

Non-standard interactions: constraints and prospects

Mariam Tórtola

IFIC, Universitat de València/CSIC

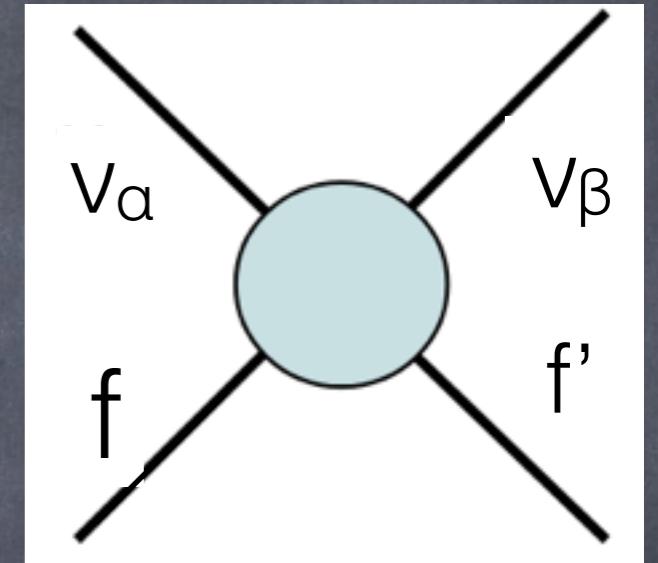
CERN Neutrino Platform Week, January 31st, 2018

Based on Y. Farzan and MT, Frontiers in Physics, arXiv: 1710.09360 [hep-ph]



NSI: Motivation

- NSI appear in models of neutrino masses
- NSI may affect oscillation parameters,
 - ⇒ precision measurements at current experiments
 - ⇒ sensitivity reach of upcoming experiments
(degeneracies and ambiguities)
- Information about the size of NSI could be very useful for neutrino model building



NSI: Notation

$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{ff'X} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta) (\bar{f}' \gamma_\mu P_X f)$$

⇒ may affect neutrino production and detection

$$\epsilon_{\alpha\beta}^s \quad (\text{source}) \quad \epsilon_{\alpha\beta}^d \quad (\text{detector})$$

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fX} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_X f)$$

$\epsilon_{\alpha\beta} \neq 0 \rightarrow$ NSI violate lepton flavor (FC-NSI)

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0 \rightarrow$ NSI violate LF universality (NU-NSI)

⇒ mainly affecting neutrino propagation in matter: $\epsilon_{\alpha\beta}^m$

(but also detection, e.g., Super-K and Borexino)

NSI: Notation

NSI in neutrino propagation in matter:

$$\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR} \quad (\text{NSI at detection: } \epsilon_{\alpha\beta}^{fL}, \epsilon_{\alpha\beta}^{fR})$$

In ordinary matter (e, p, n) $\rightarrow (e, u, d)$

$$\epsilon_{\alpha\beta} \equiv \epsilon_{\alpha\beta}^{eV} + \frac{N_u}{N_e} \epsilon_{\alpha\beta}^{uV} + \frac{N_d}{N_e} \quad \text{with} \quad V_{\text{NSI}} \propto \epsilon_{\alpha\beta} N_e$$

However:

$$\epsilon_{\alpha\beta} = \sum_f \frac{N_f}{N_d} \epsilon_{\alpha\beta}^{fV} \quad \text{with} \quad V_{\text{NSI}} \propto \epsilon_{\alpha\beta} N_d$$

Sun: $N_u/N_e \simeq 2N_d/N_e \simeq 1$

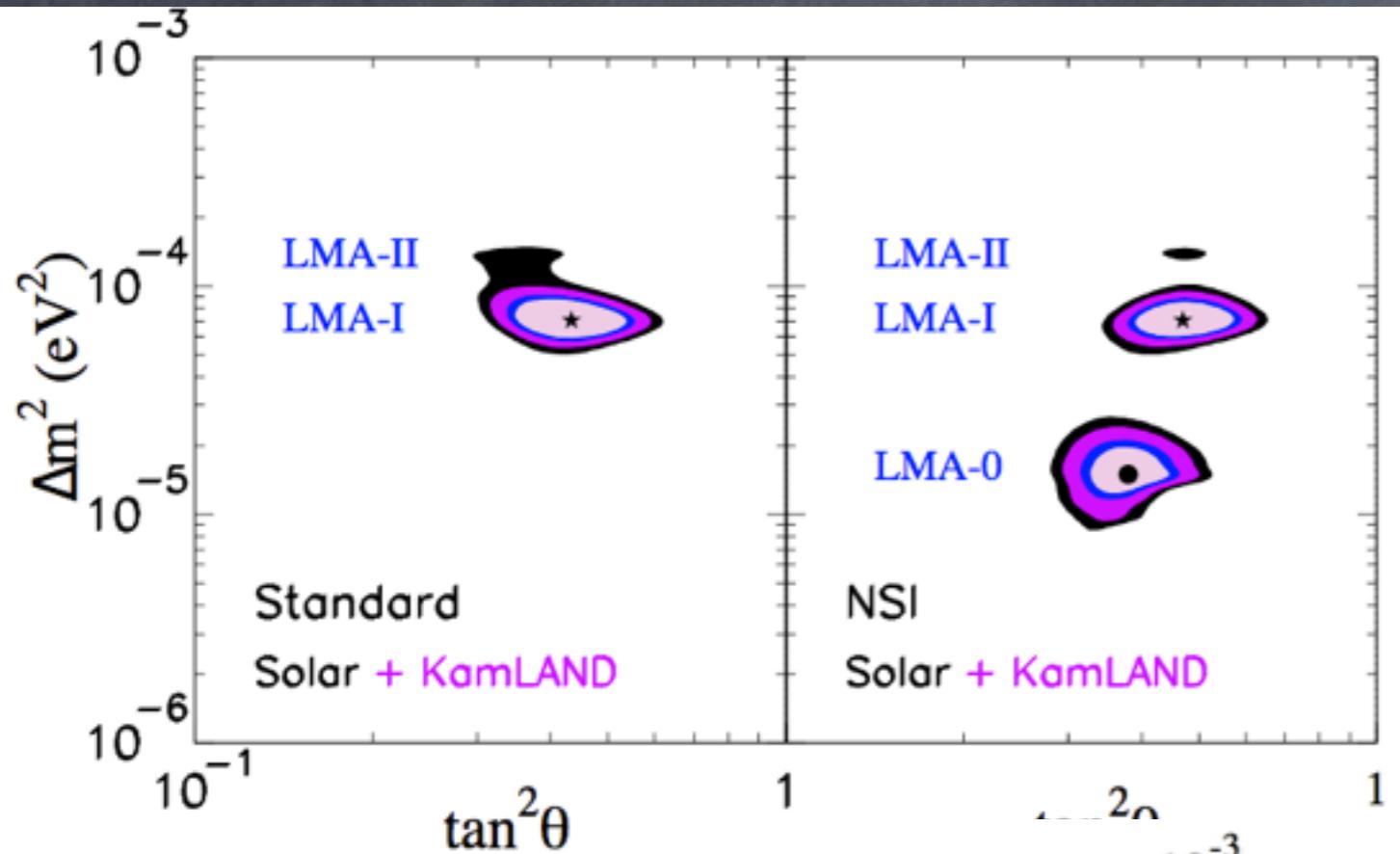
Earth: $N_u/N_e \simeq N_d/N_e \simeq 3$

Factor 3 difference!!

$$\epsilon_{\alpha\beta}^{fV}$$

Current Constraints on NSI

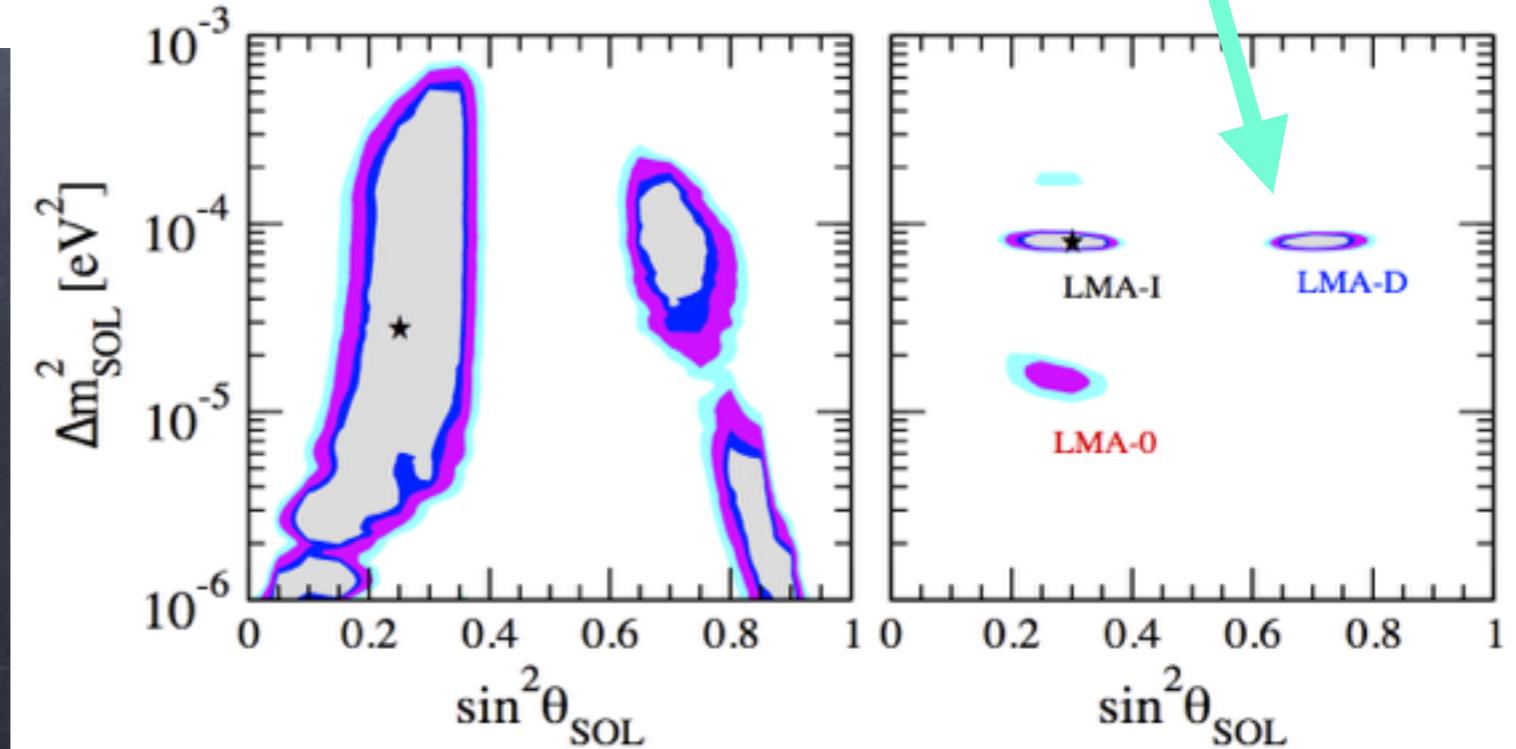
NSI in the solar sector



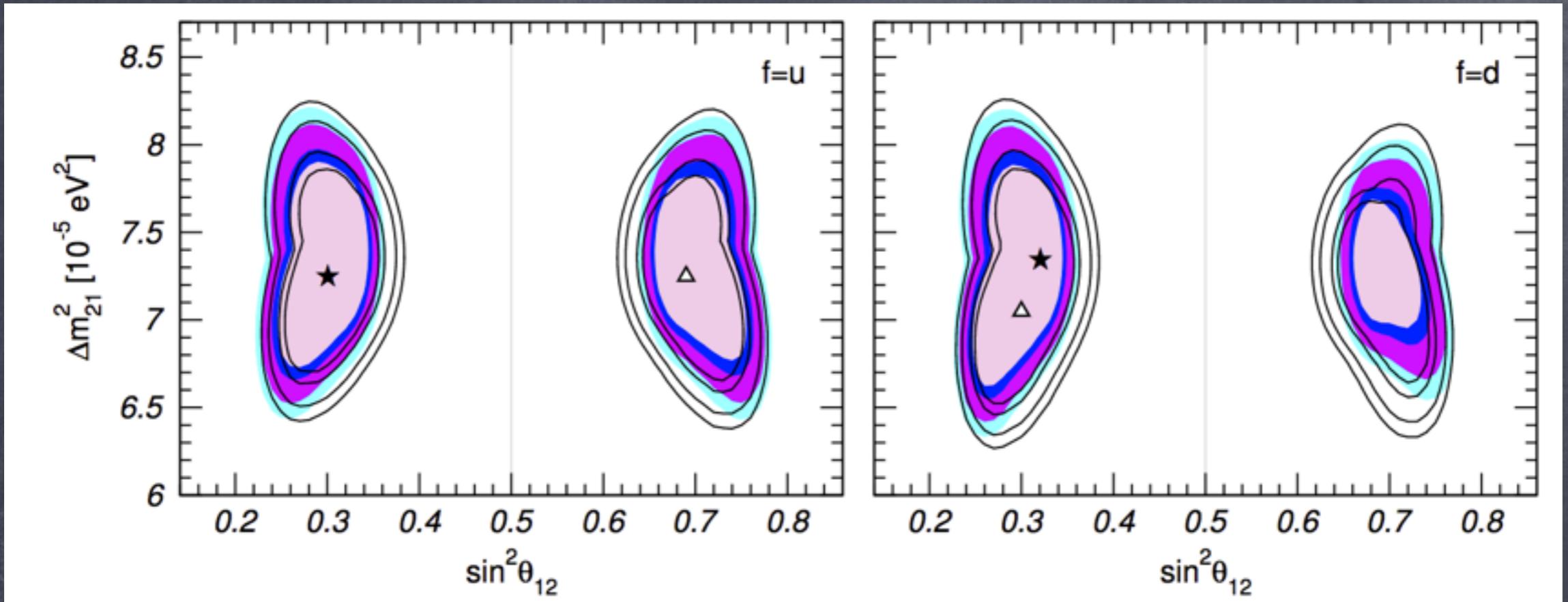
degenerate solution
LMA-Dark,
with $\theta_{12} > \pi/4$

Friedland et al, PLB 2004

Miranda et al, JHEP 2006



NSI in the solar sector



Gonzalez-Garcia et al, JHEP 2013

How to probe LMA-Dark?

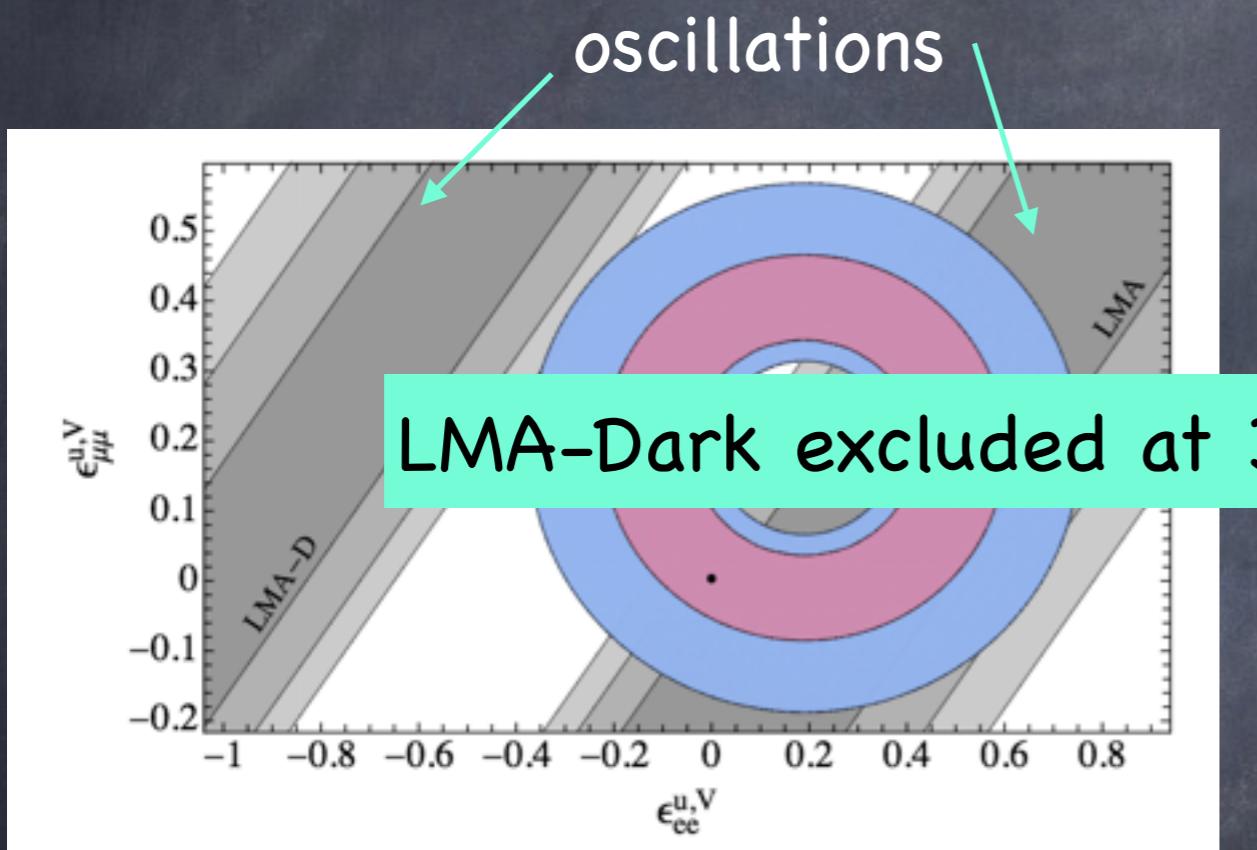
⇒ combination with neutrino scattering experiments: CHARM, NuTeV

Escrihuela et al, PRD 2009, Coloma et al, JHEP 2017

⇒ combination with coherent neutrino-nucleus scattering

Coloma et al, PRD 2017

NSI in the solar sector: impact of COHERENT results



| | $f = u$ | $f = d$ |
|-----------------------------|-----------------|-----------------|
| $\epsilon_{ee}^{f,V}$ | [0.028, 0.60] | [0.030, 0.55] |
| $\epsilon_{\mu\mu}^{f,V}$ | [-0.088, 0.37] | [-0.075, 0.33] |
| $\epsilon_{\tau\tau}^{f,V}$ | [-0.090, 0.38] | [-0.075, 0.33] |
| $\epsilon_{e\mu}^{f,V}$ | [-0.073, 0.044] | [-0.07, 0.04] |
| $\epsilon_{e\tau}^{f,V}$ | [-0.15, 0.13] | [-0.13, 0.12] |
| $\epsilon_{\mu\tau}^{f,V}$ | [-0.01, 0.009] | [-0.009, 0.008] |

caveats

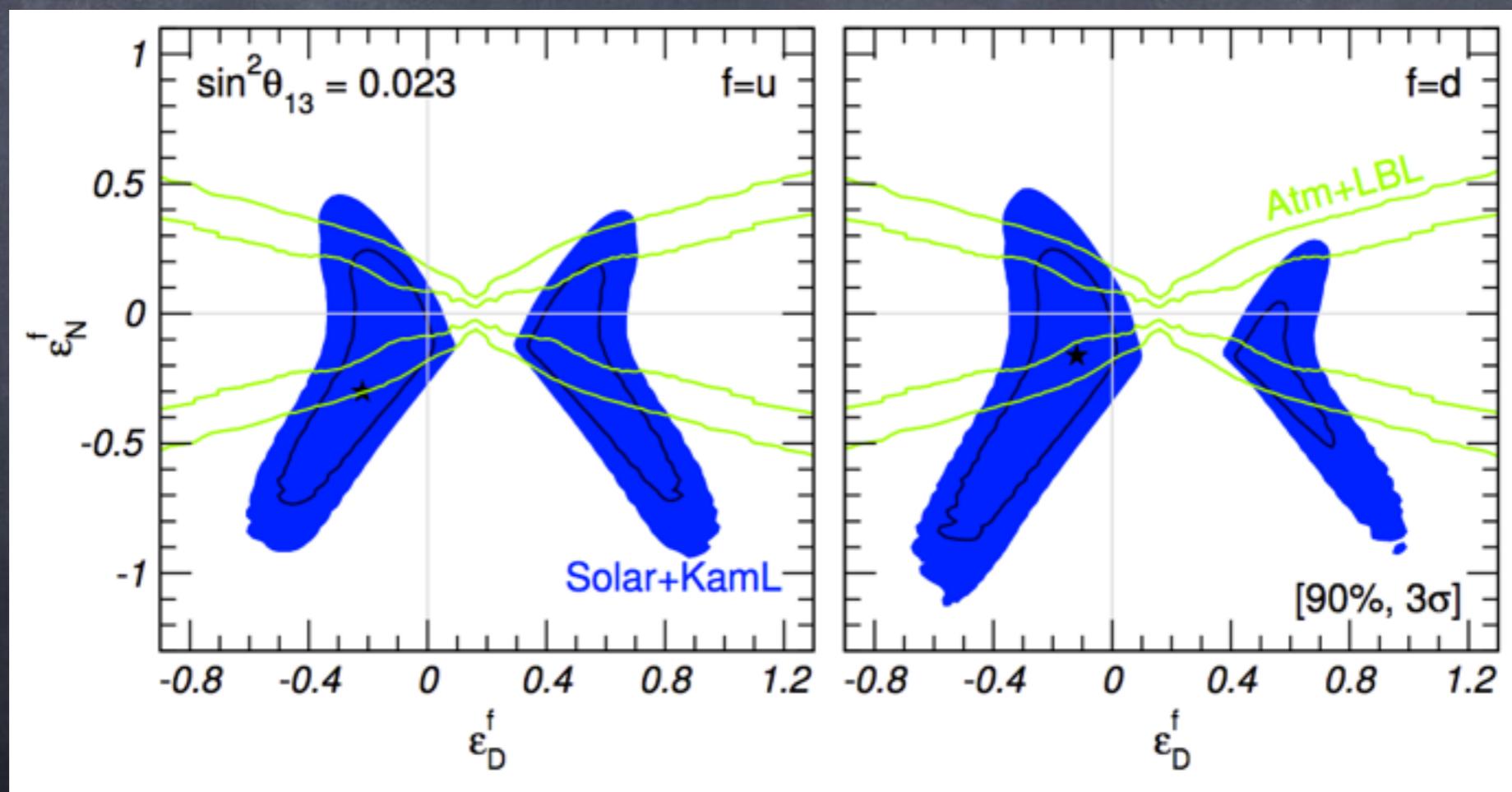
- mediator lighter than 50 MeV
- degeneracies in (ϵ_d, ϵ_u)

90% CL oscillation + COHERENT
Coloma et al, PRD 2017

NSI in the solar sector

solar + KamLAND analysis prefer non-zero NSI

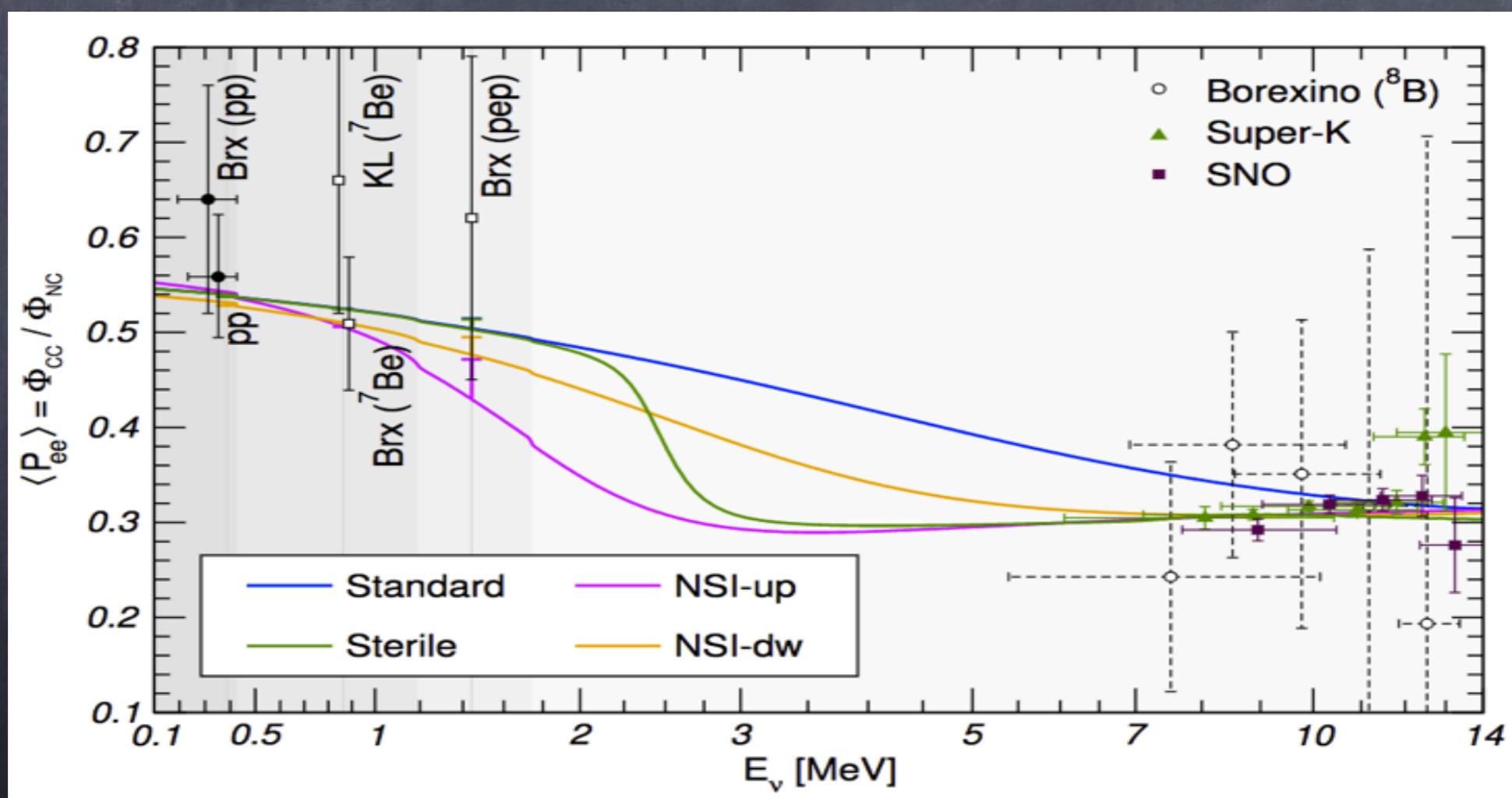
Friedland et al, Miranda et al,
Palazzo, González-García et al.



NSI in the solar sector

solar + KamLAND analysis prefer non-zero NSI

Friedland et al, Miranda et al,
Palazzo, González-García et al.



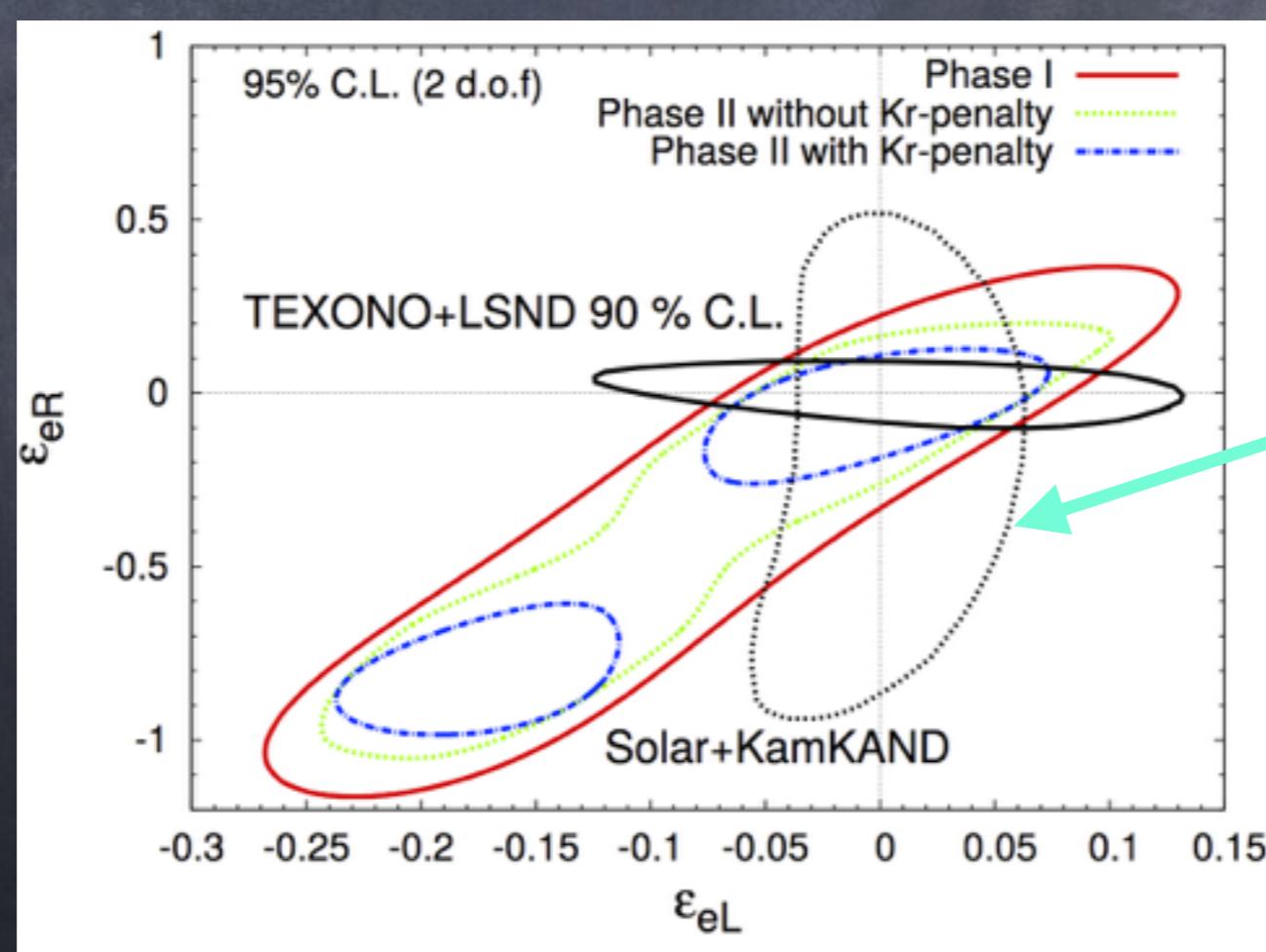
NSI in solar neutrino detection

- neutrino-electron cross section in presence of NSI:

$$\frac{d\tilde{\sigma}_{\nu_\alpha}(E_{\nu_\alpha}, T)}{dT} = \frac{2G_F^2 m_e}{\pi} \left[\tilde{g}_{\alpha L}^2 + \tilde{g}_{\alpha R}^2 \left(1 - \frac{T}{E_{\nu_\alpha}} \right)^2 - \tilde{g}_{\alpha L} \tilde{g}_{\alpha R} \frac{m_e T}{E_{\nu_\alpha}^2} \right]$$

$$\begin{aligned}\tilde{g}_L &= g_L + \epsilon_{\alpha\beta}^{eL} \\ \tilde{g}_R &= g_R + \epsilon_{\alpha\beta}^{eR}\end{aligned}$$

Berezhiani et al, NPB 2002



Borexino
Phase II

Agarwalla,
2017

ϵ_{ee}^{eL} ϵ_{ee}^{eR}

Super-K

Bolaños et al,
PRD 2009

NSI in the atmospheric sector

- From Super-K I & II phase data (2ν approx): Mitsuka et al, 2011

$$|\epsilon_{\mu\tau}^{dV}| < 0.011, \quad |\epsilon_{\mu\mu}^{dV} - \epsilon_{\tau\tau}^{dV}| < 0.049 \quad (90\% \text{ C.L.})$$

⇒ bounds relaxed in a 3-neutrino analysis Friedland et al 2004, 2005

- Three-neutrino analysis of Super-K data Gonzalez-Garcia et al, 2011

$$|\epsilon_{\mu\tau}^{eV}| < 0.035, \quad |\epsilon_{\tau\tau}^{eV} - \epsilon_{\mu\mu}^{eV}| < 0.11 \quad (90\% \text{ C.L.})$$

- IceCube data can also constrain NSI couplings Esmaili & Smirnov, 2013

$$-0.006 < \epsilon_{\mu\tau}^{dV} < 0.0054 \quad (90\% \text{ C.L.}) \quad \text{Salvado et al, 2017}$$

⇒ best limit in $\mu\tau$ sector, obtained assuming $\epsilon_{\alpha\alpha} = 0$

NSI in reactor experiments

- CC-like NSI at the production / detection processes in Daya Bay may affect the robustness of the recent θ_{13} determination

$$\begin{aligned}
 P_{\bar{\nu}_e^s \rightarrow \bar{\nu}_e^d} \simeq & \underbrace{1 - \sin^2 2\theta_{13} (c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}) - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{21}}_{\text{Standard Model terms}} \\
 & + \underbrace{4|\varepsilon_e| \cos \phi_e + 4|\varepsilon_e|^2 + 2|\varepsilon_e|^2 \cos 2\phi_e + 2|\varepsilon_\mu|^2 + 2|\varepsilon_\tau|^2}_{\text{non-oscillatory NSI terms}} \\
 & - \underbrace{4\{s_{23}^2 |\varepsilon_\mu|^2 + c_{23}^2 |\varepsilon_\tau|^2 + 2s_{23}c_{23}|\varepsilon_\mu||\varepsilon_\tau| \cos(\phi_\mu - \phi_\tau)\} \sin^2 \Delta_{31}}_{\text{oscillatory NSI terms}} \\
 & - \underbrace{4\{2s_{13}[s_{23}|\varepsilon_\mu| \cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau| \cos(\delta - \phi_\tau)]\} \sin^2 \Delta_{31}}_{\text{oscillatory NSI terms}}.
 \end{aligned}$$

shift in θ_{13} :

$$\begin{aligned}
 s_{13}^2 \rightarrow & s_{13}^2 + s_{23}^2 |\varepsilon_\mu|^2 + c_{23}^2 |\varepsilon_\tau|^2 + 2s_{23}c_{23}|\varepsilon_\mu||\varepsilon_\tau| \cos(\phi_\mu - \phi_\tau) \\
 & + 2s_{13}[s_{23}|\varepsilon_\mu| \cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau| \cos(\delta - \phi_\tau)]
 \end{aligned}$$

Leitner et al, JHEP 2011

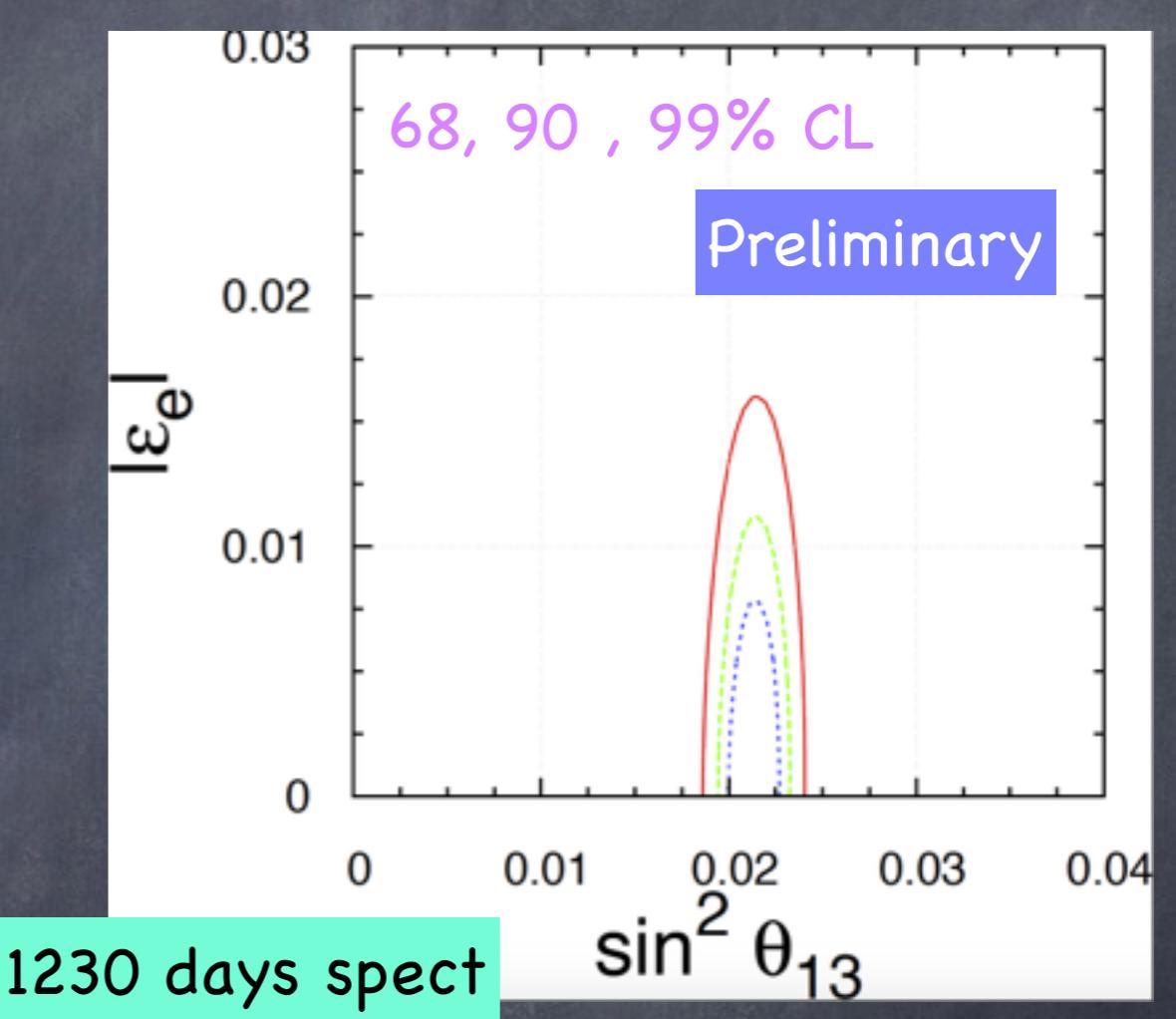
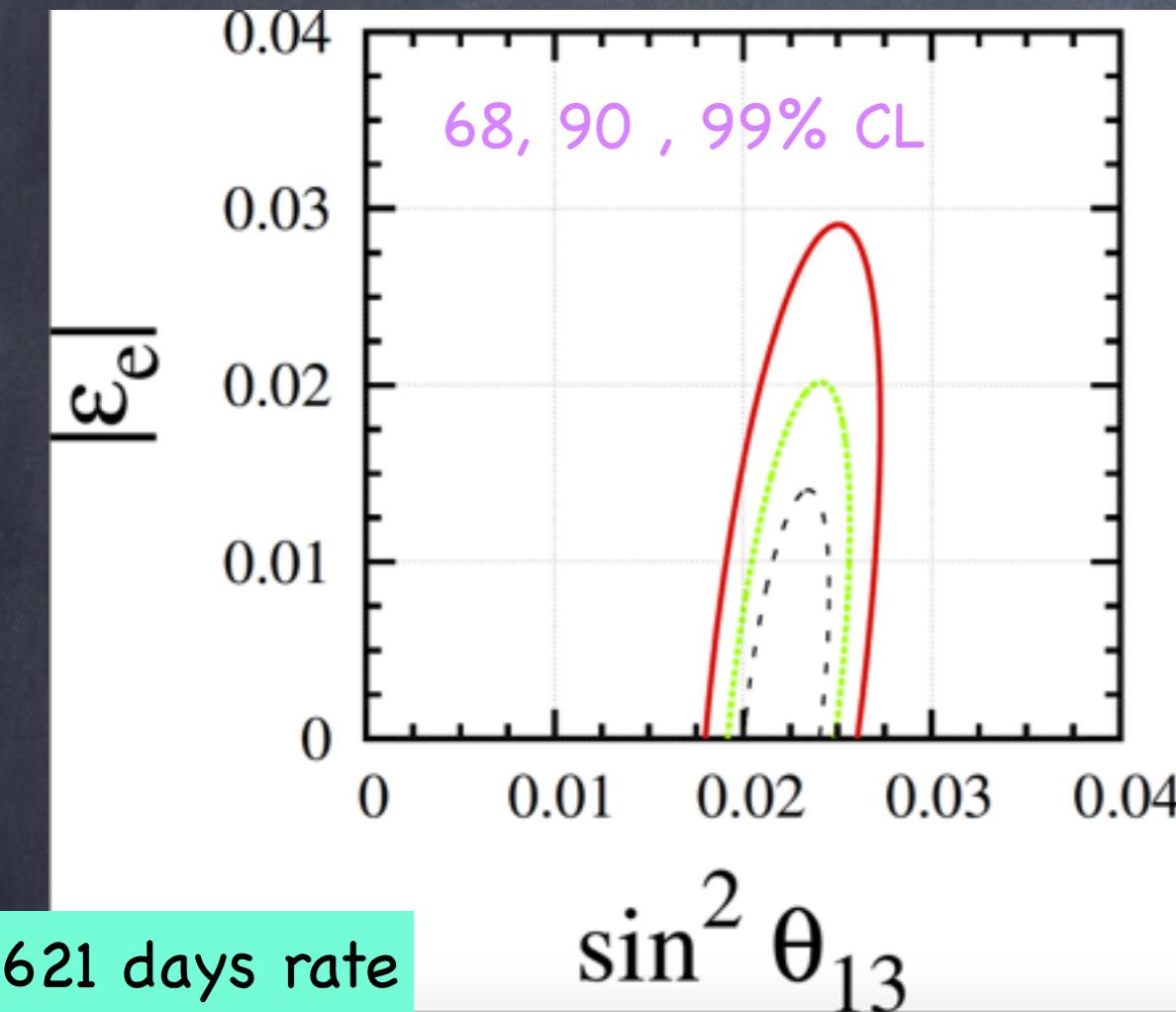
existing bounds: $|\varepsilon_{e,\tau}| < 0.041$, $|\varepsilon_\mu| < 0.026$, (90% C.L.)

Biggio et al, JHEP 2009

- study robustness of θ_{13} measurement
- derive bounds on NSI couplings with Daya Bay data

NSI in Daya Bay

Agarwalla et al, JHEP 2015



5% uncert on flux

$$|\varepsilon_e| < 0.015 \text{ (90\% C.L.)}$$

improved bound on ε_e

2% uncert on flux

$$|\varepsilon_e| < 0.007 \text{ (90\% C.L.)}$$

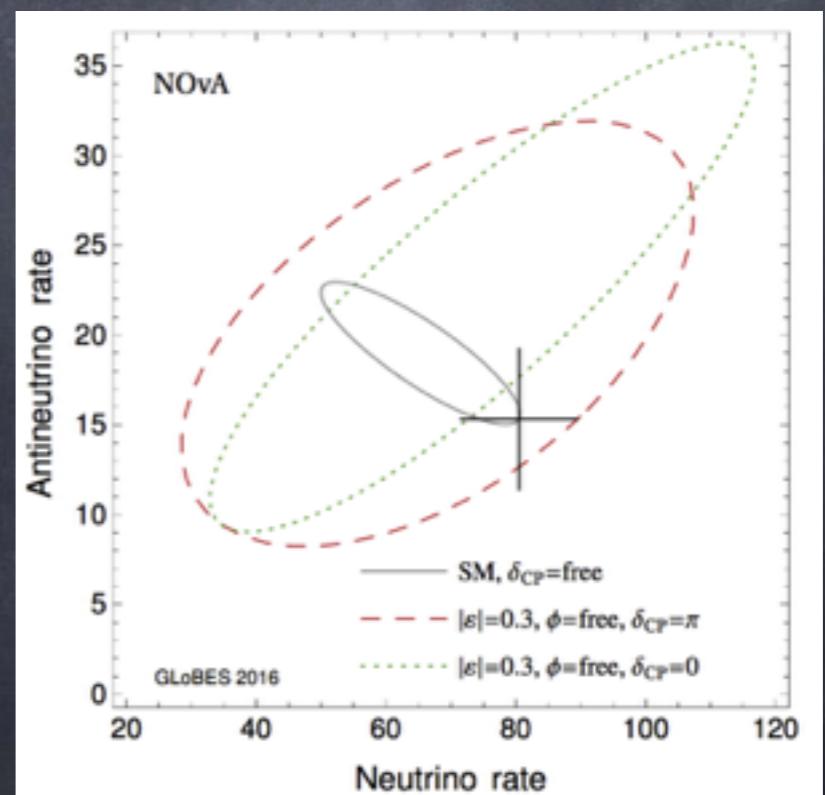
robust θ_{13} determination

See also Girardi & Meloni and Girardi et al, 2014

NSI in long-baseline experiments

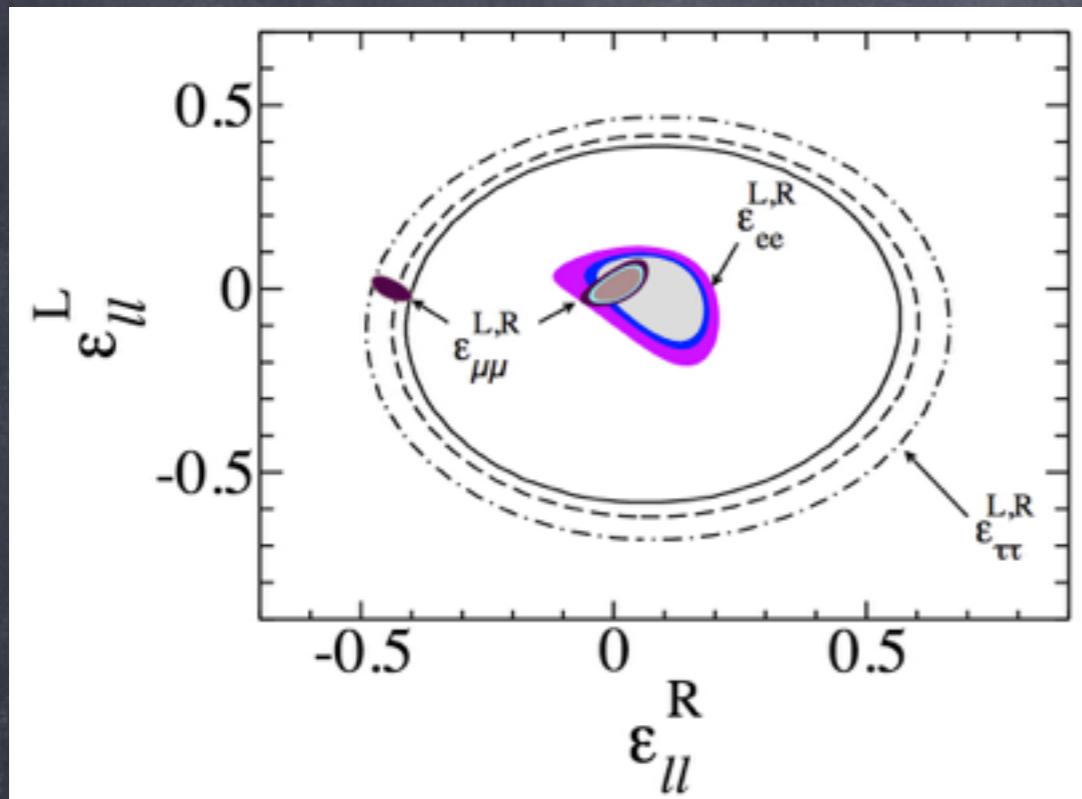
- MINOS $-0.20 < \epsilon_{\mu\tau}^{eV} < 0.07$ (90% C.L.) Adamson et al, PRD 2013
 $|\epsilon_{e\tau}^{eV}| < 3.0$ (90% C.L.) Adamson et al, PRD 2017
- Explanation for the tension in θ_{23} between T2K and NOvA Liao et al, PLB 2017
- NSI in LBL experiments may affect sensitivity to δ_{CP}
⇒ confusion between NSI and CPV

Forero & Huber, PRL 2016



NSI in non-oscillation neutrino experiments

- neutrino-electron scattering

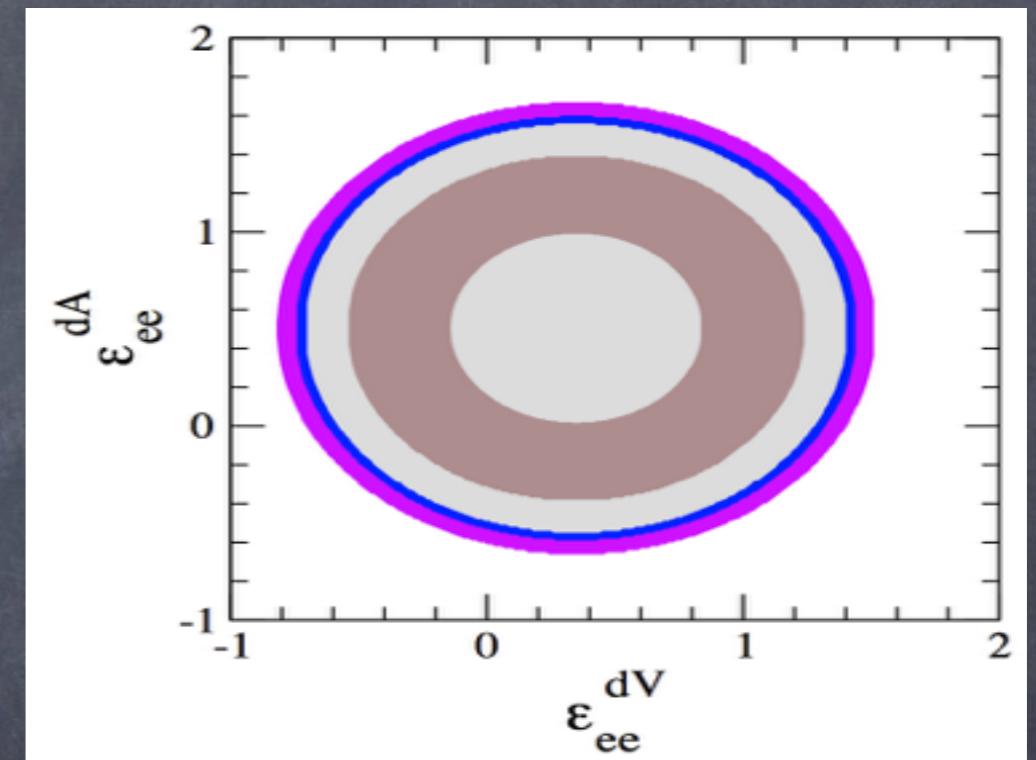


Barranco et al, PRD 2007

TEXONO

Deniz et al, PRD 2010

- neutrino-nucleus scattering



Davidson et al, JHEP 2003

Escrihuela et al, PRD 2011

- coherent neutrino-nucleus scattering

Akimov et al, Science 2017

⇒ NSI bounds

Coloma et al, Liao&Marfatia, Papoulias&Kosmas, 2017

90% C.L. bounds on NU-NSI

$$\epsilon_{\alpha\alpha}^{fP}$$

| 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] [-0.25, 0.43] | solar + KamLAND and Borexino reactor + accelerator |
| $\epsilon_{\tau\tau}^{eV}$ | [-0.11, 0.11] | atmospheric |

90% C.L. bounds on FC-NSI

$$\epsilon_{\alpha\beta}^{fP}$$

| 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] [-0.19, 0.19] | reactor + accelerator TEXONO |
| $\epsilon_{\mu\tau}^{eL}, \epsilon_{\mu\tau}^{eR}$ | [-0.10, 0.10] | reactor + accelerator |
| $\epsilon_{\mu\tau}^{eV}$ | [-0.018, 0.016] | IceCube |

90% C.L. bounds on CC-NSI

$$\epsilon_{\alpha\beta}^{ff'P}$$

| semileptonic NSI | | |
|--|-----------------|-----------------|
| ϵ_{ee}^{udP} | [-0.015, 0.015] | Daya Bay |
| $\epsilon_{e\mu}^{udL}$ | [-0.026, 0.026] | NOMAD |
| $\epsilon_{e\mu}^{udR}$ | [-0.037, 0.037] | NOMAD |
| $\epsilon_{\tau e}^{udL}$ | [-0.087, 0.087] | NOMAD |
| $\epsilon_{\tau e}^{udR}$ | [-0.12, 0.12] | NOMAD |
| $\epsilon_{\tau \mu}^{udL}$ | [-0.013, 0.013] | NOMAD |
| $\epsilon_{\tau \mu}^{udR}$ | [-0.018, 0.018] | NOMAD |
| purely leptonic NSI | | |
| $\epsilon_{\alpha e}^{\mu e L}, \epsilon_{\alpha e}^{\mu e R}$ | [-0.025, 0.025] | KARMEN |
| $\epsilon_{\alpha\beta}^{\mu e L}, \epsilon_{\alpha\beta}^{\mu e R}$ | [-0.030, 0.030] | kinematic G_F |

NSI prospects at
upcoming experiments

NSI at future atmospheric experiments

- PINGU: 3 years of data, 2-100 GeV:
(90% CL)

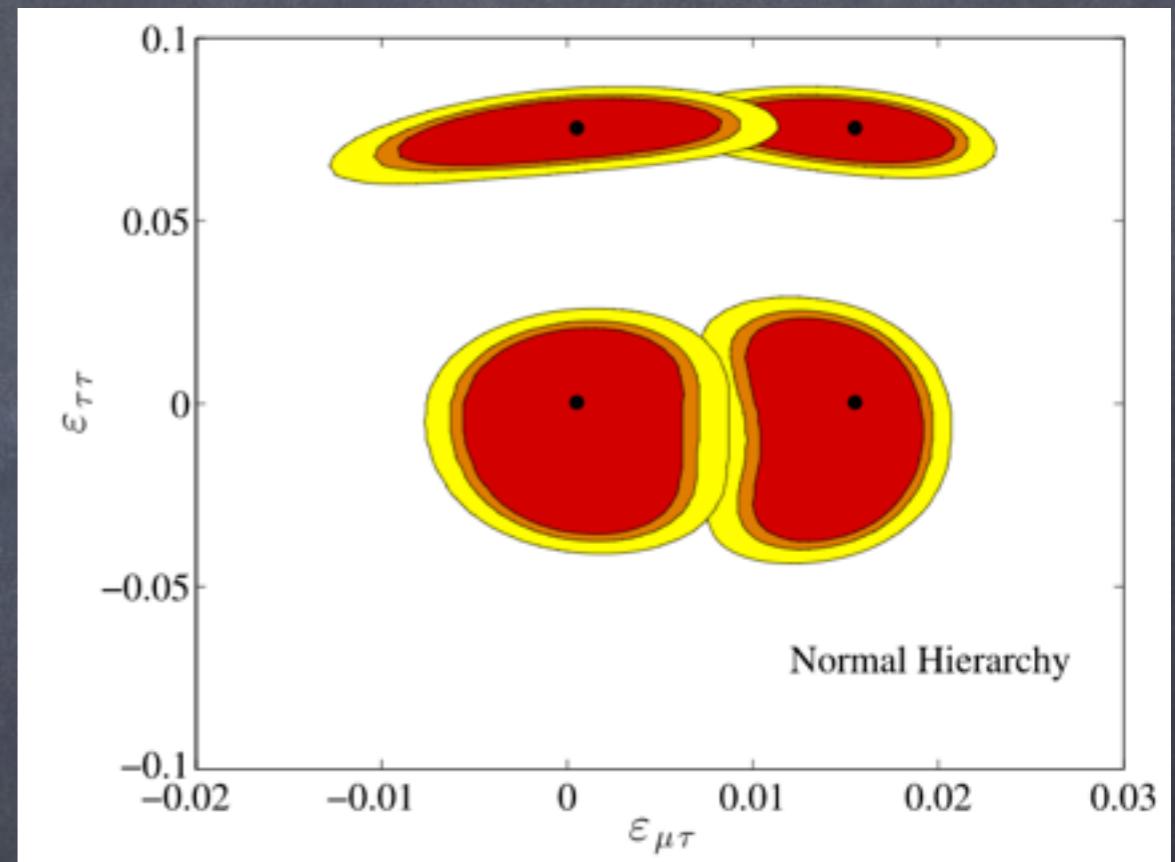
$$-0.0043 < \epsilon_{\mu\tau}^{eV} < 0.0047$$
$$-0.03 < \epsilon_{\tau\tau}^{eV} < 0.017$$

Choubey & Ohlsson, PLB 2014

- INO: 10 years of data, NH:

(90% CL)

$$-0.119 < \epsilon_{e\mu}^{eV} < 0.102$$
$$-0.127 < \epsilon_{e\tau}^{eV} < 0.1$$
$$-0.015 < \epsilon_{\mu\tau}^{eV} < 0.015$$
$$-0.073 < \epsilon_{\tau\tau}^{eV} < 0.073$$

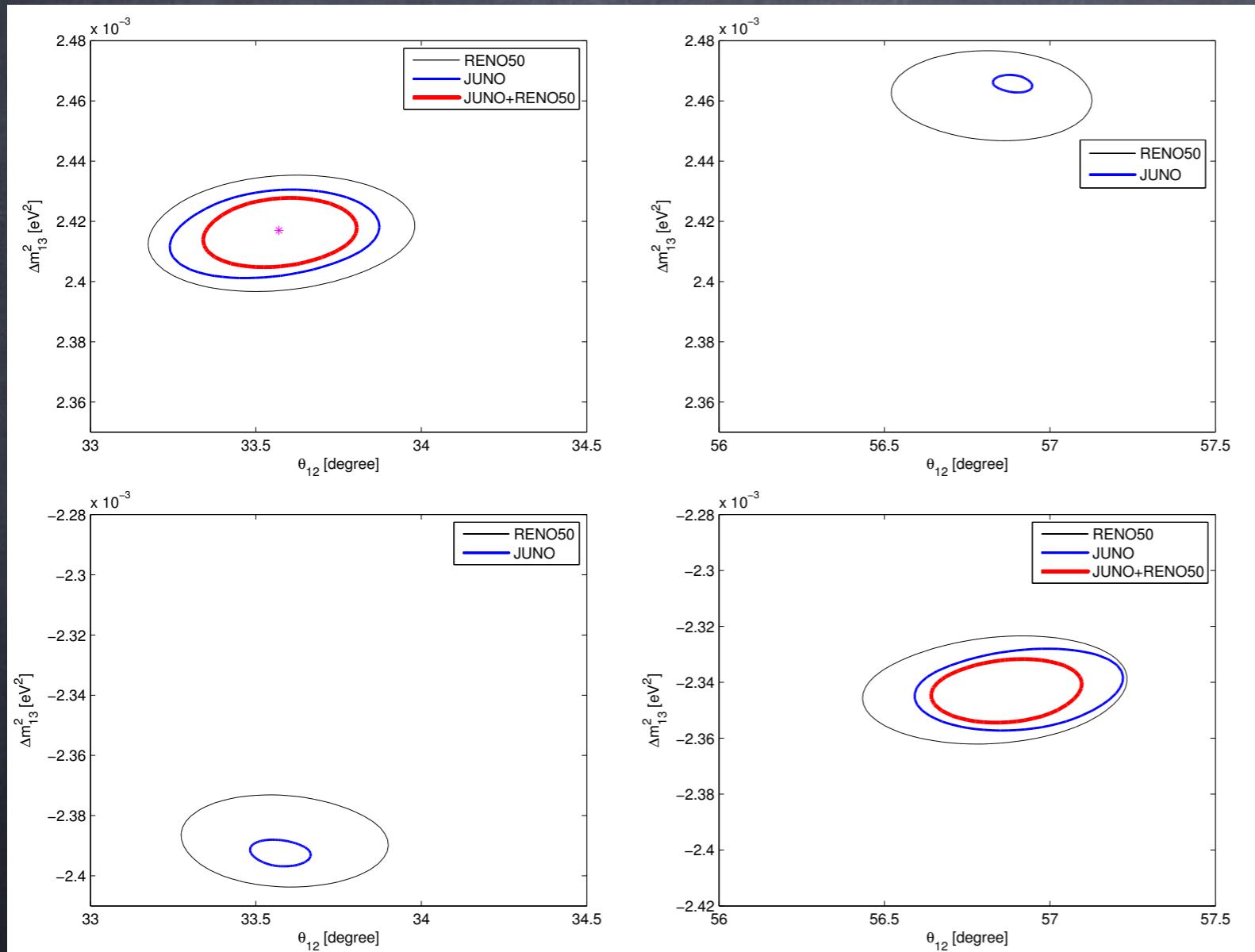


NH determination sensitive to
 $\epsilon_{e\mu}, \epsilon_{e\tau}$

Choubey et al, JHEP 2015

NSI at future reactor experiments

- JUNO and RENO-50 can test LMA-Dark solution with $\theta_{12} > \pi/4$



3σ contour levels for:

- 3% E-resolution
 - 5 years of data
- $\Rightarrow \theta_{12}$ octant determination
for a given mass ordering

However

\Rightarrow degenerate solution

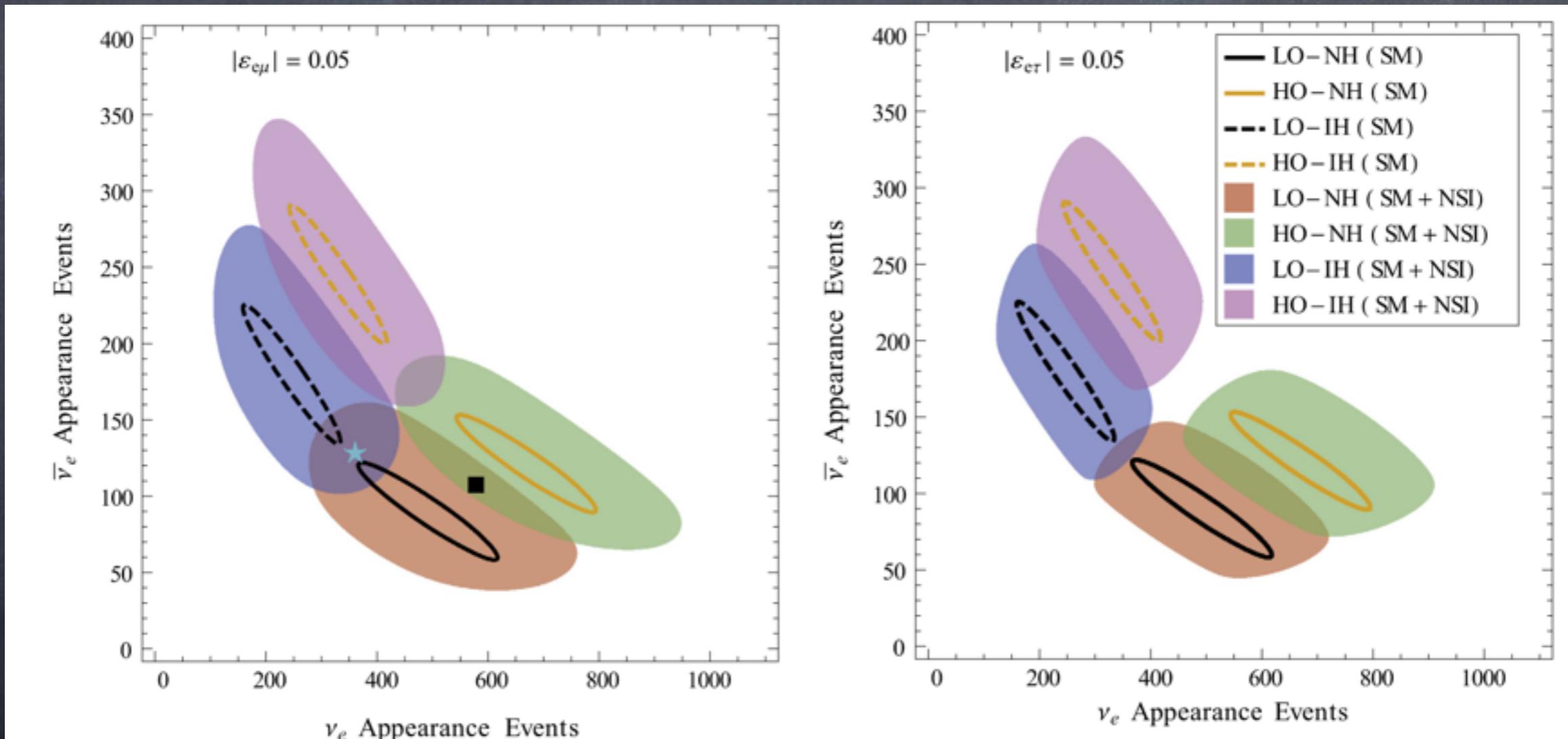
$$\theta_{12} \rightarrow \pi/2 - \theta_{12}$$

$$\Delta m_{31}^2 \rightarrow -\Delta m_{31}^2 + \Delta m_{21}^2$$

Coloma & Schwetz, PRD 2016

NSI at future LBL experiments

Degeneracies in determination of θ_{23} octant in DUNE

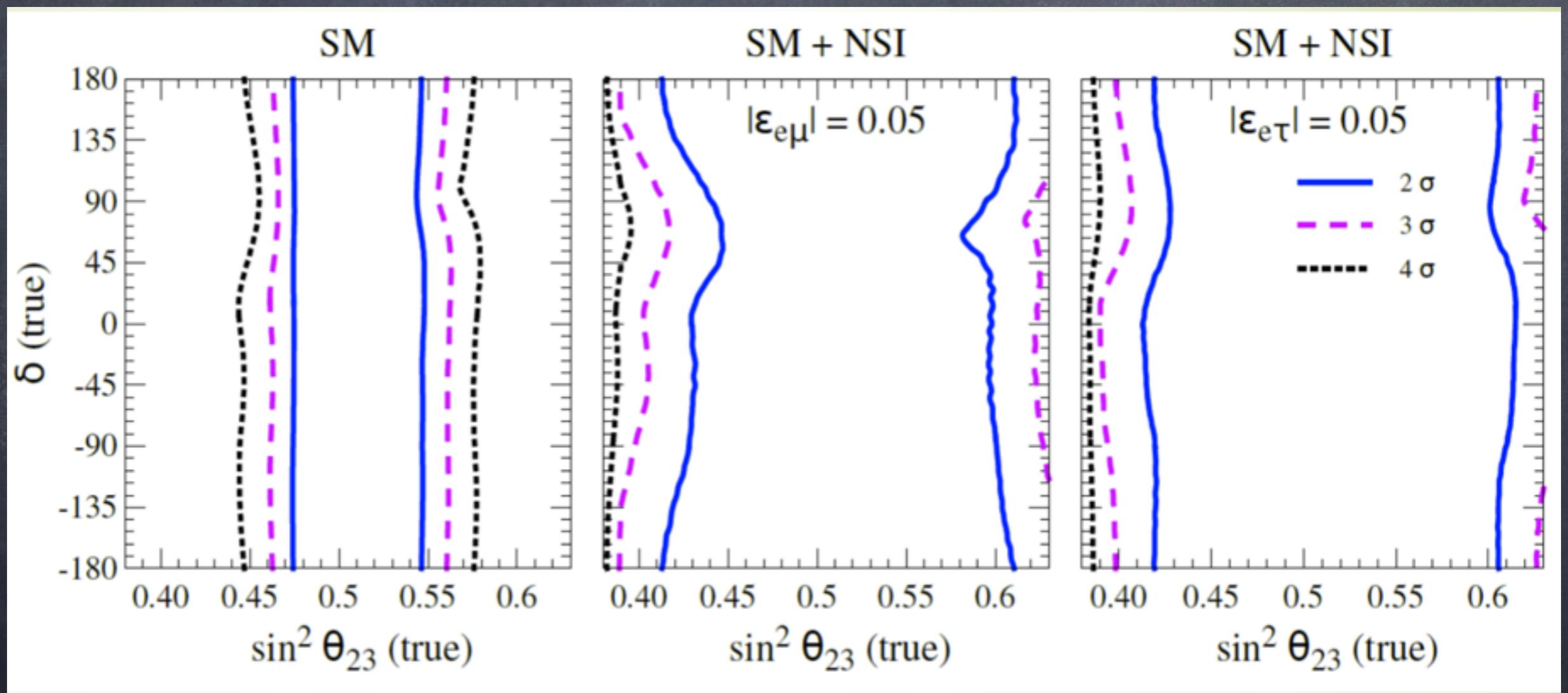


Agarwalla et al, PLB 2016

⇒ interference term in ϕe^α can mimic swap in the octant

NSI at future LBL experiments

Degeneracies in determination of θ_{23} octant in DUNE

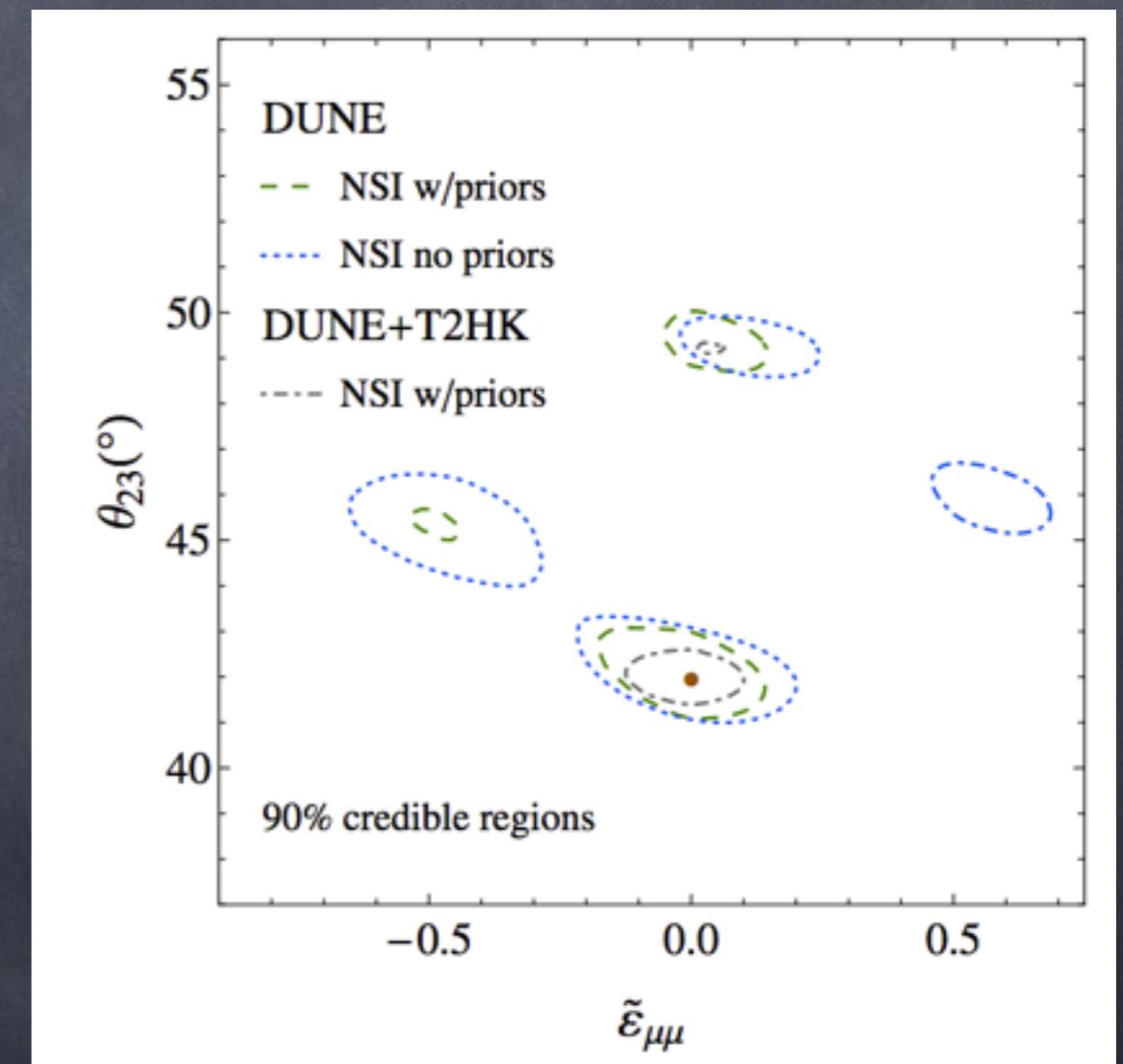
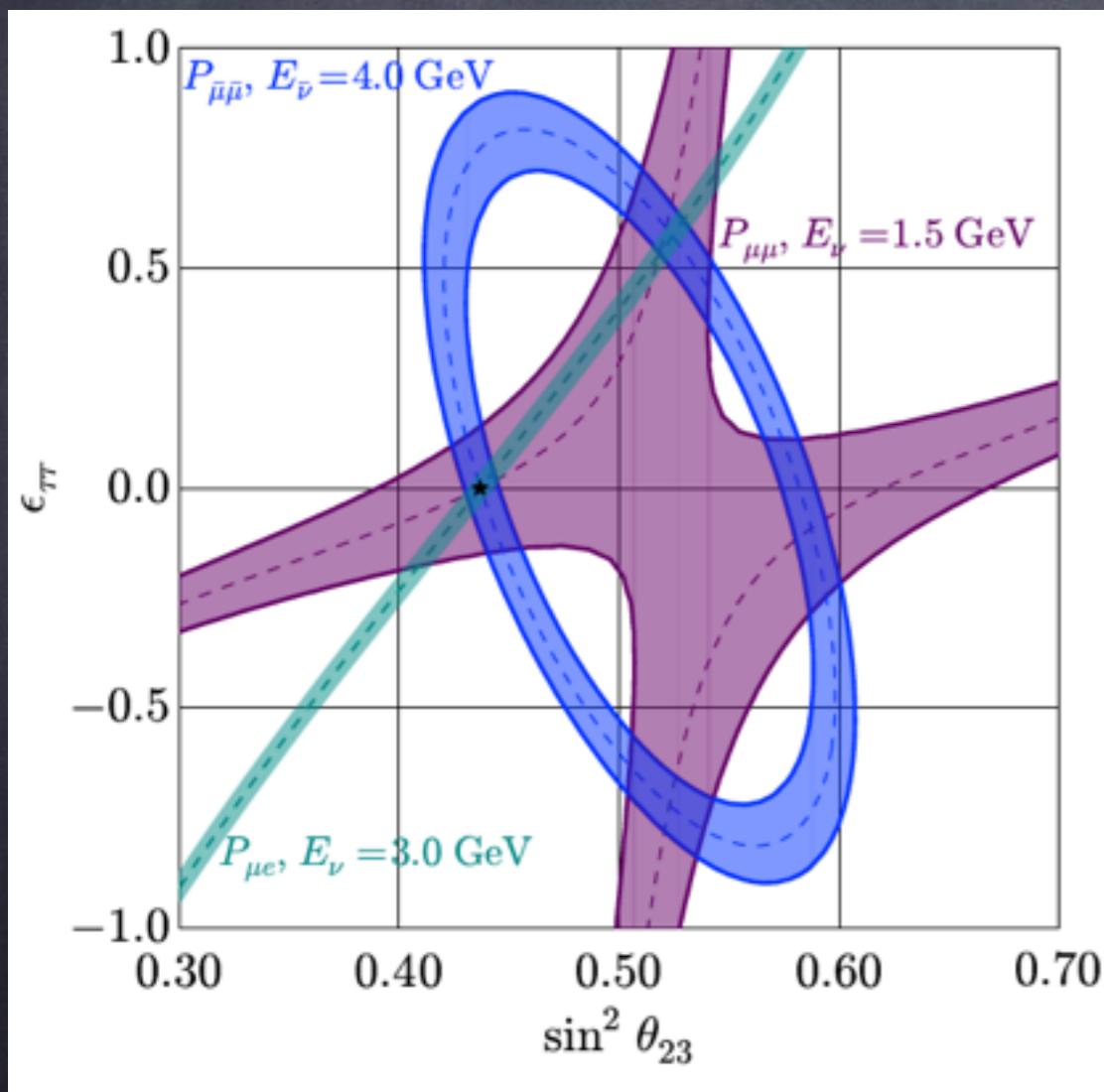


Agarwalla et al, PLB 2016

⇒ interference term in ϕe^α can mimic swap in the octant

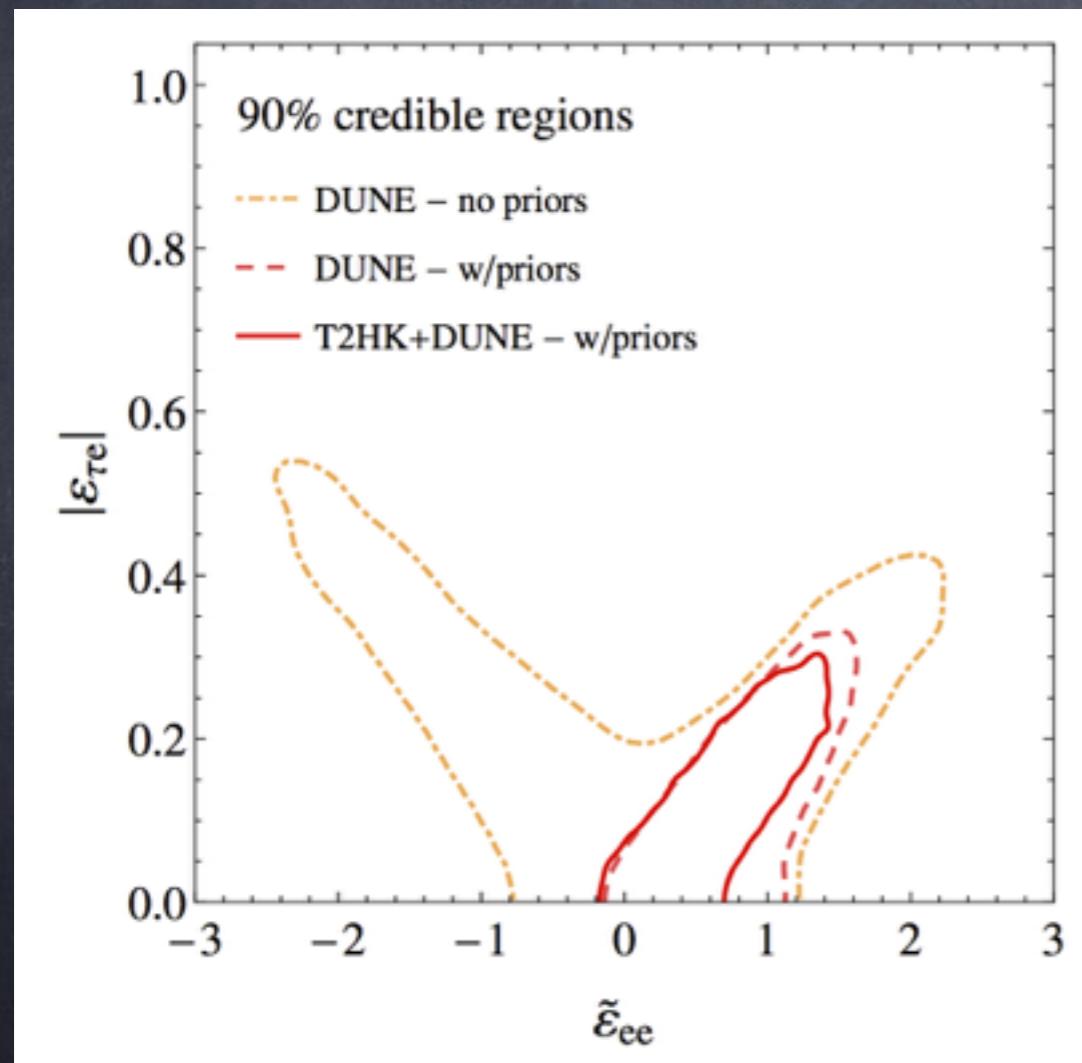
NSI at future LBL experiments

$(\theta_{23} - \epsilon_{\tau\tau})$ degeneracy in DUNE

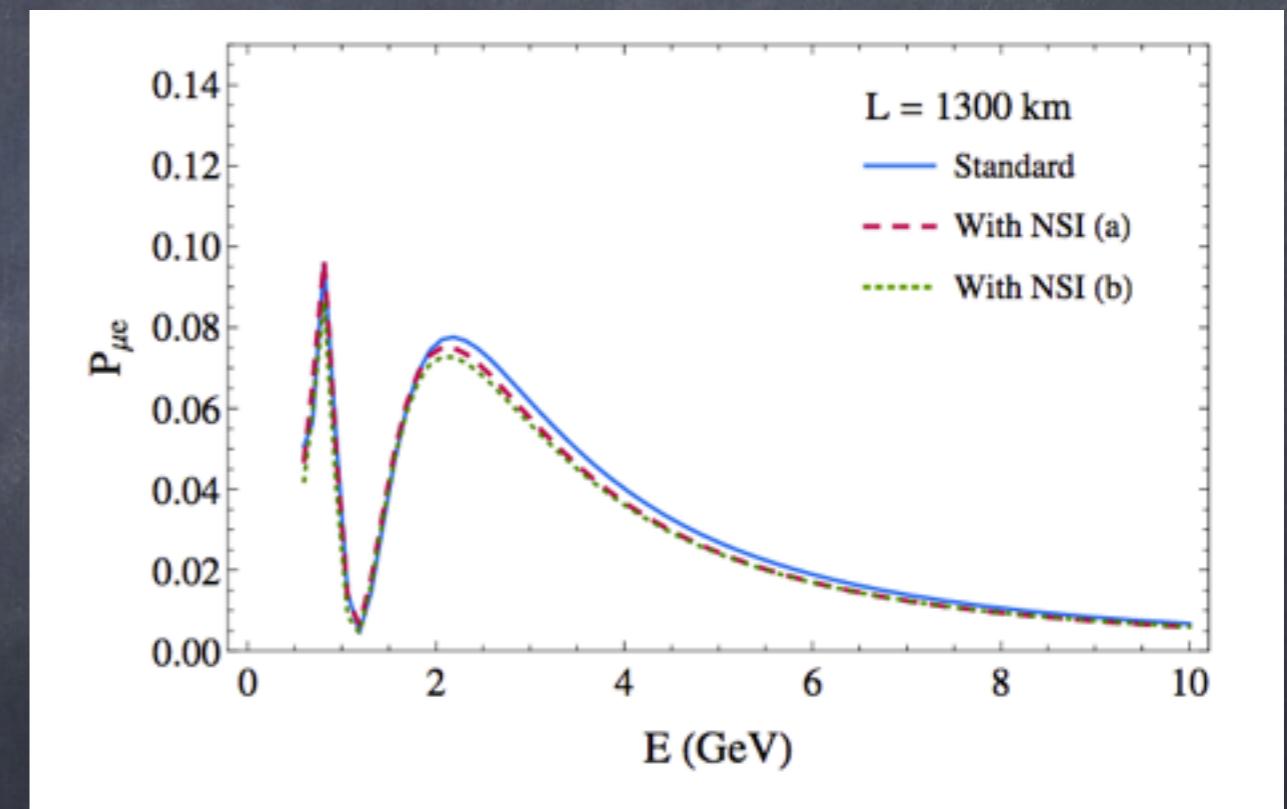


NSI at future LBL experiments

$(\delta - \epsilon_{ee} - \epsilon_{e\tau})$ degeneracy in DUNE



⇒ it may affect CP-violation sensitivity

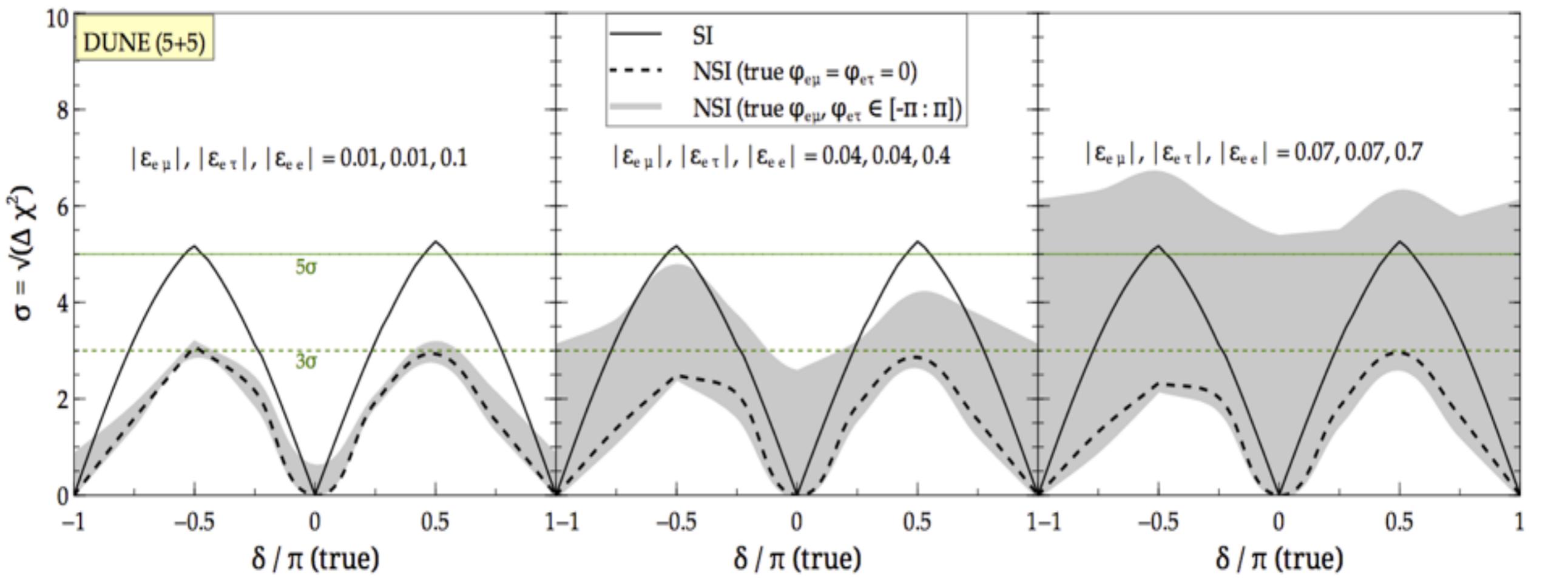


a) $\delta = -90^\circ, \epsilon_{ee} = -2, \epsilon_{e\tau} = 0.45, \phi_{\tau e} = -130^\circ$

b) $\delta = -90^\circ, \epsilon_{ee} = 1, \epsilon_{e\tau} = 0.25, \phi_{\tau e} = 100^\circ$

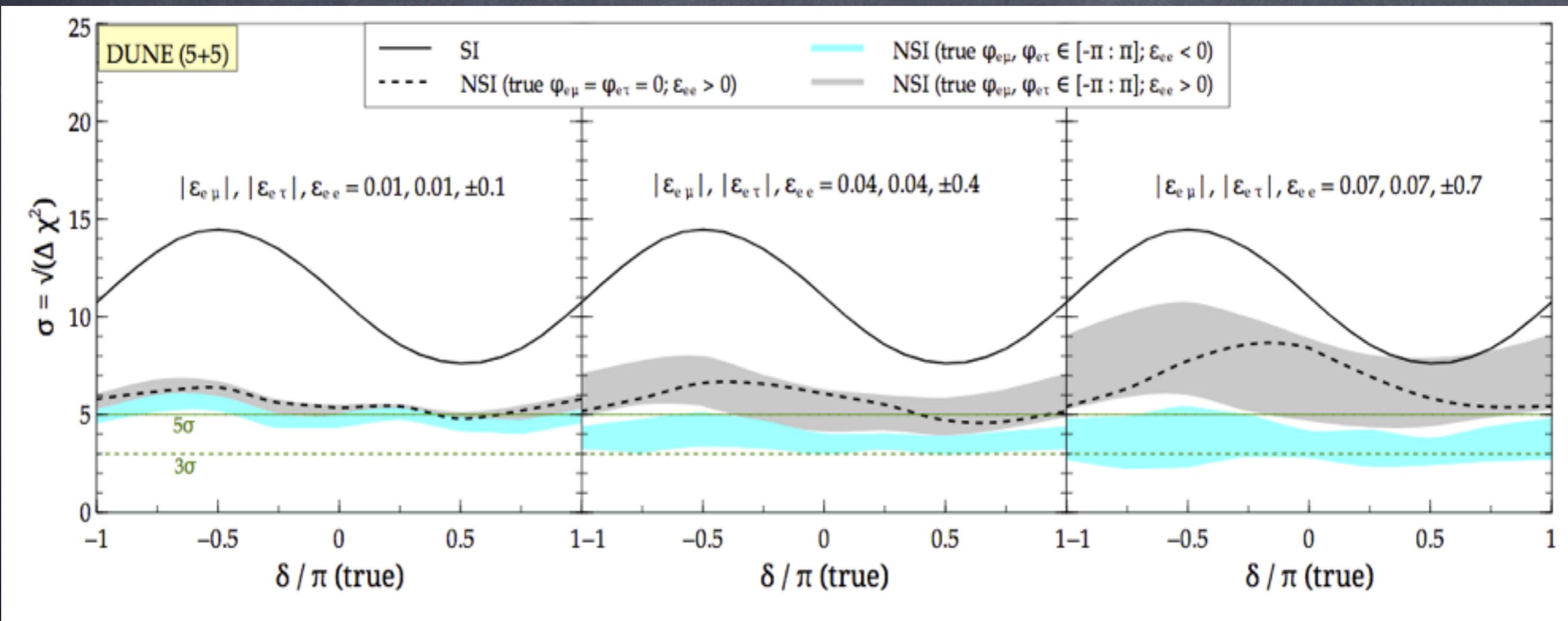
NSI at future LBL experiments

NSI significantly spoil sensitivity to CP violation in DUNE



NSI at future LBL experiments

NSI significantly spoil sensitivity to mass ordering in DUNE



NSI at future LBL experiments

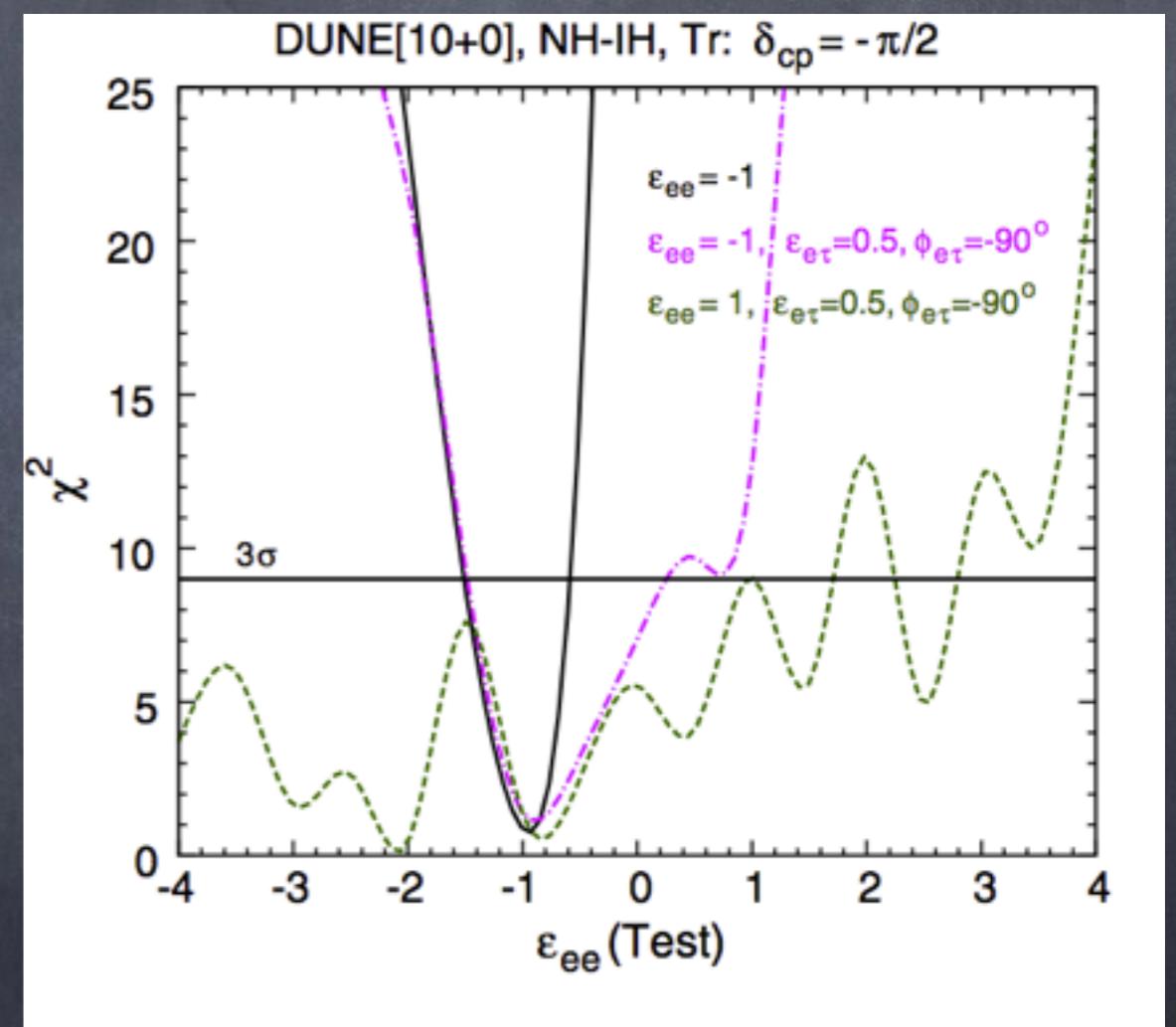
NSI can jeopardize determination of mass ordering in DUNE

⇒ degeneracies in appearance probability:

$$P_{\mu e}^{\text{NH}}(\epsilon_{ee}, \delta, \epsilon_{e\tau}, \phi_{e\tau}) = P_{\mu e}^{\text{IH}}(\epsilon'_{ee}, \delta, \epsilon'_{e\tau}, \phi_{e\tau})$$

strongly affect the sensitivity to the mass hierarchy

(less relevant for small values of NSI)



Summary

- NSI can give signals in different neutrino oscillation and non-oscillation experiments
- No evidence for NSI reported so far, but only upper bounds on its magnitude.
- We have reviewed existing direct bounds on NSI, from neutrino production, detection and propagation in matter.
- NSI will also be probed at future neutrino experiments, improving current bounds.
- The presence of degeneracies due to NSI may severely affect future sensitivity to δ , mass hierarchy or θ_{23} octant.