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SMEFT effects in neutrino and low-energy experiments

HEFT in Bologna
13 June 2024

Based on [arXiv:1901.04553], [arXiv:1910.02871] with Martin Gonzalez-Alonso, Zahra Tabrizi
and on [arXiv:2301.07036] Victor Breso-Pla, Martin Gonzalez-Alonso, Kevin Monsalvez-Pozo

Plan

***<u>Focus:</u>* constraints on SMEFT from processes where neutrinos are detected**

- Neutrinos and SMEFT
- Constraints from coherent neutrino scattering
- Constraints from reactor neutrino oscillations

SMEFT

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \cdots \\ v + h + \ldots \end{pmatrix}$$

SMEFT has many higher-dimensional operators:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

Neutrinos enter into a non-negligible fraction of these

Constraints from neutrino physics are essential to sharpen the phenomenological constraints on SMEFT Wilson coefficients

SMEFT at dimension-5

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Weinberg (1979)
Phys. Rev. Lett. 43, 1566

$$H \to \begin{pmatrix} 0 \\ \mathrm{v}/\sqrt{2} \end{pmatrix}$$

$$\mathscr{L}_{D=5} = (LH)C_5(LH) + \mathrm{h.c.} \to \frac{1}{2} \sum_{J,K=e,\mu,\tau} \mathrm{v}^2 [C_5]_{JK} (\nu_J \nu_K) + \mathrm{h.c.}$$

Dimension 5 operators in SMEFT lead to neutrino masses. The corresponding Wilson coefficients are probed (only) by neutrino oscillations experiments

$$-\mathrm{v}^2 C_5 = U_{\text{PMNS}} m_{\text{diag}} U^{\dagger}_{\text{PMNS}}$$

$$m_{\text{diag}} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

All these parameters known with good accuracy (up to ordering ambiguity), except for m_1 and δ_{CP}

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & e^{-i\delta_{\text{CP}}} s_{13} \\ -s_{12}c_{23} - e^{i\delta_{\text{CP}}} c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta_{\text{CP}}} s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta_{\text{CP}}} c_{12}s_{13}c_{23} & -c_{12}s_{23} - e^{i\delta_{\text{CP}}} s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}$$

SMEFT at dimension-6

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

Grządkowski et al
arXiv:1008.4884

At dimension-6 all hell breaks loose

$$\begin{aligned}
\mathscr{L}_{D=6} = {} & C_H (H^\dagger H)^3 + C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}|H^\dagger D_\mu H|^2 \\
& + C_{HWB} H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu} + C_{HG} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} + C_{HW} H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu} + C_{HB} H^\dagger H\, B_{\mu\nu} B_{\mu\nu} \\
& + + C_W \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_G f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \\
& + C_{H\widetilde{G}} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu} + C_{H\widetilde{W}} H^\dagger H\, \widetilde{W}^k_{\mu\nu} W^k_{\mu\nu} + C_{H\widetilde{B}} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu} + C_{H\widetilde{W}B} H^\dagger \sigma^k H\, \widetilde{W}^k_{\mu\nu} B_{\mu\nu} \\
& + C_{\widetilde{W}} \epsilon^{klm} \widetilde{W}^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_{\widetilde{G}} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \\
& + H^\dagger H(\bar{L} H C_{eH} \bar{E}^c) + H^\dagger H(\bar{Q}\tilde{H} C_{uH} \bar{U}^c) + H^\dagger H(\bar{Q} H C_{dH} \bar{D}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(\bar{L} C^{(1)}_{Hl} \bar{\sigma}^\mu L) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{L} C^{(3)}_{Hl} \bar{\sigma}^\mu \sigma^k L) + iH^\dagger \overleftrightarrow{D}_\mu H(E^c C_{He} \sigma^\mu \bar{E}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(\bar{Q} C^{(1)}_{Hq} \bar{\sigma}^\mu Q) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{Q} C^{(3)}_{Hq} \bar{\sigma}^\mu \sigma^k Q) + iH^\dagger \overleftrightarrow{D}_\mu H(U^c C_{Hu} \sigma^\mu \bar{U}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(D^c C_{Hd} \sigma^\mu \bar{D}^c) + \Big\{ i\tilde{H}^\dagger D_\mu H(U^c C_{Hud} \sigma^\mu \bar{D}^c) \\
& + (\bar{Q}\sigma^k \tilde{H} C_{uW} \bar{\sigma}^{\mu\nu} \bar{U}^c) W^k_{\mu\nu} + (\bar{Q}\tilde{H} C_{uB} \bar{\sigma}^{\mu\nu} \bar{U}^c) B_{\mu\nu} + (\bar{Q}\tilde{H} C_{uG} T^a \bar{\sigma}^{\mu\nu} \bar{U}^c) G^a_{\mu\nu} \\
& + (\bar{Q}\sigma^k H C_{dW} \bar{\sigma}^{\mu\nu} \bar{D}^c) W^k_{\mu\nu} + (\bar{Q} H C_{dB} \bar{\sigma}^{\mu\nu} \bar{D}^c) B_{\mu\nu} + (\bar{Q} H C_{dG} T^a \bar{\sigma}^{\mu\nu} \bar{D}^c) G^a_{\mu\nu} \\
& + (\bar{L}\sigma^k H C_{eW} \bar{\sigma}^{\mu\nu} \bar{E}^c) W^k_{\mu\nu} + (\bar{L} H C_{eB} \bar{\sigma}^{\mu\nu} \bar{E}^c) B_{\mu\nu} + \text{h.c.} \Big\} + \mathscr{L}^{4-\text{fermion}}_{D=6}
\end{aligned}$$

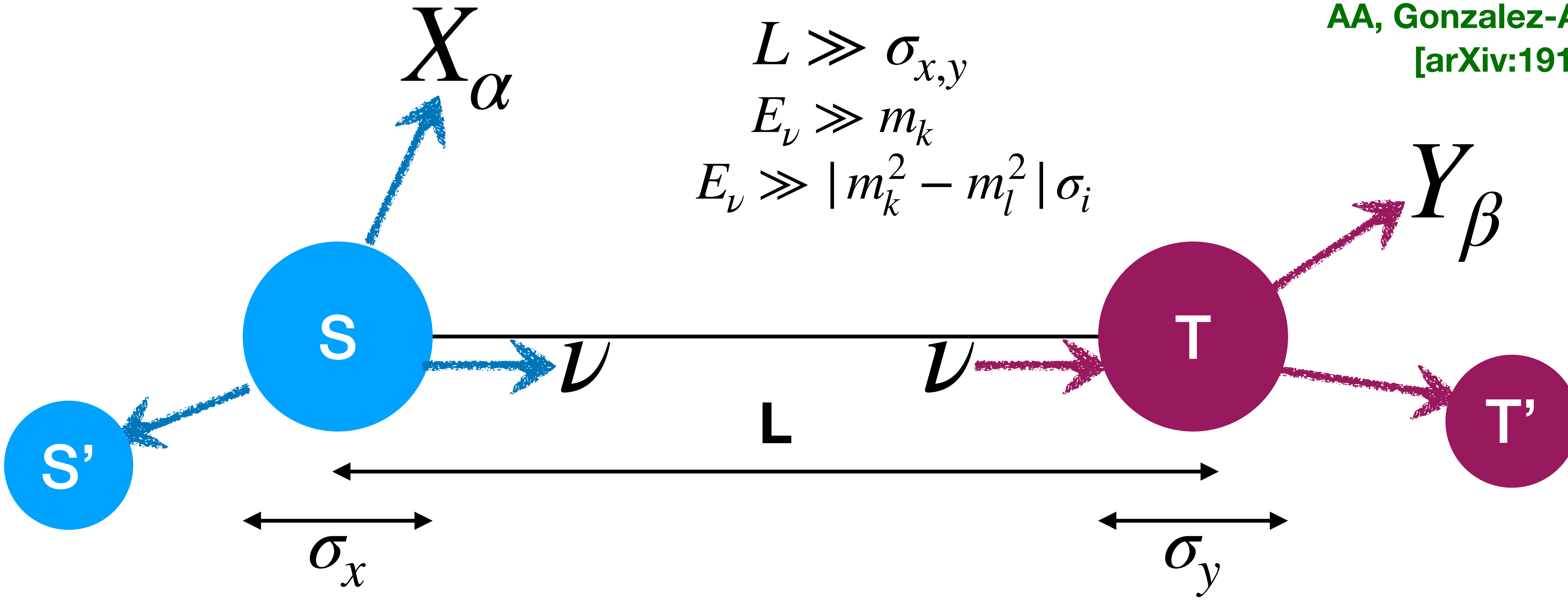
SMEFT at dimension-6

$$
\begin{aligned}
\mathscr{L}^{4-\text{fermion}}_{D=6} = {} & (\bar{L}\bar{\sigma}^{\mu}L)C_{ll}(\bar{L}\bar{\sigma}_{\mu}L) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{ee}(E^{c}\sigma_{\mu}\bar{E}^{c}) + (\bar{L}\bar{\sigma}^{\mu}L)C_{le}(E^{c}\sigma_{\mu}\bar{E}^{c}) \\
& +(\bar{L}\bar{\sigma}^{\mu}L)C^{(1)}_{lq}(\bar{Q}\bar{\sigma}_{\mu}Q) + (\bar{L}\bar{\sigma}^{\mu}\sigma^{k}L)C^{(3)}_{lq}(\bar{Q}\bar{\sigma}_{\mu}\sigma^{k}Q) \\
& +(E^{c}\sigma_{\mu}\bar{E}^{c})C_{eu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{ed}(D^{c}\sigma_{\mu}\bar{D}^{c}) \\
& +(\bar{L}\bar{\sigma}^{\mu}L)C_{lu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (\bar{L}\bar{\sigma}^{\mu}L)C_{ld}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{eq}(Q\bar{\sigma}_{\mu}Q) \\
& +\Big\{ (\bar{L}\bar{E}^{c})C_{ledq}(D^{c}Q) + \epsilon^{kl}(\bar{L}^{k}\bar{E}^{c})C^{(1)}_{lequ}(\bar{Q}^{l}\bar{U}^{c}) + \epsilon^{kl}(\bar{L}^{k}\bar{\sigma}^{\mu\nu}\bar{E}^{c})C^{(3)}_{lequ}(\bar{Q}^{l}\bar{\sigma}^{\mu\nu}\bar{U}^{c}) + \mathrm{h.c.} \Big\} \\
& +(\bar{Q}\bar{\sigma}^{\mu}Q)C^{(1)}_{qq}(\bar{Q}\bar{\sigma}_{\mu}Q) + (\bar{Q}\bar{\sigma}^{\mu}\sigma^{k}Q)C^{(3)}_{qq}(\bar{Q}\bar{\sigma}_{\mu}\sigma^{k}Q) \\
& +(U^{c}\sigma_{\mu}\bar{U}^{c})C_{uu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (D^{c}\sigma_{\mu}\bar{D}^{c})C_{dd}(D^{c}\sigma_{\mu}\bar{D}^{c}) \\
& +(U^{c}\sigma_{\mu}\bar{U}^{c})C^{(1)}_{ud}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (U^{c}\sigma_{\mu}T^{a}\bar{U}^{c})C^{(8)}_{ud}(D^{c}\sigma_{\mu}T^{a}\bar{D}^{c}) \\
& +(Q^{c}\sigma_{\mu}\bar{Q}^{c})C^{(1)}_{qu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (Q^{c}\sigma_{\mu}T^{a}\bar{Q}^{c})C^{(8)}_{qu}(U^{c}\sigma_{\mu}T^{a}\bar{U}^{c})] \\
& +(Q^{c}\sigma_{\mu}\bar{Q}^{c})C^{(1)}_{qd}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (Q^{c}\sigma_{\mu}T^{a}\bar{Q}^{c})C^{(8)}_{qd}(D^{c}\sigma_{\mu}T^{a}\bar{D}^{c}) \\
& +\Big\{ \epsilon^{kl}(\bar{Q}^{k}\bar{U}^{c})C^{(1)}_{quqd}(\bar{Q}^{l}\bar{D}^{c}) + \epsilon^{kl}(\bar{Q}^{k}T^{a}\bar{U}^{c})C^{(1)}_{quqd}(\bar{Q}^{l}T^{a}\bar{D}^{c}) + \mathrm{h.c.} \Big\} \\
& +\Big\{ (D^{c}U^{c})C_{duq}(\bar{Q}\bar{L}) + (QQ)C_{qqu}(\bar{U}^{c}\bar{E}^{c}) + (QQ)C_{qqq}(QL) + (D^{c}U^{c})C_{duu}(U^{c}E^{c}) + \mathrm{h.c.} \Big\}.
\end{aligned}
$$

The highlighted operators can be probed by processes where neutrinos are produced, detected, or exchanged.
Very often, constraints from non-neutrino processes leave important degeneracies in the space of corresponding Wilson coefficients.

Neutrino master formula

AA, Gonzalez-Alonso, Tabrizi
[arXiv:1910.02971]



$$dR_{\alpha\beta} = \frac{N_S N_T}{32\pi L^2 m_S m_T} \sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \left[d\Pi_P \mathcal{M}_{\alpha k}^{P} \mathcal{M}_{\alpha l}^{P*}\right] \left[d\Pi_D \mathcal{M}_{\beta k}^{D} \mathcal{M}_{\beta l}^{D*}\right]$$

Observable rate

$dR = \frac{dN}{dt}$

Geometric factor

Masses of source and target atoms

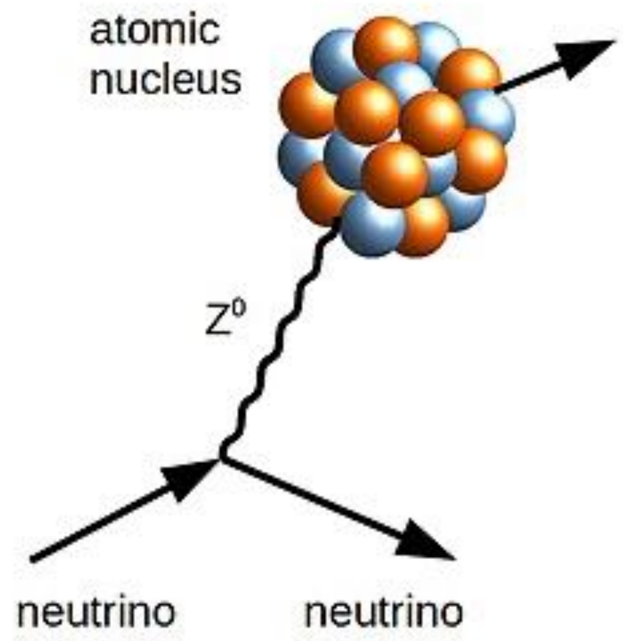
Oscillation phase

Production phase space

$\mathcal{M}_{\alpha k}^{P} \equiv \mathcal{M}[S \to S' X_\alpha \nu_k]$

Detection phase space

$\mathcal{M}_{\beta k}^{D} \equiv \mathcal{M}[\nu_k T \to T' Y_\beta]$



Part 2

Constraints from coherent neutrino scattering

Coherent neutrino scattering

- Coherent neutrino scattering occurs when neutrino scattering on a nucleus has low enough energy such that it does not resolve its internal structure. Then $\sim (A-Z)^2$ enhancement of the cross section occurs.

D. Freedman, Phys. Rev. D 9 (1974) 1389–1392

- Experimentally measured recently by the COHERENT collaboration with neutrino produced by stopped pion decays and with Argon and CsI targets.

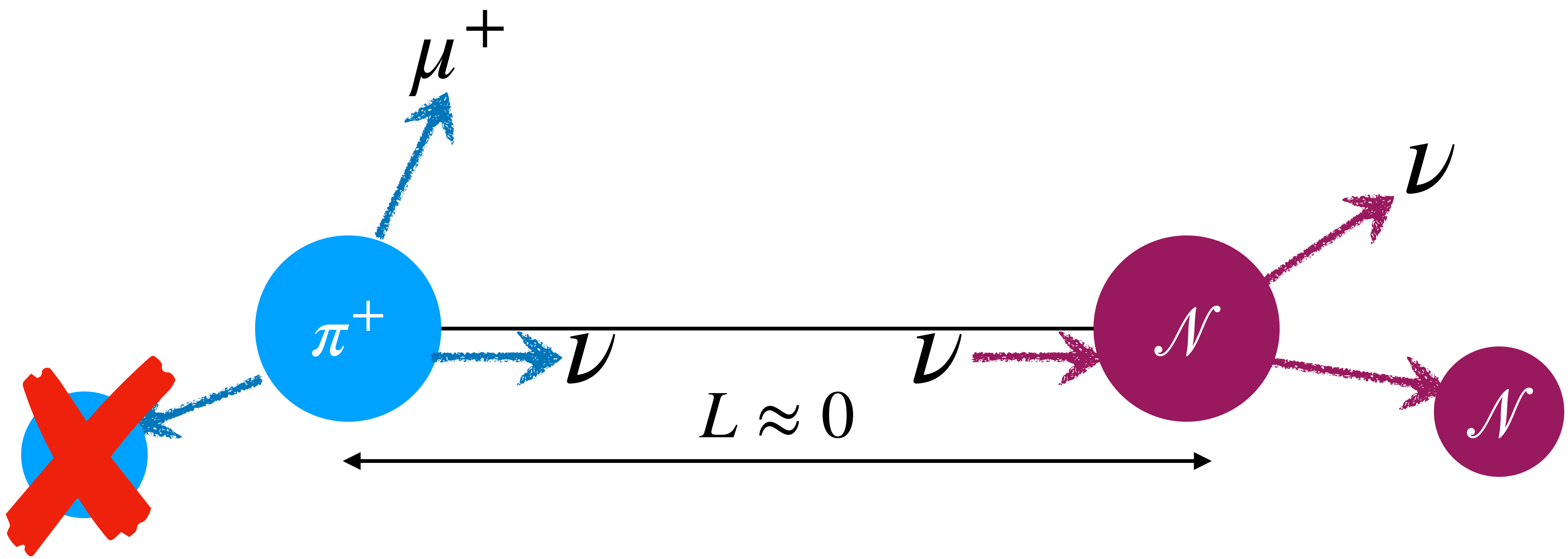
COHERENT, Science 357 [arXiv:1708.01294]

COHERENT, Phys. Rev. Lett. 126 [arXiv:2003.10630]

COHERENT, Phys. Rev. Lett. 129 [arXiv:2110.07730].

- Time and nuclear recoil distributions are available. Neutrinos from the pion decay and from the subsequent muon decay can be disentangled thanks to timing. Neutrinos and anti-neutrinos from muon decay can also be to some extent disentangled thanks to different recoil distributions.

Coherent neutrino scattering



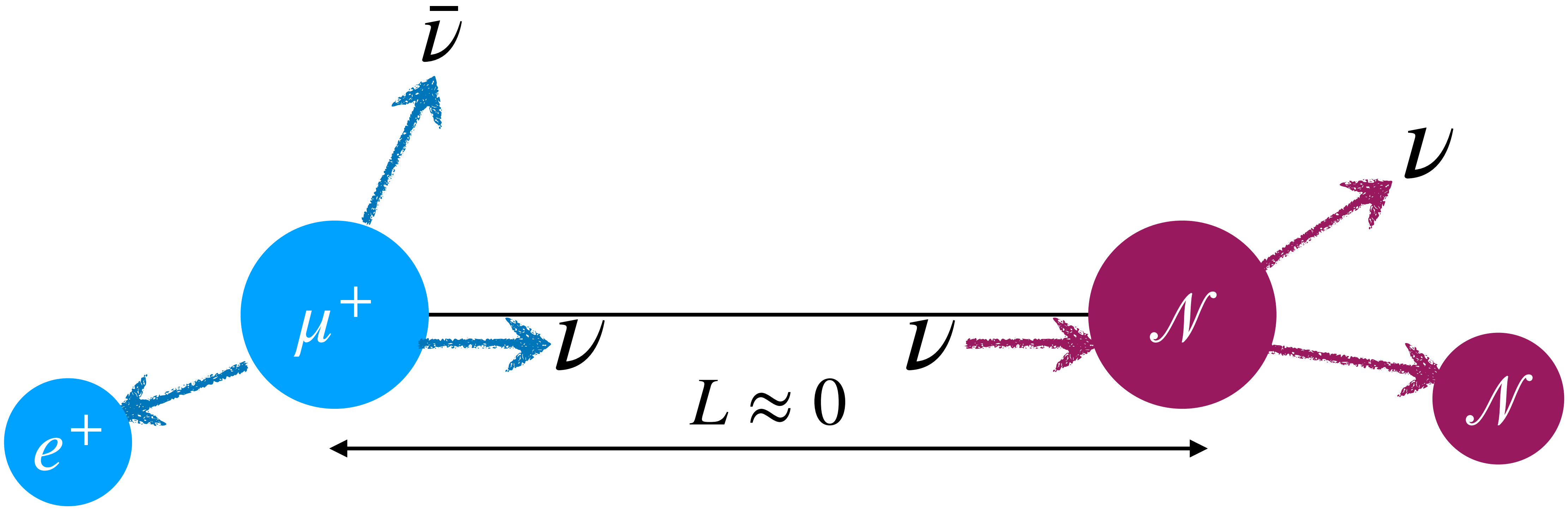
$$dR_\mu^{\text{prompt}} = \frac{N_S N_T}{32\pi L^2 m_\pi m_{\mathscr{N}}} \sum_{k,l=1}^{3} \cancel{e^{-i\frac{(m_k^2-m_l^2)L}{2E_\nu}}} \left[d\Pi_P \mathscr{M}_{\mu k}^{P} \mathscr{M}_{\mu l}^{P*}\right] \sum_\beta \left[d\Pi_D \mathscr{M}_{\beta k}^{D} \mathscr{M}_{\beta l}^{D*}\right]$$

Negligible in COHERENT setup

$$\mathscr{M}_{\alpha k}^{P} \equiv \mathscr{M}[\pi^+ \to \mu^+ \nu_k]$$

$$\mathscr{M}_{\beta k}^{D} \equiv \mathscr{M}[\nu_k \mathscr{N} \to \nu_\beta \mathscr{N}]$$

Coherent neutrino scattering



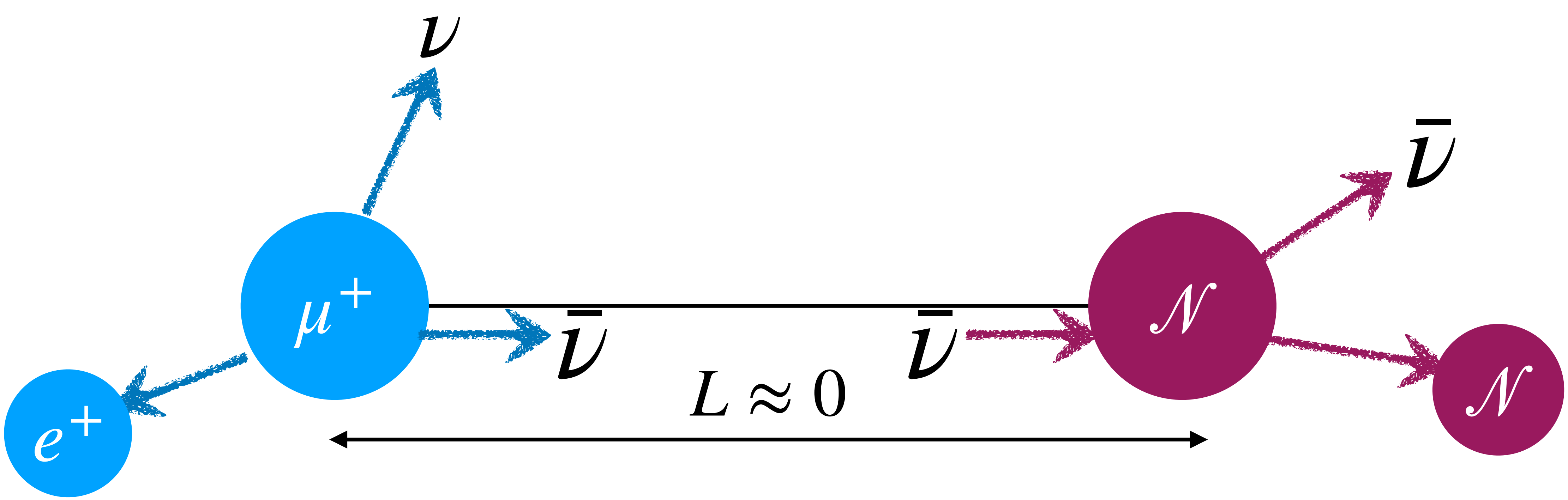
$$\boxed{dR_\mu^{\text{delayed}} = \frac{N_S N_T}{32\pi L^2 m_\mu m_{\mathcal{N}}} \sum_{k,l=1}^{3} \cancel{e^{-\frac{iL(m_k^2 - m_l^2)}{2E_\nu}}} \left[d\Pi_P \mathscr{M}^P_{\mu k} \mathscr{M}^{P*}_{\mu l}\right] \sum_\beta \left[d\Pi_D \mathscr{M}^D_{\beta k} \mathscr{M}^{D*}_{\beta l}\right]}$$

Negligible in COHERENT setup

$\mathscr{M}^P_{\alpha k} \equiv \mathscr{M}[\mu^+ \to e^+ \nu_k \bar{\nu}]$

$\mathscr{M}^D_{\beta k} \equiv \mathscr{M}[\nu_k \mathcal{N} \to \nu_\beta \mathcal{N}]$

Coherent neutrino scattering



$$d\bar{R}_\mu^{\text{delayed}} = \frac{N_S N_T}{32\pi L^2 m_\mu m_{\mathscr{N}}} \sum_{k,l=1}^{3} e^{\cancel{-i\frac{(m_k^2-m_l^2)L}{2E_\nu}}} \left[d\Pi_P \mathscr{M}^P_{\mu k} \mathscr{M}^{P*}_{\mu l}\right] \sum_\beta \left[d\Pi_D \mathscr{M}^D_{\beta k} \mathscr{M}^{D*}_{\beta l}\right]$$

Negligible in COHERENT setup

$$\mathscr{M}^P_{\alpha k} \equiv \mathscr{M}[\mu^+ \to e^+ \bar{\nu}_k \nu]$$

$$\mathscr{M}^D_{\beta k} \equiv \mathscr{M}[\bar{\nu}_k \mathscr{N} \to \bar{\nu}_\beta \mathscr{N}]$$

Coherent neutrino scattering

After integrating over phase space, one can rewrite the rate in the form

$$\frac{dR^{\text{prompt}}}{dT} = N_T \int dE_\nu \, \frac{d\Phi_{\nu_\mu}}{dE_\nu} \frac{d\tilde{\sigma}_{\nu_\mu}}{dT}$$

recoil kinetic energy
of nucleus

$$\frac{dR^{\text{delayed}}}{dT} = N_T \int dE_\nu \left(\frac{d\Phi_{\nu_e}}{dE_\nu} \frac{d\tilde{\sigma}_{\nu_e}}{dT} + \frac{d\Phi_{\bar{\nu}_\mu}}{dE_\nu} \frac{d\tilde{\sigma}_{\bar{\nu}_\mu}}{dT} \right)$$

$$\frac{d\phi_{\nu_\mu}}{dE_\nu} = \frac{N_S}{4\pi L^2} \delta(E_\nu - E_{\nu,\pi})$$

$$\frac{d\phi_{\nu_e}}{dE_\nu} = \frac{N_S}{4\pi L^2} \frac{192 E_\nu^2}{m_\mu^3} \left(\frac{1}{2} - \frac{E_\nu}{m_\mu} \right)$$

$$\frac{d\phi_{\bar{\nu}_\mu}}{dE_\nu} = \frac{N_S}{4\pi L^2} \frac{64 E_\nu^2}{m_\mu^3} \left(\frac{3}{4} - \frac{E_\nu}{m_\mu} \right)$$

The effective cross sections are

Nuclear form factor

$$\frac{d\tilde{\sigma}_{\nu_f}}{dT} = (m_{\mathcal{N}} + T) \frac{(\mathscr{F}(T))^2}{8 \mathrm{v}^4 \pi} \left(1 - \frac{(m_{\mathcal{N}} + 2E_\nu)\, T}{2E_\nu^2} \right) \tilde{Q}_f^2 \,.$$

The effective weak charges encode full information about new physics corrections, both in production and in detection

$$\tilde{Q}_f^2 = Q_{\text{SM}}^2 + \Delta_f(C_i)$$

$\sim (Z - A)^2$

Coherent neutrino scattering

V. Breso-Pla et al
[arXiv:2301.07036]

Results of our analysis for effective weak charges

$$\begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm Ar} \frac{1}{Q^2_{\rm SM,Ar}} = \begin{pmatrix} 1.00 \pm 0.82 \\ 0.4 \pm 6.2 \\ 1.9 \pm 8.2 \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & 0.29 & -0.31 \\ 0.29 & 1 & -0.99 \\ -0.31 & -0.99 & 1 \end{pmatrix} \qquad Q^2_{\rm SM,Ar} \approx 461$$

$$\begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm CsI} \frac{1}{Q^2_{\rm SM,CsI}} = \begin{pmatrix} 1.33 \pm 0.35 \\ -1.4 \pm 1.5 \\ 4.4 \pm 2.3 \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & 0.12 & -0.09 \\ 0.12 & 1 & -0.98 \\ -0.09 & -0.98 & 1 \end{pmatrix} \qquad Q^2_{\rm SM,CsI} \approx 5572$$

A more intuitive form

$$\begin{pmatrix} -0.14 & -3.48 & 4.62 \\ -0.69 & 0.98 & 0.71 \\ 0.55 & 0.25 & 0.20 \end{pmatrix} \begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm Ar} \frac{1}{Q^2_{\rm SM,Ar}} = \begin{pmatrix} 6 \pm 59 \\ \mathbf{1.0 \pm 1.2} \\ \mathbf{1.03 \pm 0.48} \end{pmatrix}$$

$$\begin{pmatrix} -0.04 & -1.80 & 2.85 \\ 0.80 & 0.12 & 0.09 \\ -0.15 & 0.71 & 0.45 \end{pmatrix} \begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm CsI} \frac{1}{Q^2_{\rm SM,CsI}} = \begin{pmatrix} 15.1 \pm 9.1 \\ \mathbf{1.28 \pm 0.28} \\ \mathbf{0.81 \pm 0.19} \end{pmatrix}$$

Coherent neutrino scattering

Translation into SMEFT constraints

V. Breso-Pla et al
[arXiv:2301.07036]

$$\mathcal{L}_{\rm SMEFT} \supset C_{lq}^{(1)}(\bar{l}_L\gamma_\mu l_L)(\bar{q}_L\gamma^\mu q_L) + C_{lq}^{(3)}(\bar{l}_L\gamma_\mu\sigma^k l_L)(\bar{q}_L\gamma^\mu\sigma^k q_L)$$
$$+C_{lu}(\bar{l}_L\gamma_\mu l_L)(\bar{u}_R\gamma^\mu u_R) + C_{ld}(\bar{l}_L\gamma_\mu l_L)(\bar{d}_R\gamma^\mu d_R).$$

Ignoring quadratic corrections in Wilson coefficients one gets the constraints

$$\begin{pmatrix} 0.63 & -0.70 & -0.22 & 0.24 \\ 0.21 & -0.24 & 0.63 & -0.70 \\ -0.68 & -0.61 & 0.30 & 0.27 \\ 0.30 & 0.27 & 0.68 & 0.61 \end{pmatrix} \begin{pmatrix} \epsilon_{ee}^{dd} \\ \epsilon_{ee}^{uu} \\ \epsilon_{\mu\mu}^{dd} \\ \epsilon_{\mu\mu}^{uu} \end{pmatrix} = \begin{pmatrix} 2.0 \pm 5.7 \\ -0.2 \pm 1.7 \\ -0.037 \pm 0.042 \\ -0.004 \pm 0.013 \end{pmatrix}$$

$$\epsilon_{\alpha\alpha}^{uu} = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8s_\theta^2}{3}\right)\delta g_L^{Z\nu_\alpha} - \frac{1}{2}[c_{lq}^{(1)} + c_{lq}^{(3)} + c_{lu}]_{\alpha\alpha 11}$$

$$c_X \equiv C_X \mathrm{v}^2$$

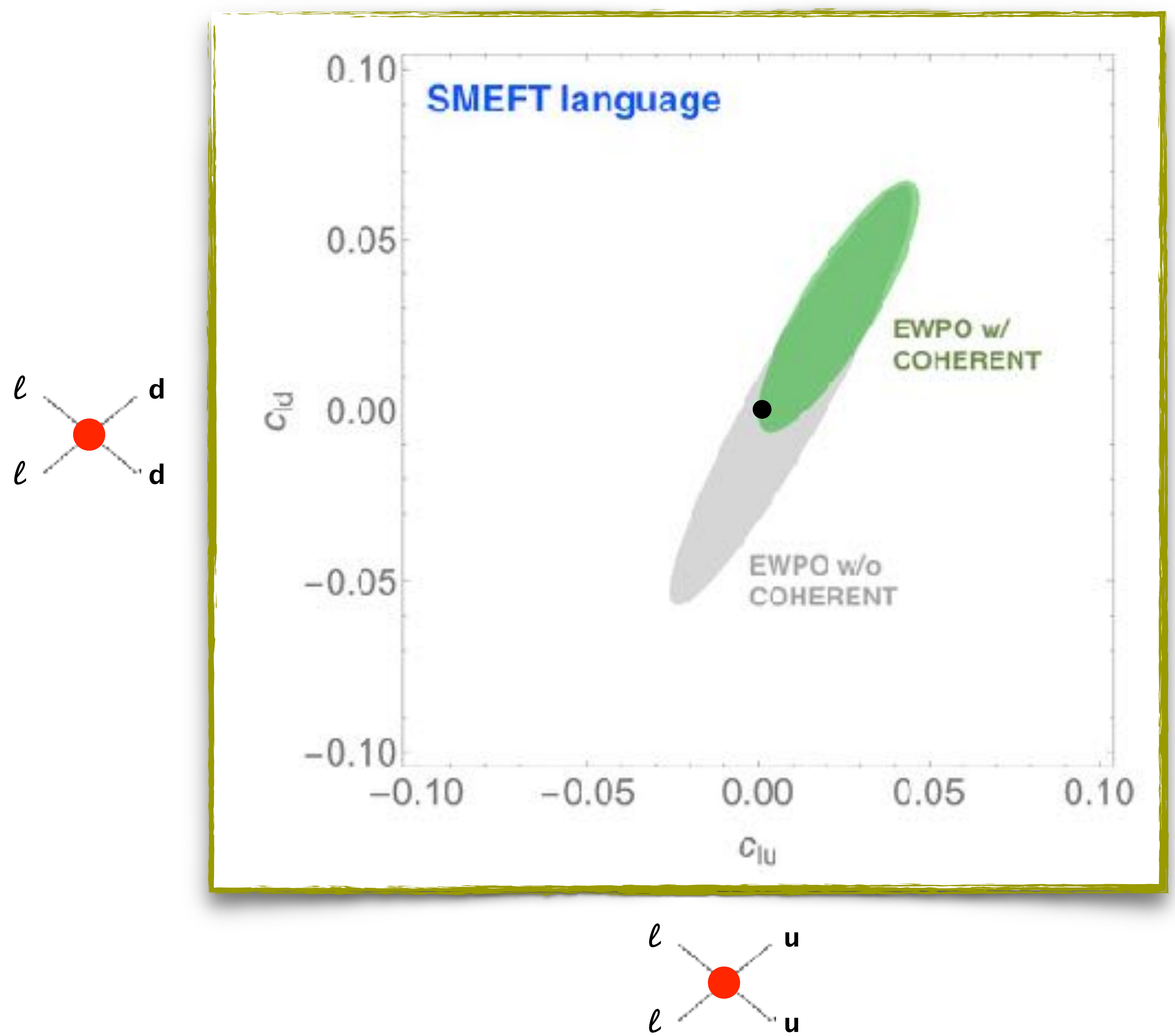
$$\epsilon_{\alpha\alpha}^{dd} = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu_\alpha} - \frac{1}{2}[c_{lq}^{(1)} - c_{lq}^{(3)} + c_{ld}]_{\alpha\alpha 11}$$

- **Only 4 constraints and not 6 because one can show that, at linear order in new physics, there are only two independent charges per nucleus, that is $\tilde{Q}_\mu = \tilde{Q}_{\bar{\mu}}$**
- **Only two combination of SMEFT parameters are efficiently constrained, at the percent level**

Coherent neutrino scattering

Combination of COHERENT constraints with other low- and high-energy electroweak precision tests

Assuming flavor symmetric $(U(3)^5)$ Wilson coefficients one see O(1) improvement in some constraints

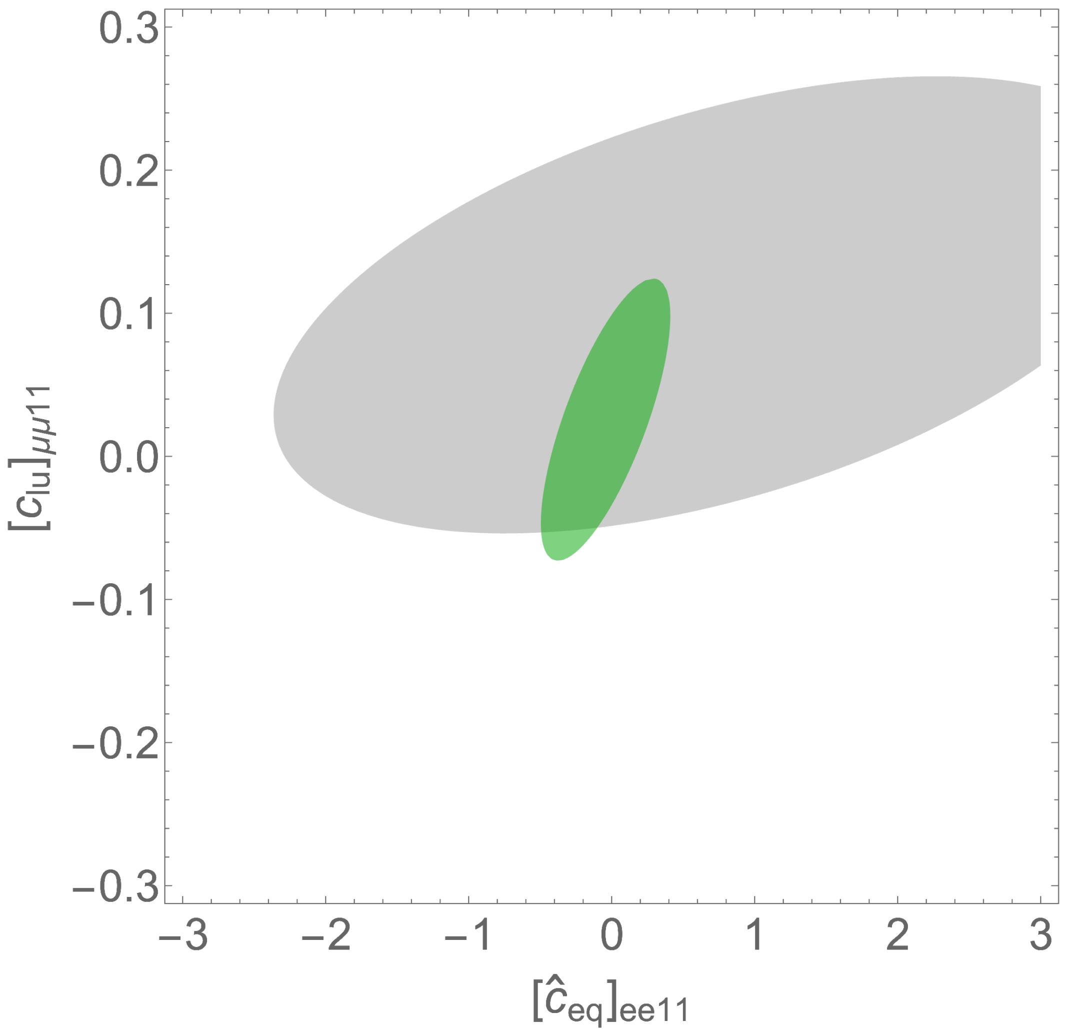


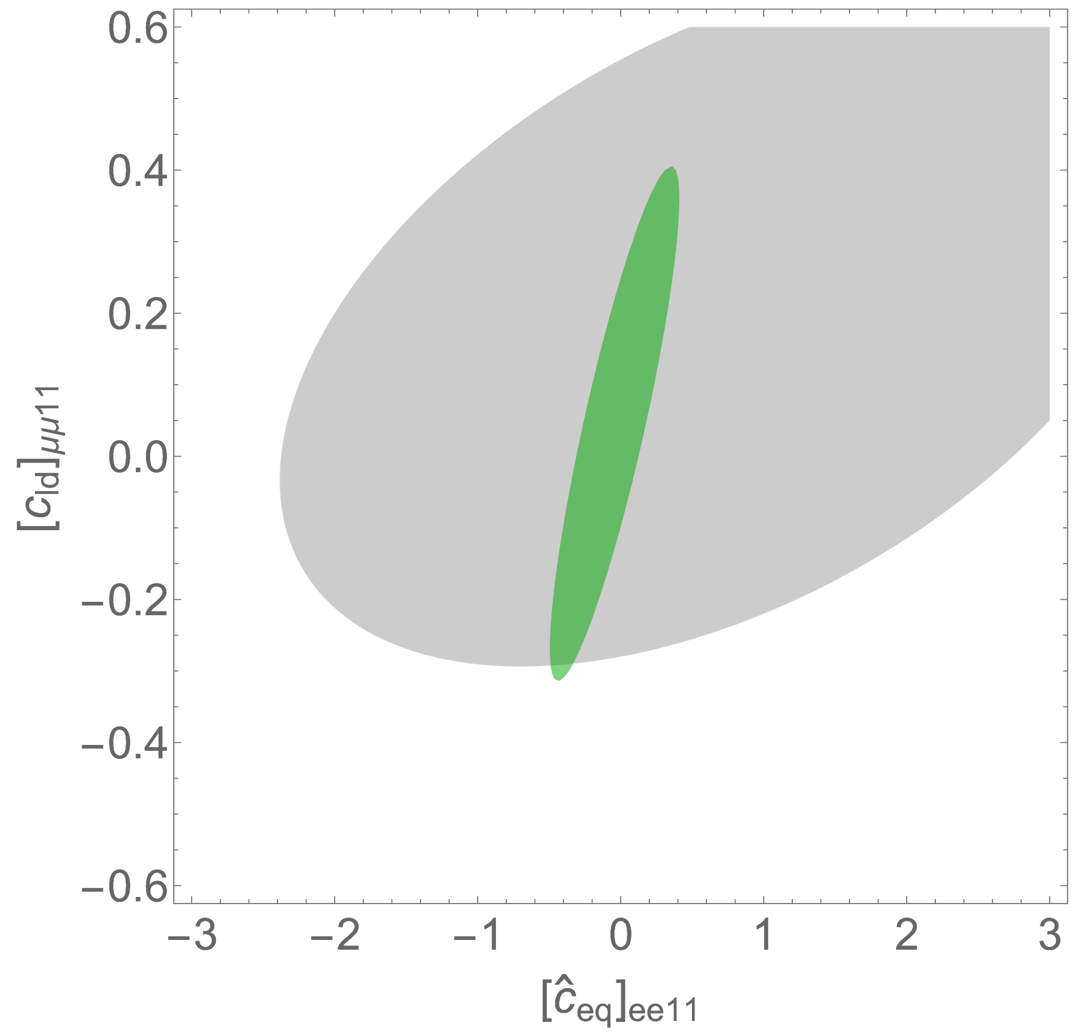
V. Breso-Pla et al [arXiv:2301.07036]

Coherent neutrino scattering

Combination of COHERENT constraints with other low- and high-energy electroweak precision tests

Assuming flavor generic Wilson coefficients the improvement is even more spectacular



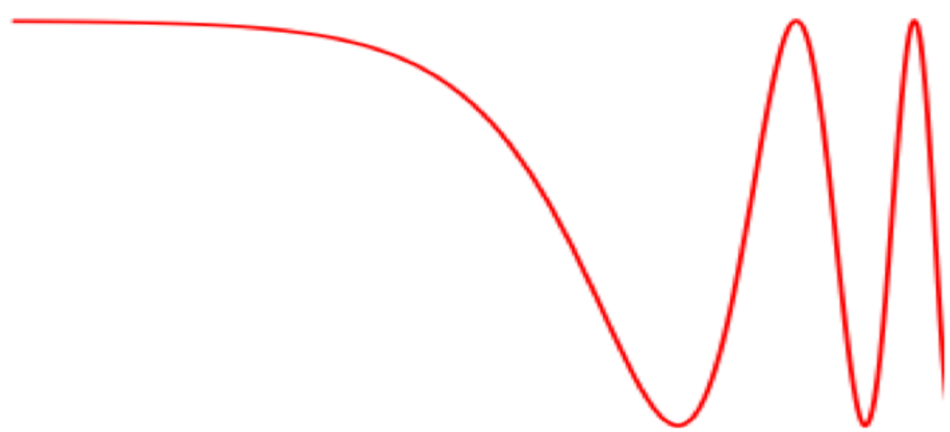


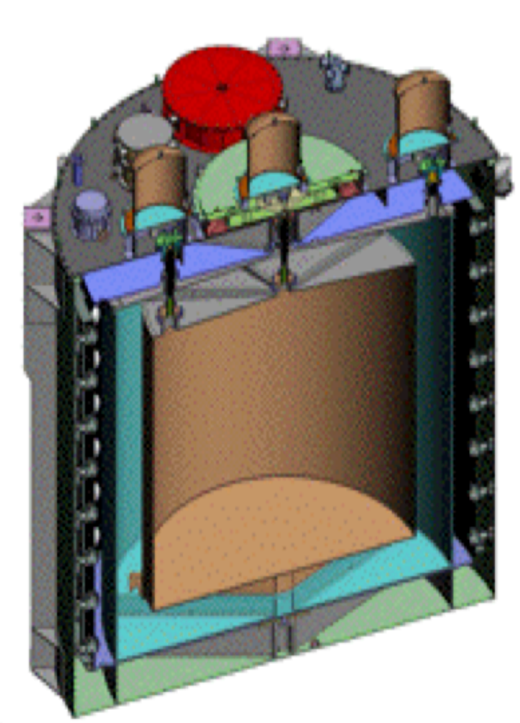
V. Breso-Pla et al
[arXiv:2301.07036]

Part 3

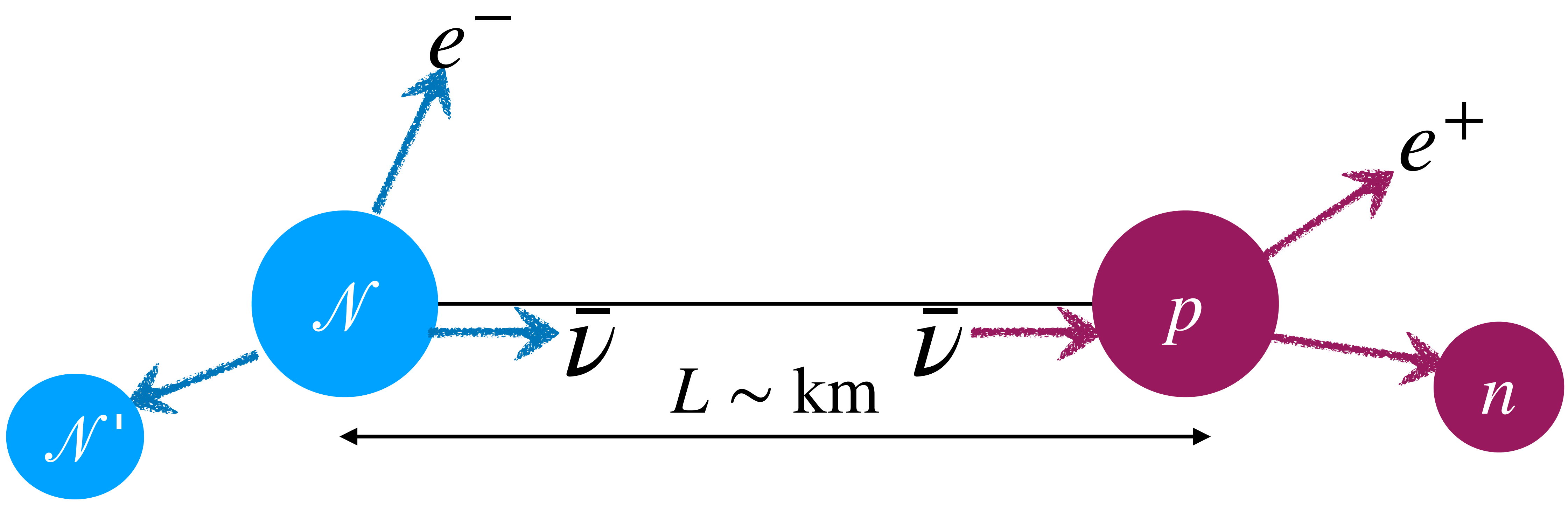
Constraints from reactor neutrino oscillations

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$





Reactor neutrino oscillations



$$d\bar{R}_{ee} = \sum_{\mathcal{N}} f_{\mathcal{N}} \frac{N_S N_T}{32\pi L^2 m_{\mathcal{N}} m_p} \sum_{k,l=1}^{3} e^{-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}} \left[d\Pi_P \mathcal{M}^P_{ek} \mathcal{M}^{P*}_{el}\right] \left[d\Pi_D \mathcal{M}^D_{ek} \mathcal{M}^{D*}_{el}\right]$$

Weighted sum over nuclei in reactor

$\mathcal{M}^P_{ek} \equiv \mathcal{M}[\mathcal{N} \to \mathcal{N}' e^- \bar{\nu}_k]$

$\mathcal{M}^D_{ek} \equiv \mathcal{M}[\bar{\nu}_k p \to e^+ n]$

Reactor neutrino oscillations

$$dR_{\alpha\beta} = \frac{N_S N_T}{32\pi L^2 m_S m_T} \sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) d\Pi_P \mathscr{M}^P_{\alpha k} \bar{\mathscr{M}}^P_{\alpha l} d\Pi_D \mathscr{M}^D_{\beta k} \bar{\mathscr{M}}^D_{\beta l}$$

The rate above is already an observable in neutrino experiments, and this is what is used in practical analyses, but to compare to commonly used language we can define oscillation probability

$$\frac{dP_{\alpha\beta}}{dE_\nu} = \frac{\int \frac{dR_{\alpha\beta}}{dE_\nu}}{\frac{d\Phi_\alpha}{dE_\nu}\sigma_\beta}$$

Neutrino flux at the source

Neutrino cross section at the target

$$\frac{dP_{\alpha\beta}}{dE_\nu} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \int \frac{d\Pi_P}{dE_\nu} \mathscr{M}^P_{\alpha k} \bar{\mathscr{M}}^P_{\alpha l} \int d\Pi_D \mathscr{M}^D_{\beta k} \bar{\mathscr{M}}^D_{\beta l}}{\sum_{k,l=1}^{3} \int \frac{d\Pi_P}{dE_\nu} |\mathscr{M}^P_{\alpha k}|^2 \int d\Pi_D |\mathscr{M}^D_{\beta l}|^2}$$

Reactor neutrino oscillations

Leading order Ccarged current Lagrangian at low energy can be parametrized as

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\Bigg[\Big[1+\epsilon_L\Big]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_L\gamma^\mu d_L$$

$$+\Big[\epsilon_R\Big]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_R\gamma^\mu d_R$$

$$+\frac{1}{2}\bar{e}_\alpha P_L\nu_\beta\cdot\bar{u}\Big[\epsilon_S-\epsilon_P\gamma_5\Big]_{\alpha\beta}d$$

$$+\frac{1}{4}\Big[\epsilon_T\Big]_{\alpha\beta}\bar{e}_\alpha\sigma_{\mu\nu}P_L\nu_\beta\cdot\bar{u}_R\sigma^{\mu\nu}d_L\Bigg]+\mathrm{h.c.}$$

Matching to SMEFT

$$[\epsilon_L]_{\alpha\beta}=\frac{\mathrm{v}^2}{V_{ud}}\left(V_{ud}[C^{(3)}_{Hl}]_{\alpha\beta}+V_{jd}[C^{(3)}_{Hq}]_{1j}\delta_{\alpha\beta}-V_{jd}[C^{(3)}_{lq}]_{\alpha\beta 1j}\right)$$

$$[\epsilon_R]_{\alpha\beta}=\frac{\mathrm{v}^2}{2V_{ud}}[C_{Hud}]_{11}\delta_{\alpha\beta}$$

$$[\epsilon_S]_{\alpha\beta}=-\frac{\mathrm{v}^2}{2V_{ud}}\left(V_{jd}[C^{(1)}_{lequ}]^*_{\beta\alpha j1}+[C_{ledq}]^*_{\beta\alpha 11}\right)$$

$$[\epsilon_P]_{\alpha\beta}=-\frac{\mathrm{v}^2}{2V_{ud}}\left(V_{jd}[C^{(1)}_{lequ}]^*_{\beta\alpha j1}-[C_{ledq}]^*_{\beta\alpha 11}\right)$$

$$[\epsilon_T]_{\alpha\beta}=-\frac{2\mathrm{v}^2}{V_{ud}}V_{jd}[C^{(3)}_{lequ}]^*_{\beta\alpha j1}$$

Reactor neutrino oscillations

AA, M. Gonzalez-Alonso, Z. Tabrizi
[arXiv:1901.04553]

In the limit $\frac{\Delta m_{21}^2 L}{E_\nu} \ll 1$, the survival probability takes the form

$$\boxed{\begin{aligned} P_{\bar\nu_e\to\bar\nu_e} &= 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde\theta_{13} - \alpha_D \frac{m_e}{E_\nu - \Delta} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right) \\ &+ \sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde\theta_{13})\left(\beta_D \frac{m_e}{E_\nu - \Delta} - \beta_P \frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(\Delta m_{21}^2)\end{aligned}}$$

Approximately known function depending on distribution of radioactive nuclei in reactor

$$\alpha_D = \frac{g_S}{3g_A^2+1}\mathrm{Re}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Re}\,[T] \qquad \alpha_P = \frac{g_T}{g_A}\mathrm{Re}\,[T] \qquad \tilde\theta_{13} = \theta_{13} + \mathrm{Re}[L]$$

$$\beta_D = \frac{g_S}{3g_A^2+1}\mathrm{Im}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Im}\,[T], \qquad \beta_P = \frac{g_T}{g_A}\mathrm{Im}\,[T] \qquad [X] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

Short baseline reactor neutrino oscillations sensitive to 5 distinct linear combinations of dimension-6 SMEFT operators

Effects of SM-like V-A interactions parametrized by ϵ_L are absorbed into mixing angle, thus they are not observable in reactor oscillations alone!

Reactor neutrino oscillations

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde{\theta}_{13} - \alpha_D\frac{m_e}{E_\nu - \Delta} - \alpha_P\frac{m_e}{f_T(E_\nu)}\right)$$

$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})\left(\beta_D\frac{m_e}{E_\nu - \Delta} - \beta_P\frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(\Delta m_{21}^2)$$

The real parts of scalar and tensor parameters lead to "energy-dependent mixing angle":

$$\alpha_D = \frac{g_S}{3g_A^2+1}\mathrm{Re}\left[S\right] - \frac{3g_Ag_T}{3g_A^2+1}\mathrm{Re}\left[T\right]$$

$$\beta_D = \frac{g_S}{3g_A^2+1}\mathrm{Im}\left[S\right] - \frac{3g_Ag_T}{3g_A^2+1}\mathrm{Im}\left[T\right], \qquad [X] \equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

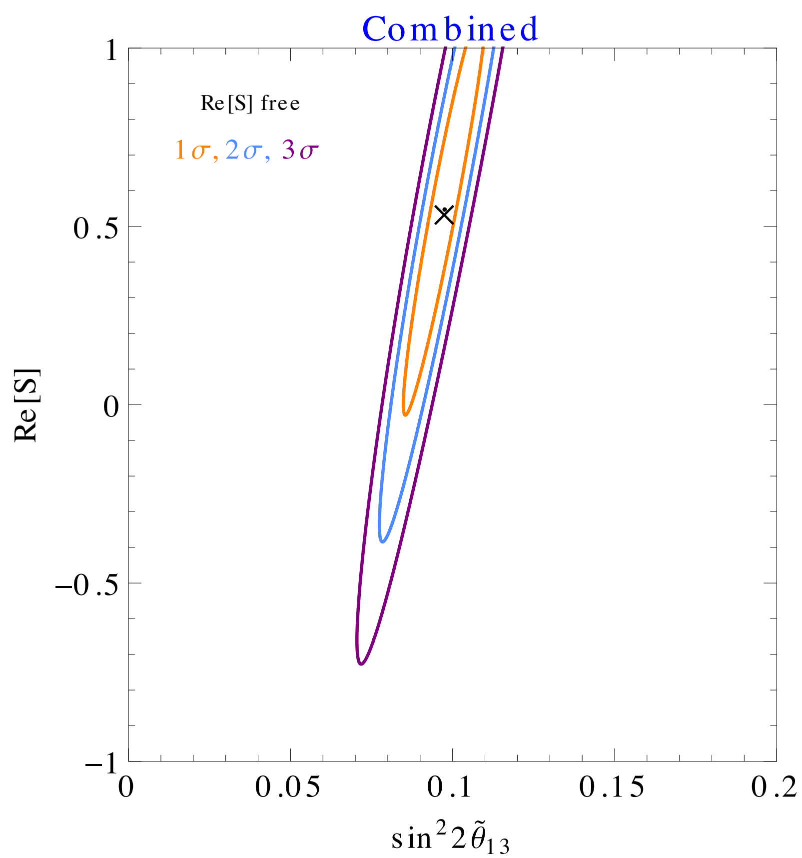
The imaginary parts of scalar and tensor parameters lead to qualitatively distinct oscillation pattern

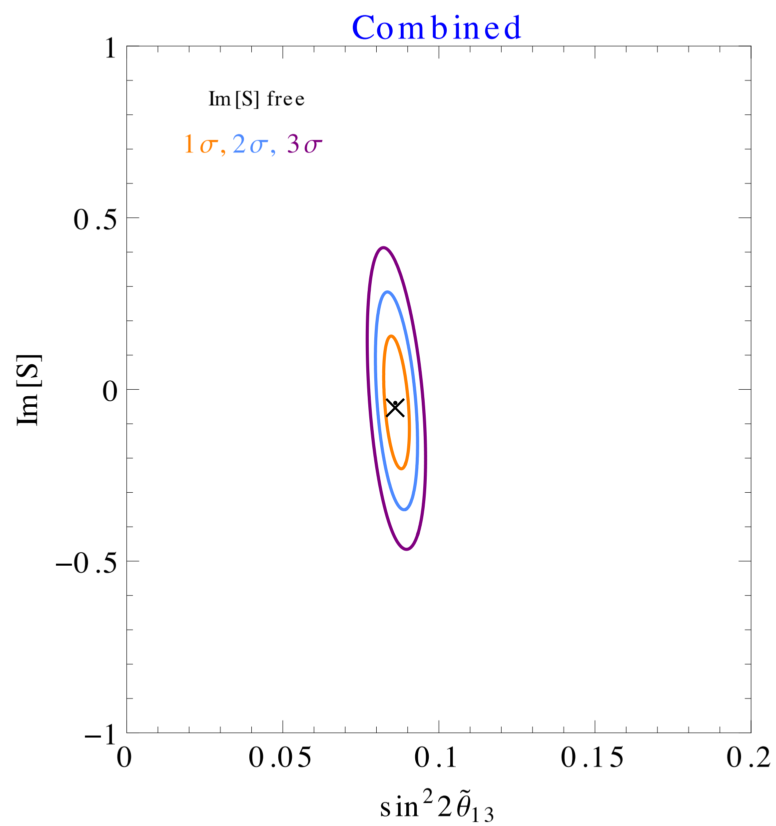
A possible handle to constrain these effects, as neutrino experiments quote results in energy bins

Reactor neutrino oscillations

Combined constraints using RENO and Daya Bay data

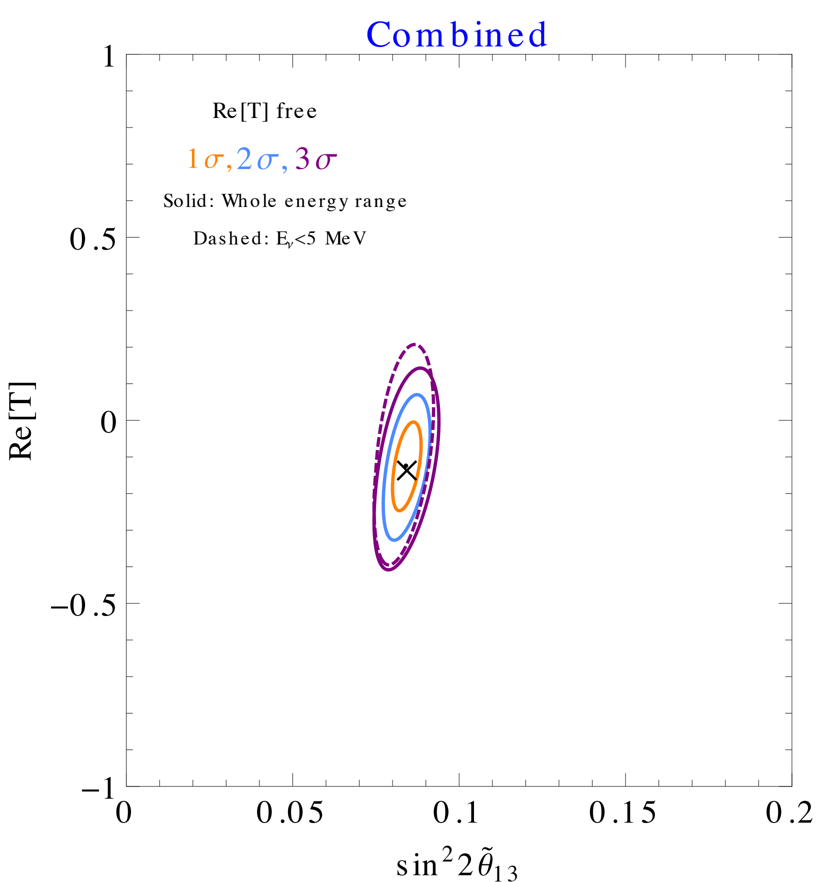
AA, M. Gonzalez-Alonso, Z. Tabrizi
[arXiv:1901.04553]

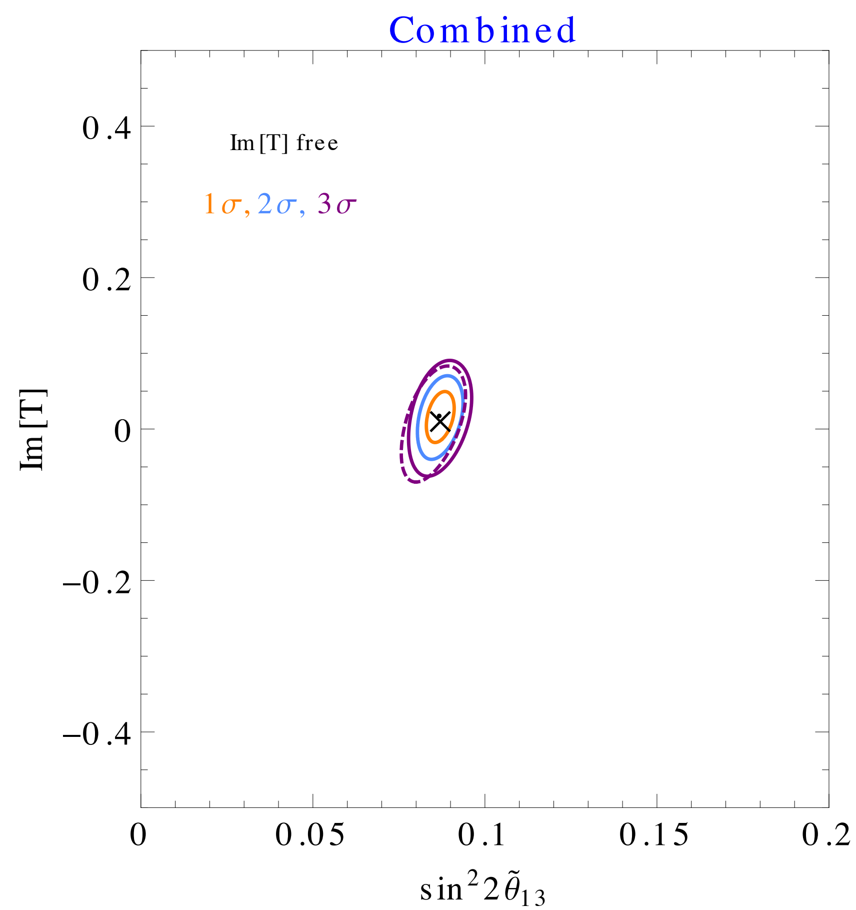




$$-[\epsilon_S]_{\alpha\beta}\frac{2V_{ud}}{v^2}\frac{1}{2}\bar{e}_\alpha P_L \nu_\beta \cdot \bar{u}d$$

Better constraints on real than imaginary parts





Somewhat better constraint on tensor than scalar

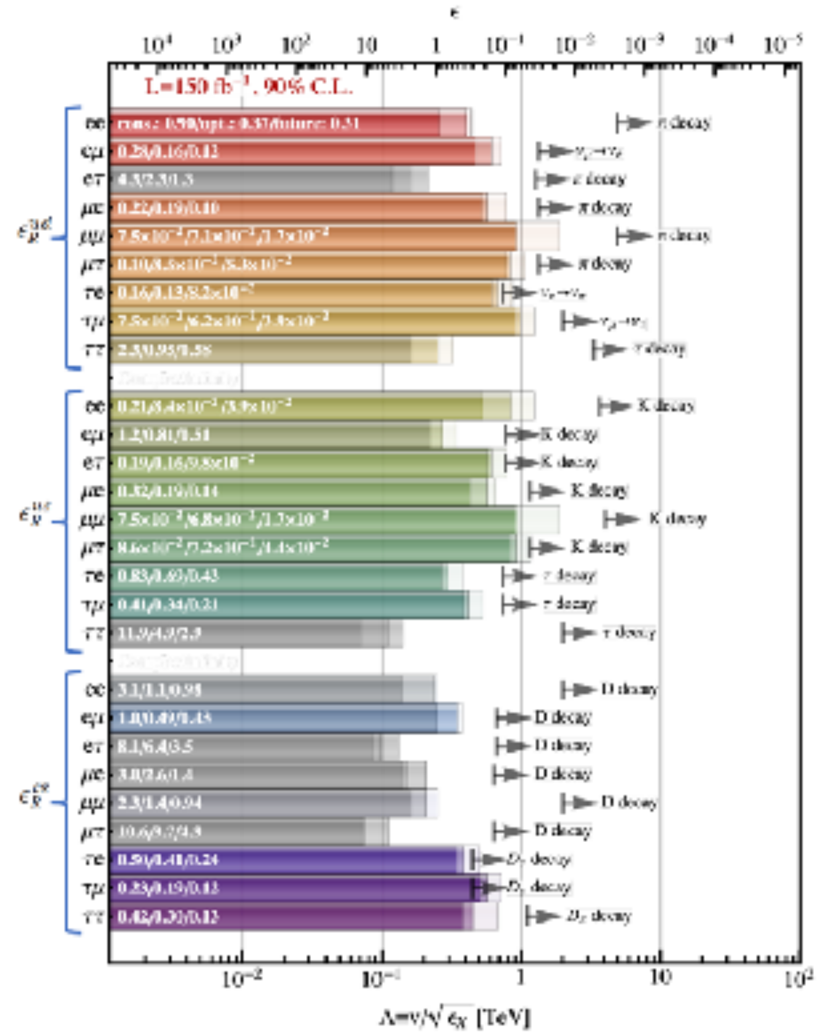
$$-\left[\epsilon_T\right]_{\alpha\beta}\frac{2V_{ud}}{v^2}\frac{1}{4}\bar{e}_\alpha\sigma_{\mu\nu}P_L\nu_\beta \cdot \bar{u}_R\sigma^{\mu\nu}d_L$$

See also the analysis by Daya Bay
[arXiv:2401.02901]

See also

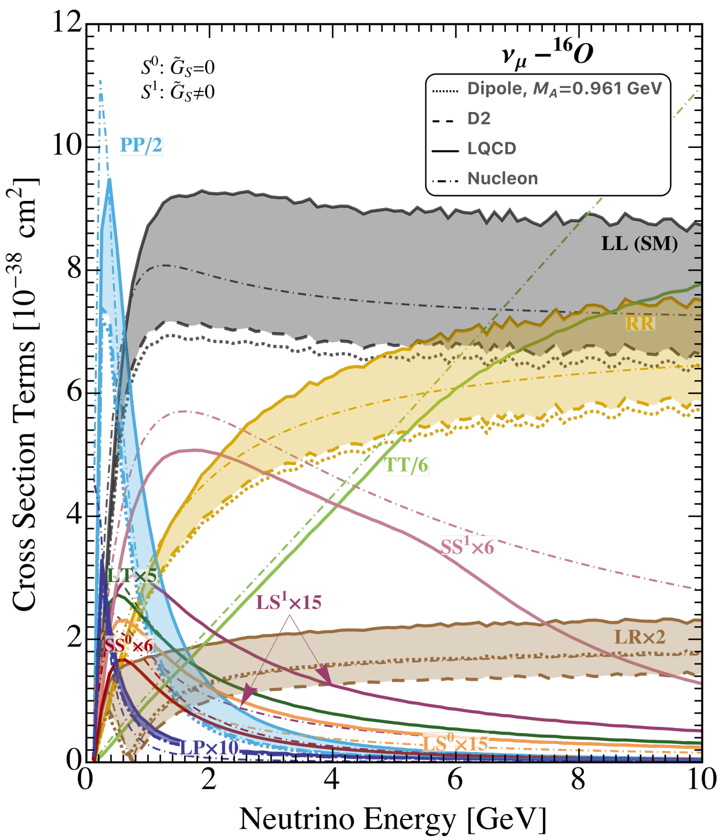
EFT Faserν sensitivity study

AA, M. Gonzalez-Alonso, J. Kopp, Y. Soreq, Z. Tabrizi [arXiv:1901.04553]

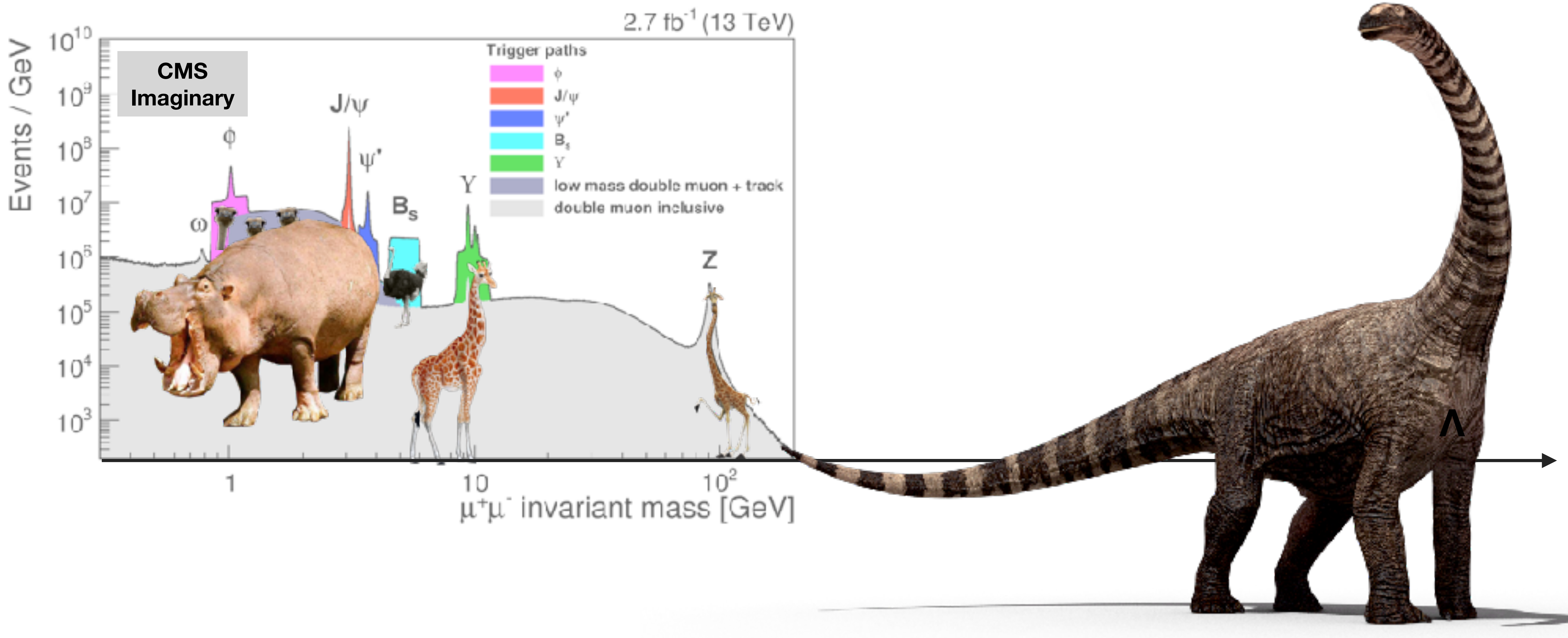


Discussion of neutrino detection in the quasi-elastic regime

J. Kopp, N. Rocco, Z. Tabrizi [arXiv::2401.07902]



Fantastic Beasts and Where To Find Them



THANK YOU

Neutrino conventions

$$\nu_\alpha \qquad \alpha = e, \mu, \tau$$

Neutrinos carry the "flavor index" α but these are not "flavor eigenstates" !

Kinetic and mass terms:

$$\mathcal{L}_{\mathrm{WEFT}} \supset i \sum_\alpha \bar{\nu}_\alpha \gamma_\mu \partial_\mu \nu_\alpha - \frac{1}{2} \sum_{\alpha\beta} \left(\nu_\alpha M_{\alpha\beta} \nu_\beta + \mathrm{h.c.} \right)$$

Diagonal kinetic terms **In general non-diagonal mass terms**

We also define the neutrino mass eigenstates

$$\nu_k \qquad k = 1,2,3$$

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k$$

3x3 unitary matrix called PMNS matrix

$$U_{\alpha j} M_{\alpha\beta} U_{\beta k} = \delta_{jk} m_k$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ -s_{12}c_{23} - e^{i\delta_{\mathrm{CP}}} c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta_{\mathrm{CP}}} s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta_{\mathrm{CP}}} c_{12}s_{13}c_{23} & -c_{12}s_{23} - e^{i\delta_{\mathrm{CP}}} s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}$$

Constraints from non-oscillation experiments

(Not completely robust) constraints due to quadratic contributions of off-diagonal NSI to several observables

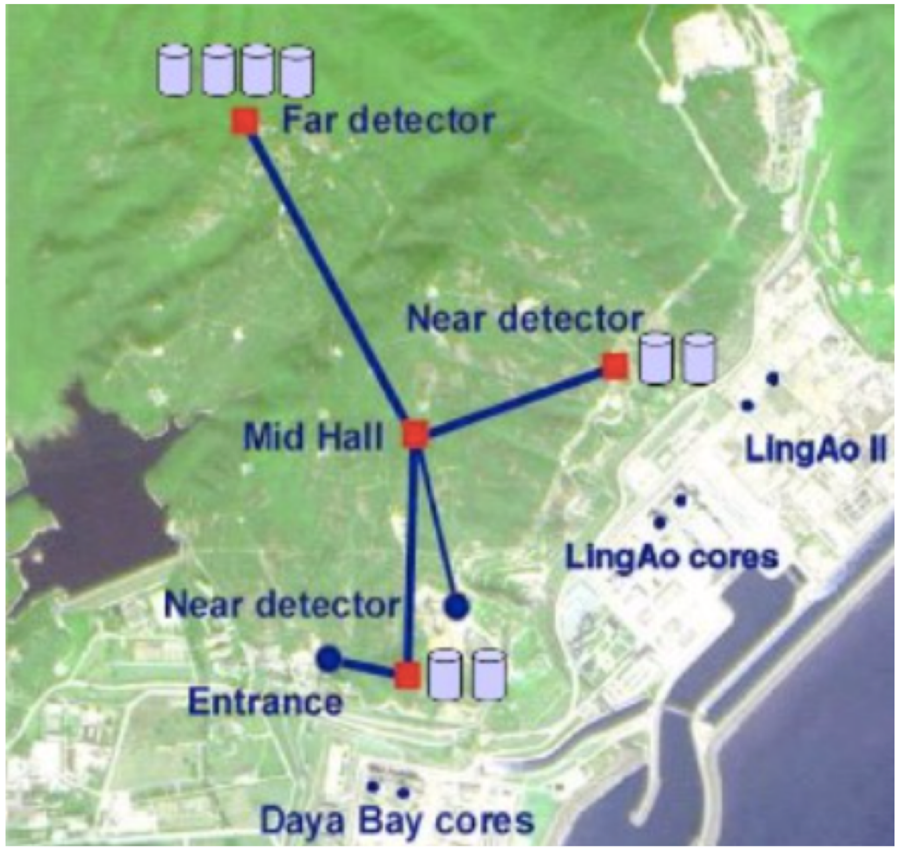
- Beta decays: $|[\epsilon_S]_{e\alpha}| \leq 6.4 \times 10^{-2}\,, \qquad |[\epsilon_T]_{e\alpha}| \leq 4.4 \times 10^{-2}$
- CKM unitarity $|[\epsilon_S]_{e\alpha}| \leq 2.0 \times 10^{-2}$
- Pion decays
$$|[\epsilon_P]_{e\alpha}|_{\mu=2\,\mathrm{GeV}} \leq 7.5 \times 10^{-6}\,.$$
$$\left|[\epsilon_T]_{e\alpha} + 3 \times 10^{-4}[\epsilon_S]_{e\alpha}\right|_{\mu=2\,\mathrm{GeV}} \leq 1.0 \times 10^{-3}$$
- Drell-Yan LHC $\left(\sum_\alpha |[\epsilon_S]_{e\alpha}|^2\right)^{1/2} \lesssim 2 \times 10^{-3}\,, \qquad \left(\sum_\alpha |[\epsilon_T]_{e\alpha}|^2\right)^{1/2} \lesssim 2 \times 10^{-3}$
- Muon Conversion $\left|[\epsilon_S]_{e\mu}\right| \lesssim 3 \times 10^{-6}$
- $\tau \to e\,\pi\,\pi$ $\left|[\epsilon_S]_{e\tau}\right| \lesssim 4 \times 10^{-4}$

Setting EFT bounds at Daya Bay and RENO

Daya Bay:

- 6 reactor cores;
- 8 anti-neutrino detectors;
- 3 near and far experimental halls located at 400 m, 512 m and 1610 m;
- Has observed ~ 4 million anti-neutrino events in 1958 days of data taking;

Daya Bay Collaboration, D. Adey et al., arXiv:1809.02261



RENO:

- 6 reactor cores;
- 2 near and far anti-neutrino detectors located at 367 m and 1440 m;
- Has observed ~ 1 million anti-neutrino events in 2200 days of data taking

RENO Collaboration, G. Bak et al., arXiv:1806.00248.