Glimpses of new physics through neutrinos

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Dark Matter as a Portal to New Physics
February 1(Mon.) ~ 5(Fri.), 2021
Online

apctp
아시아태평양이론물리센터
asia pacific center for theoretical physics

Plan of the talk

- Basics of oscillation physics and pending issues
- Hint for a light (eV) sterile neutrino
- Non-Standard Neutrino Interaction (NSI)
- Other BSM options (Dark sector?)
- Summary

standard oscillation probability

- $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\, |\nu_k\rangle \;\; (\alpha = e, \mu, \tau)$ ← *Flavor & Mass related by mixing*
- $H\,|\nu_k\rangle = E_k\,|\nu_k\rangle$

← *Solve Schrodinger's eqn.*

- $i\frac{d}{dt}\,|\nu_k(t)\rangle = H\,|\nu_k(t)\rangle$
- $P_{\alpha\beta}(L, E) = |\,\langle\nu_\beta|\nu_\alpha(x)\rangle\,|^2$
  $= \delta_{\alpha\beta} - 4\sum_{k>j} Re[U^*_{\alpha k}U^*_{\beta j}U_{\beta k}U_{\alpha j}]\sin^2\Delta_{kj}$
  $+ \sum_{k>j} Im[U^*_{\alpha k}U^*_{\beta j}U_{\beta k}U_{\alpha j}]\sin 2\Delta_{kj},$

  (where, $\Delta_{ij} = 1.27 \times \frac{\Delta m^2_{ij}[\mathrm{eV}^2]\times L[km]}{E[GeV]}$)

- Parameters responsible for neutrino oscillation:
  $\theta_{13}, \theta_{12}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{31}, \delta_{cp}$

Status of oscillation parameters

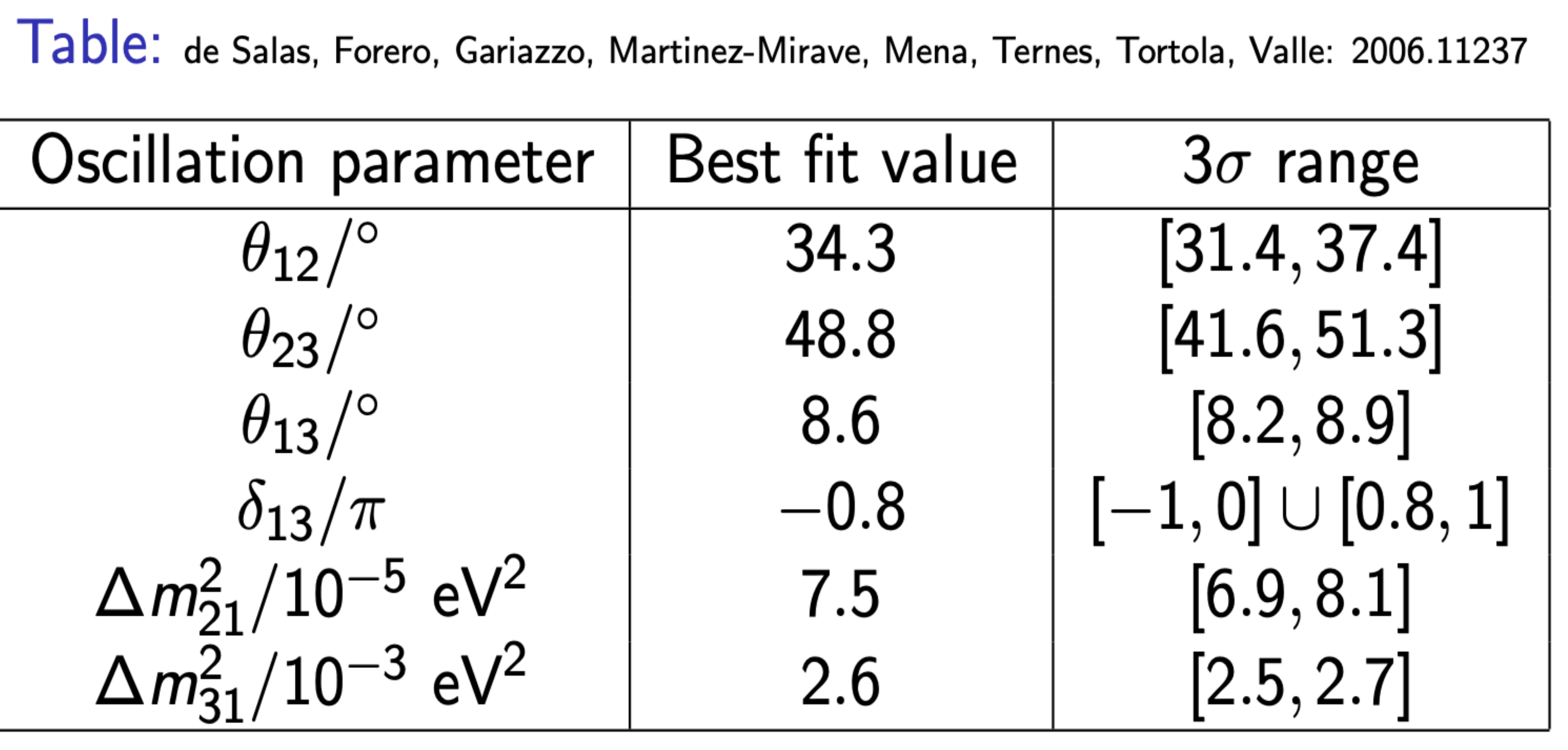

Table: de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle: 2006.11237

Oscillation parameter	Best fit value	3σ range
$\theta_{12}/^\circ$	34.3	$[31.4, 37.4]$
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δ_{13}/π	-0.8	$[-1, 0] \cup [0.8, 1]$
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3 mixing angles

1 CP phase

2 mass squared differences

$$\begin{aligned} P_{\mu e} &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} \\ &+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A} \\ &+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta+\Delta) \end{aligned}$$

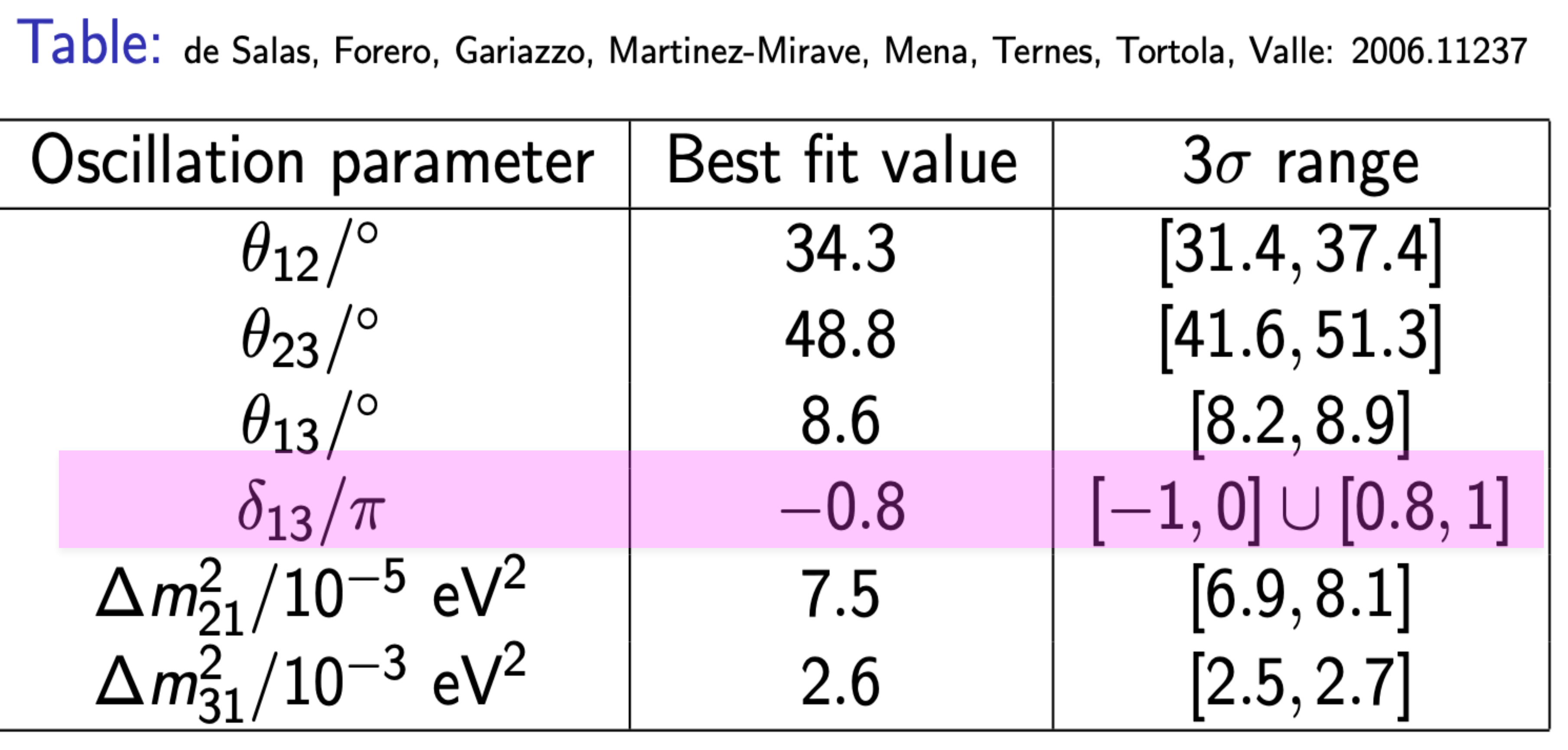
where,

$$A = \frac{2\sqrt{2} E G_F n_E}{\Delta m^2_{31}}$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Leptonic CP violation?



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Is the CP phase non-zero?

could help explain baryon asymmetry

$$\begin{aligned} P_{\mu e} \quad = \quad & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} \\ + \quad & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A} \\ + \quad & \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta) \end{aligned}$$

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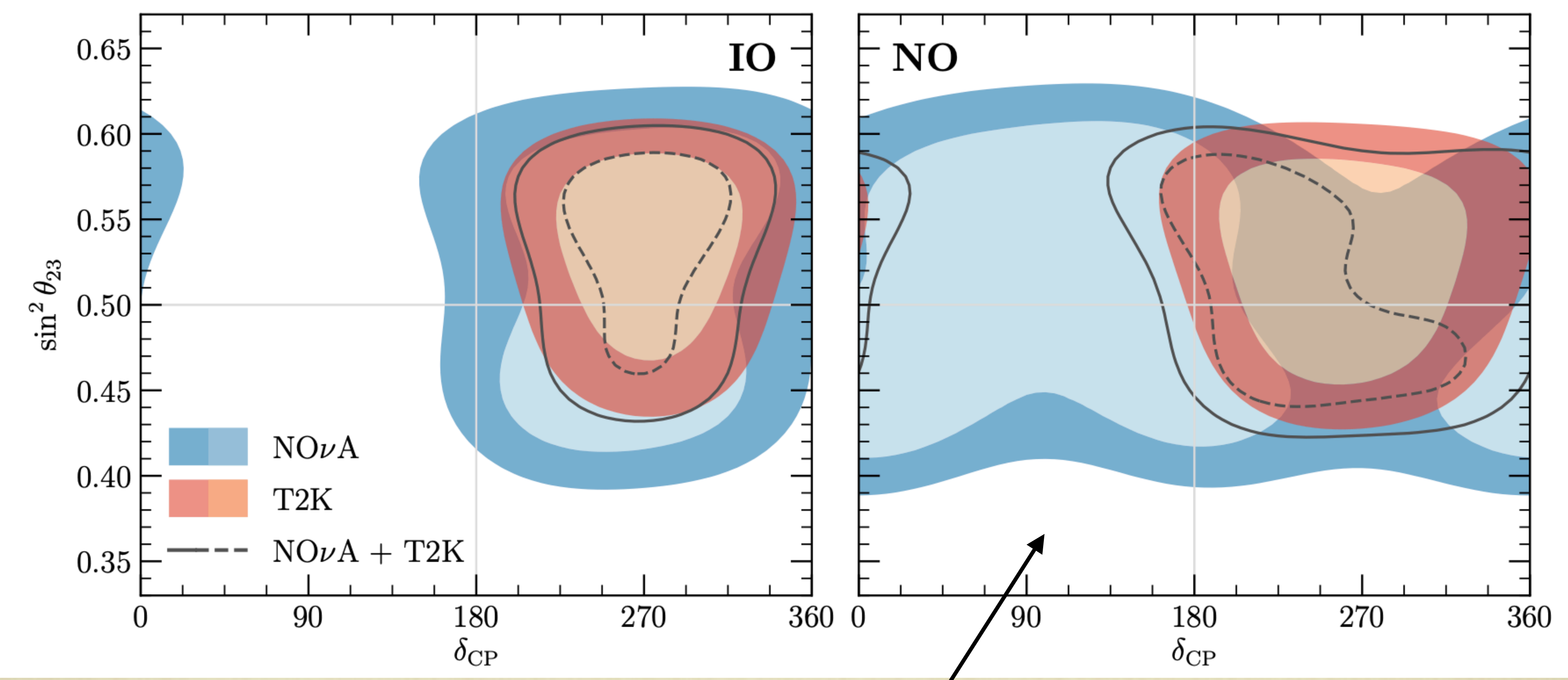
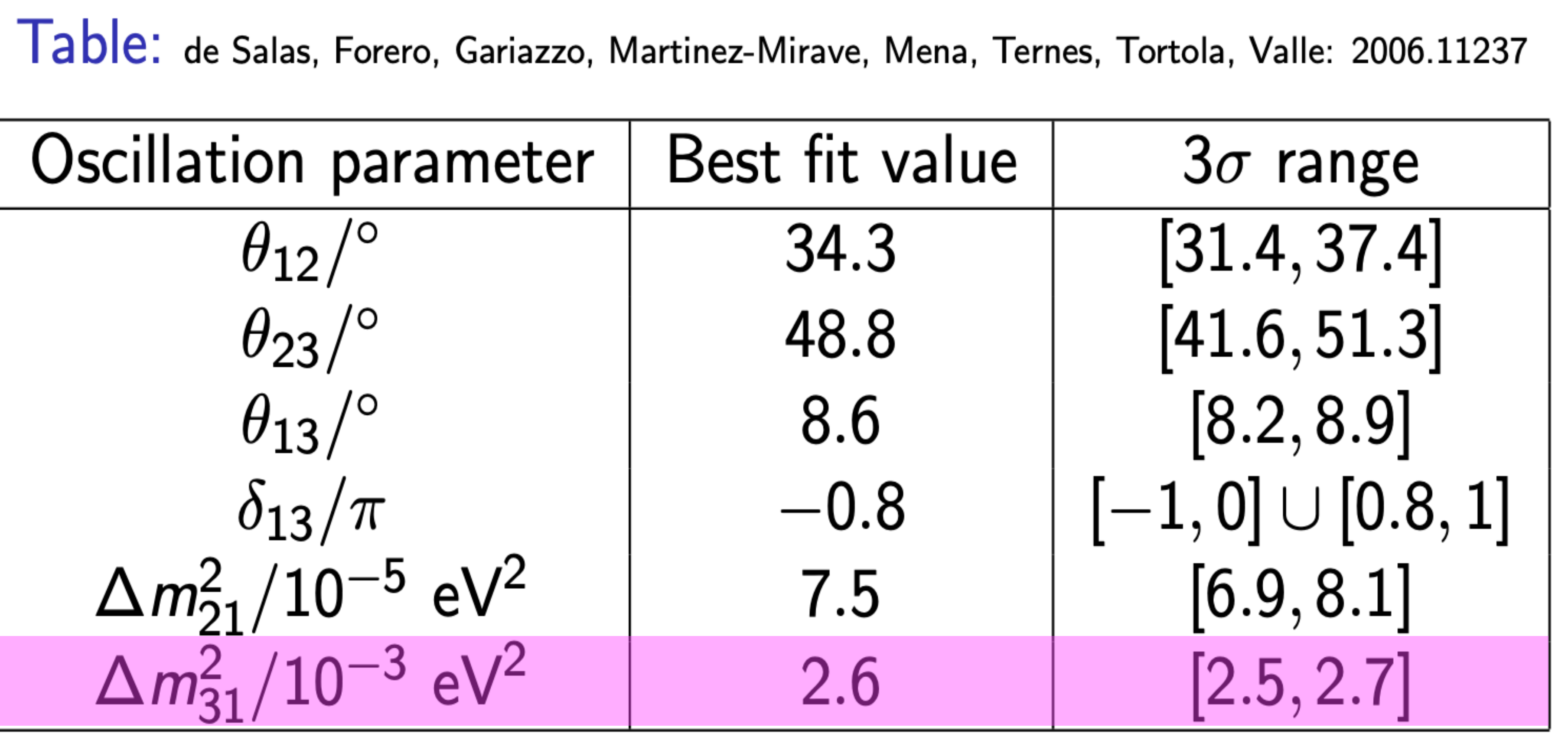
Leptonic CP violation (Tension between NOvA & T2K)



Tension () between allowed regions in $\delta_{13} - \sin^2\theta_{23}$ plane by NOvA and T2K (for NO)

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou : 2007.14792

Mass ordering ambiguity



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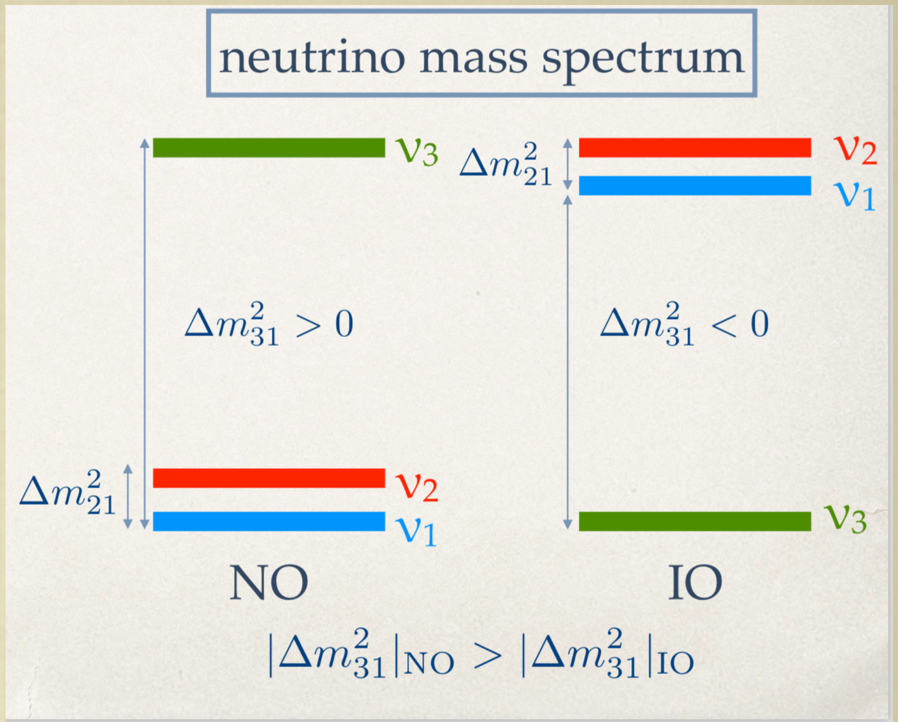

What is the sign of Δm^2_{31} ?

$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{1-A}$$

$$+ \quad \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A}$$

$$+ \quad \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta+\Delta)$$

where,

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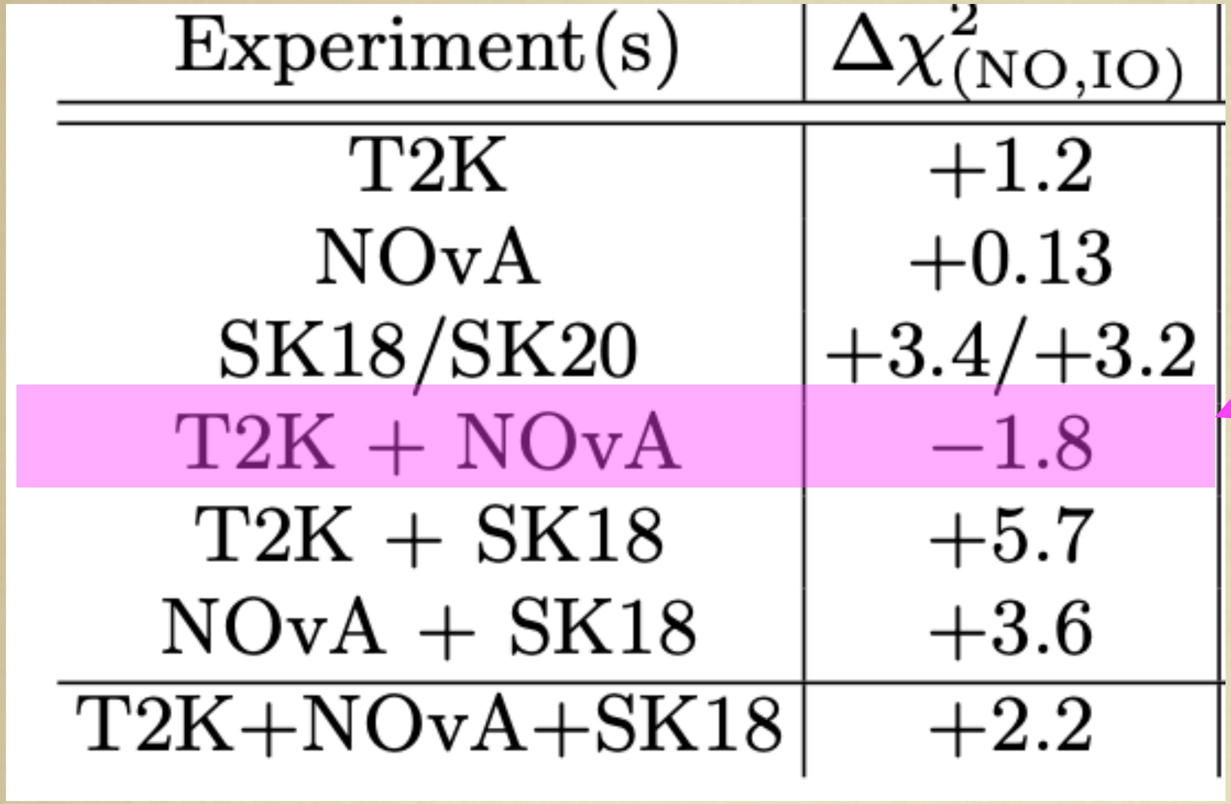
Mass ordering ambiguity (Tension between NOvA & T2K)

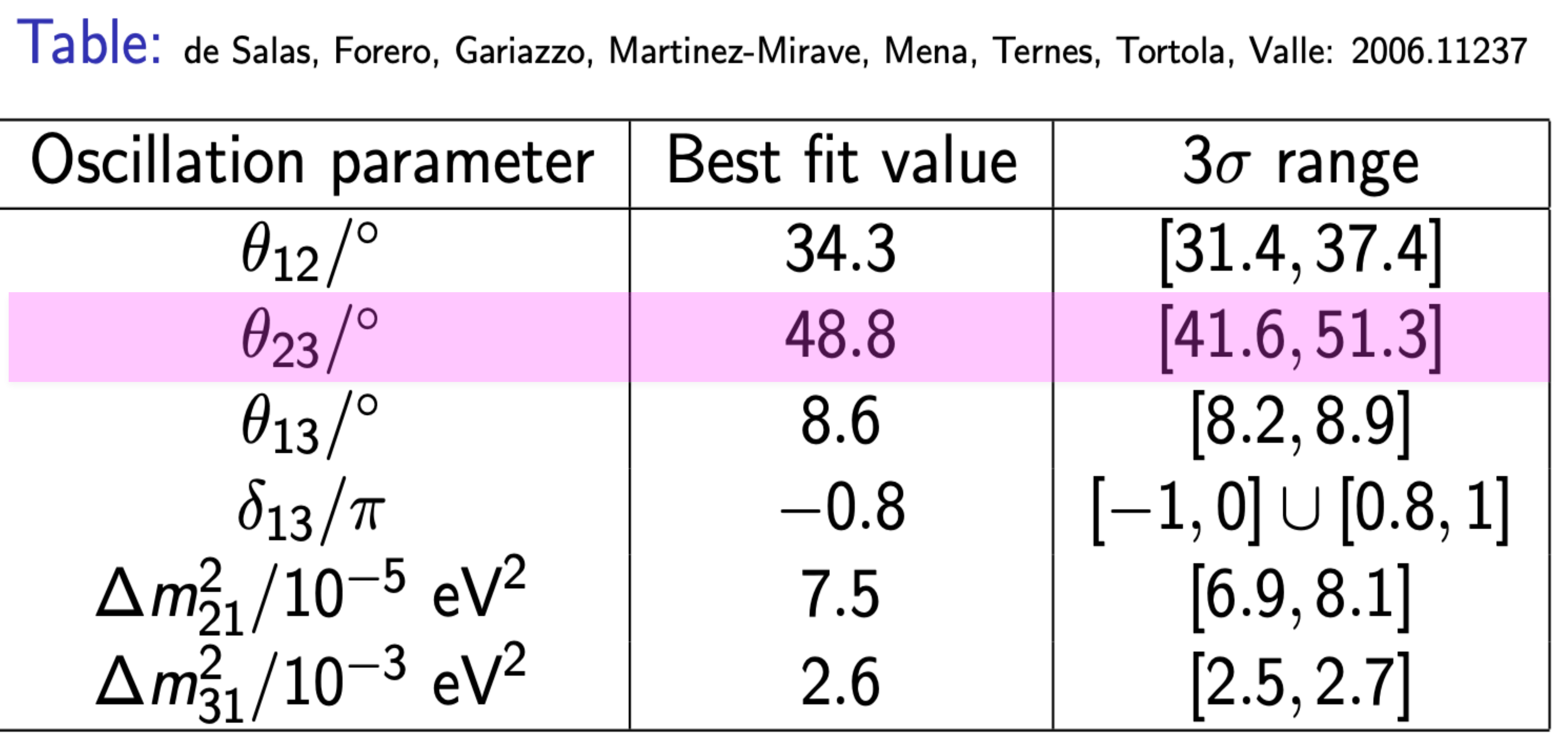


Experiment(s)	$\Delta\chi^2_{(\mathrm{NO,IO})}$
T2K	$+1.2$
NOvA	$+0.13$
SK18/SK20	$+3.4/+3.2$
T2K + NOvA	-1.8
T2K + SK18	$+5.7$
NOvA + SK18	$+3.6$
T2K+NOvA+SK18	$+2.2$

Tension happens because they prefer different value of δ_{13}

Kelly, Machado, Parke, Perez-Gonzalez, Funchal : 2007.08526

Octant degeneracy



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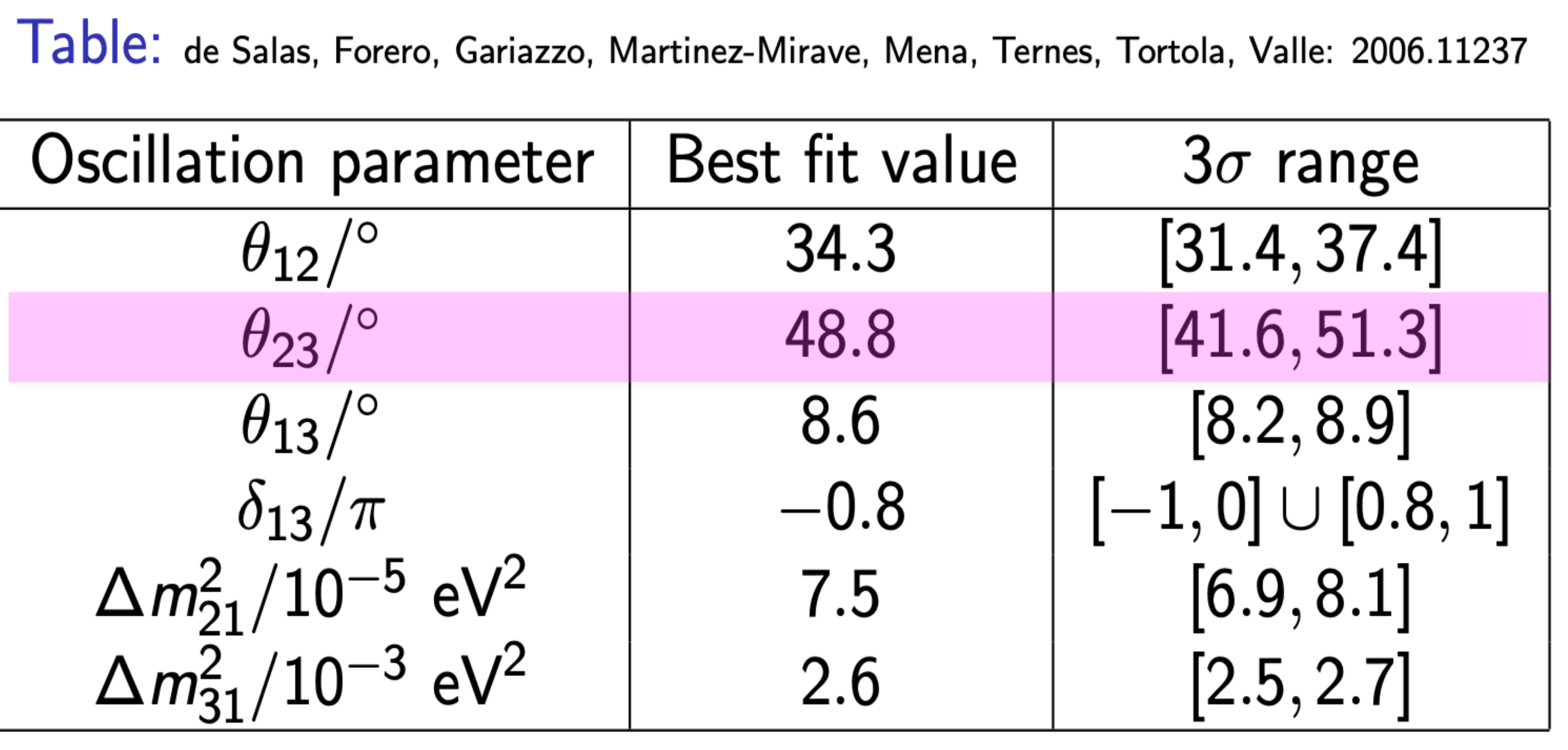
$\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$?

$$
\begin{aligned}
P_{\mu e} &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} \\
&+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A} \\
&+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \boxed{\sin 2\theta_{23}} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta)
\end{aligned}
$$

$$\boxed{\sin 2\theta_{23} = \sin 2(\pi/2 - \theta_{23})}$$

Octant degeneracy



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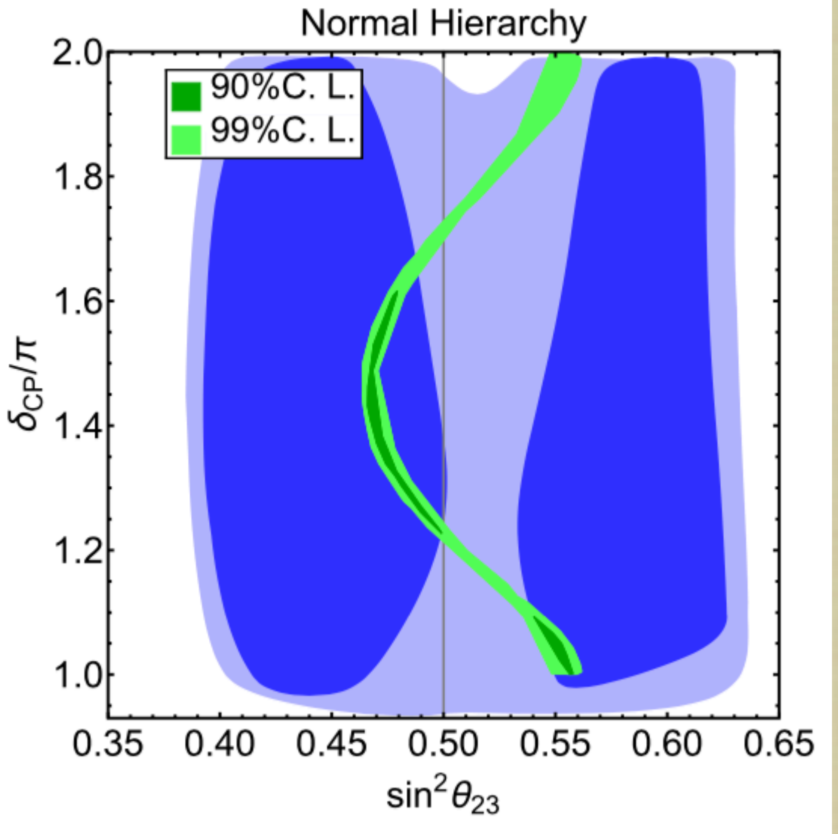


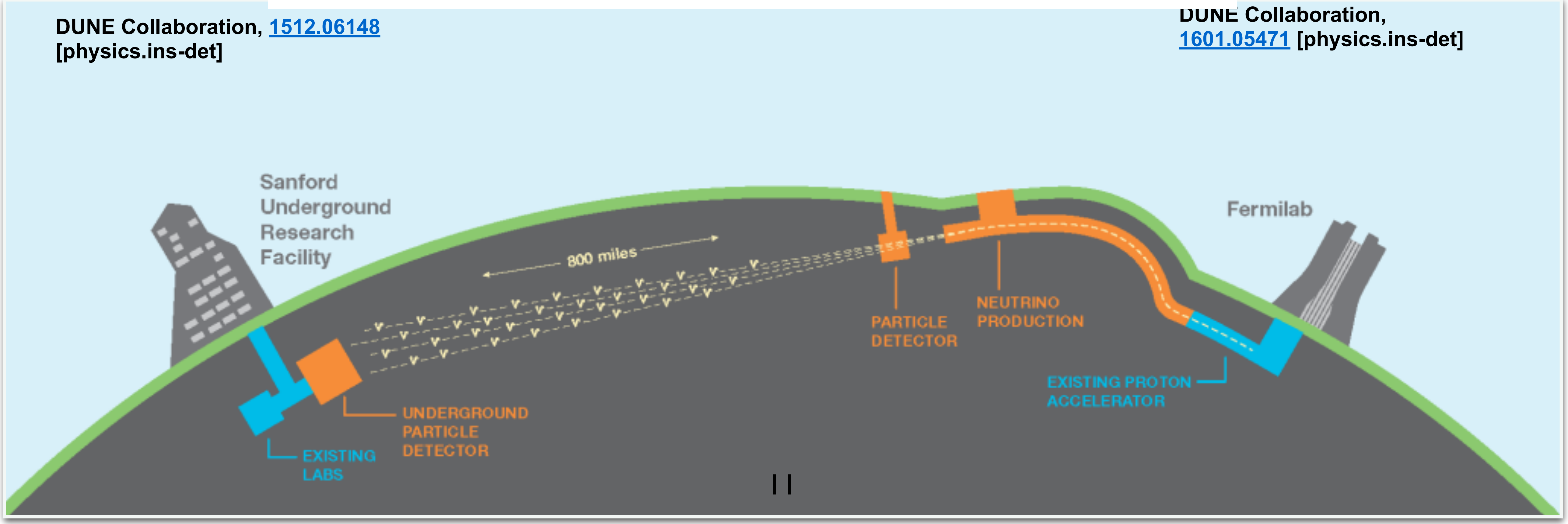
Chatterjee, MM, Pasquini, Valle (2017)

$$
\begin{aligned}
P_{\mu e} &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} \\
&+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2 A\Delta}{A} \\
&+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta)
\end{aligned}
$$

$$\sin 2\theta_{23} = \sin 2(\pi/2 - \theta_{23})$$

Deep Underground Neutrino Experiment (DUNE)

- A proposed long baseline experiment (the erstwhile LBNE) with 1300 km baseline
- likely to have a 40 kt FD with 3.5 yrs. of ν and 3.5 yrs. of $\bar{\nu}$ run.
- The incident ν_μ beam is generated by 80 GeV proton beam delivered at 1.07 MW with a POT of 1.47×10^{21}
- Total exposure : 300 kt-MW-yr.



DUNE Collaboration, 1512.06148 [physics.ins-det]

DUNE Collaboration, 1601.05471 [physics.ins-det]

Plan of the talk

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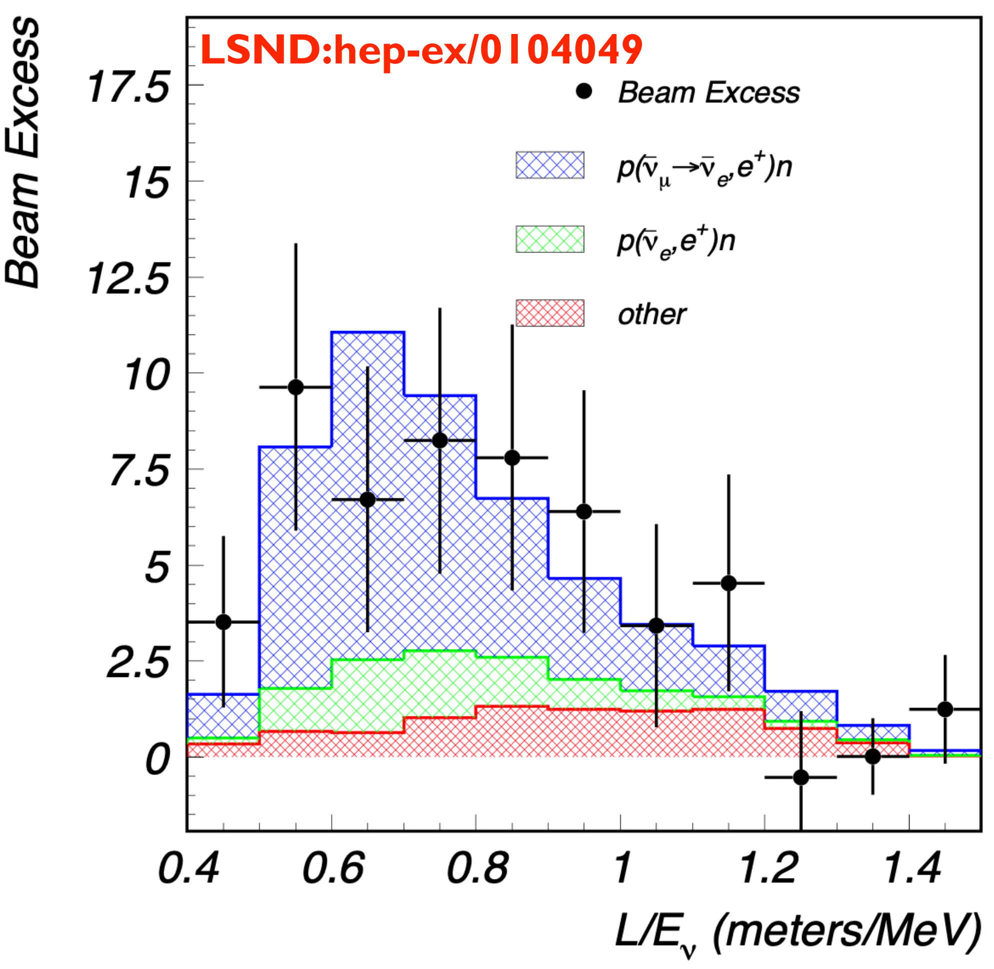
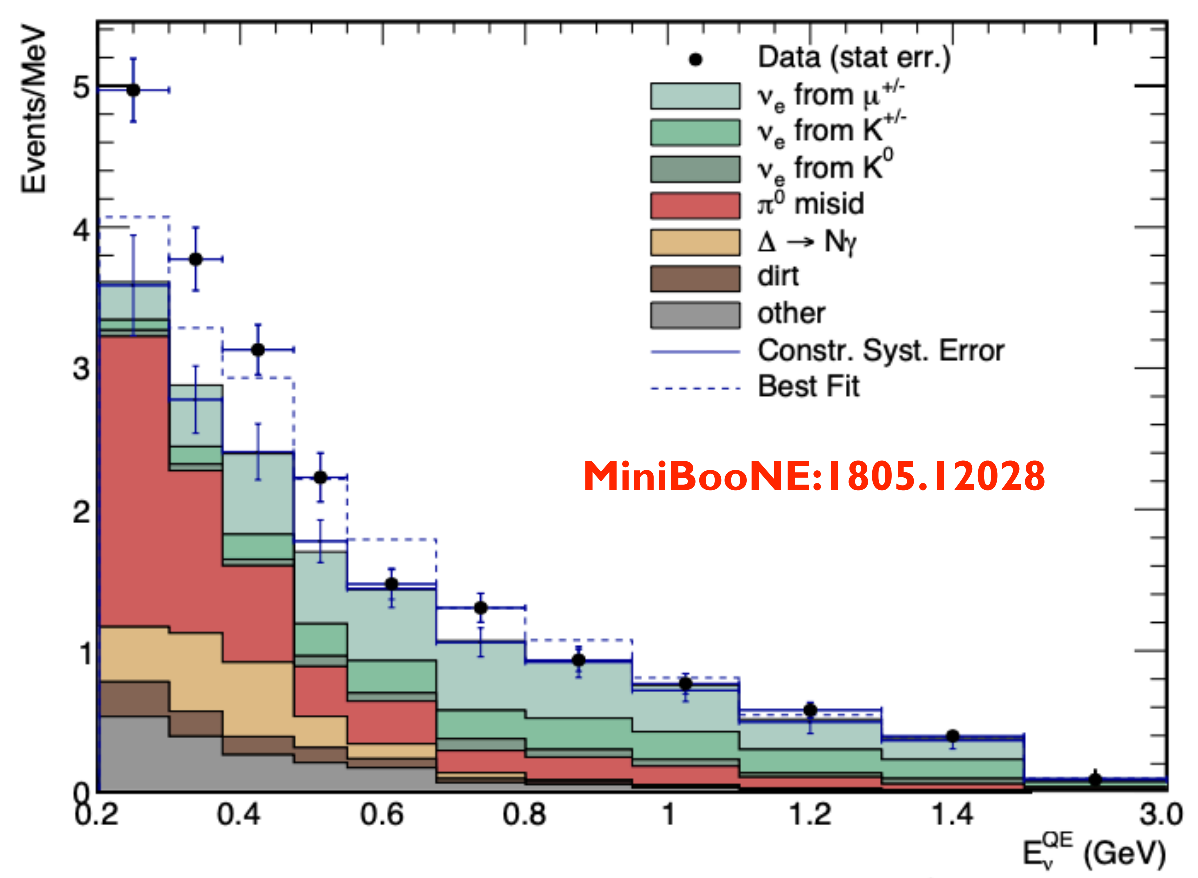
Hint for new physics?





VERY intense proton beam

$$p + X \to \pi^+ + X'$$

(800 MeV)

$$\hookrightarrow \mu^+ \nu_\mu \text{ (DAR)}$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

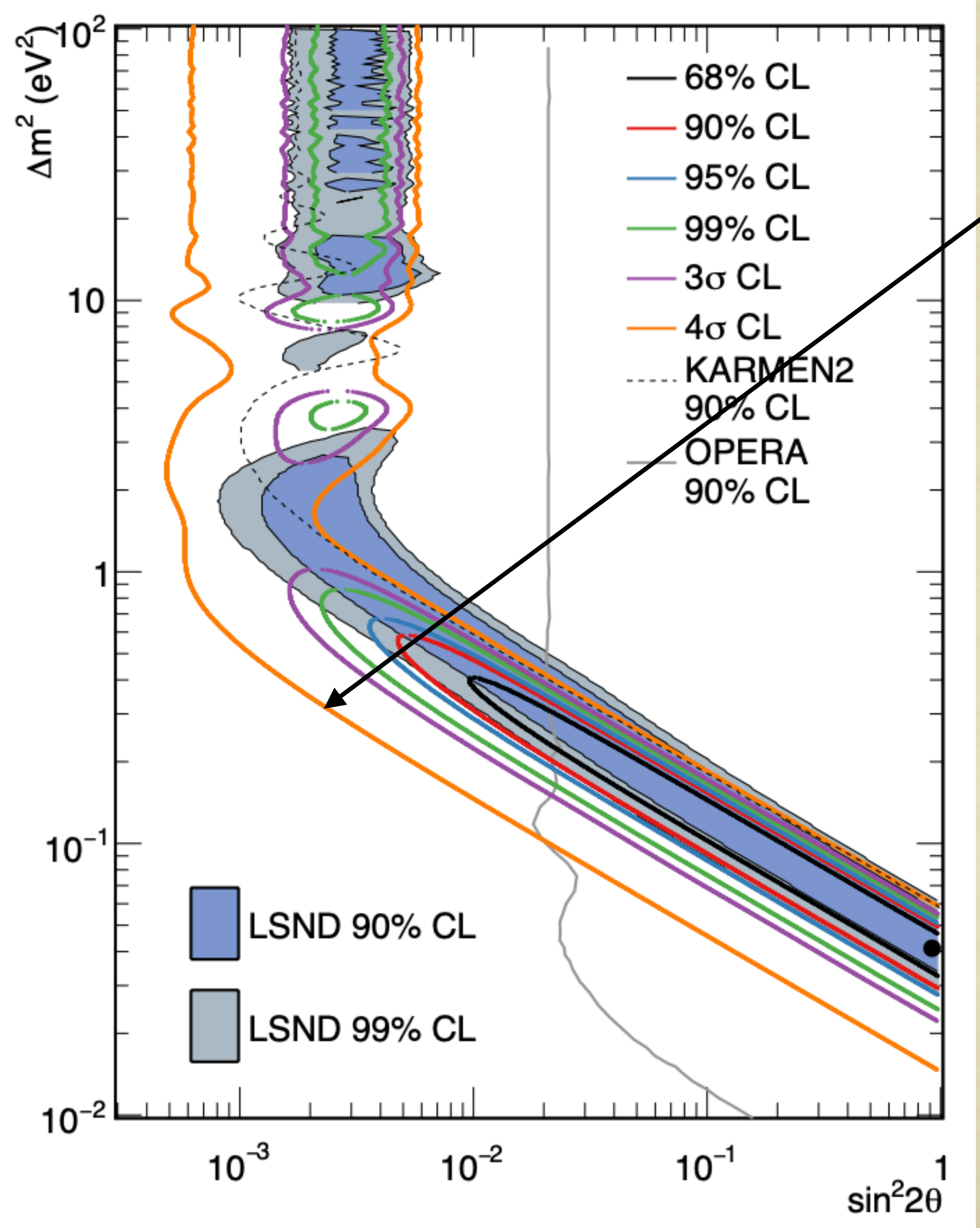
Detection signature:
IBD ($\bar{\nu}_e\, p \to e^+ n$)

LSND detected more $\bar{\nu}_e$ than expected: 87.9 ± 23.2 events (3.8σ excess)

Measures $\nu_\mu \to \nu_e$ osc.

Event excess: 381.2 ± 85.2 (4.5σ)

Hint for new physics?



MiniBooNE:1805.12028

4σ by MiniBooNE

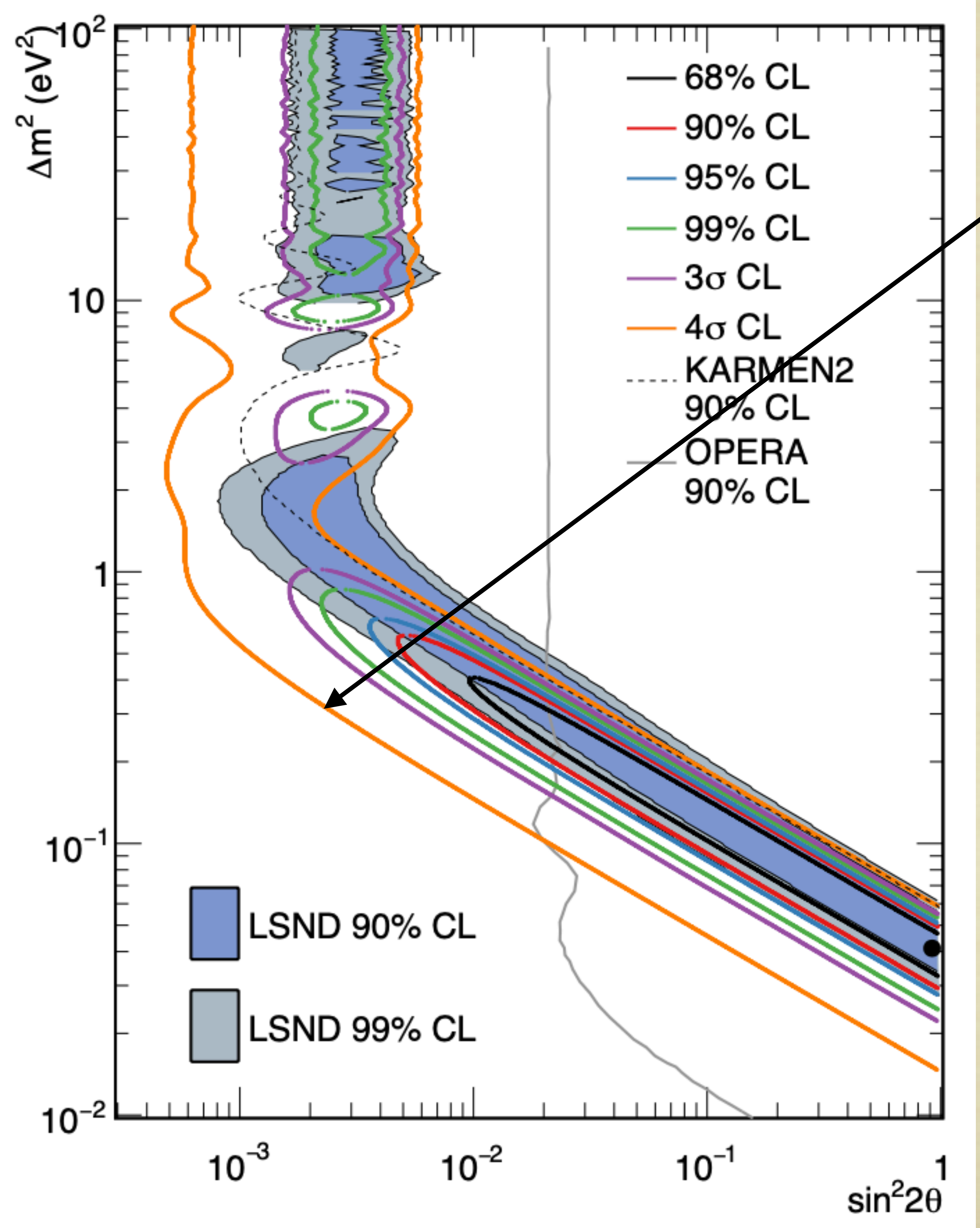
MB + LSND $\sim 6\sigma$ excess

- Light sterile ν

👍 DANSS, Neutrino-4

👎 Icecube, Cosmology

Hint for new physics?



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Stay tuned for Fermilab SBN

- Light sterile ν

…NSS, Neutrino-4

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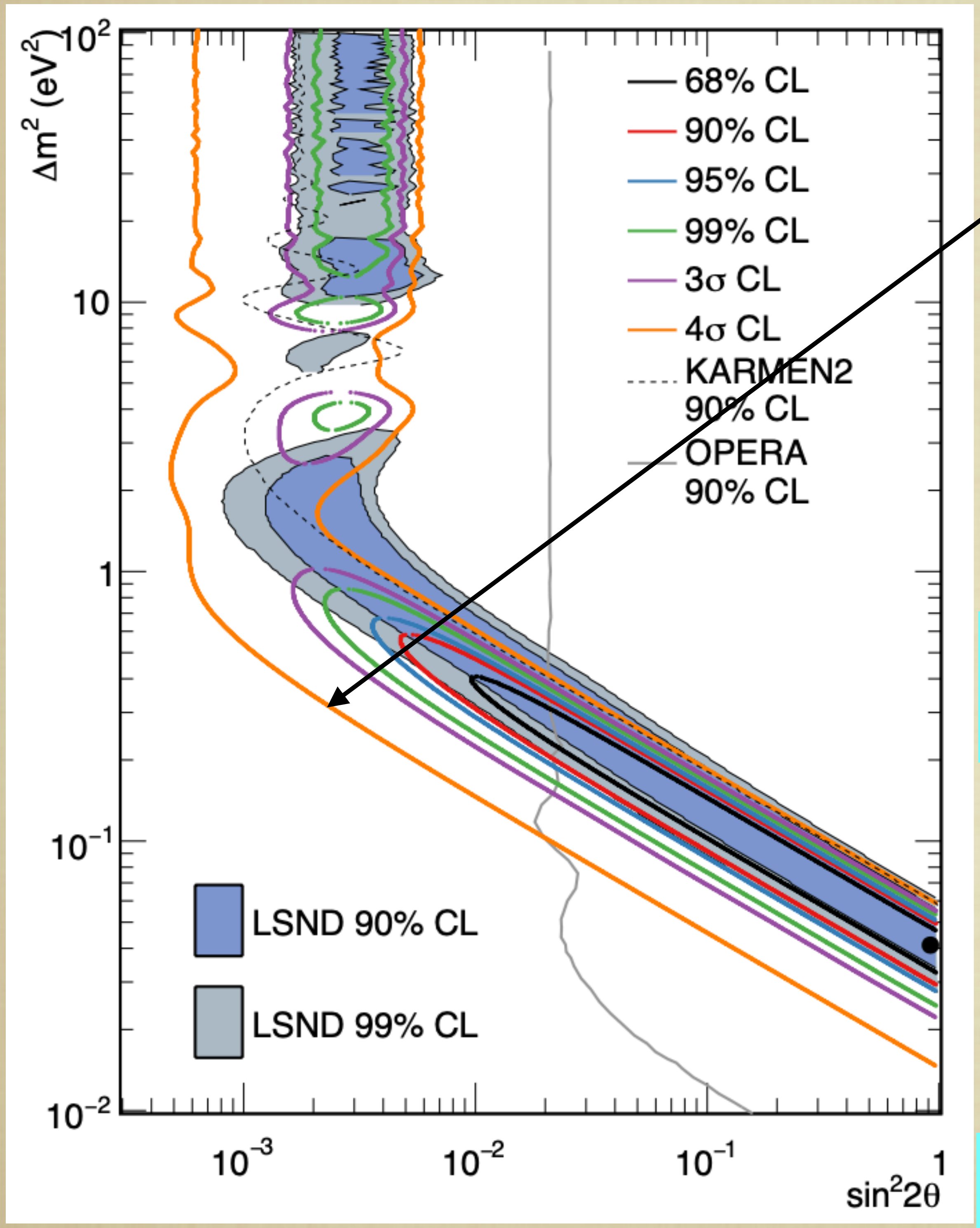

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- Light sterile ν

NSS, Neutrino-4

👎 Icecube, Cosmology

- Decay of heavy sterile ν

Dentler, Esteban, Kopp, Machado: 1911.01427

Ballett, Pascoli, Ross-Lonergan: 1808.02915

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- The Dark Sector

Bertuzzo, Jana, Machado, Funchal: 1807.09877

Abdallah, Gandhi, Roy: 2006.01948

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- ??

Light sterile neutrino (3+1) & oscillation phenomenology

Gandhi, Kayser, MM,Prakash : JHEP (2015)

Agarwalla, Chatterjee, Palazzo : JHEP (2016)

Giunti : NPB (2016)

Coloma, Forero, Parke : JHEP (2018)

……

3+1 case :basics

$$P_{\alpha\beta} = \delta_{\alpha\beta} - \sum_{k>j} \text{Re}[U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} U_{\beta k}] \sin^2 \Delta_{kj} - \sum_{k>j} \text{Im}[U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} U_{\beta k}] \sin 2\Delta_{kj}$$

$$\text{where } \Delta_{ij} = 1.27 \times \frac{\Delta m^2_{ij}[\text{eV}^2] \times L[\text{km}]}{E[\text{GeV}]}$$

- 3 more mixing angles and 2 additional CP phases
- Unitarity in 4x4 sector : $\sum_{k=1,2,3,4} U_{\alpha k} U^*_{\beta k} = \delta_{\alpha\beta}$
- $\Delta m^2_{41} \sim 1\ \text{eV}^2, \Delta m^2_{21} \approx 7.5 \times 10^{-5}\ \text{eV}^2, \Delta m^2_{31} \approx 2.5 \times 10^{-3}\ \text{eV}^2$

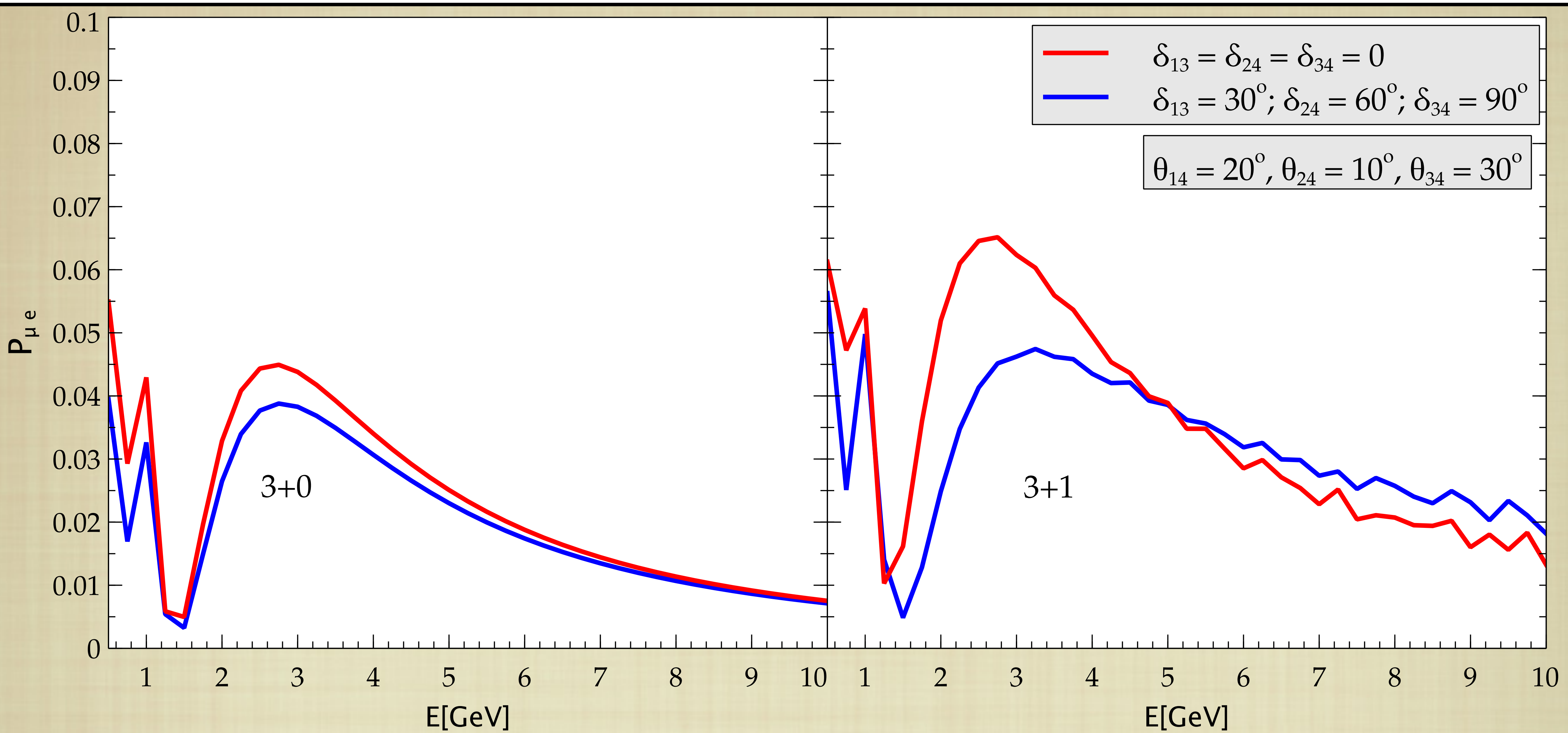
$$\Delta m^2_{41} \approx \Delta m^2_{42} \approx \Delta m^2_{43} >> \Delta m^2_{31} >> \Delta m^2_{21}$$

$$P_{\alpha\beta} \approx P^{3+0}_{\alpha\beta} + |U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \Delta_{41} \quad (\alpha \neq \beta)$$ Excess

$$P_{\alpha\alpha} \approx P^{3+0}_{\alpha\alpha} - |U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \sin^2 \Delta_{41}$$ Dip

Gandhi, Kayser, MM,Prakash : JHEP (2015)

3+1 case: Effect on probability



- Significant modification of vacuum probability for both CP conserving and CP violating case

Gandhi, Kayser, MM,Prakash (2015)

3+1 case :Global analysis

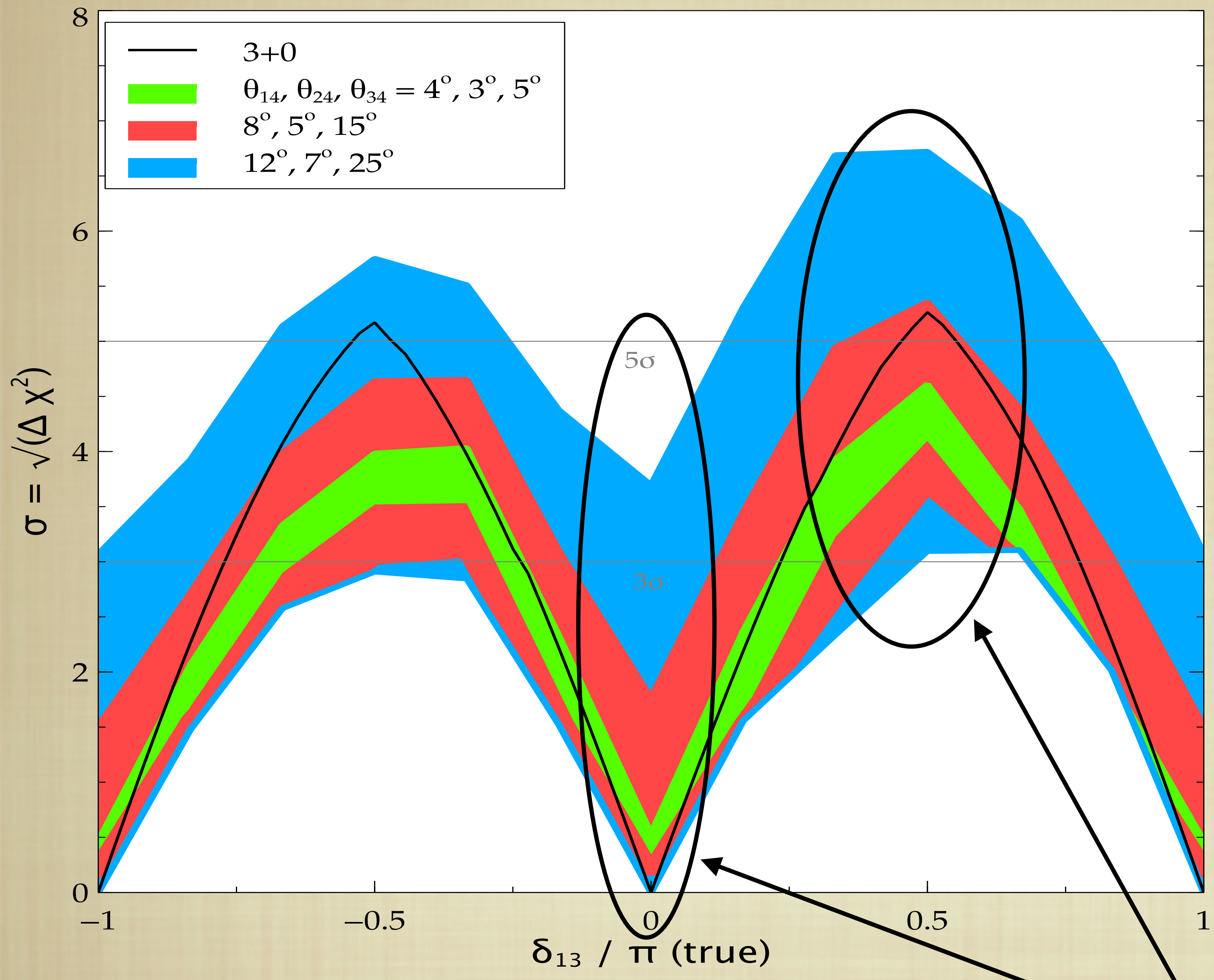
$$|U_{e4}|^2 \lesssim 0.1, \quad |U_{\mu 4}|^2 \lesssim 0.01, \quad |U_{\tau 4}|^2 \lesssim 0.17$$

$$\theta_{14} \lesssim 18.4^\circ, \quad \theta_{24} \lesssim 6.05^\circ, \quad \theta_{34} \lesssim 25.6^\circ$$

Phases are unconstrained

Dentler, Kopp, Harnandez, Machado, Maltoni, Martinez-Soler, Schwetz (2018)

3+1 case: Impact on CPV sensitivity

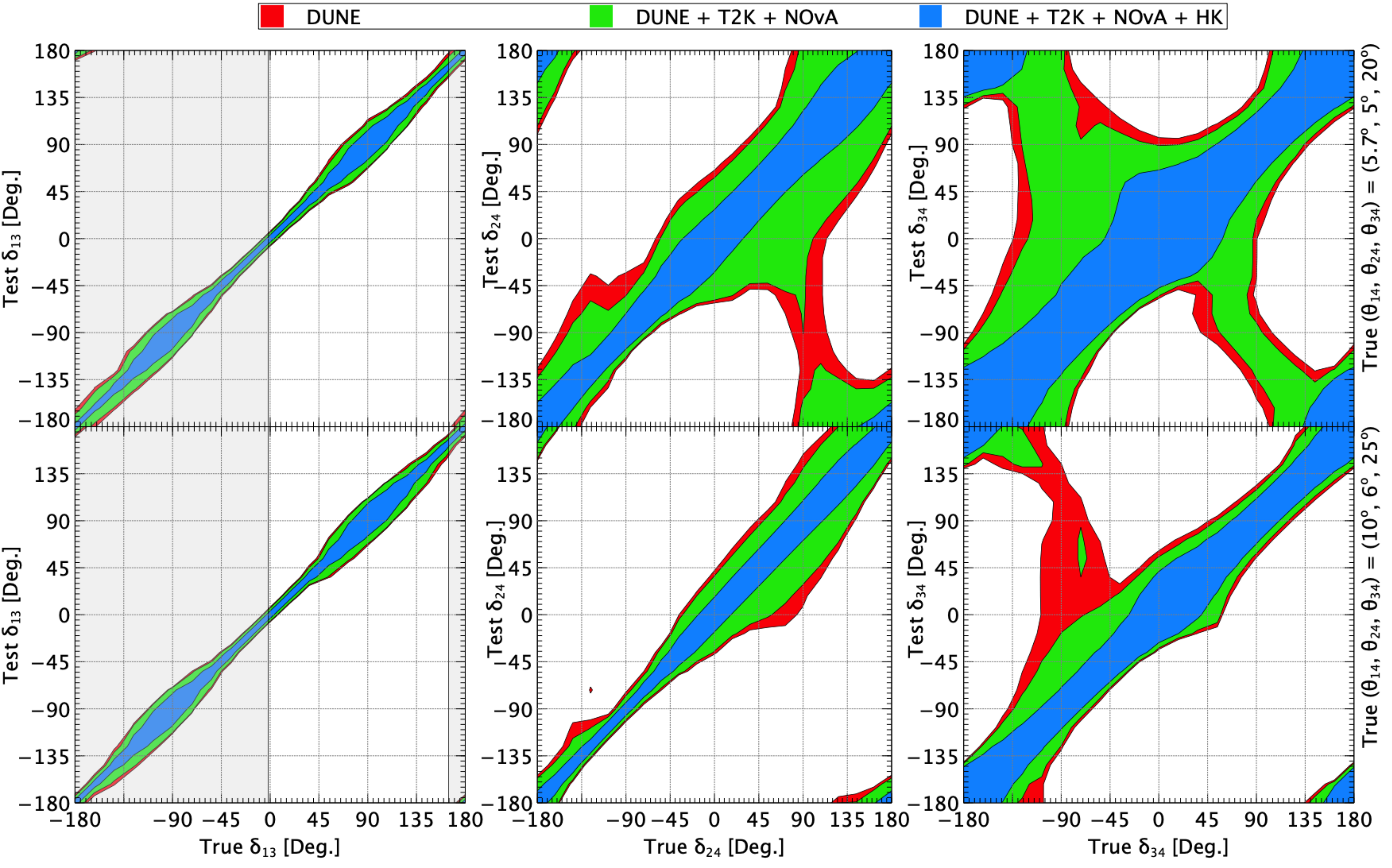


- Fitted with, $\delta_{13}, \delta_{24}, \delta_{34} = 0$ or π
- The band shows the variation in data for $\delta_{24}^{true}, \delta_{34}^{true} \in [-\pi, \pi]$

CP conservation/ violation?

Dutta, Gandhi, Kayser, MM, Prakash (2016)

3+1 case:Exploring the phases



Fiza, MM, Mitra (coming soon)

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Non-standard interaction (NSI)

MM, Chatterjee, Mehta : JPG (2016)

de Gouvea, Kelly : NPB (2016)

Liao, Marfatia, Whisnant : PRD (2016)

Deepthi, Goswami, Nath : NPB (2018)

Farzan, Tortola : Review (2018)

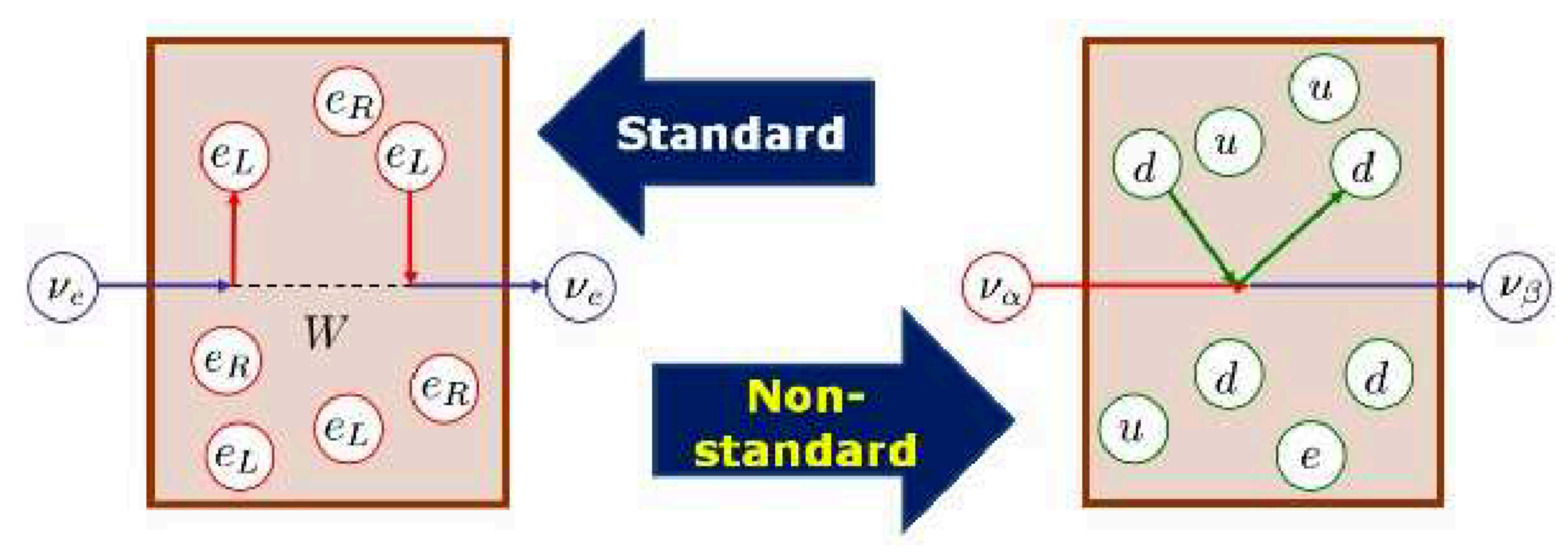
…….

NSI theory background

Wolfenstein (1978), Barger et al. (1991), Grossman (1995), Ohlsson (2012)...

$$\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{ff'X}\left(\bar{\nu}_\alpha\gamma^\mu P_L \ell_\beta\right)\left(\bar{f}'\gamma_\mu P_X f\right), \qquad f \neq f' \in (u,d)$$

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\left(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_X f\right). \qquad f \in (e,u,d)$$



Theory background

Wolfenstein (1978), Barger et al. (1991), Grossman (1995), Ohlsson (2012)...

$$\epsilon_{\alpha\beta} \equiv \epsilon^{eV}_{\alpha\beta} + \frac{N_u}{N_e}\epsilon^{uV}_{\alpha\beta} + \frac{N_d}{N_e}\epsilon^{dV}_{\alpha\beta}$$

1. Osc. expts. (DUNE, T2HK, NOvA, INO)
2. Scattering expts. (COHERENT..)

Inside sun: $\frac{N_u}{N_e} \approx 2\frac{N_d}{N_e} \approx 1$

Inside earth: $\frac{N_u}{N_e} \approx \frac{N_d}{N_e} \approx 3$

$$H = H_{vac} + H_{mat} + H_{NSI}$$

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

NSI at long baseline experiment

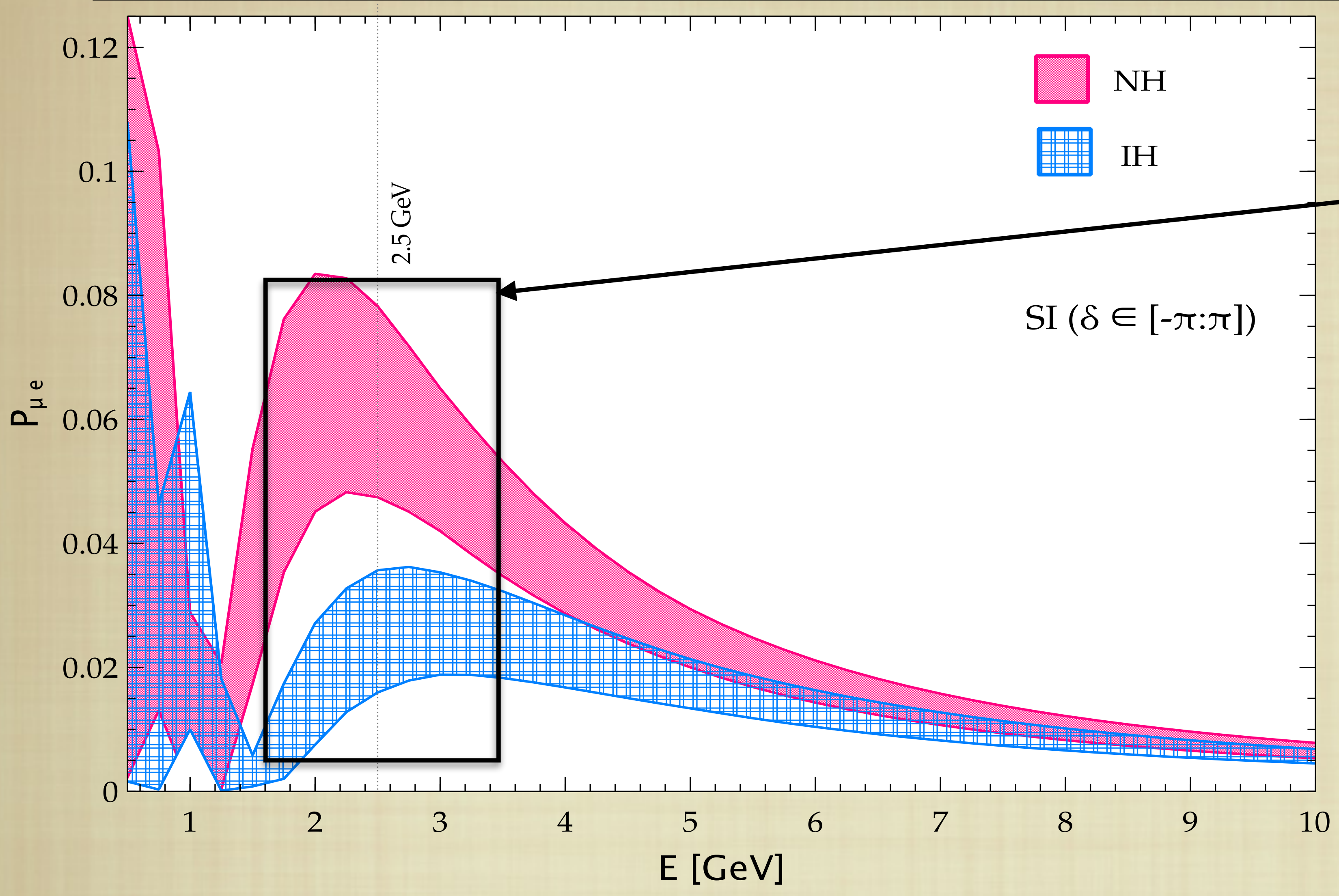
- NSI amplitudes with their new CP phases can potentially spoil CPV, MH and octant sensitivities

- Most relevant for $\nu_\mu \to \nu_e : \varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{ee}$

  $\nu_\mu \to \nu_\mu : \varepsilon_{\mu\mu}, \varepsilon_{\mu\tau}$

$$
\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}
$$

NSI at long baseline experiment (MH)



high sensitivity for SI

changes signs for IH

$$A = \frac{2\sqrt{2}EG_F n_E}{\Delta m^2_{31}}$$

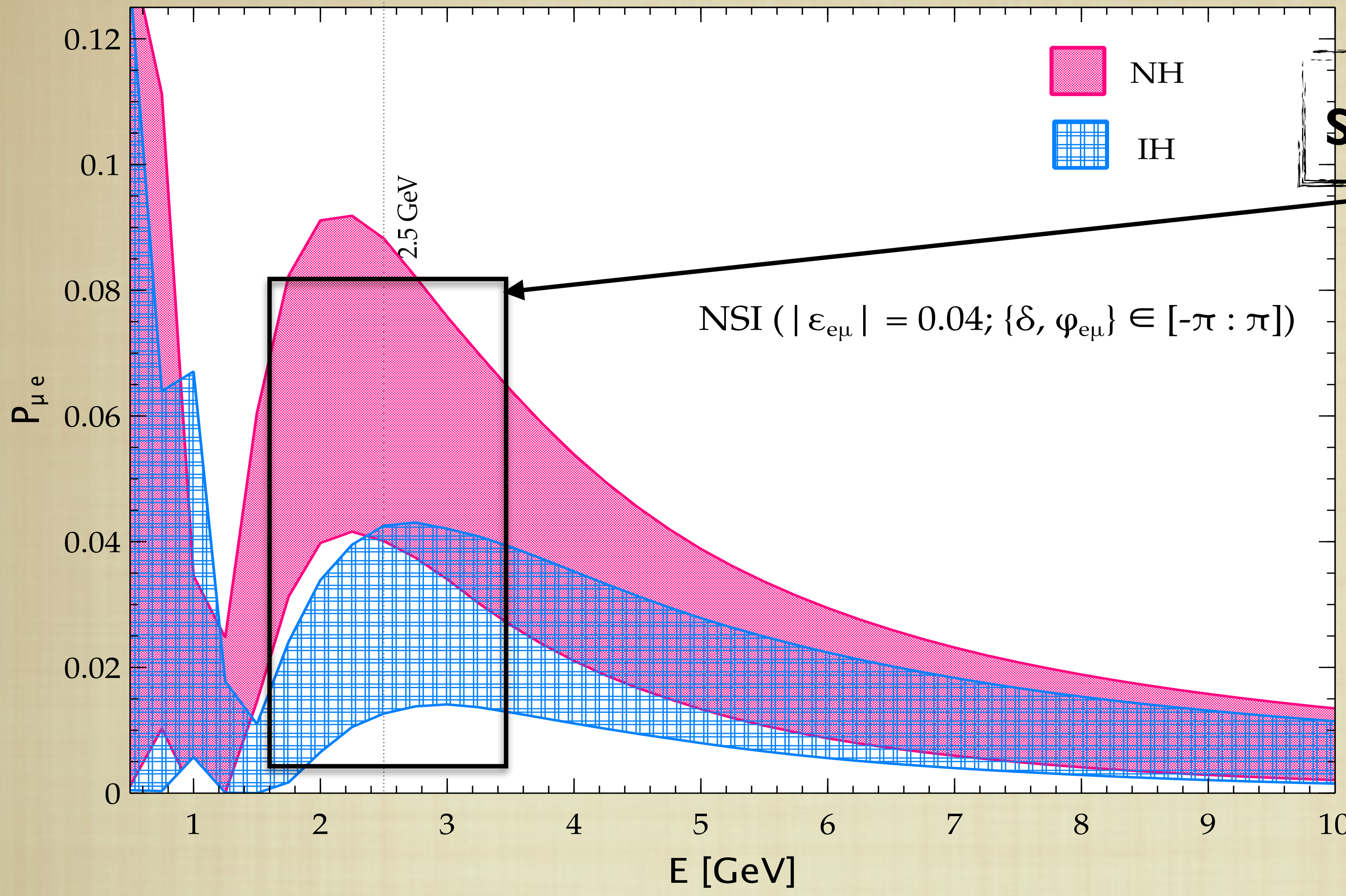
$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$\begin{aligned} P_{\mu e} &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} \\ &+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A} \\ &+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta) \end{aligned}$$

MM,Mehta (2016)

NSI at long baseline experiment (MH)



sensitivity decreases for NSI

changes signs for IH

$$
\begin{aligned}
P_{\mu e} &= \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2(1-A)\Delta}{1-A} \\
&+ \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A} \\
&+ \alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\frac{\sin(1-A)\Delta}{1-A}\frac{\sin A\Delta}{A}\cos(\delta+\Delta)
\end{aligned}
$$

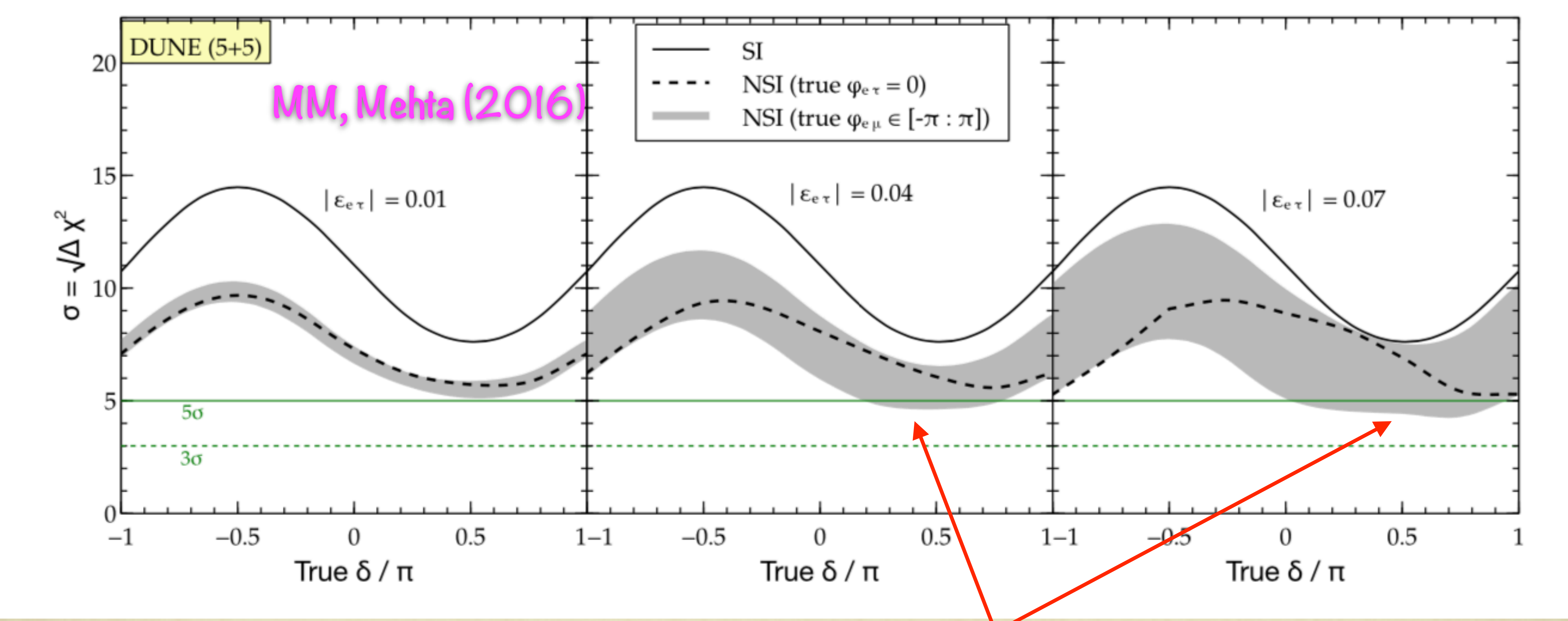
$$
A = \frac{2\sqrt{2}EG_F n_E}{\Delta m^2_{31}}
$$

$$
\Delta = \frac{\Delta m^2_{31}L}{4E}
$$

$$
\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}
$$

MM,Mehta (2016)

NSI at long baseline experiment (MH)



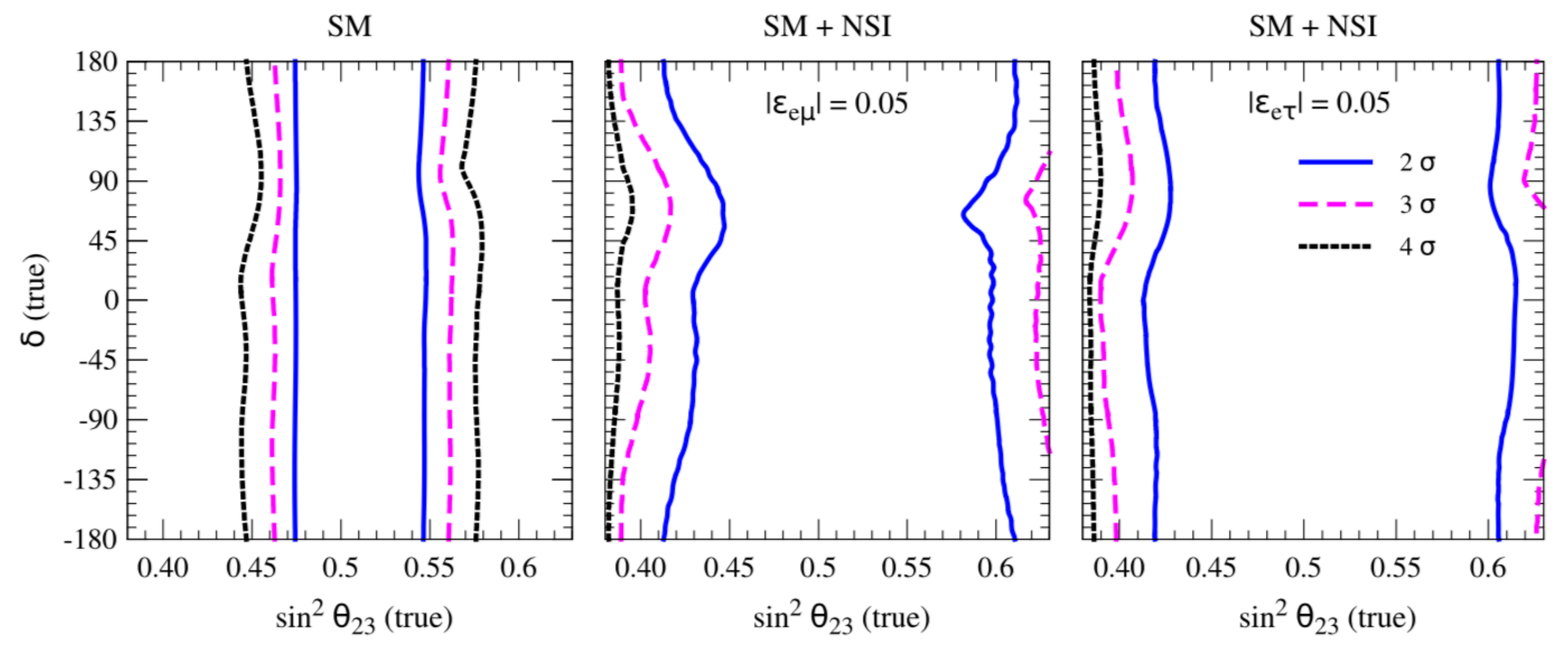
MM, Mehta (2016)

MH sensitivity < 5sigma

MH sensitivity at DUNE

Also see, Soumya, Mohanta (2017); Deepthi, Goswami, Nath (2017)

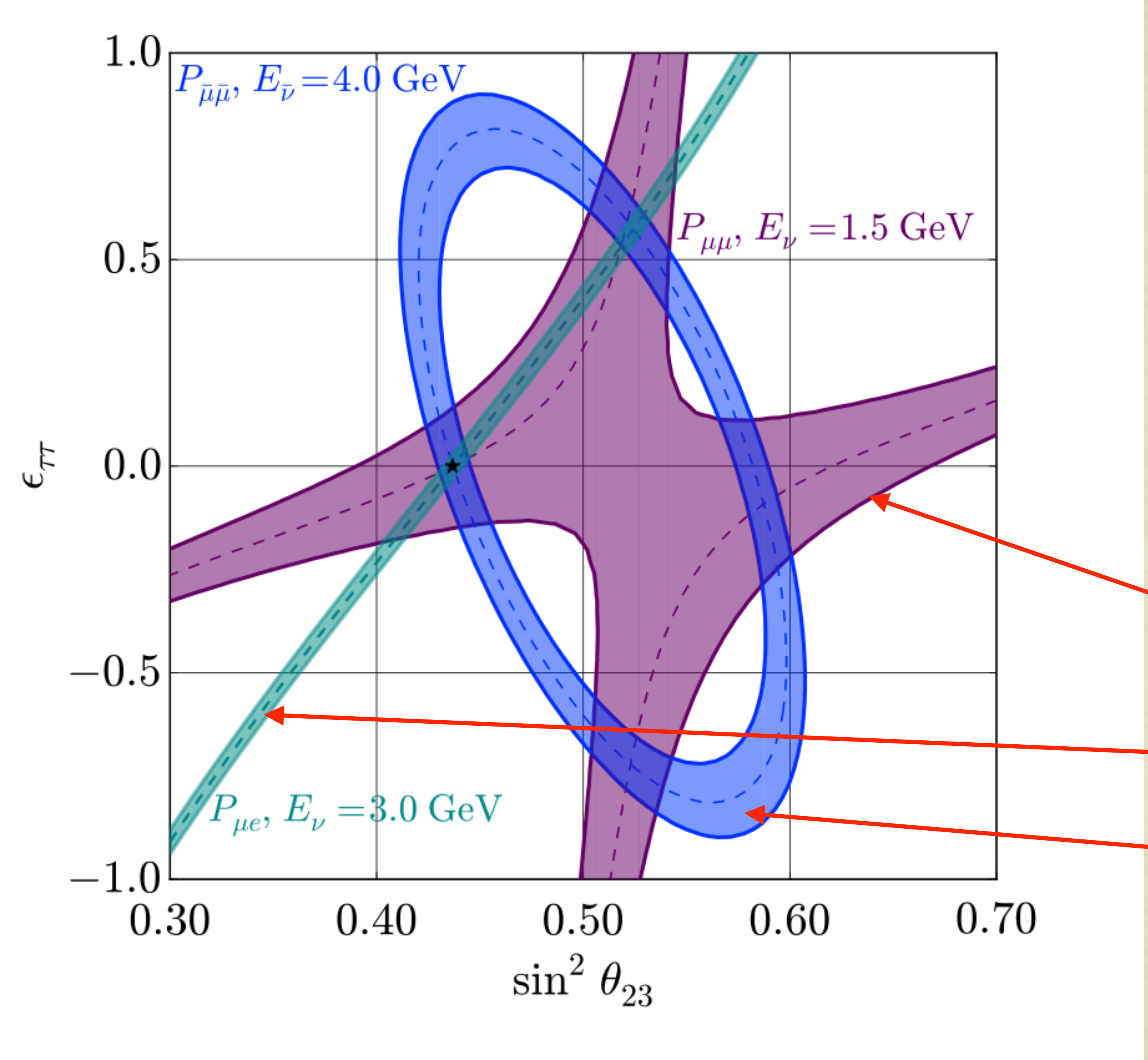
NSI at long baseline experiment (Octant)



Agarwalla, Chatterjee, Palazzo (2016)

$\theta_{23} - \delta$ exclusion region at DUNE

NSI at long baseline experiment (SI-NSI degeneracy)



De Gouvea, Kelly (2016)

Degeneracy in:

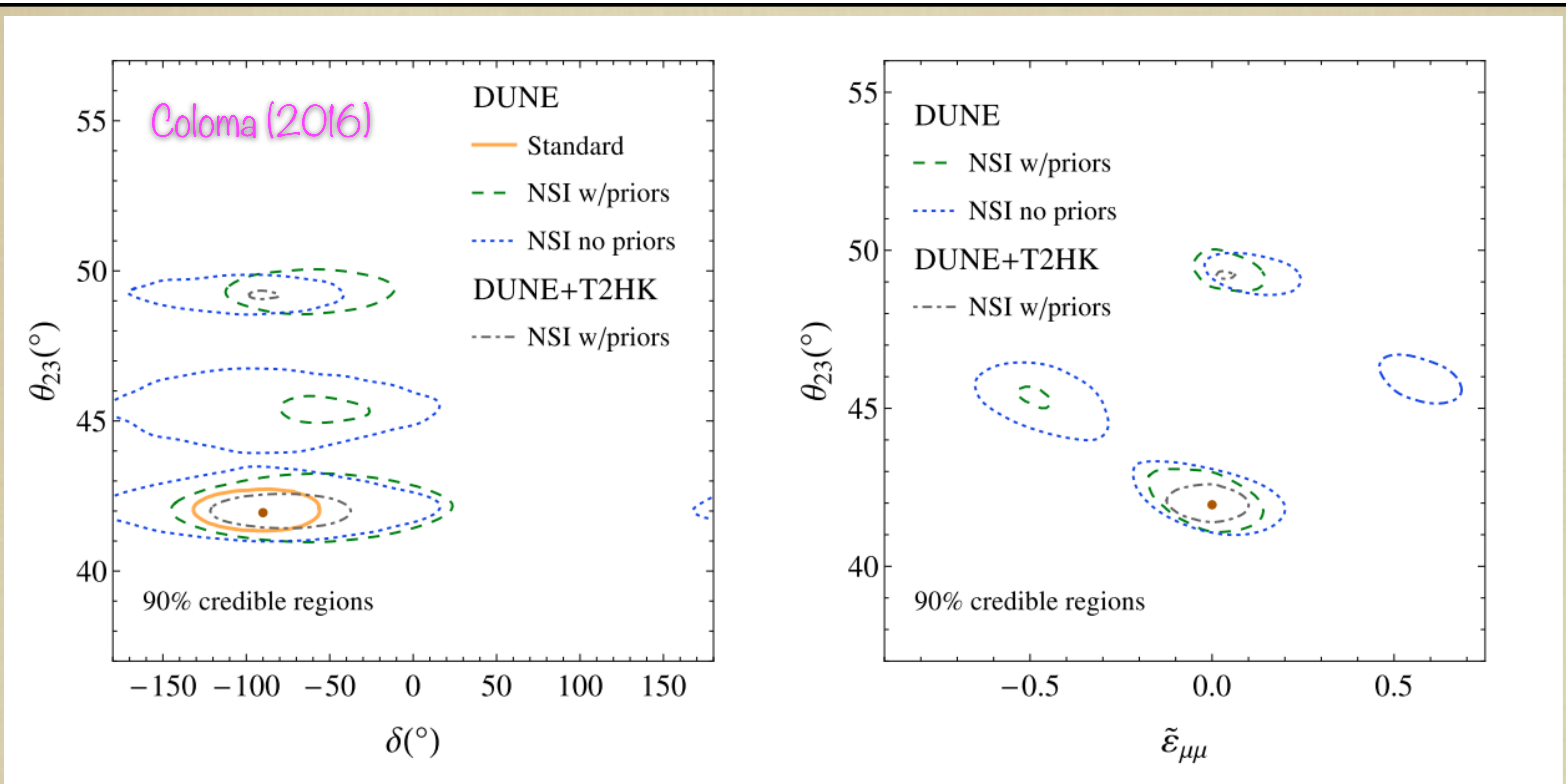
$P_{\mu\mu}$

$P_{\mu e}$

$\bar{P}_{\mu\mu}$

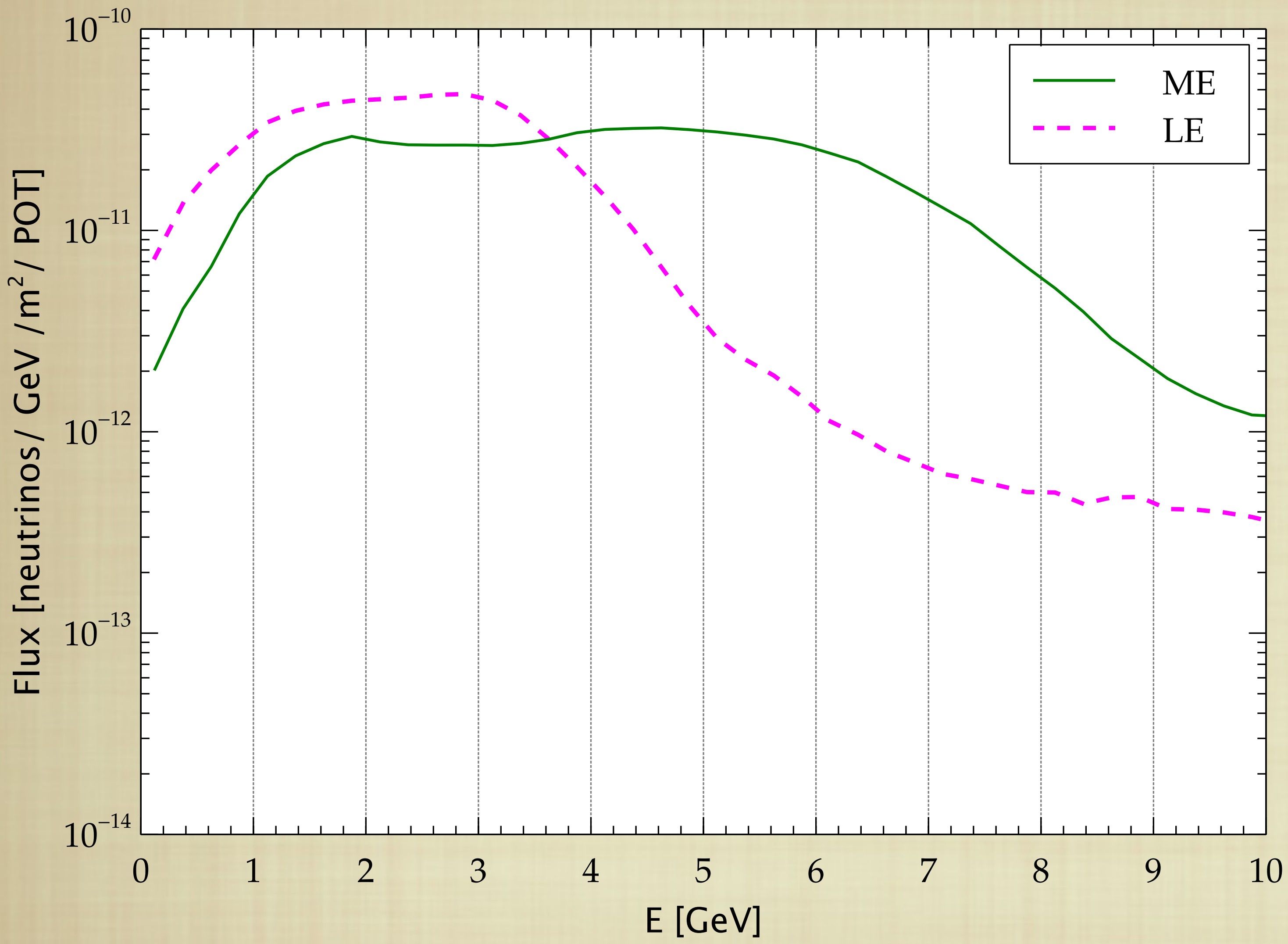
Also see Liao, Marfatia, Whisnant (2017) for degeneracy in the χ^2 level

SI-NSI degeneracy and priors


Coloma (2016)

- Using priors and adding T2HK data help to reduce degeneracy

Can we distinguish NSI from SI?

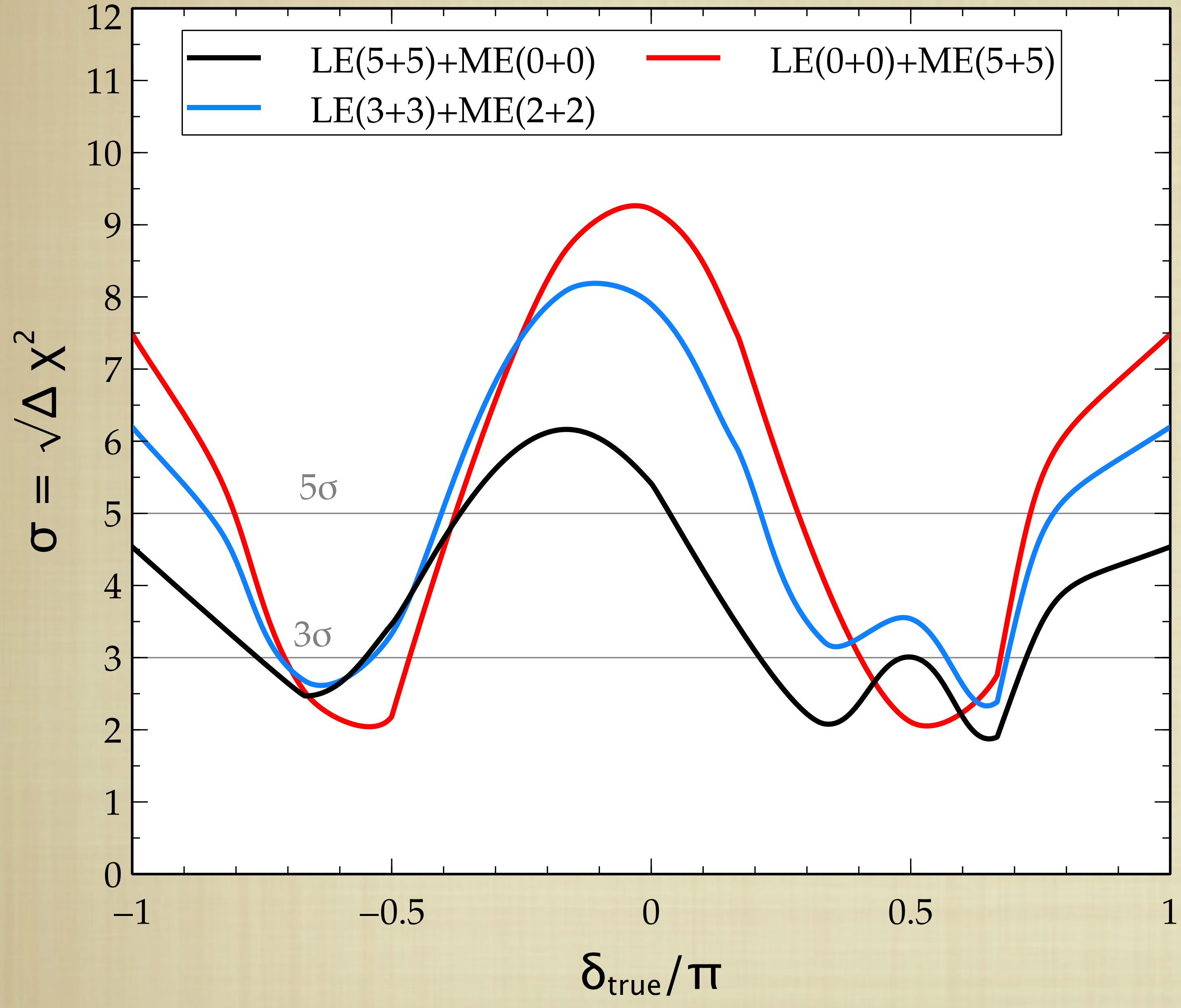


Standard (LE) flux falls quickly!

$\Longrightarrow$ Exploit a medium energy (ME) tuned flux

Bishai, MM,Mehta (2018)

Can we distinguish NSI from SI?

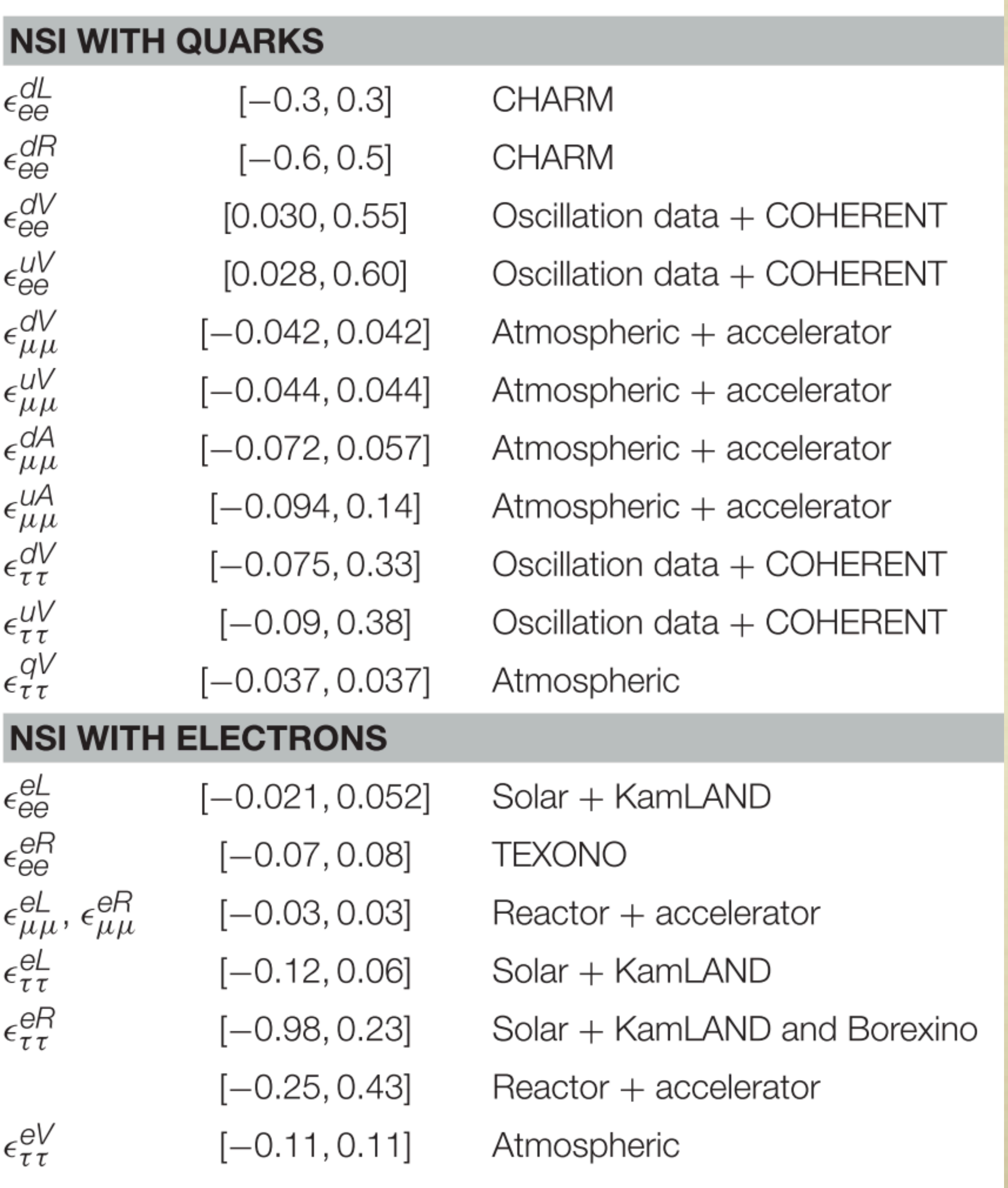


data simulated assuming
$\varepsilon_{e\mu} = 0.05$

Significant improvement of separability

Bishai, MM,Mehta (2018)

NSI Global analysis (complementarity of experiments)

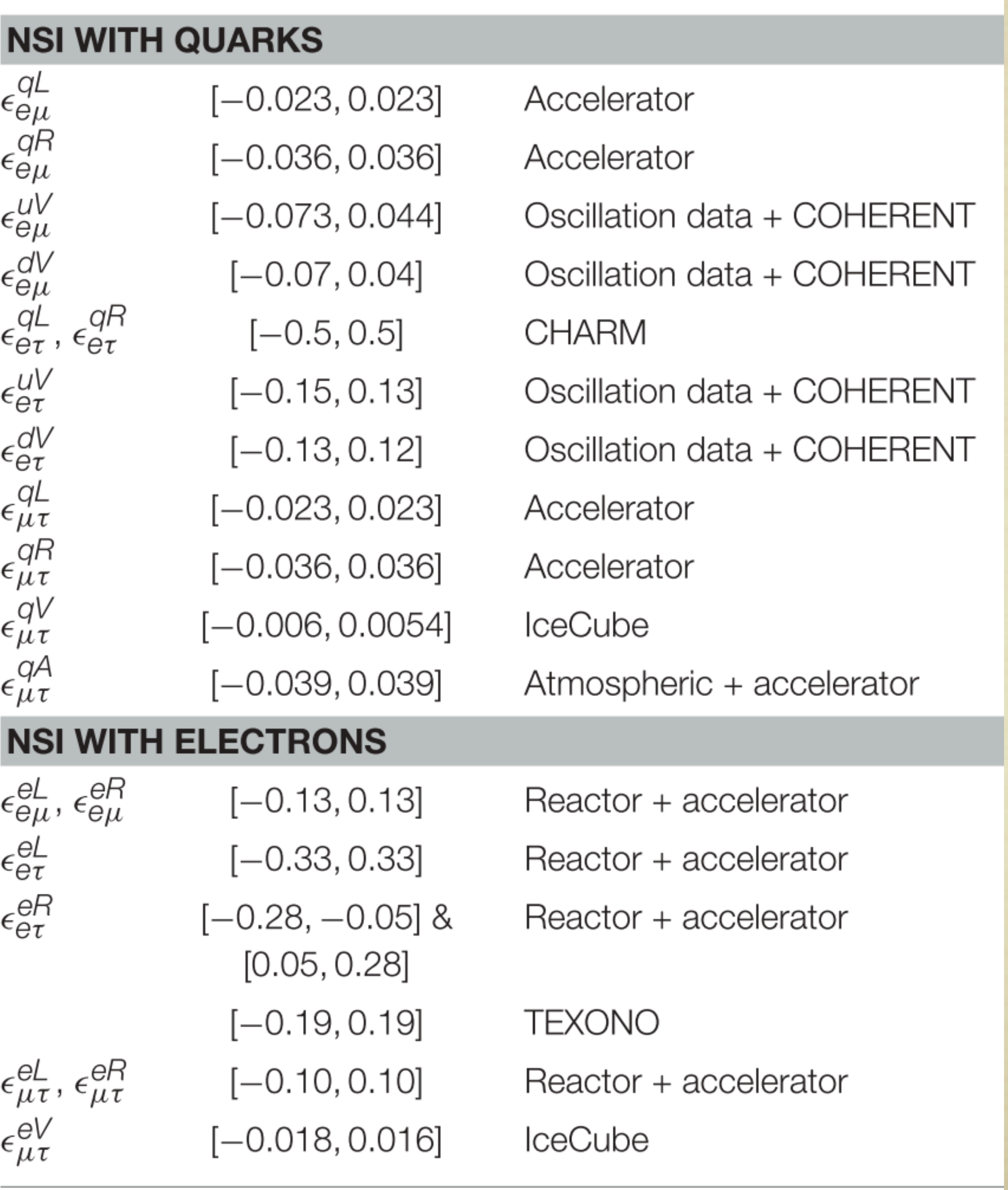


NSI WITH QUARKS		
ϵ_{ee}^{dL}	$[-0.3, 0.3]$	CHARM
ϵ_{ee}^{dR}	$[-0.6, 0.5]$	CHARM
ϵ_{ee}^{dV}	$[0.030, 0.55]$	Oscillation data + COHERENT
ϵ_{ee}^{uV}	$[0.028, 0.60]$	Oscillation data + COHERENT
$\epsilon_{\mu\mu}^{dV}$	$[-0.042, 0.042]$	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{uV}$	$[-0.044, 0.044]$	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{dA}$	$[-0.072, 0.057]$	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{uA}$	$[-0.094, 0.14]$	Atmospheric + accelerator
$\epsilon_{\tau\tau}^{dV}$	$[-0.075, 0.33]$	Oscillation data + COHERENT
$\epsilon_{\tau\tau}^{uV}$	$[-0.09, 0.38]$	Oscillation data + COHERENT
$\epsilon_{\tau\tau}^{qV}$	$[-0.037, 0.037]$	Atmospheric
NSI WITH ELECTRONS		
ϵ_{ee}^{eL}	$[-0.021, 0.052]$	Solar + KamLAND
ϵ_{ee}^{eR}	$[-0.07, 0.08]$	TEXONO
$\epsilon_{\mu\mu}^{eL}, \epsilon_{\mu\mu}^{eR}$	$[-0.03, 0.03]$	Reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	$[-0.12, 0.06]$	Solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$	Solar + KamLAND and Borexino
	$[-0.25, 0.43]$	Reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	Atmospheric

Biggio, Blennow, Farnandez-Martinez (2009);
Gonzalez-Garcia, Maltoni, Salvado ;
Tortola, Farzan (2018)

Diagonal NSI

NSI Global analysis (complementarity of experiments)



NSI WITH QUARKS		
$\epsilon_{e\mu}^{qL}$	$[-0.023, 0.023]$	Accelerator
$\epsilon_{e\mu}^{qR}$	$[-0.036, 0.036]$	Accelerator
$\epsilon_{e\mu}^{uV}$	$[-0.073, 0.044]$	Oscillation data + COHERENT
$\epsilon_{e\mu}^{dV}$	$[-0.07, 0.04]$	Oscillation data + COHERENT
$\epsilon_{e\tau}^{qL}, \epsilon_{e\tau}^{qR}$	$[-0.5, 0.5]$	CHARM
$\epsilon_{e\tau}^{uV}$	$[-0.15, 0.13]$	Oscillation data + COHERENT
$\epsilon_{e\tau}^{dV}$	$[-0.13, 0.12]$	Oscillation data + COHERENT
$\epsilon_{\mu\tau}^{qL}$	$[-0.023, 0.023]$	Accelerator
$\epsilon_{\mu\tau}^{qR}$	$[-0.036, 0.036]$	Accelerator
$\epsilon_{\mu\tau}^{qV}$	$[-0.006, 0.0054]$	IceCube
$\epsilon_{\mu\tau}^{qA}$	$[-0.039, 0.039]$	Atmospheric + accelerator
NSI WITH ELECTRONS		
$\epsilon_{e\mu}^{eL}, \epsilon_{e\mu}^{eR}$	$[-0.13, 0.13]$	Reactor + accelerator
$\epsilon_{e\tau}^{eL}$	$[-0.33, 0.33]$	Reactor + accelerator
$\epsilon_{e\tau}^{eR}$	$[-0.28, -0.05]$ & $[0.05, 0.28]$	Reactor + accelerator
	$[-0.19, 0.19]$	TEXONO
$\epsilon_{\mu\tau}^{eL}, \epsilon_{\mu\tau}^{eR}$	$[-0.10, 0.10]$	Reactor + accelerator
$\epsilon_{\mu\tau}^{eV}$	$[-0.018, 0.016]$	IceCube

Biggio, Blennow, Farnandez-Martinez (2009);

Gonzalez-Garcia, Maltoni, Salvado ;

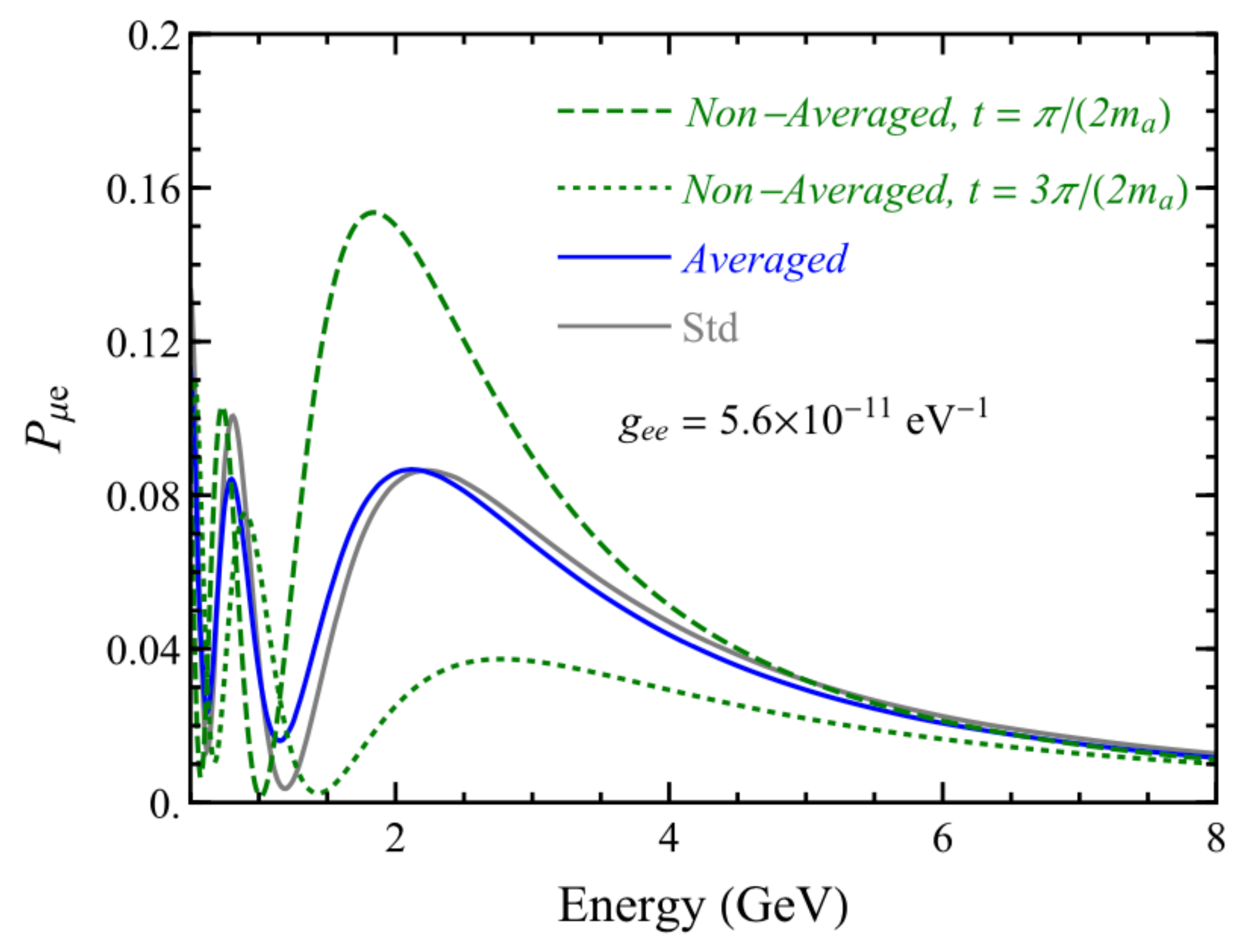
Tortola, Farzan (2018)

Off-diagonal NSI

Plan of the talk

- Basics of oscillation physics and pending issues
- Hint for a light (eV) sterile neutrino
- Non-Standard Neutrino Interaction (NSI)
- Other BSM options (Dark sector?)
- Summary

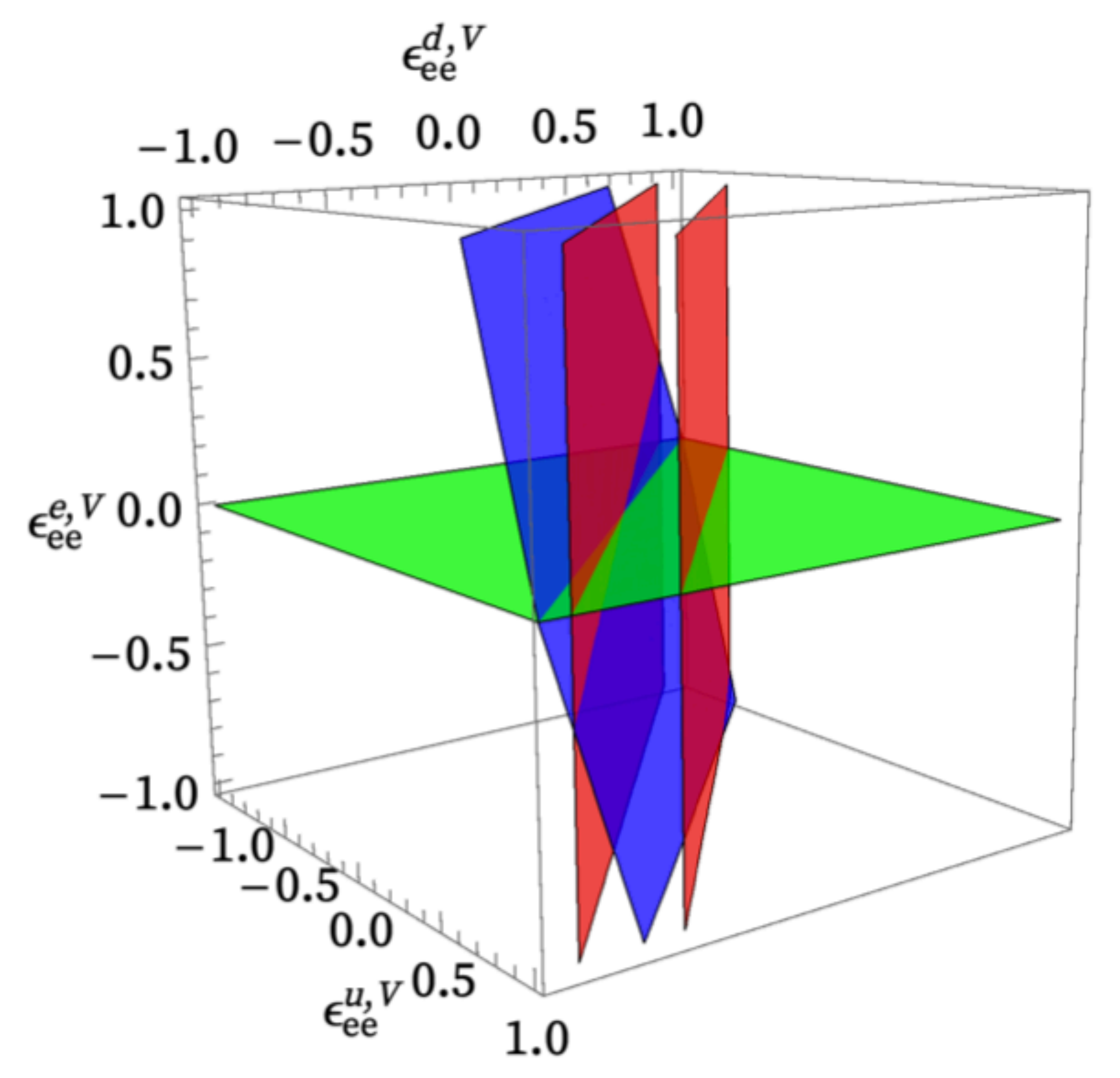
Neutrinophillic ALP



$$H(t) = \frac{1}{2E_\nu} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} V + \xi_{ee}(t) & \xi_{e\mu}(t) & \xi_{e\tau}(t) \\ \xi^*_{e\mu}(t) & \xi_{\mu\mu}(t) & \xi_{\mu\tau}(t) \\ \xi^*_{e\tau}(t) & \xi^*_{\mu\tau}(t) & \xi_{\tau\tau}(t) \end{pmatrix}$$

Huang, Nath (2018)

NSI: Complementarity of detectors



CEνNS, EνNS, Oscillation

$$\varepsilon_{\alpha\beta} = \varepsilon_{\alpha\beta}^{e,V} + 3\varepsilon_{\alpha\beta}^{u,V} + 3\varepsilon_{\alpha\beta}^{d,V}$$

Dutta, Lang, Liao, Sinha, Strigari, Thompson (2020)

Non-unitarity

- Neutral Heavy Leptons (NHL) arise naturally as an extension of SM $\Longrightarrow$ Non-unitary mixing matrix
- Can induce Lepton Flavour Violation
- Modification of CP sensitivity due to more unknown phases
- …..

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon : JHEP (2006)

Forero, Morisi, Tortola, Valle : JHEP (2011)

Blennow, Coloma, Hernandez-Garcia, Lopez-Pavon : JHEP (2017)

Summary

- Outstanding issues: CPV, mass ordering, octant
  - ➡ Tension between T2K/NOvA
  - ➡ Stay tuned for DUNE/T2HK...
- Hint for new physics (MiniBoone, LSND..)
  - ➡ MB Excess $\gtrsim 4\sigma$
  - ➡ Wait for SBN
  - ➡ Compatible with eV sterile ν!
  - ➡ DM sector? Decay of heavy ν?……
- Sterile neutrinos, NSI,
  - ➡ Spoils std. param. measurements
  - ➡ Needs more constraints from osc. (SBN, Neutrino-4, atmos expt….) & nosc. data (CEνNS)
- Other possibilities (DM sector?...)
  - ➡ Exploit the complementarity of DM and ν detectors

ধন্যবাদ!

Thank you!

감사합니다

3+1 case: Impact on CPV sensitivity

$$\Delta\chi^2(true) \simeq Min_{u,s}\left[\sum_{bins} \frac{\left\{N_{data}(true) - N_{fit}(u,s)\right\}^2}{N_{data}(true)} + \sum \frac{s_i^2}{\sigma_i^2}\right]$$

u : osc. parameters
s : systematics

- GLoBES simulation $\Longrightarrow$ DUNE data for all true CP phase(s) $\in [-\pi, \pi]$
- Fitted with CP phase(s) $= 0,\pi$
- Marginalisation over $u(=\{\theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}, |\Delta m^2_{31}|\})$ in the allowed ranges and also over the various systematics(s)
- Small $\Delta\chi^2$ $\Longrightarrow$ Better fit with data;
  large $\Delta\chi^2$ $\Longrightarrow$ fit is less compatible with data

Dutta, Gandhi, Kayser, MM,Prakash : JHEP (2016)

Theory background (backup)

- $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle \; (\alpha = e, \nu, \tau)$
- $H |\nu_k\rangle = E_k |\nu_k\rangle$
- $i \frac{d}{dt} |\nu_k(t)\rangle = H |\nu_k(t)\rangle$
- $P_{\alpha\beta}(L, E) = | \langle \nu_\beta | \nu_\alpha(x) \rangle |^2$
  $= \delta_{\alpha\beta} - 4 \sum_{k>j} Re[U^*_{\alpha k} U^*_{\beta j} U_{\beta k} U_{\alpha j}] \sin^2 \Delta_{kj}$
  $+ \sum_{k>j} Im[U^*_{\alpha k} U^*_{\beta j} U_{\beta k} U_{\alpha j}] \sin 2\Delta_{kj}$,

  (where, $\Delta_{ij} = 1.27 \times \frac{\Delta m^2_{ij} [\mathrm{eV}^2] \times L[km]}{E[GeV]}$)

Theory background (backup)

Kostelecky et al. (2012), Mavromatos et al.

$$\begin{aligned}\widehat{\mathcal{Q}}_{AB} &= \sum_I \widehat{\mathcal{Q}}^I_{AB}\gamma_I \\ &= \widehat{\mathcal{S}}_{AB} + i\widehat{\mathcal{P}}_{AB}\gamma_5 + \widehat{\mathcal{V}}^\mu_{AB}\gamma_\mu + \widehat{\mathcal{A}}^\mu_{AB}\gamma_5\gamma_\mu + \tfrac{1}{2}\widehat{\mathcal{T}}^{\mu\nu}_{AB}\sigma_{\mu\nu},\end{aligned}$$

$$\gamma^\nu p_\nu \delta_{AB} - M_{AB} + \widehat{\mathcal{Q}}_{AB} = \widehat{\Gamma}^\nu_{AB} p_\nu - \widehat{M}_{AB},$$

$$\begin{aligned}\widehat{\Gamma}^\nu_{AB} &= \gamma^\nu\delta_{AB} + \widehat{c}^{\mu\nu}_{AB}\gamma_\mu + \widehat{d}^{\mu\nu}_{AB}\gamma_5\gamma_\mu \\ &\quad + \widehat{e}^\nu_{AB} + i\widehat{f}^\nu_{AB}\gamma_5 + \tfrac{1}{2}\widehat{g}^{\kappa\lambda\nu}_{AB}\sigma_{\kappa\lambda}, \\ \widehat{M}_{AB} &= m_{AB} + im_{5AB}\gamma_5 + \widehat{m}_{AB} + i\widehat{m}_{5AB}\gamma_5 \\ &\quad + \widehat{a}^\mu_{AB}\gamma_\mu + \widehat{b}^\mu_{AB}\gamma_5\gamma_\mu + \tfrac{1}{2}\widehat{H}^{\mu\nu}_{AB}\sigma_{\mu\nu}.\end{aligned}$$

Theory background (backup)

Kostelecky et al. (2012), Mavromatos et al.

- The effective hamiltonian can be decomposed into 3x3 blocks:

$$\mathcal{Q} = \mathcal{S} + i\mathcal{P}\gamma_5 + \mathcal{V}^{\alpha}\gamma_{\alpha} + \mathcal{A}^{\alpha}\gamma_5\gamma_{\alpha} + \frac{1}{2}\mathcal{T}^{\alpha\beta}\sigma_{\alpha\beta}$$

Induce effective Hamiltonian for neutrino mixing

LIV:Theory background (backup)

Kostelecky et al. (2012), Mavromatos et al.

- The effective hamiltonian can be decomposed into 3x3 blocks:

$$(h_{eff})_{ab} = E\delta_{ab}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \frac{1}{2E}\begin{pmatrix}(m^2)_{ab} & 0\\ 0 & (m^2)^*_{ab}\end{pmatrix}$$

$$+\frac{1}{E}\begin{pmatrix}[(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]_{ab} & 0\\ 0 & [-(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]^*_{ab}\end{pmatrix}$$

CPT odd LIV parameters: $((a_L)^\alpha_{ab})^* = -(a_R)^\alpha_{\bar{a}\bar{b}}$

CPT even LIV parameters: $((c_L)^{\alpha\beta}_{ab})^* = (c_R)^{\alpha\beta}_{\bar{a}\bar{b}}$

Theory background (backup)

Kostelecky et al. (2012), Mavromatos et al.

- The effective hamiltonian can be decomposed into 3x3 blocks:

$\nu - \nu$ mixing →

$$h_{ab} = E\delta_{ab} + \frac{m_{ab^2}}{2E} + (a_L)^{\alpha}_{ab}p_{\alpha} - (c_L)^{\alpha\beta}_{ab}p_{\alpha}p_{\beta}E$$

$\bar{\nu} - \bar{\nu}$ mixing →

$$h_{\bar{a}\bar{b}} = E\delta_{\bar{a}\bar{b}} + \frac{m_{\bar{a}\bar{b}^2}}{2E} + (a_R)^{\alpha}_{\bar{a}\bar{b}}p_{\alpha} - (c_R)^{\alpha\beta}_{\bar{a}\bar{b}}p_{\alpha}p_{\beta}E$$

$\nu - \bar{\nu}$ mixing →

$$h_{a\bar{b}} = i\sqrt{2}(\epsilon)_{\alpha}(H^{\alpha}_{a\bar{b}} - g^{\alpha\beta}_{a\bar{b}}p_{\beta}E)$$

Backup

$$\begin{aligned}\Delta P_{\mu e}(\varepsilon_{e\mu}) &= P^{NSI}_{\mu e}(\varepsilon_{e\mu}) - P^{SI}_{\mu e} \\ &\approx -4A\Delta \sin\Delta |\varepsilon_{e\mu}| s_{13} s_{2(23)} c_{23} D_1^{e\mu} \sin(\delta + \varphi_{e\mu} - \gamma_1^{e\mu})\end{aligned}$$

&

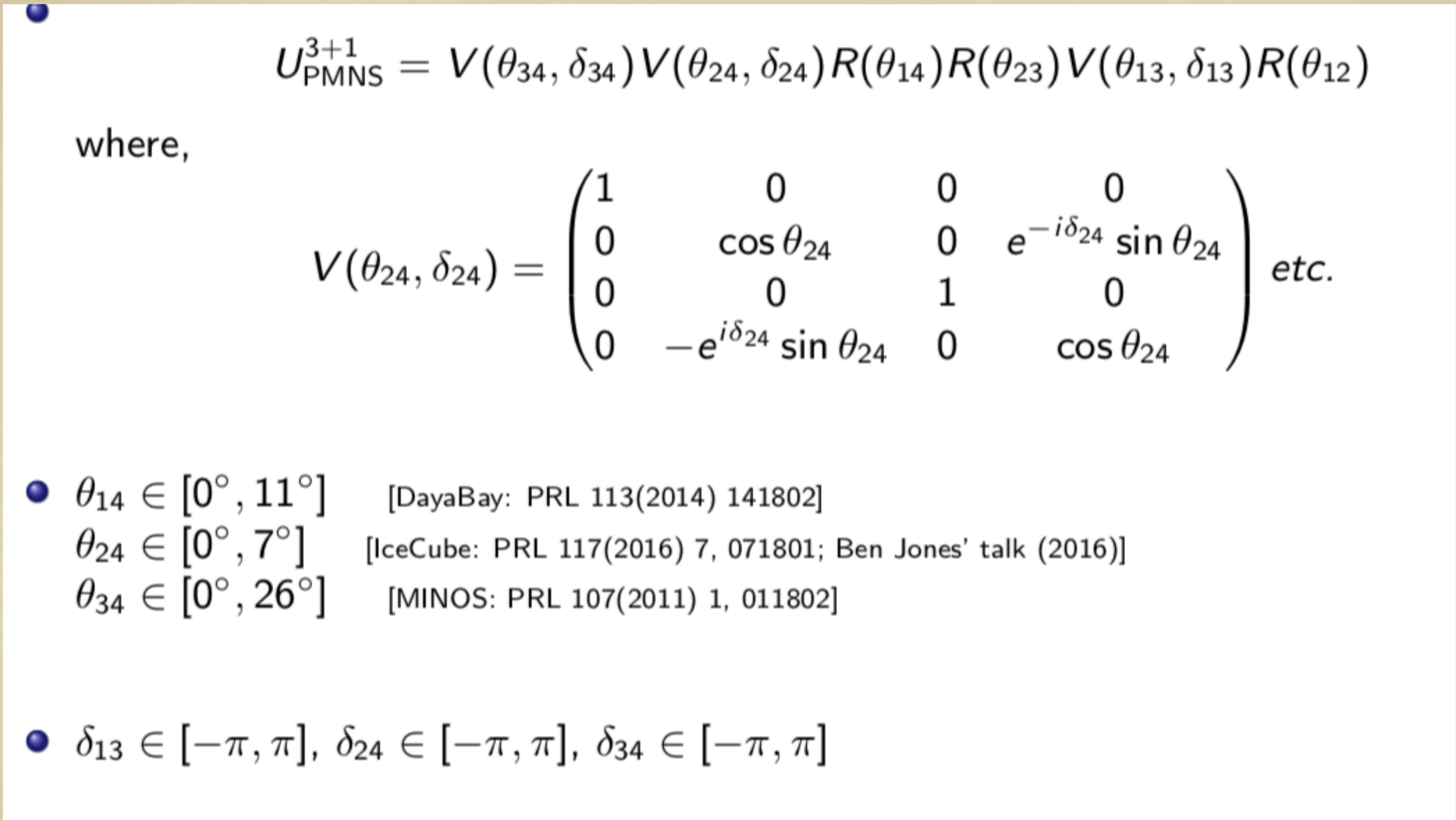
$$\Delta P_{\mu e}(\varepsilon_{e\tau}) \approx 4A\Delta \sin\Delta |\varepsilon_{e\tau}| s_{13} s_{2(23)} s_{23} D_1^{e\tau} \sin(\delta + \varphi_{e\tau} + \gamma_1^{e\tau})$$

where,

$$D_1^{e\mu} = [\sin^2\Delta + (\tan^2\theta_{23}\frac{\sin\Delta}{\Delta} + \cos\Delta)^2]^{1/2} \qquad \gamma_1^{e\mu} = \tan^{-1}(\frac{\tan^2\theta_{23}}{\Delta} + \cot\Delta)$$

$$D_1^{e\tau} = [\sin^2\Delta + (\frac{\sin\Delta}{\Delta} - \cos\Delta)^2]^{1/2}; \qquad \gamma_1^{e\tau} = \tan^{-1}(\frac{1}{\Delta} - \cot\Delta)$$

3+1 case :basics (backup)



- $$U^{3+1}_{\text{PMNS}} = V(\theta_{34}, \delta_{34}) V(\theta_{24}, \delta_{24}) R(\theta_{14}) R(\theta_{23}) V(\theta_{13}, \delta_{13}) R(\theta_{12})$$

  where,

  $$V(\theta_{24}, \delta_{24}) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{24} & 0 & e^{-i\delta_{24}} \sin\theta_{24} \\ 0 & 0 & 1 & 0 \\ 0 & -e^{i\delta_{24}} \sin\theta_{24} & 0 & \cos\theta_{24} \end{pmatrix} \; etc.$$

- $\theta_{14} \in [0^\circ, 11^\circ]$ [DayaBay: PRL 113(2014) 141802]
  $\theta_{24} \in [0^\circ, 7^\circ]$ [IceCube: PRL 117(2016) 7, 071801; Ben Jones' talk (2016)]
  $\theta_{34} \in [0^\circ, 26^\circ]$ [MINOS: PRL 107(2011) 1, 011802]

- $\delta_{13} \in [-\pi, \pi]$, $\delta_{24} \in [-\pi, \pi]$, $\delta_{34} \in [-\pi, \pi]$

- Can the new phases and mixing angles play roles to affect CPV studies?

Gandhi, Kayser, MM, Prakash : JHEP (2015)

Background and motivation: CPT violation?

- Observation of P violation in weak interactions
  C.N. Yang & T. D. Lee (Nobel 1957)
  V-A theory: Weak interaction acts on LH particles and RH antiparticles
  Marshak & Sudarshan; Feynman & Gell-Mann

- Although rare, CP violation was also observed
  Kobayashi & Maskawa (Nobel 2008)

- What about CPT violation?
  Can be related to , for e.g., Non-unitarity, Lorentz Invariance Violation (LIV)