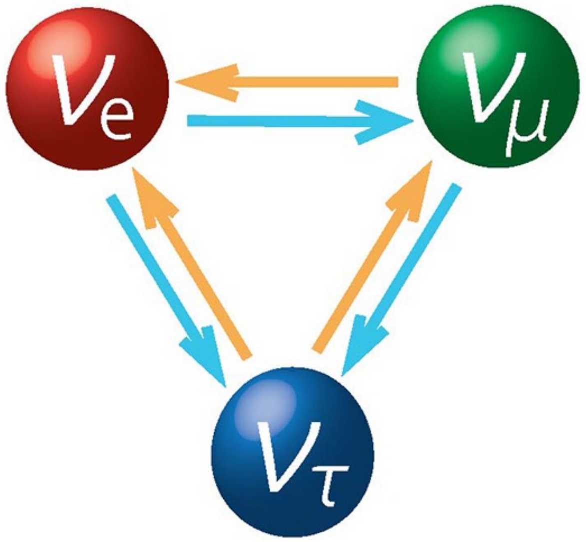
Impact of new physics in the context of long baseline experiments

Poonam Mehta



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School of Physical Sciences,
Jawaharlal Nehru University, New Delhi

Jogesh Rout, Samiran Roy, Sheeba Shafaq, Mehedi Masud, Animesh Chatterjee, Mary Bishai

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

INO Collaboration

"Neutrino Frontiers", Vietnam, 18 July 2018

Present status of 3-neutrino oscillations

Ref: de Salas et al, 1708.01186,Phys.Lett. B782 (2018) 633-640

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

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

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

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

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

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

Talk by Kayser

Goals :

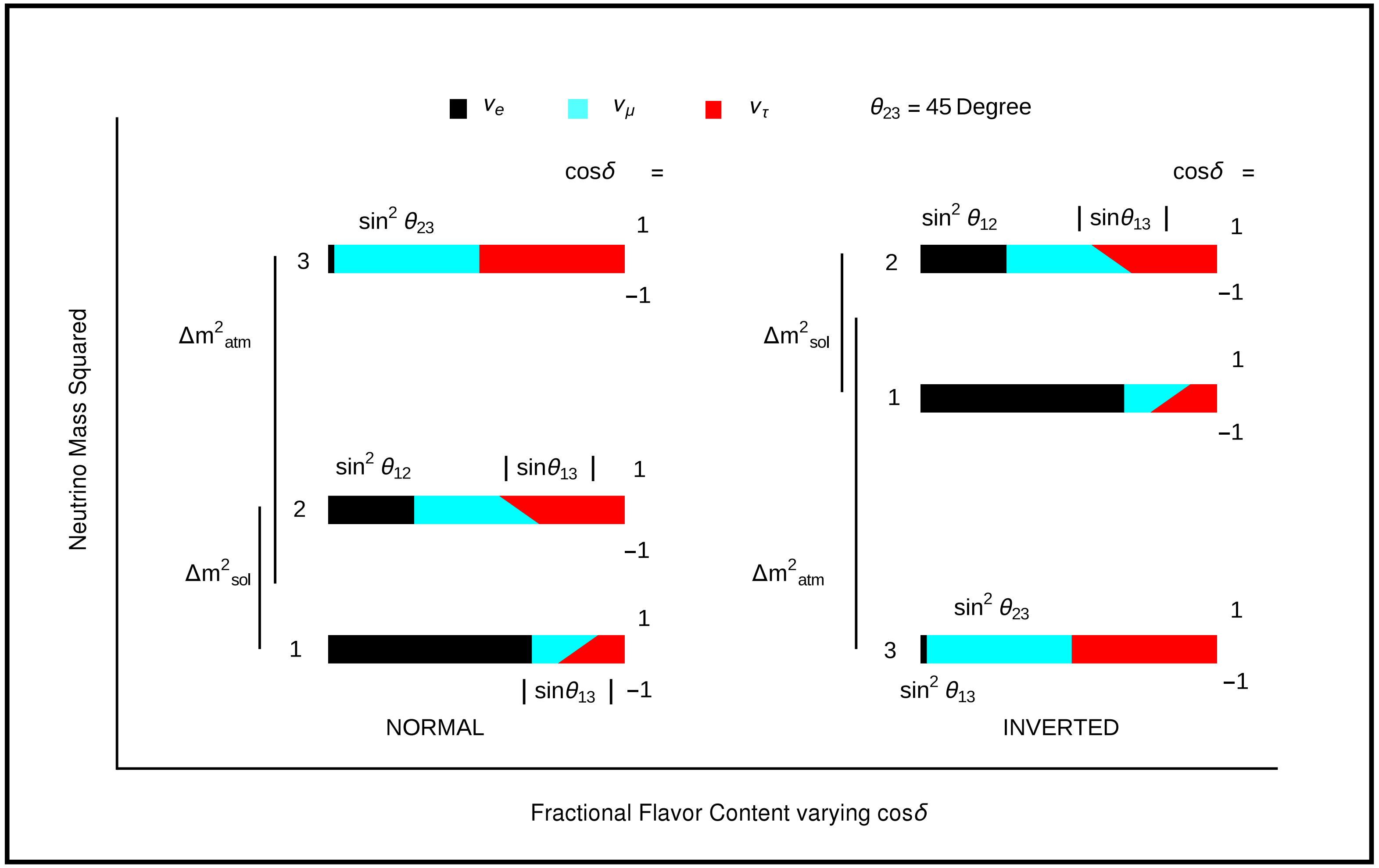
Improve precision

Mass ordering

Octant of theta23

Dirac CP phase

Absolute neutrino mass - unknown!



Ref: Mena and Parke

(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

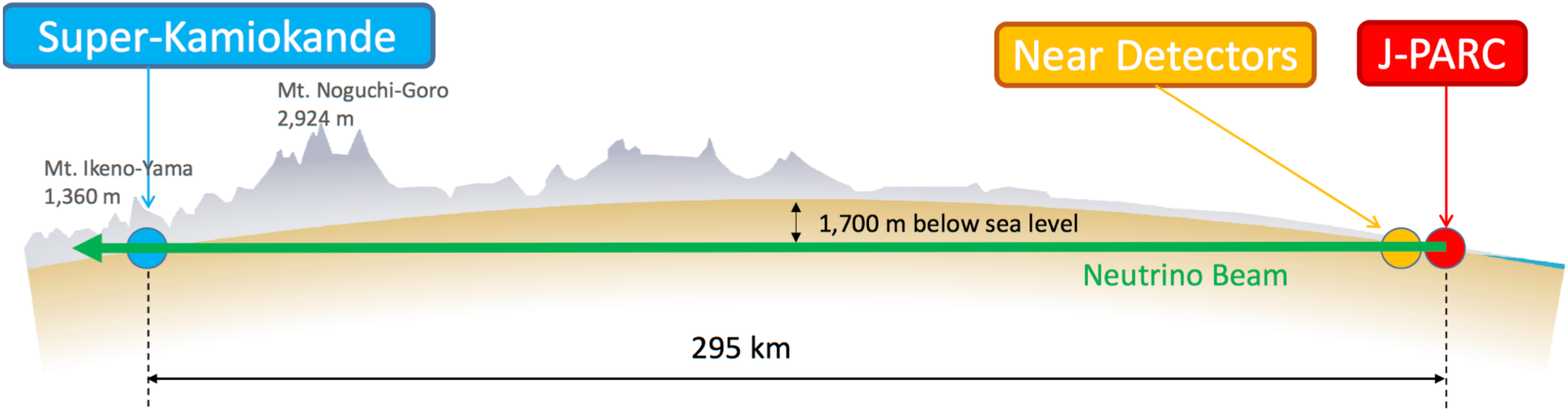
Off-axis narrow band beam, E ~ 0.6 GeV, 750 kW ~ 1MW

Baseline is 295 km (less matter effect)

Hyper-Kamiokande: HUGE water Cherenkov Detector

Measurement of CP violation

Talks by Cervera, Suzuki



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Mega-watt class beam, wide band beam 0.5 - 10 GeV
Baseline is 1300 km, Liquid Argon detector
Ideal for mass ordering/hierarchy and CP violation

Primary Science Program

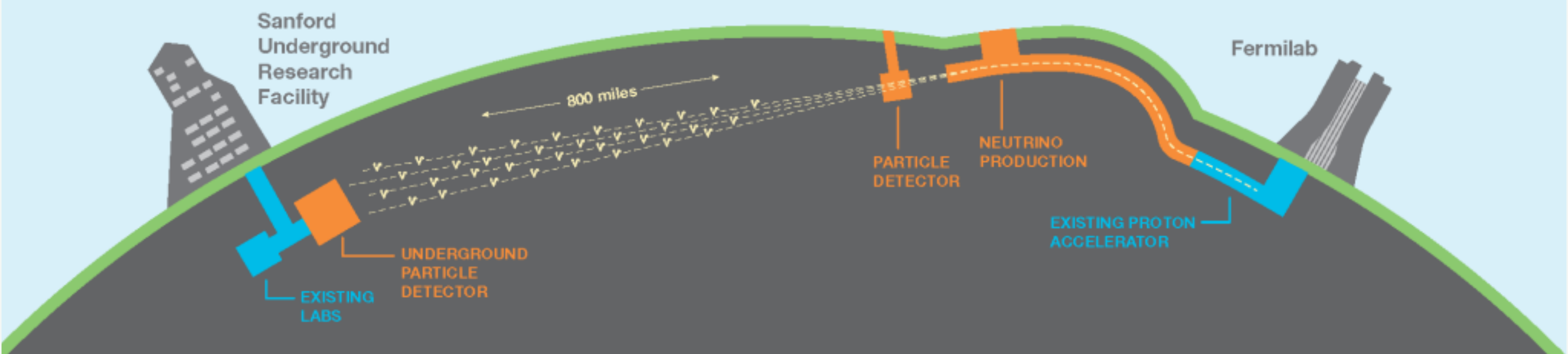
CDR, Vol 2, DUNE Collaboration,
[1512.06148](https://arxiv.org/abs/1512.06148) [physics.ins-det]

Ancillary Science Program

CDR, Vol 4, DUNE Collaboration,
[1601.02984](https://arxiv.org/abs/1601.02984) [physics.ins-det]

CDR, Vol 1, DUNE Collaboration,
[1601.05471](https://arxiv.org/abs/1601.05471) [physics.ins-det]

CDR, Vol 3, DUNE Collaboration,
[1601.05823](https://arxiv.org/abs/1601.05823) [physics.ins-det]

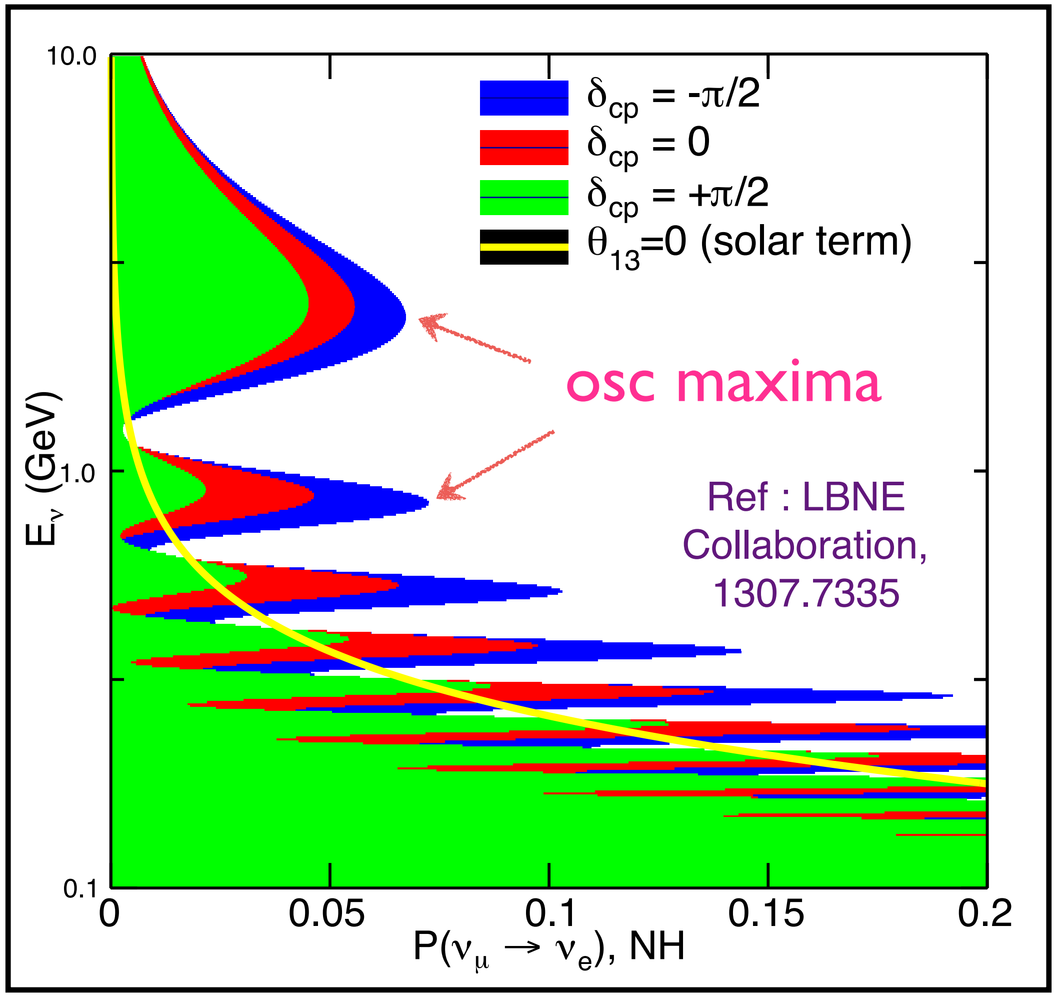


Probability at 1300 km and flux

- 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

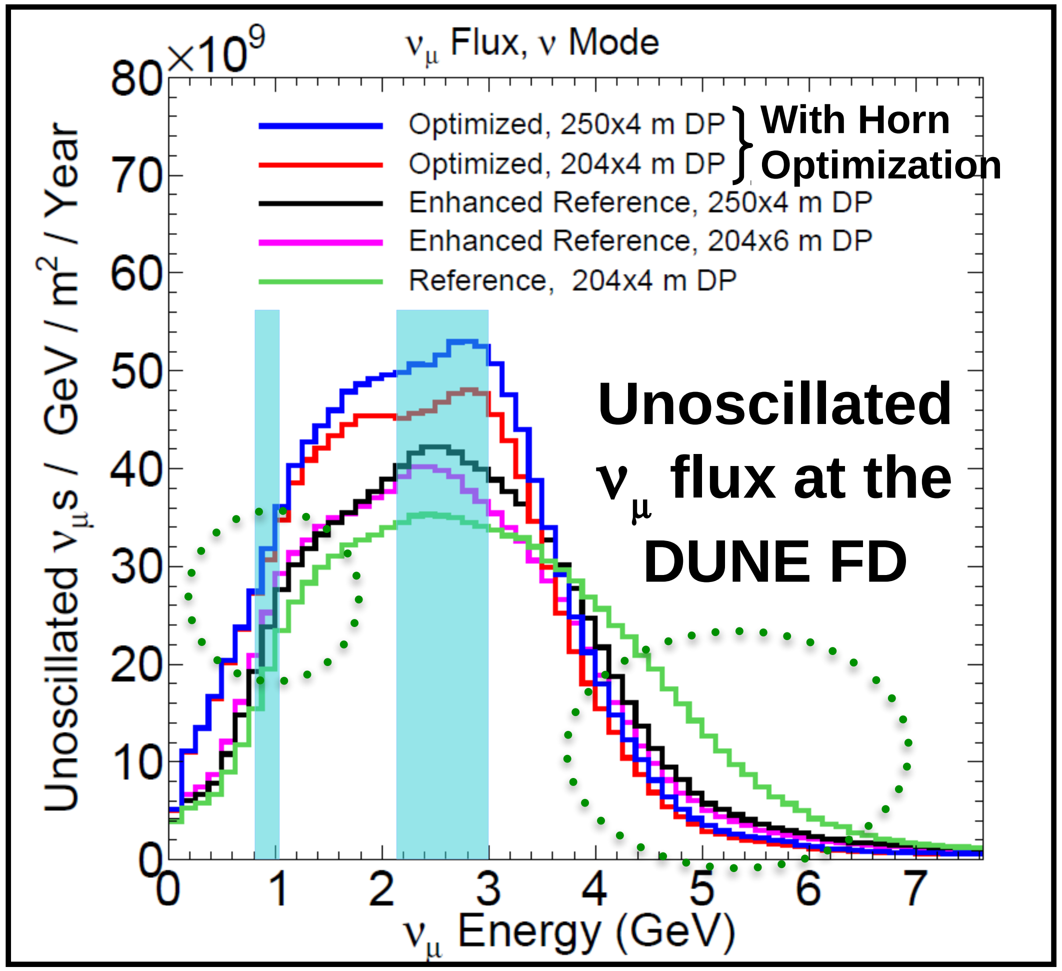
$$\begin{aligned}\frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} &= (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)}\\ &\approx (2n-1)\times 510\,\mathrm{km/GeV}\end{aligned}$$



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

New physics scenarios : NSI, Sterile, …

Talk by Quilain

Matter non-standard interactions

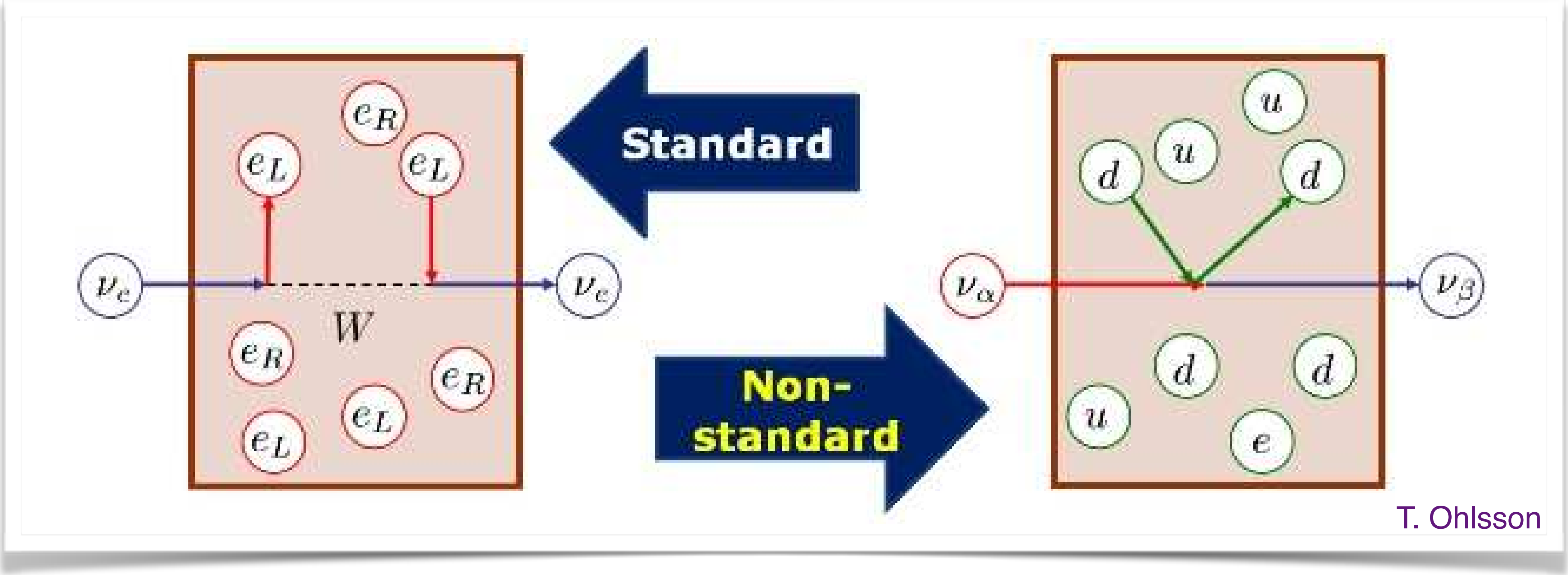
Review: Farzan and Tortola, 1710.09360

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{f\,C}_{\alpha\beta}\,[\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta]\,[\bar{f}\gamma_\mu P_C f]\,, \qquad P_C = (1\pm\gamma_5)/2.$$

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

Sterile neutrinos

- The standard 3 neutrino paradigm : 3 neutrino mass eigenstates, and 1 CP-violating phase
- Strong hints - short baseline anomalies persist (LSND, MiniBooNE…)
  - existence of short wave length oscillations (L/E ~ 1 km/GeV) driven by large mass-squared splittings ~ 1 eV^2
  - additional neutrino states beyond the 3 active states which are largely sterile.
- In the 3 active + 1 sterile model, the mixing matrix U is a 4 x 4 unitary matrix. 3 x 3 sub block is no longer unitary.
- 3 active + 1 sterile case : Additional parameters (6 mixing angles, and 3 CP-violating phases)

CP Violation in neutrino oscillations

C, P, T in neutrino oscillations

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

- 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

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

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

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

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

Interference term

To leading order in Δm^2_{21}

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

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

$\sim \cot\theta_{23}$

Grows with L and 1/E

Ref : Marciano and Parsa, hep-ph/0610258

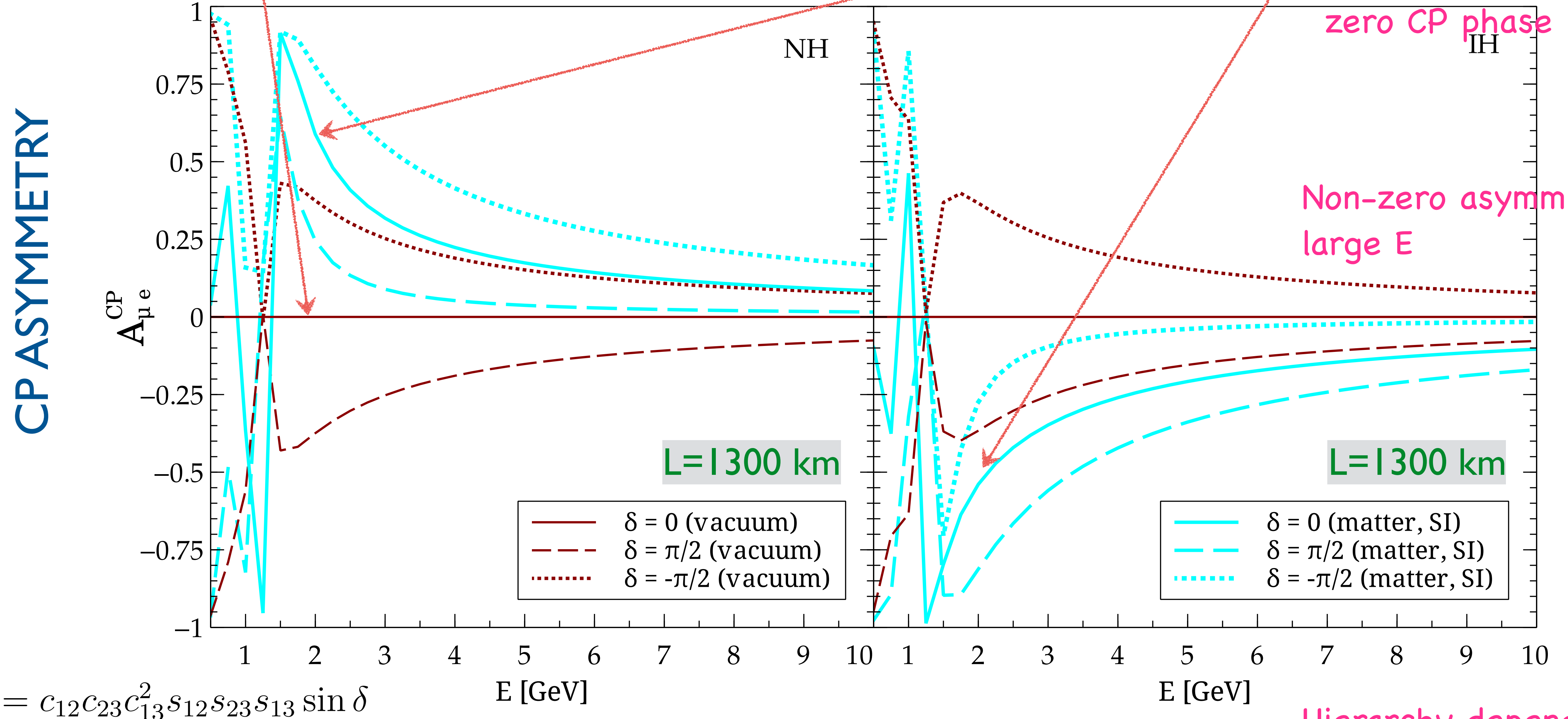
Intrinsic and extrinsic CP effects

- in vacuum

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

- 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

Non-zero asymmetry at large E

Hierarchy dependence

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

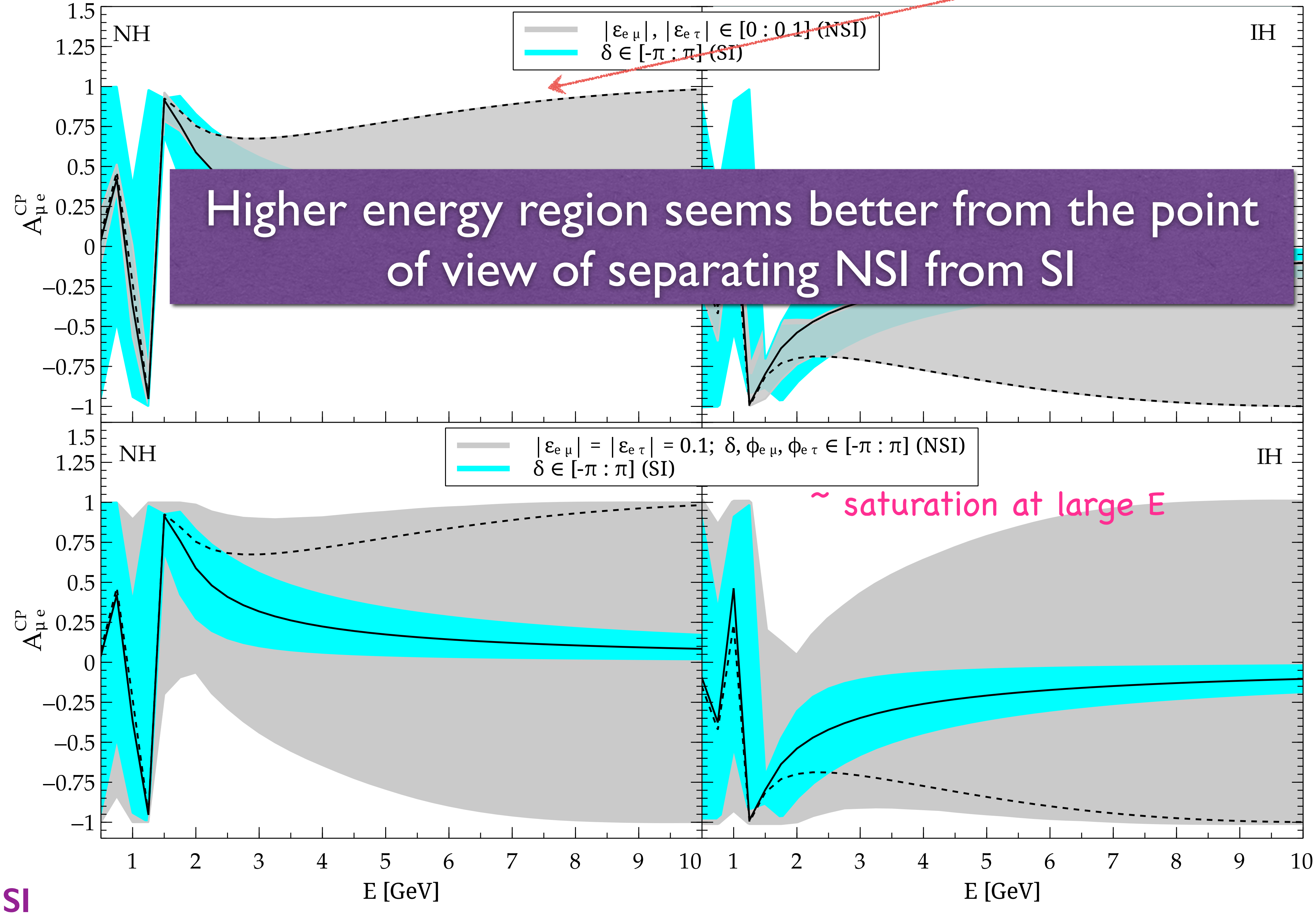
$$\lambda \equiv \frac{\delta m^2_{31}}{2E} \quad ; \quad r_\lambda \equiv \frac{\delta m^2_{21}}{\delta m^2_{31}} \quad ; \quad r_A \equiv \frac{A(x)}{\delta m^2_{31}}\ .$$

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]

Impact of NSI on the CP asymmetry

Large value implies new physics

CP ASYMMETRY



~ saturation at large E

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

- Moduli variation

Either + or -, depending on hierarchy

- Phase variation

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

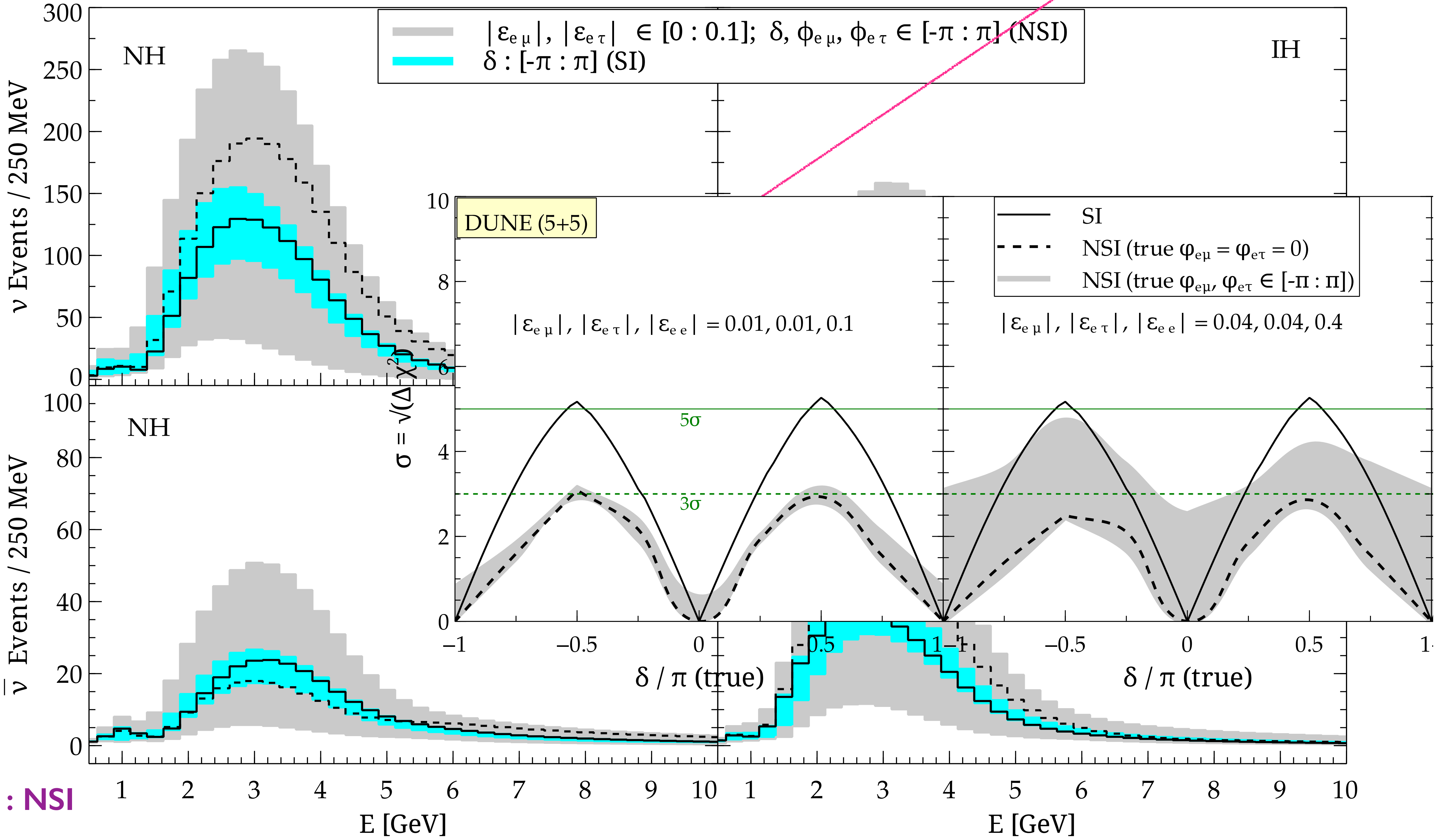
grey : NSI

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 (collective NSI)

EVENT RATES AT DUNE



Falling flux kills the large asymmetry at large E

grey : NSI

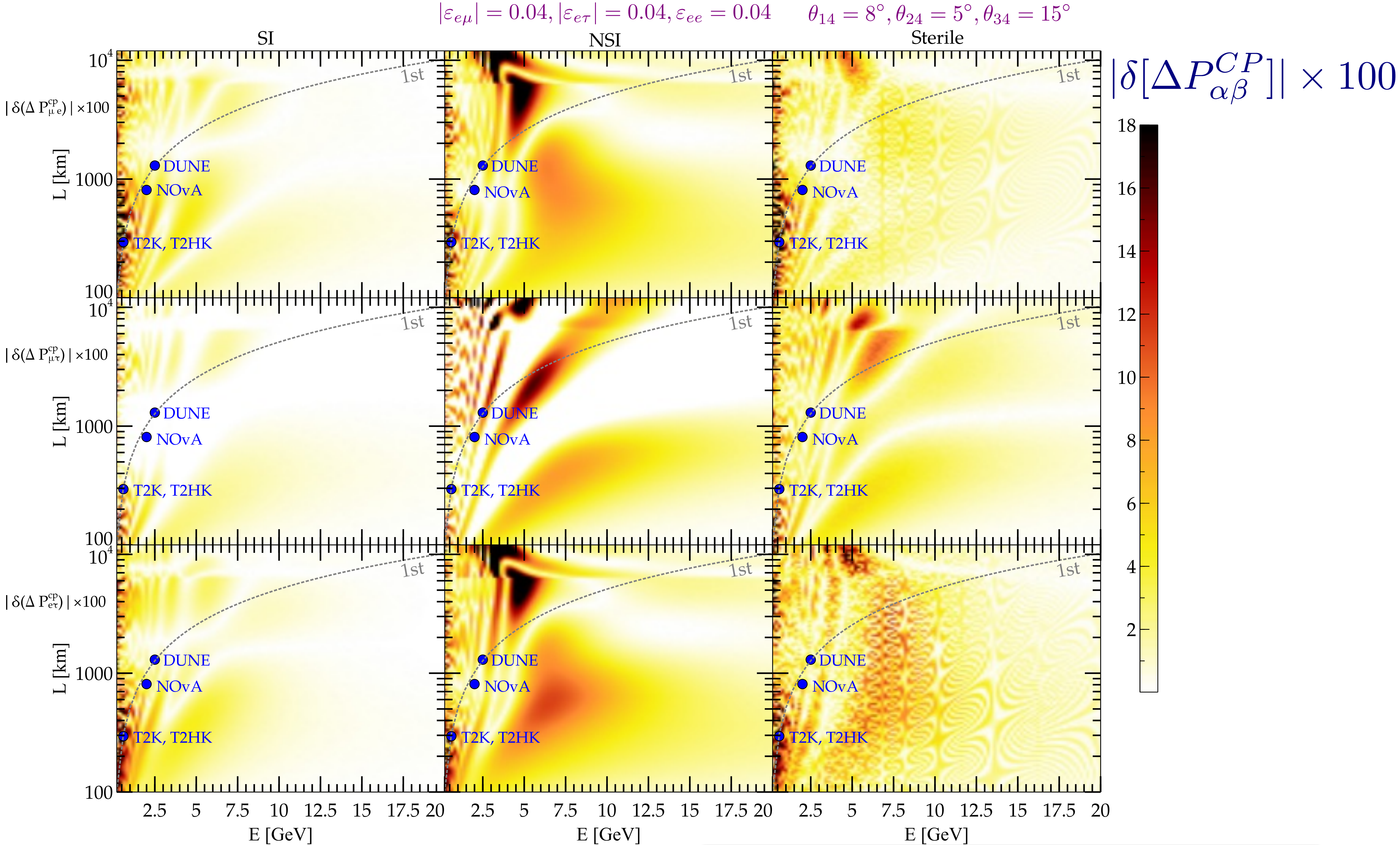
cyan : SI

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]

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

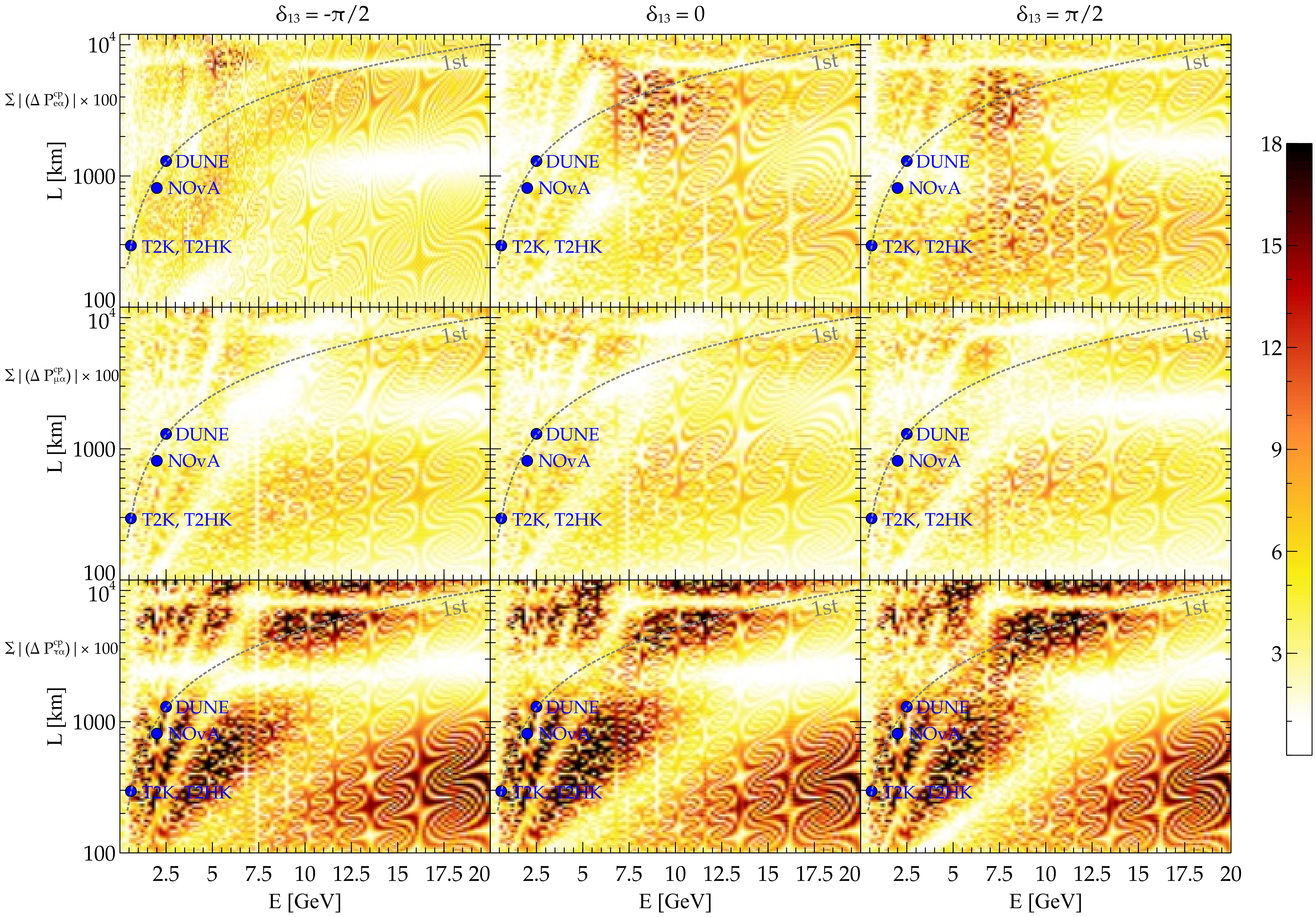
$$\delta[\Delta P^{CP}_{\alpha\beta}] = [\Delta P^{CP}_{\alpha\beta}](\delta_{13} = \pi/2) - [\Delta P^{CP}_{\alpha\beta}](\delta_{13} = 0)$$

Nunokawa, Parke, Valle (2008)

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

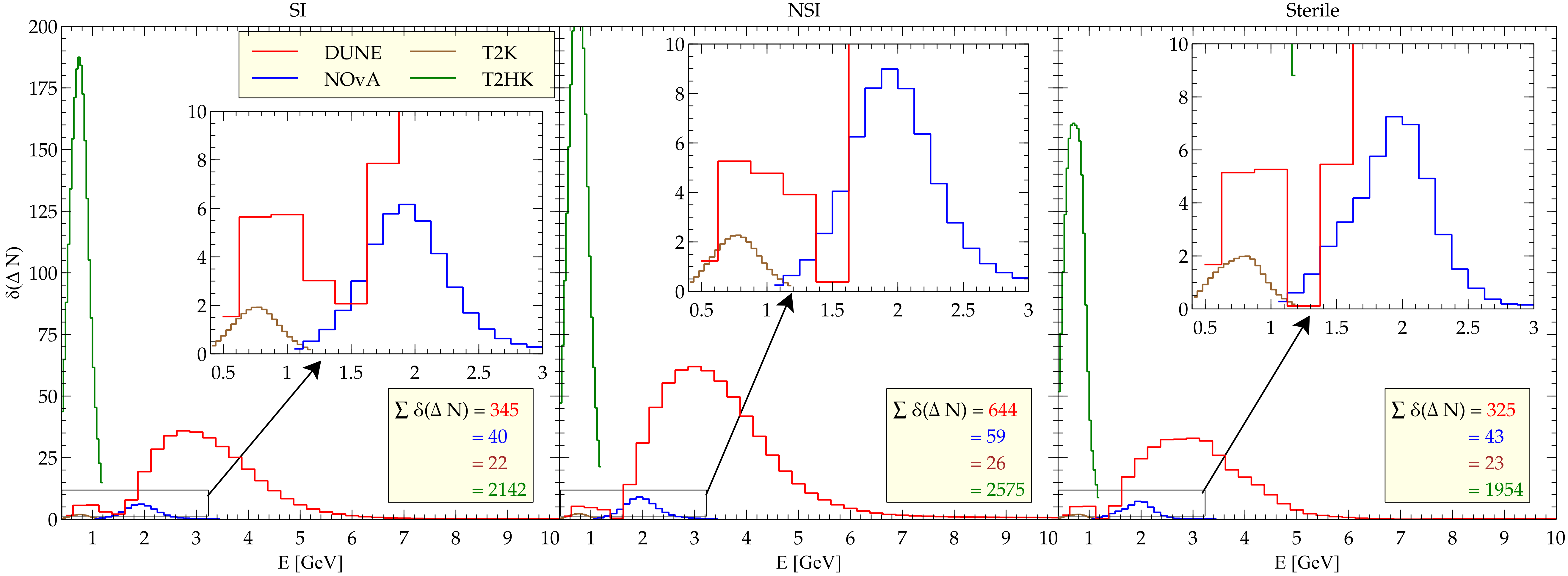
J. Rout, M. Masud and P. Mehta, PRD 95, 075035 (2017) [1702.02163]

Non-unitarity in presence of sterile neutrinos



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

Extracting the intrinsic contribution



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

Jogesh 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"

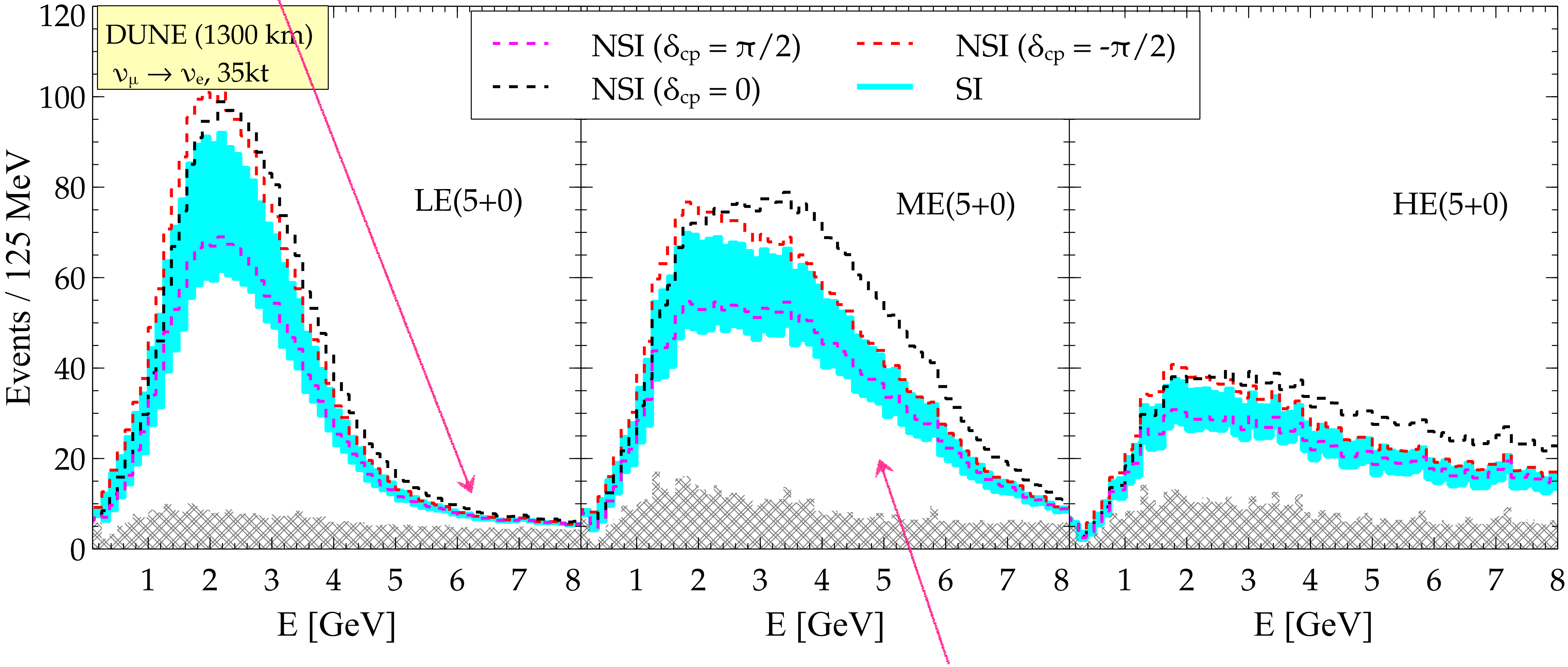
M. Masud, M. Bishai and P. Mehta, 1704.08650 [hep-ph]

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, 1704.08650 [hep-ph]

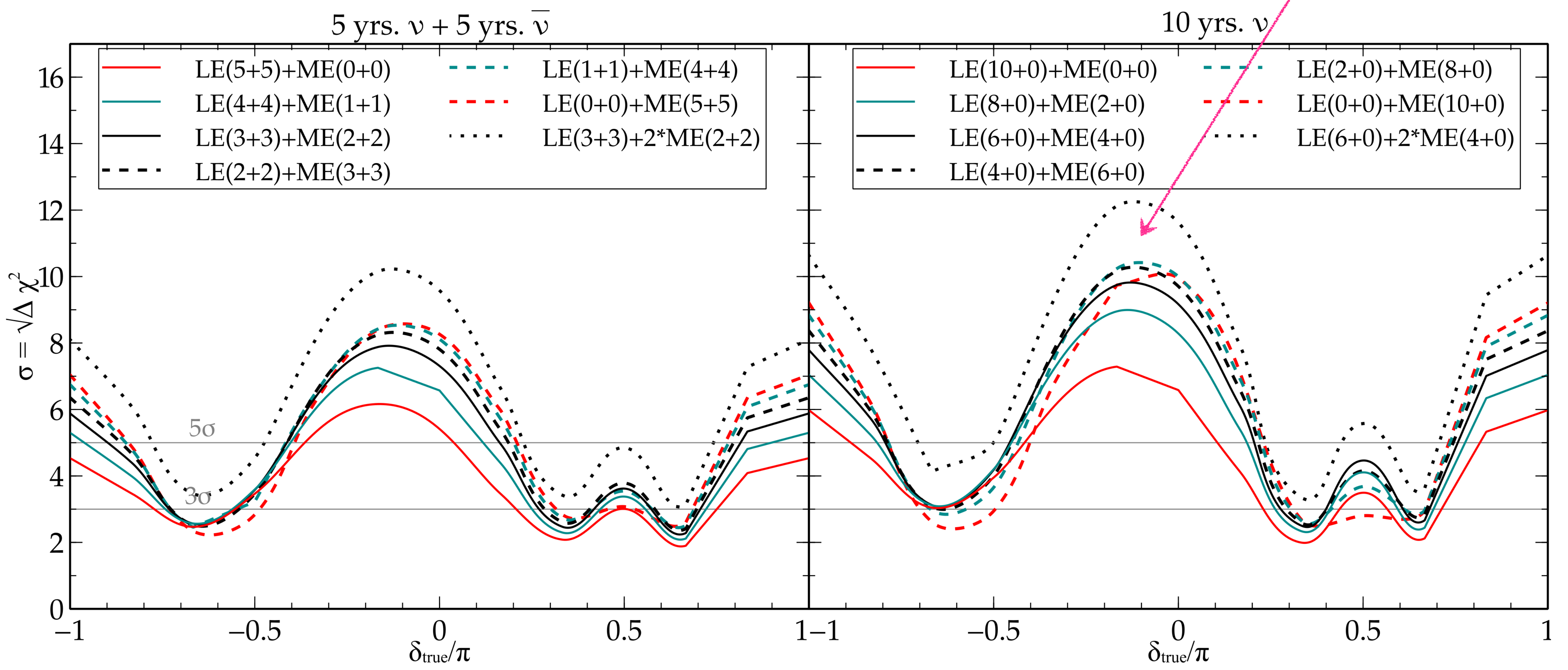
SI-NSI separation at DUNE

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



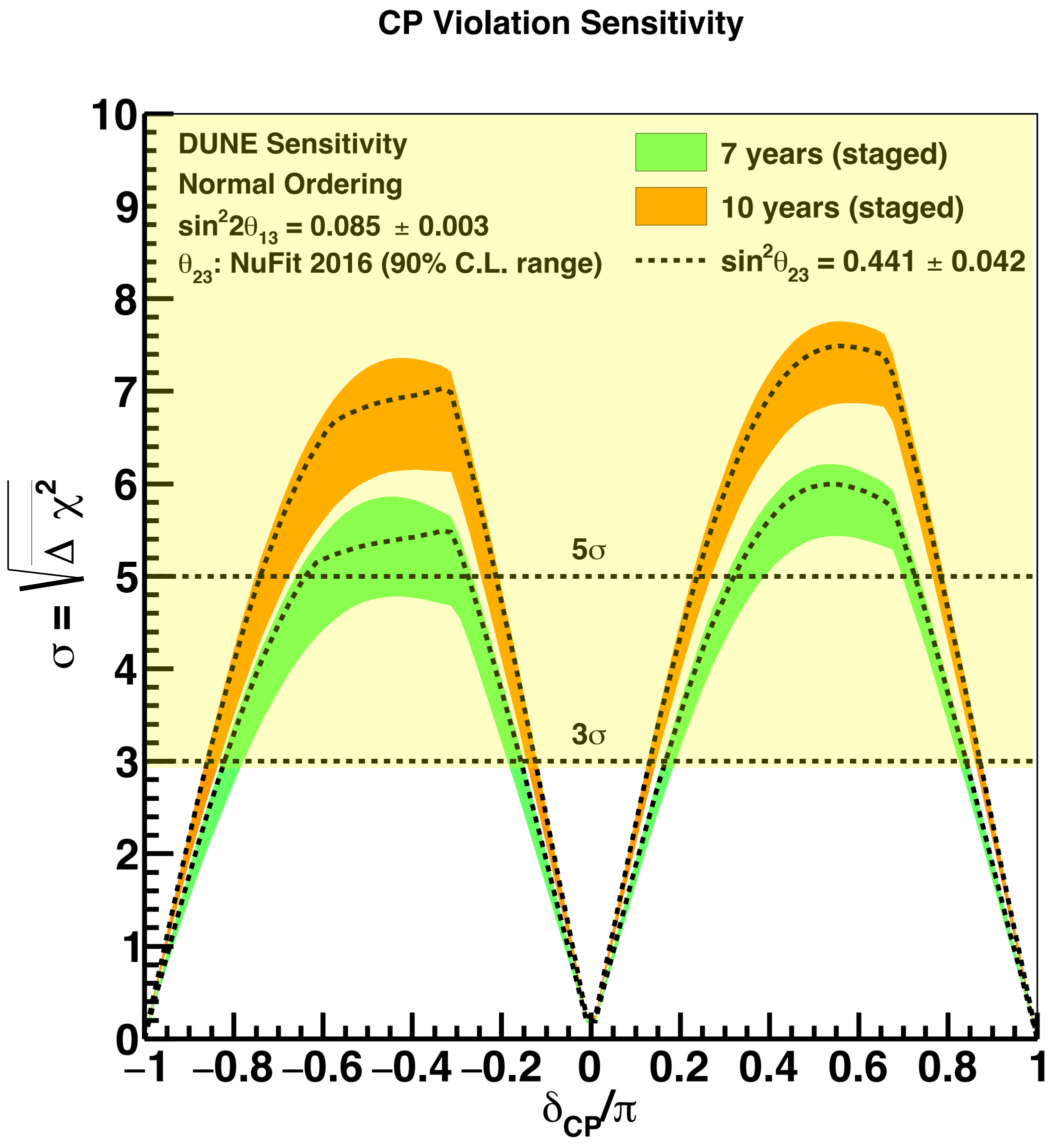
M. Masud, M. Bishai and P. Mehta, 1704.08650 [hep-ph]

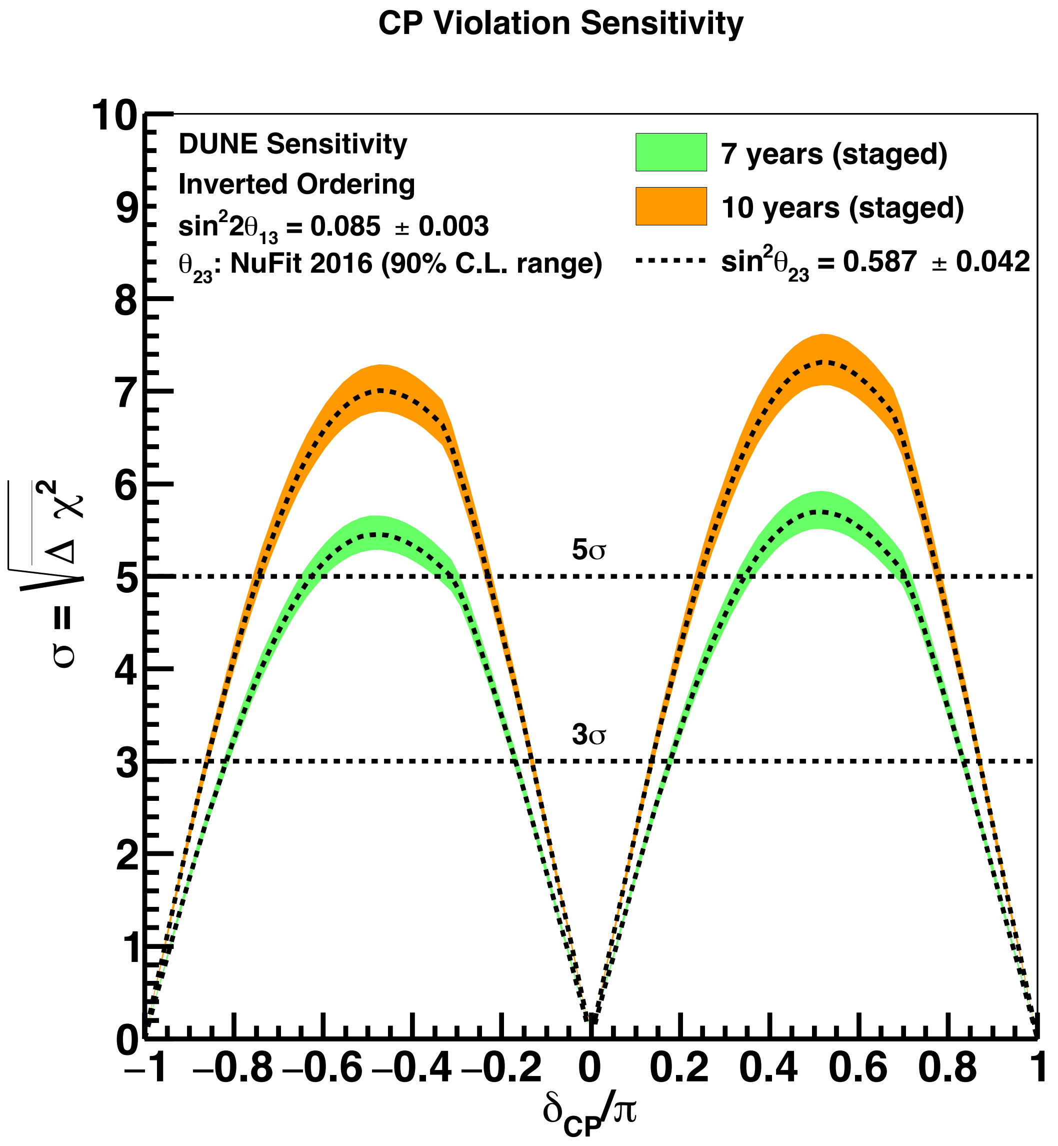
Conclusions

- Small mass and large mixing in neutrino sector… neutrino oscillations act as precise interferometer sensitive to very small perturbations caused by new physics.
- 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

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]