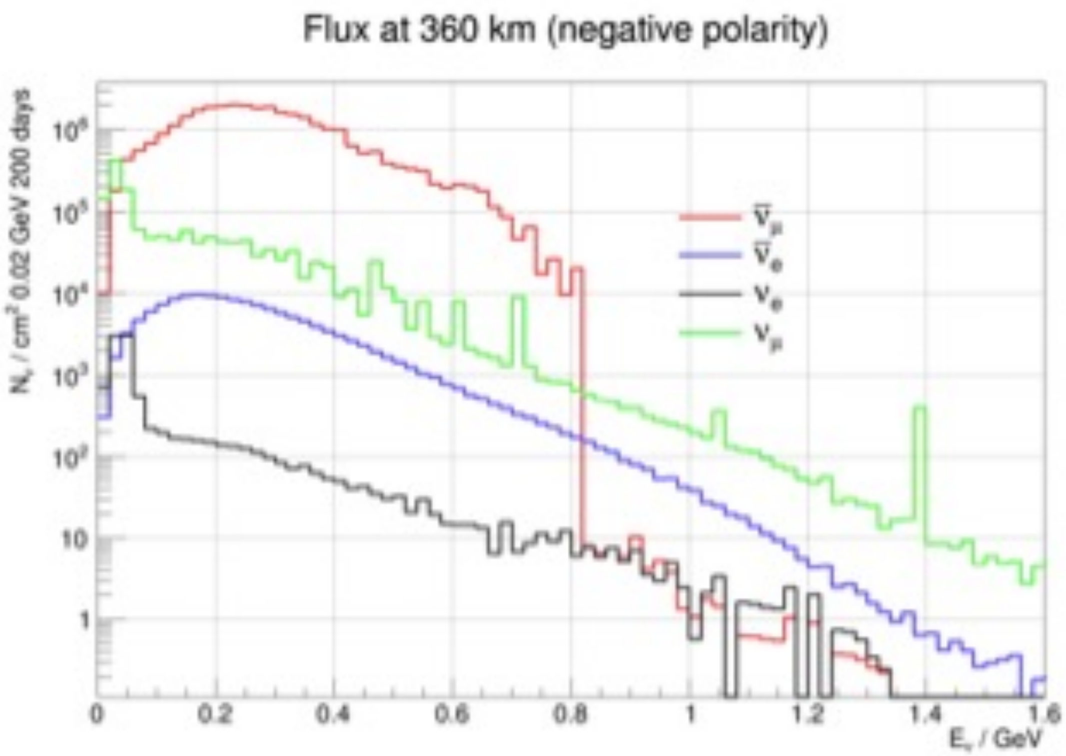
EFFICIENCY



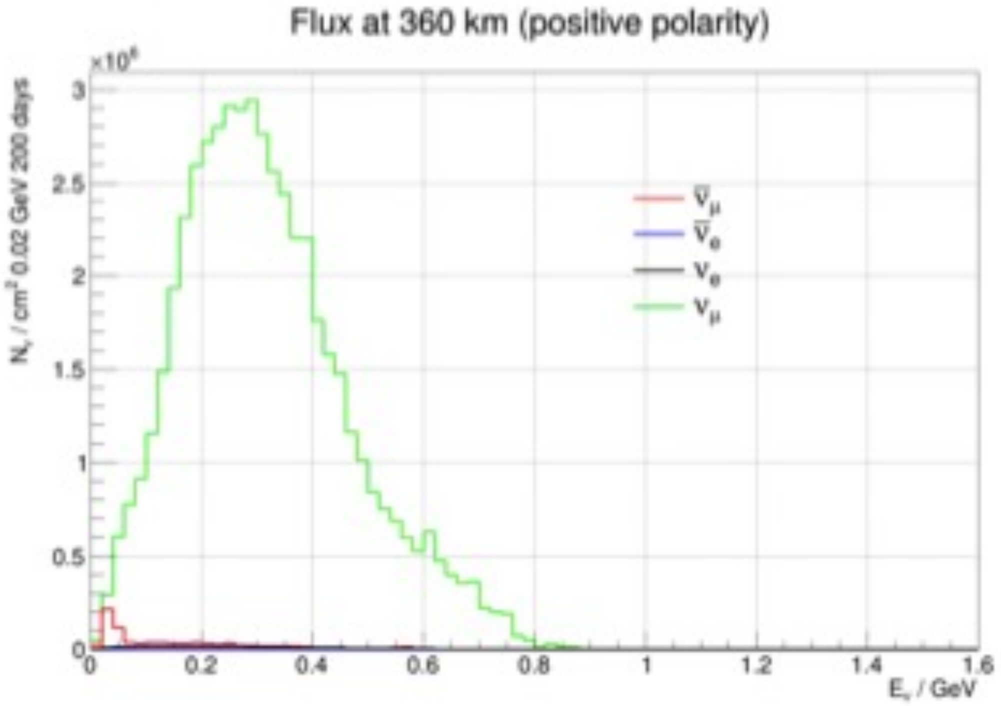
Efficiency
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
E_ν / GeV
ν_e as ν_e
ν_μ as ν_μ
$\bar{\nu}_\mu$ as $\bar{\nu}_\mu$
$\bar{\nu}_e$ as $\bar{\nu}_e$

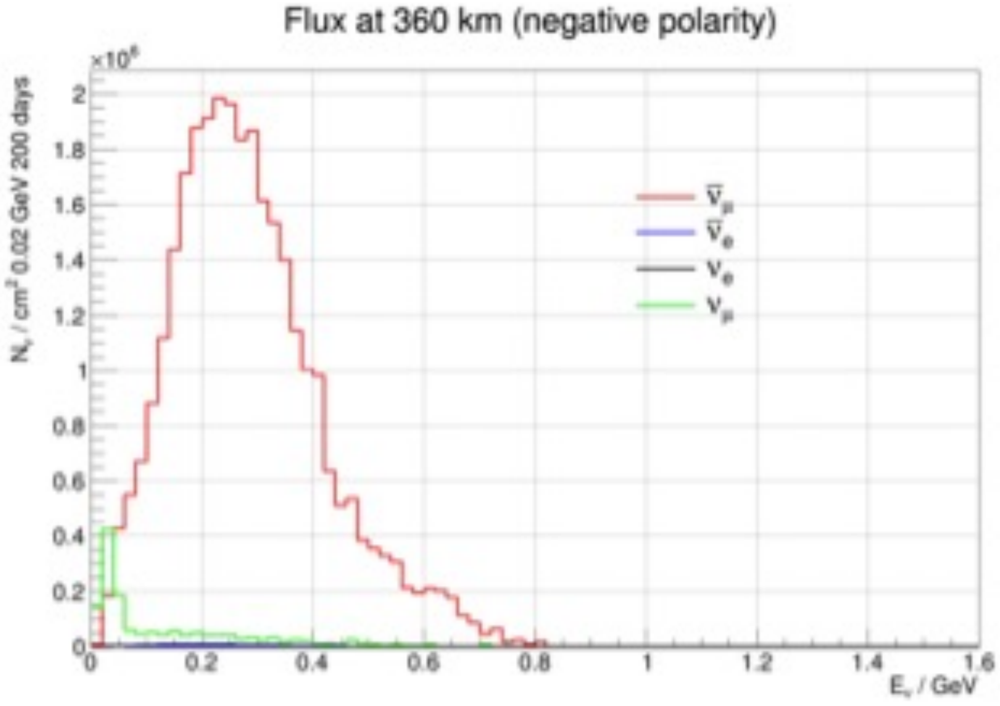
FLUXES


Flux at 360 km (positive polarity)
N_ν / cm^2 0.02 GeV 200 days
10^6
10^5
10^4
10^3
10^2
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
ν_μ
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
E_ν / GeV


Flux at 360 km (negative polarity)
N_ν / cm^2 0.02 GeV 200 days
10^6
10^5
10^4
10^3
10^2
10
1
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
ν_μ
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
E_ν / GeV

FLUXES


Flux at 360 km (positive polarity)
×10⁶
N_ν / cm² 0.02 GeV 200 days
E_ν / GeV
ν̄_μ
ν̄_e
ν_e
ν_μ


Flux at 360 km (negative polarity)
×10⁶
N_ν / cm² 0.02 GeV 200 days
E_ν / GeV
ν̄_μ
ν̄_e
ν_e
ν_μ

FLUXES

Flavour	ν Mode		$\bar{\nu}$ Mode	
	N_ν (10^5/ cm^2)	%	N_ν (10^5/ cm^2)	%
ν_μ	**520.06**	**97.6**	15.43	4.7
ν_e	**3.67**	**0.67**	0.10	0.03
$\bar{\nu}_\mu$	9.10	1.7	**305.55**	**94.8**
$\bar{\nu}_e$	0.023	0.03	**1.43**	**0.43**

Events at 360 km w/o oscillations

BSM: NSI

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E_\nu}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A_{CC}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\tilde{V}_{\mathrm{MSW}} = a_{\mathrm{CC}}\begin{pmatrix}1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau}\\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau}\\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau}\end{pmatrix}$$

BSM: STERILE

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} =$$

$$U = R(\theta_{34})R(\theta_{24})R(\theta_{23},\delta_3)R(\theta_{14})R(\theta_{13},\delta_2)R(\theta_{12},\delta_1)$$

New sources of CP violation!

$$= \left[\frac{1}{2E_\nu}U\begin{pmatrix}0&0&0&0\\0&\Delta m^2_{21}&0&0\\0&0&\Delta m^2_{31}&0\\0&0&0&\Delta m^2_{41}\end{pmatrix}U^\dagger + \begin{pmatrix}A_{CC}+A_{NC}&0&0&0\\0&A_{NC}&0&0\\0&0&A_{NC}&0\\0&0&0&0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

BSM: NU

$$N = (1 + \alpha)U_{PMNS}\,.$$

$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}|e^{i\phi_{21}} & \alpha_{22} & 0 \\ |\alpha_{31}|e^{i\phi_{31}} & |\alpha_{32}|e^{i\phi_{32}} & \alpha_{33} \end{pmatrix}$$

NEUTRINO INTERACTIONS