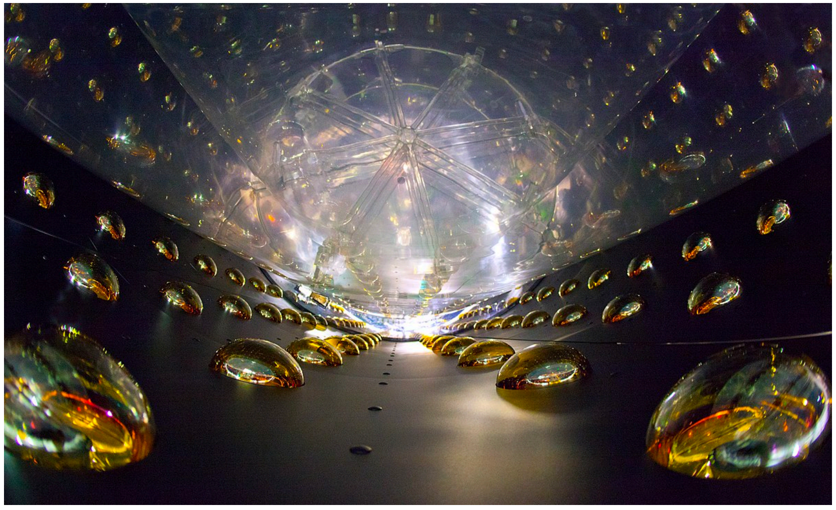
# EFT analysis of New Physics at COHERENT

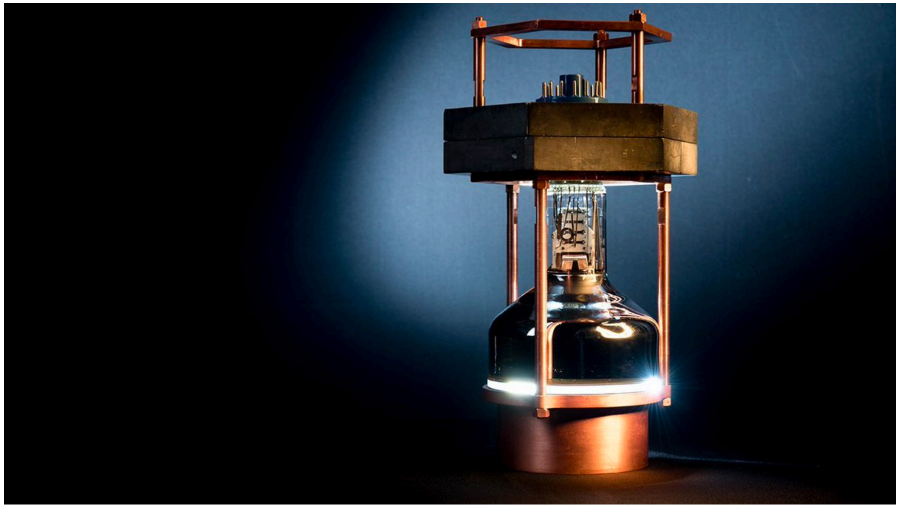
HEFT 2023 | June 2023

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

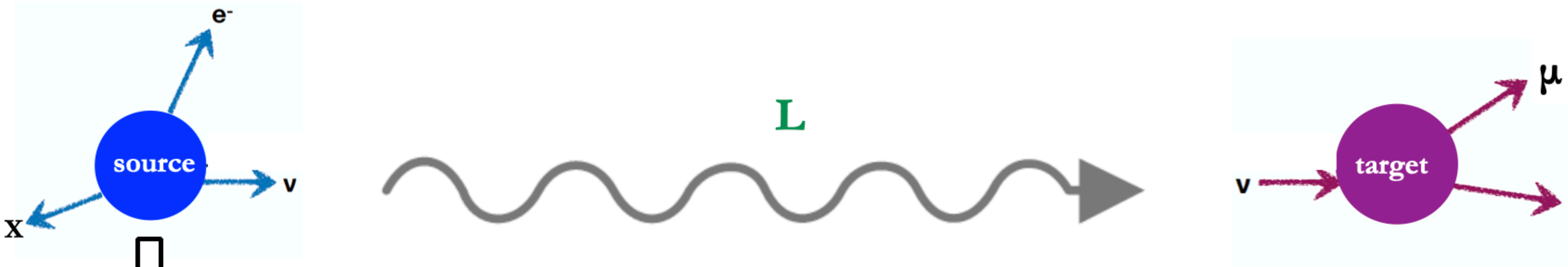
# Outline

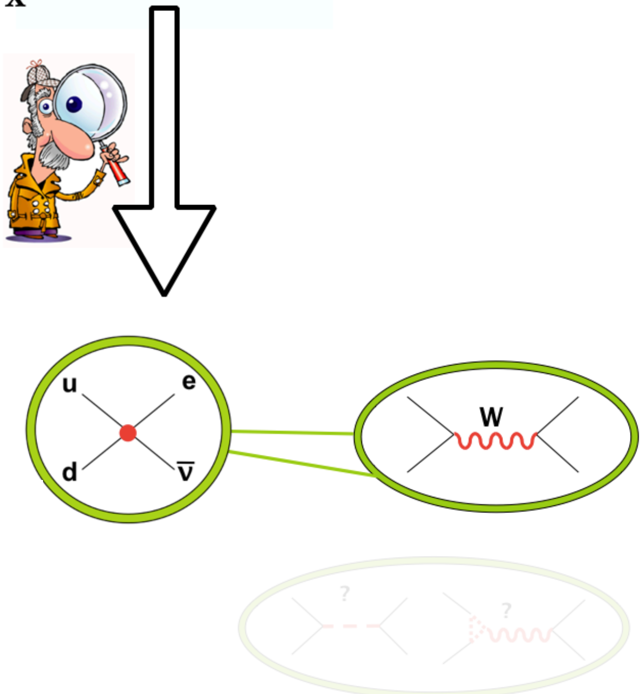
- EFT approach to NP effects in neutrino experiments
- Application to COHERENT





# Introduction




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

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

[Same in detection]

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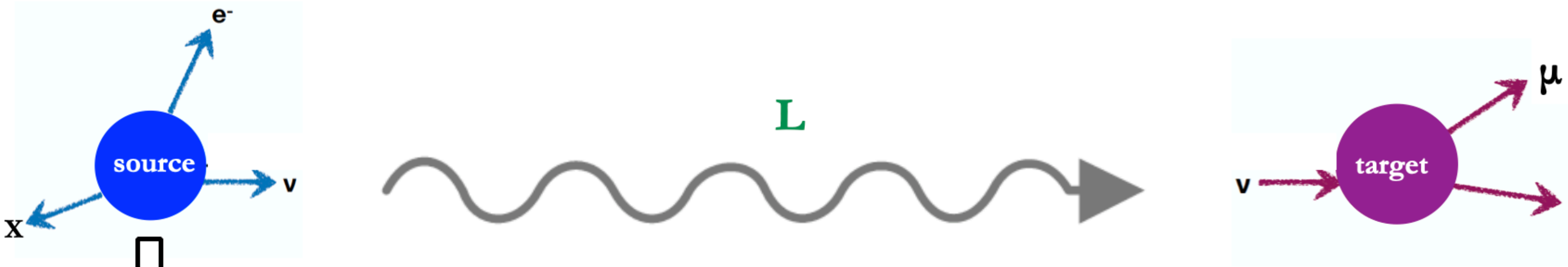


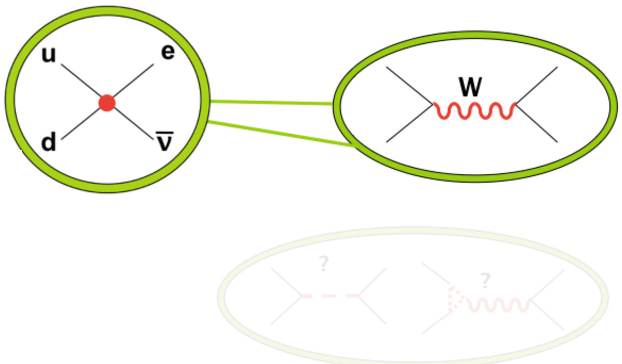


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Beyond the SM*: $\mathcal{O} = \mathcal{O}\,(\theta_i,\ \Delta m^2,\ \varepsilon_j)$

| with SK atmospheric data | Normal Ordering (best fit) | | Inverted Ordering ($\Delta\chi^2 = 7.1$) | |
|---|---|---|---|---|
| | bfp $\pm 1\sigma$ | $3\sigma$ range | bfp $\pm 1\sigma$ | $3\sigma$ range |
| $\sin^2\theta_{12}$ | $0.304^{+0.012}_{-0.012}$ | $0.269 \to 0.343$ | $0.304^{+0.013}_{-0.012}$ | $0.269 \to 0.343$ |
| $\theta_{12}/^\circ$ | $33.44^{+0.77}_{-0.74}$ | $31.27 \to 35.86$ | $33.45^{+0.78}_{-0.75}$ | $31.27 \to 35.87$ |
| $\sin^2\theta_{23}$ | $0.573^{+0.016}_{-0.020}$ | $0.415 \to 0.616$ | $0.575^{+0.016}_{-0.019}$ | $0.419 \to 0.617$ |
| $\theta_{23}/^\circ$ | $49.2^{+0.9}_{-1.2}$ | $40.1 \to 51.7$ | $49.3^{+0.9}_{-1.1}$ | $40.3 \to 51.8$ |
| $\sin^2\theta_{13}$ | $0.02219^{+0.00062}_{-0.00063}$ | $0.02032 \to 0.02410$ | $0.02238^{+0.00063}_{-0.00062}$ | $0.02052 \to 0.02428$ |
| $\theta_{13}/^\circ$ | $8.57^{+0.12}_{-0.12}$ | $8.20 \to 8.93$ | $8.60^{+0.12}_{-0.12}$ | $8.24 \to 8.96$ |
| $\delta_{CP}/^\circ$ | $197^{+27}_{-24}$ | $120 \to 369$ | $282^{+26}_{-30}$ | $193 \to 352$ |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$ | $7.42^{+0.21}_{-0.20}$ | $6.82 \to 8.04$ | $7.42^{+0.21}_{-0.20}$ | $6.82 \to 8.04$ |
| $\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$ | $+2.517^{+0.026}_{-0.028}$ | $+2.435 \to +2.598$ | $-2.498^{+0.028}_{-0.028}$ | $-2.581 \to -2.414$ |

[I.Esteban et al., 2007.14792 JHEP]

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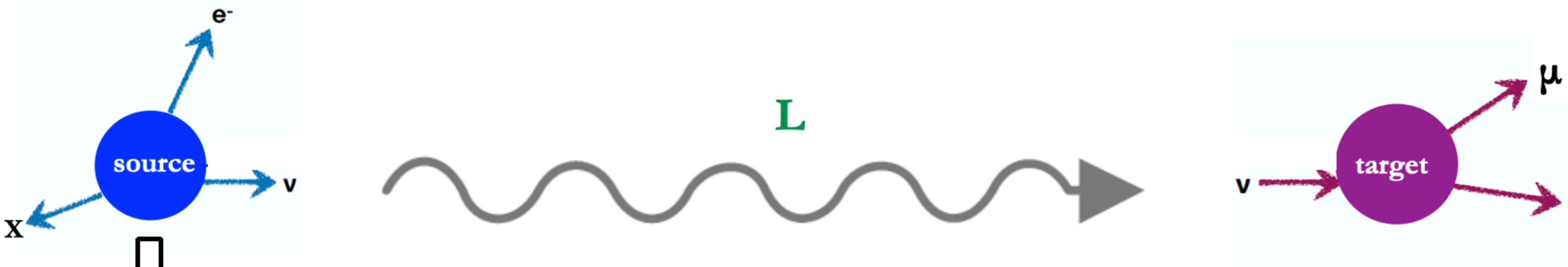


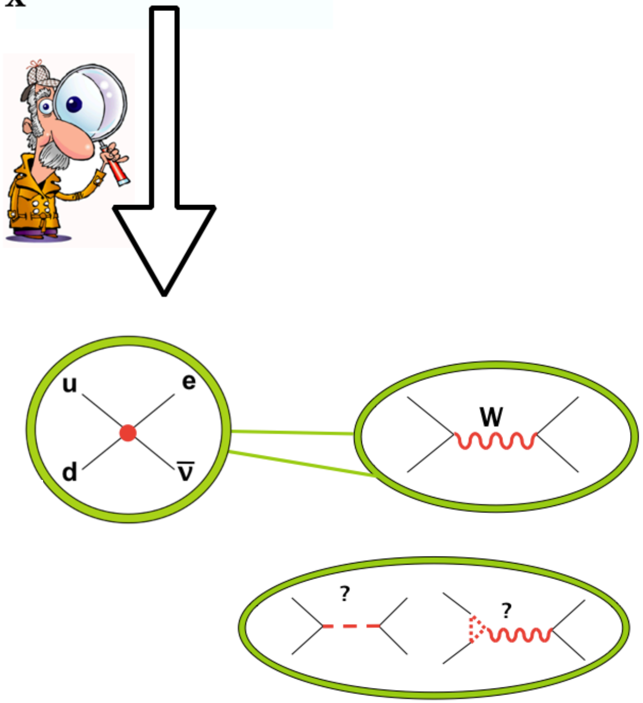


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Lagrangian parameters!

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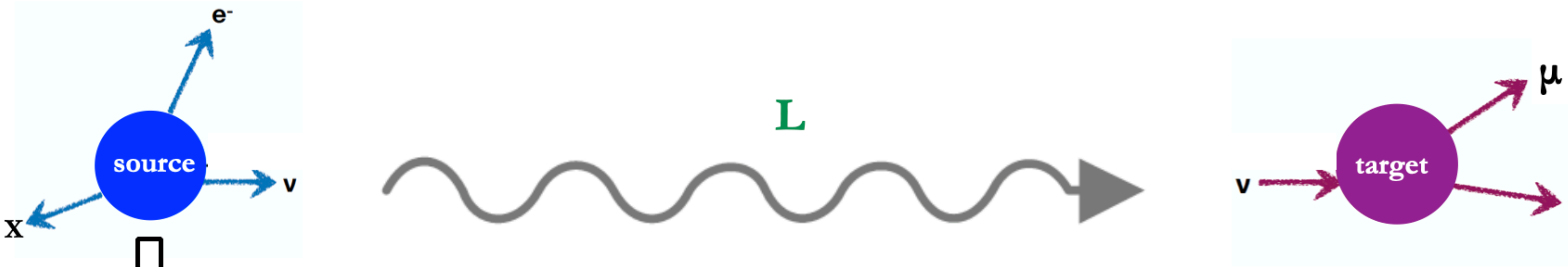


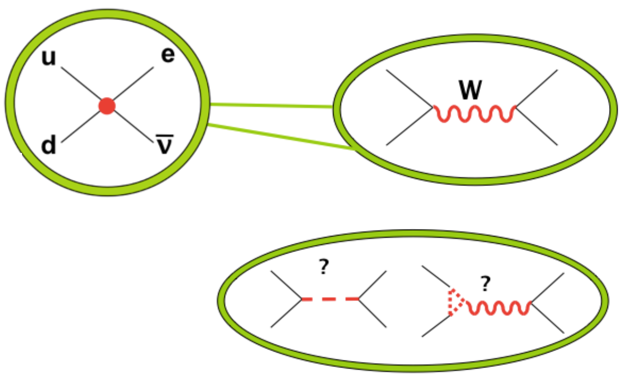


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How can I derive this formula?

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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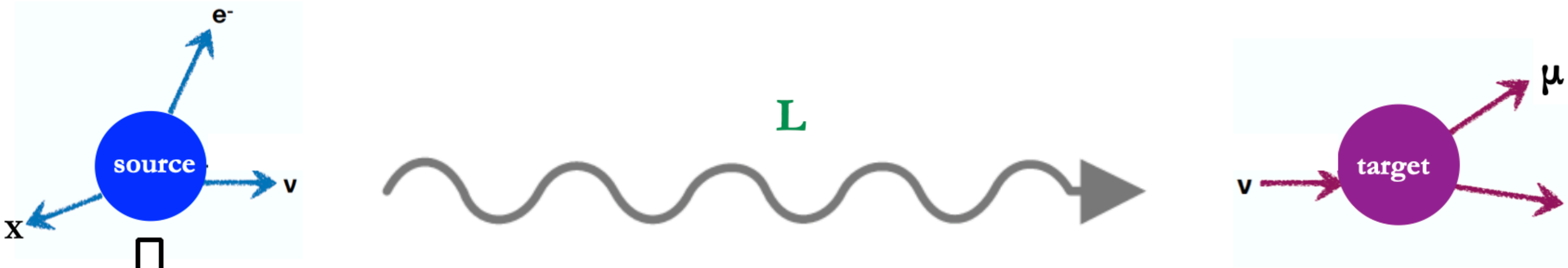


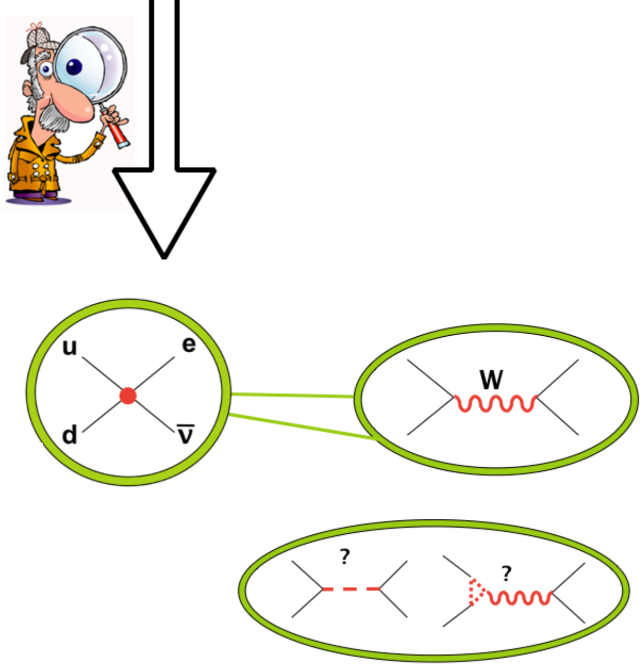


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- QM approach not useful ("source/detector NSI") → QFT approach needed

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

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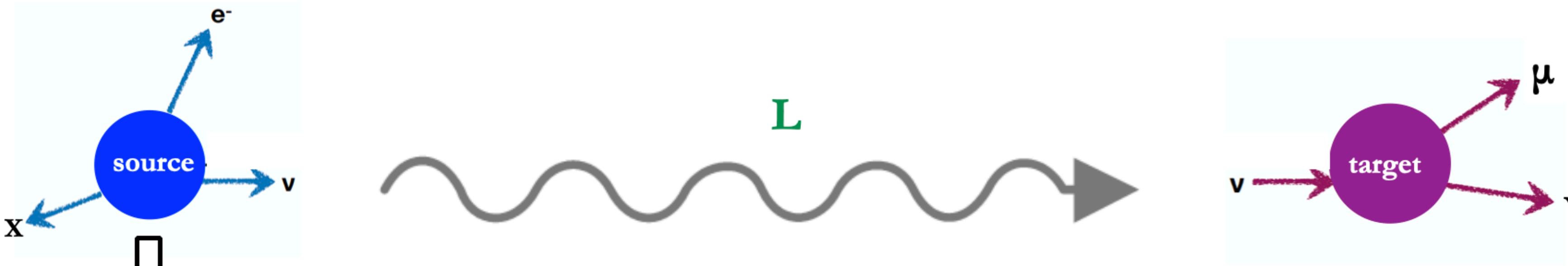


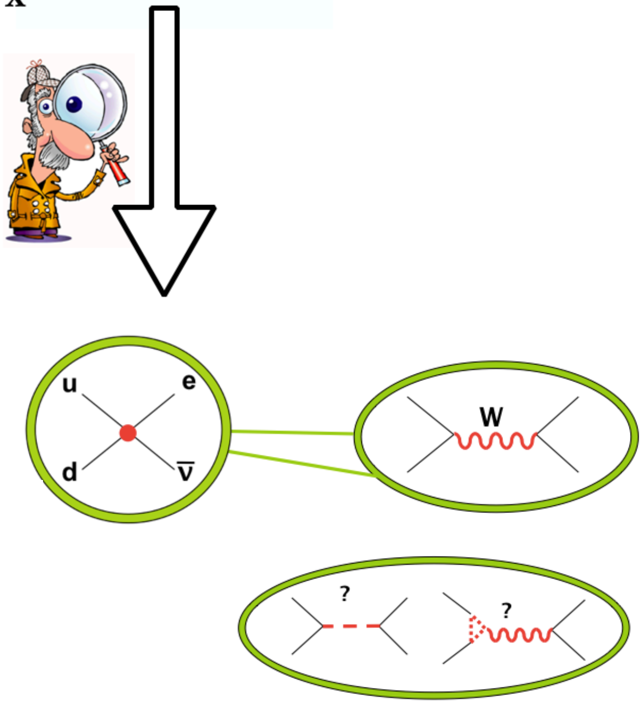


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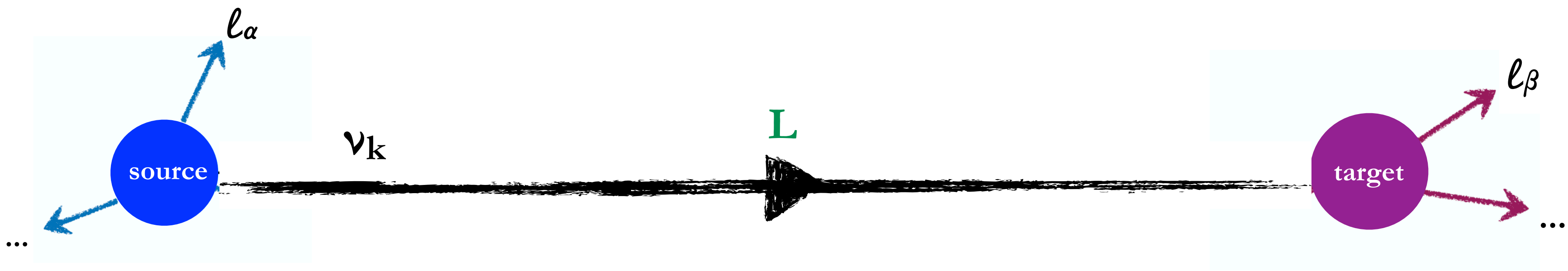
Giunti et al. [hep-ph/9305276]
Akhmedov Kopp [arXiv:1001.4815]
...

# 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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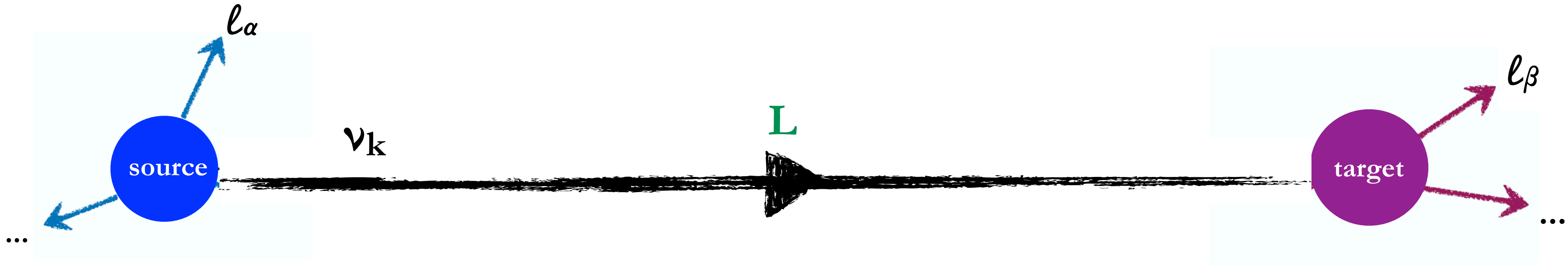


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Geometric factor

$\kappa = N_S N_T/(32\pi L^2 m_S m_T)$

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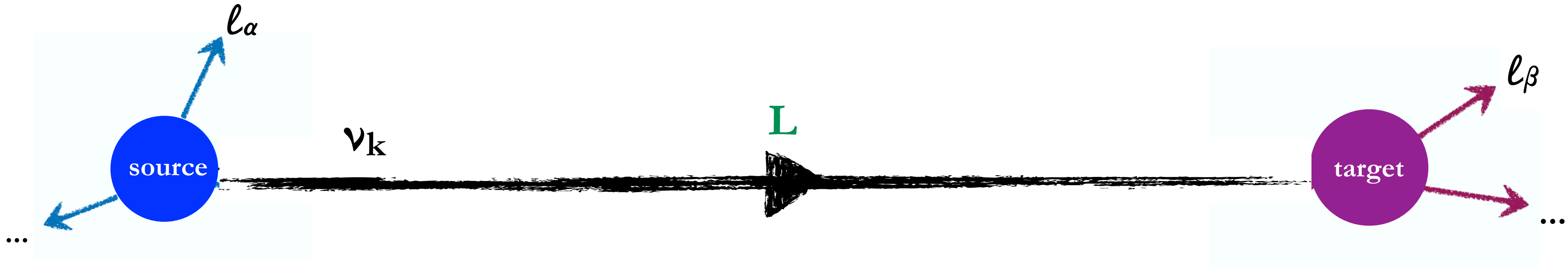


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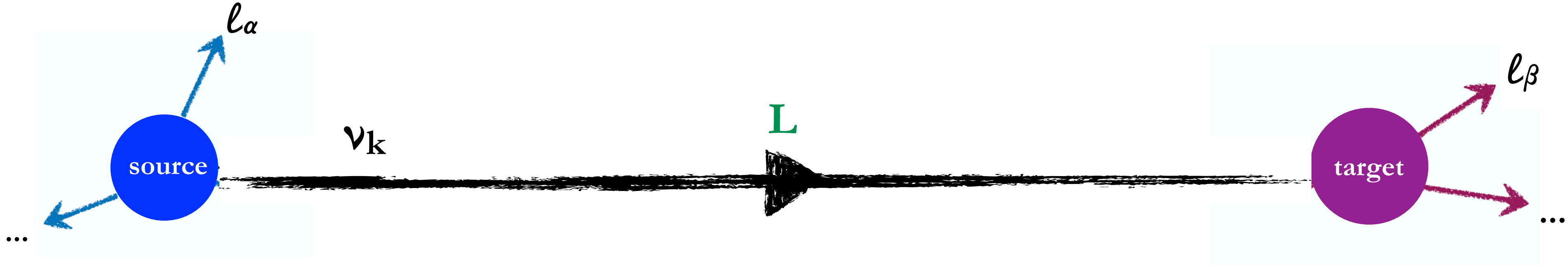


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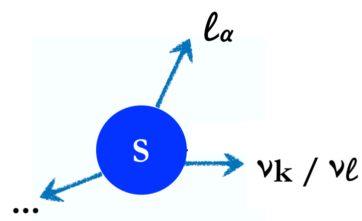

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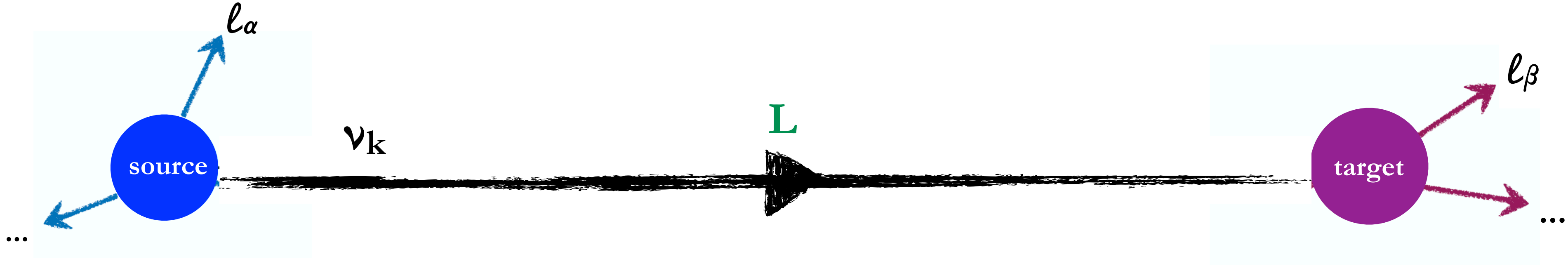


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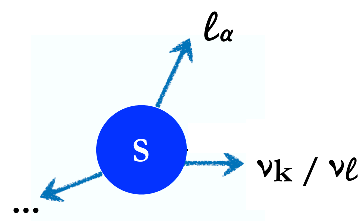


Phase space integrals: $d\Pi \equiv \frac{d^3k_1}{(2\pi)^3 2E_1} \dots \frac{d^3k_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^4(\mathcal{P} - \sum k_i)$

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

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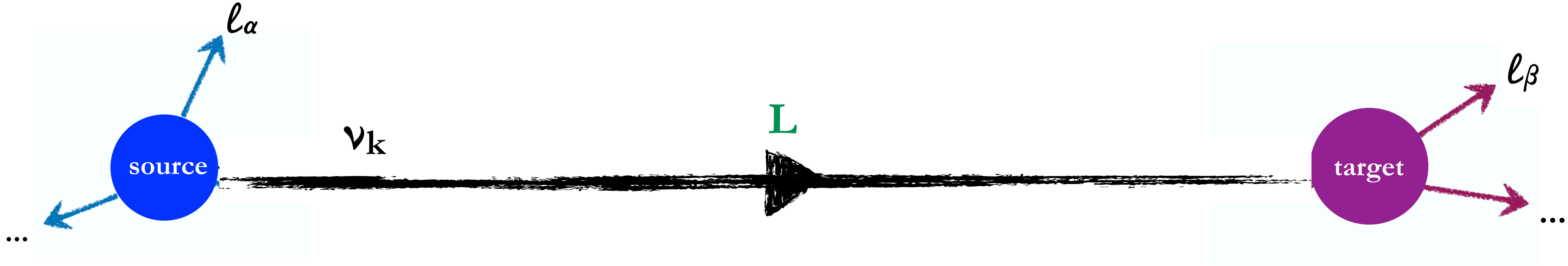


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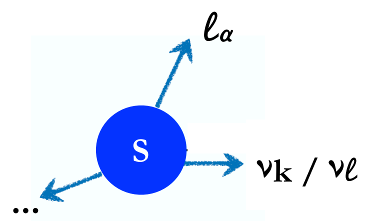
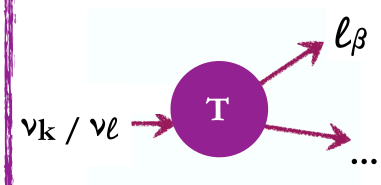



**Detection**

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

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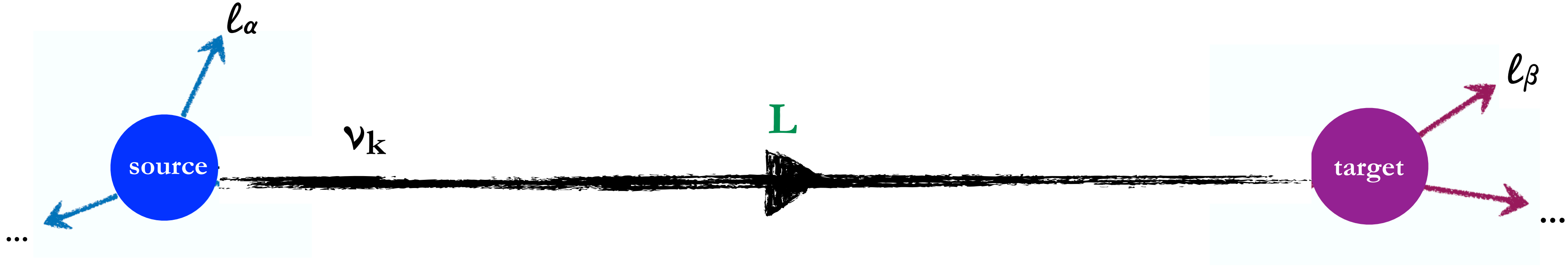


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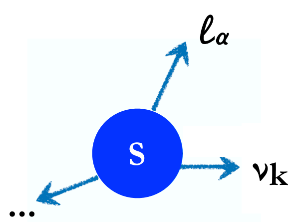
- The rest is "straightforward":
  specify the Lagrangian and calculate the production & detection amplitudes.

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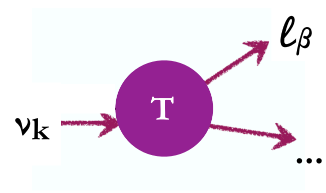
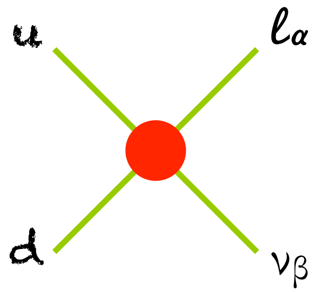


# Oscillations in QFT → EFT

Low-energy effective Lagrangian:

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




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

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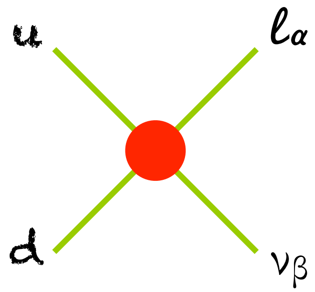


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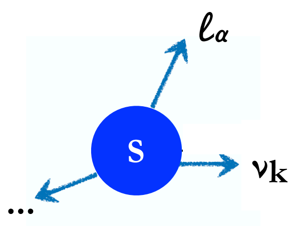


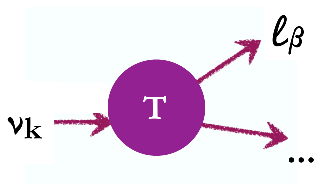


$$\mathcal{M}(S \to X_\alpha\nu_k) = U^*_{\alpha k}A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k}A^P_X$$

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

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

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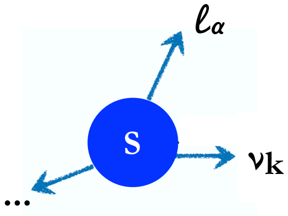


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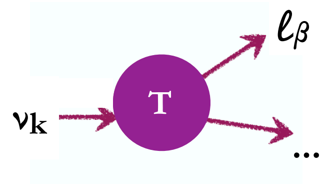


$$R_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \left[U^*_{\alpha k} U_{\alpha l} + p_{XL} (\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p^*_{XL} U^*_{\alpha k} (\epsilon_X U)_{\alpha l} + p_{XY} (\epsilon_X U)^*_{\alpha k} (\epsilon_Y U)_{\alpha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

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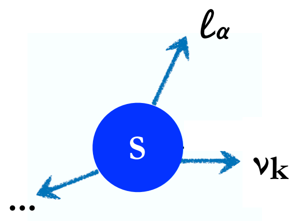


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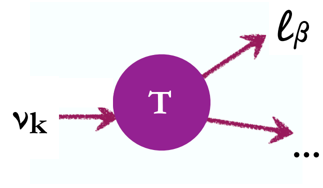
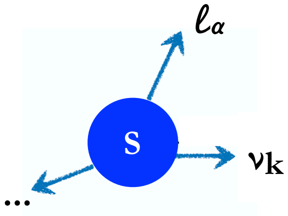



$$R_{\alpha\beta} = \Phi_\alpha^{\rm SM} \sigma_\beta^{\rm SM} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \left[U^*_{\alpha k} U_{\alpha l} + p_{XL} (\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p^*_{XL} U^*_{\alpha k} (\epsilon_X U)_{\alpha l} + p_{XY} (\epsilon_X U)^*_{\alpha k} (\epsilon_Y U)_{\alpha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

[ε=0]

# Oscillations in QFT → EFT

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

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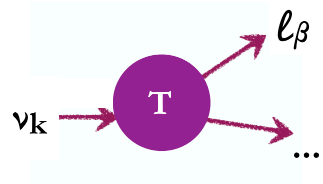


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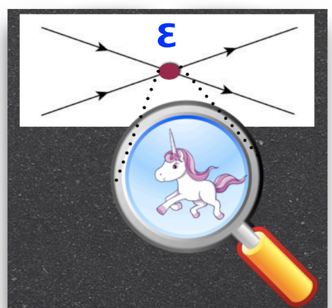
New qq'lν interactions



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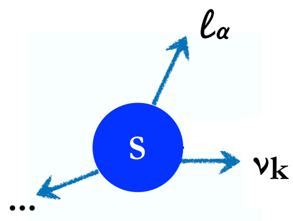


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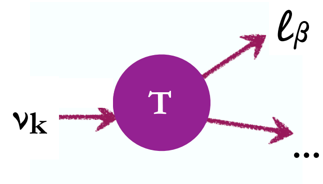


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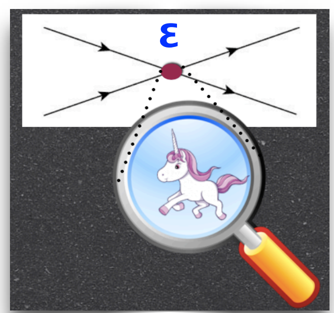
PMNS matrix

New qq'lν interactions



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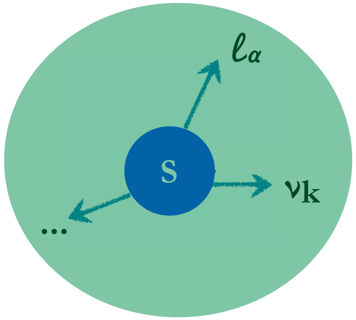
[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]

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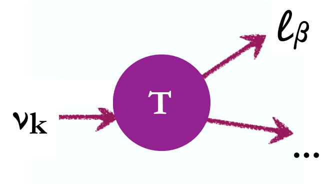


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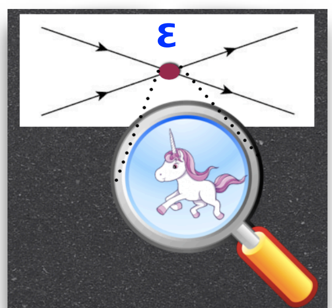
PMNS matrix

Production physics (QCD, EW)

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

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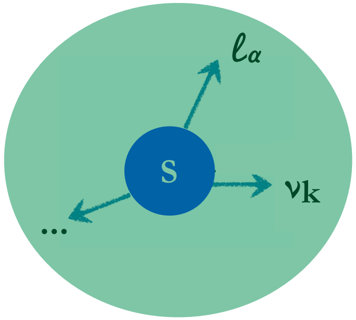


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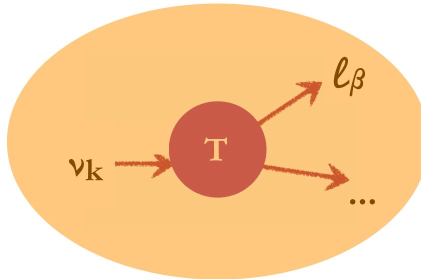


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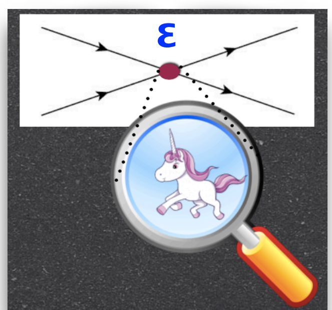
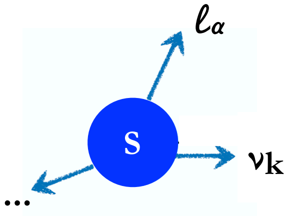
$$d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}$$

Detection physics (QCD, EW)



# Oscillations in QFT → EFT

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

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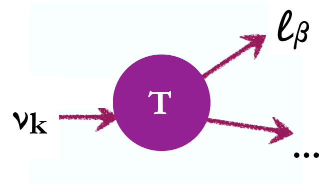


$$R_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \left[U^*_{\alpha k} U_{\alpha l} + p_{XL} (\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p^*_{XL} U^*_{\alpha k} (\epsilon_X U)_{\alpha l} + p_{XY} (\epsilon_X U)^*_{\alpha k} (\epsilon_Y U)_{\alpha l}\right]$$
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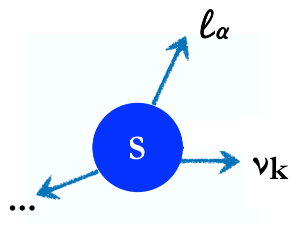
$$R^{\rm EFT}_{\alpha\beta} = R_0 + c_X\, \epsilon_X + \mathcal{O}(\epsilon^2)$$

vs.

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

# Oscillations in QFT → EFT

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

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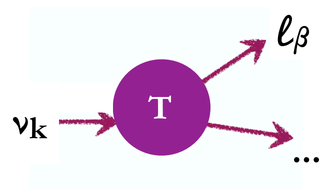


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⇒

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

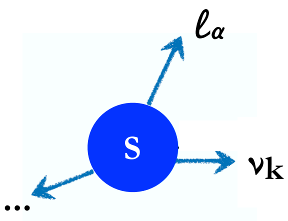
Example: $\nu p \to n e$

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

Unknown in the NSI approach!

# Oscillations in QFT → EFT

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

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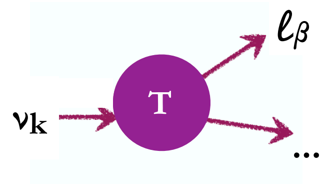


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⇒

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

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Example: νp→ne

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

Unknown in the NSI approach!

Moreover: beyond linear order, there's no matching!!!
I.e., the NSI-QM approach fails <u>in general.</u>

# 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]

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

- Choose your favourite experiment:

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

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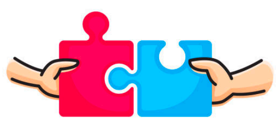
[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]

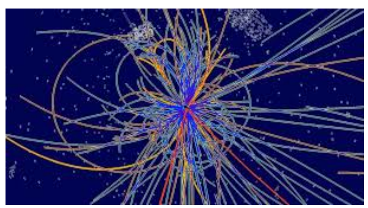
- Choose your favourite experiment:

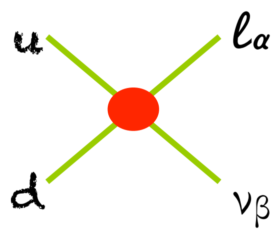
$$O = O(\theta_i, \Delta m^2, \varepsilon_j(\mu_{\rm low})) \Longrightarrow \varepsilon_j(\mu_{\rm low})$$

- 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]

- EFT analysis of COHERENT [Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, JHEP'23]



## EFT analysis of New Physics at COHERENT

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

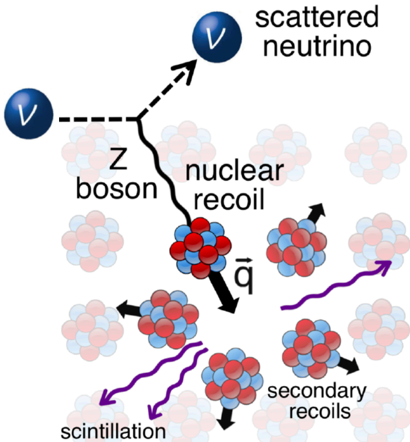
[a] *Departament de Física Teòrica, IFIC, Universitat de València - CSIC, Apt. Correus 22085, E-46071 València, Spain*

[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 $\nu_e$, $\nu_\mu$ 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): $\nu N \to \nu N$
- It occurs for $E_\nu$ 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)



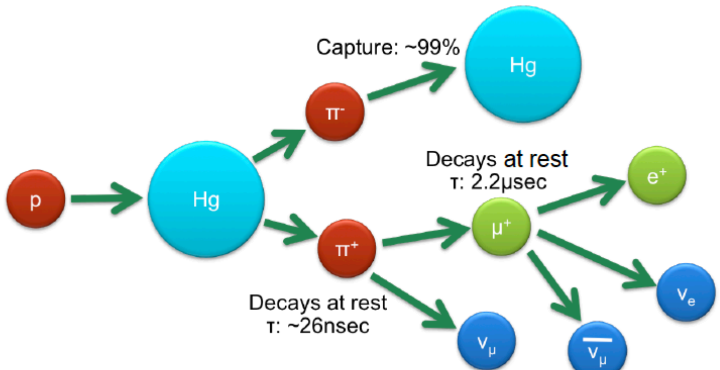

[from COHERENT coll.]

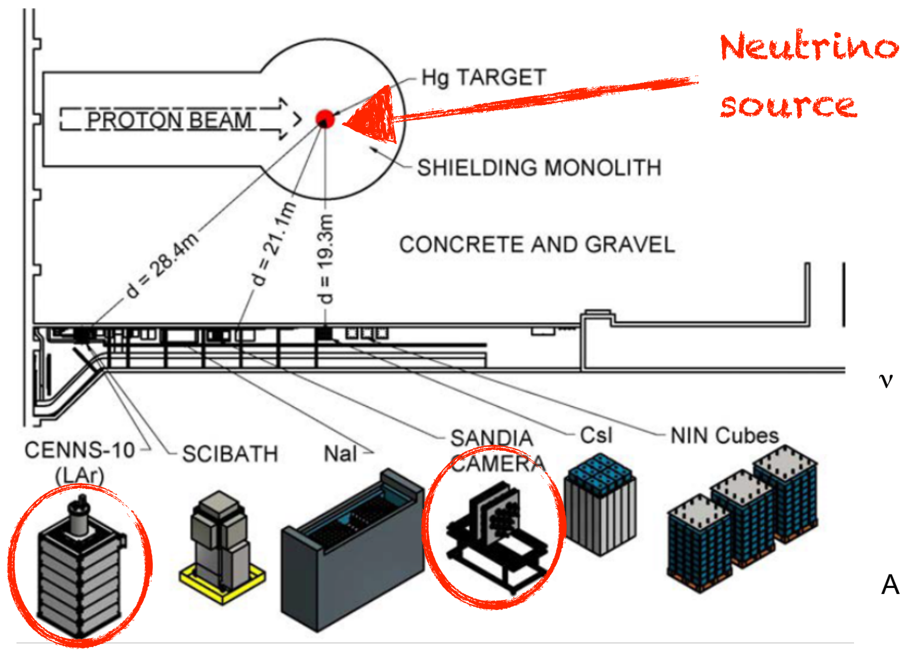

[Akimov et al.'17]

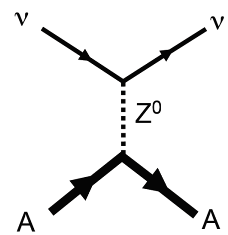
[Image credit: Duke U.]

COHERENT SNS SPALLATION NEUTRON SOURCE

# EFT analysis of NP at COHERENT

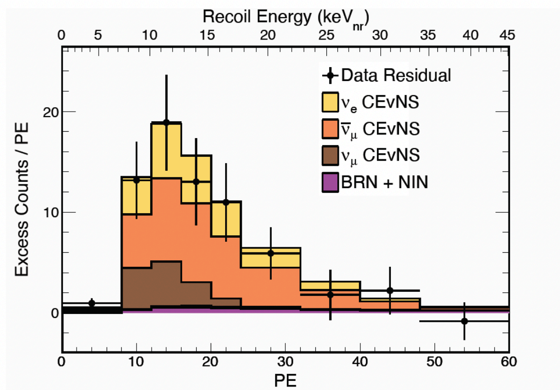



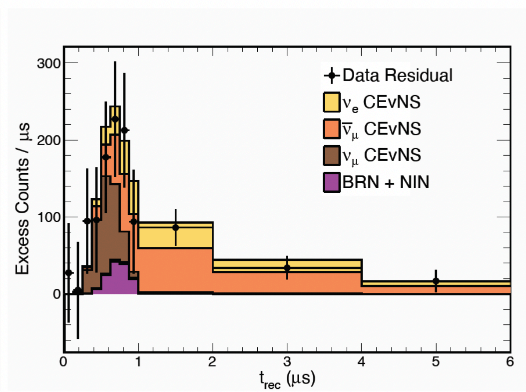




[from Scholberg's
talk at IPA18]

$$\pi^+ \to \mu^+ \, \nu_\mu \text{ (prompt)}$$

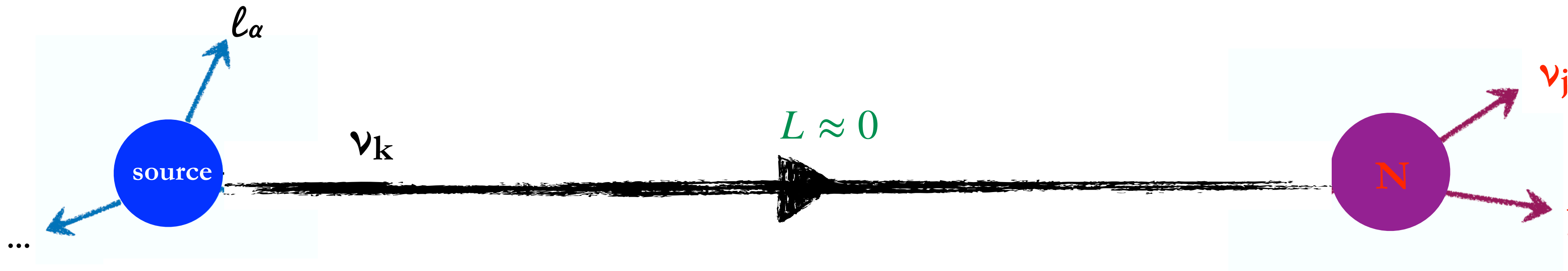
$$\hookrightarrow \mu^+ \to e^+ \, \bar{\nu}_\mu \, \nu_e \text{ (delayed)}$$



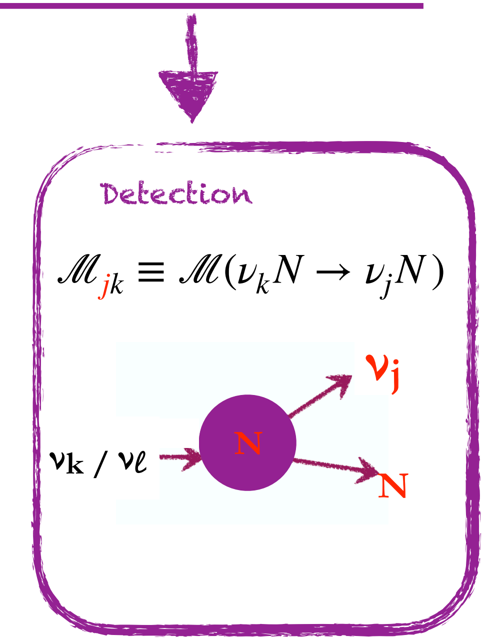
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# 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, 2301.07036 JHEP]

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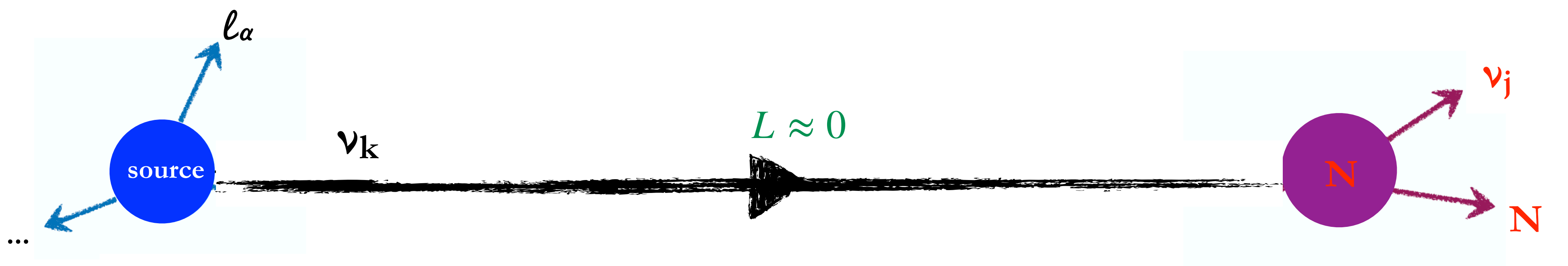


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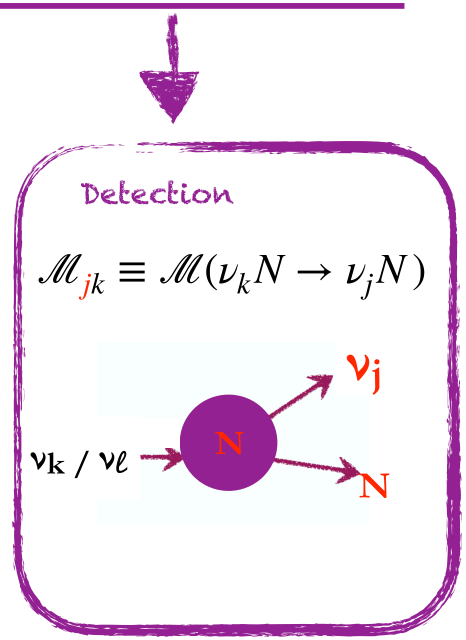
- CC production: pion and muon decays.
- NC detection: νN → νN.

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



# 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, 2301.07036 JHEP]

# 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]

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

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

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

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

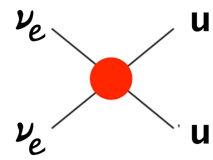
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# EFT analysis of NP at COHERENT

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

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

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



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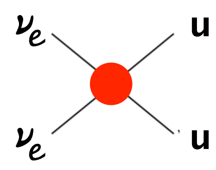


- Current COHERENT data (LAr + CsI, recoil & time distribution: 664 data) give:

$$0.68\,\epsilon^{dd}_{ee} + 0.61\,\epsilon^{uu}_{ee} - 0.30\,\epsilon^{dd}_{\mu\mu} - 0.27\,\epsilon^{uu}_{\mu\mu} = 0.037(42)$$
$$0.30\,\epsilon^{dd}_{ee} + 0.27\,\epsilon^{uu}_{ee} + 0.68\,\epsilon^{dd}_{\mu\mu} + 0.61\,\epsilon^{uu}_{\mu\mu} = -\,0.004(13)$$

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

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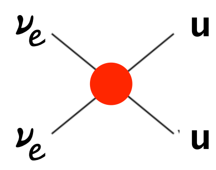


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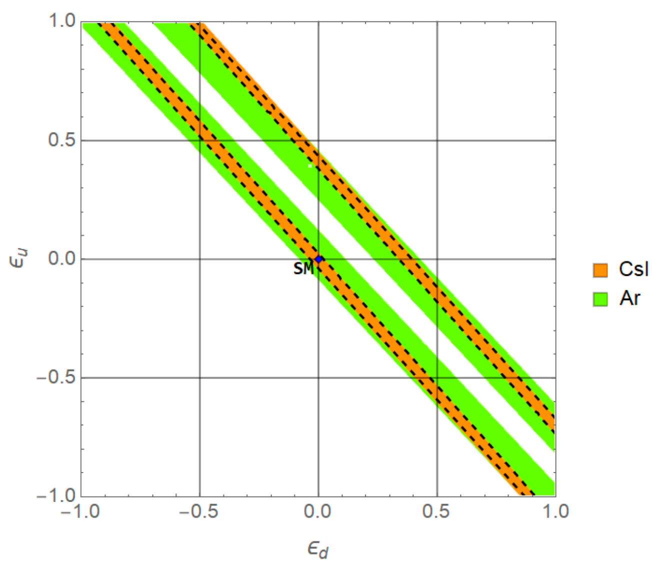
$$\epsilon^{uu}_{ee} = \epsilon^{uu}_{\mu\mu} \equiv \epsilon_u$$
$$\epsilon^{dd}_{ee} = \epsilon^{dd}_{\mu\mu} \equiv \epsilon_d$$

[Lepton-flavor universal case]

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



[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# COHERENT in the SMEFT

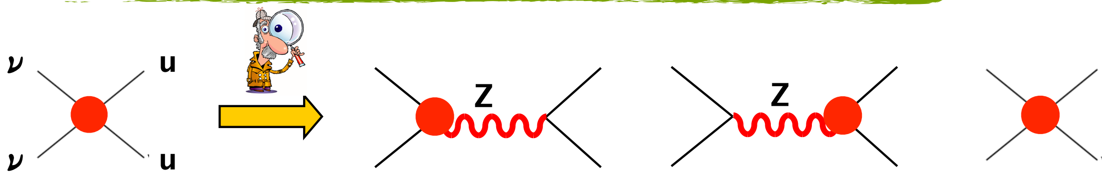
- "Flavor-blind" SMEFT ($\rightarrow U(3)^5$ symmetry)

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

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

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

WEFT/SMEFT Matching



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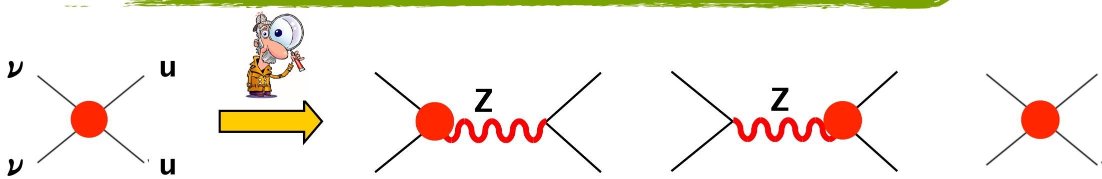


$$0.71c_{lq}^{(1)} - 0.04c_{lq}^{(3)} + 0.34c_{lu} + 0.37c_{ld} + [\delta g]_{\rm piece} = -0.003 \pm 0.010\,,$$

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

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# COHERENT in the SMEFT

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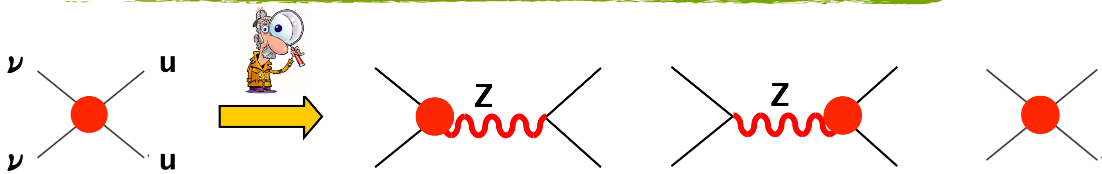


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- Is COHERENT probing a new region in the SMEFT parameter space?
  These operators are constrained by many EWPO: LEP1, LEP2, APV, … → Global fit needed!

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

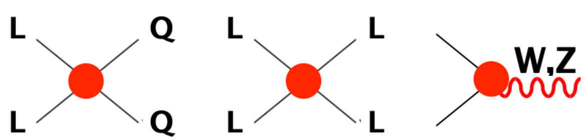
# COHERENT in the SMEFT

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


| Observable | Experimental value | Ref. | SM prediction | Definition |
|---|---|---|---|---|
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | [47] | 2.4950 | $\sum_f \Gamma(Z \to ff)$ |
| $\sigma_{\rm had}$ [nb] | $41.541 \pm 0.037$ | [47] | 41.484 | $\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$ |
| $R_e$ | $20.804 \pm 0.050$ | [47] | 20.743 | $\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$ |
| $R_\mu$ | $20.785 \pm 0.033$ | [47] | 20.743 | $\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$ |
| $R_\tau$ | $20.764 \pm 0.045$ | [47] | 20.743 | $\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_{\rm FB}^{0,e}$ | $0.0145 \pm 0.0025$ | [47] | 0.0163 | $\frac{3}{4}A_e^2$ |
| $A_{\rm FB}^{0,\mu}$ | $0.0169 \pm 0.0013$ | [47] | 0.0163 | $\frac{3}{4}A_e A_\mu$ |
| $A_{\rm FB}^{0,\tau}$ | $0.0188 \pm 0.0017$ | [47] | 0.0163 | $\frac{3}{4}A_e A_\tau$ |
| $R_b$ | $0.21629 \pm 0.00066$ | [47] | 0.21578 | $\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$ |
| $R_c$ | $0.1721 \pm 0.0030$ | [47] | 0.17226 | $\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$ |
| $A_b^{\rm FB}$ | $0.0992 \pm 0.0016$ | [47] | 0.1032 | $\frac{3}{4}A_e A_b$ |
| $A_c^{\rm FB}$ | $0.0707 \pm 0.0035$ | [47] | 0.0738 | $\frac{3}{4}A_e A_c$ |
| $A_e$ | $0.1516 \pm 0.0021$ | [47] | 0.1472 | $\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$ |
| $A_\mu$ | $0.142 \pm 0.015$ | [47] | 0.1472 | $\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$ |
| $A_\tau$ | $0.136 \pm 0.015$ | [47] | 0.1472 | $\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_e$ | $0.1498 \pm 0.0049$ | [47] | 0.1472 | $\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_\tau$ | $0.1439 \pm 0.0043$ | [47] | 0.1472 | $\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_b$ | $0.923 \pm 0.020$ | [47] | 0.935 | $\frac{\Gamma(Z\to b_L\bar{b}_L)-\Gamma(Z\to b_R\bar{b}_R)}{\Gamma(Z\to b\bar{b})}$ |
| $A_c$ | $0.670 \pm 0.027$ | [47] | 0.668 | $\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$ |
| $A_s$ | $0.895 \pm 0.091$ | [48] | 0.935 | $\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$ |
| $R_{uc}$ | $0.166 \pm 0.009$ | [45] | 0.1724 | $\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$ |

| Observable | Experimental value | Ref. | SM prediction | Definition |
|---|---|---|---|---|
| $m_W$ [GeV] | $80.385 \pm 0.015$ | [50] | 80.364 | $\frac{g_L v}{2}(1+\delta m)$ |
| $\Gamma_W$ [GeV] | $2.085 \pm 0.042$ | [45] | 2.091 | $\sum_f \Gamma(W \to ff')$ |
| ${\rm Br}(W \to e\nu)$ | $0.1071 \pm 0.0016$ | [51] | 0.1083 | $\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to ff')}$ |
| ${\rm Br}(W \to \mu\nu)$ | $0.1063 \pm 0.0015$ | [51] | 0.1083 | $\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to ff')}$ |
| ${\rm Br}(W \to \tau\nu)$ | $0.1138 \pm 0.0021$ | [51] | 0.1083 | $\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to ff')}$ |
| $R_{Wc}$ | $0.49 \pm 0.04$ | [45] | 0.50 | $\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$ |
| $R_\sigma$ | $0.998 \pm 0.041$ | [52] | 1.000 | $g_L^{Wq_3}/g_{L,{\rm SM}}^{Wq_3}$ |

$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{18}) \longrightarrow \chi^2 = \chi^2\,(c_i)$$

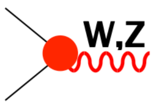


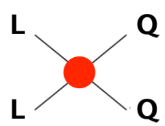

Update of [Falkowski, MGA & Mimouni, JHEP'17]

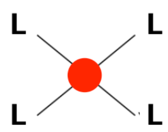
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# COHERENT in the SMEFT

- "Flavor-blind" SMEFT (→ $U(3)^5$ symmetry)
- Global fit to Electroweak precision observables:




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

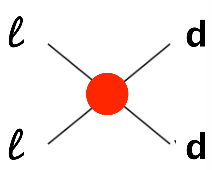
$\rho \neq 1$

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

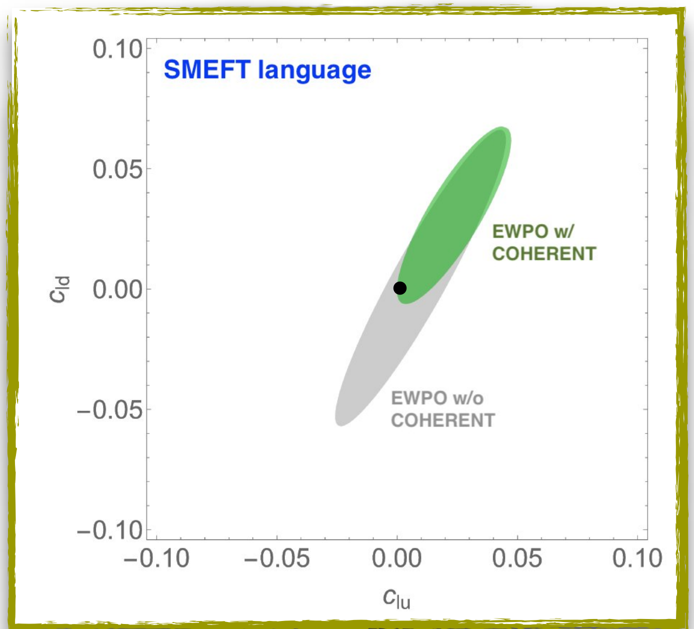
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# COHERENT in the SMEFT

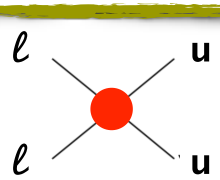
- "Flavor-blind" SMEFT ($\to$ U(3)[5] symmetry)
- Global fit to Electroweak precision observables;




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




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



[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# COHERENT in the SMEFT

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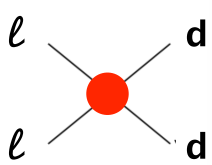
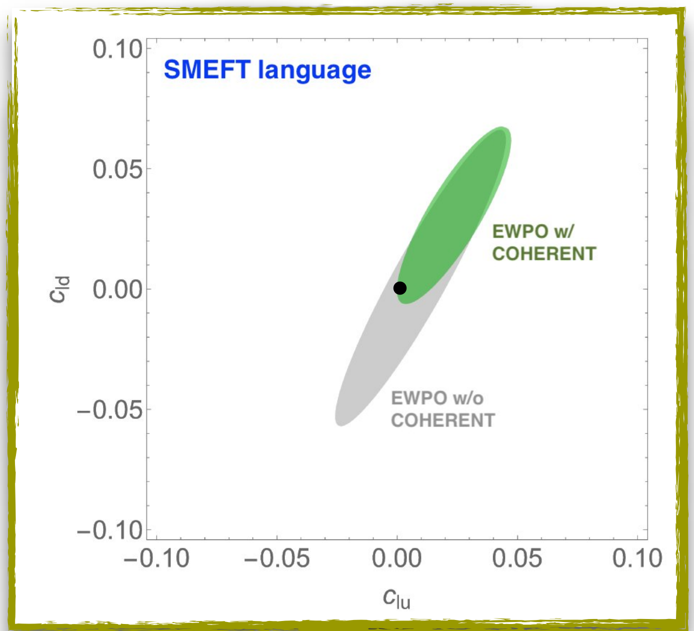
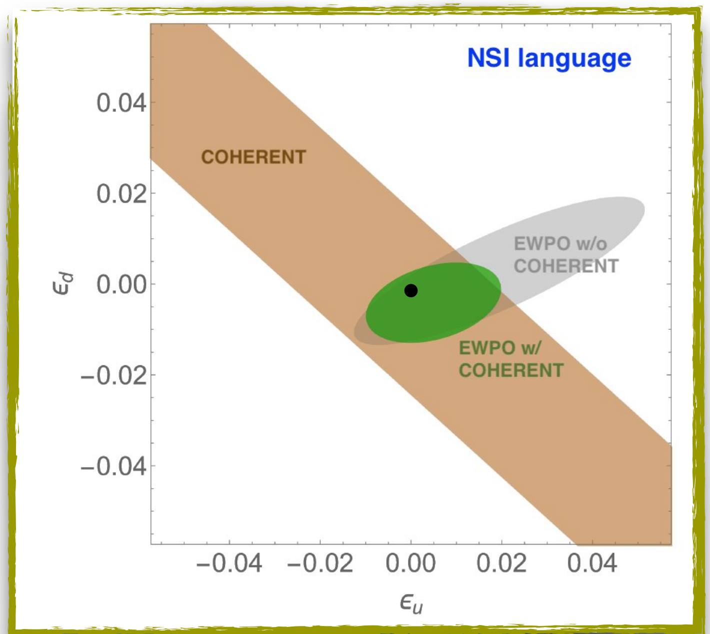
- Global fit to Electroweak precision observables;

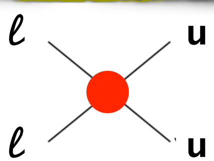



$\bar{\ell}\gamma_\mu \ell \; \bar{d}\gamma^\mu d$



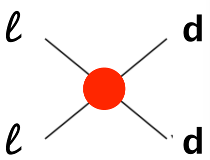

$\bar{\ell}\gamma_\mu \ell \; \bar{u}\gamma^\mu u$



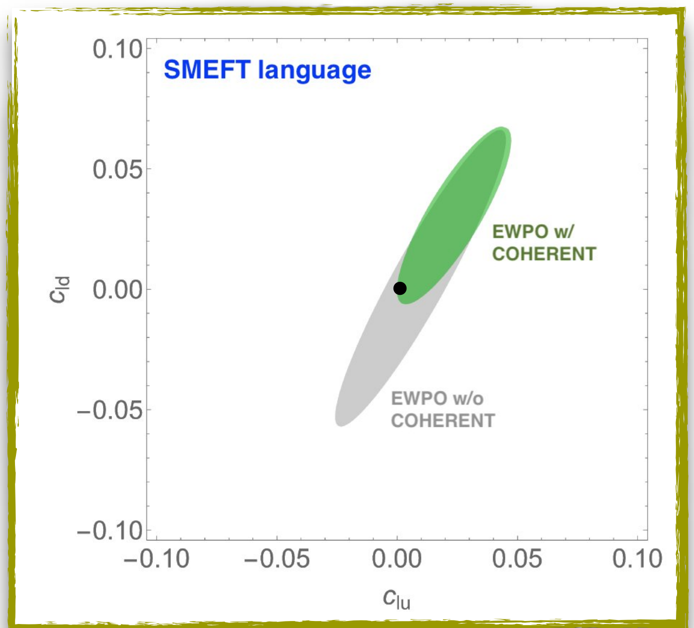
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# COHERENT in the SMEFT

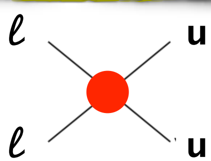
- "Flavor-blind" SMEFT ($\rightarrow$ U(3)$^5$ symmetry) → **Flavor general SMEFT**
- Global fit to Electroweak precision observables;




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




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



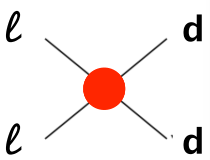

$$\mathbf{O = O_{SM} + O\,(c_1, c_2, \ldots, c_{18}) \rightarrow \chi^2 = \chi^2\,(c_i)}$$

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

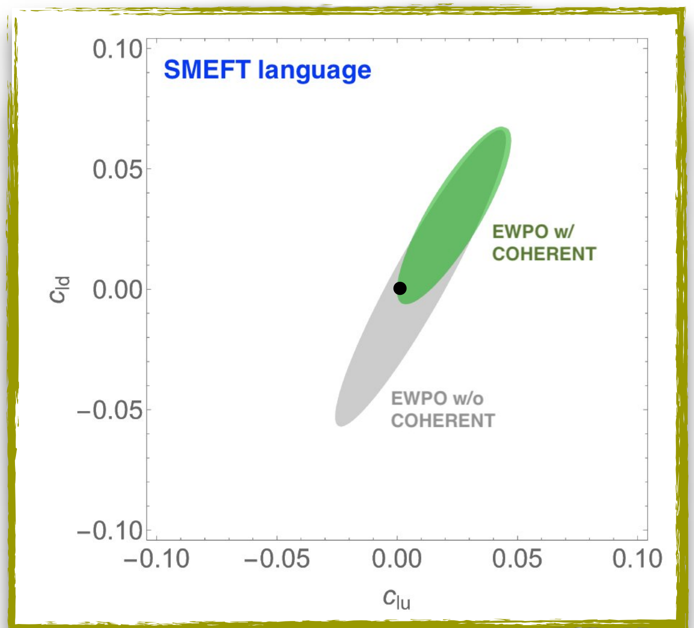
# COHERENT in the SMEFT

- "Flavor-blind" SMEFT ($\to U(3)^5$ symmetry)
- Global fit to Electroweak precision observables;

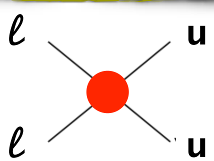
**Flavor general SMEFT**




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




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



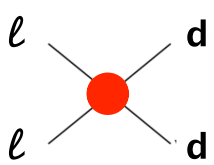

$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{18}) \to \chi^2 = \chi^2\,(c_i)$ → $O = O_{SM} + O\,(c_1, c_2, \ldots, c_{65}) \to \chi^2 = \chi^2\,(c_i)$

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

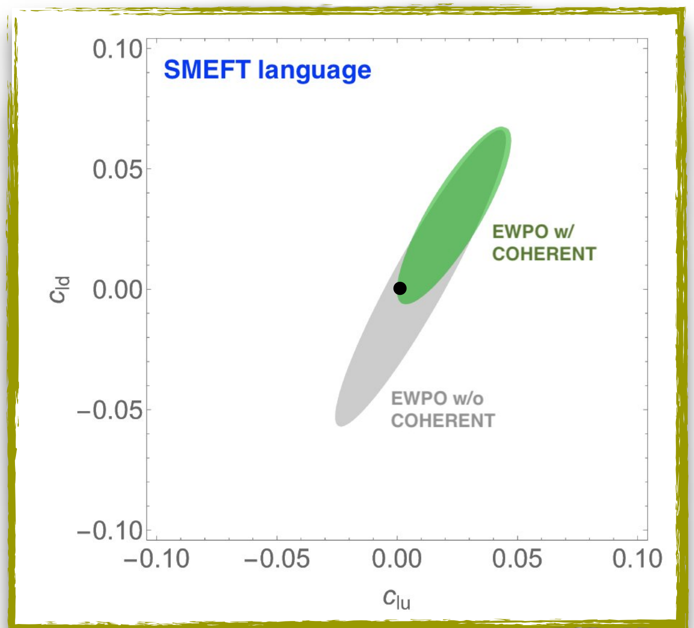
# COHERENT in the SMEFT

- "Flavor-blind" SMEFT ($\rightarrow U(3)^5$ symmetry)
- Global fit to Electroweak precision observables;

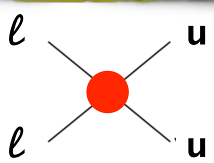
**Flavor general SMEFT**

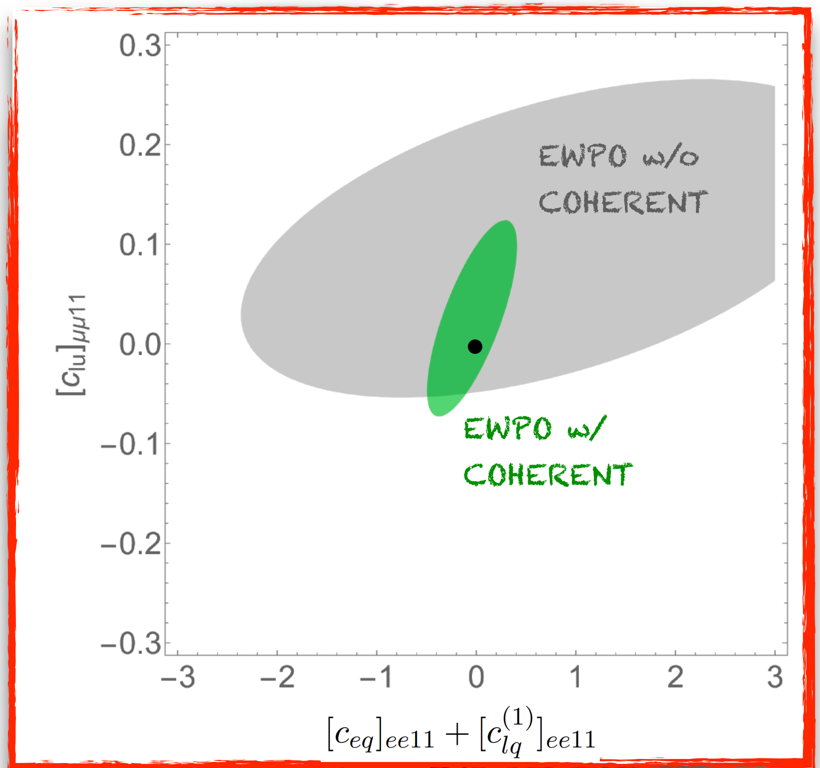



$\bar{\ell}\gamma_\mu\ell\ \bar{d}\gamma^\mu d$




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

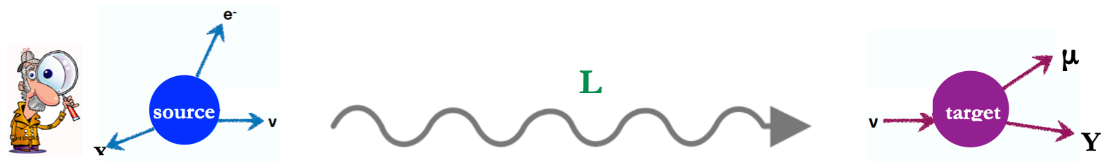



$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{18}) \rightarrow \chi^2 = \chi^2\,(c_i)$

$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{65}) \rightarrow \chi^2 = \chi^2\,(c_i)$

# Summary

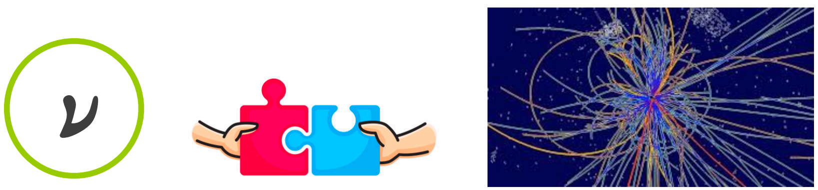


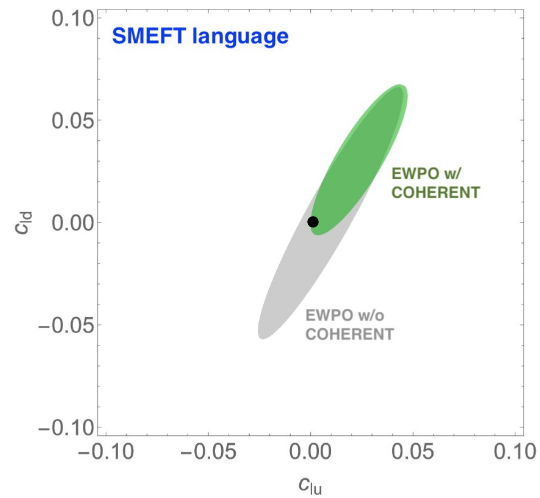

- The path to analyze any given neutrino experiment in the presence of **generic** (heavy) New Physics is now clear.

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

EFT!!

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




- COHERENT should be included in EWPO fits!

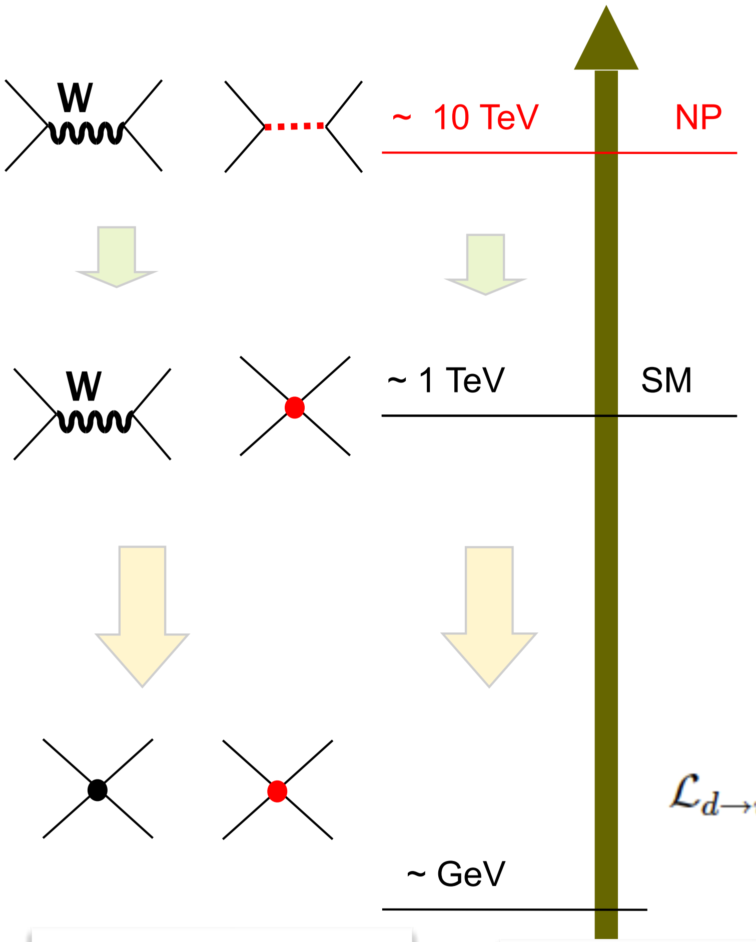
$$0.71c_{lq}^{(1)} - 0.04c_{lq}^{(3)} + 0.34c_{lu} + 0.37c_{ld} + [\delta g]_{\text{piece}} = -0.003 \pm 0.010$$


NEUTRINO
NEUTRINO
NEUTRINO
Credit: Sandbox Studio, Chicago

# Thanks!

# Backups

# Introduction




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

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

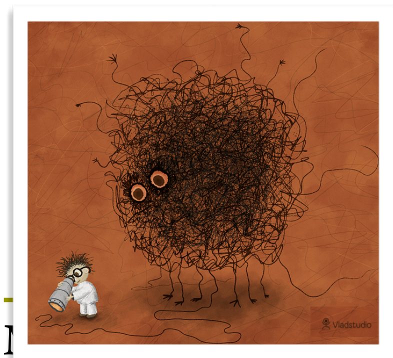
Standard Model EFT

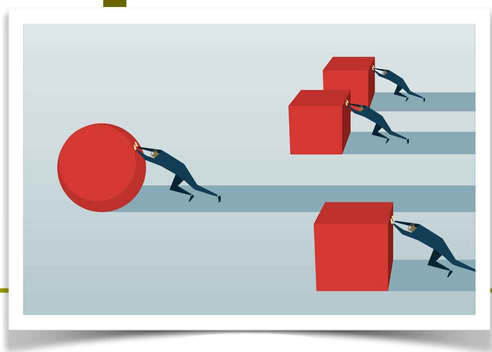
[Buchmuller & Wyler'86, Leung et al.'86, Grzadkowksi et al., 10, Jenkins et al'13, ...]

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

Low-energy EFT

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





Low-E precision data

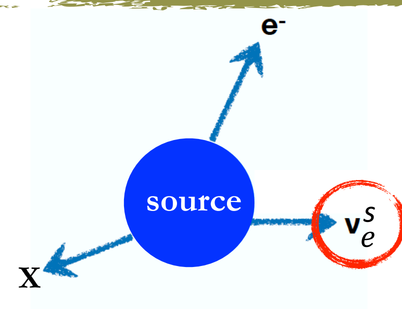
(+ SM prediction)

[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]

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# EFT analysis of NP at COHERENT

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

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

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

$$\tilde{Q}_\mu^2 \equiv \frac{\left[\mathcal{P} \mathcal{Q}^2 \mathcal{P}^\dagger\right]_{\mu\mu}}{(\mathcal{P}\mathcal{P}^\dagger)_{\mu\mu}} ,$$

$$\tilde{Q}_e^2 = \frac{\mathrm{Tr}\left(\mathcal{P}_L^* \mathcal{Q}^2 P_L^T + \mathcal{P}_R^T \mathcal{Q}^2 P_R^*\right)}{\mathrm{Tr}\left(\mathcal{P}_L \mathcal{P}_L^\dagger + \mathcal{P}_R \mathcal{P}_R^\dagger\right)} , \qquad \tilde{Q}_{\bar{\mu}}^2 \equiv \frac{\mathrm{Tr}\left(\mathcal{P}_L^T \mathcal{Q}^2 P_L^* + \mathcal{P}_R^* \mathcal{Q}^2 P_R^T\right)}{\mathrm{Tr}\left(\mathcal{P}_L \mathcal{P}_L^\dagger + \mathcal{P}_R \mathcal{P}_R^\dagger\right)} .$$

$$[\mathcal{P}]_{\alpha\beta} \equiv \delta_{\alpha\beta} + [\epsilon_L]_{\alpha\beta} - [\epsilon_R]_{\alpha\beta} - [\epsilon_P]_{\alpha\beta} \frac{m_{\pi^\pm}^2}{m_{\ell_\alpha}(m_u + m_d)} ,$$

$$[\mathcal{P}_L]_{\alpha\beta} \equiv \delta_{\alpha\mu}\delta_{\beta e} + [\rho_L]_{\mu\alpha\beta e} ,$$

$$[\mathcal{P}_R]_{\alpha\beta} \equiv [\rho_R]_{\mu\alpha\beta e} .$$

$$[\mathcal{Q}]_{\alpha\beta} = Z g_{\alpha\beta}^{\nu p} + (A - Z) g_{\alpha\beta}^{\nu n} .$$

$$g_{\alpha\beta}^{\nu p} = 2 \left[ (2\, g_V^{uu} + g_V^{dd})\, \mathbb{1} + (2\, \epsilon^{uu} + \epsilon^{dd}) \right]_{\alpha\beta} .$$

$$g_{\alpha\beta}^{\nu n} = 2 \left[ (g_V^{uu} + 2 g_V^{dd})\, \mathbb{1} + (\epsilon^{uu} + 2\epsilon^{dd}) \right]_{\alpha\beta} .$$

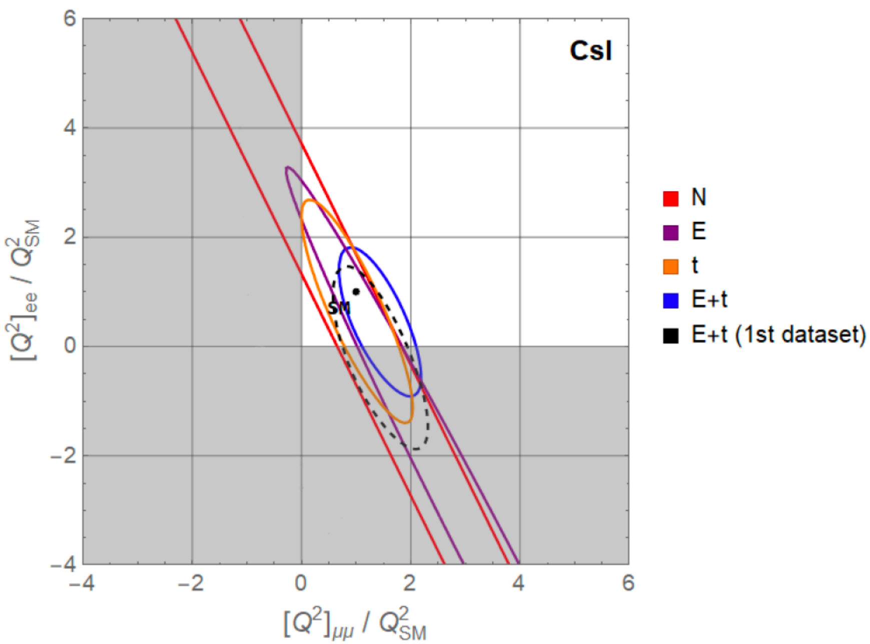
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

# EFT analysis of NP at COHERENT

- Case 2: NP only in detection (usual NSI assumption) → agreement with previous works.

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

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




- Case 3: NP only in production → NP cancel completely!
  *[this invalidates the bounds obtained in Khan, McKay, & Rodejohann, PRD'2021]*

$$Q^2_{\bar\mu} = Q^2_{\mu} = Q^2_{e} = Q^2_{SM}$$