NEW PHYSICS SEARCHES AT DUNE

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DUNE-INDIA Meeting, TIFR, Mumbai, 6 June 2025

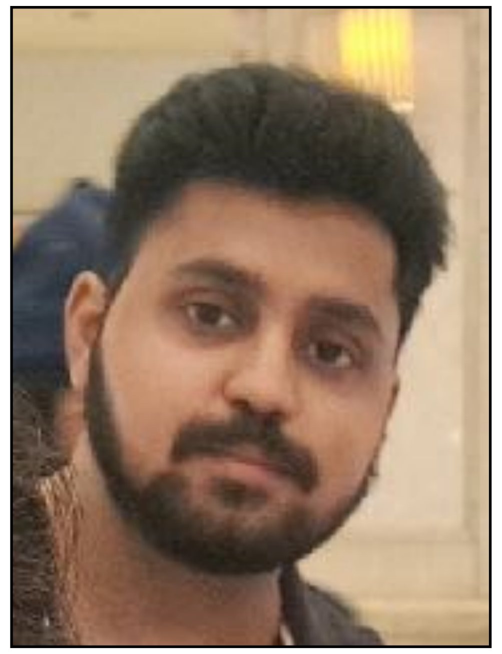
Our group

PhD students

- Sabila Parveen (expected to submit in 2025)
- Sheeba Shafaq (2022)
- Samiran Roy (2020), Rajendran Raja fellow
- Jogesh Rout (2020), Rajendran Raja fellow
- Kritika Rushiya (2022-)
- Pawan Kumar (2023-)
- 2 more students and 1 postdoc





Collaborators

- Mary Bishai
- Mehedi Masud


Plan

- Our group and Focus area
- Summary of DUNE related work
- Future possible contribution

Publications

Masud, Chattejee and Mehta, Probing CP violation signal at DUNE in presence of non-standard neutrino interactions, *J.Phys.G 43 (2016) 9, 095005* #CITATIONS = 101

Masud and Mehta, Nonstandard interactions and resolving the ordering of neutrino masses at DUNE and other long baseline experiments, *Phys.Rev.D* 94 (2016) 5, 053007 #CITATIONS = 73

Masud and Mehta, Nonstandard interactions spoiling the CP violation sensitivity at DUNE and other long baseline experiments, *Phys.Rev.D* 94 (2016) 013014 #CITATIONS = 89

Rout, Masud and Mehta, Can we probe intrinsic CP and T violations and nonunitarity at long baseline accelerator experiments? *Phys.Rev.D* 95 (2017) 7, 075035 #CITATIONS = 31

Masud, Bishai and Mehta, Extricating New Physics Scenarios at DUNE with Higher Energy Beams, *Sci.Rep. 9 (2019) 1, 352* #CITATIONS = 35

Masud, Roy and Mehta, Correlations and degeneracies among the NSI parameters with tunable beams at DUNE, *Phys.Rev.D* 99 (2019) 11, 115032 #CITATIONS = 41

Rout, Roy, Masud, Bishai and Mehta, Impact of high energy beam tunes on the sensitivities to the standard unknowns at DUNE, *Phys.Rev.D 102 (2020) 116018* #CITATIONS = 17

Rout, Shafaq, Bishai and Mehta, Physics prospects with the second oscillation maximum at the Deep Underground Neutrino Experiment, *Phys.Rev.D 103 (2021) 11, 116003* #CITATIONS = 8

Parveen, Masud, Bishai and Mehta, Sterile sector impacting the correlations and degeneracies among mixing parameters at the Deep Underground Neutrino Experiment, *JHEP 01 (2025) 139*

Parveen, Sharma, Patra and Mehta, Signals of eV-scale sterile neutrino at long baseline neutrino experiments, *Eur.Phys.J.C 85 (2025) 2, 181*

DEEP UNDERGROUND NEUTRINO EXPERIMENT

CDR, Vol 1, 1601.05471 [physics.ins-det], CDR, Vol 2, 1512.06148 [physics.ins-det], TDR vol 1, JINST 15 (2020) 08, T08008, TDR Vol 2, 2002.03005 [hep-ex]

- Beam - LBNF (FNAL), 1.2-2.4MW, Baseline 1300 km
- Far detector (LArTPC, ~ 40 kt fiducial mass) located on-axis such that observed flux is a broad spectrum (0.5-5 GeV)
- DUNE has a broad program of neutrino oscillation physics, constrain the standard three neutrino paradigm
  - Beam covers first and second oscillation maxima
  - Alternative beam tunes possible

$$\frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} = (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times 510\ \mathrm{km/GeV}$$

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- Muon neutrino beam
- Measure electron neutrino appearance and muon neutrino disappearance probability

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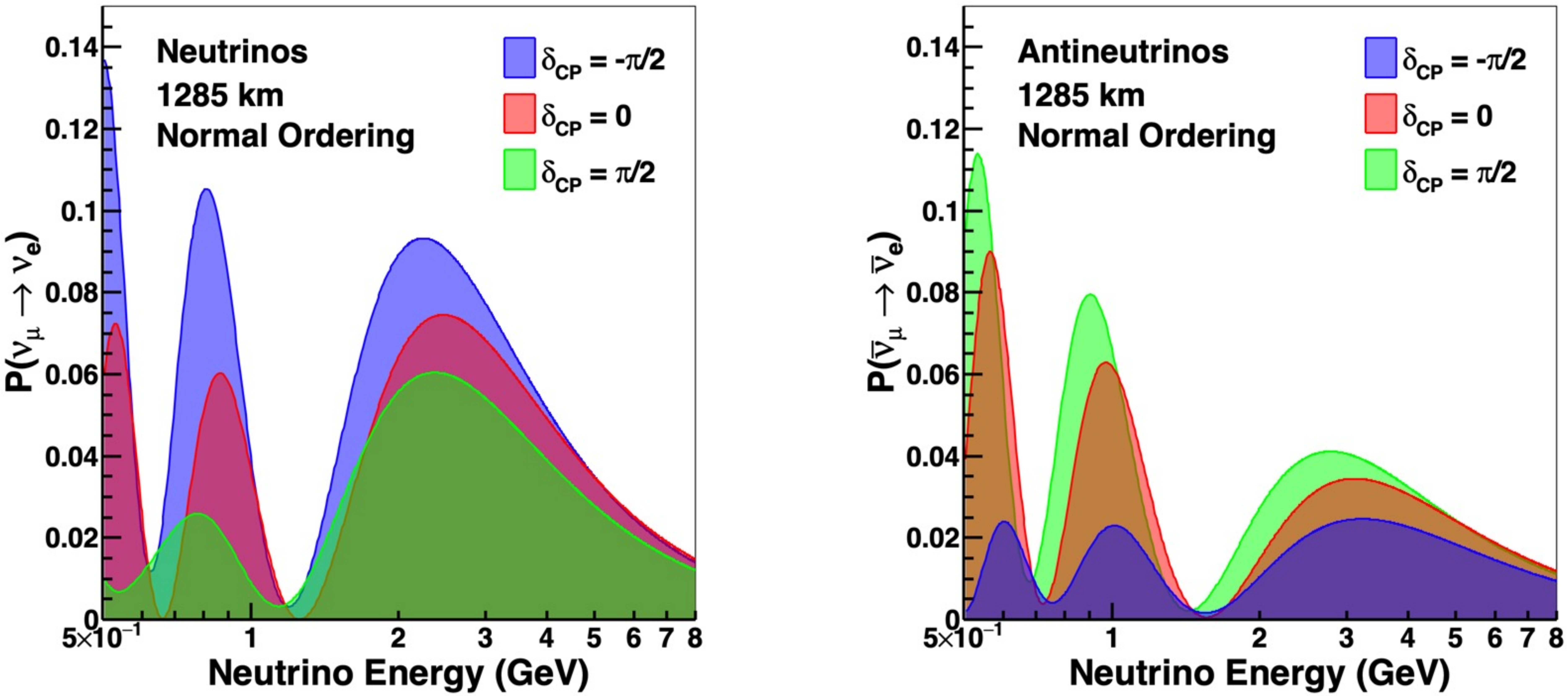
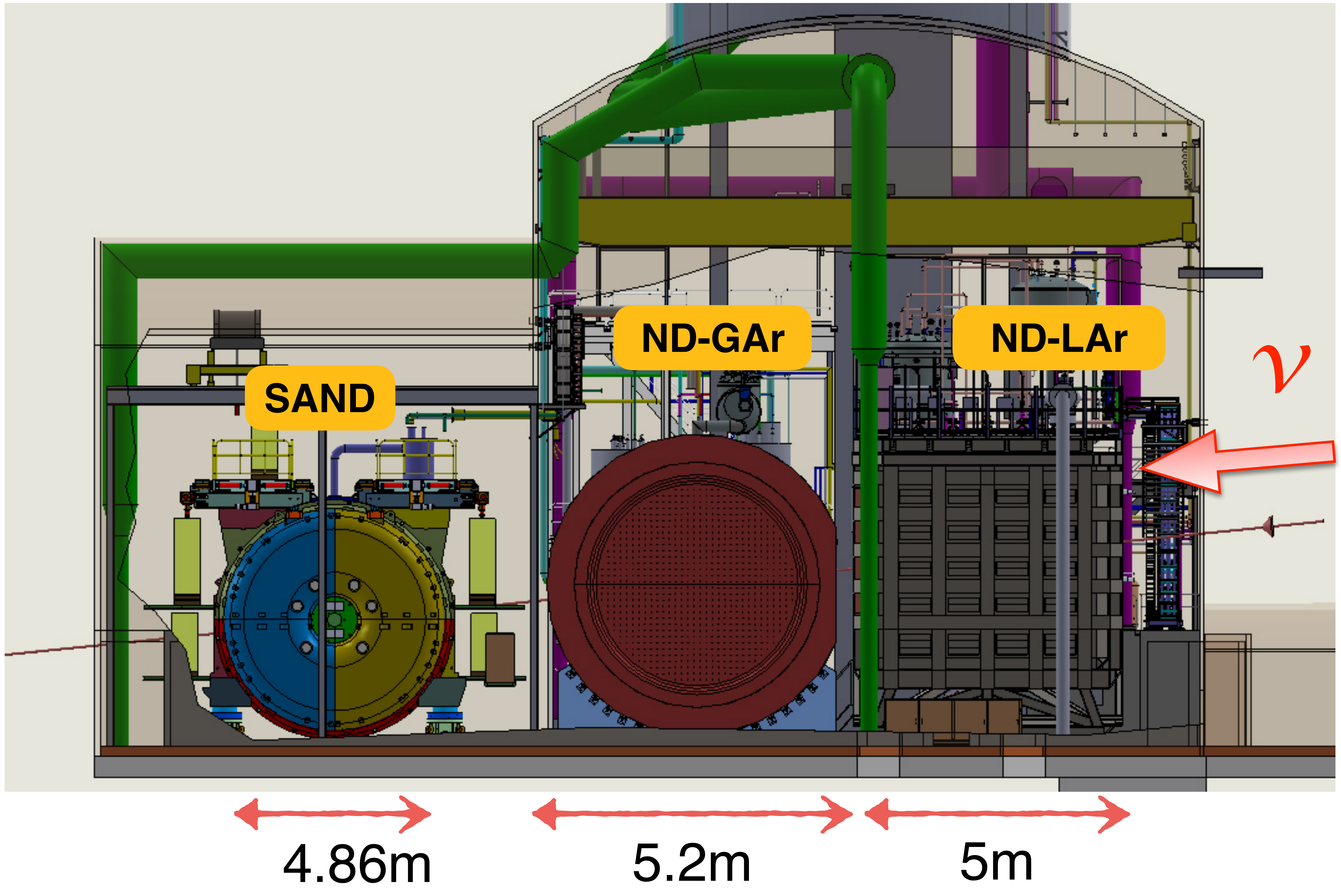


DUNE Near Detector

DUNE-ND Preliminary, 2103.13910

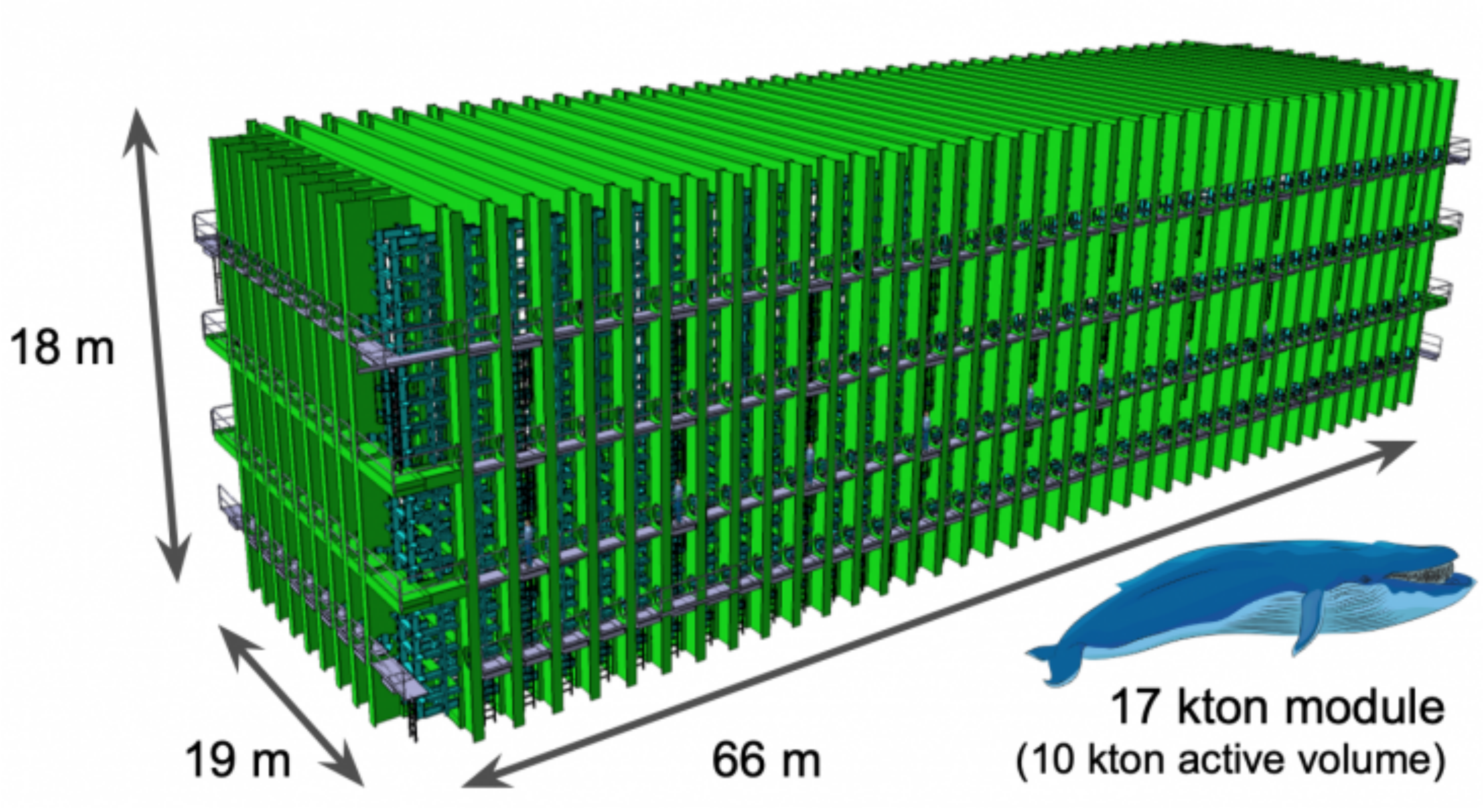
- ND Goals -
  - Constrain systematics to electron neutrino appearance measurement
  - Precision physics measurements
- Three components
  - ND-LAr - LArTPC similar to FD
  - ND-GAr - Gas Argon TPC detector
  - SAND - on-axis magnetized beam monitor
- ND-LAr and ND-GAr movable off-axis for the DUNE-PRISM program
- Each element specifically designed to fulfill requirements of oscillation measurement



DUNE Far Detector

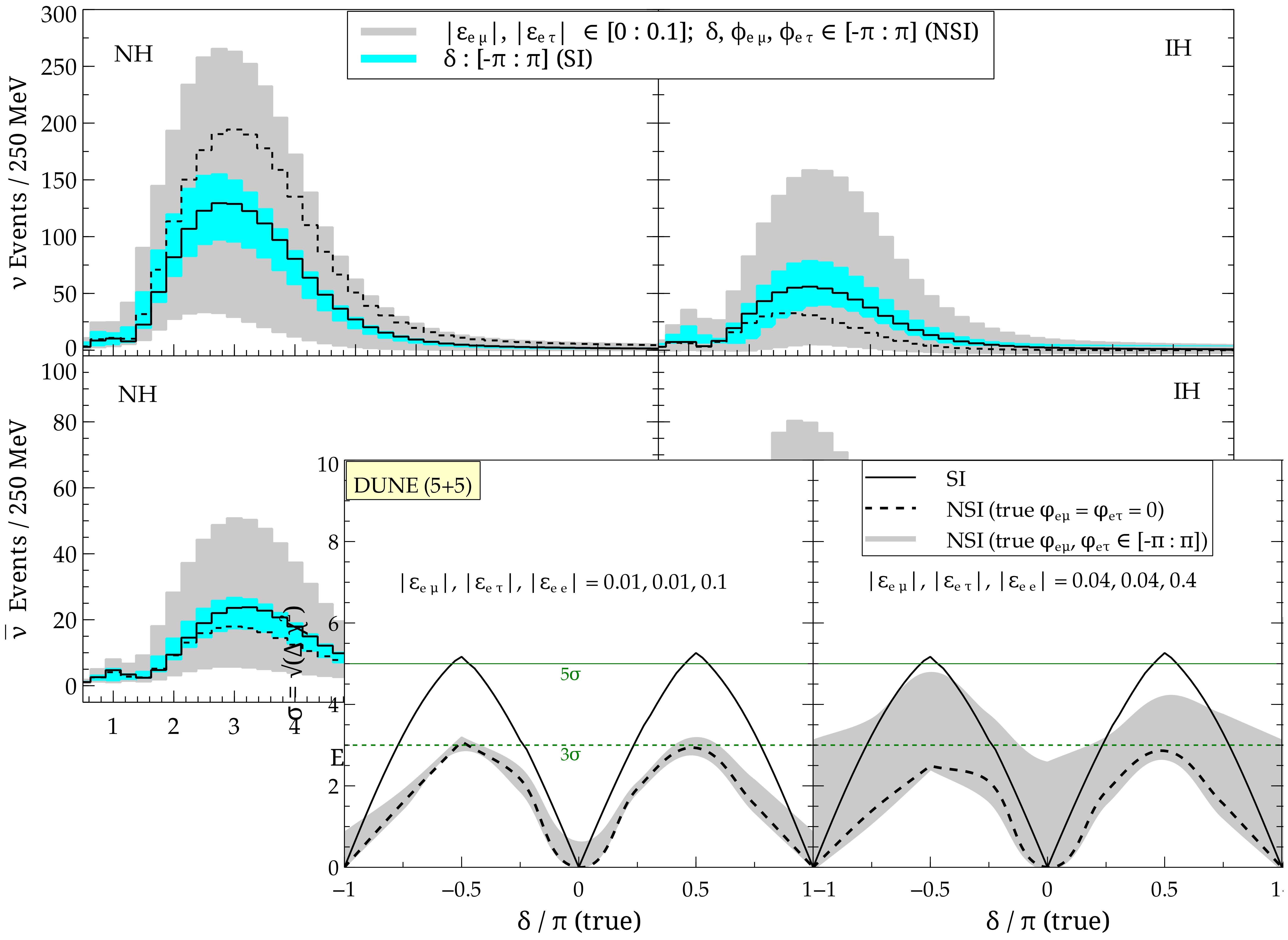
CDR, Vol 1, 1601.05471 [physics.ins-det], CDR, Vol 2, 1512.06148 [physics.ins-det], TDR vol 1, JINST 15 (2020) 08, T08008, TDR Vol 2, 2002.03005 [hep-ex]

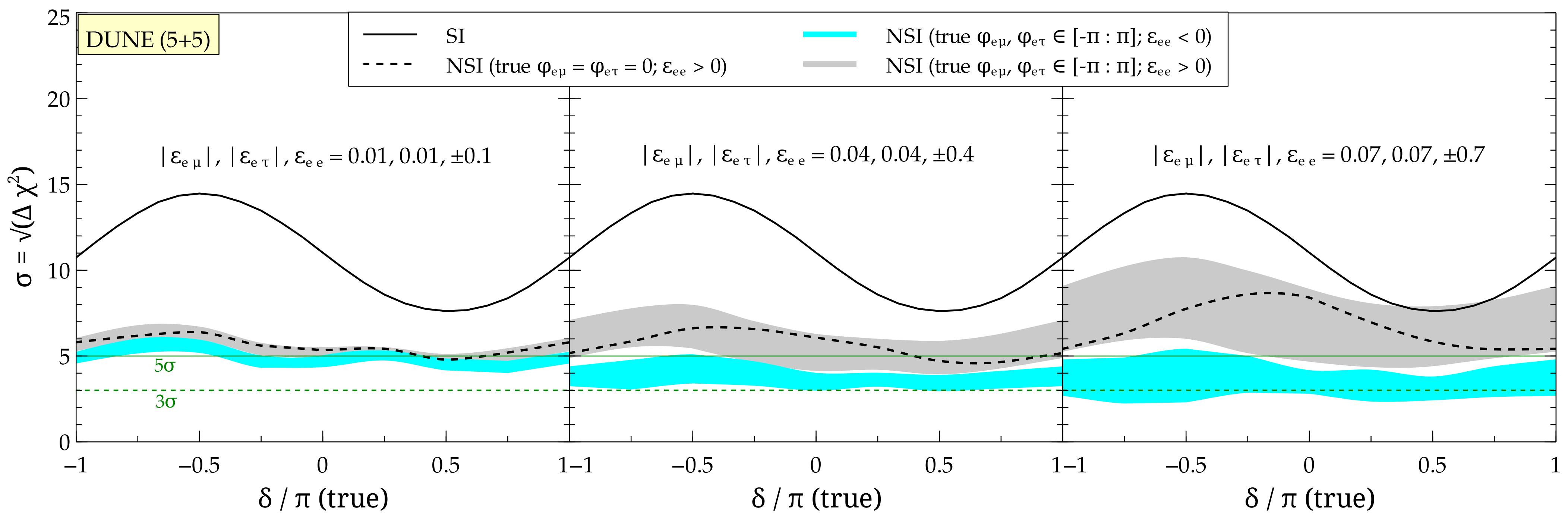
- 1300 km baseline
- Liquid Argon time projection chamber (LArTPC) - high resolution neutrino interaction imaging
- 4x17 kton LArTPC modules



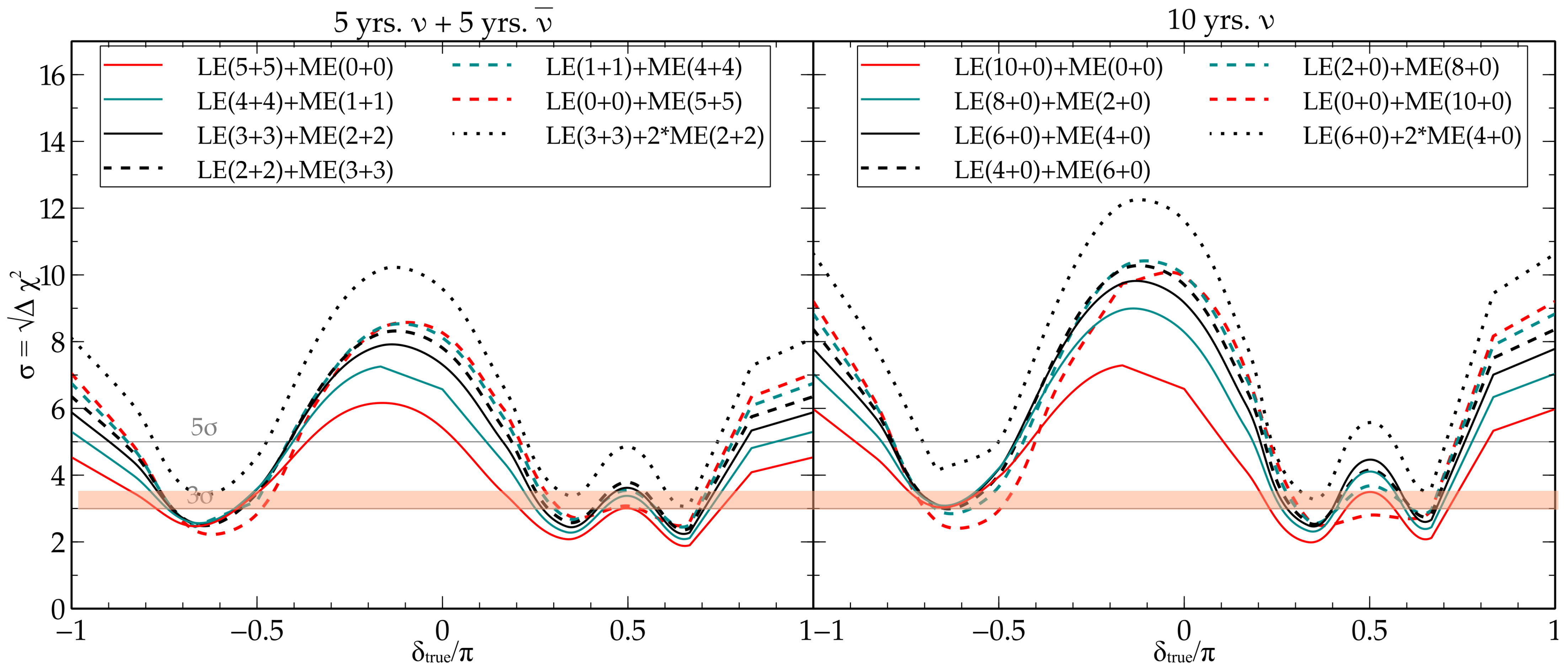
Imprint of NSI on CP violation & mass hierarchy sensitivities

Mehedi Masud, Animesh Chatterjee, PM, J Phys G 2016, Mehedi Masud, PM, PRD 2016, Jogesh Rout, Mehedi Masud, PM, PRD 2017, Mehedi Masud, Mary Bishai and PM, Scientific Reports (2019)



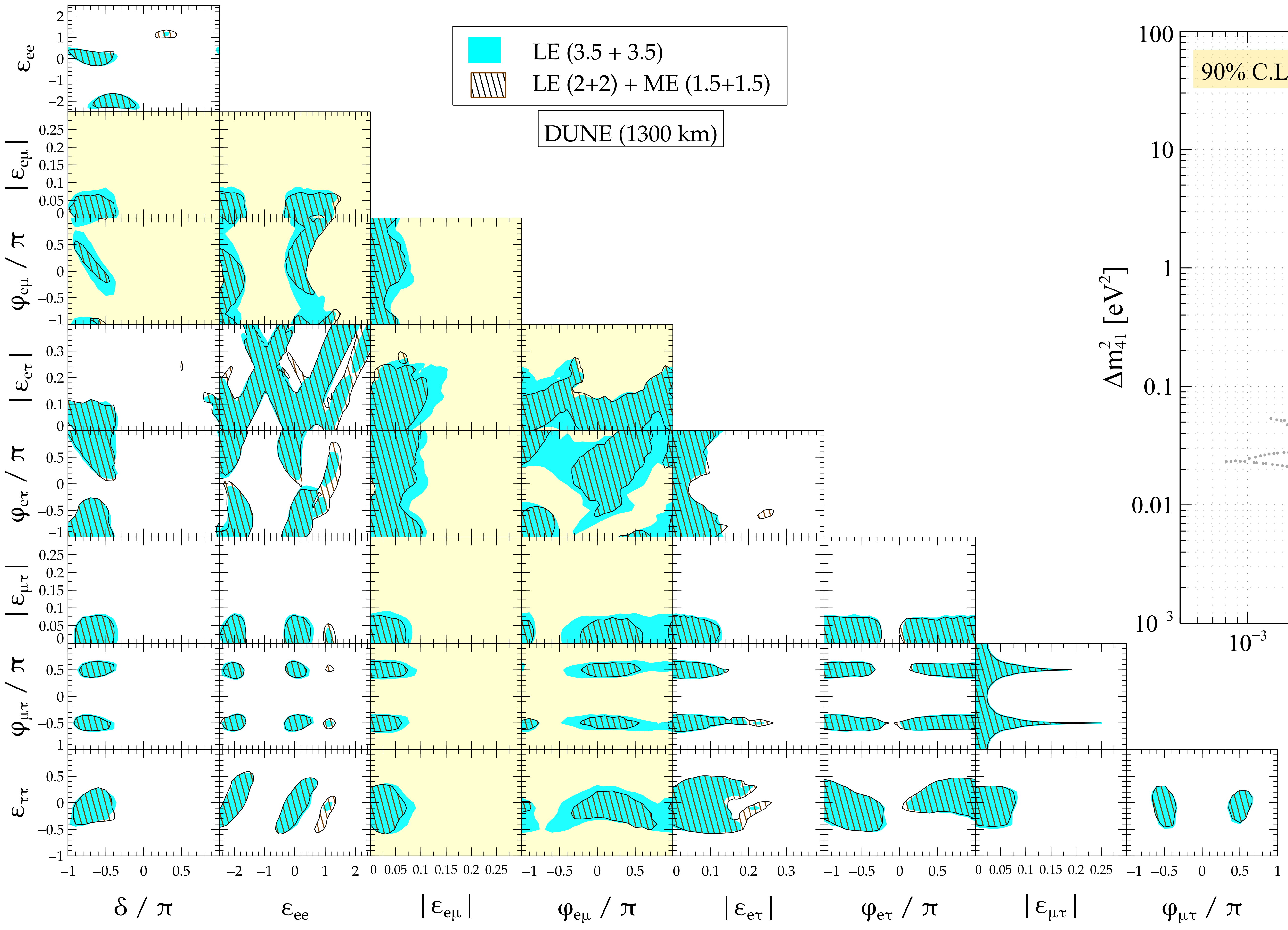


SI-NSI separation at DUNE

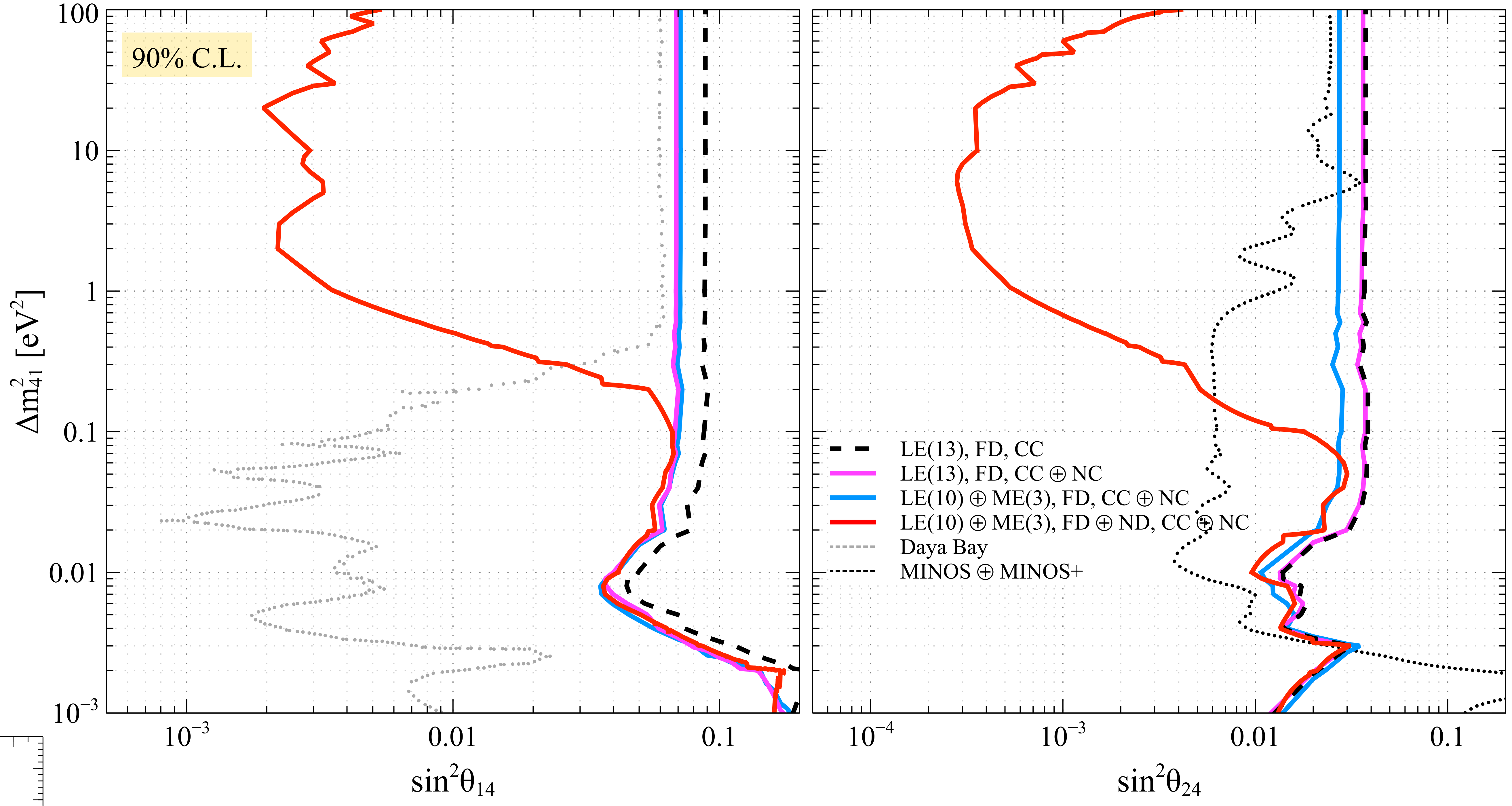


IMPACT OF NEW PHYSICS ON CORRELATIONS AND DEGENERACIES AMONG PARAMETERS

Masud, Roy and PM, Phys.Rev.D 99 (2019) 11, 115032

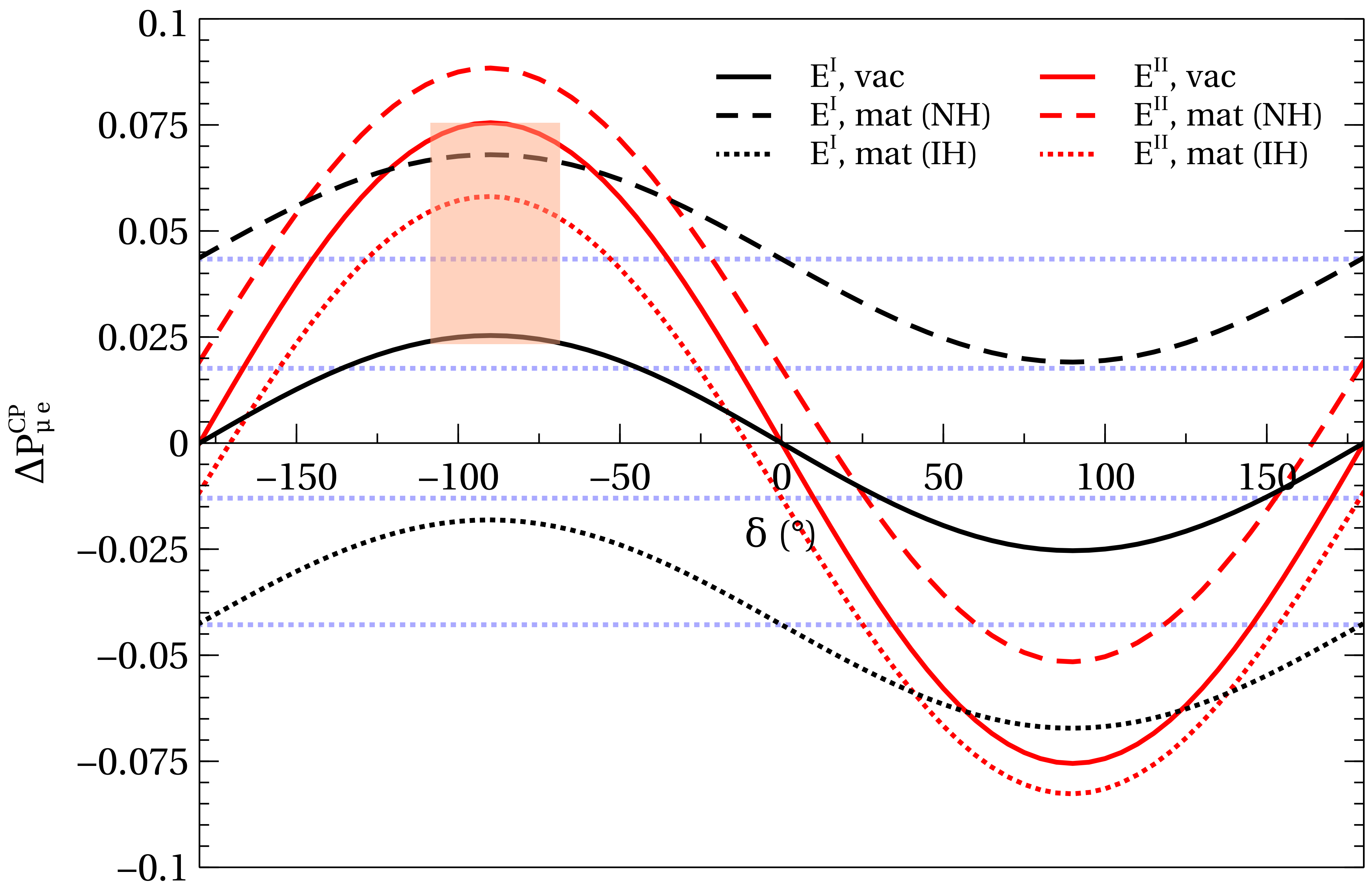


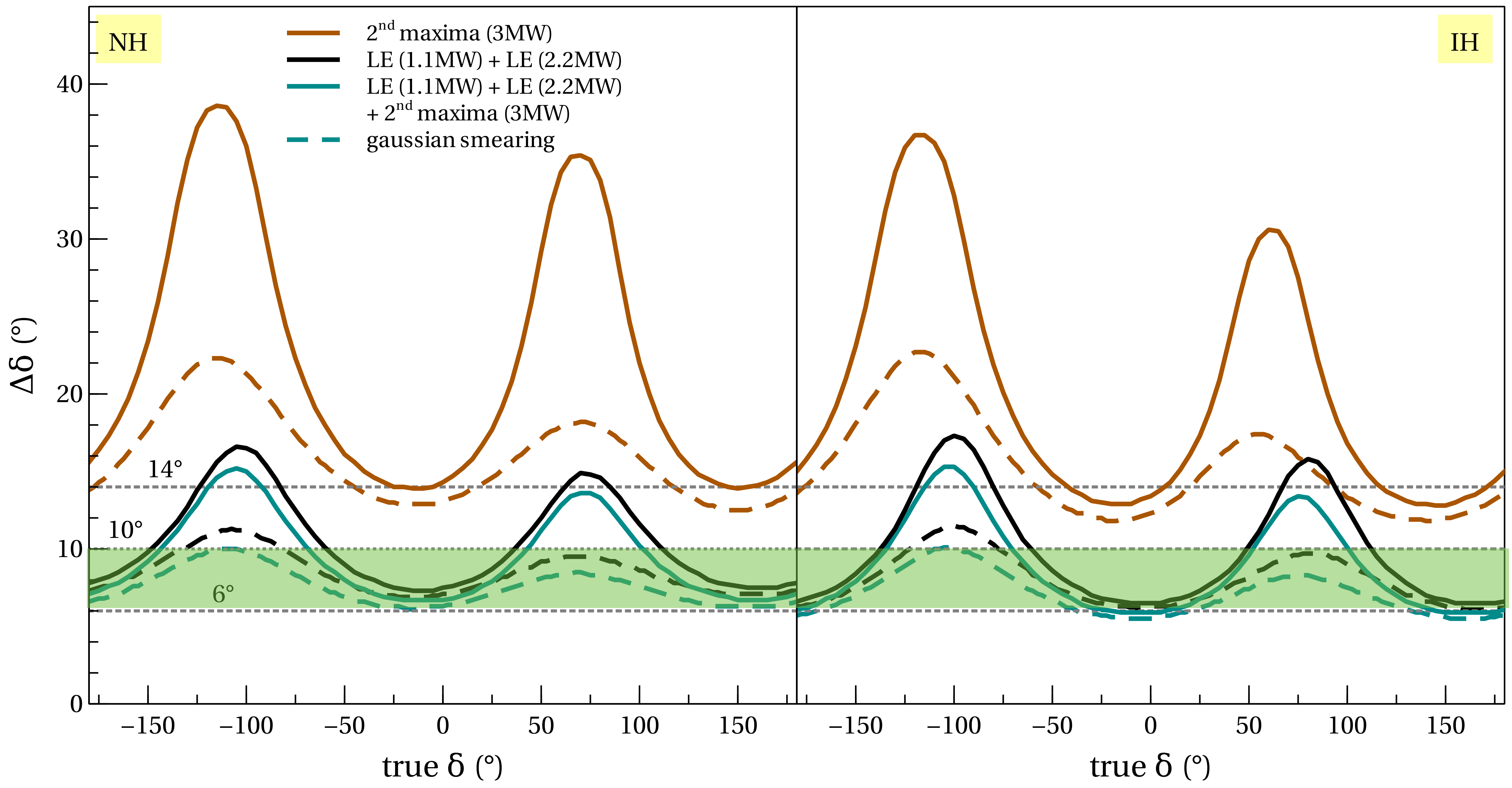
Parveen, Masud, Bishai and PM, JHEP 01 (2025) 139



Second oscillation maximum at DUNE

factor of ~3 Jogesh Rout, Sheeba Shafaq, Mary Bishai and PM, Phys.Rev.D 103 (2021) 11, 116003 CP resolution





$E^{I} \simeq 2.6\ GeV$

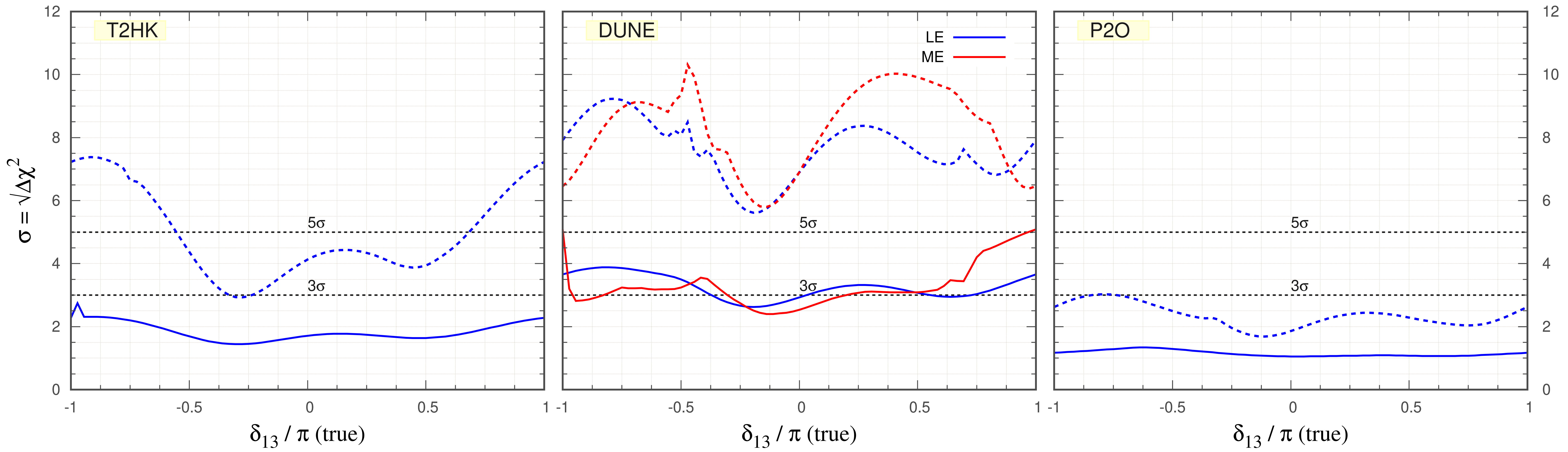
$E^{II} \simeq 0.8\ GeV$

The CP phase resolution (with improved energy resolution) is better than 10 degrees

Signals of eV-scale sterile neutrino at long baseline neutrino experiments

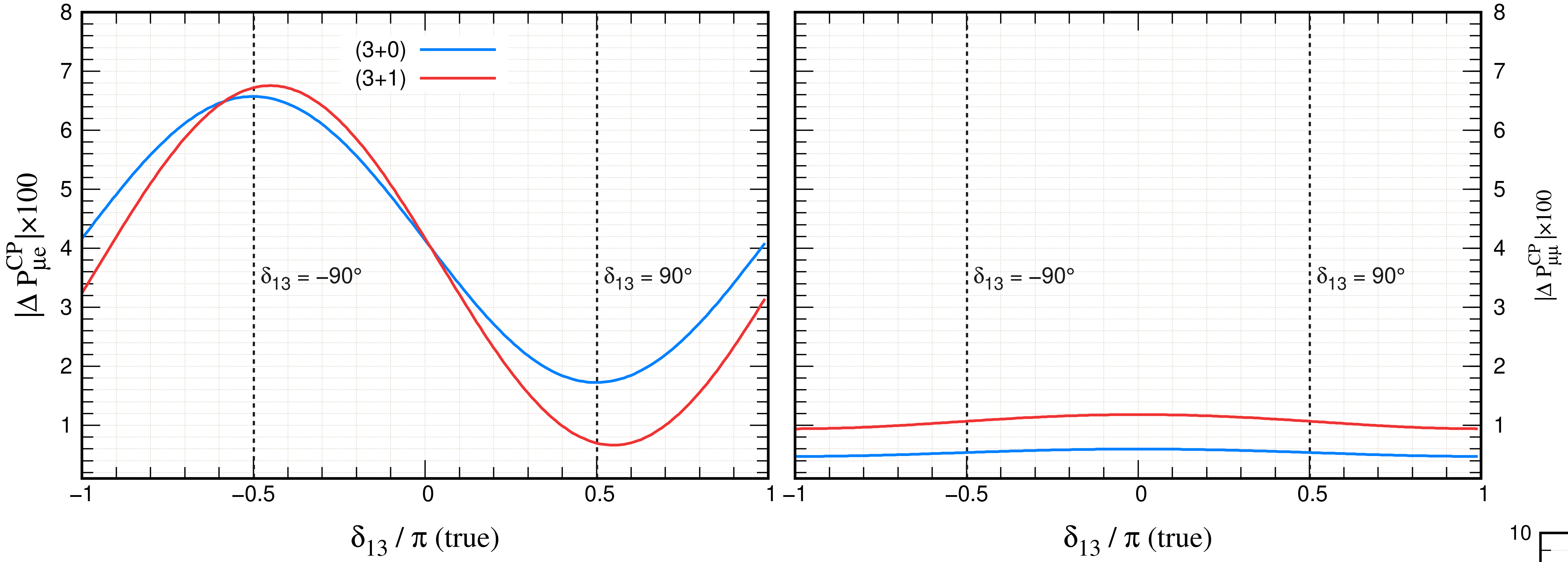
Parveen, Sharma, Patra and PM, EPJC 85, 181 (2025)

Can we distinguish between 3+0 and 3+1 effects ?

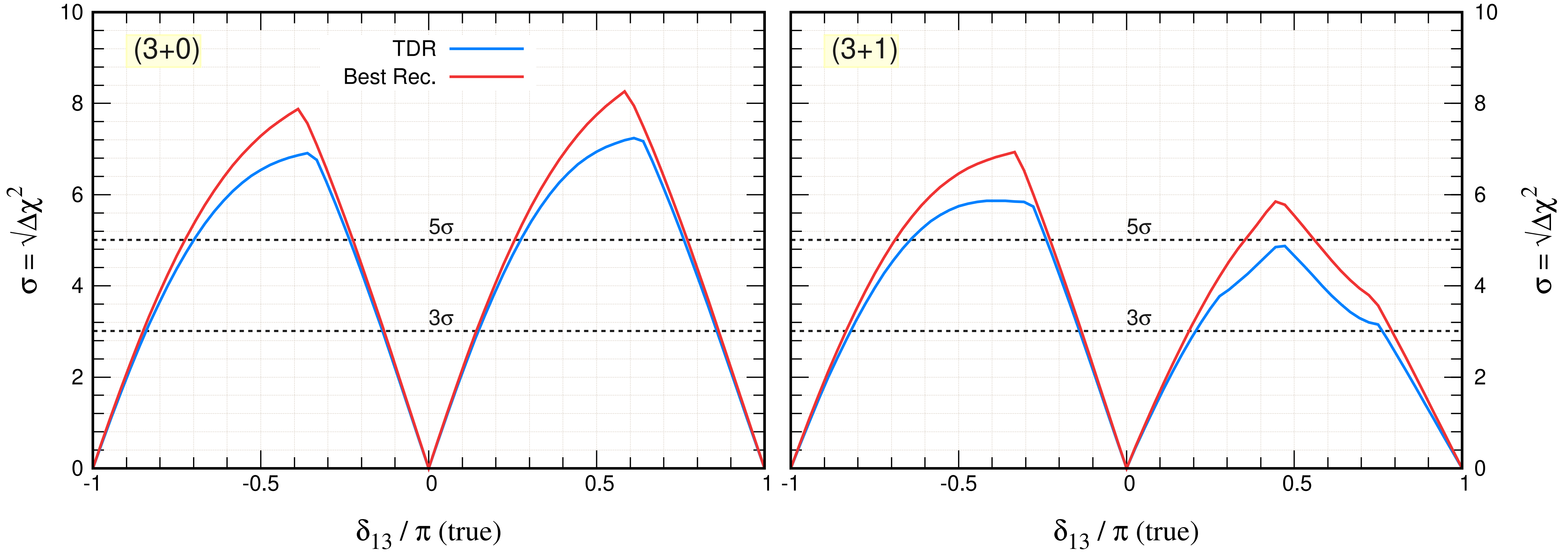


Role of improved energy resolution on the standard unknowns

Parveen, Rout and PM, to appear



PRELIMINARY



Future Plan

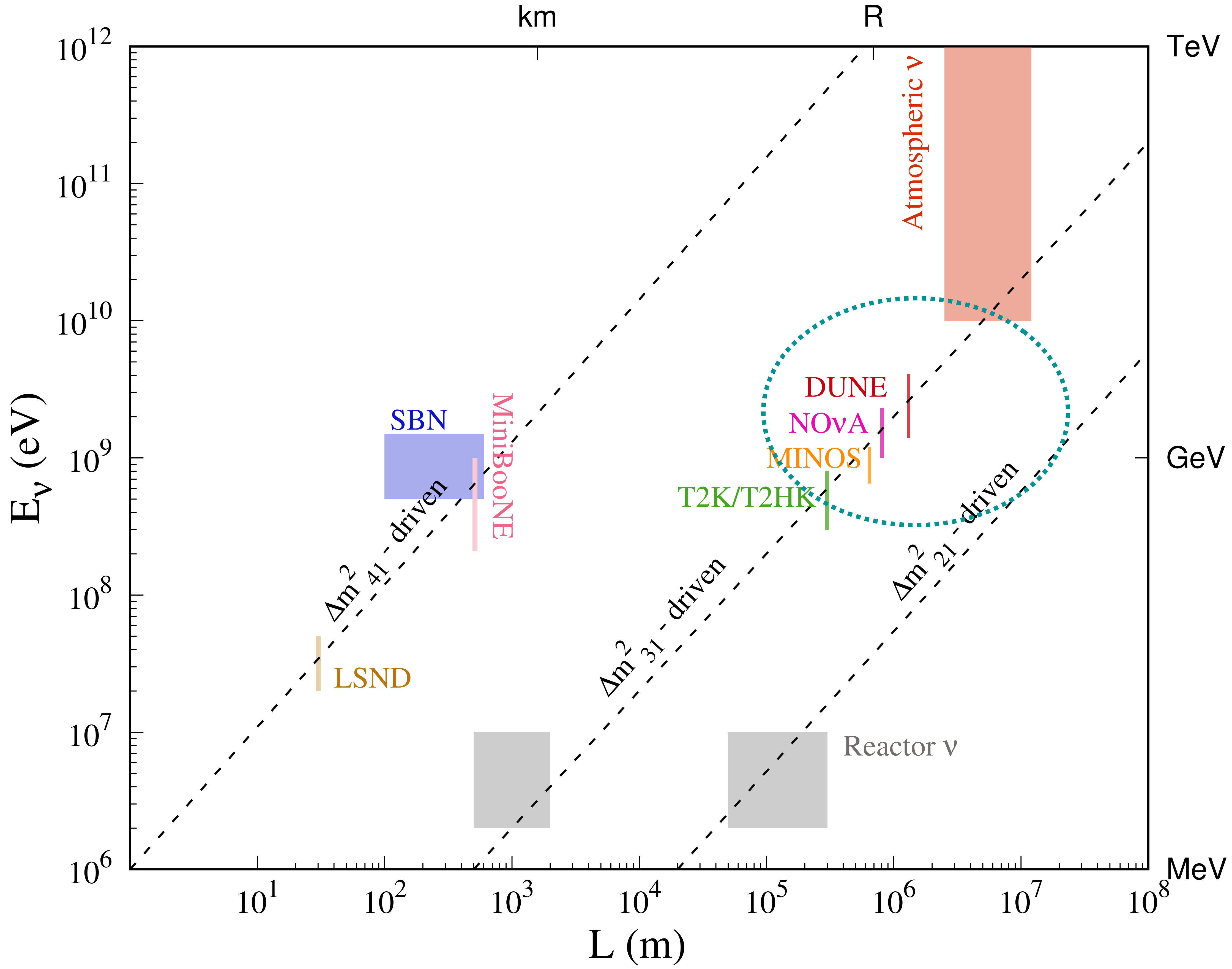
- Organisational roles - Member of the Authorship and Publications Board (2022 onwards)
- Deviation from the three flavour neutrino oscillations
  - Non-standard Interactions, Sterile neutrinos, Neutrino decay, PMNS non-unitarity, CPT violation
- Deep Underground Neutrino Experiment
  - Near and Far Detectors - to take into account systematics carefully (with Sabila Parveen, Navaneeth Poonthottathil)
  - Beam optimisations for new physics NSI (with Jogesh Rout, Laura Fields)
  - Machine learning approaches to extricate new physics (with Abhishek Iyer, Kolin Paul and Srikanta Bedathur)
- Other Physics opportunities - Tau neutrinos at DUNE, nature of neutrinos, supernova neutrinos
- Testing foundations of QM such as Leggett-Garg Inequalities at DUNE

Research areas

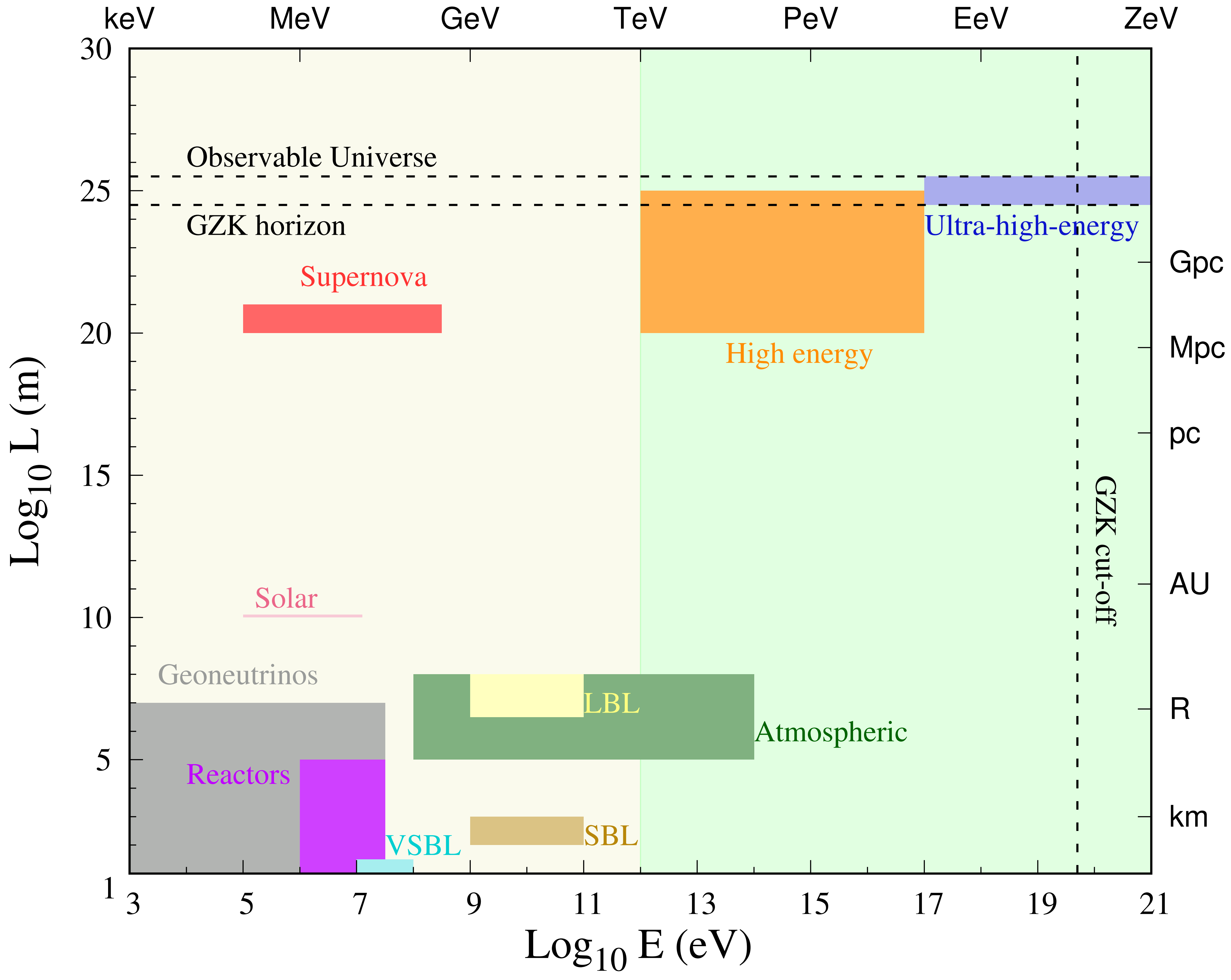
1 TeV = 1.6 x 10^{-19} x 10^{12} Joules = 1.6 x 10^{-7} Joules

1/2 m v^2 = 1.6 x 10^{-7} Joules, m = 2 x 10^{-6} kg therefore v = 0.4 m/s = 1.4 kph

TeV : Energy of a flying mosquito!



Credit : 1111.0507 [astro-ph.HE]



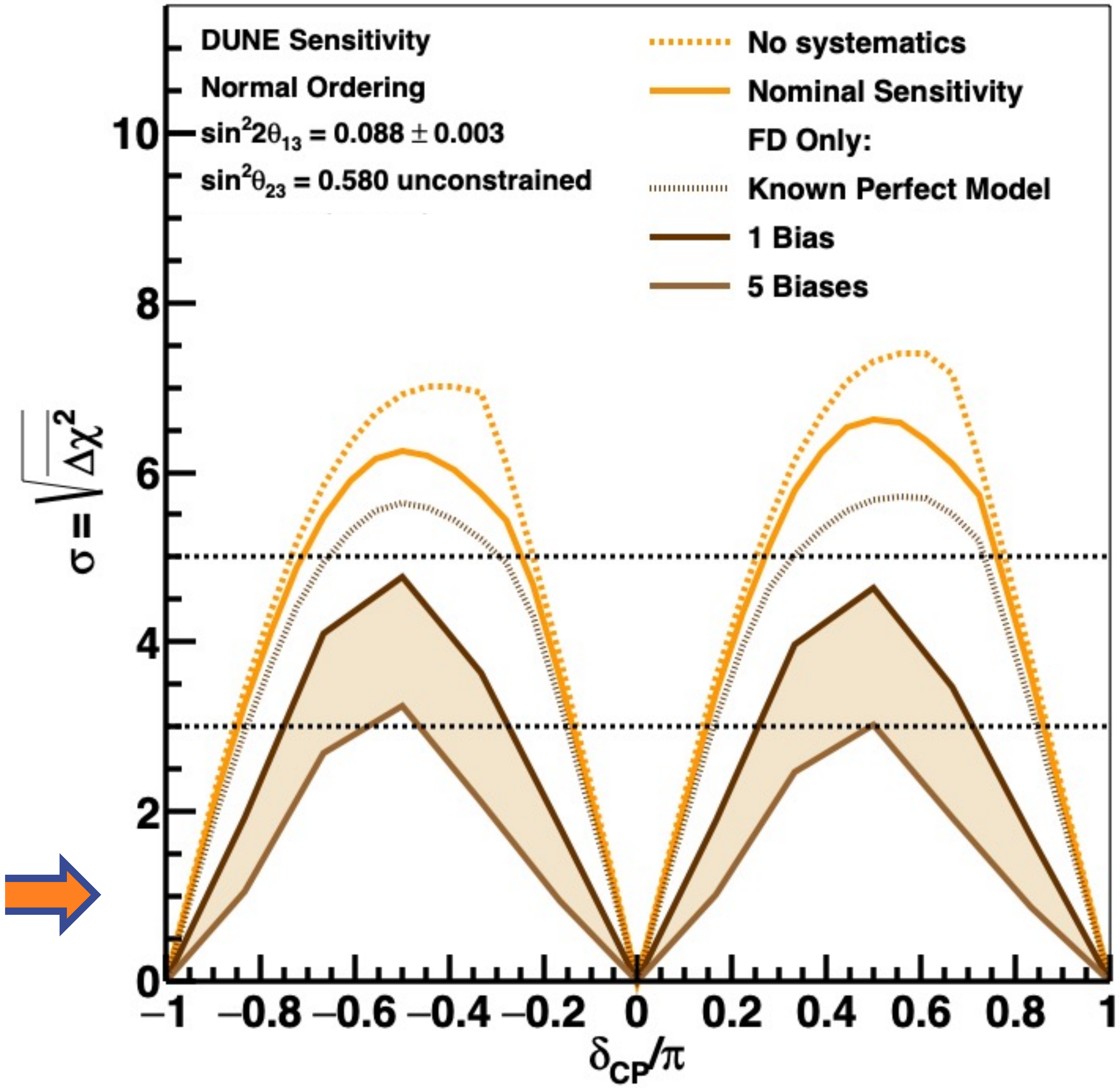
Credit : Sabila Parveen, adapted from 1911.05088

Backup slides

Systematic uncertainty

Phased Construction arXiv:2203.06100, Talk by Elizabeth Worcester, NDM22

- Order few percent uncertainty required for precision measurements
- Sources of uncertainty :
  - Neutrino flux
  - Neutrino interaction model
  - Detector effects
- Impact of biases due to shortcomings in the interaction model is large
- Near detectors critical to achieve precision measurement goals



What about tau neutrinos at DUNE ?

Barbara Yaeggy, talk at NuFact 2022, 2203.05591 Snowmass white paper

- Among all fermions of the SM, tau neutrinos are least experimentally seen. Only 9 tau neutrino + tau anti neutrinos CC events seen in DONuT experiment and 10 tau neutrino CC events seen in OPERA experiment.
- Current generation of neutrino experiments provides nearly complete description of 3 flavor paradigm.
- All information about tau sector is taken from
    - Lepton universality for cross-sections
    - PMNS unitarity for oscillations
- We need to test these assumptions.

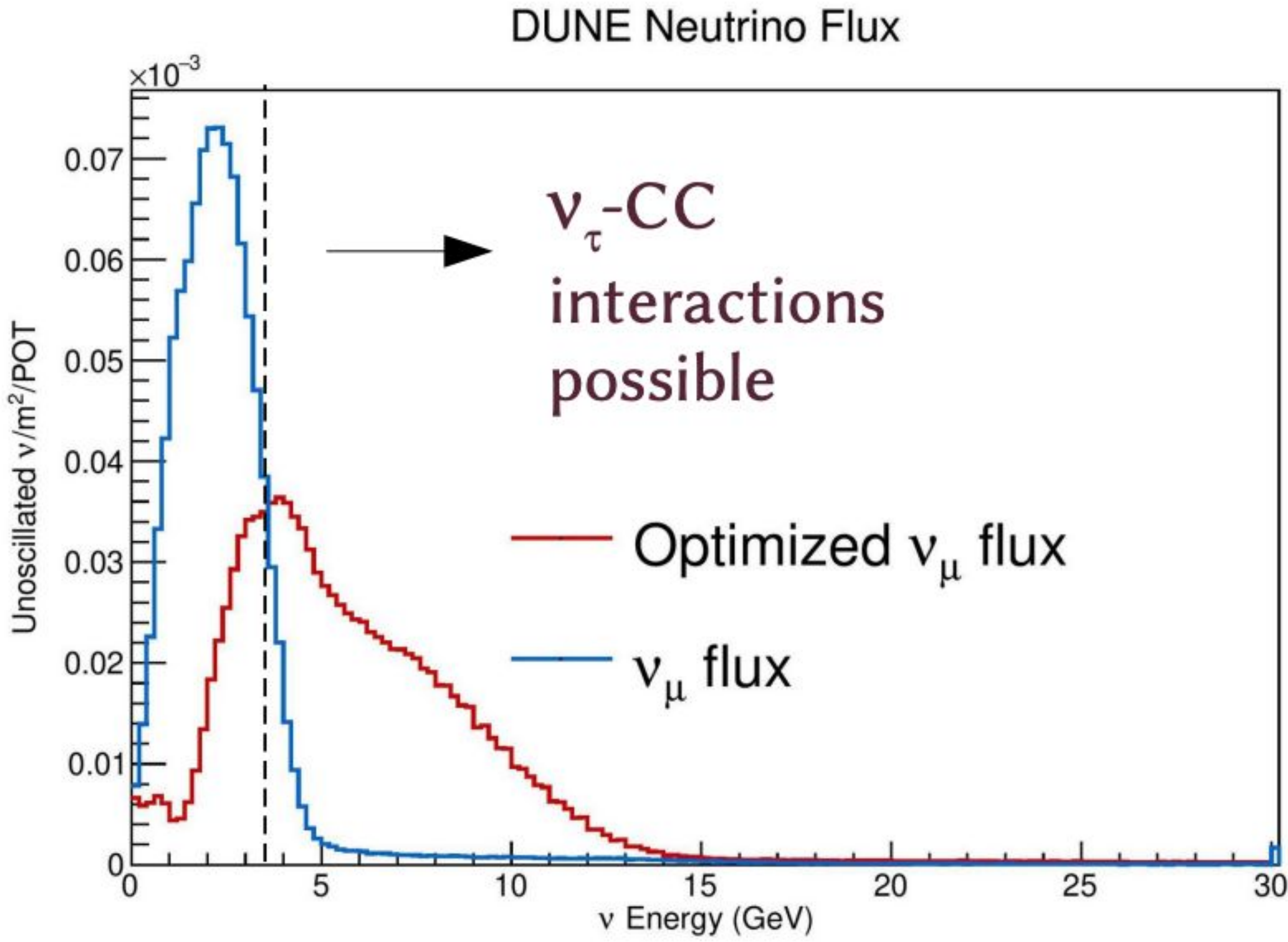
CP optimized configuration (3 horns)

~130 tau neutrino counts/year

~30 tau anti-nu counts/year

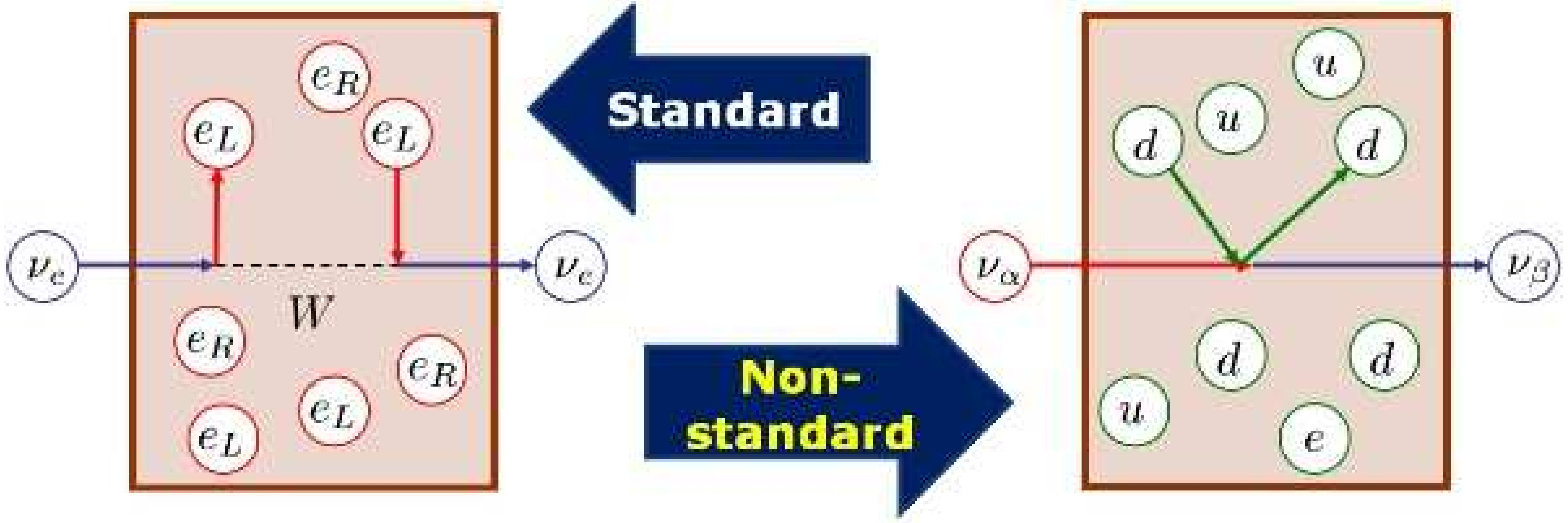
Tau optimized configuration (2 horns)

~800 tau nu counts/year



What are non-standard interactions ?

Ref: Wolfenstein (1978), Grossman (1995), Berezhiani, Rossi (2002), Davidson et al. (2003) , Ohlsson, Tortola and Farzan



T. Ohlsson

9 new parameters

$$\mathcal{H} = \frac{1}{2E}\left\{\mathcal{U}\begin{pmatrix} 0 & & \\ & \delta m^2_{21} & \\ & & \delta m^2_{31}\end{pmatrix}\mathcal{U}^\dagger + A(x)\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}{}^\star & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}{}^\star & \epsilon_{\mu\tau}{}^\star & \epsilon_{\tau\tau}\end{pmatrix}\right\},$$

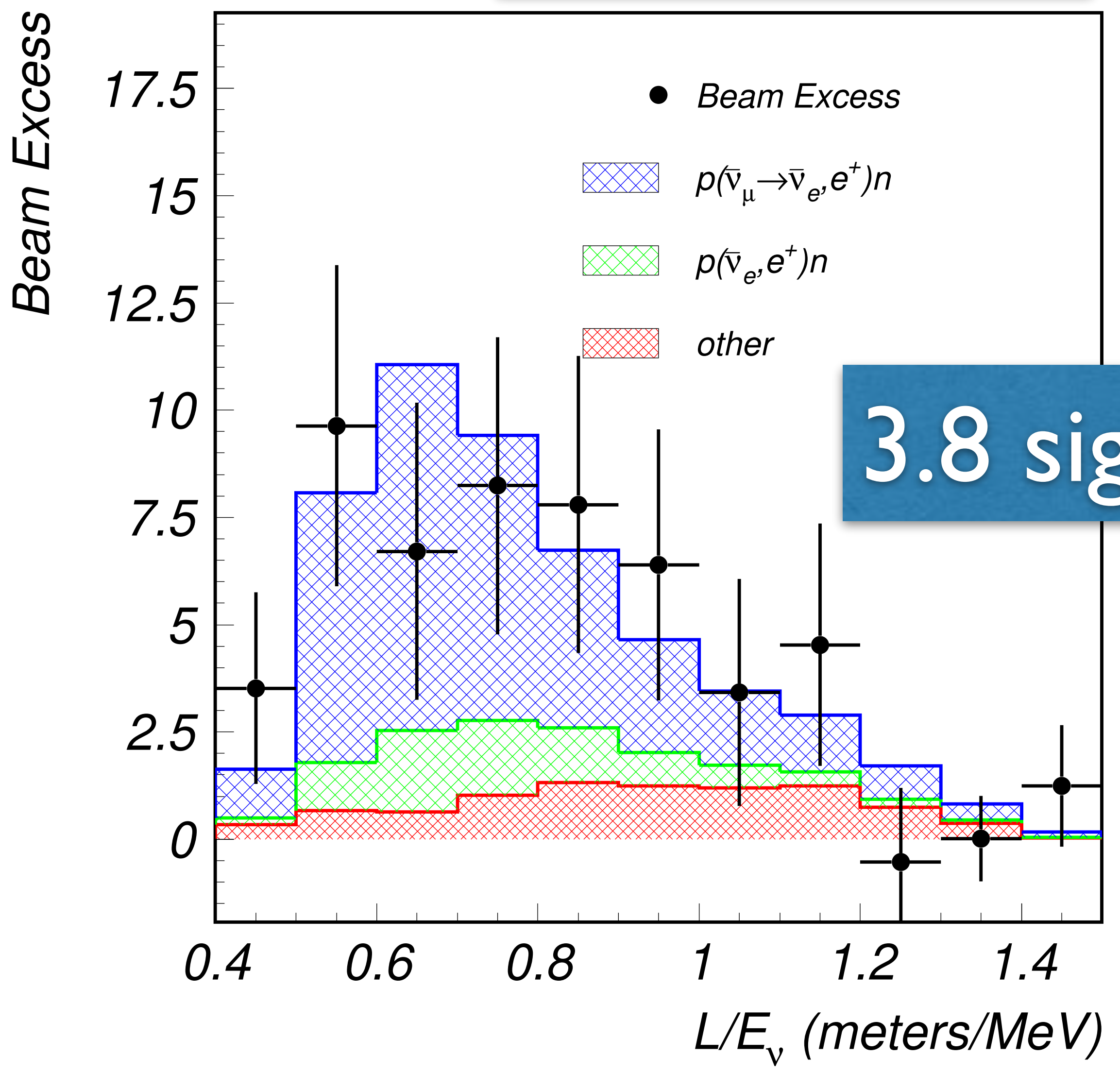
Flavour dependent refraction in the NC piece (diagonal as well as off-diagonal NSI terms)

Sterile neutrino

Dasgupta and Kopp, 2106.05913

LSND

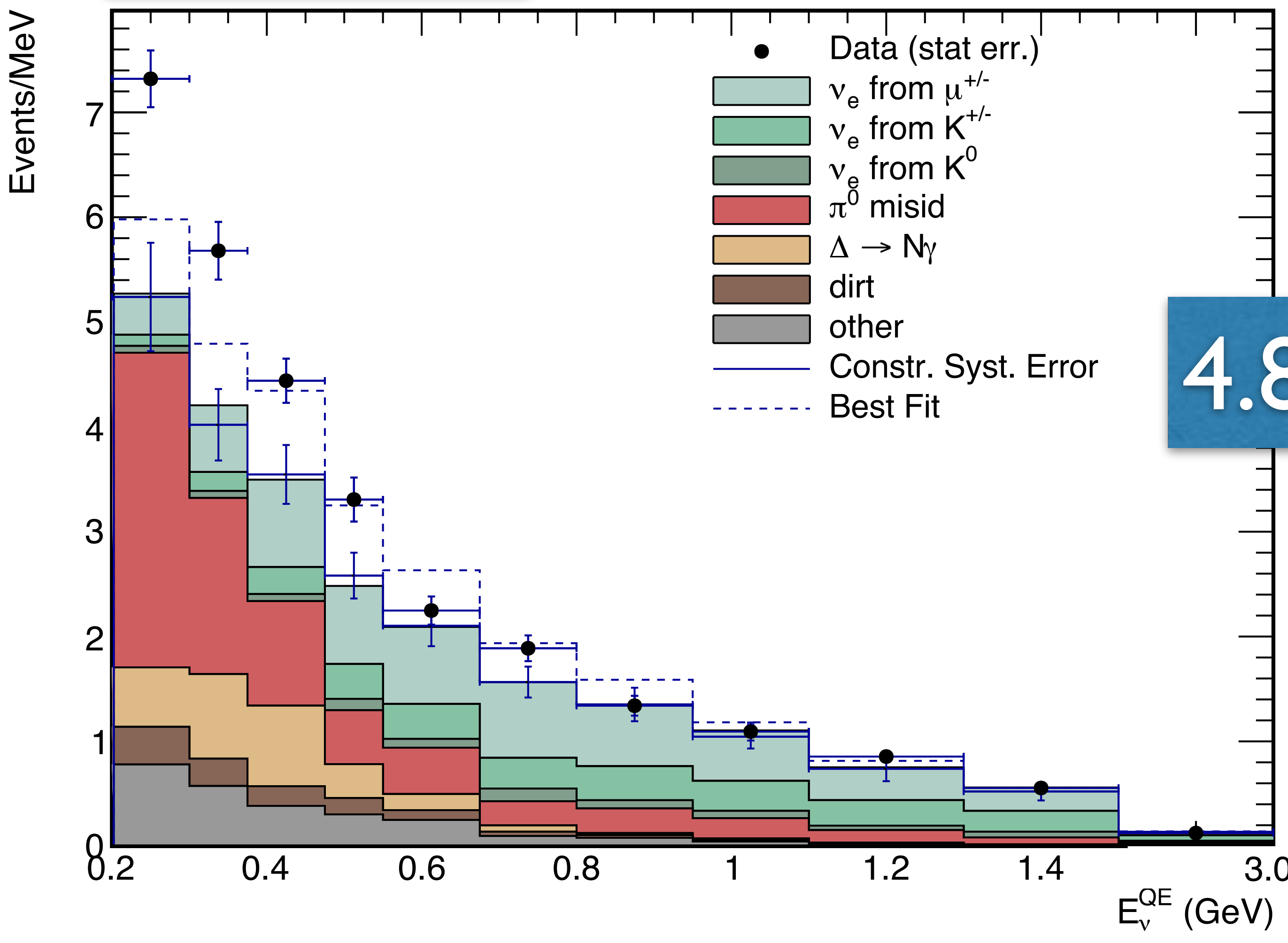
Antineutrino



PRD64, 112007 (2001)

MiniBooNE

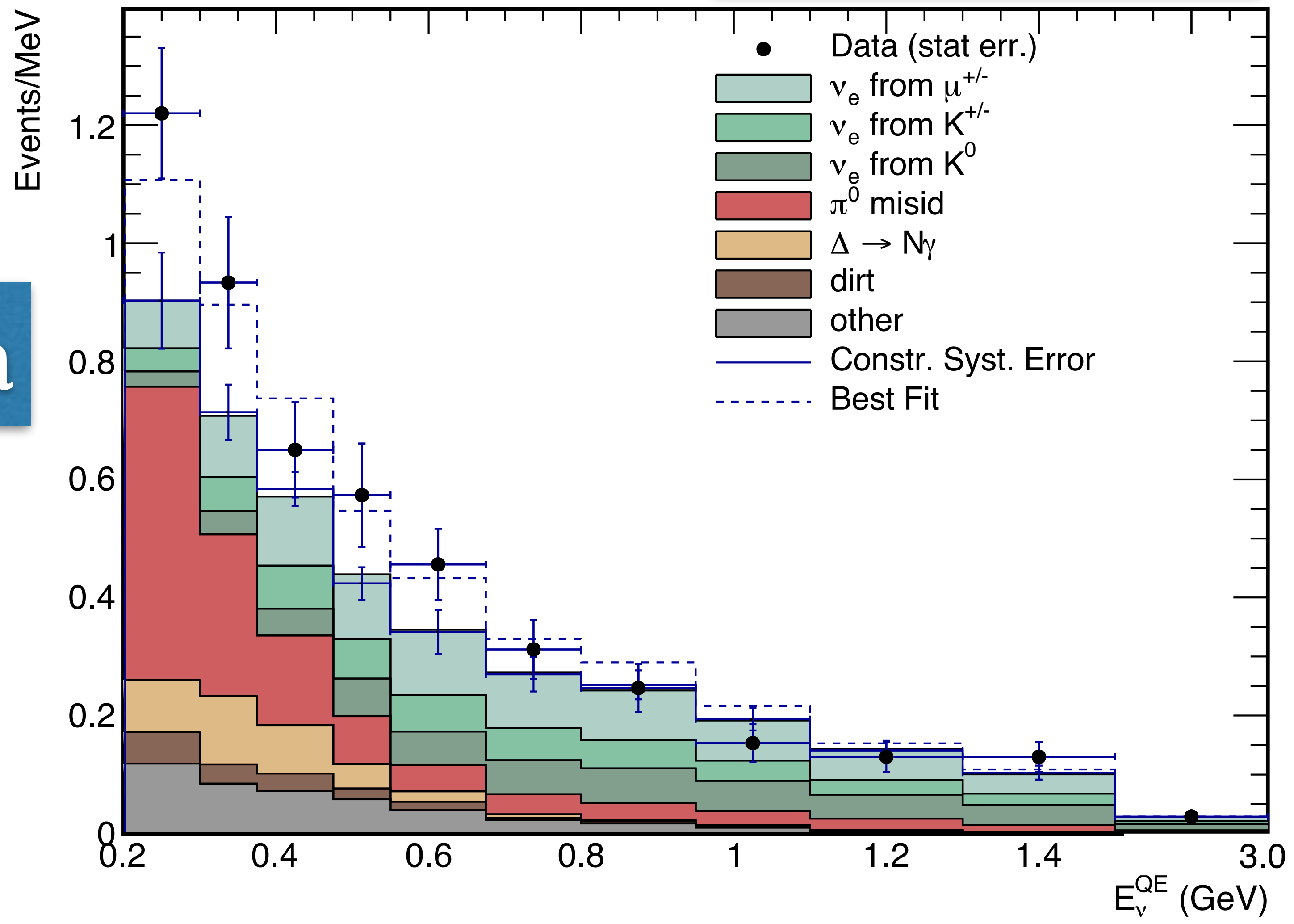
Neutrino



4.8 sigma

2006.16883

Antineutrino



1805.12028

Experiment	L	E	Channel
LSND	30 m	20-200 MeV	Electron antinu Appearance
MiniBooNE	541 m	0.2-3 GeV	Electron anti(nu) Appearance + Disappearance
MicroBooNE	541 m	0.5-3 GeV	Appearance + Disappearance