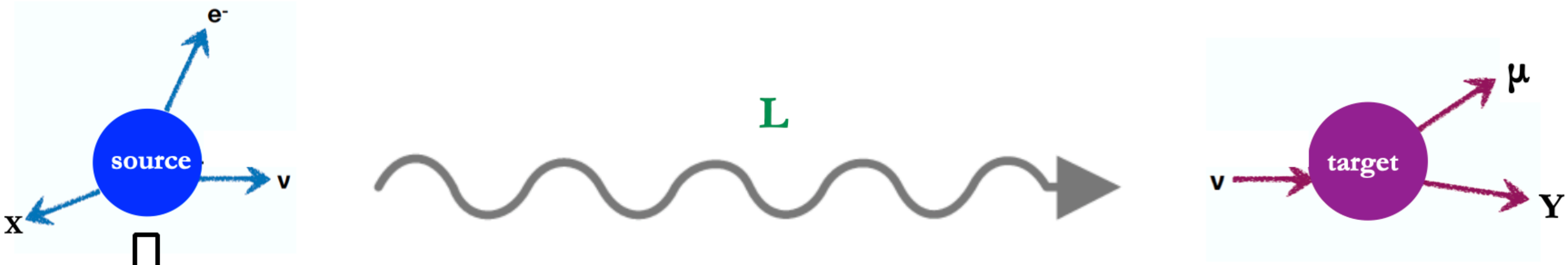
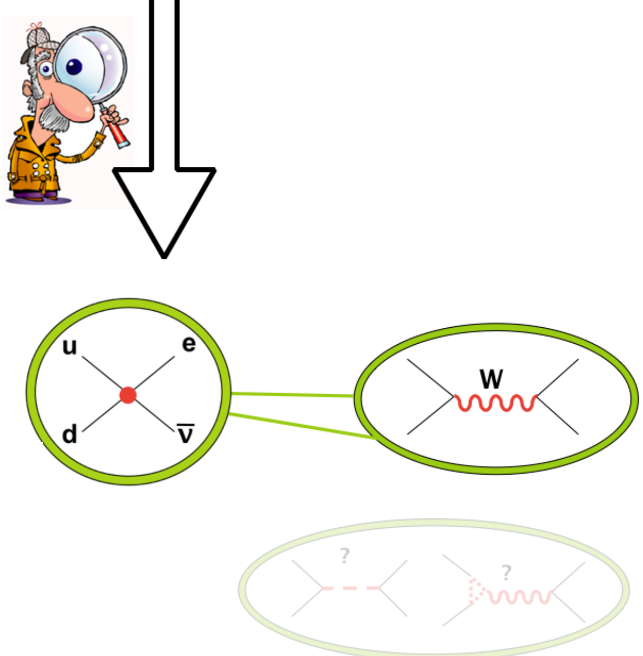
EFT analysis of neutrino experiments

Moriond EW **March 2023**

Martín González-Alonso
IFIC, Univ. of Valencia / CSIC

Introduction





[Same in detection]

In the SM*: $O = O(\theta_i, \Delta m^2)$

Beyond the SM*: $O = O(\theta_i, \Delta m^2, \varepsilon_j)$

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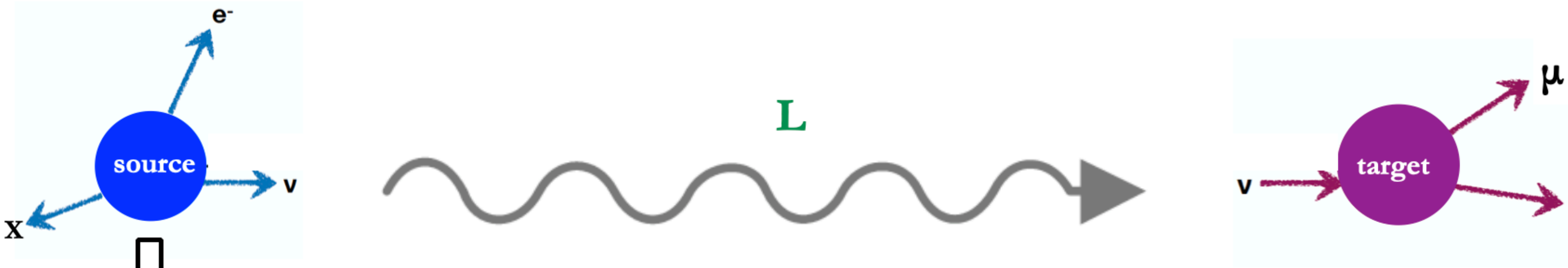

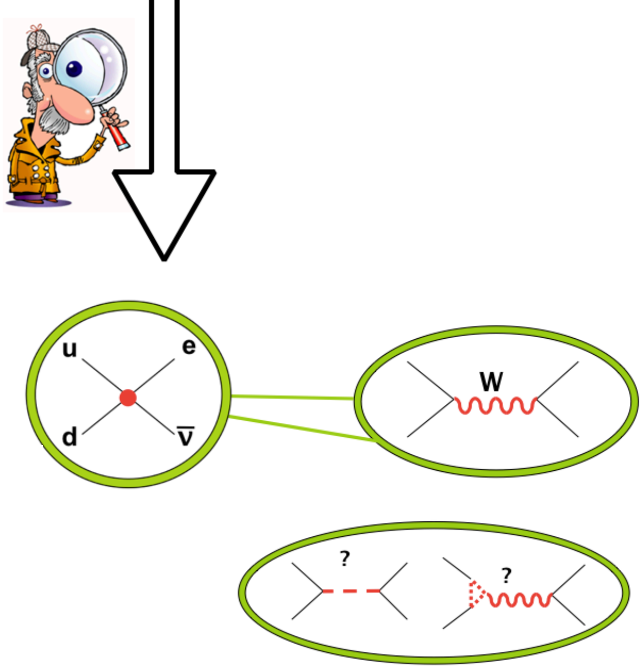

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Lagrangian parameters!

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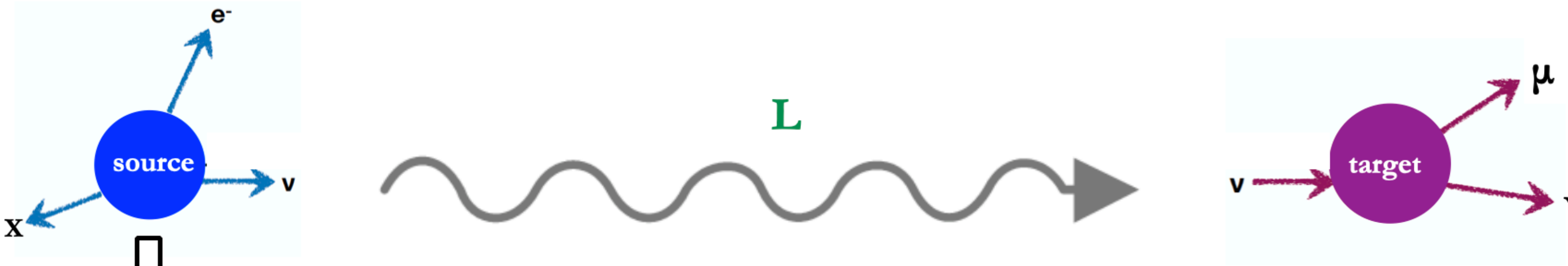

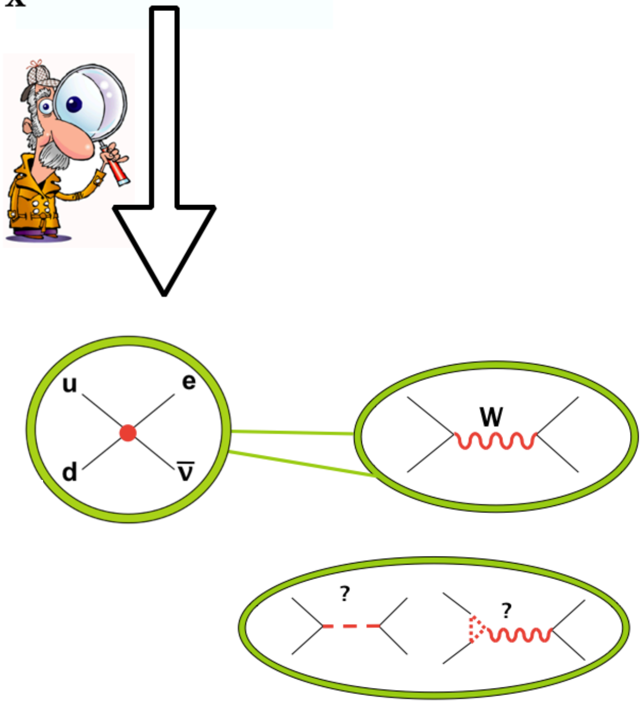

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How can I derive this formula?

In other words:
how are oscillations affected by a charged Higgs?
A leptoquark? Which part of their parameter space is ruled out by current oscillation data?

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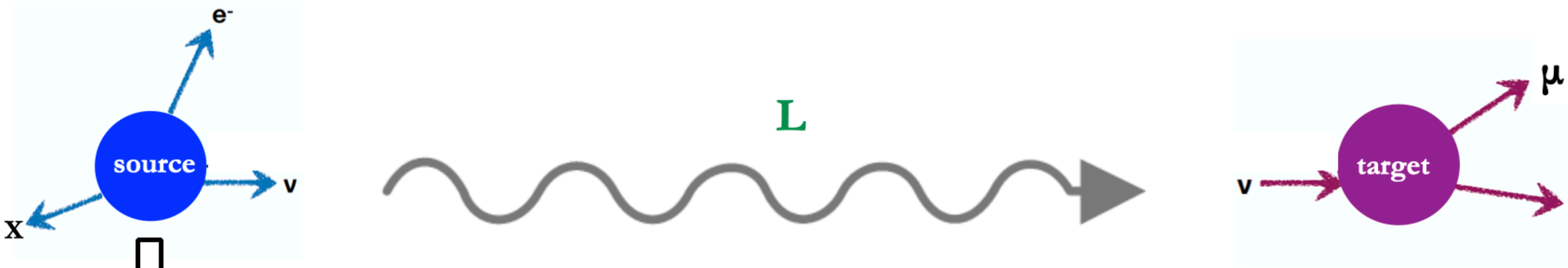

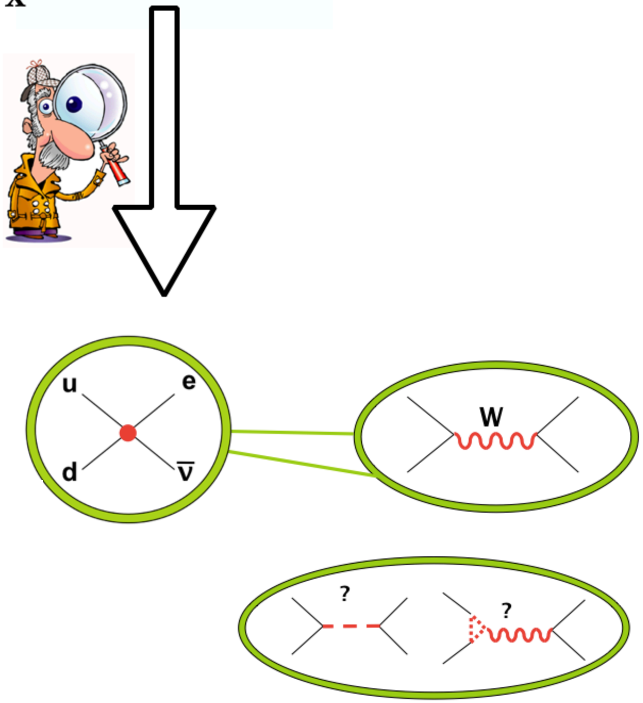

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How can I derive this formula?

- QM approach not useful ("source/detector NSI") → QFT approach needed

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle \qquad \varepsilon^s = f\,(\,?\,)$$

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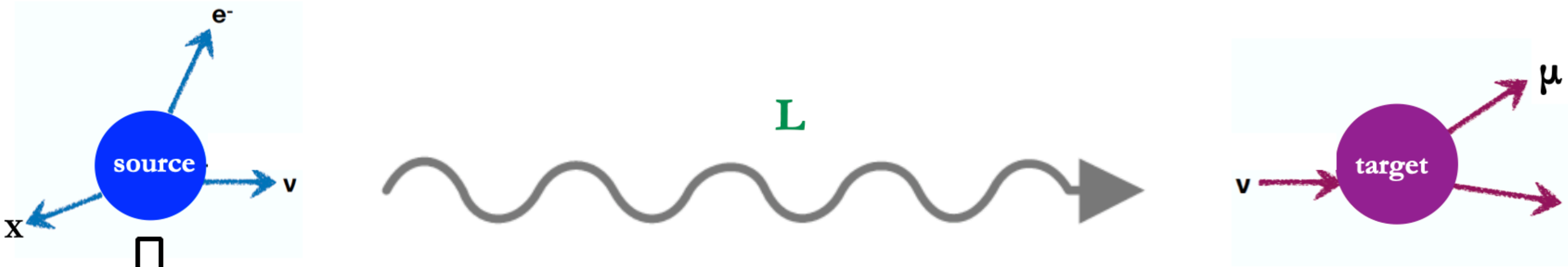

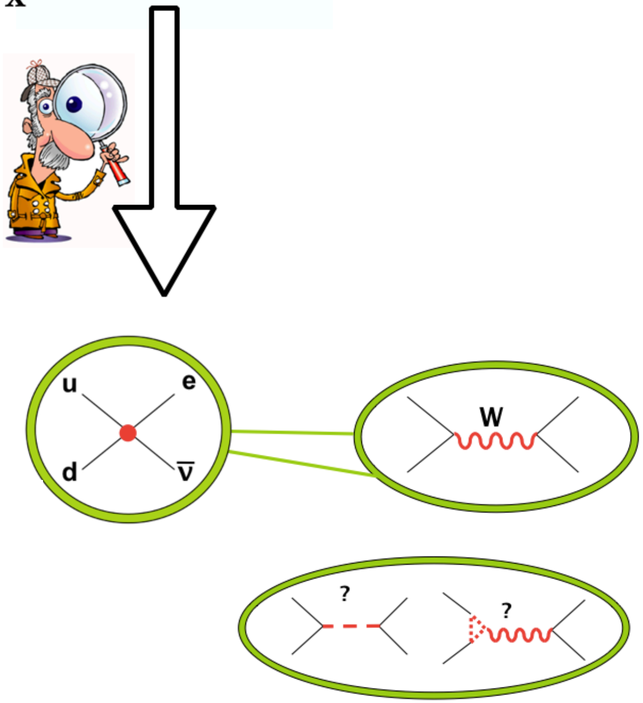

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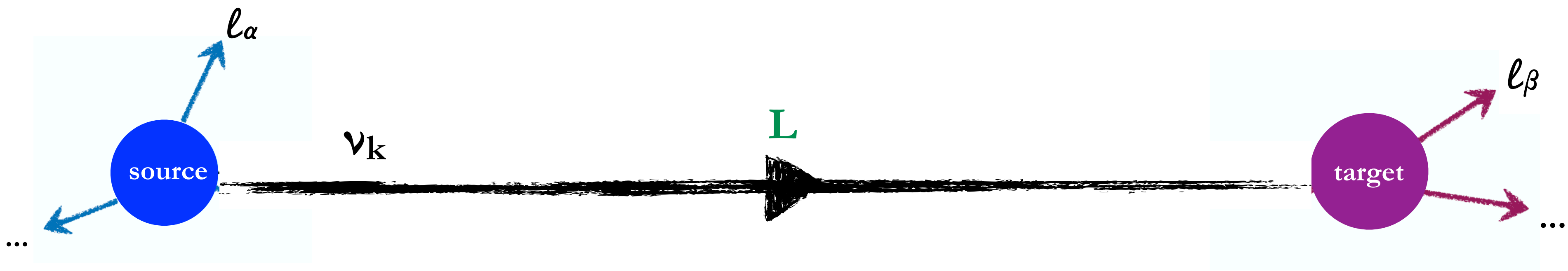
Giunti et al. [hep-ph/9305276]
Akhmedov Kopp [arXiv:1001.4815]
...

Oscillations in QFT

[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



$$R_{\alpha\beta} \equiv \frac{dN_{\alpha\beta}}{dt dE_\nu} = \quad \ldots \quad = \frac{\kappa}{E_\nu} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}$$

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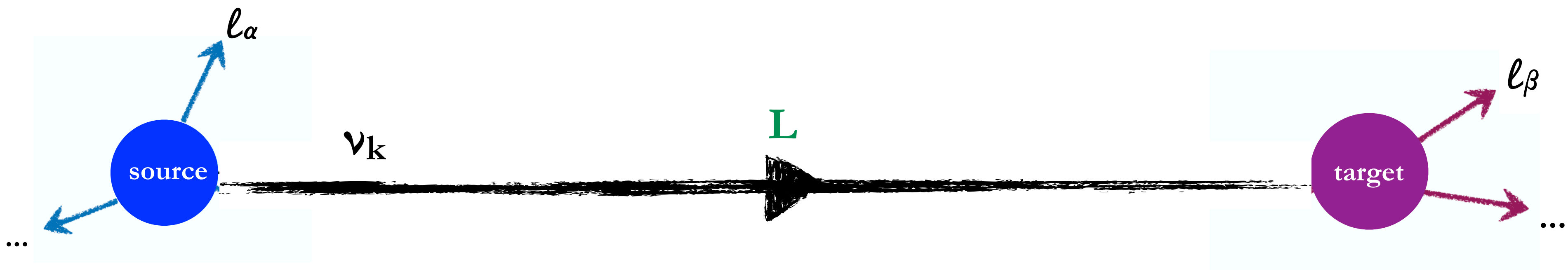

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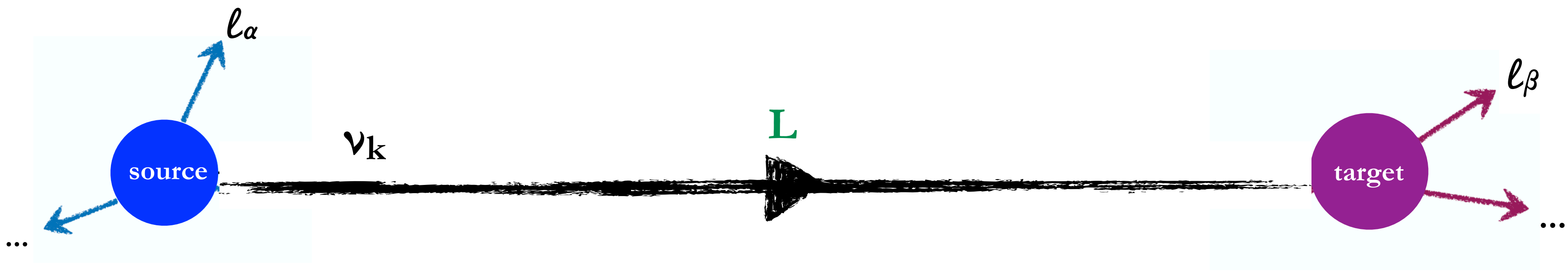

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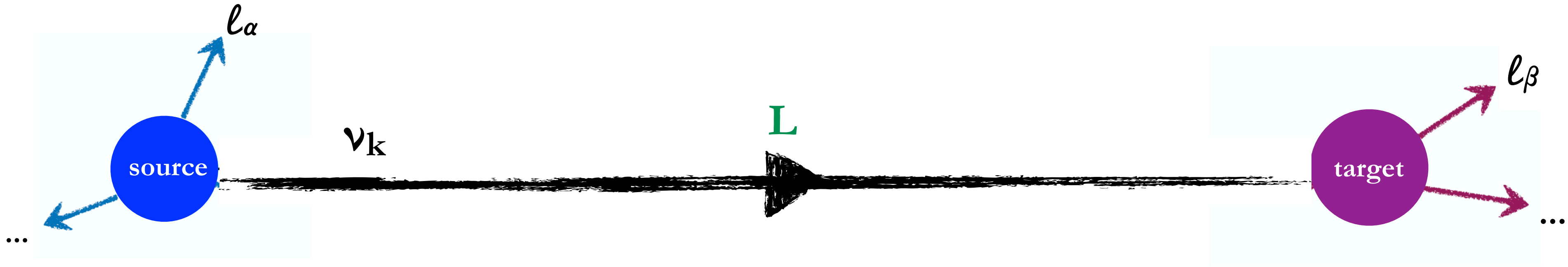

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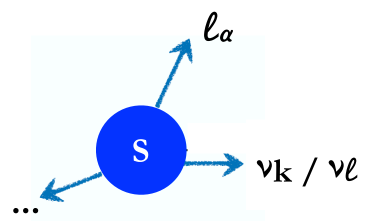

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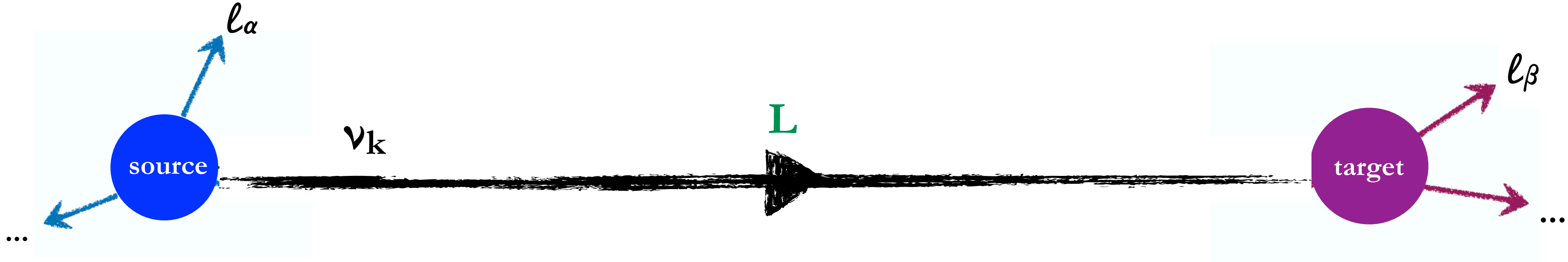

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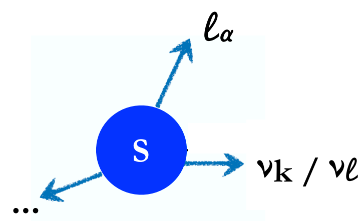

Phase space integrals: $d\Pi \equiv \frac{d^3k_1}{(2\pi)^3 2E_1} \ldots \frac{d^3k_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^4(\mathcal{P} - \sum k_i)$

$d\Pi_P \equiv d\Pi_{P'} dE_\nu$

Oscillations in QFT

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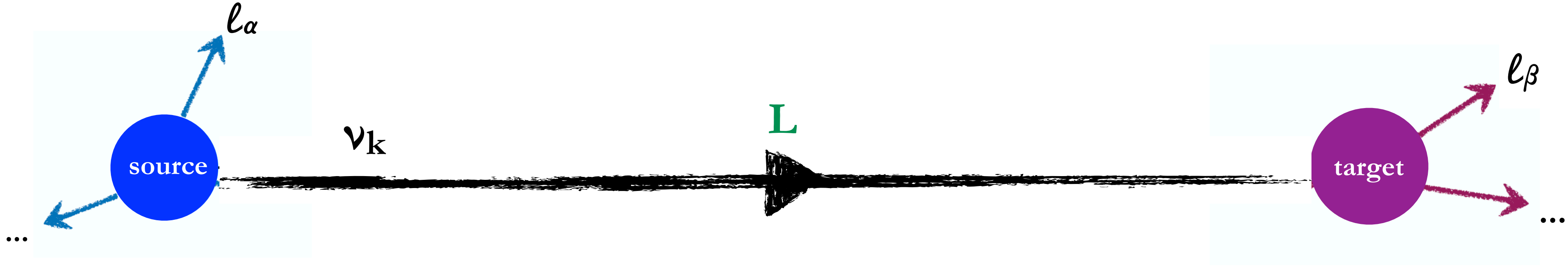

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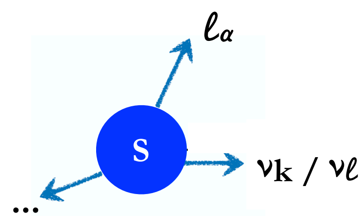
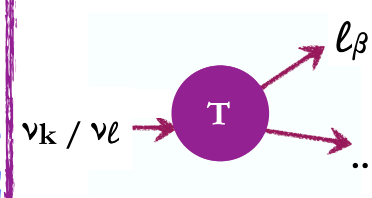


Detection

$\mathcal{M}^D_{\beta k} \equiv \mathcal{M}(\nu_k T \to Y_\beta)$



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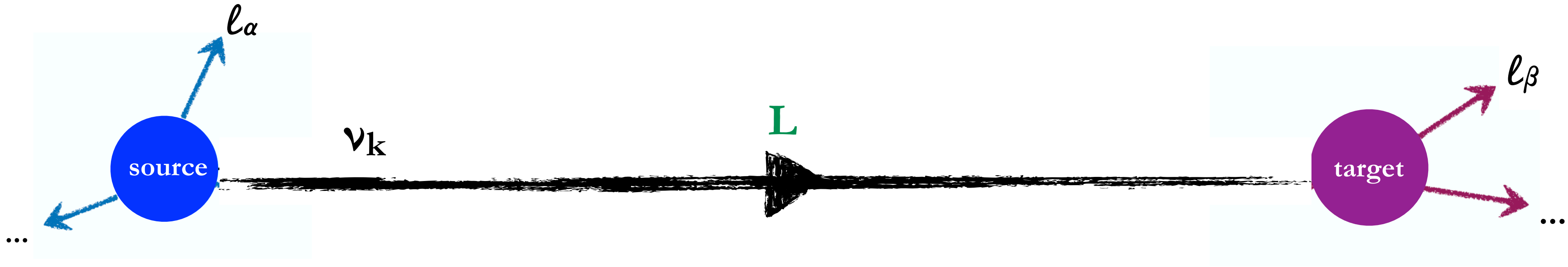

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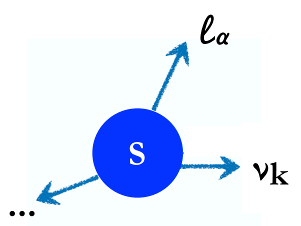
- The rest is "straightforward":
  specify the Lagrangian and calculate the production & detection amplitudes.



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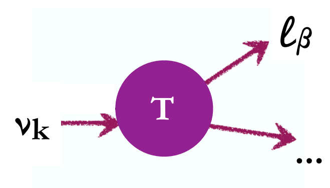
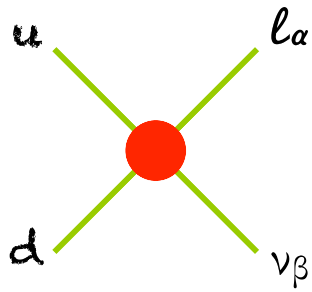


Oscillations in QFT → EFT

Low-energy effective Lagrangian:

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



NP models: W', charged scalar, LQ, ...

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$$
\begin{aligned}
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& + [\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
& + \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L \nu_\beta) \\
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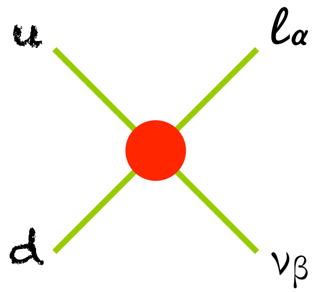
\end{aligned}
$$



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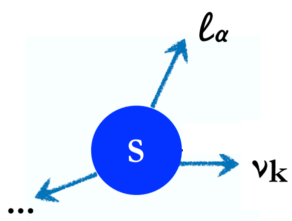

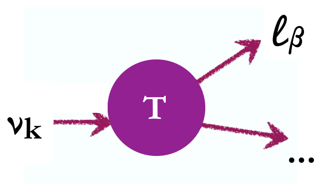

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\mathcal{M}(S \to X_\alpha \nu_k) = U^*_{\alpha k} A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k} A^P_X
$$

$$
\mathcal{M}(\nu_k T \to Y_\beta) = U_{\beta k} A^D_L + \sum_X [\epsilon_X U]_{\beta k} A^D_X
$$

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

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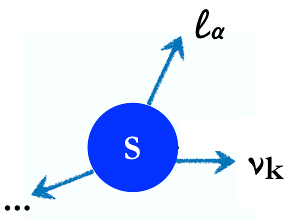

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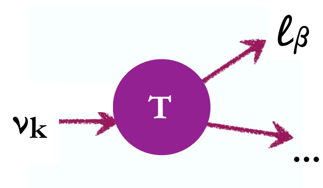

$$R_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \left[U^*_{\alpha k} U_{\alpha l} + p_{XL} (\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p^*_{XL} U^*_{\alpha k} (\epsilon_X U)_{\alpha l} + p_{XY} (\epsilon_X U)^*_{\alpha k} (\epsilon_Y U)_{\alpha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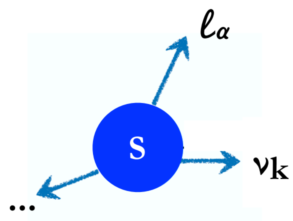

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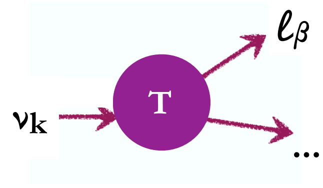

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$[\varepsilon = 0]$

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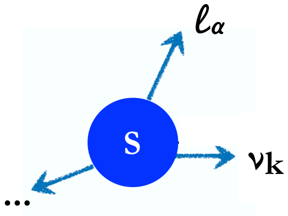

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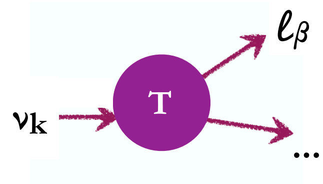

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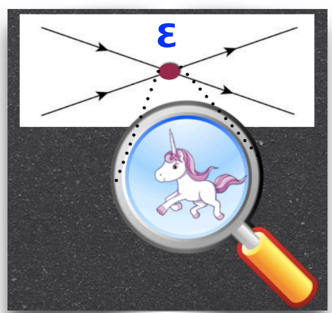
New qq'lν interactions



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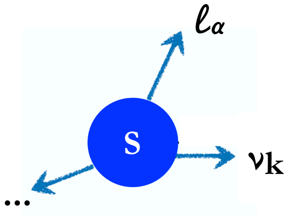

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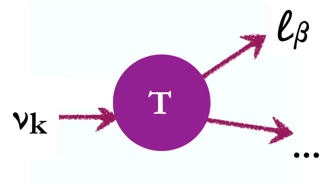

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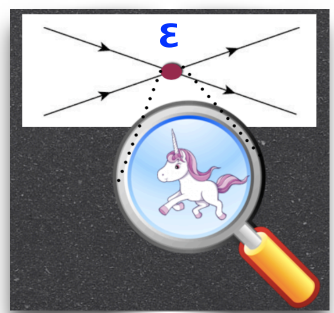
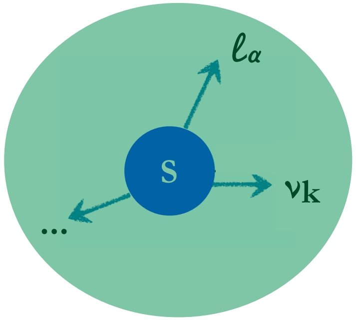
New qq'lν interactions



Oscillations in QFT → EFT

[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



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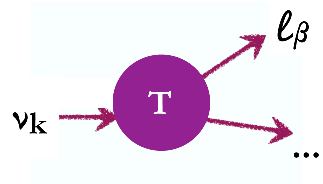

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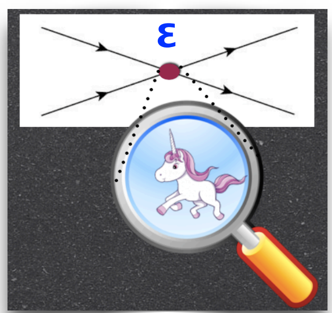
New qq'lν interactions

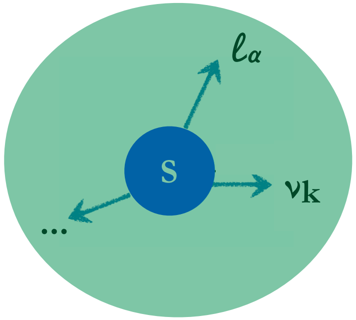
$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}$$

$$d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}$$



Oscillations in QFT → EFT

[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



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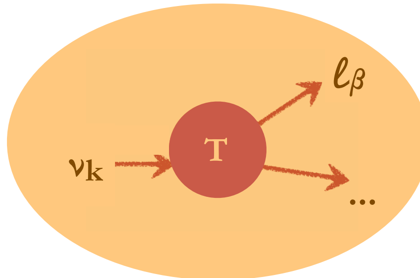

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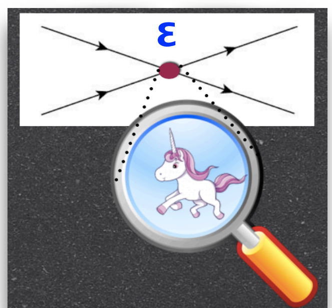
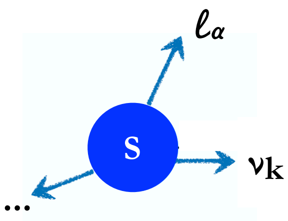


Oscillations in QFT → EFT

[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



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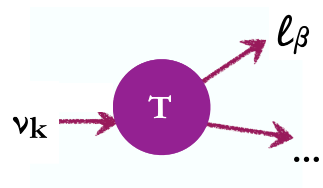

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$$R^{\rm EFT}_{\alpha\beta} = R_0 + c_X\,\epsilon_X + \mathcal{O}(\epsilon^2)$$

vs.

$$R^{\rm NSI}_{\alpha\beta} = R_0 + c^{s,d}\,\epsilon^{s,d} + \mathcal{O}(\epsilon^2)$$

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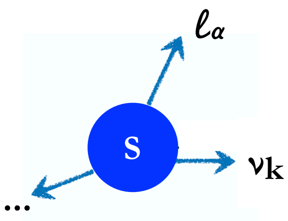

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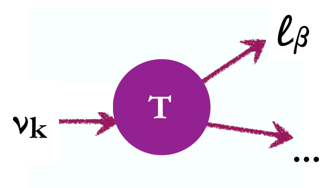

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⇒

$$\epsilon^s_{\alpha\beta} = \sum p_{XL}[\epsilon_X]^*_{\alpha\beta}$$

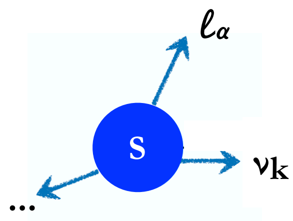
$$\epsilon^d_{\beta\alpha} = \sum_X d_{XL}[\epsilon_X]_{\alpha\beta}$$

Example: νp→ne

$$\epsilon^d_{\beta e} = \left[\epsilon_L + \frac{1-3g_A^2}{1+3g_A^2}\epsilon_R - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S - \frac{3g_A g_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta}$$

Oscillations in QFT → EFT

[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



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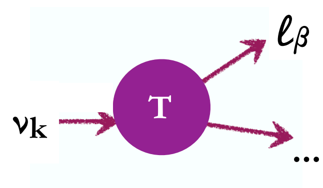

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But beyond linear order, there's no matching!!!
I.e., the NSI-QM approach fails in general.

Phenomenology

- Oscillation observable calculated in QFT in the presence of (heavy) CC NP

$$R_{\alpha\beta} = \Phi_\alpha^{\rm SM}\sigma_\beta^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m_{kl}^2}{2E_\nu}}\left[U_{\alpha k}^* U_{\alpha l} + p_{XL}(\epsilon_X U)_{\alpha k}^* U_{\alpha l} + p_{XL}^* U_{\alpha k}^*(\epsilon_X U)_{\alpha l} + p_{XY}(\epsilon_X U)_{\alpha k}^*(\epsilon_Y U)_{\alpha l}\right]$$
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[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]

- Choose your favourite experiment:

$$O = O\left(\theta_i, \Delta m^2, \varepsilon_j(\mu_{\text{Low}})\right) \Longrightarrow \varepsilon_j(\mu_{\text{Low}})$$

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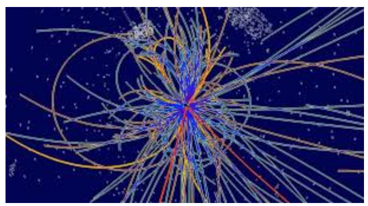
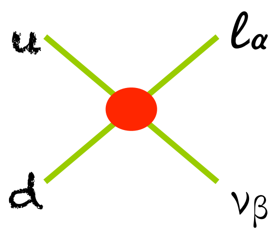
- Choose your favourite experiment:

$$O = O(\theta_i, \Delta m^2, \varepsilon_j(\mu_{\rm Low})) \Longrightarrow \varepsilon_j(\mu_{\rm Low})$$

- Now you can run, match, run, …

- Compare and combine with other searches.





Phenomenology

- Short-baseline reactor data [A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]

- FASERν [A. Falkowski, MGA, J. Kopp, Y. Soreq & Z. Tabrizi, JHEP'21]

Phenomenology

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- EFT analysis of COHERENT [Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of New Physics at COHERENT

Víctor Bresó-Pla[a] , Adam Falkowski[b] , Martín González-Alonso[a] , Kevin Monsálvez-Pozo[a]

[a] *Departament de Física Teòrica, IFIC, Universitat de València - CSIC, Apt. Correus 22085, E-46071 València, Spain*

[b] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*

ABSTRACT: Using an effective field theory approach, we study coherent neutrino scattering on nuclei, in the setup pertinent to the COHERENT experiment. We include non-standard effects both in neutrino production and detection, with an arbitrary flavor structure, with all leading Wilson coefficients simultaneously present, and without assuming factorization in flux times cross section. A concise description of the COHERENT event rate is obtained by introducing three generalized weak charges, which can be associated (in a certain sense) to the production and scattering of ν_e, ν_μ and $\bar{\nu}_\mu$ on the nuclear target. Our results are presented in a convenient form that can be trivially applied to specific New Physics scenarios. In particular, we find that existing COHERENT

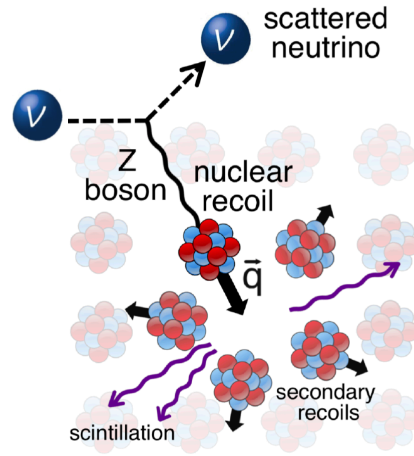
EFT analysis of NP at COHERENT

- COHERENT observed for the first time CEνNS (Coherent Elastic Neutrino-Nucleus Scattering): νN → νN

- It occurs for E_ν small enough so that the neutrino does not resolve the nucleus → CEνNS cross section enhanced by N^2. Theoretically known since the 70's [Freedman'74; Kopeliovich & Frankfurt'74]

- Extremely challenging experimentally (very small nuclear recoil)

- Observable: recoil and time distribution! (with LAr & CsI)

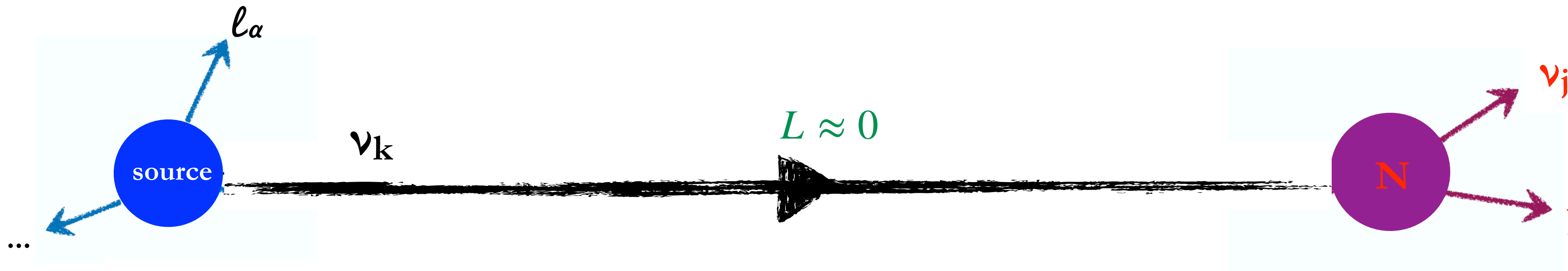


[from COHERENT coll.]

[Akimov et al.'17]

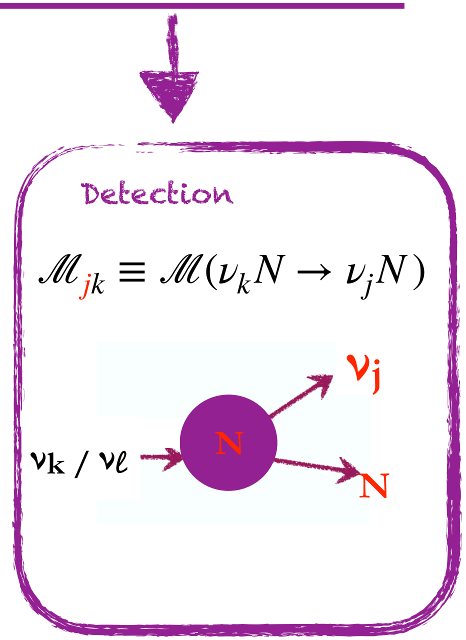
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of NP at COHERENT



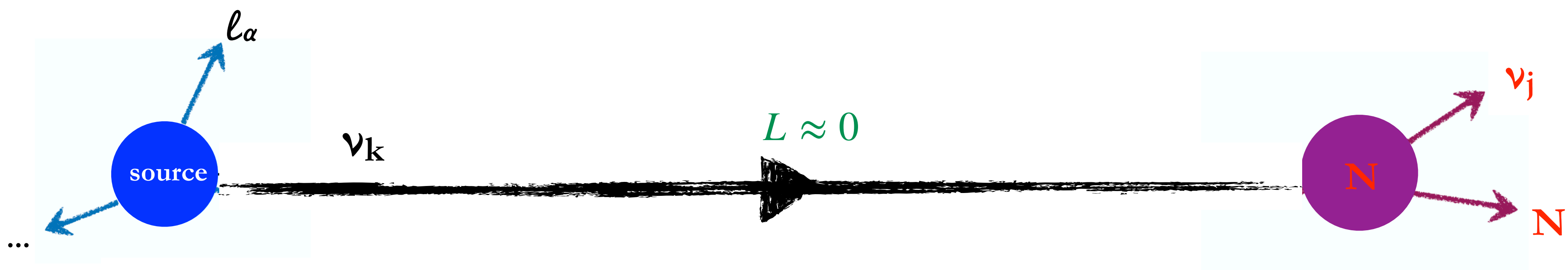
$$\sum_j R^S_{\alpha j} \equiv \frac{dN^S_{\alpha j}}{dt\,dE_\nu\,dT} = \frac{\kappa}{E_\nu}\sum_{k,l,j} \cancel{e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}}} \int d\Pi_{P'}\mathcal{M}^P_{\alpha k}\bar{\mathcal{M}}^P_{\alpha l}\int d\Pi_D \mathcal{M}^D_{jk}\bar{\mathcal{M}}^D_{jl}$$

- CC production: pion and muon decays.



[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of NP at COHERENT



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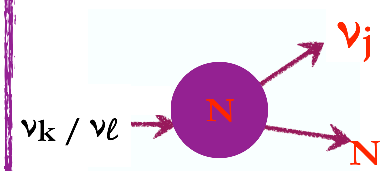
- CC production: pion and muon decays.
- NC detection: $\nu N \to \nu N$.

$$\mathcal{L}_{\rm WEFT} \subset -\frac{1}{v^2}\sum_{q=u,d}\Big\{\ [g_V^{qq}\,\mathbb{1} + \epsilon_V^{qq}]_{\alpha\beta}\,(\bar q\gamma^\mu q)\,(\bar\nu_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+\ [g_A^{qq}\,\mathbb{1} + \epsilon_A^{qq}]_{\alpha\beta}\,(\bar q\gamma^\mu\gamma^5 q)\,(\bar\nu_\alpha\gamma_\mu P_L\nu_\beta)\Big\}\,,$$

Detection

$$\mathcal{M}_{jk} \equiv \mathcal{M}(\nu_k N \to \nu_j N)$$



EFT analysis of NP at COHERENT

- SM prediction → one weak charge (per target nucleus)

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

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

$$\frac{d\sigma}{dT} = (m_{\mathcal{N}} + T) \frac{(\mathcal{F}(T))^2}{2 v^4 \, \pi} \left(1 - \frac{(m_{\mathcal{N}} + 2E_\nu)\, T}{2E_\nu^2} \right) Q^2$$

Weak charge: $Q^2_{SM} \sim N^2$

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of NP at COHERENT

- SM prediction → one weak charge (per target nucleus)
- EFT prediction → three weak charges (per target nucleus) [including, for the 1st time, generic NP in production & detection]

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

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

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

$$\tilde{Q}_f^2 \equiv Q_{SM}^2 + g_f(\epsilon_{NC}, \epsilon_{CC})$$

- These CC interactions *also* affect the pion/muon BR measurements, which are used to calculate the neutrino flux! → Crucial to take it into account.

EFT analysis of NP at COHERENT

- Simple case: linear NP effects → only (flavor-diagonal) detection NP remain:

$$Q_{\bar{\mu}}^2 = Q_{\mu}^2 = Q_{SM}^2 + 4\, Q_{SM} \left((A+Z)\epsilon_{\mu\mu}^{uu} + (2A-Z)\epsilon_{\mu\mu}^{dd} \right)$$

$$Q_{e}^2 = Q_{SM}^2 + 4\, Q_{SM} \left((A+Z)\epsilon_{ee}^{uu} + (2A-Z)\epsilon_{ee}^{dd} \right)$$

EFT analysis of NP at COHERENT

- Simple case: linear NP effects → only (flavor-diagonal) detection NP remain:

$$Q^2_{\bar{\mu}} = Q^2_{\mu} = Q^2_{SM} + 4\,Q_{SM}\left((A+Z)\epsilon^{uu}_{\mu\mu} + (2A-Z)\epsilon^{dd}_{\mu\mu}\right)$$
$$Q^2_{e} = Q^2_{SM} + 4\,Q_{SM}\left((A+Z)\epsilon^{uu}_{ee} + (2A-Z)\epsilon^{dd}_{ee}\right)$$

- Current COHERENT data (LAr + CsI, recoil & time distribution) give:

$$0.68\,\epsilon^{dd}_{ee} + 0.61\,\epsilon^{uu}_{ee} - 0.30\,\epsilon^{dd}_{\mu\mu} - 0.27\,\epsilon^{uu}_{\mu\mu} = 0.037(42)$$
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[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of NP at COHERENT

- Simple case: linear NP effects → only (flavor-diagonal) detection NP remain:

$$Q^2_{\bar{\mu}} = Q^2_{\mu} = Q^2_{SM} + 4\,Q_{SM}\left((A+Z)\epsilon^{uu}_{\mu\mu} + (2A-Z)\epsilon^{dd}_{\mu\mu}\right)$$
$$Q^2_{e} = Q^2_{SM} + 4\,Q_{SM}\left((A+Z)\epsilon^{uu}_{ee} + (2A-Z)\epsilon^{dd}_{ee}\right)$$

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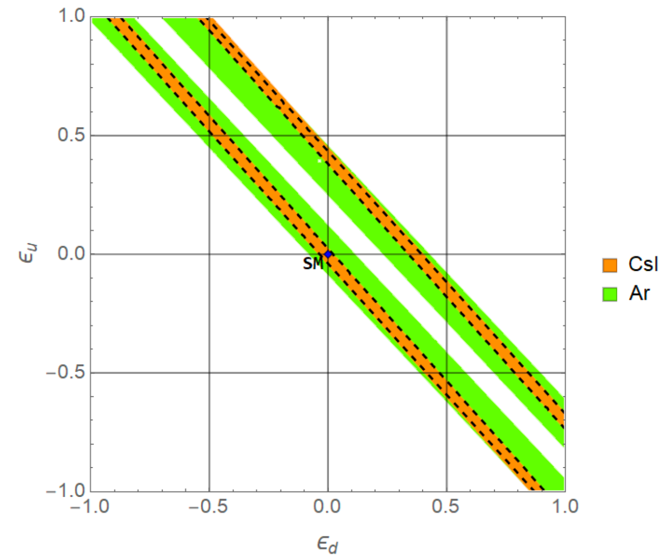
$$\epsilon^{uu}_{ee} = \epsilon^{uu}_{\mu\mu} \equiv \epsilon_u$$
$$\epsilon^{dd}_{ee} = \epsilon^{dd}_{\mu\mu} \equiv \epsilon_d$$

[Lepton-flavor universal case]

$$0.67\epsilon_u + 0.74\epsilon_d = -\,0.002 \pm 0.010,$$



[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

COHERENT in the SMEFT

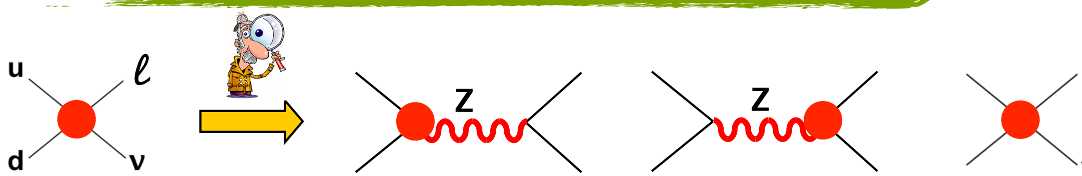
- "Flavor-blind" SMEFT (→ U(3)⁵ symmetry)

$$0.67\epsilon_u + 0.74\epsilon_d = -\,0.002 \pm 0.010,$$

$$\epsilon_u = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8s_\theta^2}{3}\right)\delta g_L^{Z\nu} - \frac{1}{2}\left(c_{lq}^{(1)} + c_{lq}^{(3)} + c_{lu}\right)$$

$$\epsilon_d = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu} - \frac{1}{2}\left(c_{lq}^{(1)} - c_{lq}^{(3)} + c_{ld}\right)$$

WEFT/SMEFT Matching



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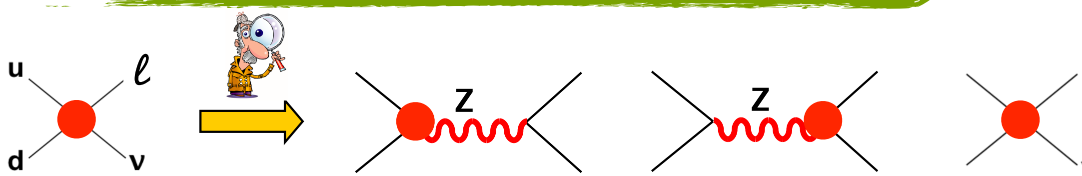

$$0.71c_{lq}^{(1)} - 0.04c_{lq}^{(3)} + 0.34c_{lu} + 0.37c_{ld} + [\delta g]_{\rm piece} = -0.003 \pm 0.010\,,$$

$$[\delta g]_{\rm piece} \equiv -0.67(\delta g_L^{Zu} + \delta g_R^{Zu}) - 0.74(\delta g_L^{Zd} + \delta g_R^{Zd}) + 0.26\delta g_L^{Z\nu}$$

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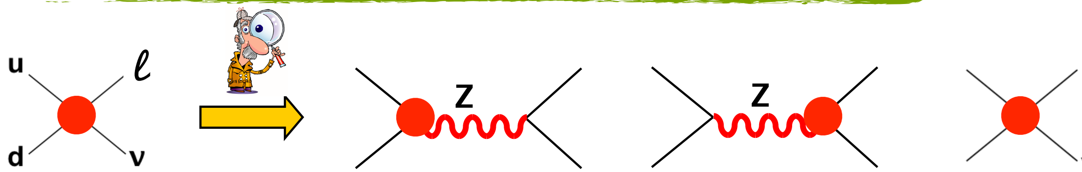

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- Is COHERENT probing a new region in the SMEFT parameter space?
  These operators are constrained by many EWPO: LEP1, LEP2, APV, … → Global fit needed!

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

COHERENT in the SMEFT

- "Flavor-blind" SMEFT (→ $U(3)^5$ symmetry)
- Global fit to Electroweak precision observables:
  - Z- & W-pole data
  - $e^+e^- \to l^+l^-$, qq
  - Low-energy processes:
    Atomic PV, d→ulν, tau decays, …
    + COHERENT!

Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to ff)$
σ_{had} [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\text{FB}}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\text{FB}}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\text{FB}}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to bb)}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
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A_e	0.1516 ± 0.0021	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
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A_e	0.1498 ± 0.0049	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_τ	0.1439 ± 0.0043	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[47]	0.935	$\frac{\Gamma(Z\to b_L b_L)-\Gamma(Z\to b_R b_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[47]	0.668	$\frac{\Gamma(Z\to c_L \bar{c}_L)-\Gamma(Z\to c_R \bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[48]	0.935	$\frac{\Gamma(Z\to s_L \bar{s}_L)-\Gamma(Z\to s_R \bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
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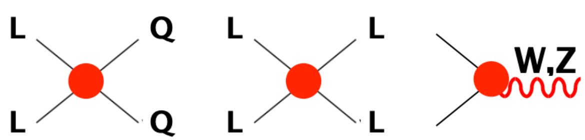

Update of [Falkowski, MGA & Mimouni, JHEP'17]

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

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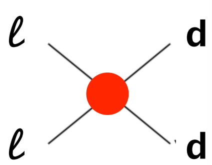
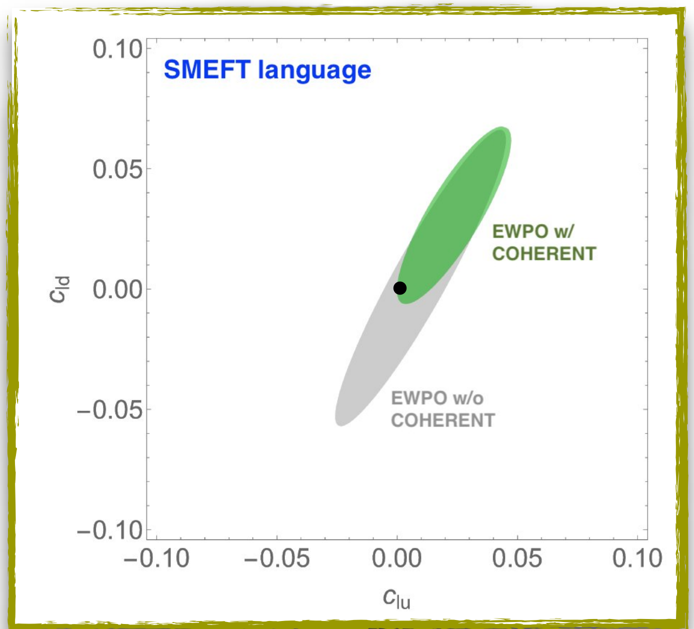


$\bar{\ell}\gamma_\mu \ell \; \bar{d}\gamma^\mu d$



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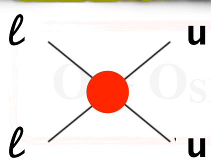

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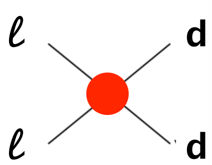
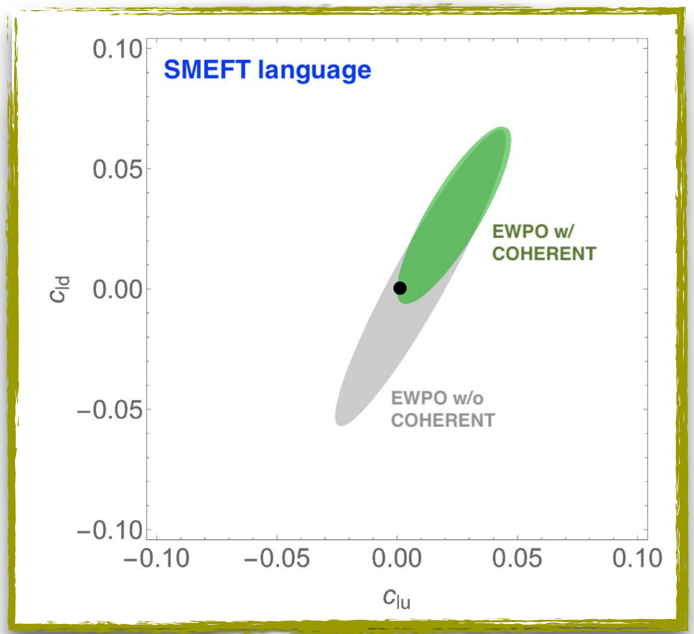
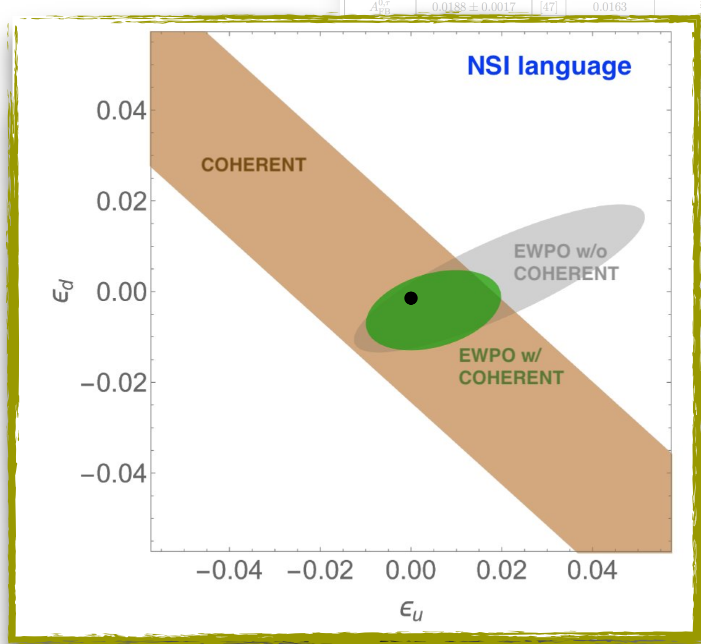
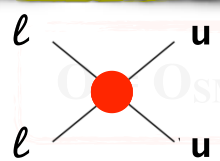


$\bar{\ell}\gamma_\mu\ell\ \bar{d}\gamma^\mu d$





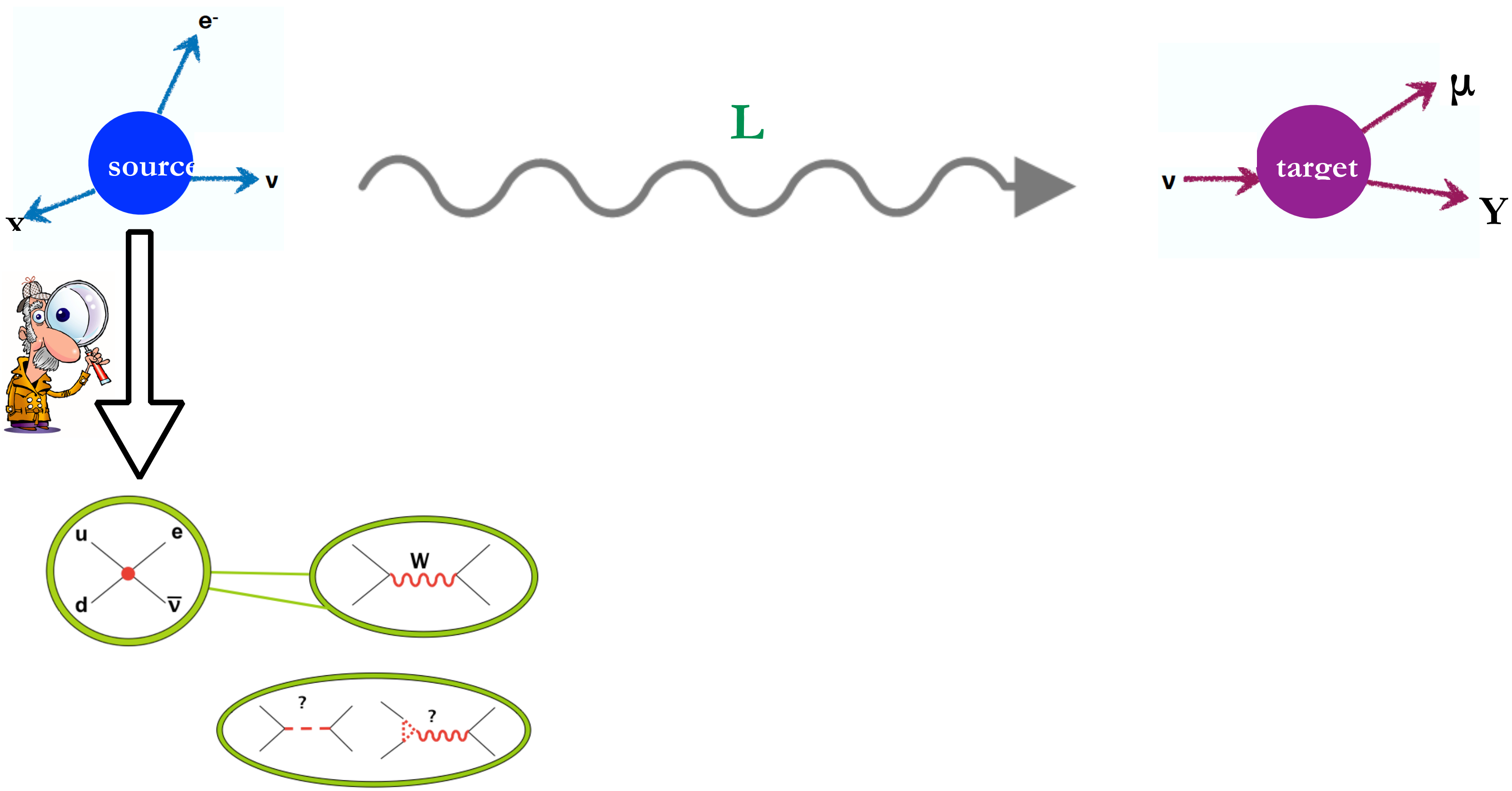
$\bar{\ell}\gamma_\mu\ell\ \bar{u}\gamma^\mu u$



Summary

- The path to analyze any given neutrino experiment in the presence of **generic** (heavy) New Physics is now clear.

$$O = O(\theta_i, \Delta m^2, \varepsilon_j)$$



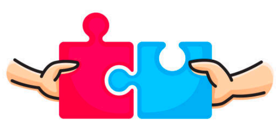
Summary

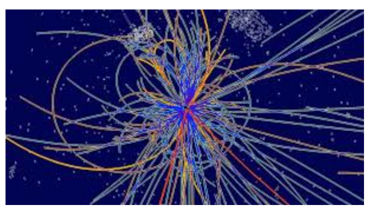
- The path to analyze any given neutrino experiment in the presence of **generic** (heavy) New Physics is now clear.

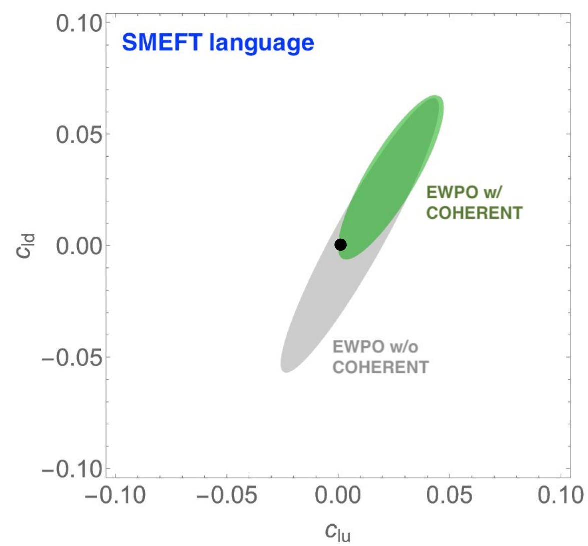
$$O = O\,(\theta_i,\ \Delta m^2,\ \varepsilon_j)$$

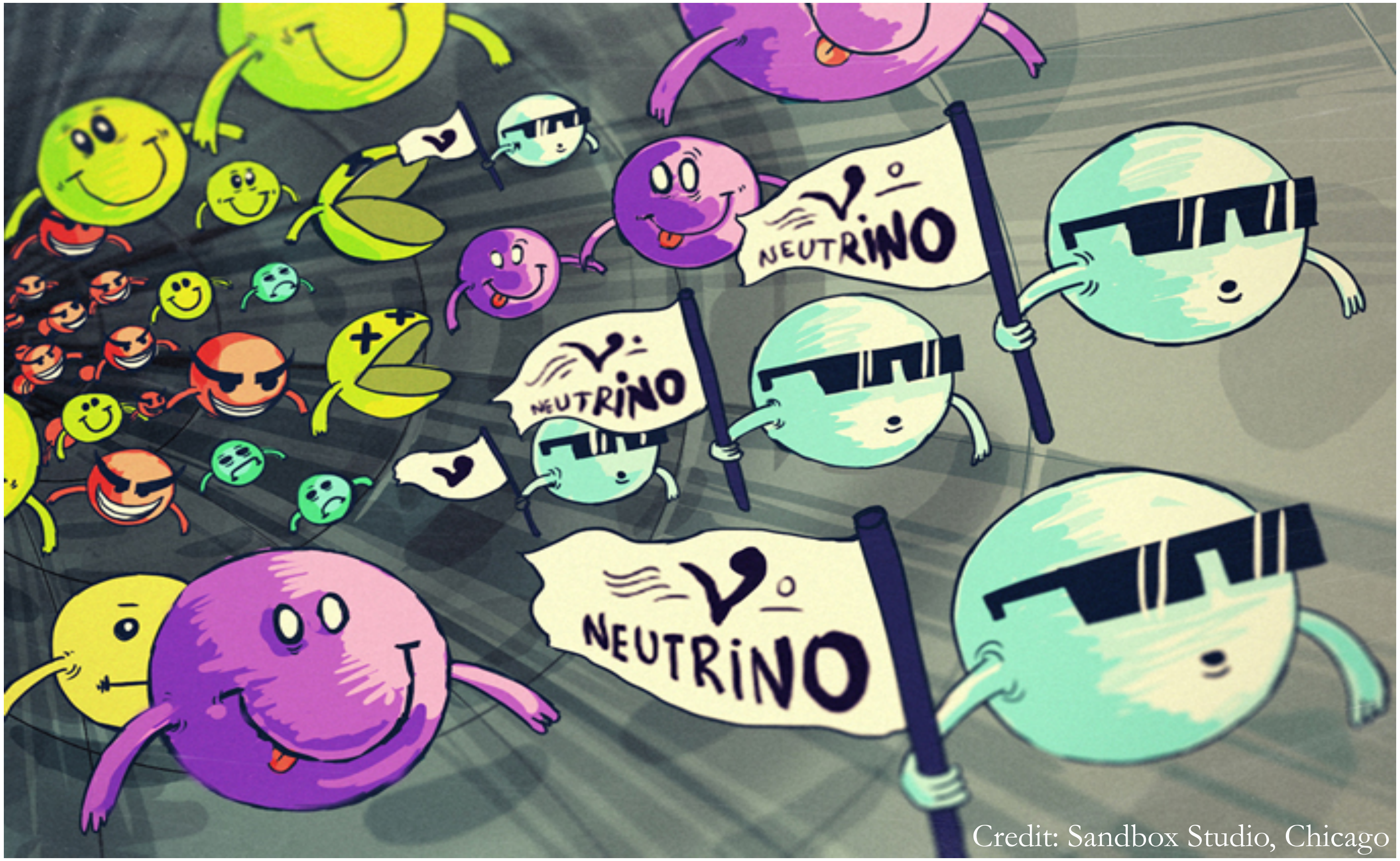
- We have done it for several experiments.

- This allows us to:
  - Understand the UV meaning of that experiment;
  - Have a general description (parametrization) of it;
  - Compare/combine with any other experiment;





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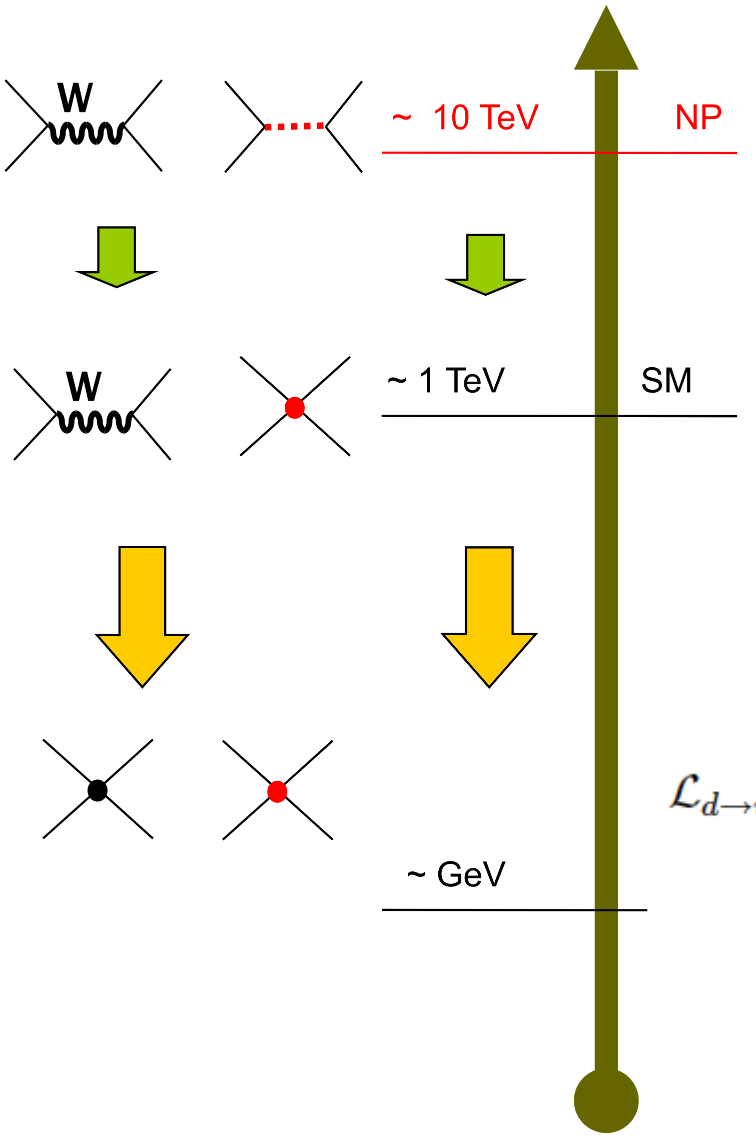
Credit: Sandbox Studio, Chicago

Thanks!

Backups

Introduction



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields}, \text{ bSM fields})$$

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\, \mathcal{O}_i$$

Standard Model EFT

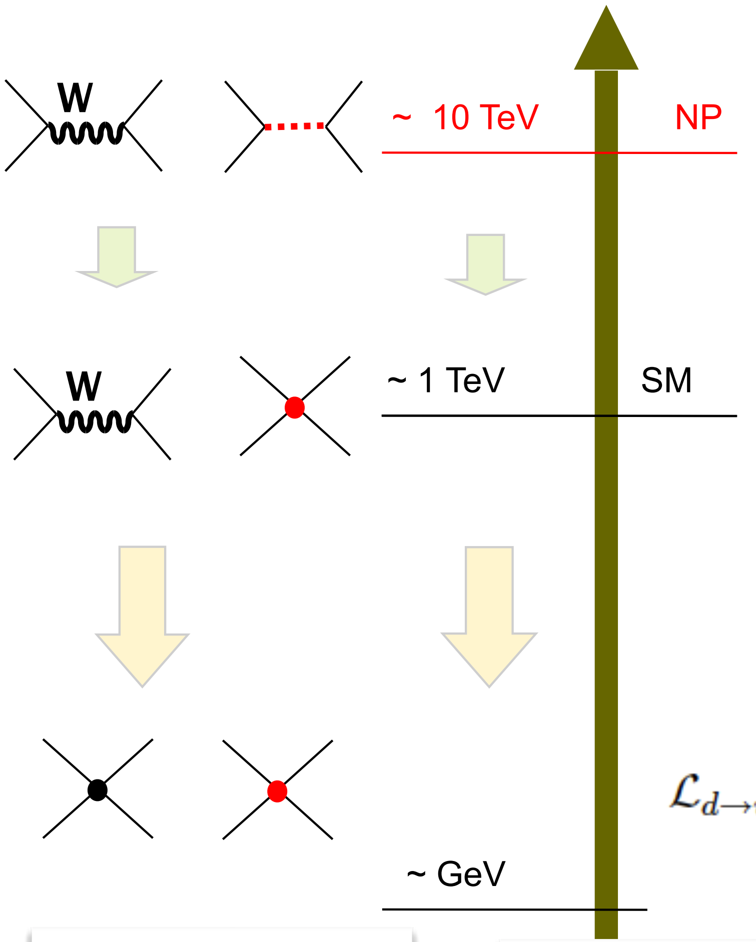
[Buchmuller & Wyler'86,
Leung et al.'86,
Grzadkowksi et al., 10,
Jenkins et al'13, ...]

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\;\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

Low-energy EFT

[Cirigliano et al'09,
Aebischer al.'15,
Jenkins et al'18, ...]

Introduction



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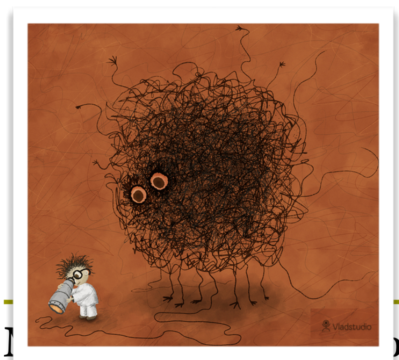
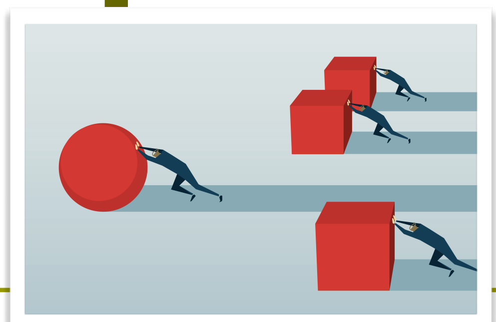
Low-E precision data

(+ SM prediction)



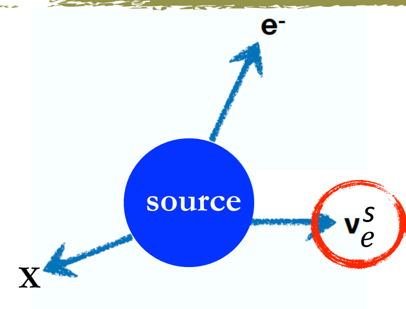


[Grossman'95, Gonzalez-Garcia et al.'01, Ohlsson'13, Farzan & Tortola'17, ...]

Traditional QM-NSI approach

- Source / detection NSIs are NOT Lagrangian parameters.

$$P^{s\to d}_{\nu_\alpha\to\nu_\beta} = |\langle \nu^d_\beta(L)|\nu^s_\alpha\rangle|^2 = f\,(\,U_{ij}\,,\,\Delta m^2,\,\varepsilon^s,\,\varepsilon^d\,)$$



$$|\nu^s_\alpha\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N^s_\alpha}|\nu_\gamma\rangle$$

Normalization:

$$N^s_\alpha = \sqrt{[(1+\epsilon^s)(1+\epsilon^{s\,\dagger})]_{\alpha\alpha}}$$

- But... $\varepsilon^s,\ \varepsilon^d = f\,(\ ?\ )$

- NSI parameters are process-dependent!
  - Comparison of NSIs for 2 different production processes?
  - Comparison of NSIs with non-oscillation searches?
  - Meaning of these NSI in terms of fundamental BSM parameters?

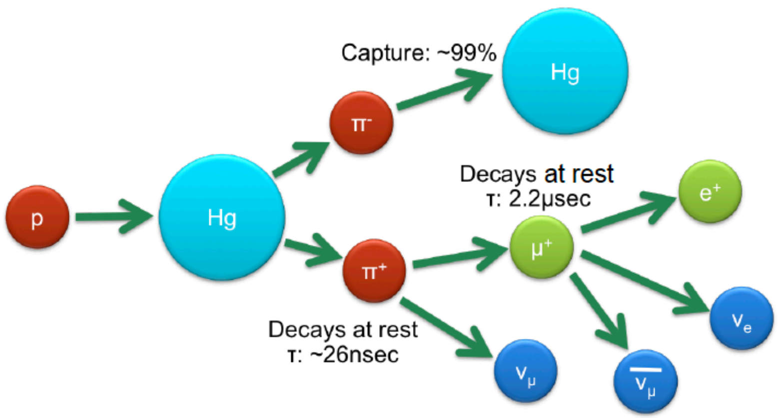
- Also: are production & detection NSI unrelated? Are they energy independent?

- Conclusion:
  we need to match NSI to a Lagrangian → QFT approach needed

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

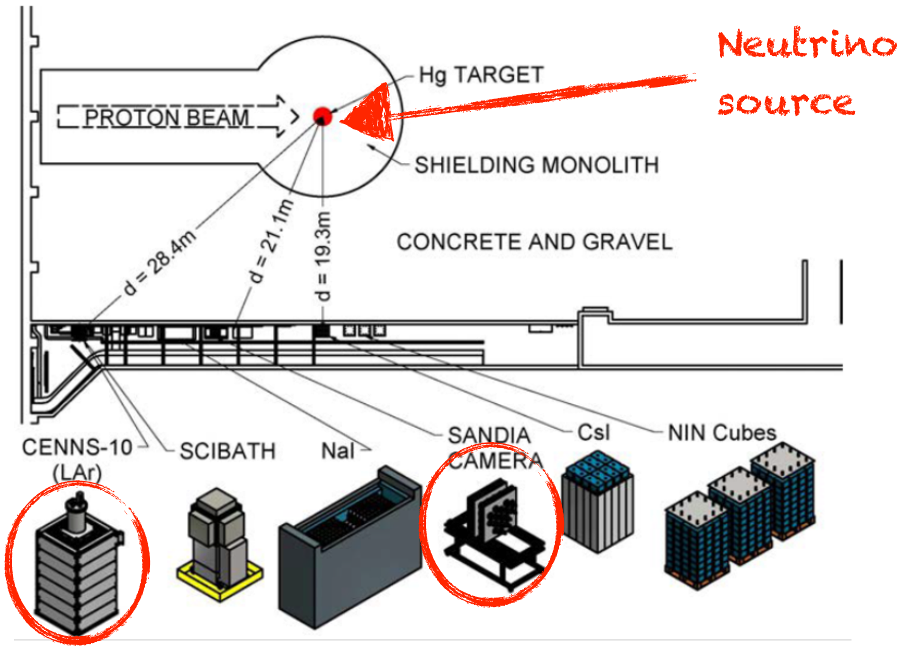
EFT analysis of NP at COHERENT

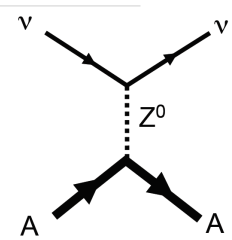
Neutrino production



[from Scholberg's talk at IPA18]

Neutrino detection





[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of NP at COHERENT

- Case A:
  NP only in detection (usual NSI assumption) → agreement with previous works.

$$Q^2_{\bar{\mu}} = Q^2_{\mu} = Q^2_{SM} + g_f(\epsilon^{uu}_{\alpha\mu}, \epsilon^{dd}_{\alpha\mu})$$
$$Q^2_{e} = Q^2_{SM} + g_f(\epsilon^{uu}_{\alpha e}, \epsilon^{dd}_{\alpha e})$$

$$\tilde{Q}^2_{\mu} = \tilde{Q}^2_{\bar{\mu}} = \left[\mathcal{Q}^2\right]_{\mu\mu} = \sum_{\alpha} |[\mathcal{Q}]_{\alpha\mu}|^2 = \sum_{\alpha} \left| Z g^{\nu p}_{\alpha\mu} + (A-Z) g^{\nu n}_{\alpha\mu} \right|^2$$
$$= 4 \sum_{\alpha} \left[(A+Z)(g_V^{uu}\,\mathbb{1} + \epsilon^{uu}) + (2A-Z)(g_V^{dd}\,\mathbb{1} + \epsilon^{dd}) \right]^2_{\alpha\mu},$$
$$\tilde{Q}^2_{e} = \left[\mathcal{Q}^2\right]_{ee} = \sum_{\alpha} |[\mathcal{Q}]_{\alpha e}|^2 = \sum_{\alpha} \left| \left(Z g^{\nu p}_{\alpha e} + (A-Z) g^{\nu n}_{\alpha e} \right) \right|^2$$
$$= 4 \sum_{\alpha} \left[(A+Z)(g_V^{uu}\,\mathbb{1} + \epsilon^{uu}) + (2A-Z)(g_V^{dd}\,\mathbb{1} + \epsilon^{dd}) \right]^2_{\alpha e}.$$

- Case B:
  NP only in production → NP cancel completely!
  [this invalidates the bounds obtained in Khan, McKay, & Rodejohann, PRD'2021]

$$Q^2_{\bar{\mu}} = Q^2_{\mu} = Q^2_{SM} + 4\, Q_{SM} \left((A+Z)\epsilon^{uu}_{\mu\mu} + (2A-Z)\epsilon^{dd}_{\mu\mu} \right)$$
$$Q^2_{e} = Q^2_{SM} + 4\, Q_{SM} \left((A+Z)\epsilon^{uu}_{ee} + (2A-Z)\epsilon^{dd}_{ee} \right)$$

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

EFT analysis of NP at COHERENT

- Case A:
  NP only in detection (usual NSI assumption) → agreement with previous works.

$$
\begin{aligned}
Q_{\bar{\mu}}^2 = Q_{\mu}^2 &= Q_{SM}^2 + g_f(\epsilon_{\alpha\mu}^{uu}, \epsilon_{\alpha\mu}^{dd}) \\
Q_{e}^2 &= Q_{SM}^2 + g_f(\epsilon_{\alpha e}^{uu}, \epsilon_{\alpha e}^{dd})
\end{aligned}
$$

$$
\begin{aligned}
\tilde{Q}_{\mu}^2 = \tilde{Q}_{\bar{\mu}}^2 &= [\mathcal{Q}^2]_{\mu\mu} = \sum_{\alpha} |[\mathcal{Q}]_{\alpha\mu}|^2 = \sum_{\alpha} \left| Z g_{\alpha\mu}^{\nu p} + (A-Z) g_{\alpha\mu}^{\nu n} \right|^2 \\
&= 4 \sum_{\alpha} \left[(A+Z)(g_V^{uu}\mathbb{1} + \epsilon^{uu}) + (2A-Z)(g_V^{dd}\mathbb{1} + \epsilon^{dd}) \right]_{\alpha\mu}^2 , \\
\tilde{Q}_{e}^2 &= [\mathcal{Q}^2]_{ee} = \sum_{\alpha} |[\mathcal{Q}]_{\alpha e}|^2 = \sum_{\alpha} \left| \left(Z g_{\alpha e}^{\nu p} + (A-Z) g_{\alpha e}^{\nu n} \right) \right|^2 \\
&= 4 \sum_{\alpha} \left[(A+Z)(g_V^{uu}\mathbb{1} + \epsilon^{uu}) + (2A-Z)(g_V^{dd}\mathbb{1} + \epsilon^{dd}) \right]_{\alpha e}^2 .
\end{aligned}
$$

- Case B:
  NP only in production → NP cancel completely!
  [this invalidates the bounds obtained in Khan, McKay, & Rodejohann, PRD'2021]

$$
Q_{\bar{\mu}}^2 = Q_{\mu}^2 = Q_{e}^2 = Q_{SM}^2
$$

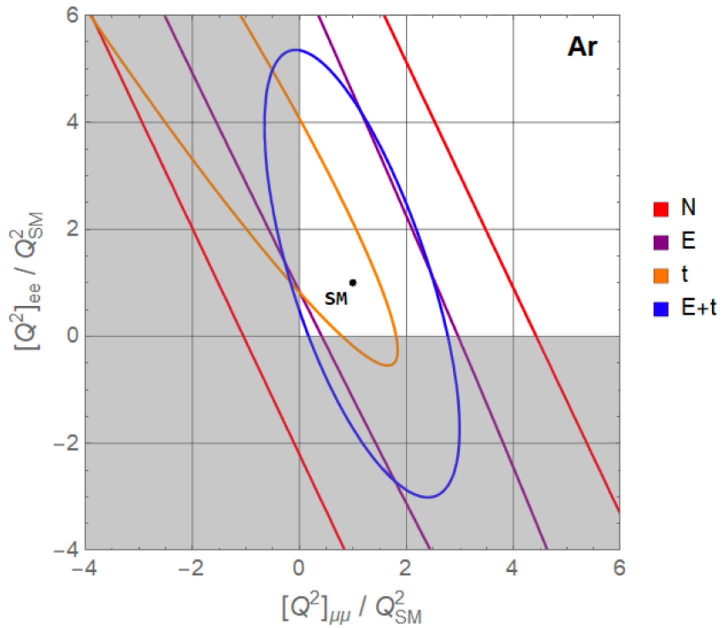
- Case C:
  linear NP effects → only (flavor-diagonal) detection NP remain:

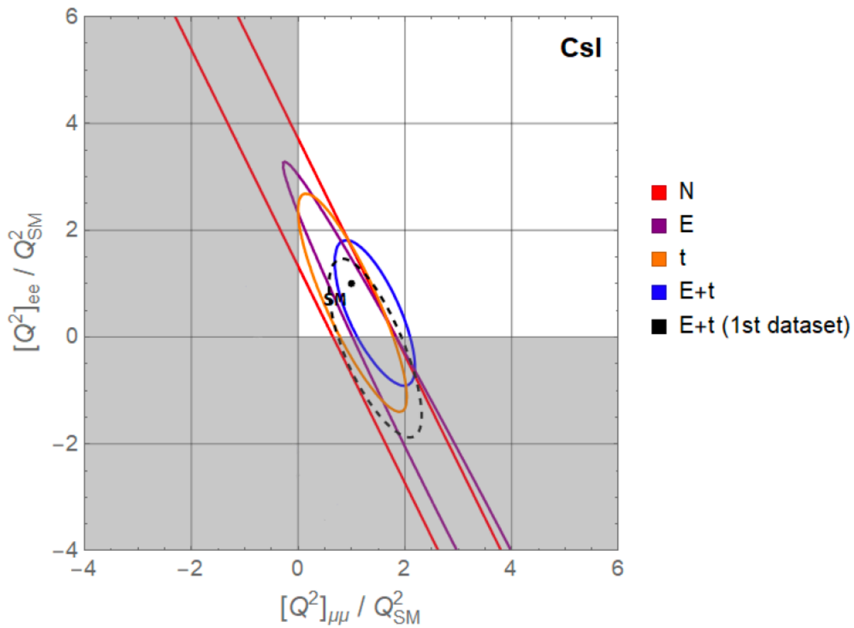
$$
\begin{aligned}
Q_{\bar{\mu}}^2 = Q_{\mu}^2 &= Q_{SM}^2 + 4\,Q_{SM}\left((A+Z)\epsilon_{\mu\mu}^{uu} + (2A-Z)\epsilon_{\mu\mu}^{dd}\right) \\
Q_{e}^2 &= Q_{SM}^2 + 4\,Q_{SM}\left((A+Z)\epsilon_{ee}^{uu} + (2A-Z)\epsilon_{ee}^{dd}\right)
\end{aligned}
$$

EFT analysis of NP at COHERENT

- Case A:
  NP only in detection (usual NSI assumption) → agreement with previous works.

$$Q^2_{\bar{\mu}} = Q^2_{\mu} = Q^2_{SM} + g_f(\epsilon^{uu}_{\alpha\mu}, \epsilon^{dd}_{\alpha\mu})$$
$$Q^2_{e} = Q^2_{SM} + g_f(\epsilon^{uu}_{\alpha e}, \epsilon^{dd}_{\alpha e})$$



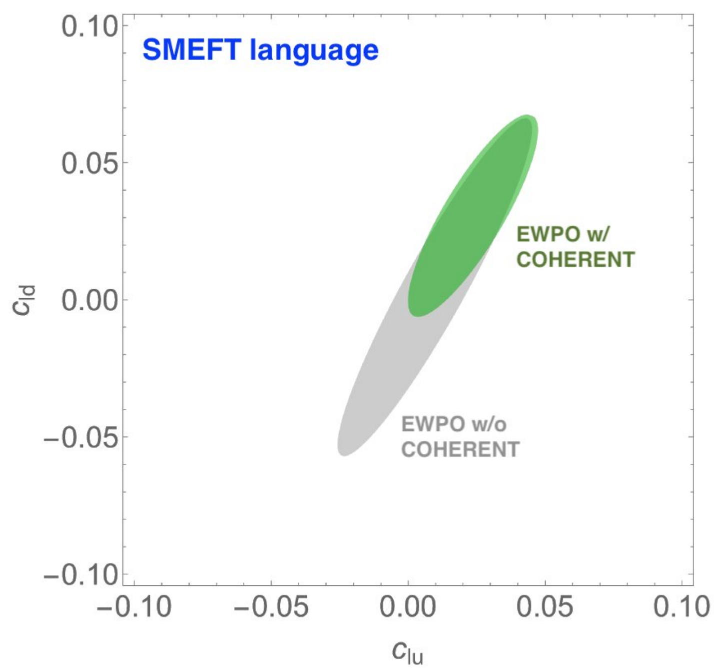


[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

COHERENT in the SMEFT

- "Flavor-blind" SMEFT (more precisely: U(3)^5 symmetry)
- Global fit to EWPO

$$
\begin{pmatrix}
\delta g_L^{W\ell} \\ \delta g_L^{Ze} \\ \delta g_R^{Ze} \\ \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \\ c_{lq}^{(1)} \\ c_{lq}^{(3)} \\ c_{lu} \\ c_{ld} \\ c_{eq} \\ c_{eu} \\ c_{ed} \\ c_{ll}^{(1)} \\ c_{ll}^{(3)} \\ c_{le} \\ c_{ee}
\end{pmatrix}
=
\begin{pmatrix}
\text{w/o COHERENT} \\ -0.27(79) \\ -0.10(0.21) \\ -0.20(22) \\ -1.0(1.6) \\ -0.5(3.2) \\ 1.5(1.3) \\ 12.8(6.7) \\ -16.6(9.0) \\ -2.4(1.9) \\ 10(23) \\ 5(41) \\ -13(22) \\ 7(10) \\ 25(18) \\ 5.4(3.2) \\ -0.9(1.6) \\ 0.2(1.3) \\ -2.7(3.0)
\end{pmatrix}
\times 10^{-3} \rightarrow
\begin{pmatrix}
\text{w/ COHERENT} \\ -0.26(78) \\ -0.09(21) \\ -0.17(22) \\ -1.3(1.6) \\ -1.1(3.1) \\ 1.1(1.2) \\ 10.4(5.8) \\ -18.3(8.7) \\ -2.2(1.8) \\ 23(16) \\ 29(24) \\ -1(15) \\ 3.5(9.4) \\ 29(17) \\ 5.3(3.2) \\ -0.9(1.6) \\ 0.2(1.3) \\ -2.7(3.0)
\end{pmatrix}
\times 10^{-3}.
$$

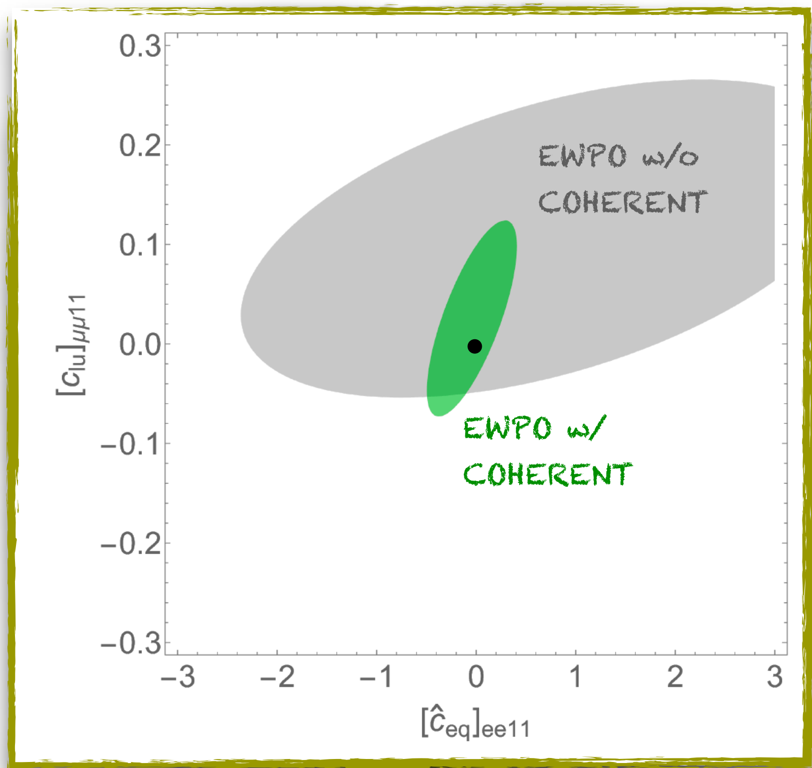


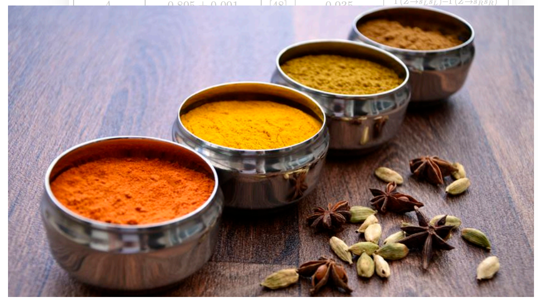
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, arXiv:2301.07036]

COHERENT in the *flavorful* SMEFT

- "Flavor-blind" SMEFT (more precisely: $U(3)^5$ symmetry)
- Electroweak precision observables;

Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to ff)$
σ_{had} [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{FB}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{FB}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{FB}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to bb)}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
A_c^{FB}	0.0707 ± 0.0035	[47]	0.0738	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_e	0.1498 ± 0.0049	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_τ	0.1439 ± 0.0043	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[47]	0.935	$\frac{\Gamma(Z\to b_L b_L)-\Gamma(Z\to b_R b_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[47]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$



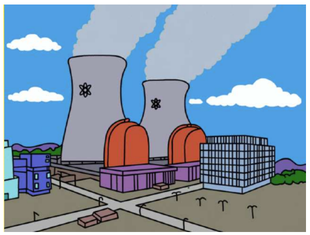


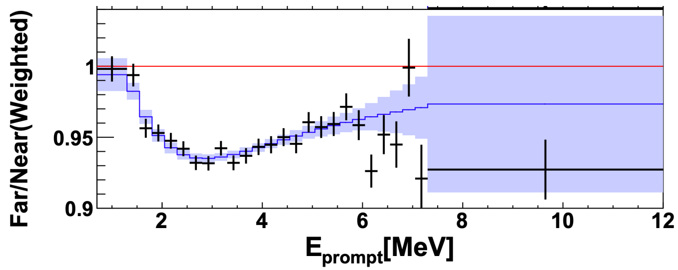
χ^2 (c_i)

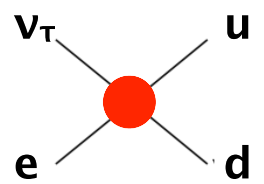
Other EFT studies of neutrino data

- Short-baseline reactor data [A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]
  $L \neq 0 \rightarrow$ PMNS factors, Δm_{ij} & linear effects from flavor off-diagonal interactions!

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\theta_{13}\right) + f\left([\varepsilon_S]_{e\mu,e\tau}, [\varepsilon_T]_{e\mu,e\tau}\right)$$







% level bounds (TeV scale)

- FASERν [A. Falkowski, MGA, J. Kopp, Y. Soreq & Z. Tabrizi, JHEP'21]
  - $L \approx 0 \rightarrow$ PMNS factors & Δm_{ij} gone
  - High-E $\rightarrow$ many flavor and Lorentz structures available!