Extricating new physics scenarios at DUNE with high energy beams

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CP Violation in neutrino oscillations

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

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

Jarlskog's factor

CP asymmetries : in vacuum

$\nu_\mu \to \nu_e$

- The best channel is mu to e, the CP asymmetry is $\mathcal{A}_{CP} = \dfrac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}$

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

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

Interference term

talk by Winter

To leading order in Δm^2_{21}

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

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

$\sim \cot\theta_{23}$

Grows with L and 1/E

Ref : Marciano and Parsa, hep-ph/0610258

CP violation : matter effects

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

$\nu_\mu \to \nu_e$

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

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

talk by Winter

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., Marciano and Parsa, hep-ph/0610258

Intrinsic and extrinsic CP effects

- in vacuum

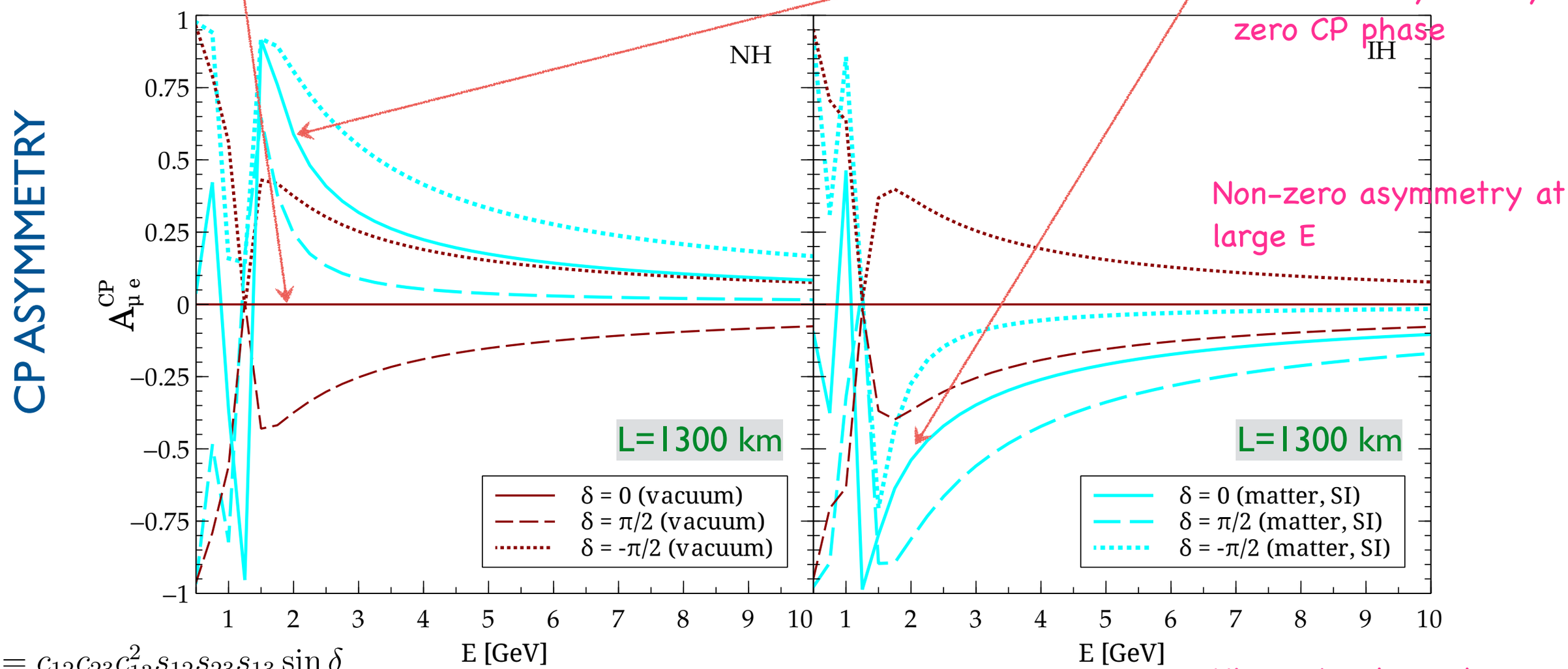
$$\Delta P_{\mu e}(\delta) = 8\,\mathcal{J}\left[\sin(r_\lambda \lambda L)\sin^2\frac{\lambda L}{2} - \sin(\lambda L)\sin^2\frac{r_\lambda \lambda L}{2}\right]$$
$$= 4\sin\delta\,\mathcal{J}_r\,[\sin\lambda L/2\,\sin r_\lambda \lambda L/2\,\sin(1-r_\lambda)\lambda L/2]$$

- 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



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

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

Hierarchy dependence

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]

Matter 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)

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

- 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

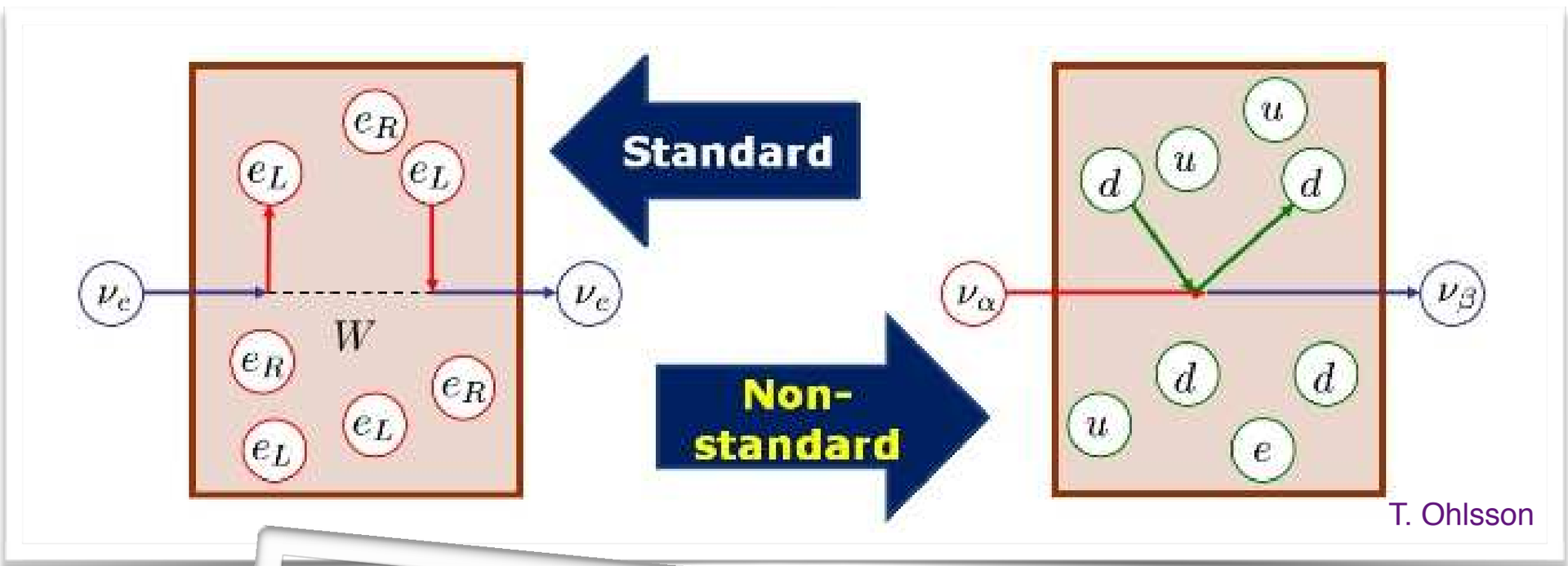
Talks by Li, Kayser, Marfatia, Mocioiu,…

Matter 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)



T. Ohlsson

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

Deep Underground Neutrino Experiment

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

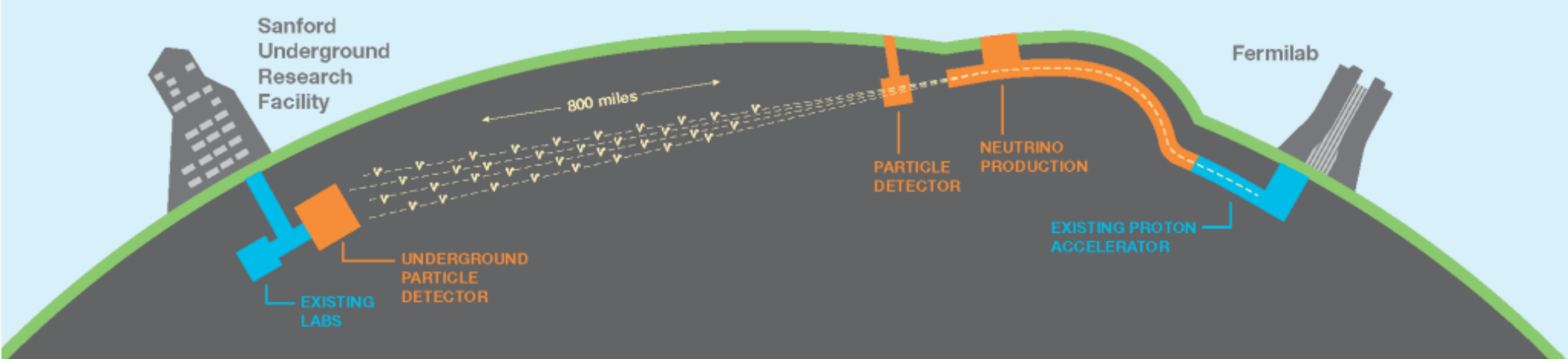
CDR, Vol 2, DUNE Collaboration, 1512.06148 [physics.ins-det]

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]



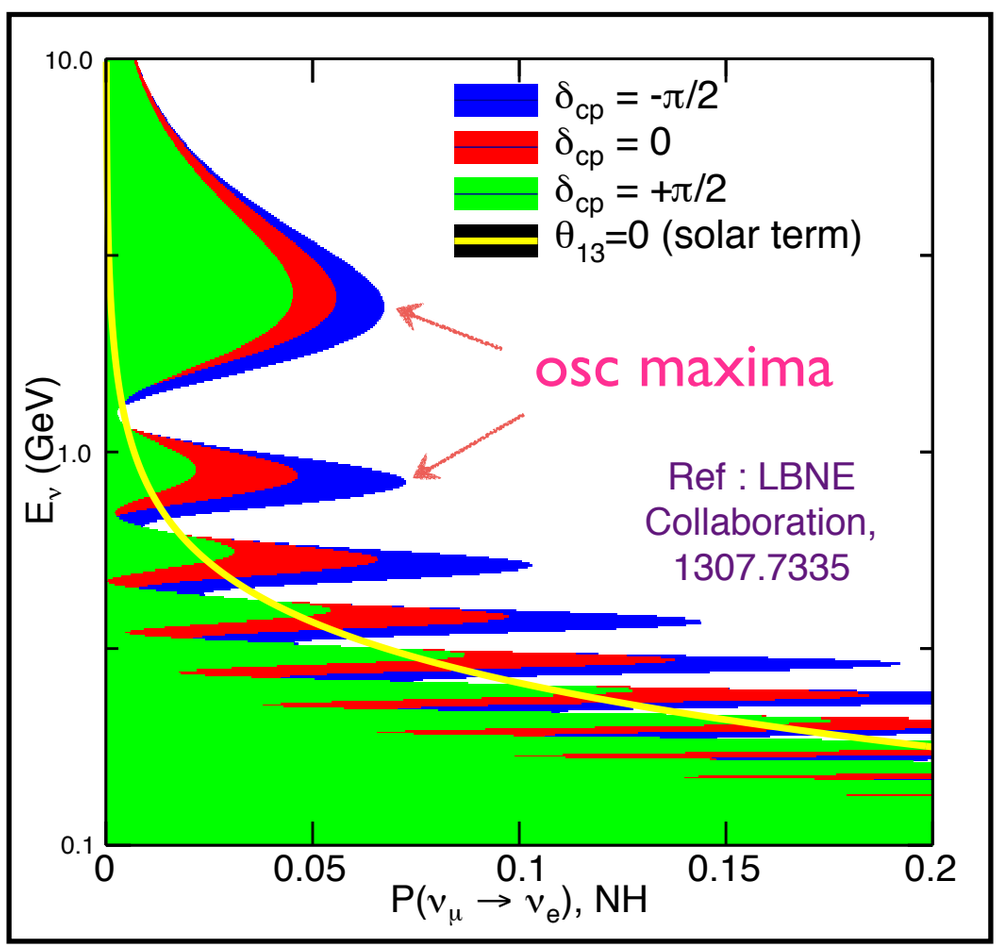
Probability at 1300 km and flux

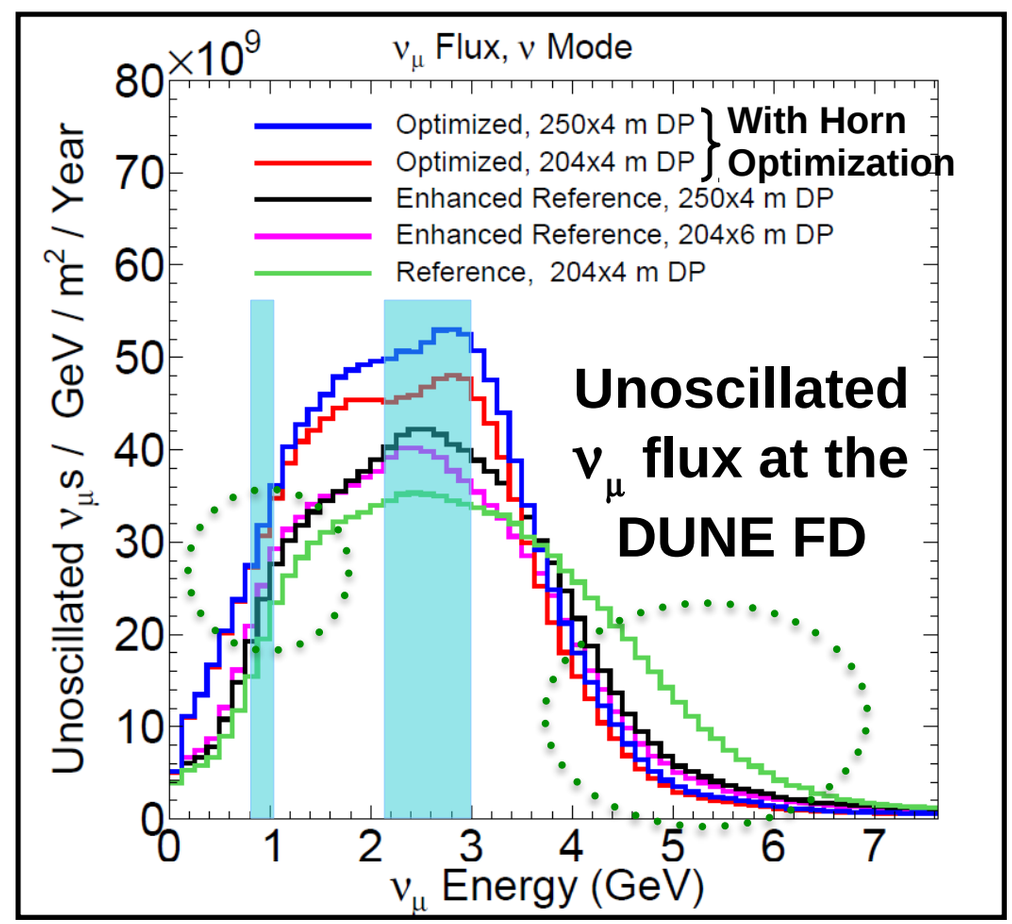
- To exploit the full three flavour effects in neutrino oscillations
  - constrain the known parameters and measure the unknown parameters

- 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

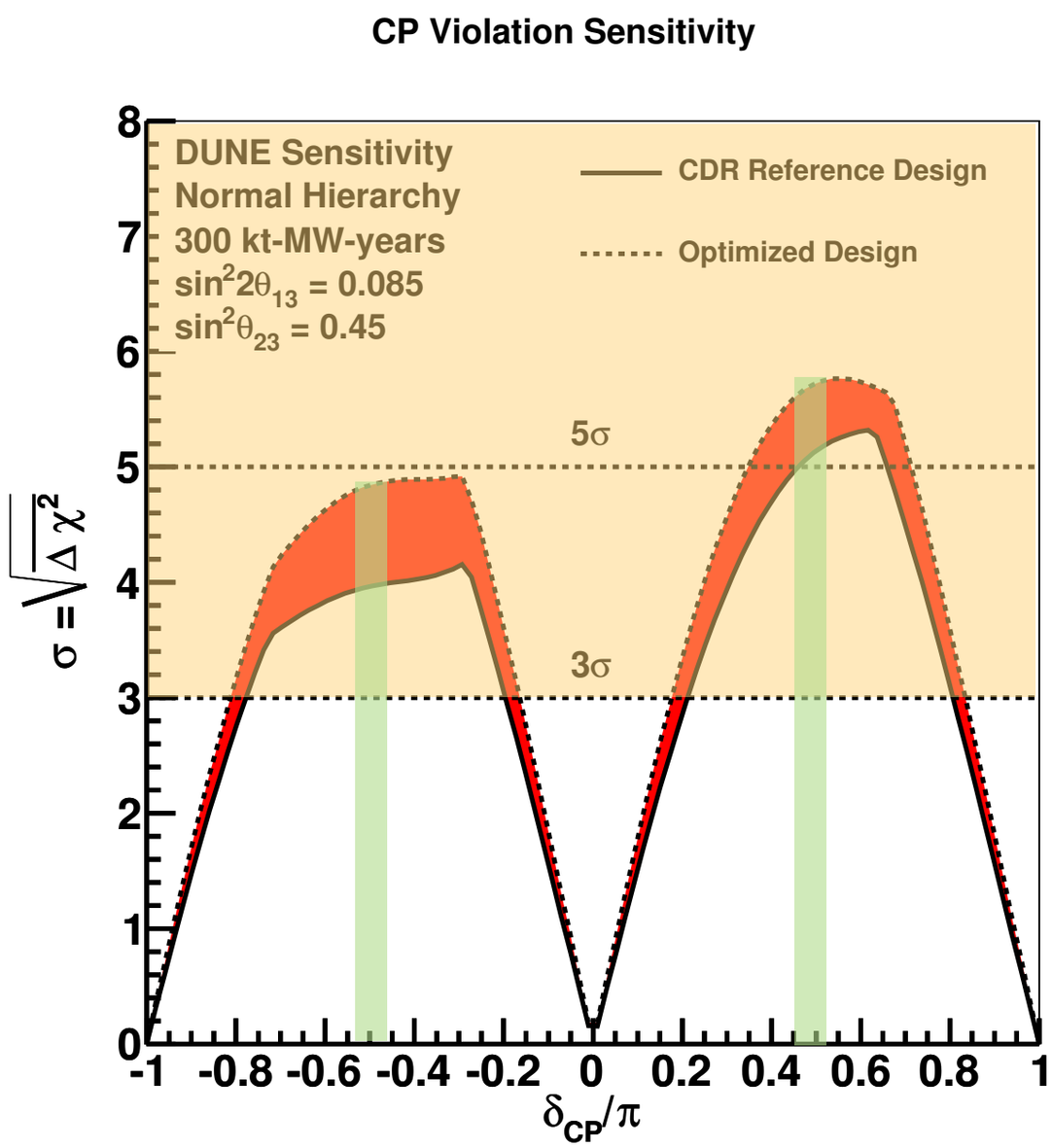
$$\frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} = (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times 510\ \mathrm{km/GeV}$$

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





CP Violation sensitivity



- Red band : Reference - optimised beam design
- Sensitivity depends on
  - systematics
  - statistics (300 kt.MW.yr)
  - true value of

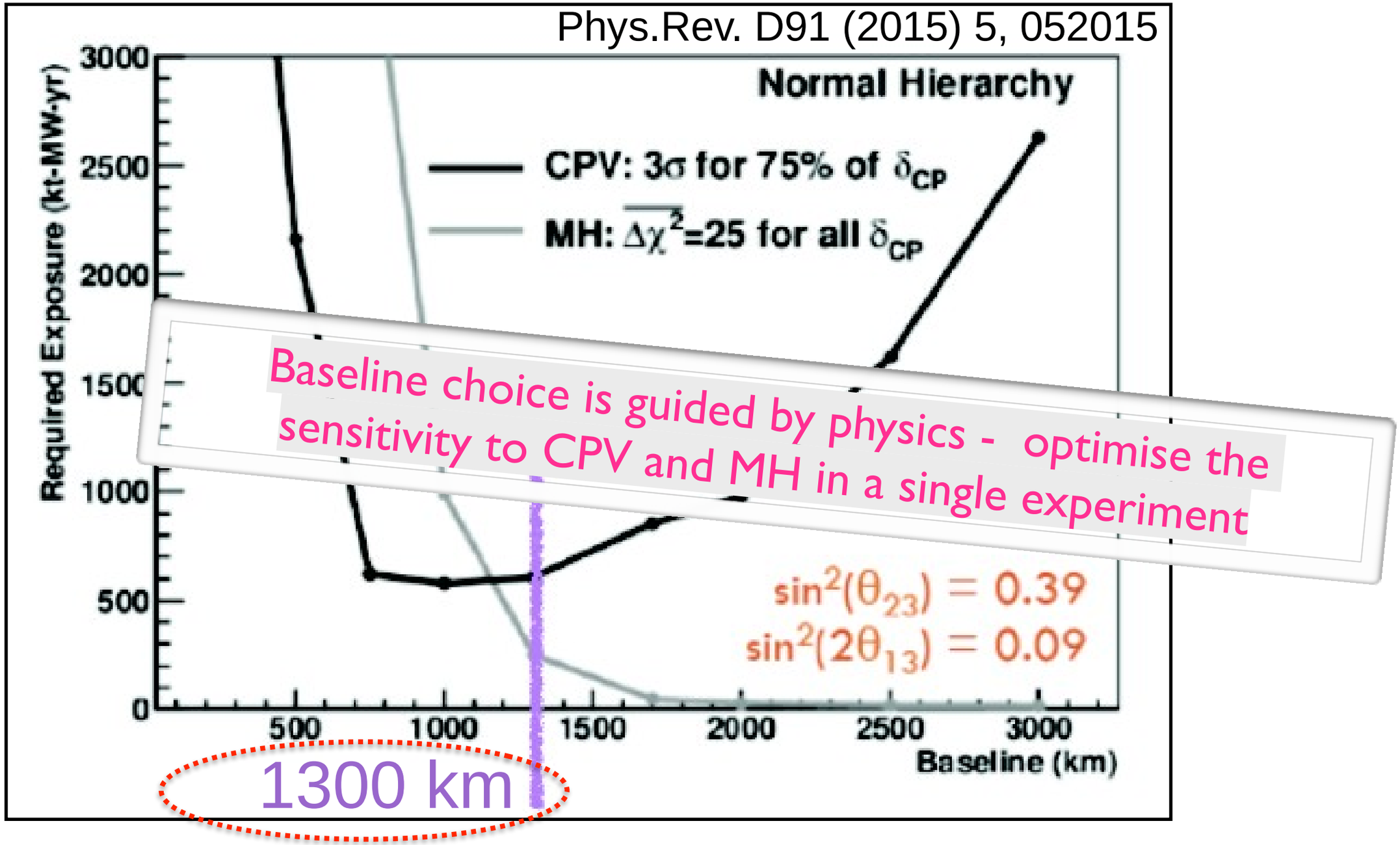
$$\delta_{\rm CP}, \theta_{23}, \delta m^2_{31}$$

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

Talks by Sousa, Bian

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

Why 1300 km ?



M. Bass et al, Phys.Rev. D91 (2015) no.5, 052015 - PRE-DUNE era / LBNE, see also M. V. Diwan et al, Ann. Rev. Nucl. Part. Sci. (2016) 66, 47-71 for review on long baseline neutrino experiments

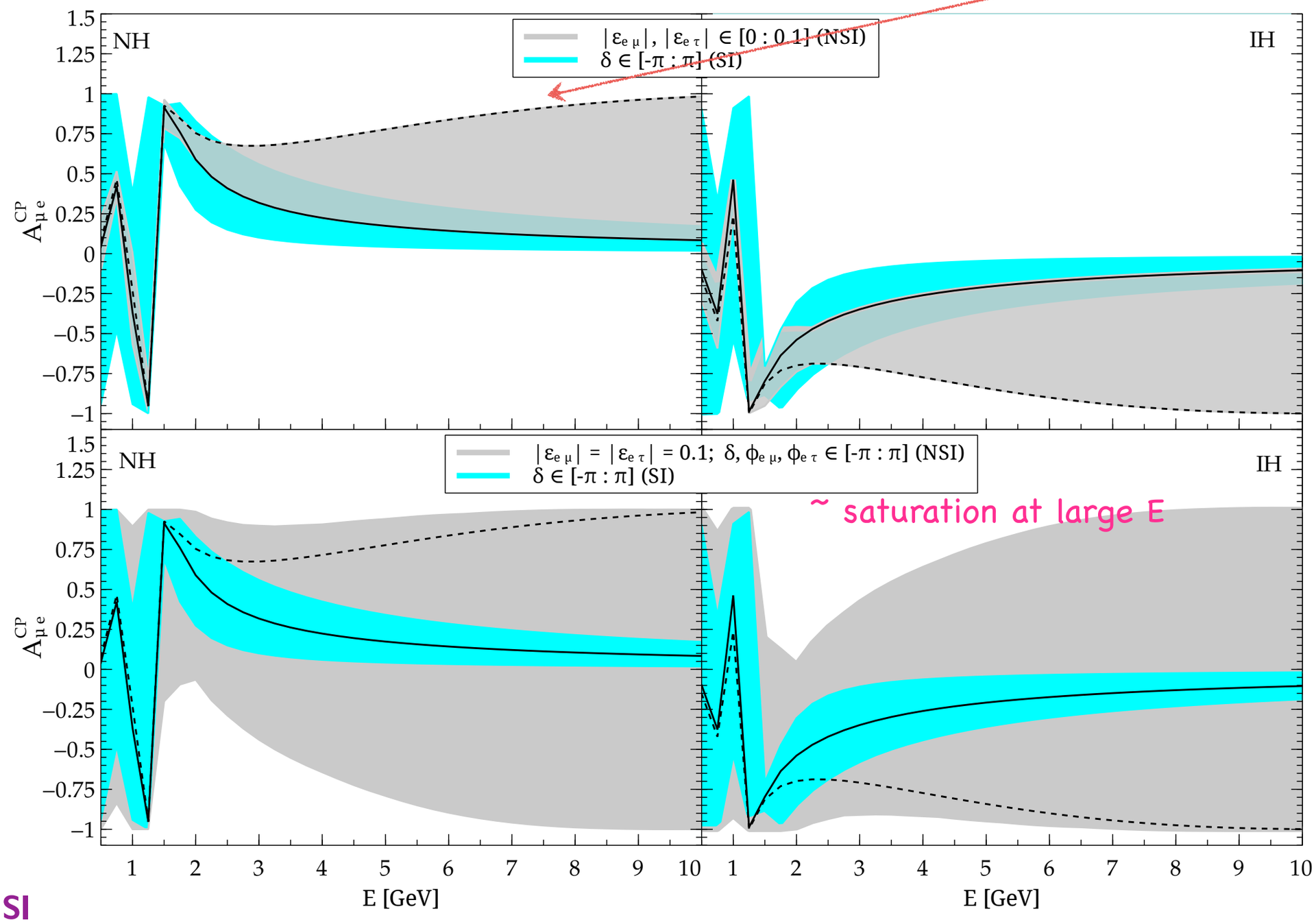
The subdominant NSI terms complicate the inferences of oscillation parameters drastically at long baselines… and make extraction of intrinsic CP phase very hard !

Talks by Li, Kayser, Marfatia, Mocioiu,…

Impact of NSI on the CP asymmetry

Large value implies new physics

CP ASYMMETRY



~ saturation at large E

- 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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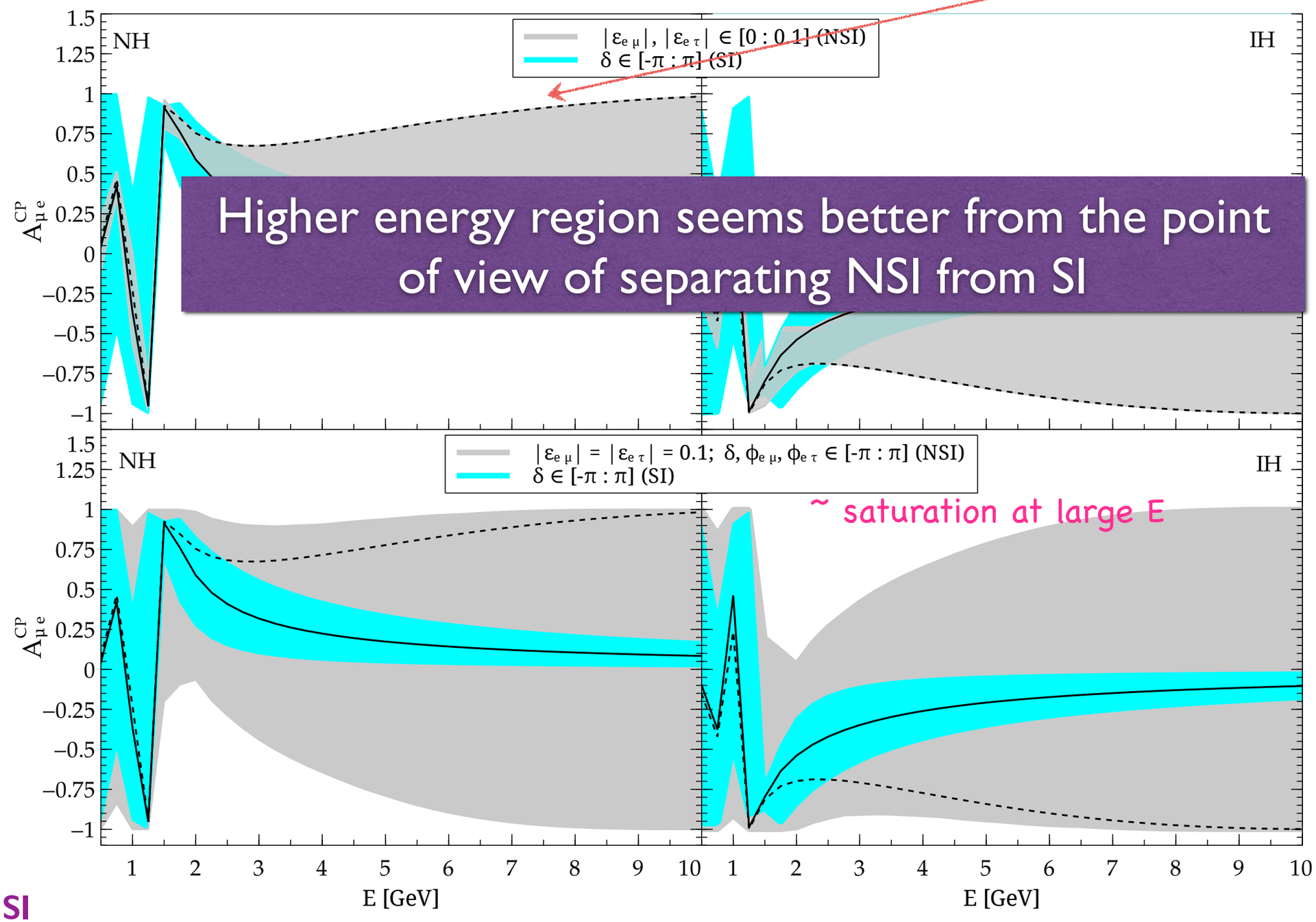
CP ASYMMETRY



Higher energy region seems better from the point of view of separating NSI from SI

~ saturation at large E

- Moduli variation

Either + or -, depending on hierarchy

- Phase variation

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

grey : NSI

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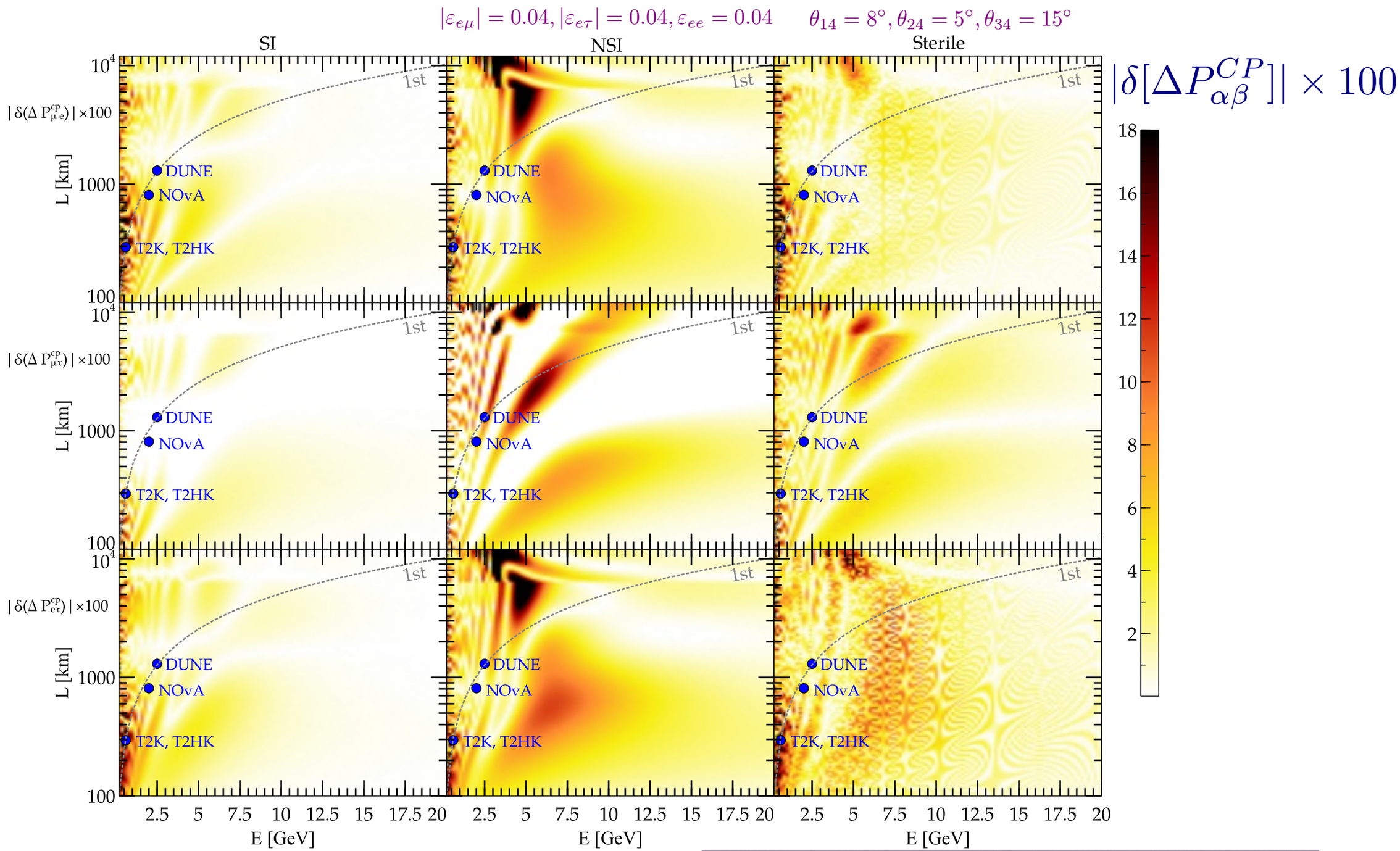
Extracting the intrinsic CP phase



A useful quantity for separating intrinsic and extrinsic components

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

Nunokawa, Parke, Valle (2008)

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

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

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, 1704.08650 [hep-ph]

High energy Beam tunes at DUNE

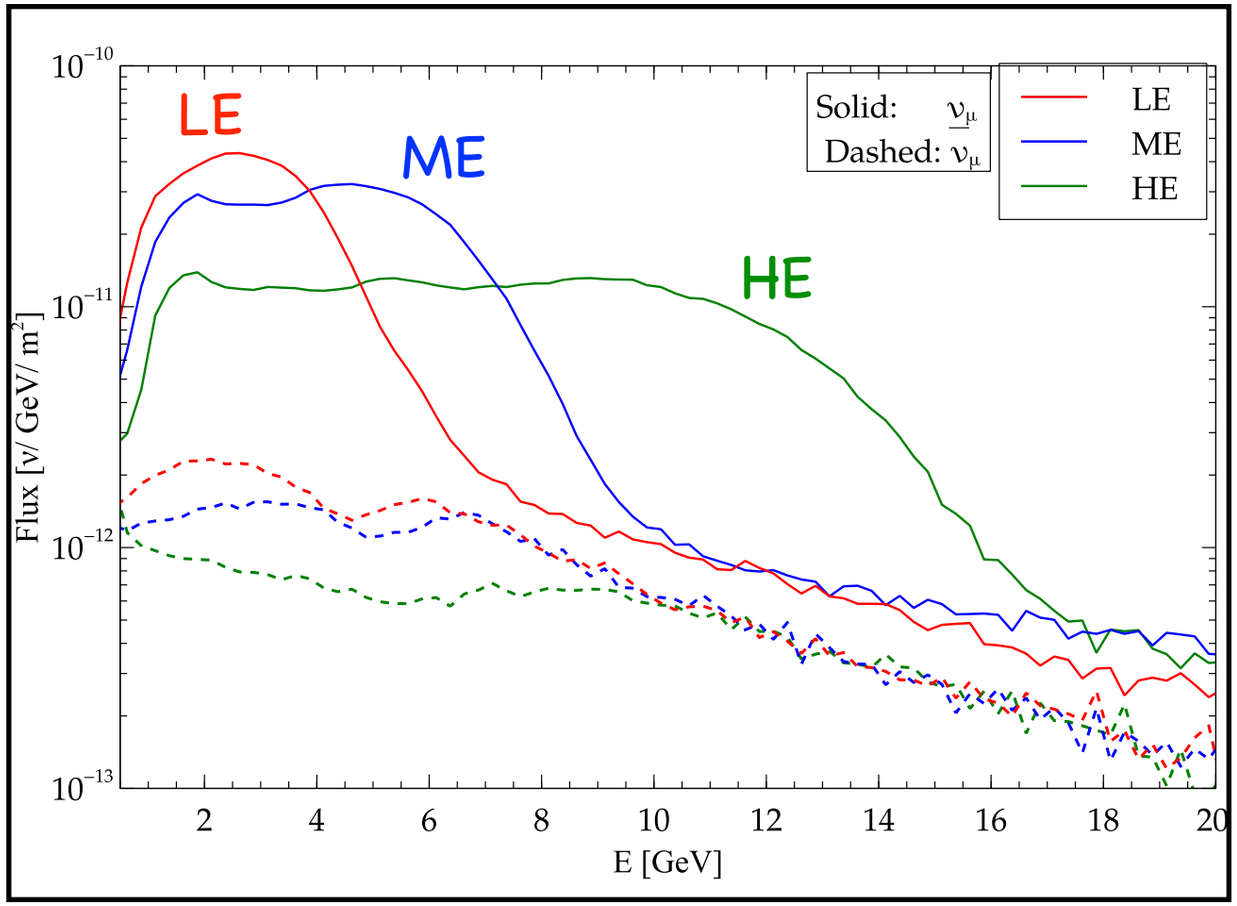
- Can we have other possible beam options other than the optimised one used in CDR ?
- The aim is to get better separability of SI from NSI...

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



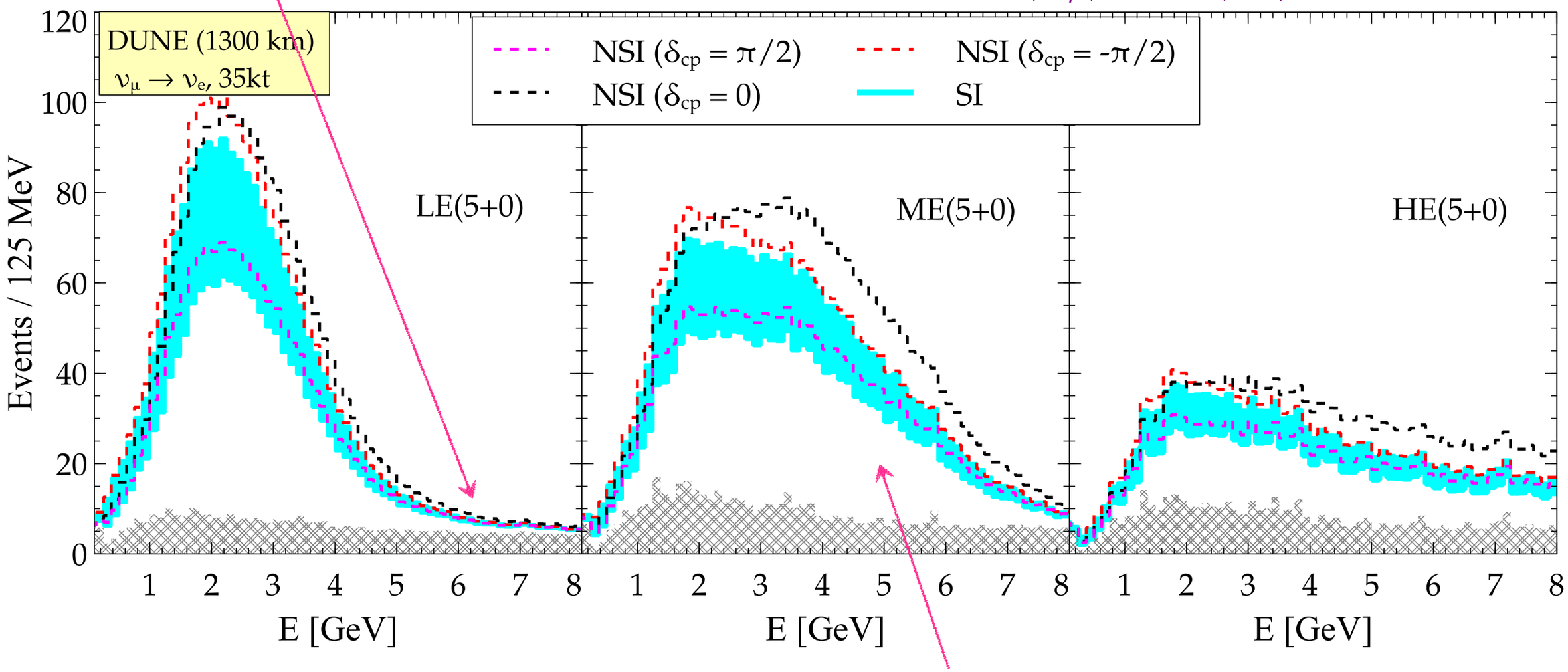
M. Masud, M. Bishai and P. Mehta, 1704.08650 [hep-ph]

Event spectrum at DUNE for different tunes

$\nu_\mu \to \nu_e$

Falling flux kills the large asymmetry and large E

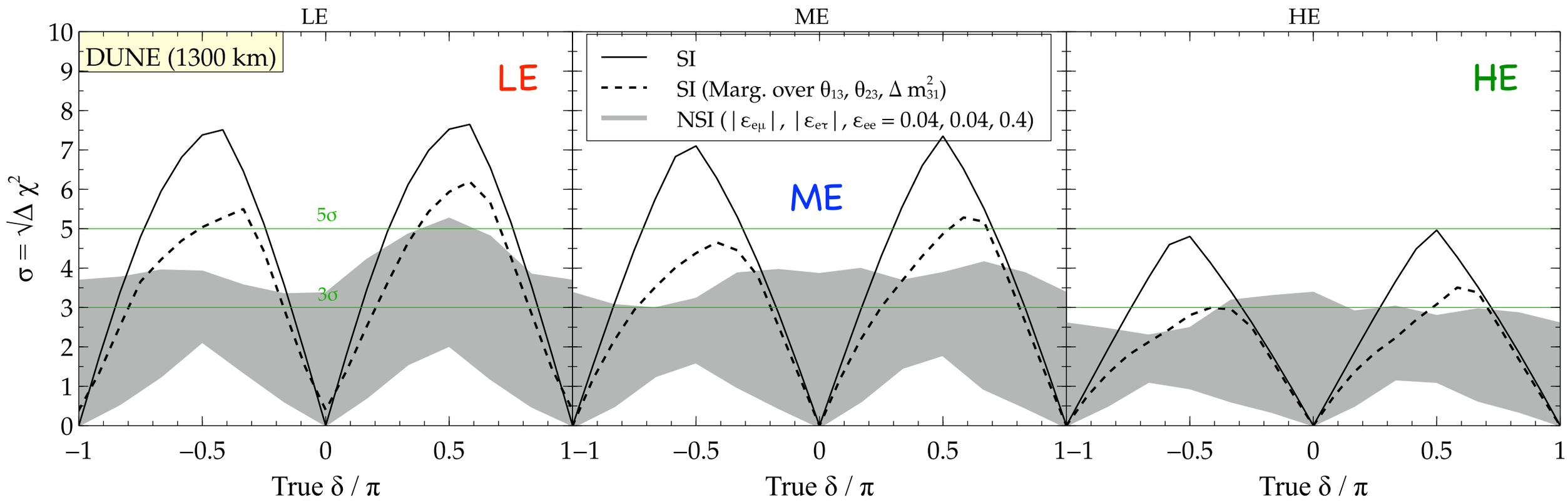
$|\varepsilon_{e\mu}| = 0.04, |\varepsilon_{e\tau}| = 0.04, \varepsilon_{ee} = 0.4$



Better ability to separate black curve from cyan band

M. Masud, M. Bishai and P. Mehta, 1704.08650 [hep-ph]

CPV sensitivity at DUNE for different tunes



Black solid curves (SI case) and grey bands (NSI case with variation in NSI phases) - without marginalization

Dashed black curves (SI) - with marginalization

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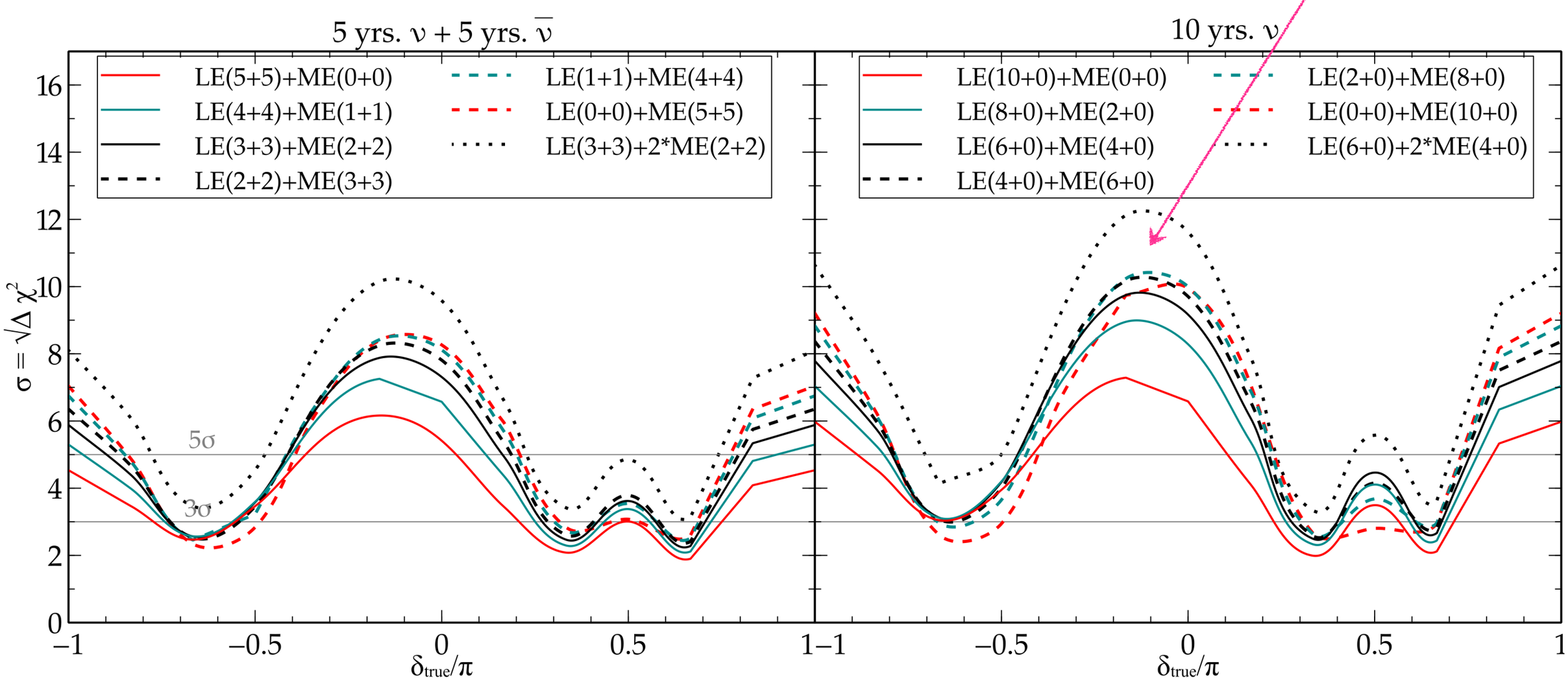
SI-NSI separation at DUNE

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



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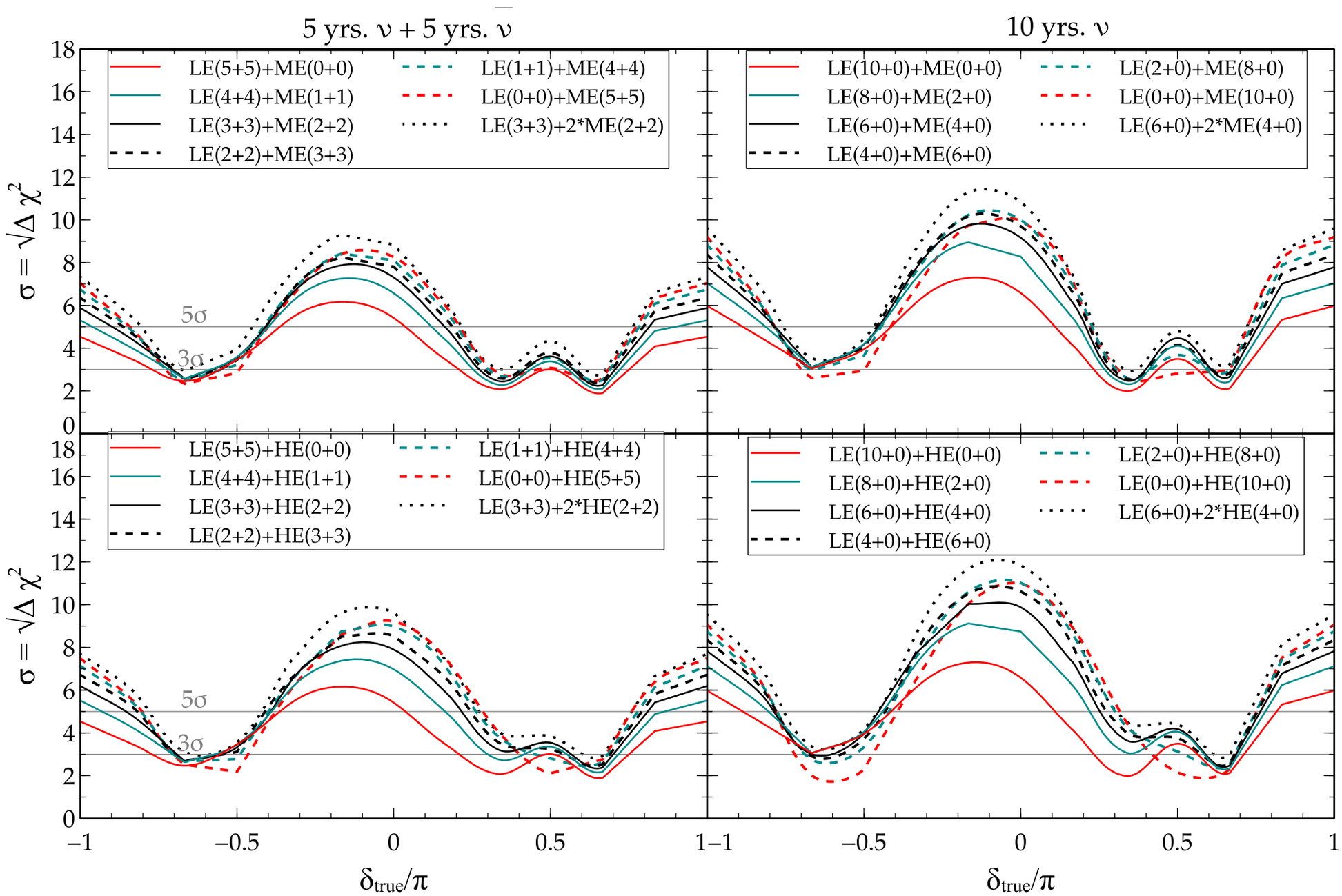
SI-NSI separation at DUNE

LE+HE is slightly better than LE+ME



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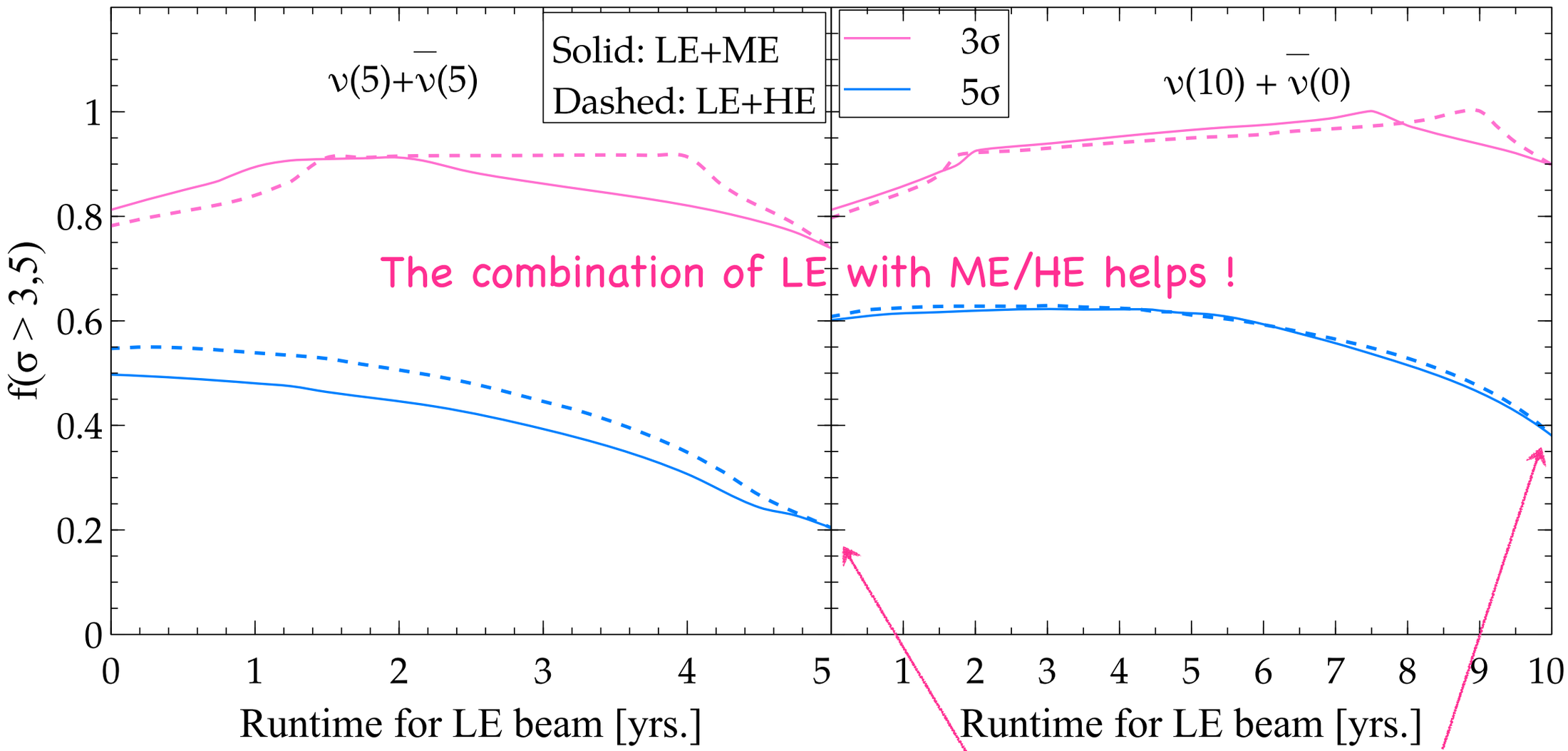
Fraction for SI/NSI separation



The combination of LE with ME/HE helps !

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

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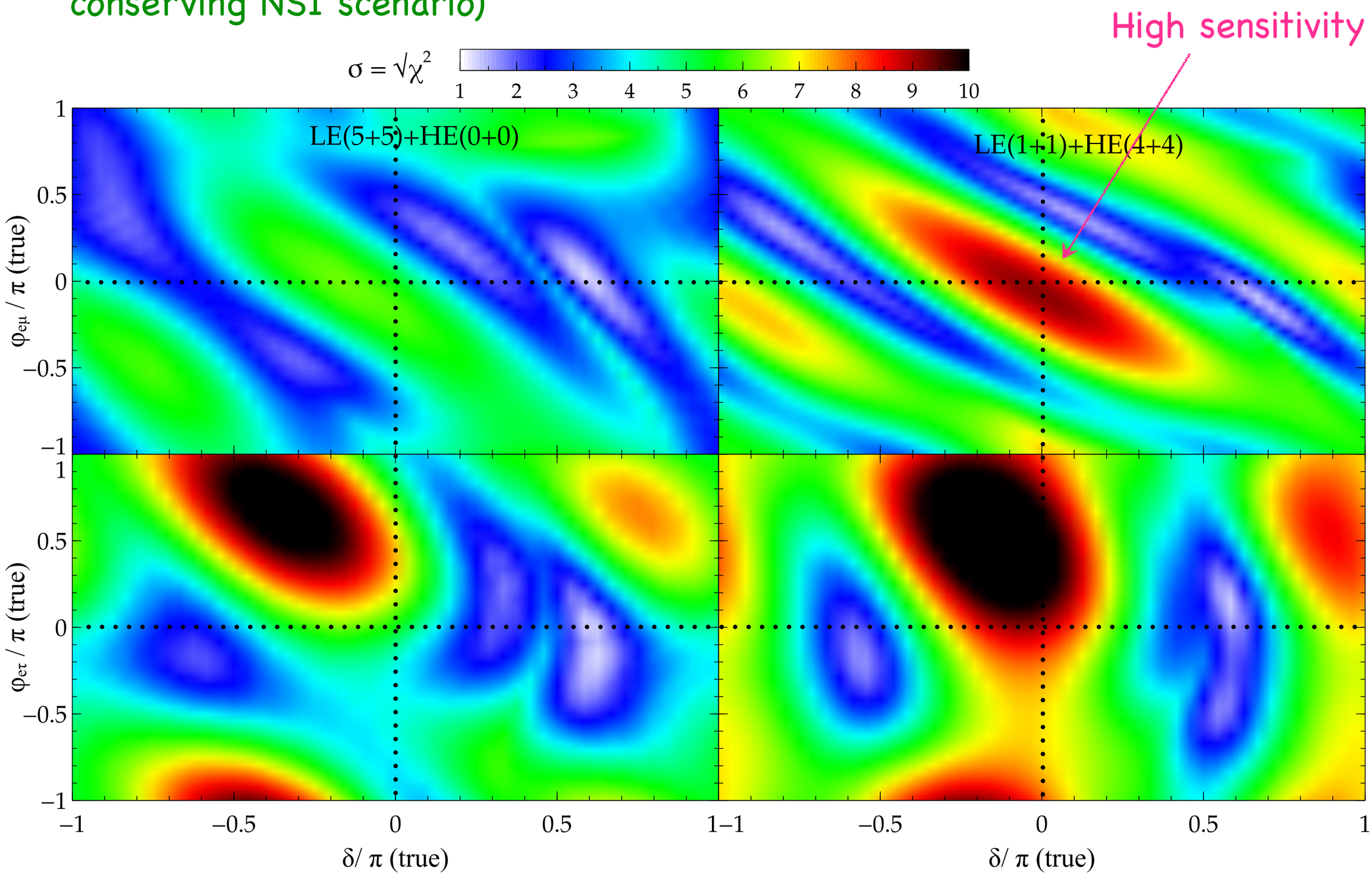
Impact of non-zero NSI phases

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



M. Masud, M. Bishai and P. Mehta, 1704.08650 [hep-ph]

Conclusions

- Establishing whether CP is violated or not and measuring its value is an important primary science goal of the long baseline experiment, DUNE and we would like to answer this question as cleanly as possible.
- 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 an important usefulness of high energy beam tunes... i.e. those could be used to address the question of separation between SI and NSI (or any other new physics scenarios).

Extra

Direct bounds on matter NSI

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

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

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)

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

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

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

more restrictive

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

MINOS Collaaboration