EFT analysis of New Physics at COHERENT

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In collaboration with

Adam Falkowski, Martín González-Alonso and Kevin Monsálvez Pozo

Two big questions

-Can we use the effective field theory approach to study non-standard effects both in neutrino production and detection at COHERENT?

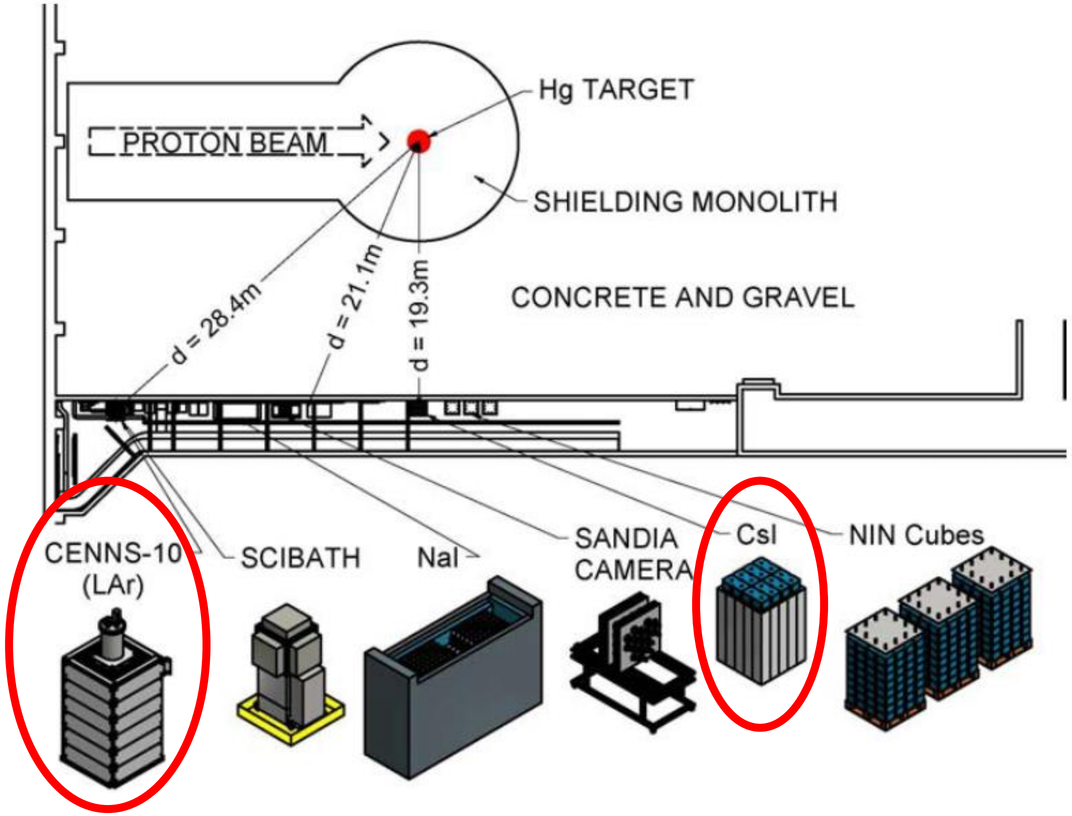
-Does COHERENT have a place in the electroweak EFT precision global fits?

Two big questions

-Can we use the effective field theory approach to study non-standard effects both in neutrino production and detection at COHERENT? YES

-Does COHERENT have a place in the electroweak EFT precision global fits? YES

COHERENT experiment



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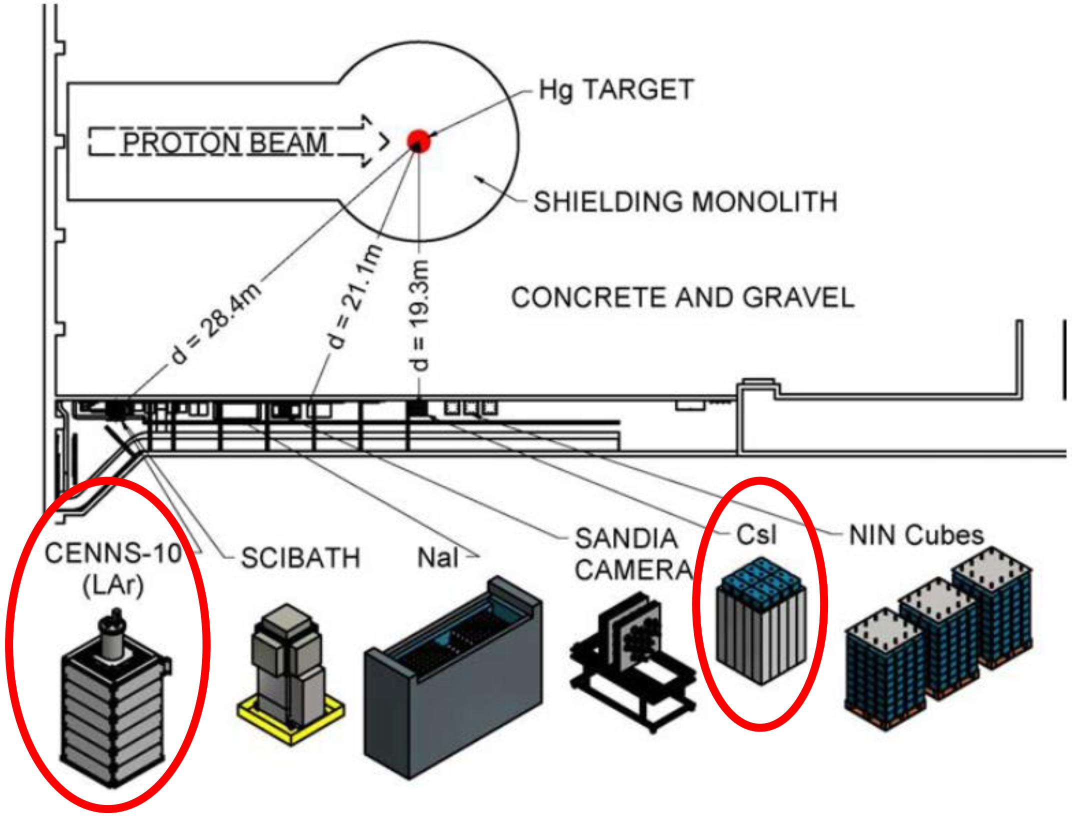

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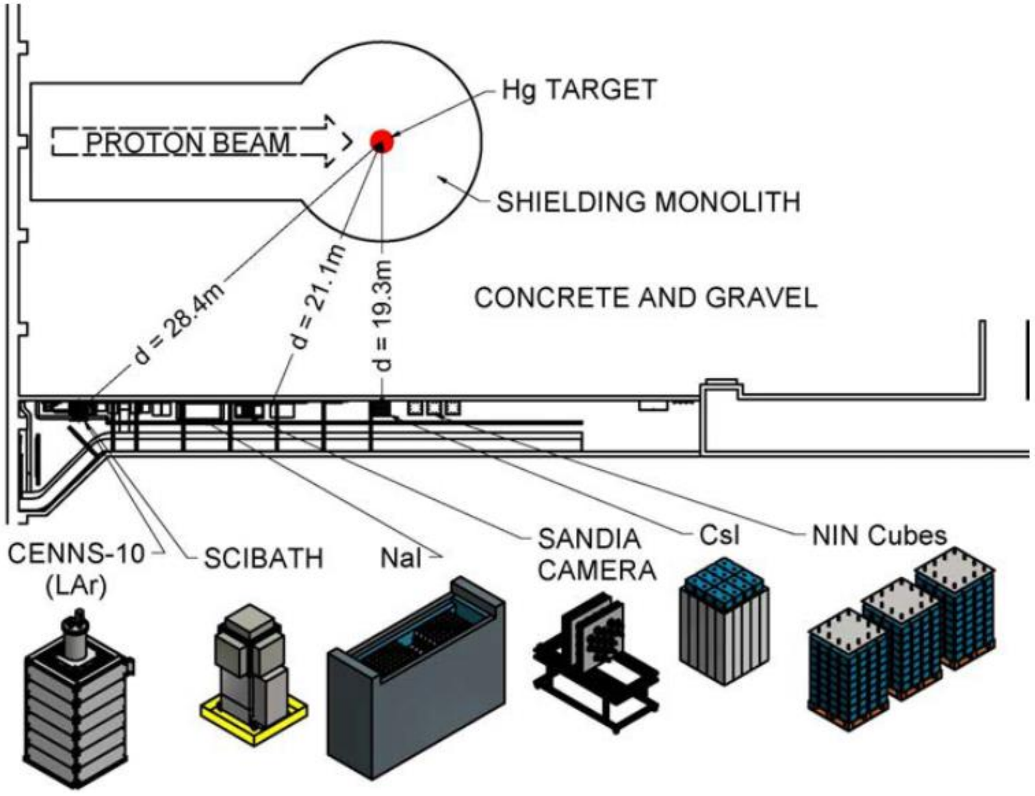

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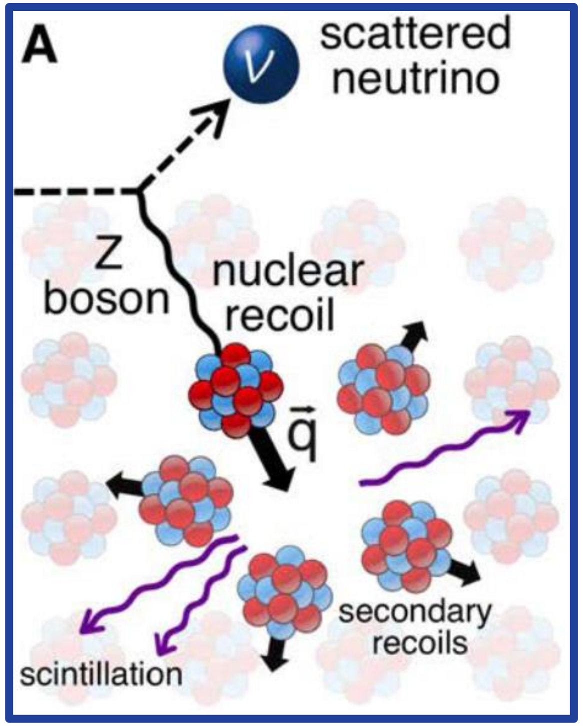
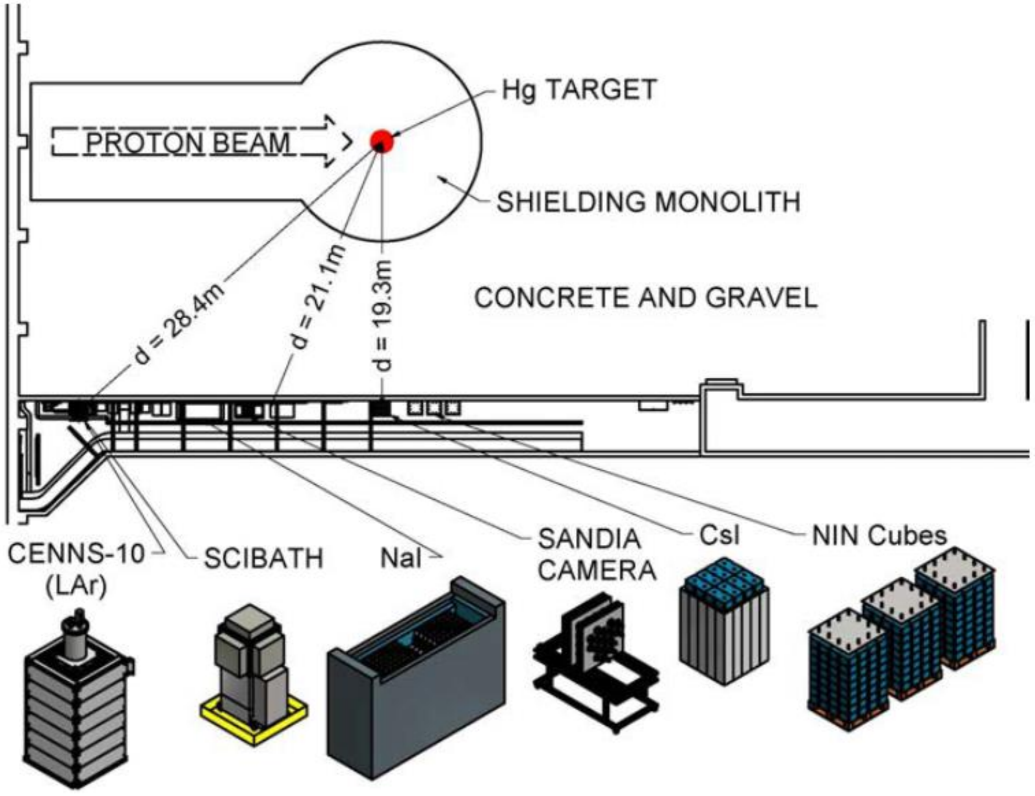


-Interaction enhanced for heavy nuclei

-Excellent probe for NP at the neutrino sector

COHERENT experiment



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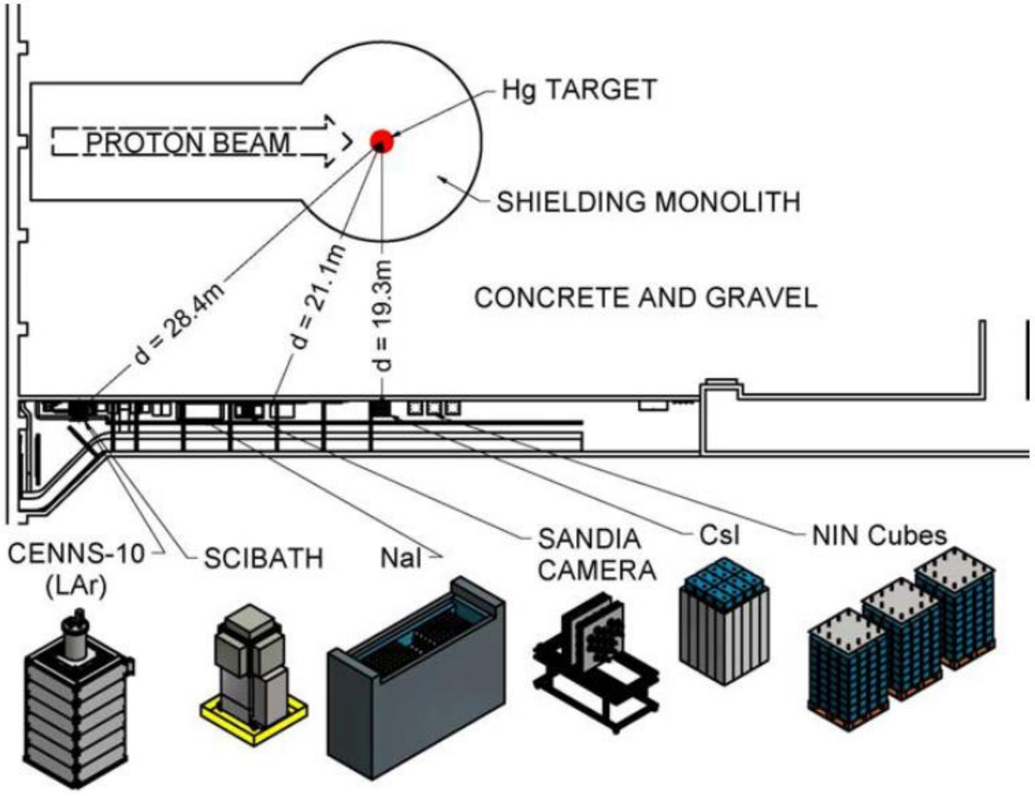

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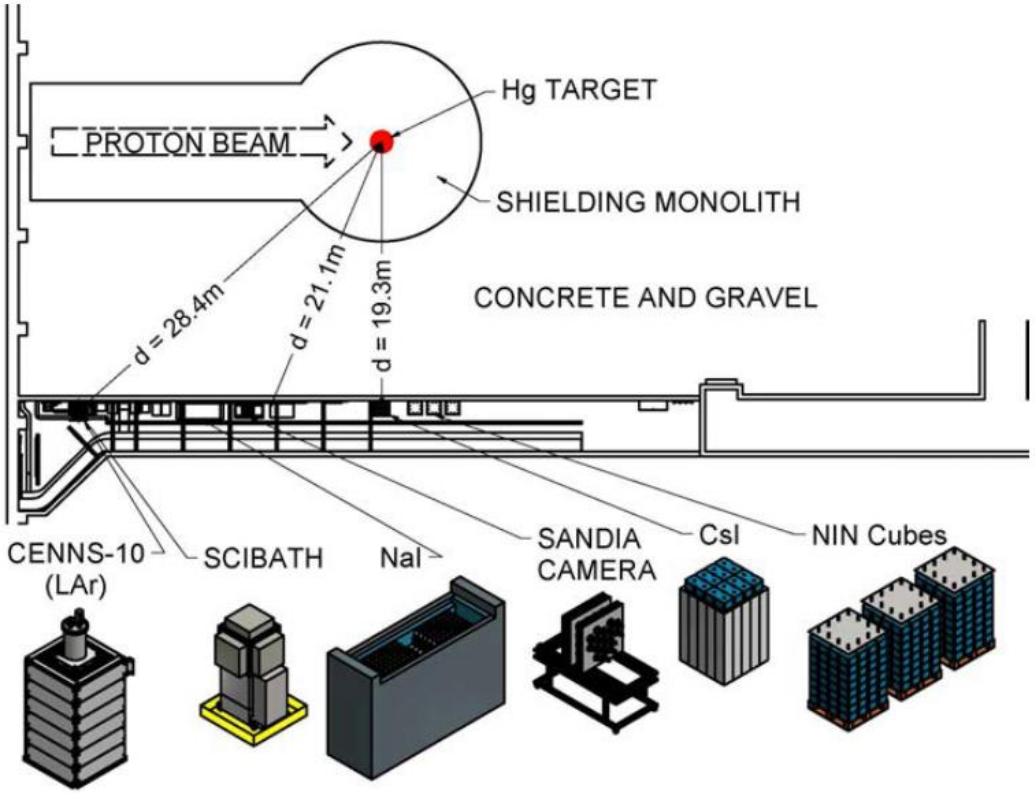

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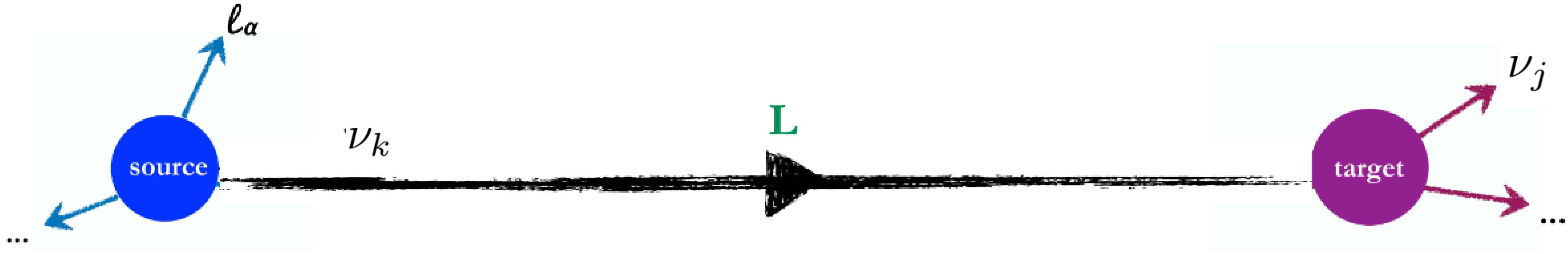
-How to introduce NP into this setup? We borrow from a recent theoretical description of neutrino oscillation observables in a QFT framework [Falkowski, González-Alonso, & Tabrizi, '20].

Adapted from [Falkowski, González-Alonso, & Tabrizi, ‘20]

Neutrino oscillation observables in QFT



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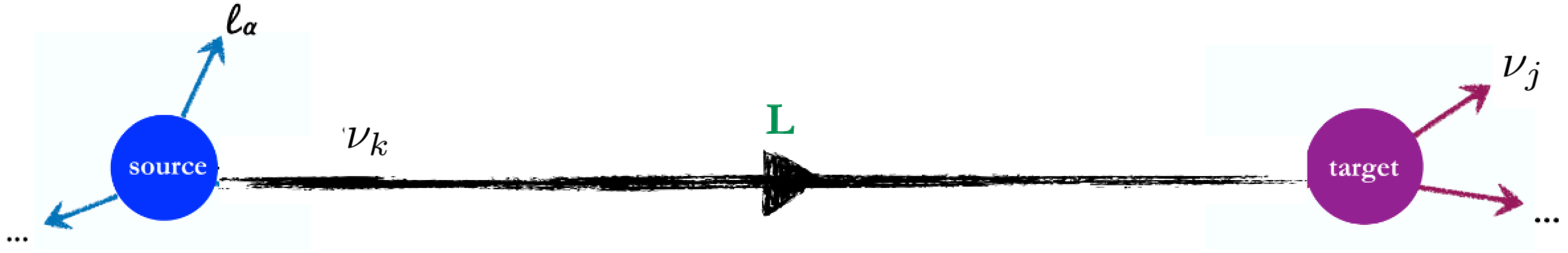

$$R_\alpha = \sum_j \frac{\kappa}{E_\nu} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_{D'} \mathcal{M}^D_{jk} \bar{\mathcal{M}}^D_{jl}$$

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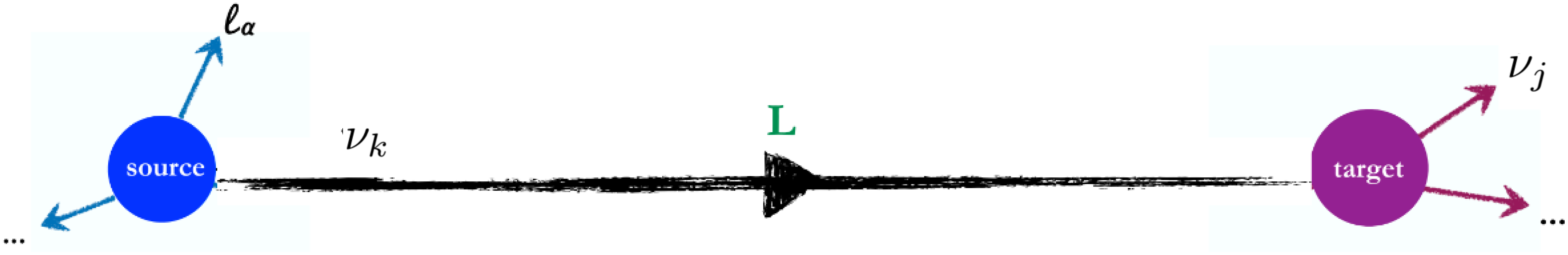

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Geometric factor

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

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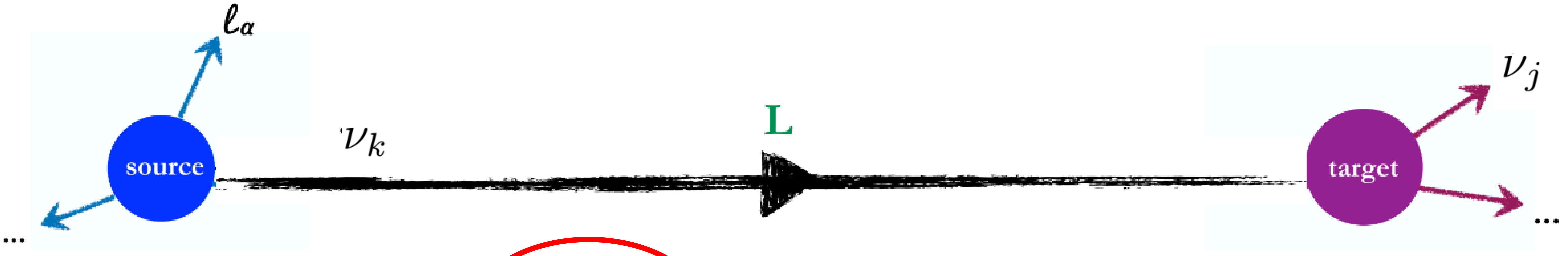

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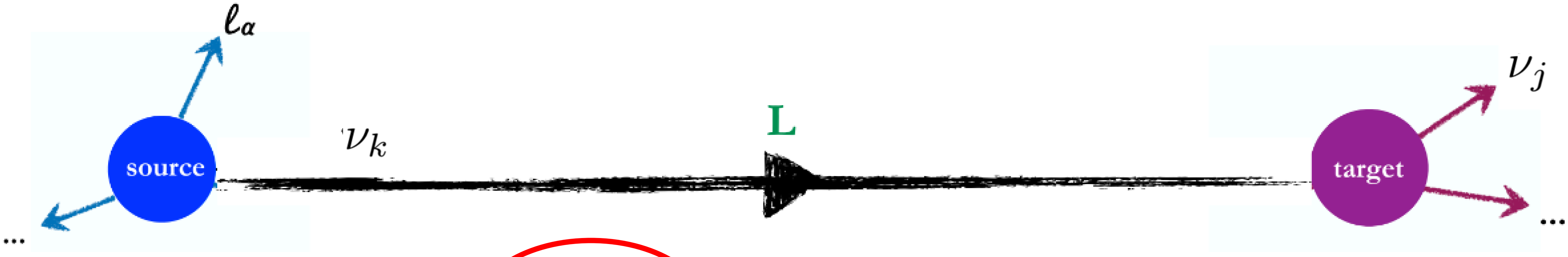

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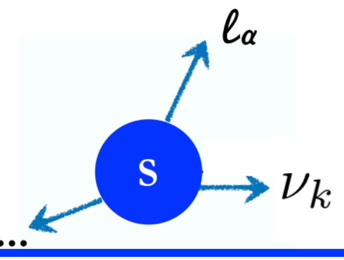
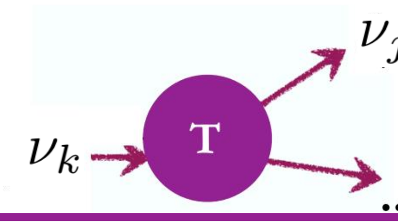
Production piece

$$\mathcal{M}^P_{\alpha k} \equiv \mathcal{M}(S \to X_\alpha \nu_k)$$



Detection piece

$$\mathcal{M}^{\bar{D}}_{jk} \equiv \mathcal{M}(\nu_k T \to Y \nu_j)$$



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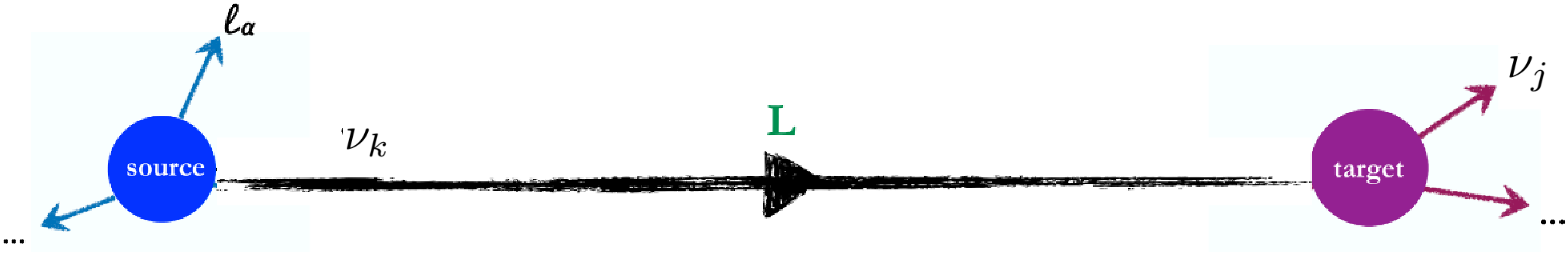

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Unique features when:

-NP effects present both on production and detection

-Flavor-violating couplings

Adapted from [Falkowski, González-Alonso, & Tabrizi, ‘20]

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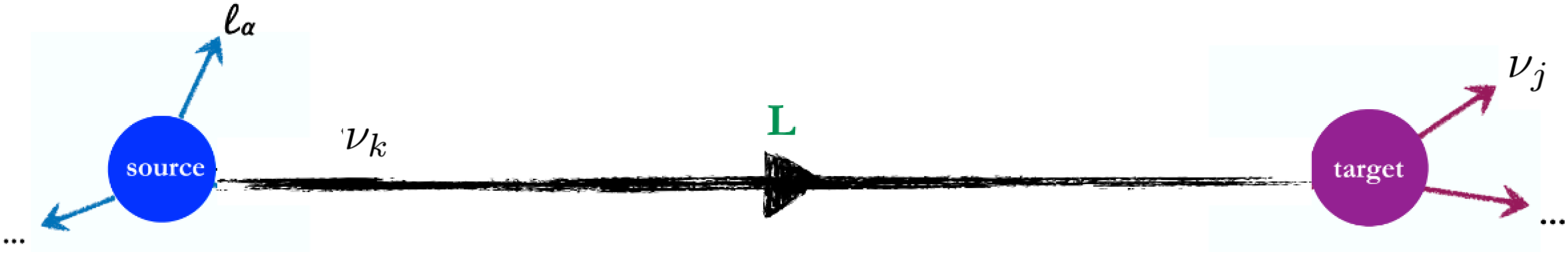

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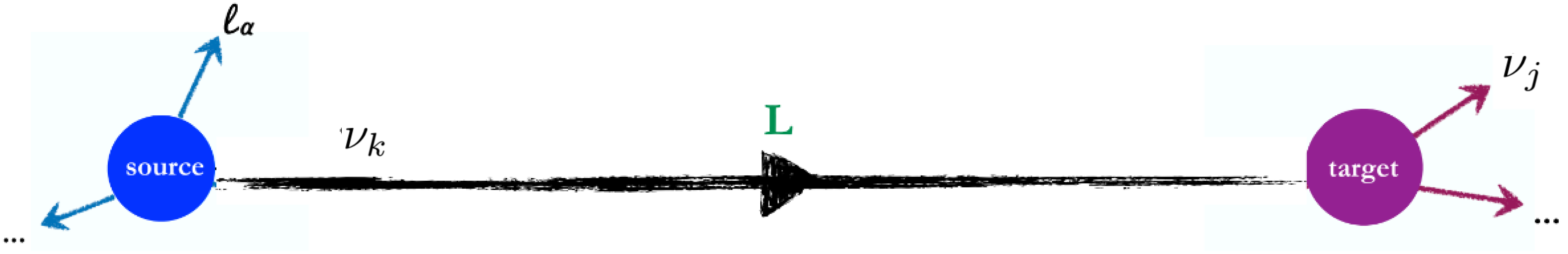

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NP effects easy to implement in the production/detection amplitudes!

WEFT

NP at the COHERENT experiment

What NP contributions enter the COHERENT observables?

-Pion decay production piece:

$$\mathcal{L}_{\text{WEFT}} \subset -\frac{2\,V_{ud}}{v^2}\Big\{[1+\epsilon_L^{ud}]_{\alpha\beta}\,(\bar{u}\gamma^\mu P_L d)\,(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R^{ud}]_{\alpha\beta}\,(\bar{u}\gamma^\mu P_R d)\,(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$-\frac{1}{2}\left[\epsilon_P^{ud}\right]_{\alpha\beta}(\bar{u}\gamma^5 d)\,(\bar{\ell}_\alpha P_L\nu_\beta)\Big\}$$

-Muon decay production piece:

$$\mathcal{L}_{\text{WEFT}} \subset -\frac{2}{v_0^2}\Big\{\left(\delta_{\alpha a}\delta_{\beta b} + [\rho_L]_{a\alpha\beta b}\right)(\bar{\ell}_a\gamma^\mu P_L\nu_\alpha)\,(\bar{\nu}_\beta\gamma_\mu P_L\ell_b) - 2\,[\rho_R]_{a\alpha\beta b}\,(\bar{\ell}_a P_L\nu_\alpha)\,(\bar{\nu}_\beta P_R\ell_b)\Big\}$$

-Detection piece:

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

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NP at the COHERENT experiment

NEW!
Indirect NP effects
from SM inputs

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NP at the COHERENT experiment

-Main observable at COHERENT:

$$\frac{dN}{dt\,dT} = g_\pi(t)\,\frac{dN^{\text{prompt}}}{dT} + g_\mu(t)\,\frac{dN^{\text{delayed}}}{dT}$$

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Extracted from our knowledge about the pion and muon decay laws

$\boldsymbol{N_s \to N_S(t)}$

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Calculated to include NP contributions, nuclear effects and experimental corrections

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$$\begin{pmatrix} 0.63 & -0.70 & -0.22 & 0.24 \\ 0.21 & -0.24 & 0.63 & -0.70 \\ -0.68 & -0.61 & 0.30 & 0.27 \\ 0.30 & 0.27 & 0.68 & 0.61 \end{pmatrix} \begin{pmatrix} \epsilon_{ee}^{dd} \\ \epsilon_{ee}^{uu} \\ \epsilon_{\mu\mu}^{dd} \\ \epsilon_{\mu\mu}^{uu} \end{pmatrix} = \begin{pmatrix} 2.0 \pm 5.7 \\ -0.2 \pm 1.7 \\ -0.037 \pm 0.042 \\ -0.004 \pm 0.013 \end{pmatrix}$$

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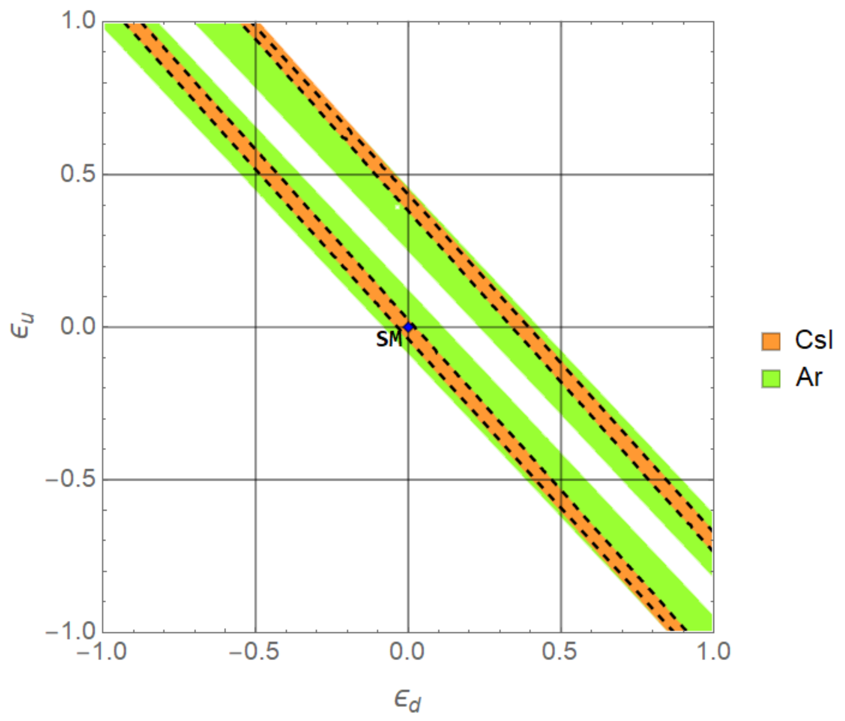
$$\epsilon_{ee}^{uu} = \epsilon_{\mu\mu}^{uu} \equiv \epsilon_u$$
$$\epsilon_{ee}^{dd} = \epsilon_{\mu\mu}^{dd} \equiv \epsilon_d$$

(Lepton-flavor universal limit)

$$\boxed{0.67\epsilon_u + 0.74\epsilon_d = -0.002 \pm 0.010}$$



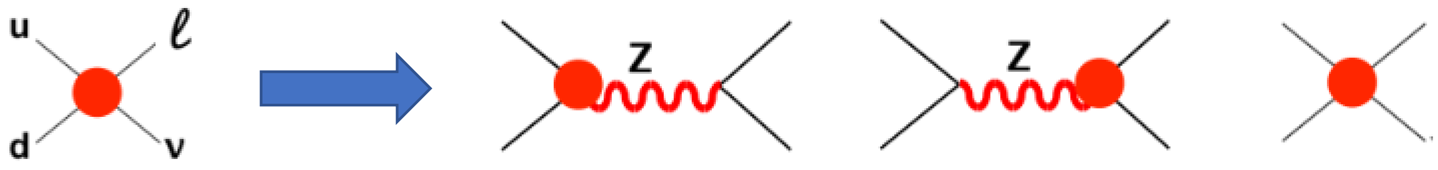
Results

-Flavor blind SMEFT matching $(U(3)^5$ scheme):

$$\boxed{0.67\epsilon_u + 0.74\epsilon_d = -0.002 \pm 0.010}$$

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

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



$$\boxed{0.71c_{lq}^{(1)} - 0.04c_{lq}^{(3)} + 0.34c_{lu} + 0.37c_{ld} - 0.67(\delta g_L^{Zu} + \delta g_R^{Zu}) - 0.74(\delta g_L^{Zd} + \delta g_R^{Zd}) + 0.26\delta g_L^{Z\nu} = -0.003 \pm 0.010}$$

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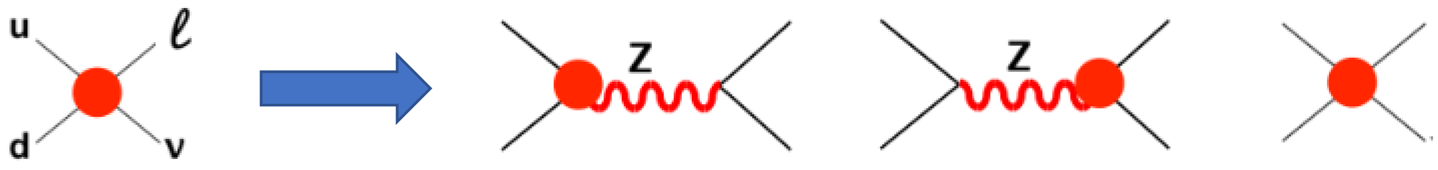

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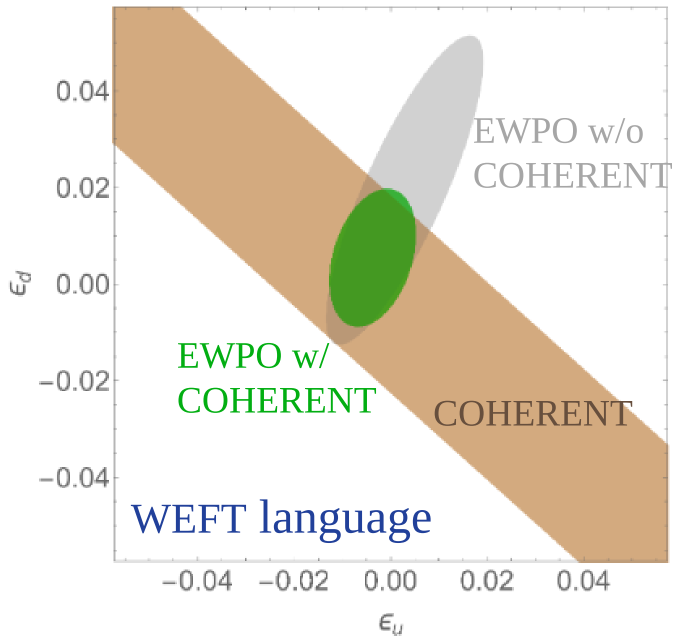
How do these results fit into the EWPO global fit?
(Z & W-pole data, atomic PV, tau decays…)

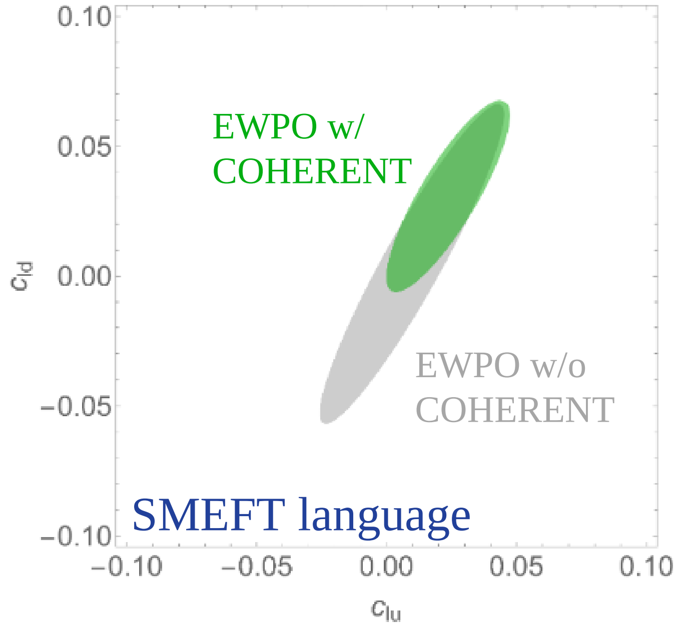
Update of [Falkowski, González-Alonso, & Mimouni, ‘17]

Results

-Impact on the SMEFT EW global fit:

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





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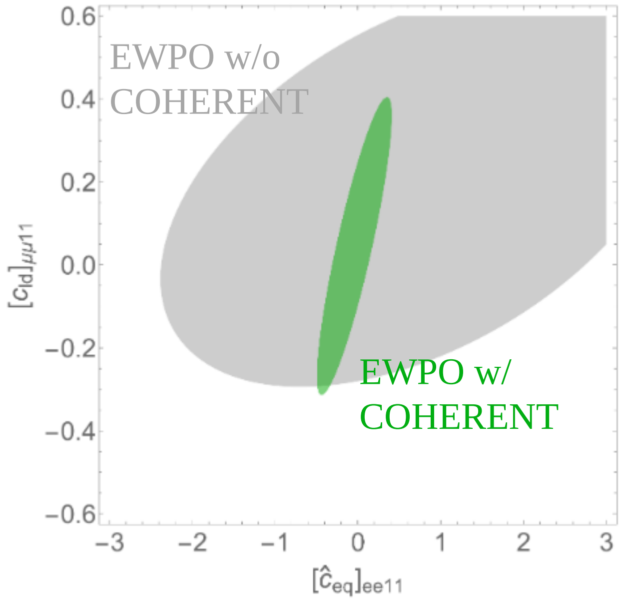
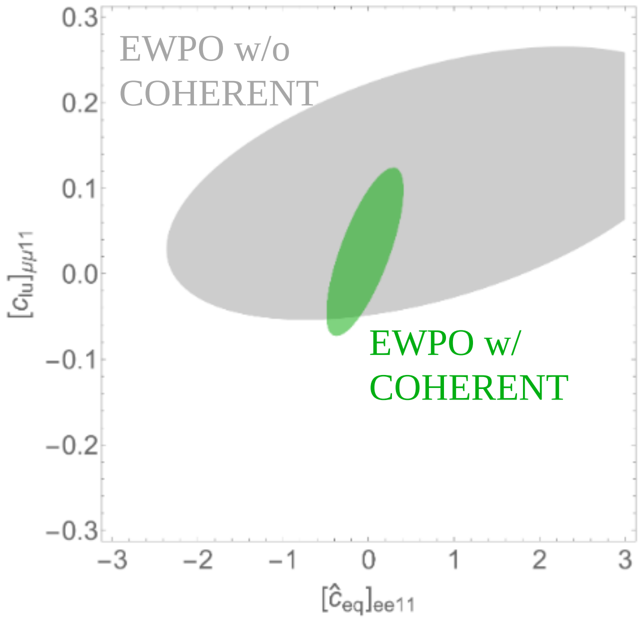
Results

-Impact on the SMEFT EW global fit (general scheme):

$$\begin{pmatrix} [c^{(3)}_{lq}]_{ee11} \\ [\hat{c}_{eq}]_{ee11} \\ [\hat{c}_{lu}]_{ee11} \\ [\hat{c}_{ld}]_{ee11} \\ [\hat{c}_{eu}]_{ee11} \\ [\hat{c}_{ed}]_{ee11} \\ [c^{(1)}_{lequ}]_{ee11} \\ [c_{ledq}]_{ee11} \\ [c^{(3)}_{lequ}]_{ee11} \\ [\hat{c}^{(3)}_{lq}]_{ee22} \\ [c_{lu}]_{ee22} \\ [\hat{c}_{ld}]_{ee22} \\ [c_{eq}]_{ee22} \\ [c_{eu}]_{ee22} \\ [\hat{c}_{ed}]_{ee22} \\ [\hat{c}^{(3)}_{lq}]_{ee33} \\ [c_{ld}]_{ee33} \\ [c_{eq}]_{ee33} \\ [c_{ed}]_{ee33} \end{pmatrix} = \begin{pmatrix} 0.1(2.8) \\ -4(30) \\ -2.5(8.7) \\ -2(18) \\ -3.1(9.4) \\ -2(17) \\ -0.017(60) \\ -0.018(57) \\ 0.023(66) \\ -61(32) \\ 2.4(8.0) \\ -300(130) \\ -21(28) \\ -87(46) \\ 250(140) \\ -8.5(8.0) \\ -1(10) \\ -3.1(5.1) \\ 18(20) \end{pmatrix} \times 10^{-2}, \quad \begin{pmatrix} [c^{(3)}_{lq}]_{\mu\mu 11} \\ [c^{(1)}_{lq}]_{\mu\mu 11} \\ [c_{lu}]_{\mu\mu 11} \\ [c_{ld}]_{\mu\mu 11} \\ [\hat{c}_{eq}]_{\mu\mu 11} \\ \epsilon_P^{d\mu}(2\text{ GeV}) \\ [c^{(3)}_{lq}]_{\tau\tau 11} \\ [c^{(3)}_{lequ}]_{\tau\tau 11} \\ \epsilon_P^{d\tau}(2\text{ GeV}) \end{pmatrix} = \begin{pmatrix} 3.0(3.5) \\ -0.2(5.8) \\ 2.5(6.5) \\ 5(24) \\ 3(41) \\ -0.080(95) \\ -0.3(2.8) \\ -0.3(1.2) \\ 0.93(85) \end{pmatrix} \times 10^{-2}.$$



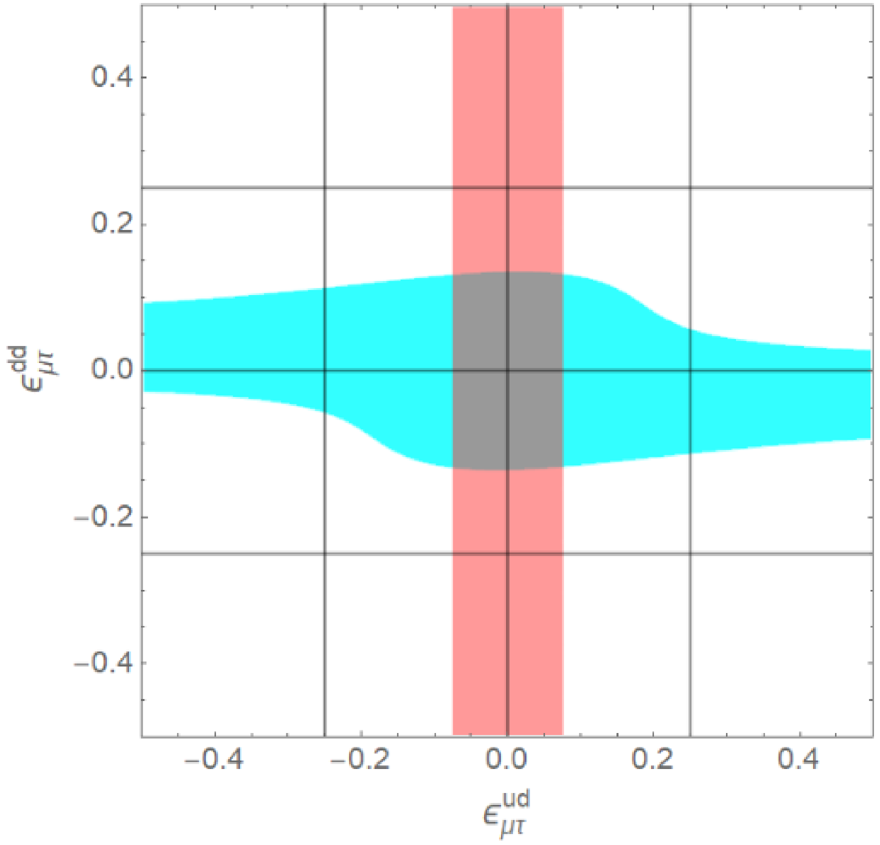


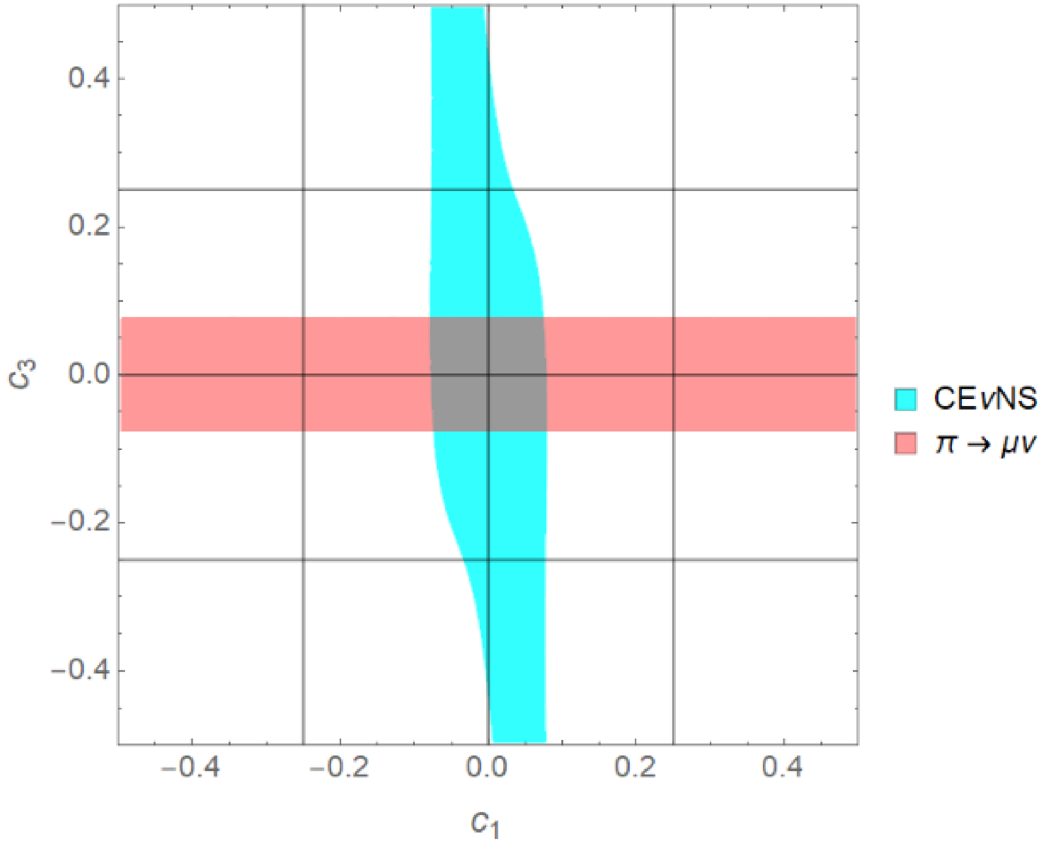
Results

Relevant setup for models with explicit EW symmetry:

$$[\epsilon_L^{ud}]_{\mu\tau} = c_3 \ , \qquad \epsilon_{\mu\tau}^{uu} = c_1 - c_3 \ , \qquad \epsilon_{\mu\tau}^{dd} = c_1 + c_3$$

-Production and detection WCs together:





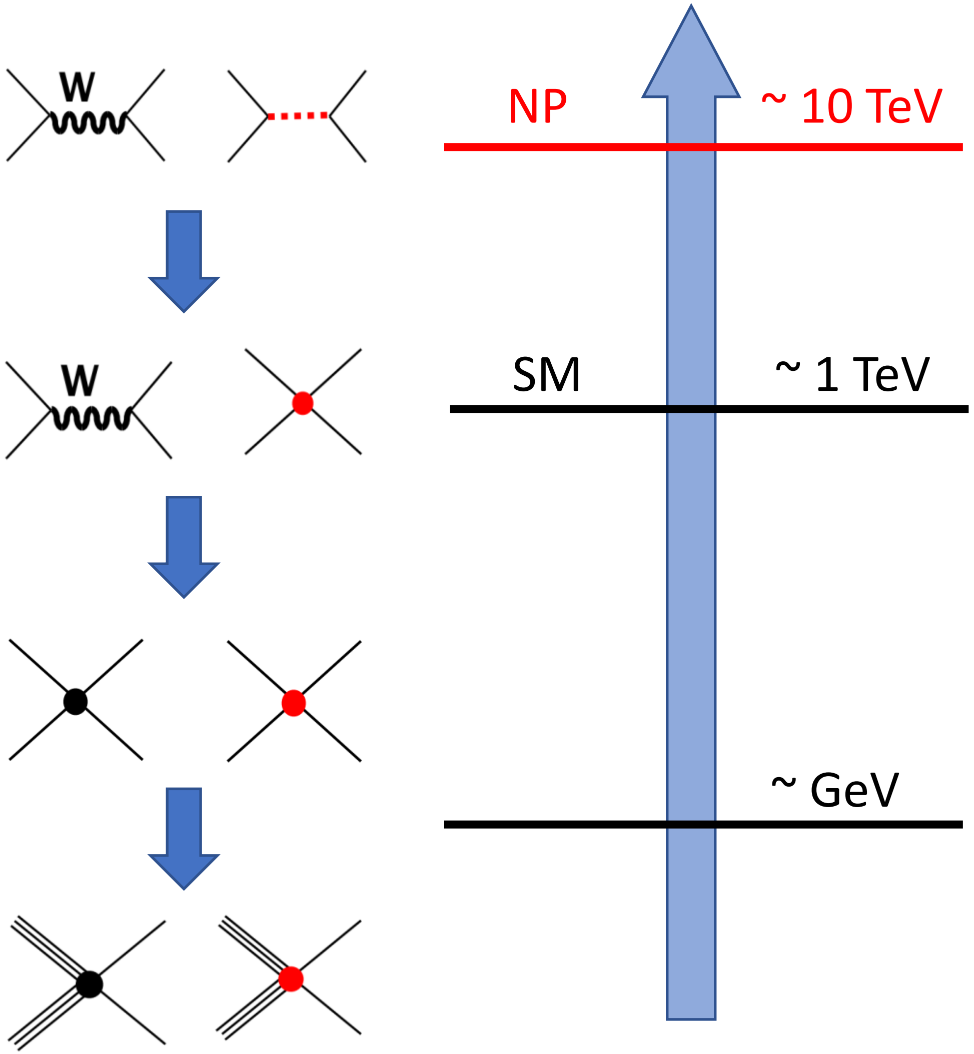
Conclusions

- We have succesfully applied an EFT-based formalism for the description of **BSM physics at the COHERENT experiment**:
  - understand the UV meaning and limitations of the production/detection NSIs
  - take into account NP in production & detection
  - take into account NP affecting SM input
  - connect with specific NP models or interactions (e.g. leptoquarks)"

- We have quantitatively determined the impact of NP coming from production

- We have incorporated the COHERENT information into the **SMEFT electroweak global fit**

Extra: EFTs for low energy observables



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

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i O_i^{d=6}$$

Standard Model EFT

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

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

Low energy EFT

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

$$\mathcal{L}_{\pi,N,\dots} = \cdots$$

Extra: COHERENT observable expanded

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

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

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

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

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SM → 1 weak charge (per target nucleus)

EFT → 3 weak charges (per target nucleus)

$$\boxed{\frac{d\tilde{\sigma}_f}{dT} = (m_{\mathcal{N}} + T) \frac{(\mathcal{F}(T))^2}{2v^4\,\pi} \left(1 - \frac{(m_{\mathcal{N}} + 2E_\nu)\,T}{2E_\nu^2}\right) \tilde{Q}_f^2} \longrightarrow \tilde{Q}_f^2 \equiv Q_{\text{SM}}^2 + g_f\left(\epsilon_{CC}, \epsilon_{NC}\right)$$

-Generalized weak charges:

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

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

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

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

$$[\mathcal{P}_R]_{\alpha\beta} \equiv [\rho_R]_{\mu\alpha\beta e} . \qquad [\mathcal{Q}]_{\alpha\beta} = Z g_{\alpha\beta}^{\nu p} + (A - Z) g_{\alpha\beta}^{\nu n}$$

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

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

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