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Constraints on EFT from neutrino oscillations

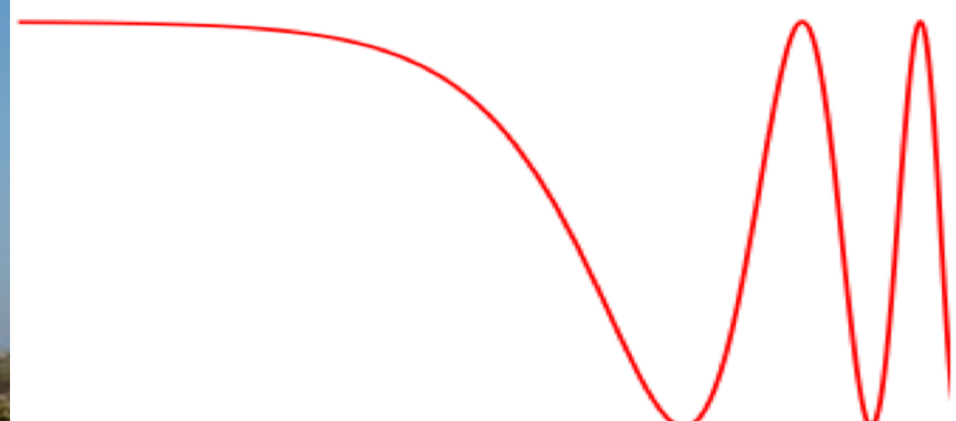
Heidelberg, 06 May 2019

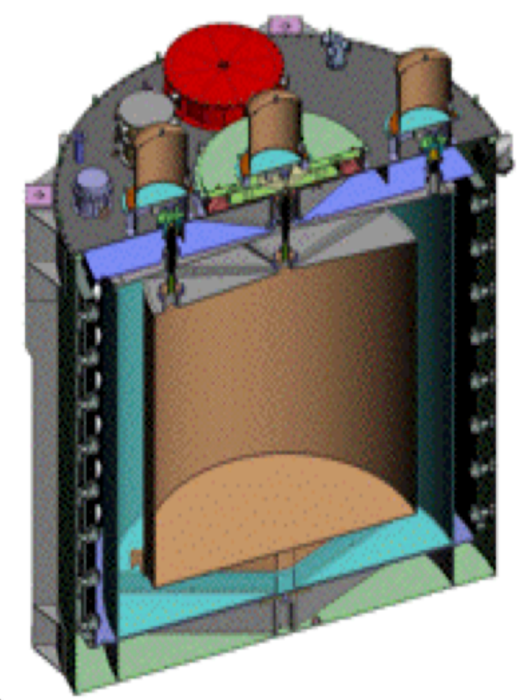
Based on [arXiv:1901.04553] with Martin Gonzalez-Alonso and Zahra Tabrizi

In this talk

Focus on reactor antineutrino oscillations

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





Borrowed from
Zahra Tabrizi

but with some obvious modifications discussion applicable to other neutrino experiments

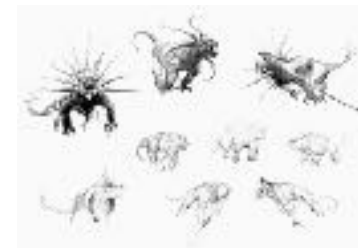
Why EFT

- Efficient and model-independent description can be developed under assumption that no non-SM degrees of freedom are produced on-shell in a given experiment. This leads to the universal language of effective field theory (EFT)

- Wealth of low-energy observables probing different aspects of particle interactions are described within one consistent framework. Constraints from different observables can be meaningfully compared

- Results obtained in the language of EFT can be easily translated into constraints on any particular new physics model

EFT ladder

Energy Scale	Theory	Particles	Expansion Parameter
Λ = ???	New Physics		**?**
1 TeV	SMEFT		$\frac{E}{\Lambda}$
100 GeV			
10 GeV	WEFT (aka Fermi theory, LEFT, WET)	**γ,g,ν,e,μ,τ + N_f q**	$\frac{E}{m_W}$
1 GeV			
100 MeV	χPT	**γ,ν,e,μ,π,K**	$\frac{E}{4\pi f_\pi}$
10 MeV	Lee-Yang	**p,n,e,ν,γ**	$\frac{E_k}{m_p}$
10 MeV	…		
1 MeV	Euler-Heisenberg	**γ,ν**	$\frac{E}{m_e}$

EFT below the weak scale

- For most low-energy precision observables, the characteristic energy scale is much smaller than the W and Z boson mass

- Below m_W, the only SM degrees of freedom available are leptons, photon, gluons, and 3, 4, or 5 flavors of quark, while H/W/Z bosons and top quark are integrated out

- I refer to it as the WEFT (also known as the Fermi theory, WET, LEFT ,…)

- WEFT is an EFT with SU(3)xU(1) local symmetry group and fermionic matter spectrum, where the expansion parameter is E/m_W, $m_W \approx 80$ GeV.

- Huge parameter space to explore and constrain - every experimental input counts!

In the context of neutrino physics, WEFT implies important assumptions:
only SM neutrinos are present;
no additional sterile neutrinos and no right-handed neutrinos!

Charged currents in WEFT at LO

CKM element

Part relevant for (inverse) beta decays

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

"V-A"

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

"V+A"

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

"(Pseudo)Scalar"

"Tensor"

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

Normalization scale, by convention set by Fermi constant

$$\mathrm{v} = \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246\ \mathrm{GeV}$$

Charged currents with different Lorentz structure

NSI relevant for beta decays parametrized by five 3-vectors $[\epsilon_X]_{e\beta}$, and these parameters can be probed also in reactor oscillation experiments

We keep track of linear effects in ϵ_X only

Neutrino conventions

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

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

Quadratic terms in this basis:

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

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

We also define the neutrino mass eigenstates $\nu_k \quad k = 1,2,3$

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \qquad U_{\alpha j} M_{\alpha\beta} U_{\beta k} = \delta_{jk} m_k$$

3x3 unitary matrix called PMNS matrix

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

Neutrino conventions

- "Flavor basis" ν_α is not uniquely defined. Any unitary transformation takes ν_α to a different but equivalent basis with different values of the NSI parameters $[\epsilon_X]_{\alpha\beta}$. Physics does not depend on which basis is used

- "Flavor eigenstates" cannot be defined in the presence of general WEFT interactions. In general, one charged flavor l_α couples to one linear combination of neutrinos $\nu_\alpha + [\epsilon_L]_{\alpha\beta}\, \nu_\beta$ in the V-A term, and to a different linear combination $[\epsilon_X]_{\alpha\beta}\, \nu_\beta$ in the remaining terms

- Flavor eigenstates could be defined if only V-A interactions are present, eigenstate(α) = $\nu_\alpha + [\epsilon_L]_{\alpha\beta}\, \nu_\beta$. However eigenstate(α) corresponding to different flavor α in general would not be orthogonal. In our analysis we never define neutrino flavor eigenstates.

- Mass eigenstate basis is uniquely defined (up to Majorana phases)

- I use standard parametrization of the PMNS matrix, but one should keep in mind that in the presence of NSI mixing angles and CP phase may have different values than those determined in the SM context

Down the EFT rabbit hole

Lee-Yang Lagrangian for nucleon interactions with electrons and τ/μ neutrinos, matched to the WEFT Lagrangian

Jackson et al (1957)

$$\mathscr{L}_{\mathrm{LY}} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{g_V\left[\epsilon_L+\epsilon_R\right]_{e\beta}(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu P_L\nu_\beta) - g_A\left[\epsilon_L-\epsilon_R\right]_{e\beta}(\bar{p}\gamma^\mu\gamma_5 n)(\bar{e}\bar{\gamma}_\mu P_L\nu_\beta)$$

$$+g_S\left[\epsilon_S\right]_{e\beta}(\bar{p}n)(\bar{e}P_L\nu_\beta) - g_P\left[\epsilon_P\right]_{e\beta}(\bar{p}\gamma_5 n)(\bar{e}P_L\nu_\beta) + \frac{1}{2}g_T\left[\epsilon_T\right]_{e\beta}(\bar{p}\sigma^{\mu\nu}n)(\bar{e}\sigma_{\mu\nu}P_L\nu_\beta)\Big\}$$

$$+\mathrm{h.c.}$$

$$\beta = e, \mu, \tau$$

Non-perturbative physics of nucleons summarized by charges g_X

Lattice + theory + experiment fix SM parameters (perturbative and non-perturbative)

Further down the EFT rabbit hole

Leading order non-relativistic effective Lagrangian

$$\mathscr{L}_{\rm LY}^{\rm NR} = -\frac{V_{ud}}{\mathrm{v}^2}(\bar\psi_p\psi_n)\Big\{\big[1+\epsilon_L+\epsilon_R\big]_{e\beta}(\bar e\gamma^0 P_L\nu_\beta) + g_S\big[\epsilon_S\big]_{e\beta}(\bar e P_L\nu_\beta)\Big\}$$

$\beta = \mu, \tau$

$$+\frac{V_{ud}}{\mathrm{v}^2}(\bar\psi_p\sigma^k\psi_n)\Big\{g_A\big[1+\epsilon_L-\epsilon_R\big]_{e\beta}(\bar e\gamma^0\sigma^k P_L\nu_e) - g_T\big[\epsilon_T\big]_{e\beta}(\bar e\sigma^k P_L\nu_\beta)\Big\} + \mathrm{h.c.} + \ldots$$

non-relativistic proton and neutron fields

Higher-order in $\frac{\nabla\psi}{2m_p}$

No dependence on ε_P here !
No sensitivity to pseudo-scalar interactions at leading order!

Scalar and vector (tensor and axial) interactions are almost the same
They only differ by electron chirality flip, leading to relative suppression of the former by m_e/E_e (Fierz interference terms)

Caveat for lepton-flavor diagonal terms

Lee-Yang Lagrangian for nucleon interactions with electrons and neutrinos matched to the WEFT Lagrangian

$$\mathscr{L}_{\rm LY} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{g_V\left(1+\left[\epsilon_L+\epsilon_R\right]_{ee}\right)(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu P_L\nu_e) - g_A\left(1+\left[\epsilon_L-\epsilon_R\right]_{ee}\right)(\bar{p}\gamma^\mu\gamma_5 n)(\bar{e}\bar{\gamma}_\mu P_L\nu_e)$$

$$+g_S\left[\epsilon_S\right]_{ee}(\bar{p}n)(\bar{e}P_L\nu_e) - g_P\left[\epsilon_P\right]_{ee}(\bar{p}\gamma_5 n)(\bar{e}P_L\nu_e) + \frac{1}{2}g_T\left[\epsilon_T\right]_{ee}(\bar{p}\sigma^{\mu\nu}n)(\bar{e}\sigma_{\mu\nu}P_L\nu_e)\Big\} + \mathrm{h.c.}$$

Rescale SM parameters: $V_{ud} \to V_{ud}\left(1-\left[\epsilon_L+\epsilon_R\right]_{ee}\right), \quad g_A \to g_A\left(1+2\left[\epsilon_R\right]_{ee}\right)$

$$\mathscr{L}_{\rm LY} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{g_V(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu P_L\nu_e) - g_A(\bar{p}\gamma^\mu\gamma_5 n)(\bar{e}\bar{\gamma}_\mu P_L\nu_e)$$

$$+g_S\left[\epsilon_S\right]_{ee}(\bar{p}n)(\bar{e}P_L\nu_e) - g_P\left[\epsilon_P\right]_{ee}(\bar{p}\gamma_5 n)(\bar{e}P_L\nu_e) + \frac{1}{2}g_T\left[\epsilon_T\right]_{ee}(\bar{p}\sigma^{\mu\nu}n)(\bar{e}\sigma_{\mu\nu}P_L\nu_e)\Big\} + \mathrm{h.c.}$$

Dependence on diagonal BSM parameters $[\varepsilon_L]_{ee}$ and $[\varepsilon_R]_{ee}$ is absorbed into phenomenological values of SM parameters. These parameters are totally <u>unobservable</u> in reactor oscillation experiments!
(theoretically, one can just better measure V_{ud} and g_A in these experiments)

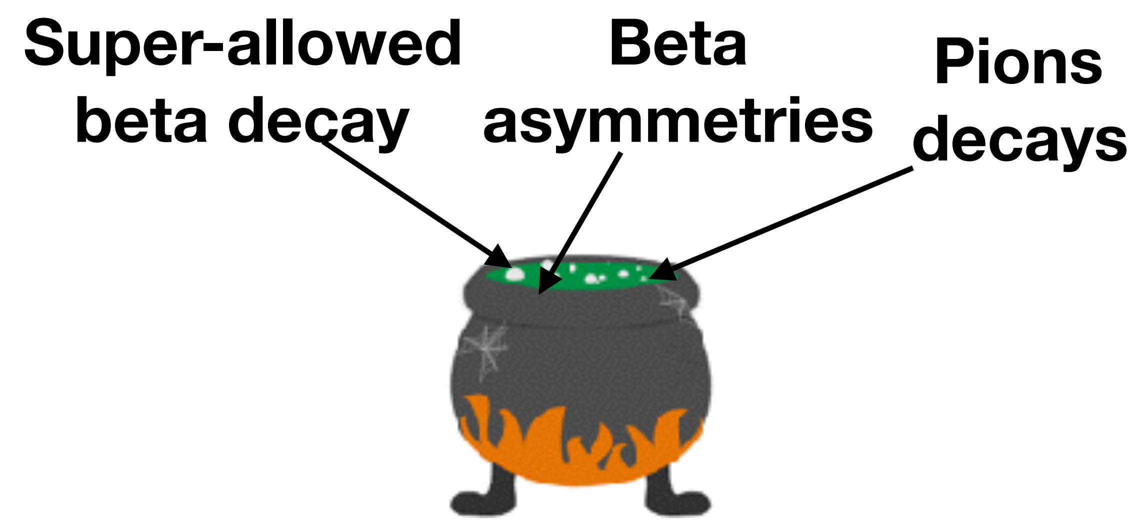
Gonzalez-Alonso et al
arXiv:1803.08732

$$V_{ud} = 0.974569 \pm 0.000038, \quad g_V \approx 1, \quad g_A = 1.2728 \pm 0.0017, \quad g_S = 0.987 \pm 0.055, \quad g_P = 349 \pm 9, \quad g_T = 1.278 \pm 0.033.$$

Model independent constraints on diagonal NSI

Diagonal NSI probed at linear level by many non-oscillation experiments

$$\begin{pmatrix} V_{ud} \\ [\epsilon_R]_{ee} \\ [\epsilon_S^e]_{ee} \\ [\epsilon_P^e]_{ee} \\ [\epsilon_T^e]_{ee} \end{pmatrix} = \begin{pmatrix} 0.974569(38) \\ -0.0006(48) \\ 0.0016(12) \\ -0.0000005(21) \\ -0.0012(22) \end{pmatrix}$$



$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\Big[e\beta\bar{e}\gamma_\mu P_L\nu_e \cdot \bar{u}_L\gamma^\mu d_L$$

$$+\left[\epsilon_R\right]_{ee}\bar{e}\gamma_\mu P_L\nu_e \cdot \bar{u}_R\gamma^\mu d_R$$

$$+\frac{1}{2}\bar{e}P_L\nu_e \cdot \bar{u}\left[\epsilon_S - \epsilon_P\gamma_5\right]_{ee} d$$

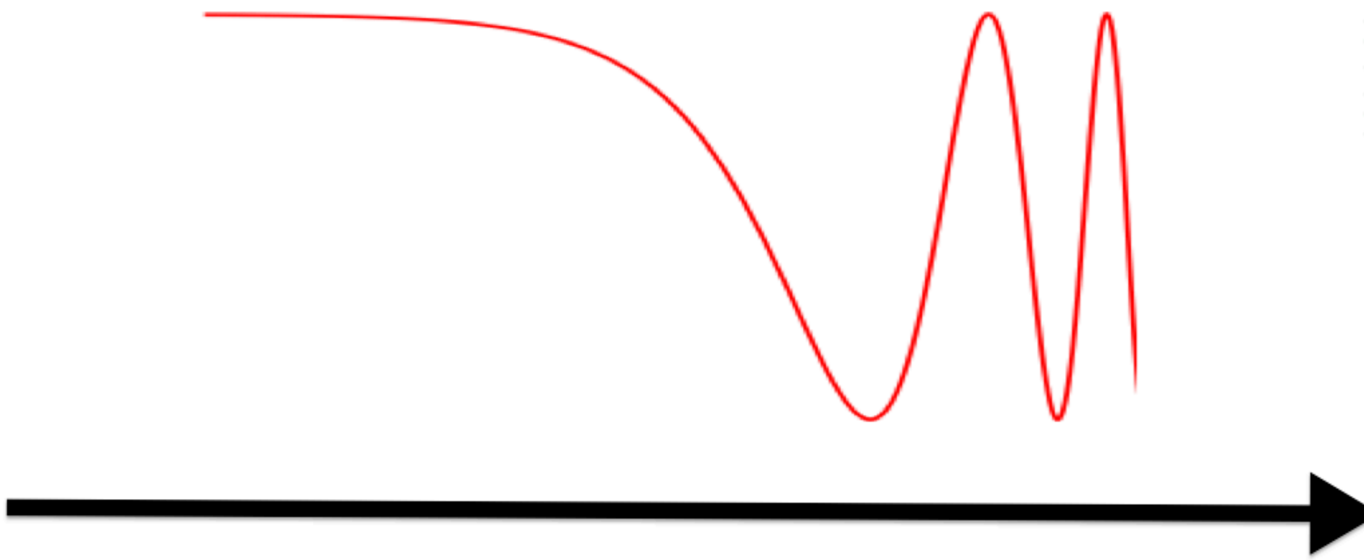
$$+\frac{1}{4}\left[\epsilon_T\right]_{ee}\bar{e}\sigma_{\mu\nu}P_L\nu_e \cdot \bar{u}_L\sigma^{\mu\nu}d_L\Big] + \mathrm{h.c.}$$

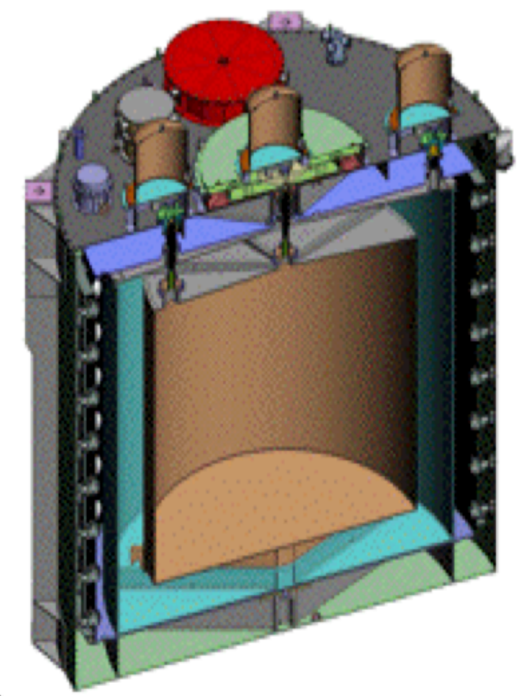
Gonzalez-Alonso, Camalich
1605.07114
+ updates

Diagonal NSI probed at linear level by many different (non-)oscillation experiments
Lepton-flavor off-diagonal NSI probed at linear level only by oscillation experiments!

In the following, constraint on off-diagonal NSI from reactor neutrino oscillations

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





$$P_{survival} = F?(\varepsilon)$$

Standard NSI formalism

NSI parameters

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \epsilon^s_{\alpha\beta} |\nu_\beta\rangle$$

Flavor eigenstate at the source

$$|\nu_\beta^d\rangle = |\nu_\beta\rangle + \sum_{\alpha=e,\mu,\tau} \epsilon^d_{\beta\alpha} |\nu_\alpha\rangle$$

Flavor eigenstate at the detector

Oscillation probability (in absence of NSI in propagation):

$$P_{\nu_\alpha^s \to \nu_\beta^d} = \langle \nu_\beta^d | e^{-iHL} | \nu_\alpha^s \rangle |^2$$

$$H_{\alpha\beta} = \frac{1}{2E_\nu} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger_{k\beta}$$

Neutrino energy

Neutrino mass squared differences

PMNS matrix relating neutrino flavor and mass eigenstates

Standard NSI formalism

NSI parameters

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=} \epsilon^s_{\alpha\beta} |\nu_\beta\rangle$$

Flavor eigenstate at the source

$$|\nu_\beta^d\rangle = |\nu_\beta\rangle + \sum_{\alpha=e,\mu,\tau}$$

Fl… state at the detector

Oscillation probability … in propagation):

$$P_{\nu_\alpha^s \to \nu_\beta^d} = \langle \quad HL |\nu_\alpha^s\rangle|^2$$

Impossible to define “flavor eigenstates” for general WEFT interactions

$$H_{\alpha\beta} = \quad U^\dagger_{k\beta}$$

Neutrino energy

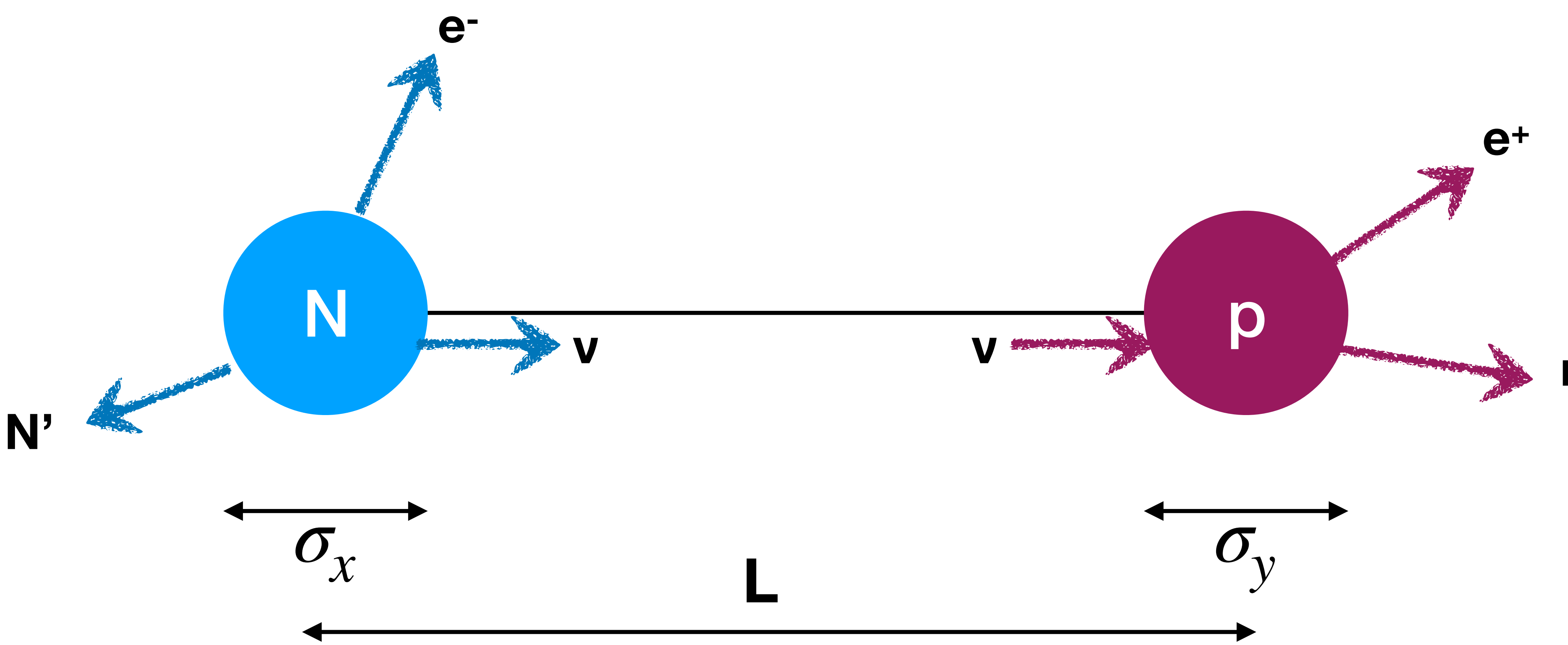
Neutrino mass squared differences

PMNS matrix relating neutrino flavor and mass eigenstates

Neutrino oscillations in QFT

see e.g.
Giunti et al. [hep-ph/9305276]
Akhmedov Kopp [arXiv:1001.4815]
Kobach et al. [arXiv:1711.07491]

Neutrino oscillations can be consistently derived in QFT



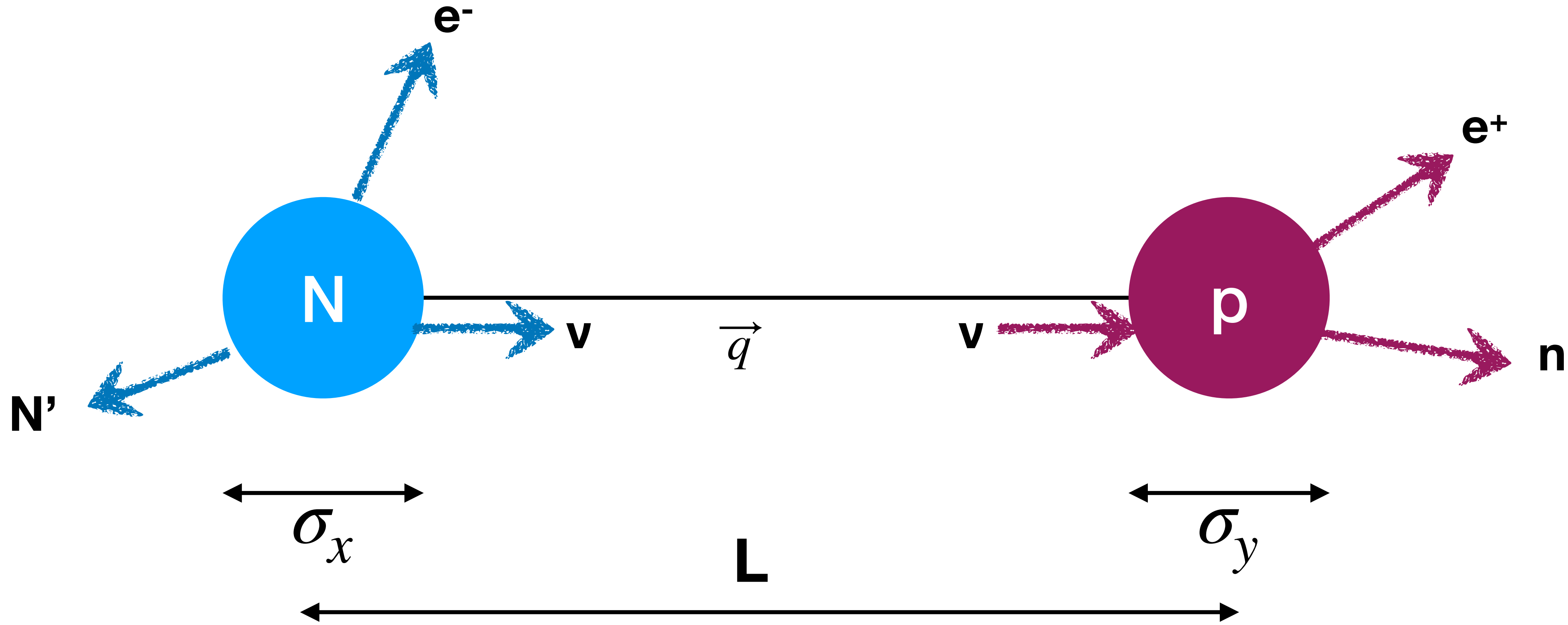
Process described by matrix element

$$_{\text{out}}\langle k_{e^-} k_{N'} k_{e^+} k_n \,|\, N_x p_y \rangle$$

Neutrinos are simply intermediate particles in Feynman diagrams

Localized wave packets (superposition of "in" momentum states)

Neutrino oscillations in QFT

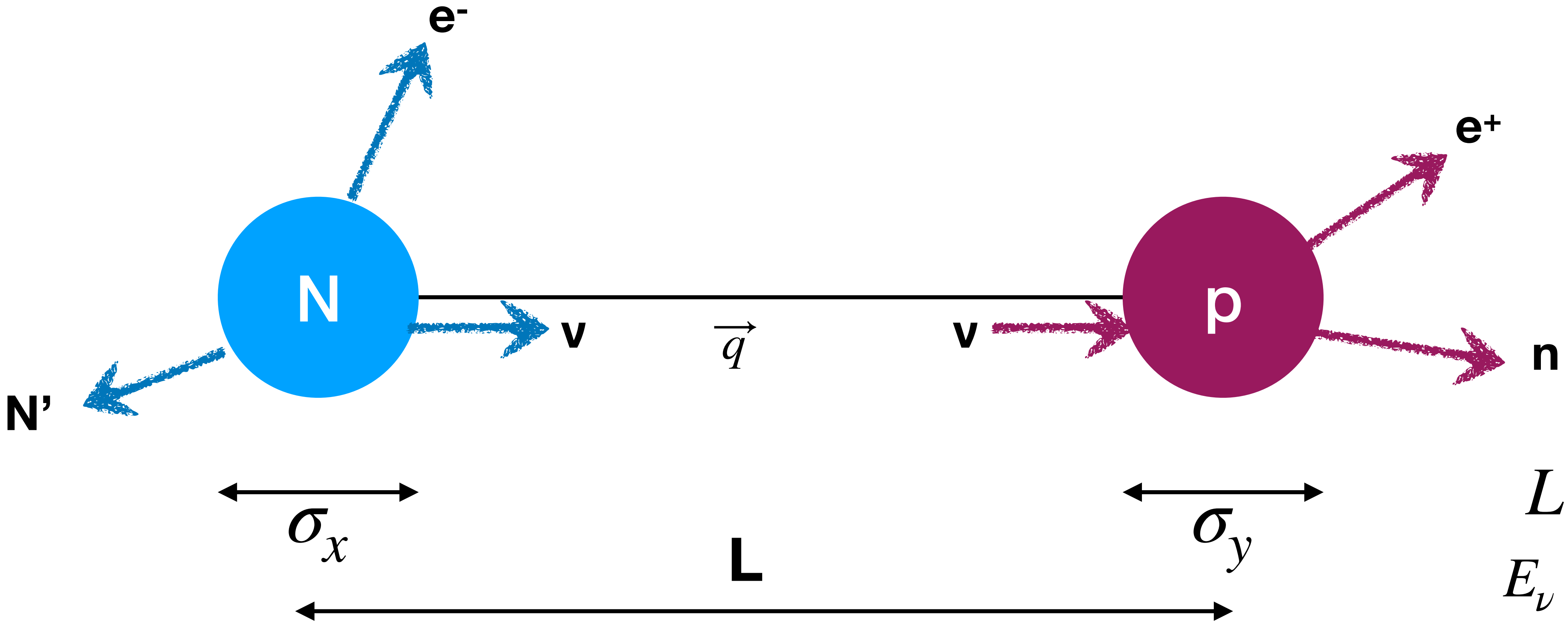


Process dominated by intermediate neutrinos close to mass shell, where amplitudes factorize into production and detection parts

$$\mathscr{M}(Np \to N'e^- ne^+) = \sum_{k=1}^{3} \frac{\mathscr{M}(N \to N'e^-\nu_k)\mathscr{M}(\nu_k p \to ne^-)}{q^2 - m_k^2 + i\epsilon} \equiv \sum_{k=1}^{3} \frac{\mathscr{M}_k^P \mathscr{M}_k^D}{q^2 - m_k^2 + i\epsilon}$$

Oscillations due to interference between different neutrino mass eigenstates, possible thanks to momentum spread of source and target particles

Neutrino oscillations in QFT



$$L \gg \sigma_{x,y}$$

$$E_\nu \gg m_k$$

$$E_\nu \gg |m_k^2 - m_l^2| \sigma_i$$

$$\frac{dR}{dE_\nu} = \frac{1}{128\pi^4 L^2 m_N m_p} \sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D$$

Rate
per source particle
per target particle

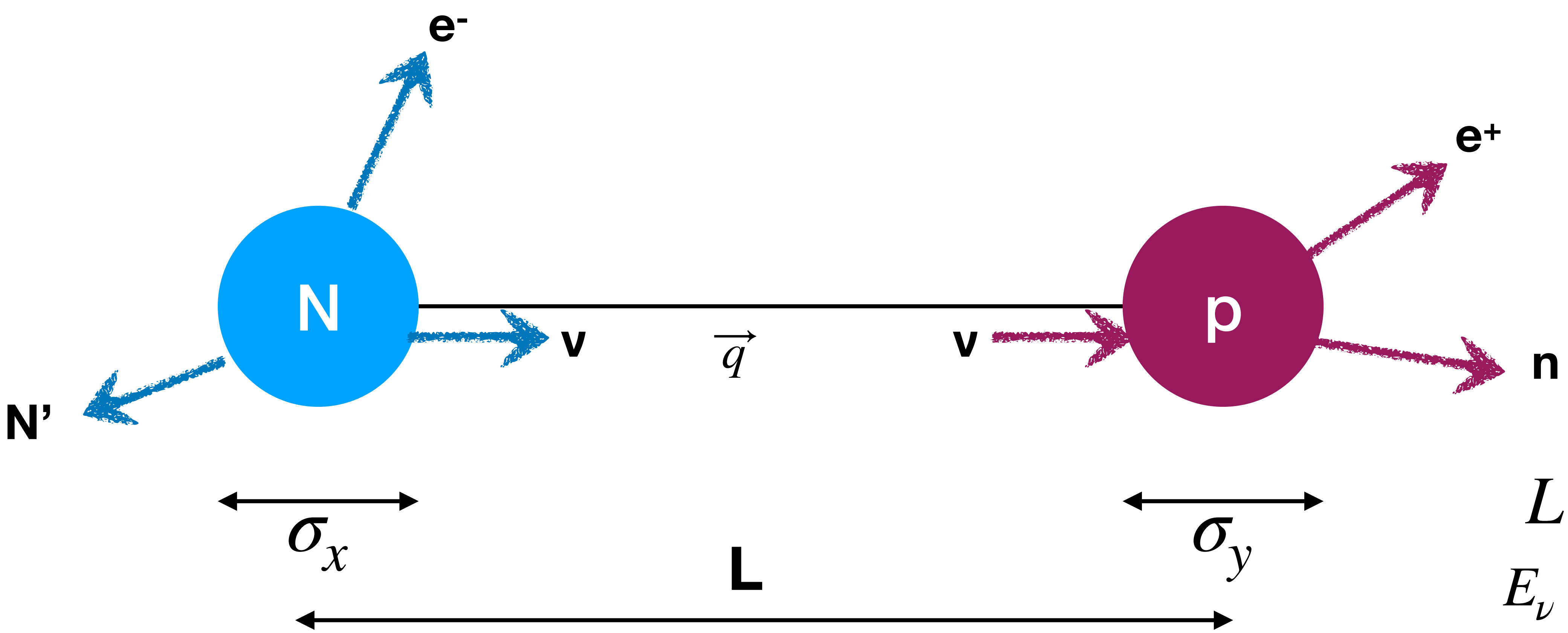
Geometric
factor

Oscillation
phase

Production
phase space
(without integration
over neutrino momenta)

Detection
phase space

Neutrino oscillations in QFT



$L \gg \sigma_i$

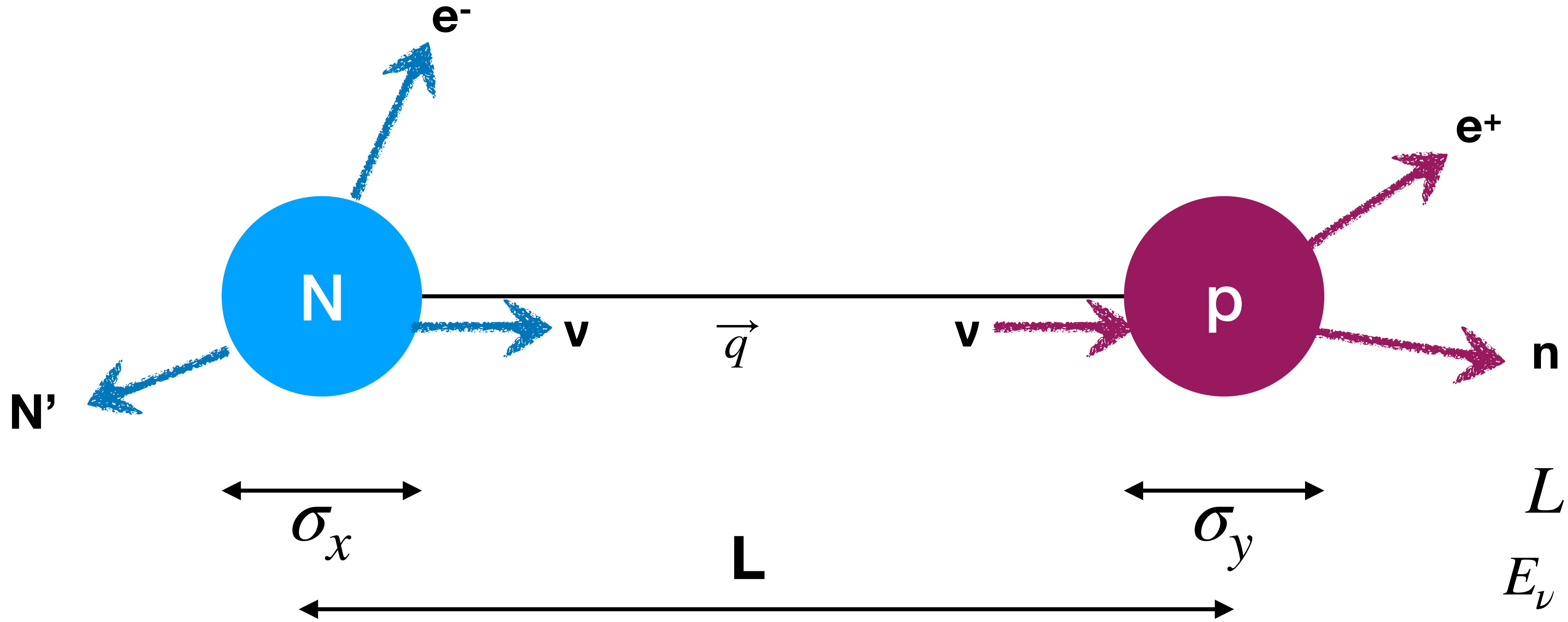
$E_\nu \gg m_k$

$E_\nu \gg |m_k^2 - m_l^2| \sigma_i$

For massless neutrinos one would instead get

$$\frac{dR^{\text{n.o.}}}{dE_\nu} = \frac{1}{128\pi^4 L^2 m_N m_p} \int d\Pi'_P \sum_{k=1}^{3} |\mathscr{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^{3} |\mathscr{M}_l^D|^2$$

Neutrino oscillations in QFT



$$L \gg \sigma_i$$
$$E_\nu \gg m_k$$
$$E_\nu \gg |m_k^2 - m_l^2| \sigma_i$$

Survival probability:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = \frac{\frac{\partial R}{\partial E\nu}}{\frac{\partial R^{\text{n.o.}}}{\partial E\nu}}$$

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D}{\int d\Pi'_P \sum_{k=1}^{3} |\mathcal{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^{3} |\mathcal{M}_l^D|^2}$$

C. Giunti, C. W. Kim (2007)

Reactor neutrino oscillations in WEFT

The rest is totally straightforward…

$$\boxed{P_{\bar{\nu}_e\to\bar{\nu}_e} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2-m_l^2)}{2E_\nu}\right)\int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D}{\int d\Pi'_P \sum_{k=1}^{3} |\mathcal{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^{3} |\mathcal{M}_l^D|^2}}$$

Relevant Lagrangian describing production and detection in reactor experiments:

$$\mathcal{L}_{WEFT} \supset -\frac{2V_{ud}}{v^2}\Bigg[\left[1+\epsilon_L\right]_{e\beta}\bar{e}\gamma_\mu P_L\nu_\beta\cdot\bar{u}_L\gamma^\mu d_L$$
$$+\left[\epsilon_R\right]_{e\beta}\bar{e}\gamma_\mu P_L\nu_\beta\cdot\bar{u}_R\gamma^\mu d_R$$
$$+\frac{1}{2}\bar{e}P_L\nu_\beta\cdot\bar{u}\left[\epsilon_S-\epsilon_P\gamma_5\right]_{e\beta}d$$
$$+\frac{1}{4}\left[\epsilon_T\right]_{e\beta}\bar{e}\sigma_{\mu\nu}P_L\nu_\beta\cdot\bar{u}_L\sigma^{\mu\nu}d_L\Bigg]+\mathrm{h.c.}$$

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

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

Calculate and expand in WEFT:

$$\mathcal{M}_k^P \equiv \mathcal{M}(N\to N'e^-\nu_k) \qquad \mathcal{M}_k^D \equiv \mathcal{M}(\nu_k p\to ne^-)$$

Two-flavor oscillation limit

In typical reactor oscillation experiments: $$\frac{L(m_2^2 - m_1^2)}{E_\nu} \ll 1$$

Then one can set: $$m_2^2 - m_1^2 = 0, \qquad m_3^2 - m_1^2 = m_3^2 - m_2^2 = \Delta m_{31}^2$$

The survival probability has a simple form:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = A + B\cos\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right) + C\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)$$

$$= \underbrace{A'}_{\text{"Zero-distance" oscillations}} - \underbrace{B'\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)}_{\text{CP-conserving oscillations}} + \underbrace{C\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)}_{\text{CP-violating oscillations}}$$

Simple application: SM limit

$$\boxed{P_{\bar\nu_e\to\bar\nu_e} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2-m_l^2)}{2E_\nu}\right)\int d\Pi'_P \mathscr{M}_k^P \bar{\mathscr{M}}_l^P \int d\Pi_D \mathscr{M}_k^D \bar{\mathscr{M}}_l^D}{\int d\Pi'_P \sum_{k=1}^{3} |\mathscr{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^{3} |\mathscr{M}_l^D|^2}}$$

$$\mathscr{L}_{\rm LY}^{\rm NR} = -\frac{V_{ud}}{\mathrm{v}^2}(\bar\psi_p\psi_n)\left\{\left[1+\cancel{\epsilon_L}+\cancel{\epsilon_R}\right]_{e\beta}(\bar e\gamma^0 P_L\nu_\beta) + g_S\left[\cancel{\epsilon_S}\right]_{e\beta}(\bar e P_L\nu_\beta)\right\}$$

$$+\frac{V_{ud}}{\mathrm{v}^2}(\bar\psi_p\sigma^k\psi_n)\left\{g_A\left[1+\cancel{\epsilon_L}-\cancel{\epsilon_R}\right]_{e\beta}(\bar e\gamma^0\sigma^k P_L\nu_e) - g_T\left[\cancel{\epsilon_T}\right]_{e\beta}(\bar e\sigma^k P_L\nu_\beta)\right\} + \mathrm{h.c.} + \ldots$$

PMNS

Matrix elements factorize as $\mathscr{M}_k^P = [U]_{ek} M^P$ $\qquad$ $\mathscr{M}_k^P = [U^*]_{ek} M^D$

Same for all mass eigenstates k

Standard formula:

$$P_{\bar\nu_e\to\bar\nu_e} = \sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2-m_l^2)}{2E_\nu}\right)[U]_{ek}[U^*]_{el}[U^*]_{ek}[U]_{el}$$

$$= 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$

Simple application: V-A NSI

$$\boxed{P_{\bar{\nu}_e \to \bar{\nu}_e} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D}{\int d\Pi'_P \sum_{k=1}^{3} |\mathcal{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^{3} |\mathcal{M}_l^D|^2}}$$

$$\mathcal{L}_{\rm LY}^{\rm NR} = -\frac{V_{ud}}{\mathrm{v}^2}(\bar{\psi}_p \psi_n)\left\{\left[1 + \epsilon_L + \cancel{\epsilon_R}\right]_{e\beta}(\bar{e}\gamma^0 P_L \nu_\beta) + g_S\left[\cancel{\epsilon_S}\right]_{e\beta}(\bar{e}P_L\nu_\beta)\right\}$$

$$+\frac{V_{ud}}{\mathrm{v}^2}(\bar{\psi}_p \sigma^k \psi_n)\left\{g_A\left[1 + \epsilon_L - \cancel{\epsilon_R}\right]_{e\beta}(\bar{e}\gamma^0\sigma^k P_L \nu_e) - g_T\left[\cancel{\epsilon_T}\right]_{e\beta}(\bar{e}\sigma^k P_L \nu_\beta)\right\} + \mathrm{h.c.} + \ldots$$

Matrix elements factorize as $\mathcal{M}_k^P = [U + \epsilon_L U]_{ek} M^P \qquad \mathcal{M}_k^D = [U + \epsilon_L U]_{ek}^* M^D$

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right)[U+\epsilon_L U]_{ek}[U+\epsilon_L U]_{el}^*[U+\epsilon_L U]_{ek}^*[U+\epsilon_L U]_{el}^*}{\sum_k [U+\epsilon_L U]_{ek}[U+\epsilon_L U]_{ek}^* \sum_l [U+\epsilon_L U]_{el}^*[U+\epsilon_L U]_{el}}$$

$$= 1 - \sin^2(2\tilde{\theta}_{13})\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \qquad \tilde{\theta}_{13} = \theta_{13} + \mathrm{Re}[e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)] + \mathcal{O}(\epsilon_L^2)$$

Effects of left-handed (V-A) currents $[\epsilon_L]_{e\mu}$ and $[\epsilon_L]_{e\tau}$ are unobservable in reactor experiments alone!

T. Ohlsson and H. Zhang [arXiv:0809.4835]

Reactor neutrino oscillations in general WEFT

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D}{\int d\Pi'_P \sum_{k=1}^{3} |\mathcal{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^{3} |\mathcal{M}_l^D|^2}$$

Short-baseline oscillations of electron antineutrinos produced in reactors

Relevant for Daya Bay, RENO, Double Chooz

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde{\theta}_{13} - \alpha_D \frac{m_e}{E_e} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right)$$
$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})\left(\gamma_R + \beta_D \frac{m_e}{E_e} - \beta_P \frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(\Delta m_{21}^2)$$

Matches Kopp et al. [arXiv:0708.0152]

Reactor neutrino oscillations in WEFT

Usual CP-conserving oscillation pattern

$$\boxed{\begin{aligned} P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \sin^2\left(2\tilde{\theta}_{13} - \alpha_D \frac{m_e}{E_e} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right) \\ + \sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right) \sin(2\tilde{\theta}_{13}) \left(\gamma_R + \beta_D \frac{m_e}{E_e} - \beta_P \frac{m_e}{f_T(E_\nu)}\right) \end{aligned}}$$

CP-violating oscillations
(flips the sign for electron neutrinos)

Reactor neutrino oscillations in WEFT

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

Standard Θ13 mixing angle replaced by effective angle:

$$\tilde{\theta}_{13} = \theta_{13} + \mathrm{Re}[L] - \frac{3g_A^2}{3g_A^2+1}\mathrm{Re}[\mathrm{R}]$$

Original PMNS mixing angle

$$[X] \equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\left[\left[1+\epsilon_L\right]_{e\beta}\bar{e}\gamma_\mu P_L\nu_\beta\cdot\bar{u}_L\gamma^\mu d_L + \left[\epsilon_R\right]_{e\beta}\bar{e}\gamma_\mu P_L\nu_\beta\cdot\bar{u}_R\gamma^\mu d_R + \ldots\right] + \mathrm{h.c.}$$

Reactor neutrino oscillations in WEFT

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

$$\tilde{\theta}_{13} = \theta_{13} + \mathrm{Re}[L] - \frac{3g_A^2}{3g_A^2+1}\mathrm{Re}[\mathrm{R}]$$

$$[X] \equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\left[\left[1+\epsilon_L\right]_{e\beta}\bar{e}\gamma_\mu P_L \nu_\beta \cdot \bar{u}_L \gamma^\mu d_L + \ldots\right] + \mathrm{h.c.}$$

Part of BSM effects absorbed into effective Θ_{13} mixing angle, and are unobservable in reactor experiments alone

Effects of left-handed (V-A) currents $[\varepsilon_L]_{e\mu}$ and $[\varepsilon_L]_{e\tau}$ are unobservable

T. Ohlsson and H. Zhang [arXiv:0809.4835]

Reactor neutrino oscillations in WEFT

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

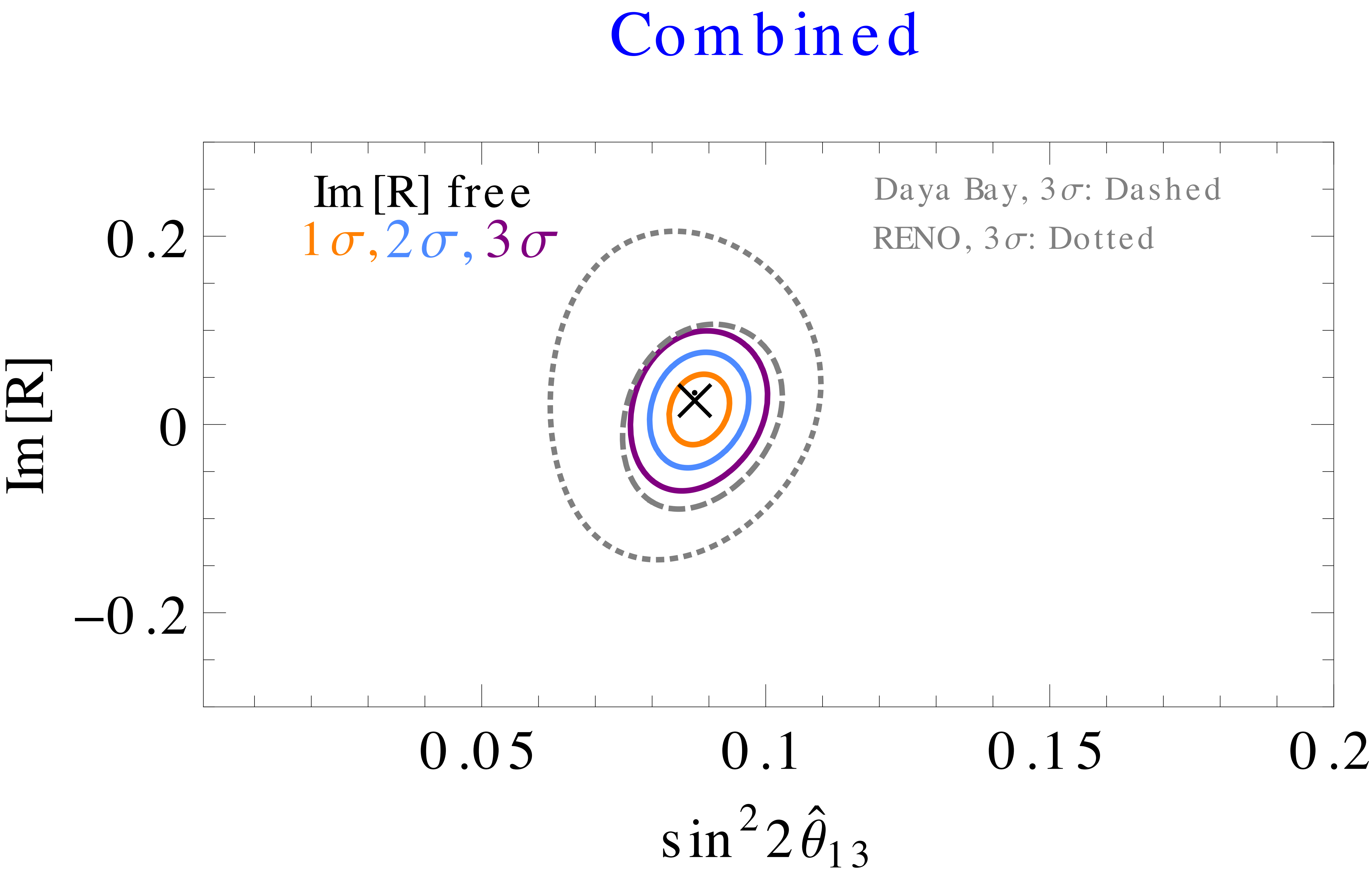
$$\gamma_R = -\frac{2}{3g_A^2 + 1}\mathrm{Im}[R]$$

$$[X] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\left[\left[\epsilon_R\right]_{e\beta}\bar{e}\gamma_\mu P_L \nu_\beta \cdot \bar{u}_R \gamma^\mu d_R + \ldots\right] + \mathrm{h.c.}$$

CP-violating combination of right-handed off-diagonal currents
is observable,
as it affects CP-violating part of survival probability

Reactor neutrino oscillations in WEFT



Reactor neutrino oscillations in WEFT

$$P_{\bar\nu_e\to\bar\nu_e} \approx 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde\theta_{13} - \alpha_D\frac{m_e}{E_e} - \alpha_P\frac{m_e}{f_T(E_\nu)}\right)$$

$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde\theta_{13})\left(\gamma_R + \beta_D\frac{m_e}{E_e} - \beta_P\frac{m_e}{f_T(E_\nu)}\right)$$

Effects of scalar and tensor currents on detection amplitude lead to "energy-dependent mixing angle":

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

$$\beta_D = \frac{g_S}{3g_A^2+1}\mathrm{Im}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Im}\,[T],$$

$$[X] \equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

$$\mathscr{L}_{WEFT} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big[\left[\bar e P_L \nu_\beta \cdot \bar u \epsilon_S\right]_{e\beta} d + \frac{1}{2}\left[\epsilon_T\right]_{e\beta}\bar e\sigma_{\mu\nu}P_L\nu_\beta\cdot\bar u_L\sigma^{\mu\nu}d_L + \dots\Big] + \mathrm{h.c.}$$

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

Reactor neutrino oscillations in WEFT

$$P_{\bar\nu_e\to\bar\nu_e} \approx 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde\theta_{13} - \alpha_D\frac{m_e}{E_e} - \alpha_P\frac{m_e}{f_T(E_\nu)}\right)$$
$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde\theta_{13})\left(\gamma_R + \beta_D\frac{m_e}{E_e} - \beta_P\frac{m_e}{f_T(E_\nu)}\right)$$

Effects of tensor currents on production amplitude lead to "energy-dependent mixing angle" :

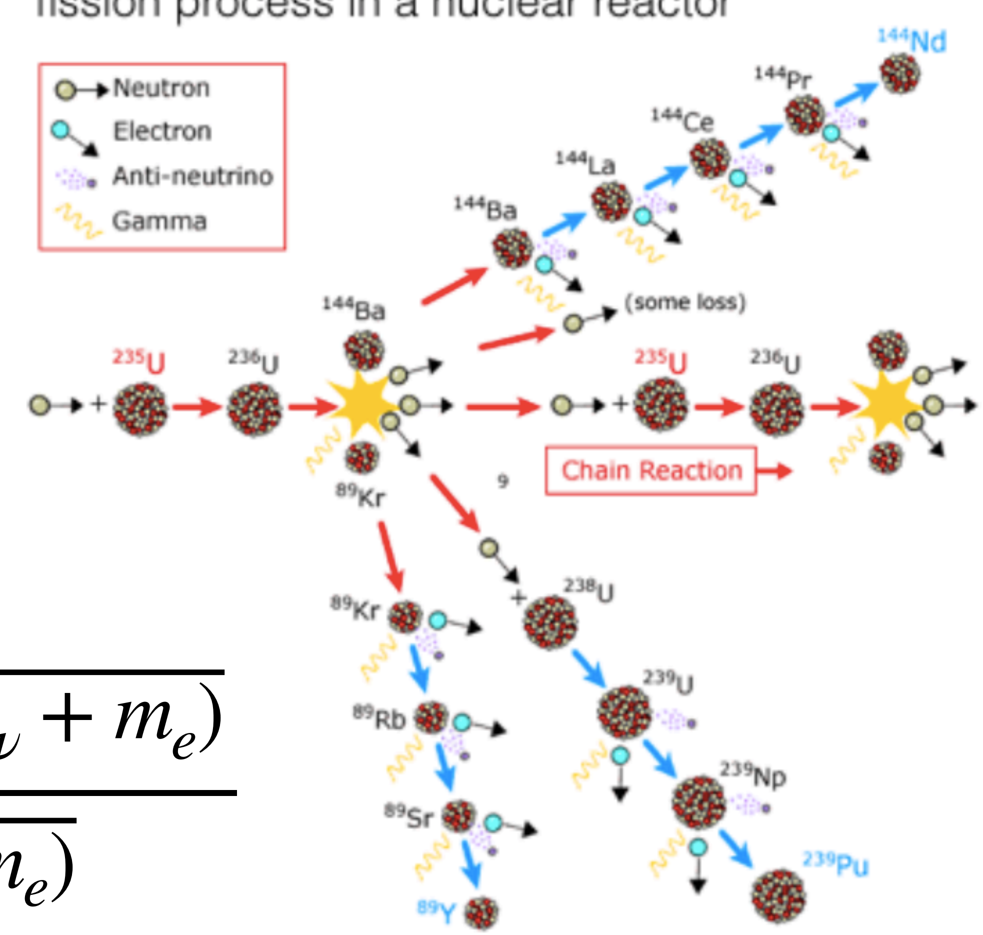
$$\alpha_P = \frac{g_T}{g_A}\mathrm{Re}\,[T]$$

$$[X] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

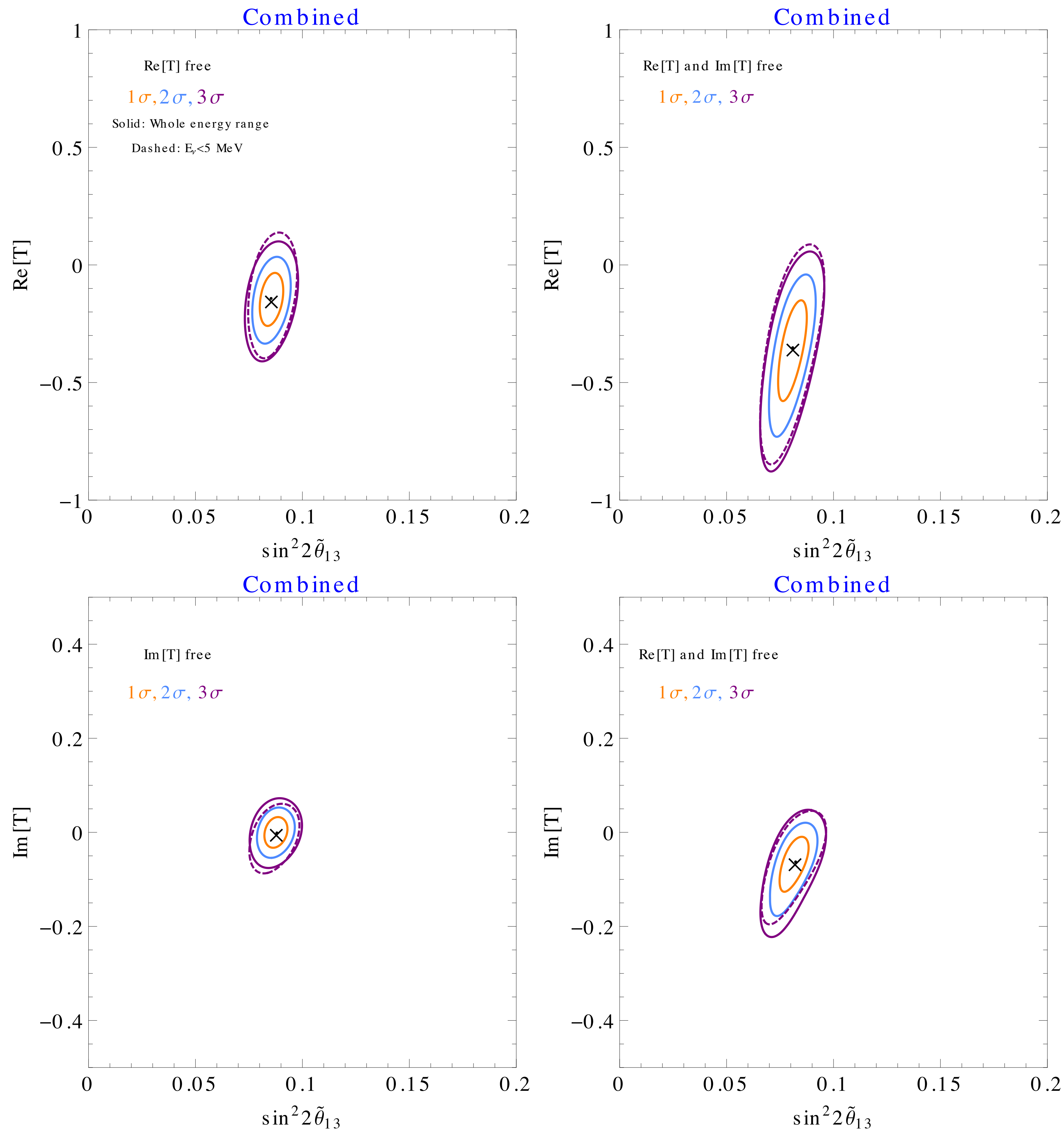
$$\beta_P = \frac{g_T}{g_A}\mathrm{Im}\,[T]$$

$$f_T(E_\nu) = \frac{\sum_{i=1}^n w_i(\Delta_i - E_\nu)\sqrt{(\Delta_i - E_\nu - m_e)(\Delta_i - E_\nu + m_e)}}{\sum_{i=1}^n w_i\sqrt{(\Delta_i - E_\nu - m_e)(\Delta_i - E_\nu + m_e)}}$$

fission process in a nuclear reactor



Reactor neutrino oscillations in WEFT



Reactor neutrino oscillations in WEFT

$$\boxed{\begin{aligned} P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde{\theta}_{13} - \alpha_D\frac{m_e}{E_e} - \alpha_P\frac{m_e}{f_T(E_\nu)}\right) \\ +\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})\left(\gamma_R + \beta_D\frac{m_e}{E_e} - \beta_P\frac{m_e}{f_T(E_\nu)}\right)\end{aligned}}$$

$$\alpha_D = \frac{g_S}{3g_A^2+1}\mathrm{Re}\,[S] - \frac{3g_Ag_T}{3g_A^2+1}\mathrm{Re}\,[T] \qquad \alpha_P = \frac{g_T}{g_A}\mathrm{Re}\,[T] \qquad \gamma_R = -\frac{2}{3g_A^2+1}\mathrm{Im}[R]$$

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

No dependence of survival probability on lepton-flavor diagonal Wilson coefficients

$$\mathscr{L}_{\mathrm{LY}}^{\mathrm{NR}} = -\frac{V_{ud}}{v^2}(\bar{\psi}_p\psi_n)\left\{(\bar{e}\gamma^0P_L\nu_e) + g_S\left[\epsilon_S\right]_{ee}(\bar{e}P_L\nu_e)\right\}$$
$$+\frac{V_{ud}}{v^2}(\bar{\psi}_p\sigma^k\psi_n)\left\{g_A(\bar{e}\gamma^0\sigma^kP_L\nu_e) - g_T\left[\epsilon_T\right]_{ee}(\bar{e}\sigma^kP_L\nu_e)\right\} + \mathrm{h.c.}$$

Reactor neutrino oscillations in WEFT

$$P_{\bar\nu_e\to\bar\nu_e} \approx 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde\theta_{13} - \alpha_D\frac{m_e}{E_e} - \alpha_P\frac{m_e}{f_T(E_\nu)}\right)$$
$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde\theta_{13})\left(\gamma_R + \beta_D\frac{m_e}{E_e} - \beta_P\frac{m_e}{f_T(E_\nu)}\right)$$

No dependence of survival probability on lepton-flavor diagonal Wilson coefficients

Dependence on $[\epsilon_S]_{ee}$ and $[\epsilon_T]_{ee}$ cancels in survival probability

$$P_{\bar\nu_e\to\bar\nu_e} = \frac{\sum_{k,l=1}^3 \exp\left(-i\frac{L(m_k^2-m_l^2)}{2E_\nu}\right)\int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D}{\int d\Pi'_P \sum_{k=1}^3 |\mathcal{M}_k^P|^2 \int d\Pi_D \sum_{l=1}^3 |\mathcal{M}_l^D|^2}$$

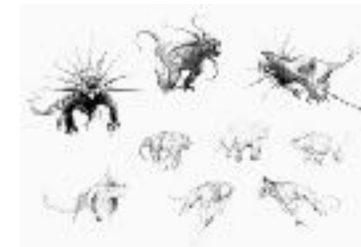
In any case, model-independent per-mille level on $[\epsilon_S]_{ee}$ and $[\epsilon_T]_{ee}$ from global fit

Gonzalez-Alonso, Camalich 1605.07114

But in does not cancel in (differential) rate, which is observable

$$\frac{dR}{dE_\nu} = \frac{1}{128\pi^4 L^2 m_N m_p}\sum_{k,l=1}^3 \exp\left(-i\frac{L(m_k^2-m_l^2)}{2E_\nu}\right)\int d\Pi'_P \mathcal{M}_k^P \bar{\mathcal{M}}_l^P \int d\Pi_D \mathcal{M}_k^D \bar{\mathcal{M}}_l^D$$

EFT ladder

Energy Scale	Theory	Particles	Expansion Parameter
Λ = ???	New Physics		?
1 TeV	SMEFT		$\frac{E}{\Lambda}$
100 GeV			
10 GeV	WEFT (aka Fermi theory, LEFT, WET)	γ,g,ν,e,μ,τ + N_f q	$\frac{E}{m_W}$
1 GeV			
100 MeV			
10 MeV			
1 MeV			

χPT $\frac{E}{4\pi f_\pi}$

γ,ν,e,μ,π,K

Lee-Yang $\frac{E_k}{m_p}$

p,n,e,ν,γ

…

Euler-Heisenberg $\frac{E}{m_e}$

γ,ν

Dimension-6 operators in SMEFT

Warsaw basis

Bosonic CP-even			
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\lvert H^\dagger D_\mu H\right\rvert^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$
O_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$
O_W	$\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_G	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Table 2.2: Bosonic D=6 operators in the Warsaw basis.

$(\bar{R}R)(\bar{R}R)$	
O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$	
$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$

$(\bar{L}R)(\bar{L}R)$	
O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu}q^k)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Table 2.4: Four-fermion D=6 operators in the Warsaw basis. Flavor indices are suppressed here to reduce the clutter. The factor η is equal to $1/2$ when all flavor indices are equal (e.g. in $[O_{ee}]_{1111}$), and $\eta=1$ otherwise. For each complex operator the complex conjugate should be included.

Yukawa	
$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

Vertex	
$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\bar{\sigma}_\mu\ell_J H^\dagger\overleftrightarrow{D}_\mu H$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\sigma^i\bar{\sigma}_\mu\ell_J H^\dagger\sigma^i\overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar{e}^c_J H^\dagger\overleftrightarrow{D}_\mu H$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I\bar{\sigma}_\mu q_J H^\dagger\overleftrightarrow{D}_\mu H$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I\sigma^i\bar{\sigma}_\mu q_J H^\dagger\sigma^i\overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar{u}^c_J H^\dagger\overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar{d}^c_J H^\dagger\overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar{d}^c_J\tilde{H}^\dagger D_\mu H$

Dipole	
$[O^\dagger_{eW}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O^\dagger_{eB}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O^\dagger_{uG}]_{IJ}$	$u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{uW}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{uB}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O^\dagger_{dG}]_{IJ}$	$d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{dW}]_{IJ}$	$d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{dB}]_{IJ}$	$d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Table 2.3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.

Full set has 2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014, Henning et al 1512.03433

What changes in SMEFT vs WEFT

Several dimension-6 SMEFT operators affecting left-handed WEFT NSI parameters

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

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

Right-handed NSI lepton-flavor diagonal at leading order !

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

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

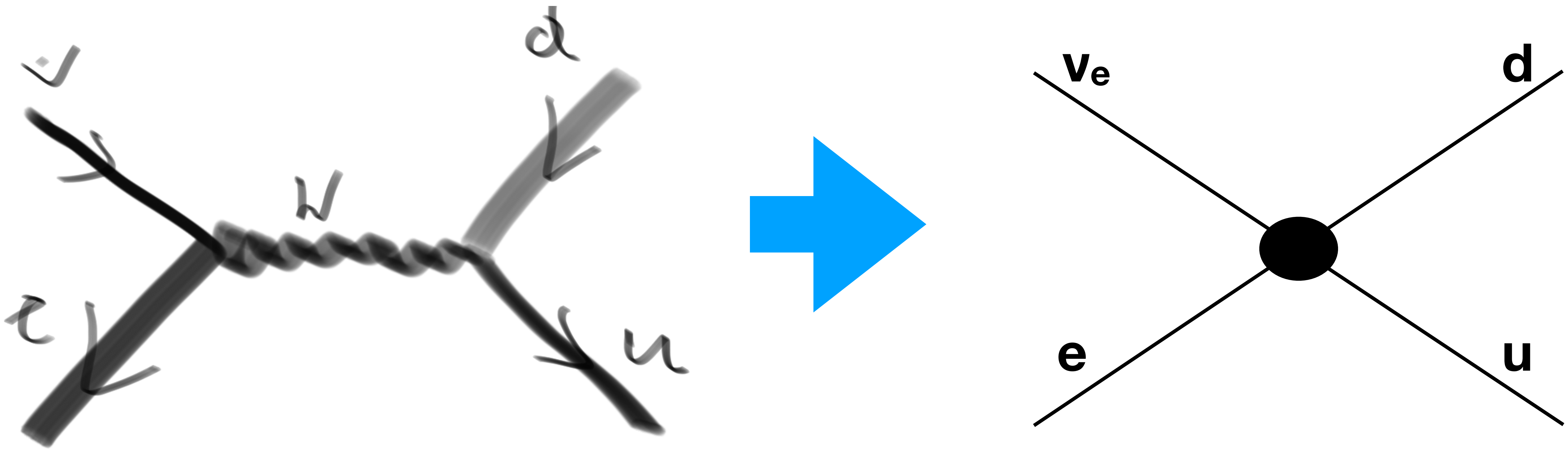
$$[\epsilon_T]_{\alpha\beta} = -\frac{2\mathrm{v}^2}{\Lambda^2 V_{ud}} V_{jd}[c_{lequ}^{(3)}]^*_{\beta\alpha j1}$$

For scalar, pseudoscalar, and tensor one-to-one mapping between dimension-6 SMEFT and WEFT NSI parameters

WEFT from SMEFT

In the SMEFT, at the level of dimension-6 operators, two types of effects leading to contact interactions between quarks and leptons at low-energies:

One is via W exchange, much as in the SM



Dimension-6 operators generate W coupling to right-handed quarks, in addition to the usual SM one to left-handed quarks

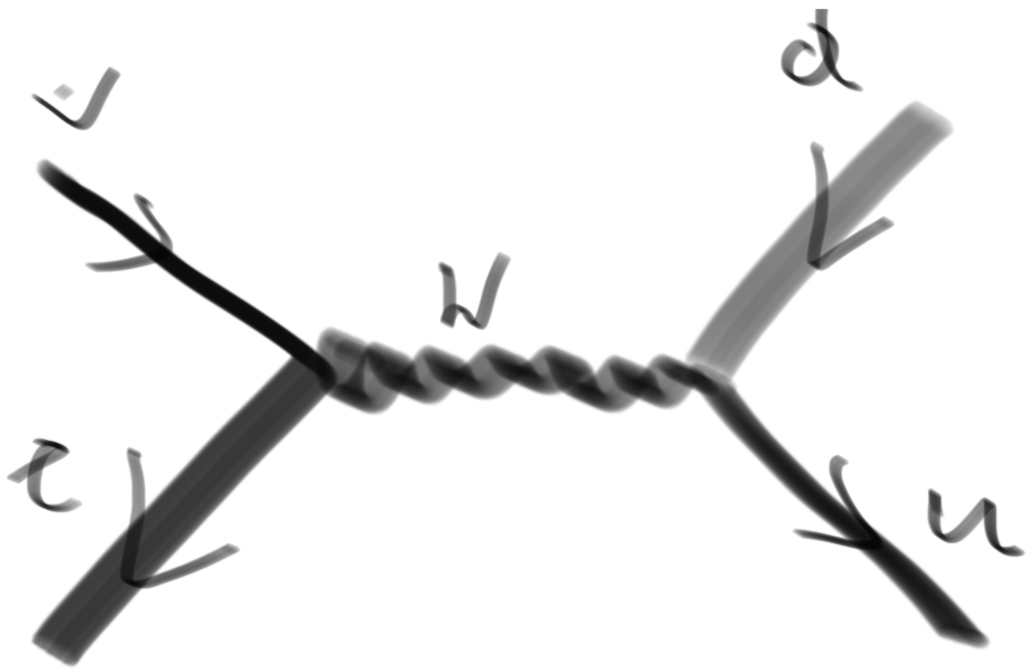
$$\mathscr{L}_{\rm SMEFT} \supset \frac{c_{Hud}}{\Lambda^2}(\tilde{H}^\dagger D_\mu H)(\bar{u}_R \gamma_\mu d_R) + \mathrm{h.c.} \longrightarrow \delta g_R^{Wq_1} = c_{Hud}\frac{\mathrm{v}^2}{2\Lambda^2}$$

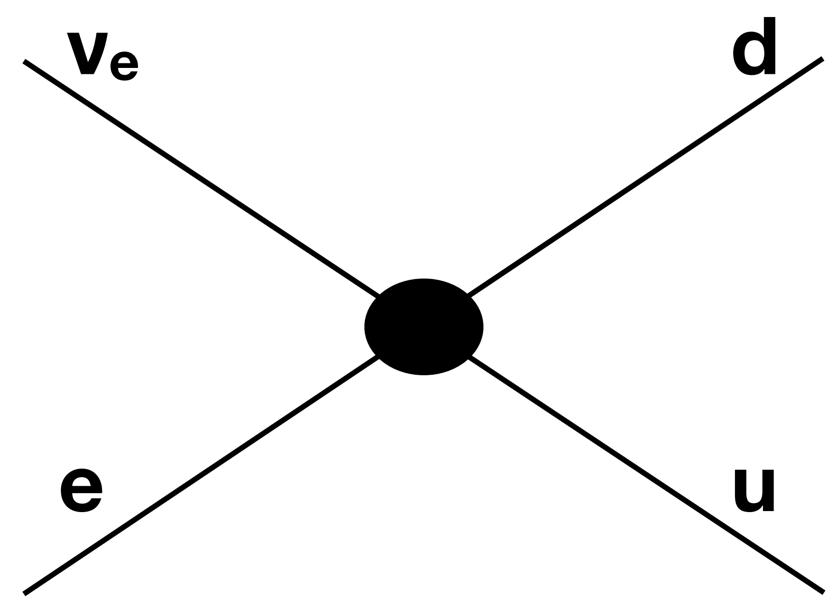
$$\mathscr{L}_{\rm SMEFT} \supset \frac{g_L}{\sqrt{2}} W^{\mu +}\left[\bar{\nu}_e \gamma_\mu (1 + \delta g_L^{We}) e_L + \bar{u}_L \gamma_\mu \left(V_{ud} + \delta g_L^{Wq_1}\right) d_L + \delta g_R^{Wq_1} \bar{u}_R \gamma_\mu d_R\right] + \mathrm{h.c.}$$

WEFT from SMEFT

In the SMEFT, at the level of dimension-6 operators, two types of effects leading to contact interactions between quarks and leptons at low-energies:

One is via W exchange, much as in the SM





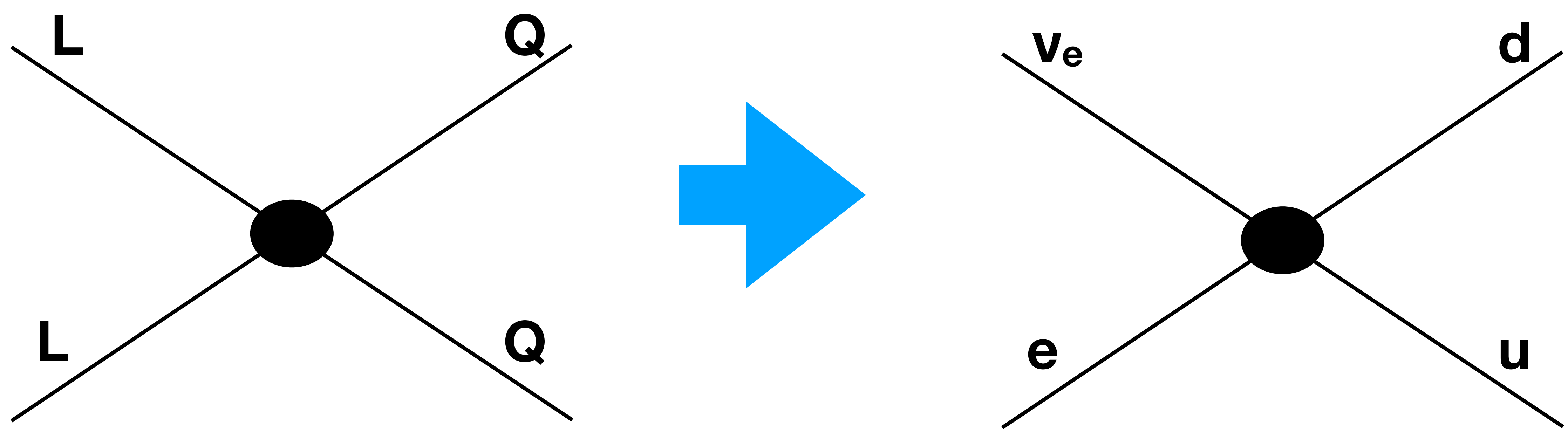
$$\mathscr{L}_{\mathrm{SMEFT}} \supset \frac{g_L}{\sqrt{2}} W^{\mu +} \left[\bar{\nu}_e \gamma_\mu (1 + \delta g_L^{We}) e_L + \bar{u}_L \gamma_\mu \left(V_{ud} + \delta g_L^{Wq_1} \right) d_L + \delta g_R^{Wq_1} \bar{u}_R \gamma_\mu d_R \right] + \mathrm{h.c.}$$

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\frac{g_L^2}{2m_W^2} \left[\bar{\nu}_e \gamma_\mu (1 + \delta g_L^{We}) e_L + \bar{u}_L \gamma_\mu \left(V_{ud} + \delta g_L^{Wq_1} \right) d_L + \delta g_R^{Wq_1} \bar{u}_R \gamma_\mu d_R \right]$$
$$\times \left[\bar{e}_L \gamma_\mu (1 + \delta g_L^{We}) \nu_e + \bar{d}_L \gamma_\mu \left(V_{ud} + \delta g_L^{Wq_1} \right) u_L + \left(\delta g_R^{Wq_1} \right)^* \bar{d}_R \gamma_\mu u_R \right]$$

WEFT from SMEFT

In the SMEFT, at the level of dimension-6 operators, two types of effects leading to contact interactions between quarks and leptons at low-energies:

The other is contact 4-fermion interactions in SMEFT



$$\mathscr{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2}\left[c_{lq}^{(3)}(\bar{L}\gamma_\mu\sigma^i L)(\bar{Q}\gamma^\mu\sigma^i Q) + c_{lequ}(\bar{L}e)(\bar{Q}u) + c_{ledq}(\bar{L}e)(\bar{d}Q) + c_{lequ}^{(3)}(\bar{L}\sigma_{\mu\nu}e)(\bar{Q}\sigma^{\mu\nu}u)\right]$$

Only left-handed, scalar, pseudoscalar, and tensor generated. None leads to right NSI!

Off-diagonal right-handed NSI generated only by dimension-8 SMEFT operators e.g.

$$\mathscr{L}_{\rm SMEFT} \supset (\bar{L}_\alpha H\gamma_\mu L H_\beta)(\bar{u}\gamma^\mu\sigma^i d)$$

Reactor neutrino oscillations in SMEFT

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

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

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

In SMEFT, simplified expression for effective mixing angle and for CP violating oscillations

All in all, short baseline reactor neutrino oscillations sensitive to 5 distinct linear combinations of dimension-6 SMEFT operators

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
$$|[\epsilon_P]_{e\alpha}|_{\mu=2\,\mathrm{GeV}} \leq 7.5 \times 10^{-6}\,.$$
$$\Big|[\epsilon_T]_{e\alpha} + 3 \times 10^{-4}[\epsilon_S]_{e\alpha}\Big|_{\mu=2\,\mathrm{GeV}} \leq 1.0 \times 10^{-3}$$
- 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 $\left|[\epsilon_S]_{e\mu}\right| \lesssim 3 \times 10^{-6}$
- $\tau \to e\,\pi\,\pi$ $\left|[\epsilon_S]_{e\tau}\right| \lesssim 4 \times 10^{-4}$

Summary

- EFTs offers a concise and efficient language to discuss low-energy precision measurement, including neutrino oscillations

- Reactor oscillation experiments can be interpreted as constraint on Wilson coefficients in the WEFT, leading to novel constraints on lepton-flavor-off-diagonal scalar, tensor, and right-handed charged currents involved in beta decays

- To my knowledge, neutrino oscillations are the only observables where these parameters can be probed at the linear level in WEFT Wilson coefficients

- Systematic EFT approach facilitates separating SM input parameters from genuinely observable effects of new physics

Summary

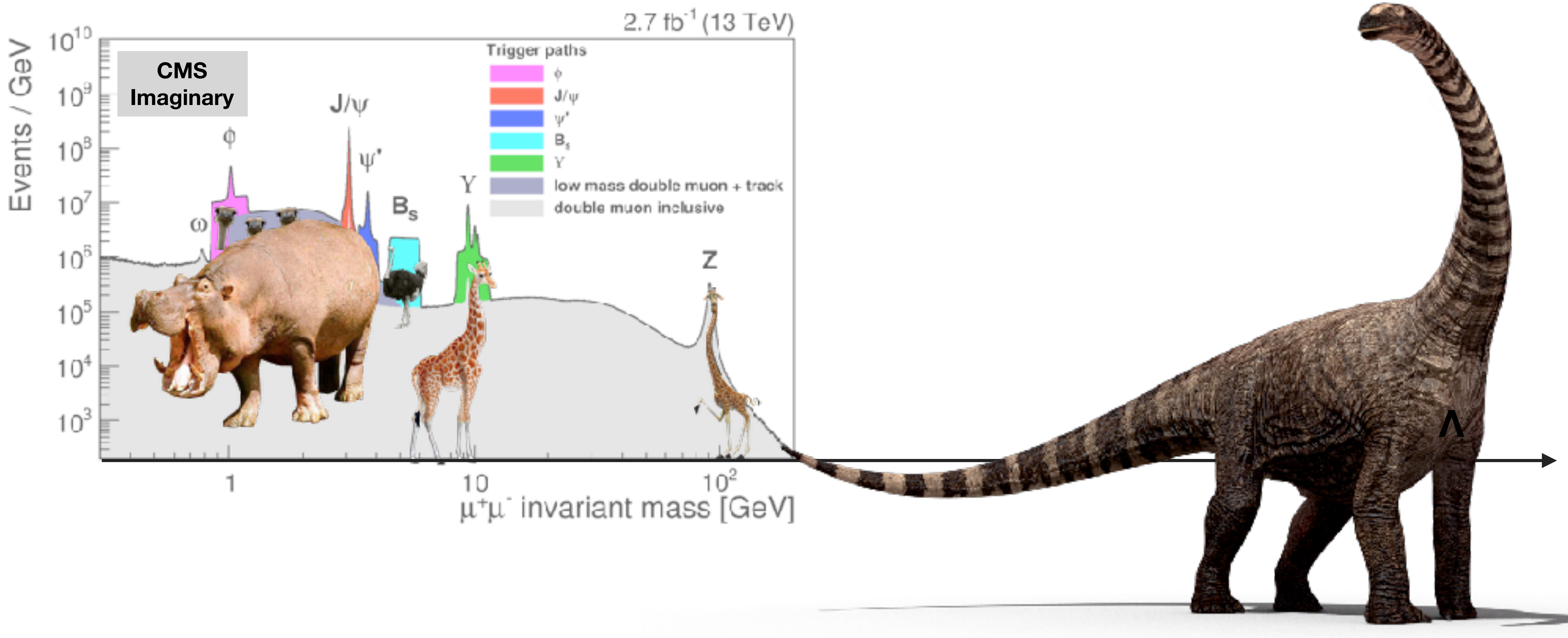
- Recast of current bounds from Daya Bay and RENO leads to percent level bounds on WEFT Wilson coefficients parametrizing scalar, tensor, and right-handed charged currents in beta decays.

- These can be improved in the future by more statistics, more targeted experimental analyses, and extension of the analysis to other types of neutrino oscillation experiments

- From the point of the WEFT, these are novel constraints on the parameter space, probing different linear combinations of parameters than other observables

- In concrete BSM models, there is a competition of constraints from CKM unitarity, beta decays, pion decays, LHC Drell-Yan ev production, charged lepton-flavor violation, which typically lead to stronger bounds than current oscillation experiments

Fantastic Beasts and Where To Find Them



THANK YOU