CP Violation in neutrino oscillations and non-standard interactions

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

INO Collaboration

Frontiers in Electroweak interactions of leptons and hadrons, AMU, 06 Nov 2016

Plan of the talk

- Deep Underground Neutrino Experiment (DUNE) : what is it best suited for ?
- CP violation signal at DUNE assuming standard interactions (SI)
- CP violation in Neutrino oscillations
  - CP asymmetries in appearance channel : SI and NSI
- Impact of nonstandard interactions (NSI) on the CP violation signal at DUNE
  - event rates, sensitivity studies, baseline optimisation, exposure optimisation etc
- Other ongoing work on long baselines

CP violation sensitivity @ DUNE

DUNE 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

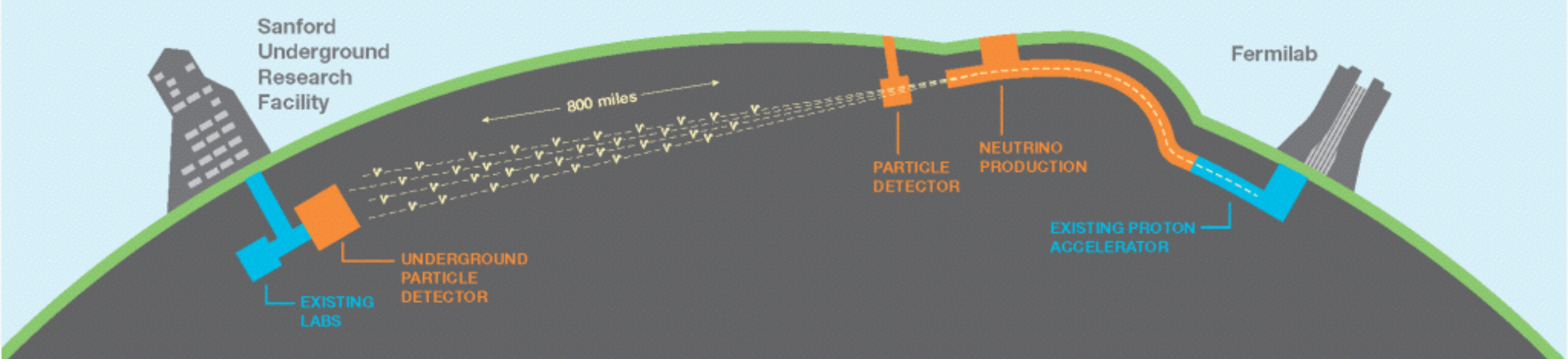
CDR, Vol 2, DUNE Collaboration, 1512.06148 [physics.ins-det]

Ancillary Science Program

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

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

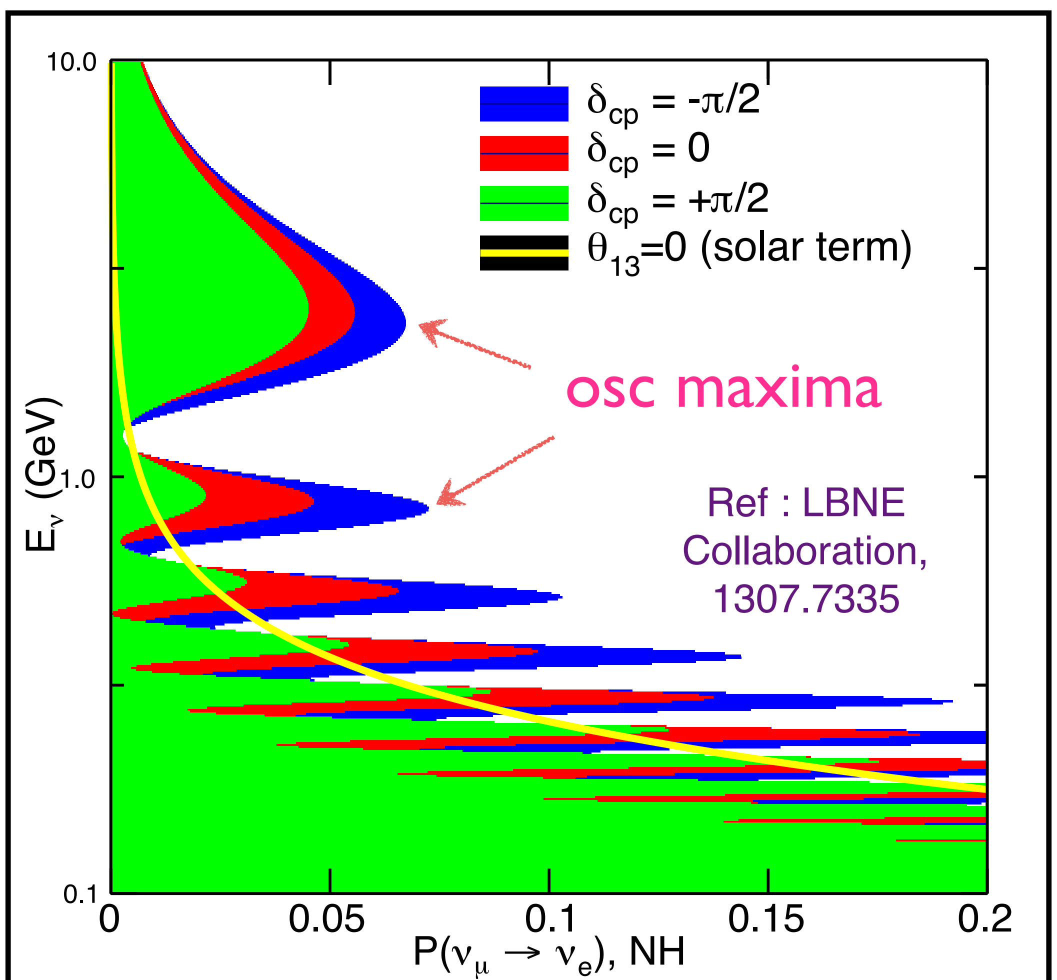
CDR, Vol 3, DUNE Collaboration, 1601.05823 [physics.ins-det]



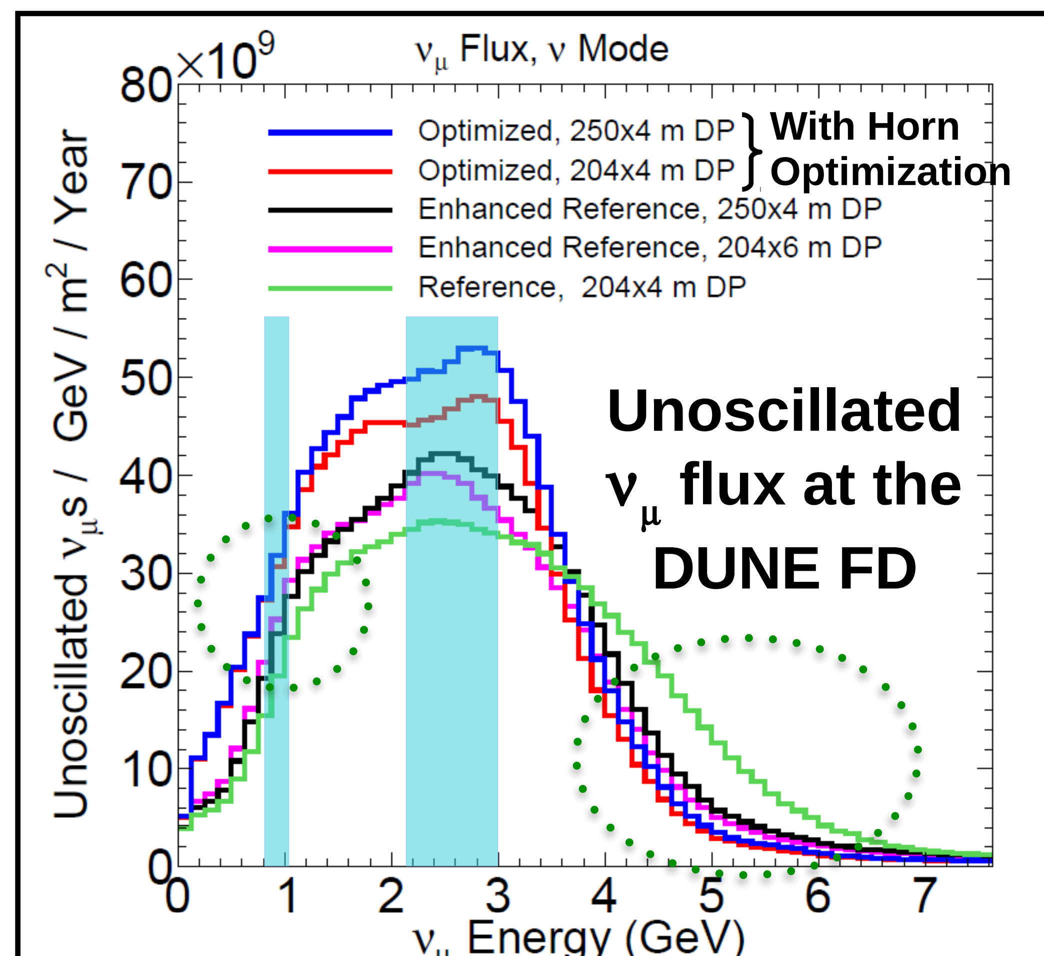
Probability at 1300 km and flux

- 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

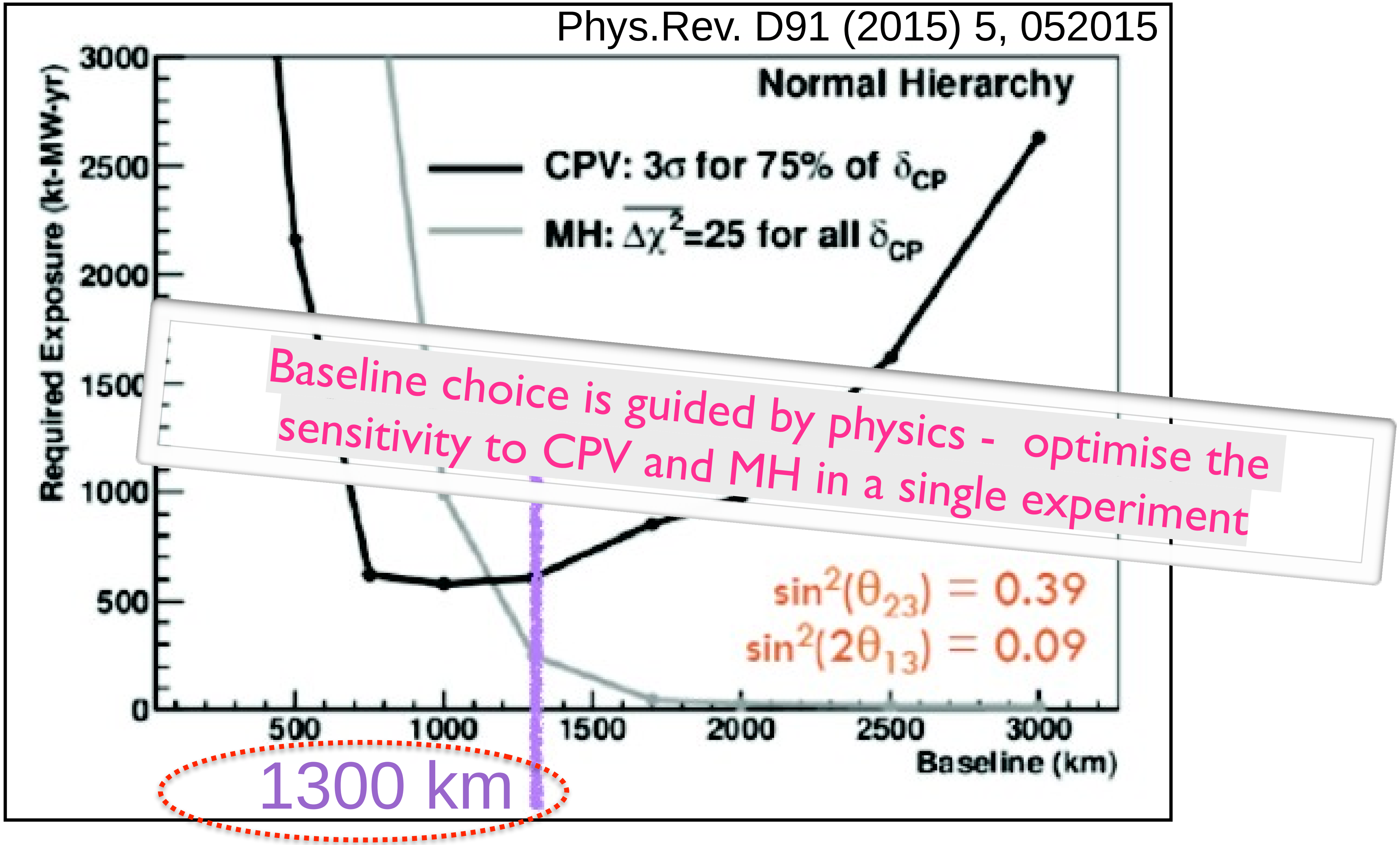
$$\frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} = (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times 510\ \mathrm{km/GeV}$$



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



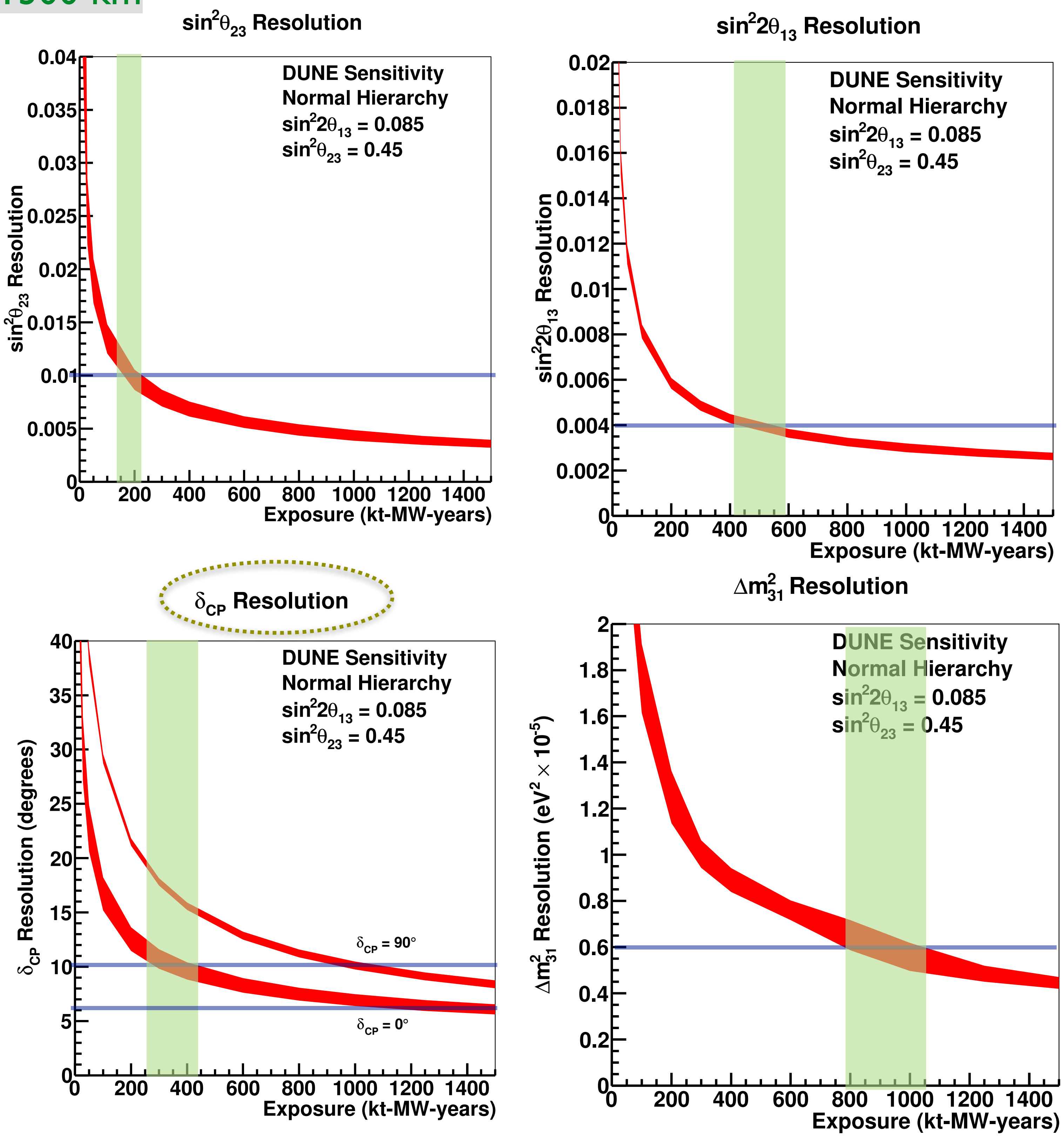
Why 1300 km ?



Phys.Rev. D91 (2015) 5, 052015
Normal Hierarchy
CPV: 3σ for 75% of δCP
MH: Δχ²=25 for all δCP
Required Exposure (kt-MW-yr)
Baseline (km)
sin²(θ23) = 0.39
sin²(2θ13) = 0.09
1300 km
Baseline choice is guided by physics - optimise the sensitivity to CPV and MH in a single experiment

Precision on standard mixing angles, phase

L=1300 km



- Red bands : Reference - optimised beam design
- Delta CP
  - precision better for vanishing CP phase (CPC) and worse for maximal CPV value (90 degrees)
  - Range of delta CP resolution : 6-10 degrees for 10 year run

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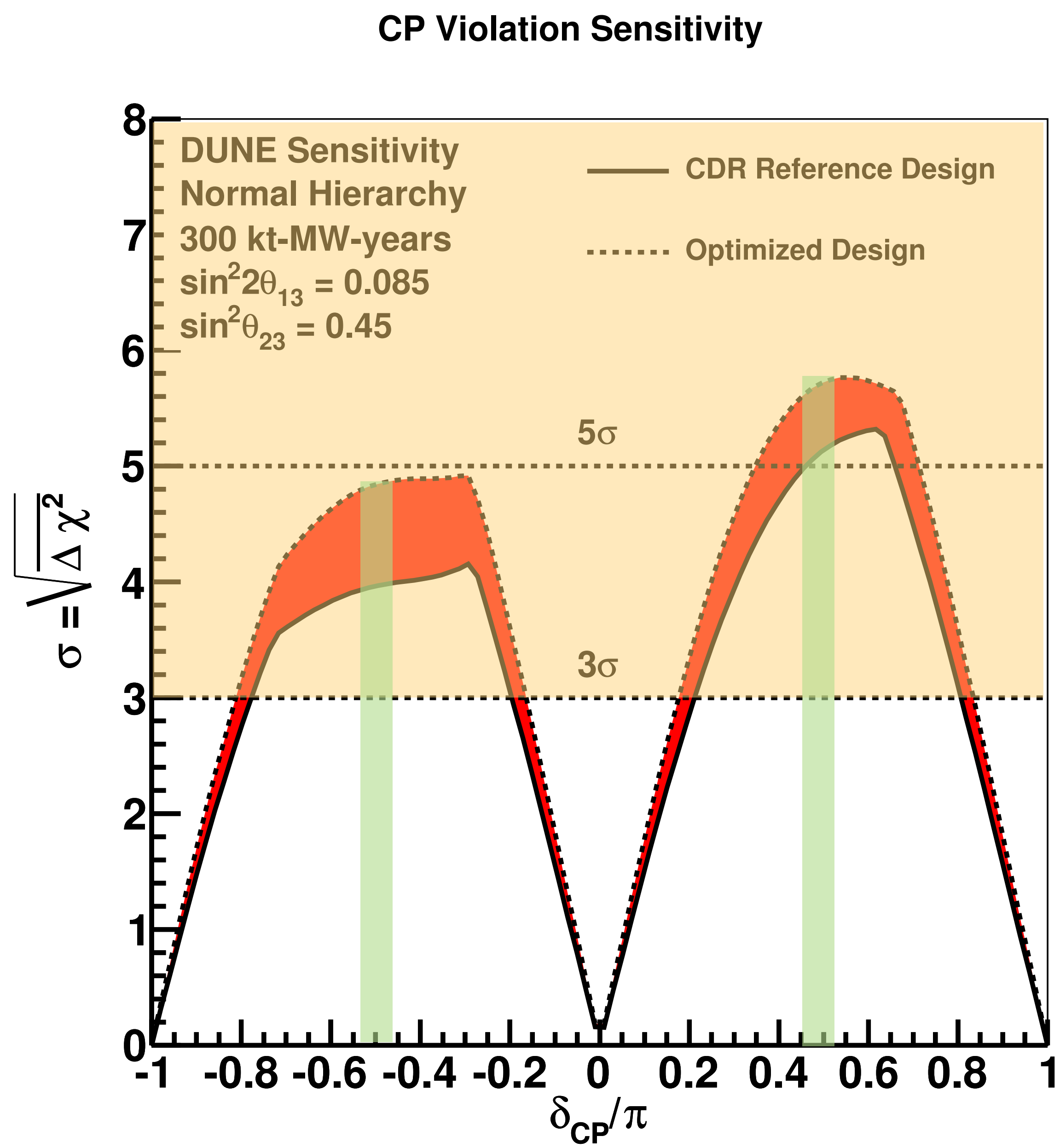
CP Violation sensitivity

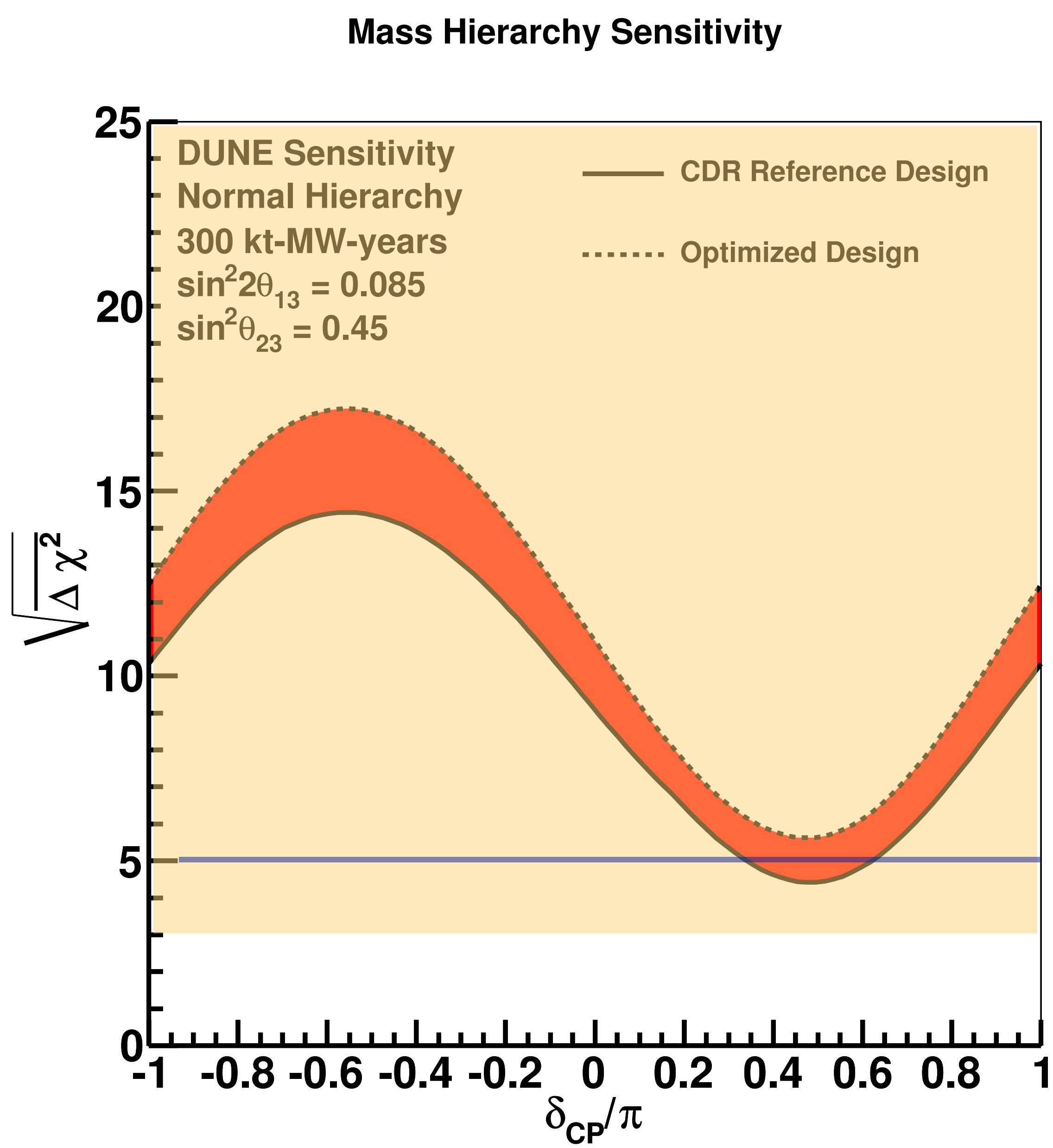


- Red band : Reference - optimised beam design
- Sensitivity to delta CP depends on
  - systematics
  - statistics (300 kt.MW.yr)
  - true value of delta CP, theta23, delta m^2_{31}, MH

100% not possible - at least the CPC values (0,pi) are to be excluded !

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

Mass ordering sensitivity



- Red band : Reference - optimised beam design
- Sensitivity to mass ordering depends on
  - systematics
  - statistics (300 kt.MW.yr)
  - true value of delta CP, theta23, delta m^2_{31}, MH

> 5 sigma for almost all values of delta CP !

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

Standard neutrino oscillations and beyond that…

Two flavor case

- Flavor states are connected to mass states by :

$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

- Each mass eigenstate propagates as

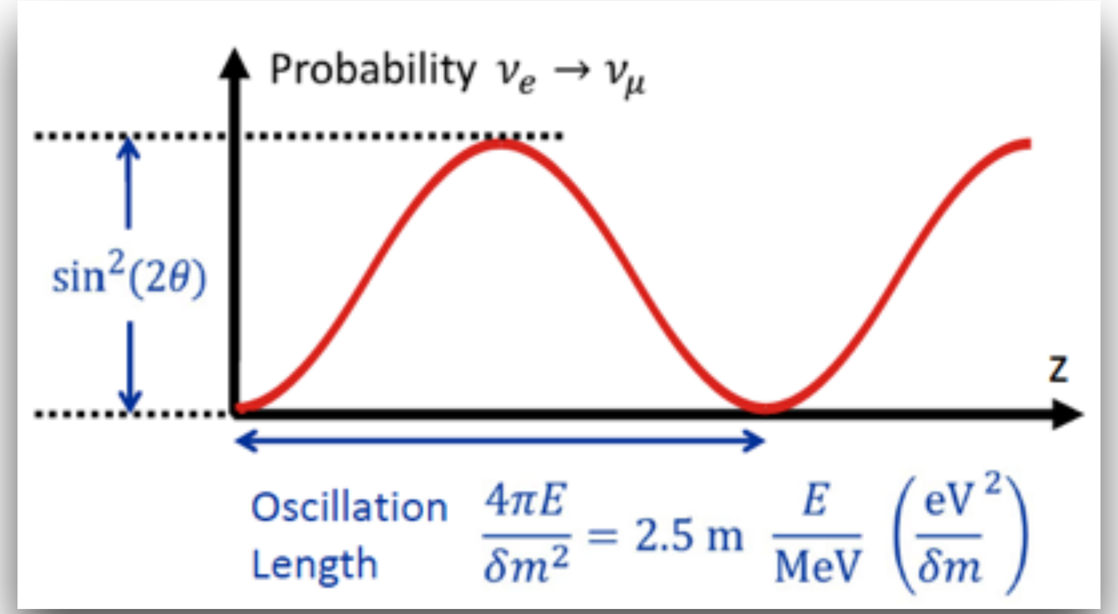
$$e^{ipz} \text{ with } p = \sqrt{E^2 - m^2} \simeq E - m^2/2E$$

- Oscillation arises due to phase difference between mass eigenstates $\frac{\delta m^2}{2E} z$

- Oscillation probability

$$P_{e\mu}(L/E) = \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4E}\right)$$

$$\delta m^2 = m_2^2 - m_1^2$$



Visualizing oscillations

$$|\vartheta,+\rangle = \begin{pmatrix}\cos(\vartheta/2)\\ \sin(\vartheta/2)\end{pmatrix}$$

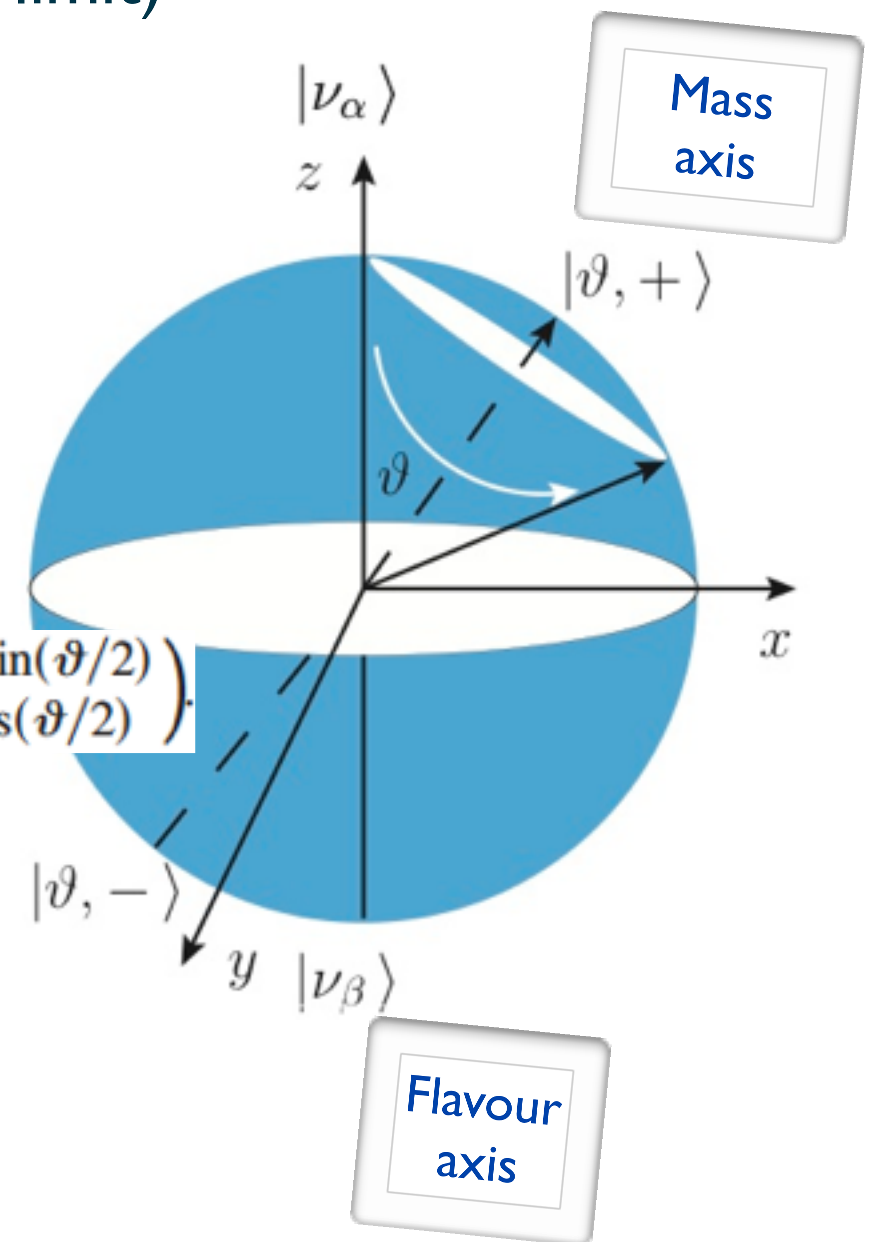
- Schrodinger equation in terms of flavour spinor (in the UR limit)

$$i\partial_t \begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \mathbb{H}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{\delta m^2}{2E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

- Neutrino flavor density matrix and commutator form

$$\rho = \begin{pmatrix}\langle\nu_e|\nu_e\rangle & \langle\nu_e|\nu_\mu\rangle\\ \langle\nu_\mu|\nu_e\rangle & \langle\nu_\mu|\nu_\mu\rangle\end{pmatrix} \qquad i\partial_t\rho = [\mathbb{H},\rho]$$

$$|\vartheta,-\rangle = \begin{pmatrix}-\sin(\vartheta/2)\\ \cos(\vartheta/2)\end{pmatrix}.$$



- Expand 2 by 2 Hermitian matrices in terms of Pauli matrices

$$\rho = \frac{1}{2}[Tr(\rho) + P\cdot\sigma]$$

$$\mathbb{H} = \frac{\delta m^2}{2E}B\cdot\sigma$$

$$B = (\sin 2\theta, 0, \cos 2\theta)$$

- Analogous to spin precession in a magnetic field

$$\dot{P} = \omega B\times P$$

Ref: Mehta, PRD79 (2009);
see also Kim, Sze and Nussinov, PRD35 (1987); Kim, Kim and Sze, PRD37 (1988).

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

Standard interactions

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

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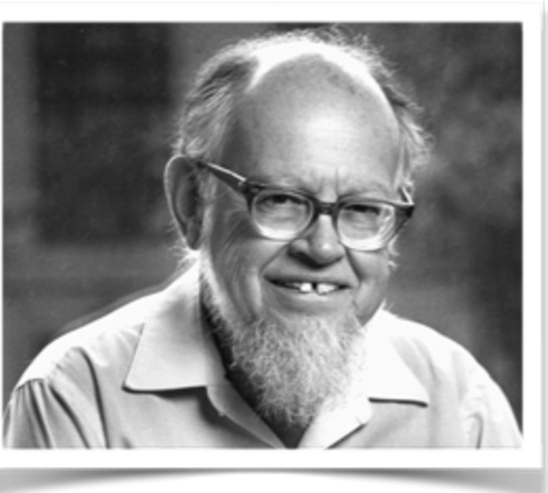
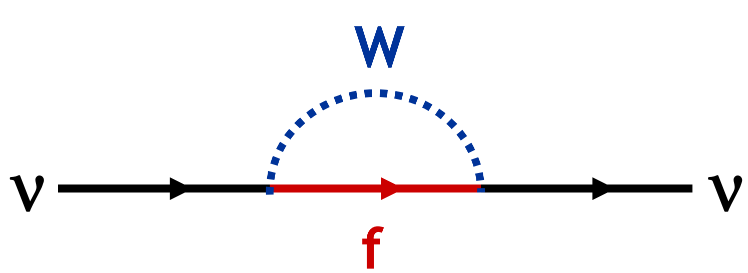
(Received 6 October 1977; revised manuscript received 5 December 1977)

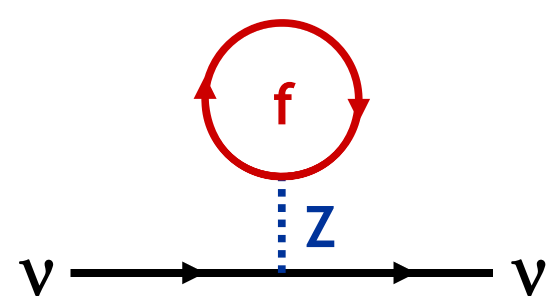
The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal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



L.Wolfenstein

Neutrinos in a medium suffer flavor-dependent refraction





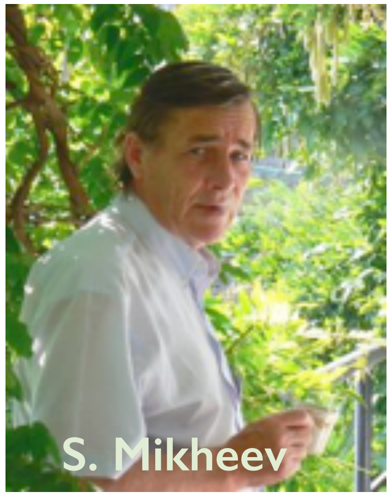
- Elastic forward scattering dominates at low E (real part)
- Incoherent scattering cross section is usually very small

$$V_{\rm weak} = \sqrt{2}G_F \times \begin{cases} N_e - N_n/2 & \text{for } \nu_e \\ -N_n/2 & \text{for } \nu_\mu \end{cases}$$

Typical density of Earth: 5 g/cm^3

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

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.

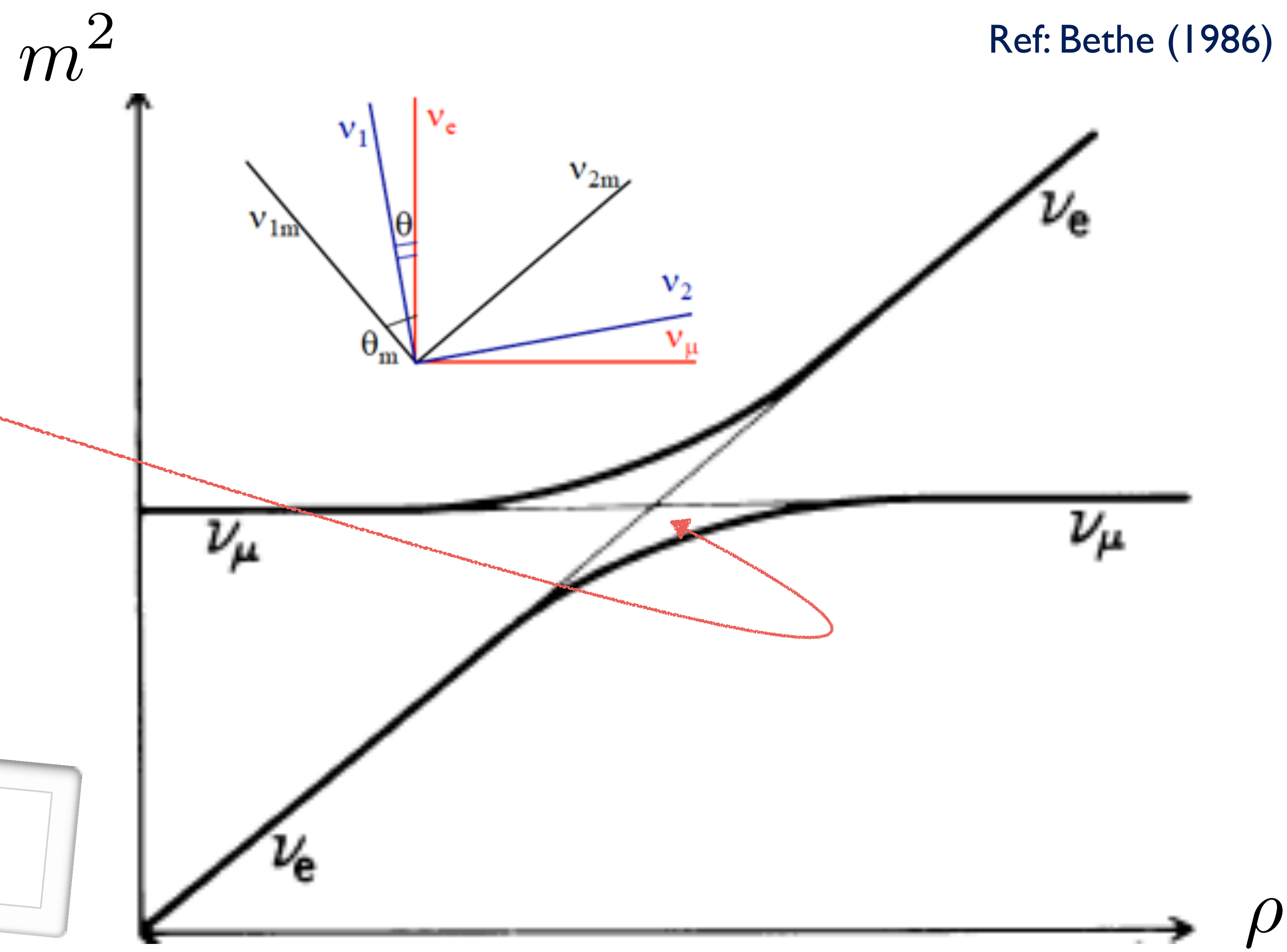
$$\frac{V_C}{\omega} = \cos 2\theta$$

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

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

Complete conversion in the adiabatic limit !

Ref: Bethe (1986)



Neutrino oscillations and present status

Oscillation Parameter	Best-fit value	3σ range	Precision (%)
$\sin^2\theta_{12}/10^{-1}$	3.23	2.78 - 3.75	14.85
$\sin^2\theta_{23}/10^{-1}$ (NH)	5.67 (4.67)[a]	3.92 - 6.43	24.25
$\sin^2\theta_{23}/10^{-1}$ (IH)	5.73	4.03 - 6.40	22.72
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	1.77 - 2.94	24.84
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	1.83 - 2.97	23.75
δm^2_{21} $[10^{-5}$ eV$^2]$	7.60	7.11 - 8.18	7.00
$\lvert\delta m^2_{31}\rvert$ $[10^{-3}$ eV$^2]$ (NH)	2.48	2.30 - 2.65	7.07
$\lvert\delta m^2_{31}\rvert$ $[10^{-3}$ eV$^2]$ (IH)	2.38	2.30 - 2.54	5.00
δ/π (NH)	1.34	0.0 - 2.0	-
δ/π (IH)	1.48	0.0 - 2.0	-

[a]This is a local minimum in the first octant of θ_{23} with $\Delta\chi^2 = 0.28$ with respect to the global minimum.

Ref: D. Forero, M. Tortola, and J. Valle (2014), 1405.7540.

- Presently unknown
  - mass hierarchy
  - CP phase
  - octant of theta23

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 !

Beyond the SM

- Simplest extension of SM -
  - introduce new right-handed sterile fermions into the SM so we have new fields with weird properties
- New parameters needed -
  - 3 masses, 3 mixing angles and 1 phase (more if Majorana)
- Very small masses suggest
  - new mass mechanisms - seesaw mechanism or else fine tuning needed
- Quark-lepton unification - quark and lepton mixing angles are very different

CP Violation in vacuum and matter

C, P, T in neutrino oscillations

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

- Assume CPT Invariance -

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

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

No CP asymmetry in survival probability

- Assume 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

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

Jarlskog's factor

CP violation in the appearance channel

$\nu_\mu \to \nu_e$

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

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

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

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

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

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

Ref : Cervera et al, Freund, Akhmedov et al.

Genuine and fake CP effects

- in vacuum

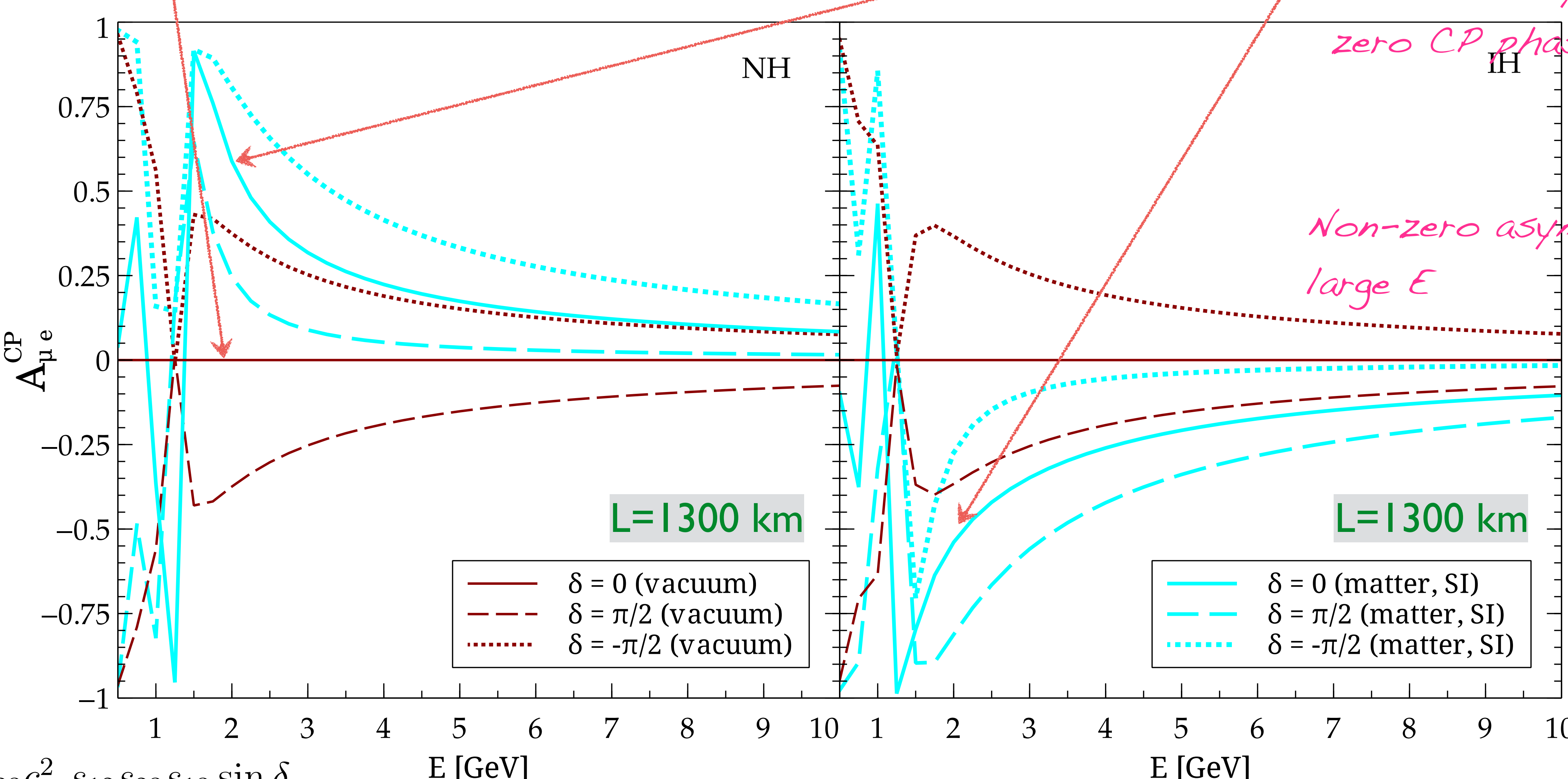
$$\Delta P_{\mu e}(\delta) = 8\,\mathcal{J}\left[\sin(r_\lambda \lambda L)\sin^2\frac{\lambda L}{2} - \sin(\lambda L)\sin^2\frac{r_\lambda \lambda L}{2}\right]$$
$$= 4\sin\delta\,\mathcal{J}_r\,\left[\sin\lambda L/2\,\sin r_\lambda \lambda L/2\,\sin(1-r_\lambda)\lambda L/2\right]$$

- in matter with standard interactions

$$\Delta P_{\mu e}(\delta) = 8\,r_\lambda \mathcal{J}\frac{\sin r_A \lambda L/2}{r_A}\left[\Theta_-\cot\delta\cos\lambda L/2 + \Theta_+\sin\lambda L/2\right]$$
$$\Theta_\pm = \sin[(r_A-1)\lambda L/2]/(r_A-1) \pm \sin[(r_A+1)\lambda L/2]/(r_A+1)$$

Non-zero asymmetry for zero CP phase

CP ASYMMETRY



Non-zero asymmetry at large E

Hierarchy dependence

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

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

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]

Non-standard Interactions

Ref: Review by T. Ohlsson (2012)

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

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

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

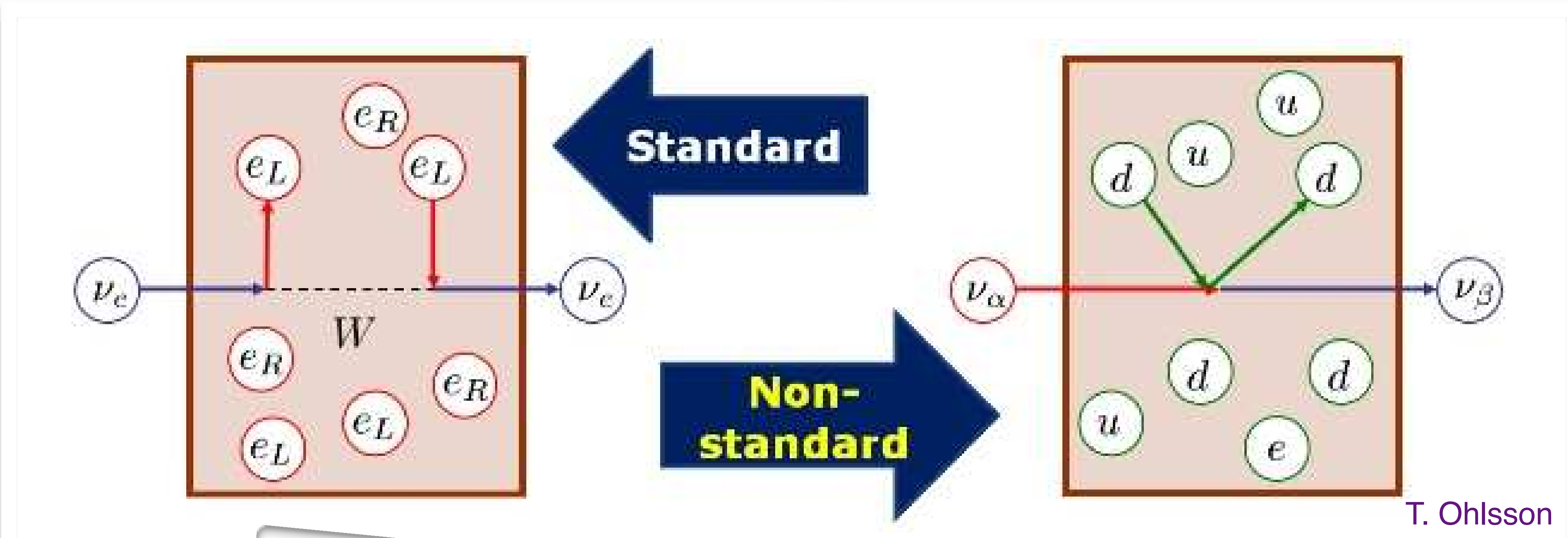
- Oscillation parameters such as the mixing angles and mass-squared splittings have been measured with great precision
- New physics interactions were initially proposed to provide an alternative to the oscillation formalism. However, this is now ruled out and we can study new physics effects as sub-leading effects in the discussion of oscillation formalism
- The new physics effects can impact determination of standard oscillation parameters and lead to more complicated parameter degeneracies

Non-standard interactions

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

9 new parameters

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)



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

Direct bounds on matter NSI

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

$$\epsilon^f_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

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)

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

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)

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

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

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

more restrictive

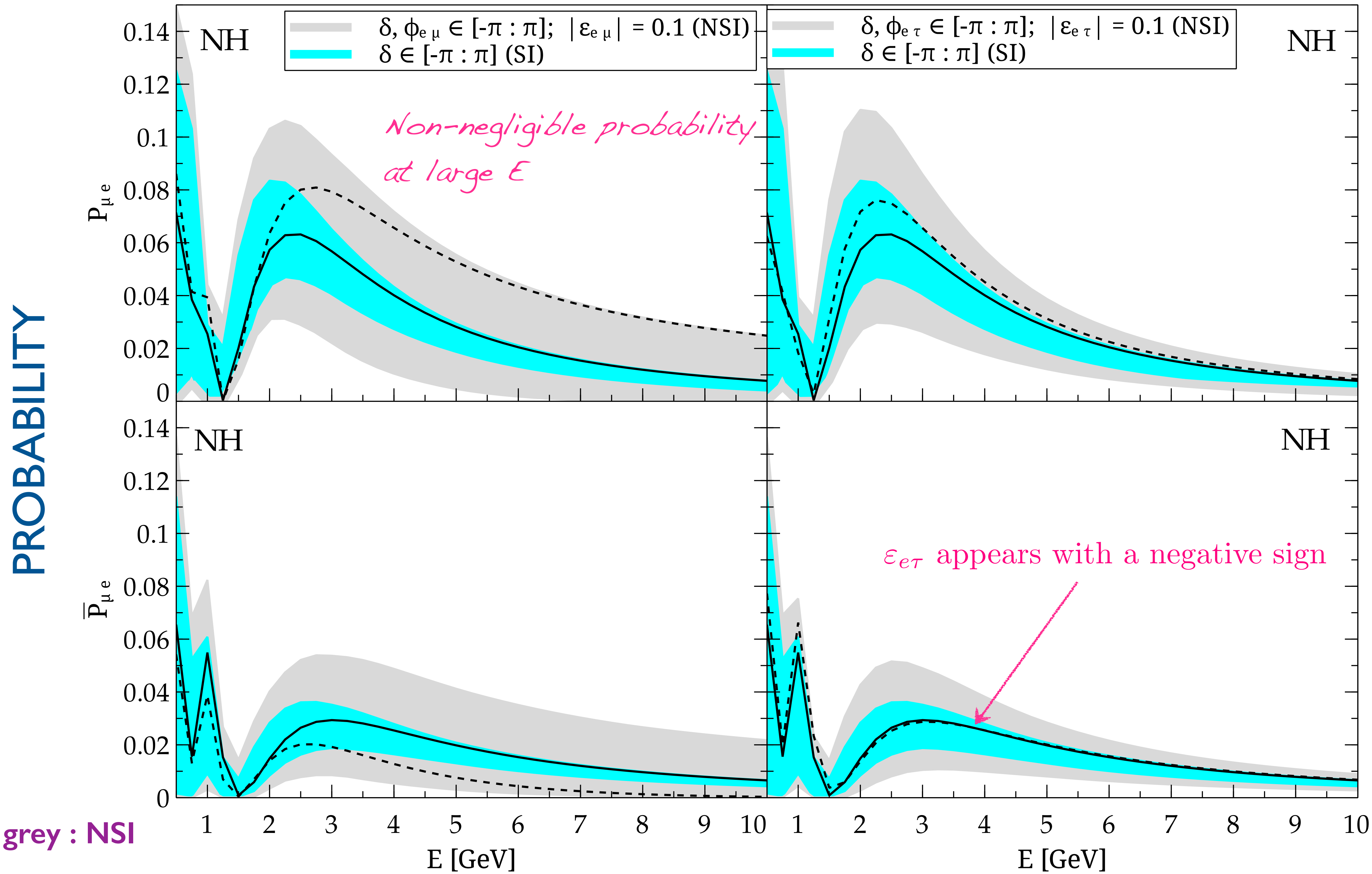
Mitsuka et al. (Super-Kamiokande Collaboration), arXiv:1109.1889,

MINOS Collaaboration

What are the consequences of these subdominant NSI terms for CP-violation studies at long baselines ?

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

Impact of single NSI : probability level



grey : NSI

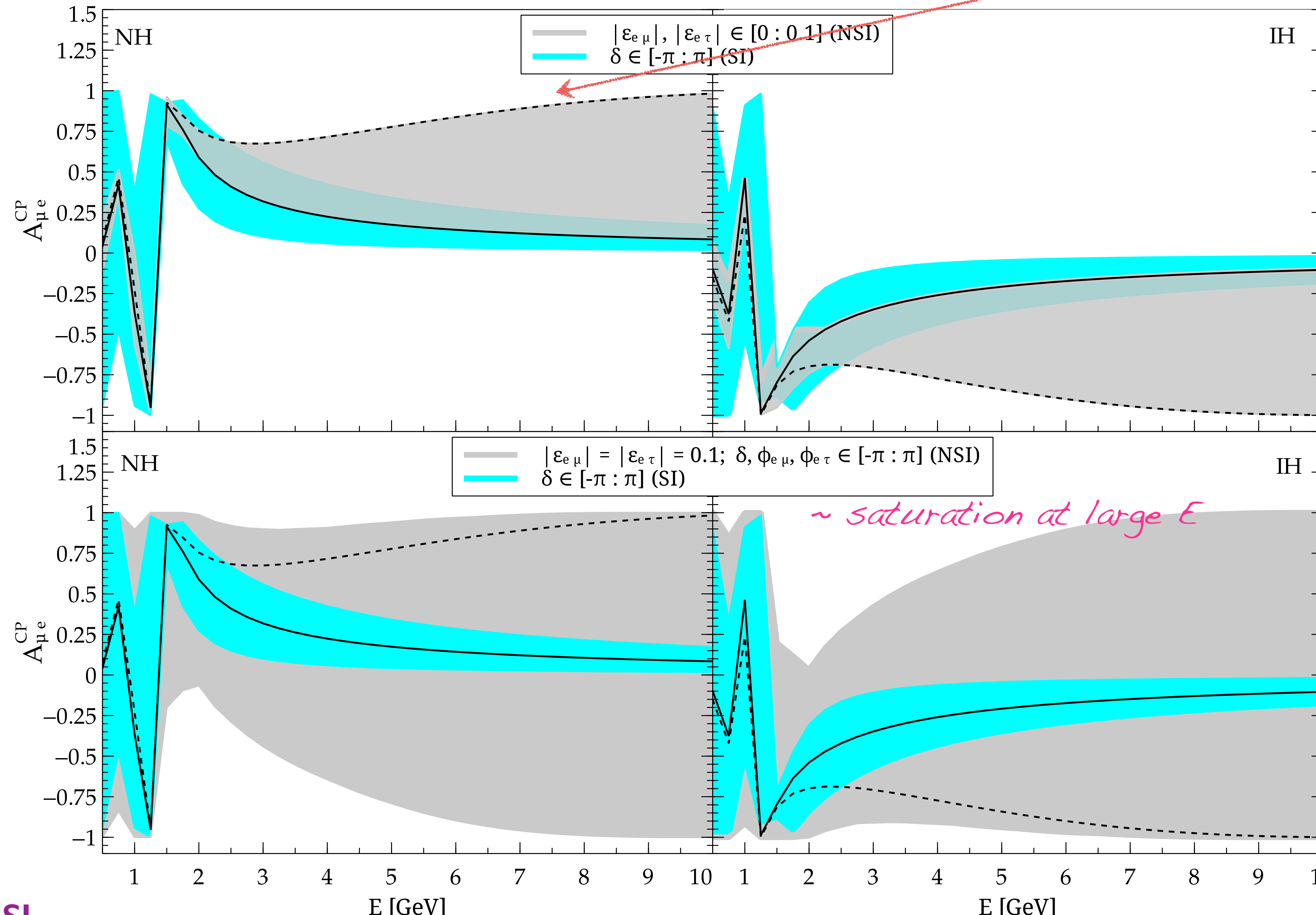
cyan : SI

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]

Impact of collective NSI : CP asymmetry

Large value implies new physics

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] ;
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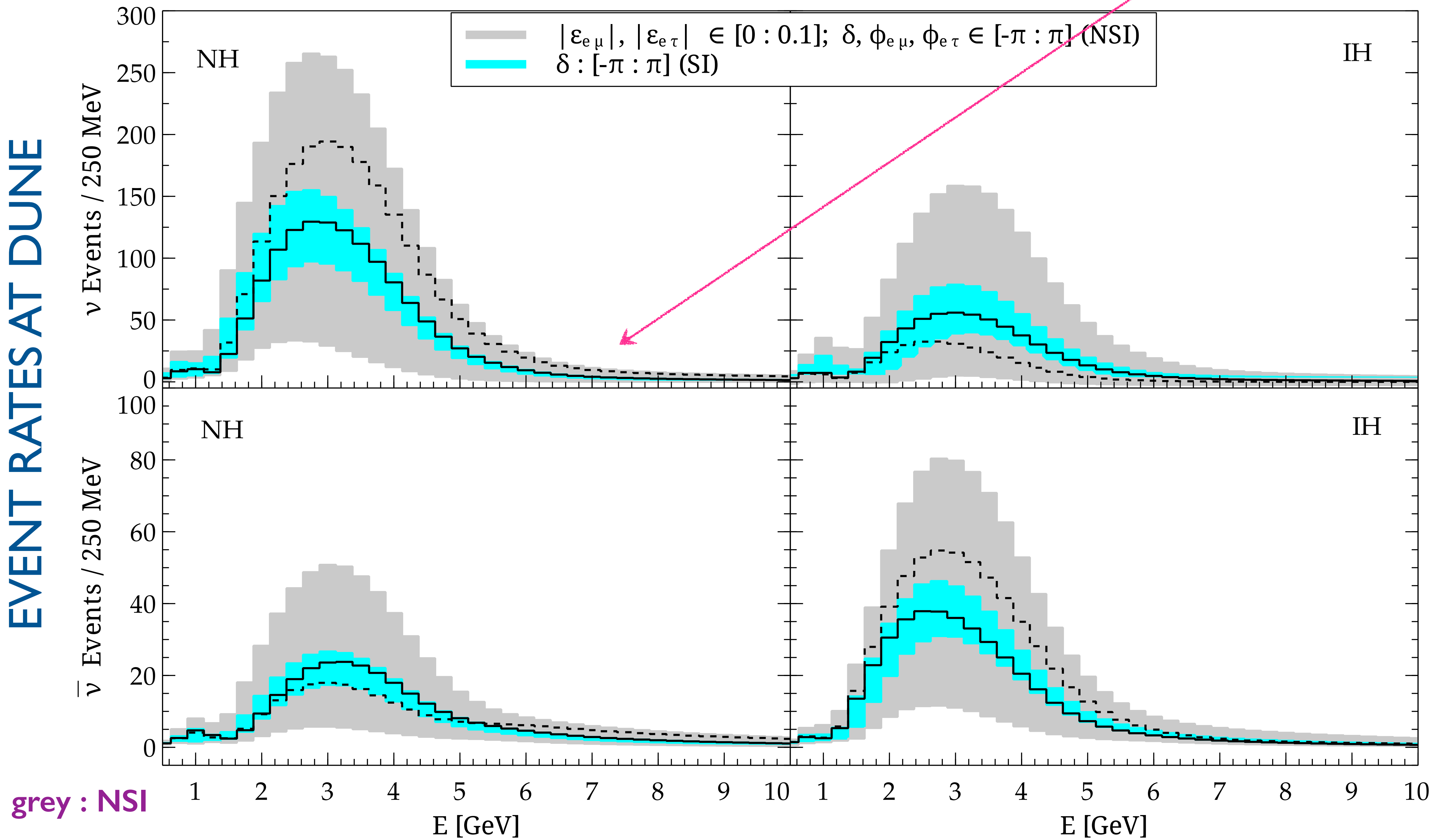
Event rates (collective NSI)

Falling flux kills the large asymmetry at large E



grey : NSI

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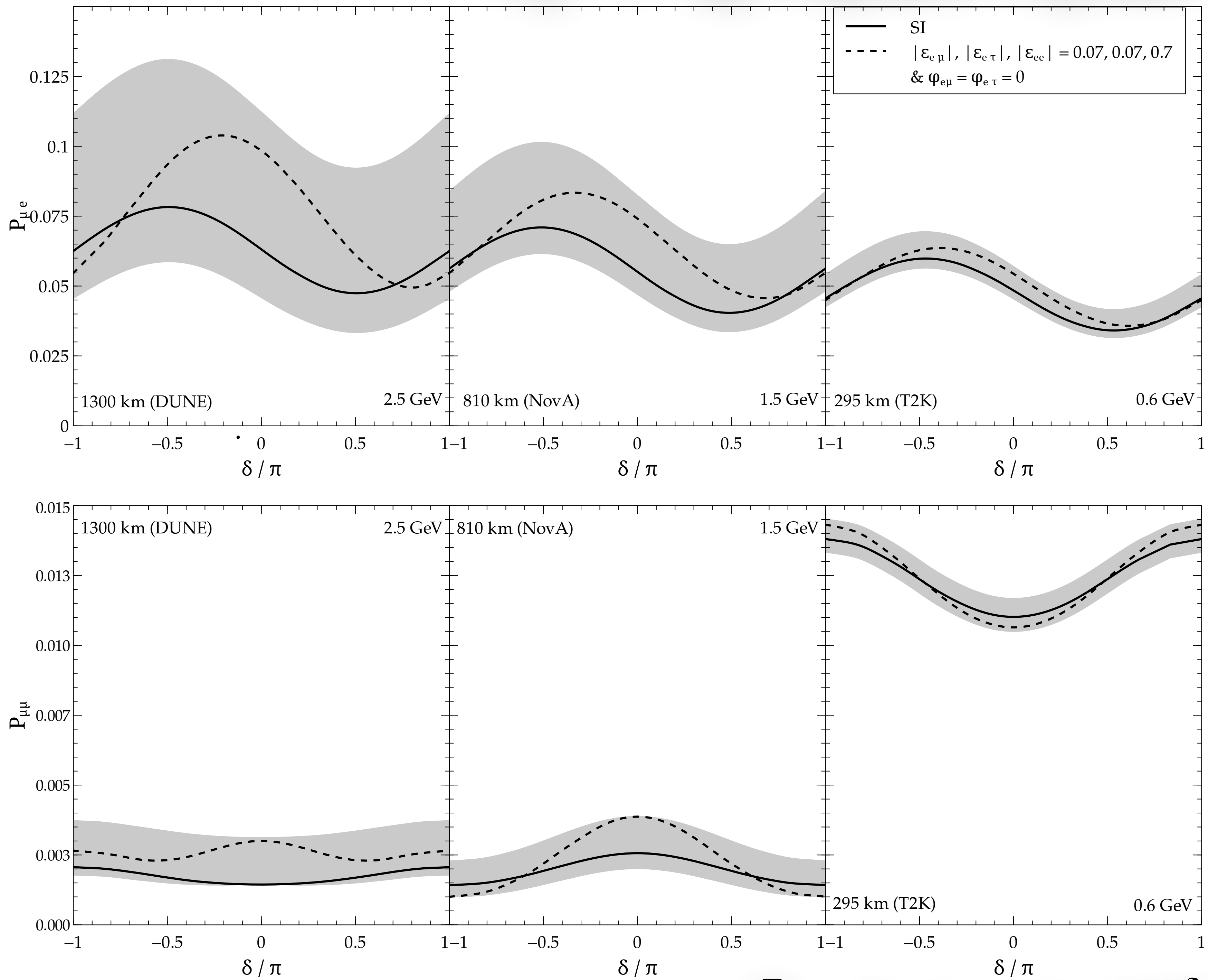
see also M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

Probability as a function of delta CP

$$P_{\mu e} = a_{\mu e} + b_{\mu e} \sin\delta + c_{\mu e}\cos\delta$$

$\nu_\mu \rightarrow \nu_e$



$\nu_\mu \rightarrow \nu_\mu$

Impact of NSI increases with increase in L

Smaller by an order of magnitude

$$P_{\mu\mu} \simeq a_{\mu\mu} + c_{\mu\mu}\cos\delta$$

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

M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

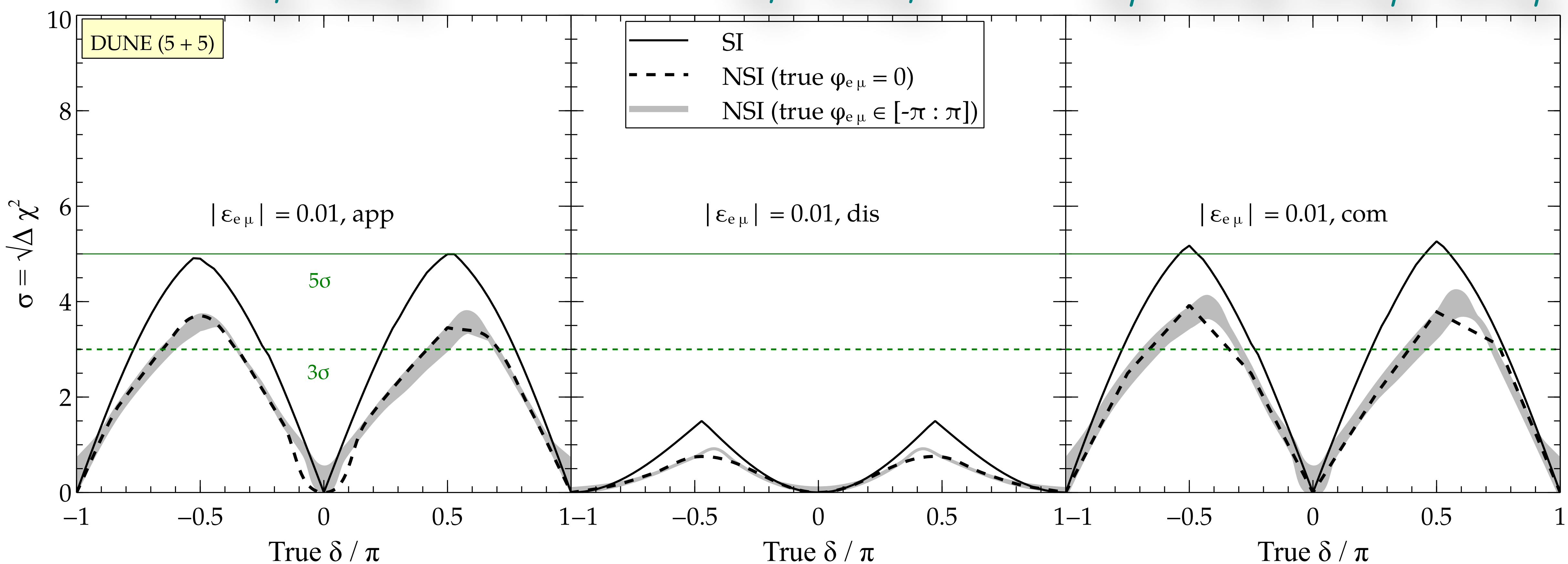
Sensitivity to CP violation

$$\chi^2_{tot} \propto \min_{0,\pi} \Big\{ \left[b_{\mu e}\sin\delta_{true} + c_{\mu e}\cos\delta_{true} - c_{\mu e}\cos\delta|_{0,\pi}\right]^2$$
$$+ \left[-\bar{b}_{\mu e}\sin\delta_{true} + \bar{c}_{\mu e}\cos\delta_{true} - \bar{c}_{\mu e}\cos\delta|_{0,\pi}\right]^2$$
$$+ \left[c_{\mu\mu}\cos\delta_{true} - c_{\mu\mu}\cos\delta|_{0,\pi}\right]^2 + \left[\bar{c}_{\mu\mu}\cos\delta_{true} - \bar{c}_{\mu\mu}\cos\delta|_{0,\pi}\right]^2 \Big\}$$

$\sin\delta|_{0,\pi} = 0$

$\cos\delta|_{0,\pi} \neq 0$

$\nu_\mu \to \nu_e$ $\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_e + \nu_\mu \to \nu_\mu$



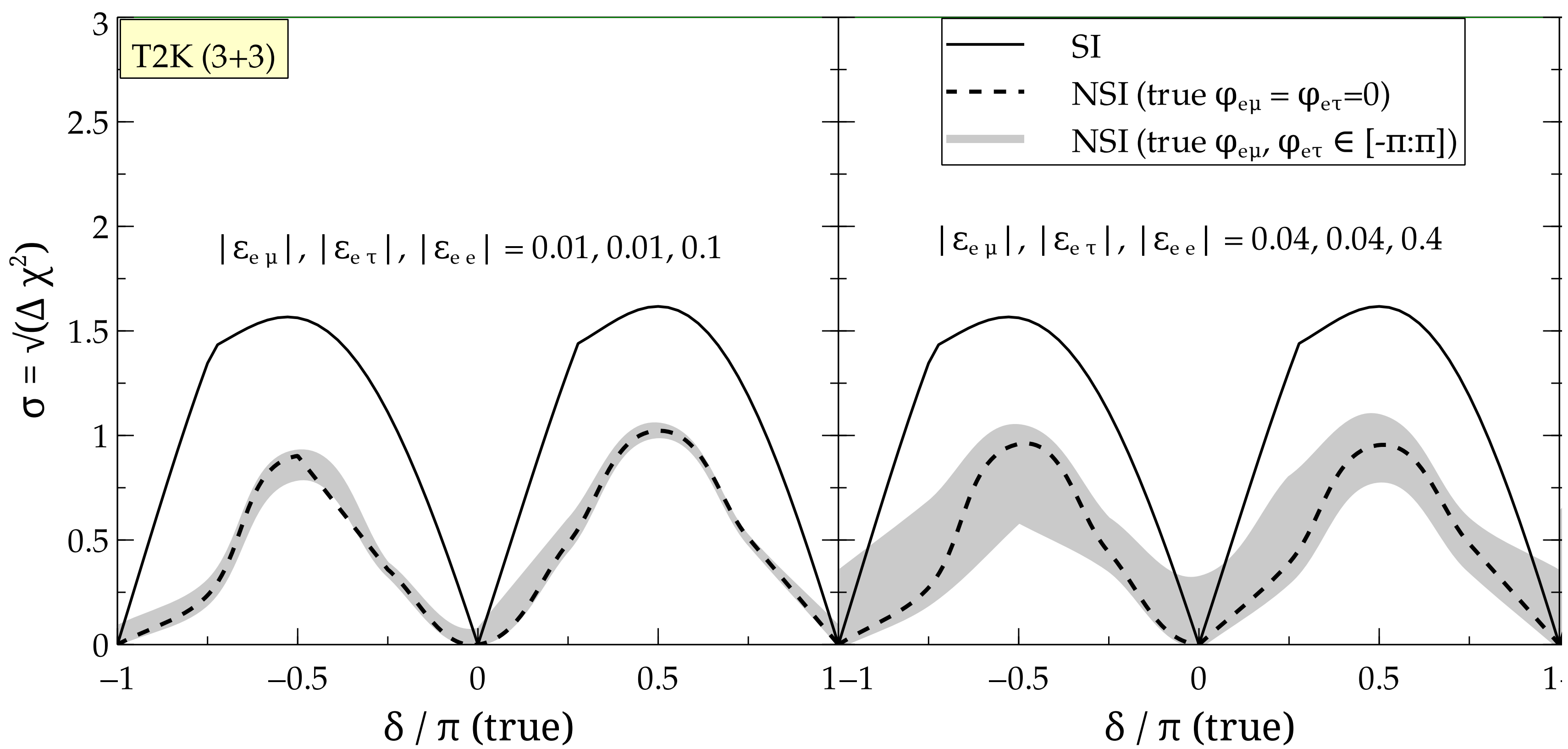
M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

CPV sensitivity - T2K, NoVA

- T2K (295 km)

  3 nu + 3 nu bar

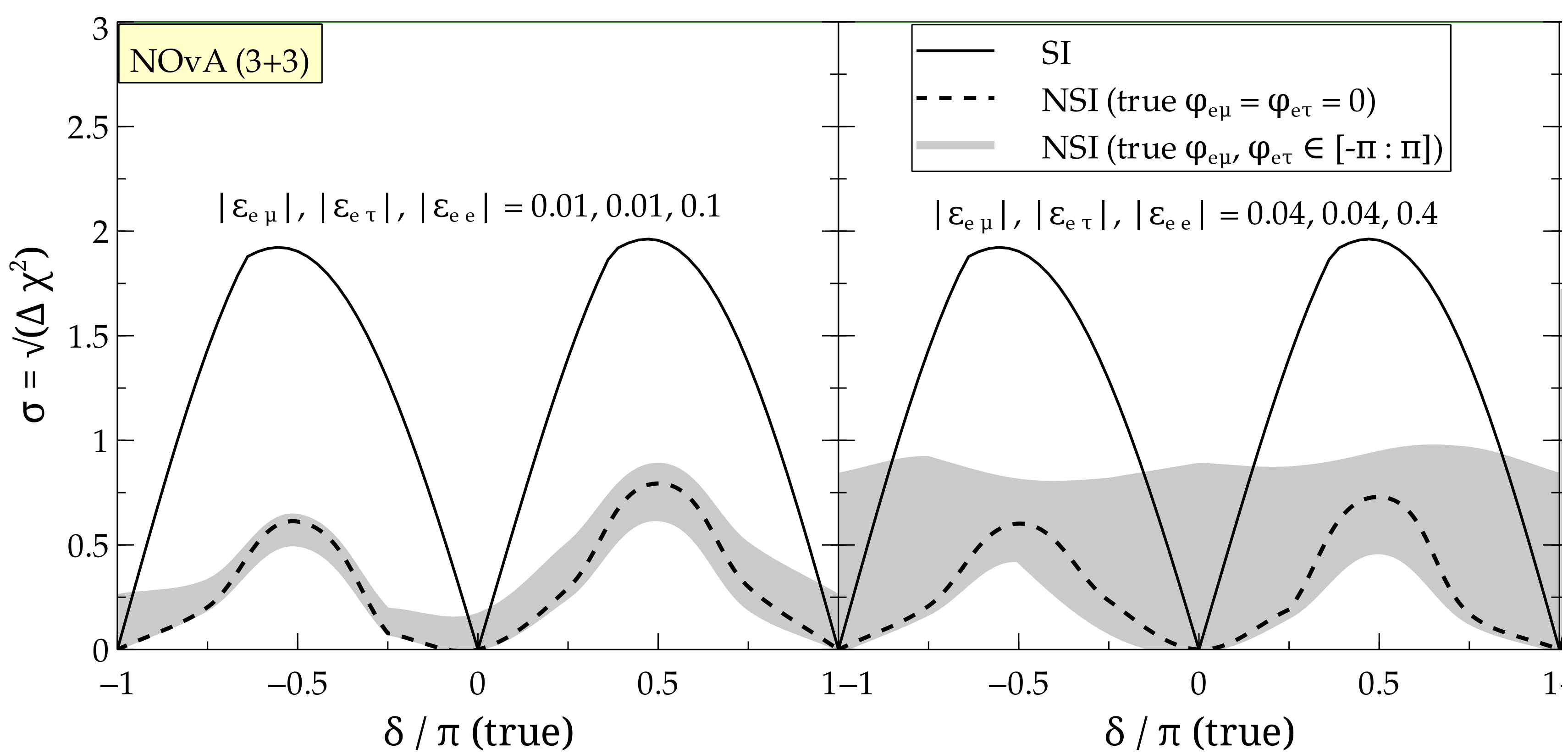
  22.5 kton, WC



- NOvA (810 km)

  3 nu + 3 nu bar

  14 kton, TASD



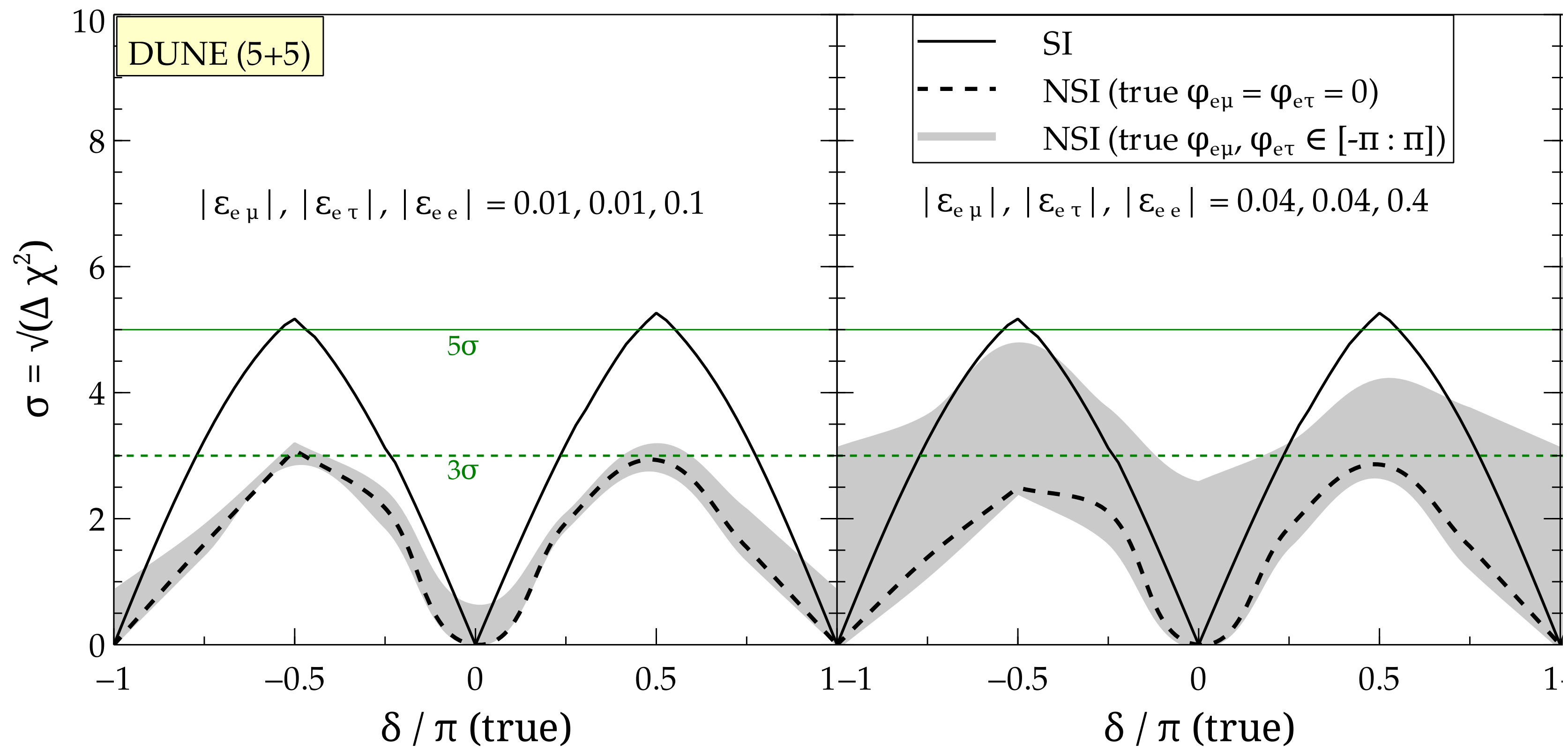
M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

CPV sensitivity - DUNE, T2HK

- DUNE (1300 km)

  Runtime = 5 nu + 5 nu bar

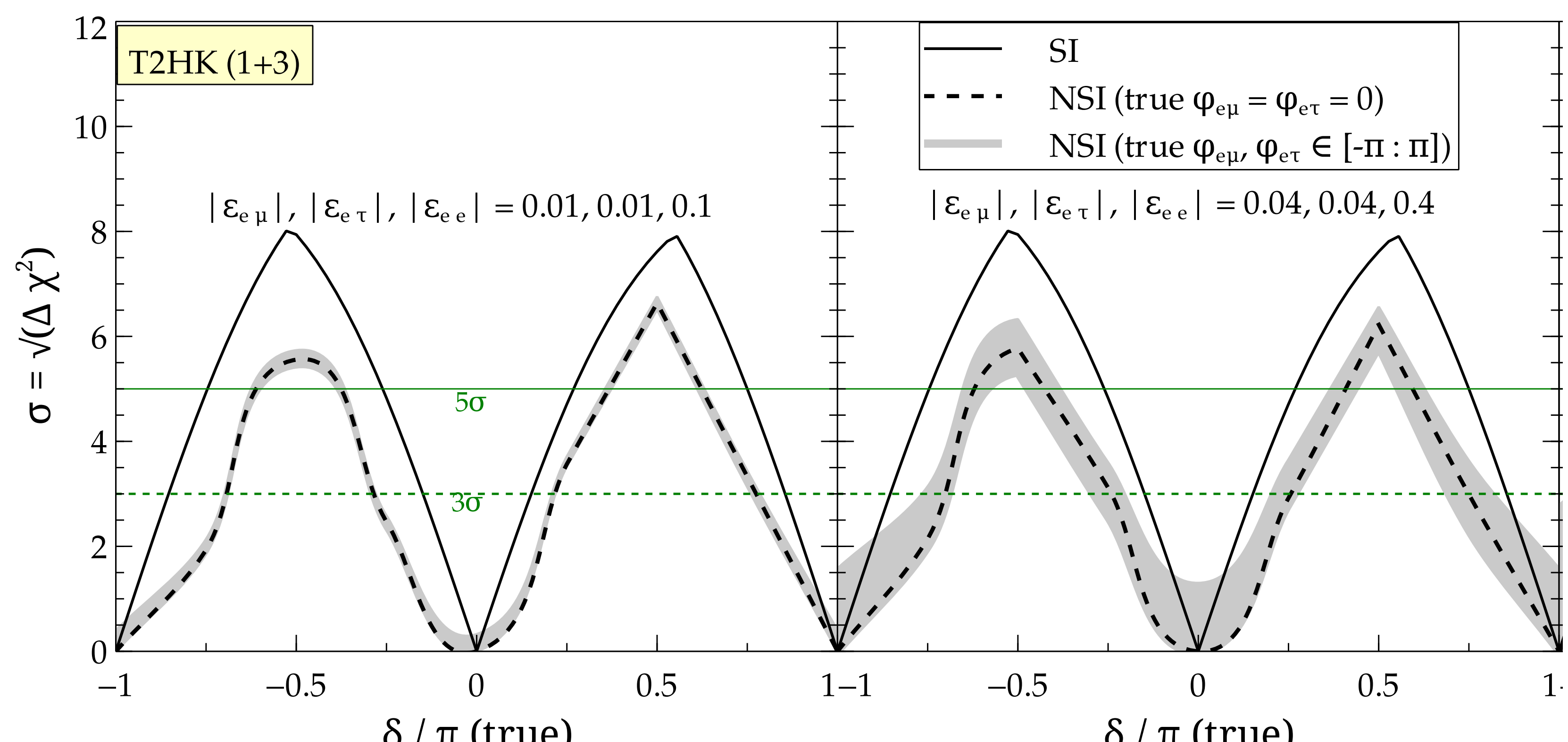
  35 kton, LArTPC



- T2HK

  Runtime = 1 nu + 3 nu bar

  560 kton, WC



M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

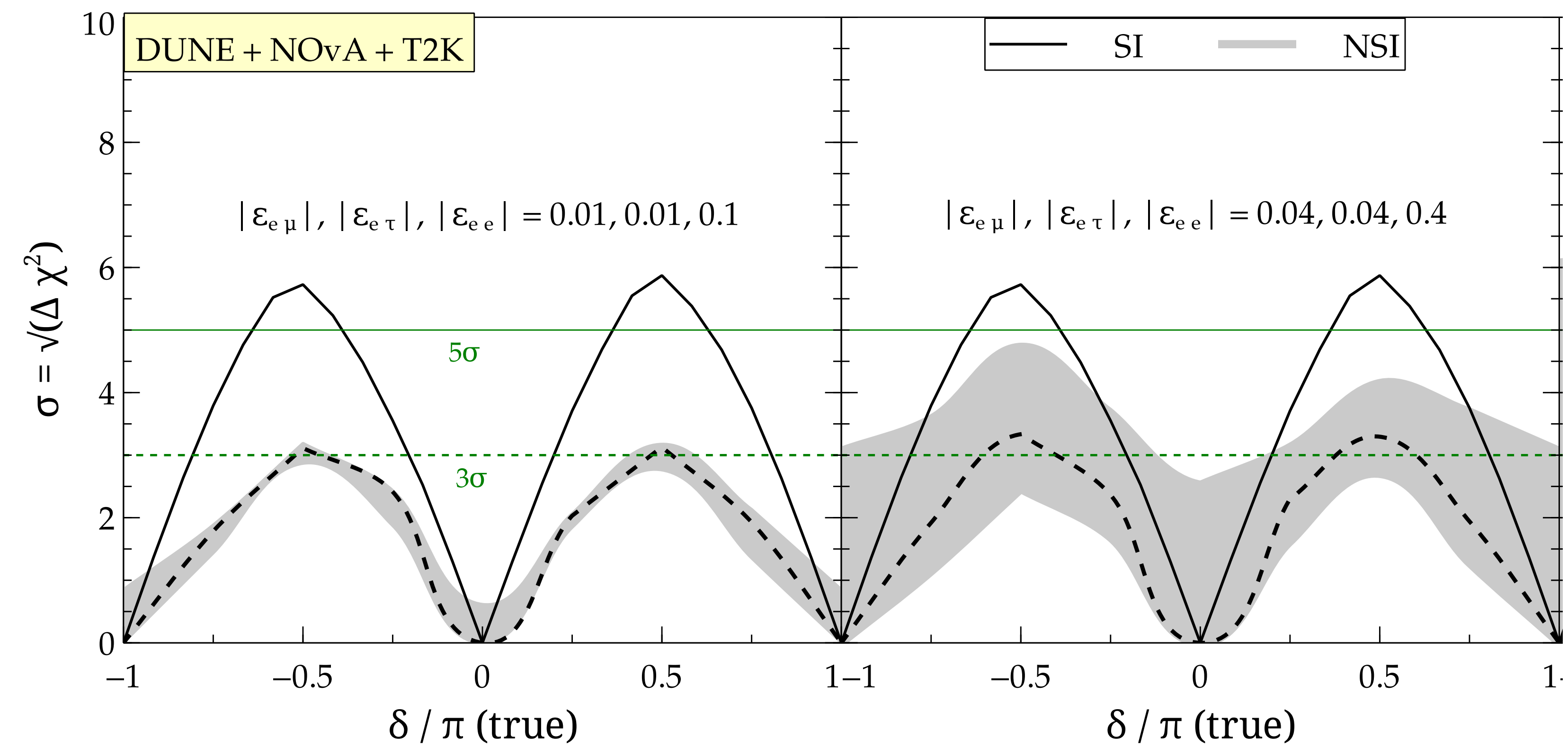
CPV sensitivity - DUNE+NoVA+T2K, T2HK

- DUNE + NoVA + T2K

  combination helps in

  lifting the curves above

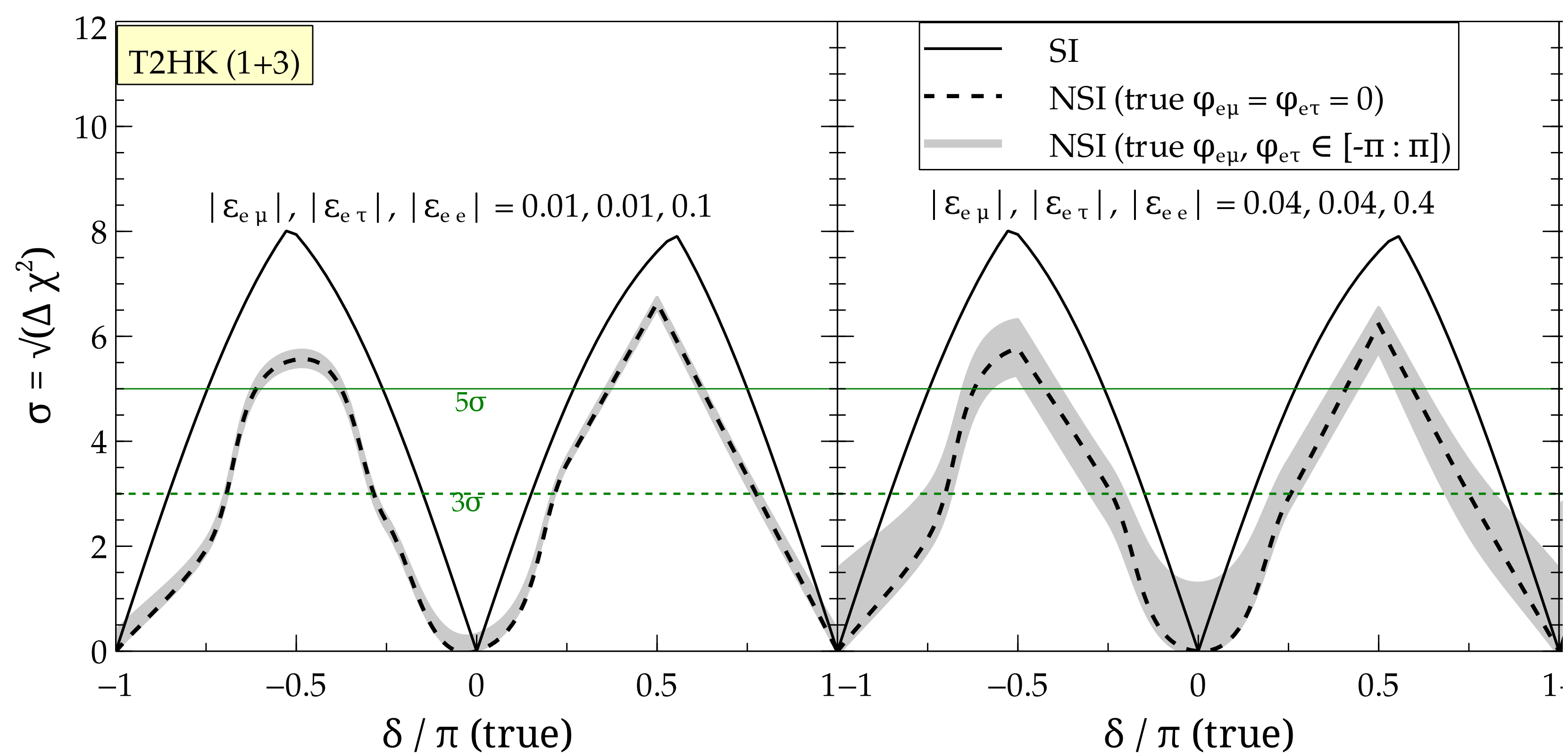
  5 sigma



- T2HK

  Runtime = 1 nu + 3 nu bar

  560 kton, WC

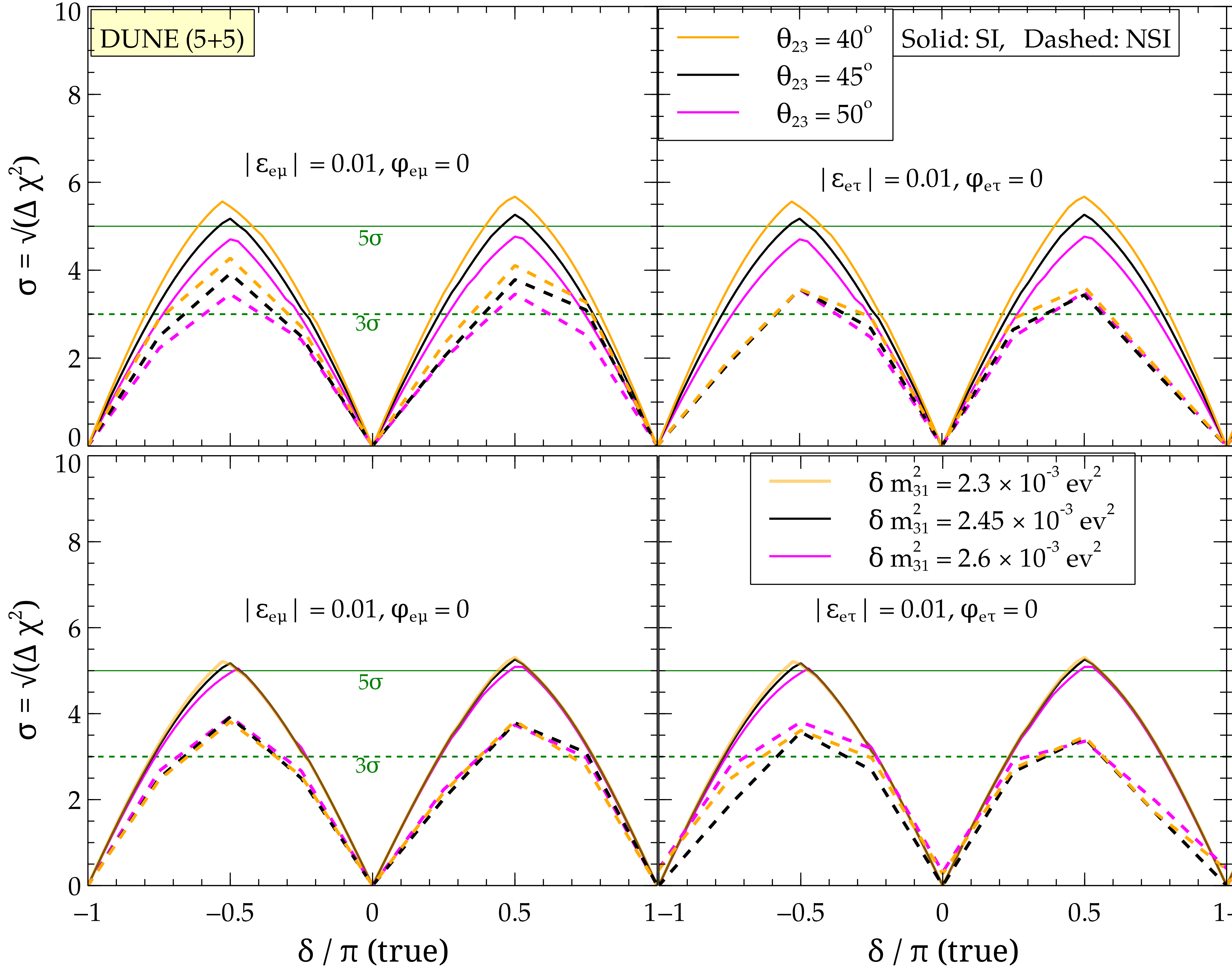


M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

Dependence on true values of parameters

θ_{23}

δm^2_{31}



Ref : M. Masud and P. Mehta, 1603.01389

CP fraction : SI and NSI

- Off-diagonal NSI

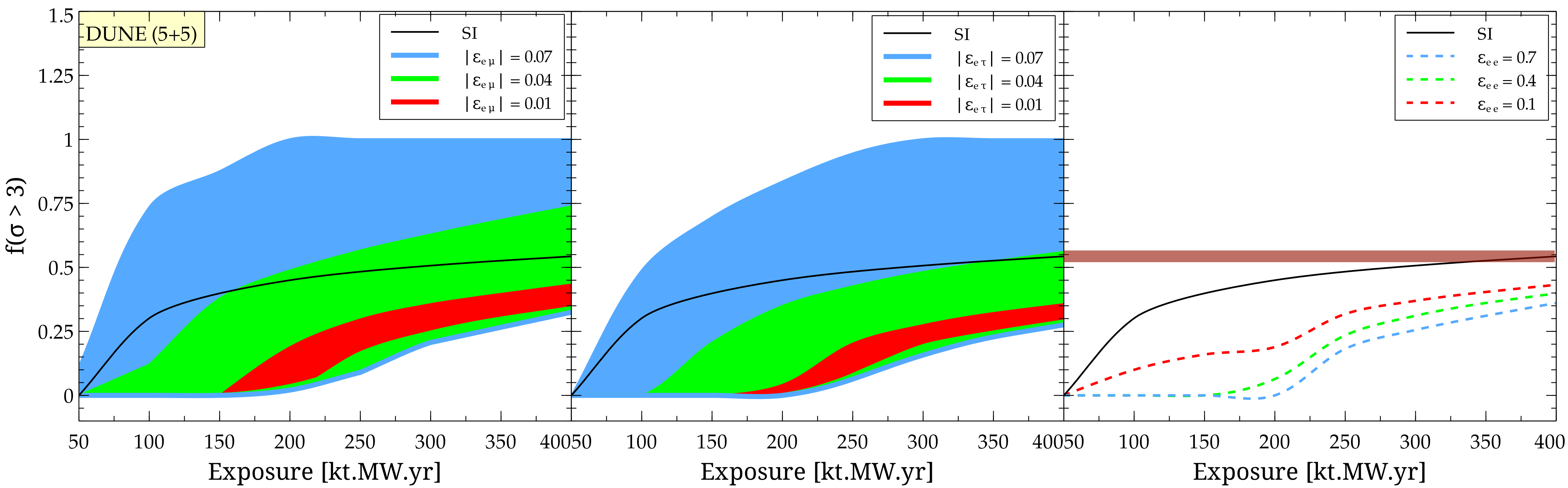
  Above 3 sigma, CPV can be resolved for a broad range of values 0.25-1 (non-diagonal NSI terms) due to additional phases

- SI

  Above 3 sigma, CPV can be resolved for ~0.55 of delta values

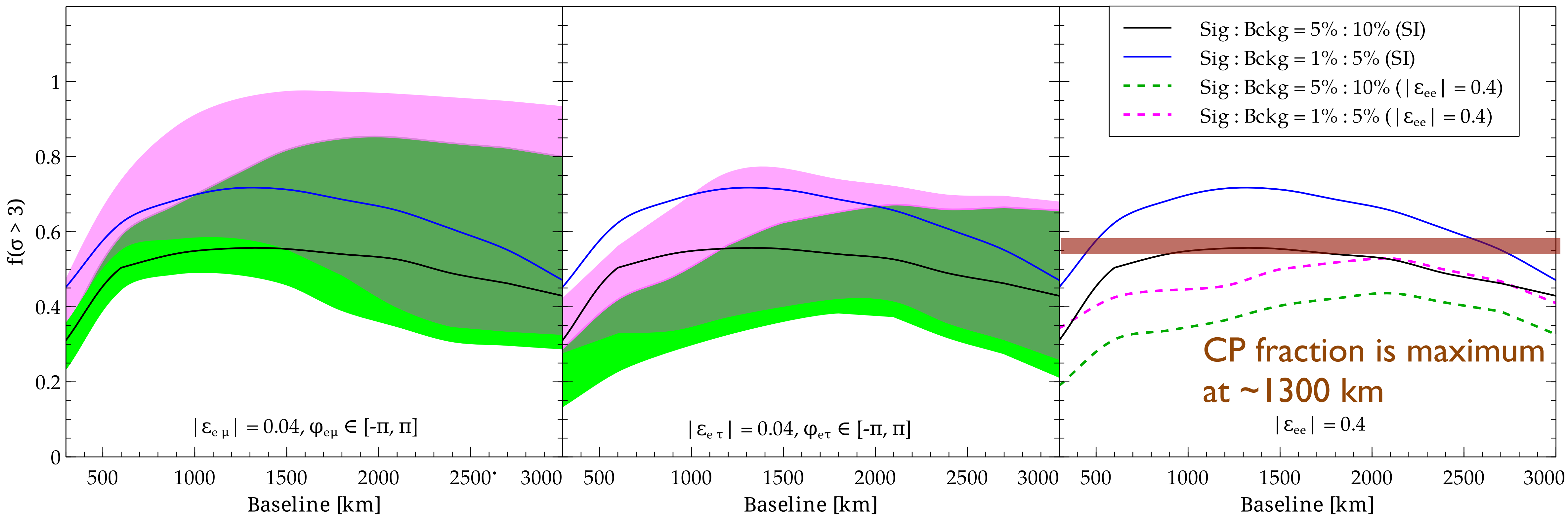
- Diagonal NSI

  Above 3 sigma, CPV can be resolved for a range of values, but not exceeding 0.55



M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

Role of systematics



<table>
<tr><td rowspan="3">NSI term</td><td colspan="2">Nominal systematics (green)</td><td colspan="2">Optimal systematics (magenta)</td></tr>
<tr><td>NSI</td><td>SI</td><td>NSI</td><td>SI</td></tr>
<tr><td>$f(\sigma > 3)$ L_{opt} km</td><td>$f(\sigma > 3)$ L_{opt} km</td><td>$f(\sigma > 3)$ L_{opt} km</td><td>$f(\sigma > 3)$ L_{opt} km</td></tr>
<tr><td>$|\varepsilon_{e\mu}| = 0.04$</td><td>0.85 (1800 – 2500)
0.49 (800 – 1300)</td><td>0.52 (1300)</td><td>0.97 (1500 – 3000)
0.59 (800 – 1300)</td><td>0.71 (1300)</td></tr>
<tr><td>$|\varepsilon_{e\tau}| = 0.04$</td><td>0.65 (2000 – 3000)
0.37 (1800 – 2000)</td><td>0.52 (1300)</td><td>0.77 (1300 – 1500)
0.40 (1800 – 2000)</td><td>0.71 (1300)</td></tr>
<tr><td>$\varepsilon_{ee} = 0.04$</td><td>0.43 (1900 – 2100)</td><td>0.52 (1300)</td><td>0.52 (1900 – 2100)</td><td>0.71 (1300)</td></tr>
</table>

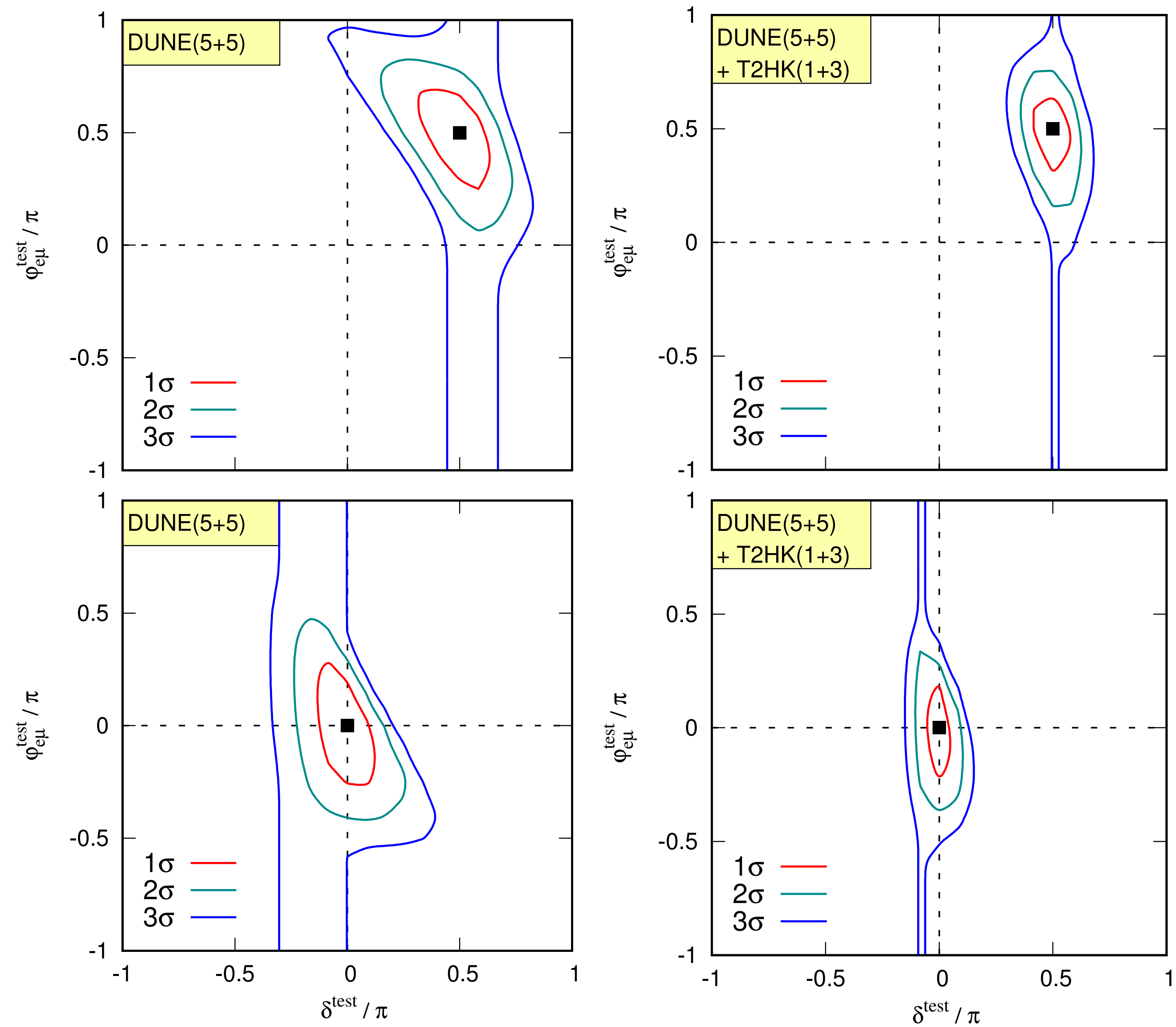
M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

Reconstruction of phases

- Smaller enclosed region better ability to measure the given pair of phases

- DUNE + T2HK

  combination helps

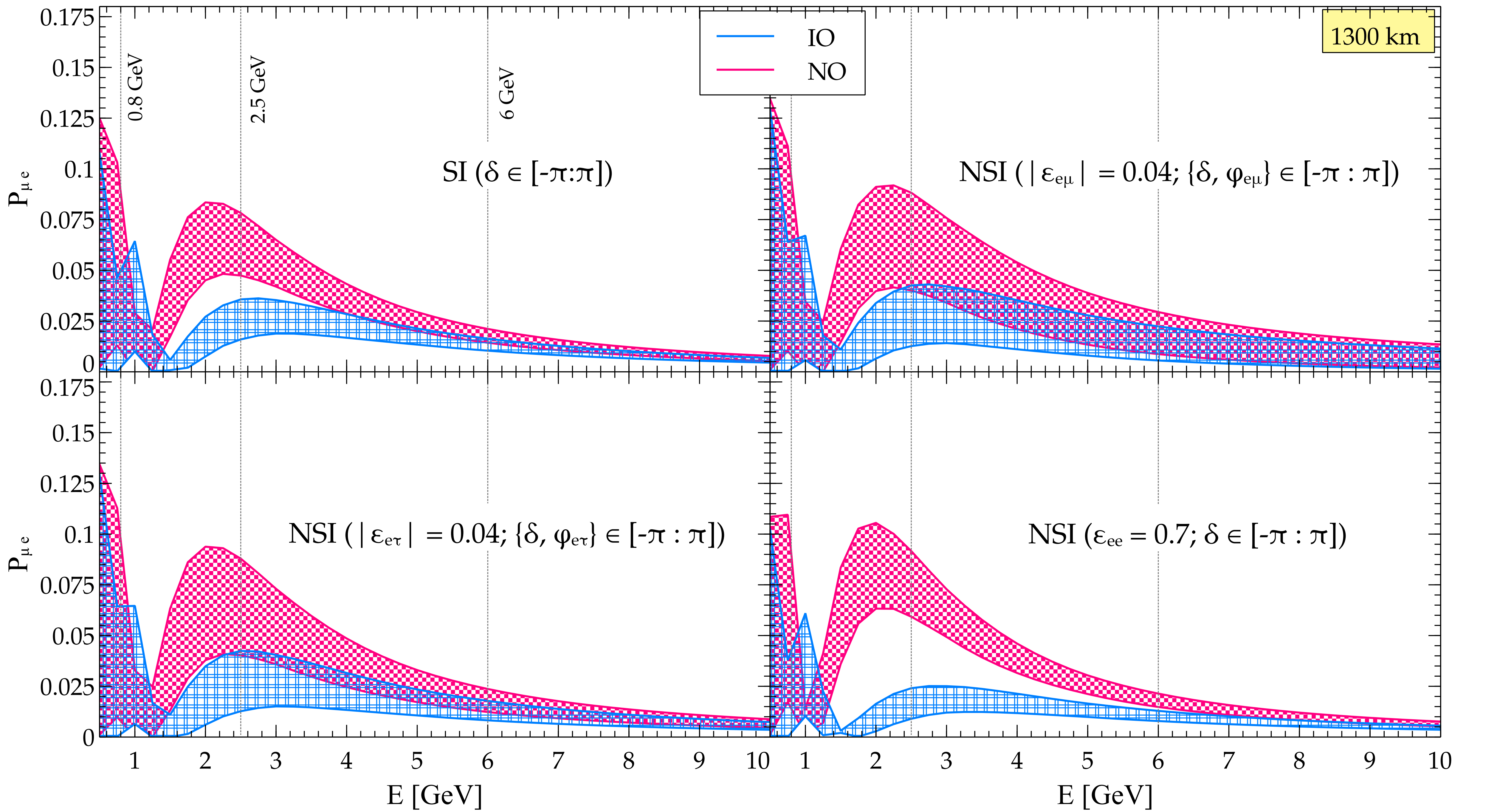


M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

What are the consequences of these subdominant NSI terms for mass ordering studies at long baselines ?

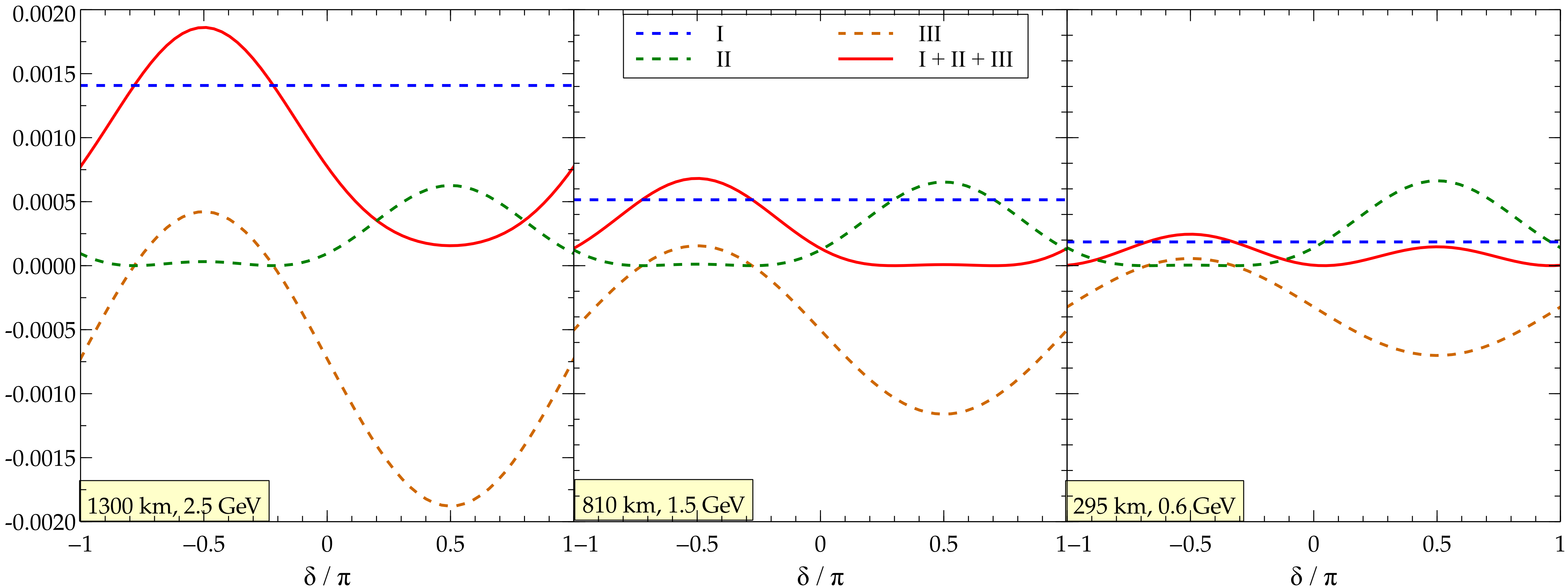
M. Masud and P. Mehta, Phys. Rev. D (2016); 1606.05662

Mass ordering sensitivity at long baselines



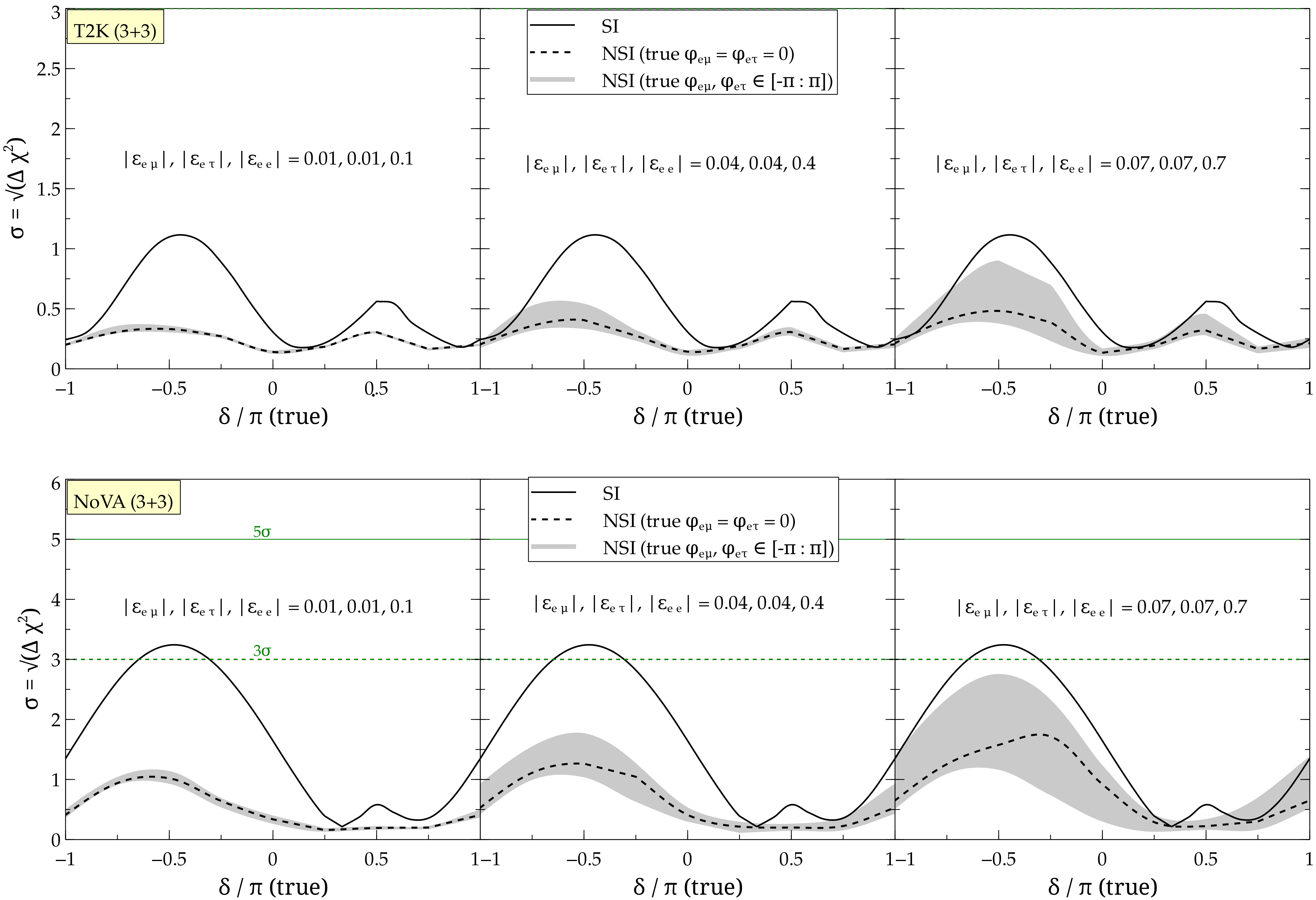
Ref : M. Masud and P. Mehta, Phys Rev D (2016); 1606.05662

Shape of the sensitivity curve



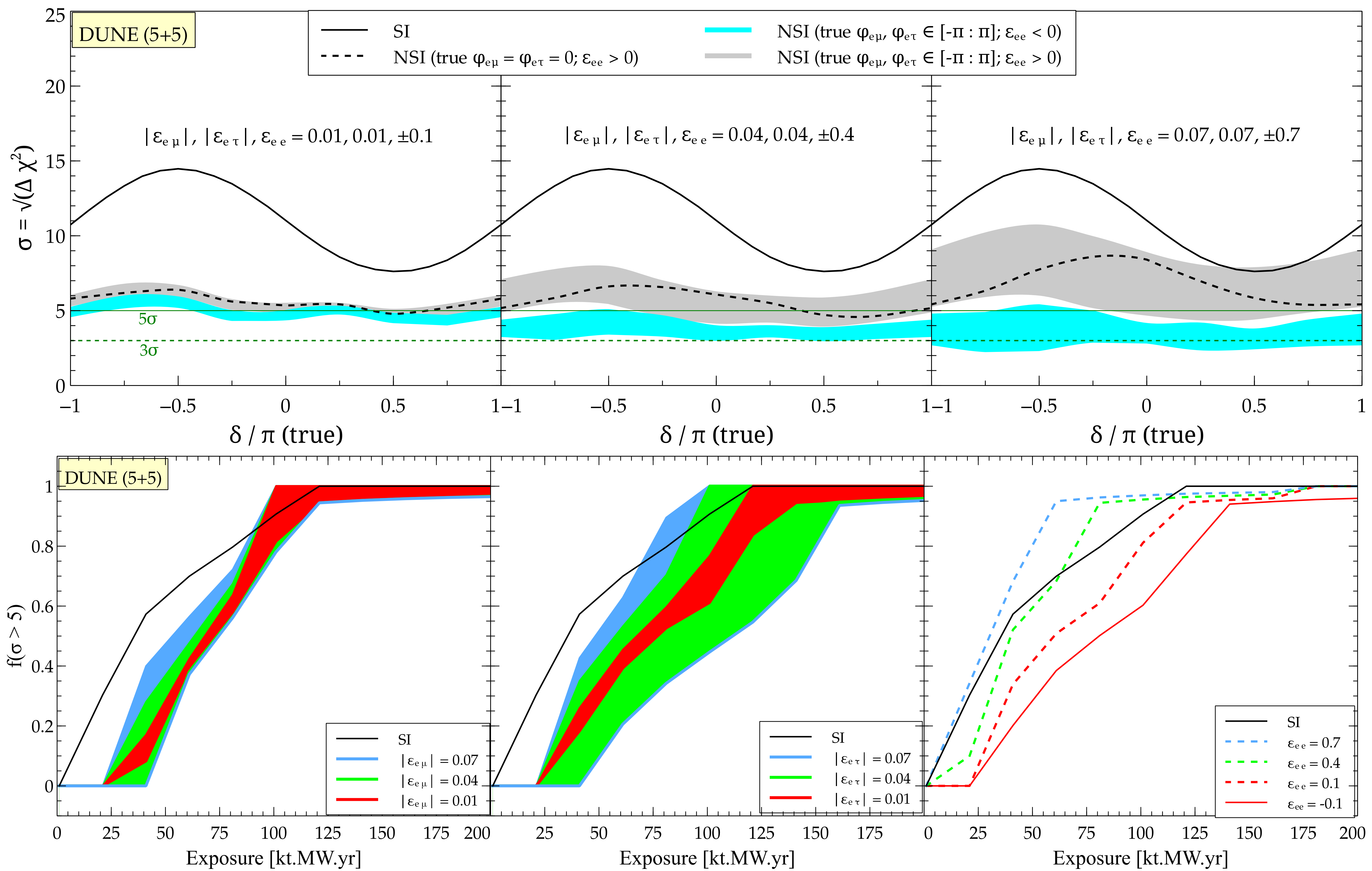
Ref : M. Masud and P. Mehta, Phys Rev D (2016); 1606.05662

Mass ordering sensitivity at long baselines



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

Mass ordering sensitivity at long baselines



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

Conclusions

- Neutrino oscillations have been confirmed beyond doubt. Goals have changed from "measuring the angles and mass-squared differences and establishing neutrino oscillation" —> precision era.

- Effects at sub-leading level such as NSI in propagation can confuse the inferences about some of the unknowns especially those that heavily rely on the matter effects e.g. CP violation or neutrino mass ordering at long baseline experiments such as DUNE

- The primary science goal of DUNE is to determine CP violation and the ancillary science program is to study sub-dominant effects such as NSI. The two are intimately related and feedback the inferences in either sector.

- It could be that different new physics scenarios could give rise to similar distortion in shape of asymmetry curves, so it calls for the need to isolate fine differences between them where the role of a precise near detector may be crucial.