THE EUROPEAN SPALLATION SOURCE NEUTRINO SUPER BEAM PLUS (ESSNUSB+) PROJECT

ALESSIO GIARNETTI, ON BEHALF OF THE ESSNUSB+ PROJECT

ESS neutrino Super Beam plus

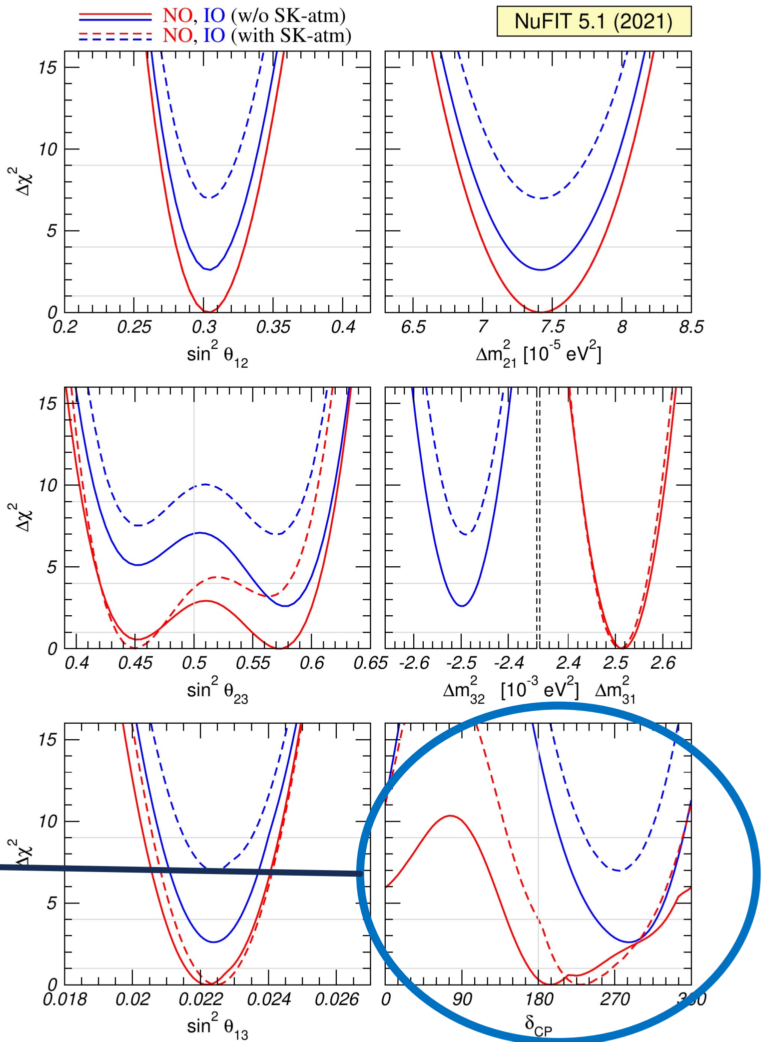
Co-funded by the European Union

ICHEP, PRAGUE, 20/07/2024

ROMA TRE UNIVERSITÀ DEGLI STUDI

ESSNUSB/ESSNUSB+: NEUTRINO OSCILLATION AT SECOND MAXIMUM

ESSnuSB/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 2nd atmospheric oscillation maximum.



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!

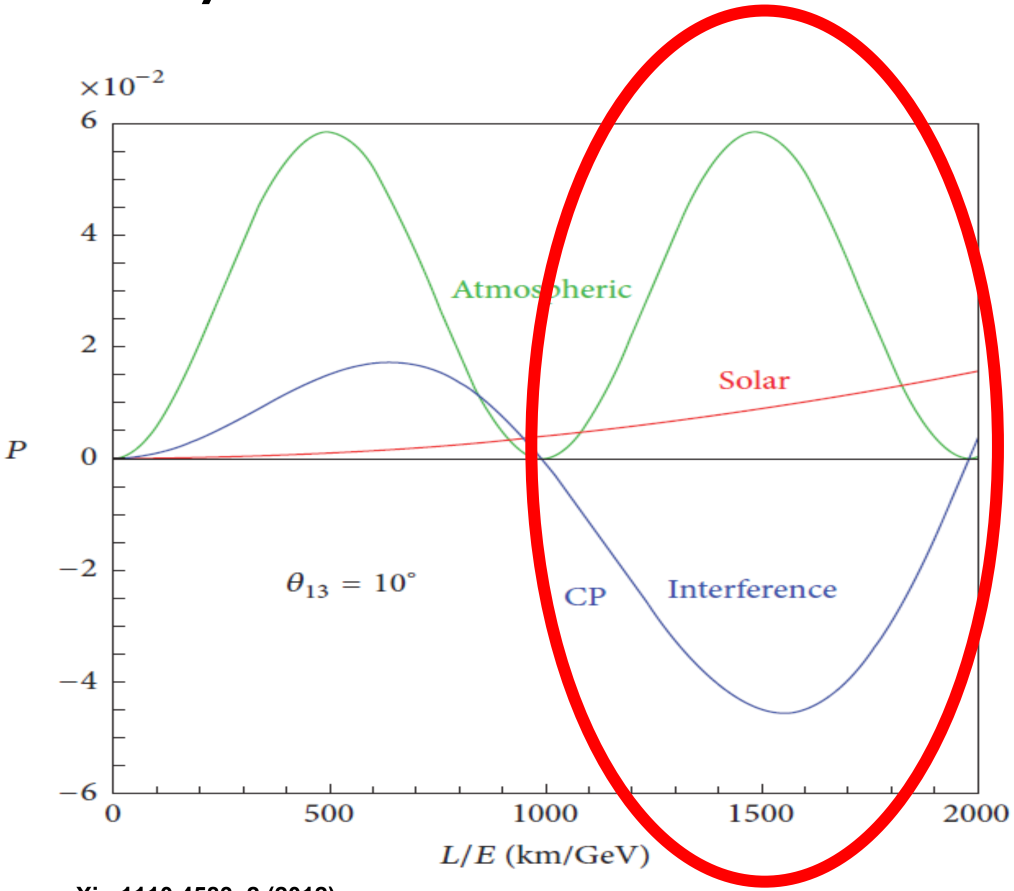
CP VIOLATION → $P_{\nu_\mu \to \nu_e} \neq P_{\overline{\nu}_\mu \to \overline{\nu}_e}$ $(\delta \to -\delta)$

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 2° maximum?



arXiv:1110.4583v2 (2012)

At the second oscillation maximum the interference term is large!

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

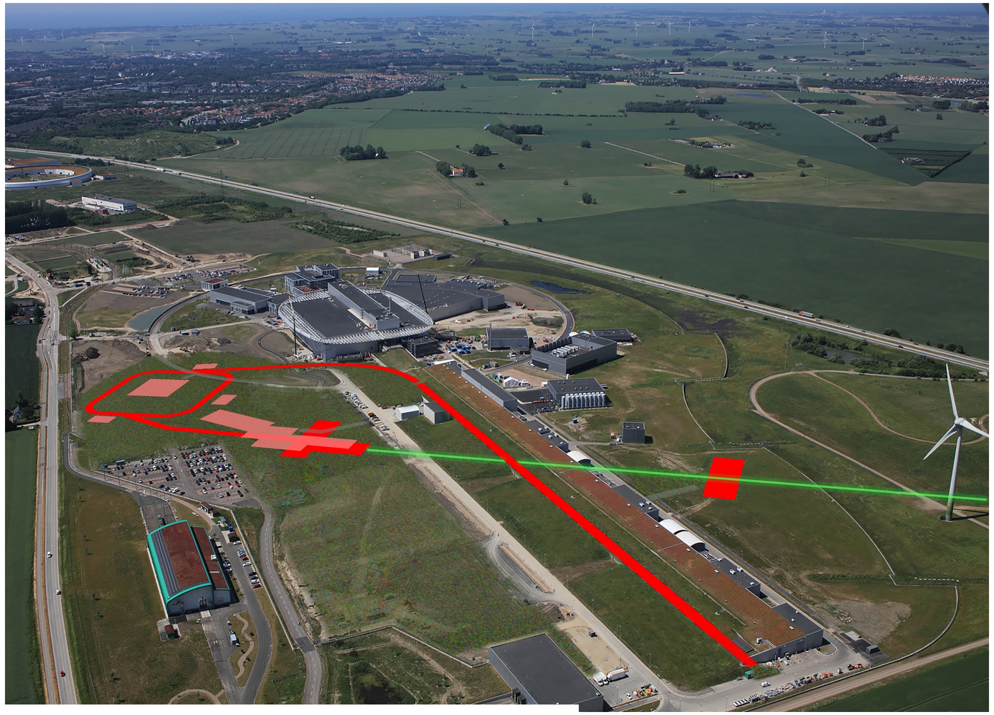
In electron neutrino appearance,

$$\frac{A_{CP}@\,2nd\ max.}{A_{CP}@\,1nd\ max.} \sim 2.5$$

arXiv:1310.5992

THE ESSNUSB PROJECT (2018-2022)

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 proton beam power.

•14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).

•Duty cycle 4%.

•2.0 GeV kinetic energy protons

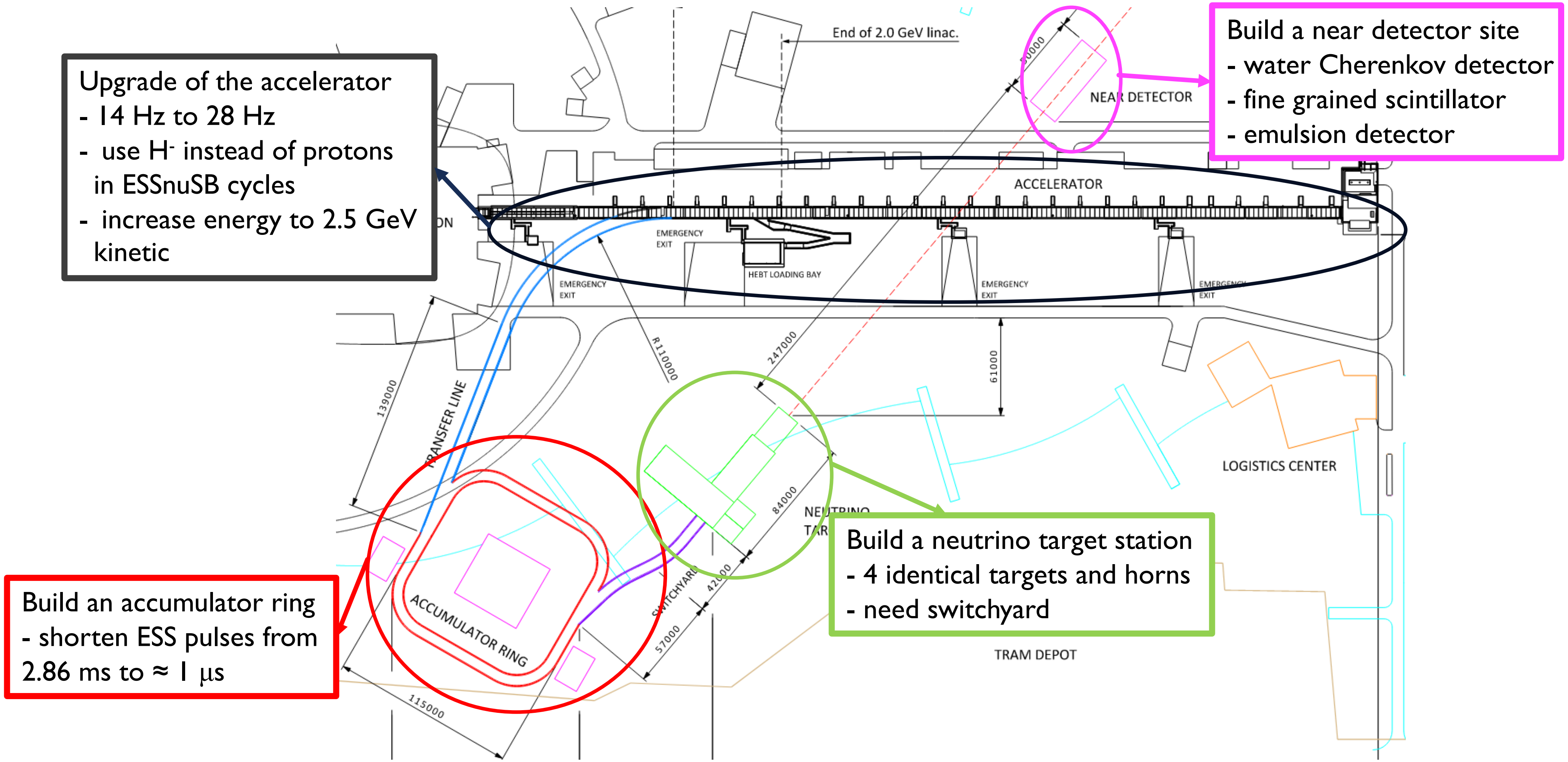
•○ up to 3.5 GeV with linac upgrades

•>2.7x10^{23} p.o.t/year.

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

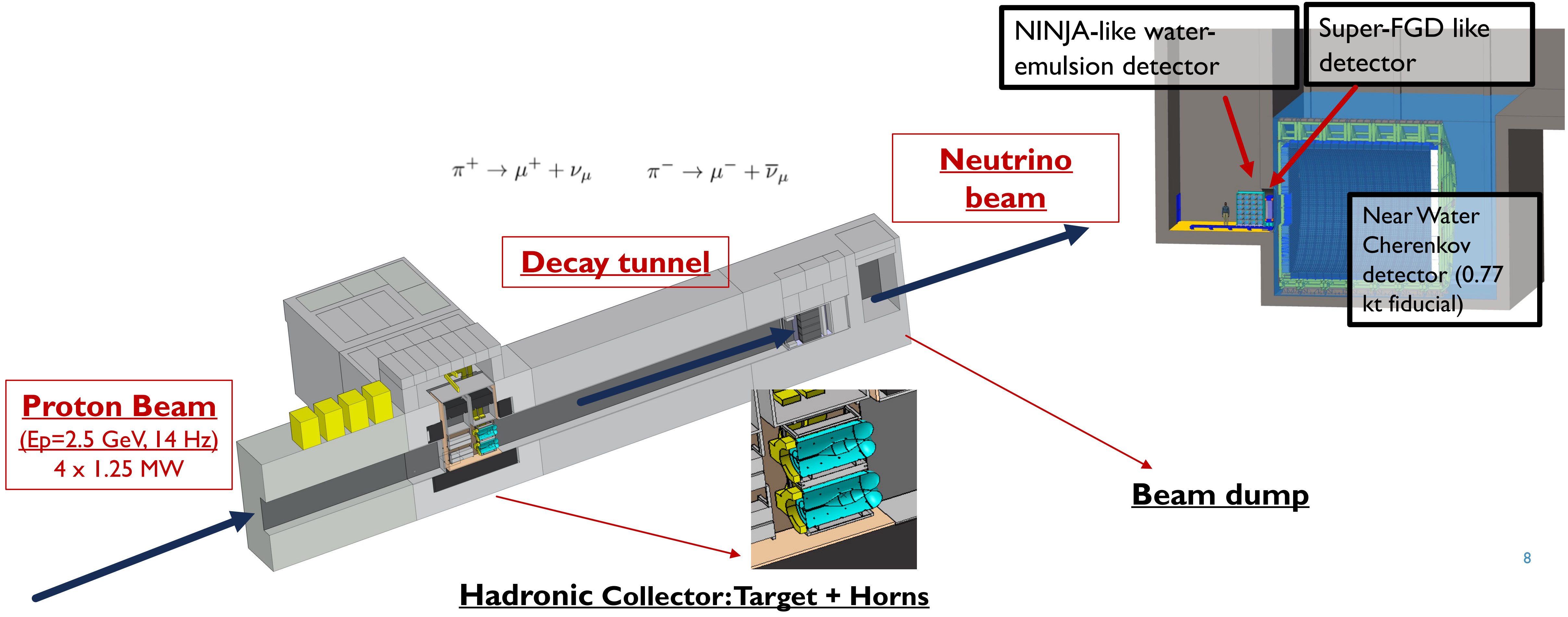
The European Spallation Source neutrino Super Beam (ESSνSB)

UPGRADE OF THE ESS SITE

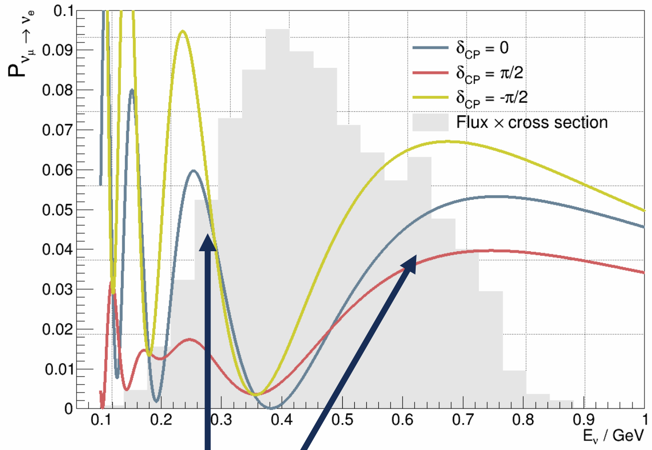


NEUTRINO PRODUCTION: TARGET STATION AND ND

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

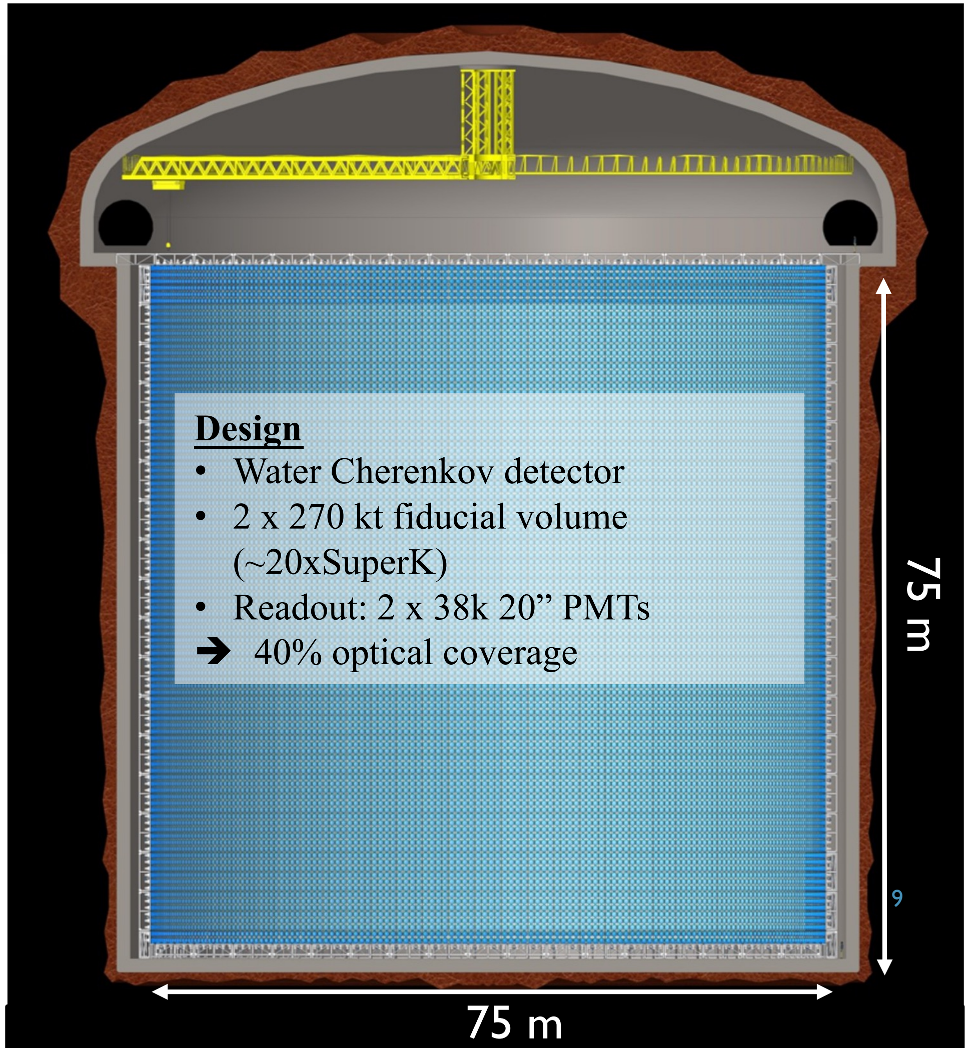


THE FAR DETECTOR



First and second oscillation maxima covered at 360 km baseline!

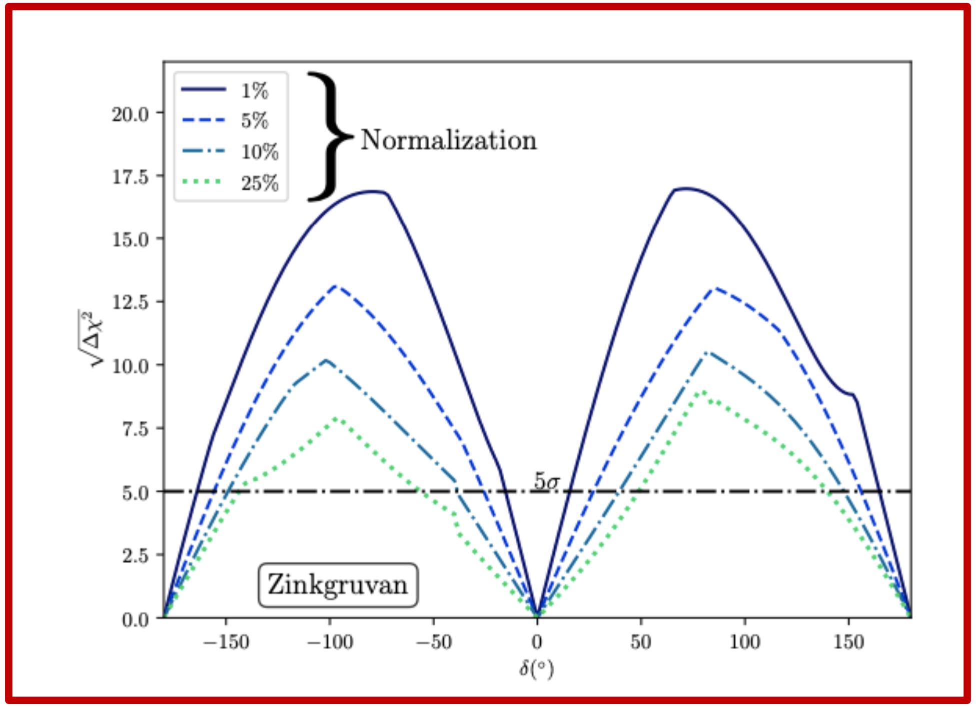
- ➢ Almost pure ν_μ beam
- ➢ Small ν_e contamination -> ν_e cross-sections at the ND



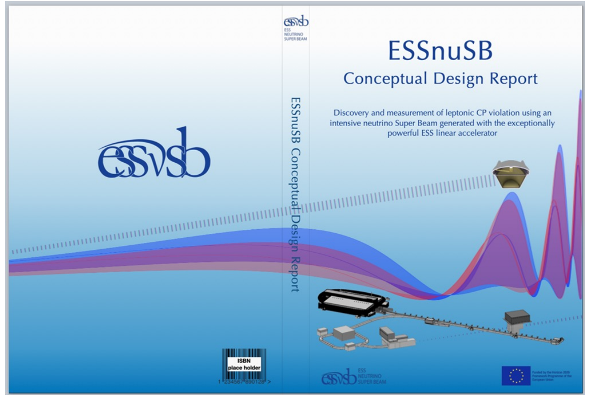
THE PHYSICS AT ESSNUSB

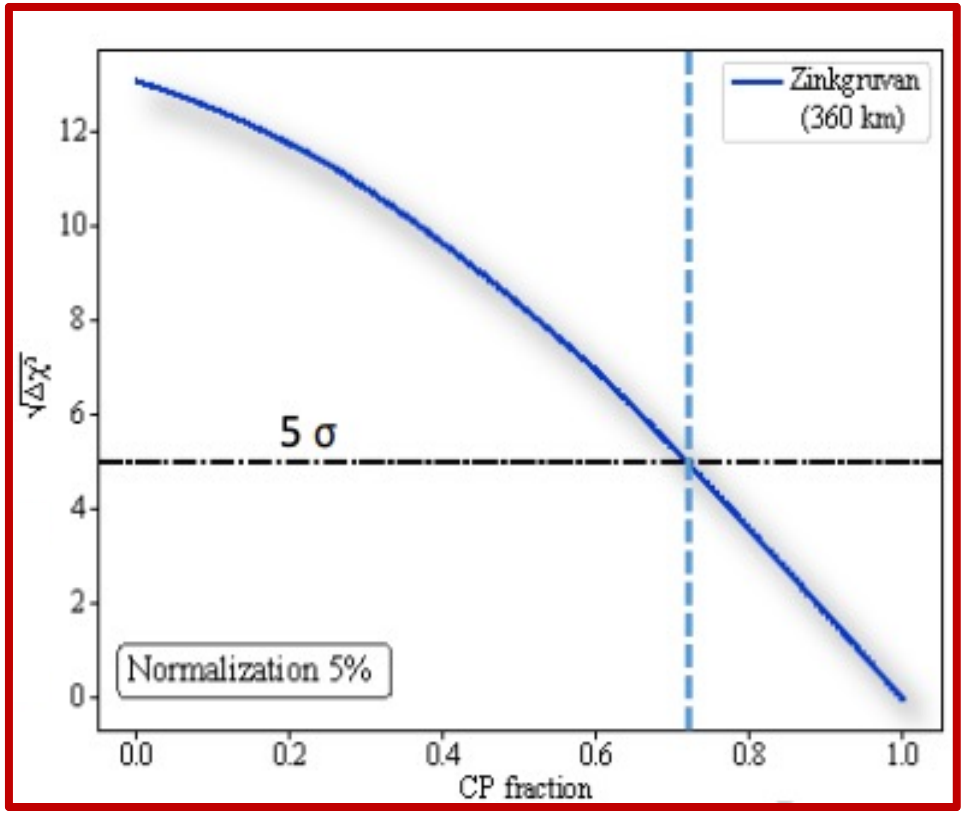
CP VIOLATION

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



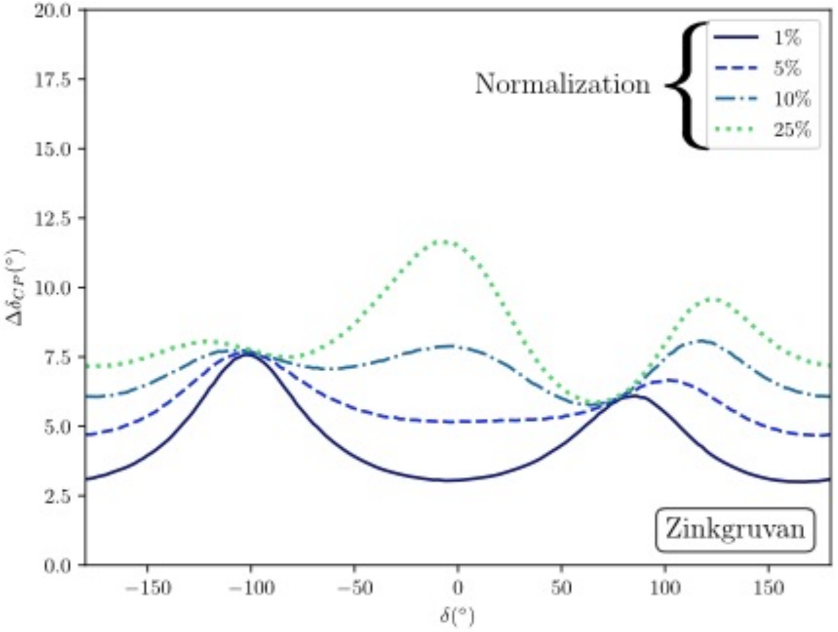
With 5% systematic uncertainty, up to 12.5 σ for maximum CPV!

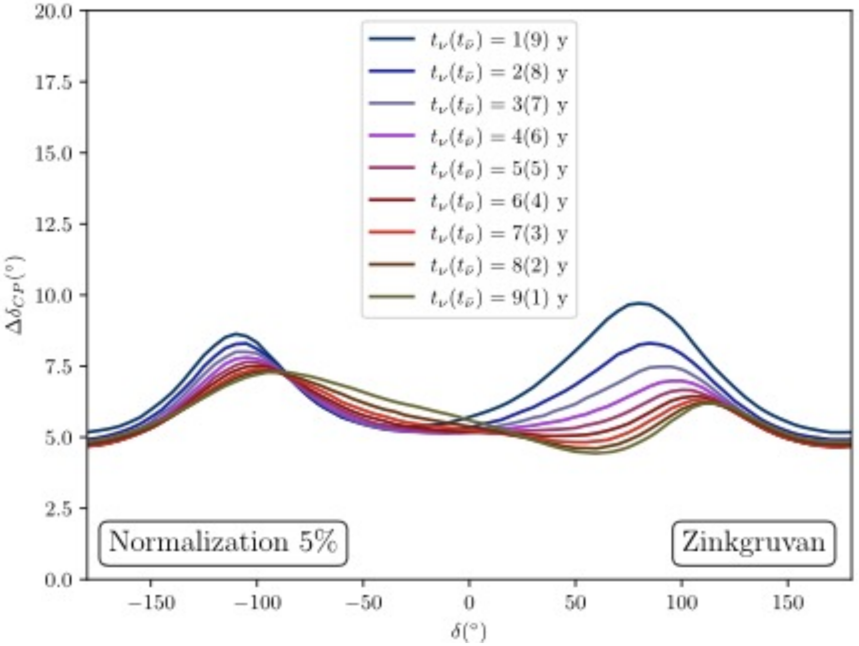




72% CP coverage at 5 σ

CP VIOLATION





CP precision always under 7.5° for 5% sys

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

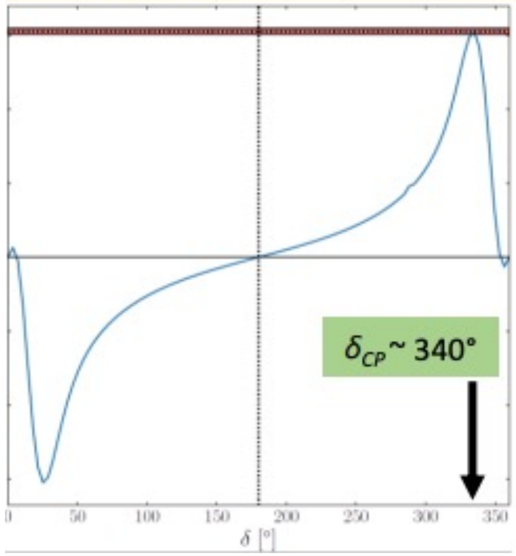
WHY DO WE NEED THIS PRECISION?

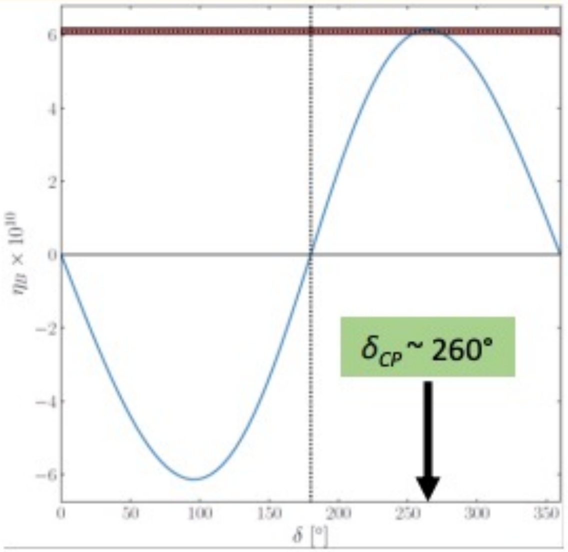
In the precision era for the oscillation measurements, precision is mandatory to probe theories which might explain matter-antimattery asymmetry in the Universe (leptogenesis) and the flavor structure of the SM

Leptogenesis Theories K. Moffat et al., arXiv:1809.08251 (2019)

Low mass flavor regime M_1 (GeV) < 10^9

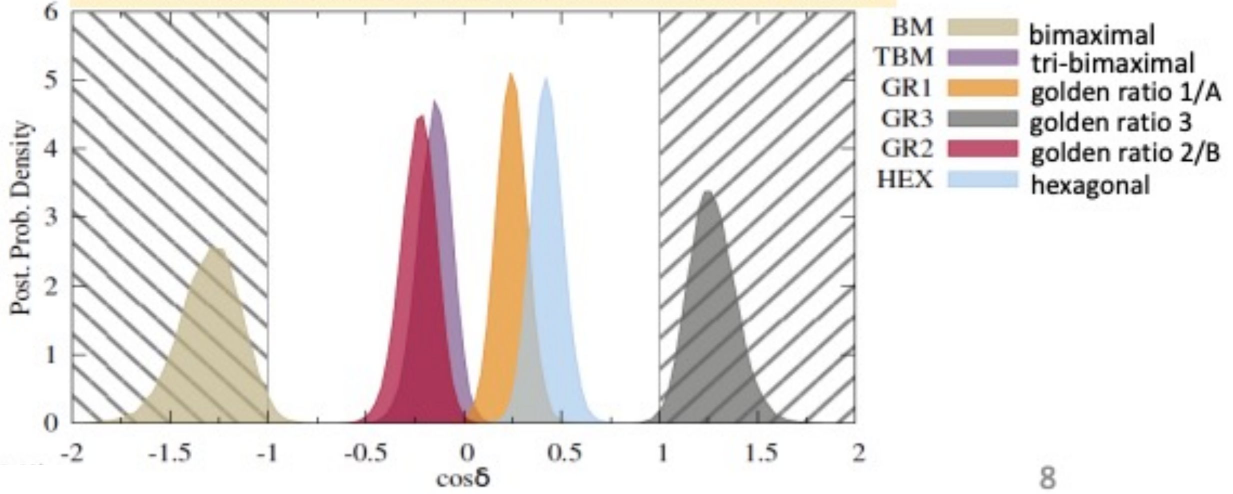
Intermediate mass flavor regime $10^9 < M_1$ (GeV) < 10^{12}





Flavour Theories P. Ballett *et al.*, JHEP12 (2014) 122

four different symmetry forms of the neutrino mixing matrix



δ will need an uncertainty below 12° → only ESSnuSB might reach such value!

(S.T. Petcov, NPB 2024, IAS, HKUST, Hong Kong 20/02/2024)

WHAT ABOUT BSM? THE SCALAR NSI CASE

Non-standard four-fermion interactions between neutrino and matter mediated by heavy scalar particles

$$\mathcal{L}^{eff}_{\text{scalar NSI}} = y_f Y_{\alpha\beta}(\bar{\nu}_\alpha \nu_\beta)(\bar{f} f) \quad \longrightarrow \quad \delta\tilde{M} = \sqrt{\Delta m^2_{31}} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

$$\eta_{\alpha\beta} = \frac{1}{m^2_\phi \sqrt{|\Delta m^2_{31}|}} \sum_f N_f y_f y_{\alpha\beta}.$$

Mediator mass (m_ϕ)

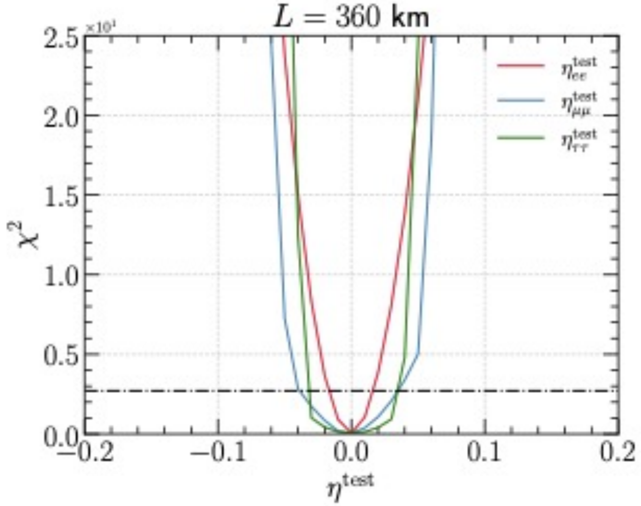
Matter density (N_f)

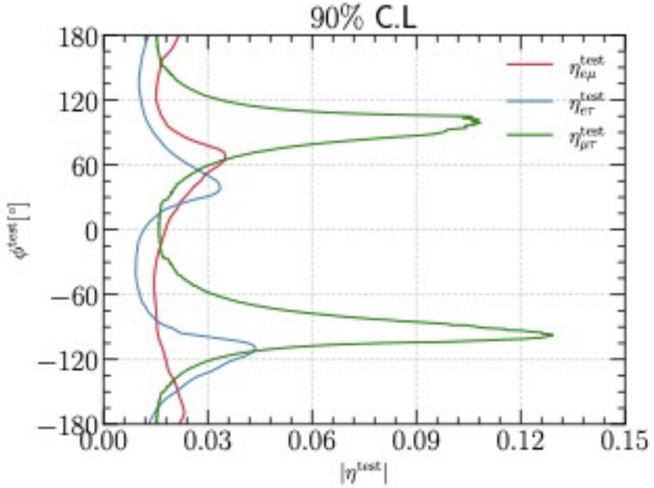
Couplings ($y_f y_{\alpha\beta}$)

Neutrino oscillation probabilities are modified!

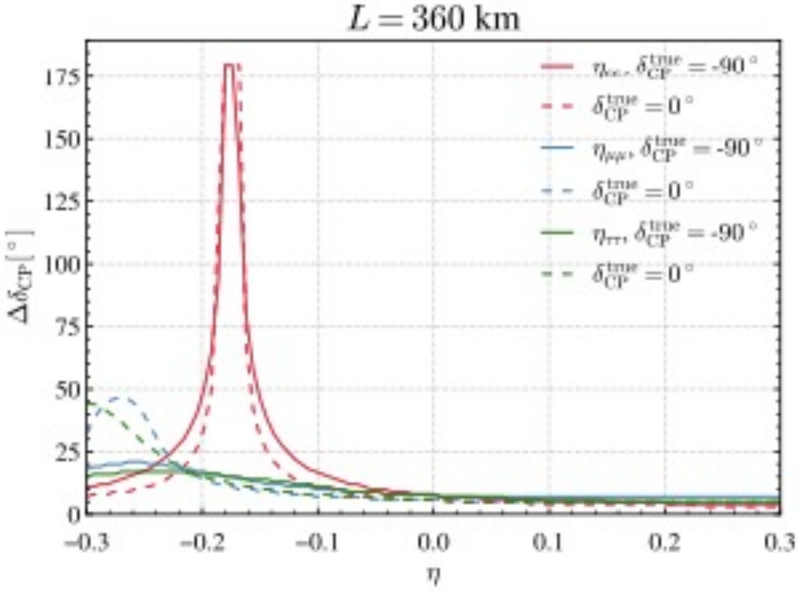
WHAT ABOUT BSM? THE SCALAR NSI CASE

ESSnuSB constraints on scalar NSI parameters





CP violation precision unaffected except for specific (very big and already excluded) values of etas for which standard oscillation are suppressed



PRD109, (2024) 115010

WHAT ABOUT BSM? THE DECOHERENCE CASE

Coherence in different neutrino mass eigenstates may get lost because, for instance, of interaction of neutrinos with the environment

$$\frac{\partial \rho(t)}{\partial t} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

$$\mathcal{D}[\rho(t)] = \frac{1}{2} \sum_{i=1}^{N^2-1} \left([\mathcal{L}_i, \rho(t)\mathcal{L}_i^\dagger] + [\mathcal{L}_i \rho(t), \mathcal{L}_i^\dagger] \right)$$

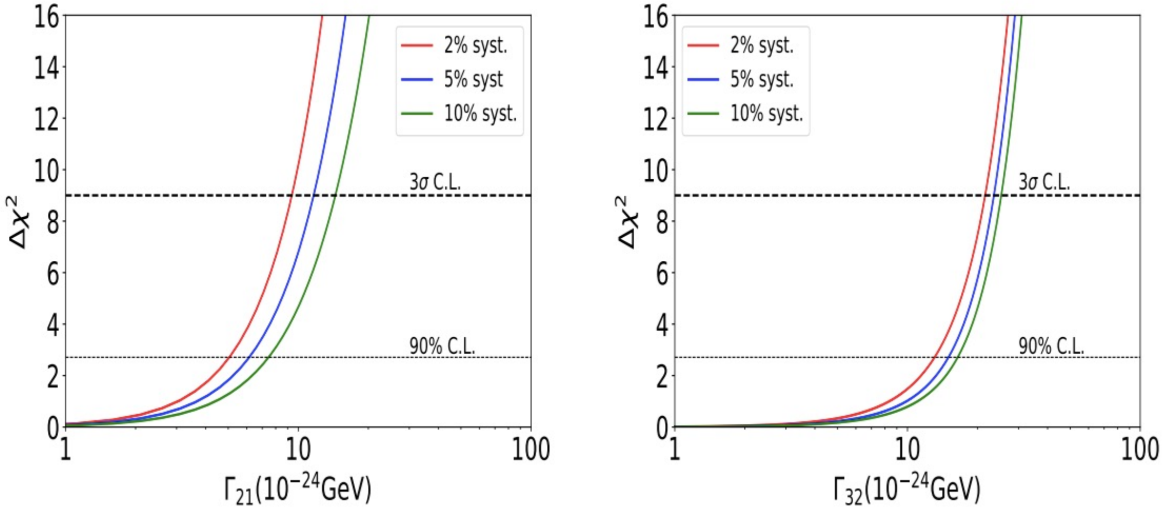
Dissipator → Probability dumping

We choose one particular form $\mathcal{D} = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$

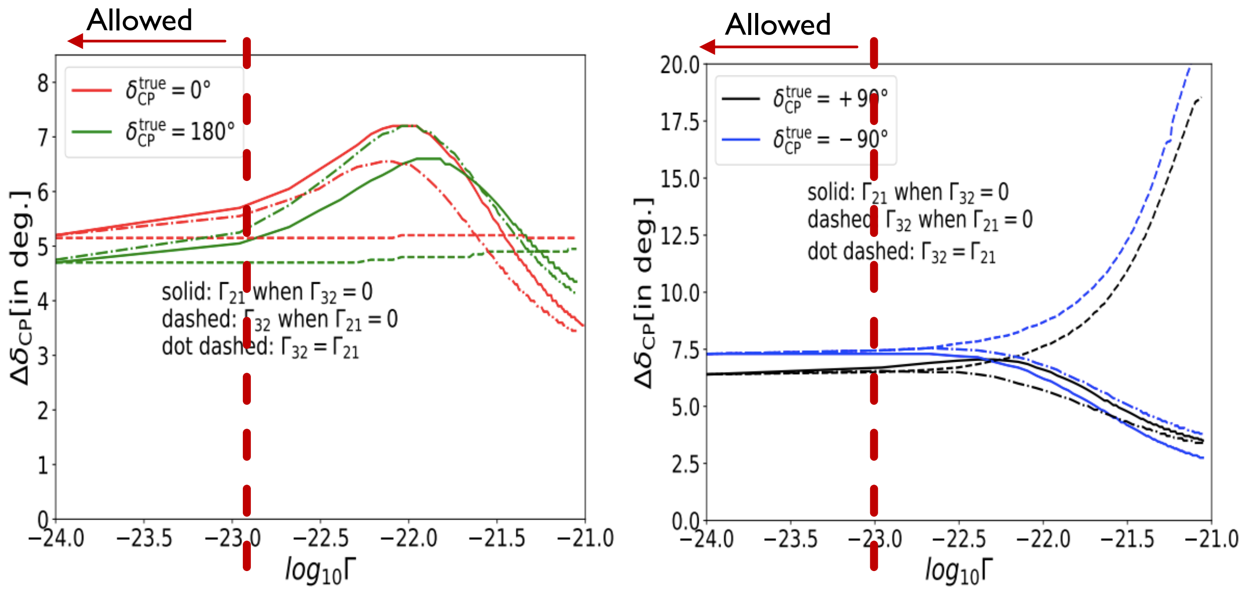
with $\Gamma_{31} = \Gamma_{21} + \Gamma_{32} - 2\sqrt{\Gamma_{21}\Gamma_{32}}$

WHAT ABOUT BSM? THE DECOHERENCE CASE

ESSnuSB constraints on decoherence parameters



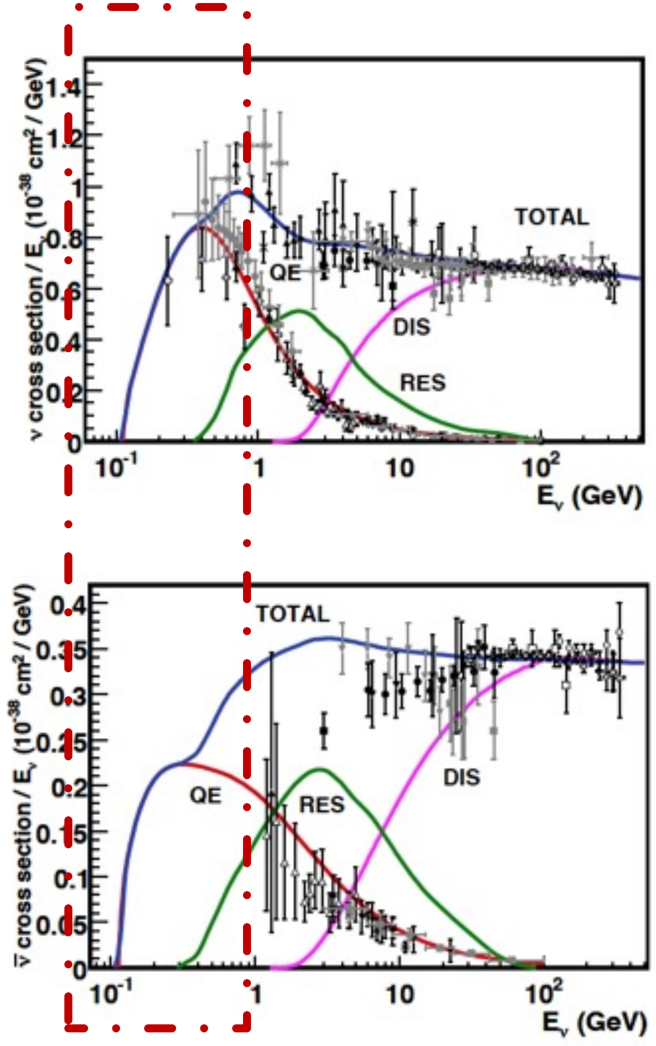
CP violation precision unaffected for reasonable values of the decoherence parameters



arXiv:2404.17559, accepted in JHEP

THE FUTURE: ESSNUSB+

THE LOW ENERGY NEUTRINO CROSS SECTION



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

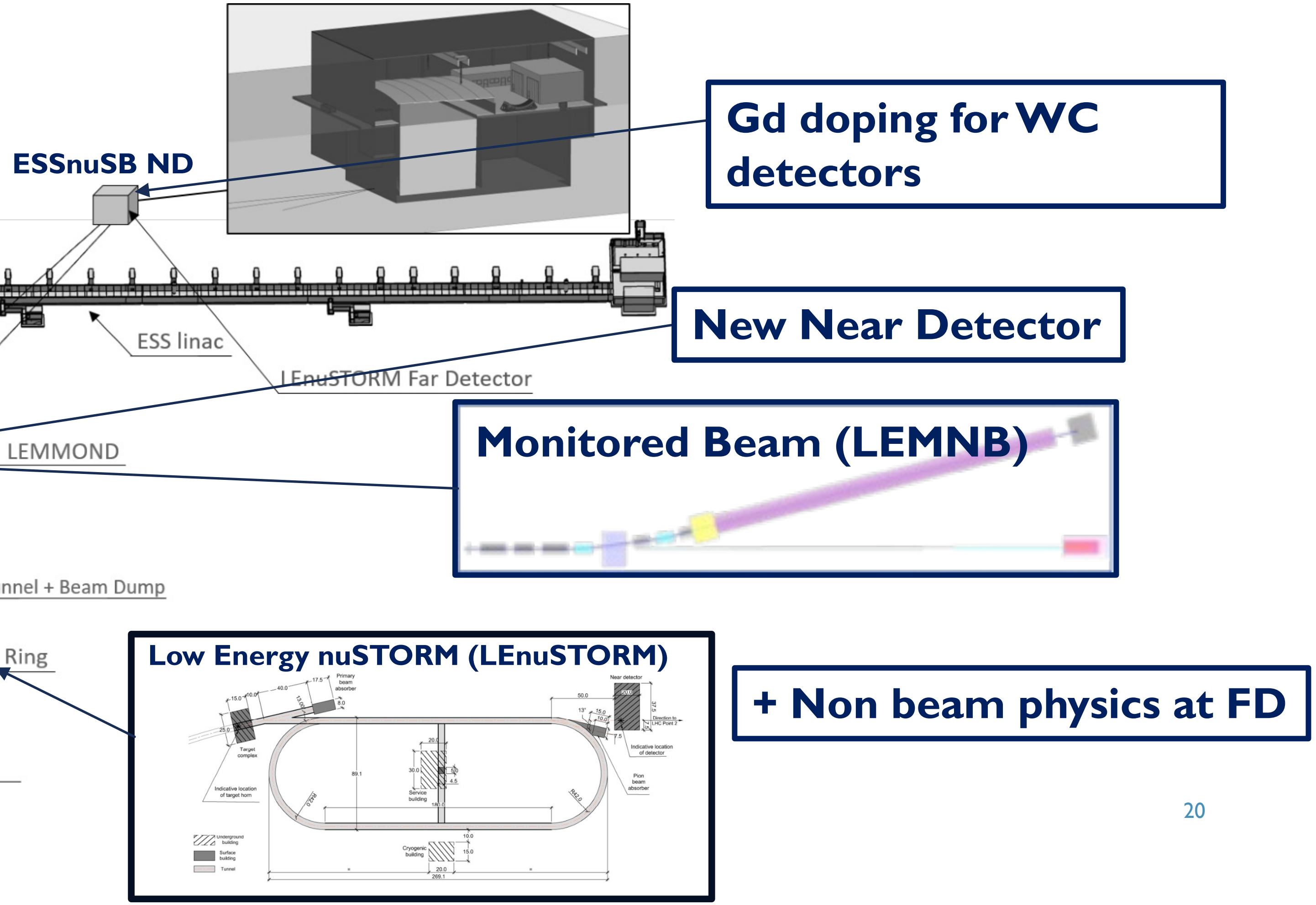
Even though the effect of systematics for the CP violation measurement is much less in ESSnuSB is crucial to obtain new precise results in this direction

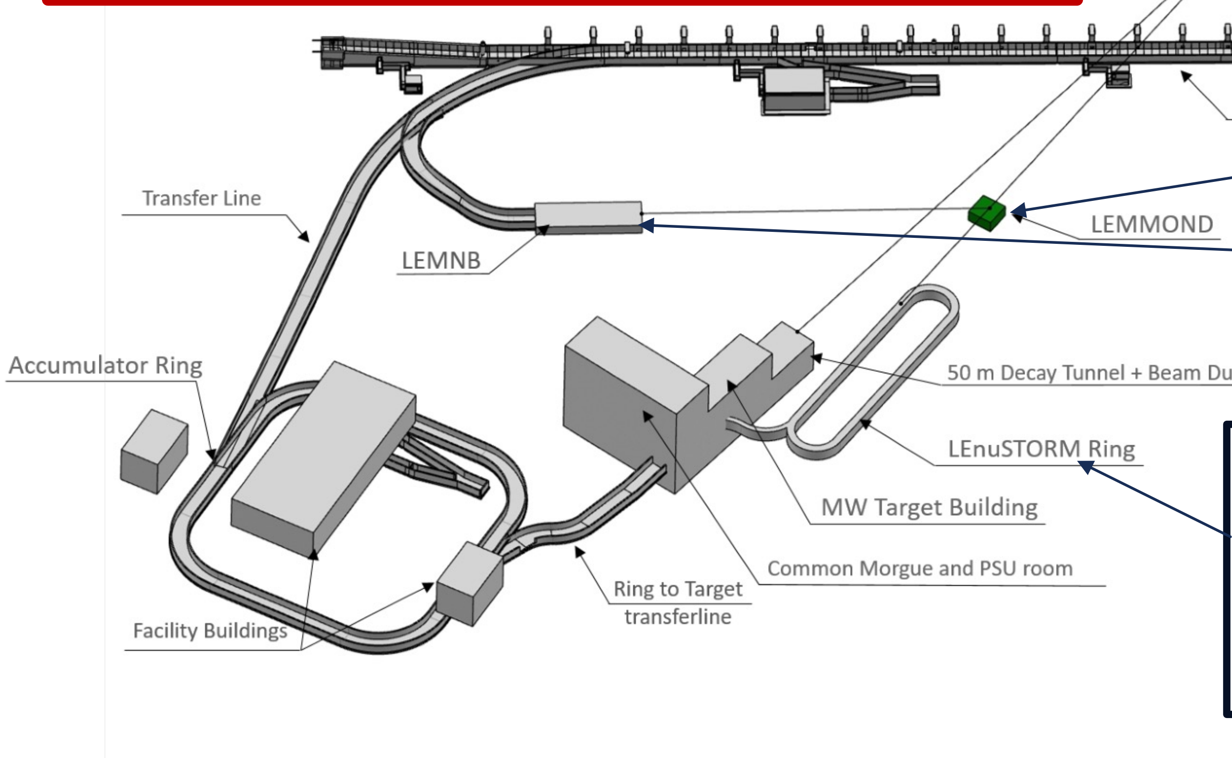
From eV to EeV: Neutrino cross sections across energy scales, *Rev. Mod. Phys. 84, 1307* – *Published 24 September 2012*

ESSNUSB+

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+

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

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

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

- 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 large far detectors can also be used for rich BSM studies

- The ESSnuSB Design Study has been supported by EU-Horizon 2020 during the period 2018-2022 and the ESSnuSB+ Project which started in 2023 has further enriched the great physics program of the experiment

ESS neutrino Super Beam plus

Co-funded by
the European Union

Δημόκριτος

Св. Климент Охридски

Çukurova University 1973

Università degli Studi di Milano Bicocca

CERN

Luleå University of Technology

ess

Université de Strasbourg

Roma Tre Università degli Studi

Università degli Studi di Padova

Aristotle University of Thessaloniki

Uppsala Universitet

Lunds Universitet

KTH Vetenskap och Konst

名古屋大学
Nagoya University

INFN Istituto Nazionale di Fisica Nucleare

cnrs

IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg

AGH

Universiteit Gent

ESS bilbao

Universität Hamburg
Der Forschung | Der Lehre | Der Bildung

Hellenic Open University

RB

THANK YOU FOR YOUR ATTENTION

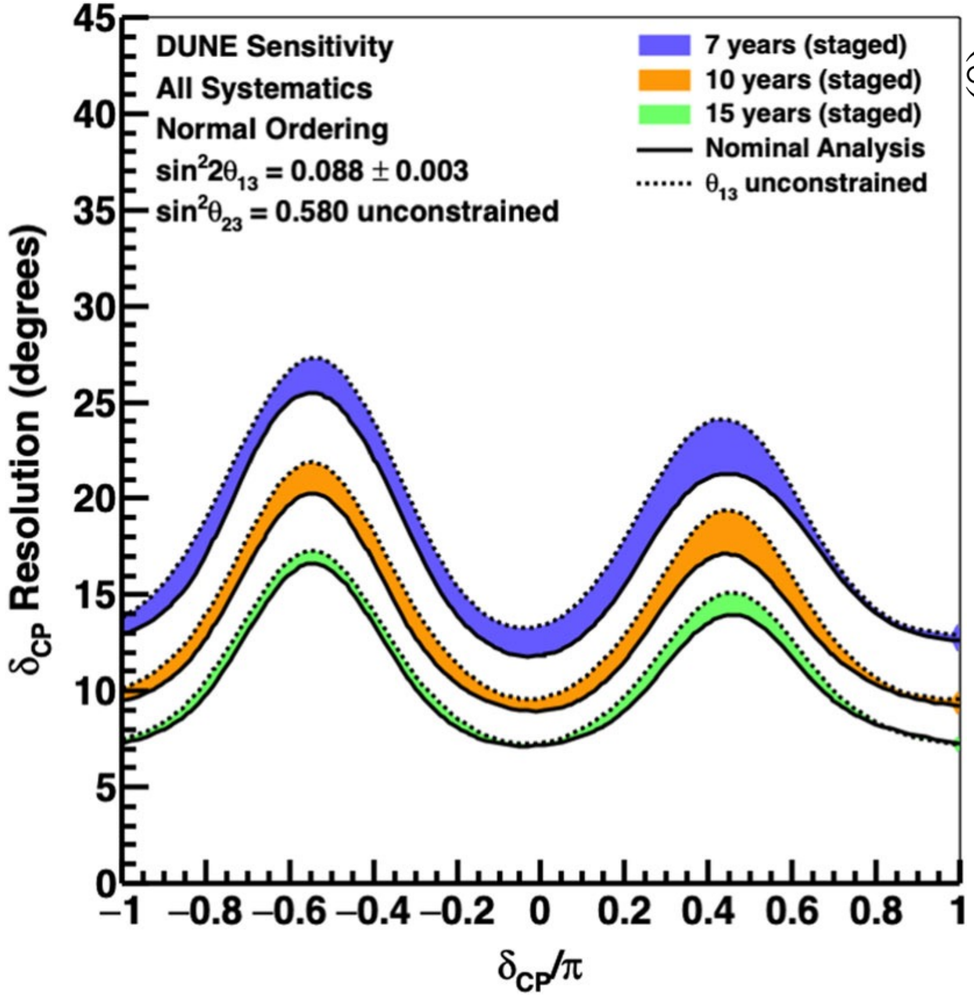
BACKUP

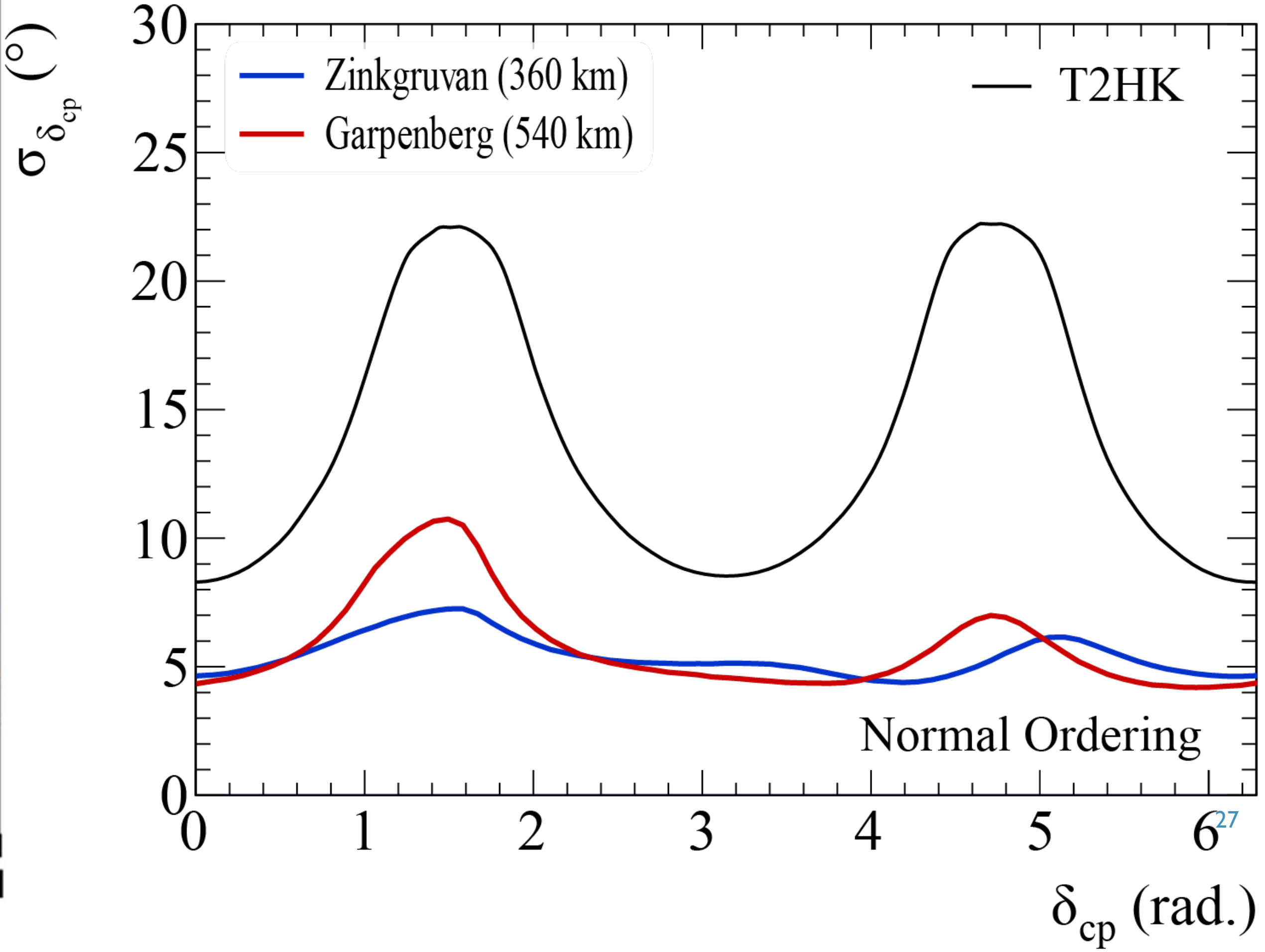
SYSTEMATICS

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 × 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%

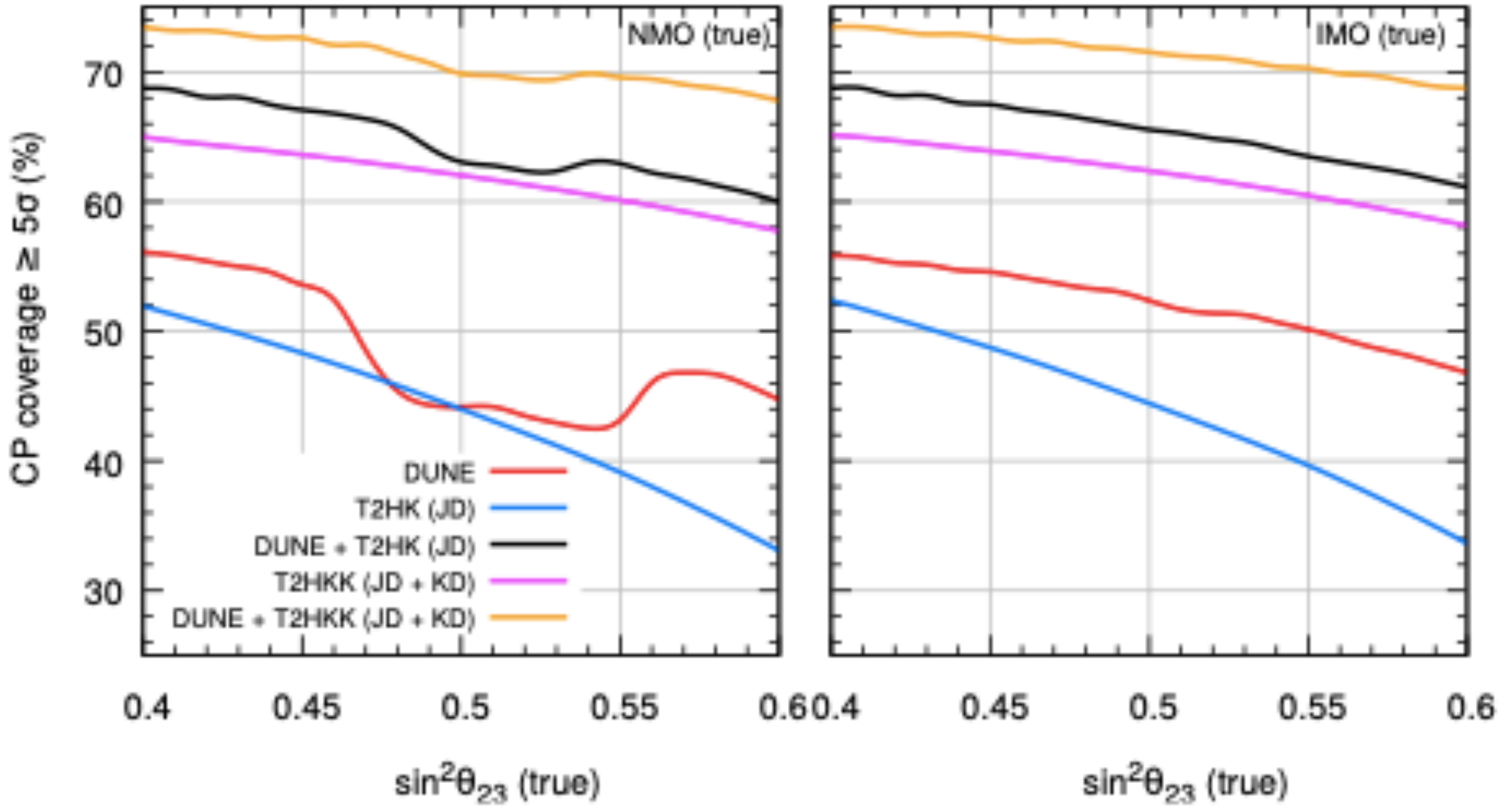
Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

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

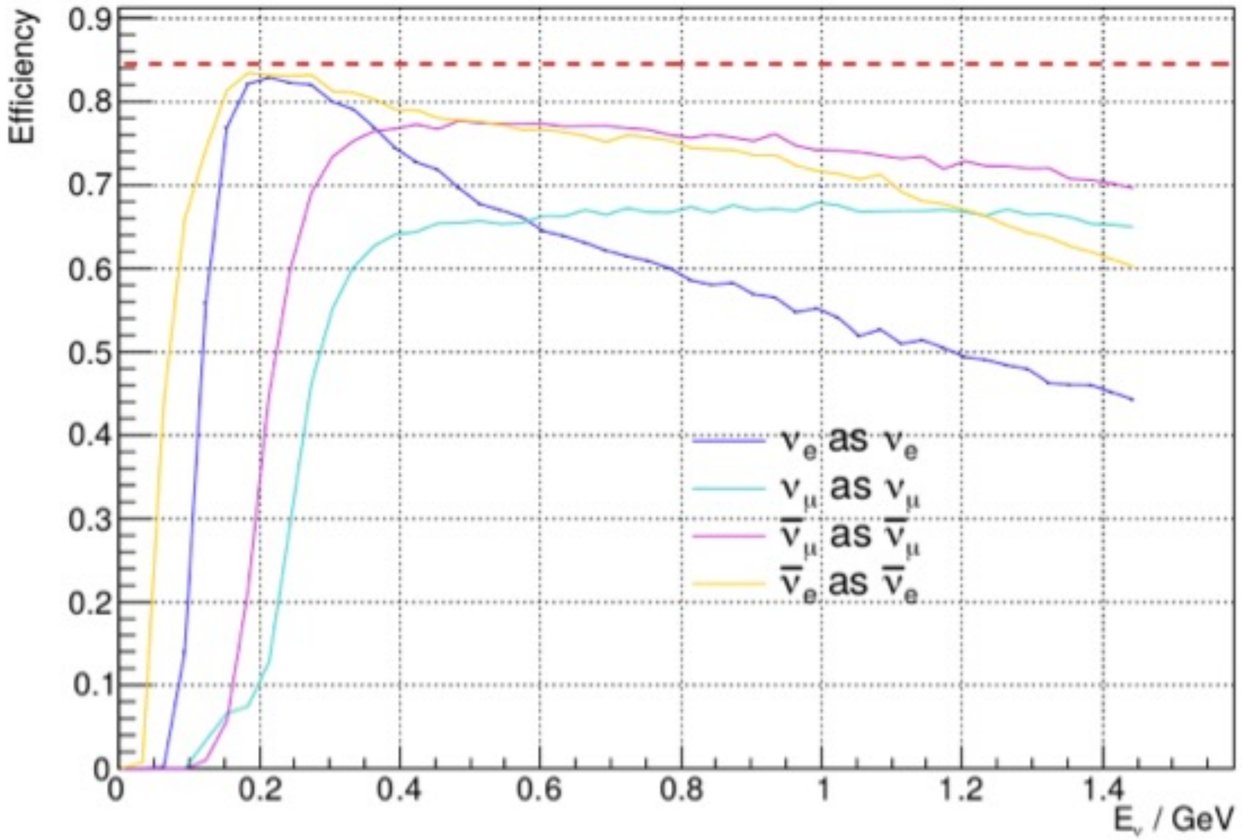
	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	272.22 (63.75)	578.62 (101.18)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	31.01 (3.73)	67.23 (11.51)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	67.49 (7.31)	151.12 (16.66)
	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)

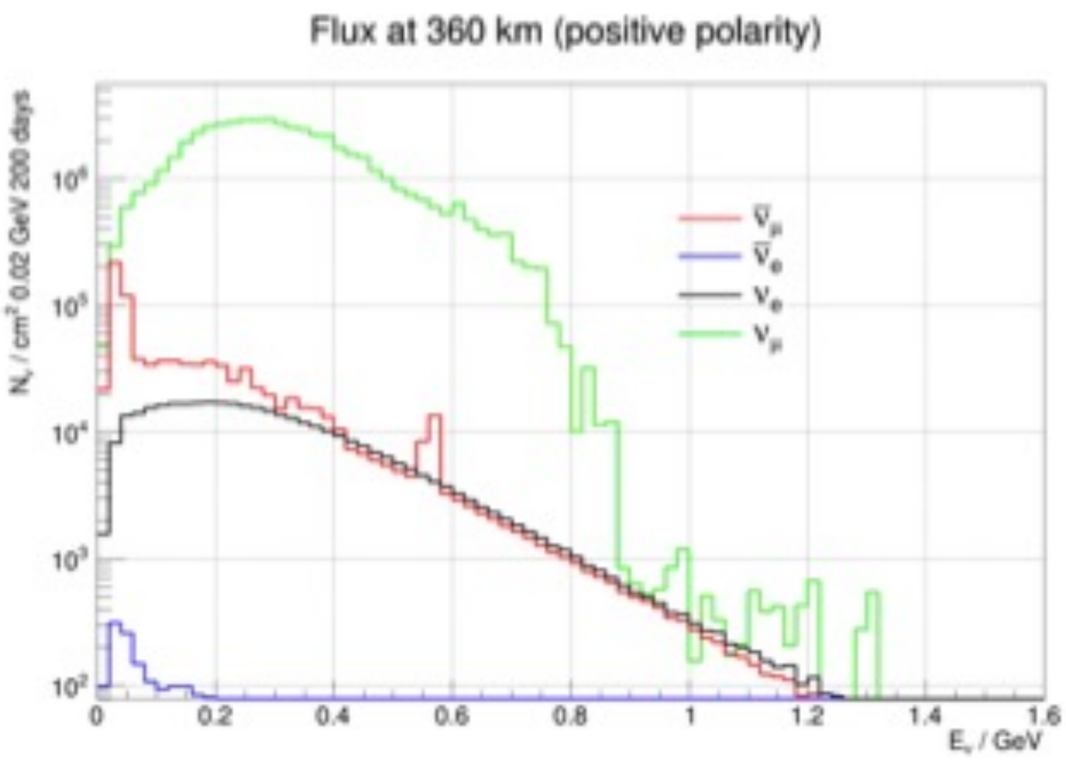
Table 2: Signal and major background events for the disappearance channel corresponding to positive (negative) polarity per year for $\delta_{CP} = 0°$.

EFFICIENCY

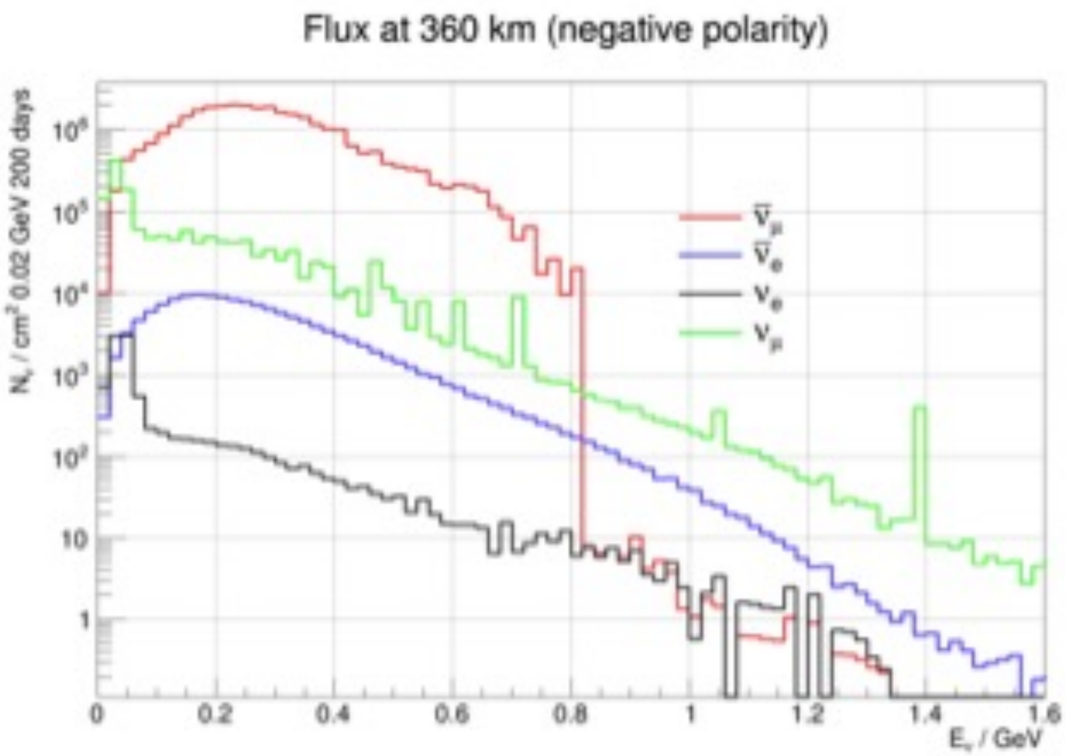


Efficiency
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
E_ν / GeV
ν_e as ν_e
ν_μ as ν_μ
$\bar{\nu}_\mu$ as $\bar{\nu}_\mu$
$\bar{\nu}_e$ as $\bar{\nu}_e$

FLUXES

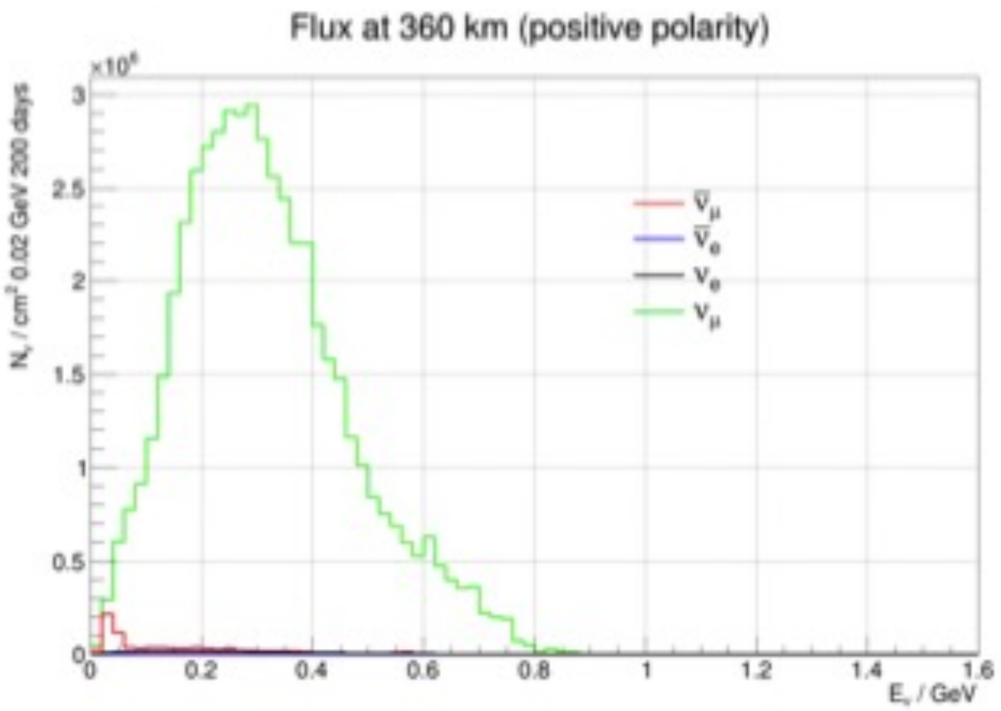


Flux at 360 km (positive polarity)
N_ν / cm^2 0.02 GeV 200 days
E_ν / GeV
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
ν_μ

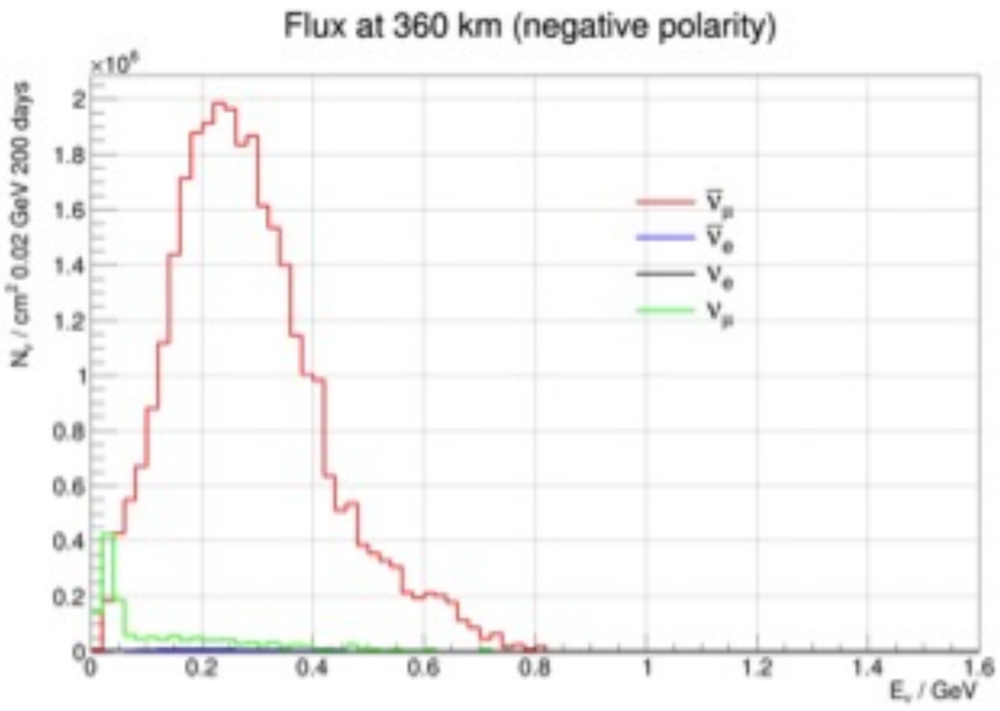


Flux at 360 km (negative polarity)
N_ν / cm^2 0.02 GeV 200 days
E_ν / GeV
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
ν_μ

FLUXES



Flux at 360 km (positive polarity)
×10^6
3
2.5
2
1.5
1
0.5
0
N_ν / cm² 0.02 GeV 200 days
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
E_ν / GeV
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
ν_μ



Flux at 360 km (negative polarity)
×10^6
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
N_ν / cm² 0.02 GeV 200 days
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
E_ν / GeV
$\bar{\nu}_\mu$
$\bar{\nu}_e$
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

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

New sources of CP violation!

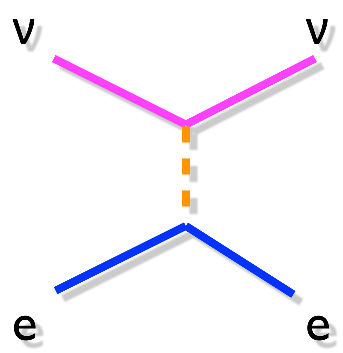
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[\frac{1}{2E_\nu}U\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0 & 0\\ 0 & 0 & \Delta m^2_{31} & 0\\ 0 & 0 & 0 & \Delta m^2_{41}\end{pmatrix}U^\dagger + \begin{pmatrix}A_{CC}+A_{NC} & 0 & 0 & 0\\ 0 & A_{NC} &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

BSM: NU

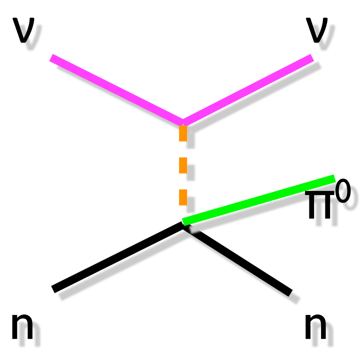
$$N = (1 + \alpha) U_{PMNS} \cdot$$

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

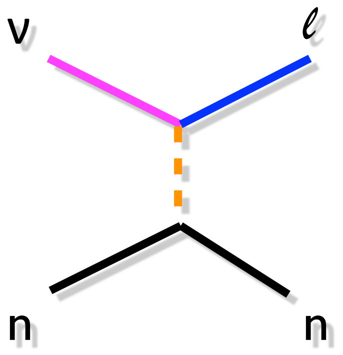
NEUTRINO INTERACTIONS



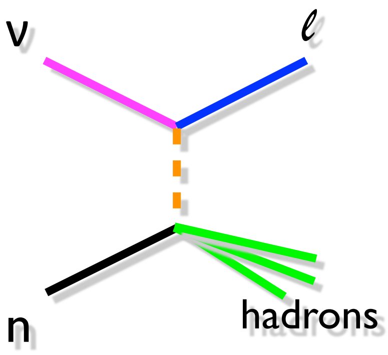
Elastic



Resonant (RES)

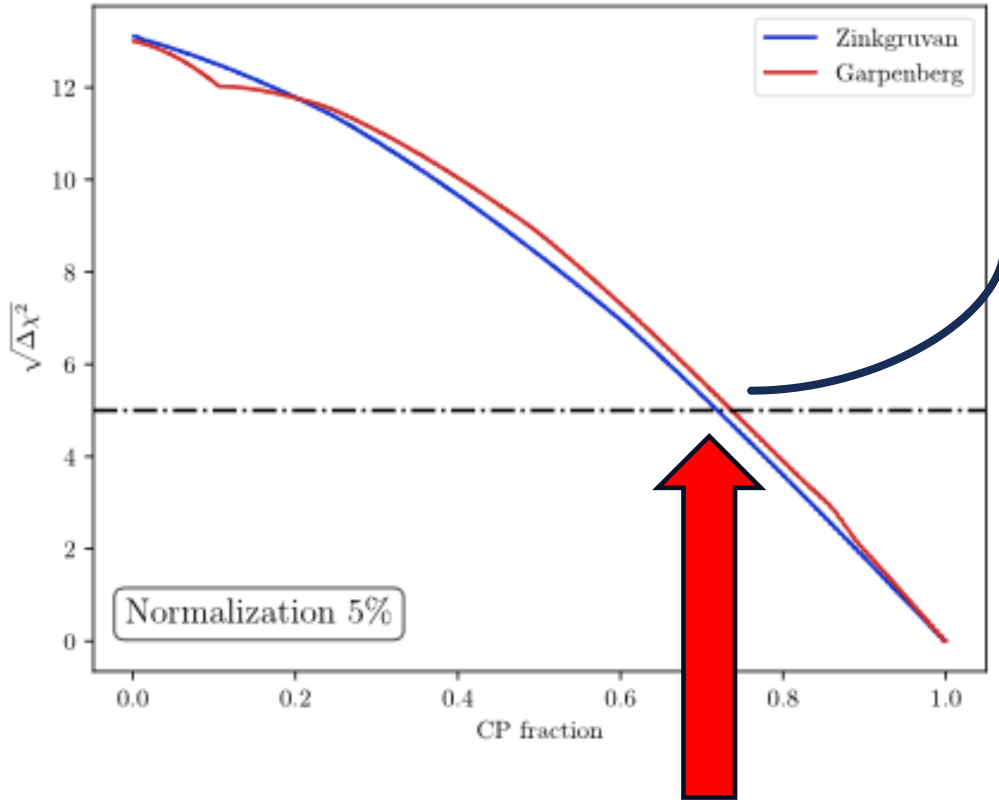


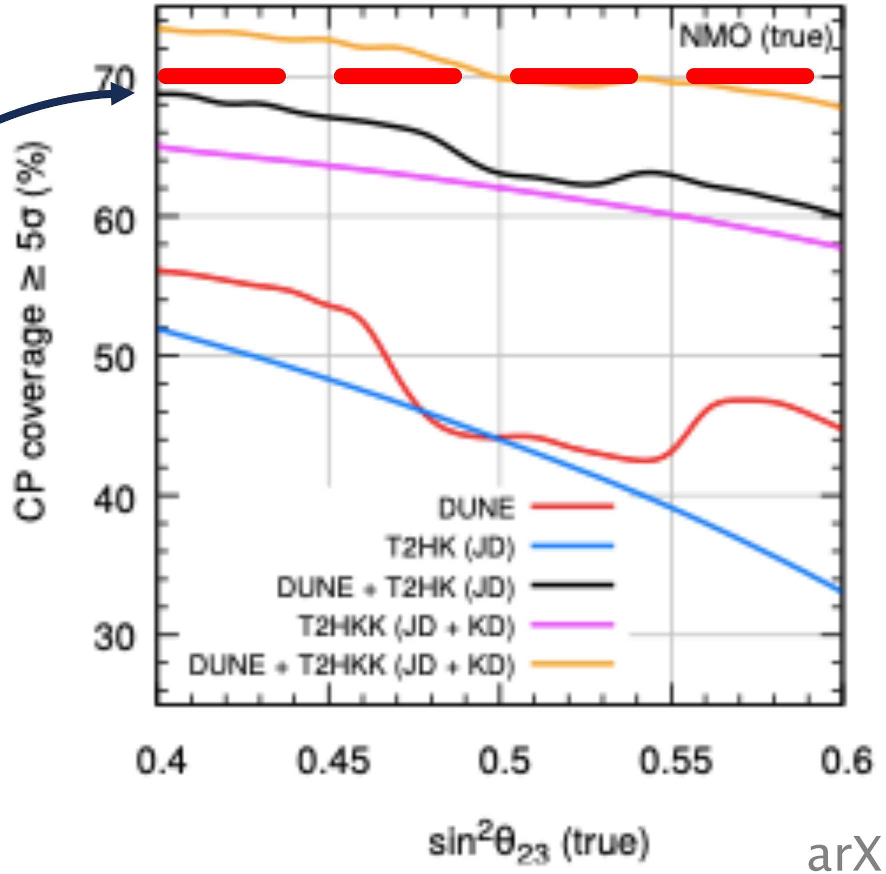
Quasi-Elastic (QE)



Deep inelastic (DIS)

COMPARISON WITH NEXT-GEN LBL



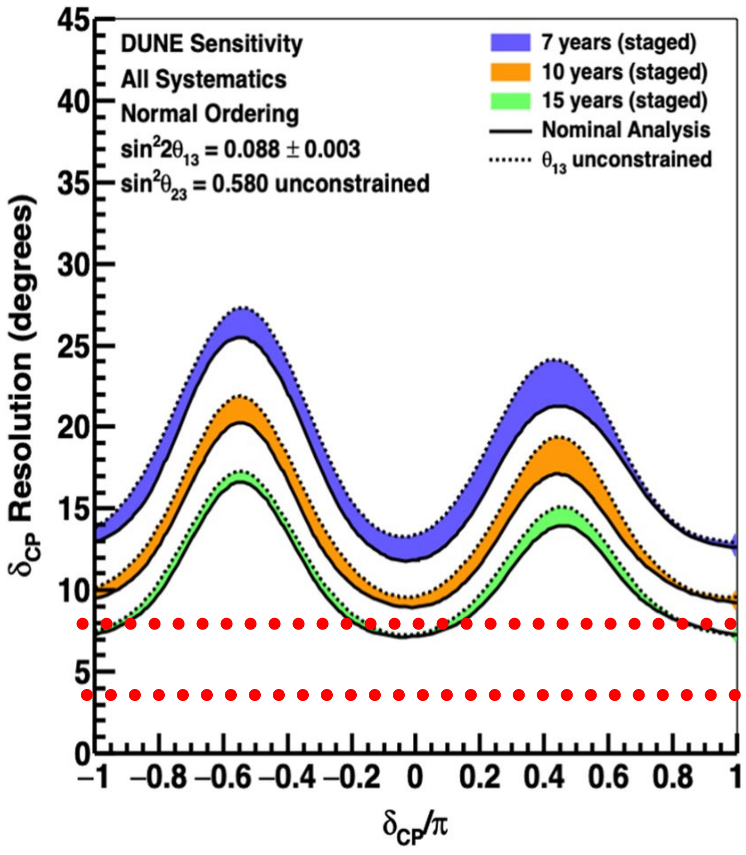


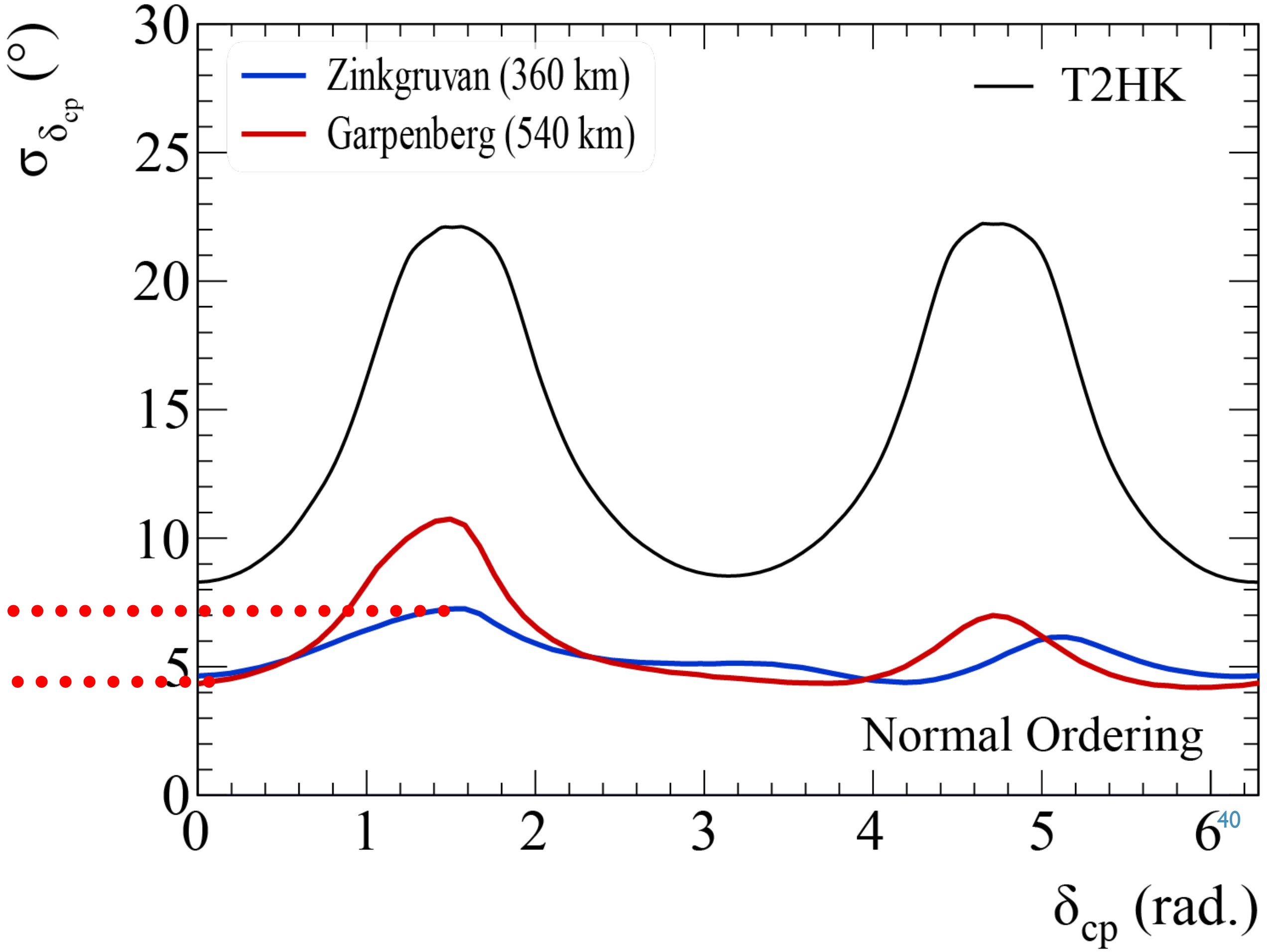
The same coverage might be reached only by DUNE+T2HKK (also, next-to-next gen proposed upgrade of T2HK) for LO values of th23

arXiv:2211.10620

COMPARISON WITH NEXT-GEN LBL

Great improvement with respect to DUNE and T2HK!!





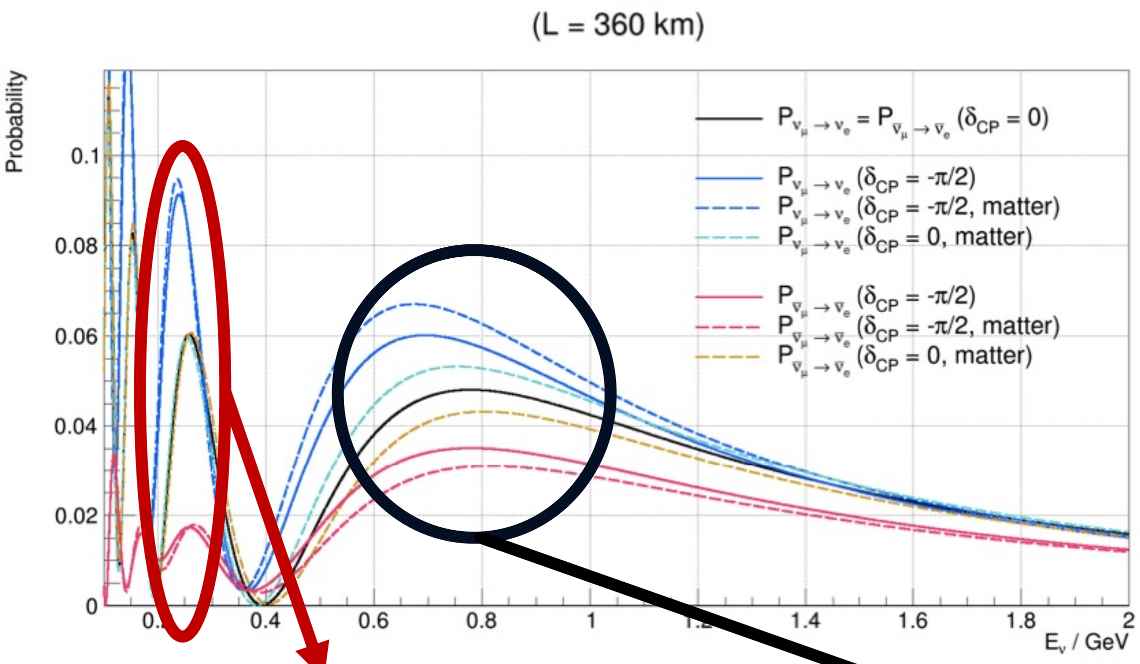
OSCILLATION PHYSICS AT THE SECOND MAXIMUM

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

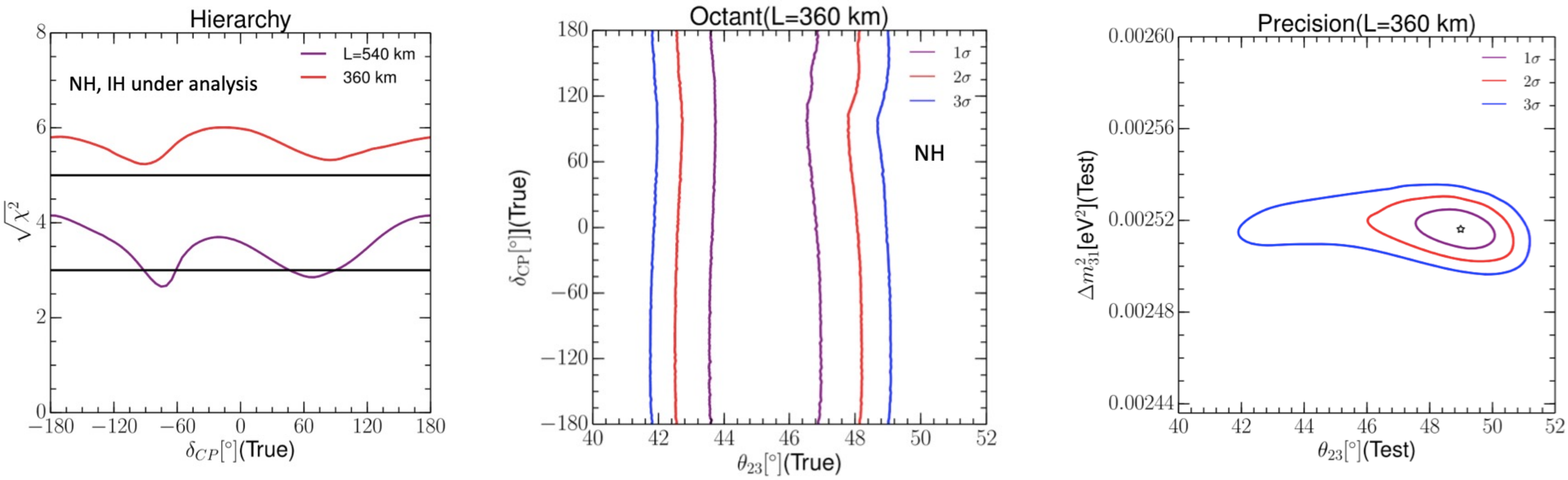
FAKE CP VIOLATION



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

First maximum, matter and CP phase have the same effect

OSCILLATION BEYOND CPV



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

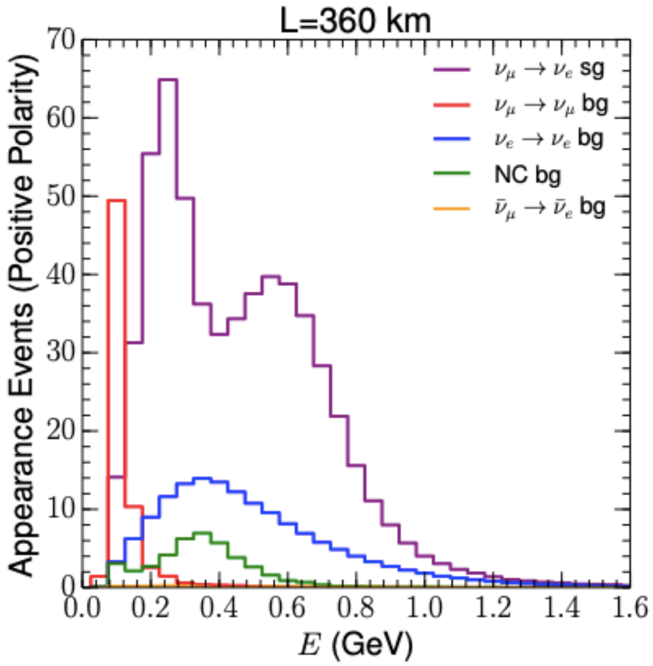
THE EVENT SPECTRA AT 360 KM

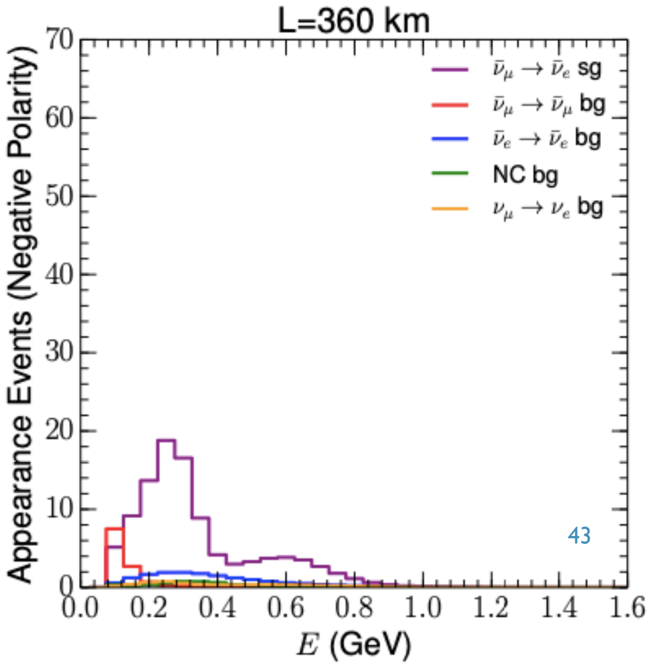
Table 29 Number of expected neutrino interactions in the detector per running year, per flavour and interaction type, and per each horn polarity

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

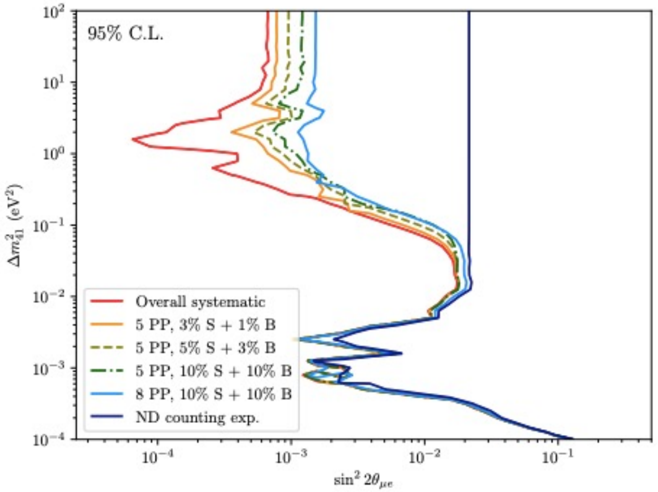
Initial flux

At FD w oscillation



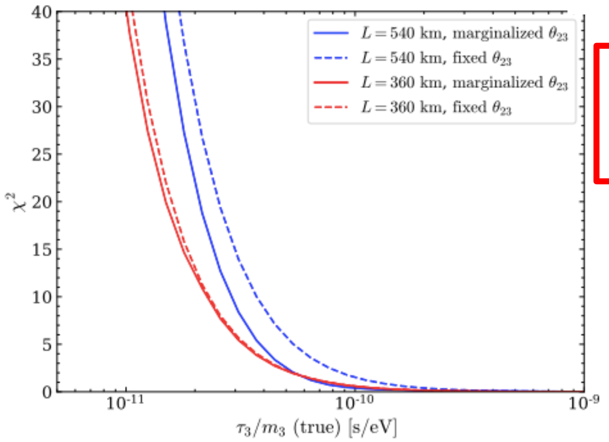


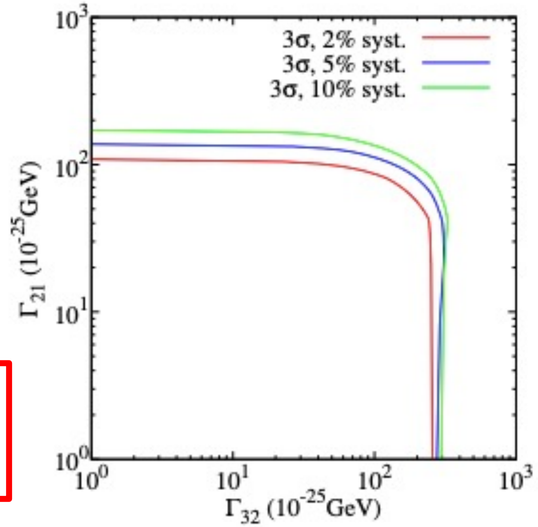
WHAT ABOUT BSM?



Light sterile neutrino [JHEP03(2020)026]

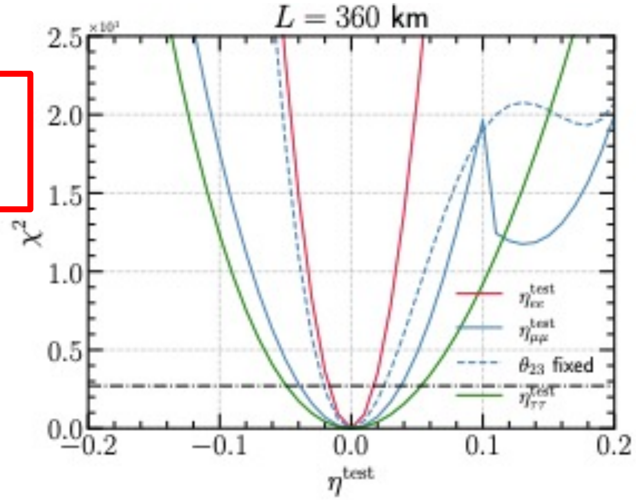
Neutrino invisible decay [JHEP 05 (2021), 133]





Quantum Decoherence [arXiv:2404.17559]

Scalar NSI [PRD109, (2024) 115010]

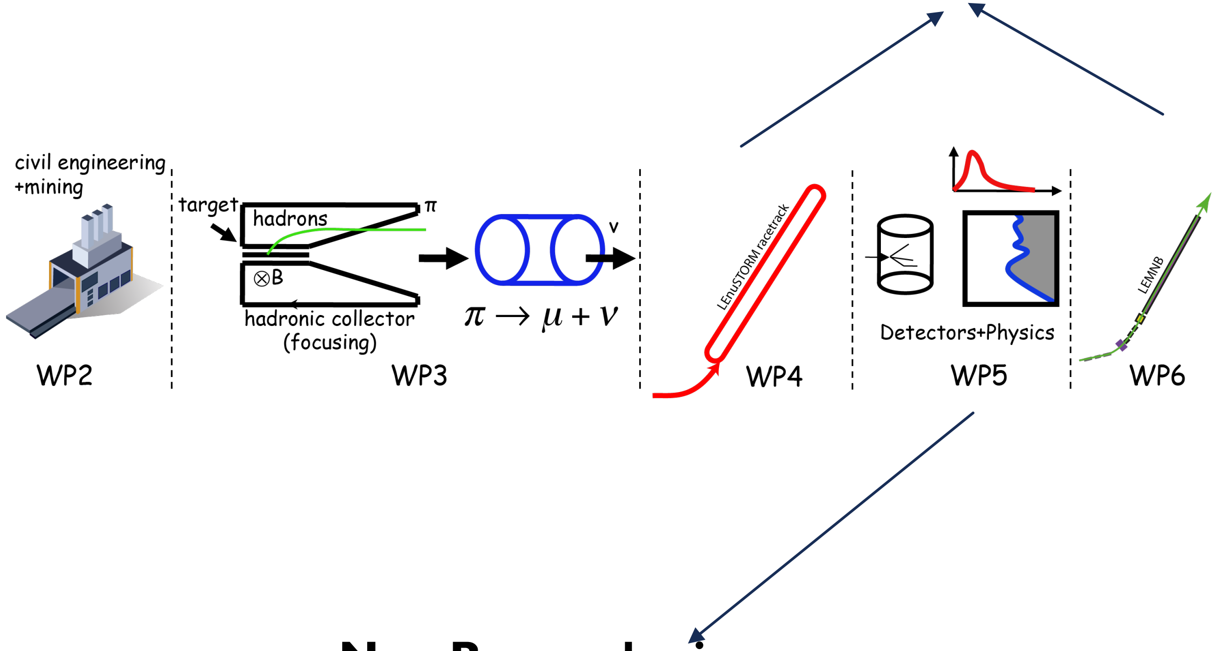


ESSNUSB+

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



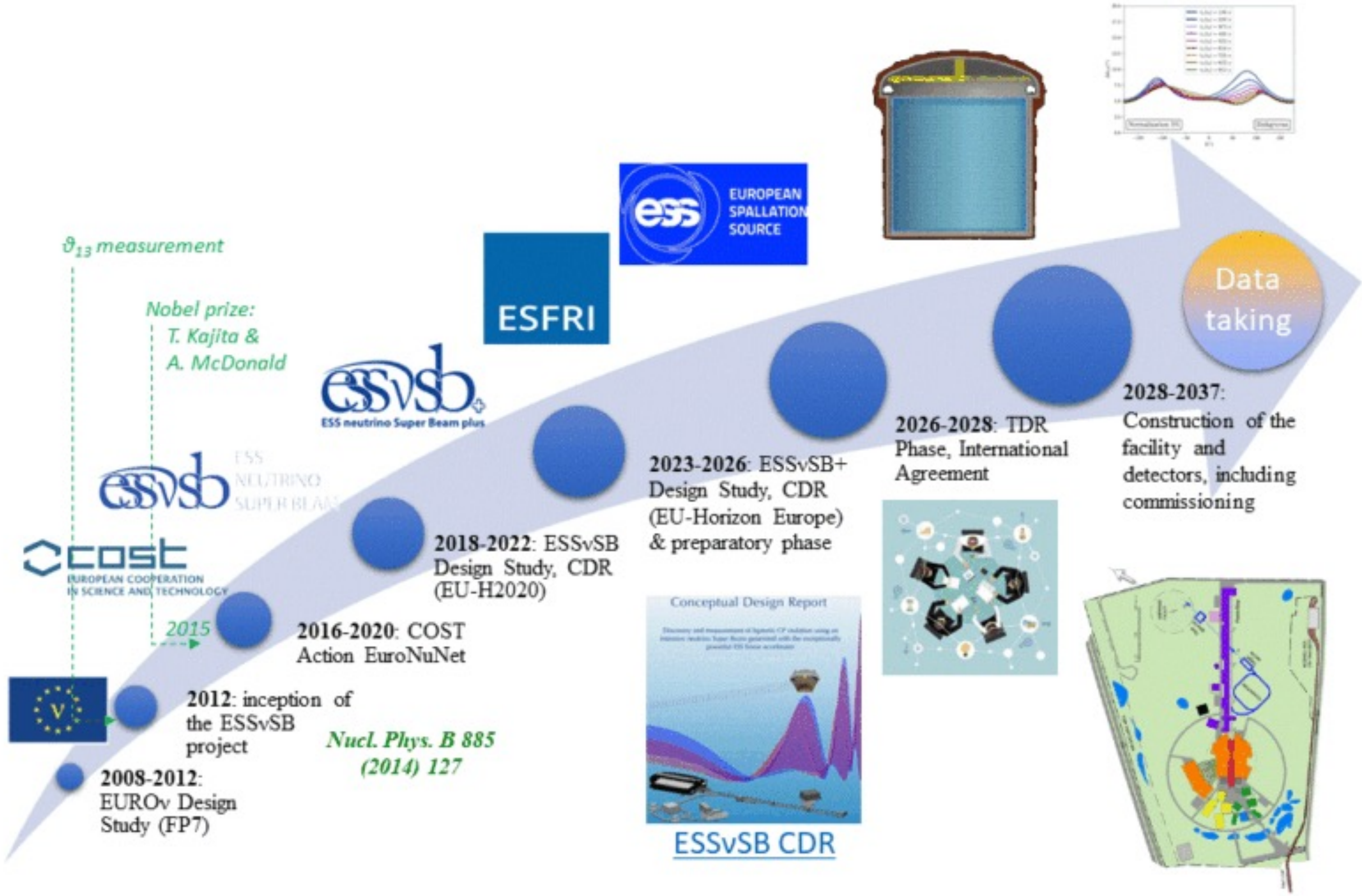
Non Beam physics:

-Atmospheric

-Supernovae

-…

TIMELINE



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