EFT analysis of New Physics at Neutrino Experiments

WIN 2023 July 2023

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

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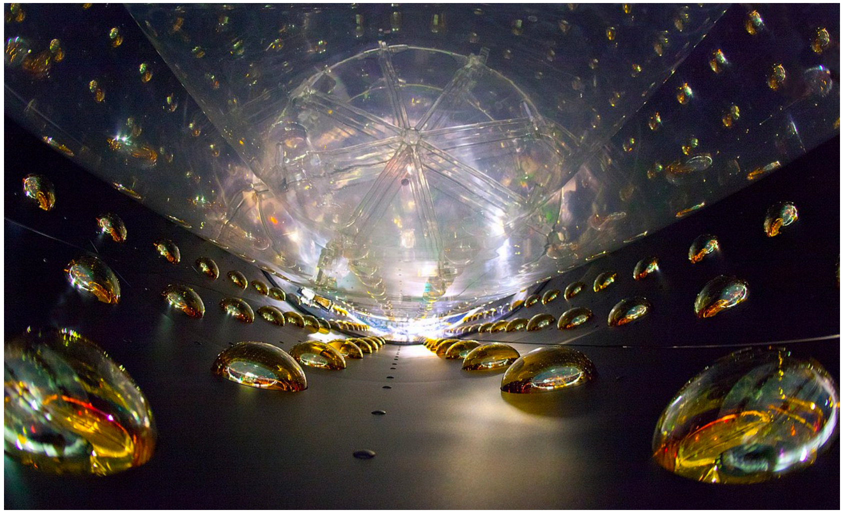
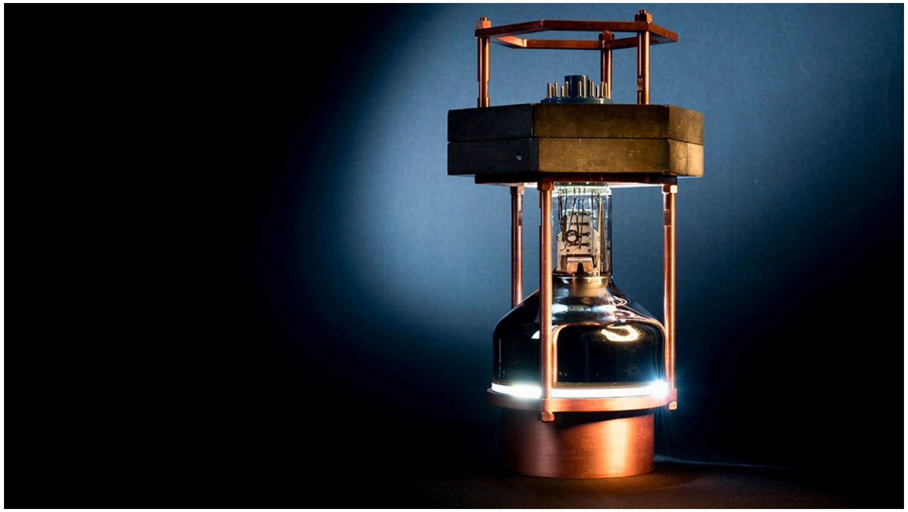
Outline

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





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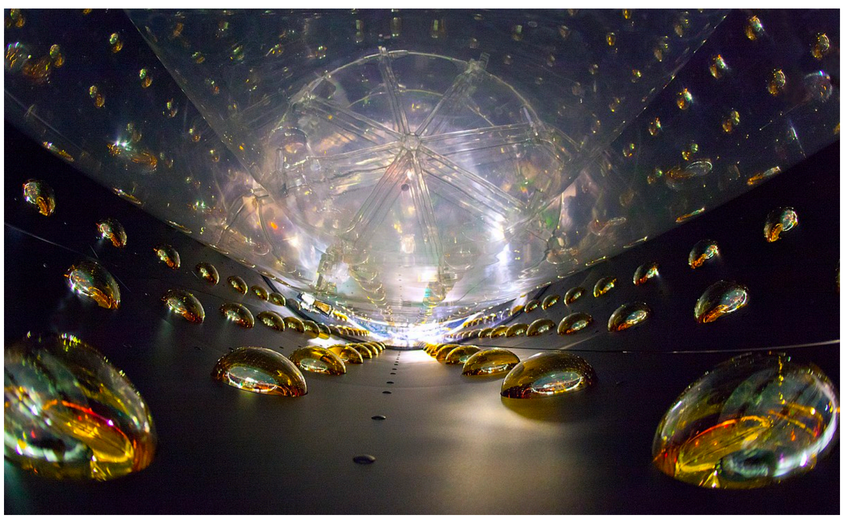
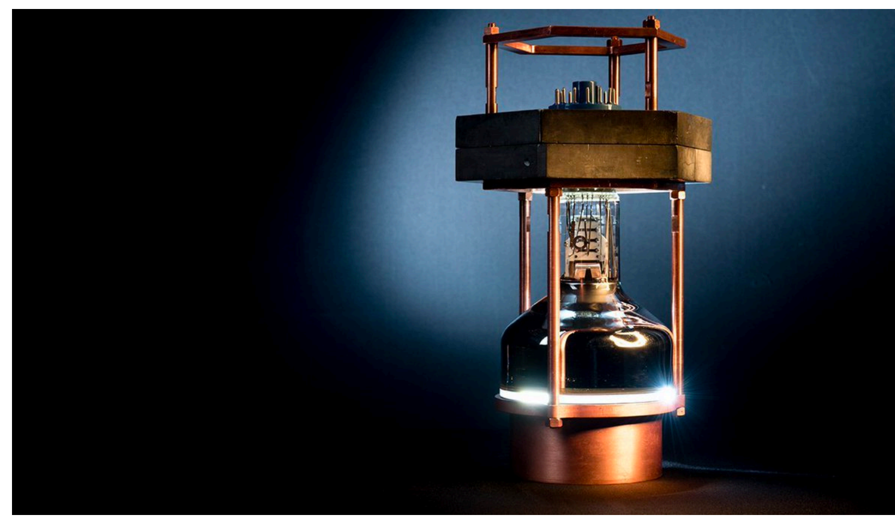
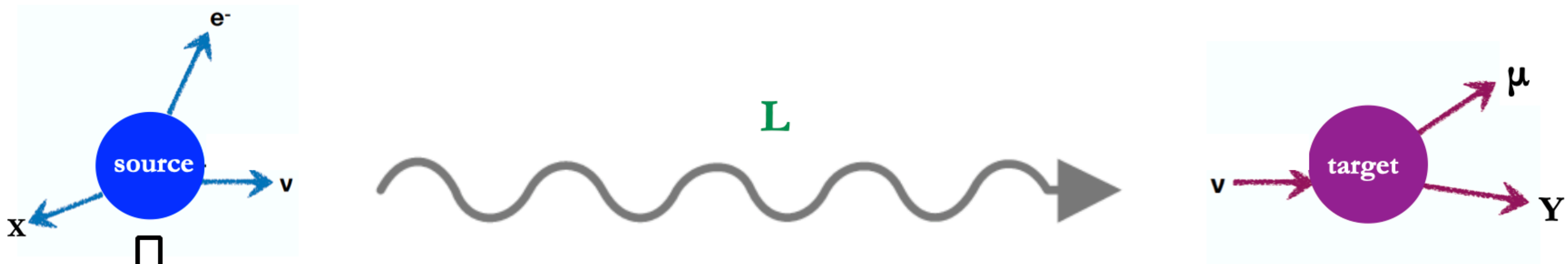
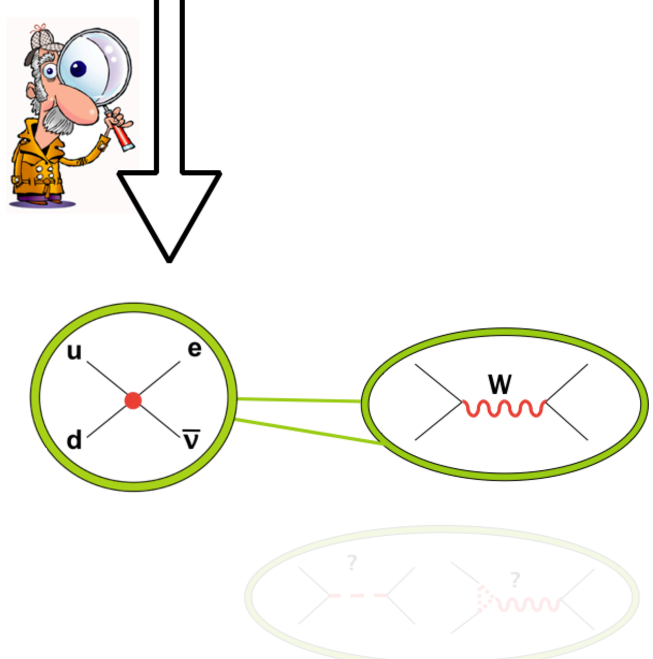




Introduction





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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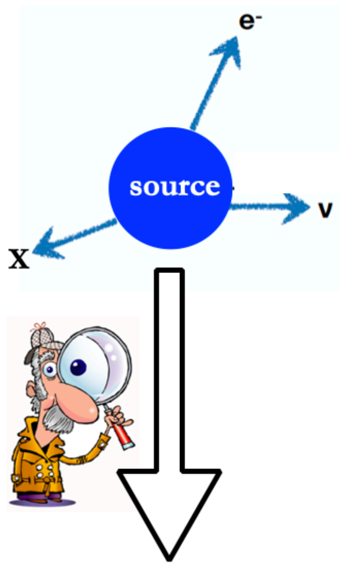

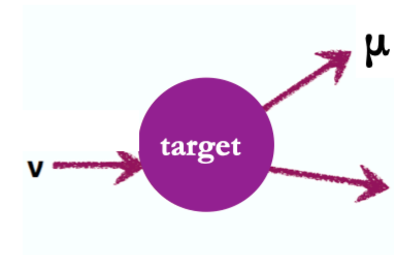

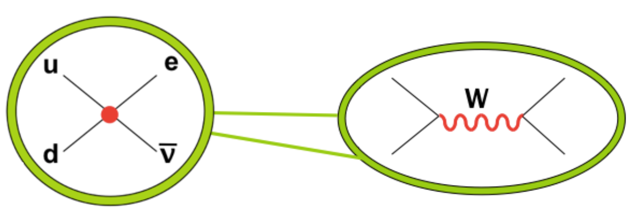

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with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	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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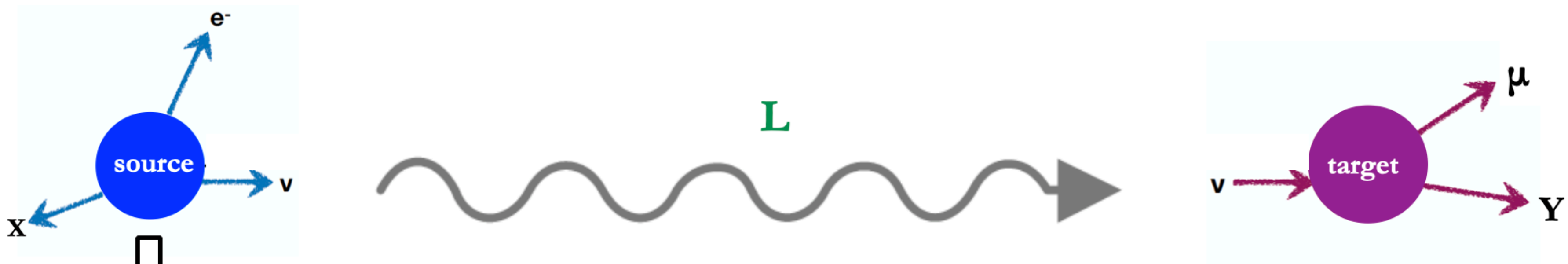

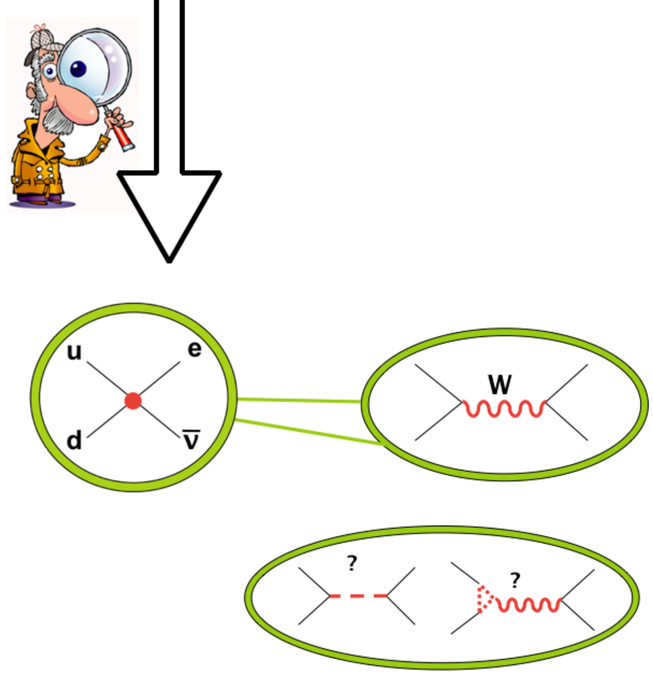

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Lagrangian parameters!

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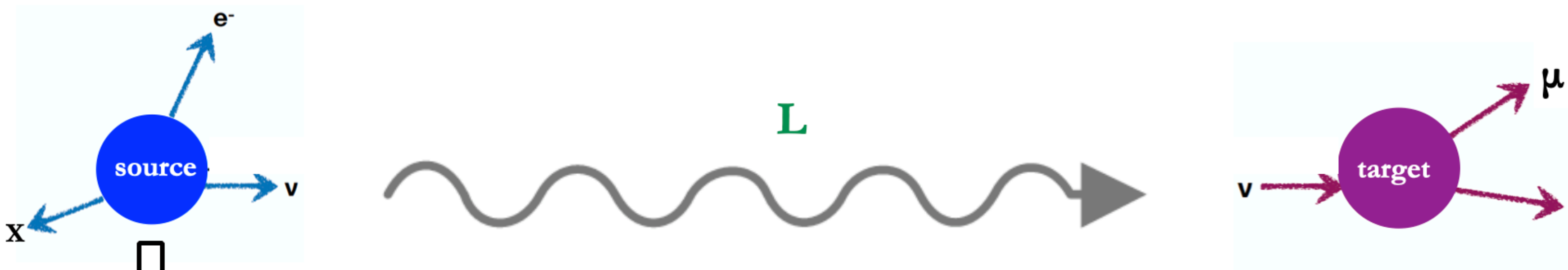

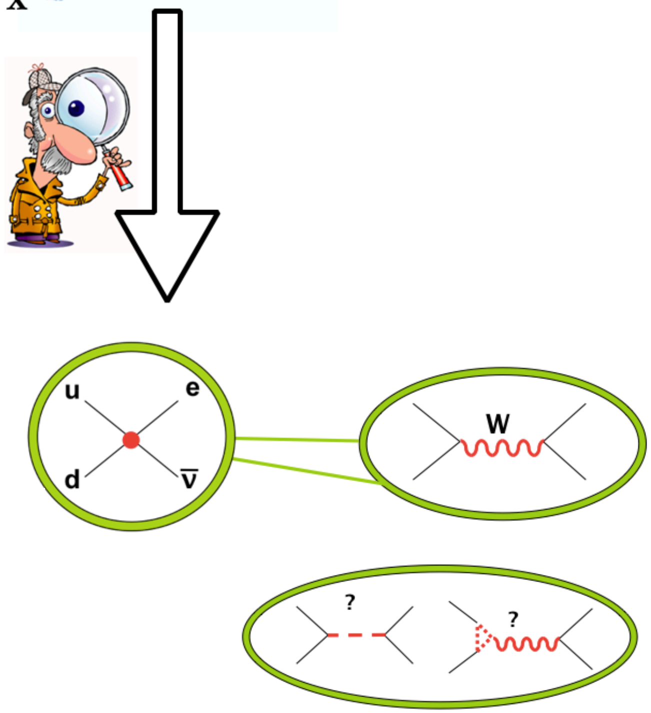

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how are oscillations affected by a charged Higgs?
A leptoquark? Which part of their parameter space
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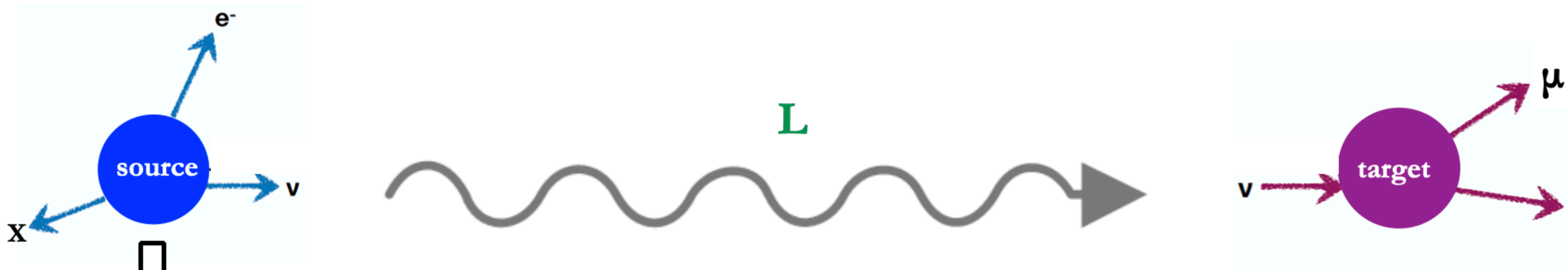

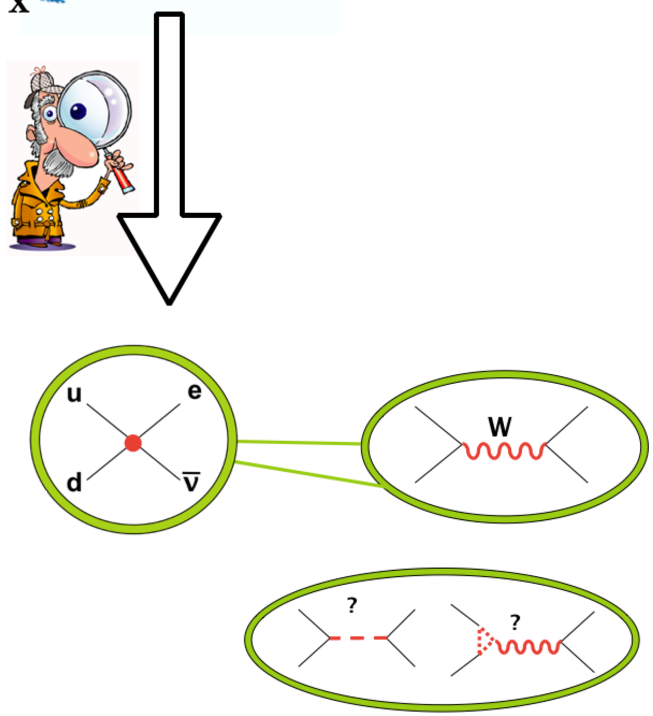

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- QM approach not useful ("source/detector NSI") → QFT approach needed

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

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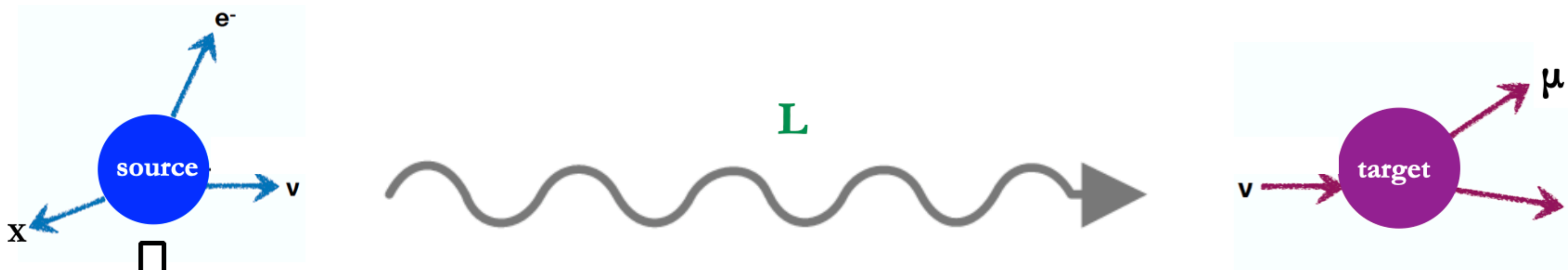

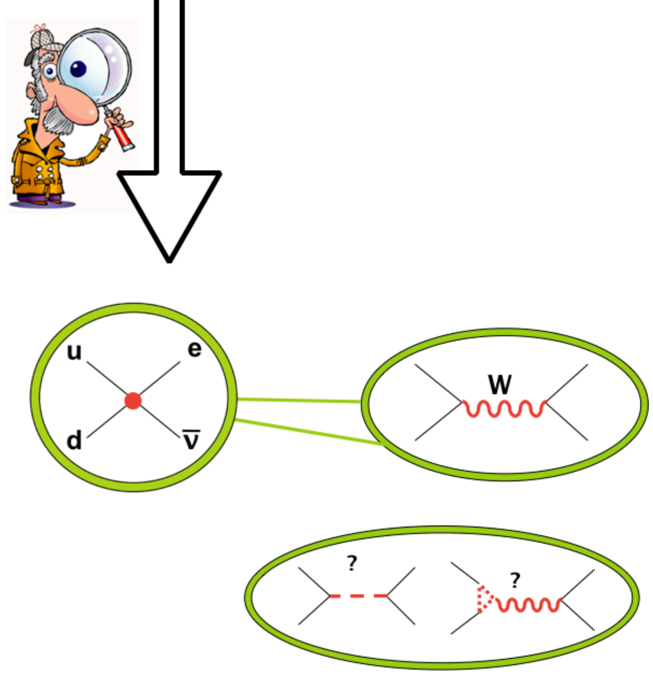

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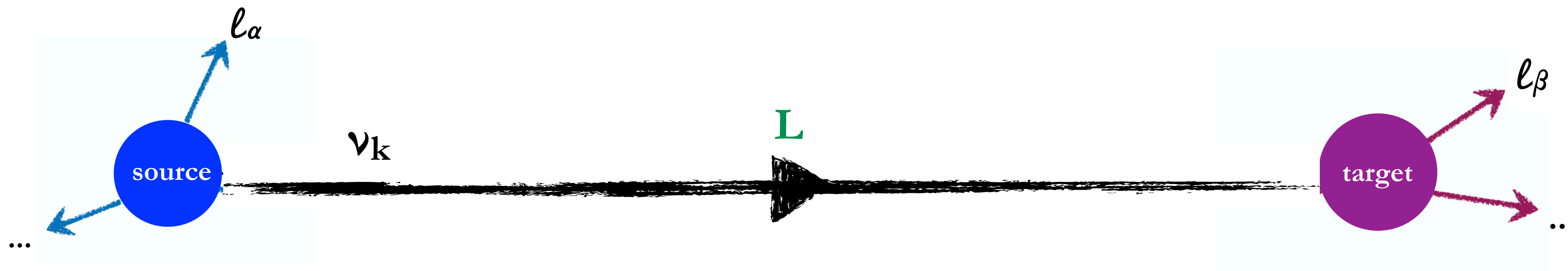
Giunti et al. [hep-ph/9305276]
Akhmedov Kopp [arXiv:1001.4815]
...

Oscillations in QFT

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



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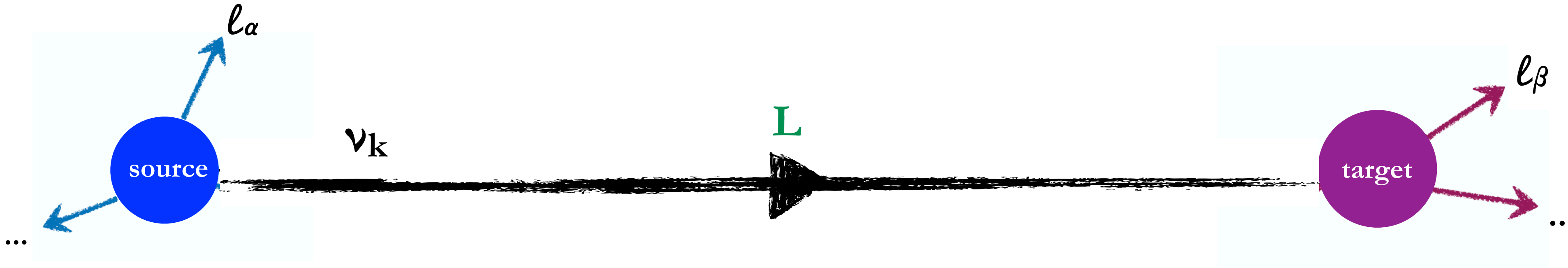

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Geometric factor

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

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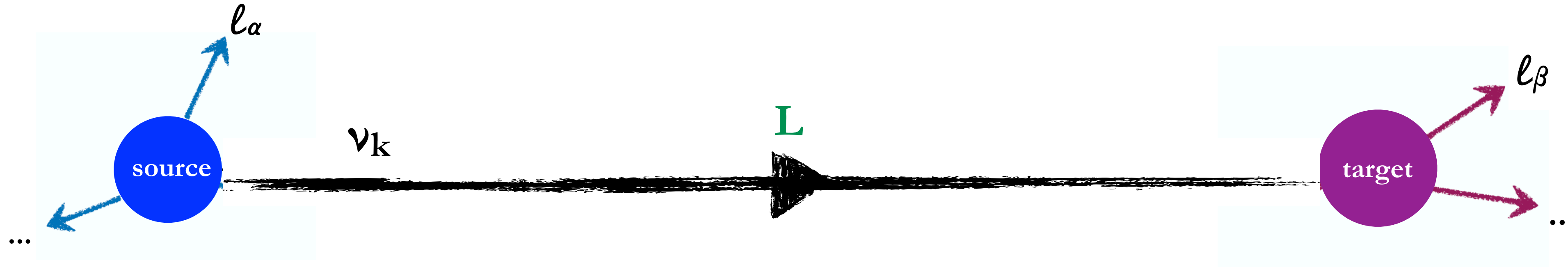

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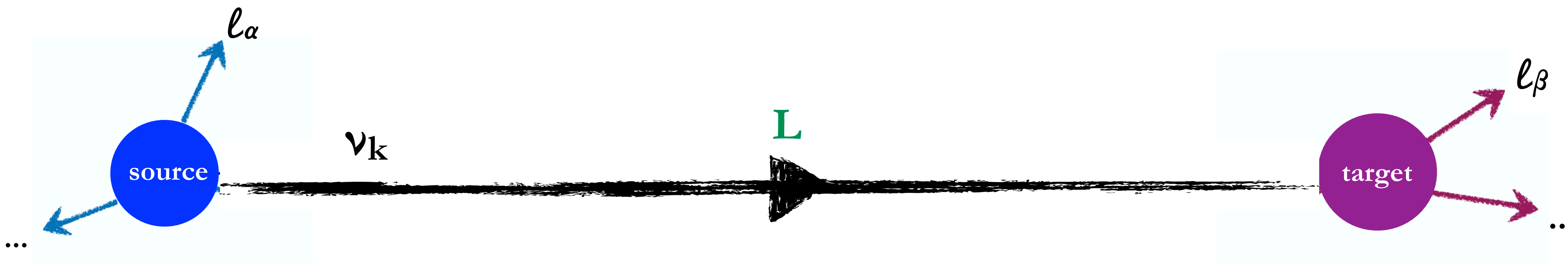

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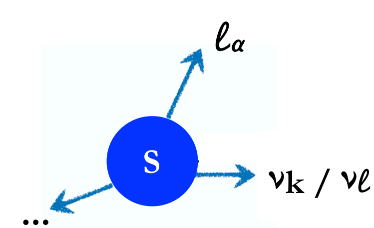
$\mathcal{M}^P_{\alpha k} \equiv \mathcal{M}(S \to X_\alpha \nu_k)$



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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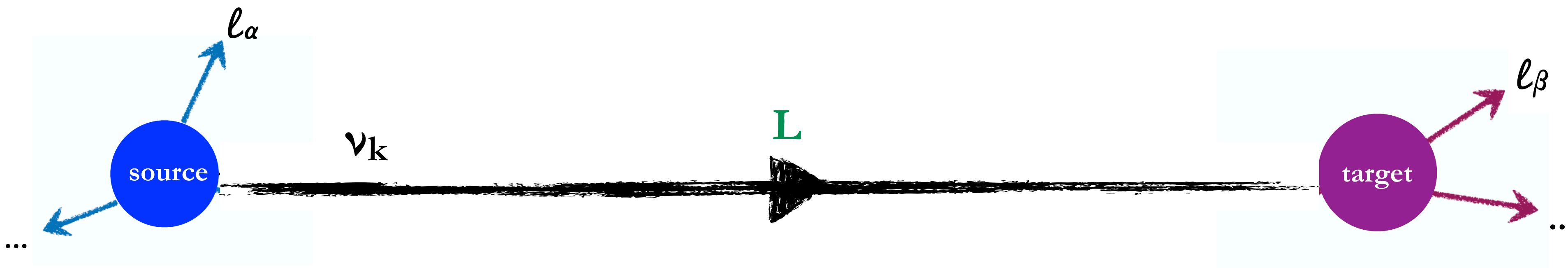

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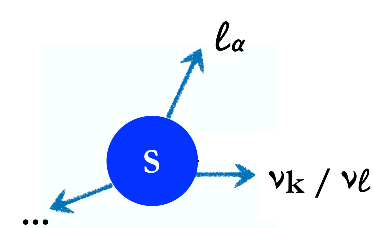
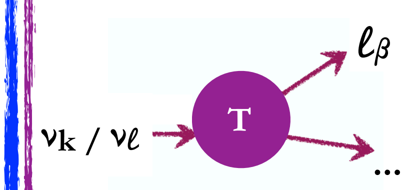


Detection

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



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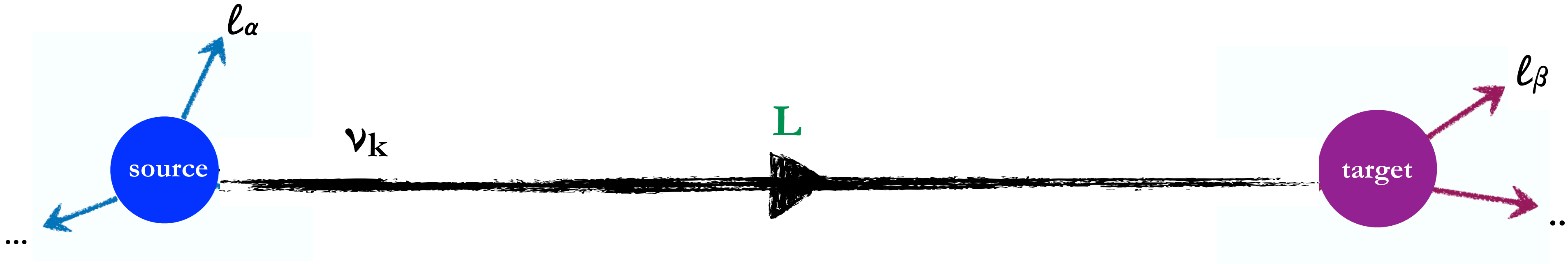

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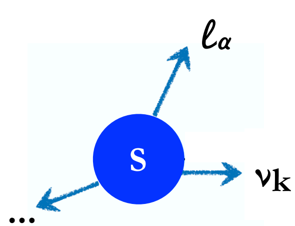
- The rest is "straightforward":
  specify the Lagrangian and calculate the production & detection amplitudes.



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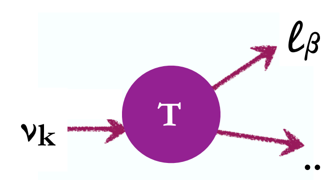
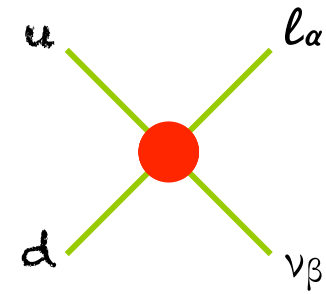


Oscillations in QFT → EFT

Low-energy effective Lagrangian:

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



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

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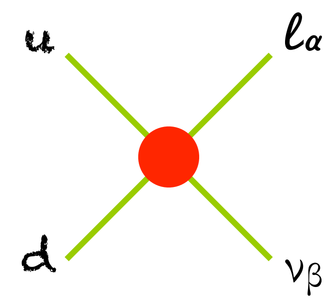

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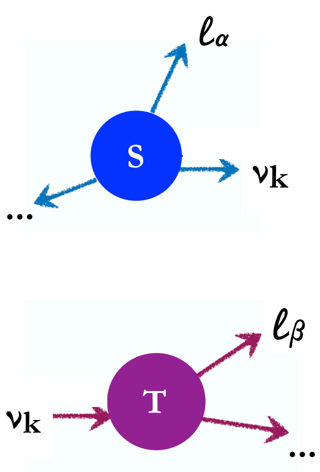

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$$\begin{pmatrix}\nu_e\\ \nu_\mu \\ \nu_\tau\end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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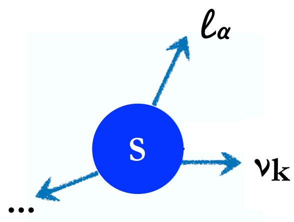

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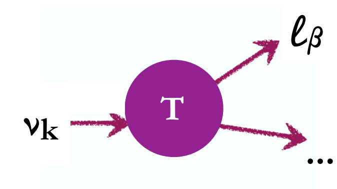

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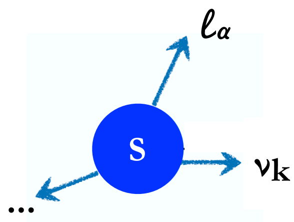

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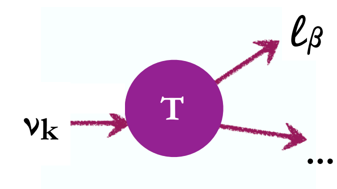

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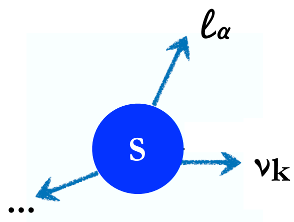
$[\varepsilon = 0]$

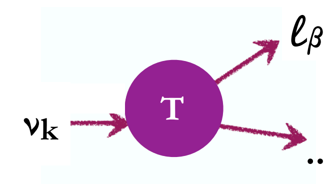
Oscillations in QFT → EFT

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



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

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



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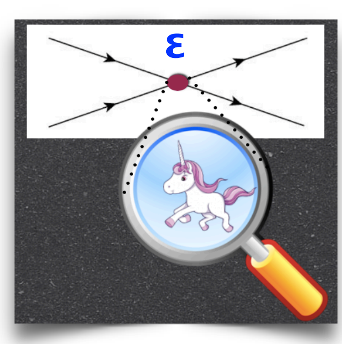
New qq'lν interactions



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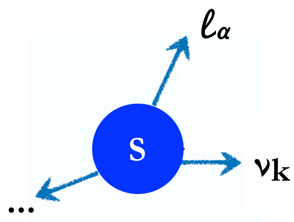
[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



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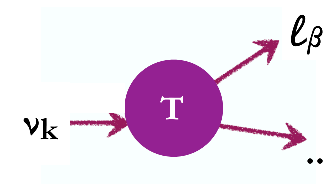

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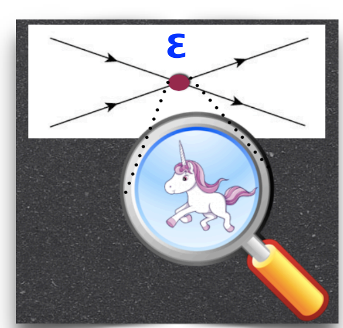
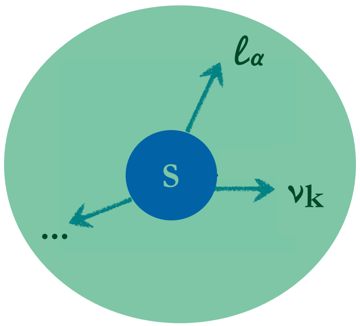
PMNS matrix

New qq'lν interactions



Oscillations in QFT → EFT

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



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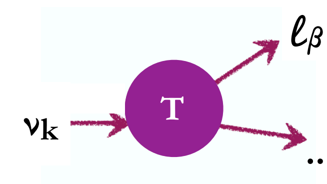

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Production physics (QCD, EW)

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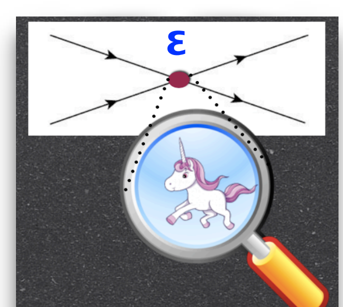

$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}$$

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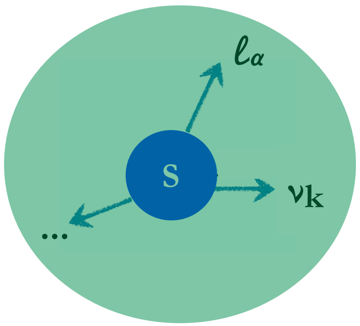
Oscillations in QFT → EFT

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



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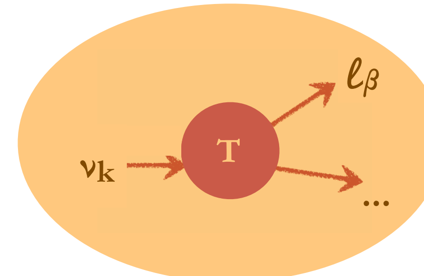

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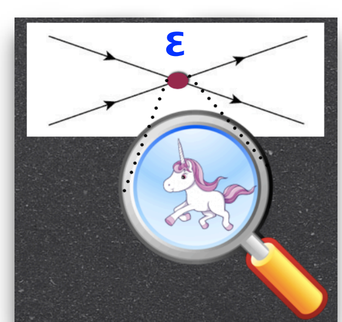

Production physics (QCD, EW)

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

Detection physics (QCD, EW)

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

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:

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

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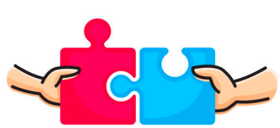
[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]

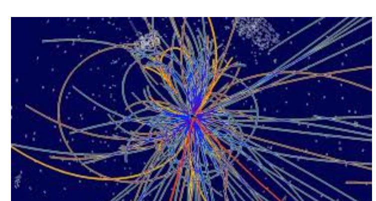
- Choose your favourite experiment:

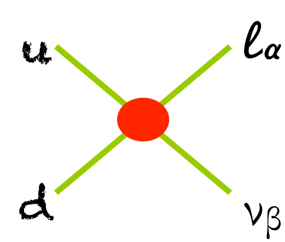
$$O = O(\theta_i, \Delta m^2, \varepsilon_j(\mu_{Low})) \Longrightarrow \varepsilon_j(\mu_{Low})$$

- Now you can run, match, run, …

- Compare and combine with other searches.

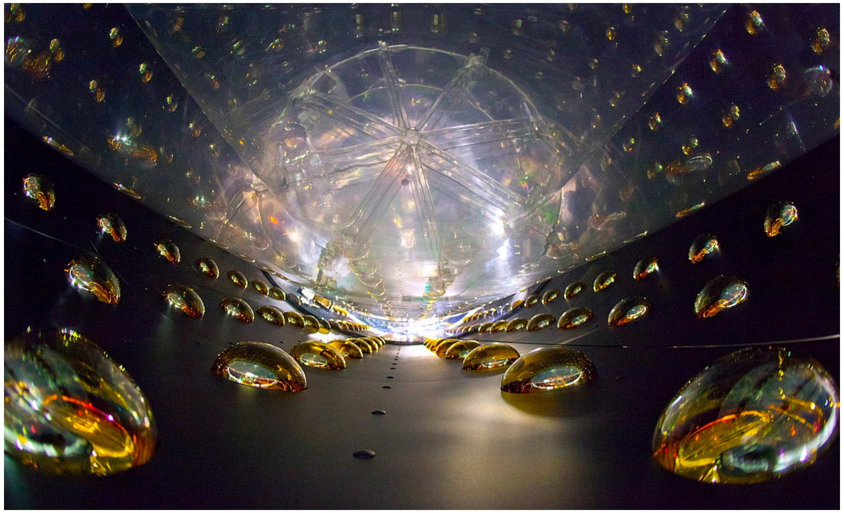


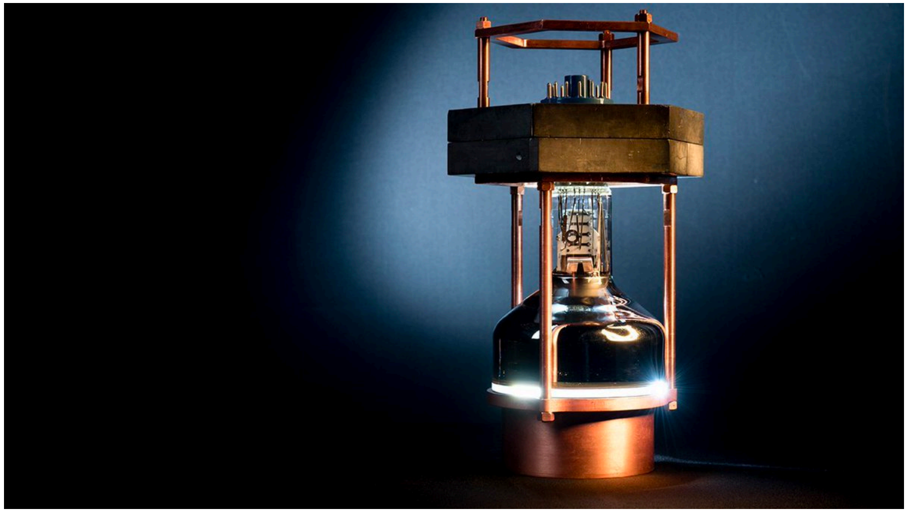




Outline

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





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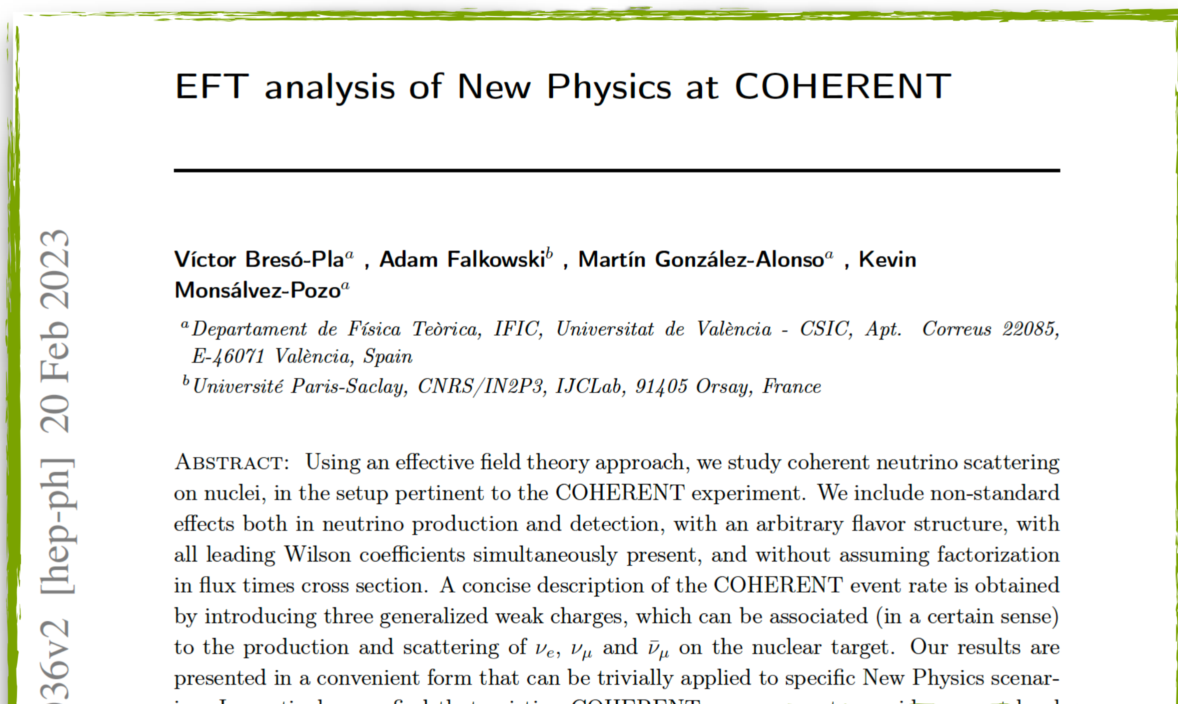
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]



036v2 [hep-ph] 20 Feb 2023

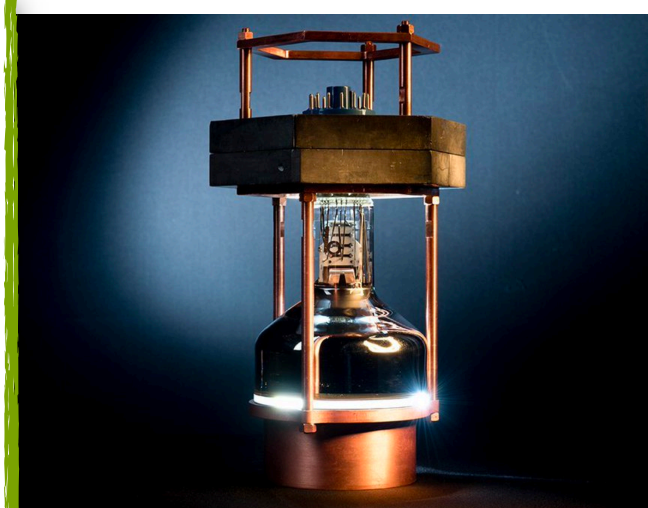
EFT analysis of New Physics at COHERENT

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 scenar-

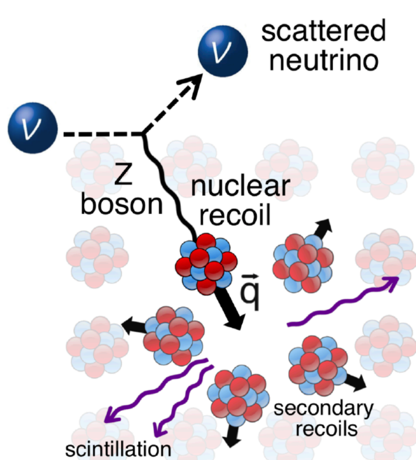


EFT analysis of NP at COHERENT

- COHERENT observed for the first time CEνNS (Coherent Elastic Neutrino-Nucleus Scattering): $\nu N \to \nu N$

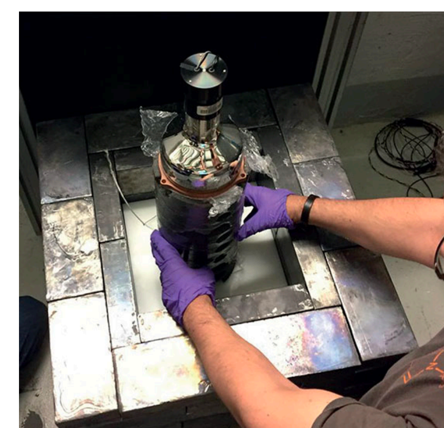
- It occurs for E_ν small enough so that the neutrino does not resolve the nucleus → CEνNS cross section enhanced by N^2.
  Theoretically known since the 70's
  [Freedman'74; Kopeliovich & Frankfurt'74]

- Extremely challenging experimentally (very small nuclear recoil)



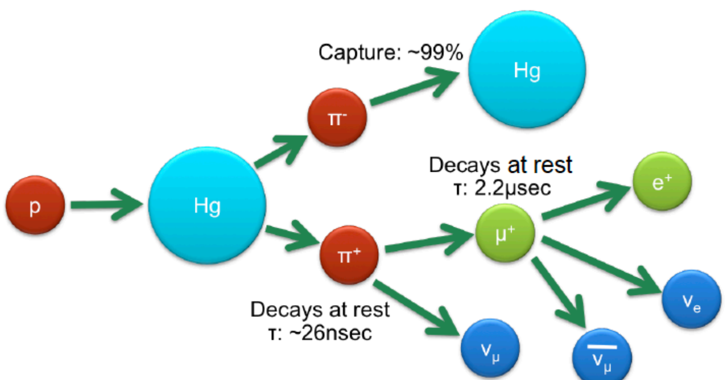
[from COHERENT coll.]

[Akimov et al.'17]



[Image credit: Duke U.]

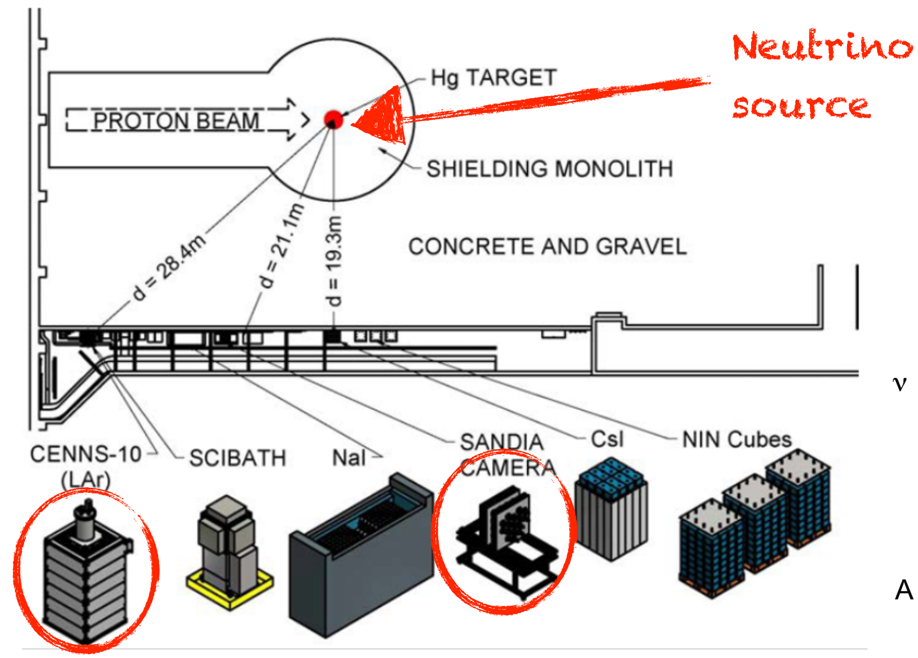
EFT analysis of NP at COHERENT

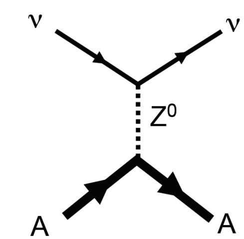


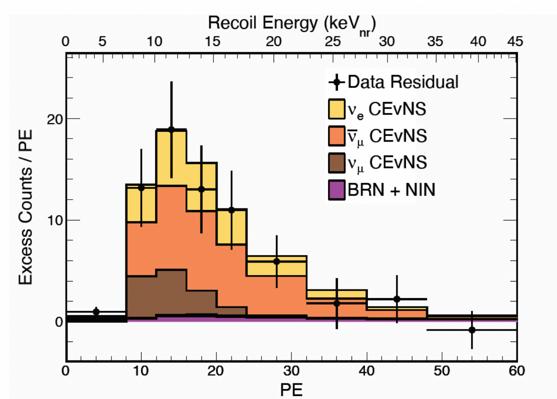
[from Scholberg's talk at IPA18]

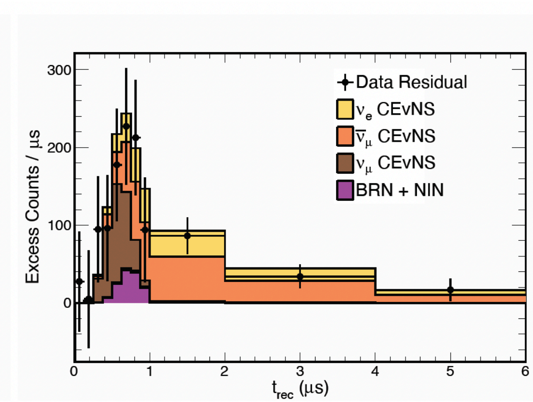
$\pi^+ \to \mu^+ \, \nu_\mu$ (prompt)

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

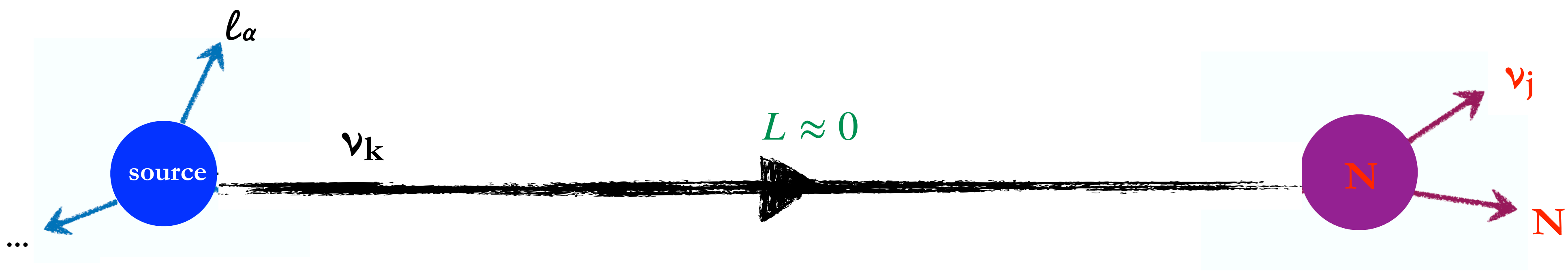








EFT analysis of NP at COHERENT



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

- CC production: pion and muon decays.

$\pi^+ \to \mu^+ \nu_\mu$ (prompt)

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

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

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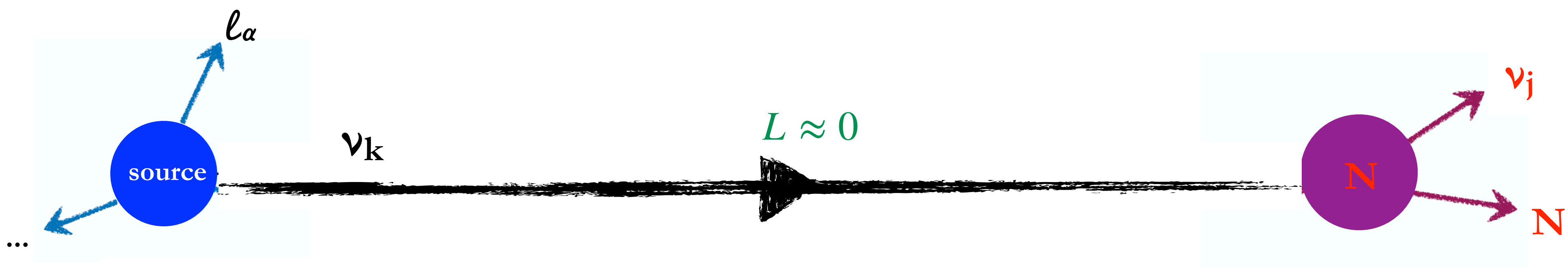

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- CC production: pion and muon decays.
- NC detection: νN → νN.

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

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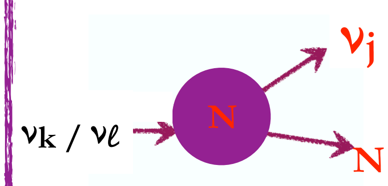
Detection

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



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

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: $Q_{SM}^2 \sim N^2$

[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]

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

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

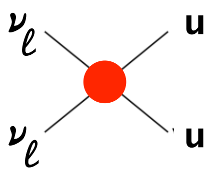
$$\frac{d\tilde{\sigma}_f}{dT} = (m_{\mathcal{N}} + T) \frac{(\mathcal{F}(T))^2}{2v^4 \pi} \left(1 - \frac{(m_{\mathcal{N}} + 2E_\nu)\,T}{2E_\nu^2}\right) \tilde{Q}_f^2$$

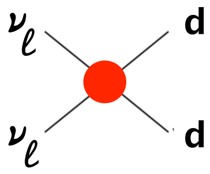
$$\tilde{Q}_f^2 \equiv Q_{SM}^2 + g_f(\epsilon_{NC}, \epsilon_{CC})$$

- 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:
  - LFU effects: $\epsilon_{ee}^{uu} = \epsilon_{\mu\mu}^{uu} \equiv \epsilon_u$
    $\epsilon_{ee}^{dd} = \epsilon_{\mu\mu}^{dd} \equiv \epsilon_d$





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

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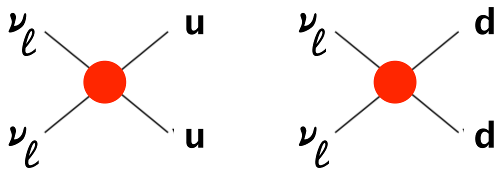
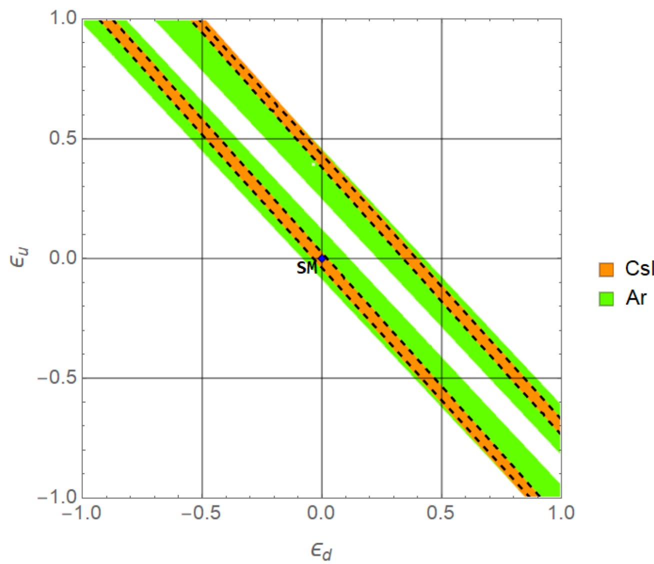


COHERENT data (LAr + CsI, recoil & time distribution: 664 data) give:

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



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

COHERENT in the SMEFT

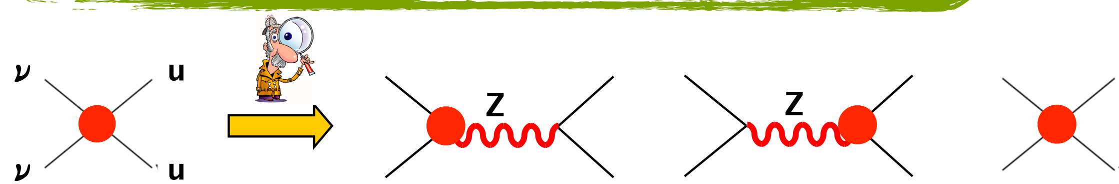
- "Flavor-blind" SMEFT (→ U(3)⁵ symmetry)

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

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

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

WEFT/SMEFT Matching



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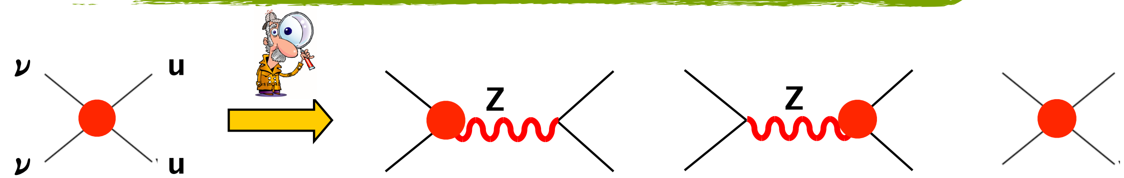

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$$[\delta g]_{\rm piece} \equiv -0.67(\delta g_L^{Zu} + \delta g_R^{Zu}) - 0.74(\delta g_L^{Zd} + \delta g_R^{Zd}) + 0.26\delta g_L^{Z\nu}$$

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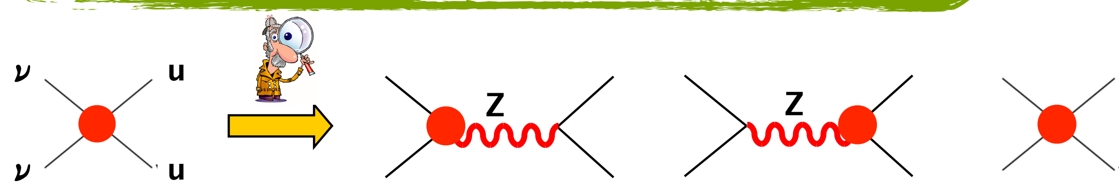

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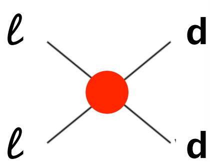
- These operators are constrained by many EWPO: LEP1, LEP2, APV, …
  Is COHERENT probing a new region in the SMEFT parameter space? → Global fit needed!

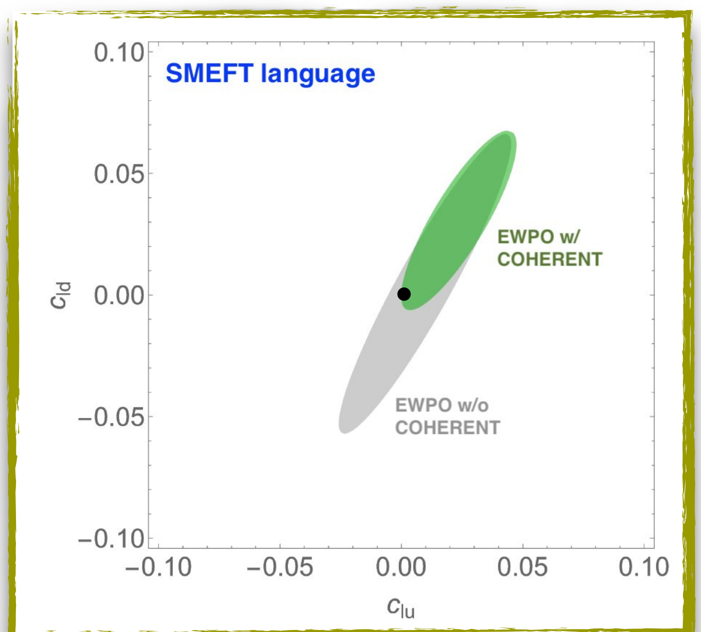
[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

COHERENT in the SMEFT

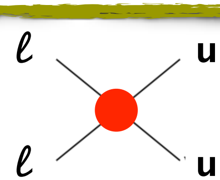
- "Flavor-blind" SMEFT ($\to U(3)^5$ symmetry)
- Global fit to Electroweak precision observables [*Update of* Falkowski, MGA & Mimouni, JHEP'17]



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



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



18 free parameters

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

COHERENT in the SMEFT

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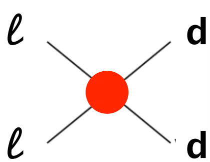

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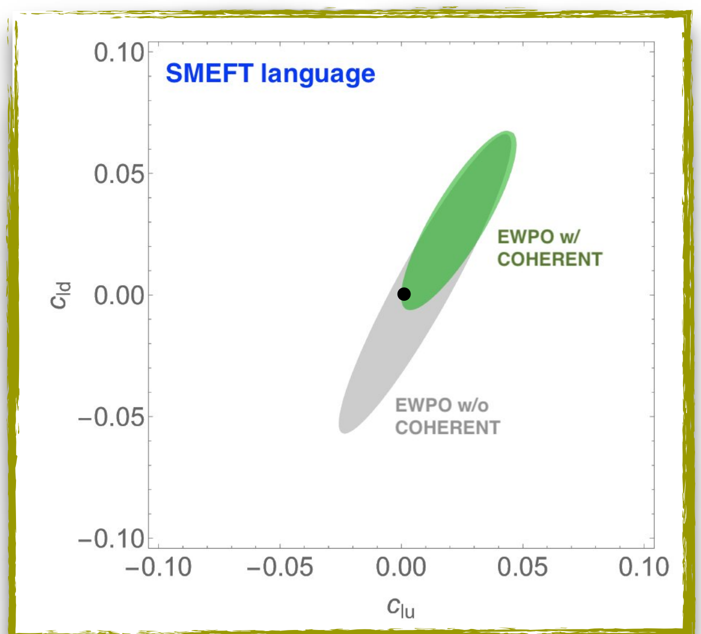

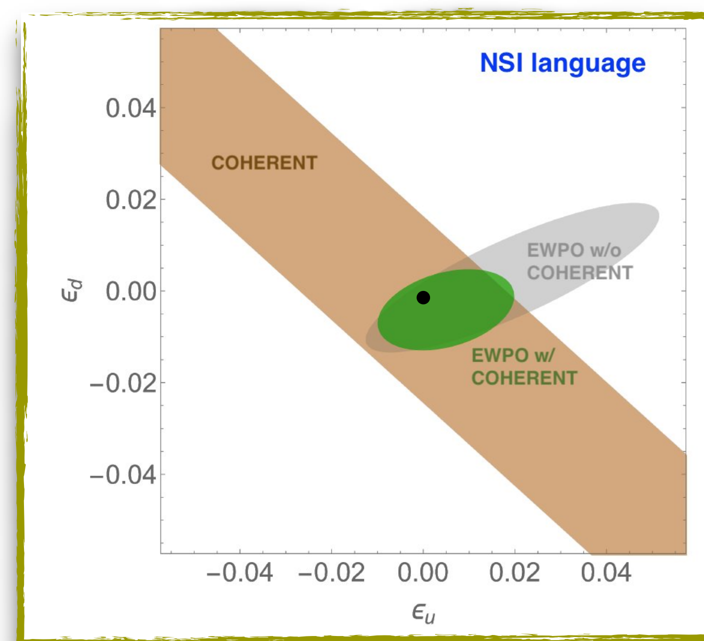

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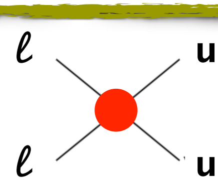

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[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

COHERENT in the SMEFT

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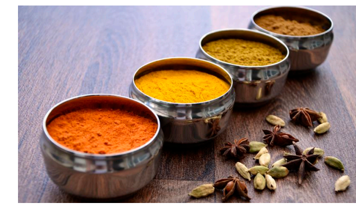
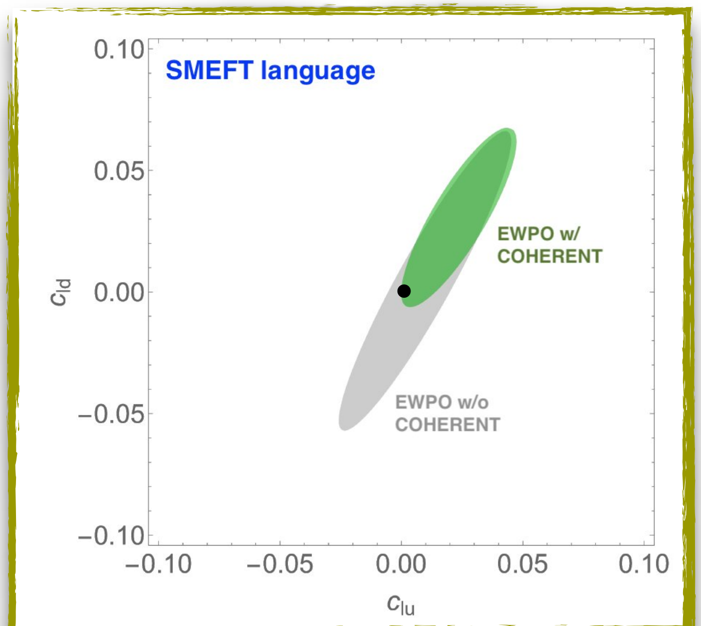
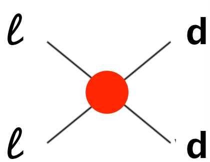
- Global fit to Electroweak precision observables;

Flavor general SMEFT







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

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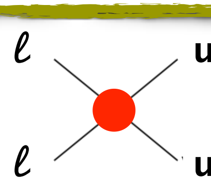

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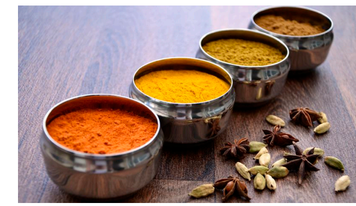

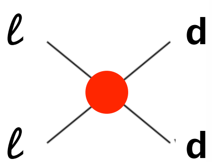

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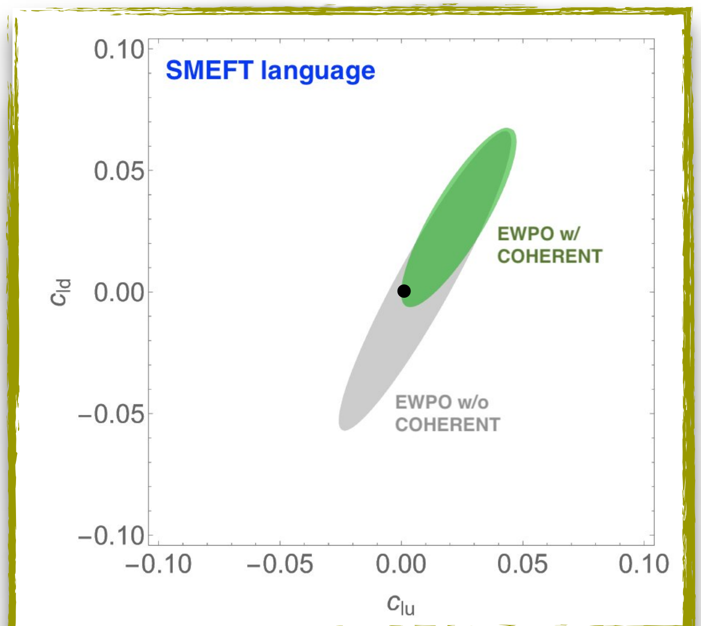

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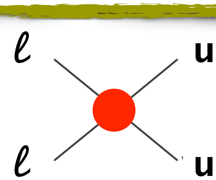
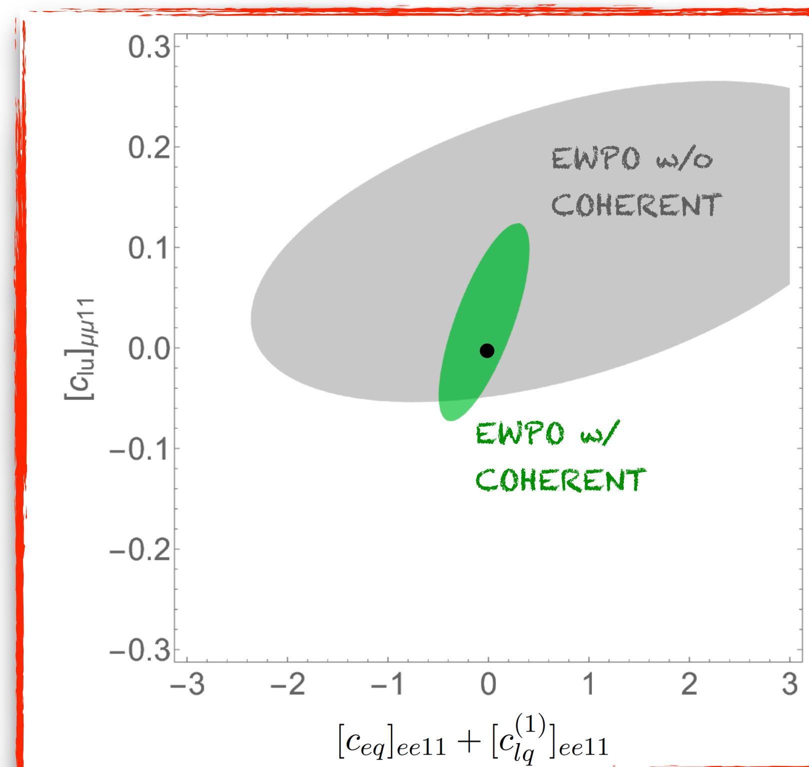
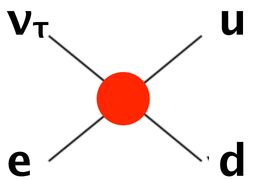




18 free parameters → 65 free parameters

DayaBay in the SMEFT



[A. Falkowski, MGA, & Z. Tabrizi, 1901.04553, JHEP]

- $L \neq 0 \longrightarrow$ oscillations! $\longrightarrow \mathcal{O} = \mathcal{O}\,(\theta_i,\ \Delta m^2)$
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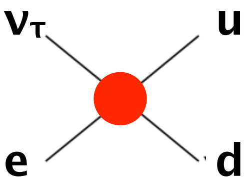

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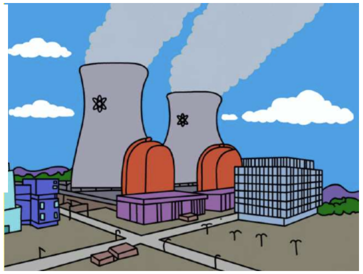
  short-baseline reactor neutrino experiments

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



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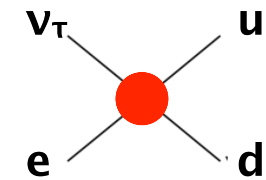

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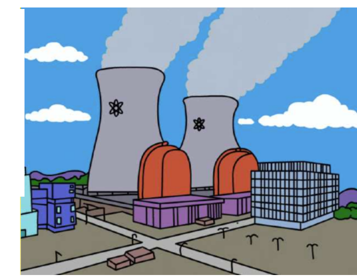
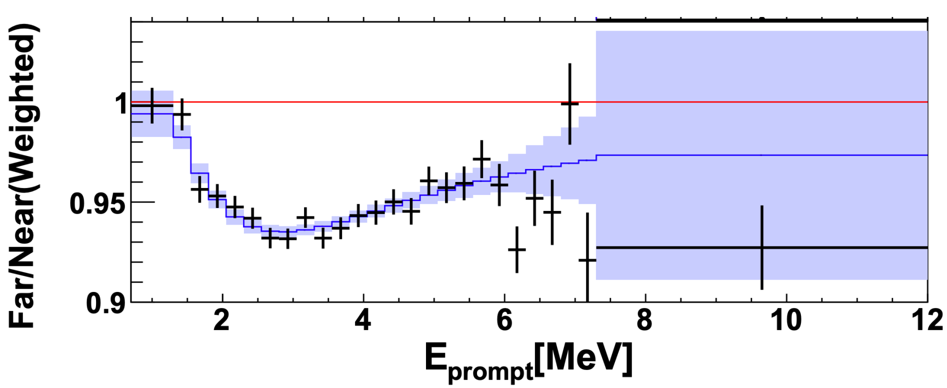
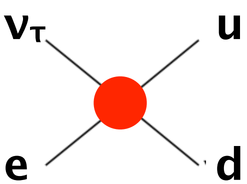


- Precision: θ_{13} = 0.0856(29)
  [DayaBay'18, ~4M neutrino events!]





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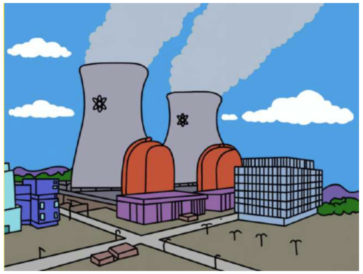

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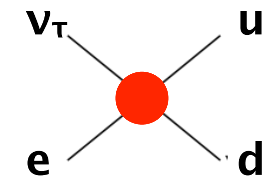

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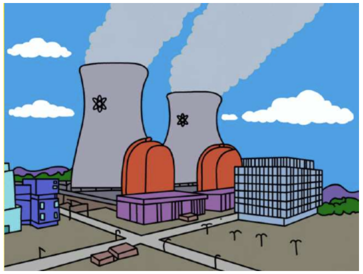

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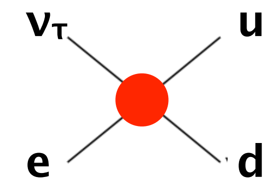

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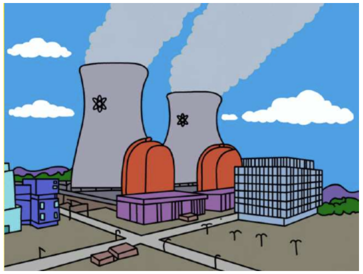
$$+ \sin\left(\frac{\Delta m^2_{31} L}{2E_\nu}\right) \sin(2\theta_{13}) \left(\beta_D \frac{m_e}{E_\nu - \Delta} - \beta_P \frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2)$$



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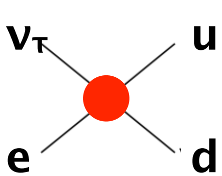
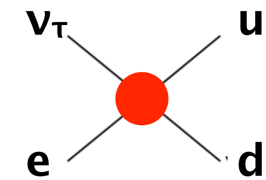


DayaBay in the SMEFT



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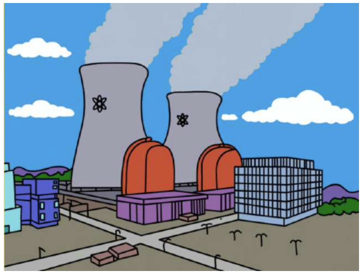

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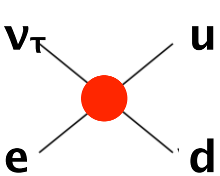
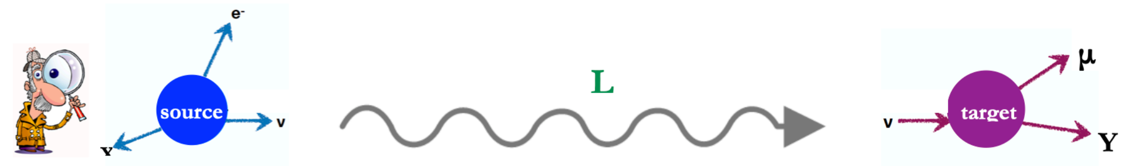
    - S, T and Im(V+A) can be probed → % level bounds (TeV scale)



Summary

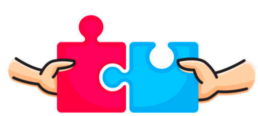


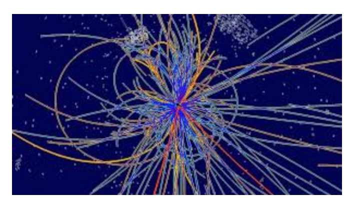
- The path to analyze any given neutrino experiment in the presence of **generic** (heavy) New Physics is now clear.

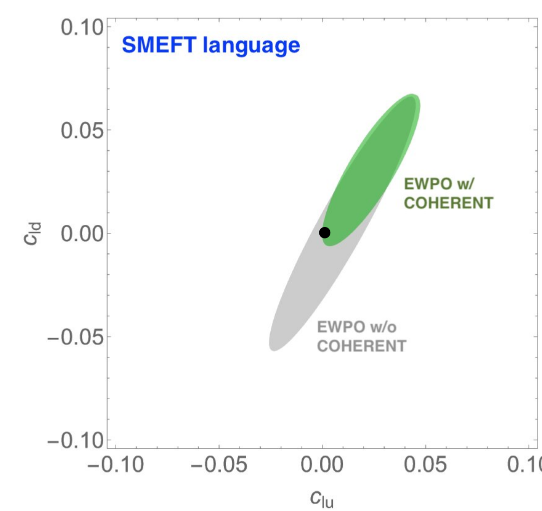
$$O = O(\theta_i, \Delta m^2, \varepsilon_j)$$

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!

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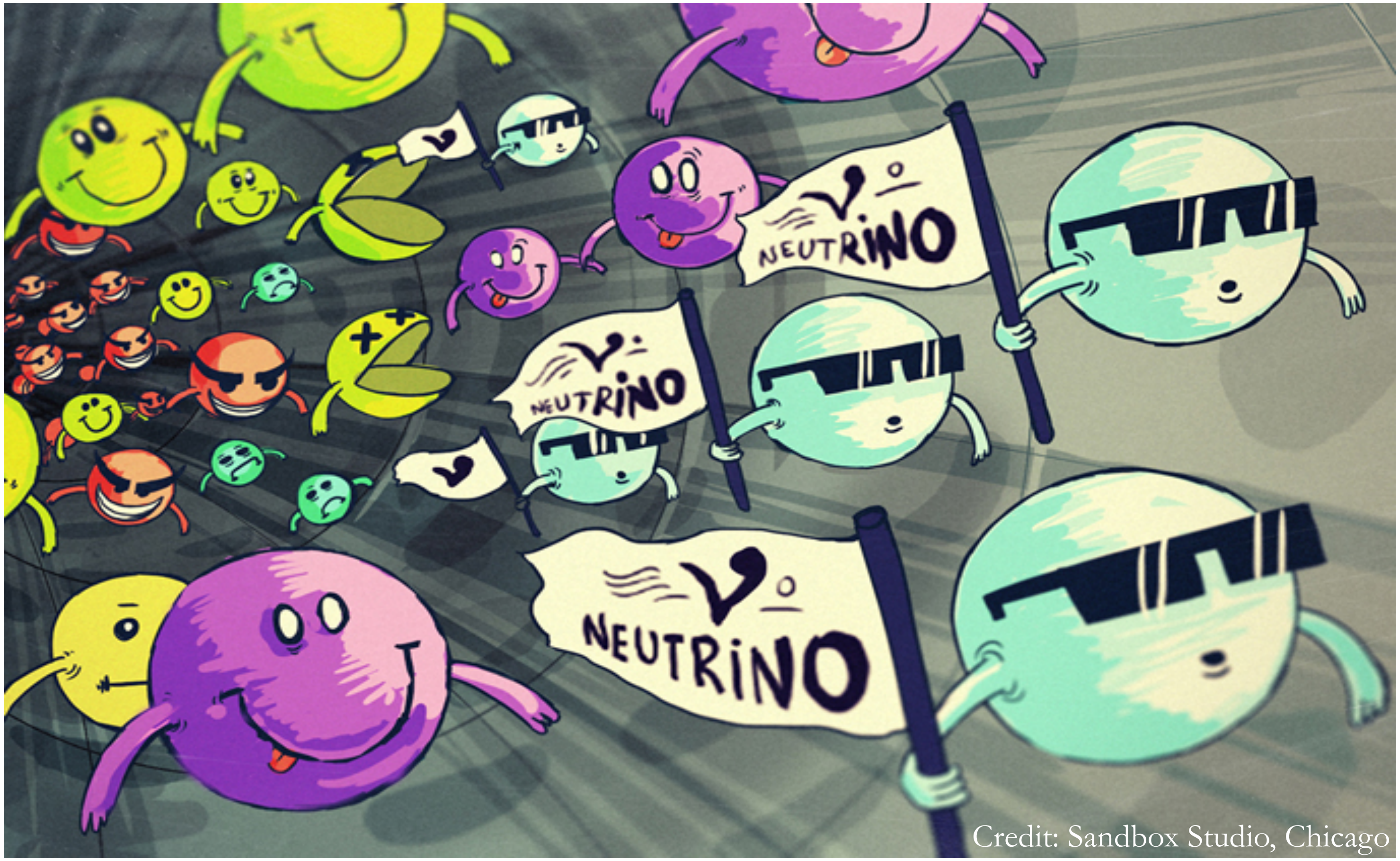
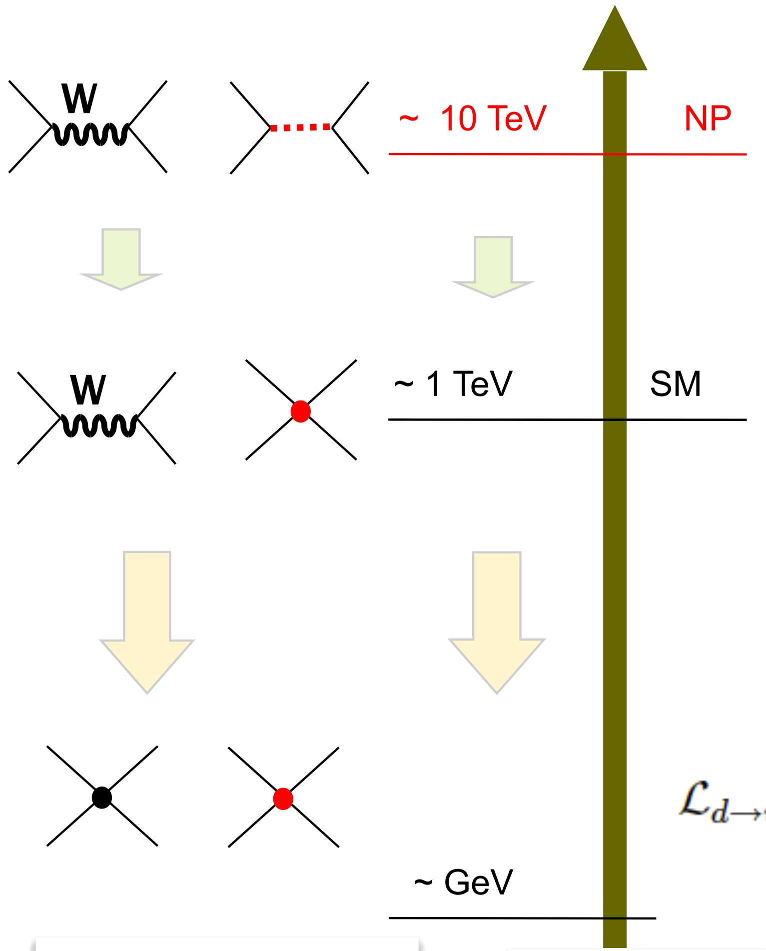

NEUTRINO
NEUTRINO
NEUTRINO
Credit: Sandbox Studio, Chicago

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, ...]

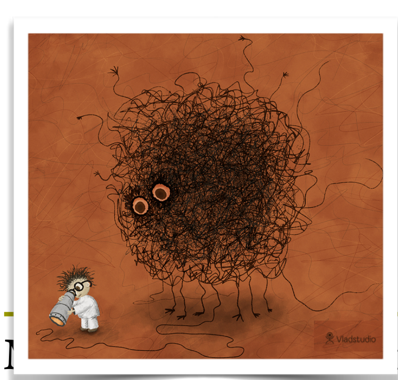
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

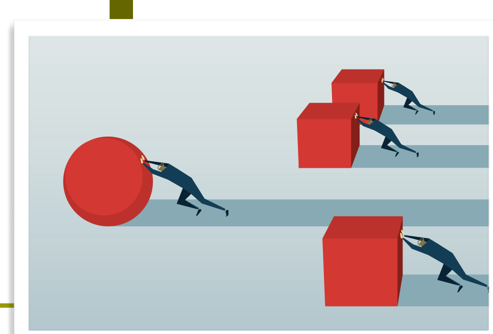
Low-energy EFT

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

Low-E precision data

(+ SM prediction)



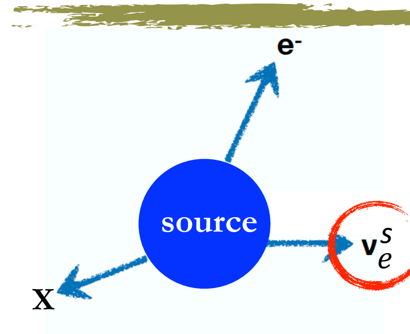


[Grossman'95, Gonzalez-Garcia et al.'01, Ohlsson'13, Farzan & Tortola'17, ...]

Traditional QM-NSI approach

- Source / detection NSIs are NOT Lagrangian parameters.

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



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

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

Normalization:

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

- 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?

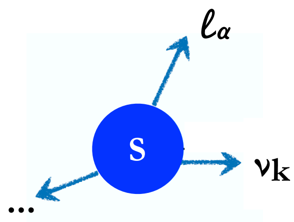
- Also: are production & detection NSI unrelated? Are they energy independent?

- 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]

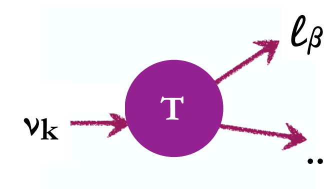
Oscillations in QFT → EFT

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



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

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



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

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

vs.

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

⇒

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

Example: νp→ne

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

Unknown in the NSI approach!

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

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

EFT analysis of NP at COHERENT

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

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

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

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

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

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

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

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

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

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

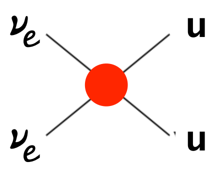
$$g_{\alpha\beta}^{\nu n} = 2 \left[(g_V^{uu} + 2 g_V^{dd})\, \mathbb{1} + (\epsilon^{uu} + 2\epsilon^{dd}) \right]_{\alpha\beta} .$$

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

EFT analysis of NP at COHERENT

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

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



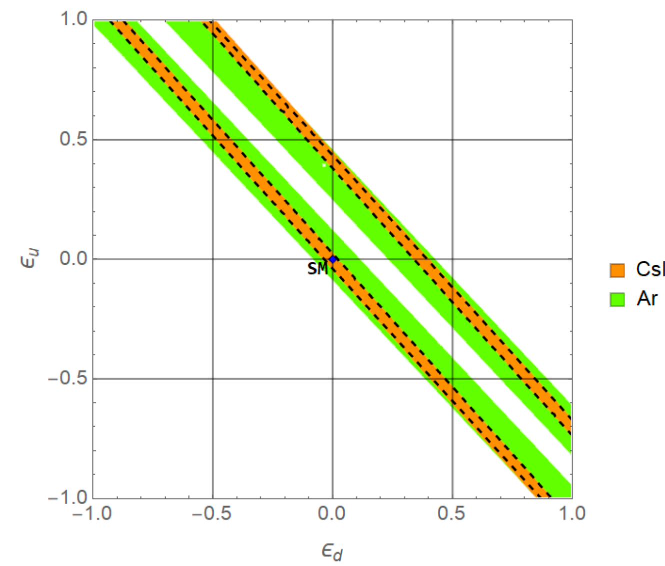
- Current COHERENT data (LAr + CsI, recoil & time distribution: 664 data) give:

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

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

[Lepton-flavor universal case]

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

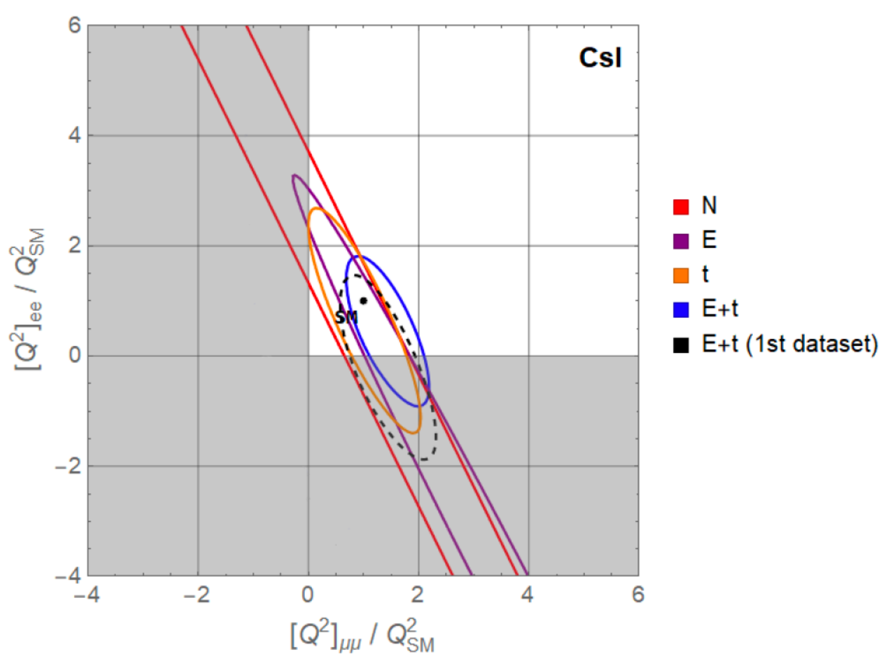


[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

EFT analysis of NP at COHERENT

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

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



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

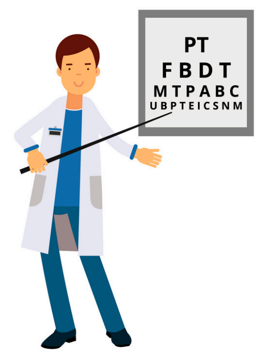
- Case 3: NP only in production → NP cancel completely!
  [this invalidates the bounds obtained in Khan, McKay, & Rodejohann, PRD'2021]

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

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

COHERENT in the SMEFT

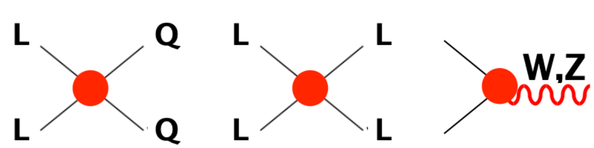
- "Flavor-blind" SMEFT (→ $U(3)^5$ symmetry)
- Global fit to Electroweak precision observables:
  - Z- & W-pole data
  - $e^+e^- \to l^+l^-$, qq
  - Low-energy processes:
    Atomic PV, $d \to ul\nu$, tau decays, …
    + COHERENT!



Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to f f)$
$\sigma_{\rm had}$ [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	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\rm FB}^{0,\tau}$	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	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
$A_c^{\rm FB}$	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	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[48]	0.935	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 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 ± 0.015	[50]	80.364	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \to f f')$
${\rm Br}(W \to e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to f f')}$
${\rm Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[51]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to f f')}$
${\rm Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[51]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to f f')}$
R_{Wc}	0.49 ± 0.04	[45]	0.50	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	0.998 ± 0.041	[52]	1.000	$g_L^{Wq_3}/g_{L,{\rm SM}}^{Wq_3}$

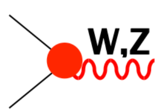
$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{18}) \to \chi^2 = \chi^2\,(c_i)$$

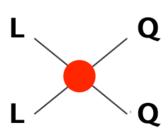


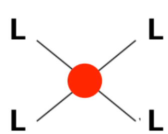
Update of [Falkowski, MGA & Mimouni, JHEP'17]

COHERENT in the SMEFT

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



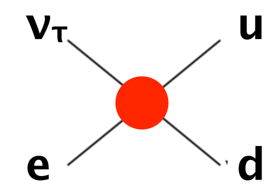




	w/o COHERENT ($\times 10^{-3}$)	→ w/ COHERENT ($\times 10^{-3}$)
$\delta g_L^{W\ell}$	$-0.27(79)$	$-0.26(78)$
δg_L^{Ze}	$-0.10(0.21)$	$-0.09(21)$
δg_R^{Ze}	$-0.20(22)$	$-0.17(22)$
δg_L^{Zu}	$-1.0(1.6)$	$-1.3(1.6)$
δg_R^{Zu}	$-0.5(3.2)$	$-1.1(3.1)$
δg_L^{Zd}	$1.5(1.3)$	$1.1(1.2)$
δg_R^{Zd}	$12.8(6.7)$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

$\rho \neq 1$

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



Short-baseline reactor exp.

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

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

$$\left[Q_{\ell equ}^{(3)}\right]_{\alpha 111} = (\bar{\ell}_\alpha^m \sigma_{\mu\nu} e_1)\epsilon_{mn}(\bar{q}_1^n \sigma^{\mu\nu} u_1)$$