New physics with DUNE alternative configurations

Poonam Mehta

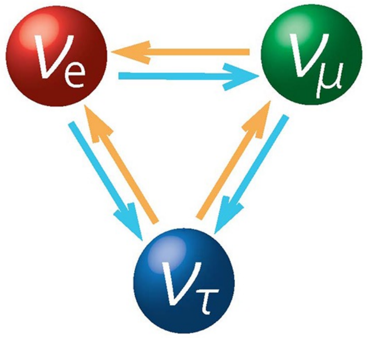

Image posted on facebook by shamim.a.ali.9

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NSI workshop at Washington University in St. Louis

Neutrino interactions - standard and non-standard

Present status : 3 neutrino flavours

Ref: de Salas et al, 1708.01186; see also Esteban et al, JHEP 01 (2019) 106 and NuFIT 4.0 (2018)

$$\theta_{23}/^\circ = 50.5(\mathrm{IH}) \quad 41.0(\mathrm{NH})$$

$$\Delta m^2_{21} = 7.56 \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{13}/^\circ = 8.41(\mathrm{IH}) \quad 8.44(\mathrm{NH})$$

$$|\Delta m^2_{31}| = 2.49 \times 10^{-5}\ \mathrm{eV}^2 (IH)$$
$$= 2.55 \times 10^{-5}\ \mathrm{eV}^2 (NH)$$

$$\theta_{12}/^\circ = 34.5$$

$$\delta/^\circ = 259(\mathrm{IH}) \quad 252(\mathrm{NH})$$

Issues :

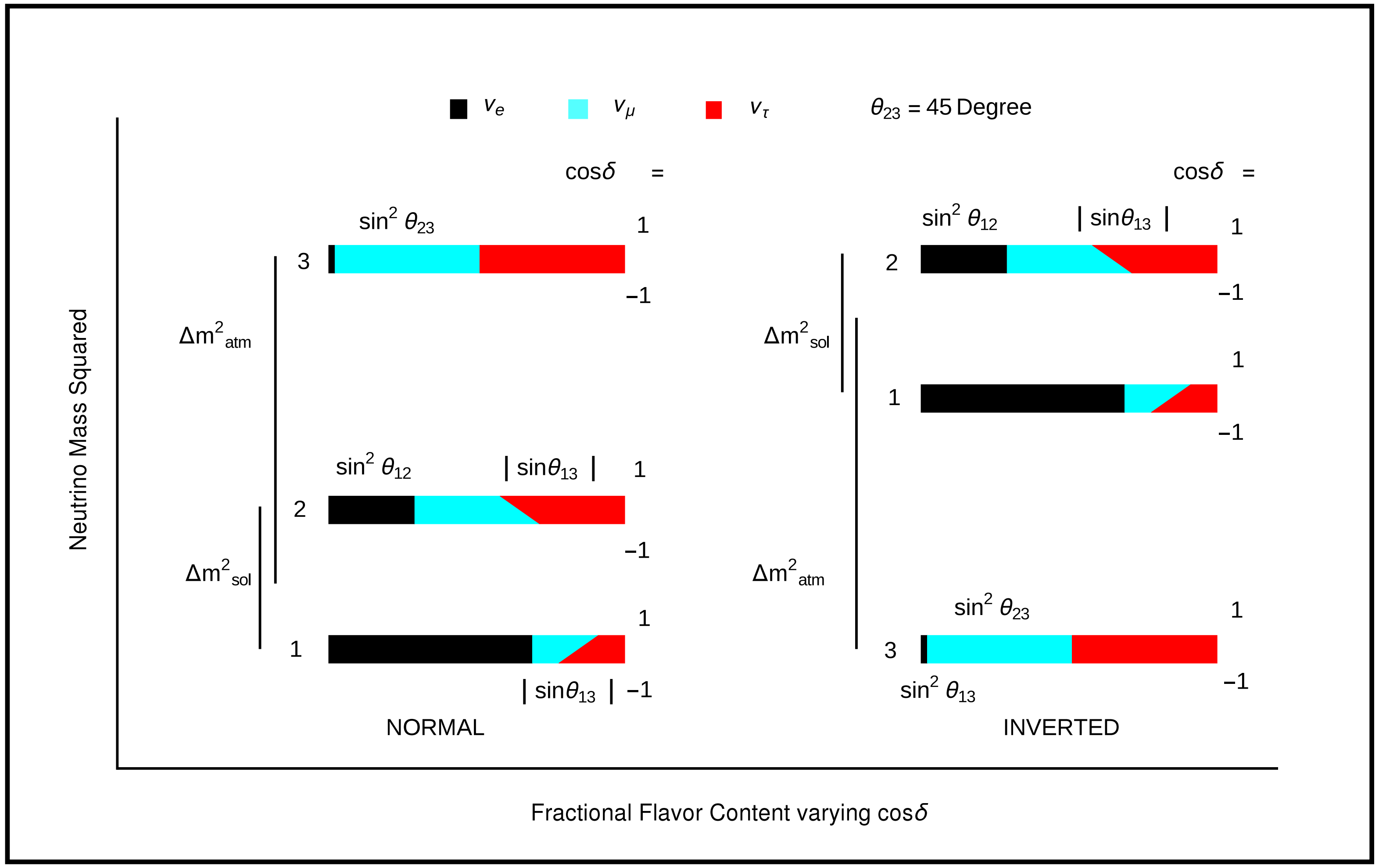
Improve precision

Mass ordering

Octant of theta23

Dirac CP phase

Absolute neutrino mass – unknown!



Ref: Mena and Parke

Neutrino oscillations require - physics beyond the SM

Standard Model ingredients :

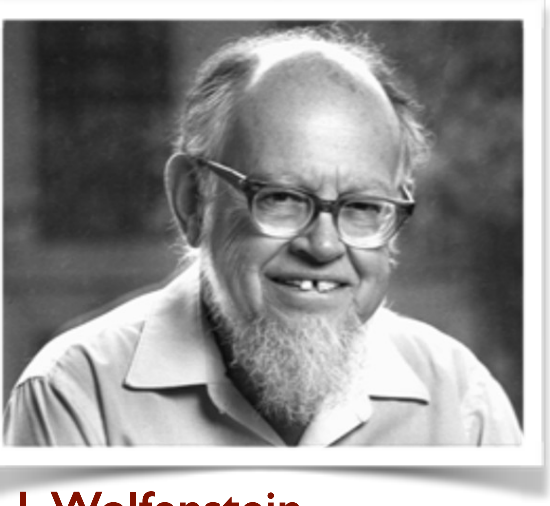
1. No right-handed neutrinos
2. Only Higgs doublet of SU(2)
3. Only renormalizable terms

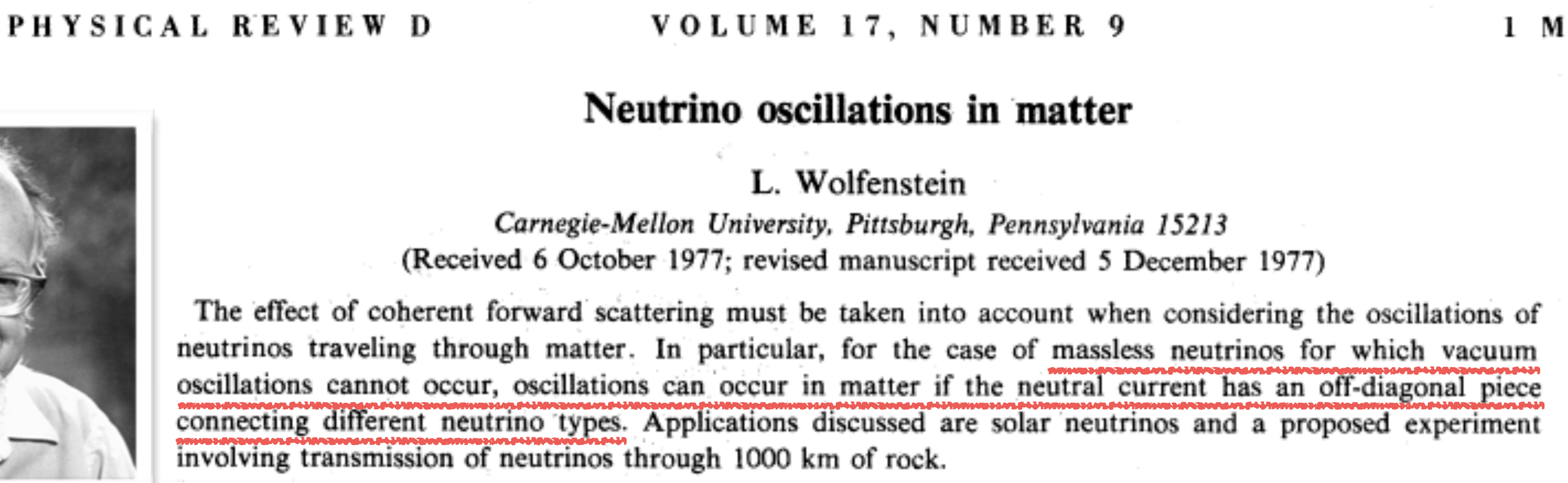
Beyond the new physics that gives rise to neutrino mass

- Neutrinos are massless in the SM with the three neutrino flavours distinguished by separate Lepton numbers
- Total lepton number distinguishes the neutrinos and anti-neutrinos
- Need to relax the above conditions 1 and/or 2 and/or 3 to generate neutrino mass
- Staying within SM is not an option !

Earlier work : S. Nussinov, Phys.Lett.B63 (1976) 201

Standard interactions


L.Wolfenstein


PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein

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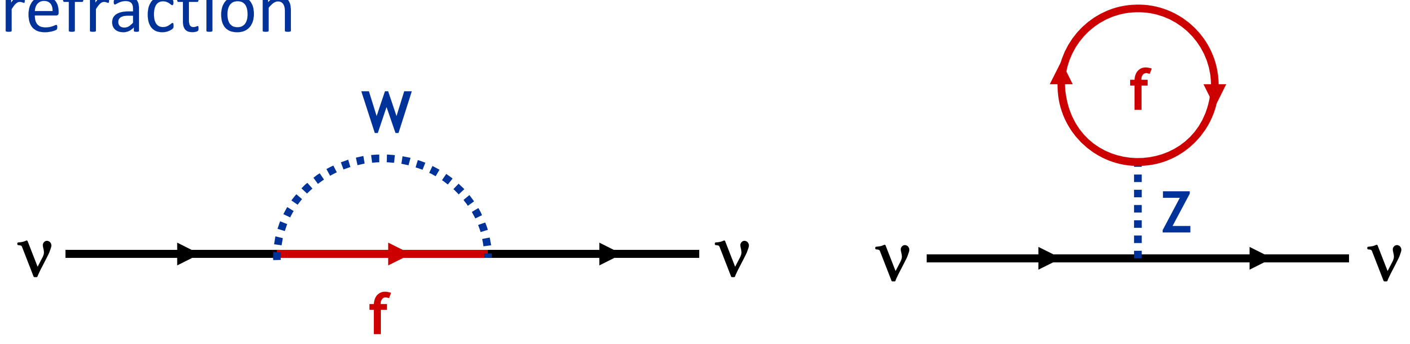
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

Neutrinos in a medium suffer flavor-dependent refraction



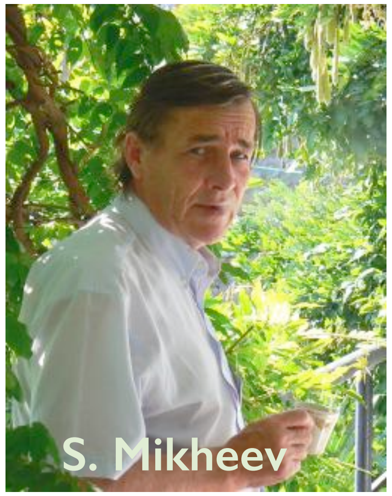
$$V_{\text{weak}} = \sqrt{2}G_{\text{F}} \times \begin{cases} N_{\text{e}} - N_{\text{n}}/2 & \text{for } \nu_{\text{e}} \\ -N_{\text{n}}/2 & \text{for } \nu_{\mu} \end{cases}$$

Typical density of Earth: 5 g/cm^3

$$\Delta V_{\text{weak}} \approx 2 \times 10^{-13} \text{ eV} = 0.2 \text{ peV}$$

- Elastic forward scattering dominates at low E (real part)
- Incoherent scattering cross section is usually very small

The potential changes sign for anti neutrinos



The MSW effect

In electrically neutral matter, UR limit

$$\mathbb{H}_\nu = \left(p + \frac{m_1^2+m_2^2}{4p} + \frac{V_C}{2} + V_N\right)\mathbb{I} + \frac{1}{2}\begin{pmatrix} V_C - \omega\cos 2\theta & \omega \sin 2\theta \\ \omega\sin 2\theta & -(V_C - \omega\cos 2\theta)\end{pmatrix}$$

$V_C = \sqrt{2}G_F n_e$ and $V_N = -\sqrt{2}G_F n_n/2$

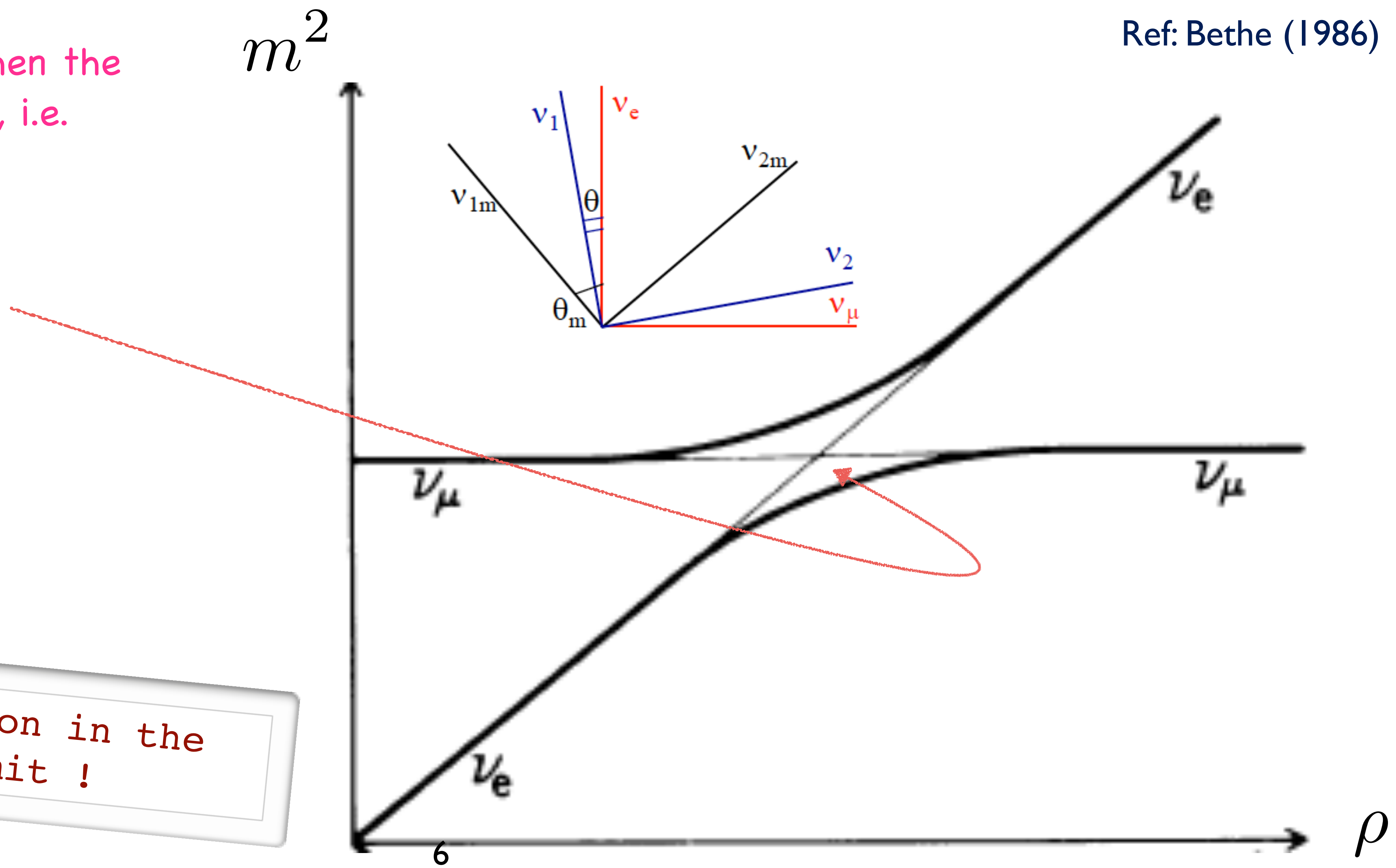
Mixing becomes maximal when the diagonal elements vanish, i.e.

$$\frac{V_C}{\omega} = \cos 2\theta$$

$$V_C = \sqrt{2}G_F n_e$$

$$\omega = \frac{\delta m^2}{2E}$$

Complete conversion in the adiabatic limit !



Ref: Bethe (1986)

Matter non-standard interactions

Ref: Review by T. Ohlsson (2012) ; M. Tortola and Y. Farzan (2018)

$$\mathcal{L}_{NSI} = -2\sqrt{2} G_F \epsilon^{f\,C}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right] \left[\bar{f} \gamma_\mu P_C f\right] \, ,$$

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

$$P_C = (1 \pm \gamma_5)/2.$$

- These are referred to as "matter or propagation NSI"
- New physics effects act as sub-leading effects in the discussion of oscillation formalism
- These can severely impact determination of standard oscillation parameters and lead to more complicated parameter degeneracies

Talk by Sabya Sachi

Beyond the new physics that gives rise to neutrino mass

Matter non-standard interactions

Ref: Review by T. Ohlsson (2012) ; M. Tortola and Y. Farzan (2018)

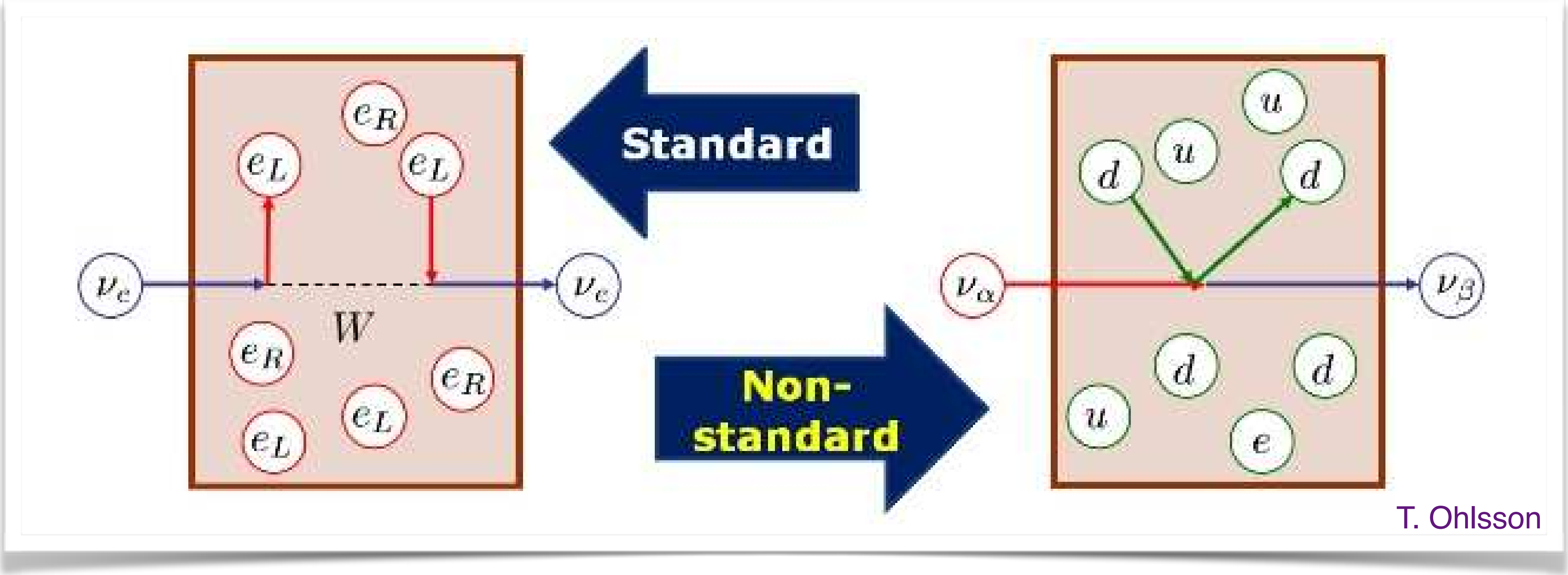
$$\mathcal{L}_{NSI} = -2\sqrt{2} G_F \epsilon^{f\,C}_{\alpha\beta} \, [\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta] \, [\bar{f} \gamma_\mu P_C f] \; ,$$

$$P_C = (1 \pm \gamma_5)/2.$$

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

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

Ref: Wolfenstein (1978), Valle (1987); Guzzo, Masiero, Petcov (1991); Roulet (1991), Kukuchi et al (2008), Asano et al (2009), Kopp et al (2007), Blennow et al (2008)



T. Ohlsson

CP Violation in neutrino oscillations

C, P, T in neutrino oscillations

$$\boxed{A^{CP}_{\alpha\beta} = \frac{P_{\alpha\beta} - \bar{P}_{\alpha\beta}}{P_{\alpha\beta} + \bar{P}_{\alpha\beta}} \,, \quad A^{T}_{\alpha\beta} = \frac{P_{\alpha\beta} - P_{\beta\alpha}}{P_{\alpha\beta} + P_{\beta\alpha}} \,, \quad A^{CPT}_{\alpha\beta} = \frac{P_{\alpha\beta} - \bar{P}_{\beta\alpha}}{P_{\alpha\beta} + \bar{P}_{\beta\alpha}}}$$

- CPT Invariance -

$$A^{CP}_{\alpha\beta} = -A^{CP}_{\beta\alpha}$$

$$A^{CP}_{\alpha\alpha} = 0$$

No CP asymmetry in survival probability

- Unitarity - $\sum_\beta P_{\alpha\beta} = 1 = \sum_\beta \bar{P}_{\alpha\beta}$

For three flavours, there can be only three independent CP asymmetries

$$A^{CP}_{e\mu} = A^{CP}_{\mu\tau} = A^{CP}_{\tau e} \propto \Delta P$$

$$A^{T}_{e\mu} = A^{T}_{\mu\tau} = A^{T}_{\tau e} \propto \Delta P$$

Single CP / T asymmetry

In the standard three flavour paradigm, there is only one CP phase

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$$

Jarlskog's factor

CP asymmetries : in vacuum

$\nu_\mu \to \nu_e$

- CP asymmetry is $\mathcal{A}_{CP} = \dfrac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}$

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e) + \text{ matter } + \text{smaller terms}$$

$$\boxed{\begin{aligned}
P_I(\nu_\mu \to \nu_e) &= \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\\
P_{II}(\nu_\mu \to \nu_e) &= \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\\
&\quad \sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right)\times\left[\boxed{\sin\delta}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.\\
&\quad \left.+\cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]\\
P_{III}(\nu_\mu \to \nu_e) &= \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)
\end{aligned}}$$

Interference term

To leading order in Δm^2_{21}

$$\boxed{\mathcal{A}_{CP} = \frac{\cos\theta_{23}\sin 2\theta_{12}\boxed{\sin\delta}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E}\right) + \text{matter effects}}$$

$\sim 1/\sin\theta_{13}$

$\sim \cot\theta_{23}$

Grows with L and 1/E

Ref : Marciano and Parsa, hep-ph/0610258

CP violation : matter effects

$$\boxed{\nu_\mu \to \nu_e}$$

$$P_{\mu e} = P_{atm} + P_{int}(\delta) + P_{sol}$$

$$\theta_{13}^2 \qquad \theta_{13} \qquad \theta_{13} - \text{indep}$$

$$\begin{aligned} P_{\mu e}(\delta) \quad \simeq \quad & 4 s_{13}^2 s_{23}^2 \left[\frac{\sin^2 (1-r_A)\lambda L/2}{(1-r_A)^2} \right] \\ + \quad & 8 r_\lambda \mathcal{J}_r \boxed{\cos\delta} \left[\cos \frac{\lambda L}{2} \frac{\sin r_A \lambda L/2}{r_A} \frac{\sin(1-r_A)\lambda L/2}{(1-r_A)} \right] \\ - \quad & 8 r_\lambda \mathcal{J}_r \boxed{\sin\delta} \left[\sin \frac{\lambda L}{2} \sin \frac{r_A \lambda L/2}{r_A} \frac{\sin(1-r_A)\lambda L/2}{(1-r_A)} \right] \\ + \quad & r_\lambda^2 c_{23}^2 s_{2\times 12}^2 \frac{\sin^2(r_A \lambda L/2)}{r_A^2} , \end{aligned}$$

$$\mathcal{J} = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$$

$$\boxed{\lambda \equiv \frac{\delta m_{31}^2}{2E} \quad ; \quad r_\lambda \equiv \frac{\delta m_{21}^2}{\delta m_{31}^2} \quad ; \quad r_A \equiv \frac{A(x)}{\delta m_{31}^2} \, .}$$

Ref : Cervera et al, Freund, Akhmedov et al., Marciano and Parsa, hep-ph/0610258

Intrinsic and extrinsic CP effects

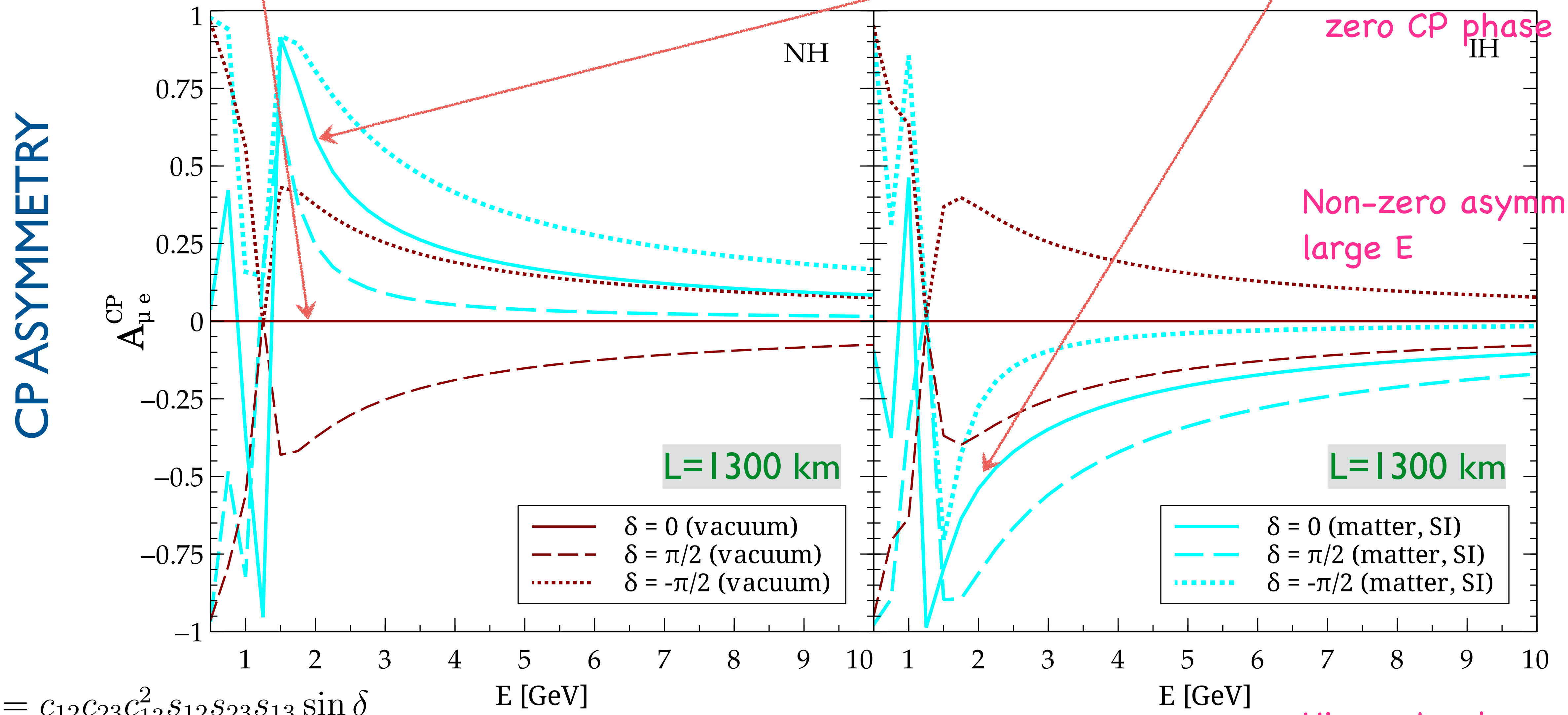
- in vacuum

$$\begin{aligned}\Delta P_{\mu e}(\delta) &= 8\,\mathcal{J}\left[\sin(r_\lambda \lambda L)\sin^2\frac{\lambda L}{2} - \sin(\lambda L)\sin^2\frac{r_\lambda \lambda L}{2}\right]\\ &= 4\sin\delta\,\mathcal{J}_r\;[\sin\lambda L/2\,\sin r_\lambda \lambda L/2\,\sin(1-r_\lambda)\lambda L/2]\end{aligned}$$

- in matter with standard interactions

$$\Delta P_{\mu e}(\delta) = 8\,r_\lambda \mathcal{J}\frac{\sin r_A \lambda L/2}{r_A}\,[\Theta_- \cot\delta\cos\lambda L/2 + \Theta_+ \sin\lambda L/2]$$

$$\Theta_\pm = \sin[(r_A-1)\lambda L/2]/(r_A-1) \pm \sin[(r_A+1)\lambda L/2]/(r_A+1)$$



Non-zero asymmetry for zero CP phase

Non-zero asymmetry at large E

Hierarchy dependence

$$\mathcal{J} = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta$$

$$\boxed{\lambda \equiv \frac{\delta m^2_{31}}{2E} \quad ; \quad r_\lambda \equiv \frac{\delta m^2_{21}}{\delta m^2_{31}} \quad ; \quad r_A \equiv \frac{A(x)}{\delta m^2_{31}}\ .}$$

M. Masud, A. Chatterjee, P. Mehta, J. Phys. G (2016) [1510.08261] ; see also M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

(Future) Long baseline experiments

leading efforts in precision determination of the as yet unknown parameters of leptonic mixing matrix and studying new physics

T2HK: Tokai-to-Hyper-Kamiokande

JPARC upgrade plan for future and beyond T2K

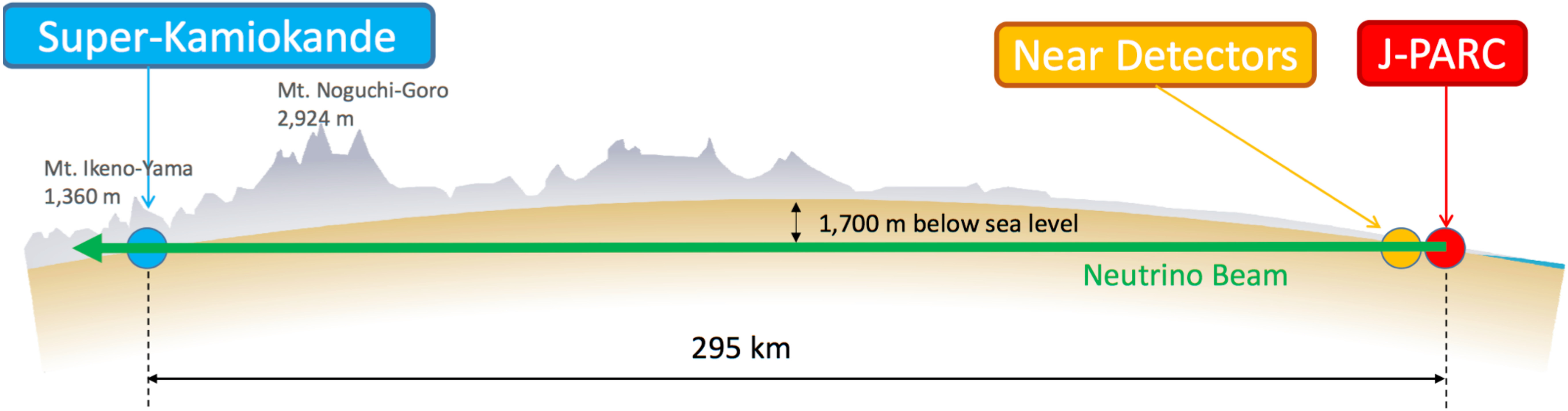
http://arxiv.org/abs/1109.3262

Off-axis narrow band beam, E ~ 0.6 GeV, 750 kW ~ 1MW

Baseline is 295 km (less matter effect)

Hyper-Kamiokande: HUGE water Cherenkov Detector

Measurement of CP violation



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Mega-watt class beam, **wide band beam** 0.5 - 10 GeV
Baseline is 1300 km
Ideal for mass ordering and CP violation

Primary Science Program

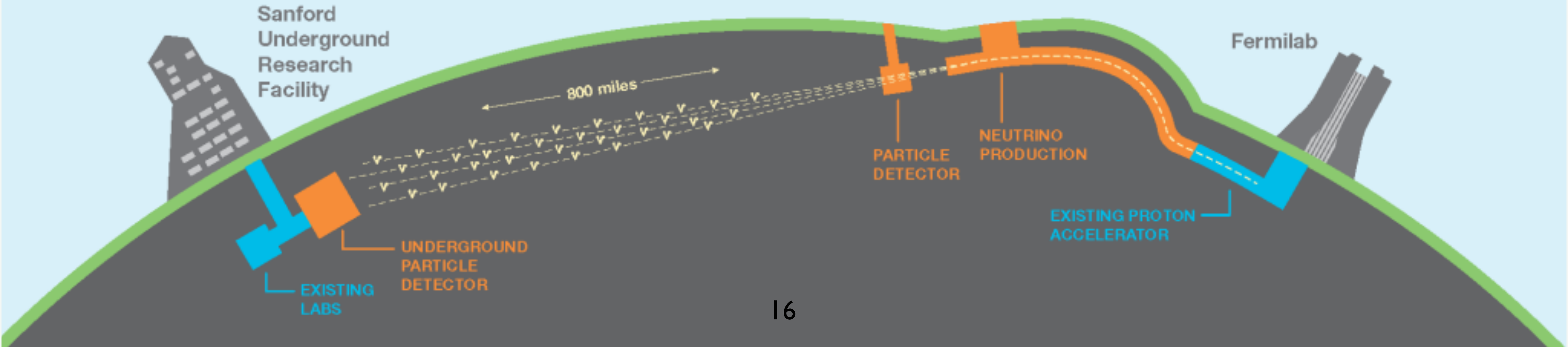
CDR, Vol 2, DUNE Collaboration, 1512.06148 [physics.ins-det]

Ancillary Science Program

CDR, Vol 4, DUNE Collaboration, 1601.02984 [physics.ins-det]

CDR, Vol 1, DUNE Collaboration, 1601.05471 [physics.ins-det]

CDR, Vol 3, DUNE Collaboration, 1601.05823 [physics.ins-det]

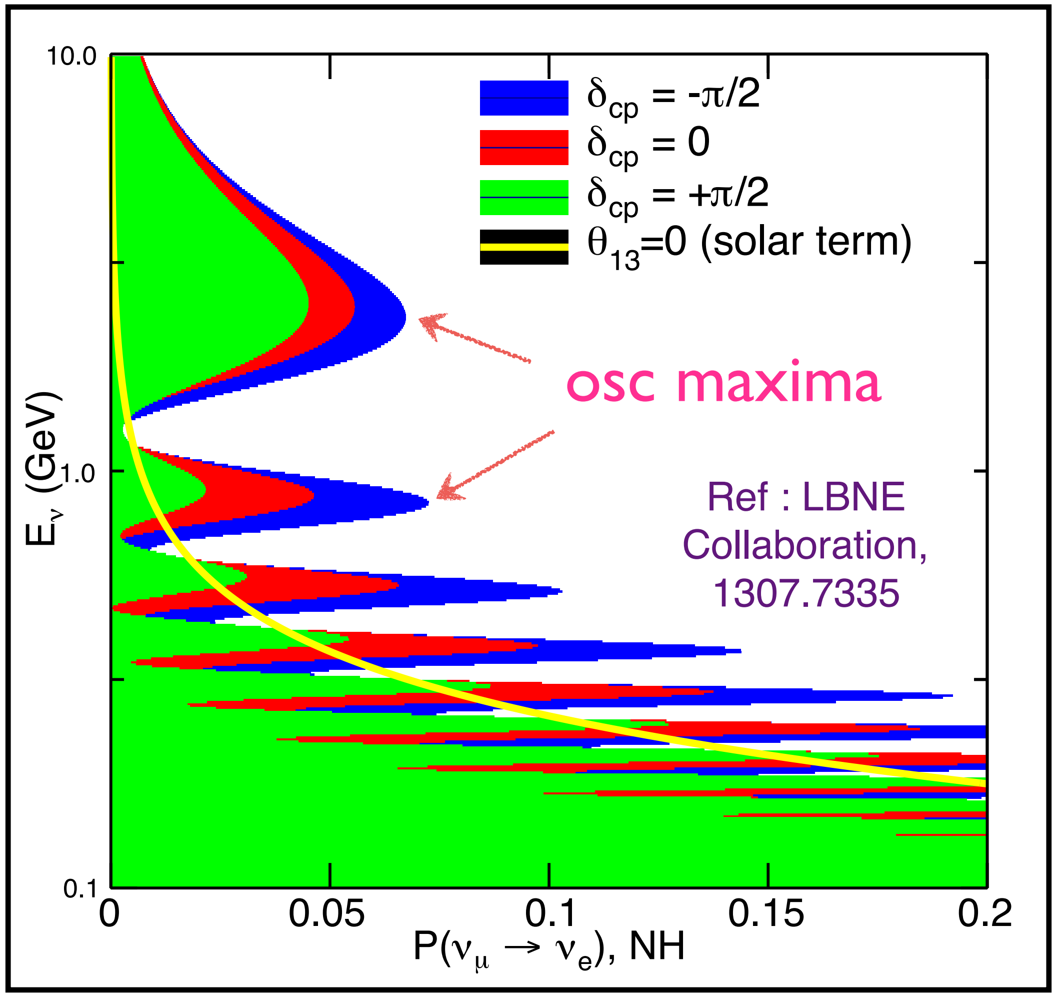


Probability at 1300 km and flux

- To exploit the full three flavour effects in neutrino oscillations
  - constrain the known parameters and measure the unknown parameters

- DUNE has a broad program of neutrino oscillation physics
  - Beam covers first (2.5 GeV) and second (0.8 GeV) oscillation maxima
  - will run in both neutrino and antineutrino mode for ~6-10 years

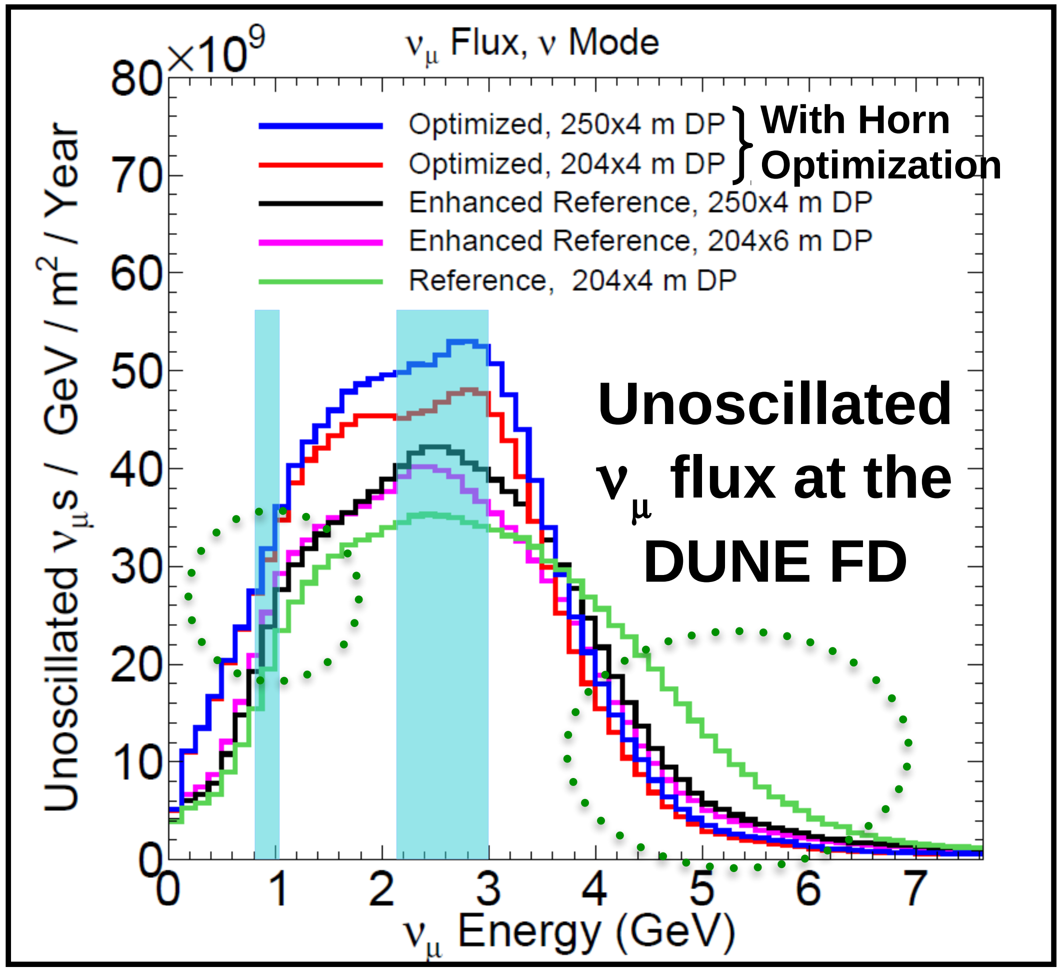
$$\frac{L(\text{km})}{E_\nu(\text{GeV})} = (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\text{eV}^2)} \approx (2n-1)\times 510\ \text{km/GeV}$$



osc maxima

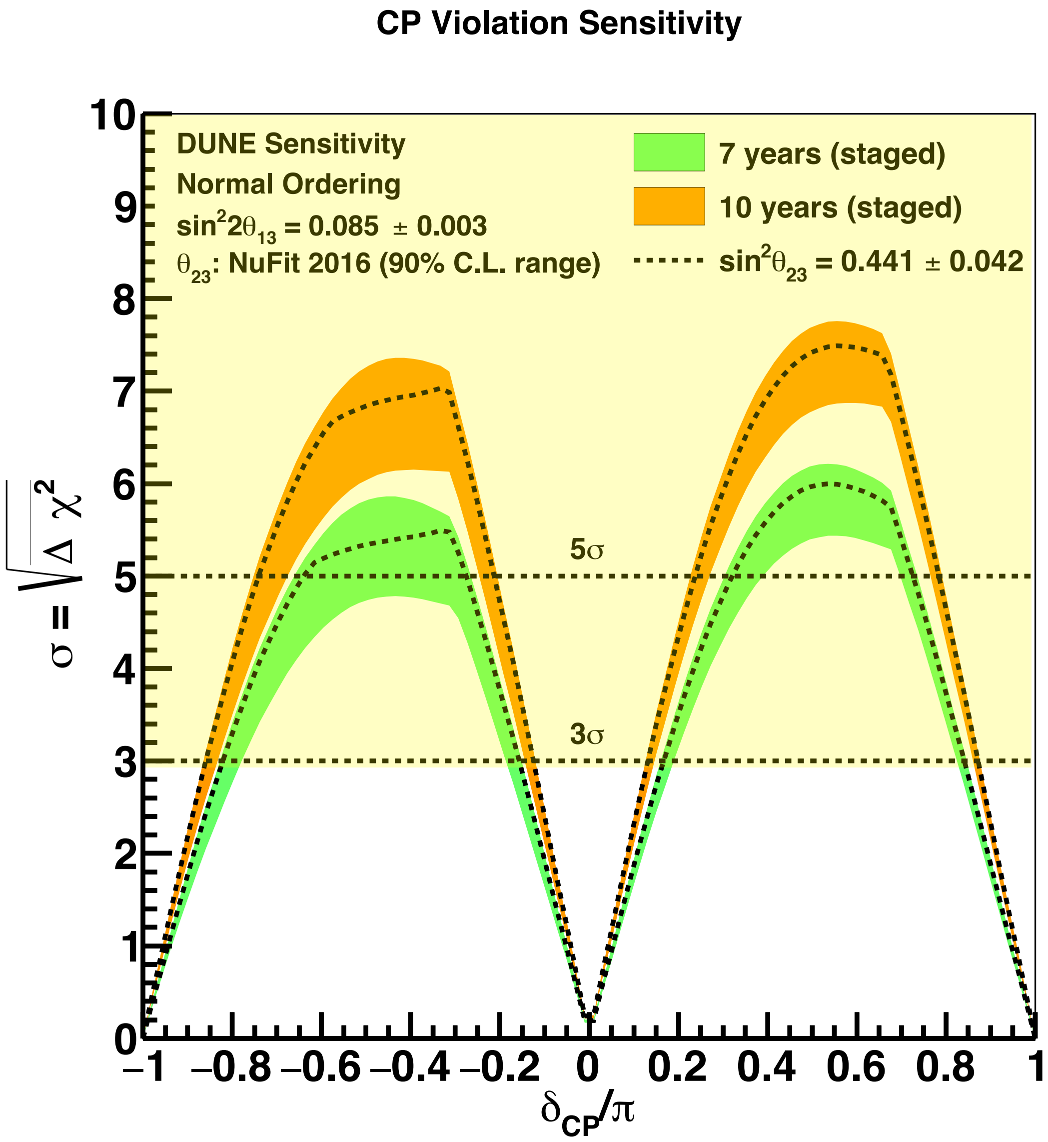
Ref : LBNE Collaboration, 1307.7335

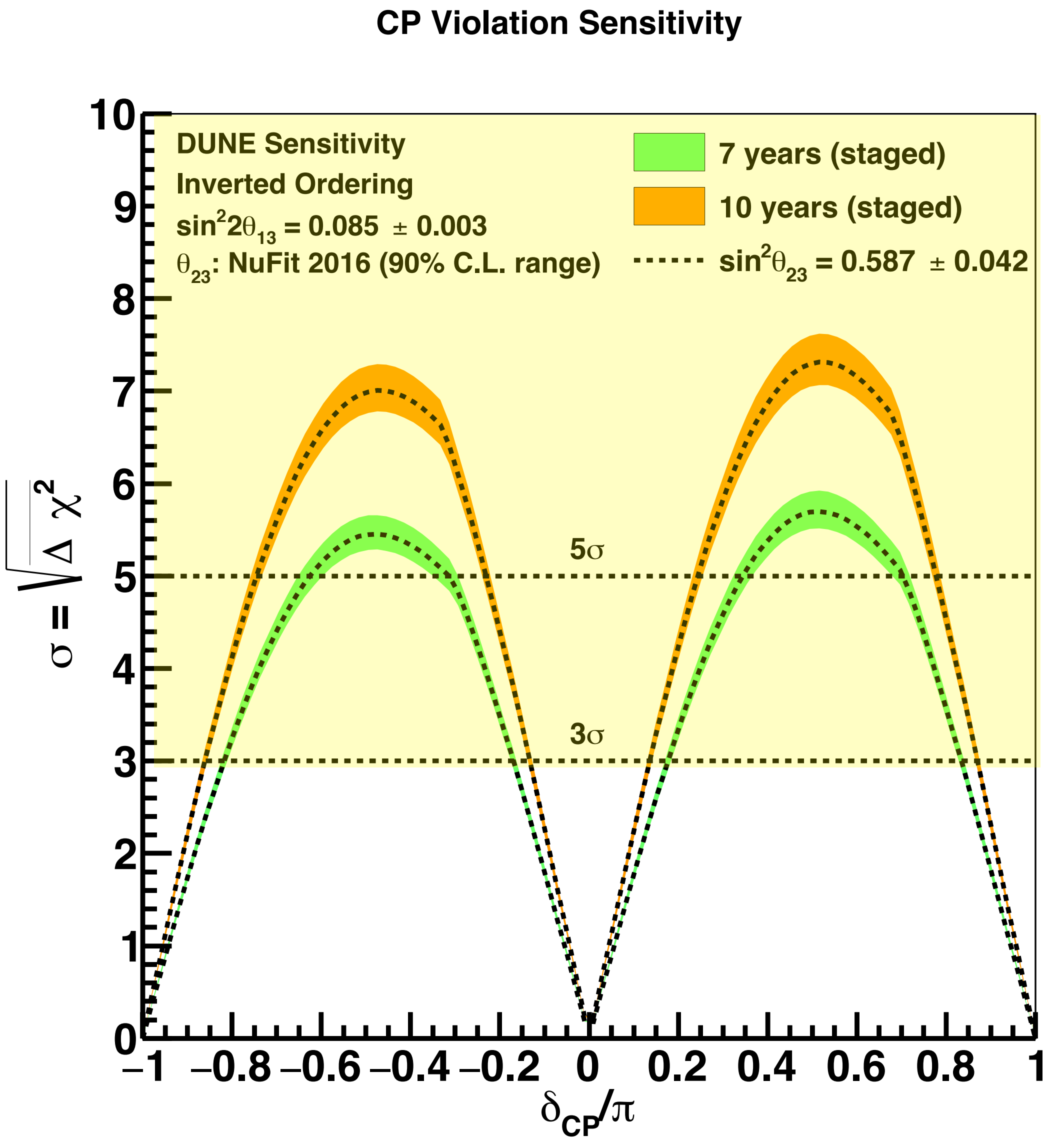
CDR, Vol 2, DUNE Collaboration, 1512.06148 [physics.ins-det]



Unoscillated ν_μ flux at the DUNE FD

CP Violation sensitivity

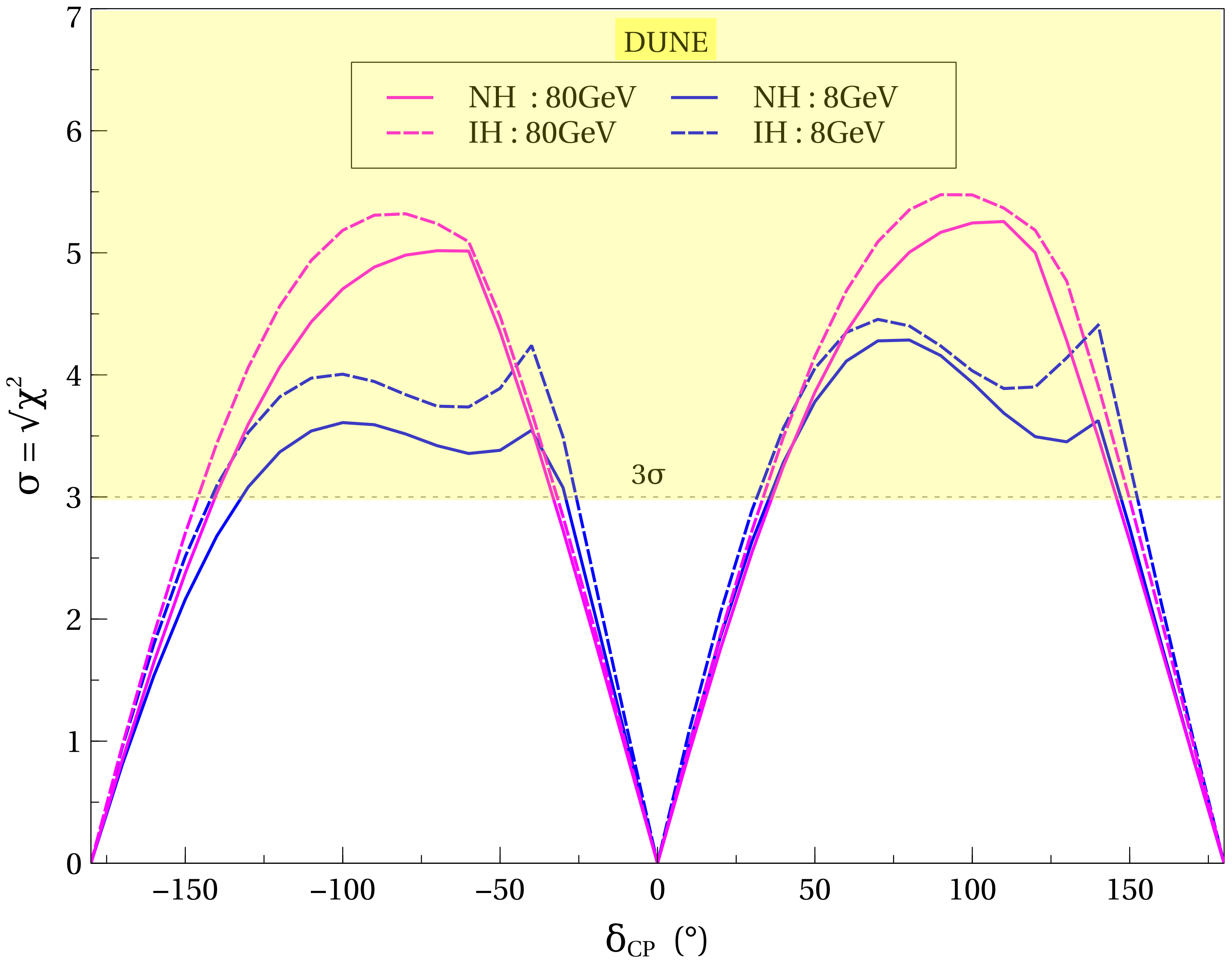

CP Violation Sensitivity


CP Violation Sensitivity

Staging assumptions - change the far detector mass, beam power etc

Talk by Ryan Patterson@CERN Neutrino Platform week, see also CDR, Vol 2, DUNE Collaboration, 1512.06148 [physics.ins-det]

With flux peaked at 2nd maxima



PRELIMINARY

Sheeba Shafaq, Jogesh Rout, Mary Bishai and PM, in progress

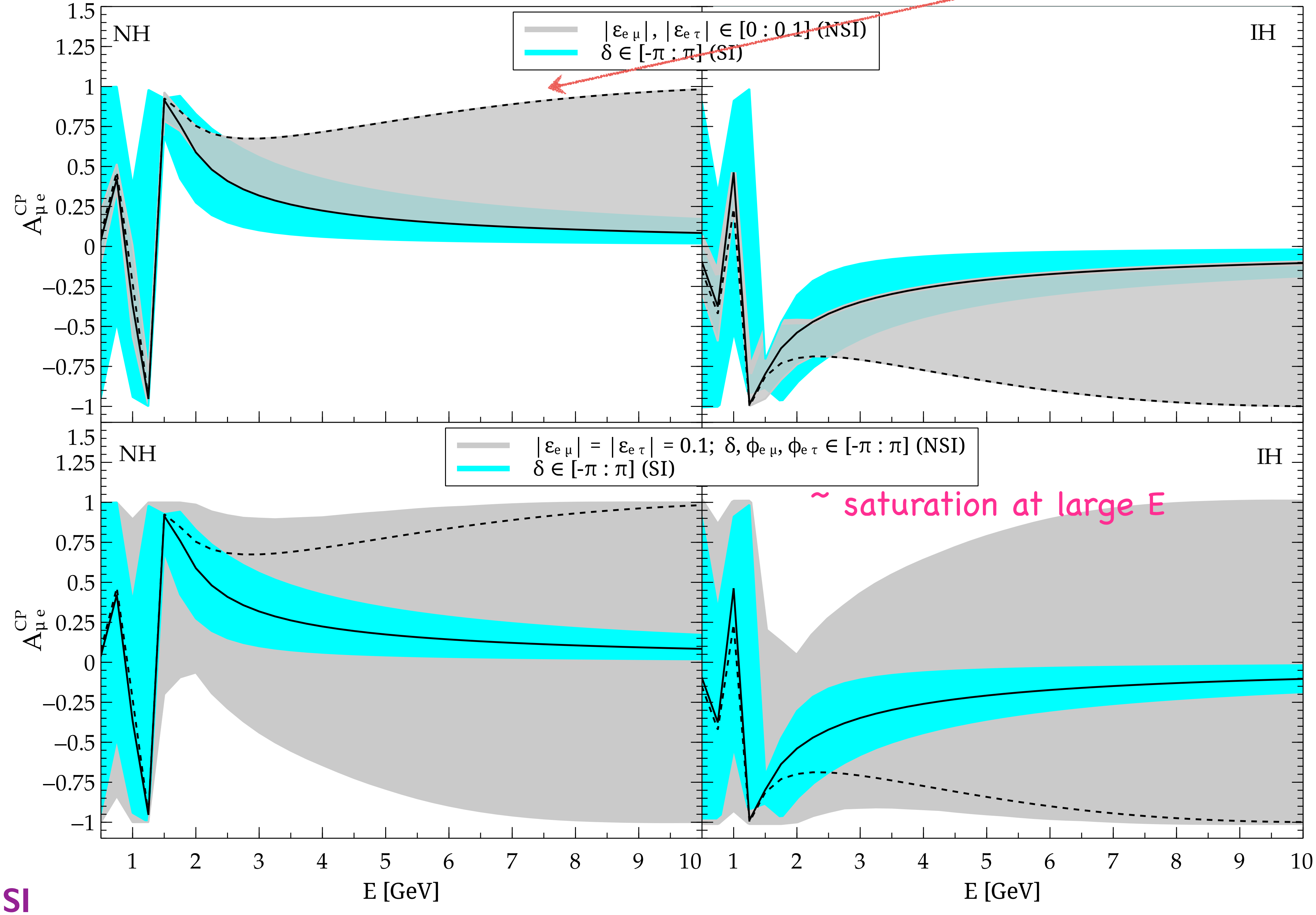
I. Impact of subdominant NSI terms on CP studies and mass ordering …

M. Masud, A. Chatterjee, P. Mehta, J. Phys. G (2016) [1510.08261] ;
M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389] ;
M. Masud and P. Mehta, Phys. Rev. D (2016) [1606.05662]

Octant degeneracy was covered by Sabya Sachi

CP asymmetry

Large value implies new physics



~ saturation at large E

CP ASYMMETRY

- Moduli variation

Either + or -, depending on hierarchy

- Phase variation

Both + and -, at large E, hierarchy dependence is lost !

grey : NSI

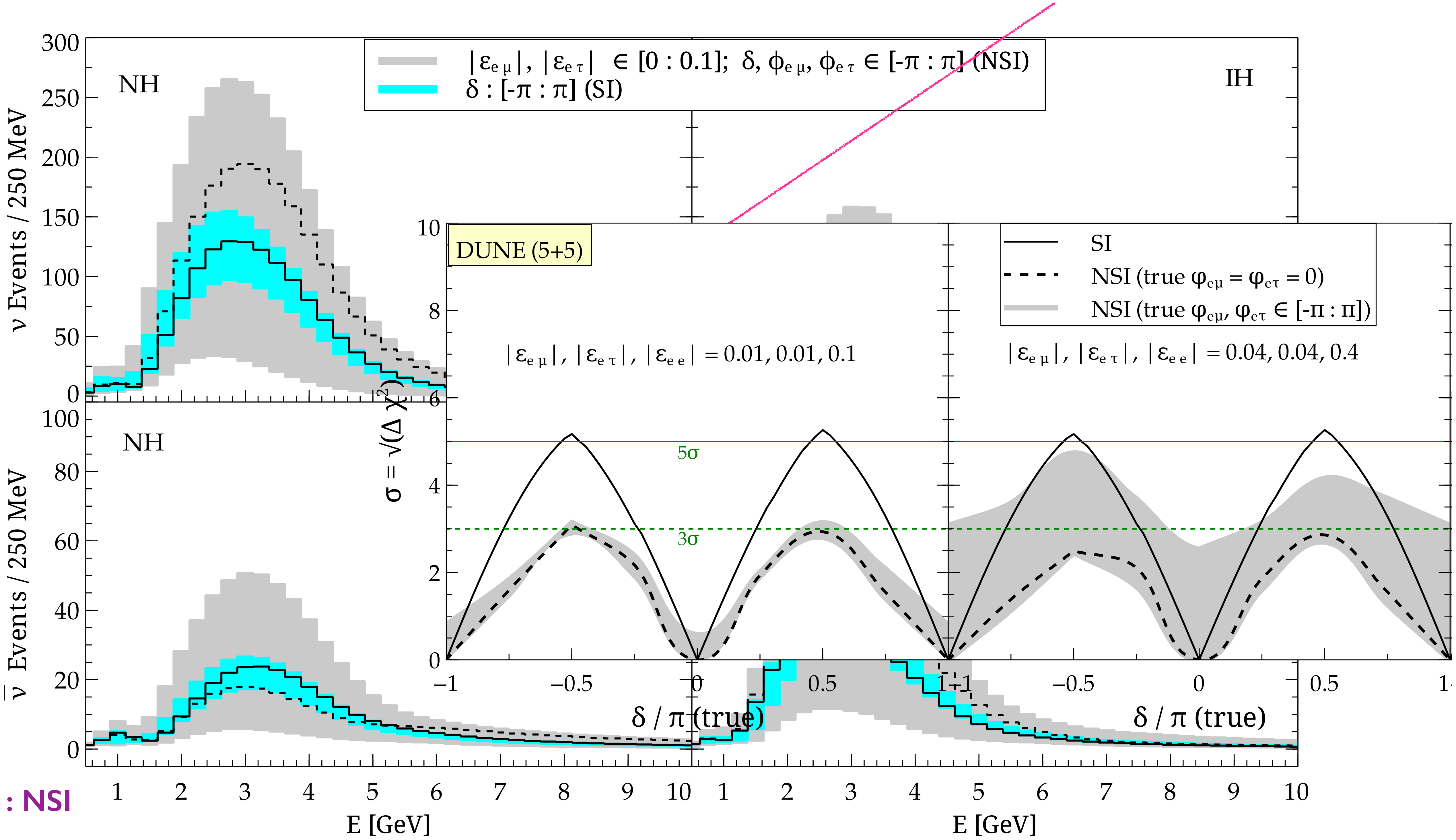
cyan : SI

M. Masud, A. Chatterjee, P. Mehta, J. Phys. G (2016) [1510.08261] ; see also M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

Event rates and CP Violation sensitivity

Falling flux kills the large asymmetry at large E

EVENT RATES AT DUNE

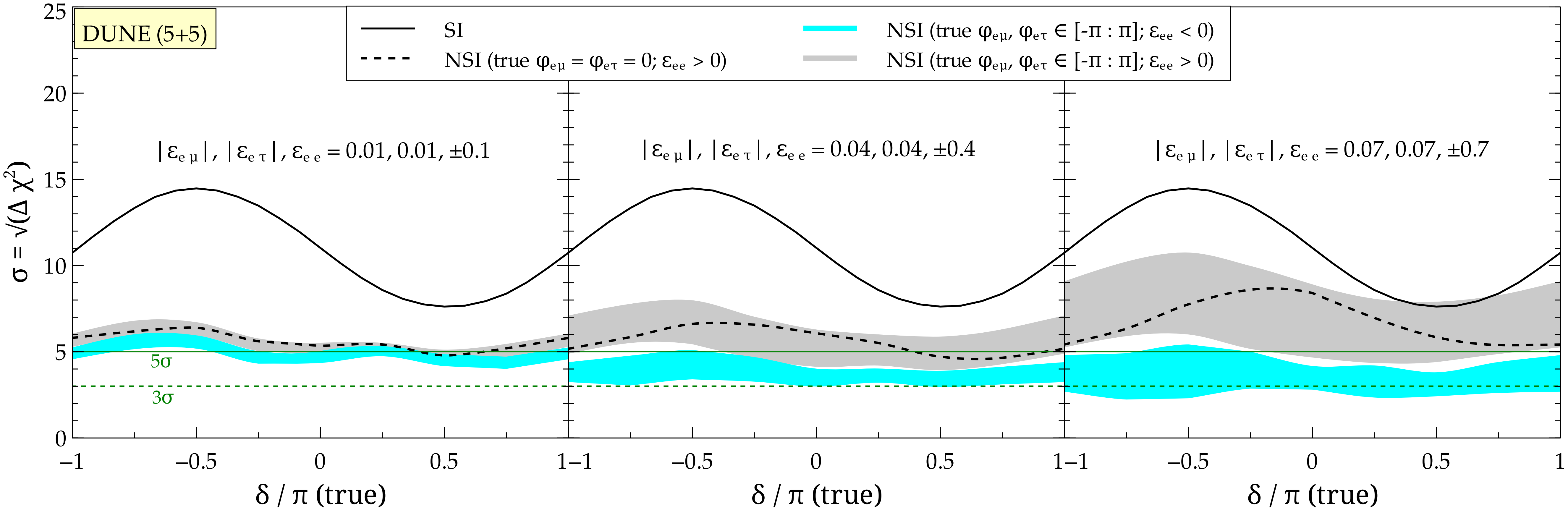


grey : NSI

cyan : SI

M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389] ;
M. Masud, A. Chatterjee, P. Mehta, J. Phys. G (2016) [1510.08261]

Mass ordering sensitivity

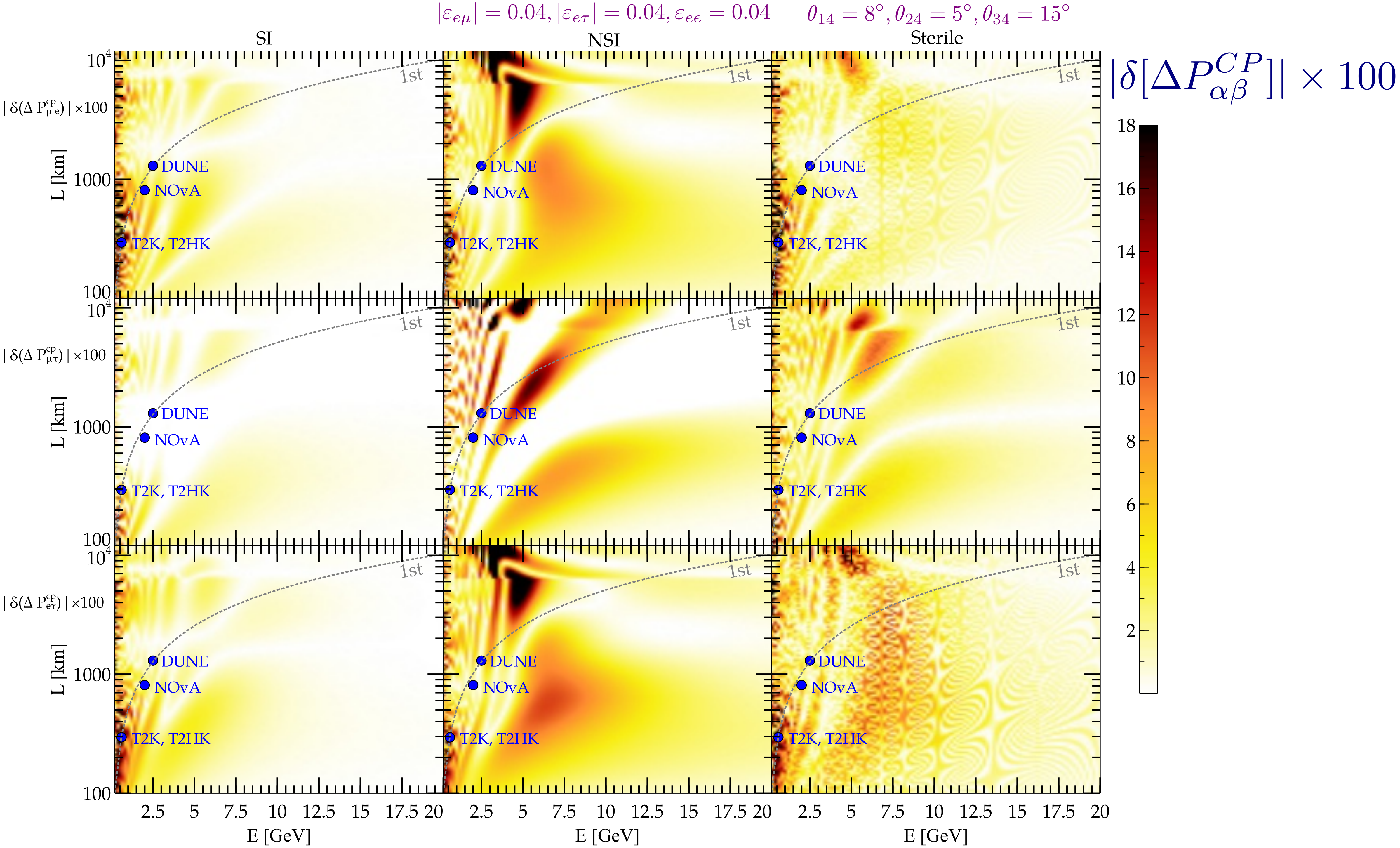


Ref : M. Masud and P. Mehta, Phys. Rev. D (2016) [1606.05662]

II. Can we probe intrinsic CP/T violation and non-unitarity at long baselines experiments ?

Jogesh Rout, M. Masud and P. Mehta, PRD 95, 075035 (2017) [1702.02163]

Extracting the intrinsic CP phase



A useful quantity for separating intrinsic and extrinsic components

$$\delta[\Delta P_{\alpha\beta}^{CP}] = [\Delta P_{\alpha\beta}^{CP}](\delta_{13} = \pi/2) - [\Delta P_{\alpha\beta}^{CP}](\delta_{13} = 0)$$

Nunokawa, Parke, Valle (2008)

Dark region in NSI/Sterile gives fake impression that we can extract intrinsic component better…

Jogesh Rout, M. Masud and P. Mehta, PRD 95, 075035 (2017) [1702.02163

III. Can we separate new physics scenarios from the standard ?

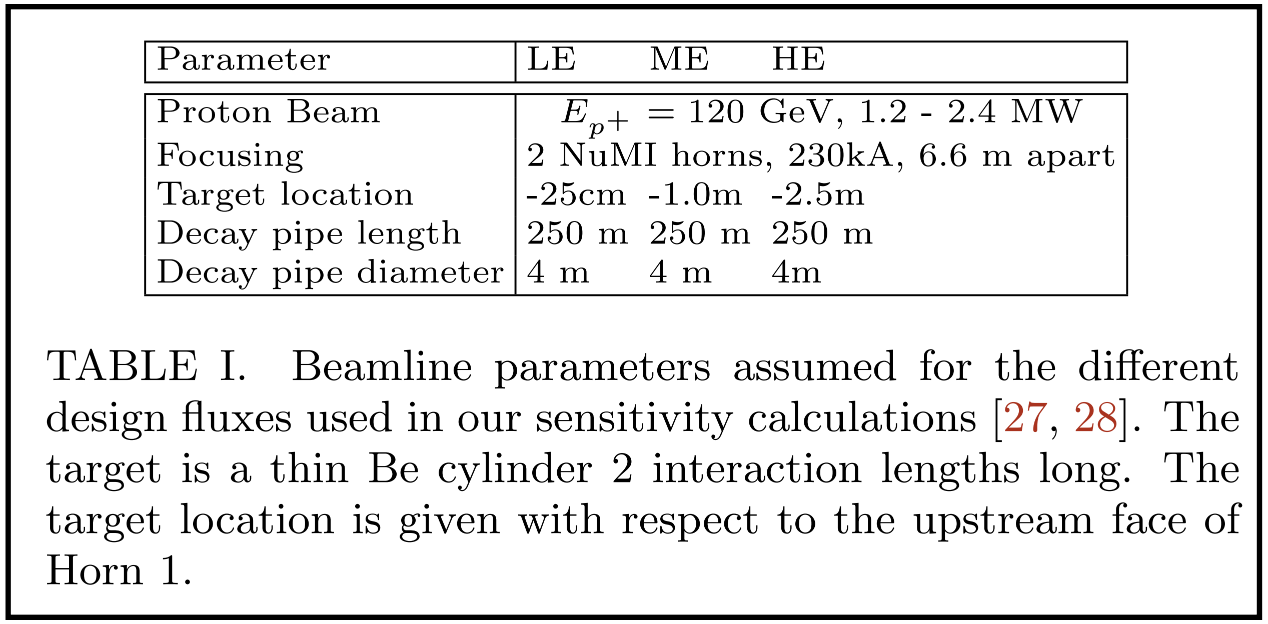
Idea - Define a “theoretical metric” and “use feasible experimental handles”

M. Masud, M. Bishai and P. Mehta, Scientific Reports (2019).

High energy Beam tunes at DUNE

- Can we have other possible beam options other than the optimised one used in CDR ?
- The aim is to get better separability of SI from NSI...

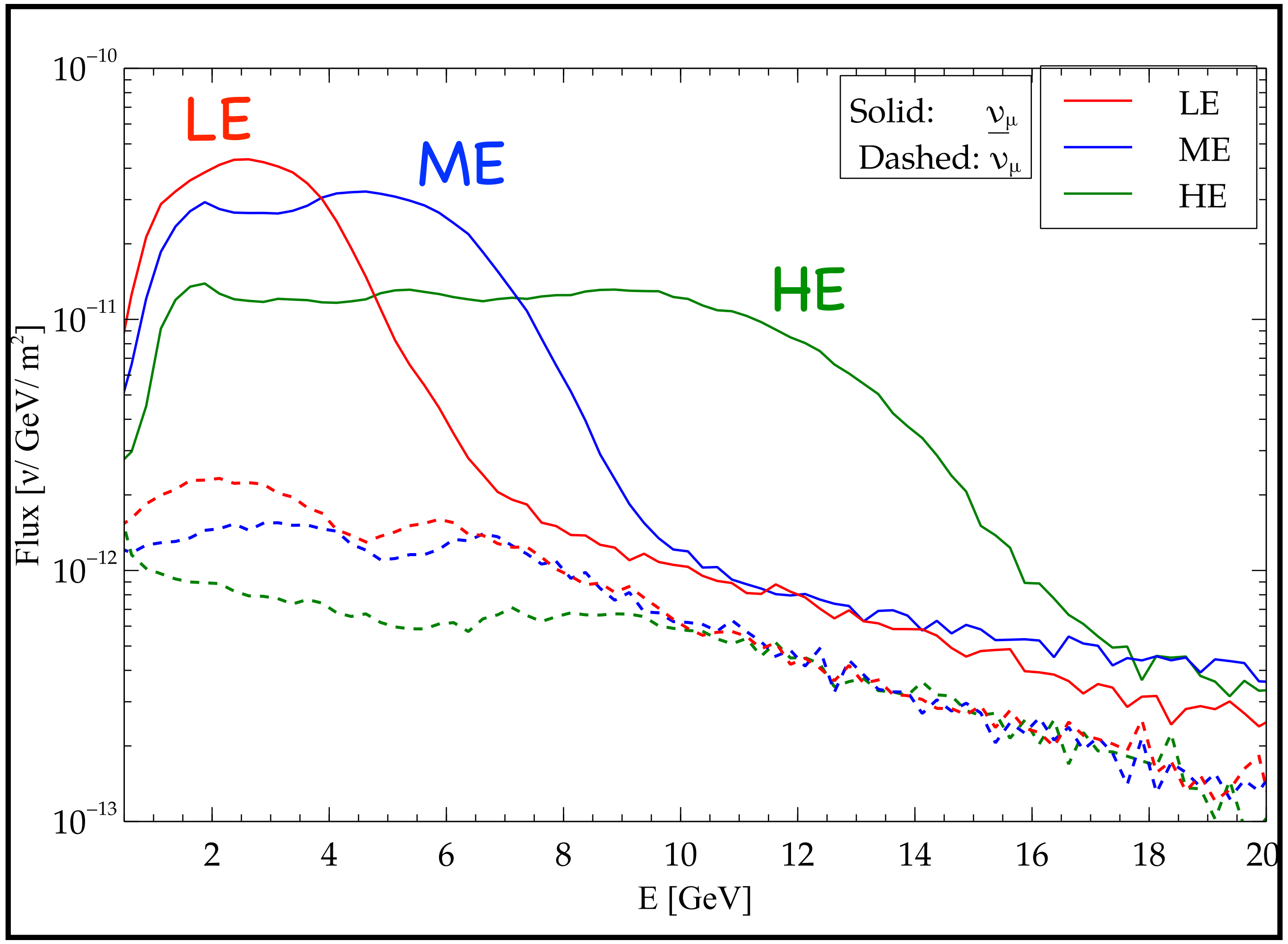
Beamline parameters



Parameter	LE	ME	HE
Proton Beam	$E_{p^+} = 120$ GeV, 1.2 - 2.4 MW		
Focusing	2 NuMI horns, 230kA, 6.6 m apart		
Target location	-25cm	-1.0m	-2.5m
Decay pipe length	250 m	250 m	250 m
Decay pipe diameter	4 m	4 m	4m

TABLE I. Beamline parameters assumed for the different design fluxes used in our sensitivity calculations [27, 28]. The target is a thin Be cylinder 2 interaction lengths long. The target location is given with respect to the upstream face of Horn 1.

Experimental configurations from Alion et al. [DUNE collaboration], 1606.09550



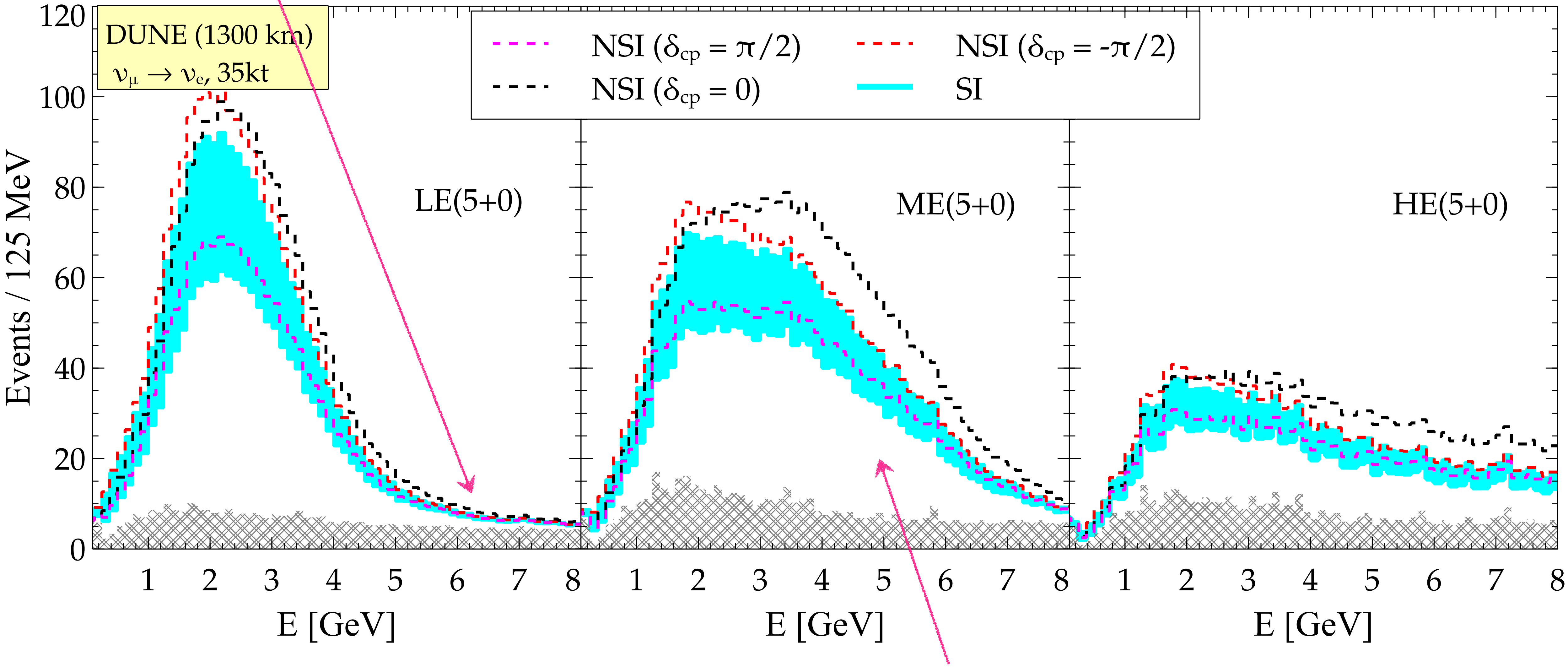
M. Masud, M. Bishai and P. Mehta, Scientific Reports (2019).

Event spectrum at DUNE for different tunes

$\nu_\mu \rightarrow \nu_e$

Falling flux kills the large asymmetry at large E

$|\varepsilon_{e\mu}| = 0.04, |\varepsilon_{e\tau}| = 0.04, \varepsilon_{ee} = 0.4$



Better ability to separate black curve from cyan band

M. Masud, M. Bishai and P. Mehta, Scientific Reports (2019).

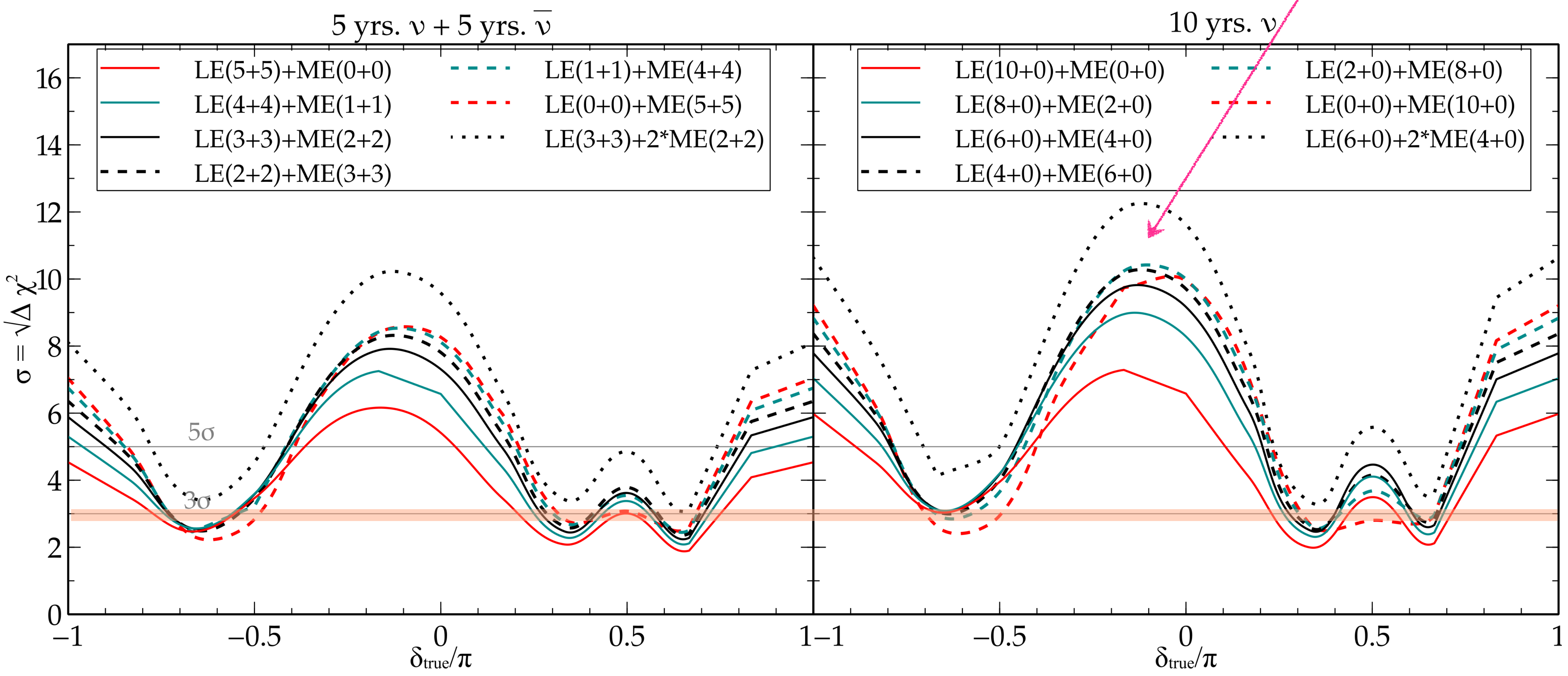
SI-NSI separation at DUNE

Theoretical metric

$$\chi^2(\delta_{tr}) = \min_{\delta_{ts}} \sum_{i=1}^{x} \sum_{j}^{2} \frac{\left[N^{i,j}_{NSI}(\delta_{tr}, |\varepsilon|, \varphi) - N^{i,j}_{SI}(\delta_{ts} \in [-\pi,\pi])\right]^2}{N^{i,j}_{NSI}(\delta_{tr}, |\varepsilon|, \varphi)}$$

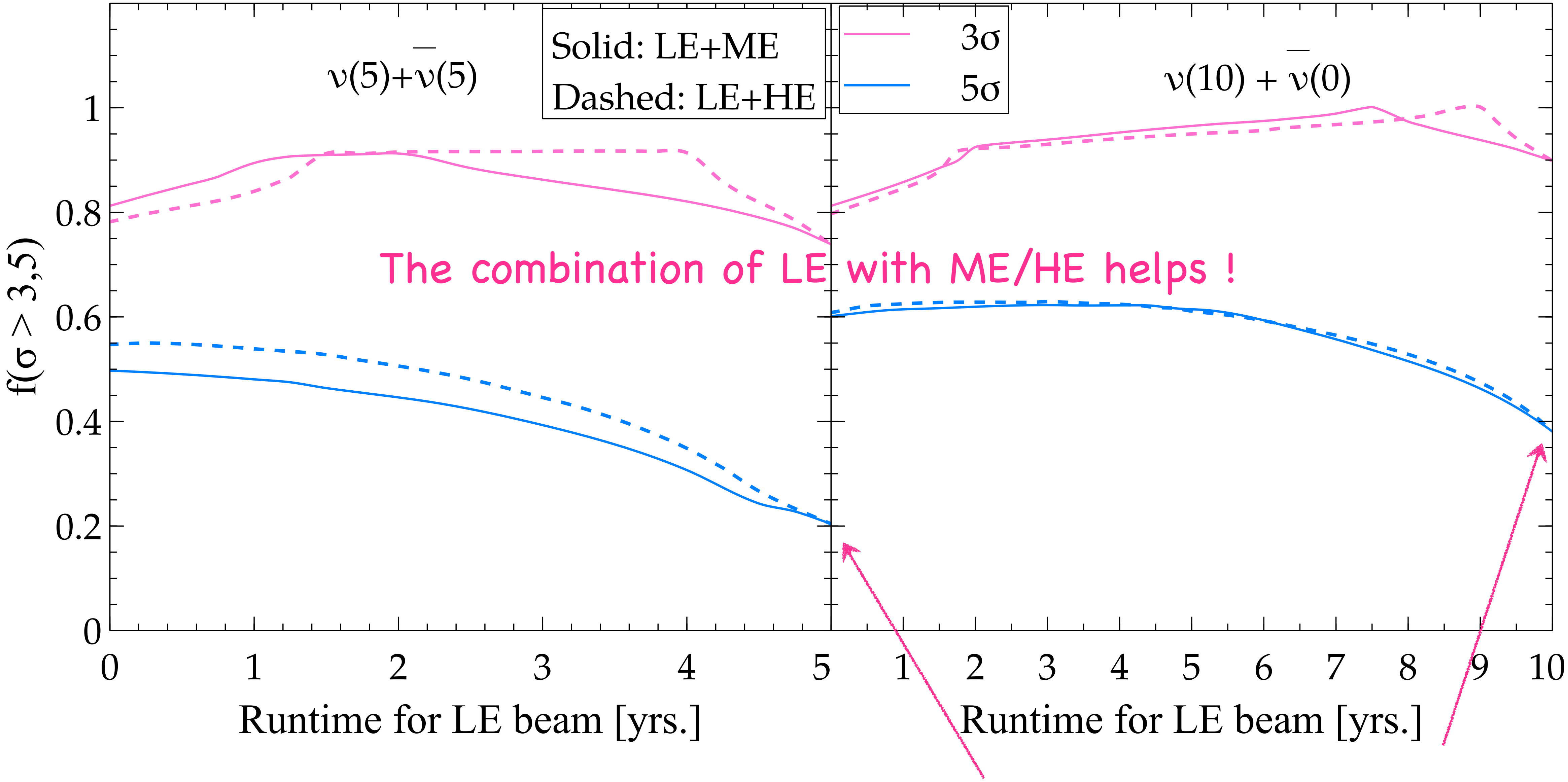
Neutrino only run allows for better discrimination between SI and NSI

Better ability at CP conserving values



M. Masud, M. Bishai and P. Mehta, Scientific Reports (2019).

Fraction for SI/NSI separation



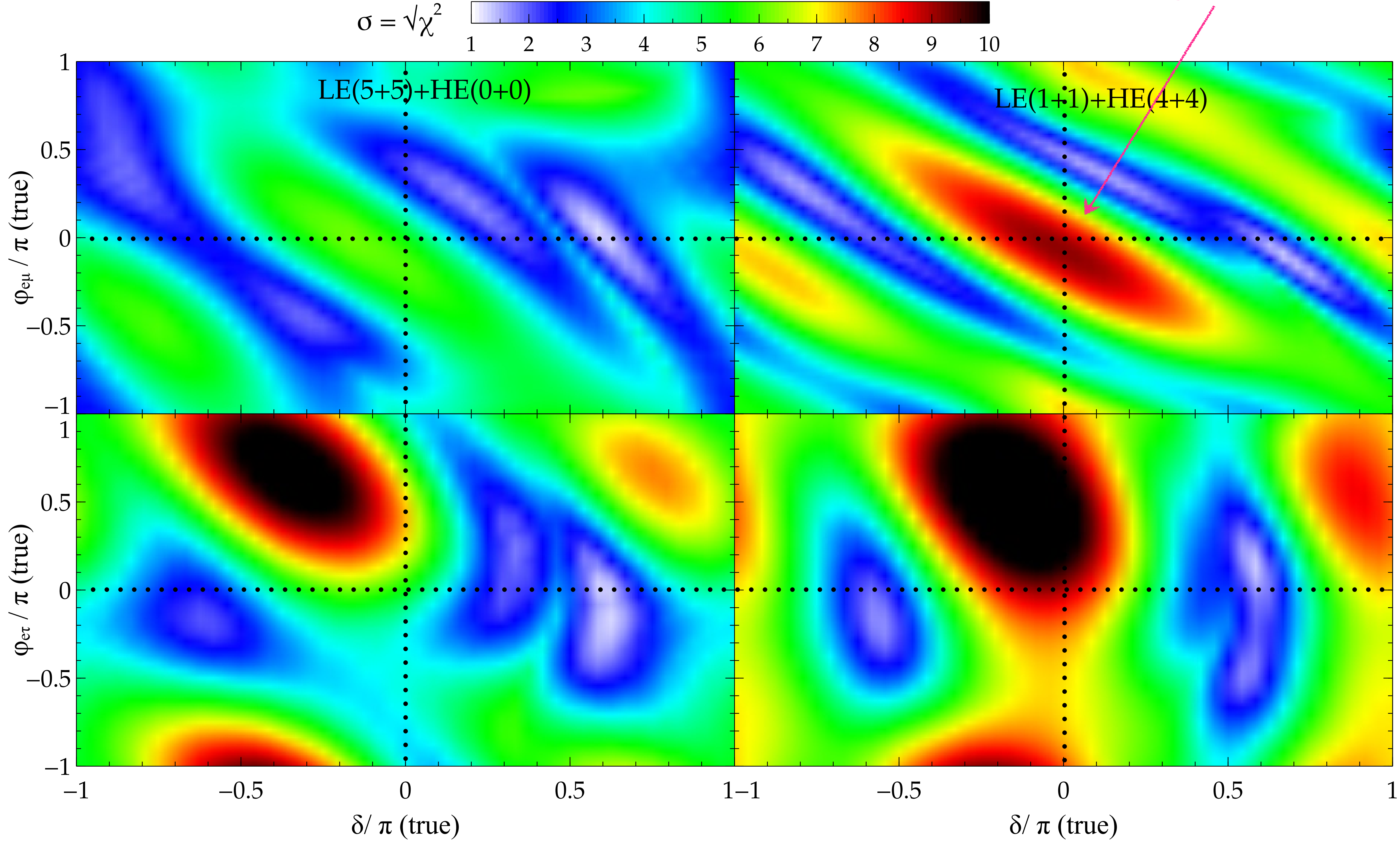
The combination of LE with ME/HE helps !

LE only case - the separability between SI and NSI is less!

M. Masud, M. Bishai and P. Mehta, Scientific Reports (2019).

Impact of non-zero NSI phases

Generalization of previous plots corresponding to zero NSI phases (CP conserving NSI scenario)

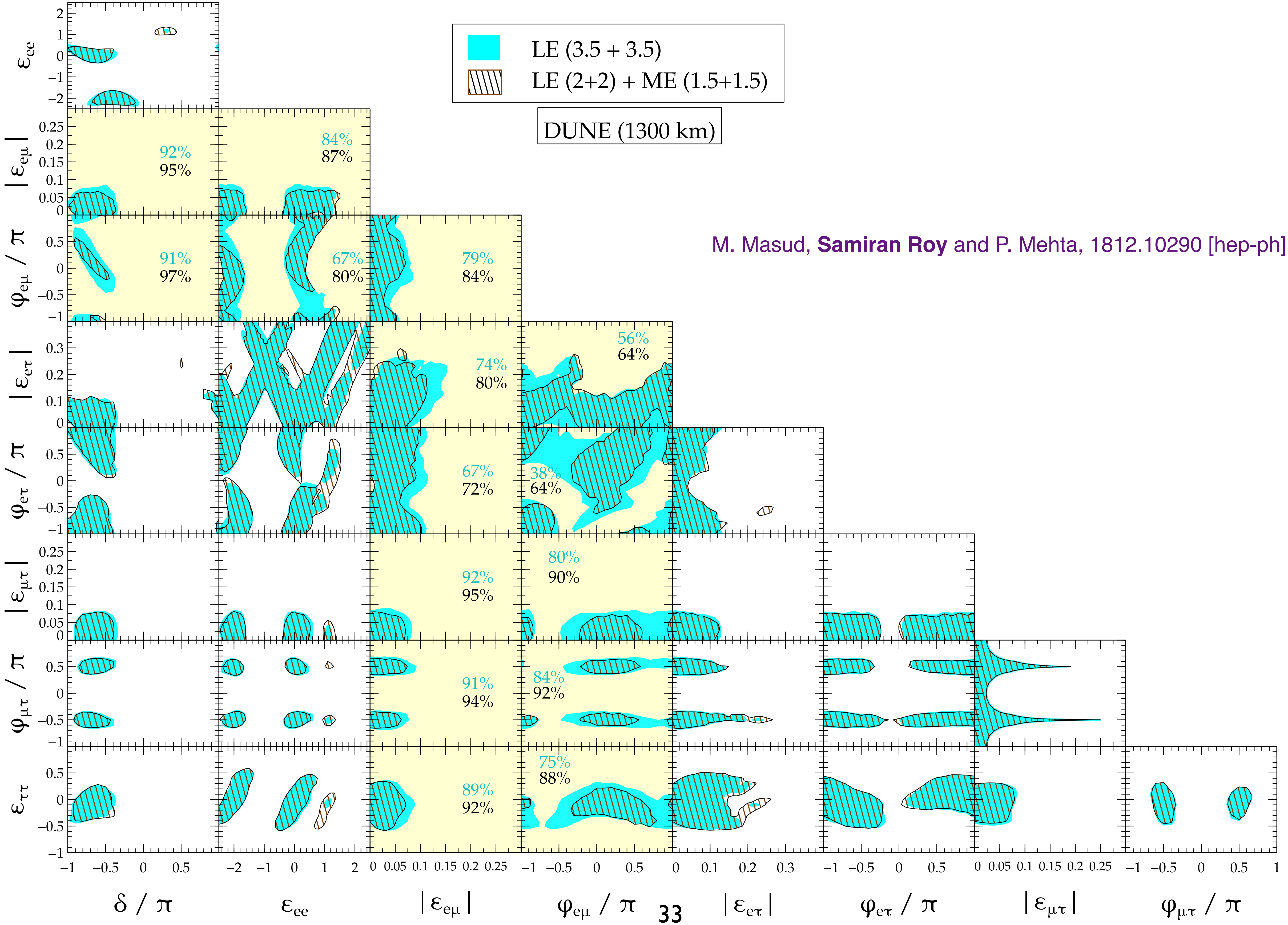


M. Masud, M. Bishai and P. Mehta, Scientific Reports (2019).

IV. Correlations and degeneracies of NSI parameters with high energy beam tunes…

M. Masud, **Samiran Roy** and P. Mehta, 1812.10290 [hep-ph]

SI-NSI degeneracies at DUNE



M. Masud, **Samiran Roy** and P. Mehta, 1812.10290 [hep-ph]

Summary

- Small mass and large mixing in neutrino sector... neutrino oscillations act as precise interferometer sensitive to very small perturbations caused by new physics.
- Effects at sub-leading level such as NSI in propagation can confuse the inferences about some of the unknowns e.g. : CP phase, mass hierarchy and octant of theta 23.
- We have demonstrated usefulness of high energy beam tunes
  - to separate SI and NSI (or any other new physics scenarios)
  - correlations and degeneracies among NSI parameters at DUNE

Direct bounds on matter NSI

$$\mathcal{L}_{NSI} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fC} \, [\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta] \, [\bar{f} \gamma_\mu P_C f] \, ,$$

$$\epsilon_{\alpha\beta}^{f} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$$

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

- Conservative (use most stringent constraint in individual NSI terms)

$$|\epsilon_{\alpha\beta}| < \begin{pmatrix} 0.06 & 0.05 & 0.27 \\ 0.05 & 0.003 & 0.05 \\ 0.27 & 0.05 & 0.16 \end{pmatrix}$$

Ref: Davidson et al (2003)

- Model-independent, assume uncorrelated errors on NSI terms (neutral Earth matter)

$$\epsilon_{\alpha\beta} \lesssim \left\{ \sum_{C=L,R} \left[(\epsilon_{\alpha\beta}^{eC})^2 + (3\epsilon_{\alpha\beta}^{uC})^2 + (3\epsilon_{\alpha\beta}^{dC})^2 \right] \right\}^{1/2} ,$$

for neutral Earth matter, leads to

$$|\epsilon_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix} .$$

~0.01-10

Ref: Biggio, Blennow, Fernandez-Martınez, arXiv:0907.0097

- Neutrino data constraining NSI (SK + MINOS)

$$|\epsilon_{\mu\tau}| < 0.033, |\epsilon_{\tau\tau} - \epsilon_{\mu\mu}| < 0.147 \qquad \text{SK}$$

$$-0.20 < \epsilon_{\mu\tau} < 0.07 \text{ (at 90\% CL) from MINOS}$$

$$|\epsilon_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.3 & 0.5 \\ 0.3 & 0.068 & 0.04 \\ 0.5 & 0.04 & 0.15 \end{pmatrix} .$$

more restrictive

Mitsuka et al. (Super-Kamiokande Collaboration), arXiv:1109.1889,

MINOS Collaaboration