Neutrino oscillations as constraints on Effective Field Theory

Fermi National Accelerator Laboratory

Theory Seminar

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Virginia Tech

1st October 2020

VIRGINIA TECH

Based on:

1- **“Consistent QFT description of non-standard neutrino interactions”,**
A. Falkowski, M. González-Alonso and Z. Tabrizi,
JHEP (2020) [arXiv:1910.02971 [hep-ph]].

2- **“Reactor neutrino oscillations as constraints on Effective Field Theory”,**
A. Falkowski, M. González-Alonso and Z. Tabrizi,
JHEP **1905**, 173 (2019) [arXiv:1901.04553 [hep-ph]].

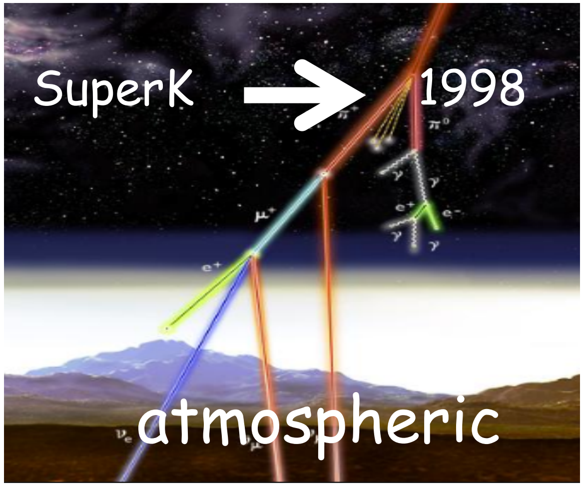
3- **“Non-Standard Neutrino Interactions at FASERν”,**
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq and Z. Tabrizi,
[arXiv:2010.XXXXX [hep-ph]].

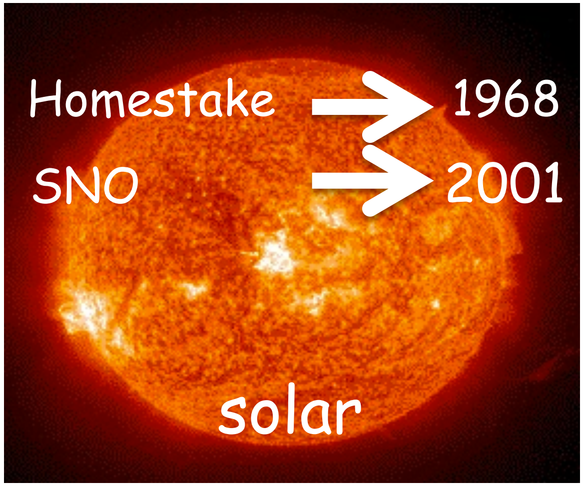
Outline

- Why EFT?
- EFT ladder
- EFT at neutrino oscillation experiments
  - Reactor experiments
  - FASERν
- Non-Oscillation experiments
- Conclusion

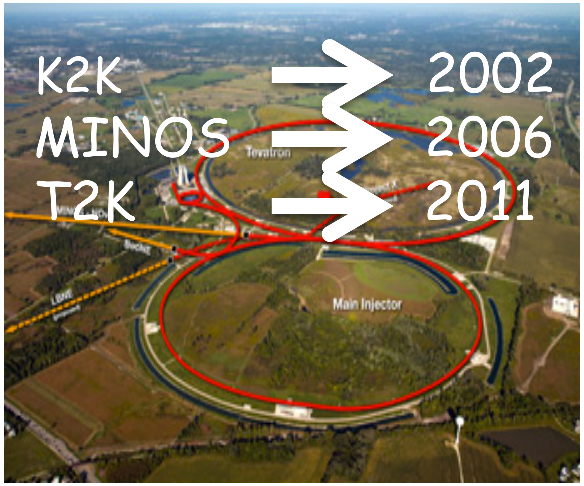
Neutrinos are massless in the SM!

However in nature.....





Neutrino oscillation needs masses and mixing!



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:

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

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

What do we know?

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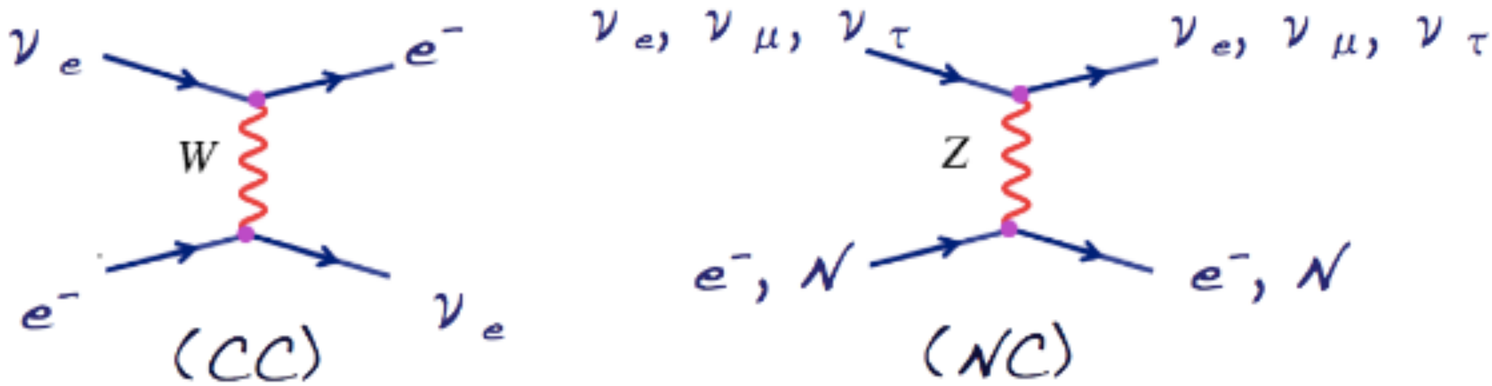
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$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

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

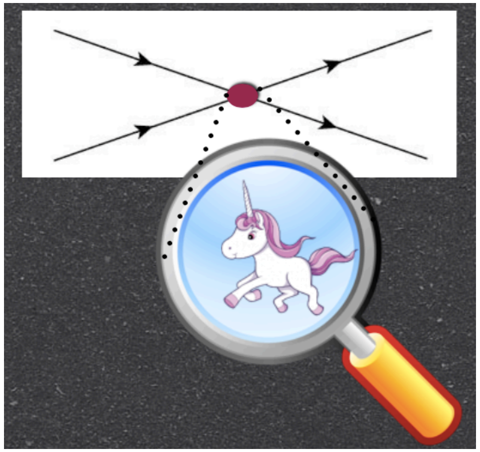
Oscillation experiments are sensitive not only to neutrino masses and mixing, but also to how neutrinos interact with matter.

- 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.

How to use EFT language to "systematically" explore new physics beyond the neutrino masses and mixing in neutrino experiments?



Why EFT?

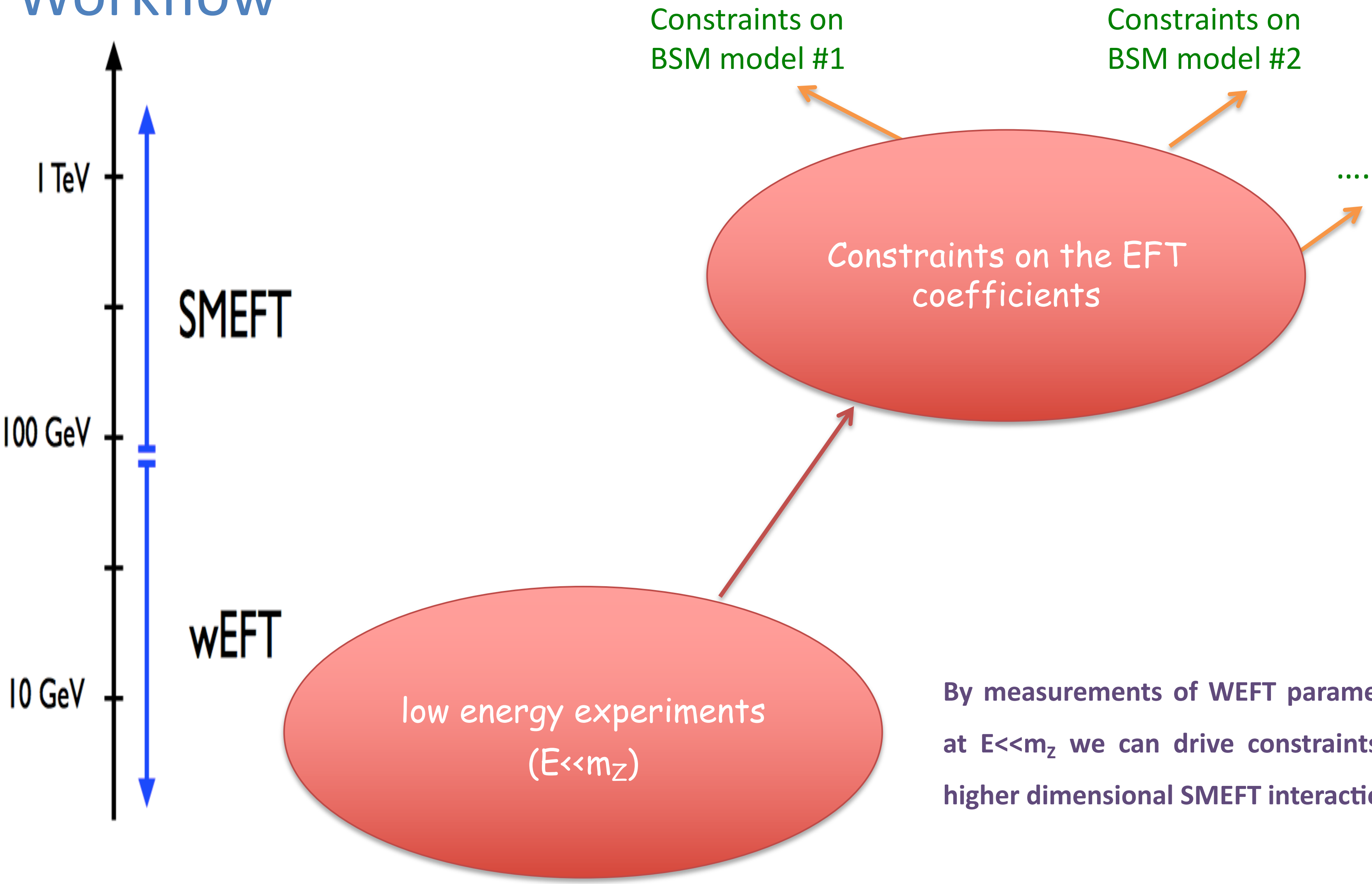
- Wealth of low-energy observables probing different aspects of particle interactions are described within one consistent framework.

- Constraints from different observables can be meaningfully compared.

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

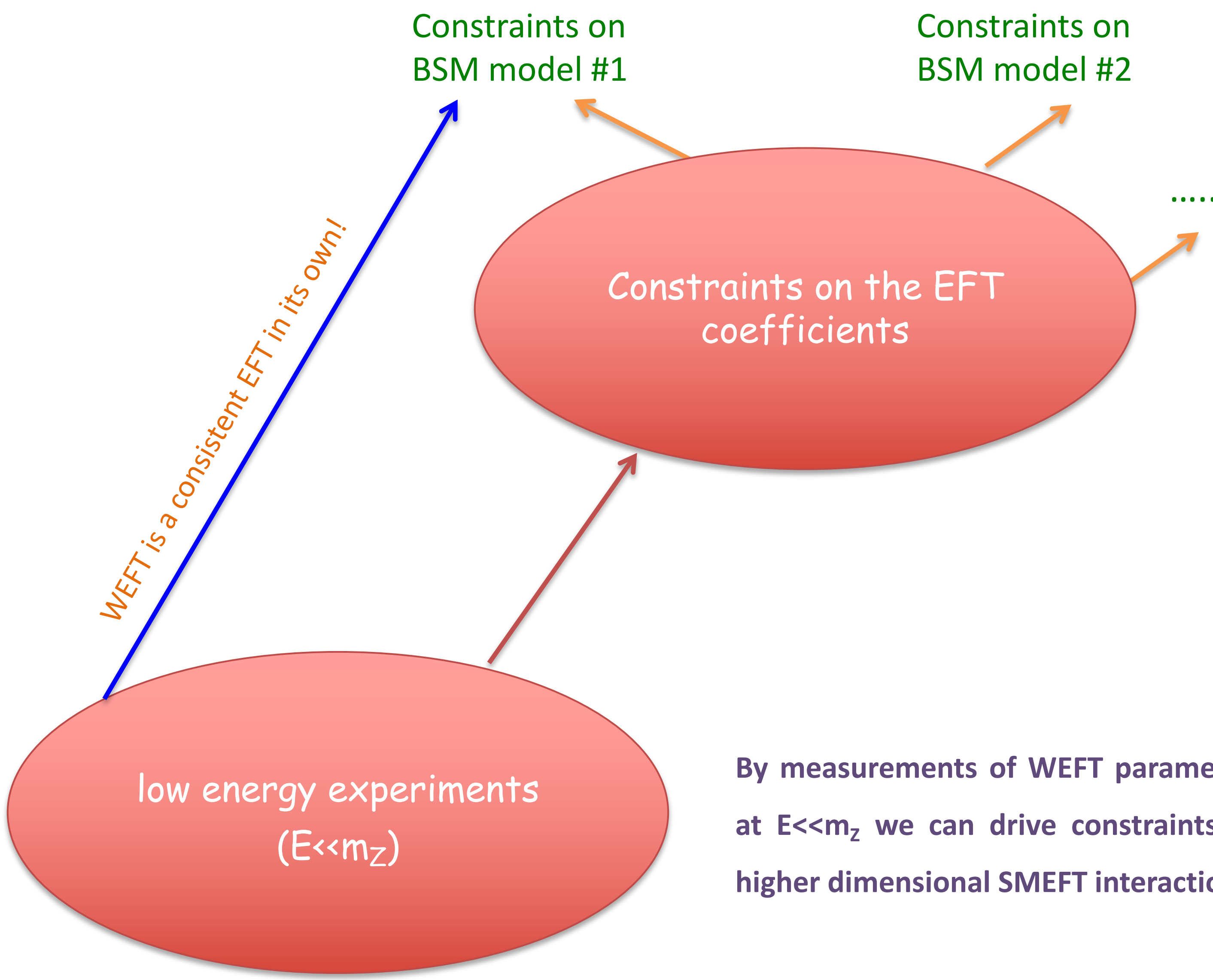
The point is that one can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables.

Workflow



By measurements of WEFT parameters at $E \ll m_Z$ we can drive constraints on higher dimensional SMEFT interactions.

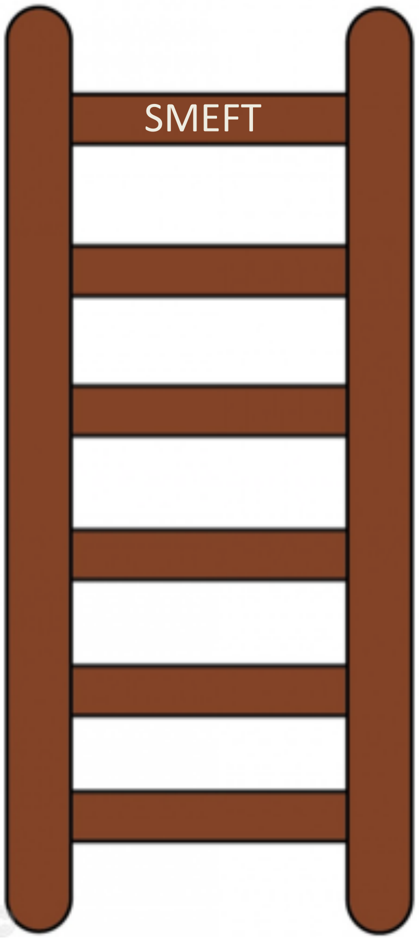
Workflow



By measurements of WEFT parameters at E<<m_Z we can drive constraints on higher dimensional SMEFT interactions.

Approach:

$E > m_Z$



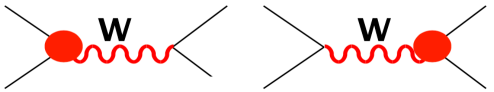
- If BSM particles are much heavier than the Z boson mass and the EWSB is linearly realized, then the relevant effective theory above the weak scale is the so-called SMEFT.

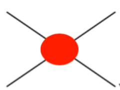
- It has the same particle content and local symmetry as the SM, but differs by the presence of higher-dimensional (non-renormalizable) interactions in the Lagrangian.

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

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

+

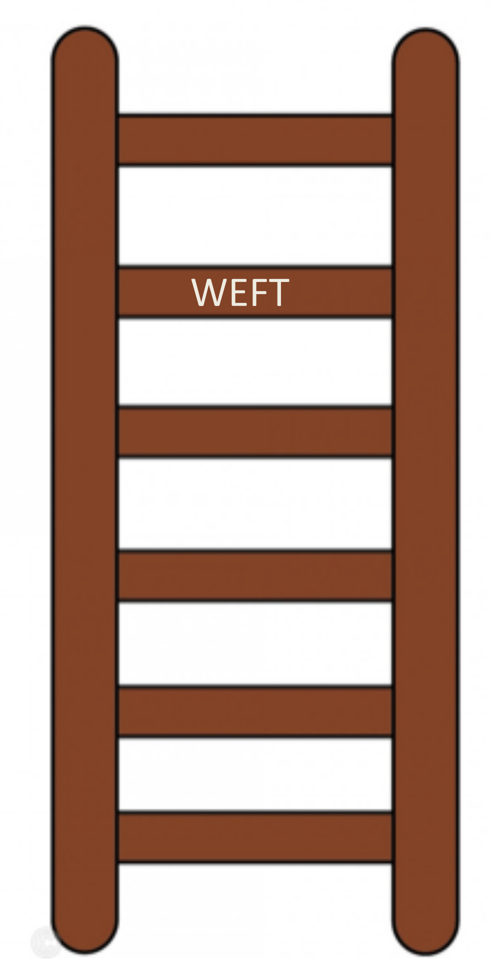




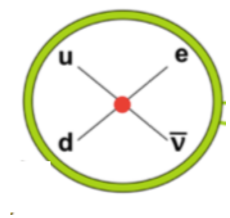
$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \mathrm{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \mathrm{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu} u) + \mathrm{h.c.}$$

Approach:

$E \ll m_Z$



- In particular, considering the CC interactions of neutrinos.



- 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).

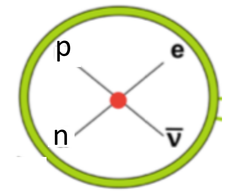
$$
\begin{aligned}
\mathcal{L}_{\text{WEFT}} \supset & -\frac{2V_{ud}}{v^2}\Big\{ [\mathbf{1} + \epsilon_L]_{\alpha\beta} (\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
& + [\epsilon_R]_{\alpha\beta} (\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
&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

- 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:



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

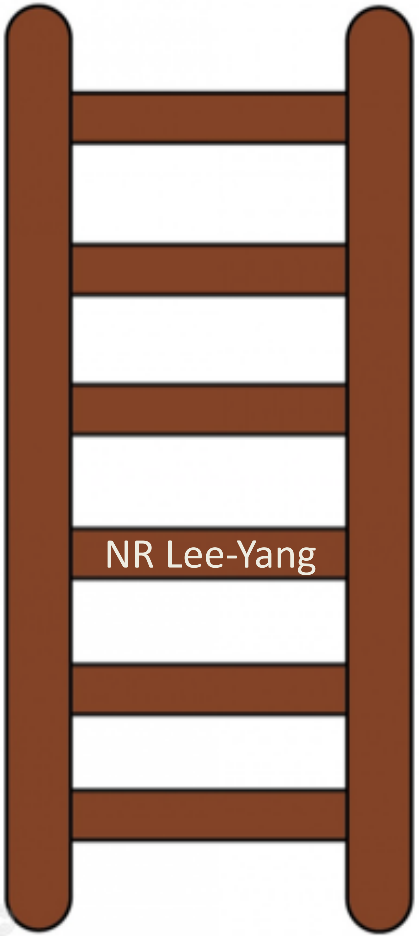
- Lattice+theory fix the non-perturbative parameters with good precision

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

- 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

$E \ll m_Z$



- Leading order non-relativistic Lagrangian for nucleons

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

NR proton and neutron fields

No dependence on ε_P!

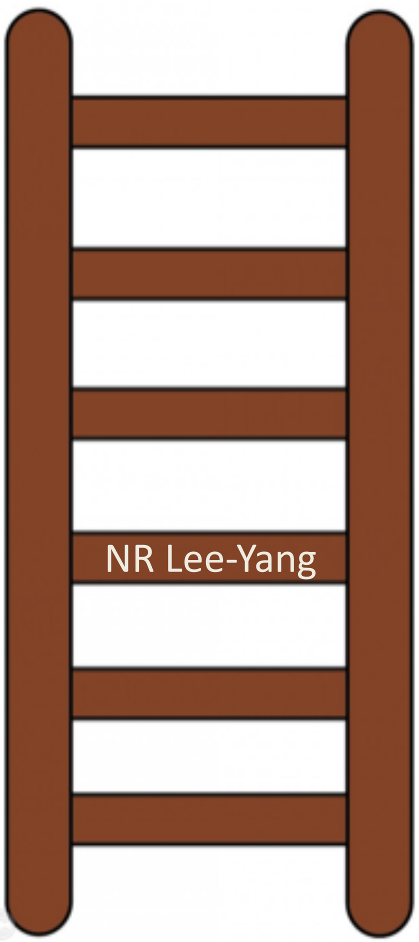
- At leading order, only two nuclear matrix eleme are needed (corresponding to Fermi and Gamow-Teller transitions)

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

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

EFT ladder

$E \ll m_Z$



- Leading order non-relativistic Lagrangian for nucleons

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

NR proton and neutron fields

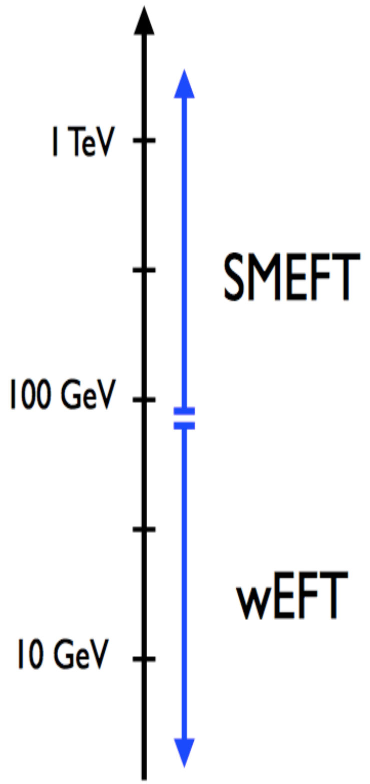
The same effective interactions at neutrino experiments also affect the phenomenological extraction of V_{ud} and g_A

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

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!

Matching WEFT and SMEFT parameters:

$$
\begin{aligned}
[\epsilon_L]_{\alpha\beta} &\approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{\alpha\beta} + V_{jd}[c_{Hq}^{(3)}]_{1j}\delta_{\alpha\beta} - V_{jd}[c_{lq}^{(3)}]_{\alpha\beta 1j}\right) \\
[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}\delta_{\alpha\beta}, \\
[\epsilon_S]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}^{(1)}]^*_{\beta\alpha j1} + [c_{ledq}]^*_{\beta\alpha 11}\right), \\
[\epsilon_P]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}^{(1)}]^*_{\beta\alpha j1} - [c_{ledq}]^*_{\beta\alpha 11}\right), \\
[\hat{\epsilon}_T]_{\alpha\beta} &\approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd}[c_{lequ}^{(3)}]^*_{\beta\alpha j1},
\end{aligned}
$$



- All ε_X arise at $O(\Lambda^{-2})$ in the SMEFT, thus they are equally important.
- No off-diagonal right handed interactions in SMEFT.

A. Falkowski, M. González-Alonso, ZT
JHEP 05 (2019) 173

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[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}\delta_{\alpha\beta}\\
[\epsilon_S]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}^{(1)}]^*_{\beta\alpha j1} + [c_{ledq}]^*_{\beta\alpha 11}\right),\\
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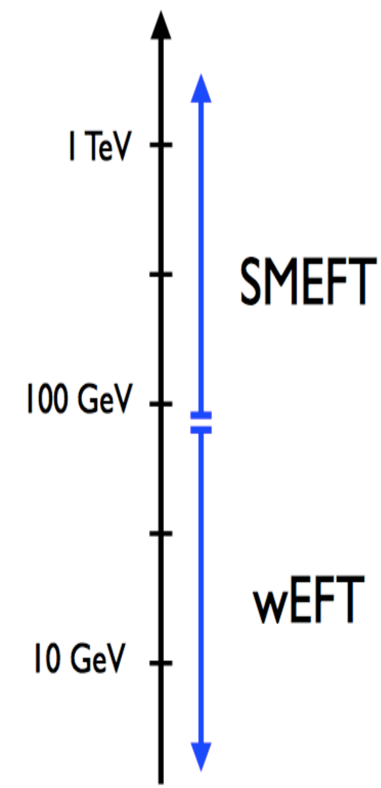
\end{aligned}
$$



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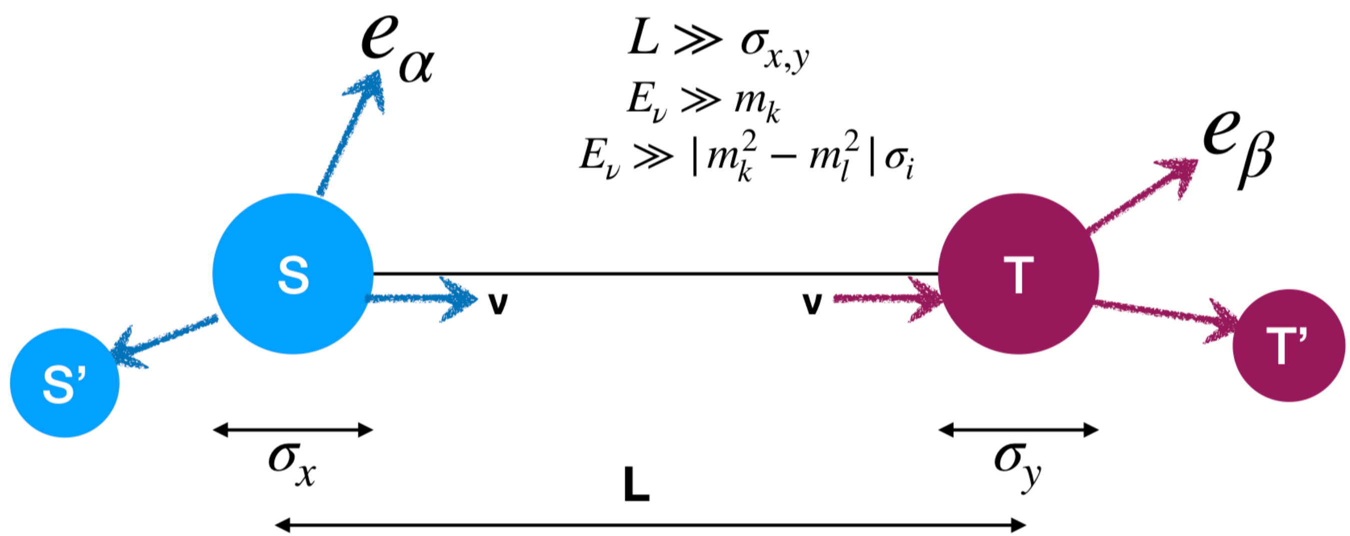
QFT Description

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971



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

$$
\boxed{
\begin{aligned}
\mathcal{M}^P_{\alpha k} &= U^*_{\alpha k} A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k} A^P_X \\
\mathcal{M}^D_{\beta k} &= U_{\beta k} A^D_L + \sum_X [\epsilon_X U]_{\beta k} A^D_X
\end{aligned}
}
$$

depend on the kinematic and spin variables

QFT Description

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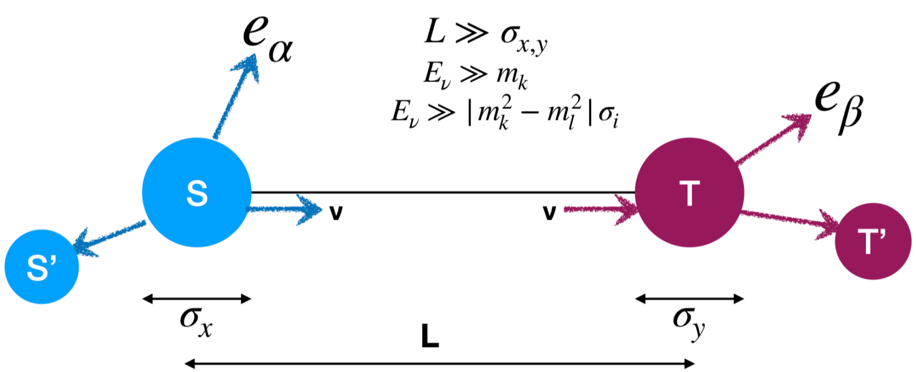
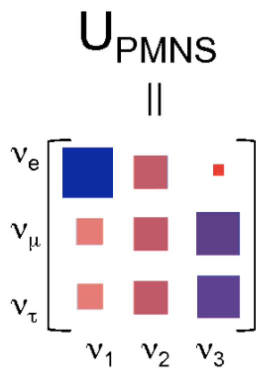
arXiv: 1910.02971

Observable: **rate of detected events**

$\sim$(flux)×(det. cross section)×(oscillation)





QFT Description

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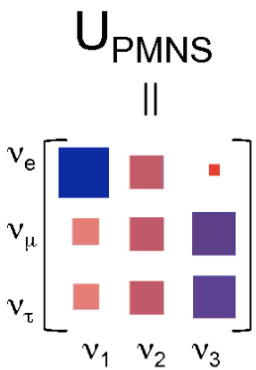
SM

$$R^{\rm SM}_{\alpha\beta} = \Phi^{\rm SM}_{\alpha}\sigma^{\rm SM}_{\beta}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} U^*_{\alpha k}U_{\alpha l}U_{\beta k}U^*_{\beta l}$$



QFT Description

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NP

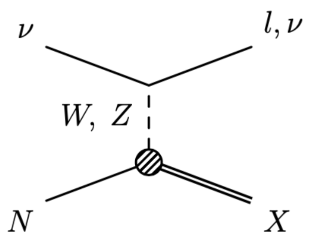
WCs of WEFT

$$R_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \left[U^*_{\alpha k}U_{\alpha l} + p_{XL}(\epsilon_X U)^*_{\alpha k}U_{\alpha l} + p^*_{XL}U^*_{\alpha k}(\epsilon_X U)_{\alpha l} + p_{XY}(\epsilon_X U)^*_{\alpha k}(\epsilon_Y U)_{\alpha l}\right]$$
$$\times \left[U_{\beta k}U^*_{\beta l} + d_{XL}(\epsilon_X U)_{\beta k}U^*_{\beta l} + d^*_{XL}U_{\beta k}(\epsilon_X U)^*_{\beta l} + d_{XY}(\epsilon_X U)_{\beta k}(\epsilon_Y U)^*_{\beta l}\right]$$

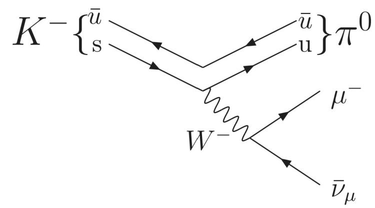
production and detection coefficients

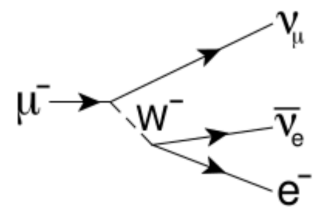
$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}.$$

DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

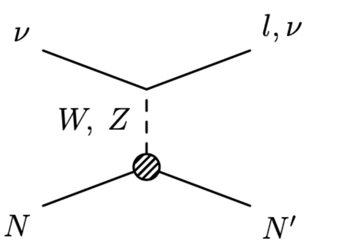
^{7}Be $\boxed{{}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e}$

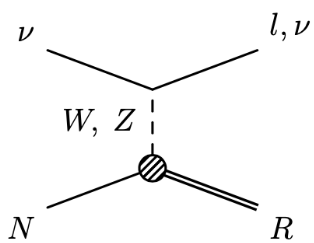
$\boxed{{}^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e}$ **hep**

(hep)

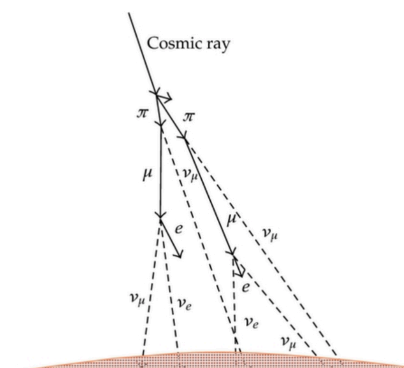
$\boxed{p + e^- + p \to {}^2\mathrm{H} + \nu_e}$ ***pep***

QE, Resonances: MINOS, NOvA, DUNE

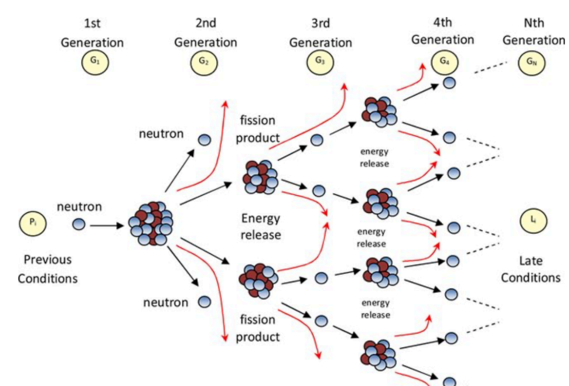




Atmospheric Neutrinos: IceCube



Beta decay and IBD: Reactor Experiments

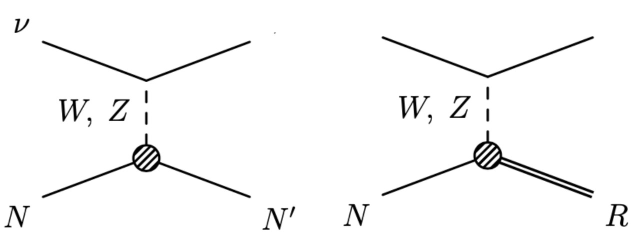


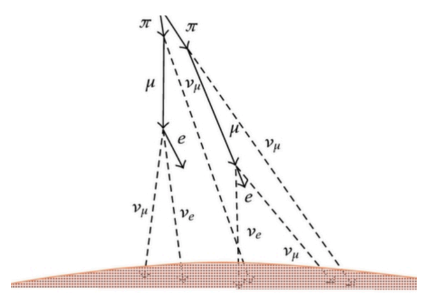
DIS: FASERν

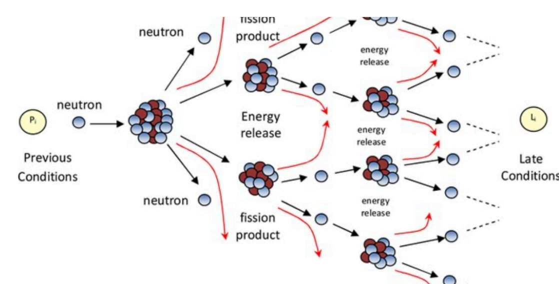
Kaon/Muon decay:

Solar neutrinos:

Well…



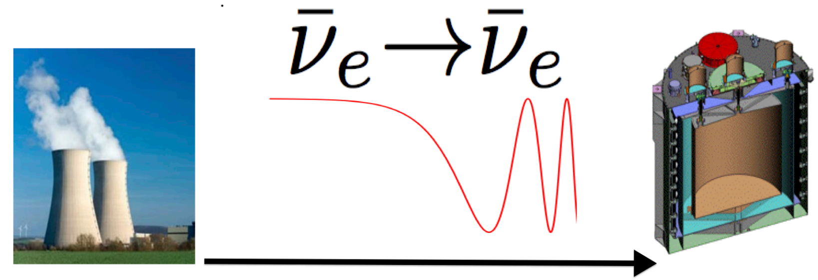




Inverse Beta Decay

Detection Through IBD Process:

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



Starting from the non-relativistic effective Lagrangian:

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

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

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IBD will be sensitive to the scalar and tensor NP!

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

- 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

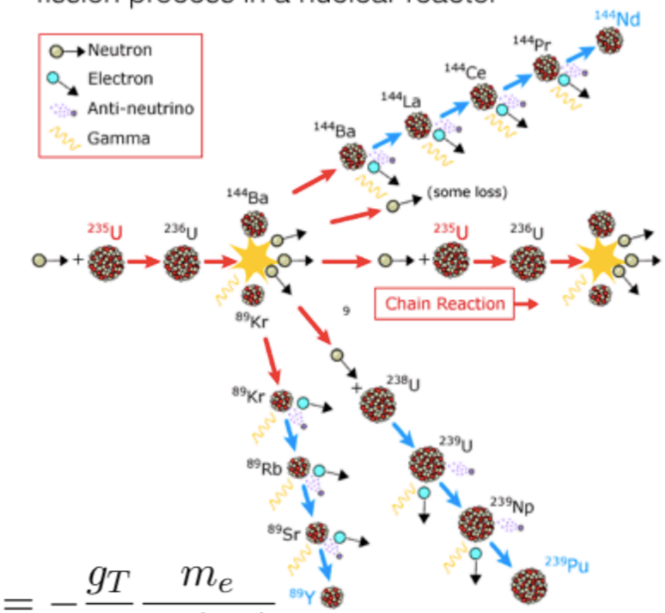
Nuclear Beta Decay

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

fission process in a nuclear reactor



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

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

- Reactor experiments will probe tensor and scalar NP!
- They depend on the neutrino energy.

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Leptonic Pion Decay:

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

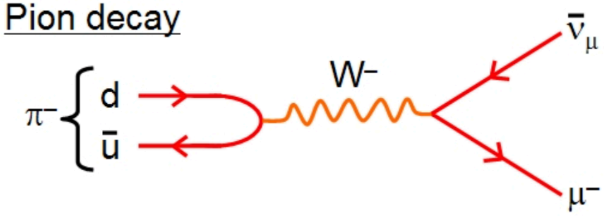
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ϵ_L-ϵ_R) and pseudo-scalar (ϵ_P) interactions.

$$p_{LL} = -p_{RL} = 1, \quad p_{PL} = -p_{PR} = -\frac{m_\pi^2}{m_\mu(m_u + m_d)},$$

$$p_{RR} = 1, \quad p_{PP} = \frac{m_\pi^4}{m_\mu^2(m_u + m_d)^2}.$$

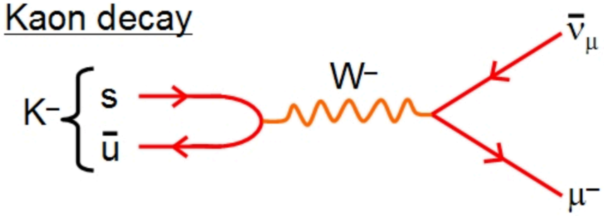
~-27

Pion decay



$\pi^-(d\bar{u}) \to \mu^- + \bar{\nu}_\mu$

Kaon decay



$K^-(s\bar{u}) \to \mu^- + \bar{\nu}_\mu$

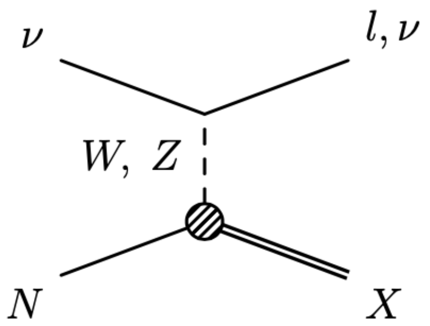
- We will have a great chiral enhancement for the pseudoscalar.
- Same for kaon decay, with $m_\pi \to m_K$ and $m_d \to m_s$

Deep Inelastic:

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2010.XXXXX

(Preliminary)

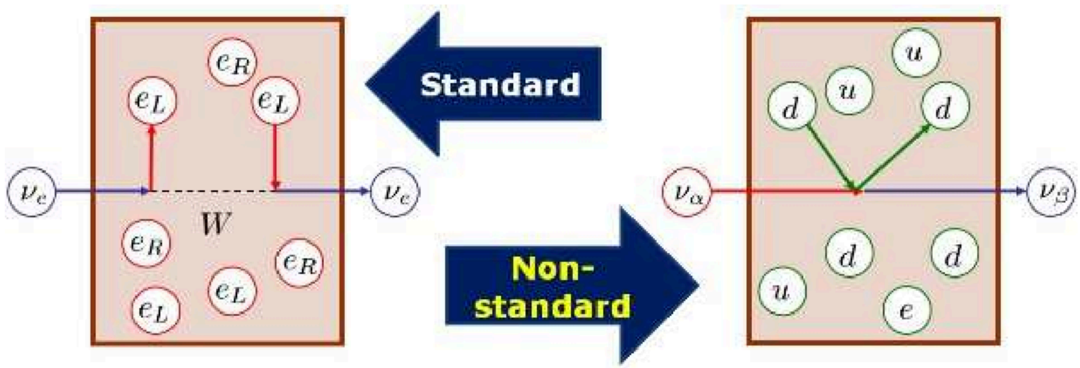
	$d^{ud}_{RR,\beta}$	$d^{ud}_{SS,\beta} = d^{ud}_{PP,\beta}$	$d^{ud}_{TT,\beta}$	$d^{ud}_{PT,\beta} = -d^{ud}_{ST,\beta}$
$\nu_{e,\mu}$	0.422	0.040	0.630	0.083
$\bar{\nu}_{e,\mu}$	2.574	0.101	1.586	0.208
ν_τ	0.423	0.040	0.631	0.084
$\bar{\nu}_\tau$	2.572	0.102	1.585	0.207



- No new physics at the linear order!
- Good sensitivity to the right handed and tensor interactions.

QM-NSI Description

Neutrinos are not pure flavor states:



Standard NSI approach

NSI parameters

$$|\nu_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left[|\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau}\epsilon^s_{\alpha\gamma}|\nu_\gamma\rangle\right]$$

Rotation of flavor states at the source

$$\langle\nu_\beta^d| = \frac{1}{N_\beta^d}\left[\langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau}\langle\nu_\gamma|\epsilon^d_{\gamma\beta}\right]$$

Rotation of flavor states at the detector

Normalization

QM-NSI Description

Neutrinos are not pure flavor states:

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

Observable: **rate of detected events**

~(flux)×(det. cross section)×(oscillation)

$$R_{\alpha\beta}^{\mathrm{QM}} = \Phi_\alpha^{\mathrm{SM}}\sigma_\beta^{\mathrm{SM}}\sum_{k,l} e^{-i\frac{L\Delta m_{kl}^2}{2E_\nu}}[x_s]_{\alpha k}[x_s]_{\alpha l}^*[x_d]_{\beta k}[x_d]_{\beta l}^*$$

$$x_s \equiv (1+\epsilon^s)U^* \ \& \ x_d \equiv (1+\epsilon^d)^T U$$

QFT vs QM-NSI

- Can one “validate” QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation?

QFT vs QM-NSI

- Can one "validate" QM-NSI approach from the QFT results? Yes…
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation? No…

Observable is the same, we can match the two

(only at the linear level)

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

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

Comparing QM and QFT

At the linear order we have:

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

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	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

- Different NP interactions appear at the source or detection simultaneously.
- Some of the p/d coefficients depend on the neutrino energy.
- There are chiral enhancements in some cases.

These correlations, energy dependence etc. cannot be seen in the traditional QM approach.

Comparing QM and QFT

Beyond the linear order in new physics parameters, the NSI formula matches the (correct) one derived in the EFT
only if the consistency condition is satisfied

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

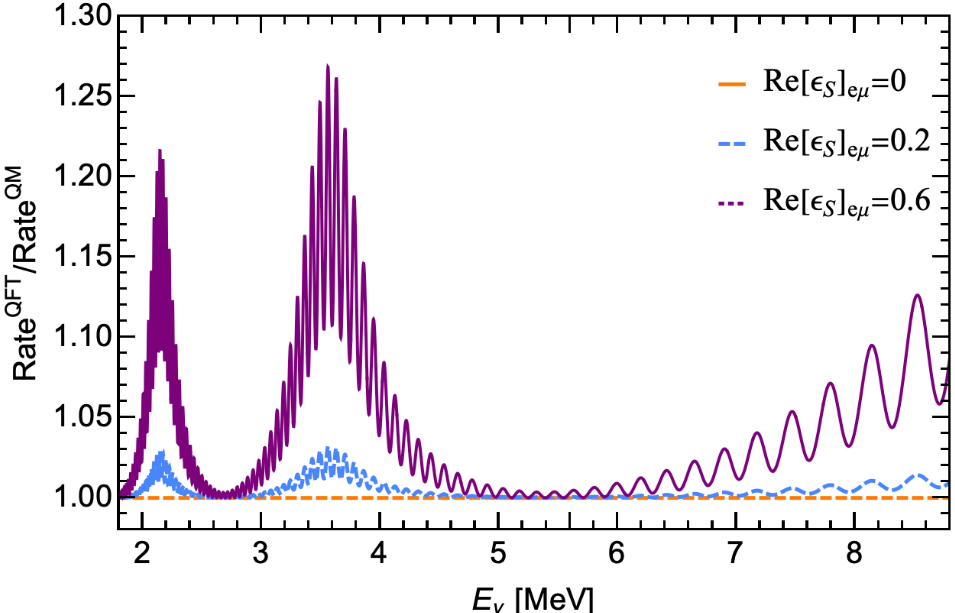
$$p_{XL} p^*_{YL} = p_{XY}, \quad d_{XL} d^*_{YL} = d_{XY}$$

This is always satisfied for new physics correcting V-A interactions only as $p_{LL} = d_{LL} = 1$ by definition

However for non-V-A new physics the consistency condition is not satisfied in general

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

e.g. at KamLAND experiment



EFT in reactor experiments

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

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

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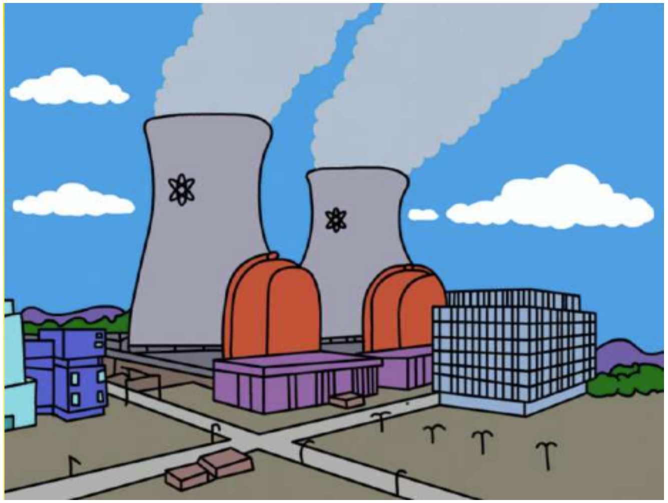
No sensitivity to V-A NSI!!! It can be absorbed into a redefinition of the PMNS mixing angle θ_{13} into the effective mixing angle $\tilde{\theta}_{13}$!

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

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:

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

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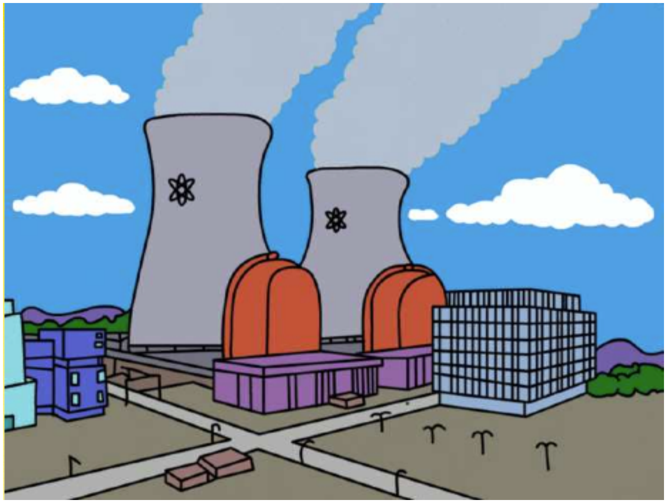
New Physics at the production side: only tensor interaction is present!!

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

$$
\boxed{
\begin{aligned}
\alpha_D &= \frac{g_S}{3g_A^2+1}\mathrm{Re}\,\underline{[S]} - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Re}\,\underline{[T]}\,, &\quad \alpha_P &= \frac{g_T}{g_A}\mathrm{Re}\,\underline{[T]} \\
\beta_D &= \frac{g_S}{3g_A^2+1}\mathrm{Im}\,\underline{[S]} - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Im}\,\underline{[T]}\,, &\quad \beta_P &= \frac{g_T}{g_A}\mathrm{Im}\,\underline{[T]}
\end{aligned}
}
$$

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



EFT in reactor experiments

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

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

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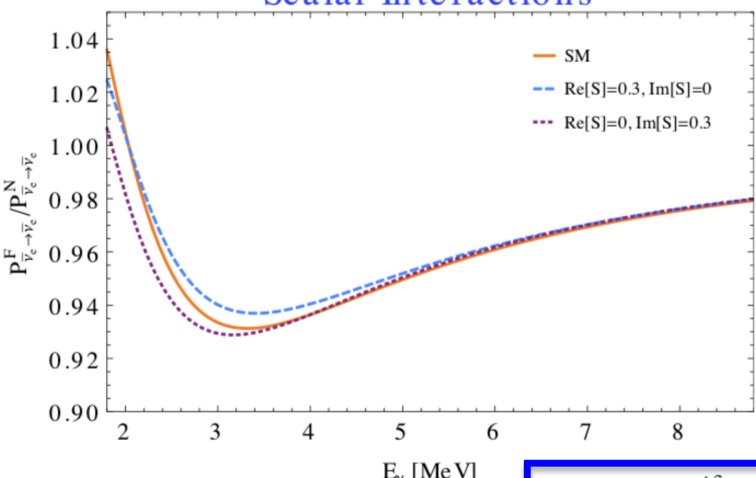
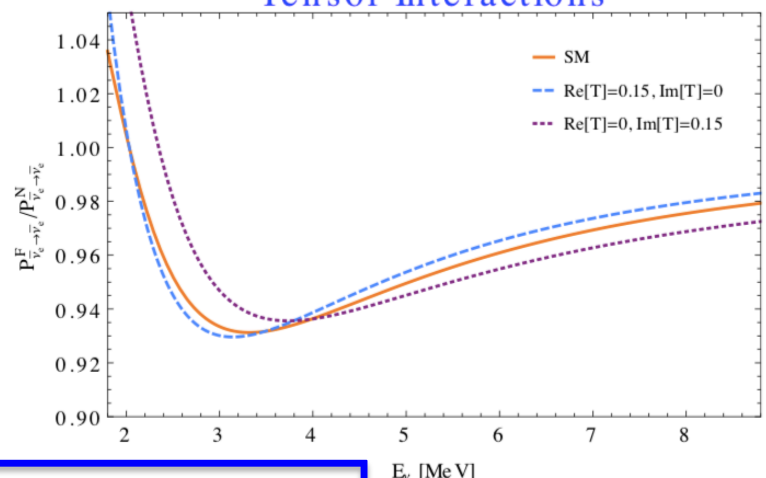
Scalar Interactions



Tensor Interactions



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

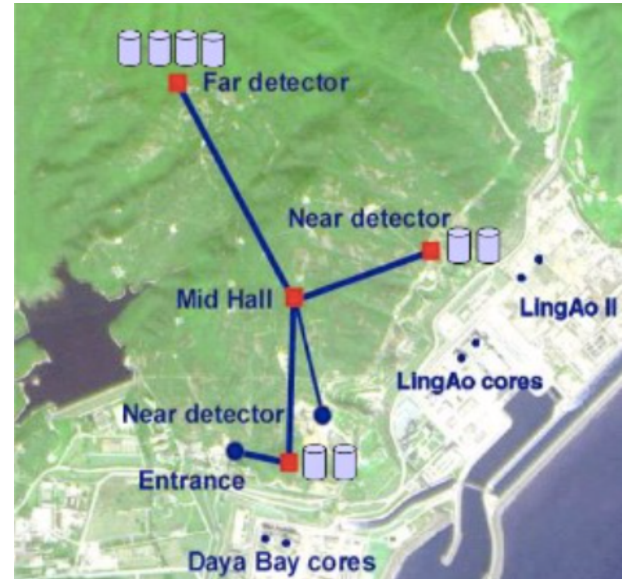
The effect of both scalar and tensor interactions is to shift the amplitude and also distort the E_ν spectrum due to the different energy dependence of the scalar and tensor interactions.

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;

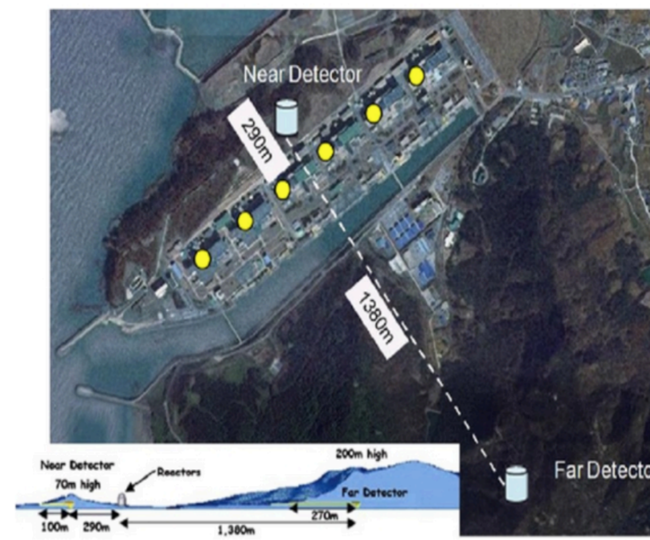
Daya Bay Collaboration, D. Adey et al., arXiv:1809.02261



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

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

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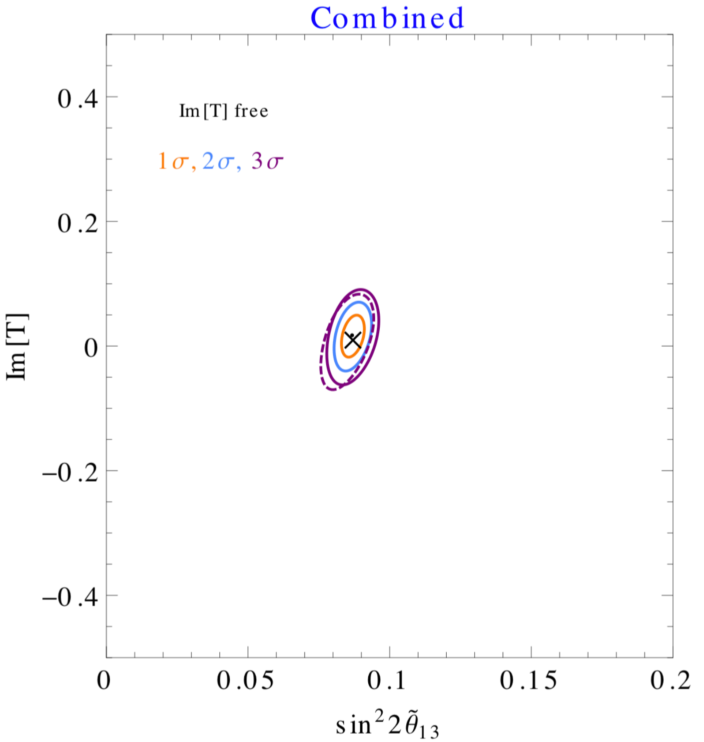
$$\tilde{\theta}_{13}=\theta_{13}+\mathrm{Re}\,[L]$$

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

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

$$\mathrm{Re}\,[T]=-0.26\pm0.14\,,\qquad \mathrm{Im}\,[T]=-0.034\pm0.042$$

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



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

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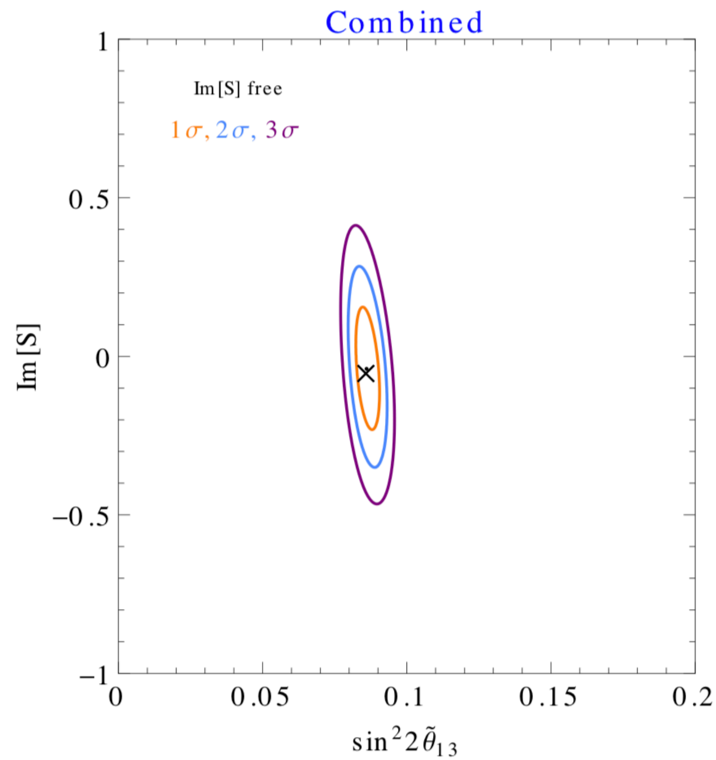
Scalar: $\epsilon_S \neq 0,\ \epsilon_{R,P,T}=0$

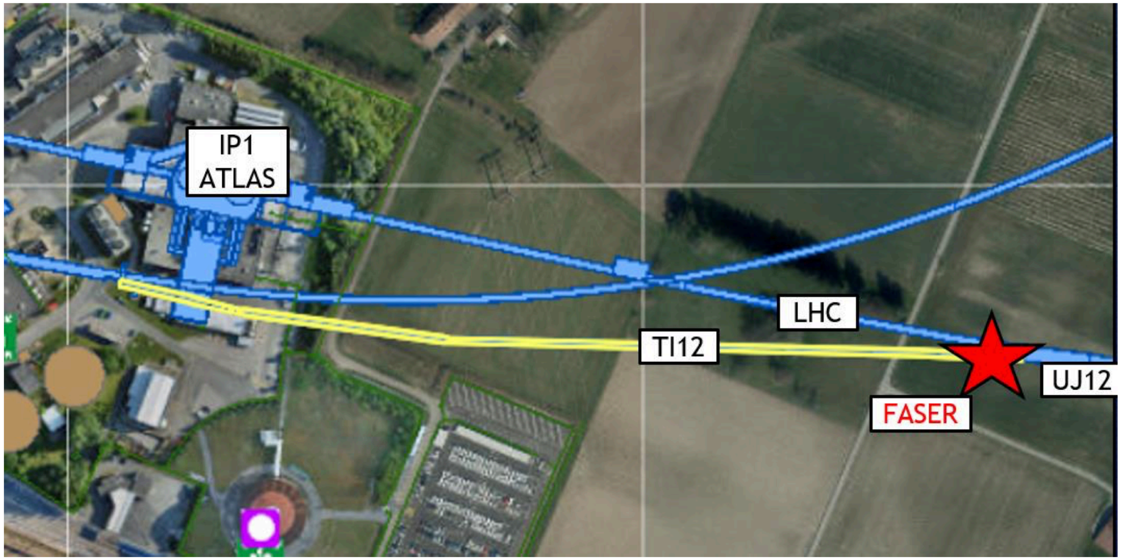
$$\mathrm{Im}\,[S]=0.08\pm0.14$$

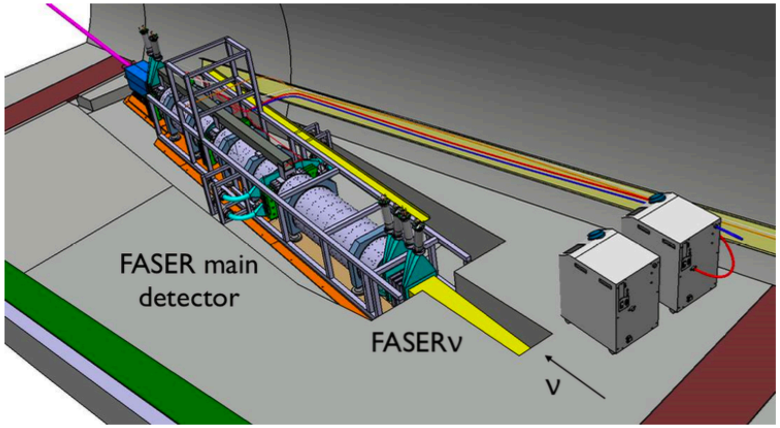
$$[S] \equiv e^{i\delta_{CP}}\left(s_{23}[\epsilon_S]_{e\mu}+c_{23}[\epsilon_S]_{e\tau}\right)$$



EFT at FASERν

- will be located downstream of the ATLAS interaction point at a distance of 480 m.
- Ideal for detecting high-energy neutrinos produced at LHC.
- 1.2-t of tungsten material.

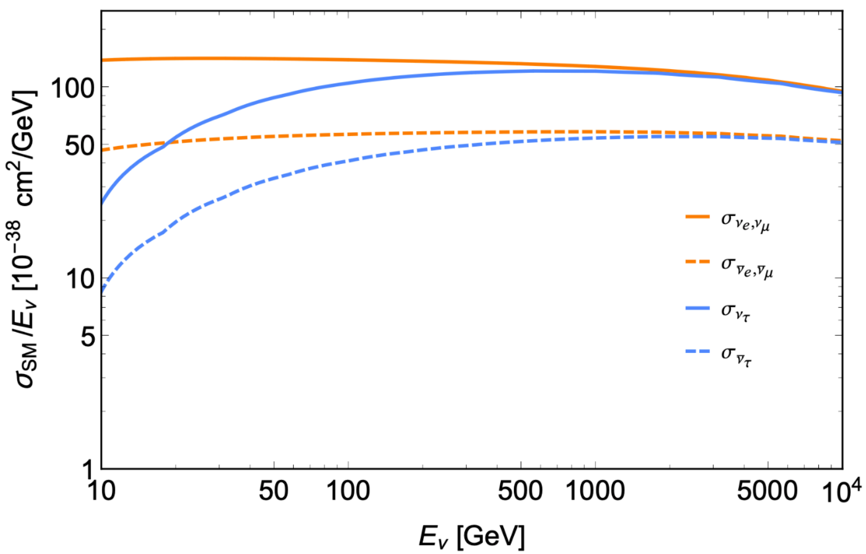




EFT at FASERν

Why FASERν?

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2010.XXXXX



DIS detection, easy to include NP
(compared with QE and Resonances)

	$d^{ud}_{RR,\beta}$	$d^{ud}_{SS,\beta} = d^{ud}_{PP,\beta}$	$d^{ud}_{TT,\beta}$	$d^{ud}_{PT,\beta} = -d^{ud}_{ST,\beta}$
$\nu_{e,\mu}$	0.422	0.040	0.630	0.083
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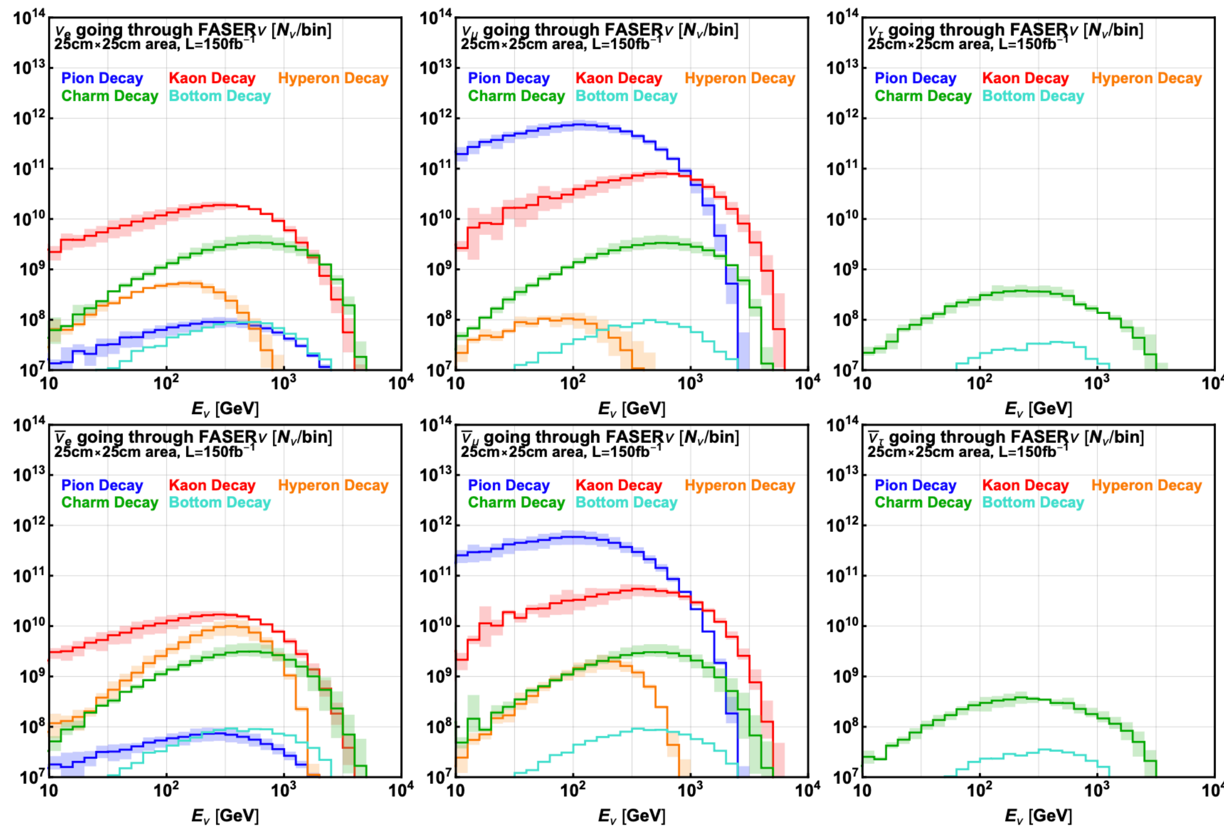
- No new physics at the linear order!
- Good sensitivity to the right handed and tensor interactions.

EFT at FASERν

H. Abreu et al,
Eur. Phys. J. C 80 (2020) no.1, 61

Why FASERν?

- Several production modes
- Pion and Kaon decays are the dominant ones
- All (anti)neutrino flavors are available



	Number of CC Interactions	Number of Reconstructed Vertices	Mean Energy
$\nu_e+\bar{\nu}_e$	1296^{+77}_{-58}	1037^{+52}_{-36}	827 GeV
$\nu_\mu+\bar{\nu}_\mu$	20439^{+1545}_{-2314}	15561^{+1103}_{-1514}	631 GeV
$\nu_\tau+\bar{\nu}_\tau$	$21^{+3.3}_{-2.9}$	$17^{+2.6}_{-2.6}$	965 GeV

EFT at FASERν

(pseudo)probability:

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2010.XXXXX

$$\tilde{P}_{\alpha\beta}\big|_{L=0} \simeq \underbrace{\Big(1 + 2\sum_{X,j,k} p^{jk}_{XL,\alpha}|\epsilon^{jk}_{X,\alpha\beta}|\cos\phi^{jk}_{X,\alpha\beta}\Big)\delta_{\alpha\beta}}_{\text{Only the diagonal elements at the linear order}} + \sum_{X,Y,j,k} \underbrace{|\epsilon^{jk}_{X,\alpha\beta}|^2 p^{jk}_{XY,\alpha} + \sum_{X,Y,r,s}|\epsilon^{rs}_{X,\beta\alpha}|^2 d^{rs}_{XY,\beta}}_{\text{Off diagonal elements at the quadratic order}}\,,$$

No oscillation, only zero-distance effect!

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No oscillation, only zero-distance effect!

$$|\epsilon_T| = \begin{pmatrix} < 0.25 & < 0.026 & < 1.84 \\ < 0.56 & < 0.36 & < 3.3 \\ < 0.077 & < 0.020 & < 0.6 \end{pmatrix} \qquad |\epsilon_P| = \begin{pmatrix} < 1.01 & < 0.24 & < 7.3 \\ < 6.8\times10^{-4} & < 1.33\times10^{-3} & < 1.53\times10^{-3} \\ < 0.30 & < 0.79 & < 2.4 \end{pmatrix}$$

WEFT without SMEFT

$$
\begin{aligned}
[\epsilon_L]_{\alpha\beta} &\approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{\alpha\beta} + V_{jd}[c_{Hq}^{(3)}]_{1j}\delta_{\alpha\beta} - V_{jd}[c_{lq}^{(3)}]_{\alpha\beta 1j}\right)\\
[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}\delta_{\alpha\beta}\\
[\epsilon_S]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}^{(1)}]^*_{\beta\alpha j1} + [c_{ledq}]^*_{\beta\alpha 11}\right),\\
[\epsilon_P]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}^{(1)}]^*_{\beta\alpha j1} - [c_{ledq}]^*_{\beta\alpha 11}\right),\\
[\hat{\epsilon}_T]_{\alpha\beta} &\approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]^*_{\beta\alpha j1}\ ,
\end{aligned}
$$

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- No off-diagonal right handed interactions in SMEFT.

WEFT without SMEFT

Reactor experiments:

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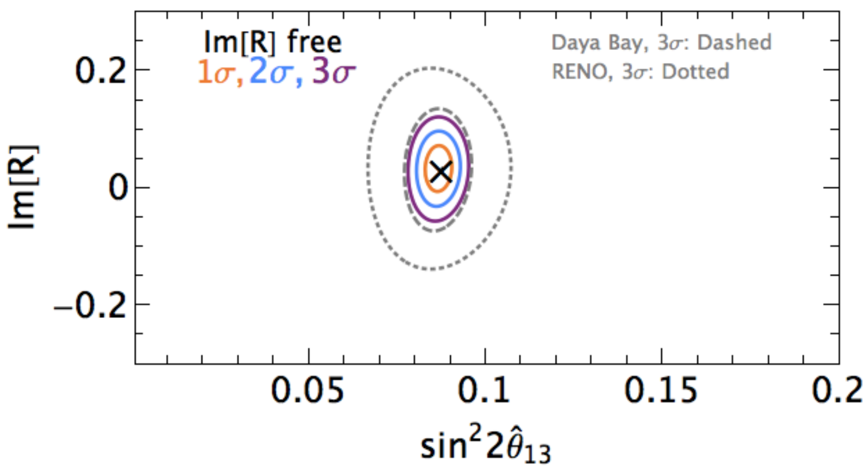
Combined

$$\mathrm{Im}\,[R] = 0.034 \pm 0.026$$



FASERν:

$$|\epsilon_R^{ud}| = \begin{pmatrix} < 1.01 & < 0.25 & < 7.29 \\ < 0.060 & < 1.94 & < 0.0184 \\ < 0.31 & < 0.079 & < 2.37 \end{pmatrix}$$

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2010.XXXXX

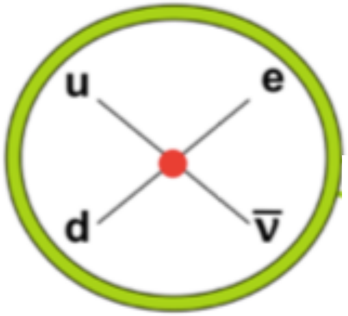
Non-oscillation constraints on EFT parameters

- The oscillations are sensitive to linear effects $[\varepsilon_X]_{e\alpha}$.
- The non-oscillation observables are sensitive to absolute values squared of these parameters. We cannot distinguish between real and imaginary parts.
- The dependence on $[\varepsilon_X]_{e\alpha}$ enters at $O(\Lambda^{-4})$ in the SMEFT expansion.
- Their effects might cancel against linear effects in $[\varepsilon_X]_{ee}$, coming from dimension-6 or dimension-8 SMEFT operators.
- These bounds are less robust!

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

$$|[\epsilon_S]_{e\alpha}| \leq 6.4 \times 10^{-2} \,, \qquad |[\hat{\epsilon}_T]_{e\alpha}| \leq 4.4 \times 10^{-2}$$

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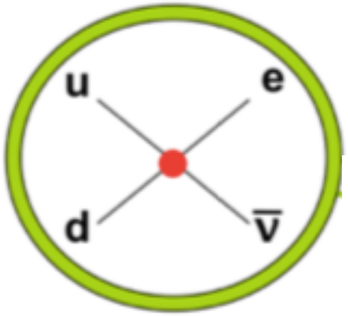

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- CKM unitarity

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

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

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

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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 $[\epsilon_X]_{e\alpha}$ appear in the Lagrangian together with 4-fermion charged-lepton-flavor violating (CLFV) interactions.

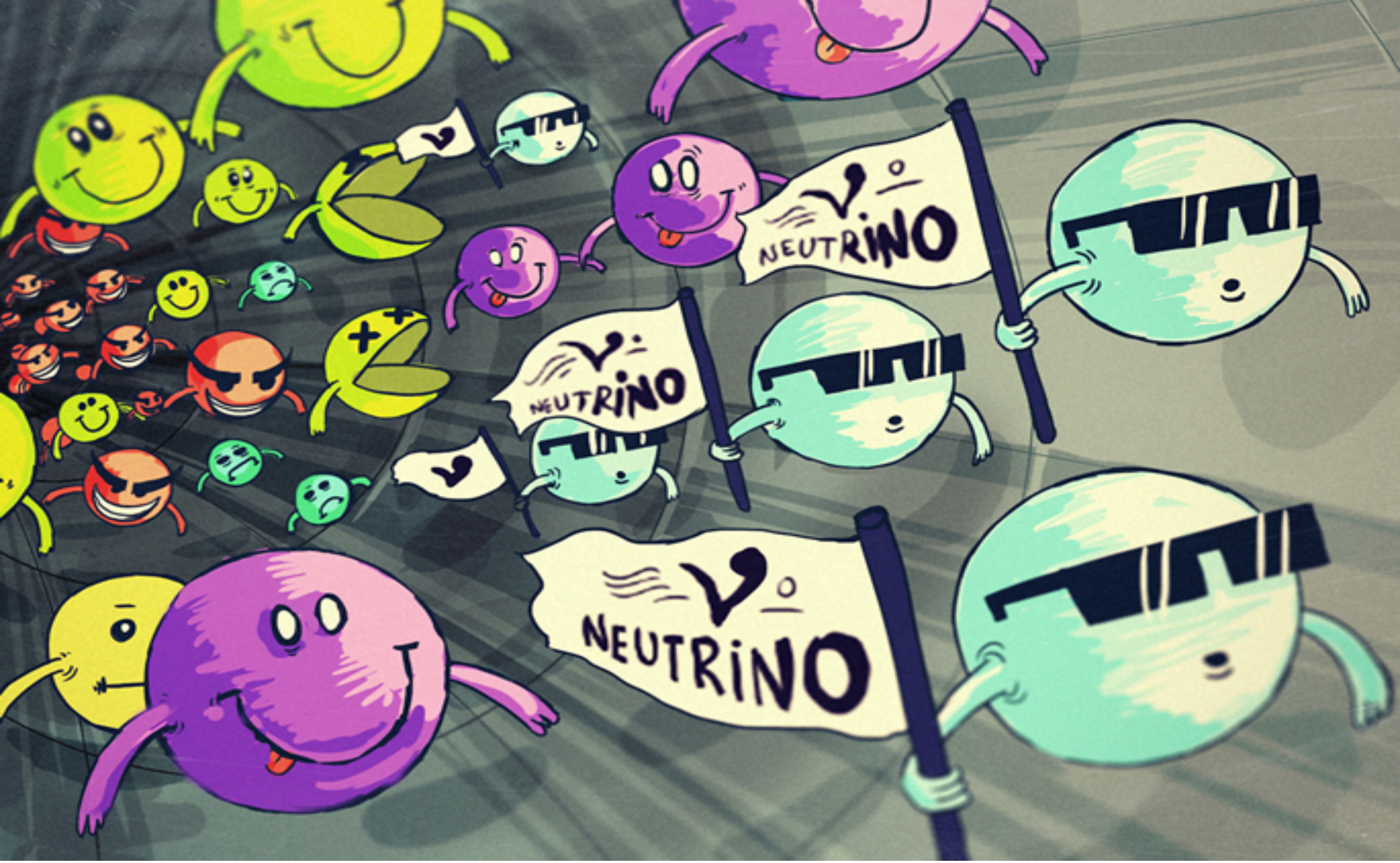
$$|[\epsilon_S]_{e\mu}| \lesssim 3\times 10^{-6} \qquad |[\epsilon_S]_{e\tau}| \lesssim 4\times 10^{-4}$$

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!

Conclusion:

- We have proposed a systematic approach to neutrino oscillations in the SMEFT framework.
- We applied the formalism to oscillations in short-baseline experiments, however the formalism can be readily extended to other types of neutrino experiments.
- As of today, constraints at a few percent level can be extracted from the publicly available reactor experiment data.
- Constraints of the order of 10^{-4} can be derived for pseudo-scalar interaction at FASERν.
- We give matching between EFT Wilson coefficients and NSI parameters, and discuss the conditions this matching is correct.
- We compared the constraints with non-oscillation experiments.



Thanks for your attention