(Reactor) Neutrino oscillations as constraints on Effective Field Theory

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University of Campinas

Neutrino Platform Week 2019:

Hot Topics in Neutrino Physics

With Adam Falkowski and Martin Gonzalez-Alonso

Based on: JHEP 1905 (2019) 173, arXiv:1901.04553
and arXiv: 1910.XXXXX

The mass and flavor eigenstates do not coincide

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The coefficient of the linear combination of neutrino mass eigenstates that couple to each flavor eigenstate!

three mixing angles, θ_{12},θ_{13} and θ_{23} and one CP- violating phase δ_{cp}.

Oscillation probability in vacuum:

$$\Delta m^2_{kj} \equiv m^2_k - m^2_j$$

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2 \sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

What do we know?

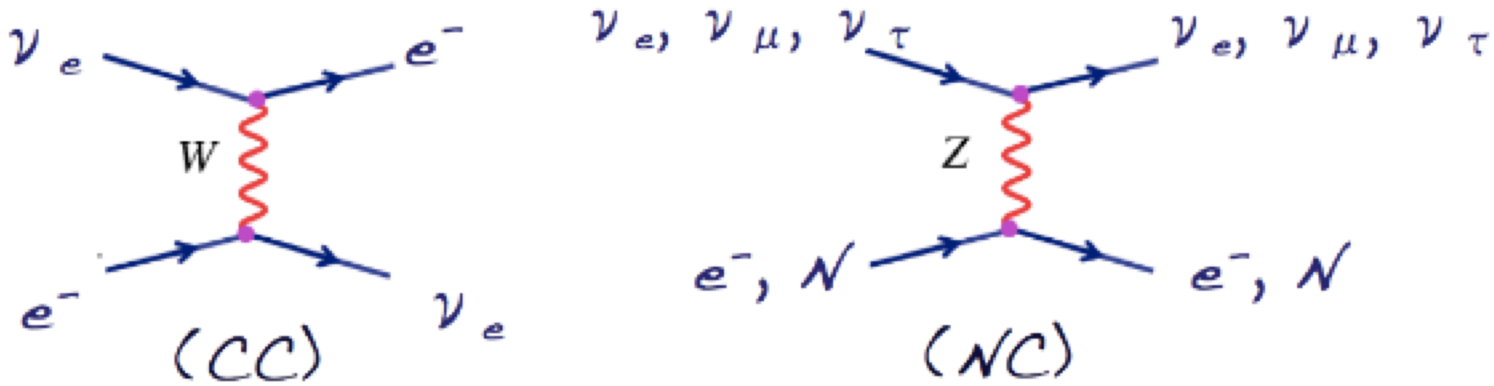
I.Esteban, M.C. Gonzalez-Garcia, A.Hernandez-Cabezudo, M. Maltoni, T.Schwetz
JHEP 01 (2019) 106

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

Oscillation experiments can become an ingredient in the broad program of precision measurements!

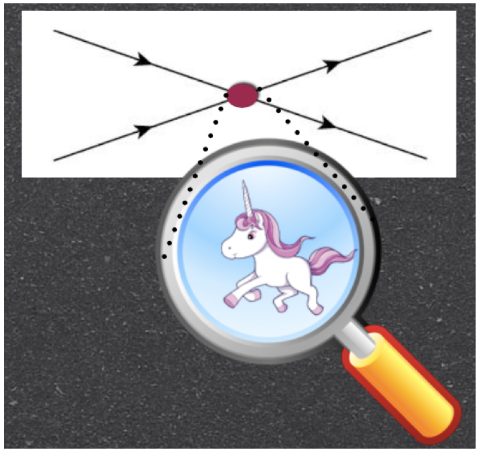
Oscillation experiments are sensitive not only to neutrino masses and mixing, but also to how neutrinos interact with matter.

- Coherent CC and NC forward scattering of neutrinos



New effective 4-fermion interactions between leptons and quarks may give observable effects in neutrino production, propagation, and detection.

We use EFT language to “systematically” explore new physics beyond the neutrino masses and mixing in neutrino experiments.



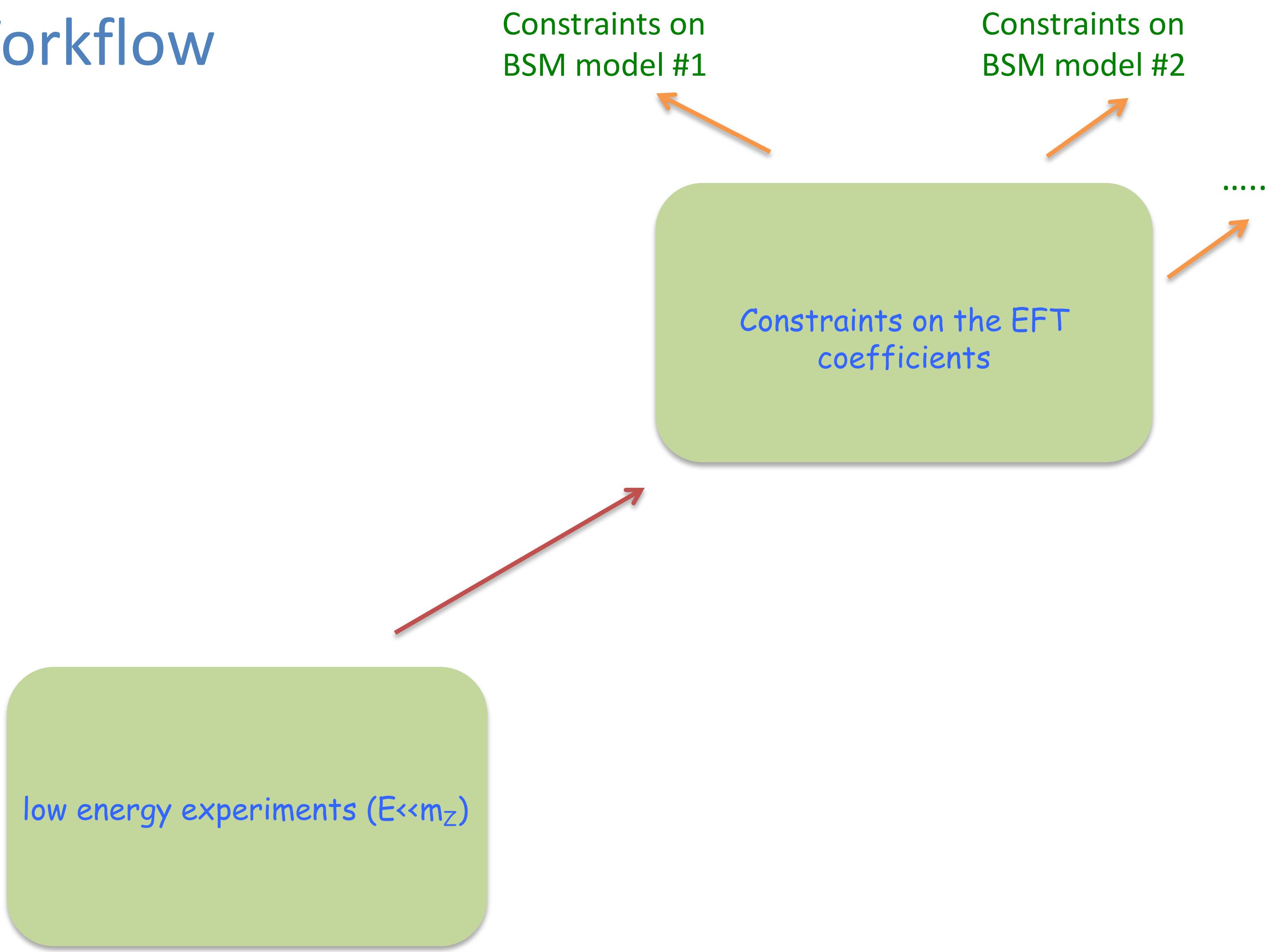
Why EFT?

- 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.

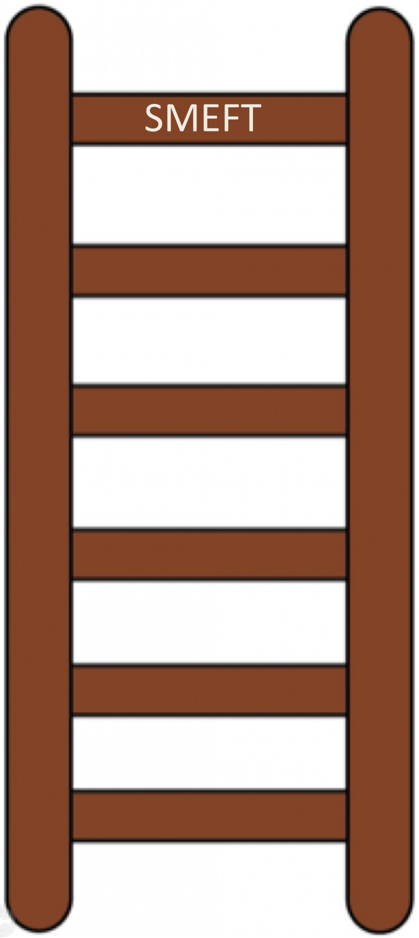
- Results obtained in the language of EFT can be easily translated into constraints on any particular new physics model.

Workflow


Constraints on BSM model #1
Constraints on BSM model #2
.....
Constraints on the EFT coefficients
low energy experiments (E<<m_Z)

EFT ladder

$E > m_Z$



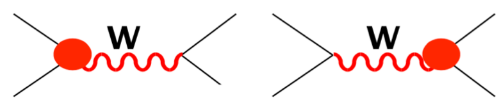
- If BSM particles are much heavier than the Z mass and the EWSB is linearly realized, then the relevant effective theory above the weak scale is the so-called SMEFT.

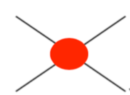
- It has the same particle content and local symmetry as the SM, but differs by the presence of higher-dimensional (non-renormalizable) interactions in the Lagrangian.

$$\mathcal{L}_{\mathrm{SM\ EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_L}\mathcal{L}^{D=5} + \boxed{\frac{1}{\Lambda^2}\mathcal{L}^{D=6}}$$

- The SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way

+

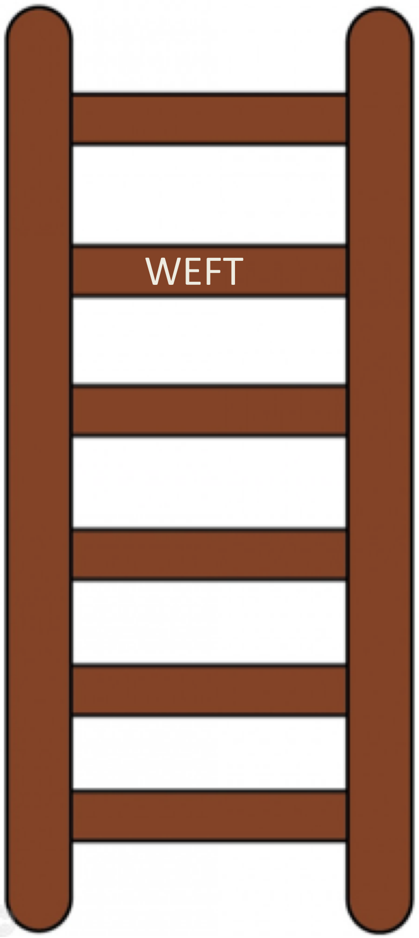




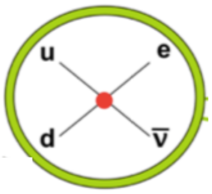
$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \mathrm{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \mathrm{h.c.}$$
$$O_{lq}^t = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \mathrm{h.c.}$$

EFT ladder

$E \ll m_Z$



- In particular, focusing on reactor experiments, only CC interactions are relevant.



- At this scale heavy particles such as W and Z bosons, Higgs and top can be integrated out from the SMEFT, leading to Weak EFT (WEFT).

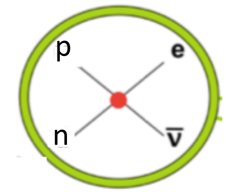
$$\begin{aligned}\mathcal{L}_{\rm WEFT} \supset & -\frac{2V_{ud}}{v^2}\{\, [\mathbf{1}+\epsilon_L]_{\alpha\beta}\,(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\ & +[\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\ & +\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L\nu_\beta) \\ & +\frac{1}{4}[\hat{\epsilon}_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\}\end{aligned}$$

- Apart from the SM-like V-A interactions ($1+\varepsilon_L$), right-handed (ε_R), scalar (ε_S), pseudoscalar (ε_P), and tensor (ε_T) interactions are allowed.

EFT ladder

$E \ll m_Z$

- At the energy scale of reactor neutrino experiments the relevant degrees of freedom are not quarks, but nucleons and nuclei. Matching this EFT to the WEFT Lagrangian we obtain the Lee-Yang Lagrangian:



$$\begin{aligned}
\mathcal{L}_{\rm LY} \supset\; & -\frac{V_{ud}}{v^2}\{g_V\,[\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& - g_A\,[\mathbf{1}+\epsilon_L-\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu\gamma_5 n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& + g_S[\epsilon_S]_{\alpha\beta}(\bar{p}n)(\bar{\ell}_\alpha P_L\nu_\beta) - g_P[\epsilon_P]_{\alpha\beta}(\bar{p}\gamma_5 n)(\bar{\ell}_\alpha P_L\nu_\beta) \\
& + \frac{1}{2}g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{p}\sigma^{\mu\nu}P_L n)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\},
\end{aligned}$$

- Lattice+theory fix the non-perturbative parameters with good precision

$$g_A = 1.2728 \pm 0.0017, \quad g_S = 1.02 \pm 0.11, \quad g_P = 349 \pm 9, \quad g_T = 0.987 \pm 0.055.$$

- T. Bhattacharya et al, Phys. Rev. D94 (2016), no. 5 054508
- M. Gonzalez-Alonso and J. Martin Camalich, Phys. Rev. Lett. 112 (2014), no. 4 042501
- M. Gonzalez-Alonso et al, Prog. Part. Nucl. Phys. 104 (2019) 165–223

EFT ladder

E << m_Z

- Leading order non-relativistic Lagrangian for nucleons

$$\mathcal{L}_{\rm NRLY} \supset -\frac{V_{ud}}{v^2}(\bar{\psi}_p\psi_n)\{[\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}(\bar{\ell}_\alpha\gamma^0 P_L\nu_\beta)+g_S[\epsilon_S]_{\alpha\beta}(\bar{\ell}_\alpha P_L\nu_\beta)\}$$
$$+\frac{V_{ud}}{v^2}(\bar{\psi}_p\sigma^k\psi_n)\{g_A[\mathbf{1}+\epsilon_L-\epsilon_R]_{\alpha\beta}(\bar{\ell}_\alpha\gamma^0\sigma^k P_L\nu_\beta)-g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{\ell}_\alpha\sigma^k P_L\nu_\beta)\}+\text{h.c.}$$

NR proton and neutron fields

No dependence on ε_P!

- At leading order, only two nuclear matrix eleme are needed (corresponding to Fermi and Gamow-Teller transitions)

$$M_{\rm F} \equiv \langle N'|\bar{\psi}_p\psi_n|N\rangle$$ **Fermi matrix element**

$$M^k_{\rm GT} \equiv \langle N'|\bar{\psi}_p\sigma^k\psi_n|N\rangle$$ **Gamow-Teller matrix element**

EFT ladder

$E \ll m_Z$

- Leading order non-relativistic Lagrangian for nucleons

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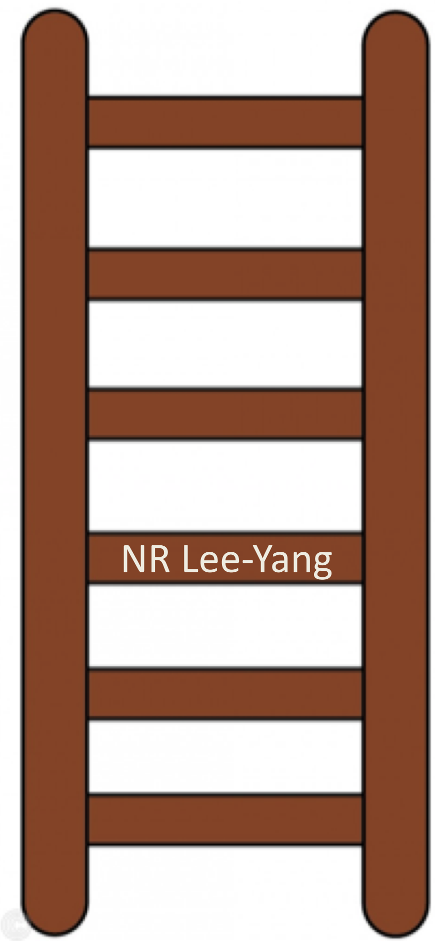
EFT ladder

$E \ll m_Z$



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$$\mathcal{L}_{\rm NRLY} \supset -\frac{V_{ud}}{v^2}(\bar{\psi}_p \psi_n)\{ [\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}(\bar{\ell}_\alpha \gamma^0 P_L \nu_\beta) + g_S[\epsilon_S]_{\alpha\beta}(\bar{\ell}_\alpha P_L \nu_\beta)\}$$
$$\frac{V_{ud}}{v^2}(\bar{\psi}_p \sigma^k \psi_n)\{ g_A [\mathbf{1}+\epsilon_L-\epsilon_R]_{\alpha\beta}(\bar{\ell}_\alpha \gamma^0 \sigma^k P_L \nu_\beta) - g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{\ell}_\alpha \sigma^k P_L \nu_\beta)\} + \text{h.c.}$$

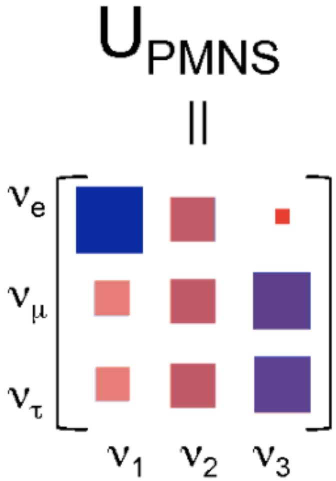
NR proton and neutron fields

The same effective interactions at neutrino experiments also affect the phenomenological extraction of V_{ud} and g_A

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

Dependence on diagonal BSM parameters $[\varepsilon_L]_{ee}$ and $[\varepsilon_R]_{ee}$ is absorbed into phenomenological values of SM parameters. These parameters are totally “unobservable” in reactor oscillation experiments!

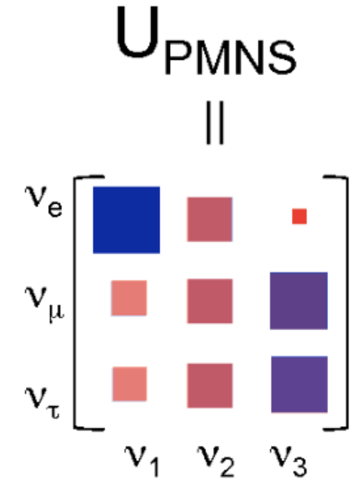
Oscillations in EFT



Oscillation in the SM:

$$P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}(L, E) = \sum_{k,j} U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

Oscillations in EFT



Oscillation in the SM:

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Oscillation in EFT:

$$P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}(L, E_\nu) = \sum_{JK} C^\alpha_{JK} \exp\left(-i \frac{\Delta m^2_{JK} L}{2E_\nu}\right), \qquad C^\alpha_{JK} \equiv \frac{(\int A^P_{\alpha J} A^{P*}_{\alpha K})(\int A^D_{J\alpha} A^{D*}_{K\alpha})}{\left(\sum_I \int |A^P_{\alpha I}|^2\right)\left(\sum_{I'} \int |A^D_{I'\alpha}|^2\right)}$$

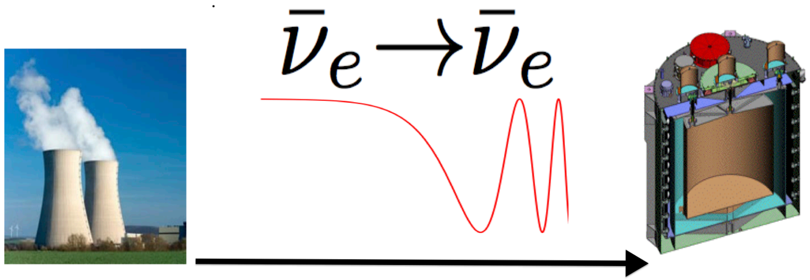
$$\begin{aligned} C^\alpha_{JK} &= U_{\alpha J} U^\dagger_{K\alpha} U_{\alpha K} U^\dagger_{J\alpha} \\ &+ U_{\alpha K} U^\dagger_{J\alpha} \sum_{X=L,R,S,P,T} \sum_{\gamma \neq \alpha} \left\{ p_X [\epsilon_X]_{\alpha\gamma} U_{\gamma J} U^\dagger_{K\alpha} + p^*_X U_{\alpha J} U^\dagger_{K\gamma} [\epsilon^\dagger_X]_{\gamma\alpha} \right\} \\ &+ U_{\alpha J} U^\dagger_{K\alpha} \sum_{X=L,R,S,P,T} \sum_{\gamma \neq \alpha} \left\{ d^*_X [\epsilon_X]_{\alpha\gamma} U_{\gamma K} U^\dagger_{J\alpha} + d_X U_{\alpha K} U^\dagger_{J\gamma} [\epsilon^\dagger_X]_{\gamma\alpha} \right\} + \mathcal{O}(\epsilon^2_X) \end{aligned}$$

$$p_X \equiv \frac{\int M^P_X M^{P*}_L}{\int |M^P_L|^2}, \qquad d_X \equiv \frac{\int M^D_X M^{D*}_L}{\int |M^D_L|^2}$$

$$A^P_{\alpha J} = U_{\alpha J} M^P_L + \sum_{X=L,R,S,P,T} [\epsilon_X U]_{\alpha J} M^P_X, \qquad A^D_{J\alpha} = U^\dagger_{J\alpha} M^D_L + \sum_{X=L,R,S,P,T} [U^\dagger \epsilon^\dagger_X]_{J\alpha} M^D_X$$

EFT in reactor experiments: Detection

Detection Through IBD Process:



$$p^+ + \bar{\nu}_e \to e^+ + n^0$$

Neutrino energy:

$$E_\nu \sim E_{\rm prompt} + 0.78 \text{ MeV}$$

Starting from the non-relativistic effective Lagrangian:

$$d_L \equiv 1, \quad d_R = -\frac{3g_A^2 - 1}{3g_A^2 + 1}, \quad d_S = -\frac{g_S}{3g_A^2 + 1}\frac{m_e}{E_\nu - \Delta}, \quad d_T = \frac{3g_A g_T}{3g_A^2 + 1}\frac{m_e}{E_\nu - \Delta}, \quad d_P = 0$$

depend on neutrino energy

$$\Delta \equiv m_n - m_p \approx 1.29 \text{ MeV}$$

EFT in reactor experiments: Production

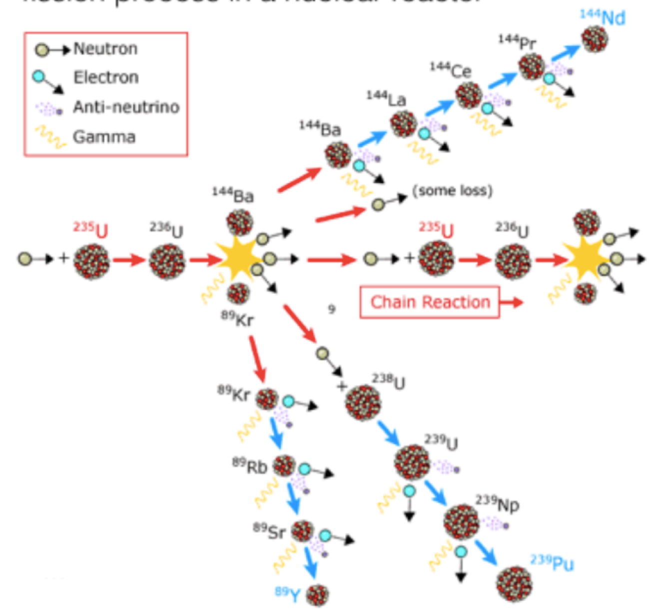
Hundreds of different beta decay processes contribute to the antineutrino flux in the reactor

We assume all beta decays contributing to the reactor antineutrino flux above the detection threshold E_ν=1.8 MeV are of the Gamow-Teller type (In fact only 70% are GT!)

A. C. Hayes et al, Ann. Rev. Nucl. Part. Sci. 66 (2016) 219–244,

Also Ana's talk yesterday

fission process in a nuclear reactor



$$p_L \equiv 1, \qquad p_R = -1, \qquad p_S \approx 0, \qquad p_P \approx 0, \qquad p_T = -\frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}$$

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

EFT in reactor experiments

The survival probability in the SM + (V-A):

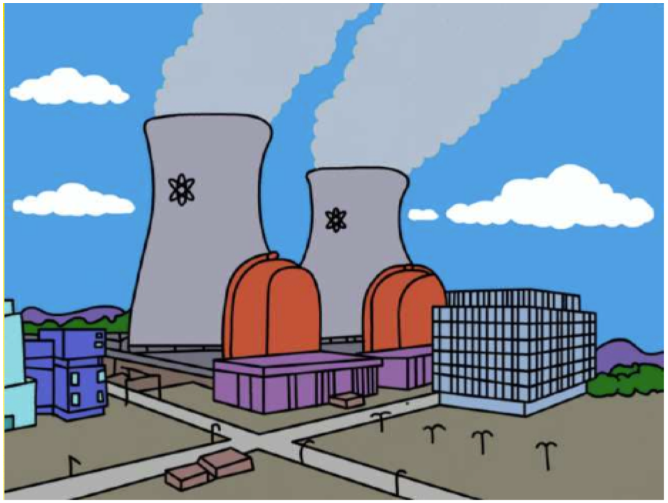
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \sin^2\left(2\tilde{\theta}_{13}\right)$$

No sensitivity to V-A NSI!!! It can be absorbed into a redefinition of the PMNS mixing angle θ_{13} into the effective mixing angle $\tilde{\theta}_{13}$!

$$\tilde{\theta}_{13} = \theta_{13} + \mathrm{Re}\,[L]$$

T. Ohlsson and H. Zhang, Phys. Lett. B671 (2009) 99–104,

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



EFT in reactor experiments

The survival probability in the SM+ (V-A) + Scalar + Tensor:

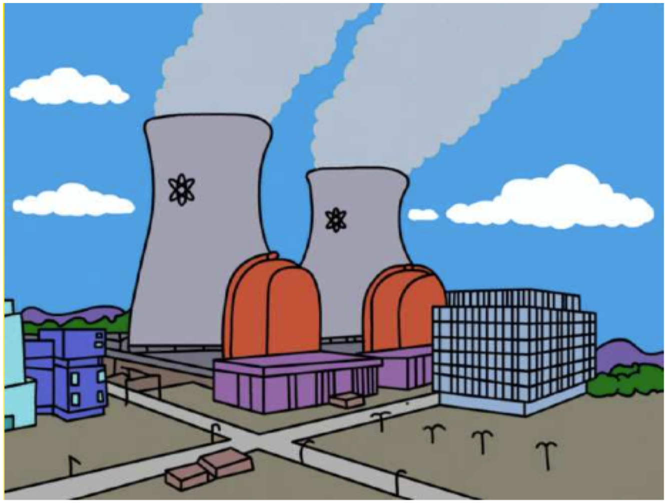
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde{\theta}_{13} - \alpha_D \frac{m_e}{E_\nu - \Delta} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right)$$
$$+ \sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})\left(\beta_D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

New Physics at the production side: only tensor interaction is present!!

$$\tilde{\theta}_{13} = \theta_{13} + \text{Re}\,[L]$$

$$\alpha_D = \frac{g_S}{3g_A^2+1}\text{Re}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\text{Re}\,[T]\,, \qquad \alpha_P = \frac{g_T}{g_A}\text{Re}\,[T]$$
$$\beta_D = \frac{g_S}{3g_A^2+1}\text{Im}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\text{Im}\,[T]\,, \qquad \beta_P = \frac{g_T}{g_A}\text{Im}\,[T]$$

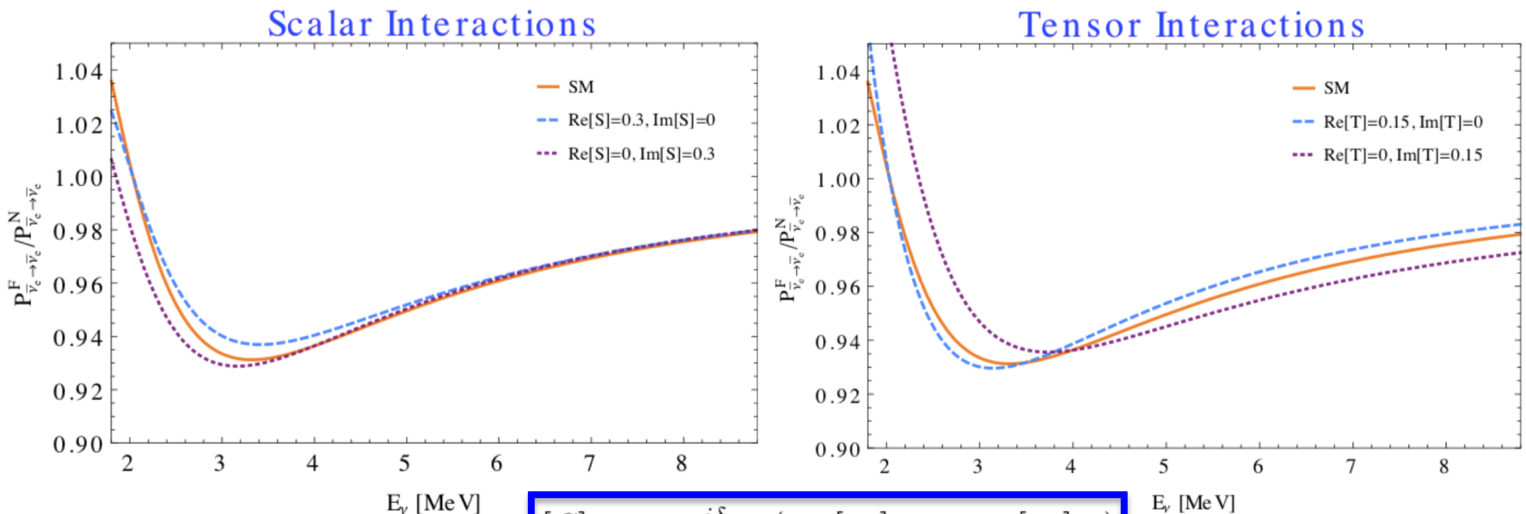
$$[L] \equiv e^{i\delta_{CP}}\left(s_{23}[\epsilon_L]_{e\mu} + c_{23}[\epsilon_L]_{e\tau}\right)$$
$$[S] \equiv e^{i\delta_{CP}}\left(s_{23}[\epsilon_S]_{e\mu} + c_{23}[\epsilon_S]_{e\tau}\right)$$
$$[T] \equiv e^{i\delta_{CP}}\left(s_{23}[\hat{\epsilon}_T]_{e\mu} + c_{23}[\hat{\epsilon}_T]_{e\tau}\right)$$



EFT in reactor experiments

The survival probability in the SM+ (V-A) + Scalar + Tensor:

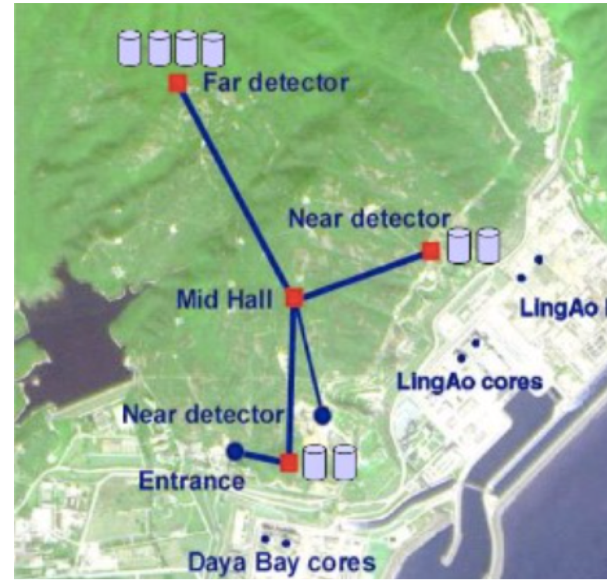
$$
\begin{aligned}
P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E_\nu) &= 1-\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde{\theta}_{13}-\alpha_D\frac{m_e}{E_\nu-\Delta}-\alpha_P\frac{m_e}{f_T(E_\nu)}\right)\\
&+ \sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})\left(\beta_D\frac{m_e}{E_\nu-\Delta}-\beta_P\frac{m_e}{f_T(E_\nu)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



$$
\begin{aligned}
[S] &\equiv e^{i\delta_{CP}}\left(s_{23}[\epsilon_S]_{e\mu}+c_{23}[\epsilon_S]_{e\tau}\right)\\
[T] &\equiv e^{i\delta_{CP}}\left(s_{23}[\hat{\epsilon}_T]_{e\mu}+c_{23}[\hat{\epsilon}_T]_{e\tau}\right)
\end{aligned}
$$

The effect of both scalar and tensor interactions is to shift the amplitude and also distort the E_ν spectrum due to the different energy dependence of the scalar and tensor interactions.

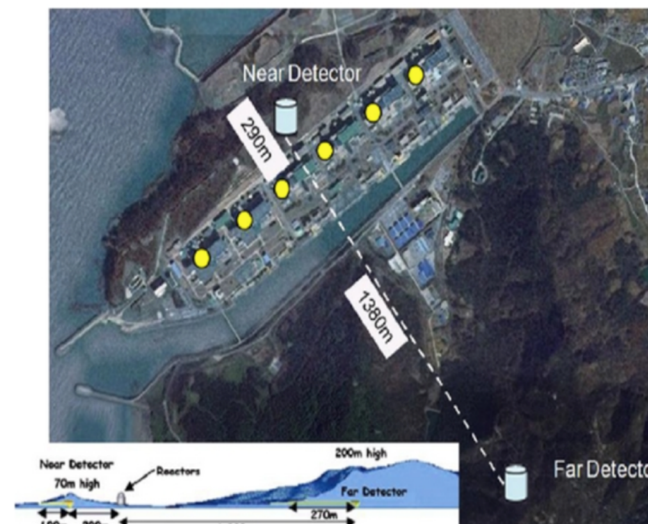
Setting EFT bounds at Daya Bay and RENO



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.

RESULTS

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

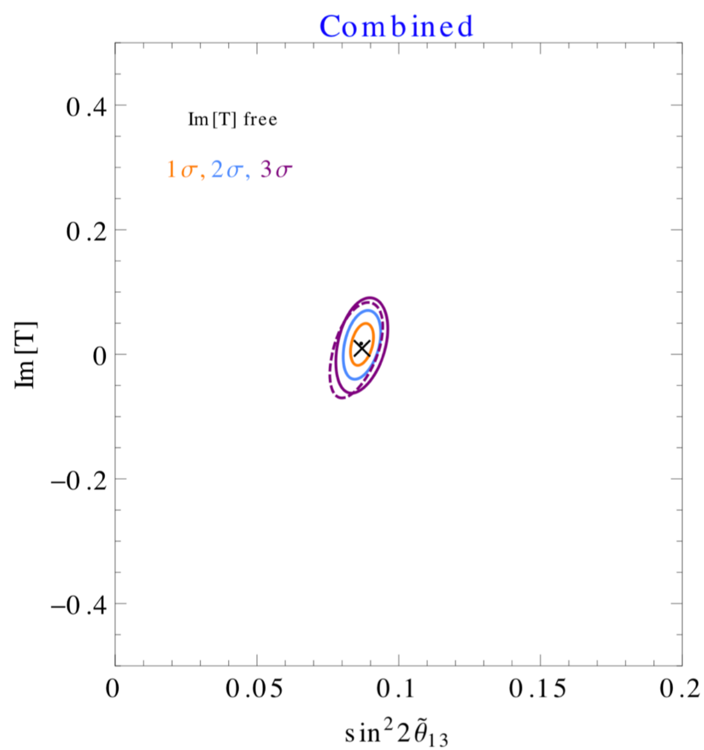
$$\tilde{\theta}_{13}=\theta_{13}+\text{Re}\,[L]$$

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

Tensor: $\hat{\epsilon}_T\neq 0,\ \epsilon_{R,S,P}=0$

$$\text{Re}\,[T]=-0.26\pm 0.14\,,\qquad \text{Im}\,[T]=-0.034\pm 0.042$$

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



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Scalar: $\epsilon_S\neq 0,\ \epsilon_{R,P,T}=0$

$$\text{Im}\,[S]=0.08\pm0.14$$

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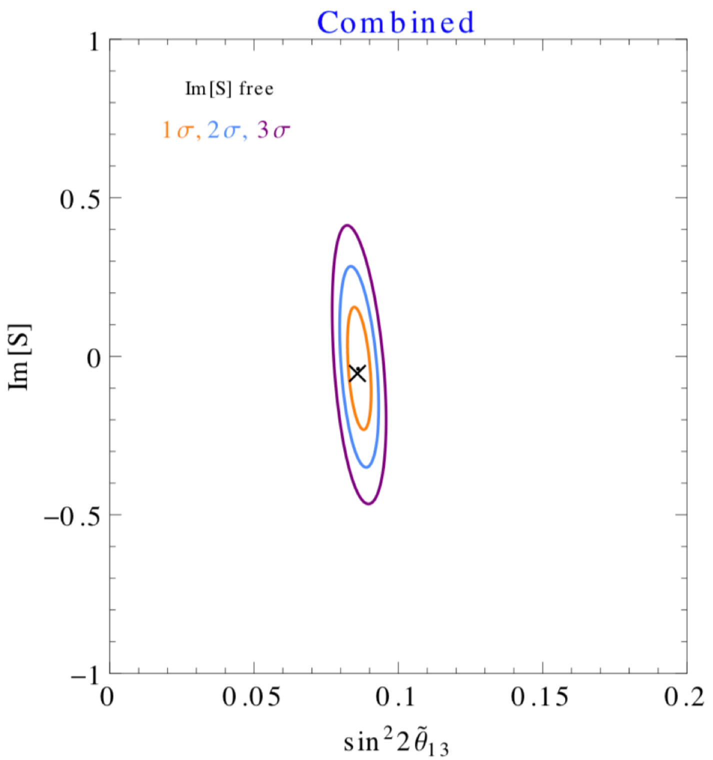
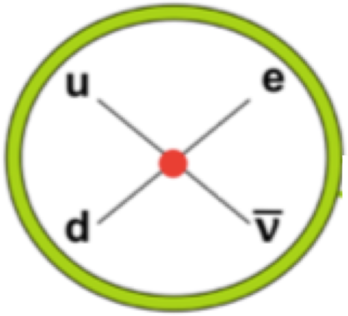


Non-oscillation constraints on EFT parameters

- Neutron and nuclear beta decay

One expects strong bounds on NSI involving wrong-flavor neutrinos from such studies, which has been used sometimes in the past as an argument to neglect e.g. scalar and tensor interactions. However, to best of our knowledge, all available beta-decay analyses focused on interactions involving electron neutrinos.



J. Kopp, M. Lindner, T. Ota, and J. Sato, Phys. Rev. D77 (2008) 013007

The bounds on tensor/scalar off-diagonals was never derived before

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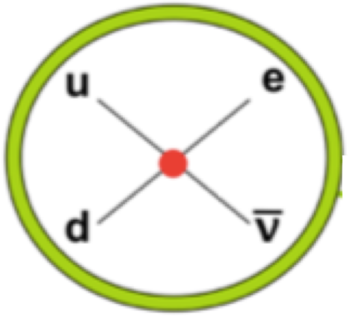

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- CKM unitarity

$$|V_{ud}^{unit.}| \equiv \left(1 - |V_{us}|^2 - |V_{ub}|^2\right)^{1/2}$$

Significant correlation between the scalar coupling and $|V_{ud}|$

$$|[\epsilon_S]_{e\alpha}| \leq 2.0 \times 10^{-2} \; (90\% \, \mathrm{CL})$$

Non-oscillation constraints on EFT parameters

- LHC

Looking at the Drell-Yan process pp→e+MET+X and neglecting dim-8 operators:

$$\left(\sum_\alpha |[\epsilon_S]_{e\alpha}|^2\right)^{1/2} \lesssim 2\times 10^{-3}\,, \qquad \left(\sum_\alpha |[\hat{\epsilon}_T]_{e\alpha}|^2\right)^{1/2} \lesssim 2\times 10^{-3}$$

The bounds might be invalid!!!

R. Gupta et al, Phys. Rev. D98 (2018) 034503, [arXiv:1806.09006

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- Charged-lepton-flavor violation

Neutrino interactions parametrized by off-diagonal $[\varepsilon_X]_{e\alpha}$ appear in the Lagrangian together with 4-fermion charged-lepton-flavor violating (CLFV) interactions.

$$|[\epsilon_S]_{e\mu}| \lesssim 3 \times 10^{-6} \qquad\qquad |[\epsilon_S]_{e\tau}| \lesssim 4 \times 10^{-4}$$

No constraints at the tree level on tensor couplings

The CLFV constraints would not hold if the WEFT were not UV-completed by the SMEFT, as the off-diagonal ε_X are not correlated in general with CLFV interactions!

Comparing QM and QFT

Neutrinos are not pure flavor states in QM approach:

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle \ , \quad \langle\nu_\beta^d| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N_\beta^d}$$

The probability are given by

$$P_{\nu_\alpha^s\to\nu_\beta^d} = |\langle\nu_\beta^d| e^{-iHL} |\nu_s^\alpha\rangle|^2$$
$$= \left|\left[(1+\epsilon^d)^T e^{-iHL}(1+\epsilon^s)^T\right]_{\beta\alpha}\right|^2$$

A. Falkowski, M Gonzalez, ZT
arXiv:1910.XXXXX
(tomorrow!)

- Can one "validate" this approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?

At *linear order* in NP, yes!

$$\epsilon^s_{\alpha\beta} = \sum_X p_{XL}[\epsilon_X]^*_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL}[\epsilon_X]_{\alpha\beta}$$

$$p_{XY} \equiv \frac{\int d\Pi_{P'} A_X^P \bar{A}_Y^P}{\int d\Pi_{P'} |A_L^P|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A_X^D \bar{A}_Y^D}{\int d\Pi_D |A_L^D|^2}$$

p_{XL} and d_{XL} are production and detection coefficients in QFT

Comparing QM and QFT

Examples:

A. Falkowski, M Gonzalez, ZT
arXiv:1910.XXXXX

Neutrino Process	**NSI Matching with EFT**
ν_e produced in beta decay	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
ν_e detected in inverse beta decay	$\epsilon^d_{\beta e} = [\epsilon_L]_{e\beta} + \frac{1-3g_A^2}{1+3g_A^2}[\epsilon_R]_{e\beta} - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}[\epsilon_S]_{e\beta} - \frac{3g_A g_T}{1+3g_A^2}[\epsilon_T]_{e\beta}\right)$
ν_μ produced in pion decay	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

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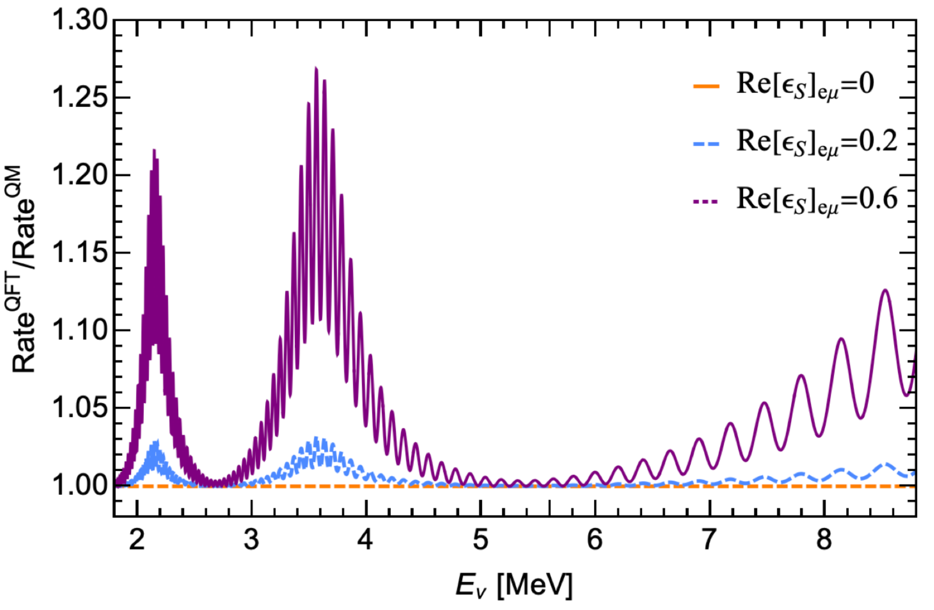
Beyond linear level the QM approach fails in general!

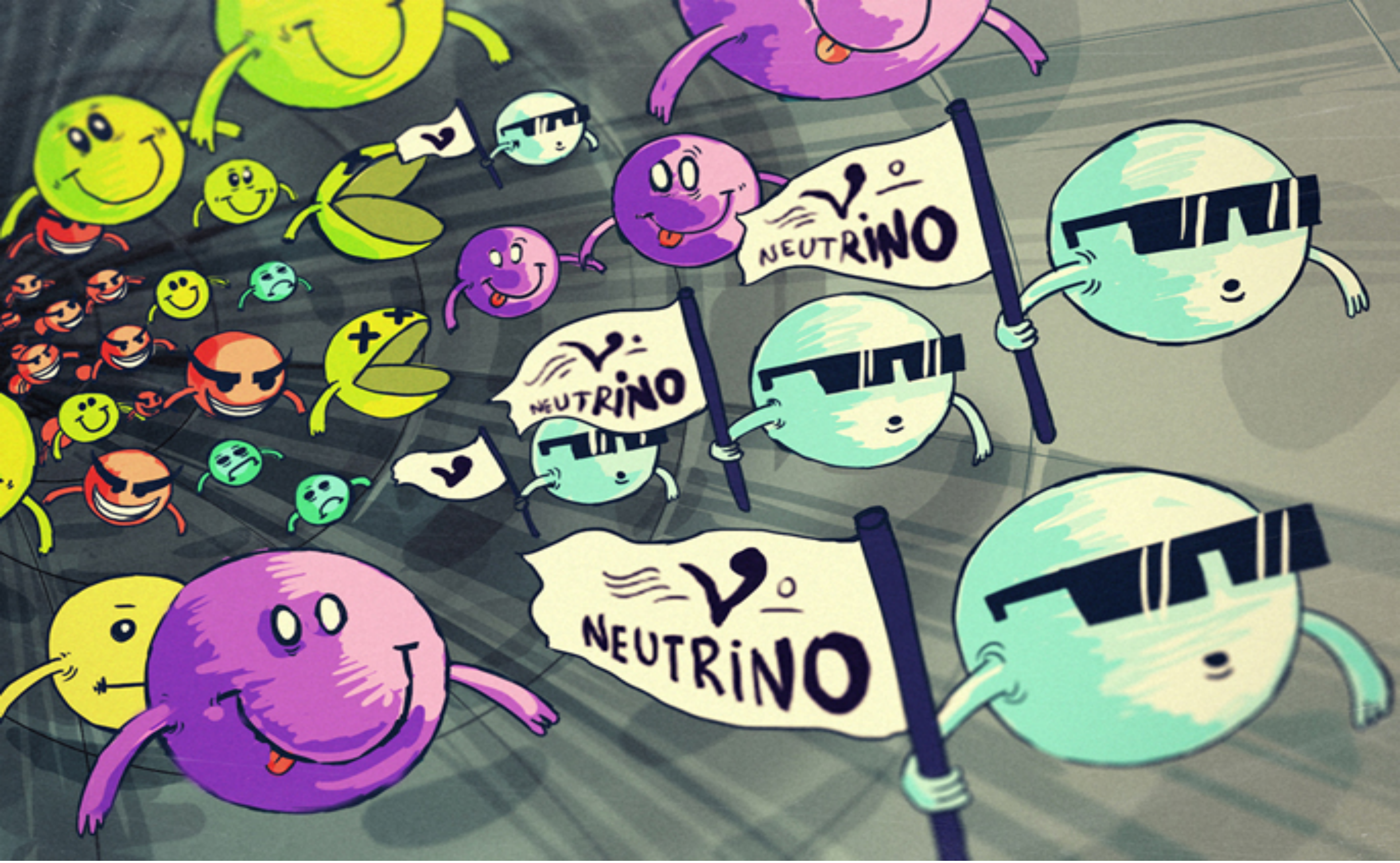
We can compare the QFT and QM rates at all orders.

e.g. at KamLAND experiment:



Conclusion:

- We have proposed a systematic approach to neutrino oscillations in the SMEFT framework.
- We applied the formalism to oscillations in short-baseline reactor experiments, however the formalism can be readily extended to other types of neutrino experiments.
- Corrections to the survival probability due to lepton-flavor off-diagonal V-A interactions ($[\epsilon_L]_{e\alpha}$) can be absorbed into a redefinition of the mixing angle θ_{13}.
- As of today, constraints at a few percent level can be extracted from the publicly available reactor experiment data.
- We give matching between EFT Wilson coefficients and NSI parameters, and discuss the conditions this matching is correct.



Thanks for your attention