DUNE Physics Week BSM Group - NSI Group update

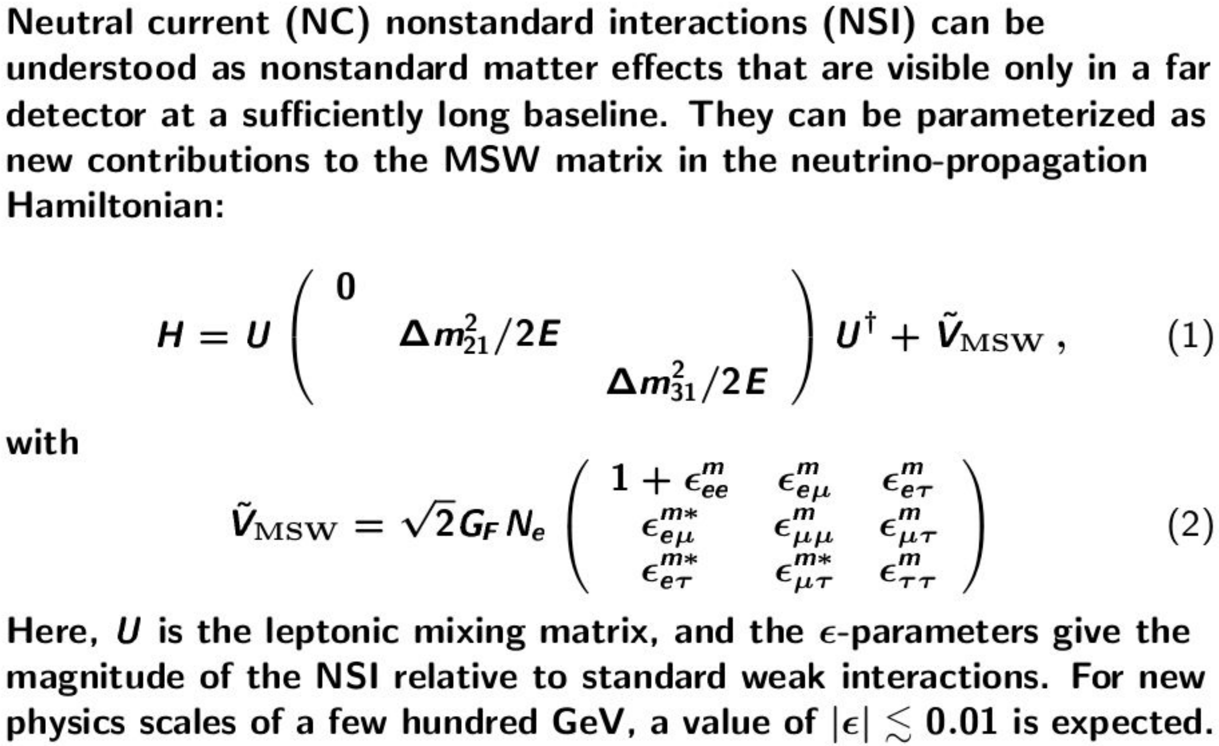
November 15, 2017

Celio A. Moura (UFABC) for the NSI group

Topics

- Present CDR bounds;
- Bounds from the literature (considering all parameters free);
- Including matter density profile;
    - Effects on standard oscillation from a detailed matter profile inclusion;
    - Effects on NSI bounds from a detailed matter profile consideration as well as letting all parameters free.

From DUNE CDR Physics Volume: arXiv:1307.7335



Neutral current (NC) nonstandard interactions (NSI) can be understood as nonstandard matter effects that are visible only in a far detector at a sufficiently long baseline. They can be parameterized as new contributions to the MSW matrix in the neutrino-propagation Hamiltonian:

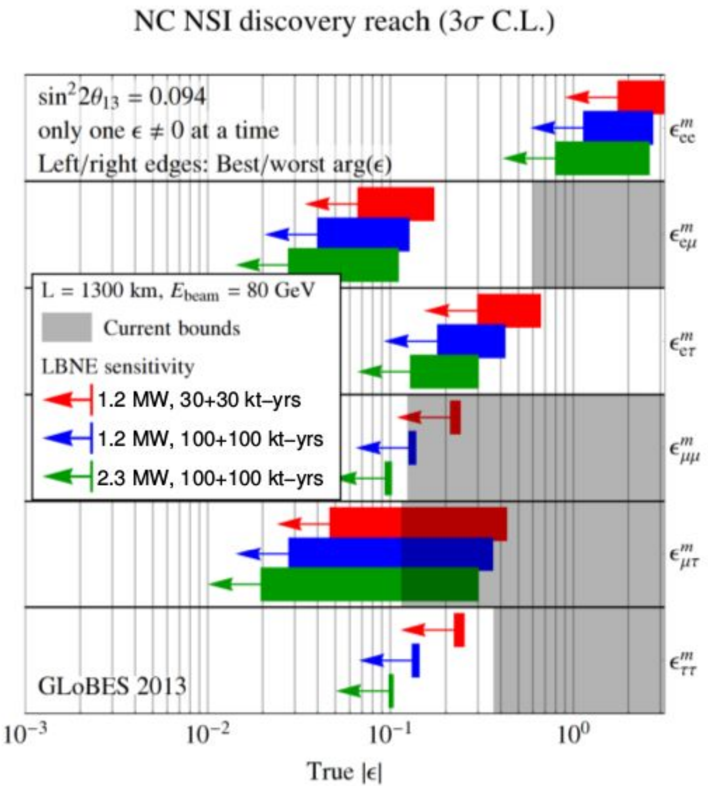
$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}} \,, \qquad (1)$$

with

$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix} \qquad (2)$$

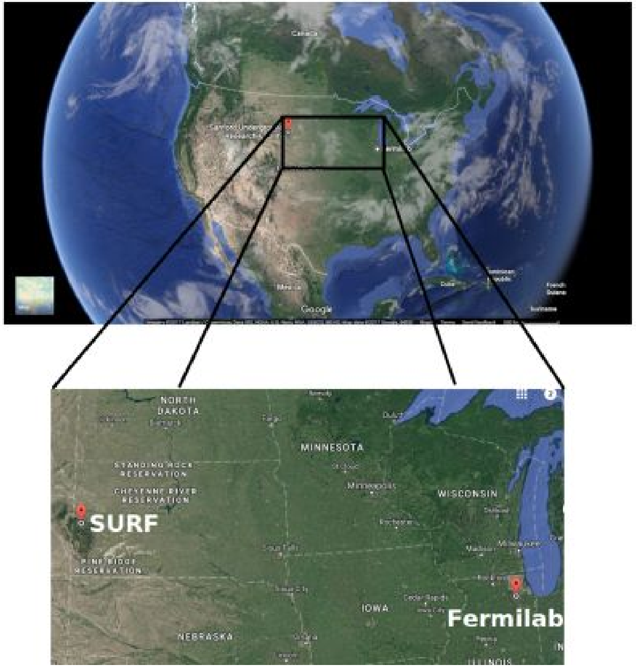
Here, U is the leptonic mixing matrix, and the ϵ-parameters give the magnitude of the NSI relative to standard weak interactions. For new physics scales of a few hundred GeV, a value of $|\epsilon| \lesssim 0.01$ is expected.

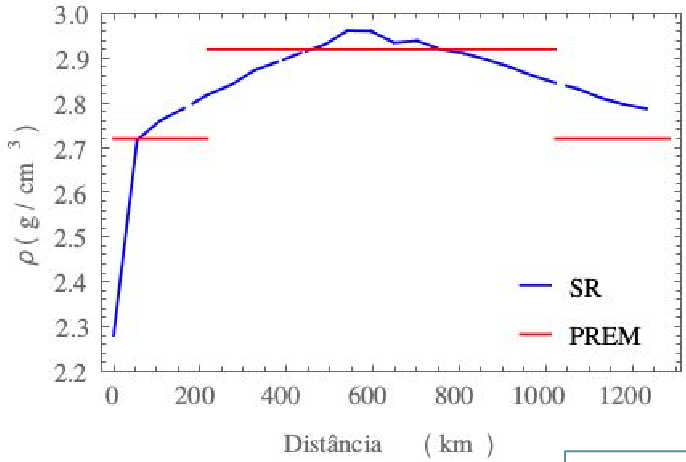
From DUNE CDR Physics Volume: arXiv:1307.7335



- Bounds for one relevant parameter at a time. Other NSI parameters considered negligible.
  - What is the effect of having two or more NSI parameters varying at the same time? Can this loosen the limits?
- What is the matter density profile effect on these bounds?
  - What about the effect on the standard oscillation parameters?
  - Is the PREM profile precise enough for the level of uncertainties DUNE admits?

Effects of the Earth profile along the DUNE baseline





- PREM → 1300 km [1,2]
- SR → 1.284,852 km [3,4]

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[1] A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Interiors 25 (1981), 297–356.

[2] F. D. Stacey, Physics of the earth, 2nd ed., Wiley, 1977.

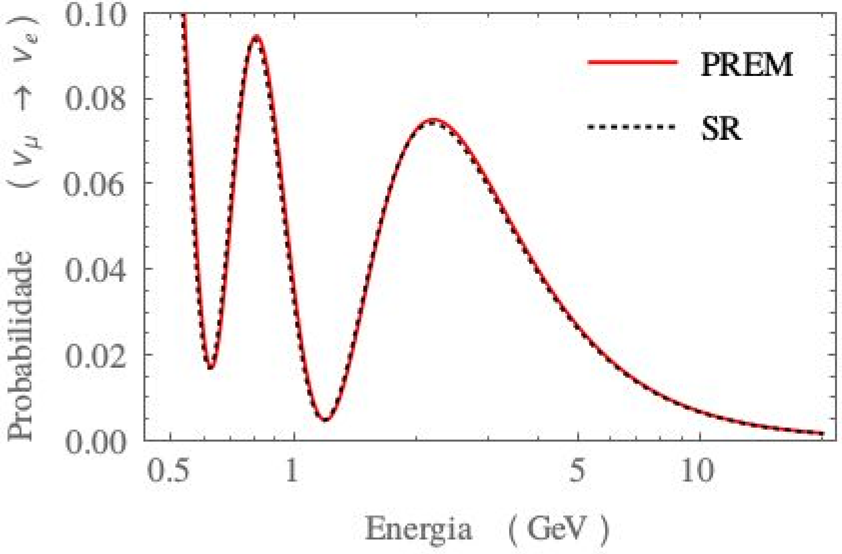
[3] W. Shen and M. H. Ritzwoller. J. of Geophys. Res.: Solid Earth (2016).

[4] B. Roe, Phys. Rev.D **95**, 113004 (2017) [arXiv:1707.02322 [hep-ex]].

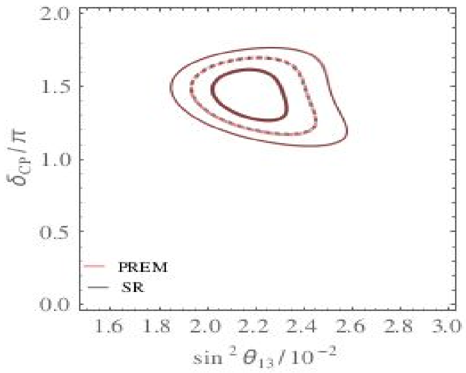
2 free parameter results. PREMxSR

F. Kamiya, O. Peres, M. Guzzo, D. Forero

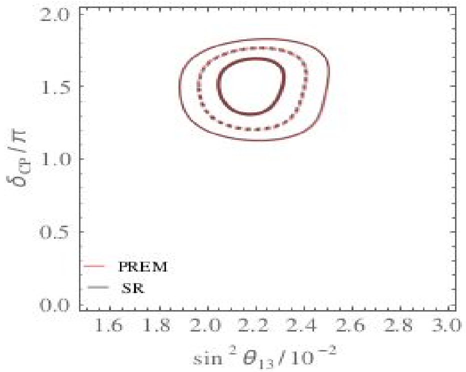
Oscillation Probability



Normal H.



Inverted H.



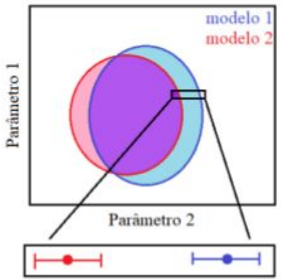
Quantitative estimate deviation. PREMxSR

F. Kamiya, O. Peres, M. Guzzo, D. Forero

Relation between parameters

$$R_\alpha = \left|\frac{\alpha_{\mathrm{min}_{\mathrm{SR}}} - \alpha_{\mathrm{min}_{\mathrm{PREM}}}}{\alpha_{\mathrm{min}_{\mathrm{Int}}}}\right| + \left|\frac{\alpha_{\mathrm{max}_{\mathrm{SR}}} - \alpha_{\mathrm{max}_{\mathrm{PREM}}}}{\alpha_{\mathrm{max}_{\mathrm{Int}}}}\right| .$$

$$\sigma_{R_\alpha} = \sigma_\alpha \left(\frac{(\alpha_{min_{PREM}} - \alpha_{min_{SR}})^2 + 4\alpha^2_{min_{Int}}}{\alpha^4_{min_{Int}}} + \frac{(\alpha_{max_{PREM}} - \alpha_{max_{SR}})^2 + 4\alpha^2_{max_{Int}}}{\alpha^4_{max_{Int}}} \right)^{1/2}$$



Relation between areas

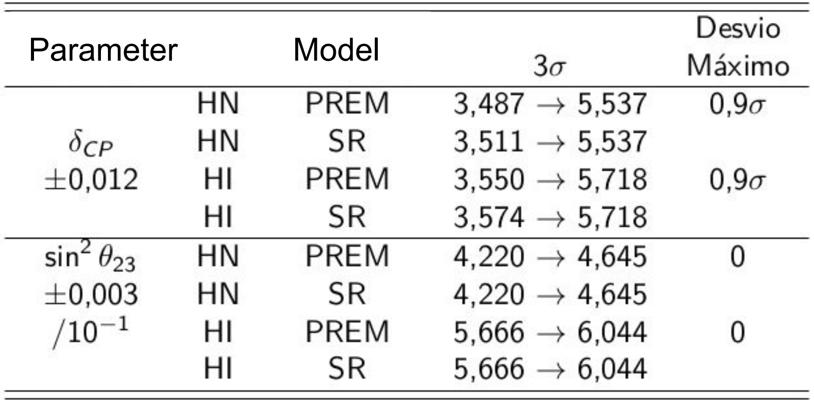
$$R_A = \frac{A_{SR} + A_{PREM} - 2A_{Int}}{A_{Int}} .$$

$$\sigma_{R_A} = \sqrt{\frac{((A_{PREM} + A_{SR})^2 n_{Int} + A^2_{Int}(n_{PREM} + n_{SR}))(\delta^2_\alpha \sigma^2_{\delta_\beta} + \delta^2_\beta \sigma^2_{\delta_\alpha})}{A^4_{Int}}} .$$

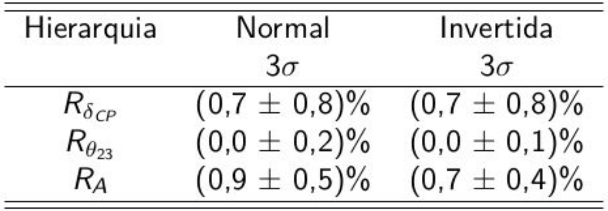
Parameter		Model	3σ	Deviation
δ_{CP} ±0,012	HN	PREM	3,416 → 5,537	$0{,}8\sigma$
	HN	SR	3,440 → 5,537	
	HI	PREM	3,550 → 5,718	$1{,}4\sigma$
	HI	SR	3,574 → 5,741	
$\sin^2\theta_{13}$ ±0,004 $/10^{-2}$	HN	PREM	1,856 → 2,576	0
	HN	SR	1,856 → 2,576	
	HI	PREM	1,885 → 2,501	1σ
	HI	SR	1,892 → 2,501	

Hierarquia	Normal 3σ	Invertida 3σ
$R_{\delta_{CP}}$	(0,7 ± 0,8)%	(1,1 ± 0,8)%
$R_{\theta_{13}}$	(0,0 ± 0,5)%	(0,4 ± 0,5)%
R_A	(1,6 ± 0,5)%	(1,8 ± 0,4)%

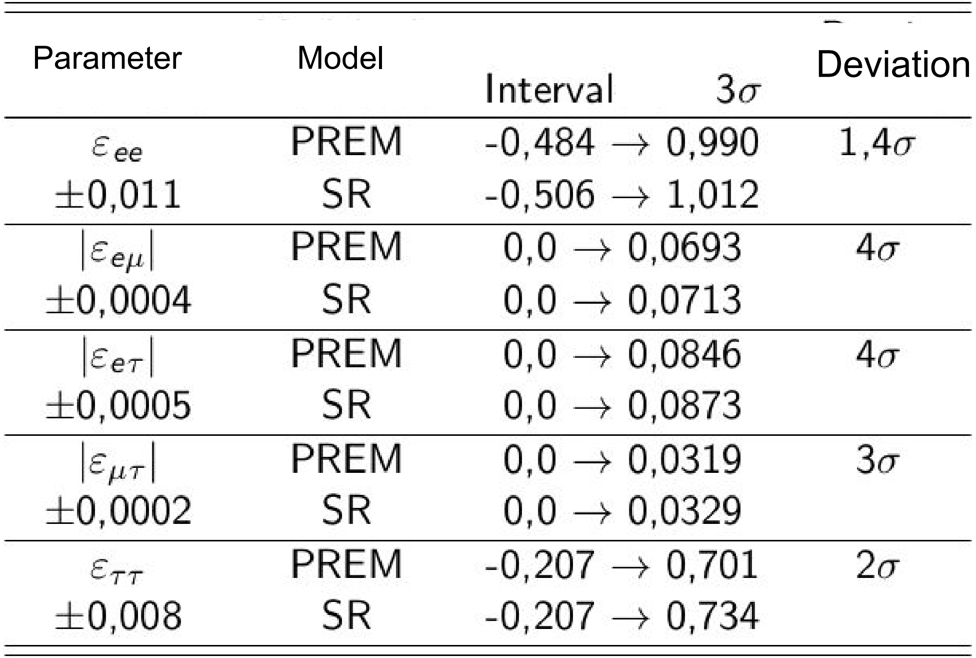
More results for oscillation and NSI



Parameter		Model	3σ	Desvio Máximo
δ_{CP} $\pm 0{,}012$	HN	PREM	3,487 → 5,537	$0{,}9\sigma$
	HN	SR	3,511 → 5,537	
	HI	PREM	3,550 → 5,718	$0{,}9\sigma$
	HI	SR	3,574 → 5,718	
$\sin^2\theta_{23}$ $\pm 0{,}003$ $/10^{-1}$	HN	PREM	4,220 → 4,645	0
	HN	SR	4,220 → 4,645	
	HI	PREM	5,666 → 6,044	0
	HI	SR	5,666 → 6,044	

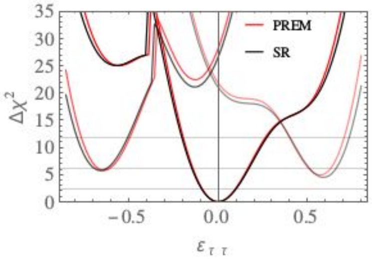


Hierarquia	Normal 3σ	Invertida 3σ
$R_{\delta_{CP}}$	(0,7 ± 0,8)%	(0,7 ± 0,8)%
$R_{\theta_{23}}$	(0,0 ± 0,2)%	(0,0 ± 0,1)%
R_A	(0,9 ± 0,5)%	(0,7 ± 0,4)%



Parameter	Model	Interval 3σ	Deviation
ε_{ee} $\pm 0{,}011$	PREM	-0,484 → 0,990	$1{,}4\sigma$
	SR	-0,506 → 1,012	
$\lvert\varepsilon_{e\mu}\rvert$ $\pm 0{,}0004$	PREM	0,0 → 0,0693	4σ
	SR	0,0 → 0,0713	
$\lvert\varepsilon_{e\tau}\rvert$ $\pm 0{,}0005$	PREM	0,0 → 0,0846	4σ
	SR	0,0 → 0,0873	
$\lvert\varepsilon_{\mu\tau}\rvert$ $\pm 0{,}0002$	PREM	0,0 → 0,0319	3σ
	SR	0,0 → 0,0329	
$\varepsilon_{\tau\tau}$ $\pm 0{,}008$	PREM	-0,207 → 0,701	2σ
	SR	-0,207 → 0,734	

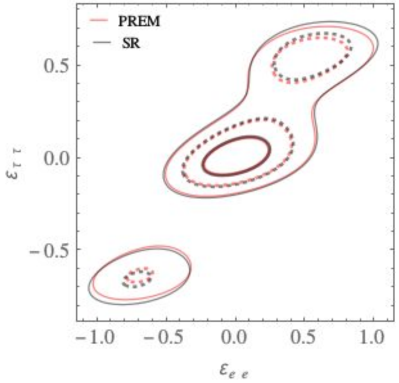
Sensitivity to ε_{ee} vs $\varepsilon_{\tau\tau}$ and $\varepsilon_{e\mu}$ vs $\varepsilon_{\mu\tau}$

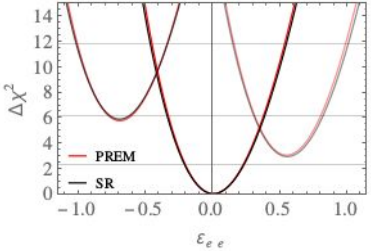


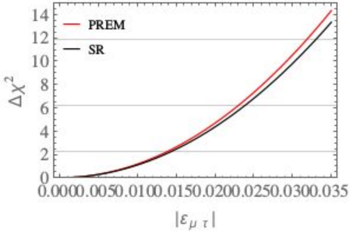
	3σ	Desvio
$R_{\varepsilon_{ee}}$	$(6{,}8 \pm 5{,}1)\%$	$1{,}3\sigma$
$R_{\varepsilon_{\tau\tau}}$	$(5 \pm 9)\%$	0,5 σ
R_A	$(6{,}4 \pm 1{,}3)\%$	

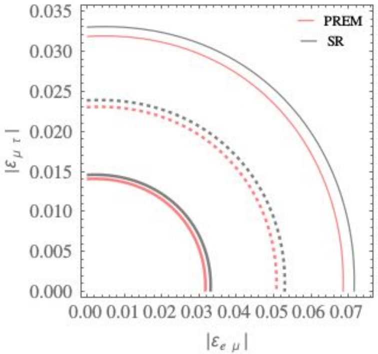
$\nu + \bar{\nu}$ 140 kt-yrs.

1, 2 and 3 sigma

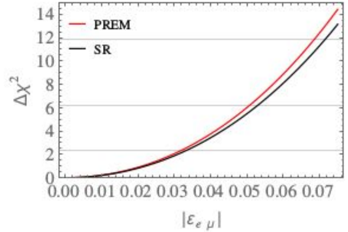








	3σ	Desvio
$R_{\lvert\varepsilon_{e\mu}\rvert}$	$(4 \pm 1)\%$	4σ
$R_{\lvert\varepsilon_{\mu\tau}\rvert}$	$(3 \pm 1)\%$	3σ
R_A	$(8{,}1 \pm 0{,}4)\%$	

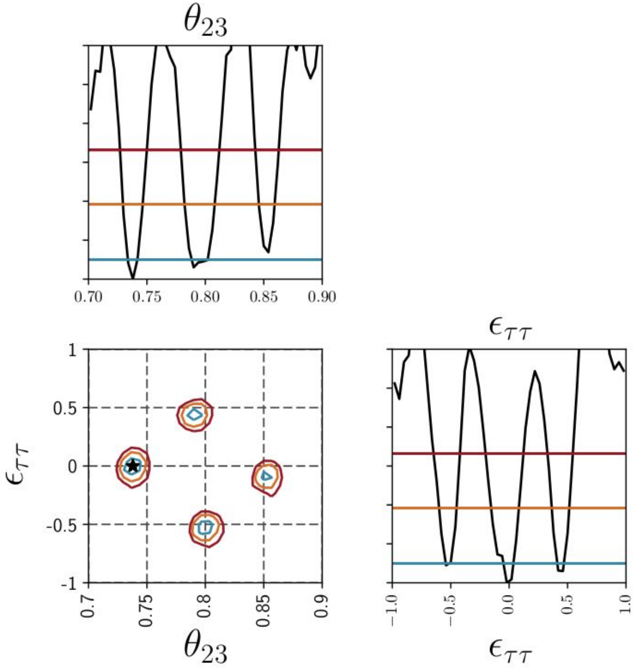


$\nu + \bar{\nu}$ 140 kt-yrs.

All parameters free - Results from A. de Gouvêa and K. Kelly - PREM

Simulation done with DUNE CDR GLoBES file: https://arxiv.org/abs/1606.09550

- PREM - 4 layers
- 3% uncertainty
- 280 kton-yr
- 1.07 MW
- 68.3%, 95%, and 99% CL

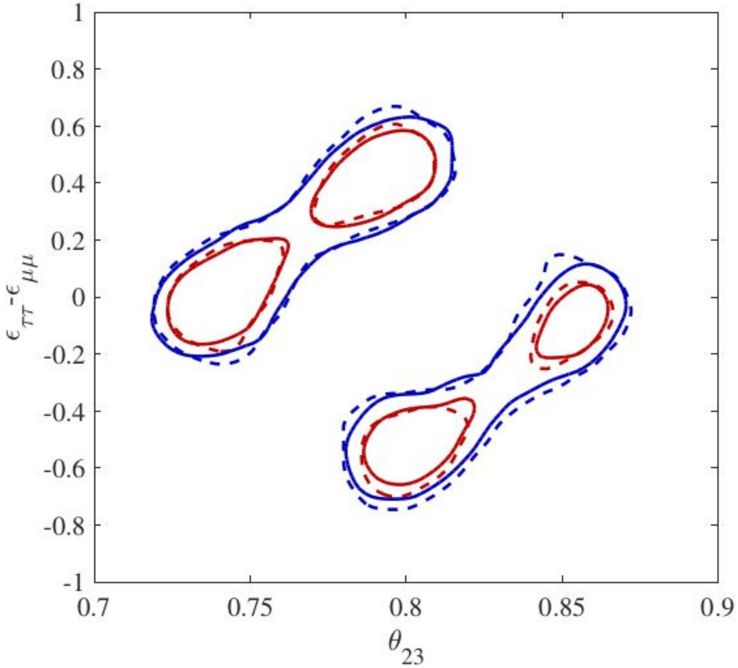


GLoBES results - PREM vs. SR - All free

G. Barenboim and E. Fernandez-Martinez

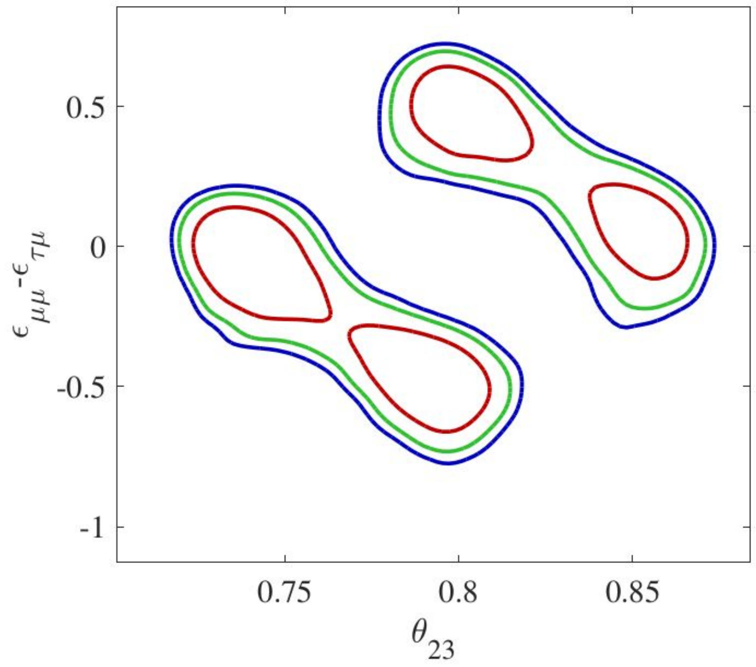
Using basically same assumptions.

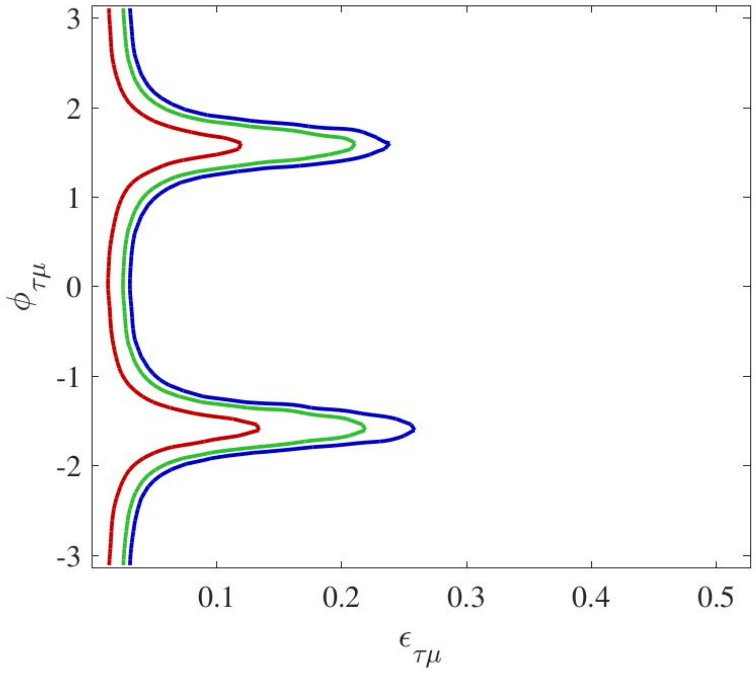
- PREM (Solid lines)
- SR (Dashed lines)
- 1 sigma and 90% CL



GLoBES results - PREM - All free

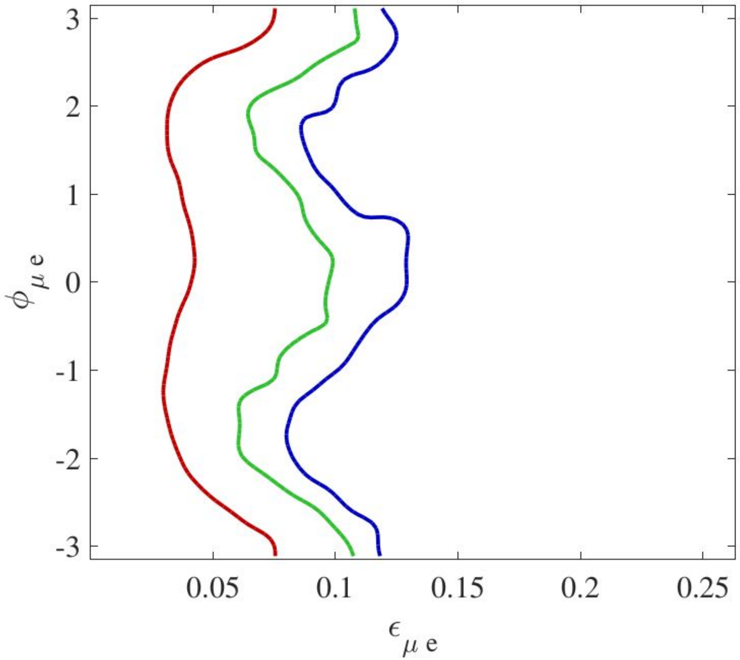
E. Fernandez-Martinez and G. Barenboim

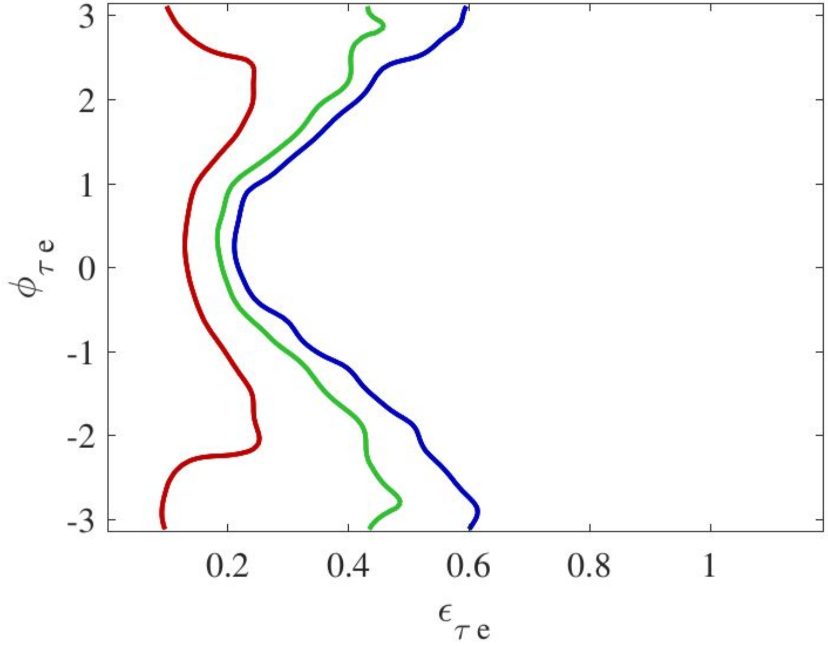




GLoBES results - PREM - All free

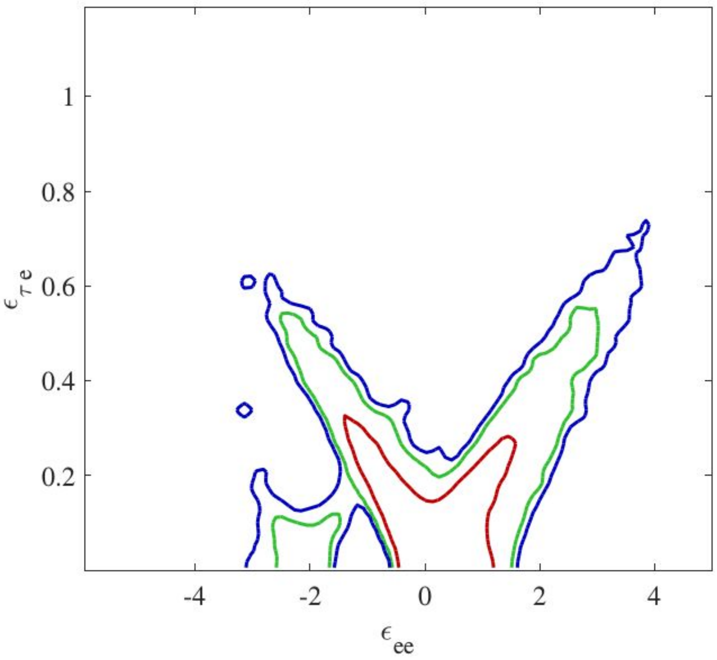
E. Fernandez-Martinez and G. Barenboim

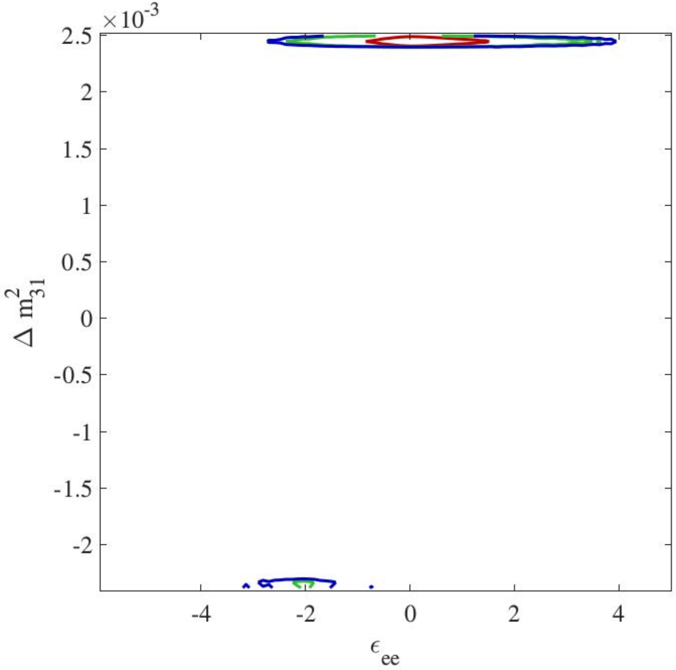




GLoBES results - PREM - All free

E. Fernandez-Martinez and G. Barenboim

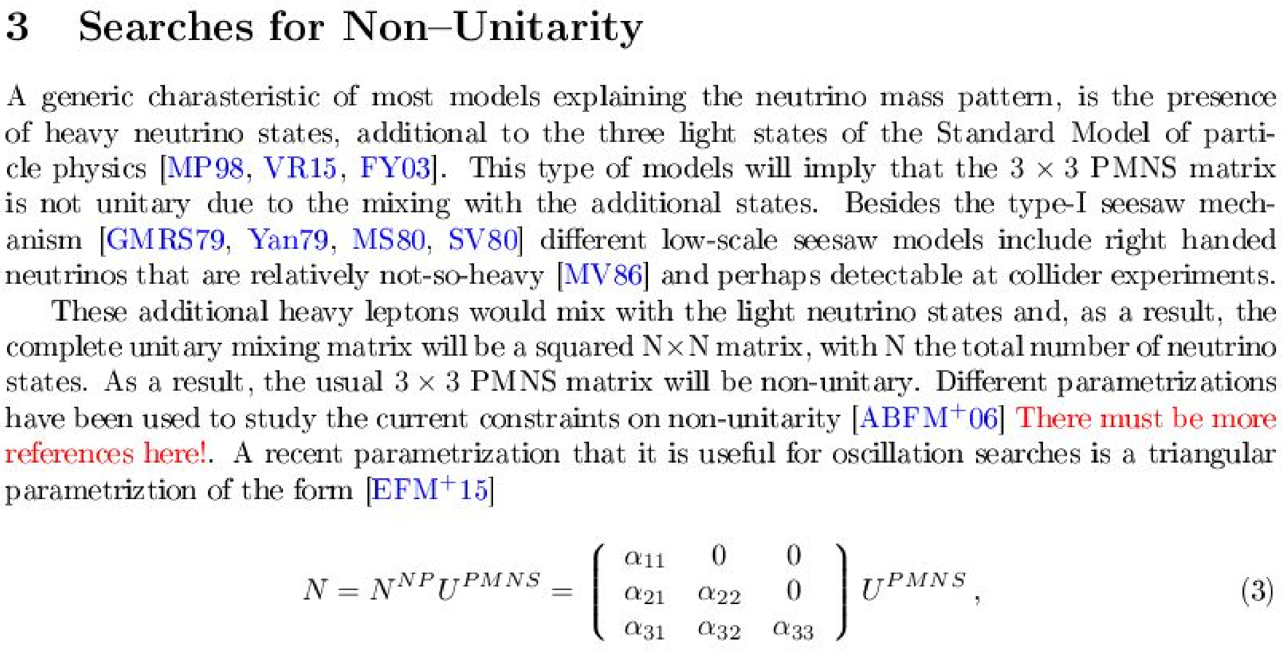




Heads up - This result is still preliminary.

Non-Unitarity group also contributing

Miranda, Forero, Tortola, and Fernandez-Martinez



3 Searches for Non–Unitarity

A generic charasteristic of most models explaining the neutrino mass pattern, is the presence of heavy neutrino states, additional to the three light states of the Standard Model of particle physics [MP98, VR15, FY03]. This type of models will imply that the 3 × 3 PMNS matrix is not unitary due to the mixing with the additional states. Besides the type-I seesaw mechanism [GMRS79, Yan79, MS80, SV80] different low-scale seesaw models include right handed neutrinos that are relatively not-so-heavy [MV86] and perhaps detectable at collider experiments.

These additional heavy leptons would mix with the light neutrino states and, as a result, the complete unitary mixing matrix will be a squared N×N matrix, with N the total number of neutrino states. As a result, the usual 3 × 3 PMNS matrix will be non-unitary. Different parametrizations have been used to study the current constraints on non-unitarity [ABFM+06] There must be more references here!. A recent parametrization that it is useful for oscillation searches is a triangular parametriztion of the form [EFM+15]

$$N = N^{NP} U^{PMNS} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{PMNS} , \qquad (3)$$

Conclusions

- We have finished an analysis with two free parameters;
  - The results for oscillation show that the Earth profile don’t have big influence in the parameter sensitivity
  - The results for NSI show that for the more constrained parameters the difference in the profile considered can be important
- The partial results with all the parameters free to vary indicate that in this case even the NSI constraints are not importantly affected by the Earth profile;
- We still need to produce the accurate plots;
- The Non-unitarity session of the TDR is being written/reviewed.

Thank you!

Backup slides

Analysis with more than one free parameter at a time and detailed density profile

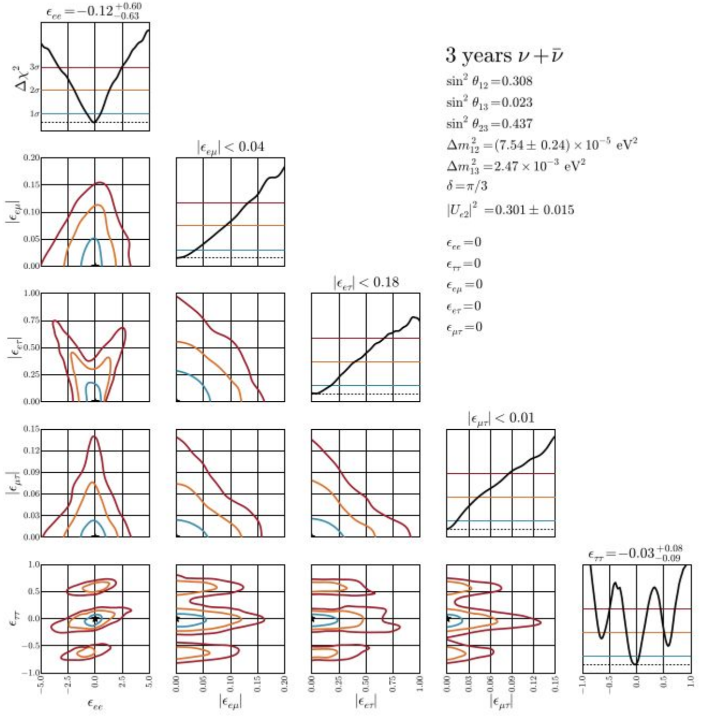


Fig. 4. Expected exclusion limits at 68.3% (red), 95% (orange), and 99% (blue) CL at DUNE assuming data consistent with the standard paradigm. The CP-violating phase δ is assumed to be $\pi/3$ and the mass hierarchy is normal. Gaussian priors are included on $\Delta m^2_{12} = (7.54 \pm 0.24) \times 10^{-5}$ eV^2 and $|U_{e2}|^2 = 0.301 \pm 0.015$. See text for details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Gouvea&Kelly, Nucl. Phys. B 908 (2016) 318

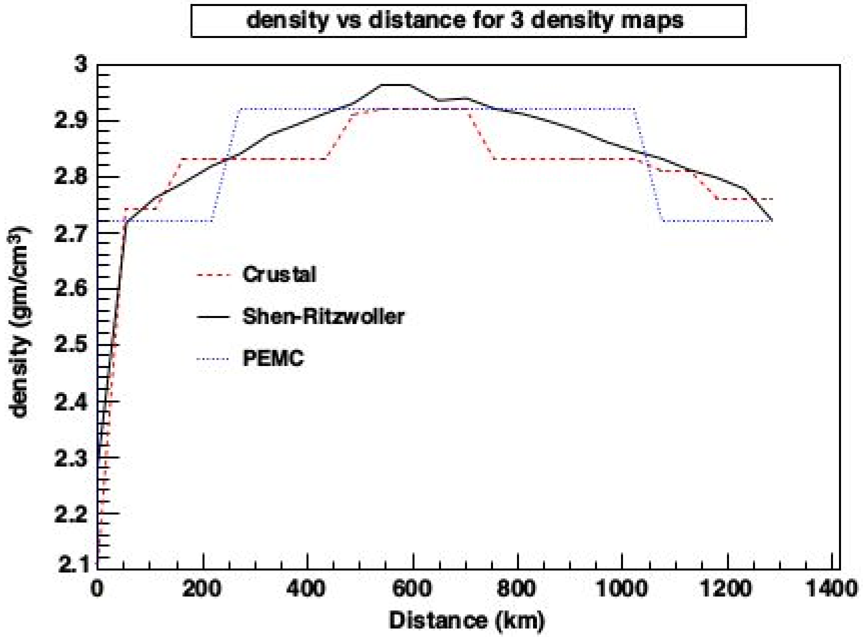
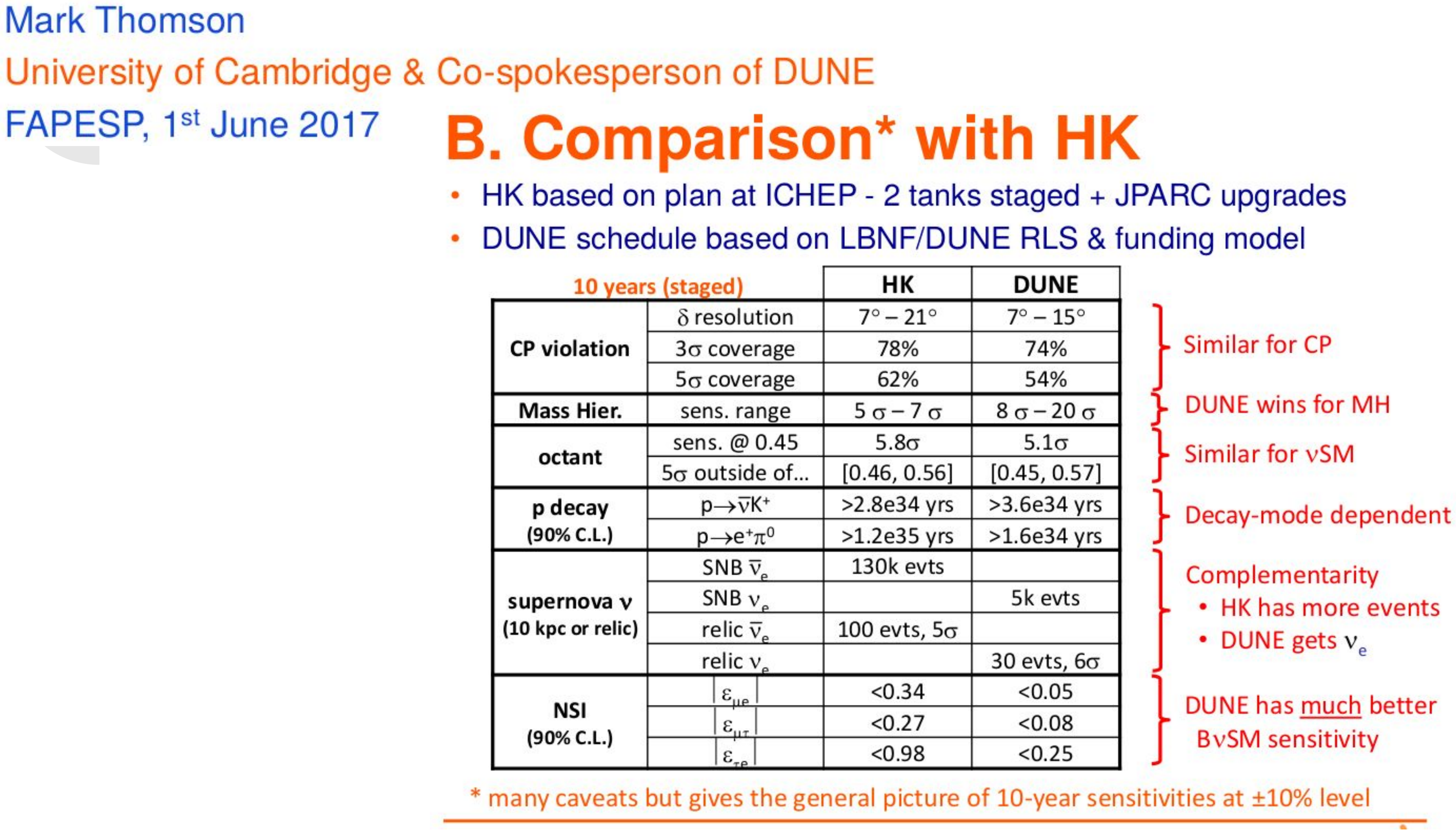


FIG. 3. Densities vs distance. The dashed line (red) is the CRUSTAL map, the solid line (black) is the Shen-Ritzwoller map, and the dotted line (blue) is the old PEMC map.

Roe, Phys. Rev. D **95**, 113004 (2017)

NSI limits from other experiments



Mark Thomson

University of Cambridge & Co-spokesperson of DUNE

FAPESP, 1st June 2017

B. Comparison* with HK

- HK based on plan at ICHEP - 2 tanks staged + JPARC upgrades
- DUNE schedule based on LBNF/DUNE RLS & funding model

10 years (staged)		HK	DUNE
CP violation	δ resolution	7° – 21°	7° – 15°
	3σ coverage	78%	74%
	5σ coverage	62%	54%
Mass Hier.	sens. range	$5\sigma - 7\sigma$	$8\sigma - 20\sigma$
octant	sens. @ 0.45	5.8σ	5.1σ
	5σ outside of…	[0.46, 0.56]	[0.45, 0.57]
p decay **(90% C.L.)**	$p\to\bar{\nu}K^+$	>2.8e34 yrs	>3.6e34 yrs
	$p\to e^+\pi^0$	>1.2e35 yrs	>1.6e34 yrs
supernova ν **(10 kpc or relic)**	SNB $\bar{\nu}_e$	130k evts	
	SNB ν_e		5k evts
	relic $\bar{\nu}_e$	100 evts, 5σ	
	relic ν_e		30 evts, 6σ
NSI **(90% C.L.)**	$\lvert\varepsilon_{\mu e}\rvert$	<0.34	<0.05
	$\lvert\varepsilon_{\mu\tau}\rvert$	<0.27	<0.08
	$\lvert\varepsilon_{\tau e}\rvert$	<0.98	<0.25

Similar for CP

DUNE wins for MH

Similar for νSM

Decay-mode dependent

Complementarity
- HK has more events
- DUNE gets ν_e

DUNE has much better BνSM sensitivity

* many caveats but gives the general picture of 10-year sensitivities at ±10% level

Curtailing the Dark Side in Non-Standard Neutrino Interactions

Pilar Coloma[a] **Peter B. Denton,**[a,b,1] **M. C. Gonzalez-Garcia,**[c,d,e] **Michele Maltoni,**[f] **Thomas Schwetz**[g]

Abstract: In presence of non-standard neutrino interactions the neutrino flavor evolution equation is affected by a degeneracy which leads to the so-called LMA-Dark solution. It requires a solar mixing angle in the second octant and implies an ambiguity in the neutrino mass ordering. Non-oscillation experiments are required to break this degeneracy. We perform a combined analysis of data from oscillation experiments with the neutrino scattering experiments CHARM and NuTeV. We find that the degeneracy can be lifted if the non-standard neutrino interactions take place with down quarks, but it remains for up quarks. However, CHARM and NuTeV constraints apply only if the new interactions take place through mediators not much lighter than the electroweak scale. For light mediators we consider the possibility to resolve the degeneracy by using data from future coherent neutrino-nucleus scattering experiments. We find that, for an experiment using a stopped-pion neutrino source, the LMA-Dark degeneracy will either be resolved, or the presence of new interactions in the neutrino sector will be established with high significance.

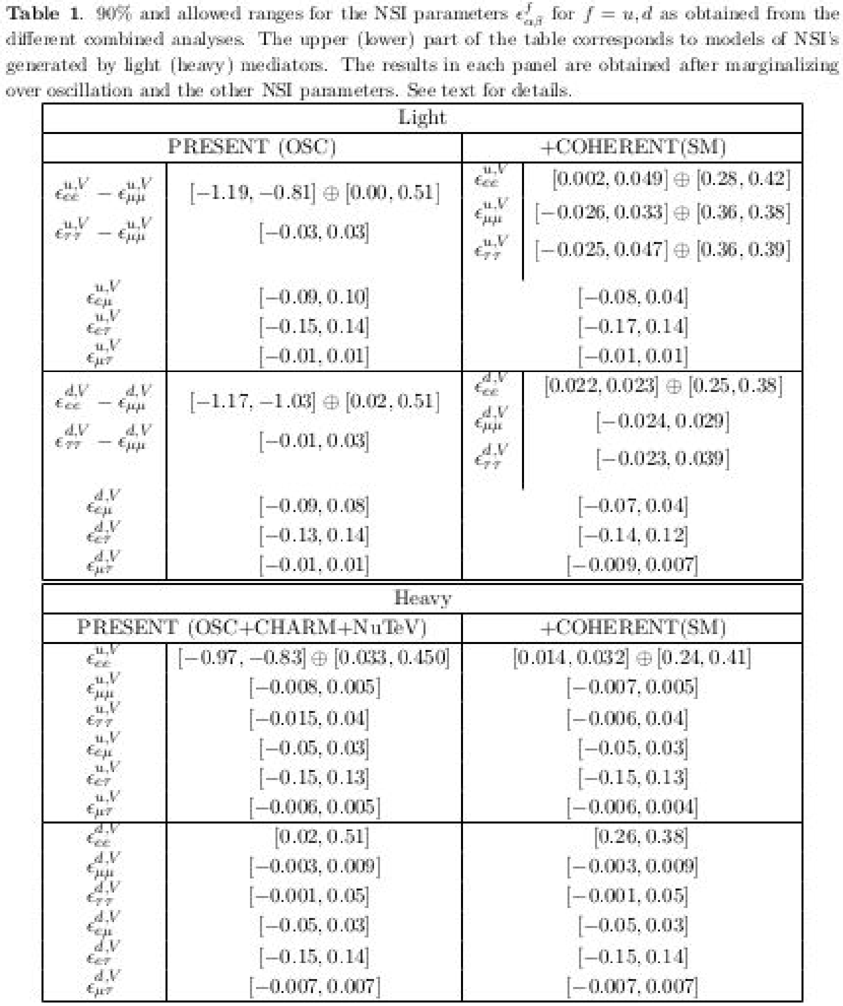


Table 1. 90% and allowed ranges for the NSI parameters $\epsilon_{\alpha\beta}^{f}$ for $f = u, d$ as obtained from the different combined analyses. The upper (lower) part of the table corresponds to models of NSI's generated by light (heavy) mediators. The results in each panel are obtained after marginalizing over oscillation and the other NSI parameters. See text for details.

Light			
PRESENT (OSC)		+COHERENT(SM)	
$\epsilon_{ee}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-1.19, -0.81] \oplus [0.00, 0.51]$	$\epsilon_{ee}^{u,V}$	$[0.002, 0.049] \oplus [0.28, 0.42]$
$\epsilon_{\tau\tau}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-0.03, 0.03]$	$\epsilon_{\mu\mu}^{u,V}$	$[-0.026, 0.033] \oplus [0.36, 0.38]$
		$\epsilon_{\tau\tau}^{u,V}$	$[-0.025, 0.047] \oplus [0.36, 0.39]$
$\epsilon_{e\mu}^{u,V}$	$[-0.09, 0.10]$		$[-0.08, 0.04]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.14]$		$[-0.17, 0.14]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.01, 0.01]$		$[-0.01, 0.01]$
$\epsilon_{ee}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-1.17, -1.03] \oplus [0.02, 0.51]$	$\epsilon_{ee}^{d,V}$	$[0.022, 0.023] \oplus [0.25, 0.38]$
$\epsilon_{\tau\tau}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-0.01, 0.03]$	$\epsilon_{\mu\mu}^{d,V}$	$[-0.024, 0.029]$
		$\epsilon_{\tau\tau}^{d,V}$	$[-0.023, 0.039]$
$\epsilon_{e\mu}^{d,V}$	$[-0.09, 0.08]$		$[-0.07, 0.04]$
$\epsilon_{e\tau}^{d,V}$	$[-0.13, 0.14]$		$[-0.14, 0.12]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.01, 0.01]$		$[-0.009, 0.007]$
Heavy			
PRESENT (OSC+CHARM+NuTeV)		+COHERENT(SM)	
$\epsilon_{ee}^{u,V}$	$[-0.97, -0.83] \oplus [0.033, 0.450]$		$[0.014, 0.032] \oplus [0.24, 0.41]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.008, 0.005]$		$[-0.007, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.015, 0.04]$		$[-0.006, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$		$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$		$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.005]$		$[-0.006, 0.004]$
$\epsilon_{ee}^{d,V}$	$[0.02, 0.51]$		$[0.26, 0.38]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$		$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$		$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$		$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$		$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$		$[-0.007, 0.007]$