LFV from the Seesaw

Enrique Fernández-Martínez

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry
Essential Asymmetries of Nature

Evidence for ν mass from oscillations

Evidence for ν mass and mixing from LFV in oscillation phenomenon in many experiments with great agreement

What we already know (1σ)

SNO, Borexino
KamLAND

"Solar sector"

$$\begin{cases} \Delta m^2_{21} = 7.4^{+0.2}_{-0.2} \cdot 10^{-5}\mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.303^{+0.012}_{-0.011} \end{cases}$$

SK, T2K, IC
MINOS, NOνA

"Atm. sector"

$$\begin{cases} |\Delta m^2_{31}| = 2.50^{+0.03}_{-0.03} \cdot 10^{-3}\mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.57^{+0.02}_{-0.02} \end{cases}$$

Daya Bay
RENO, T2K, NOνA

$$\sin^2\theta_{13} = 0.0203 \pm 0.0006$$

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou 2007.14792

The simplest SM extension

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

ν mass from right-handed neutrinos

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small mixing $\Theta \approx m_D^\dagger M_N^{-1}$

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d=5 Weinberg 1979

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d=6 A. Broncano, B. Gavela and E. Jenkins hep-ph/0210271

$$Y_\upsilon^\dagger M_N^{-2} Y_\upsilon \left(\overline{L_L} \tilde{\phi}\right) \partial\!\!\!/ \left(\tilde{\phi}^\dagger L_L\right)$$

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A lower seesaw scale

But a very high M_N leads to the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

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$$m_D \overline{N}_R \nu_L + M_N \, \overline{N}_R N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}$$

G. C. Branco, W. Grimus, and L. Lavoura 1988
J. Kersten and A. Y. Smirnov 0705.3221

Low $M \approx M_N$ and large $\Theta \approx m_D^\dagger M_N^{-1}$ even if vanishing $m_\nu = 0$

A lower seesaw scale

But a very high M_N leads to the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

$$m_D \bar{N}_R \nu_L + M_N \bar{N}_R N_L + \mu \bar{N}_L^c N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

"inverse Seesaw"

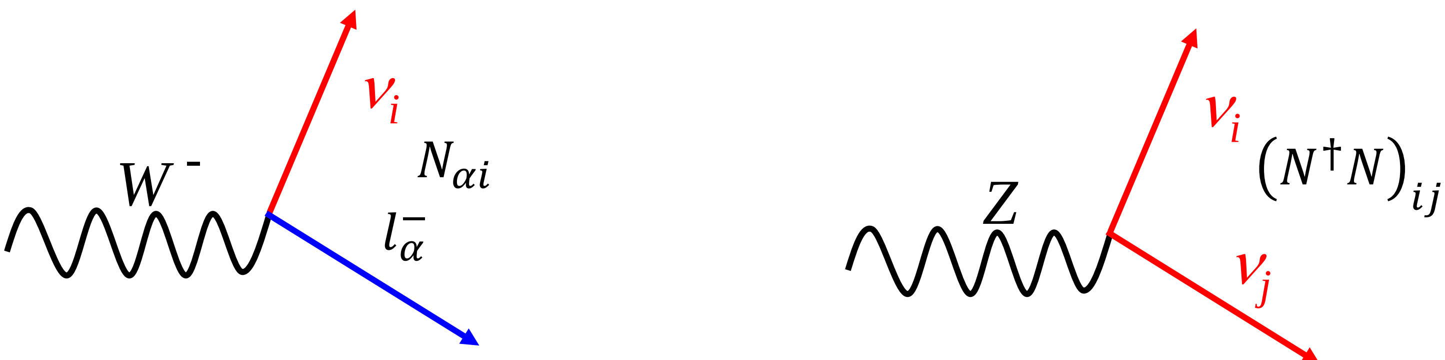
R. Mohapatra and J. Valle 1986

Low $M \approx M_N \pm \frac{\mu}{2}$ and large $\Theta \approx m_D^\dagger M_N^{-1}$ even if small $m_\nu \approx \mu \frac{m_D^2}{M_N^2}$

Looking for N_R: Non-Unitarity

$$U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U \approx \begin{pmatrix} N^t & -\Theta^* \\ \Theta^t & X^t \end{pmatrix} \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix *N* of active neutrinos will not be unitary



Effects in weak interactions…

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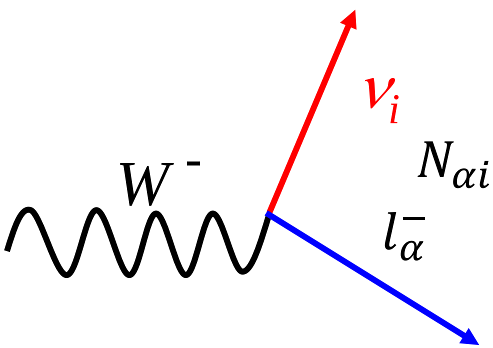
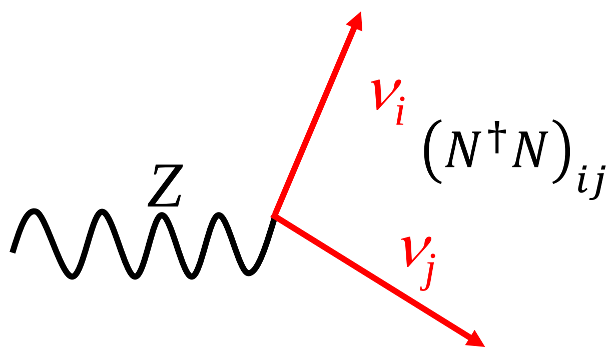




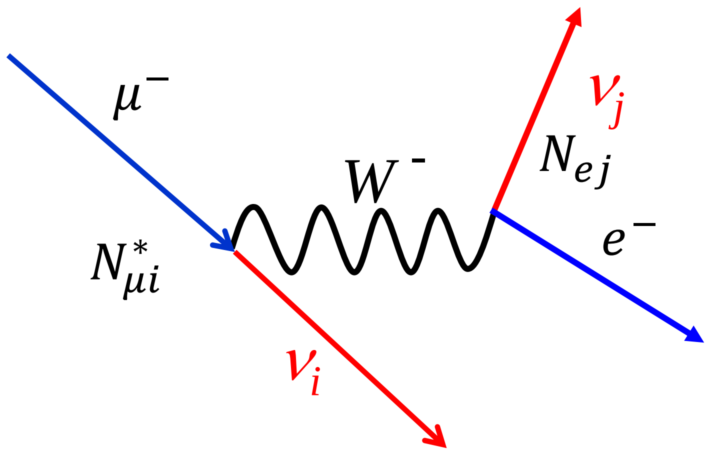
Effects in weak interactions…

When the W and Z are integrated out to obtain the Fermi theory neutrino NSI are recovered

see e.g. M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637 for the dictionary

Looking for N_R: Non-Unitarity

G_F from μ decay is affected!



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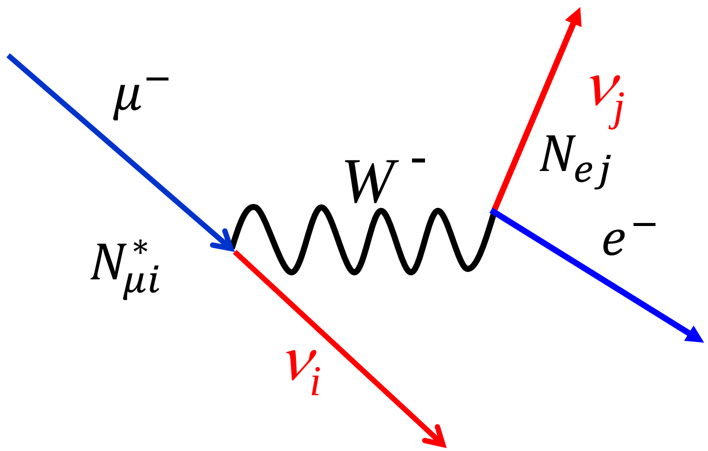

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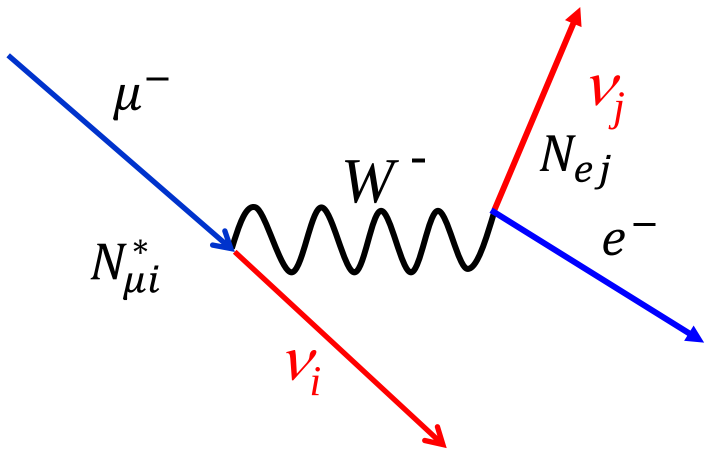

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LFU also strong bounds on ratios:

$$\frac{\left(NN^\dagger\right)_{\alpha\alpha}}{\left(NN^\dagger\right)_{\beta\beta}}$$

From ratios of π, K, and lepton decays

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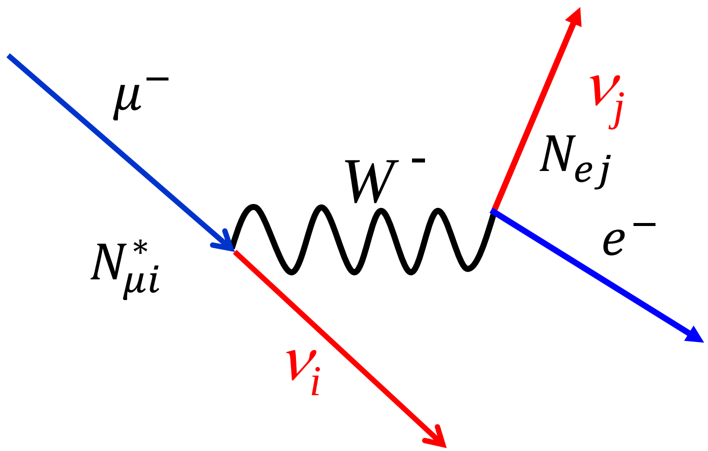

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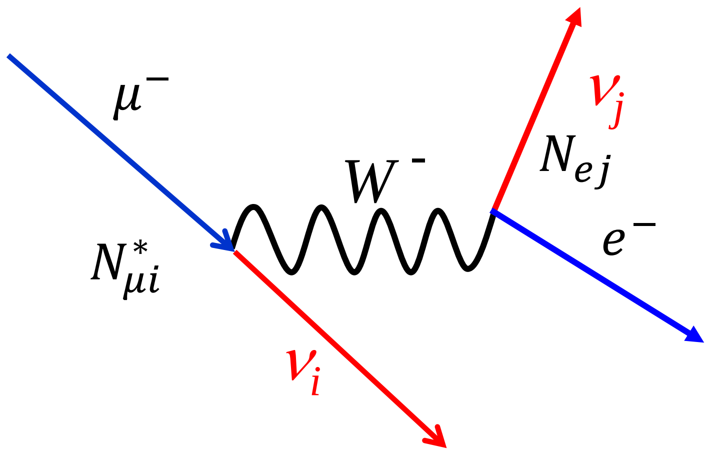

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And LFV processes such as $\mu \to e\,\gamma$ or $\tau \to e\,\gamma$ since the GIM cancellation is lost

Looking for N_R: Non-Unitarity

Bounds from a global fit to flavour and Electroweak precision

95% CL	LFC	LFV
$\eta_{ee} = \frac{1}{2}\sum_k \vert\Theta_{ek}\vert^2$	$[0.081, 1.4] \cdot 10^{-3}$	-
$\eta_{\mu\mu}$	$1.4 \cdot 10^{-4}$	-
$\eta_{\tau\tau}$	$8.9 \cdot 10^{-4}$	-
$\mathrm{Tr}\,[\eta]$	$2.1 \cdot 10^{-3}$	-
$\vert\eta_{e\mu}\vert$	$3.4 \cdot 10^{-4}$	$\mathbf{1.2 \cdot 10^{-5}}$
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$$N = (\mathbb{I} - \eta)U$$

$$\eta = \frac{\Theta\Theta^\dagger}{2} \qquad \Theta \approx m_D^\dagger M_N^{-1}$$

M. Blennow, EFM,
J. Hernandez-Garcia,
J. Lopez-Pavon
X. Marcano and
D. Naredo-Tuero
2306.01040

See also P. Langaker and D. London 1988; S. M. Bilenky and C. Giunti hep-ph/9211269 ; E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228; D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228; S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020; S. Antusch, J. Baumann and EFM 0807.1003; D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009; S. Antusch and O. Fischer 1407.6607; F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774, A. M. Coutinho, A. Crivellin, and C. A. Manzari 1912.08823…

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$$\eta = \frac{\Theta\Theta^\dagger}{2}$$

LFC constraints dominate over LFV in τ sector since η is positive definite

M. Blennow, EFM, J. Hernandez-Garcia, J. Lopez-Pavon X. Marcano and **D. Naredo-Tuero** 2306.01040

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2 σ preference for mixing with electrons ~0.03

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ν mass from type III Seesaw

Add heavy fermion triplets $\overrightarrow{\Sigma_R}$ with $Y_\Sigma \overline{L_L} \vec{\tau} \tilde{\phi} \overrightarrow{\Sigma_R}$

Integrating out the heavy triplets gives:

d=5 Weinberg 1979

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d=6 A. Abada, C. Biggio, F. Bonnet, B. Gavela and T. Hambye 0707.4058

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Modifies ν kinnetic terms

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Modifies ℓ kinnetic terms

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d=5 Weinberg 1979

$$Y_\Sigma^t M_\Sigma^{-1} Y_\Sigma \left(\overline{L_L^c} \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger L_L\right)$$

$$\langle \phi \rangle = \frac{v}{\sqrt{2}}$$

$$m_\Sigma^t M_\Sigma^{-1} m_\Sigma \overline{\nu_L^c} \nu_L$$

d=6 A. Abada, C. Biggio, F. Bonnet, B. Gavela and T. Hambye 0707.4058

$$Y_\Sigma^\dagger M_\Sigma^{-2} Y_\Sigma \left(\overline{L_L} \vec{\tau} \tilde{\phi}\right) \not{D} \left(\tilde{\phi}^\dagger \vec{\tau} L_L\right)$$

$$\langle \phi \rangle = \frac{v}{\sqrt{2}}$$

Modifies ν kinnetic terms

Modifies couplings to the W

Modifies ℓ kinnetic terms

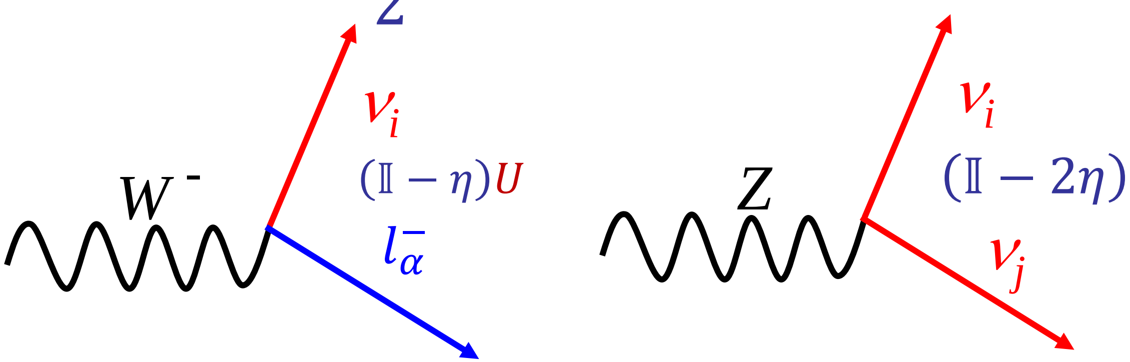
Non-unitarity in type I vs type III Seesaw

Type I

$$Y_\upsilon^\dagger M_N^{-2} Y_\upsilon \left(\overline{L_L}\tilde{\phi}\right) \not{\partial} \left(\tilde{\phi}^\dagger L_L\right)$$

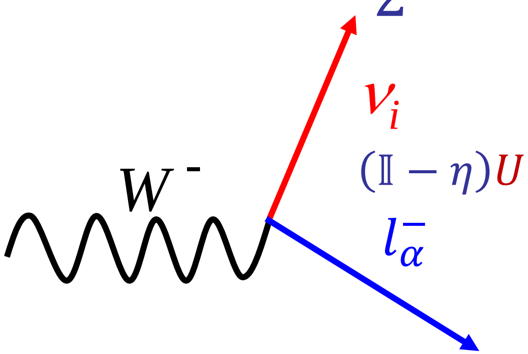
↓

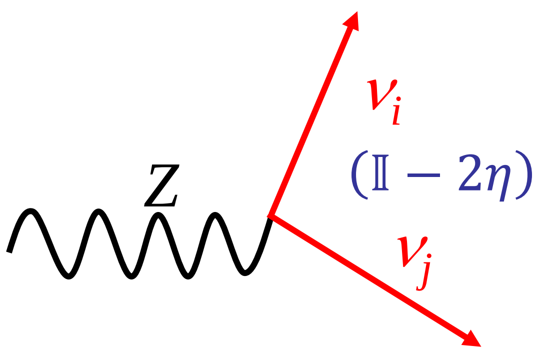
$$\eta = \frac{m_D^\dagger M_N^{-2} m_D}{2}$$



Non-unitarity in type I vs type III Seesaw

Type I	Type III
$Y_\upsilon^\dagger M_N^{-2} Y_\upsilon \left(\overline{L_L}\tilde{\phi}\right) \not{\partial} \left(\tilde{\phi}^\dagger L_L\right)$	$Y_\Sigma^\dagger M_\Sigma^{-2} Y_\Sigma \left(\overline{L_L}\vec{\tau}\tilde{\phi}\right) \not{D} \left(\tilde{\phi}^\dagger \vec{\tau} L_L\right)$
↓	↓
$\eta = \frac{m_D^\dagger M_N^{-2} m_D}{2}$	$\varepsilon = \frac{m_\Sigma^\dagger M_\Sigma^{-2} m_\Sigma}{2}$





Non-unitarity in type I vs type III Seesaw

Type I

$$Y_\nu^\dagger M_N^{-2} Y_\nu (\overline{L_L}\tilde{\phi})\, \partial\!\!\!/ \left(\tilde{\phi}^\dagger L_L\right)$$

$$\downarrow$$

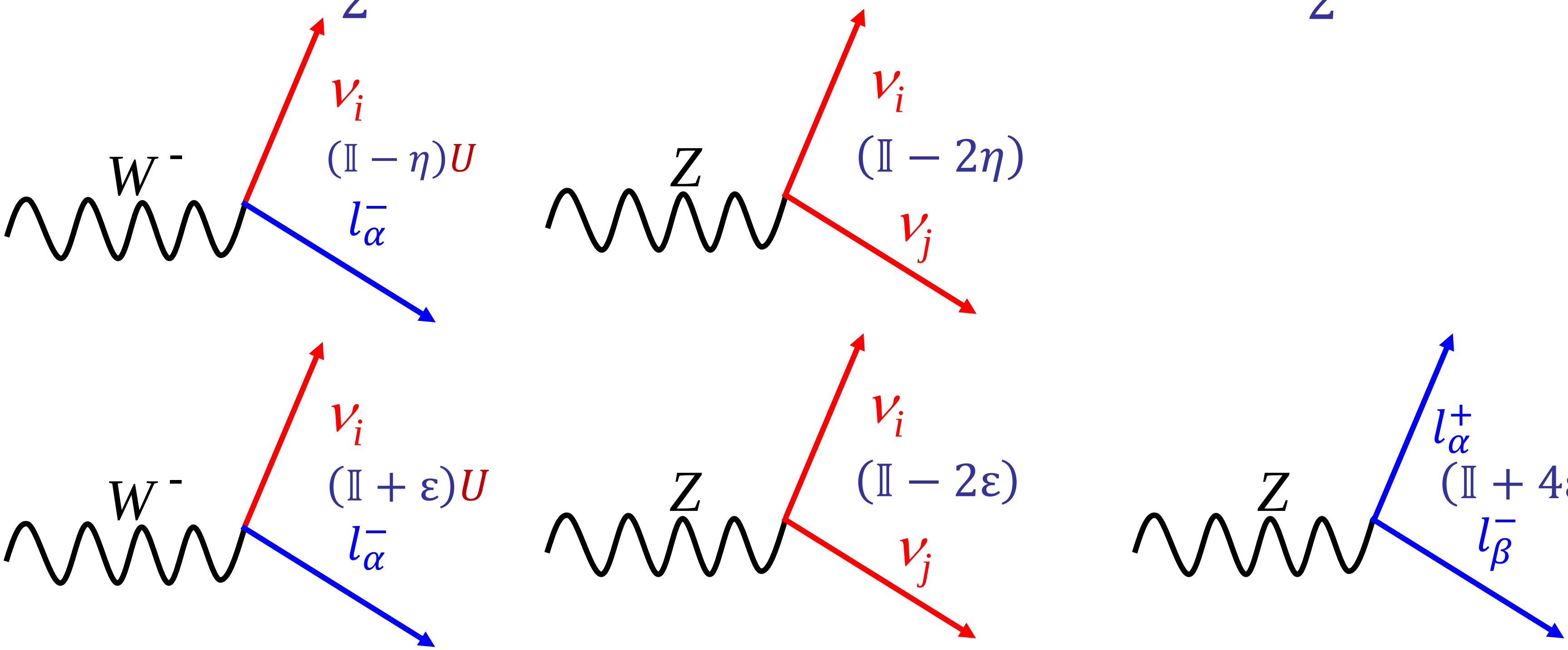
$$\eta = \frac{m_D^\dagger M_N^{-2} m_D}{2}$$

Type III

$$Y_\Sigma^\dagger M_\Sigma^{-2} Y_\Sigma (\overline{L_L}\vec{\tau}\tilde{\phi})\, D\!\!\!\!/ \left(\tilde{\phi}^\dagger \vec{\tau} L_L\right)$$

$$\downarrow$$

$$\varepsilon = \frac{m_\Sigma^\dagger M_\Sigma^{-2} m_\Sigma}{2}$$



Non-unitarity in type I vs type III Seesaw

Type I

$$Y_\nu^\dagger M_N^{-2} Y_\nu \left(\overline{L_L}\tilde{\phi}\right) \partial\!\!\!/ \left(\tilde{\phi}^\dagger L_L\right)$$

$$\downarrow$$

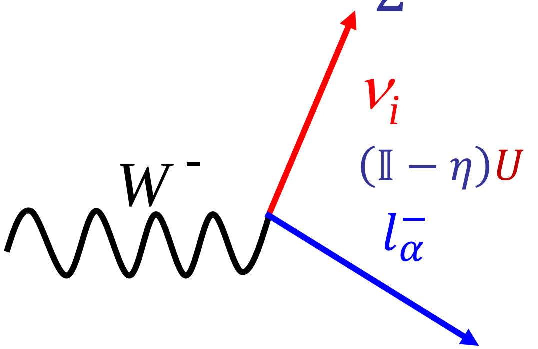
$$\eta = \frac{m_D^\dagger M_N^{-2} m_D}{2}$$

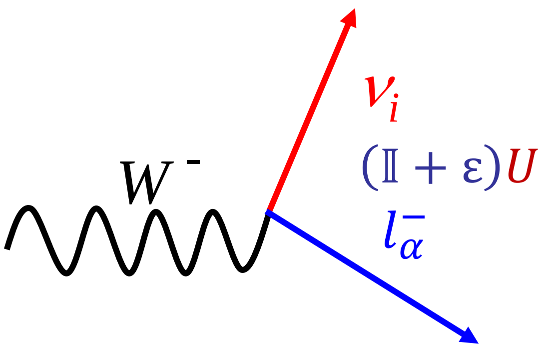
Type III

$$Y_\Sigma^\dagger M_\Sigma^{-2} Y_\Sigma \left(\overline{L_L}\vec{\tau}\tilde{\phi}\right) D\!\!\!\!/ \left(\tilde{\phi}^\dagger \vec{\tau} L_L\right)$$

$$\downarrow$$

$$\varepsilon = \frac{m_\Sigma^\dagger M_\Sigma^{-2} m_\Sigma}{2}$$





If contributions from both Type I and III are present the non-unitary contribution is no longer definite

Non-unitarity in type I + type III Seesaw

If contributions from both Type I and III are present the non-unitary contribution is no longer definite

With extra freedom is a posible solution to the Cabibbo anomaly
A. M. Coutinho, A. Crivellin, and C. A. Manzari 1912.08823

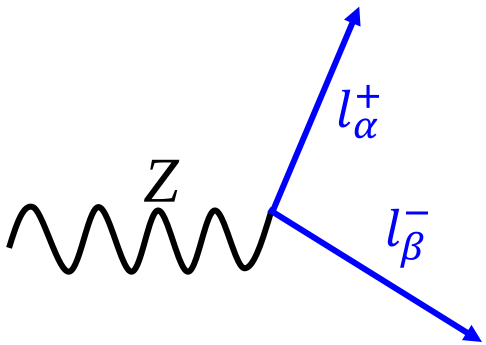
And LFV becomes independent of LFC constraints

GUV	LFC Bound			LFV Bound	
	68%CL	95%CL		68%CL	95%CL
η_{ee}	$[0.56, 1.29] \cdot 10^{-3}$	$[0.20, 1.65] \cdot 10^{-3}$	$\lvert\eta_{e\mu}\rvert$	$5.0 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$
$\eta_{\mu\mu}$	$[-8.2, -3.3] \cdot 10^{-4}$	$[-1.1, -0.088] \cdot 10^{-3}$	$\lvert\eta_{e\tau}\rvert$	$3.4 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$
$\eta_{\tau\tau}$	$[-2.2, -0.38] \cdot 10^{-3}$	$[-3.1, 0.56] \cdot 10^{-3}$	$\lvert\eta_{\mu\tau}\rvert$	$4.0 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$

M. Blennow, EFM, J. Hernandez-Garcia, J. Lopez-Pavon X. Marcano and **D. Naredo-Tuero** 2306.01040

Bound on type III Seesaw

But very strong bounds on type III from FCNC at tree level



$\boldsymbol{\mu \to e\ (\mathrm{Ti})}$	$\boldsymbol{\lvert\eta_{\mu e}\rvert < 3.0 \cdot 10^{-7}}$ [53]
$\mu \to eee$	$\lvert\eta_{\mu e}\rvert < 8.7 \cdot 10^{-7}$ [45]
$\tau \to eee$	$\lvert\eta_{\tau e}\rvert < 3.4 \cdot 10^{-4}$ [45]
$\tau \to \mu\mu\mu$	$\lvert\eta_{\tau\mu}\rvert < 3.0 \cdot 10^{-4}$ [45]
$\boldsymbol{\tau \to e\mu\mu}$	$\boldsymbol{\lvert\eta_{\tau e}\rvert < 3.0 \cdot 10^{-4}}$ [45]
$\boldsymbol{\tau \to \mu ee}$	$\boldsymbol{\lvert\eta_{\tau\mu}\rvert < 2.5 \cdot 10^{-4}}$ [45]

$Z \to \mu e$	$\lvert\eta_{\mu e}\rvert < 8.5 \cdot 10^{-4}$ [45]
$Z \to \tau e$	$\lvert\eta_{\tau e}\rvert < 3.1 \cdot 10^{-3}$ [45]
$Z \to \tau\mu$	$\lvert\eta_{\tau\mu}\rvert < 3.4 \cdot 10^{-3}$ [45]
$h \to \mu e$	$\lvert\eta_{\mu e}\rvert < 0.54$ [45]
$h \to \tau e$	$\lvert\eta_{\tau e}\rvert < 0.14$ [45]
$h \to \tau\mu$	$\lvert\eta_{\tau\mu}\rvert < 0.20$ [45]
$\mu \to e\gamma$	$\lvert\eta_{\mu e}\rvert < 1.1 \cdot 10^{-5}$ [45]
$\tau \to e\gamma$	$\lvert\eta_{\tau e}\rvert < 7.2 \cdot 10^{-3}$ [45]
$\tau \to \mu\gamma$	$\lvert\eta_{\tau\mu}\rvert < 8.4 \cdot 10^{-3}$ [45]

C. Biggio, EFM, M. Filaci J. Hernandez-Garcia, J. Lopez-Pavon 1911.11790

The type II Seesaw

Add heavy scalar triplets $\vec{\Delta}$ with $Y_\Delta \overline{L_L} \vec{\tau} \varepsilon L_L^c \vec{\Delta} + \mu_\Delta \phi^\dagger \vec{\tau} \tilde{\phi} \vec{\Delta}$

Integrating out the heavy triplets gives:

d=5 Weinberg 1979

d=6 A. Abada, C. Biggio, F. Bonnet, B. Gavela and T. Hambye 0707.4058

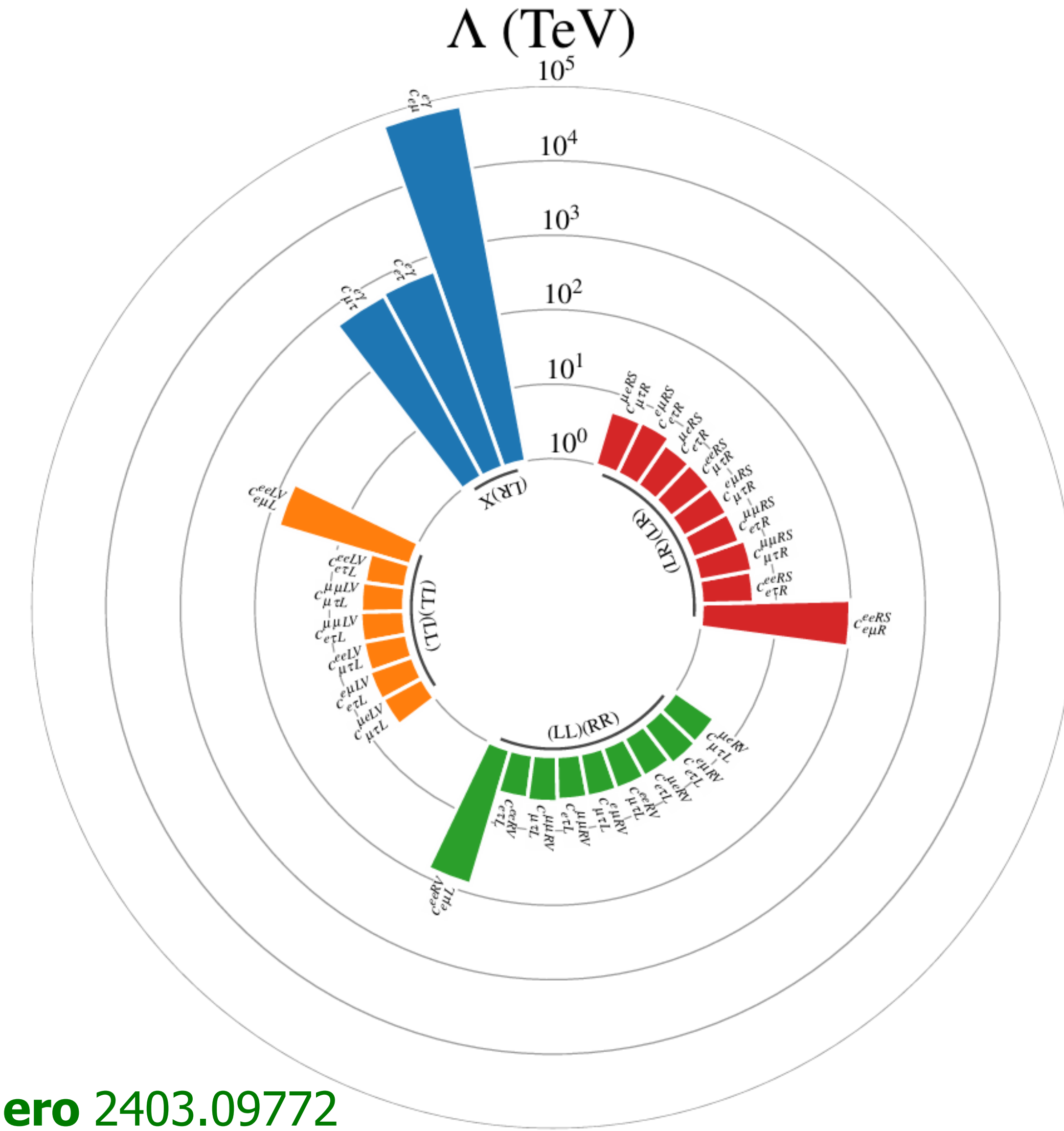
$$4 Y_\Delta \mu_\Delta M_\Delta^{-2} \left(\overline{L_L^c} \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger L_L\right) \qquad Y_\Delta Y_\Delta^\dagger M_\Delta^{-2} \left(\overline{L_L} \gamma_\mu L_L\right) \left(\overline{L_L} \gamma^\mu L_L\right)$$

If μ_Δ is small L is approximately conserved and the LNV d=5 is suppressed but the LFV d=6 operator may be sizable

Leading constraints from d=6 4-lepton LFV operators

Type II Seesaw LFV

$$\begin{pmatrix} c^{eeLV}_{e\mu L} \\ c^{eeLV}_{e\tau L} \\ c^{\mu\mu LV}_{\mu\tau L} \\ c^{\mu\mu LV}_{e\tau L} \\ c^{eeLV}_{\mu\tau L} \\ c^{e\mu LV}_{e\tau L} \\ c^{\mu e LV}_{\mu\tau L} \end{pmatrix} < \begin{pmatrix} 6.2 \times 10^{-6} \\ 2.4 \times 10^{-3} \\ 2.1 \times 10^{-3} \\ 2.0 \times 10^{-3} \\ 2.0 \times 10^{-3} \\ 1.8 \times 10^{-3} \\ 1.9 \times 10^{-3} \end{pmatrix}$$



Bounds from LFV τ decays probing close to 10 TeV and $\mu \to 3e$ close to 100 TeV

EFM, X. Marcano, **D. Naredo-Tuero** 2403.09772

bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

Type II Seesaw LFV

$$\begin{pmatrix} c^{eeLV}_{e\mu L} \\ c^{eeLV}_{e\tau L} \\ c^{\mu\mu LV}_{\mu\tau L} \\ c^{\mu\mu LV}_{e\tau L} \\ c^{eeLV}_{\mu\tau L} \\ c^{e\mu LV}_{e\tau L} \\ c^{\mu eLV}_{\mu\tau L} \end{pmatrix} < \begin{pmatrix} 6.2\times10^{-6} \\ 2.4\times10^{-3} \\ 2.1\times10^{-3} \\ 2.0\times10^{-3} \\ 2.0\times10^{-3} \\ 1.8\times10^{-3} \\ 1.9\times10^{-3} \end{pmatrix}$$

$$\begin{pmatrix} c^{eeRV}_{e\mu L} \\ c^{eeRV}_{e\tau L} \\ c^{\mu\mu RV}_{\mu\tau L} \\ c^{\mu\mu RV}_{e\tau L} \\ c^{e\mu RV}_{\mu\tau L} \\ c^{eeRV}_{\mu\tau L} \\ c^{\mu eRV}_{e\tau L} \\ c^{e\mu RV}_{e\tau L} \\ c^{\mu eRV}_{\mu\tau L} \end{pmatrix} < \begin{pmatrix} 5.2\times10^{-6} \\ 2.0\times10^{-3} \\ 1.8\times10^{-3} \\ 2.0\times10^{-3} \\ 2.0\times10^{-3} \\ 2.0\times10^{-3} \\ 2.0\times10^{-3} \\ 1.5\times10^{-3} \\ 1.6\times10^{-3} \end{pmatrix}$$

$$\begin{pmatrix} c^{eeRS}_{e\mu R} \\ c^{eeRS}_{e\tau R} \\ c^{\mu\mu RS}_{\mu\tau R} \\ c^{\mu\mu RS}_{e\tau R} \\ c^{e\mu RS}_{\mu\tau R} \\ c^{eeRS}_{\mu\tau R} \\ c^{\mu eRS}_{e\tau R} \\ c^{e\mu RS}_{e\tau R} \\ c^{\mu eRS}_{\mu\tau R} \end{pmatrix} < \begin{pmatrix} 3.1\times10^{-6} \\ 1.2\times10^{-3} \\ 1.1\times10^{-3} \\ 1.4\times10^{-3} \\ 1.4\times10^{-3} \\ 1.4\times10^{-3} \\ 1.4\times10^{-3} \\ 9.0\times10^{-4} \\ 9.6\times10^{-4} \end{pmatrix}$$

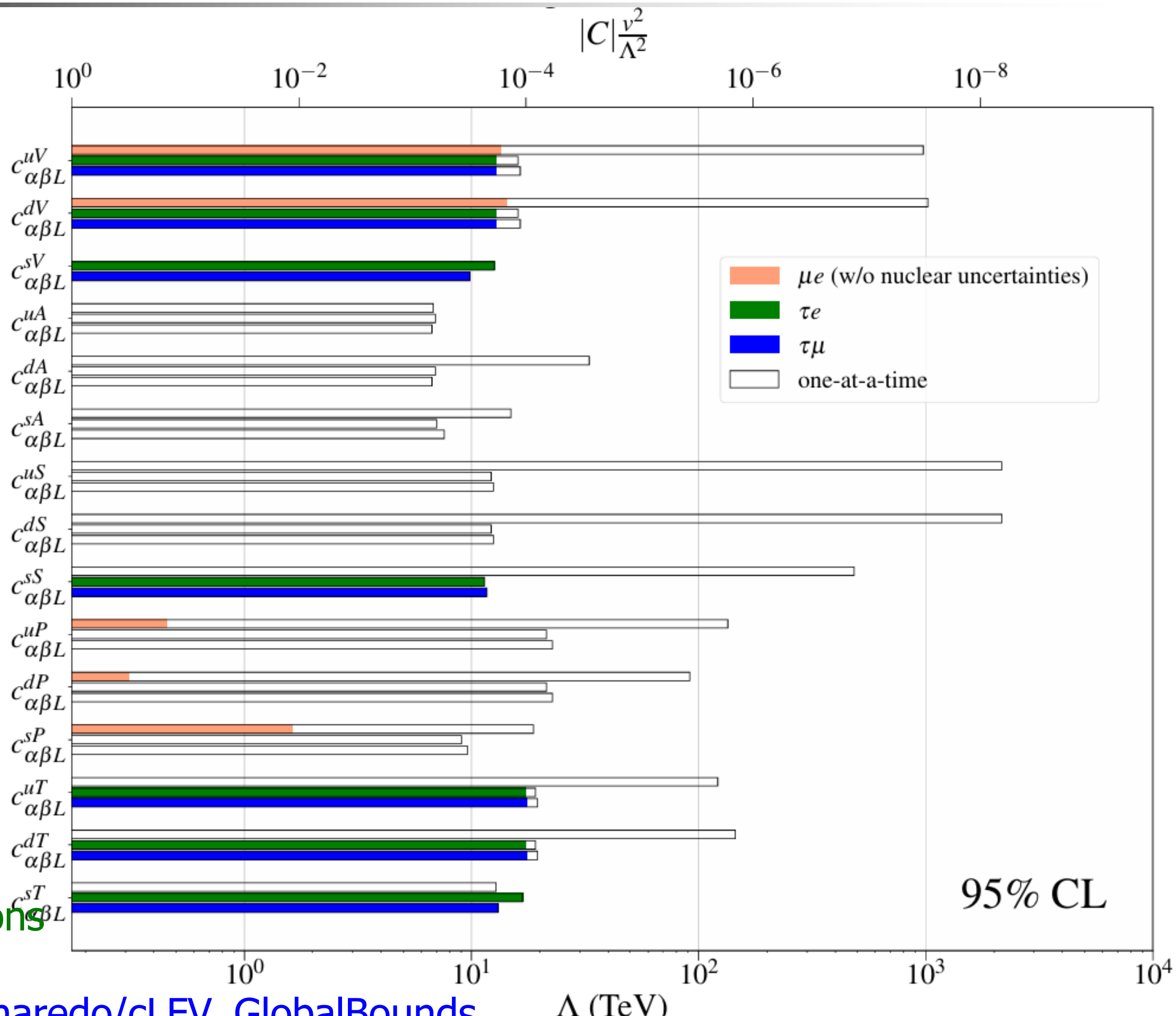
These bounds are obtained with one op at a time but also apply in a global scenario (no flat directions)

EFM, X. Marcano, **D. Naredo-Tuero** 2403.09772

bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

LFV semileptonic operators

For 4-fermion semileptonic operators many posible flat directions may be present in general prevent to set fully global constraints



EFM, X. Marcano, **D. Naredo-Tuero** 2403.09772 bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

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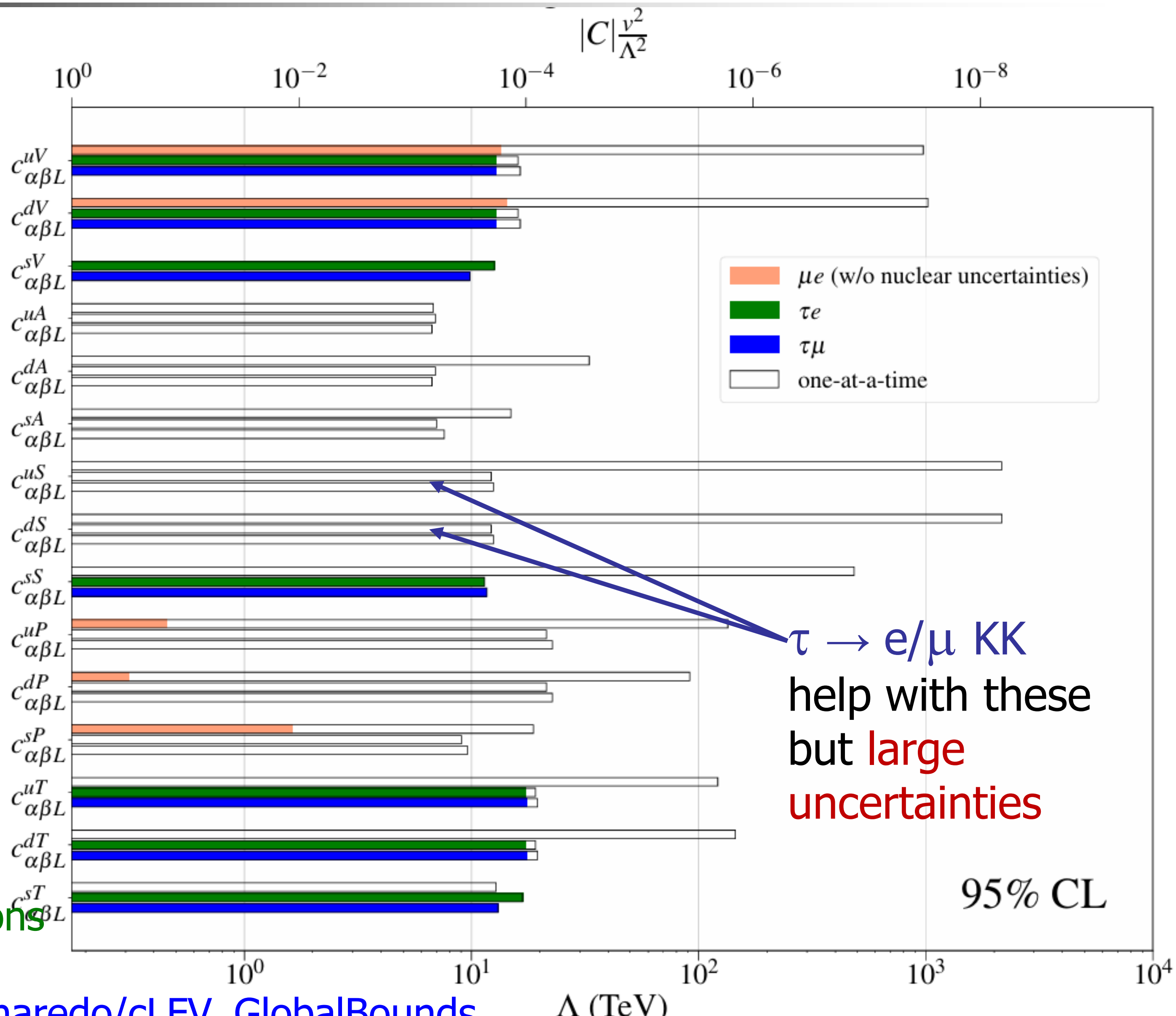
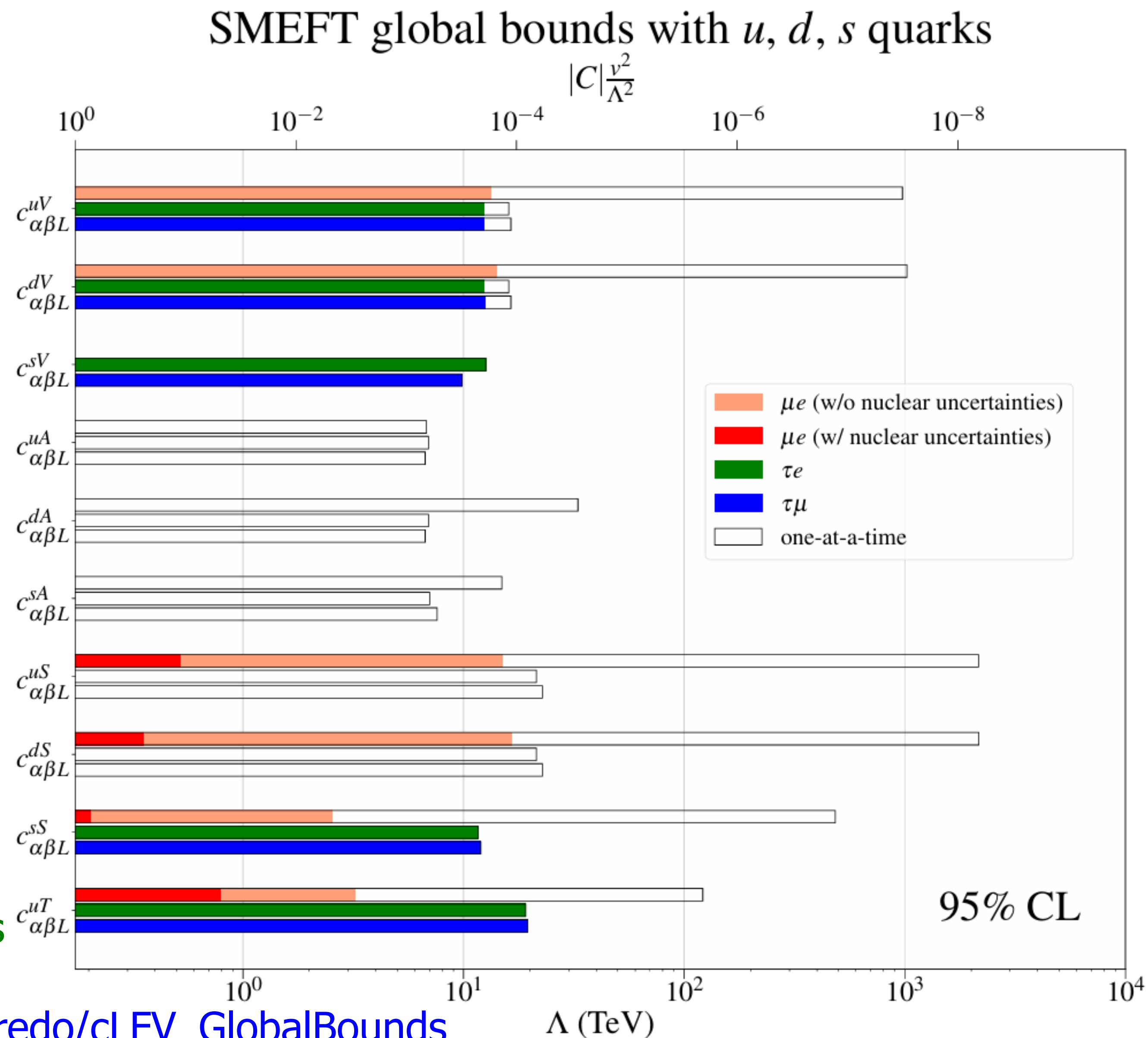


EFM, X. Marcano, **D. Naredo-Tuero** 2403.09772 bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

LFV semileptonic operators

Situation improves if only operators from low energy d=6 SMEFT are considered



EFM, X. Marcano,
D. Naredo-Tuero
2403.09772
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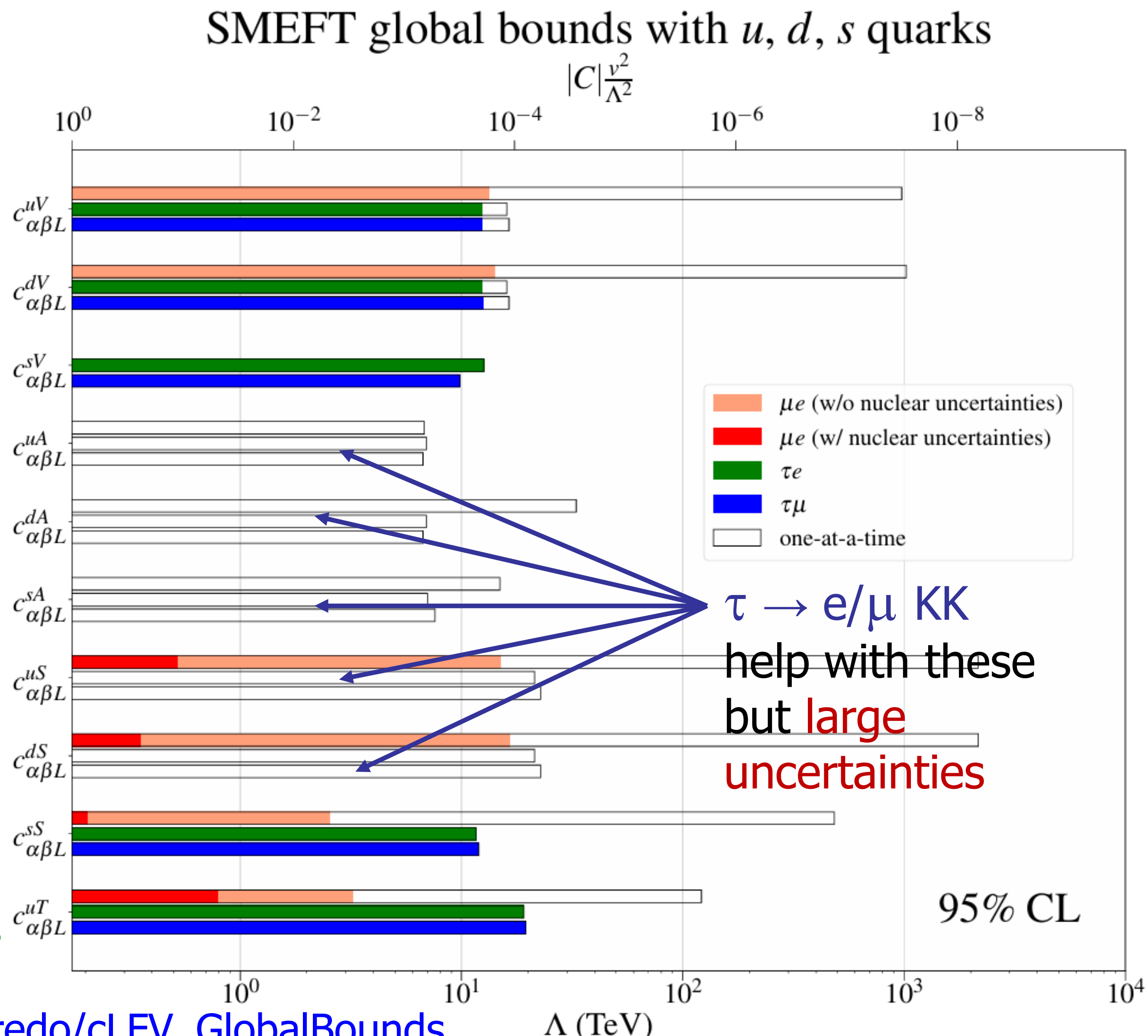

EFM, X. Marcano, **D. Naredo-Tuero**
2403.09772
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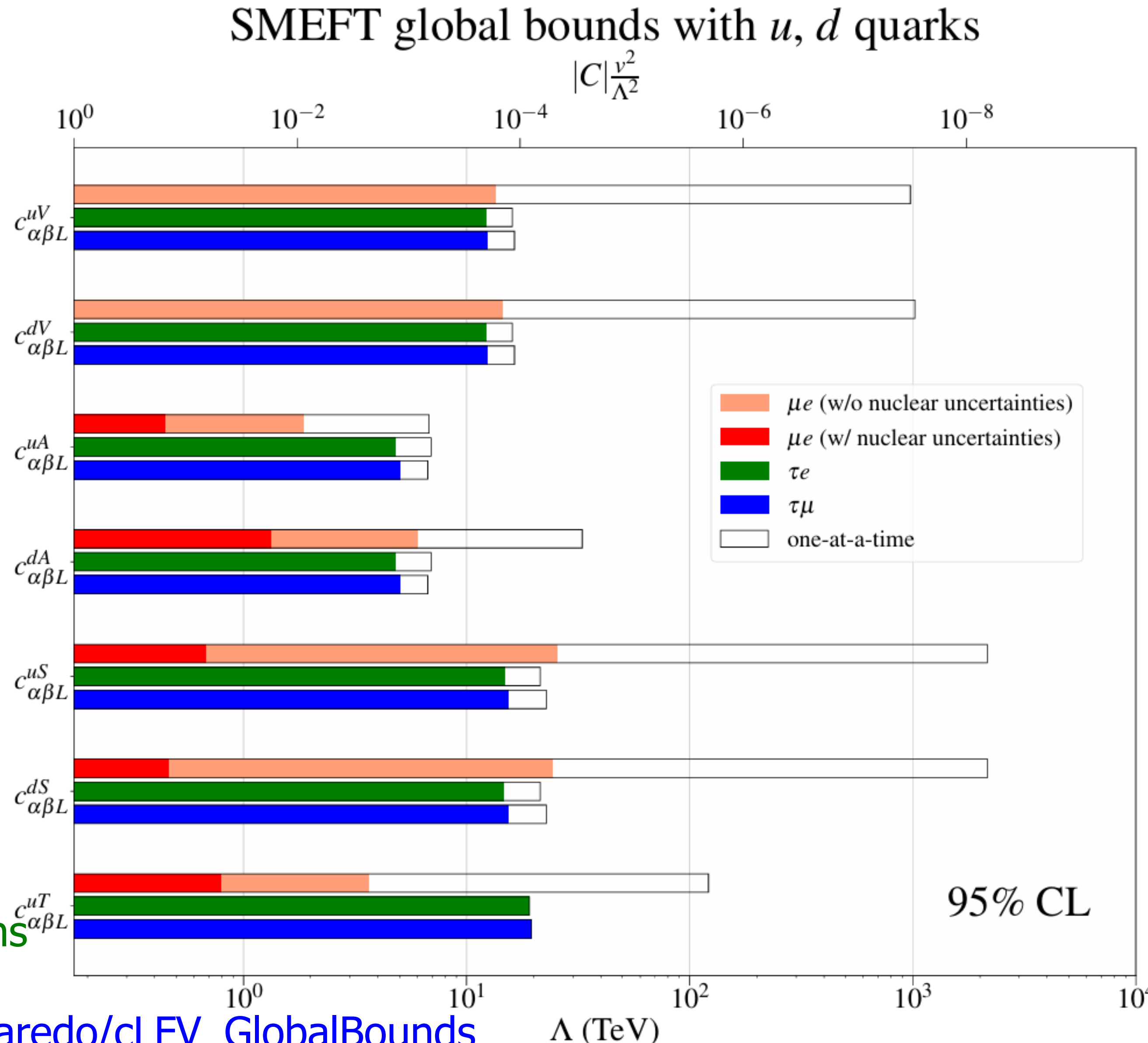
Situation improves if only operators from low energy d=6 SMEFT are considered and for only couplings with u and d

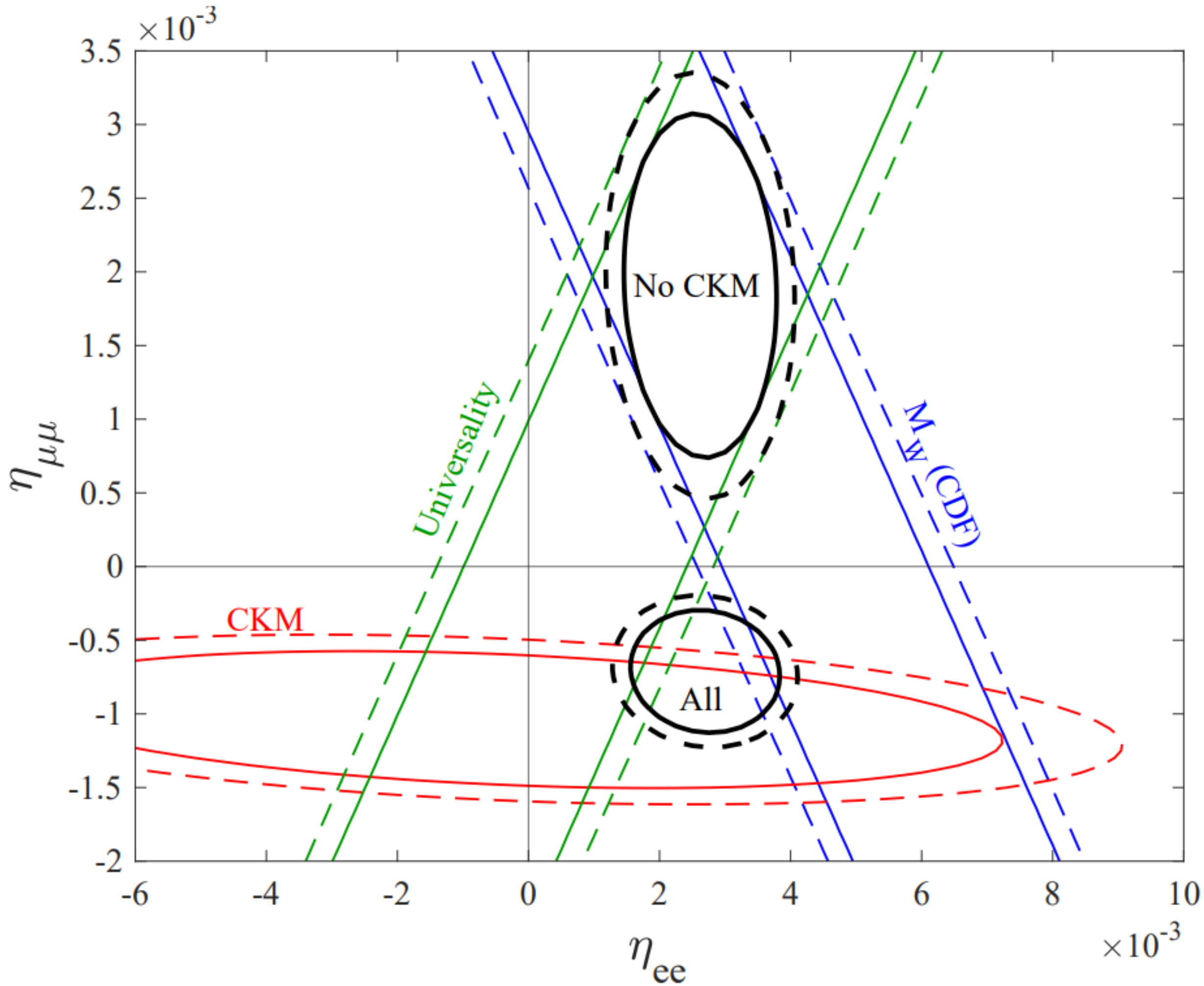


EFM, X. Marcano, **D. Naredo-Tuero** 2403.09772
bounds and correlations available at
https://github.com/dnaredo/cLFV_GlobalBounds

Conclusions

- Neutrino oscillations require neutrino masses and LFV
- The simplest extension, right-handed neutrinos, induces LFV but LFC constraints presently dominate in the τ sector
- Together with type III may solve the Cabibbo anomaly but strong bounds from LFV leptonic decays need to be avoided
- Type II and type III both induce d=6 ops with LFV leptonic decays at tree level and LFV constraints are very relevant
- In a global EFT perspective semileptonic decays suffer from flat directions and additional information would be useful

Non-unitarity and M_W from CDF

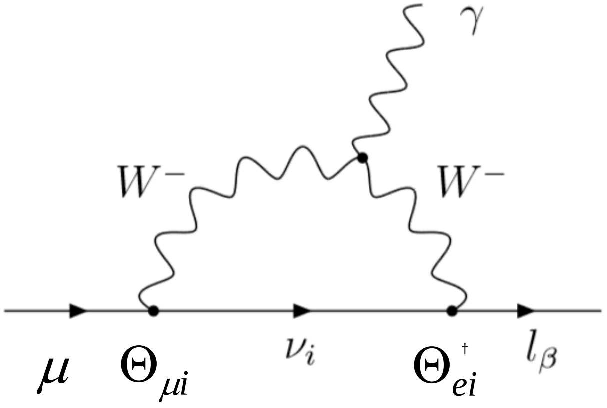


M. Blennow, P. Coloma, EFM, M-González-Lopez Phys.Rev.D 106 (2022) 7

Probing the Seesaw: Non-Unitarity

All constraints are for the limit of very heavy extra neutrinos
OK for all processes except maybe the loop LFV

Cancellations of these diagrams explored in:
D.V. Forero, S. Morisi,
M. Tortola, J.W.F. Valle 1107.6009



$$\Gamma \propto \sum_i \Theta_{\mu i} \Theta^\dagger_{ei} f\left(\frac{M_i^2}{M_W^2}\right)$$

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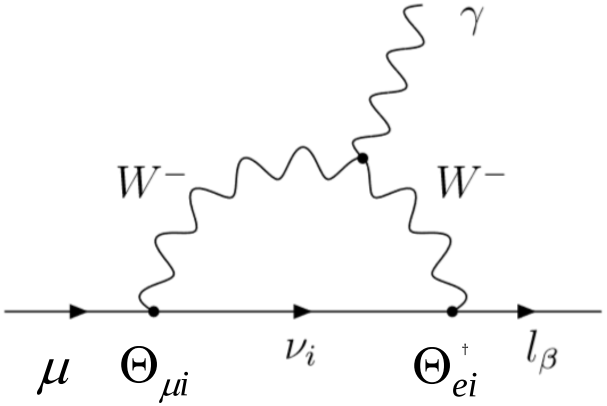

$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^\dagger_{ei} f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu} f(\infty) + \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\left(f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty)\right)$$

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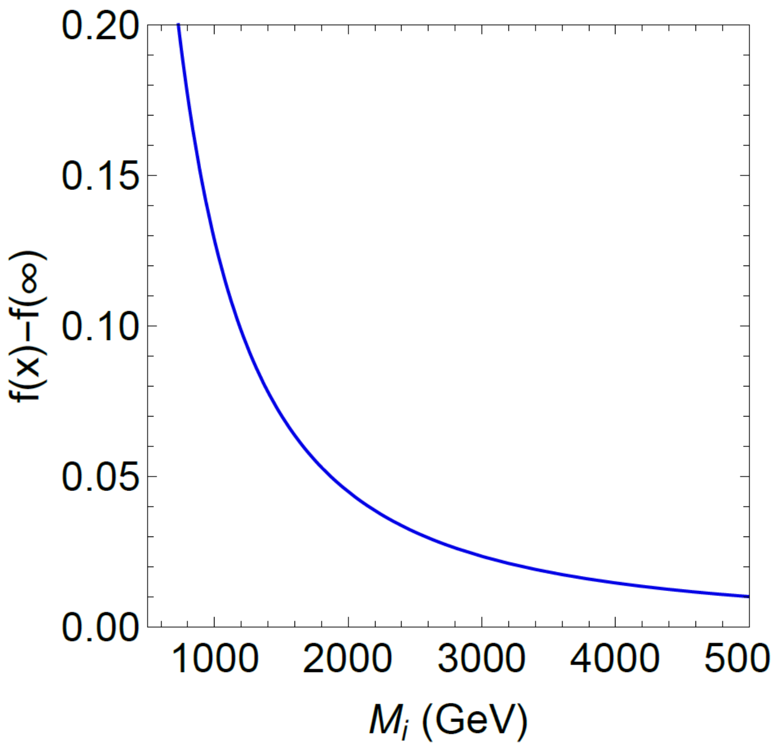

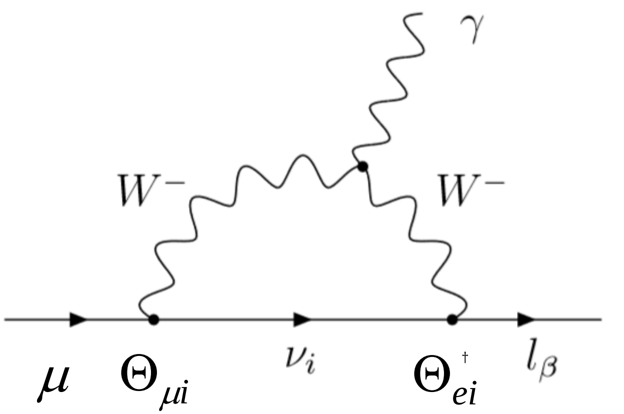

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LNV at colliders

If the HNLs are pseudoDirac, LNV signals should be very supressed

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But, if $\Delta M >> \Gamma$ they will oscillate many times between the two states before decaying, breaking the coherence and the supression of LNV

S. Antusch, E. Cazzato, and O. Fischer 1709.03797; M. Drewes, J. Klarić, and P. Klose 1907.13034; J. Gluza and T. Jeliński 1504.05568; P. S. Bhupal Dev and R. N. Mohapatra 1508.02277; G. Anamiati, M. Hirsch, and E. Nardi 1607.05641; A. Das, P. S. B. Dev, and R. N. Mohapatra 1709.06553

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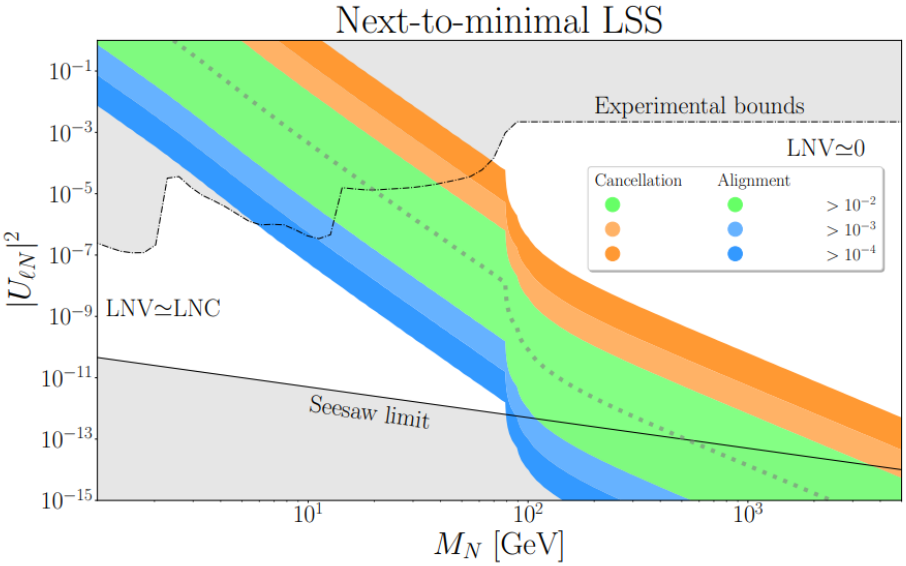

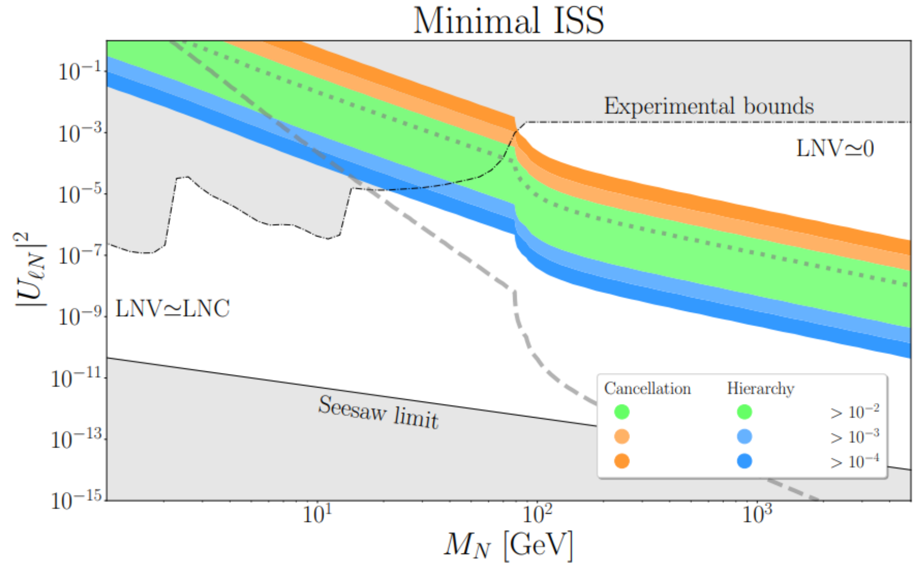

Could allow to distinguish between low scale Seesaw models!

EFM, X. Marcano and D. Naredo-Tuero 2209.04461

ν oscillations

Interaction Basis

Mass Basis

$|\nu_e\rangle$ $\xrightarrow{U_{PMNS}}$ $|\nu_1\rangle$ m$_1$

$|\nu_\mu\rangle$ $|\nu_2\rangle$ m$_2$

$|\nu_\tau\rangle$ $|\nu_3\rangle$ m$_3$

$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$ with $\alpha = e, \mu, \tau$ $i = 1, 2, 3$

Atmospheric, Solar, Majorana Phases

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}$$

$$P_{\alpha\beta} = \sin^2 2\theta_{ij} \sin^2 \frac{\Delta m^2_{ij}}{4L}$$

Evidence for ν mass from oscillations

Evidence for ν mass and mixing from oscillation phenomenon in many experiments with great agreement

What we already know (1σ)

SNO, Borexino
KamLAND

"Solar sector" $\begin{cases} \Delta m^2_{21} = 7.4^{+0.2}_{-0.2} \cdot 10^{-5}\mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.303^{+0.012}_{-0.011} \end{cases}$

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou 2007.14792

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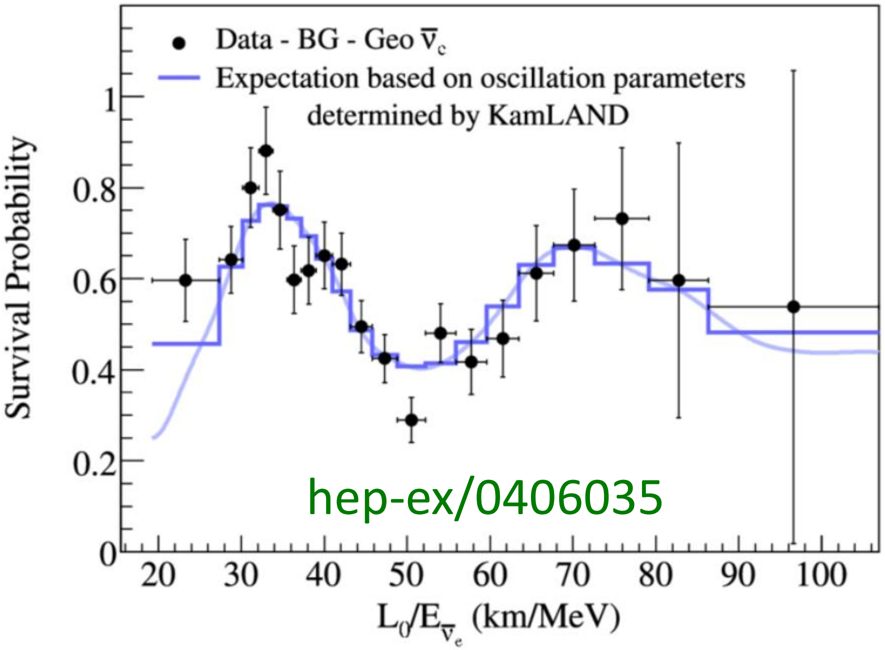

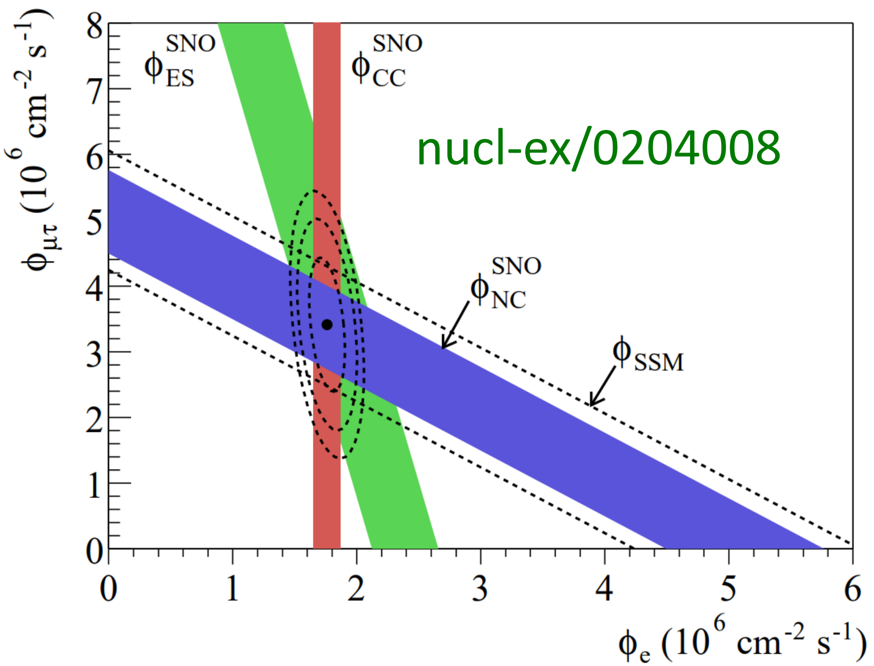

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SK, T2K, IC
MINOS, NOνA

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I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou 2007.14792

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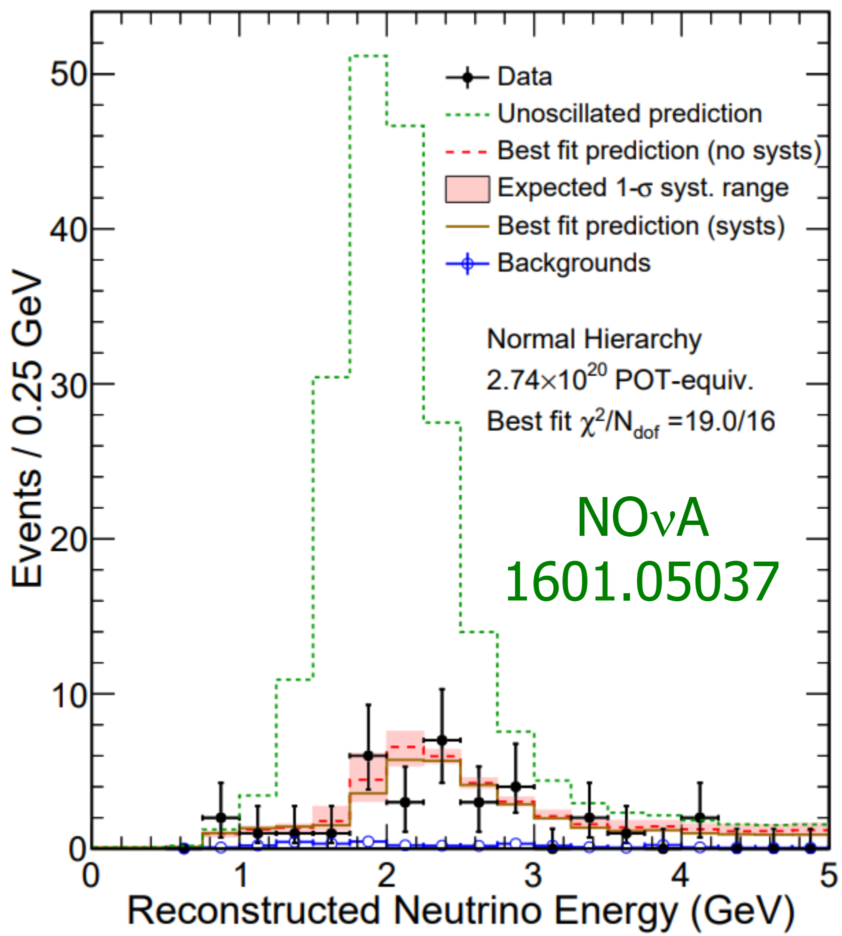

$10^{-5}\,\mathrm{eV}^2$

$3^{+0.012}_{-0.011}$

$\begin{matrix}03\\03\end{matrix} \cdot 10^{-3}\,\mathrm{eV}^2$

$.57^{+0.02}_{-0.02}$

I. Esteban, M. C. … Zhou 2007.14792

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Daya Bay
RENO, T2K, NOνA

$$\sin^2\theta_{13} = 0.0203 \pm 0.0006$$

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou 2007.14792

Evidence for ν mass from oscillations

Evidence for ν mass and mixing from oscillation phenomenon in many experiments with great agreement

SNO, Bore $)^{-5}\mathrm{eV}^2$

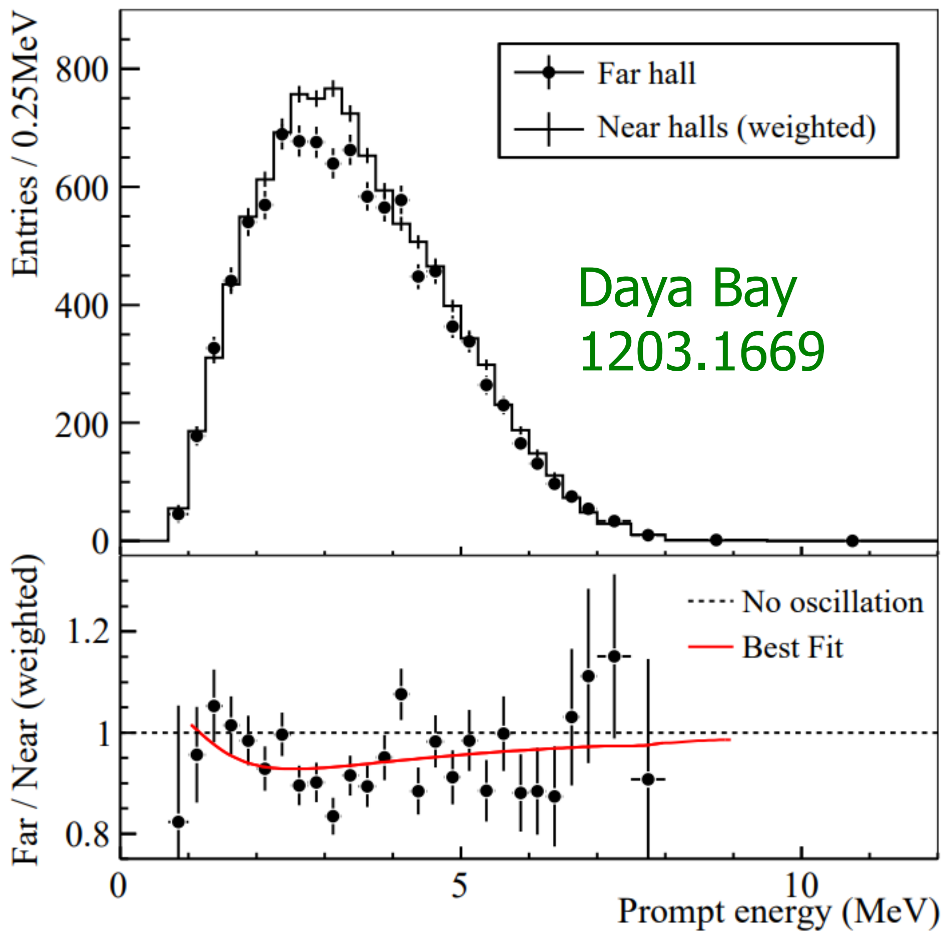
KamLAND $^{+0.012}_{-0.011}$

SK, T2K, I $\cdot 10^{-3}\mathrm{eV}^2$

MINOS, N $7^{+0.02}_{-0.02}$

Daya Bay

RENO, T2 $\pm\, 0.0006$



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