EFT analysis of neutrino, nuclear & collider physics

UNIGE seminar **Nov 29th, 2023**

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IFIC, Univ. of Valencia / CSIC

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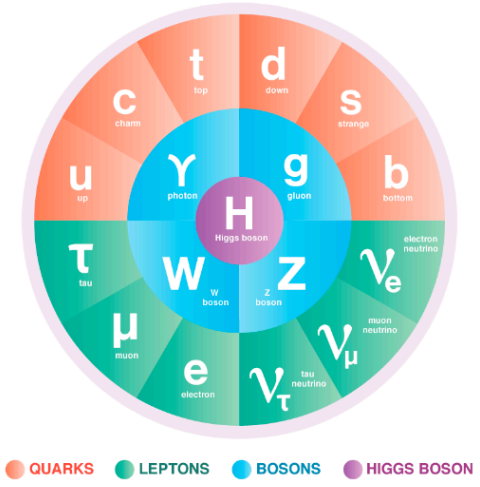
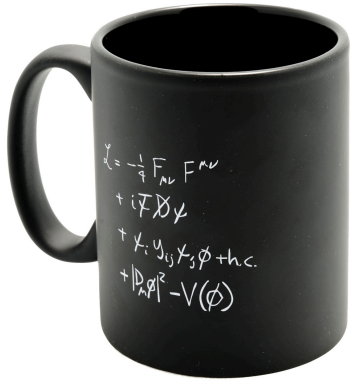
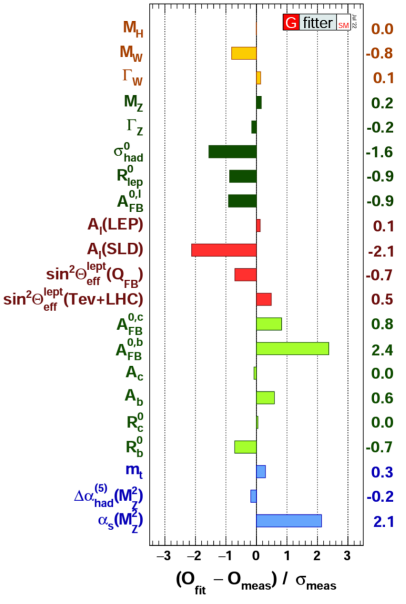
Outline

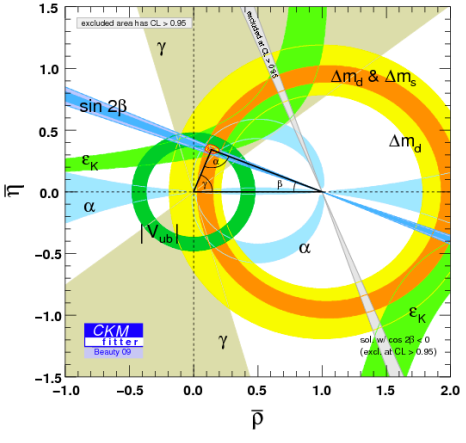
- Introduction
- Standard Model EFT (SMEFT)
- Neutrino physics in the SMEFT
- COHERENT vs Electroweak Precision Observables
- Neutrino oscillations in the SMEFT (→ DayaBay)

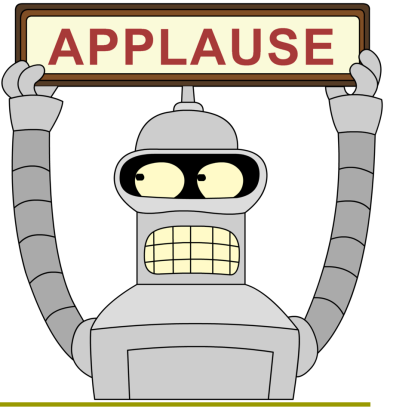
Introduction: SM



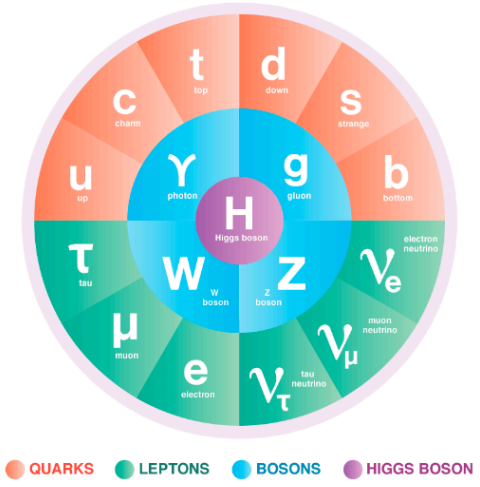


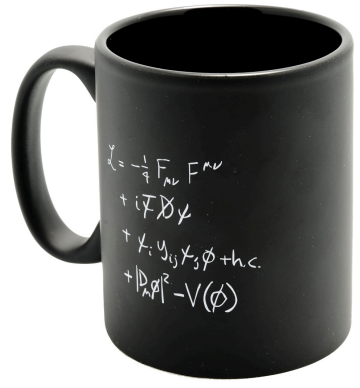


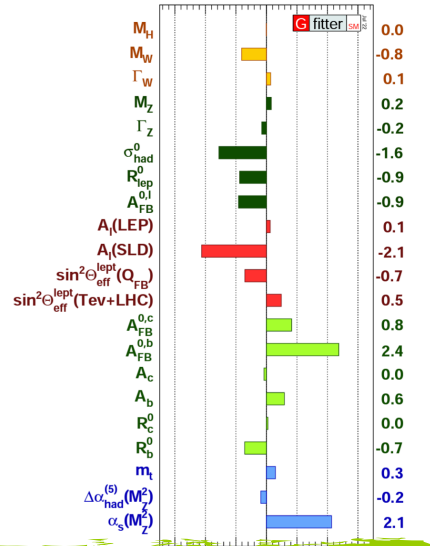




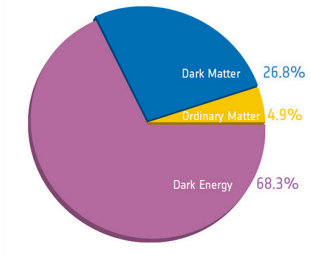
Introduction: SM

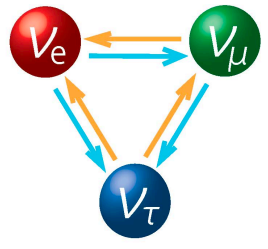


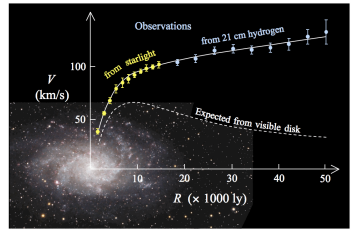


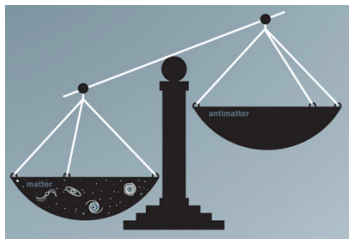


But…







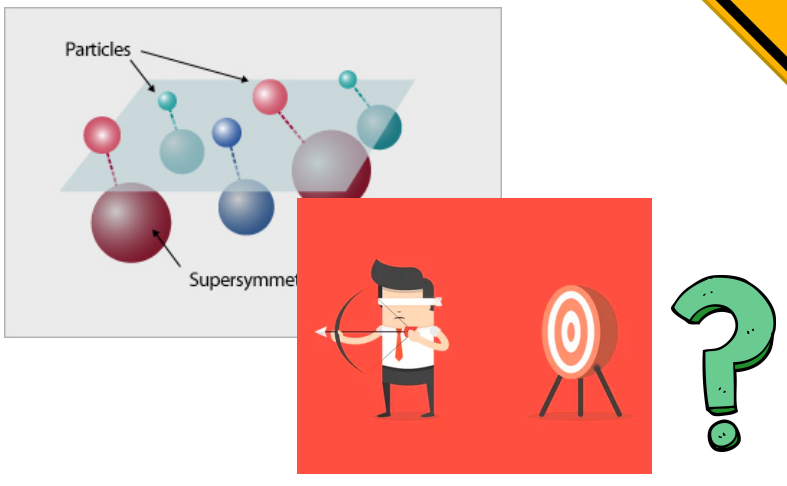


+ Flavor puzzle, strong CP problem, hierarchy problem, quantum gravity, cosmological problems, …

Introduction: SM → BSM

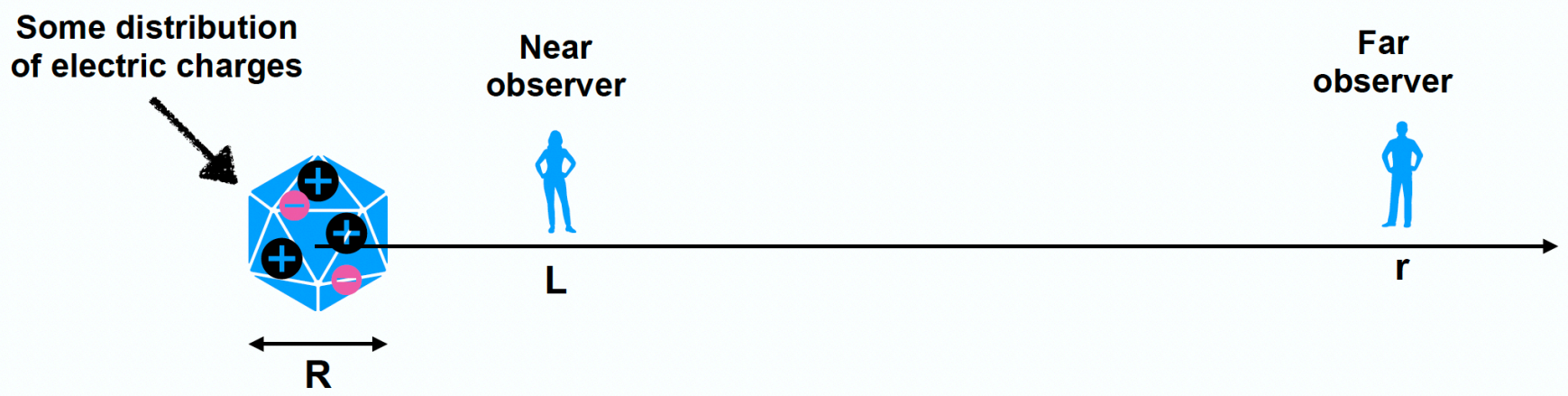
Specific BSM model

$$\mathscr{L}_{BSM} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$



Effective Field Theory (EFT) approach

Introduction: SM → BSM → EFT



Near observer, L~R, needs to know the position of every charge to describe electric field in her proximity

Far observer, $r \gg R$, can instead use multipole expansion: $$V(\vec{r}) = \frac{Q}{r} + \frac{\vec{d}\cdot\vec{r}}{r^3} + \frac{Q_{ij}r_i r_j}{r^5} + \dots$$

$$\sim 1/r \qquad \sim R/r^2 \qquad \sim R^2/r^3$$

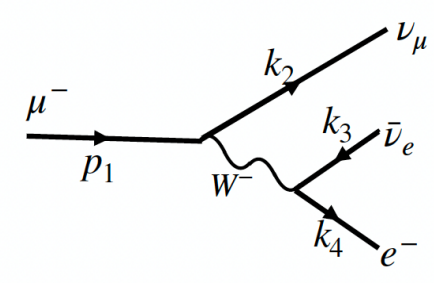
Higher order terms in the multipole expansion are suppressed by powers of the small parameter (R/r). One can truncate the expansion at some order depending on the value of (R/r) and experimental precision

Far observer is able to describe electric field in his vicinity using just a few parameters: the total electric charge Q, the dipole moment $\vec{d}$, eventually the quadrupole moment Q_{ij}, etc....

On the other hand, far observer can only guess the "fundamental" distributions of the charges, as many distinct distributions lead to the same first few moments

[Slide borrowed from A. Falkowski's CP2023 lectures]

EFT in QFT (example)

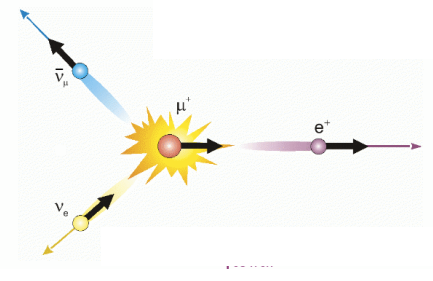


~ 100 GeV

$\mathcal{L}_{SM}$ (EW theory)

$$\mathcal{M} = \frac{g_L^2}{2}\bar{u}(k_2)\gamma_\rho P_L u(p_1)\frac{1}{q^2 - m_W^2}\bar{u}(k_4)\gamma_\rho P_L \mathrm{v}(k_3)$$

$$q = p_1 - k_2$$



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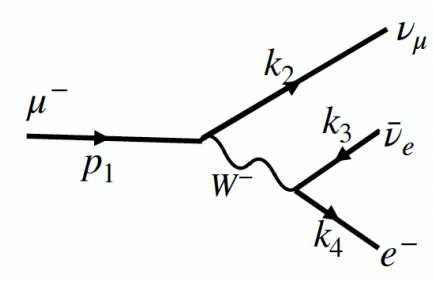

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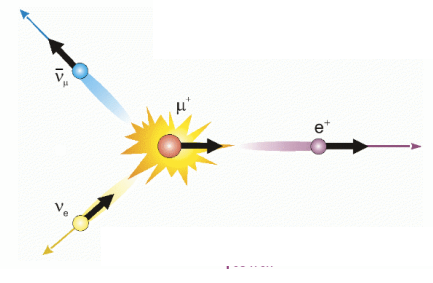
$$q = p_1 - k_2$$

$$q^2 \lesssim m_\mu^2 \ll m_W^2$$

$$\mathcal{M} = -\frac{g_L^2}{2m_W^2}\bar{u}(k_2)\gamma_\rho P_L u(p_1)\bar{u}(k_4)\gamma_\rho P_L \mathrm{v}(k_3) + \mathcal{O}(q^2/m_W^4)$$

~ GeV



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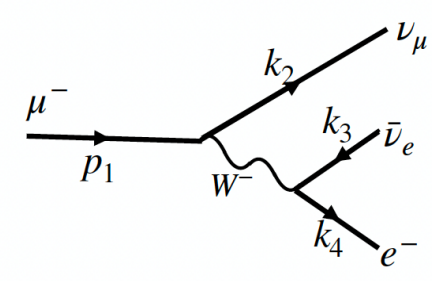

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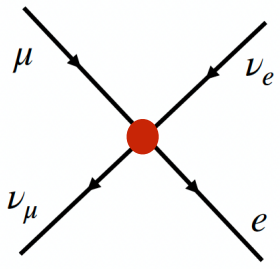
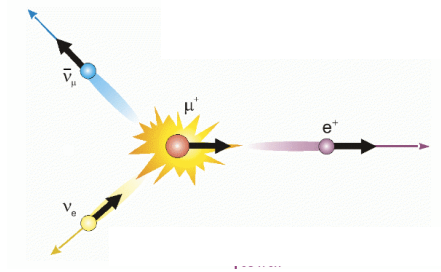


~ GeV

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu(1-\gamma_5)\,\mu$$

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



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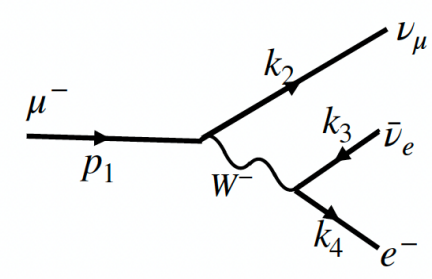

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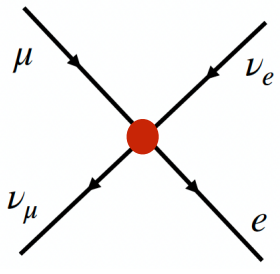

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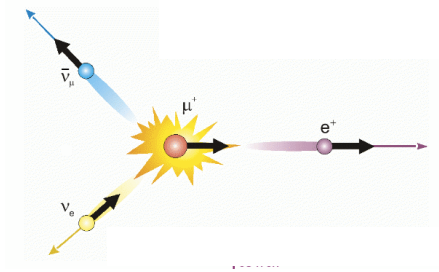
+ higher-dim terms

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



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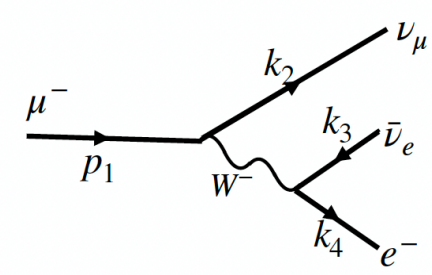

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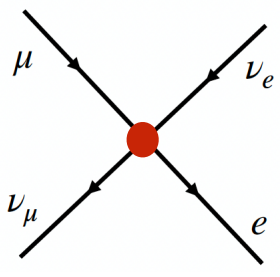


~ GeV

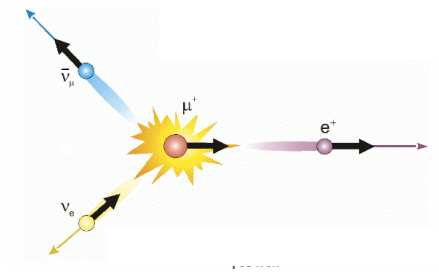
$$\mathscr{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu(1-\gamma_5)\,\mu$$

+ higher-dim terms

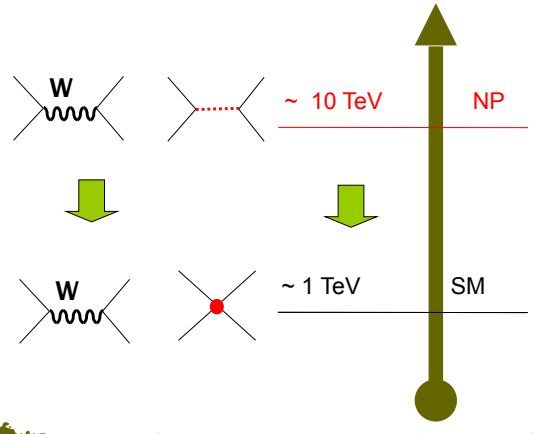
Historically the logic was quite different:
Data → Fermi EFT → SM
("Bottom-up EFT approach")

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



EFT at the EW scale: SMEFT



$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda}\mathcal{L}_5(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \ldots$$

$$\sum \alpha_i \mathcal{O}_i$$

EFT = Symmetries + Fields (gap!)

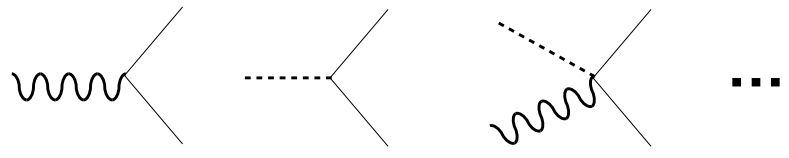
- Lorentz;
- SU(3) x SU(2) x U(1);
- Flavour sym?
- B, L;

- SM fields
- No light NP

α: Wilson coefficients (UV physics)
59 dim-6 operators (+ flavor)
[Buchmuller & Wyler'1986, Leung et al.'1986, Grzadkowksi et al., 2010]

Example:

$$(\varphi^\dagger i D_\mu \varphi)(l_p \gamma^\mu l_r)$$



$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$D_\mu = I\partial_\mu - i g_s \frac{\lambda^A}{2} G_\mu^A - i g \frac{\sigma^a}{2} W_\mu^a - i g' Y B_\mu$$

EFT at the EW scale: SMEFT

- Model independence

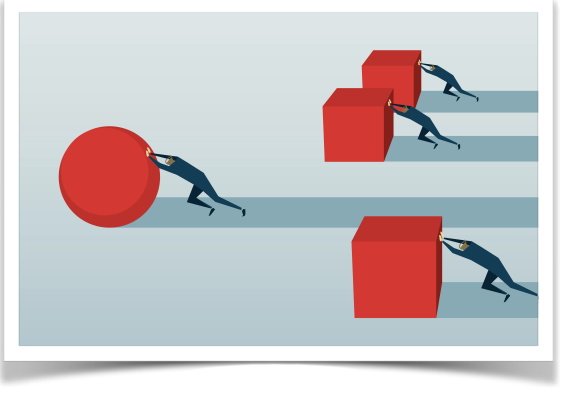
Observable = f(NP couplings)
not trivial!

- Efficiency:
  Analysis (bkg, PDFs, FF, simulations, …) done once and for all!

Data ⇨ **(Correlated) bounds on the EFT Wilson Coefficients** ⇨ **Matching with a specific NP model**

$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$$

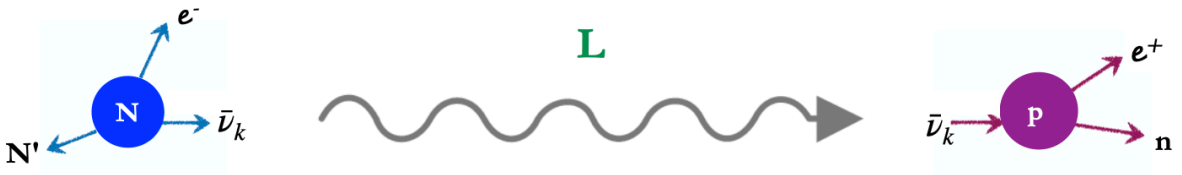
$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$



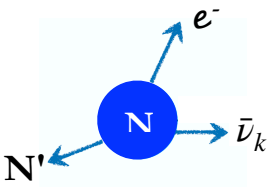
- Provides general parametrizations for observables
  - Many bins → a few parameters
- Useful especially if one avoids additional assumptions
- Assess the interplay between processes in a general setup

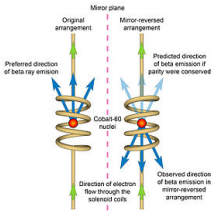
EFT at the EW scale: SMEFT

- Measurements that are disconnected in the SM can be connected in the presence of NP. Example:
  - Neutrino oscillation → PMNS factors and neutrino masses;

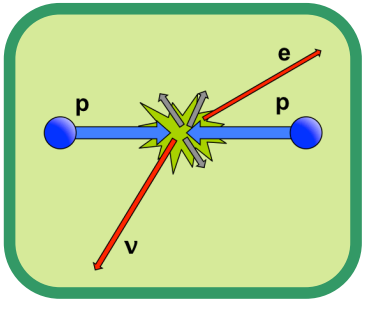


  - Nuclear beta decay → V_{ud}, g_A, …





  - CC Drell-Yan (p p → e ν) → weak angle



EFT at the EW scale: SMEFT

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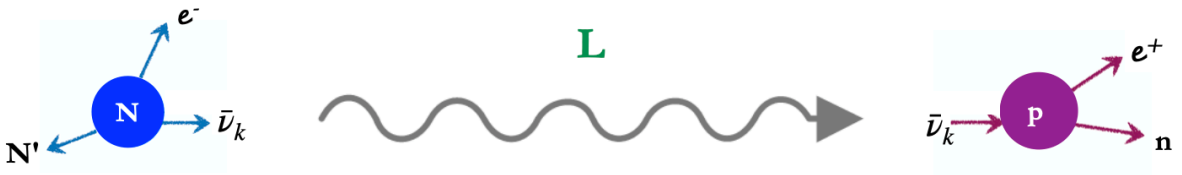

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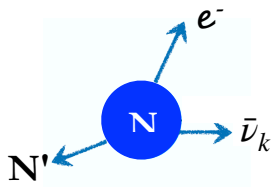

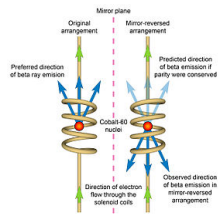

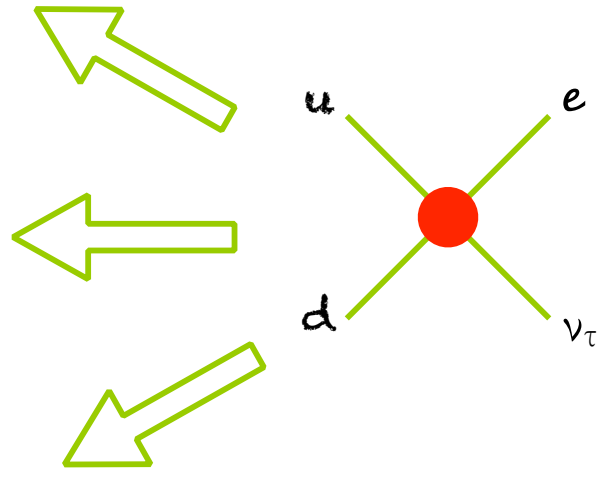

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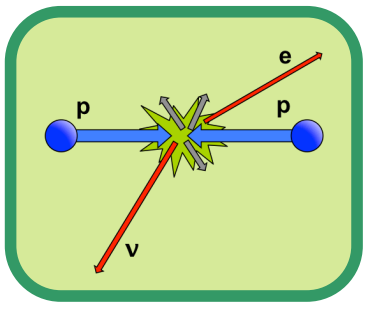
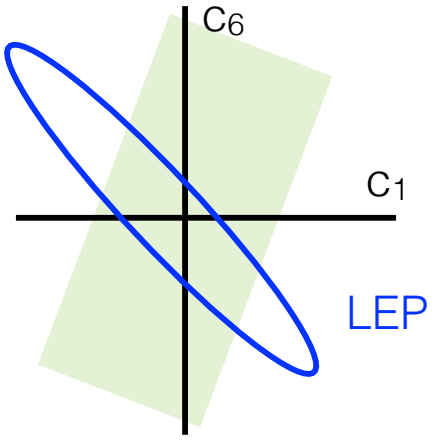


Connecting measurements

- Calculate the observable you are interested in
  e.g. $O = O_{SM} + 3C_1 - C_6$

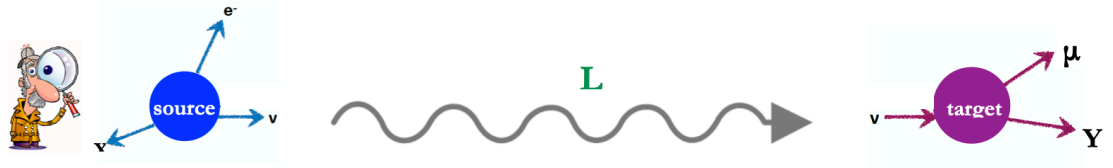
- What are the known limits on the Wilson coefficients?
  e.g. from LEP… $C_1 = 0.00(1)$, $C_6 = 0.01(3)$, + correlation
  $\rightarrow 3C_1 - C_6 = -0.01(4)$



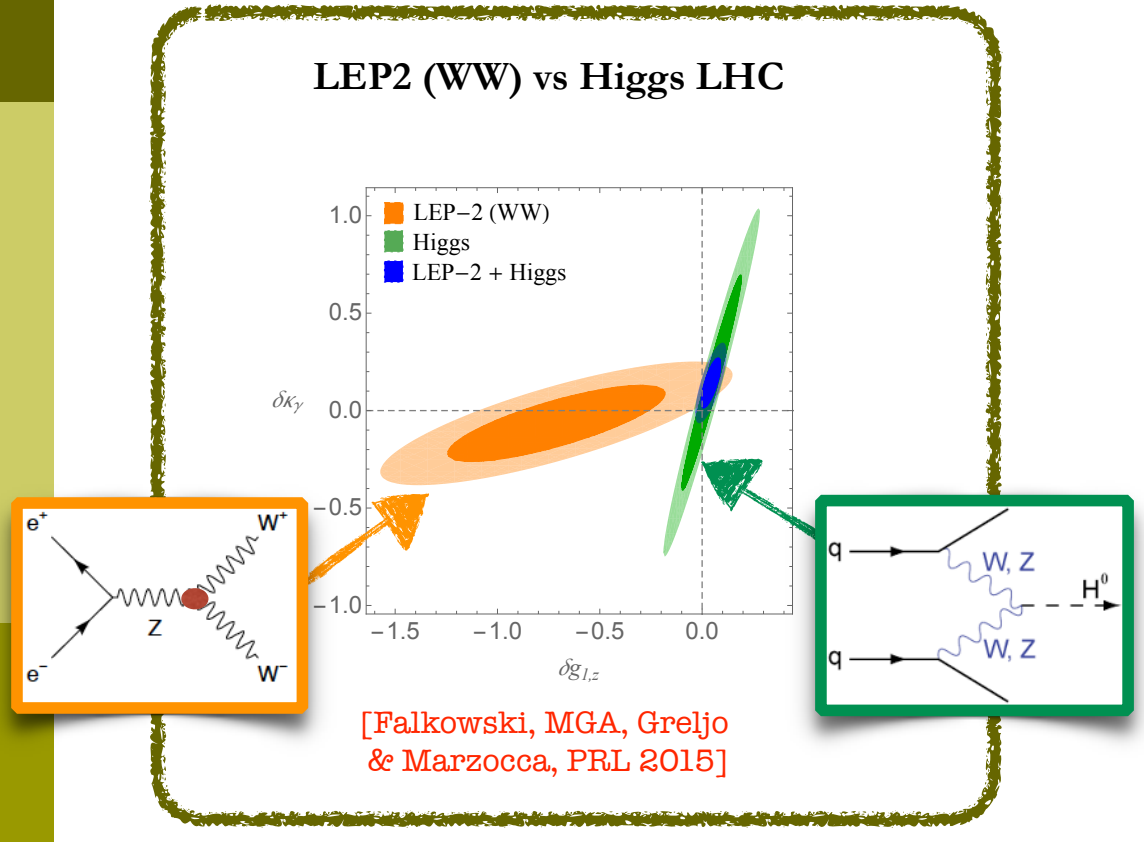
- Implications:
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - If your sensitivity is better than that, you are exploring new SMEFT territory and your measurement should be added to the big fit.
  - A deviation larger than that indicates some wrong assumptions in your EFT!

- Often we have a dataset (instead of a single data point O) and one can probe several combinations of coefficients (*e.g.* C_1, C_6). The same logic applies.

Summary

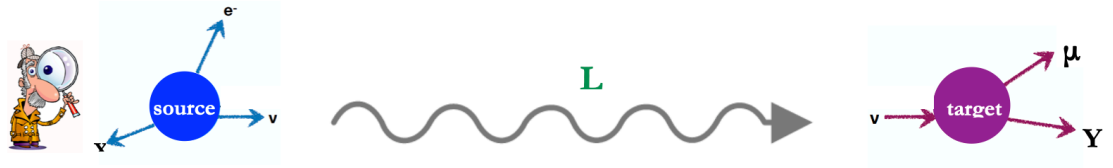


- Heavily used in precision measurements in flavor, LHC, low-energy, …



[Falkowski, MGA, Greljo & Marzocca, PRL 2015]

Summary



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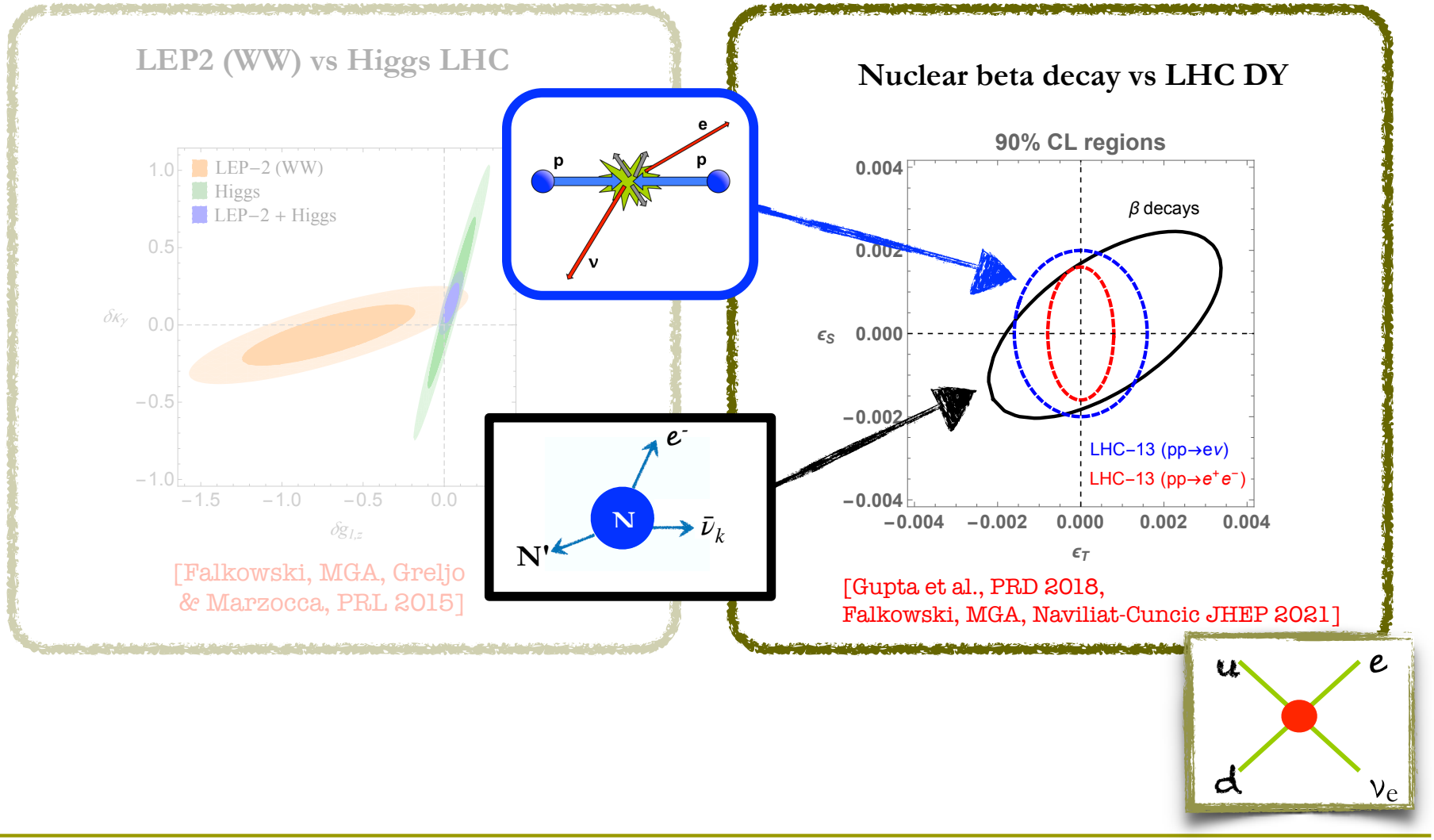
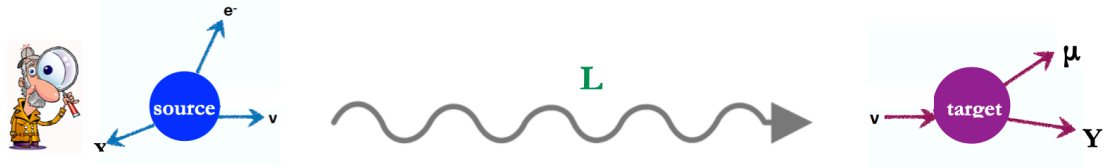


Summary



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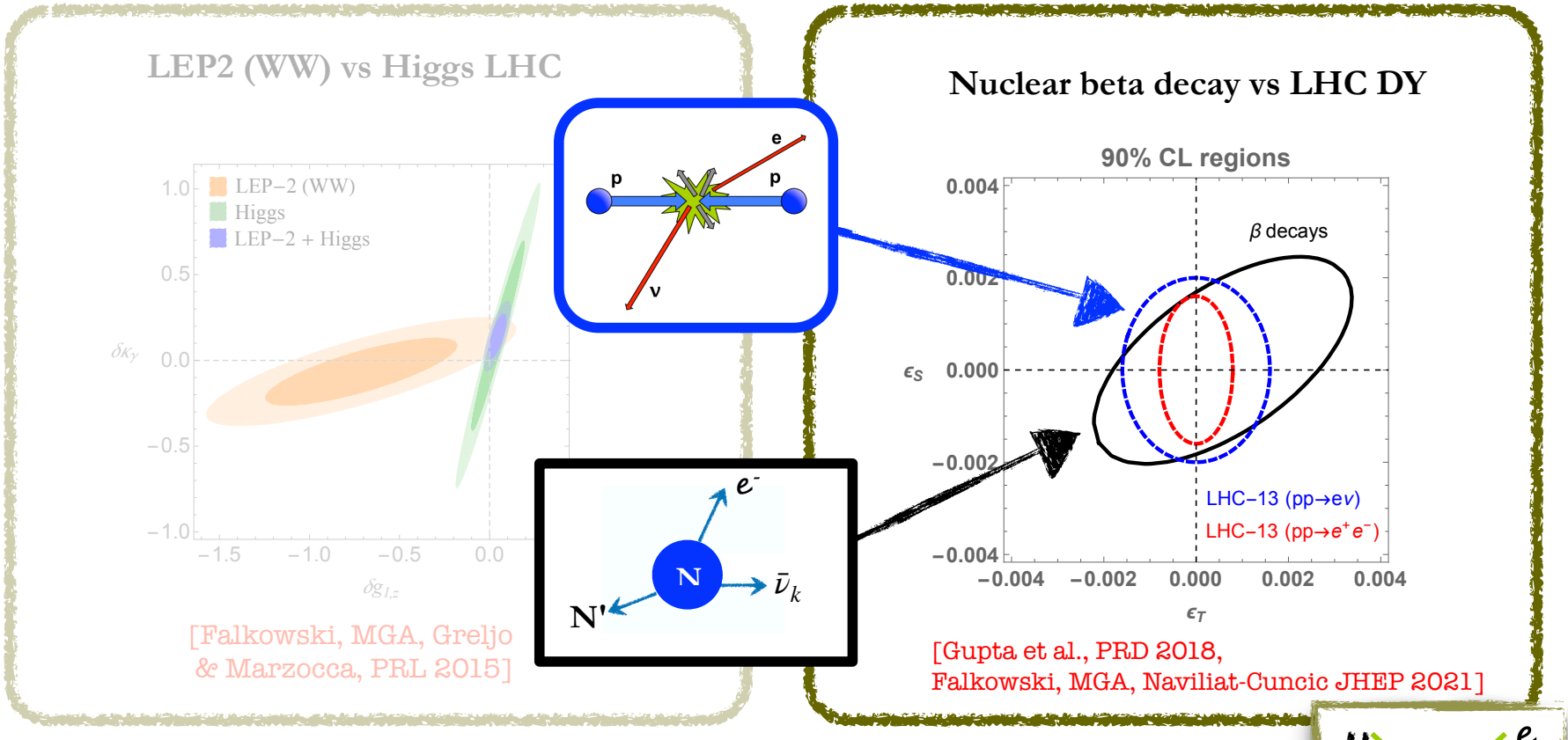
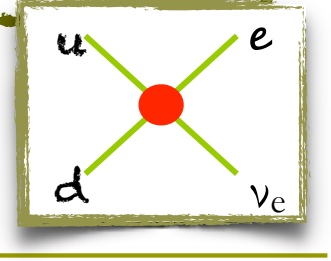


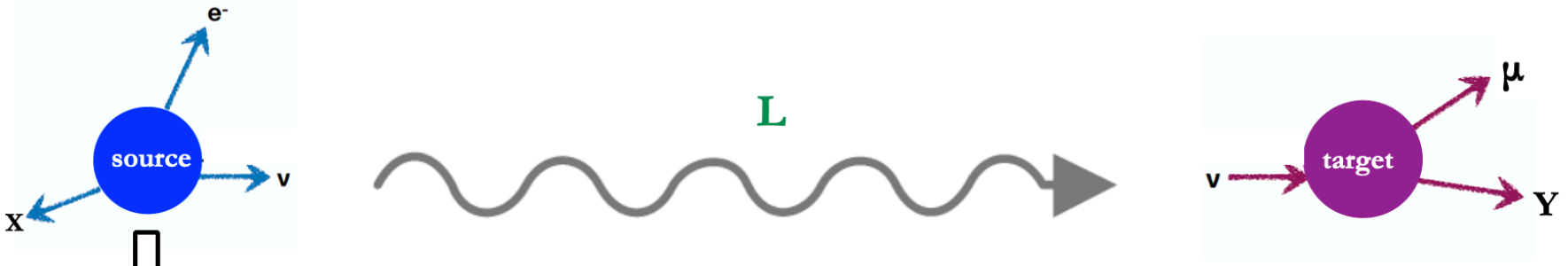


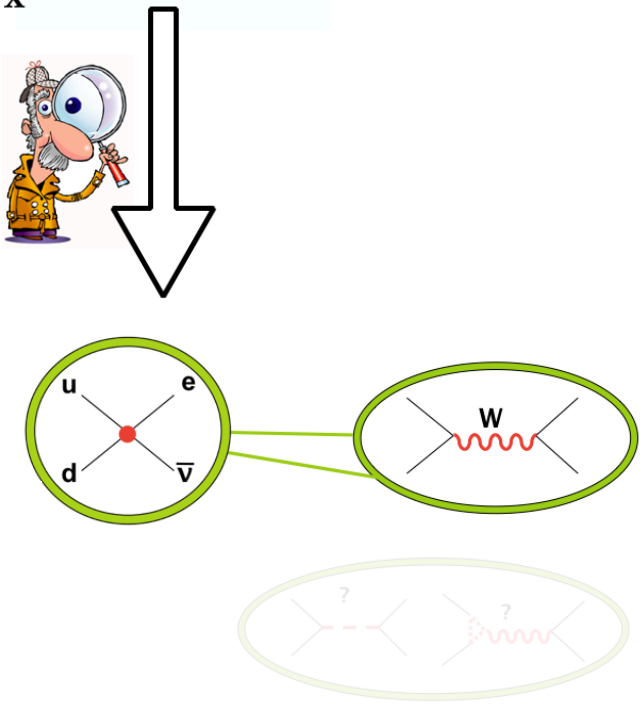
- What about neutrino physics?

Outline

- Introduction ✓
- Standard Model EFT (SMEFT) ✓
- Neutrino physics in the SMEFT
- COHERENT vs Electroweak Precision Observables
- Neutrino oscillations in the SMEFT (→ DayaBay)

NP in neutrino oscillation





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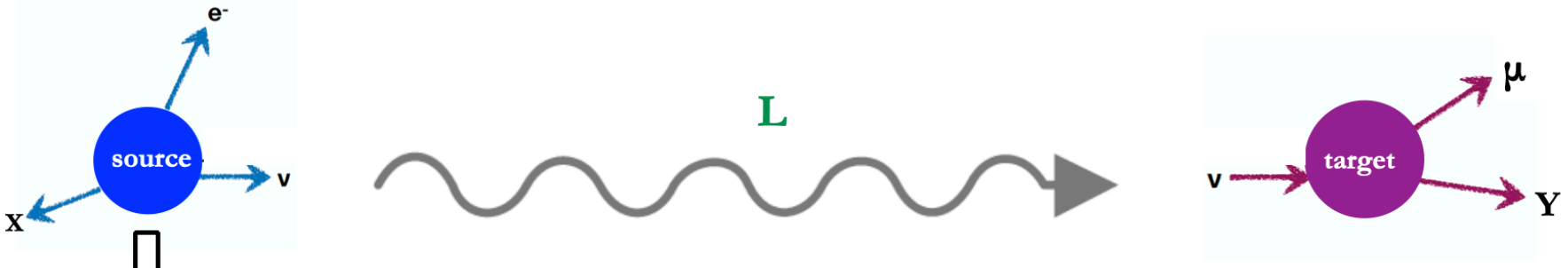
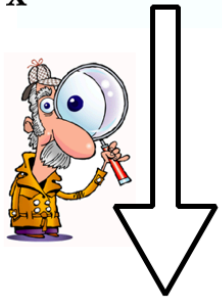
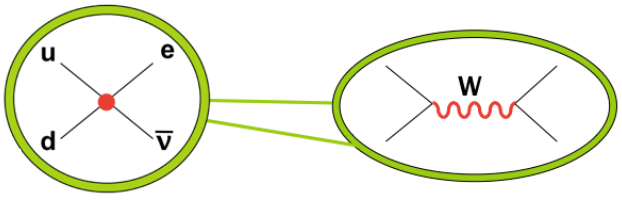
[Same in detection]

NP in neutrino oscillation







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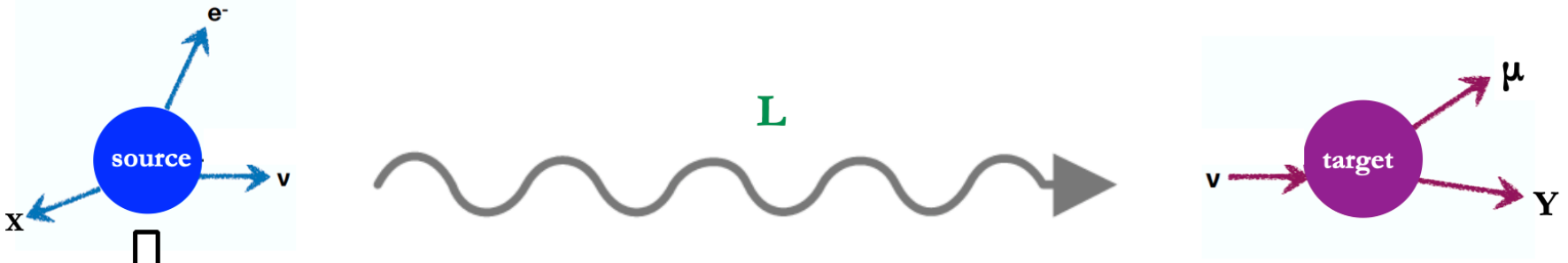
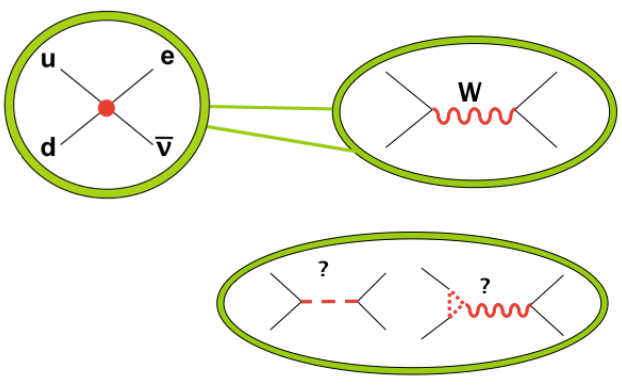
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$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

[I.Esteban et al., 2007.14792 JHEP]

NP in neutrino oscillation





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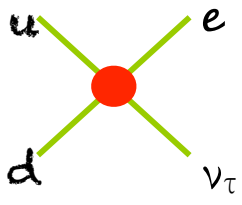

Lagrangian parameters!

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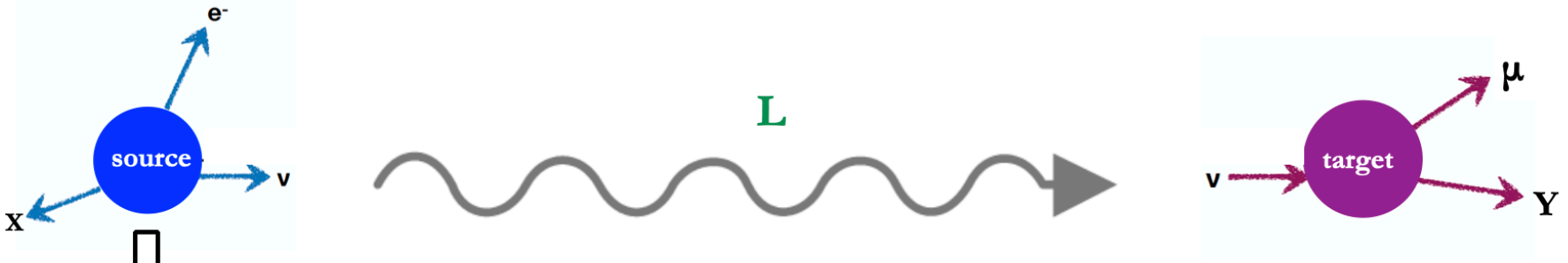

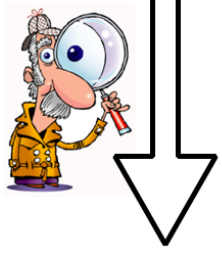

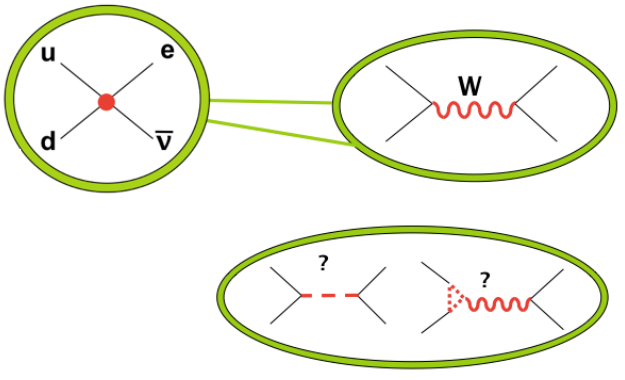

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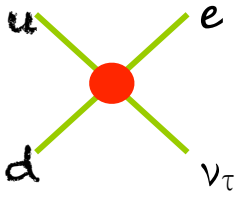

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In other words:
how are oscillations affected by a charged Higgs?
A leptoquark? Which part of their parameter space is ruled out by current oscillation data?

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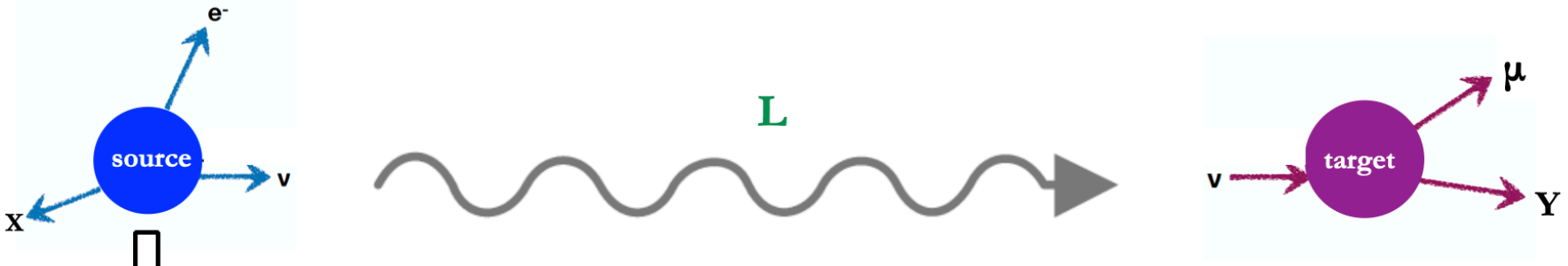

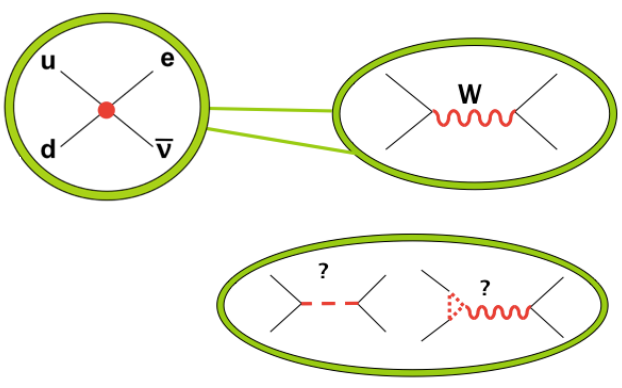

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- QM approach not useful ("source/detector NSI") → QFT approach needed

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

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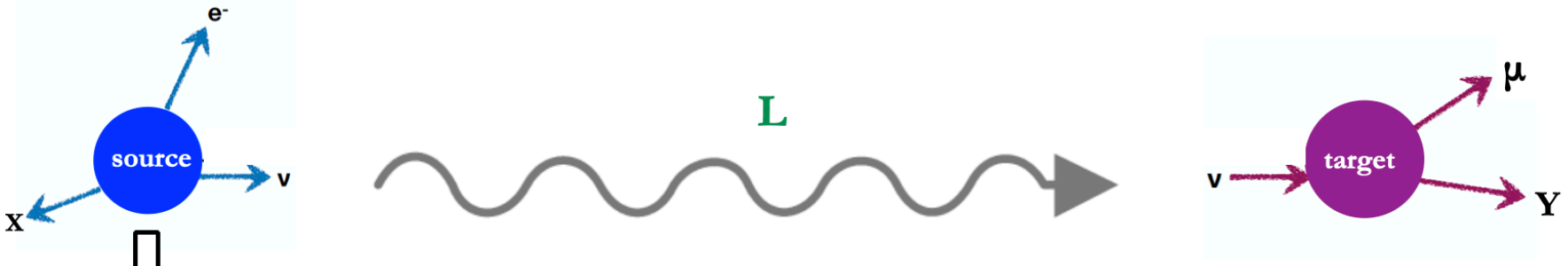

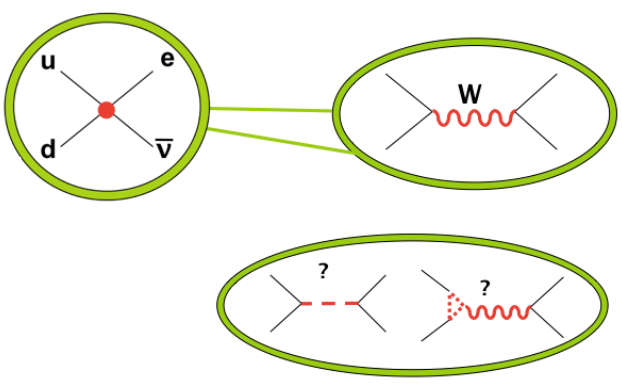

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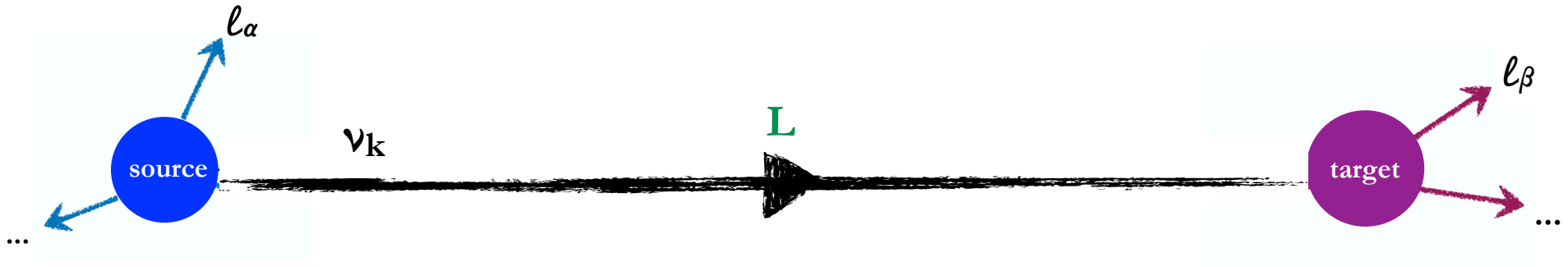
Giunti et al. [hep-ph/9305276]
Akhmedov Kopp [arXiv:1001.4815]
...

Oscillations in QFT

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



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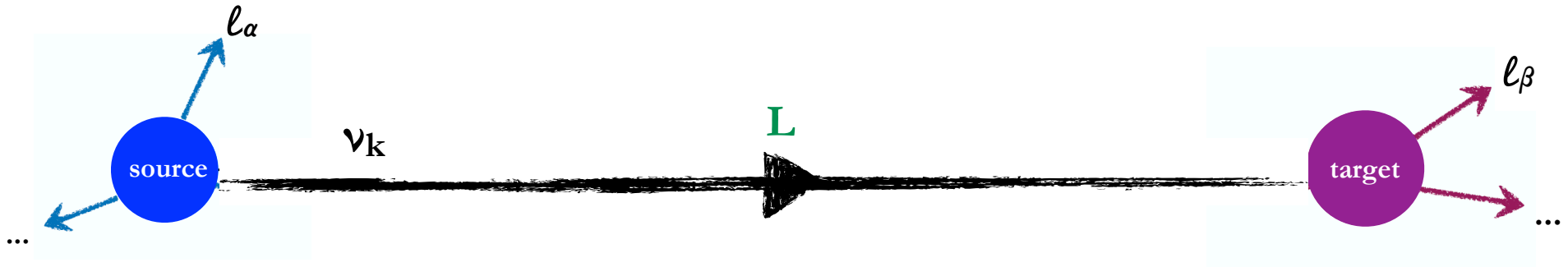

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$\kappa = N_S N_T / (32\pi L^2 m_S m_T)$

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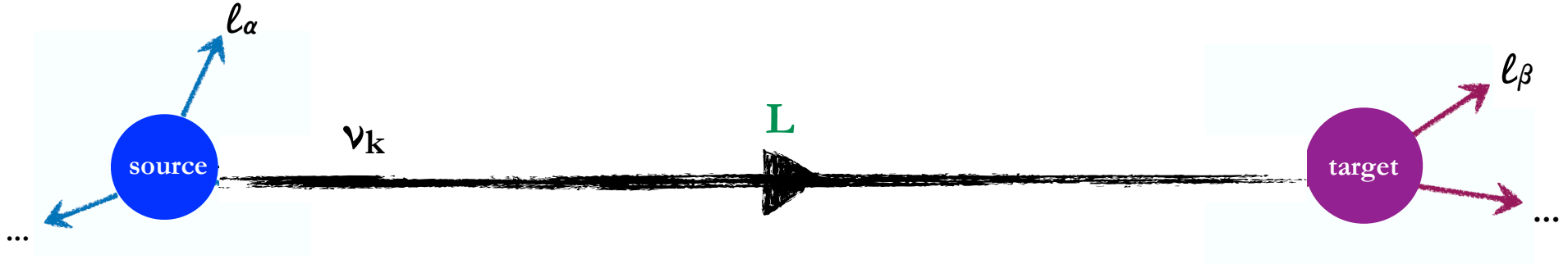

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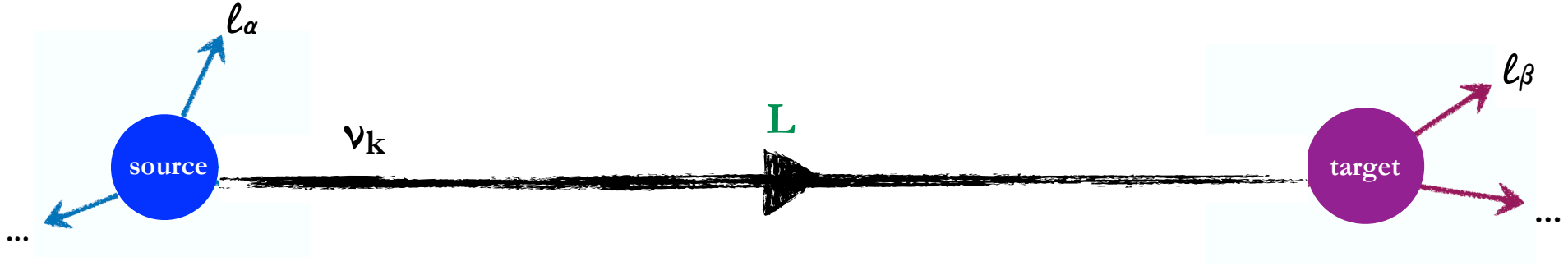

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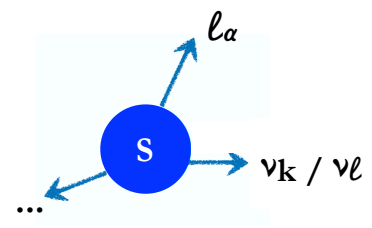
Production
(w/o integration over E_ν)

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

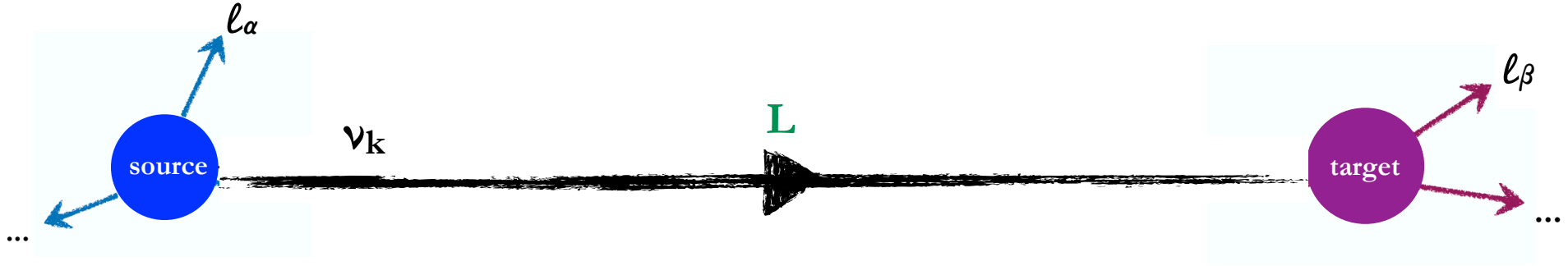


Phase space integrals: $d\Pi \equiv \frac{d^3k_1}{(2\pi)^3 2E_1} \cdots \frac{d^3k_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^4(\mathcal{P} - \sum k_i)$

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

Oscillations in QFT

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



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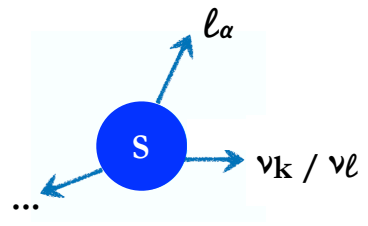
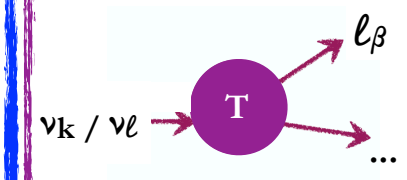


Detection

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



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Oscillations in QFT

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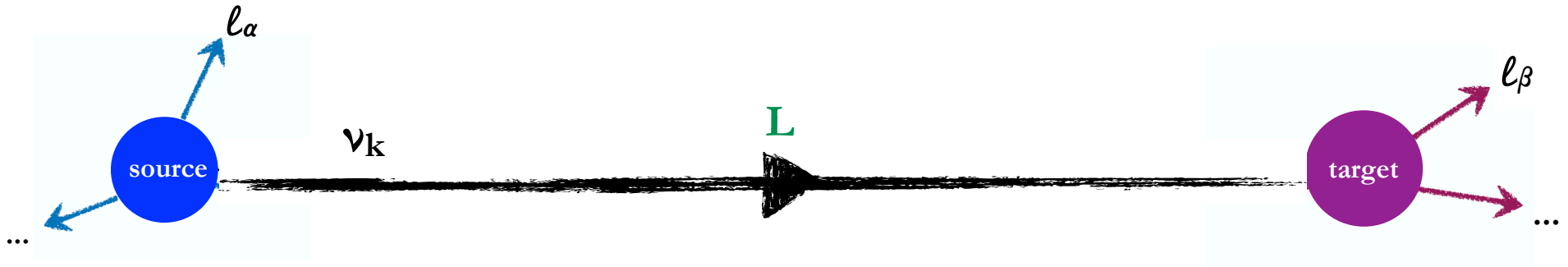

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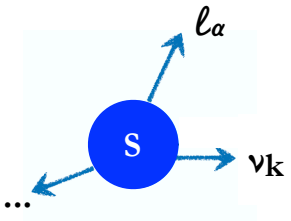
- The rest is "straightforward":
  specify the Lagrangian and calculate the production & detection amplitudes.



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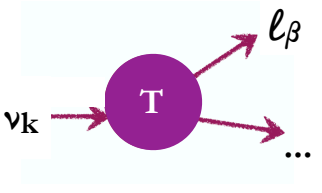
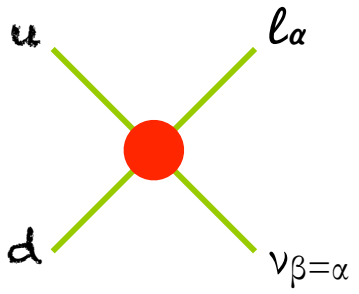


Oscillations in QFT → EFT

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



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

Oscillations in QFT → EFT

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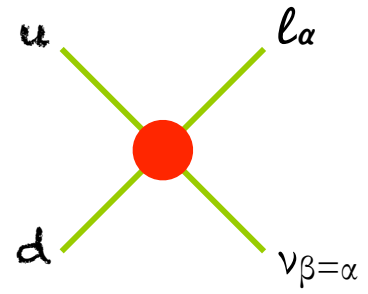
$$+ \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L \nu_\beta)$$
$$+ \frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu} P_L d)(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta) + \text{h.c.}\Big\}$$

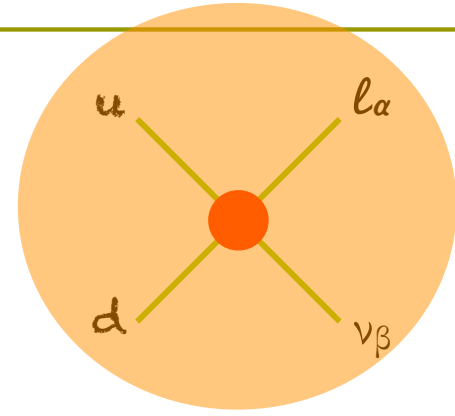


NP models: W', charged scalar, LQ, ...

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

Oscillations in QFT → EFT

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



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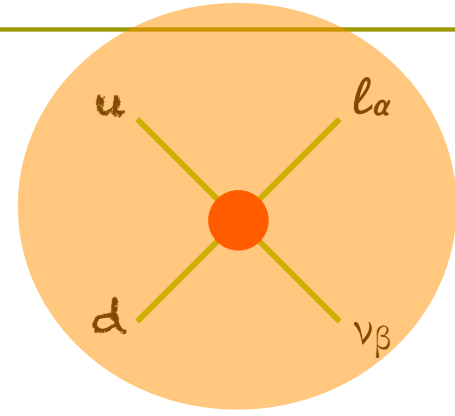
$$\times\left[U_{\beta k}U^*_{\beta l}+d_{XL}(\epsilon_X U)_{\beta k}U^*_{\beta l}+d^*_{XL}U_{\beta k}(\epsilon_X U)^*_{\beta l}+d_{XY}(\epsilon_X U)_{\beta k}(\epsilon_Y U)^*_{\beta l}\right]$$

!

Oscillations in QFT → EFT

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



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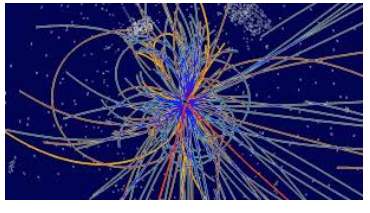
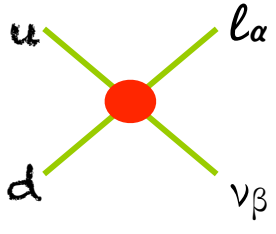
- Choose your favourite experiment: $O = O(\theta_i, \Delta m^2, \varepsilon_j) \rightarrow \varepsilon_j$
- Compare and combine with other searches.





Oscillations in QFT → EFT

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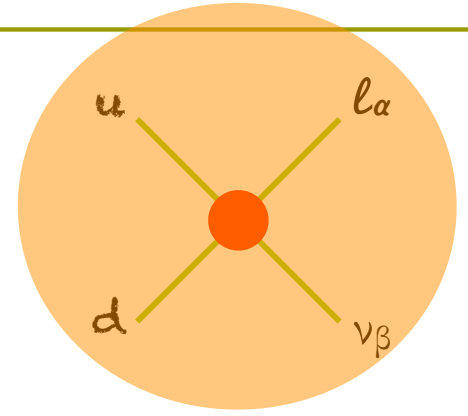

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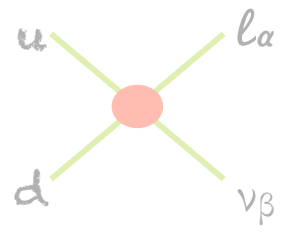
- Choose your favourite experiment: $O = O(\theta_i, \Delta m^2, \varepsilon_j) \to \varepsilon_j$
- Compare and

Example: COHERENT

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

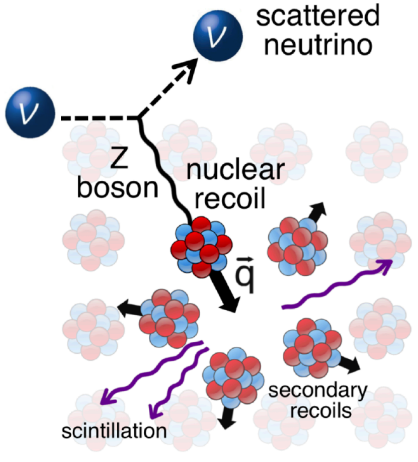


EFT analysis of NP at COHERENT

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

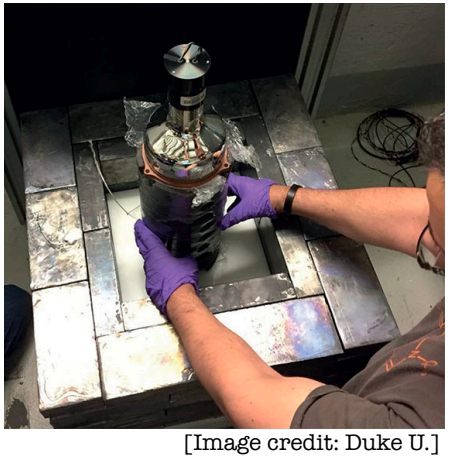
- It occurs for E_ν small enough so that the neutrino does not resolve the nucleus → CEνNS cross section enhanced by N^2.
  Theoretically known since the 70's
  [Freedman'74; Kopeliovich & Frankfurt'74]

- Extremely challenging experimentally (very small nuclear recoil)



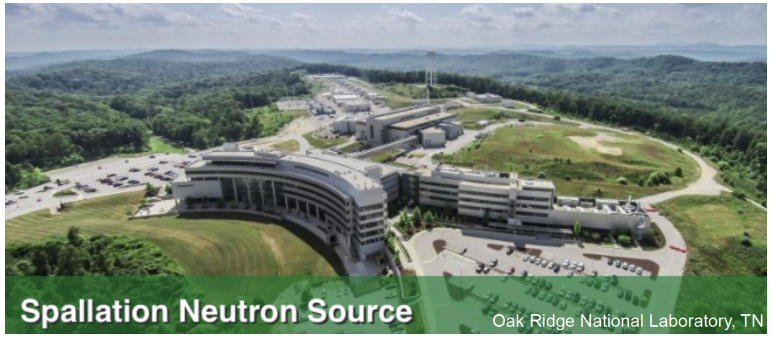
[from COHERENT coll.]

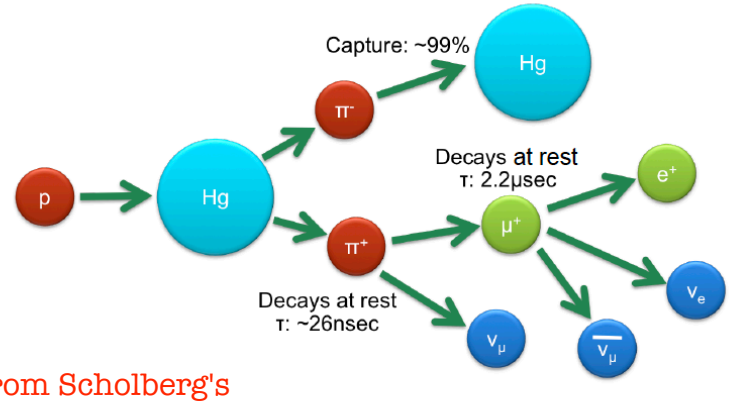
[Akimov et al.'17]


[Image credit: Duke U.]

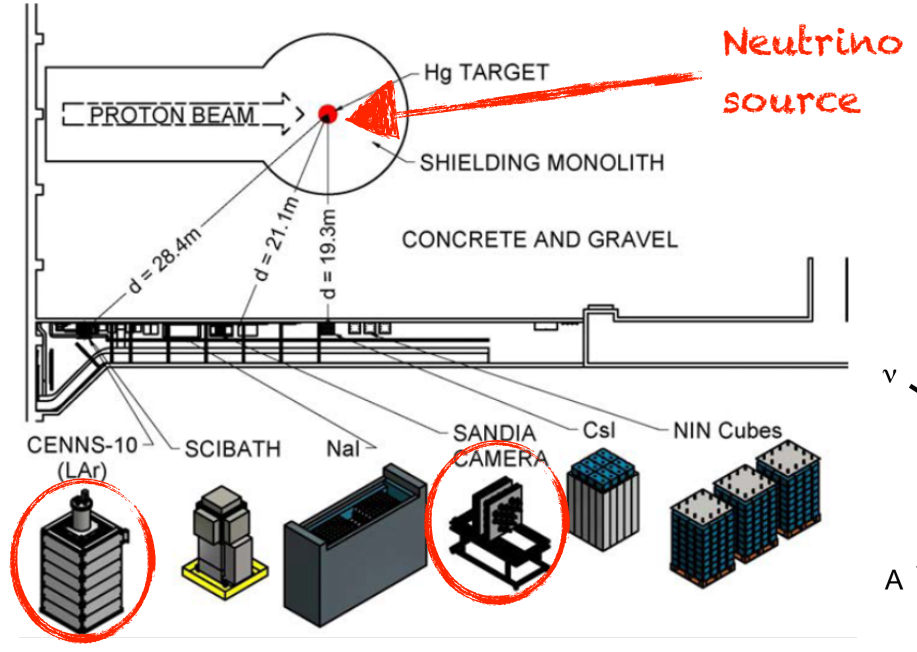
COHERENT
SNS
SPALLATION NEUTRON SOURCE

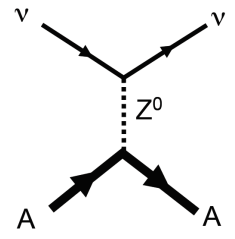
EFT analysis of NP at COHERENT



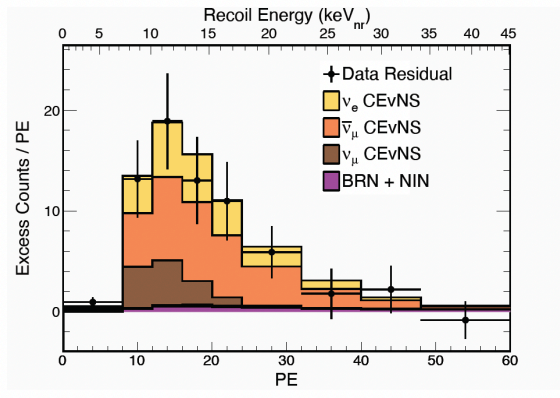


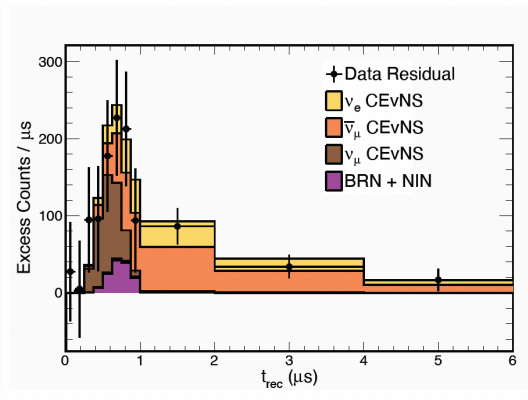
[from Scholberg's talk at IPA18]





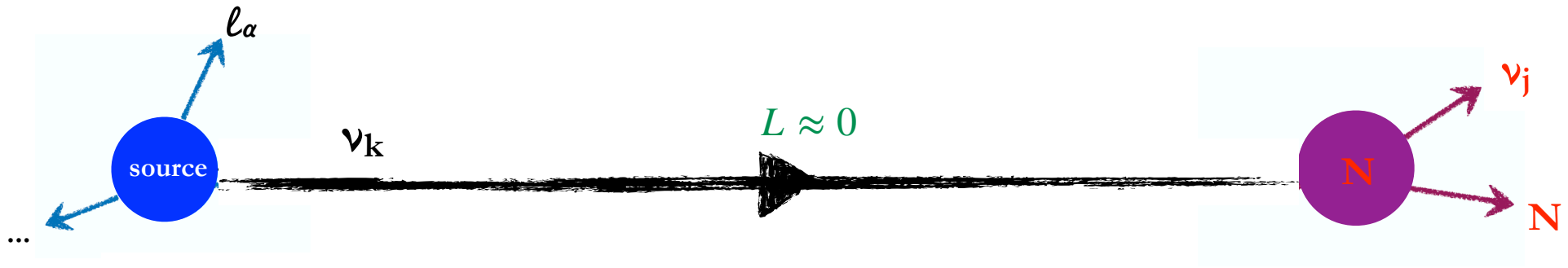
$$\pi^+ \to \mu^+ \nu_\mu \text{ (prompt)}$$
$$\hookrightarrow \mu^+ \to e^+ \bar{\nu}_\mu \nu_e \text{ (delayed)}$$





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

EFT analysis of NP at COHERENT



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

- CC production: pion and muon decays.

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

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

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

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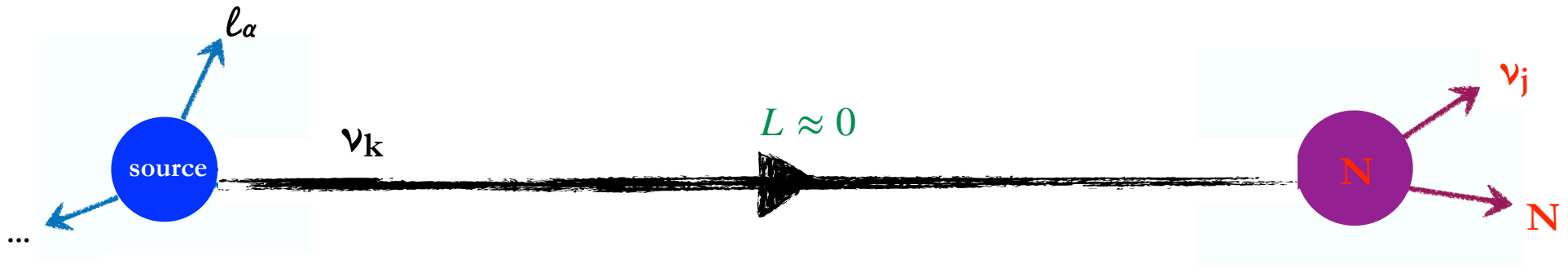

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- CC production: pion and muon decays.

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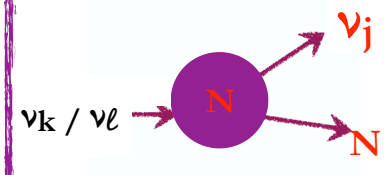
- NC detection: νN → νN.

Detection

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

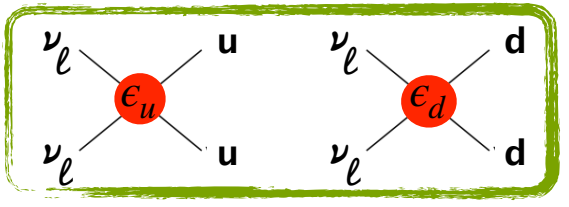


$$\mathcal{L}_{\rm WEFT} \subset -\frac{1}{v^2} \sum_{q=u,d} \Big\{ \; [g_V^{qq}\,\mathbb{1} + \epsilon_V^{qq}]_{\alpha\beta} \, (\bar{q}\gamma^\mu q) \, (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)$$
$$+ \, [g_A^{qq}\,\mathbb{1} + \epsilon_A^{qq}]_{\alpha\beta} \, (\bar{q}\gamma^\mu \gamma^5 q) \, (\bar{\nu}_\alpha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

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

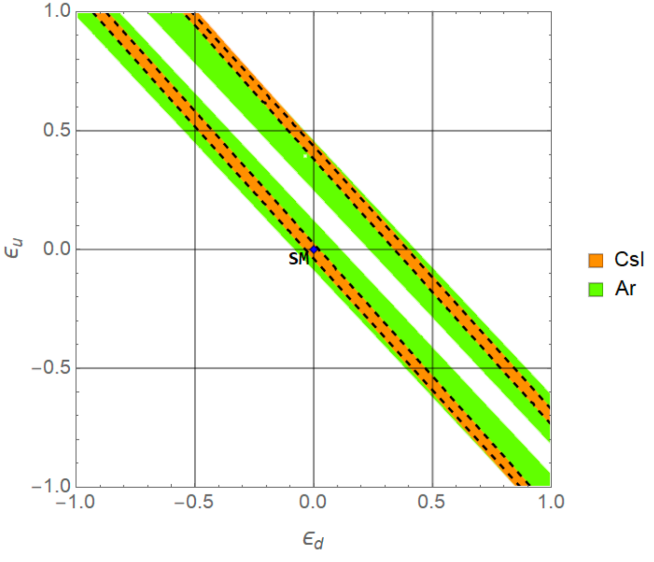
EFT analysis of NP at COHERENT

- Simple case: linear NP + flavor universality ⇨ $\frac{dN}{dtdT} = g(\epsilon_u, \epsilon_d) + \mathcal{O}(\epsilon^2)$



- 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]

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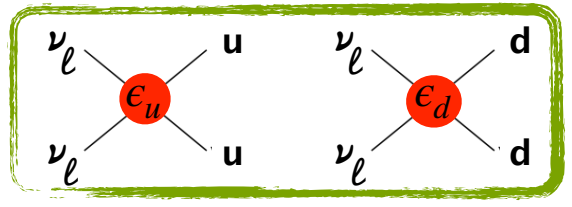

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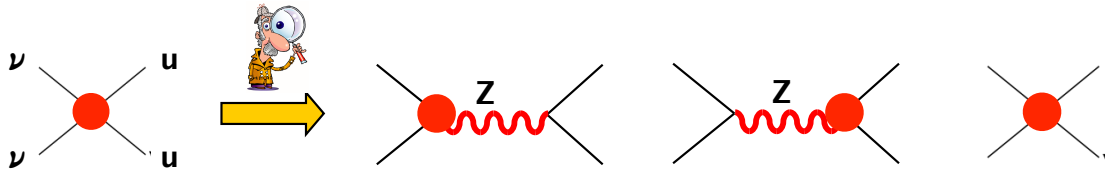
LEFT/SMEFT Matching



$$0.71\, c_{\ell q}^{(1)} - 0.04\, c_{\ell q}^{(3)} + 0.34\, c_{\ell u} + 0.37\, c_{\ell d} - 0.67(\delta g_L^{Zu} + \delta g_R^{Zu}) - 0.74(\delta g_L^{Zd} + \delta g_R^{Zd}) + 0.26\delta g_L^{Z\nu} = -0.003 \pm 0.010$$

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

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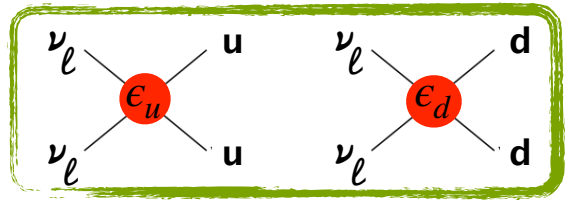

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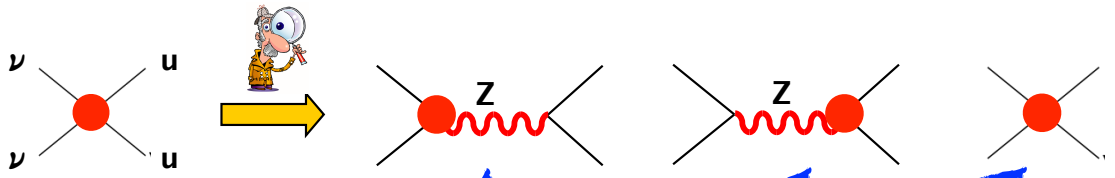

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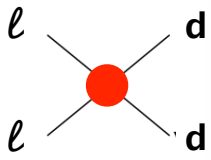
- These operators are constrained by many EWPO: LEP1, LEP2, APV, …
  Is COHERENT probing a new region in the SMEFT parameter space? → Global fit needed!

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

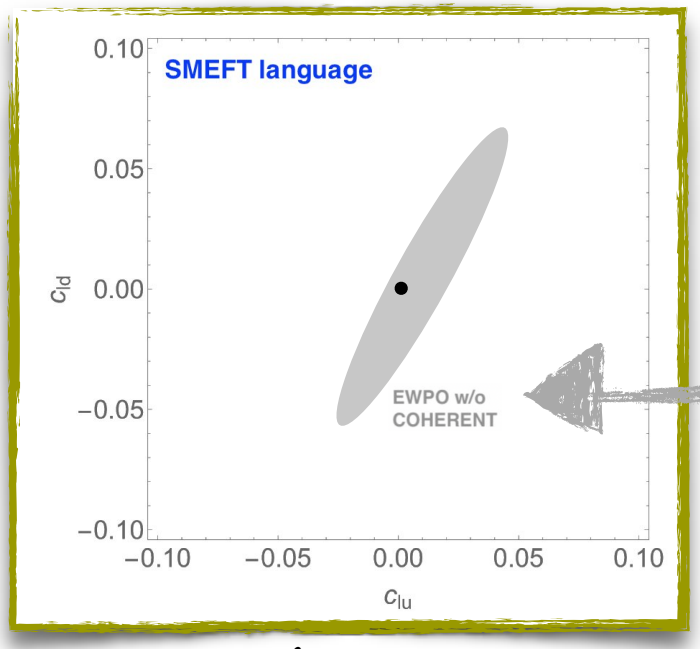
COHERENT in the SMEFT

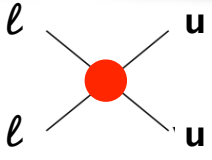
- Global fit to Electroweak precision observables in the flavor-universal SMEFT

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



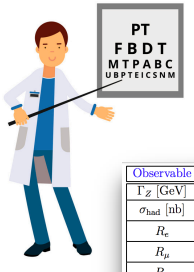
$\bar{\ell}\gamma_\mu \ell \; \bar{d}\gamma^\mu d$





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

18 free parameters



Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[50]	80.364	$\frac{g_{L,0}}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \to ff')$
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to ff')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[51]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to ff')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[51]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to ff')}$
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	$g_L^{Wqs}/g_{L,\mathrm{SM}}^{Wqs}$

Observable	Experimental value	Ref.	SM predictio	
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to ff)$
σ_{had} [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\mathrm{FB}}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\mathrm{FB}}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\mathrm{FB}}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
A_c^{FB}	0.0707 ± 0.0035	[47]	0.0738	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_e	0.1498 ± 0.0049	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
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	$\frac{\Gamma(Z\to b_Lb_L)-\Gamma(Z\to b_Rb_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[47]	0.668	$\frac{\Gamma(Z\to c_Lc_L)-\Gamma(Z\to c_Rc_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[48]	0.935	$\frac{\Gamma(Z\to s_Ls_L)-\Gamma(Z\to s_Rs_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009	[45]	0.1724	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

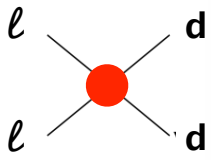
+ many more data...

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

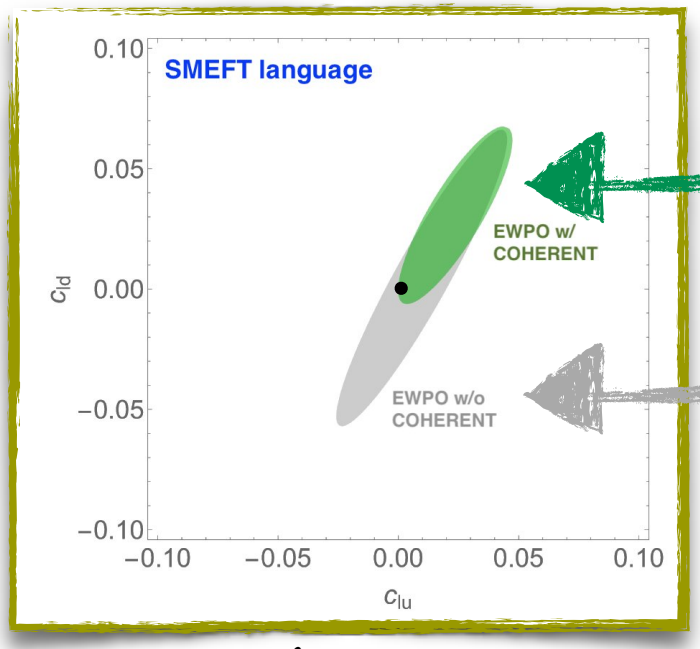
COHERENT in the SMEFT

- Global fit to Electroweak precision observables in the flavor-universal SMEFT

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



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



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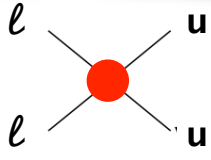
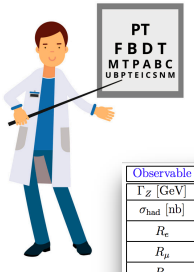


18 free parameters

+ COHERENT data!

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



Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[50]	80.364	$\frac{g_{L,0}}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \to ff')$
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to ff')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[51]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to ff')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[51]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to ff')}$
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	$g_L^{Wq_3}/g_{L,\mathrm{SM}}^{Wq_3}$

Observable	Experimental value	Ref.	SM predictio	
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to ff)$
σ_{had} [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\mathrm{FB}}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\mathrm{FB}}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\mathrm{FB}}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
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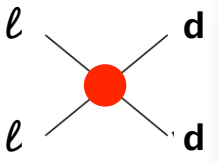
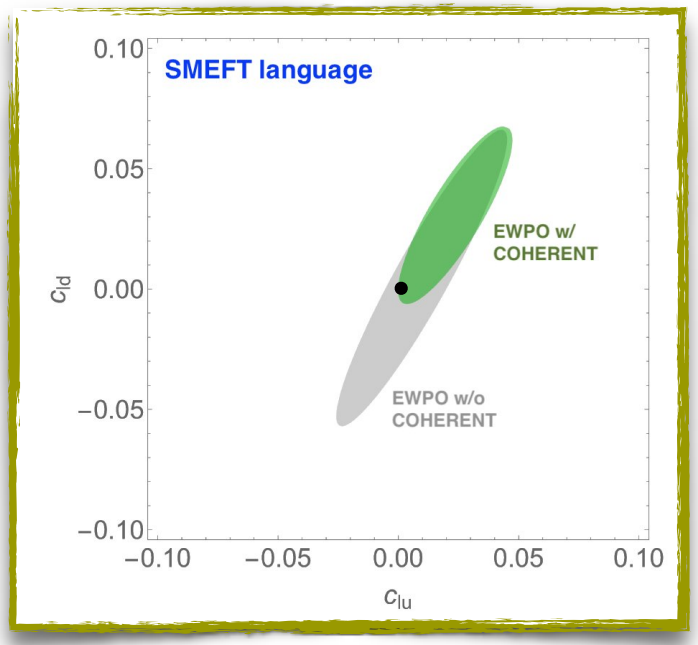
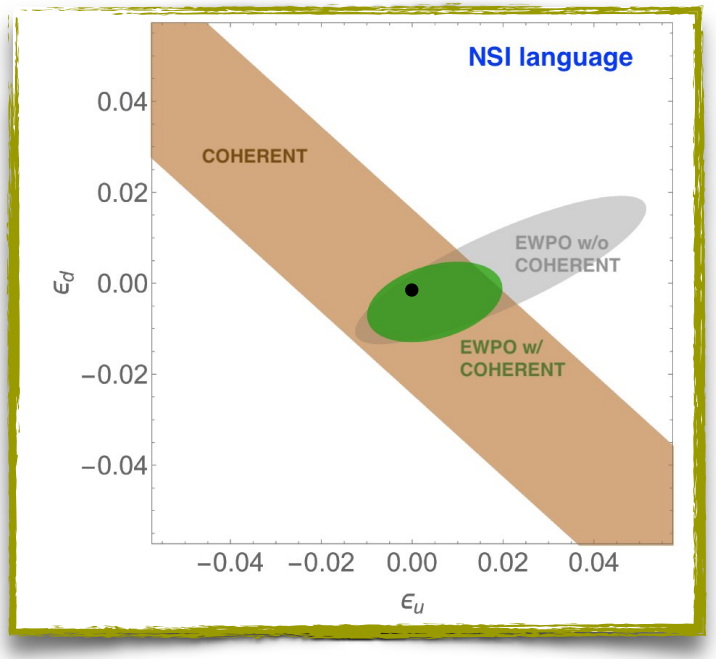


$\bar{\ell}\gamma_\mu \ell \; \bar{d}\gamma^\mu d$





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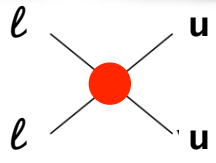

18 free parameters

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

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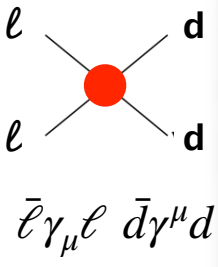
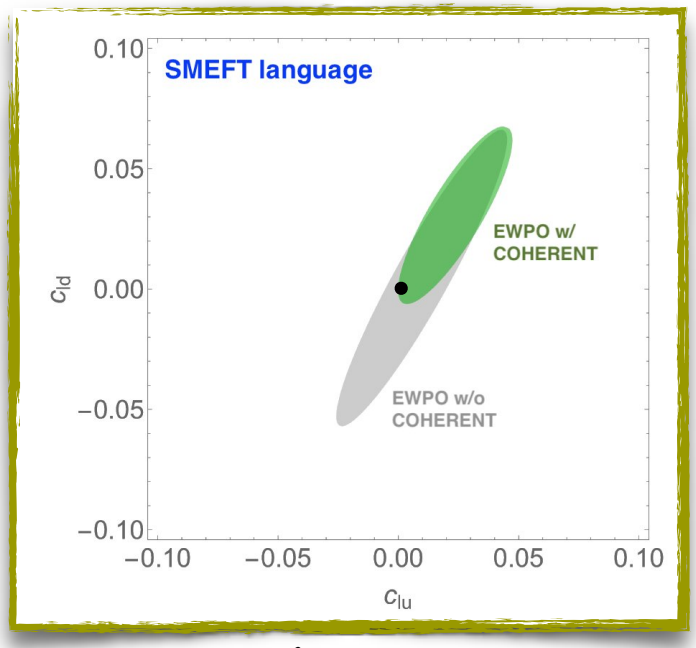


$\bar{\ell}\gamma_\mu \ell \; \bar{d}\gamma^\mu d$



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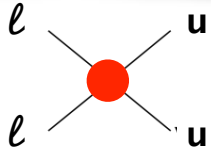
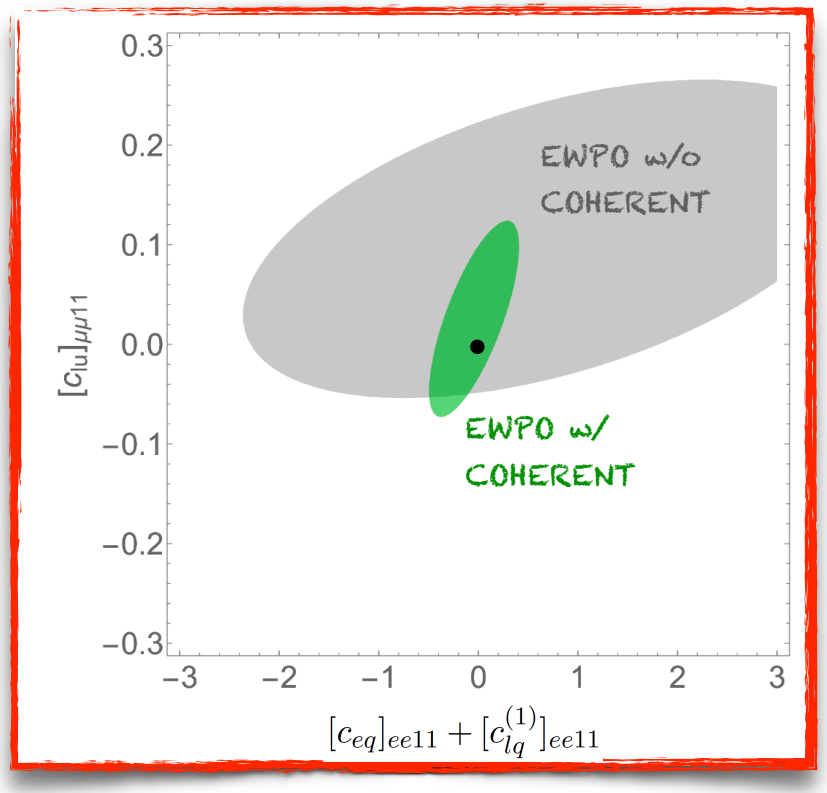
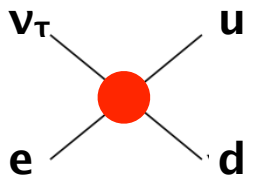




18 free parameters → 65 free parameters

Oscillation experiment



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

- $L \neq 0 \rightarrow$ oscillations! $\rightarrow$ $O = O\,(\theta_i,\ \Delta m^2)$
- Adding NP: $O = O\,(\theta_i,\ \Delta m^2,\ \varepsilon_j)$ [simultaneous fit!]

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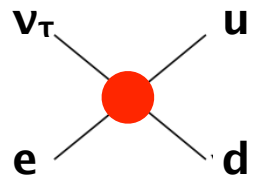

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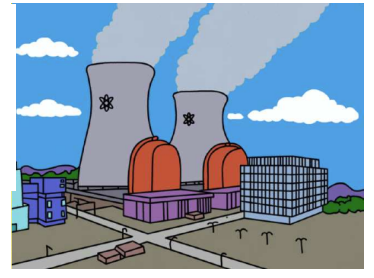

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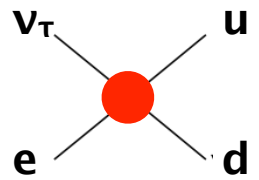

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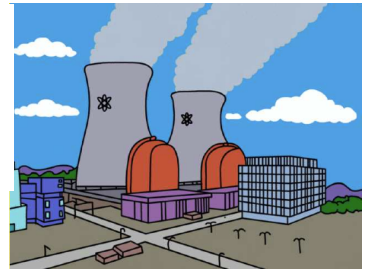
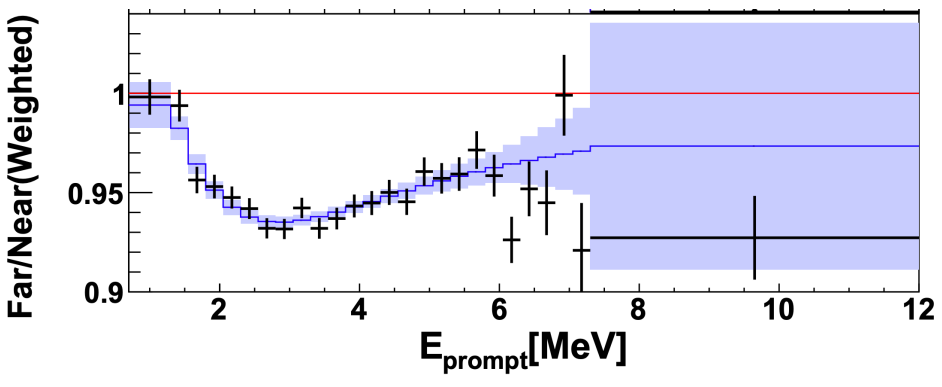


- Precision: $\theta_{13} = 0.0856(29)$
  [DayaBay'18, ~4M neutrino events!]



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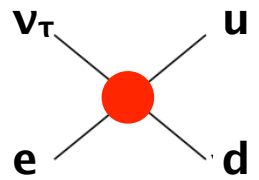

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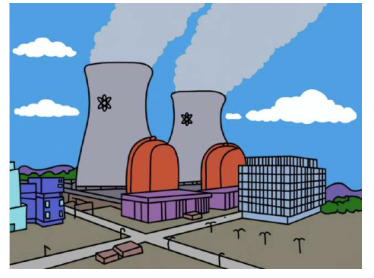

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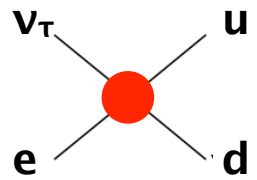

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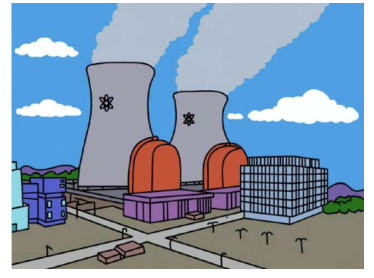

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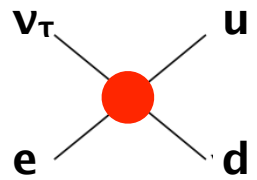
Oscillation experiment



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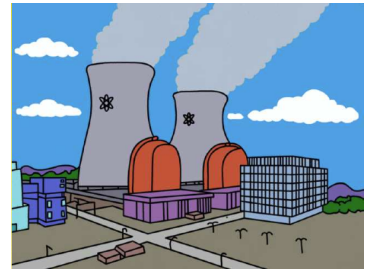

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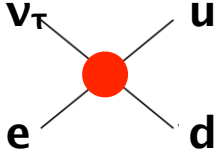
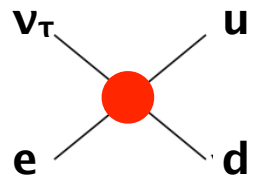


Oscillation experiment



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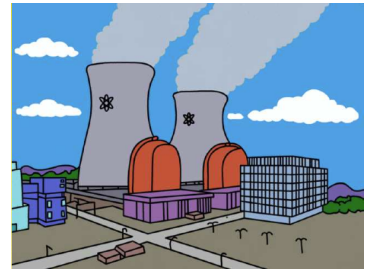

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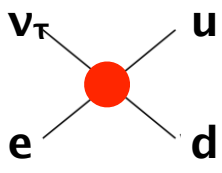


[Similar bounds from nuclear beta decays]

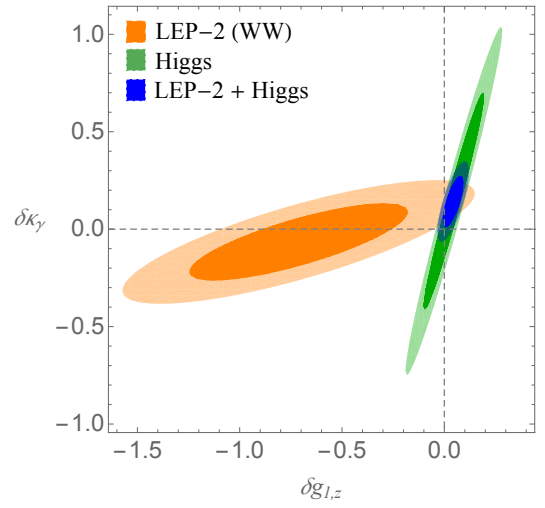
Summary

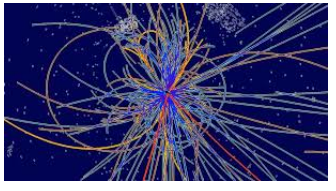
EFT!!

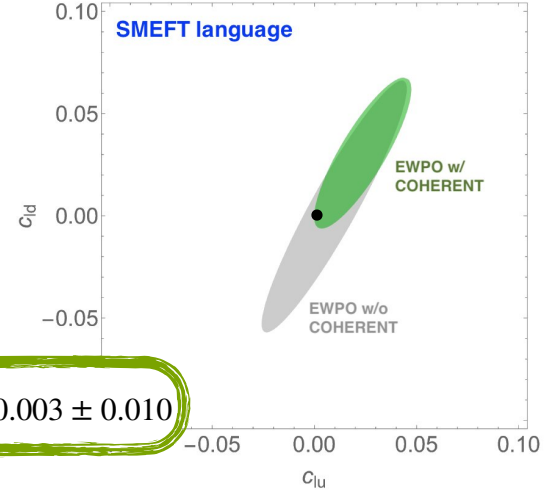
- (SM)EFT: an efficient framework to search for **generic** (heavy) New Physics.

- The path to analyze any given neutrino experiment in the presence of them is now clear: $\mathcal{O} = \mathcal{O}(\theta_i, \Delta m^2, \varepsilon_j)$

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

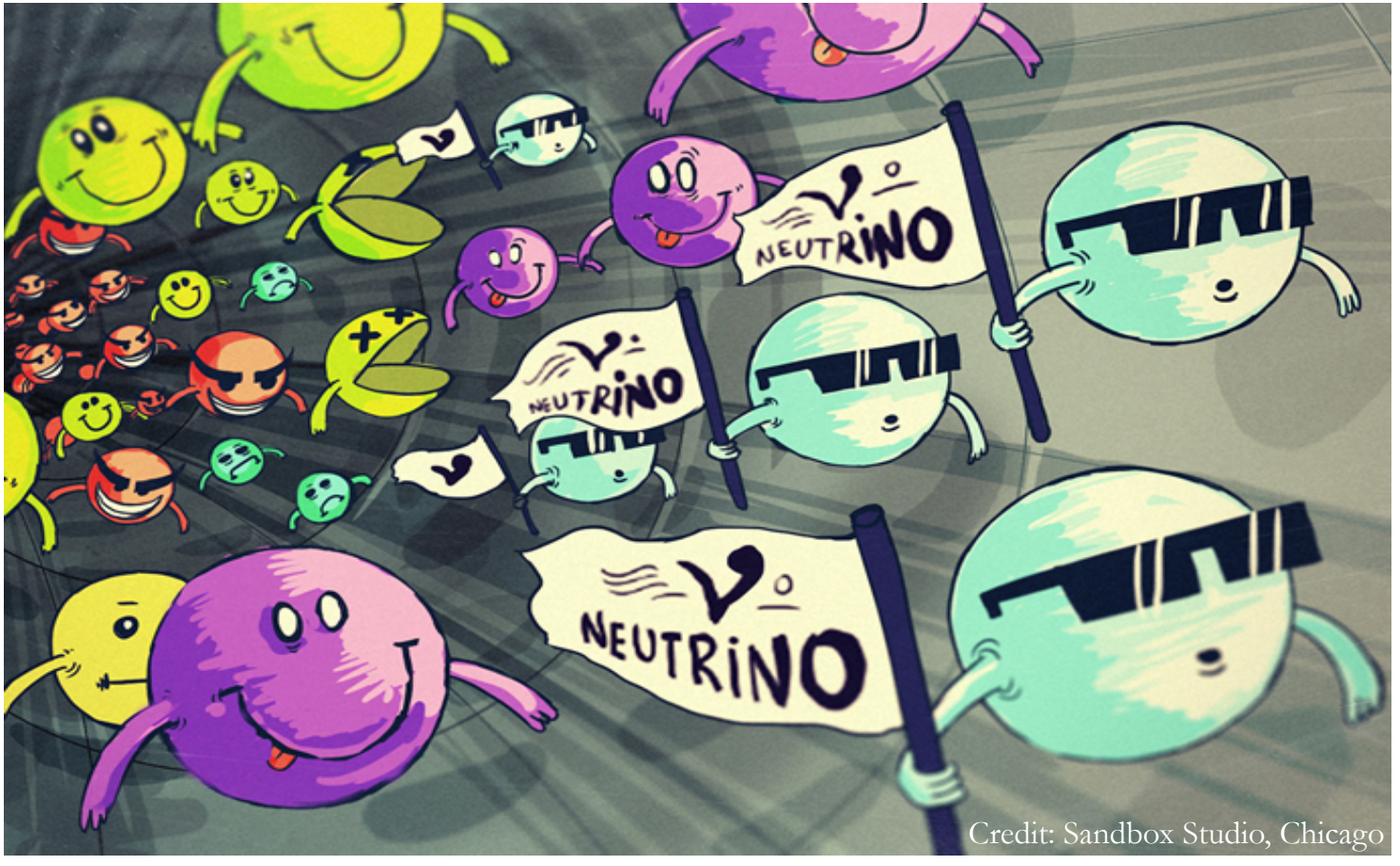






- Example: COHERENT should be included in EWPO fits!

$$0.71\, c_{\ell q}^{(1)} - 0.04\, c_{\ell q}^{(3)} + 0.34\, c_{\ell u} + 0.37\, c_{\ell d} - 0.67(\delta g_L^{Zu} + \delta g_R^{Zu}) - 0.74(\delta g_L^{Zd} + \delta g_R^{Zd}) + 0.26\delta g_L^{Z\nu} = -0.003 \pm 0.010$$



Credit: Sandbox Studio, Chicago

Thanks!

Backups

EFT in QFT

Top down

Known theory at high-E

EFT at low-E

Bottom up

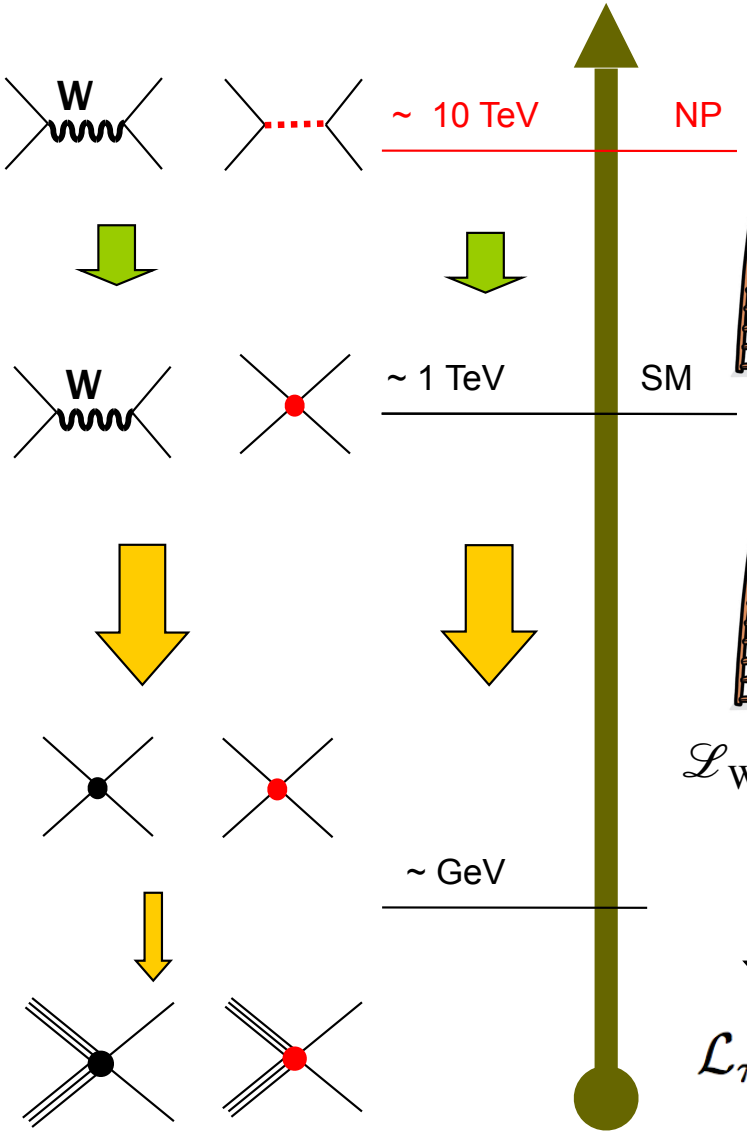
EFT that includes high-E effects

Known theory at low-E
(or at least symmetries & fields)

Given a set of low-E fields & symmetries, one builds an EFT Lagrangian putting all possible interactions and following a power counting

SMEFT → Beta-decay LEFT

$$\frac{d\vec{\epsilon}(\mu)}{d\log\mu} = \left(\frac{\alpha(\mu)}{2\pi}\gamma_{\rm ew} + \frac{\alpha_s(\mu)}{2\pi}\gamma_s\right)\vec{\epsilon}(\mu),$$



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

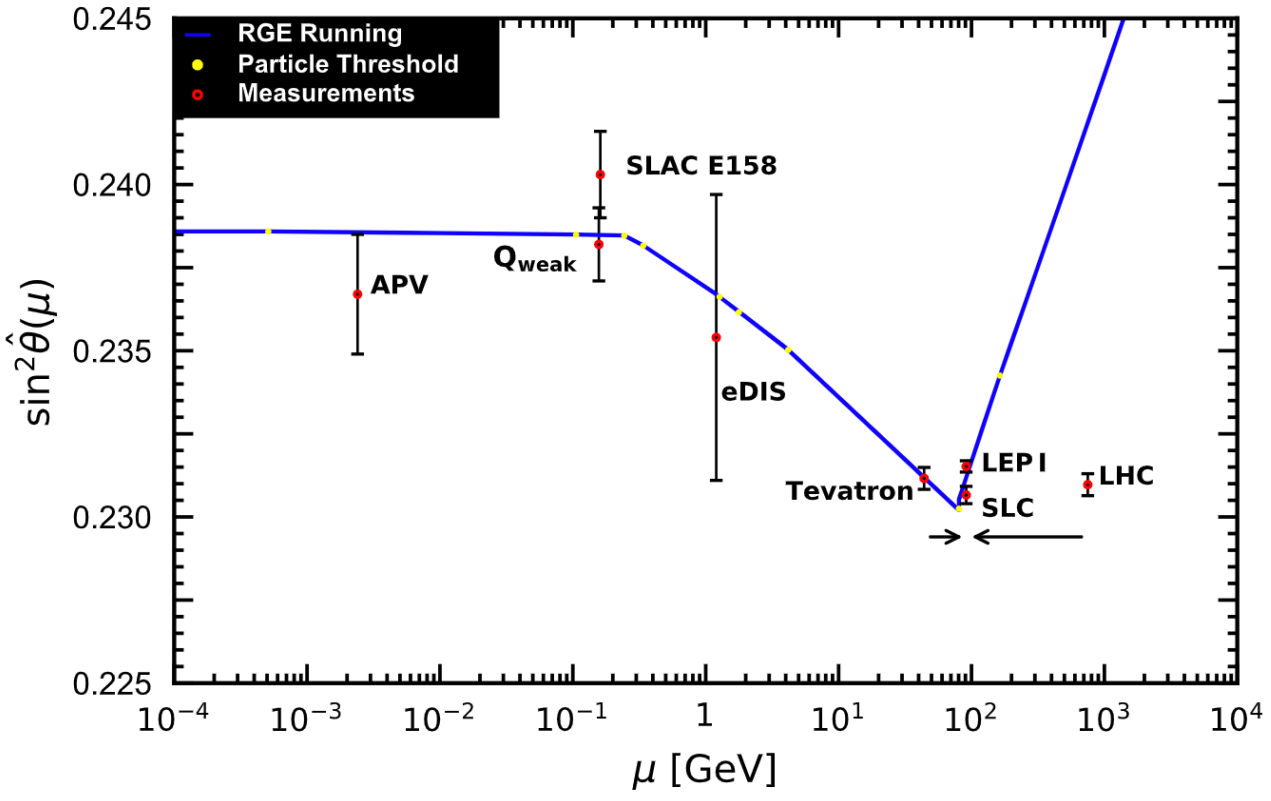
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \ldots$$

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\left\{(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \sum_\Gamma \epsilon_\Gamma (\bar{u}\Gamma d)(\bar{e}\Gamma\nu_e)\right\},$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

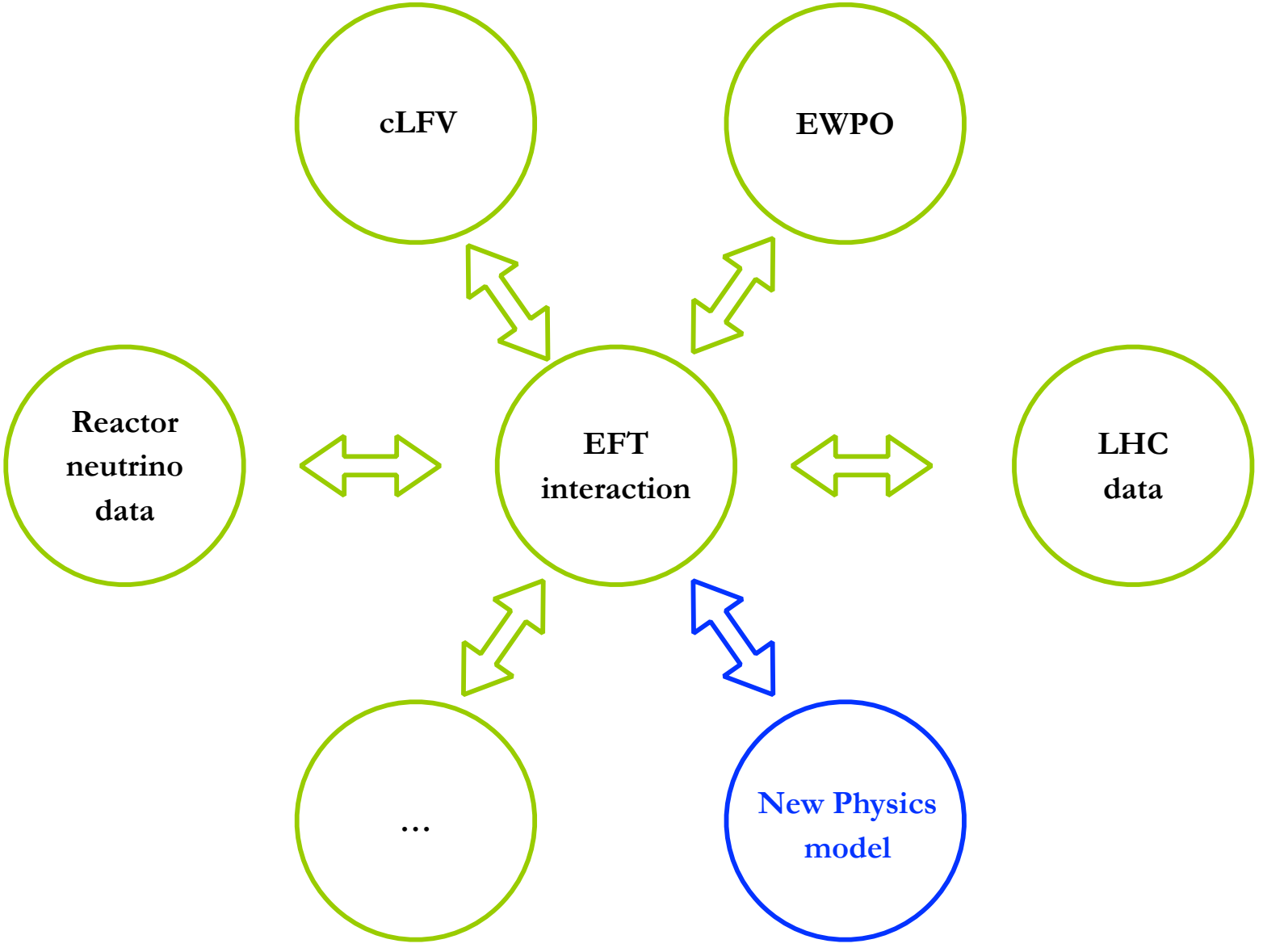
$$\frac{\epsilon_\Gamma}{v^2} = f\left(\frac{c_6^i}{\Lambda^2}\right) \rightarrow \epsilon_\Gamma = f\left(c_6^i\frac{v^2}{\Lambda^2}\right)$$

EFT at the EW scale: SMEFT



- In the SM most measurements are not competitive → no new information.
- Not true anymore if NP are present, since they are sensitive to different NP effects.
- EFT allows us the study this in a model-independent way.

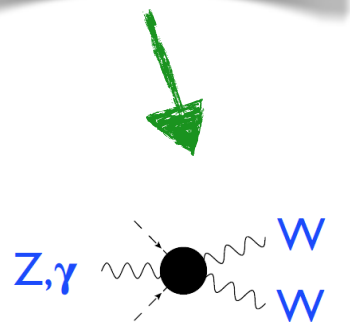
Beta decay & neutrino physics



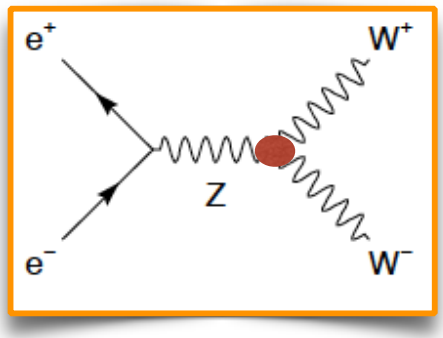
Example: LEP2 WW vs Higgs

- EFT (symmetry) connects these processes.
  See e.g.

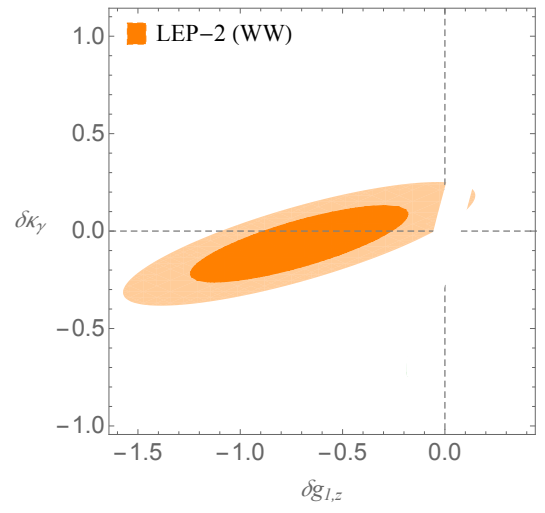
$$(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$



$e^+e^- \to W^+W^-$ (LEP2)



(Taking into account LEP1),
LEP2 probes 3 directions of the EFT space:
Triple Gauge Couplings… TGC = f (WC)



[Falkowski & Riva 2014]

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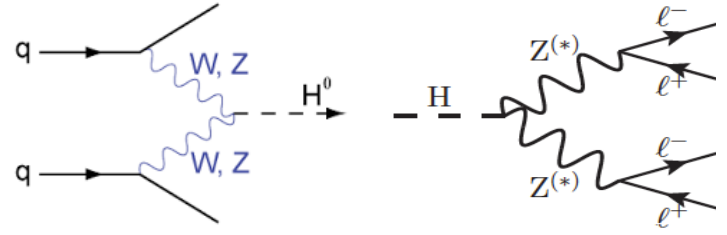

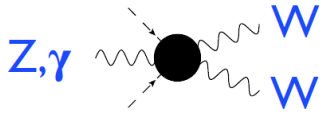

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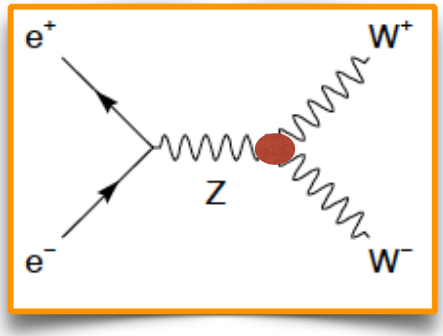

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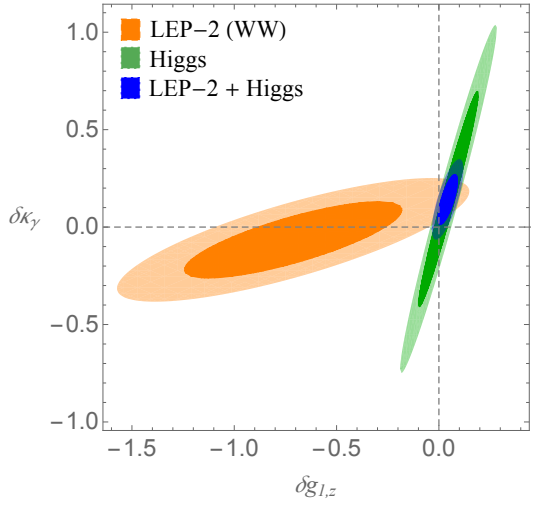


Can Higgs data cover this region?

YES!

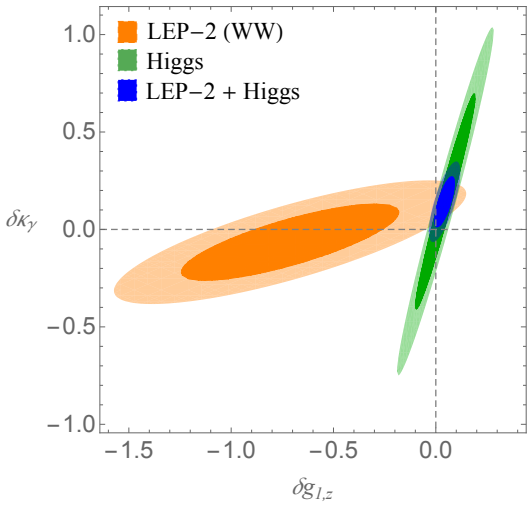
[Falkowski, MGA, Greljo & Marzocca, 2015]

[Higgs signal strengths]

Summary

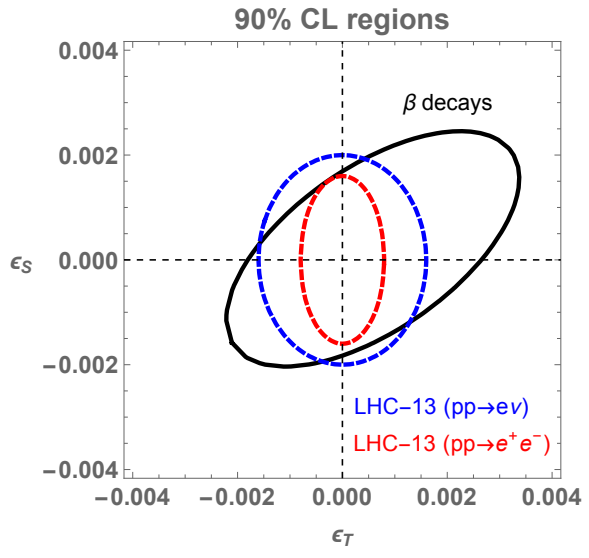
- Many other examples…

LEP2 (WW) vs Higgs LHC



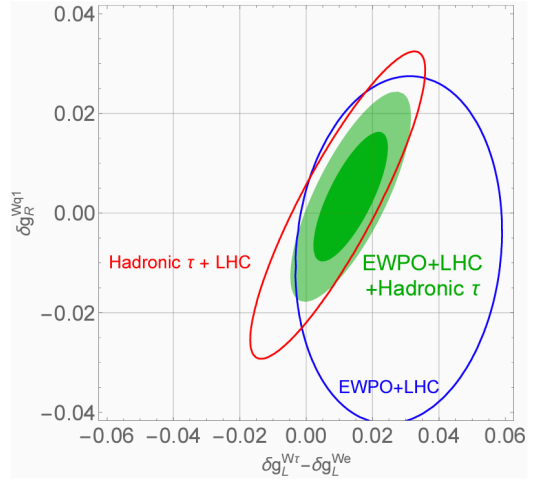
[Falkowski, MGA, Greljo & Marzocca, PRL 2015]

Nuclear beta decay vs LHC DY



[Gupta et al., PRD 2018, Falkowski, MGA, Naviliat-Cuncic JHEP 2021]

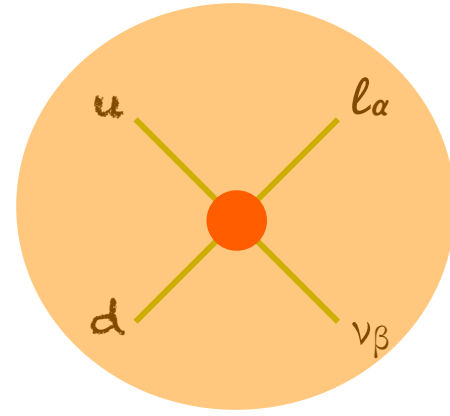
Hadronic tau decays vs EWPO



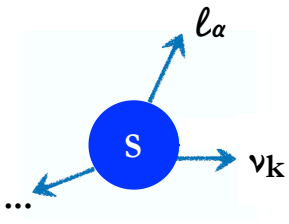
[Cirigliano, Falkowski, MGA, Rodríguez-Sánchez, PRL 2019]

Oscillations in QFT → EFT

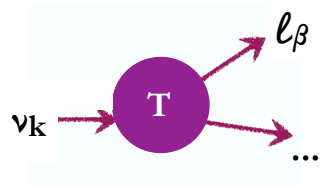
$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ [\mathbf{1}+\epsilon_L]_{\alpha\beta}\,(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta)$$
$$+[\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha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



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



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

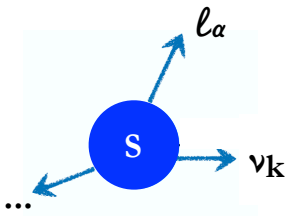


$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\text{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

Oscillations in QFT → EFT

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



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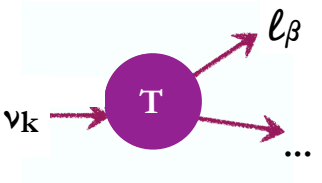

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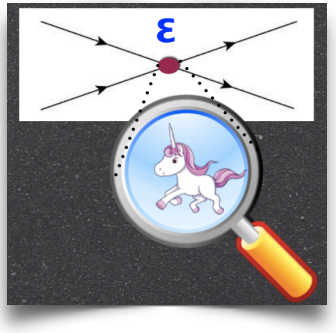
New qq'lν interactions



Oscillations in QFT → EFT

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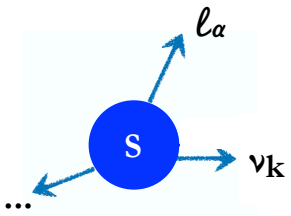

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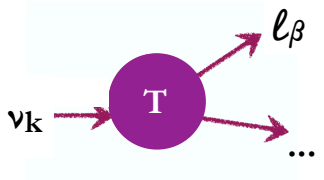

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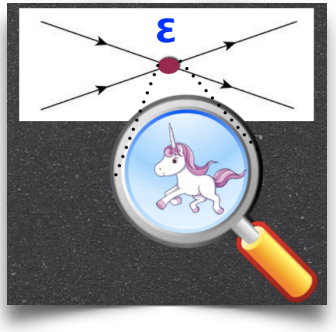
PMNS matrix

New qq'lν interactions



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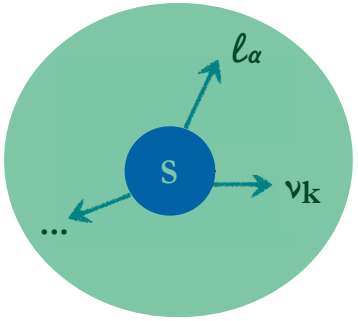

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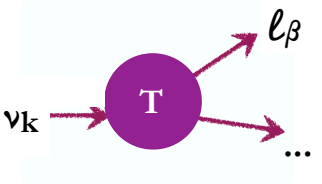

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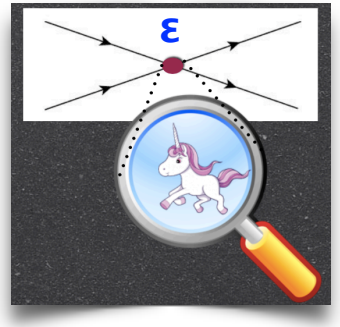
PMNS matrix

Production physics (QCD, EW)

New qq'lν interactions

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

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



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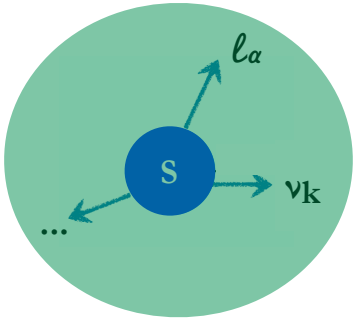

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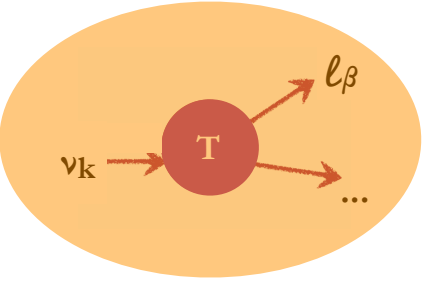

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PMNS matrix

Production physics (QCD, EW)

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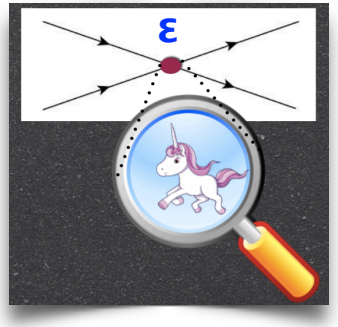
Detection physics (QCD, EW)



EFT analysis of NP at COHERENT

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

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

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

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

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]

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

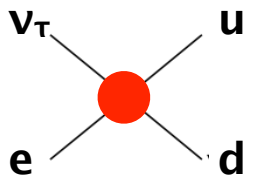
$$\frac{dN^{\text{delayed}}}{dT} = N_T \int dE_\nu \left(\frac{d\Phi_{\nu_e}}{dE_\nu} \frac{d\tilde{\sigma}_{\nu_e}}{dT} + \frac{d\Phi_{\bar{\nu}_\mu}}{dE_\nu} \frac{d\tilde{\sigma}_{\bar{\nu}_\mu}}{dT} \right) ,$$

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

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

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

Short-baseline reactor exp.



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

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