Neutrino mass matrix and LFV

Enrique Fernández-Martínez

ift

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry
Essential Asymmetries of Nature

ν oscillations

Interaction Basis		Mass Basis
$\vert\nu_e\rangle$	U_{PMNS}	$\vert\nu_1\rangle$ m_1
$\vert\nu_\mu\rangle$	$\longrightarrow$	$\vert\nu_2\rangle$ m_2
$\vert\nu_\tau\rangle$		$\vert\nu_3\rangle$ m_3

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

Atmospheric — Solar — Majorana Phases

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

$$s_{ij} = \sin\theta_{ij} \qquad \langle\nu_\beta|\nu_\alpha(L)\rangle = \sum_i U_{\beta i}\, e^{ip_iL} U^*_{\alpha i} \neq \delta_{\alpha\beta}$$

ν oscillations

Interaction Basis → U_{PMNS} → **Mass Basis**

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

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

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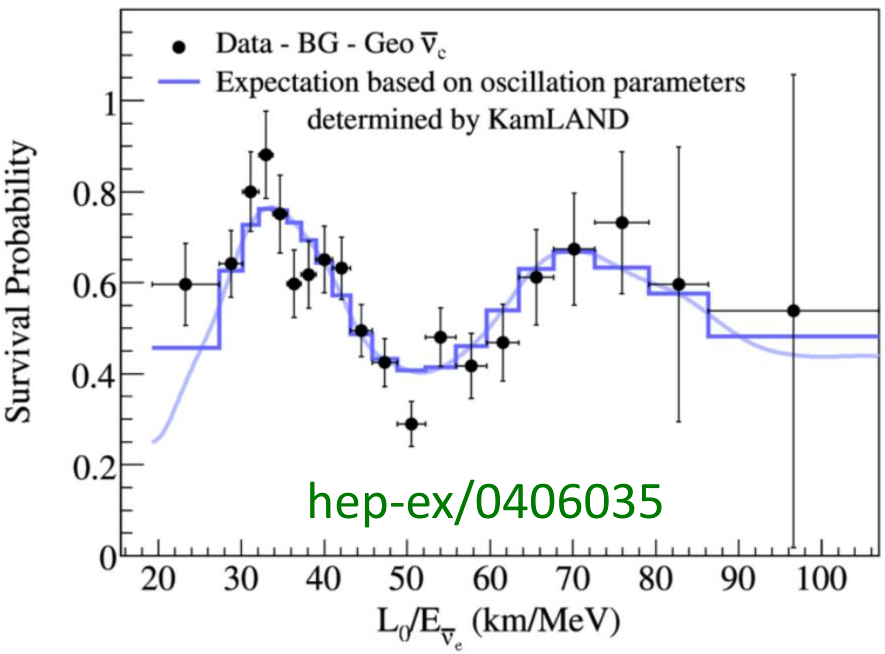

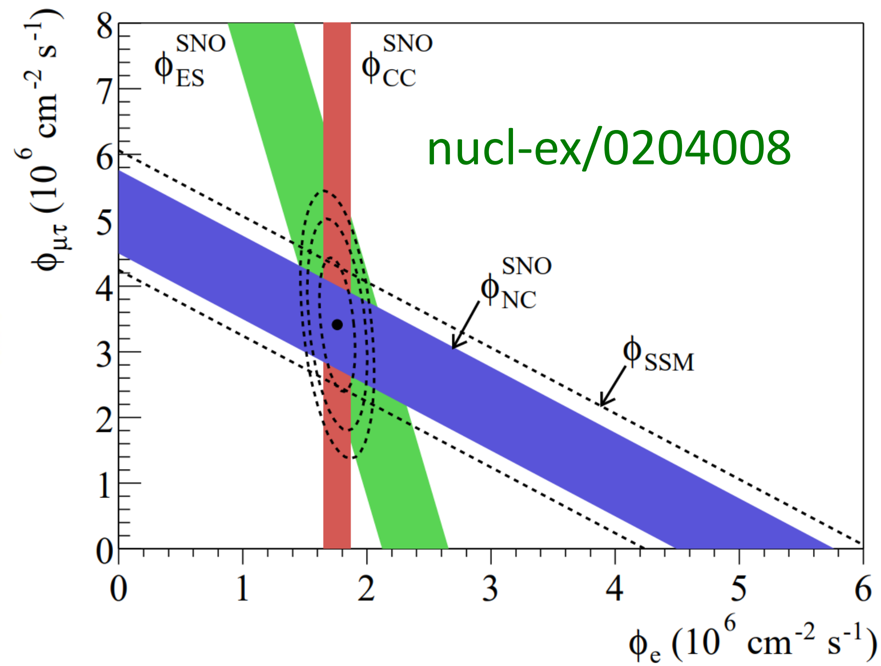

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SK, T2K, IC
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$$\begin{cases} |\Delta m^2_{31}| = 2.50^{+0.03}_{-0.03} \cdot 10^{-3}\,\mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.57^{+0.02}_{-0.02} \end{cases}$$

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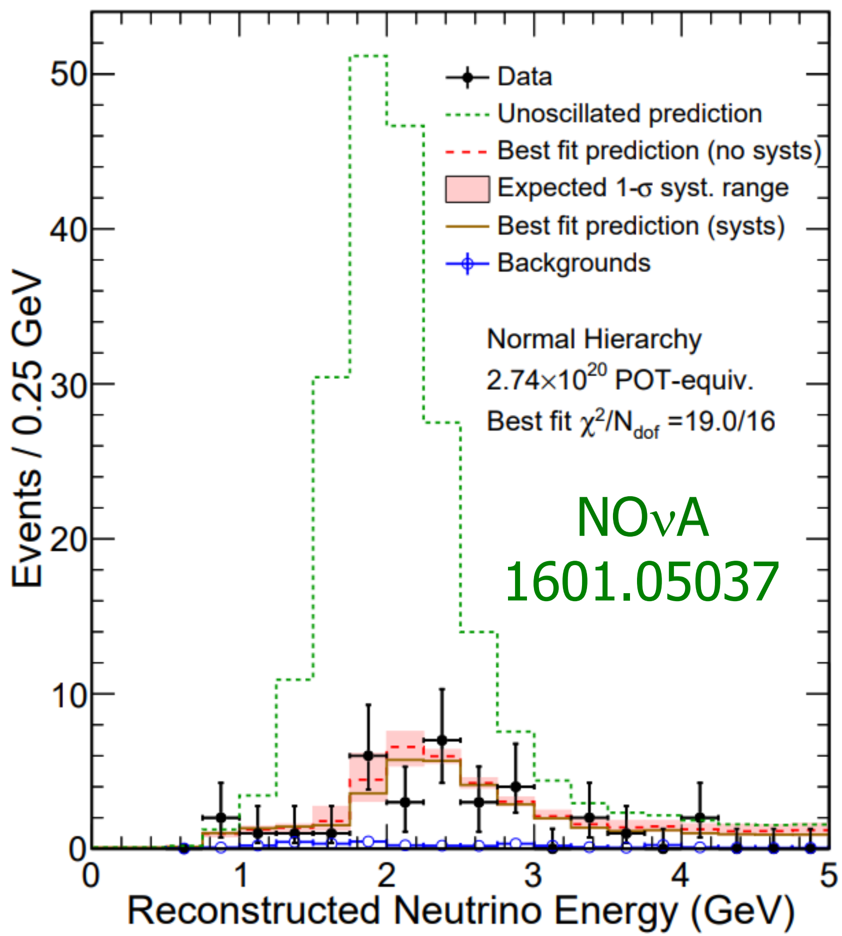

$10^{-5}\mathrm{eV}^2$

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

$^{03}_{03} \cdot 10^{-3}\mathrm{eV}^2$

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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

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SNO, Bore

KamLAND

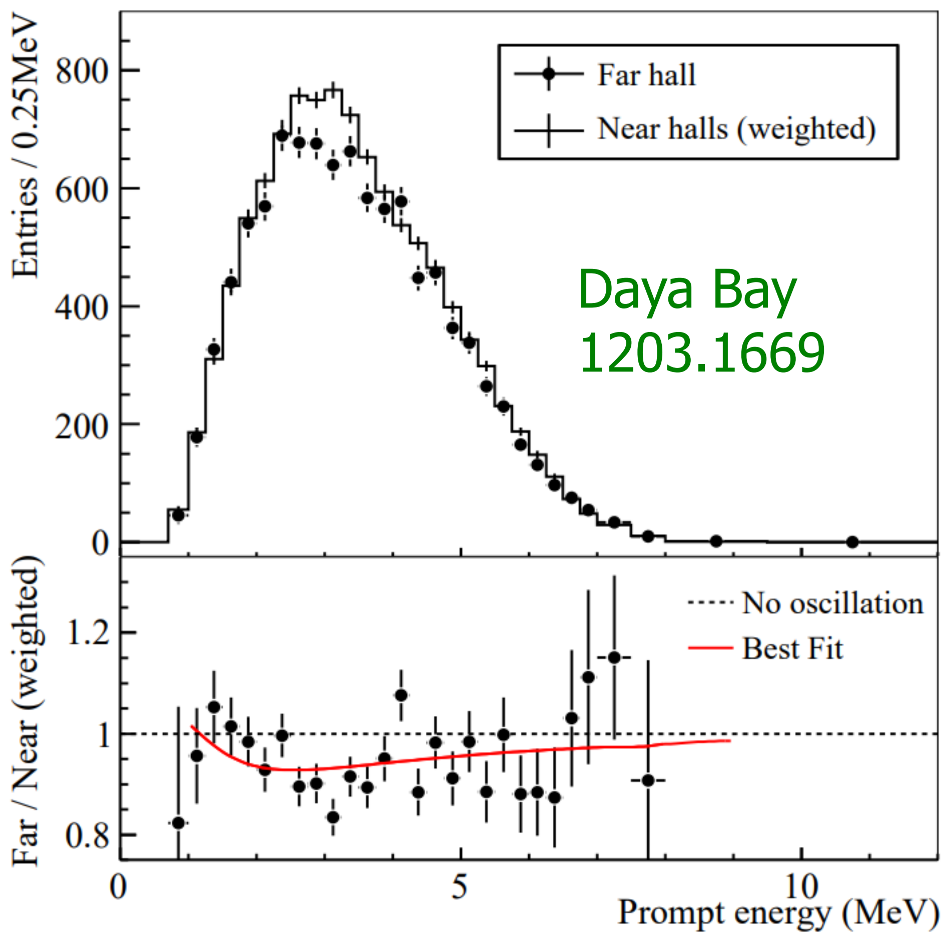
SK, T2K, I

MINOS, N

Daya Bay

RENO, T2

I. Esteban, M



$)^{-5}\mathrm{eV}^2$

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hou 2007.14792

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Evidence for ν mass from oscillations

What we still don't know

Mass hierarchy? Absolute mass scale?

$sign(\Delta m^2_{31})$? m_1 ?

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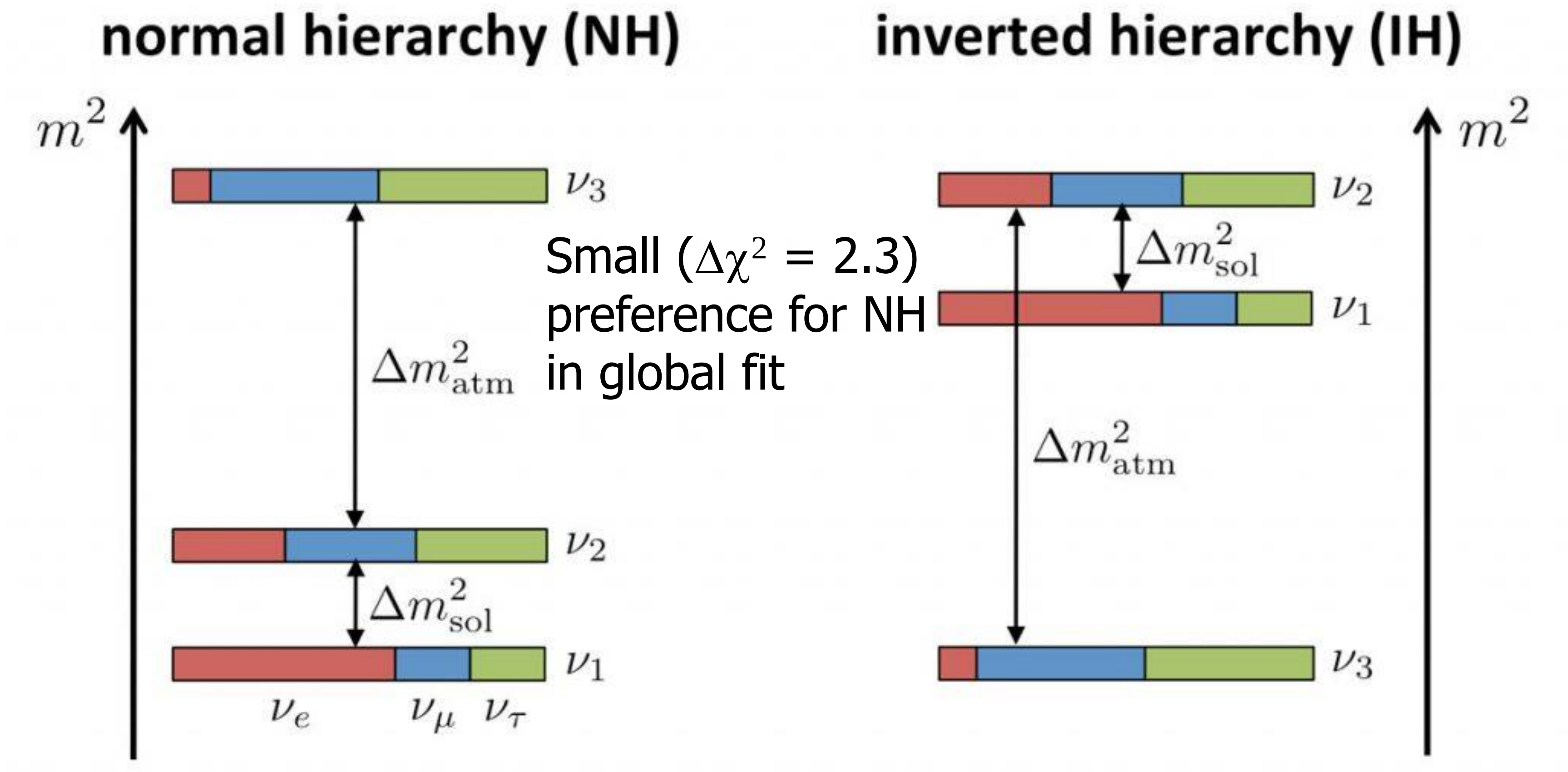

Small ($\Delta\chi^2$ = 2.3) preference for NH in global fit

Evidence for ν mass from oscillations

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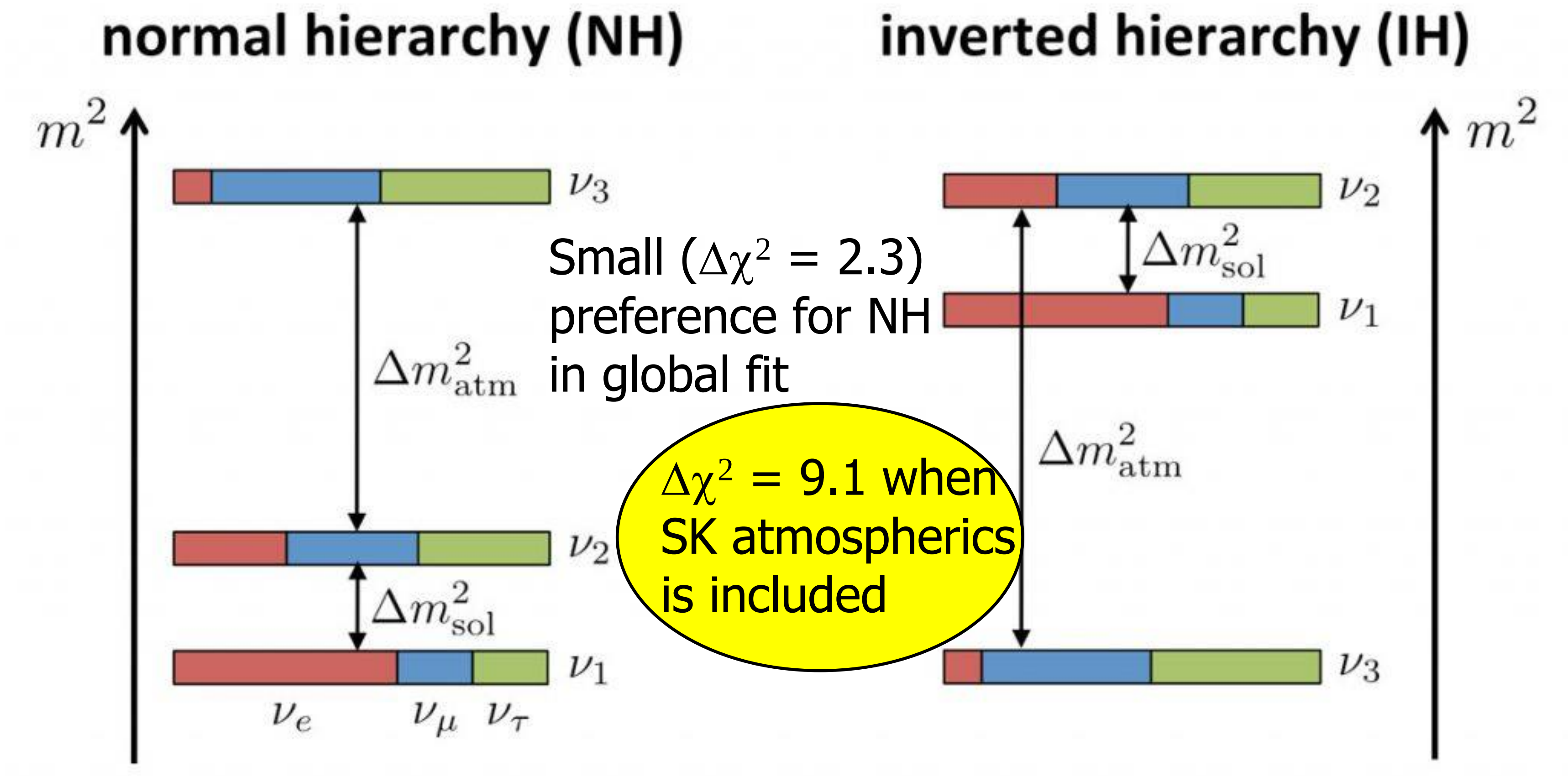
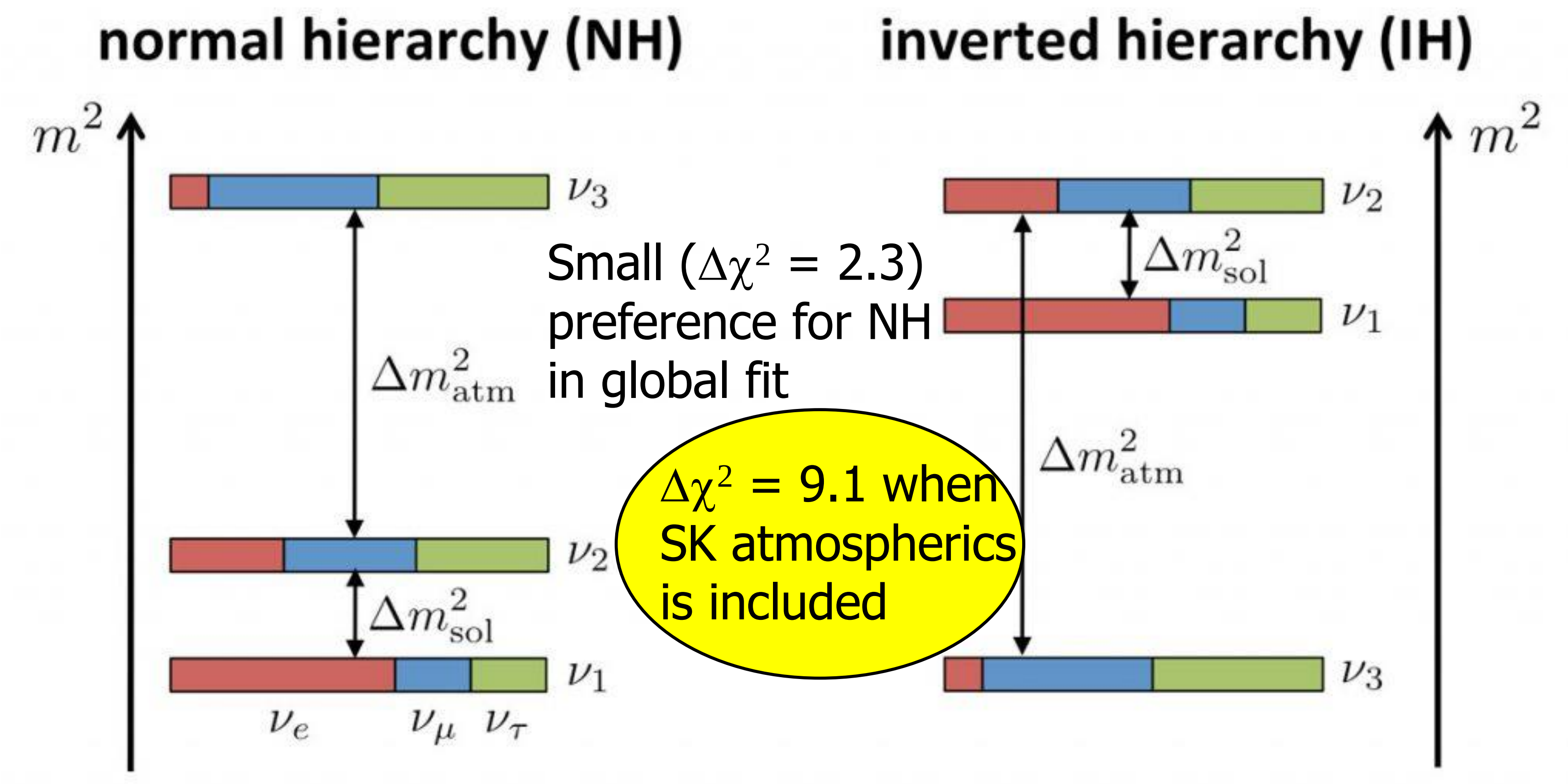


Evidence for ν mass from oscillations

Mass hierarchy? Absolute mass scale?

Between NOνA (currently running) and JUNO (expected start late 2024) should clarify the situation in a few years



Small ($\Delta\chi^2$ = 2.3) preference for NH in global fit

$\Delta\chi^2$ = 9.1 when SK atmospherics is included

Evidence for ν mass from oscillations

Mass hierarchy? Absolute mass scale?

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Datasets	Σm_ν [eV]
CDS	$< 0.093 \quad (2\,\sigma)$
CDSO	$< 0.091 \quad (2\,\sigma)$
CDSA	$< 0.071 \quad (2\,\sigma)$
CDSG	$< 0.049 \quad (2\,\sigma)$
CDSOA	$< 0.065 \quad (2\,\sigma)$
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CDSAG	$< 0.045 \quad (2\,\sigma)$
CDSOAG	$< 0.043 \quad (2\,\sigma)$

C=Planck
D=DESI
S=SN
O=Chrono
A=ADD
G=GRB

From Cosmology
IH ($\Sigma m_\nu > 0.1$eV) is disfavoured depending on the dataset analized

D. Wang, O. Mena, E. Di Valentino and S. Gariazzo 2405.03368

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Evidence for ν mass from oscillations

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KATRIN $m_{\nu_e} < 0.8$ eV

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Evidence for ν mass from oscillations

What we still don't know

Mass hierarchy? Absolute mass scale?

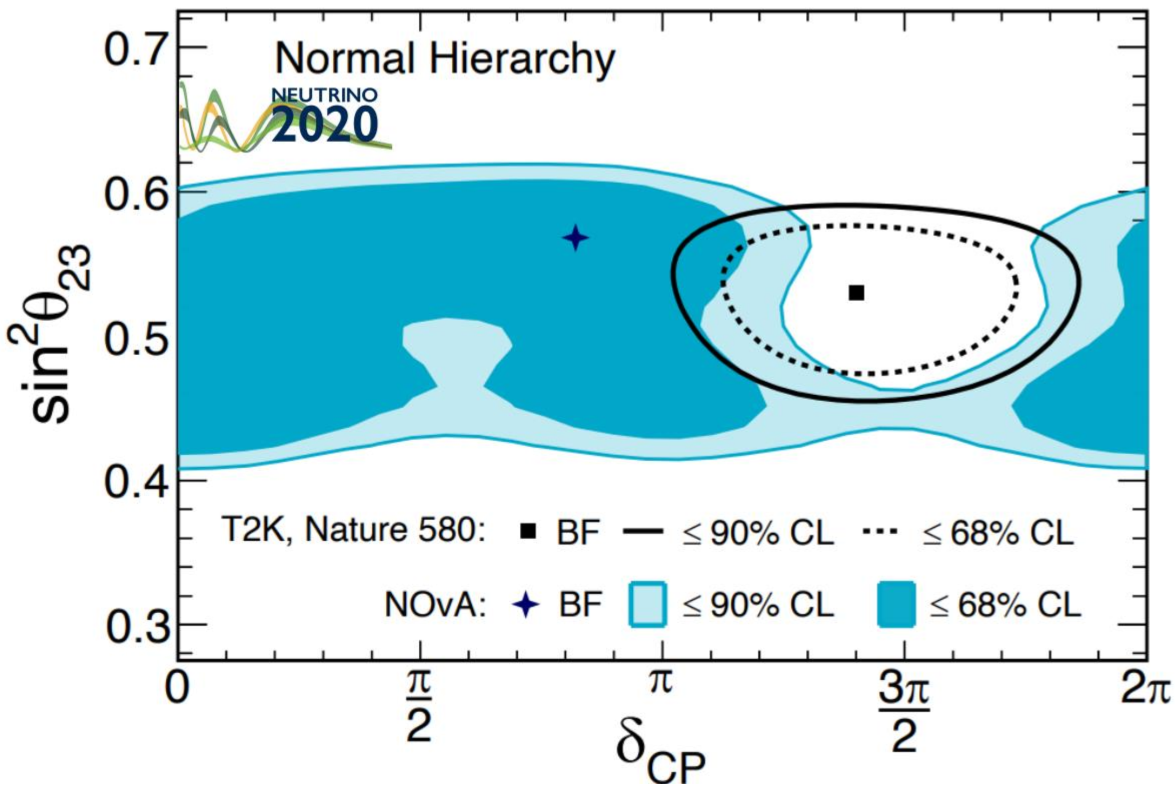
$sign(\Delta m^2_{31})$? m_1 ?

CP violation phase?

δ ?

Evidence for ν mass from oscillations

~2σ tension between the two present measurements of δ



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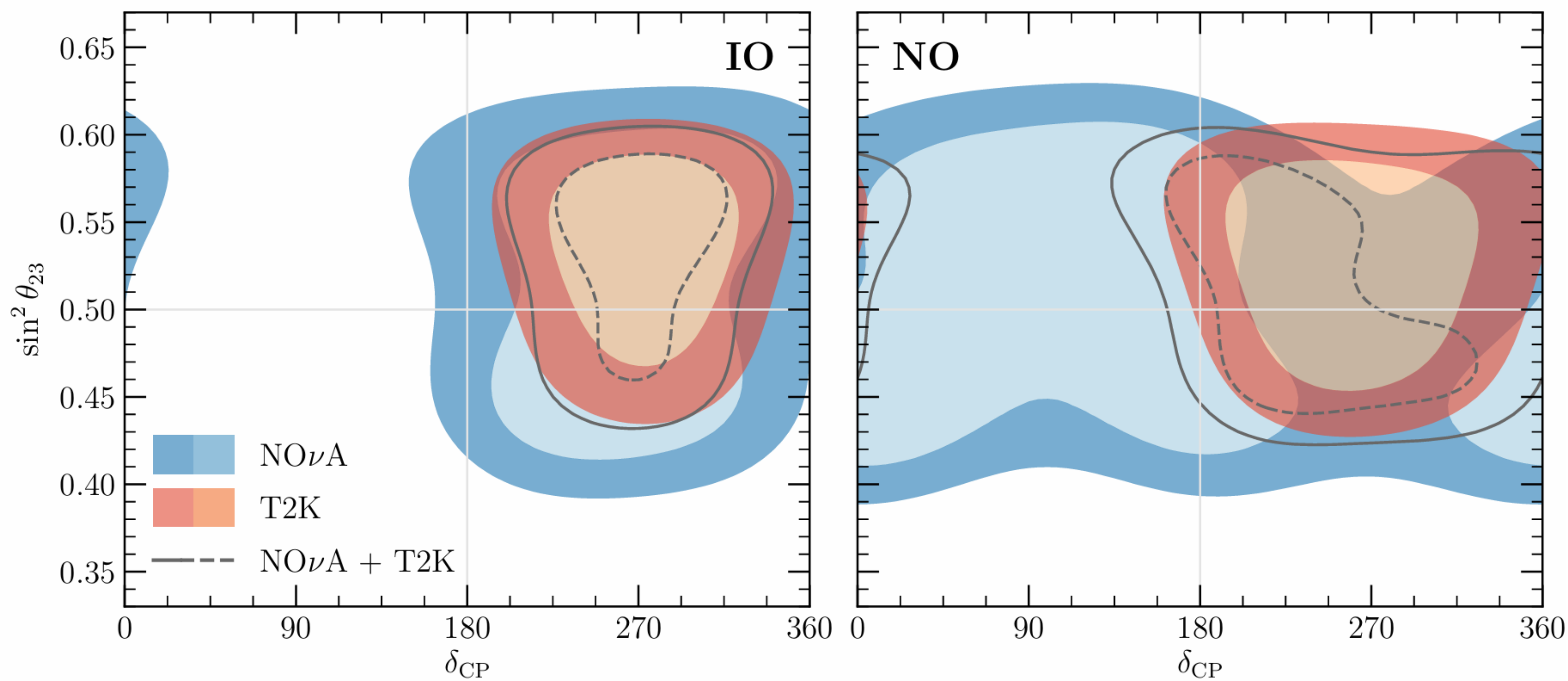

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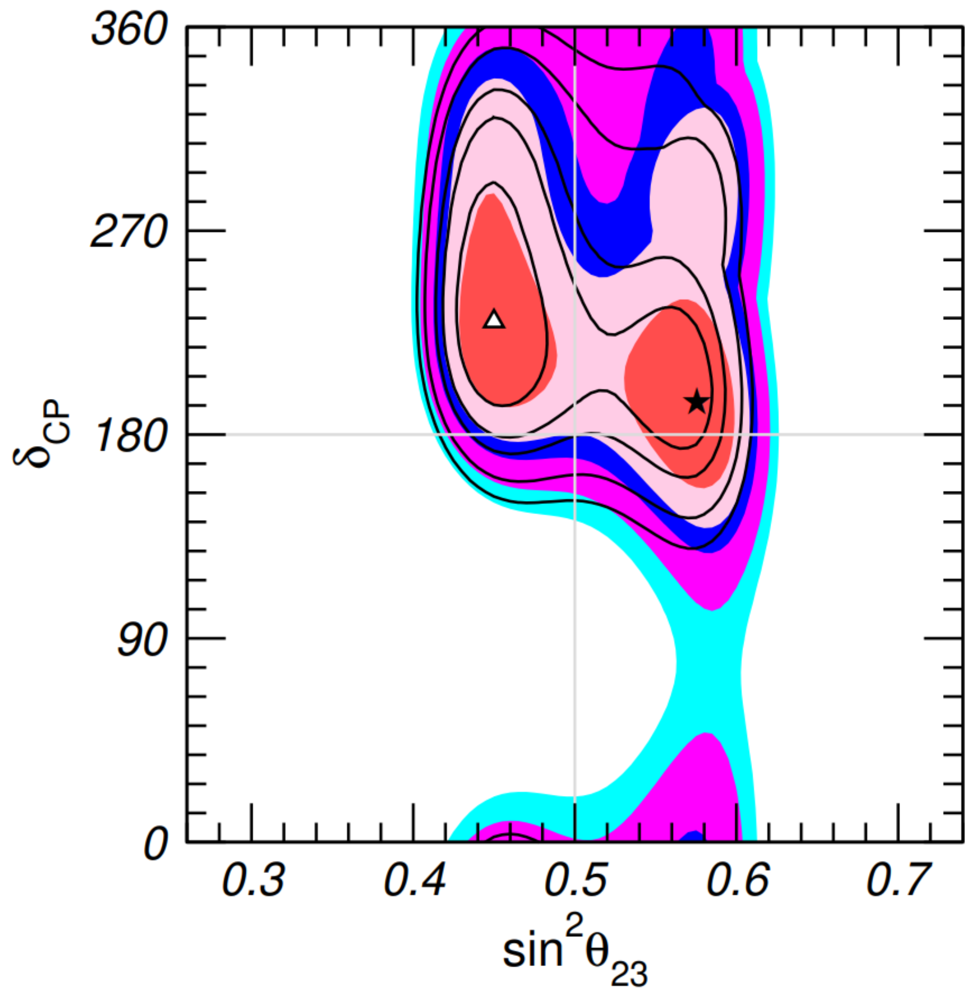

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Evidence for ν mass from oscillations

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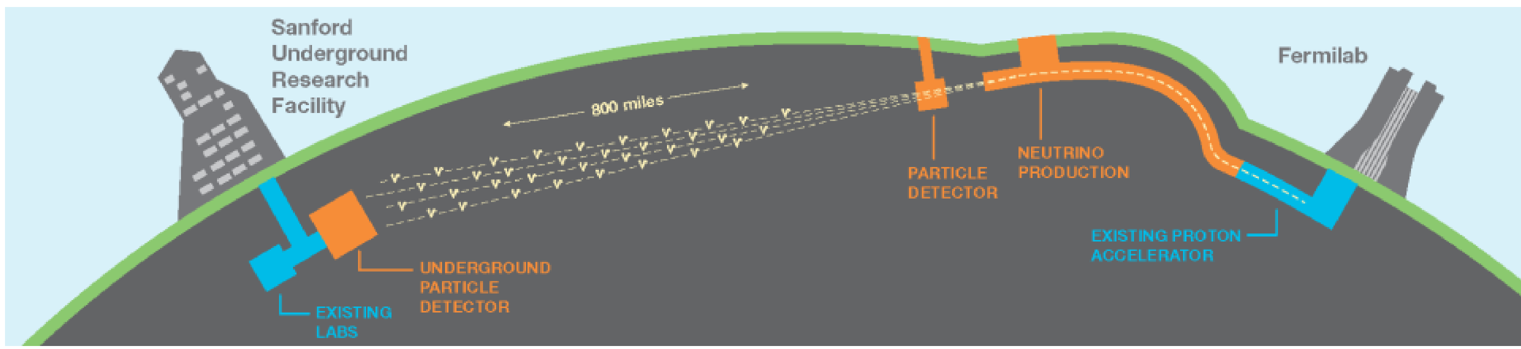
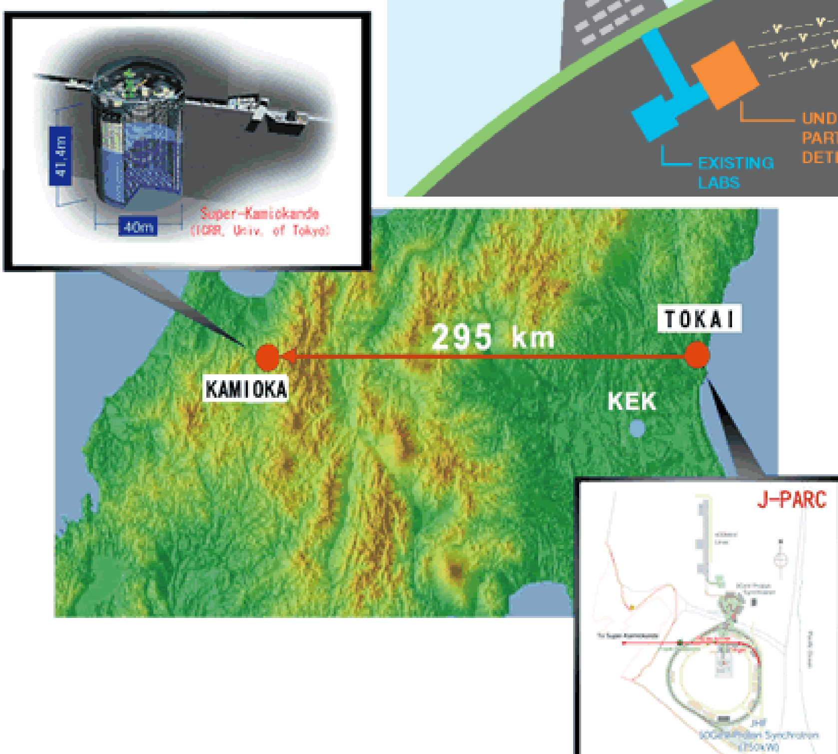
New generation to reach the 5σ mark



DUNE



T2HK

Evidence for ν mass from oscillations

What we still don't know

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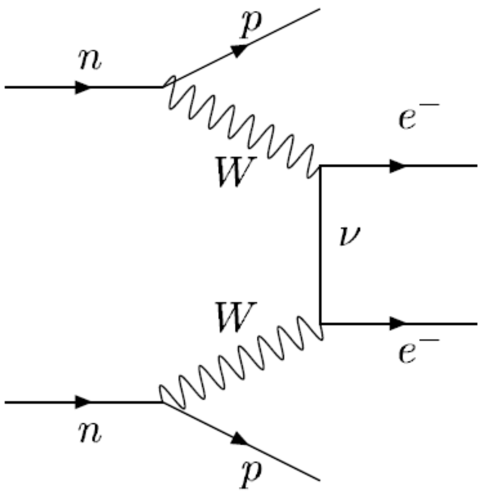
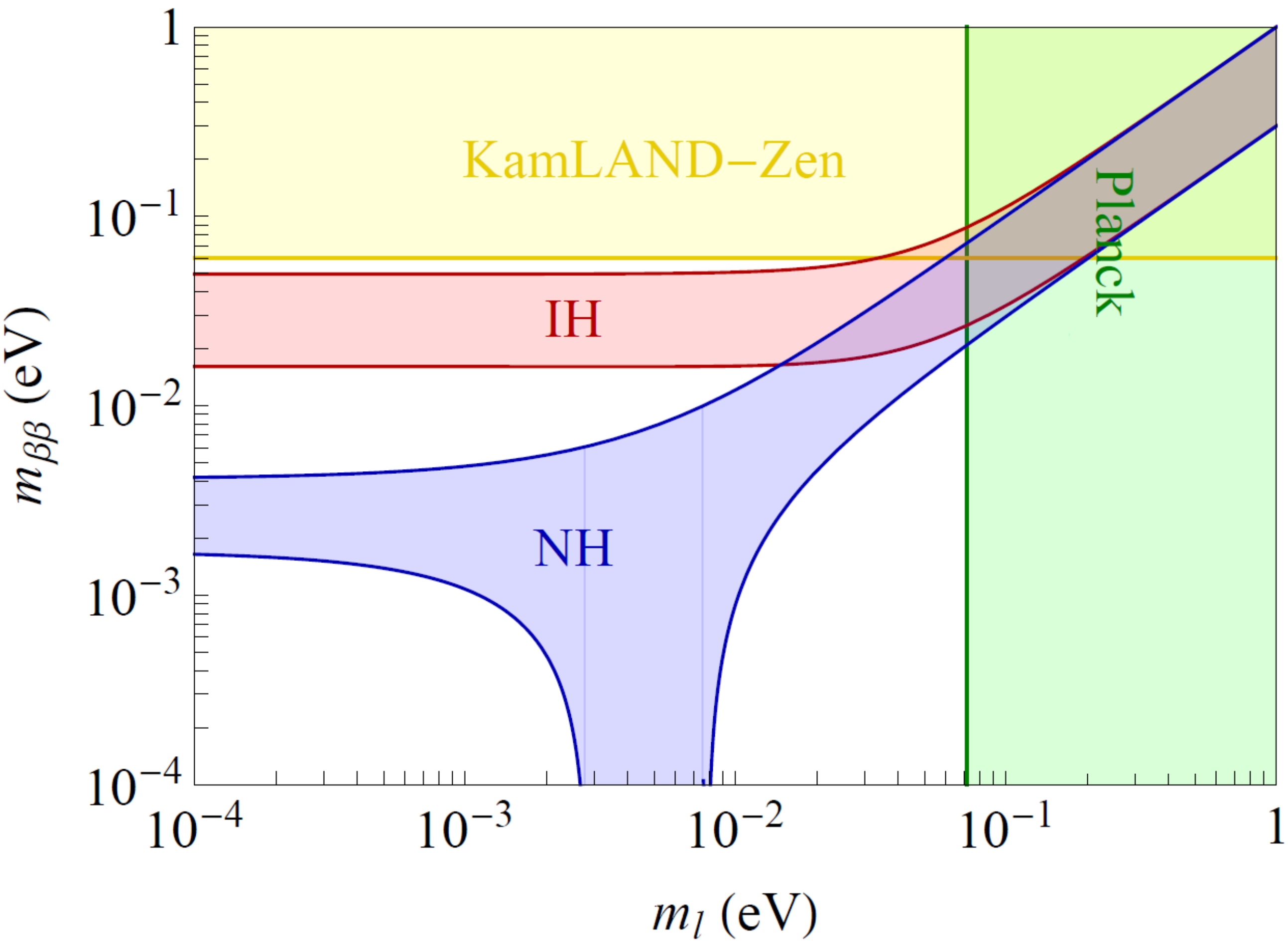
Majorana Nature and phases?

Evidence for ν mass from oscillations

Majorana Nature and phases?





ν mass from right-handed neutrinos

$$m_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \xrightarrow{\text{Seesaw}} U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

If $M_N \gg m_D$ then $M \approx M_N$ and $m \approx m_D^t M_N^{-1} m_D \rightarrow$ lightness of ν

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

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Or in EFT language integrating out the heavy neutrinos gives:

d=5 Weinberg 1979

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

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

$$m_D^t M_N^{-1} m_D \overline{\nu_L^c} \nu_L$$

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

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

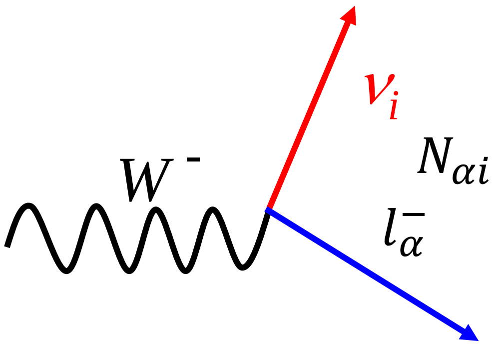
$$\Big\downarrow \; \langle\phi\rangle = \frac{v}{\sqrt{2}}$$

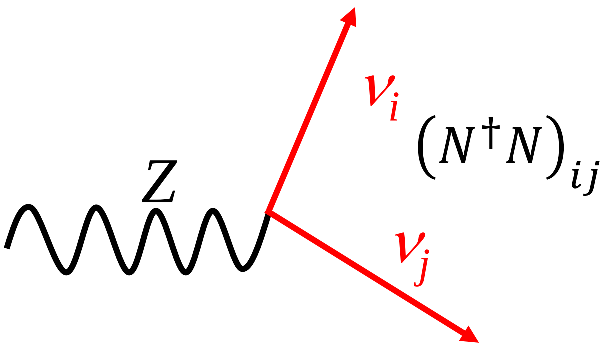
$$\Theta\Theta^\dagger \overline{\nu_L} \partial\!\!\!/ \nu_L$$

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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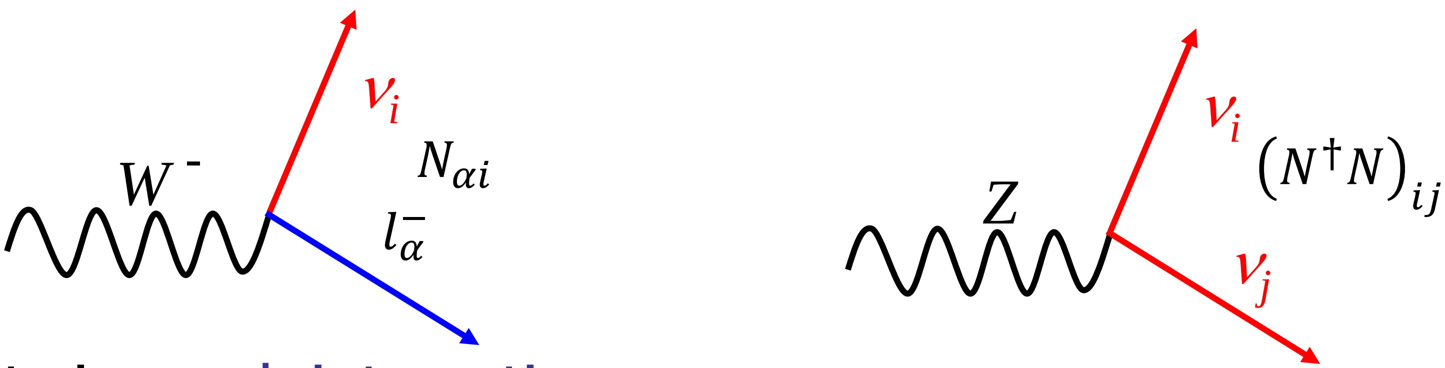

Effects in weak interactions…

G_F from μ decay vs M_W
measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and β and K decays, LFU constraints…

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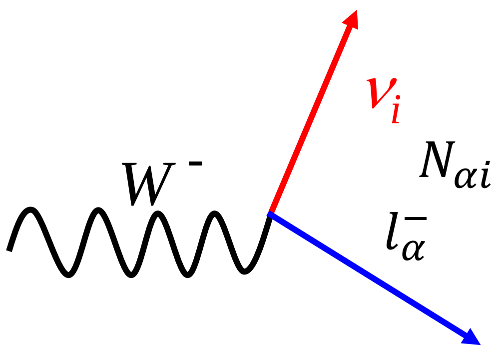

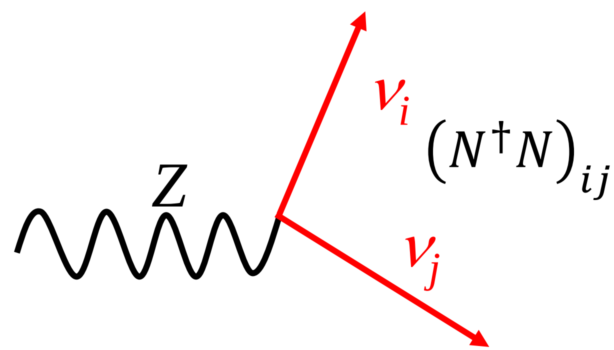

Effects in weak interactions…

G_F from μ decay vs M_W

measurents of $\sin\theta_w$ from LEP, Tevatron and LHC and β and K decays, LFU constraints…

Also the invisible width of the Z since NC are also affected

And LFV processes such as $\mu \rightarrow e\,\gamma$ or $\tau \rightarrow e\,\gamma$ 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
$\eta_{ee} = \frac{1}{2}\sum_k \lvert\Theta_{ek}\rvert^2$	$[0.081, 1.4] \cdot 10^{-3}$	-
$\eta_{\mu\mu}$	$1.4 \cdot 10^{-4}$	-
$\eta_{\tau\tau}$	$8.9 \cdot 10^{-4}$	-
$\mathrm{Tr}\,[\eta]$	$2.1 \cdot 10^{-3}$	-
$\lvert\eta_{e\mu}\rvert$	$3.4 \cdot 10^{-4}$	$\mathbf{1.2 \cdot 10^{-5}}$
$\lvert\eta_{e\tau}\rvert$	$\mathbf{8.8 \cdot 10^{-4}}$	$8.1 \cdot 10^{-3}$
$\lvert\eta_{\mu\tau}\rvert$	$\mathbf{1.8 \cdot 10^{-4}}$	$9.4 \cdot 10^{-3}$

$$N = (\mathbb{I} - \eta)U$$

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

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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2 σ preference for mixing with electrons ~0.03

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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…

ν mass from type III Seesaw

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

Integrating out the heavy triplets gives:

d=5 Weinberg 1979

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

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

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

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

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

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Modifies ν kinnetic terms

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Modifies ν kinnetic terms

Modifies ℓ kinnetic terms

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

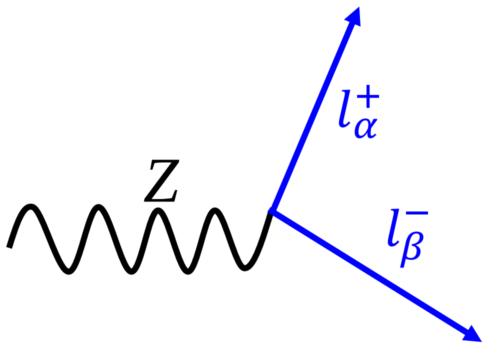
Modifies ν kinnetic terms

Modifies couplings to the W

Modifies ℓ kinnetic terms

Bound on type III Seesaw

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



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

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

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

The type II Seesaw

Add heavy scalar triplet $\vec{\Delta}$ 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

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

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

$$Y_\Delta Y_\Delta^\dagger M_\Delta^{-2} \left(\overline{L_L} \gamma_\mu L_L\right) \left(\overline{L_L} \gamma^\mu L_L\right)$$

See talk by Marco Ardu

The type II Seesaw

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

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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

See talk by Marco Ardu

The type II Seesaw

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

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Leading constraints from d=6 4-lepton LFV operators

See talk by Marco Ardu

Global status on low E cLFV through EFT

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

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

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

Constraints on fully leptonic operators

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

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

Global status on low E cLFV through EFT

Leptonic		up − quarks		down − quarks	
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})(\bar{e}_{L\gamma}\gamma_\mu e_{L\delta})$	$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar{u}\gamma_\mu u)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$	$\mathcal{O}^{dV}_{\alpha\beta L}$	$(\bar{d}\gamma_\mu d)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})(\bar{e}_{R\gamma}\gamma_\mu e_{R\delta})$	$\mathcal{O}^{uA}_{\alpha\beta L}$	$(\bar{u}\gamma_\mu\gamma_5 u)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$	$\mathcal{O}^{dA}_{\alpha\beta L}$	$(\bar{d}\gamma_\mu\gamma_5 d)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})(\bar{e}_{R\gamma}\gamma_\mu e_{R\delta})$	$\mathcal{O}^{uV}_{\alpha\beta R}$	$(\bar{u}\gamma_\mu u)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$	$\mathcal{O}^{dV}_{\alpha\beta R}$	$(\bar{d}\gamma_\mu d)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})(\bar{e}_{L\gamma}\gamma_\mu e_{L\delta})$	$\mathcal{O}^{uA}_{\alpha\beta R}$	$(\bar{u}\gamma_\mu\gamma_5 u)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$	$\mathcal{O}^{dA}_{\alpha\beta R}$	$(\bar{d}\gamma_\mu\gamma_5 d)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{\gamma\delta RS}_{\alpha\beta R}$	$(\bar{e}_{L\alpha}e_{R\beta})(\bar{e}_{L\gamma}e_{R\delta}) + \text{h.c.}$	$\mathcal{O}^{uS}_{\alpha\beta R}$	$(\bar{u}u)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$	$\mathcal{O}^{dS}_{\alpha\beta R}$	$(\bar{d}d)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$
Dipole		$\mathcal{O}^{uP}_{\alpha\beta R}$	$(\bar{u}\gamma_5 u)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$	$\mathcal{O}^{dP}_{\alpha\beta R}$	$(\bar{d}\gamma_5 d)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{e\gamma}_{\alpha\beta}$	$(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta})F_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{uT}_{\alpha\beta R}$	$(\bar{u}\sigma_{\mu\nu}u)(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta}) + \text{h.c.}$	$\mathcal{O}^{dT}_{\alpha\beta R}$	$(\bar{d}\sigma_{\mu\nu}d)(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta}) + \text{h.c.}$

Very many operators in LEFT that would contribute

Can we constrain them all?

Are there flat directions?

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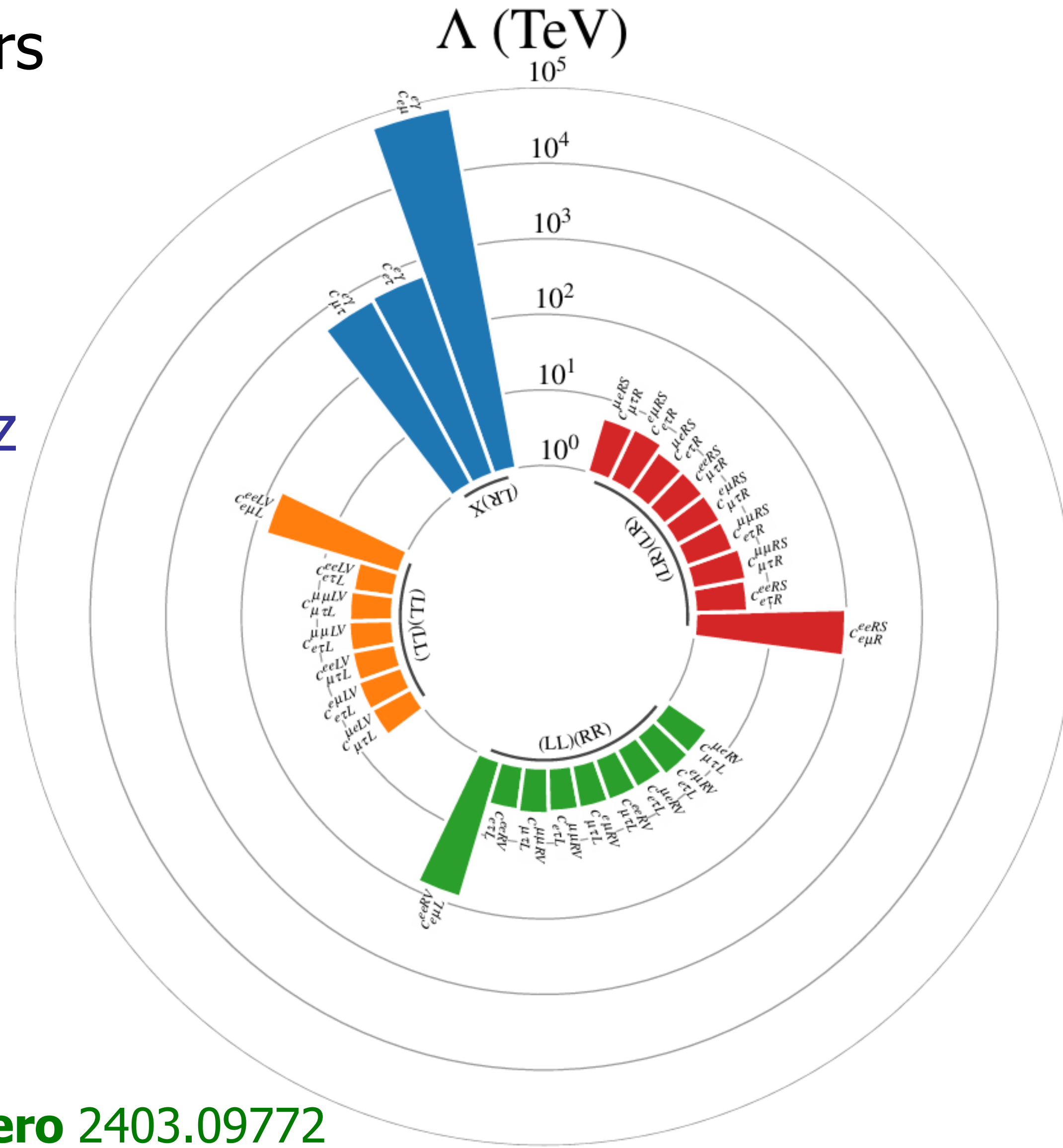
bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

Global status on low E cLFV through EFT

For fully leptonic operators and dipoles there are no flat directions!

Coherent contributions between different Lorentz structures suppressed by chirality flips → no cancellations

Global constraints = assuming one operator at a time



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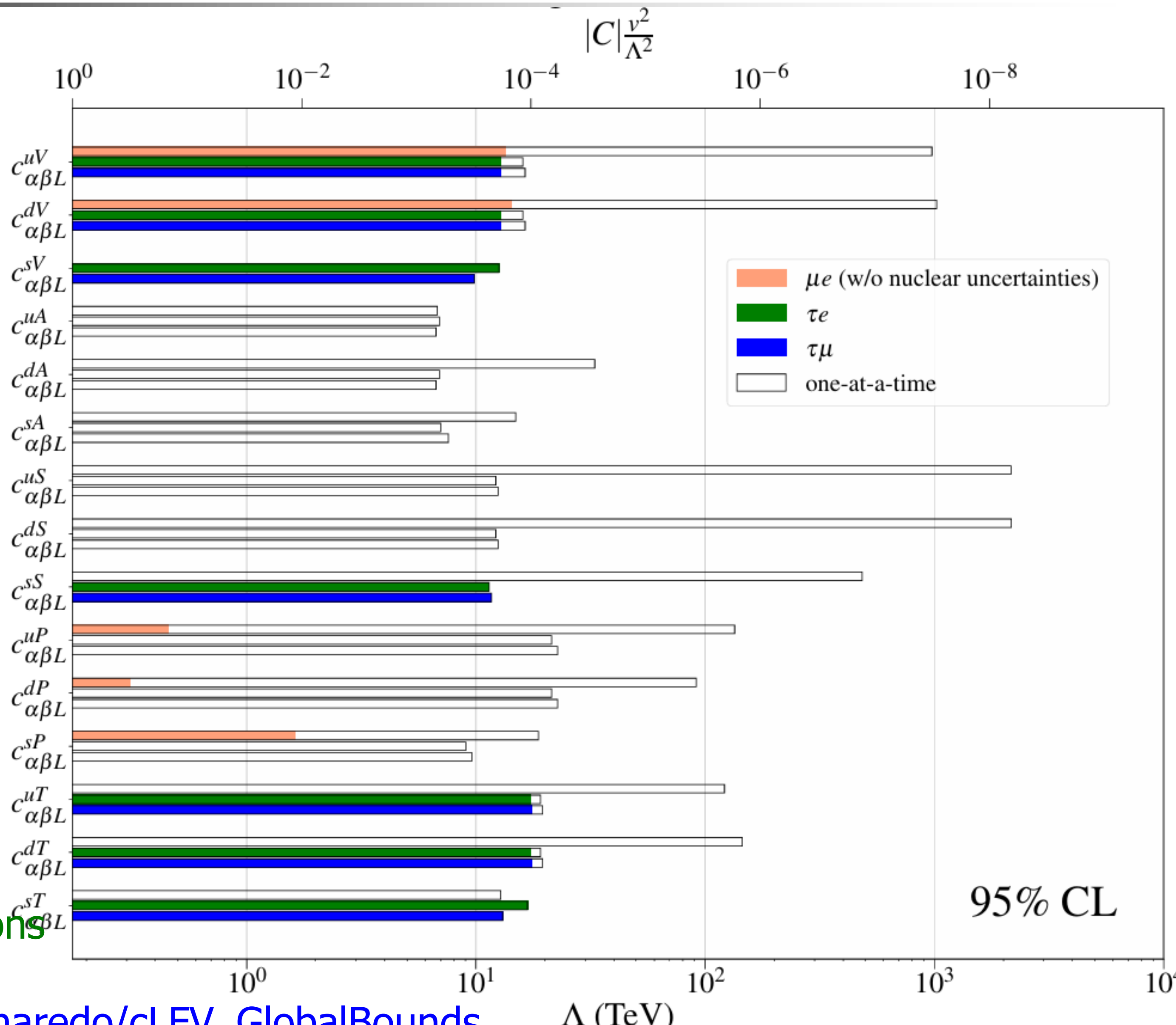
bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators

For 4-fermion semileptonic operators many flat directions are present and prevent to set fully global constraints



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bounds and correlations available at
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cLFV semileptonic operators

All in all there are 4 flat directions in the τ sectors

$\tau \to e/\mu$ KK help with these but large uncertainties

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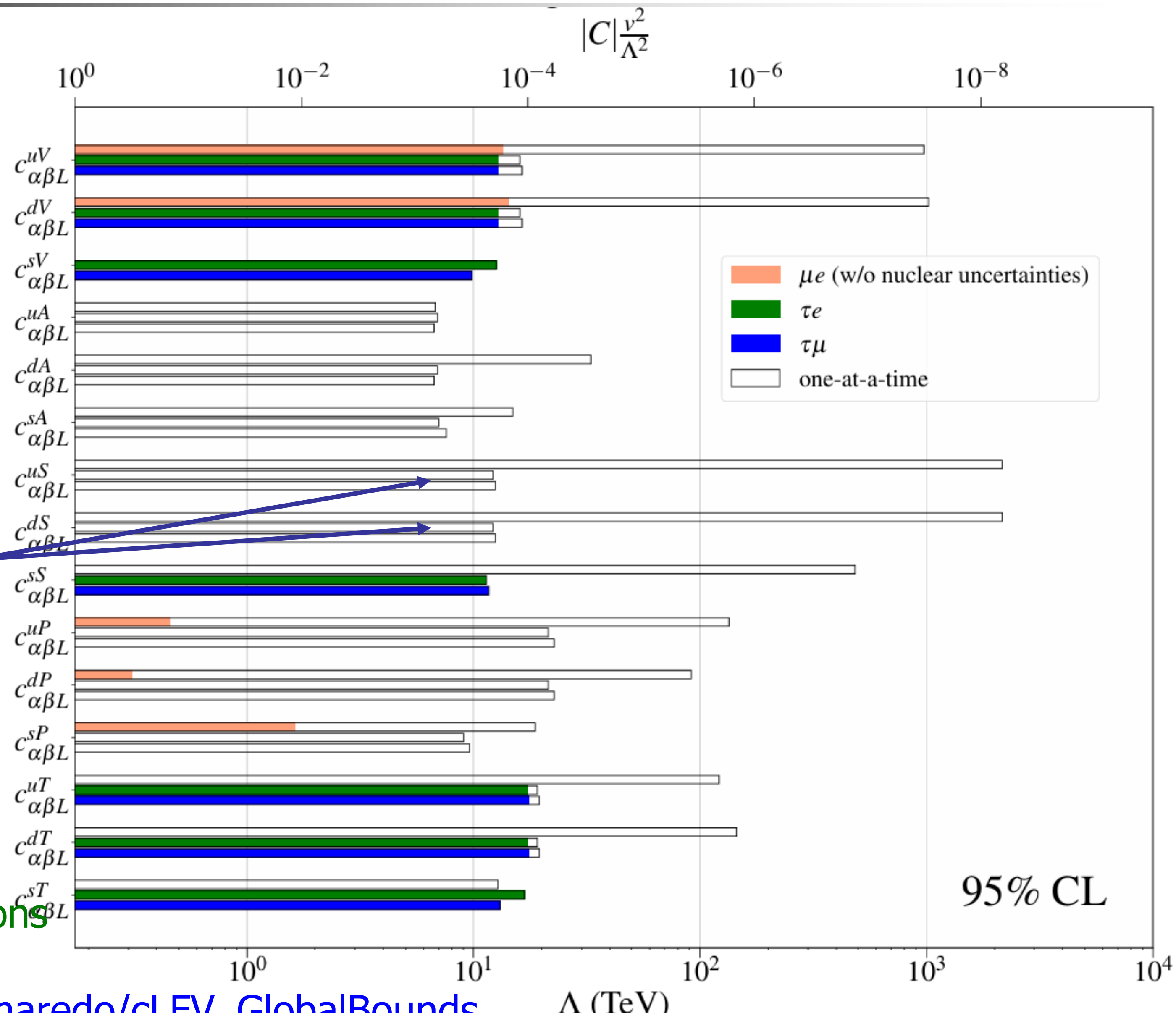
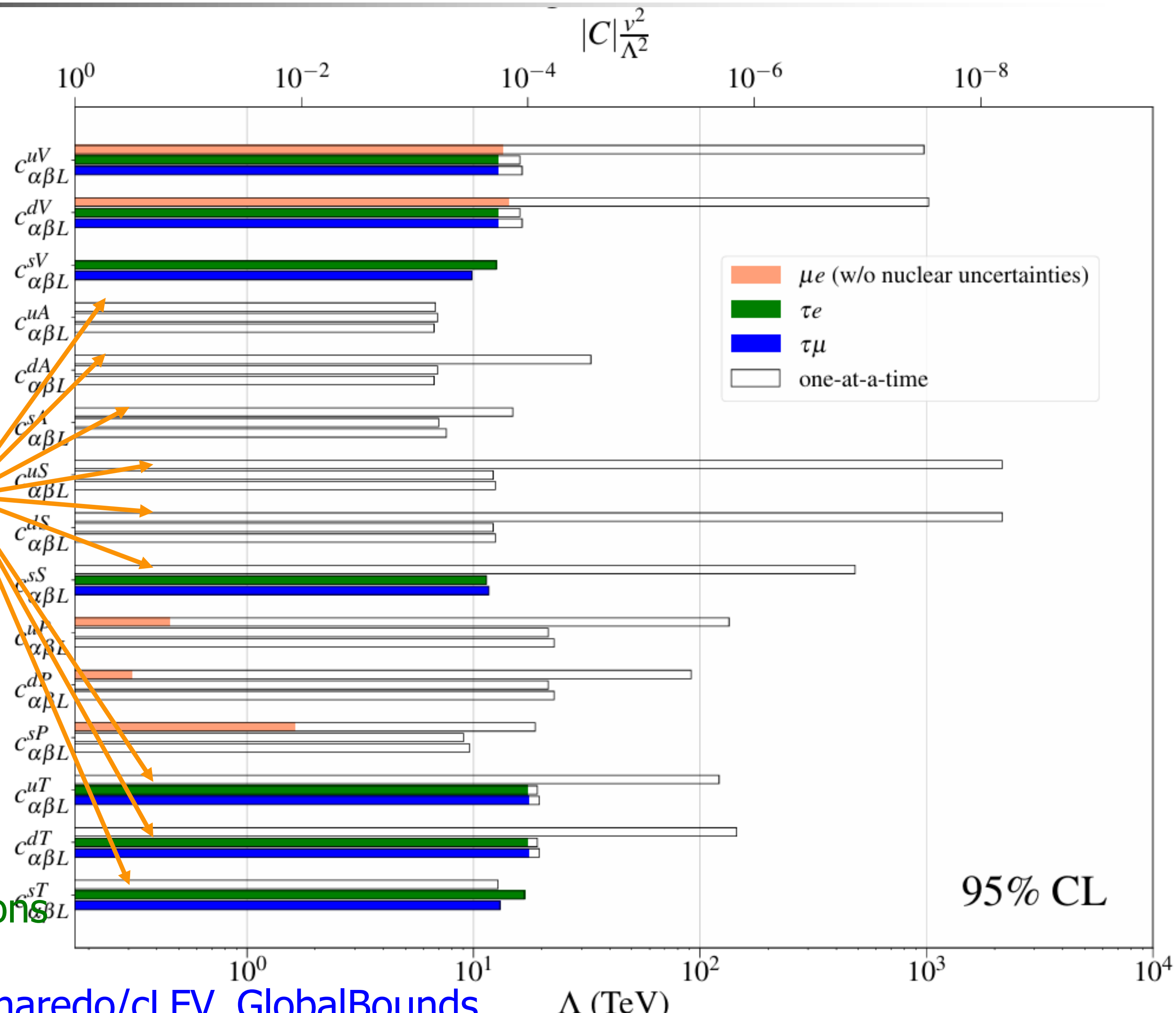


cLFV semileptonic operators



4 flat directions involving these operators

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2403.09772
bounds and correlations available at
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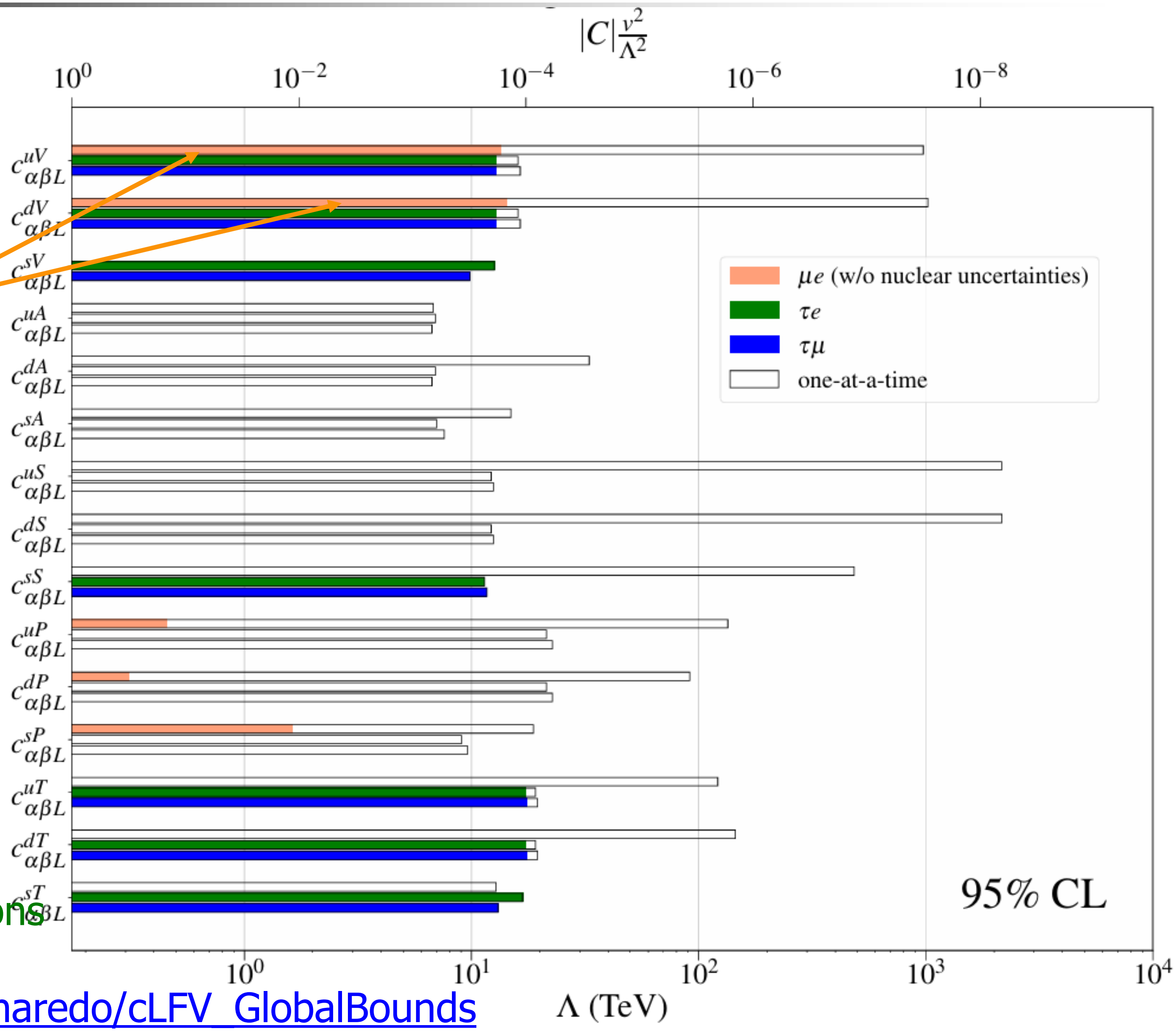
cLFV semileptonic operators

The directions probed by SI μ-e conversion are almost parallel



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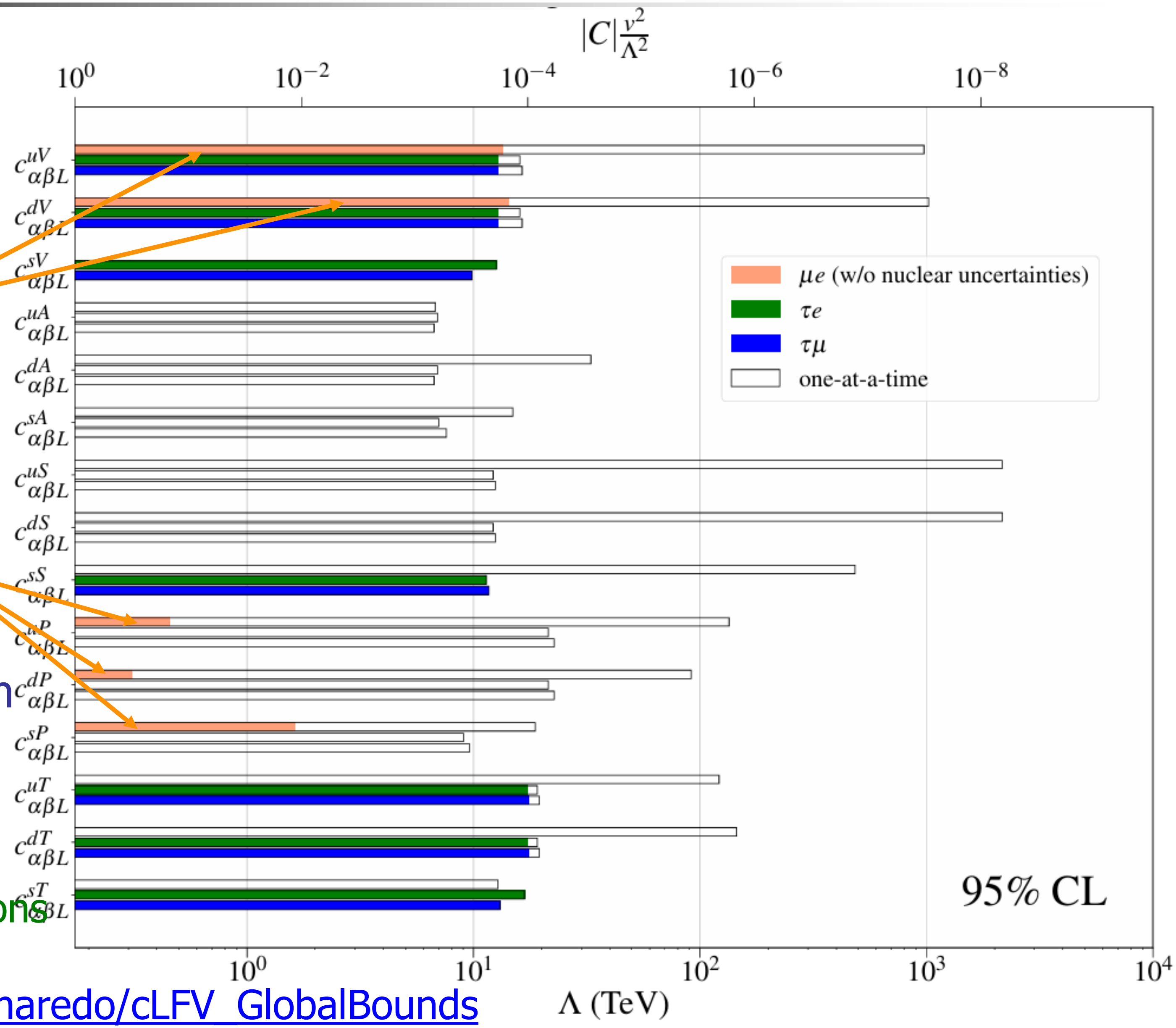
bounds and correlations available at https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators

The directions probed by SI μ-e conversion are almost parallel

π^0 and η decays to μ e needed, much weaker constraints wrt SD μ-e conversion



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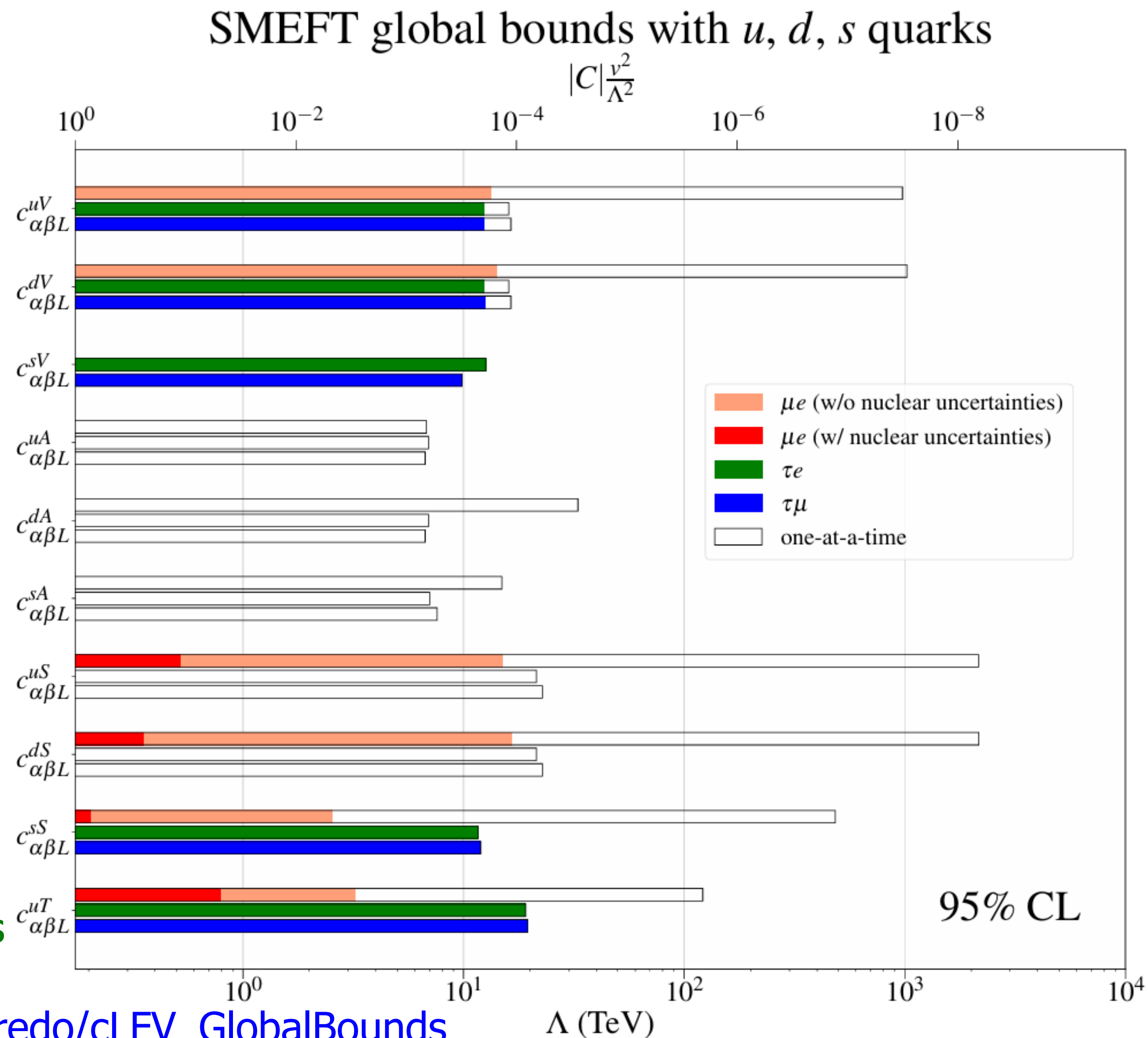
bounds and correlations available at

https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators

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



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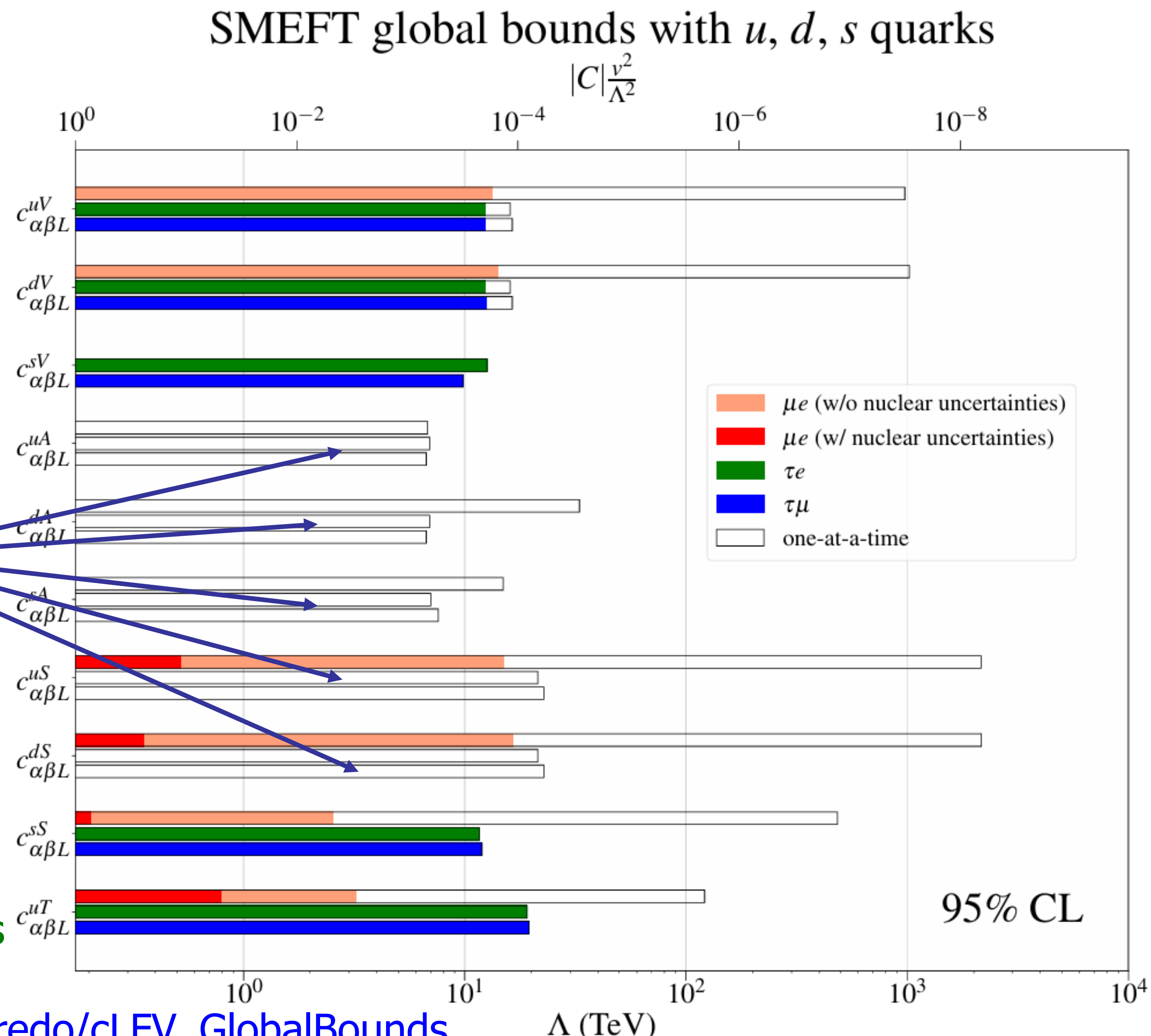
D. Naredo-Tuero
2403.09772
bounds and correlations available at
https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators



In τ sector only one flat direction left that could be lifted with

$\tau \to e/\mu$ KK

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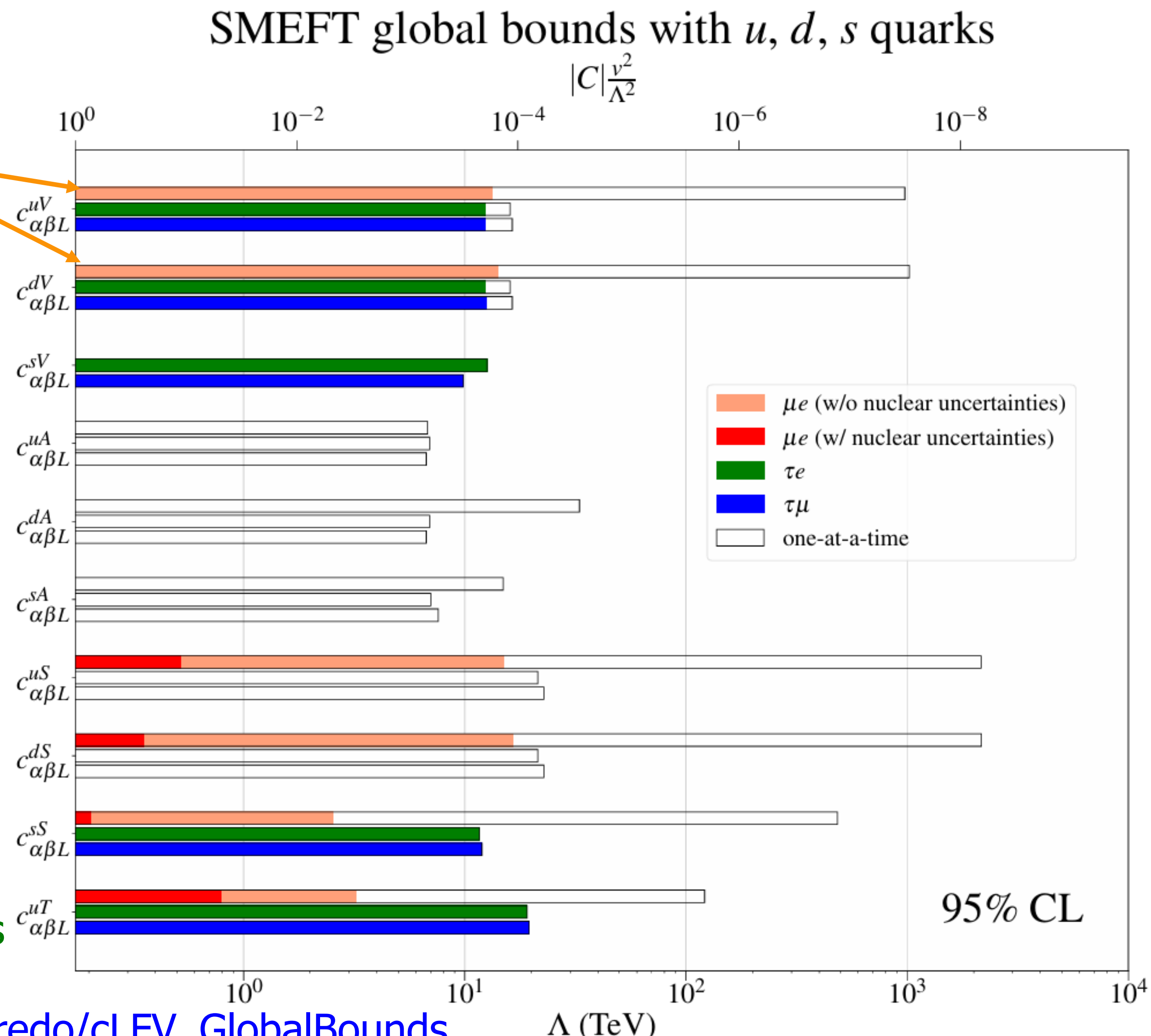
bounds and correlations available at
https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators

The directions probed by coherent μ-e conversion are almost parallel bounds are lost when nuclear uncertainties are accounted for
S. Davidson, Y. Kuno, and M. Yamanaka 1810.01884



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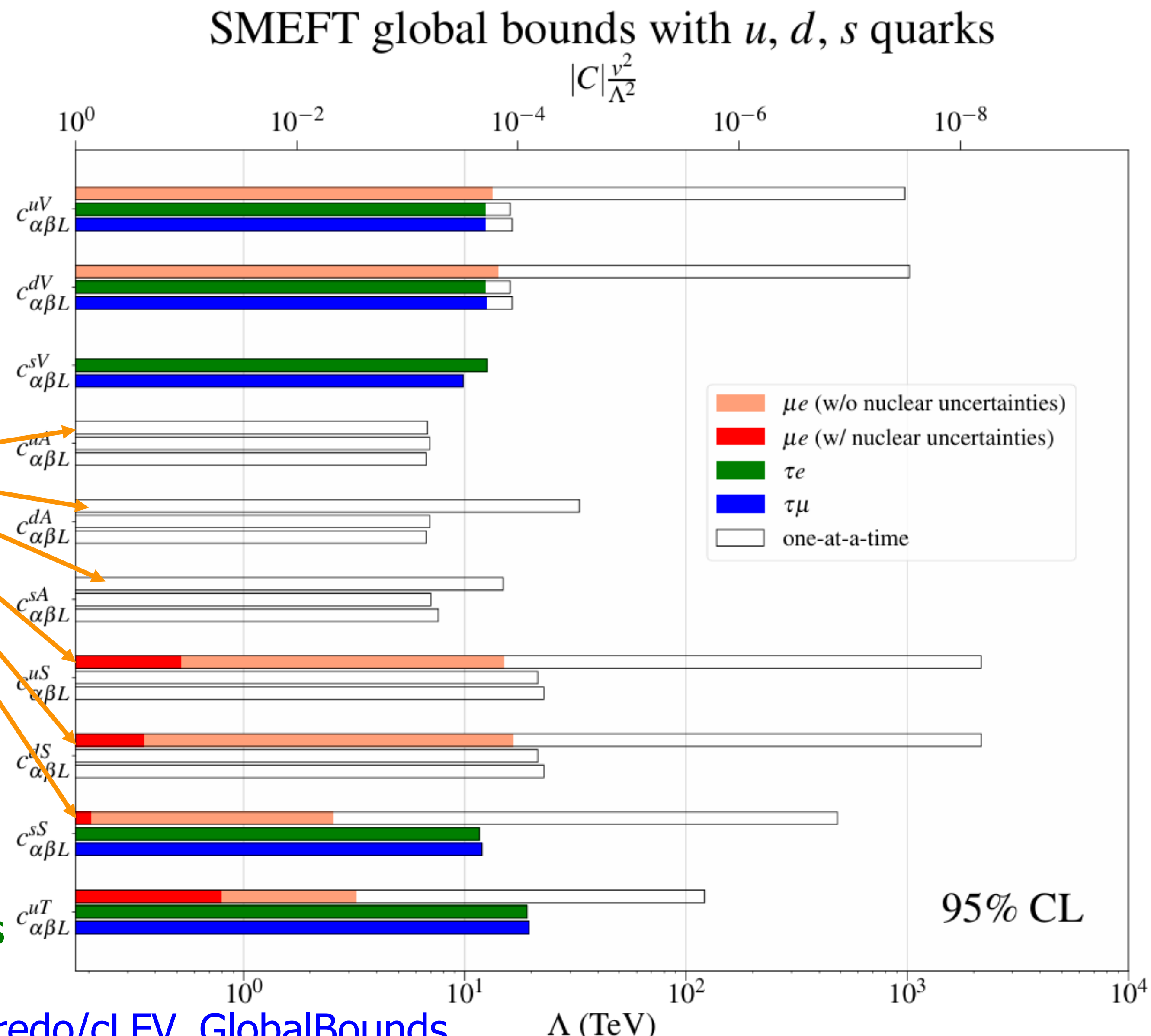
bounds and correlations available at
https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators



Very weak bounds from $\eta \to \mu$ e when nuclear uncertainties are accounted for

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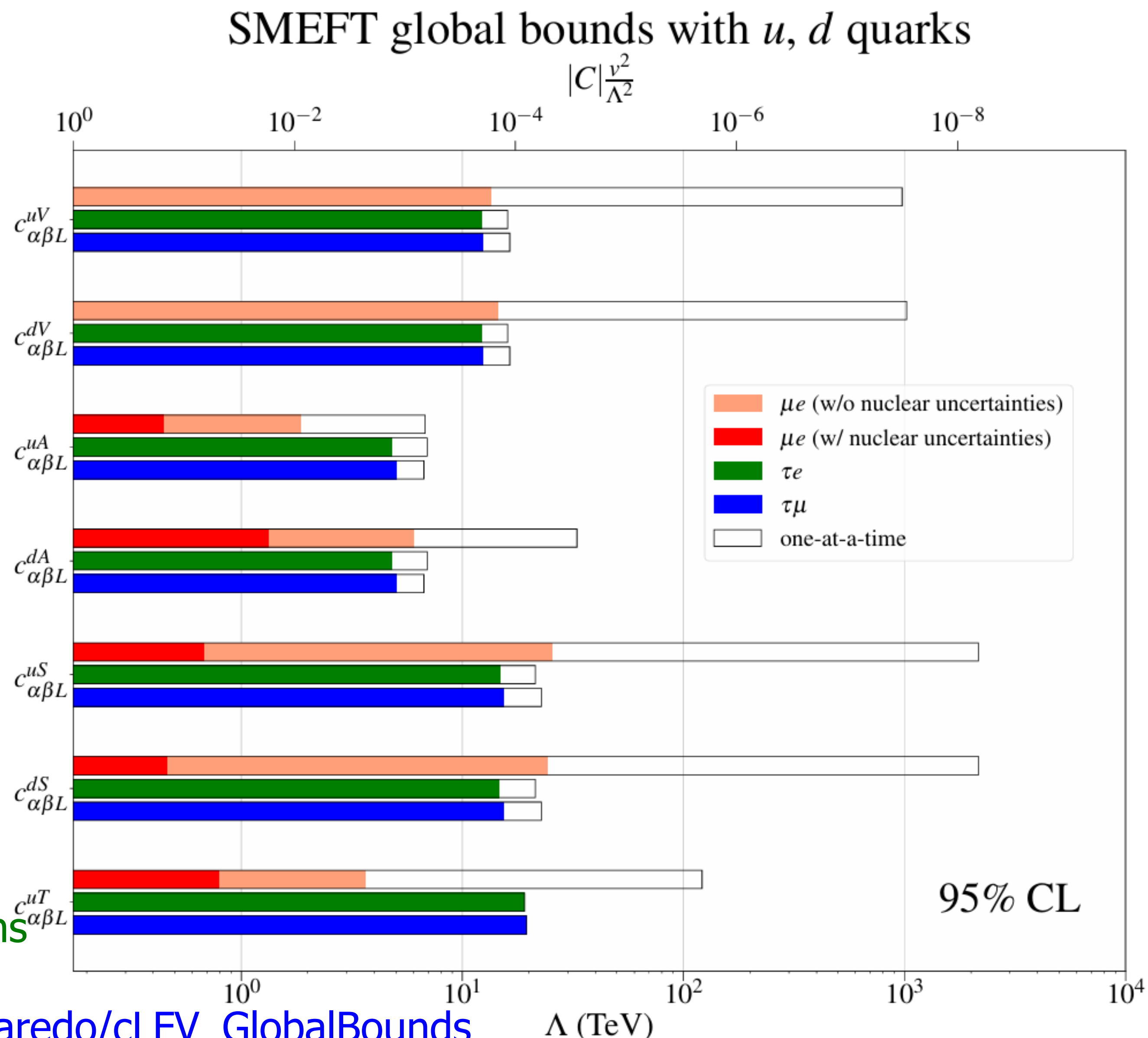
D. Naredo-Tuero
2403.09772
bounds and correlations available at
https://github.com/dnaredo/cLFV_GlobalBounds

cLFV semileptonic operators

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

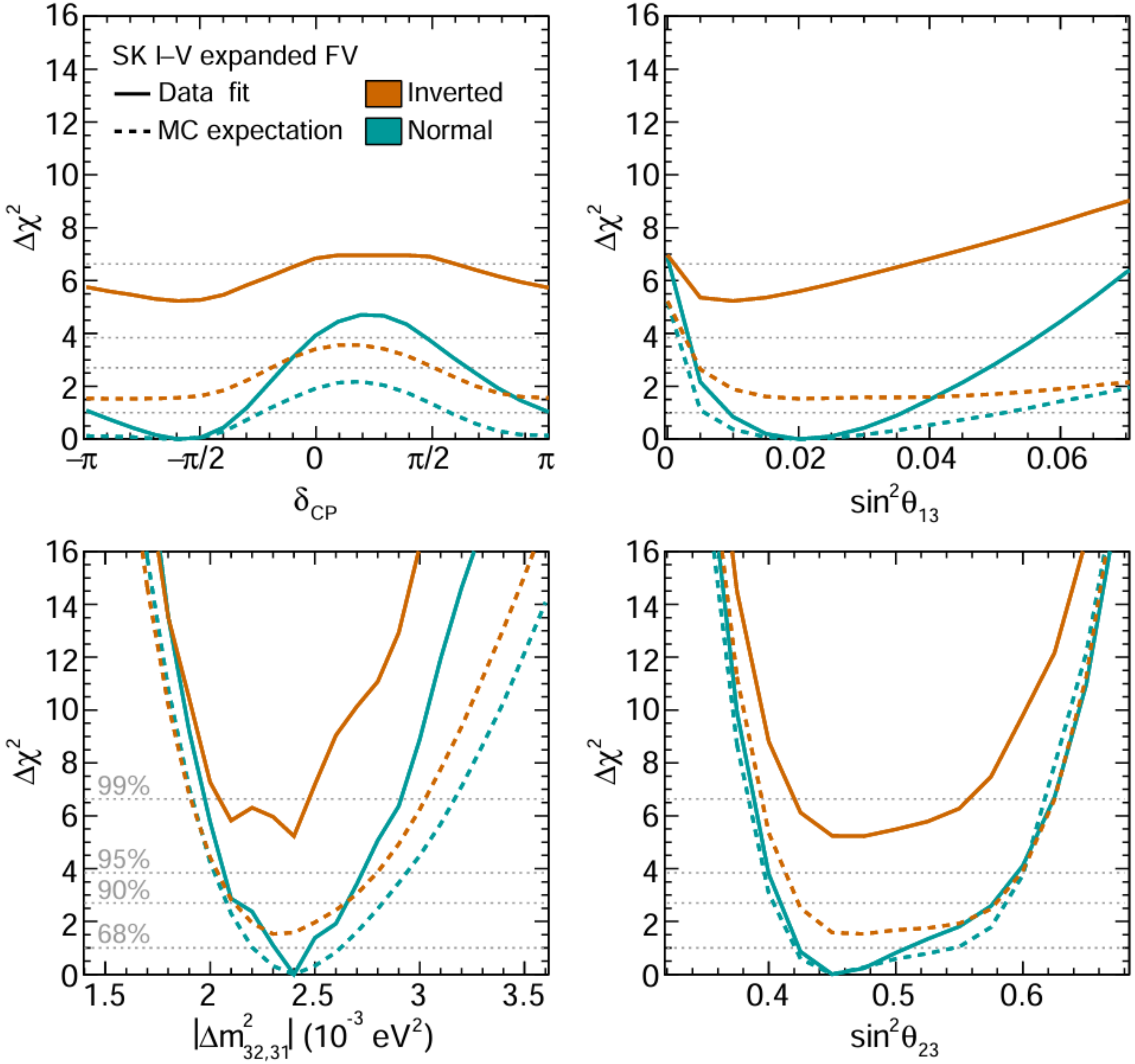
bounds and correlations available at

https://github.com/dnaredo/cLFV_GlobalBounds

Conclusions

- Neutrino oscillations are our first observation of LFV and require neutrino masses and BSM physics which generally predicts cLFV
- Our understanding of the neutrino oscillation parameters has entered the precision era, but some key properties remain to be determined
- In a global EFT perspective searching for charged LFV, constraints on leptonic operators are solid in a global fit
- Semileptonic opetarors suffer from flat directions and additional information would be useful
- $\mu \to$ e conversion can provide up to 4 independent constraints for SD and 4 for SI, regardless of number of nuclei measured and how precise nuclear uncertainties are. Meson decays still useful!

SK Atmospherics and mass hierarchy



SK coll.
2311.05105

The Golden channel in matter

$$P\left(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu\right) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{atm}}{\tilde{B}_\mp}\right)^2 \sin\left(\frac{\tilde{B}_\mp L}{2}\right)^2$$ "atmospheric"

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{sol}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ "solar"

"interference" $$+ \tilde{J} \frac{\Delta_{sol}}{A} \frac{\Delta_{atm}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{atm} L}{2}\right)$$

Expanded in

$$\sin 2\theta_{13} \sim 0.3$$

where

$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad \Delta_{atm} = \frac{\Delta m_{23}^2}{2E} \qquad \Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$$

$$A = \sqrt{2} G_F n_e \qquad \tilde{B}_\mp = \left|A \mp \Delta_{atm}\right|$$

A. Cervera *et al.* hep-ph/0002108

Global status on low E cLFV through EFT

cLFV obs.	Present upper bounds (90% CL)	
$BR(\mu \to e\gamma)$	3.1×10^{-13}	MEG II (2023)
$BR(\mu \to eee)$	1.0×10^{-12}	SINDRUM (1988)
$CR(\mu \to e, S)$	7.0×10^{-11}	Badertscher *et al.* (1982)
$CR(\mu \to e, Ti)$	4.3×10^{-12}	SINDRUM II (1993)
$CR(\mu \to e, Pb)$	4.6×10^{-11}	SINDRUM II (1996)
$CR(\mu \to e, Au)$	7.0×10^{-13}	SINDRUM II (2006)
$BR(\pi^0 \to \mu^- e^+)$	3.2×10^{-10}	NA62 (2021)
$BR(\pi^0 \to \mu^+ e^-)$	3.8×10^{-10}	E865 (2000)
$BR(\pi^0 \to \mu e)$	3.6×10^{-10}	KTeV (2007)
$BR(\eta \to \mu e)$	6.0×10^{-6}	Saturne SPES2 (1996)
$BR(\eta' \to \mu e)$	4.7×10^{-4}	CLEO (2000)
$BR(\phi \to \mu e)$	2.0×10^{-6}	SND (2009)

Very many observables constraining $\mu - e$ transitions

Global status on low E cLFV through EFT

cLFV obs.	Present upper bounds (90% CL)	
$BR(\tau \to e\gamma)$	3.3×10^{-8}	BaBar (2010)
$BR(\tau \to ee\bar{e})$	2.7×10^{-8}	Belle (2010)
$BR(\tau \to e\mu\bar{\mu})$	2.7×10^{-8}	Belle (2010)
$BR(\tau \to e\pi)$	8.0×10^{-8}	Belle (2007)
$BR(\tau \to e\eta)$	9.2×10^{-8}	Belle (2007)
$BR(\tau \to e\eta')$	1.6×10^{-7}	Belle (2007)
$BR(\tau \to e\pi\pi)$	2.3×10^{-8}	Belle (2012)
$BR(\tau \to e\omega)$	2.4×10^{-8}	Belle (2023)
$BR(\tau \to e\phi)$	2.0×10^{-8}	Belle (2023)

Very many observables constraining $\tau - e$ transitions

Global status on low E cLFV through EFT

cLFV obs.	Present upper bounds (90% CL)	
$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8}	Belle (2021)
$\mathrm{BR}(\tau \to \mu\mu\bar{\mu})$	2.1×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to \mu e\bar{e})$	1.8×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to \mu\pi)$	1.1×10^{-7}	BaBar (2006)
$\mathrm{BR}(\tau \to \mu\eta)$	6.5×10^{-8}	Belle (2007)
$\mathrm{BR}(\tau \to \mu\eta')$	1.3×10^{-7}	Belle (2007)
$\mathrm{BR}(\tau \to \mu\pi\pi)$	2.1×10^{-8}	Belle (2012)
$\mathrm{BR}(\tau \to \mu\omega)$	3.9×10^{-8}	Belle (2023)
$\mathrm{BR}(\tau \to \mu\phi)$	2.3×10^{-8}	Belle (2023)

Very many observables constraining $\tau - \mu$ transitions

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)

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)

$$m_D \bar{N}_R \nu_L + M_N \bar{N}_R N_L$$

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

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)

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

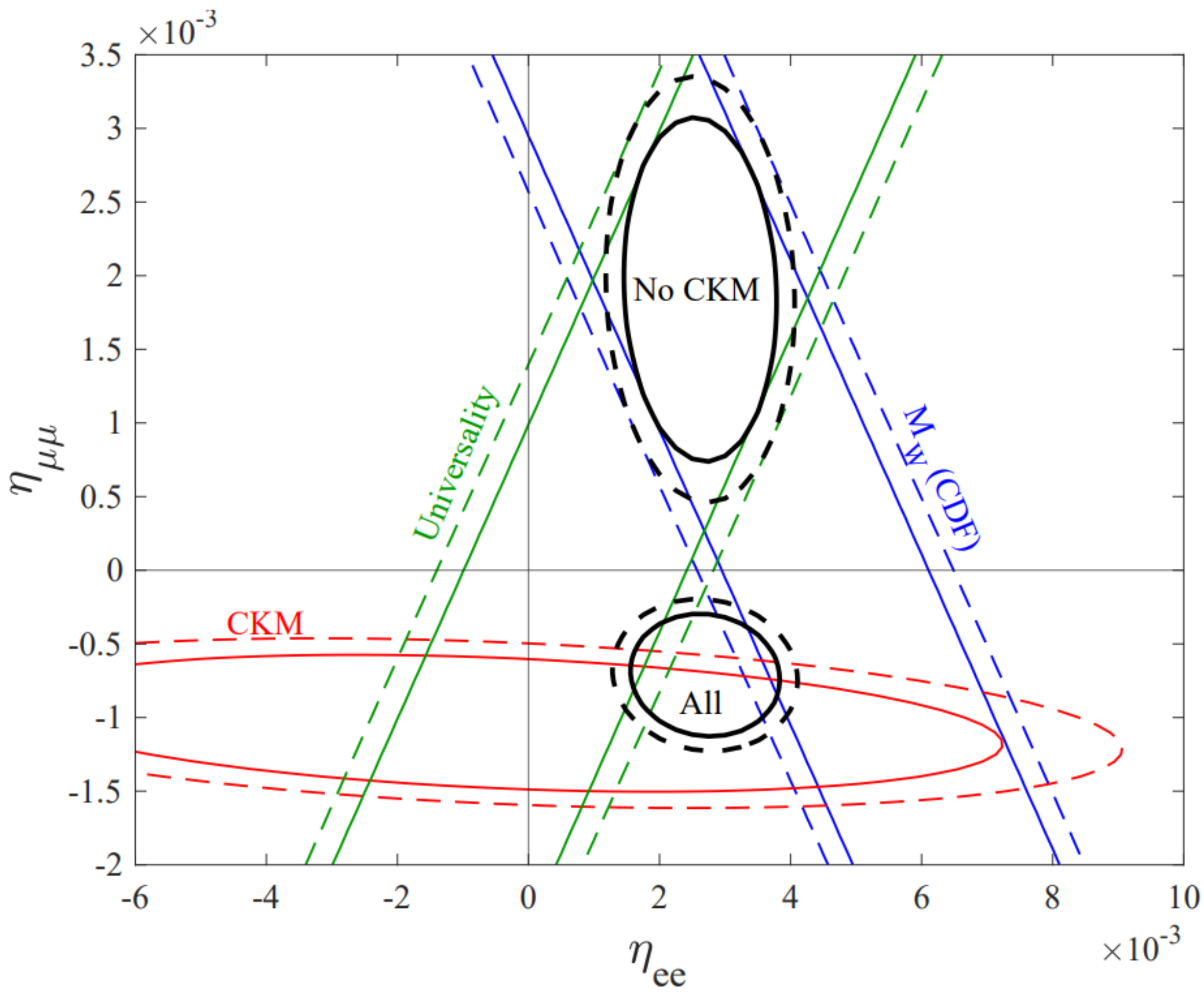
$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

"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 $m_\nu \approx \mu \frac{m_D^2}{M_N^2}$

Non-unitarity and M_W from CDF



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

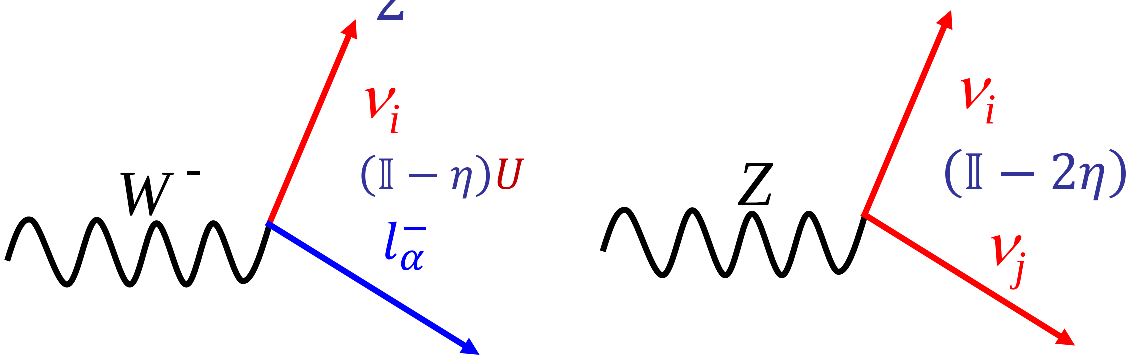
Non-unitarity in type I vs type III Seesaw

Type I

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

$$\downarrow$$

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



Non-unitarity in type I vs type III Seesaw

Type I

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

↓

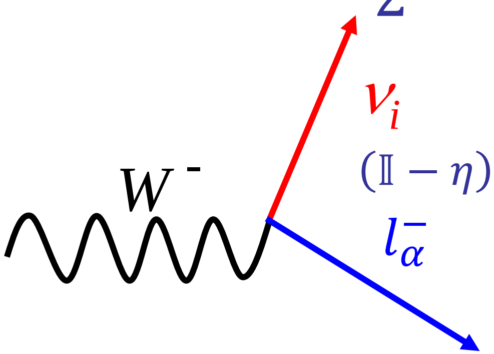
$$\eta = \frac{m_D^\dagger M_N^{-2} m_D}{2}$$

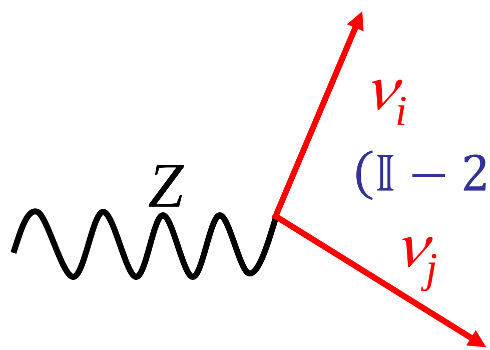
Type III

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

↓

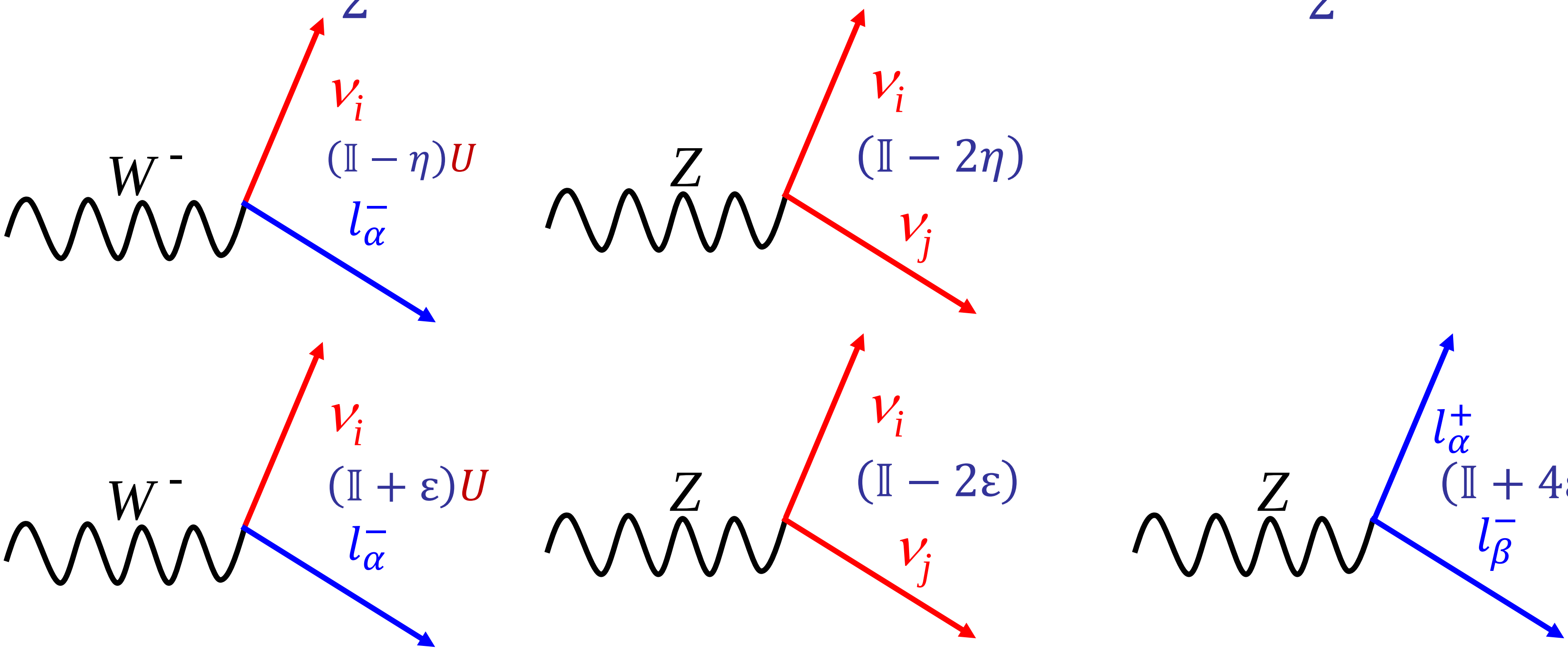
$$\varepsilon = \frac{m_\Sigma^\dagger M_\Sigma^{-2} m_\Sigma}{2}$$





Non-unitarity in type I vs type III Seesaw

Type I	Type III
$Y_\nu^\dagger M_N^{-2} Y_\nu \left(\overline{L_L}\tilde{\phi}\right) \partial\!\!\!/ \left(\tilde{\phi}^\dagger L_L\right)$	$Y_\Sigma^\dagger M_\Sigma^{-2} Y_\Sigma \left(\overline{L_L}\vec{\tau}\tilde{\phi}\right) D\!\!\!\!/ \left(\tilde{\phi}^\dagger \vec{\tau} L_L\right)$
↓	↓
$\eta = \dfrac{m_D^\dagger M_N^{-2} m_D}{2}$	$\varepsilon = \dfrac{m_\Sigma^\dagger M_\Sigma^{-2} m_\Sigma}{2}$



Non-unitarity in type I vs type III Seesaw

Type I

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

$$\downarrow$$

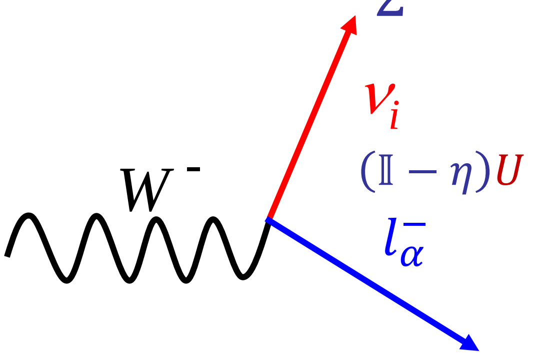
$$\eta = \frac{m_D^\dagger M_N^{-2} m_D}{2}$$

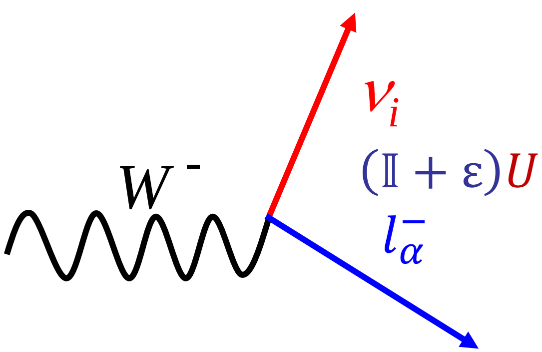
Type III

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

$$\downarrow$$

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





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

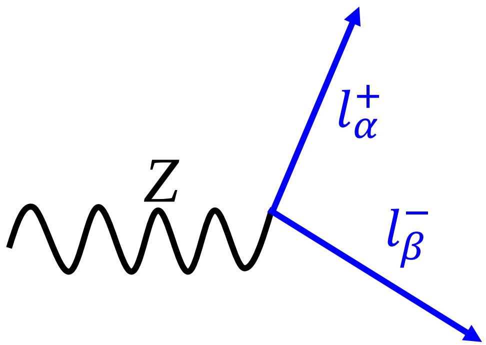
And LFV becomes independent of LFC constraints

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]

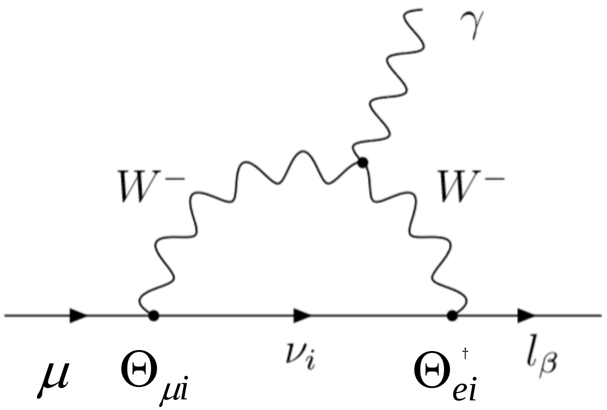
$Z \to \mu e$	$\lvert\eta_{\mu e}\rvert < 8.5 \cdot 10^{-4}$ [45]
$Z \to \tau e$	$\lvert\eta_{\tau e}\rvert < 3.1 \cdot 10^{-3}$ [45]
$Z \to \tau\mu$	$\lvert\eta_{\tau\mu}\rvert < 3.4 \cdot 10^{-3}$ [45]
$h \to \mu e$	$\lvert\eta_{\mu e}\rvert < 0.54$ [45]
$h \to \tau e$	$\lvert\eta_{\tau e}\rvert <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

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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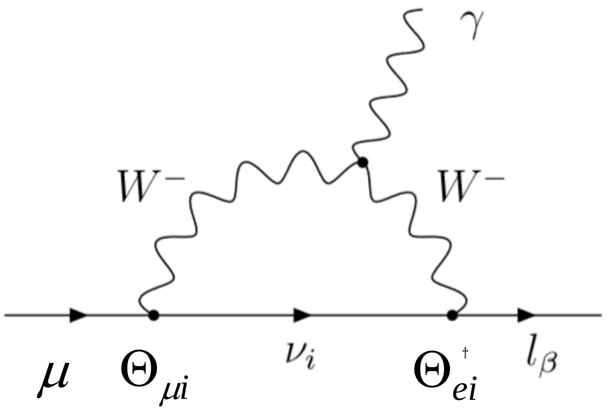

$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^\dagger_{ei} f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu} f(\infty) + \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\left(f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty)\right)$$

Probing the Seesaw: Non-Unitarity

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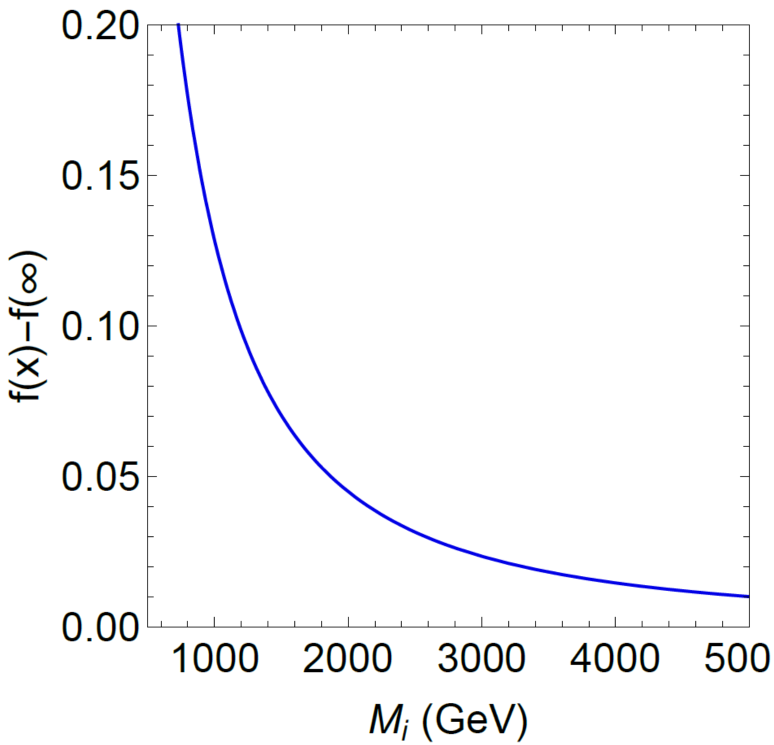

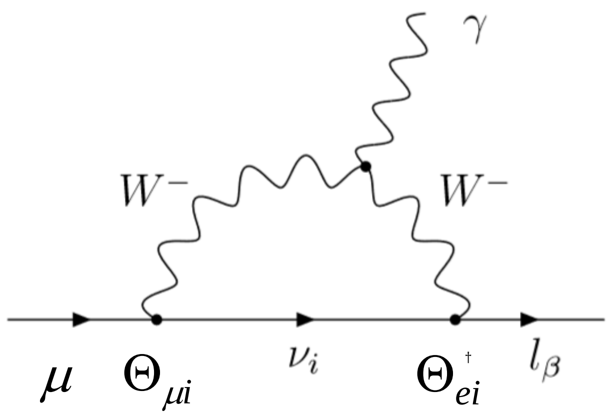

$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^\dagger_{ei} f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu} f(\infty) + \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\left(f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty)\right)$$

Funding

This work was supported by:
PID2019-108892RB-100
PID2022-137127NB-100
CEX2020-001007-S
860881-HiDDeN
101086085-ASYMMETRY