Searches for BSM physics at low energy (theory)

XXI LNF Spring school *Bruno Touschek* May 2024

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IFIC, Univ. of Valencia / CSIC

Intro: me

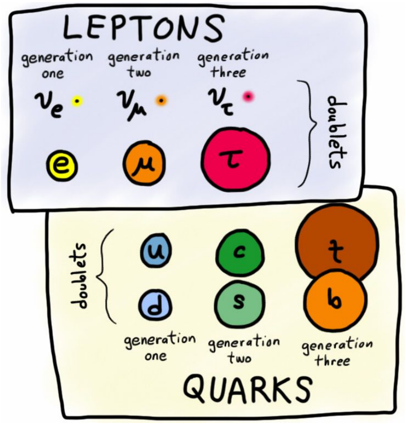
- Theoretical physicist at IFIC (Univ. Valencia & CSIC)


- Research interests: BSM searches with precision measurements, interplay of low- and high-E searches (flavor, neutrino, nuclear beta decays, LHC, …), Effective Field Theories, …

- My history with Frascati:
  - 2005: tourist
  - 2007 Spring School (student) [My 1st talk: "Condensates for the light quark V-A correlator"]
  - 2009: 2-month visitor (PhD)
  - 2013-2014: postdoc
  - 2014 Spring School (LOC member)
  - 2024 Spring School (lecturer)

Outline

- Intro: SM → BSM
- Classes of low-energy BSM searches
- Effective Field Theories
- EFT Phenomenology



Disclaimer:

- I don't think a technical 1.5h presentation of the subject would be very useful. Instead I'll give a qualitative overview, hopefully conveying some important ideas.
- For technical details, one should resort to written lectures, books, or longer courses. E.g., A. Pich's EW lectures (0705.4264), A. Falkowski SMEFT review (EPJC 83 (2023) 7, 656), MGA-Naviliat-Severijns's β decay review (1803.08732), …
- I don't expect to go over all the slides. Stop me if you get lost.
- I took advantage of these lectures to go outside my strict comfort zone in some points and learn new things. Fun but risky.

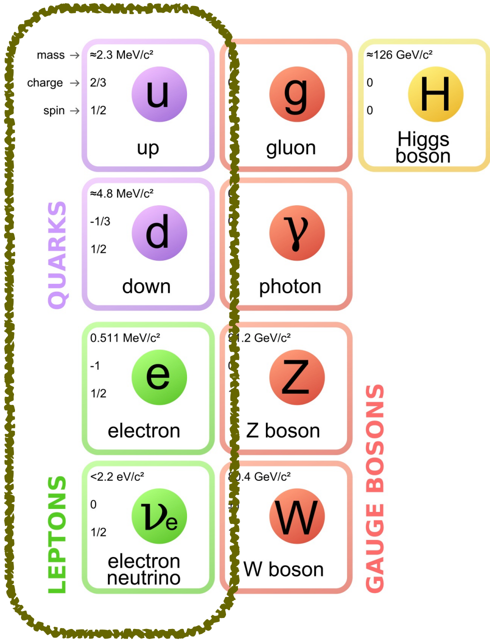
The Standard Model

- The SM is the QFT describing electromagnetic, weak & strong interactions.

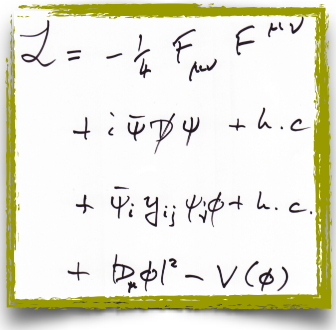
- It's the ultimate result of reductionism & unification
  [electromagnetism (→ chemistry), radioactivity, nuclear physics, …]
  Our periodic table.

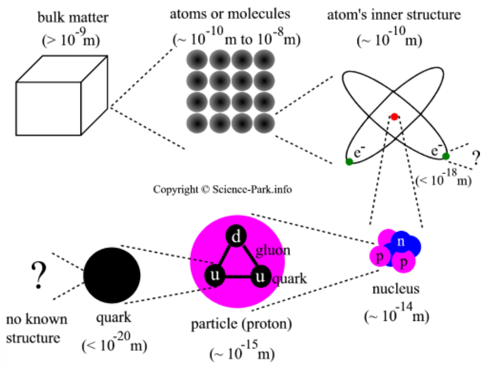
- ~50 years old, spectacularly confirmed
  [All particles have been observed (Higgs @CERN, 2012)]

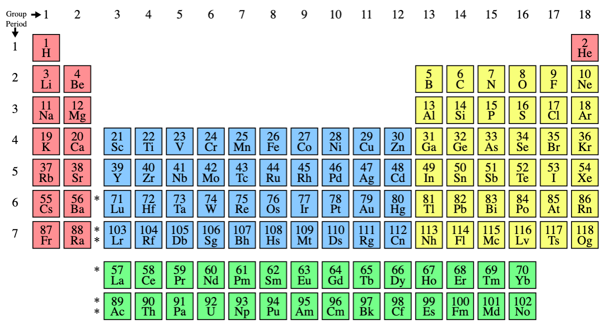
- Whatever [future experiments] find, SM has proven to be valid as an effective theory for E < TeV



x 3 !?

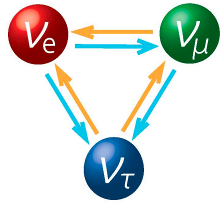




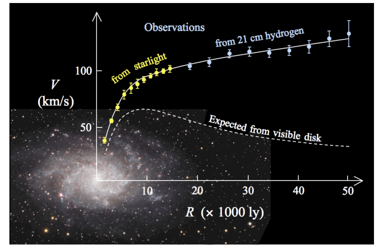


The SM is not enough (fortunately for us)

- Neutrinos oscillate → they have a mass!



- What lies under the SM periodic table?



- Dark matter, matter-antimatter asymmetry, strong CP problem, hierarchy problem, dark energy, quantum gravity, cosmological problems, …

- All SM problems are theoretical or astrophysical/cosmological, except for neutrino masses.

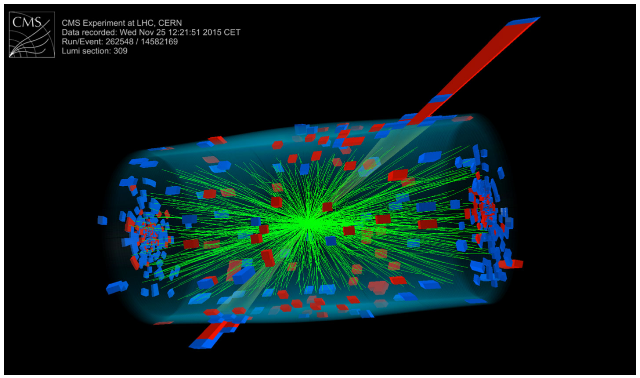
- Many BSM theories around (often not very convincing)

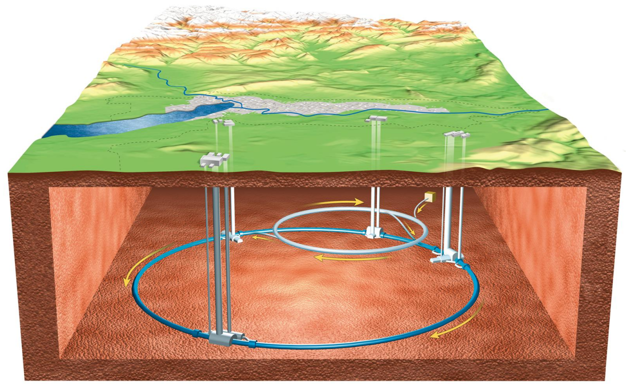
- The SM works too well (quite curious crisis).
  We need new hints. Physics = EXP + TH

BSM experimental searches

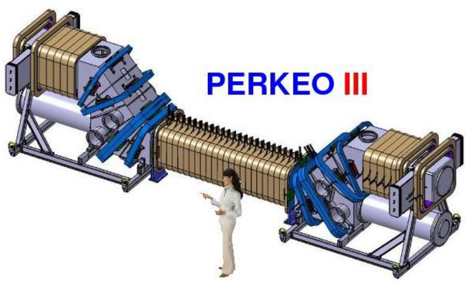
- One can divide them in high- and low-E searches.
  (my reference: low-E means energies << EW scale)

- High-energy searches (→ S. Lowette's lecture)





- Low-energy searches



BSM searches with low-E processes

- In this lecture: BSM = heavy new physics
  (heavier than the scale of the process → new particles offshell)

QCD >> QED >> EW >> BSM

BSM searches with low-E processes

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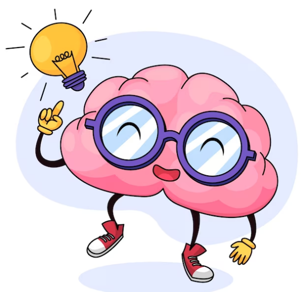
~~QCD~~ >> QED >> EW >> BSM

Choose leptonic or semileptonic processes



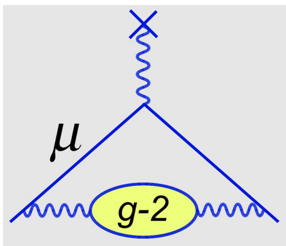
BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

- Solution 1: gargantuan TH+EXP precision (muon g-2)



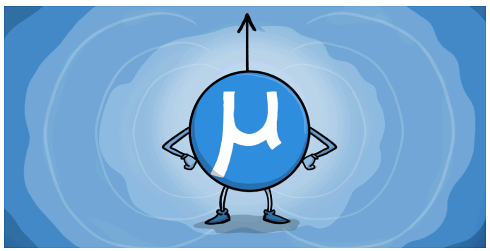
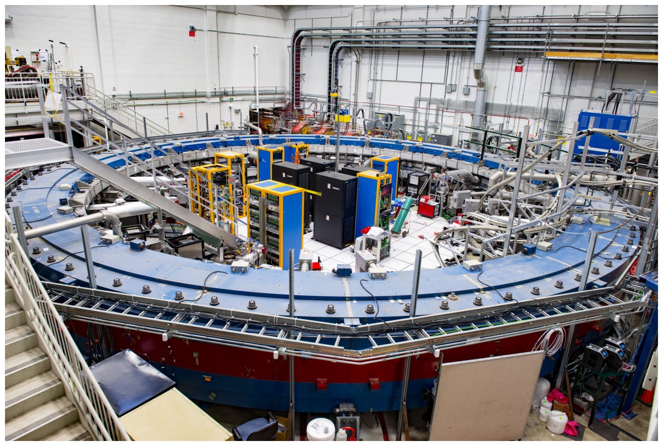
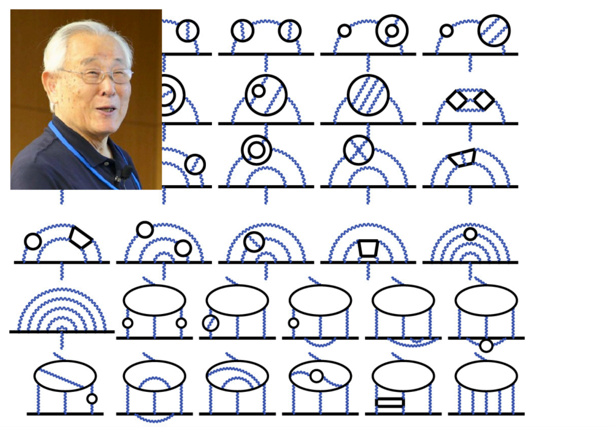


Figure Credit: APS/Jorge Cham





$$a_\mu^{\rm Exp} \;=\; 116\,592\,059(22)\times 10^{-11}\;\;(0.19\,{\rm ppm}).$$

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

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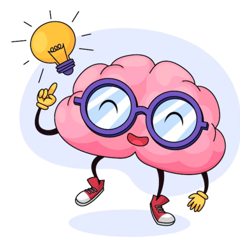
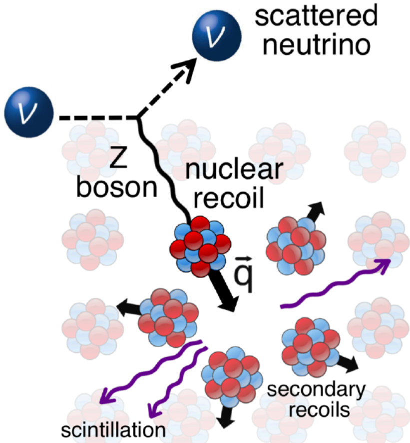
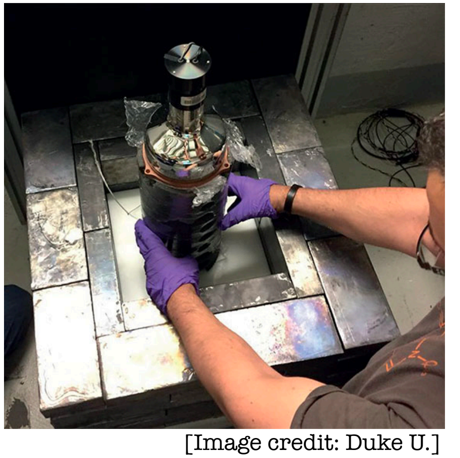
- Solution 2: choose a process with neutrinos ($\nu_i \; f \; \rightarrow \nu_i \; f$)





[from COHERENT coll.]

[Akimov et al.'17]



[Image credit: Duke U.]

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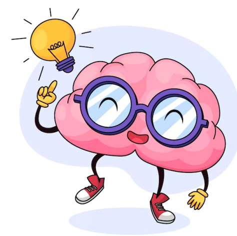
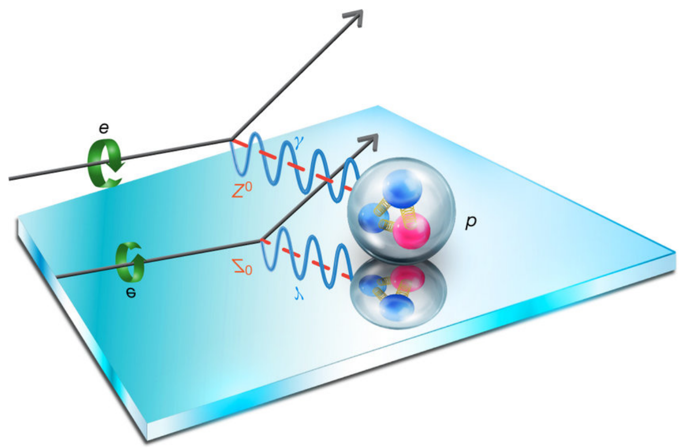
    - Parity! (Atomic PV, PVDIS, Qweak, …)





Fields	ψ_1	ψ_2	ψ_3
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
Leptons	$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L$	~~ν_R~~	ℓ^-_R

BSM searches with low-E processes

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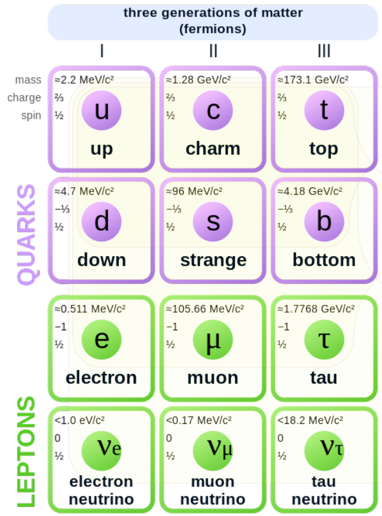

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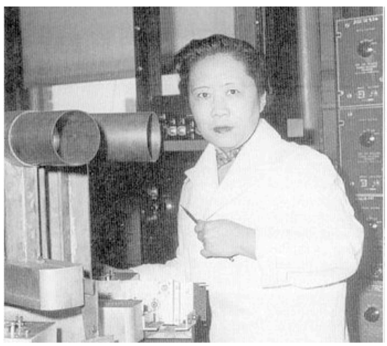

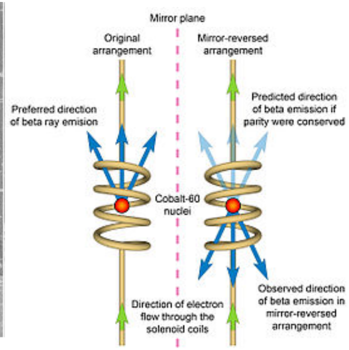

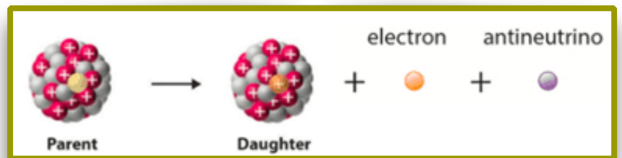

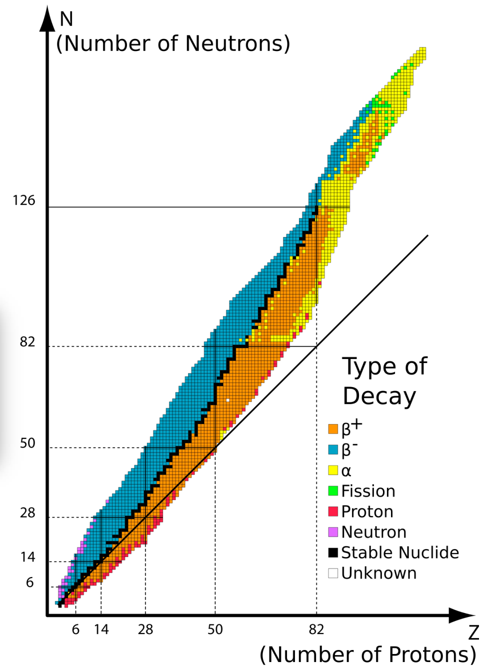

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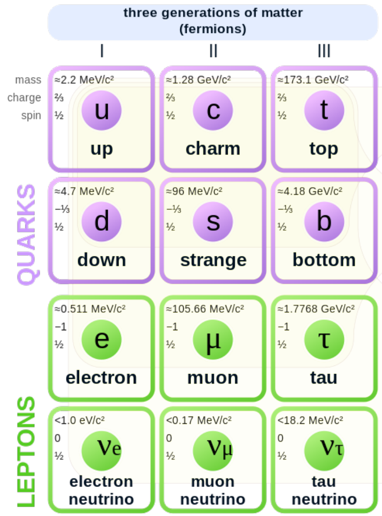

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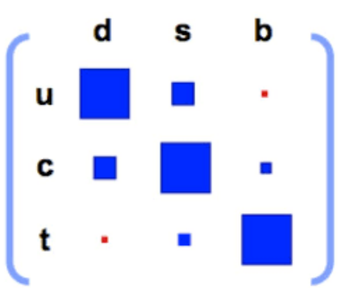
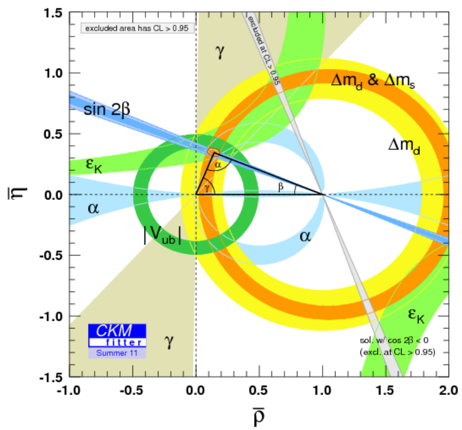
    - 3 quark families ($d_j \rightarrow u_i \ell\ \nu,\ d_j \rightarrow d_i \ell^+ \ell^-,\ \ldots$) $\rightarrow$ "flavor physics"

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx$$





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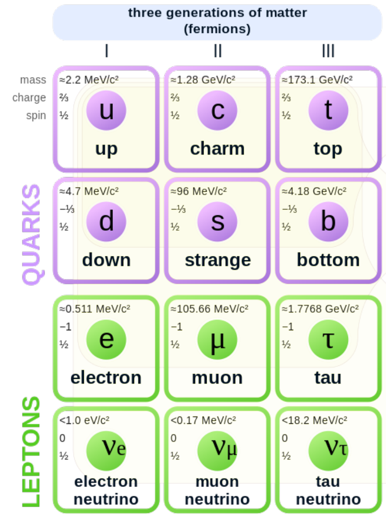

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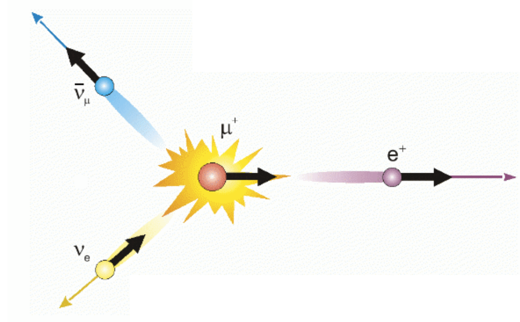

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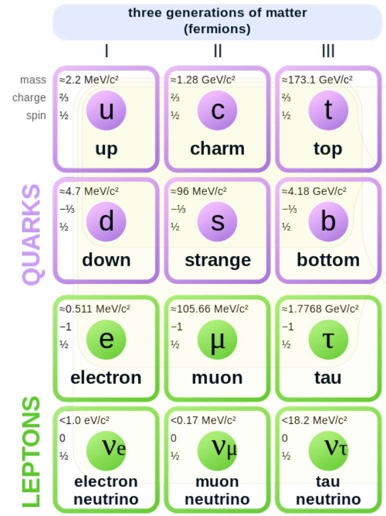

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    - Leptonic (with charged leptons): $\ell \to \ell' \nu \bar{\nu}$
    - Neutrino oscillations: $\nu_\alpha \to \nu_\beta$

$$\pi^+ \to \mu^+ \bar{\nu}_\mu \quad \rightsquigarrow \quad \bar{\nu}_e p \to n\, e^-$$

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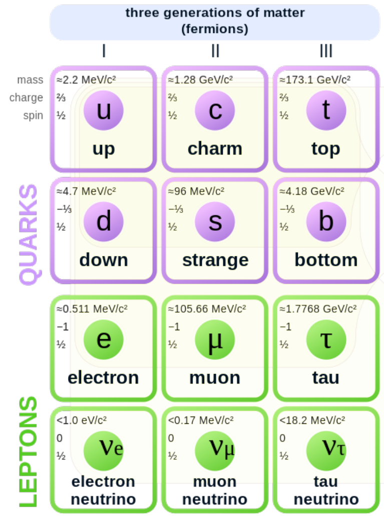

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- Even better → an observable that violates an EW symmetry: CP (electric dipole moments), B-L (proton decay), cLFV (μ→eγ)

  → Either NP is very far (??), or it has a SM-like structure (B, CP, …).
  In the 2nd case, precision experiments might find NP first.

BSM searches with low-E processes

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Precision EXP+TH

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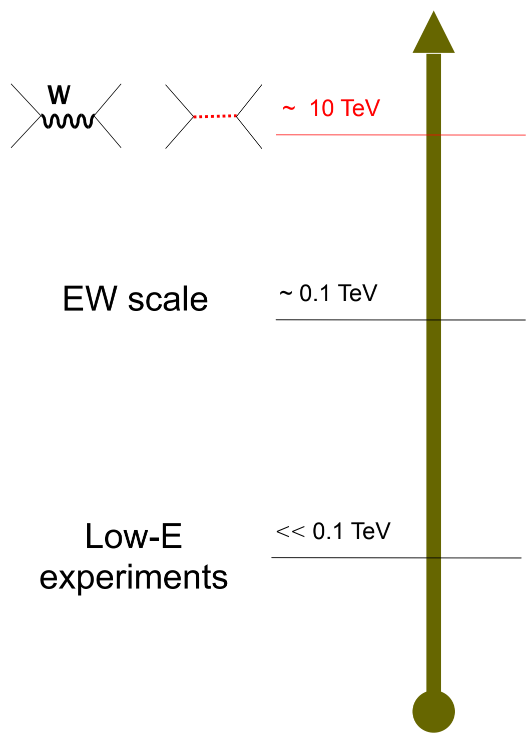
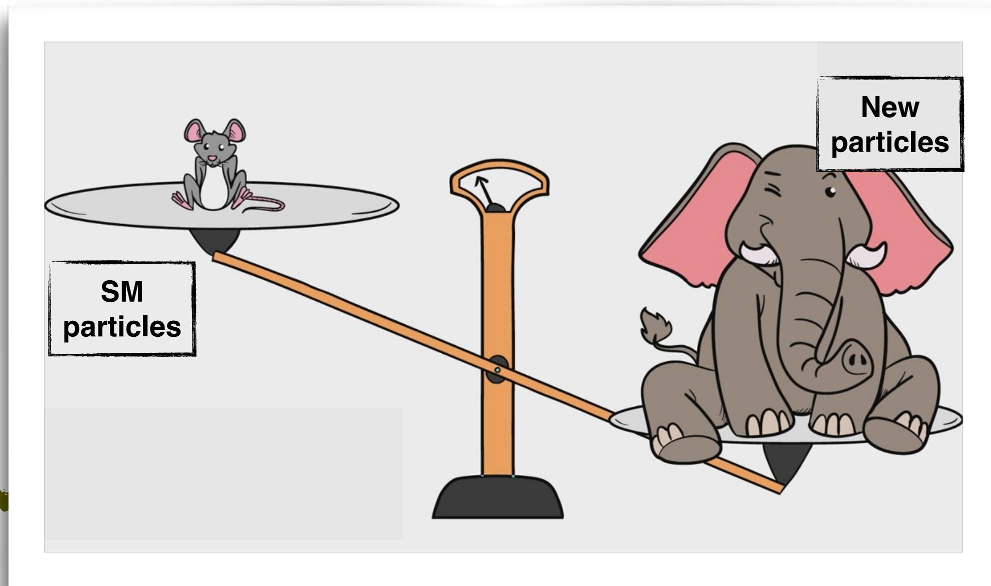
Analysing BSM searches

Theory?



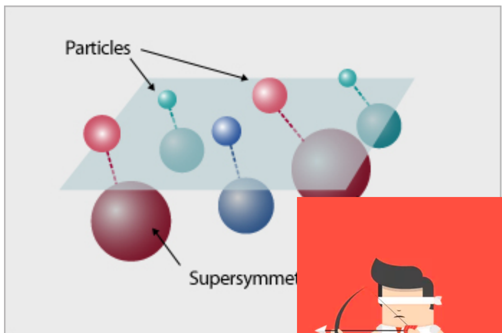
$$\mathscr{L}_{UV}(x) = \mathscr{L}(\varphi_{SM}, \Phi_{NP})$$

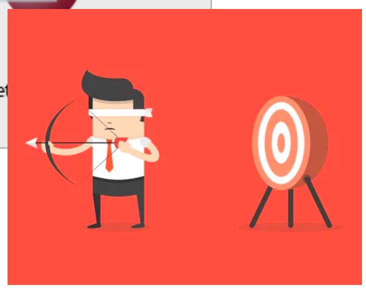


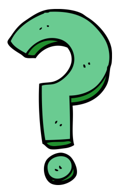
Analysing BSM searches

Specific BSM model

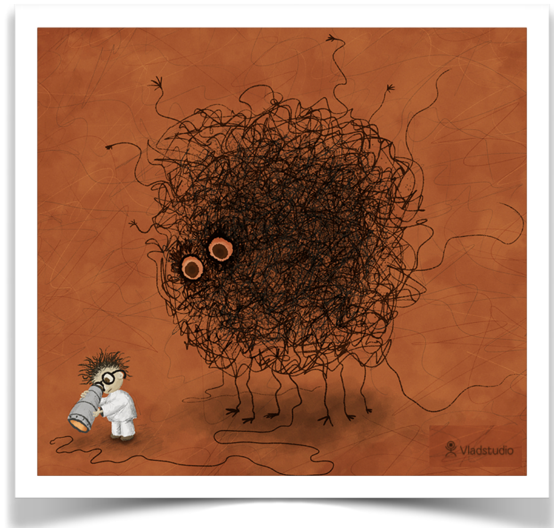
$$\mathscr{L}_{BSM} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$





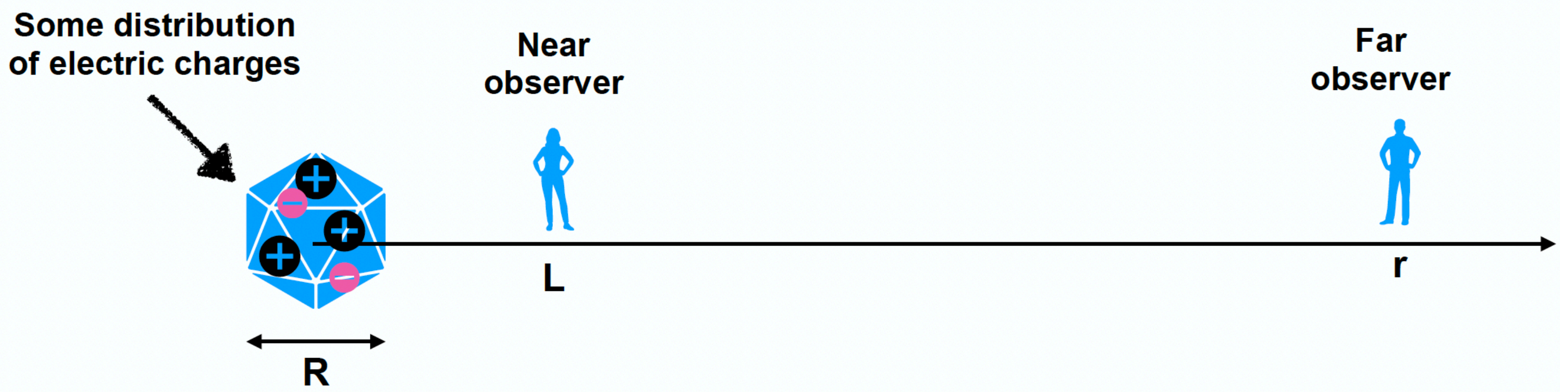


Effective Field Theory (EFT) approach



EFT detour

[A. Falkowski's CP2023 lectures]



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: $$V(\vec{r}) = \frac{Q}{r} + \frac{\vec{d}\cdot\vec{r}}{r^3} + \frac{Q_{ij}r_ir_j}{r^5} + \ldots$$

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

$d_i \sim R$

$Q_{ij} \sim R^2$

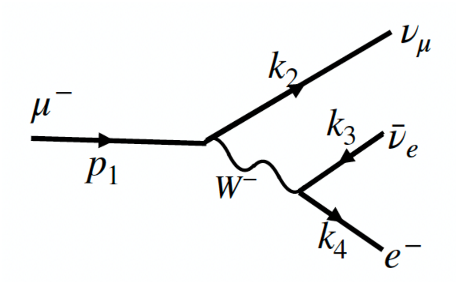
Higher order terms in the multipole expansion are suppressed by powers of the small parameter (R/r). One can truncate the expansion at some order depending on the value of (R/r) and experimental precision

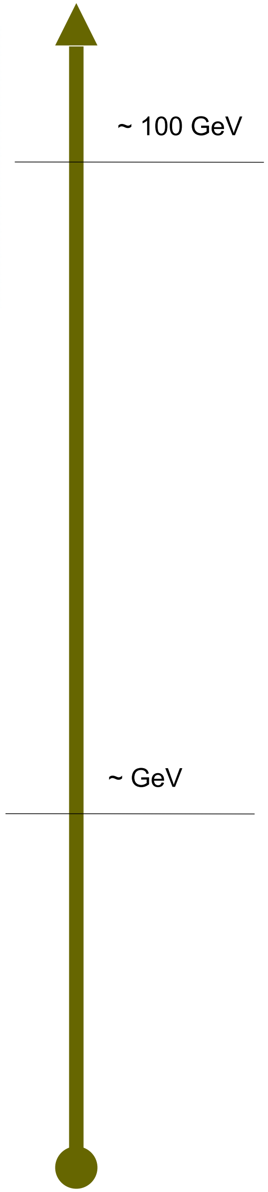
Far observer is able to describe electric field in his vicinity using just a few parameters: the total electric charge Q, the dipole moment $\vec{d}$, eventually the quadrupole moment Q_{ij}, etc....

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

Small distances ⟺ **High energies**

EFT detour: QFT example





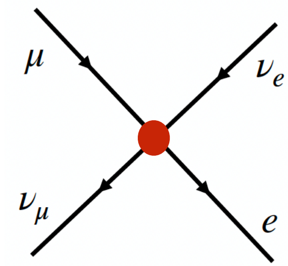
$\mathcal{L}_{SM}$ (EW theory)

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

$q = p_1 - k_2$

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

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

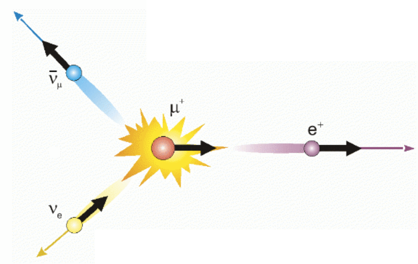


$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\,\mu$$

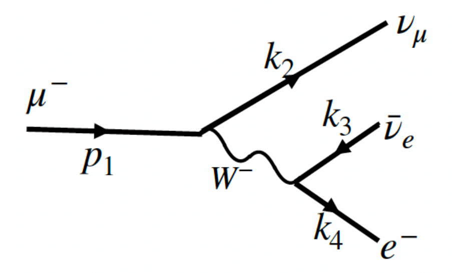
+ higher-dim terms

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

Wilson coefficient



EFT detour: QFT example



~ 100 GeV

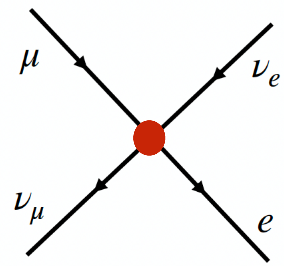
$\mathcal{L}_{SM}$ (EW theory)

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

$q = p_1 - k_2$

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

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



~ GeV

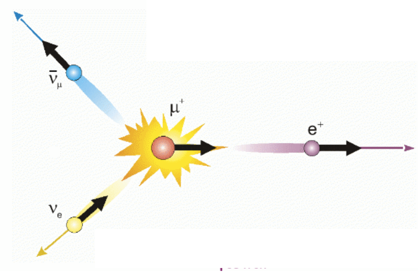
$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu\,(1-\gamma_5)\,\mu$$

+ *higher-dim terms*

Historically the logic was quite different:
Data → Fermi EFT → SM

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

Wilson coefficient



EFT detour

Known theory at high-E

↓

EFT at low-E

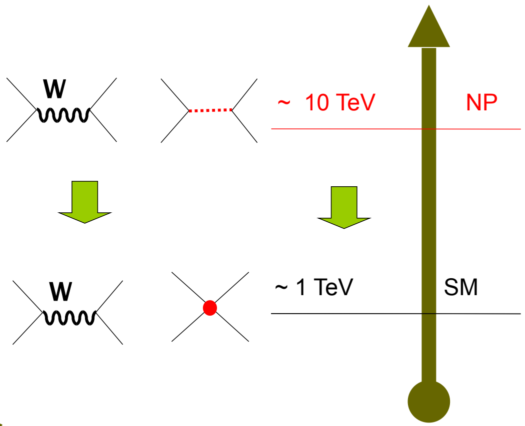
EFT that includes high-E effects

↑

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

EFT at the EW scale: SM → SMEFT

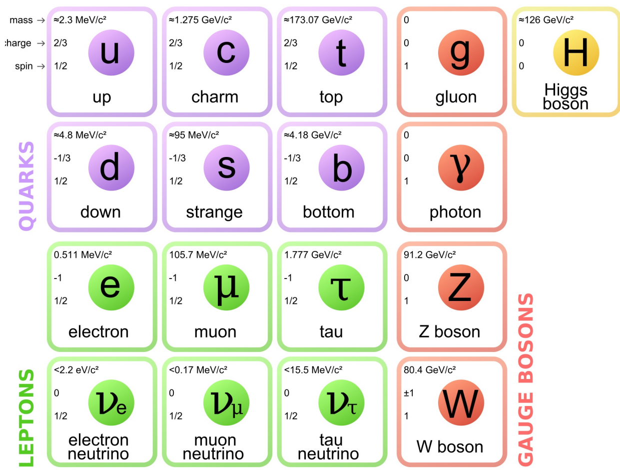


$$\mathcal{L}^{TeV}(x) = \mathcal{L}(\text{SM-fields, bSM-fields})$$

$$\mathcal{L}_{eff}(x) = \sum_i C_i \mathcal{O}_i$$

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

EFT = Model-independent approach ≠ Assumption independent



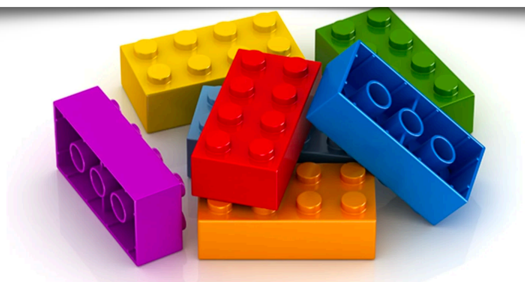
1. QFT (Lorentz inv.)
2. SM fields + gap: NP scale >> EW scale.
3. SU(3)xSU(2)xU(1) gauge symmetry

Building the SMEFT

Building blocks:

$G^a_\mu \; , \; W^k_\mu \; , \; B_\mu \; , \; q \; , \; u \; , \; d \; , \; \ell \; , \; e \; , \; \varphi$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Spin
G^a_μ	**8**	**1**	0	1
W^k_μ	**1**	**3**	0	1
B_μ	**1**	**1**	0	1
Q	**3**	**2**	1/6	1/2
u	**3**	**1**	2/3	1/2
d	**3**	**1**	-1/3	1/2
L	**1**	**2**	$-1/2$	1/2
e	**1**	**1**	-1	1/2
H	**1**	**2**	1/2	0



Rules

$$SU(3)c \times SU(2)_L \times U(1)_Y$$

$$\mathscr{L} = \sum_i C_i \, \mathscr{O}_i \left(\phi_j, D_\mu \phi_k \right)$$

Example: $\mathscr{L} = C \, \left(\varphi^\dagger \varphi \right)^3$

Building the SMEFT

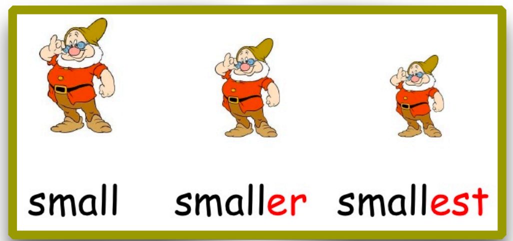
There are infinite gauge-invariant terms.
But that's OK because there's a well-defined expansion:

- Take an operator (=interaction term) $\mathcal{O}_D$ of dimension D.

- Since $[\mathcal{L}] = E^4 \;\rightarrow\; \mathcal{L} \supset C_D\,\mathcal{O}_D$ where $[C_D] \sim \dfrac{1}{\Lambda^{4-D}}$

- Its contribution to a (dimensionless) amplitude associated to a process with E>>m

$$\mathcal{M} \sim C_D\, E^{D-4} \sim \left(\frac{E}{\Lambda}\right)^{D-4}$$



- Thus, for E << Λ:
  a D=5 term gives a larger contribution than a D=6 one,
  a D=6 term gives a larger contribution than a D=7 one,
  and so on.

- For a given precision, we only need a finite amount of terms: $\mathcal{L} = \mathcal{L}_{D\leq 4} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots$

- This power counting allows us to define SMEFT at the quantum level
  (the SMEFT is renormalizable at a any finite order in the EFT expansion)

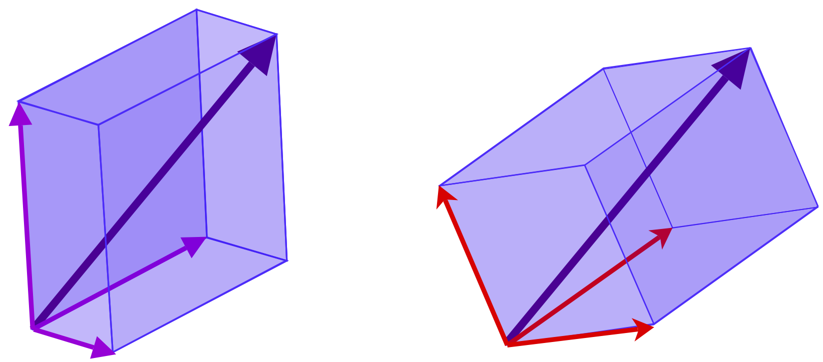
Building the SMEFT

$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

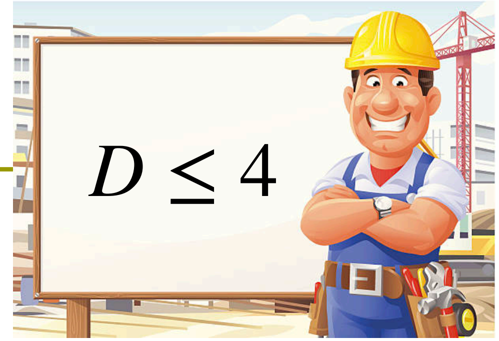
$$\mathscr{L}_6 = \sum_i C_6^i \, \mathscr{O}_6^i$$

Complete (and minimal) set of operators → "Basis"

- Finding a minimal set of operators is a subtle business.
  - It's not just (O_1, O_2) vs (O_1+O_2, O_1-O_2). Operators can be related through integration by parts, Fierz transformation and field redefinitions.
  - Solved recently [Grzadkowski et al. 1008.4884; Lehman-Martin 1510.00372; Henning et al. 1512.03433; Li et al. 2201.04639; ...]
- Any physical result will be independent of the basis chosen.



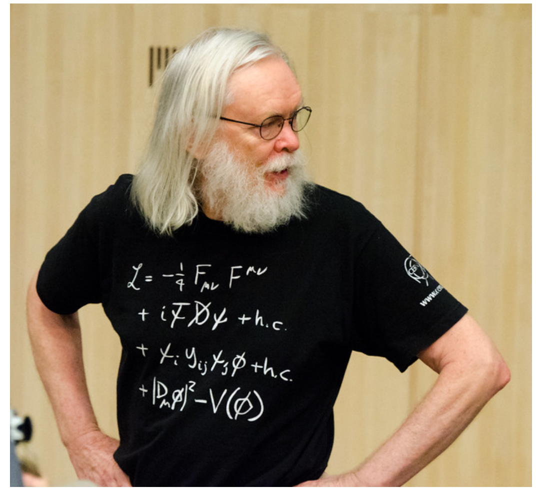
Building the SMEFT



$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- At $D \leq 4$ we find the SM

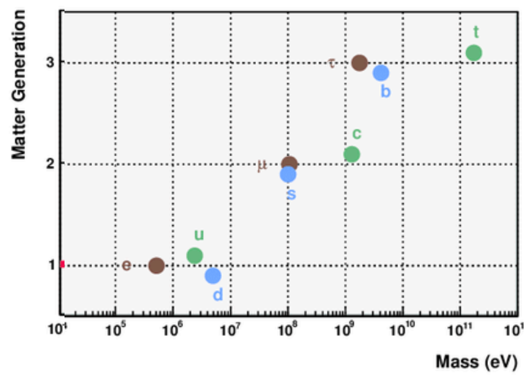
$$\mathscr{L}_{SM} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^{k\mu\nu} W^k_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$
$$+ i \sum_f \bar{f} D_\mu \gamma^\mu f$$
$$- \left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\, \varphi\, Y_d\, d + \bar{q}\, \tilde{\varphi}\, Y_u\, u \right) + h.c.$$
$$+ \left(D_\mu \varphi\right)^\dagger \left(D^\mu \varphi\right) - \mu^2 \left(\varphi^\dagger \varphi\right) - \lambda \left(\varphi^\dagger \varphi\right)^2$$



- All coefficients have been measured

  …except the theta term: $\mathscr{L}_{SM} \supset -\tilde{\theta}\, G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$

- Interaction size OK except:
  - $\mu = M_h \sqrt{2} \sim 100\,\mathrm{GeV} \ll \Lambda$ (??)
  - EFT predicts: $Y_f \sim \mathcal{O}(1) \;\rightarrow\; m_f \sim v, \;\; V_{ij} \sim \mathcal{O}(1)$



Building the SMEFT

$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- Only one operator (Weinberg'79)

$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p\right)^T C \left(\tilde{\varphi}^\dagger \ell_r\right) + h.c.$$

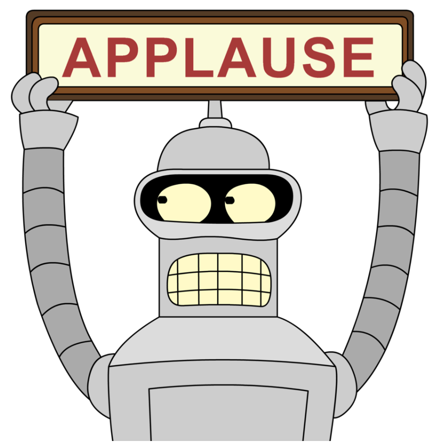
$$\tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix}$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

- After EWSB generates Majorana masses (for LH neutrinos):

$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_L^c \nu_L + h.c., \qquad \nu^c \equiv C\bar{\nu}^T$$

- Perfect! (neutrino oscillations → neutrino masses)
  Great success of the SMEFT approach: corrections to the SM Lagrangian predicted at 1st order in the EFT expansion, are indeed observed!



Building the SMEFT

$$\mathcal{L}_5 = \frac{[c_5]_{pr}}{\Lambda}\left(\tilde{\varphi}^\dagger \ell_p\right)^T C\left(\tilde{\varphi}^\dagger \ell_r\right) + h.c. \;\rightarrow\; m_\nu \sim 2\,c_5\,v^2/\Lambda$$

- Oscillation data → Δm^2.
  Other experiments (KATRIN!) /observations → bounds on m.
  All in all, m ~ O(0.01) eV. Thus:

$$v^2/\Lambda \sim 0.1 \text{ eV} \quad \rightarrow \quad \Lambda \sim 10^{15} \text{ GeV !!}$$

- The mass gap is certainly OK

- But then higher dimensional effects are then extremely suppressed
  (only hope: B-number violation)

$$\text{D} = 6 \;\rightarrow\; v^2/\Lambda^2 \sim 10^{-26} \text{ !!}$$

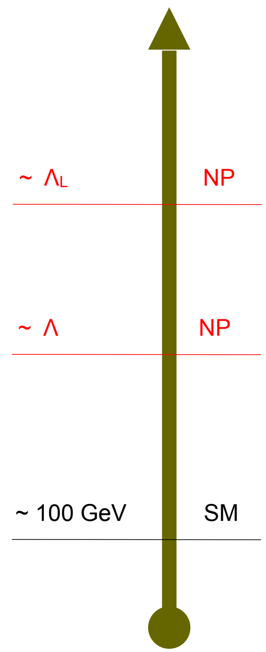
Building the SMEFT

$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda}\left(\tilde{\varphi}^\dagger \ell_p\right)^T C\left(\tilde{\varphi}^\dagger \ell_r\right) + h.c. \quad \rightarrow \quad m_\nu \sim 2\, c_5\, v^2/\Lambda$$

- Tiny neutrino masses point to huge NP scale: $\Lambda \sim 10^{15}$ GeV →

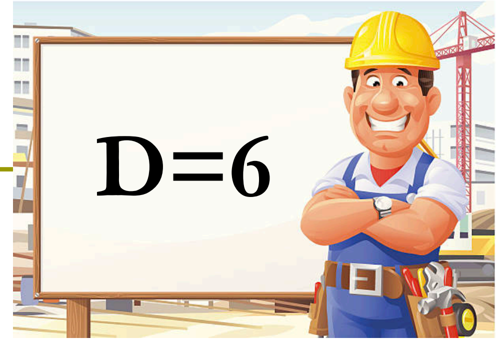
- Alternative:
  It's possible (and even natural) that there's more than one NP scale.
  This is not arbitrary since D=5 is "special": it violates B-L
  - A very high scale Λ_L associated to B-L violating physics (D=5, 7, …)
  - A (hopefully) not so high scale, Λ, associated to B-L conserving physics (D=6, 8, …)

$$\mathscr{L}_{D=5} \sim \frac{1}{\Lambda_L},\ \mathscr{L}_{D=6} \sim \frac{1}{\Lambda^2},\ \mathscr{L}_{D=7} \sim \frac{1}{\Lambda_L^3},\ \mathscr{L}_{D=8} \sim \frac{1}{\Lambda^4},$$ **and so on**



- PS: Outside the SMEFT paradigm there are other explanations for m_ν
  E.g., SM + ν_R → one has D=3 Majorana & D=4 yukawas (→ Dirac mass).

Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- First B-L conserving corrections to the SM.
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p \gamma^\mu d_r)$

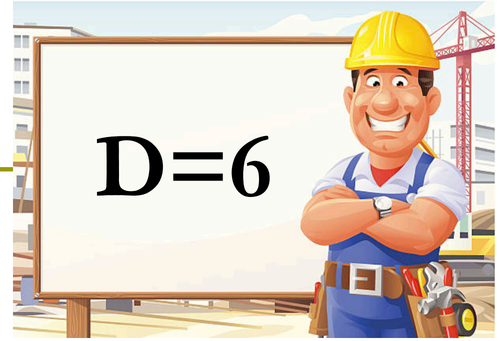
Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Table 3: Four-fermion operators.

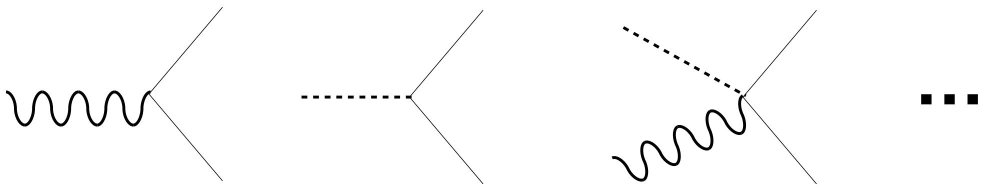
Building the SMEFT

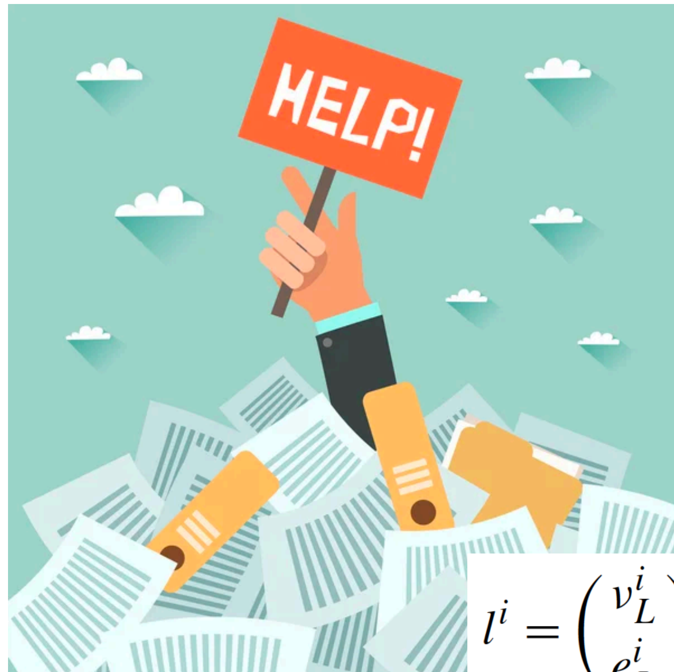


$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- First B-L conserving corrections to the SM.
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

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



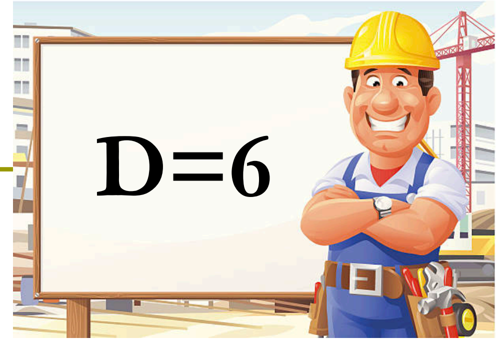


$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

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

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

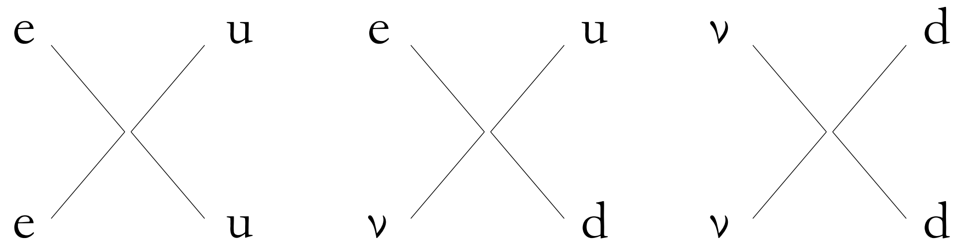
Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- First B-L conserving corrections to the SM.
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

$$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$



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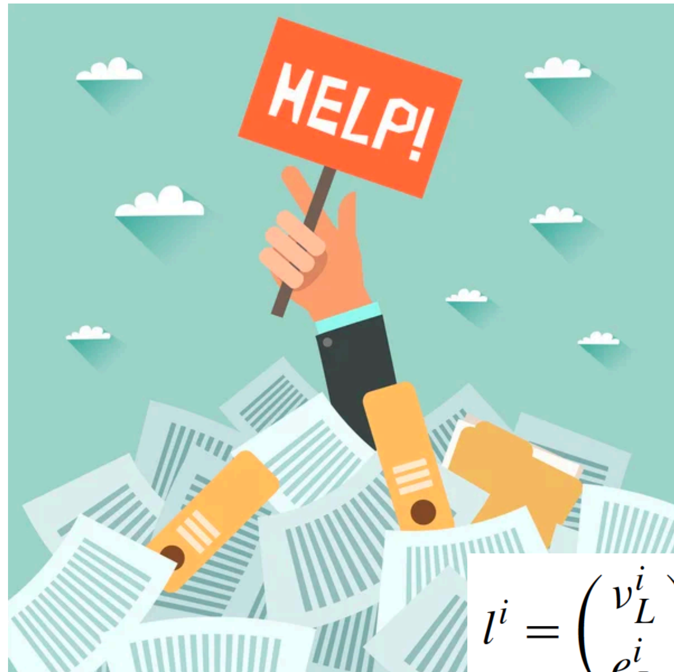
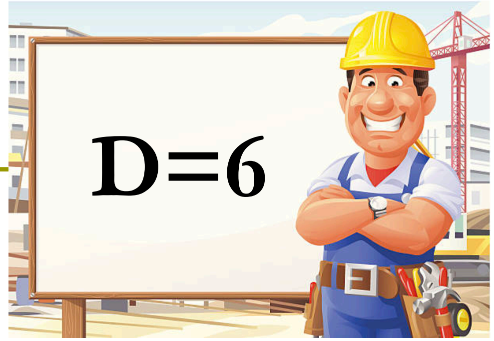


$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

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

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

Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- First B-L conserving corrections to the SM.

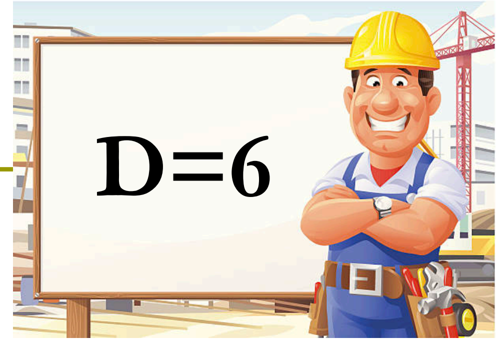
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure $\rightarrow$ 3045 coefficients

- Extremely rich phenomenology:
  colliders,
  flavor,
  low-energy searches,
  neutrino physics,
  proton decay,
  CP violation,
  …

- All results compatible with zero $\rightarrow$ Bounds on Λ

$$\left(\mathscr{L} \supset \frac{1}{\Lambda^2} \mathcal{O}_6 \right)$$

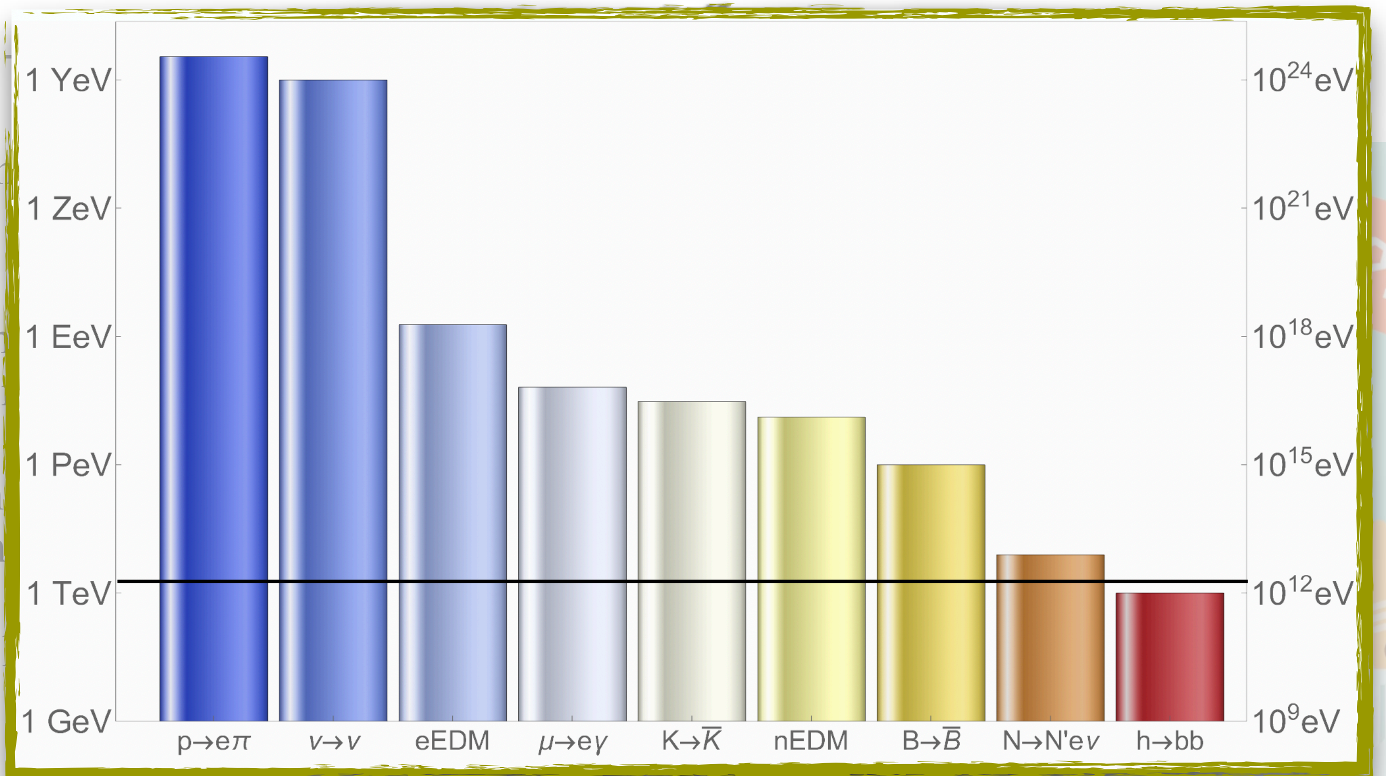
Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

[A. Falkowski, Eur.Phys.J.C 83 (2023) 7, 656]

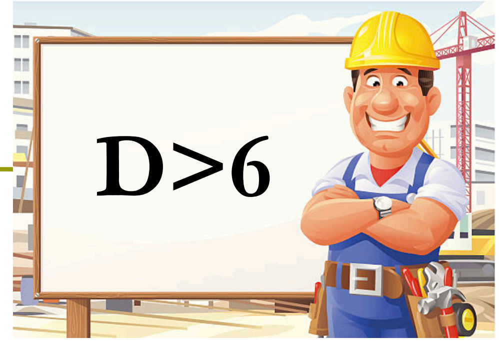
- First B
- One fi
  Flavor
- Extrem
  collide
  flavor,
  low-en
  neutrin
  proton
  CP vio
  …



- All results compatible with zero → Bounds on Λ

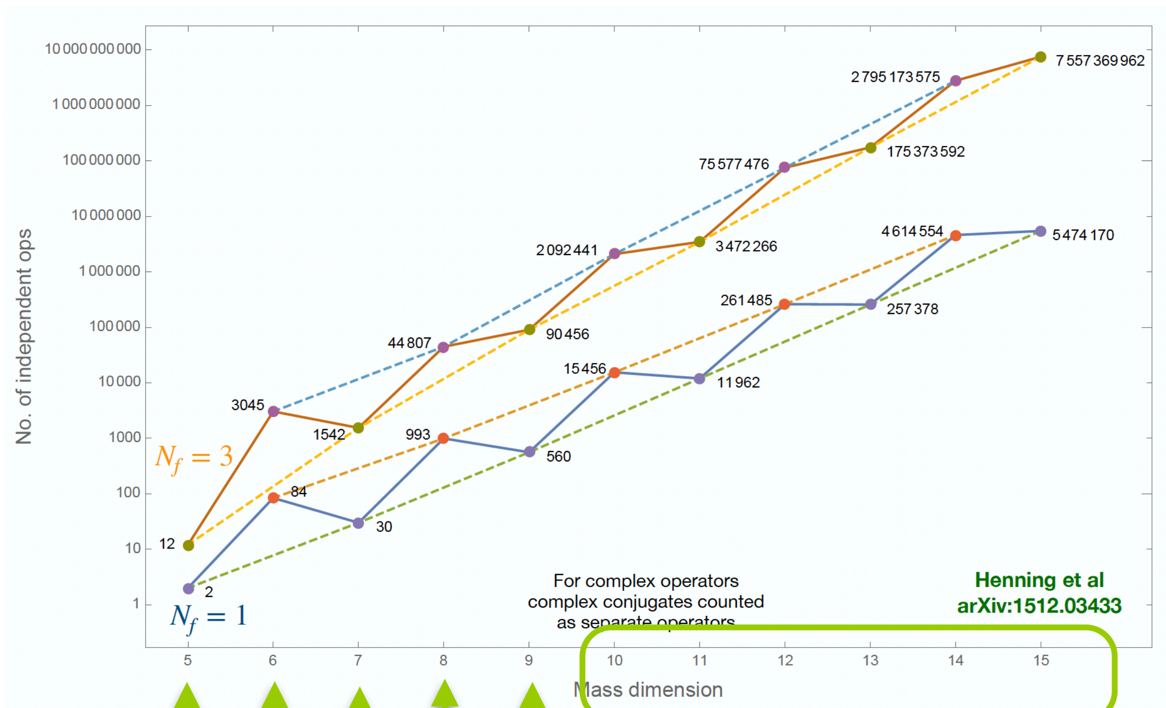
$$\left(\mathscr{L} \supset \frac{1}{\Lambda^2} \mathscr{O}_6 \right)$$

Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- At dim-6 is where all the fun starts, but it's also where it ends



Exponential growth with D

Weinberg'79

Grzadkowski et al.'10

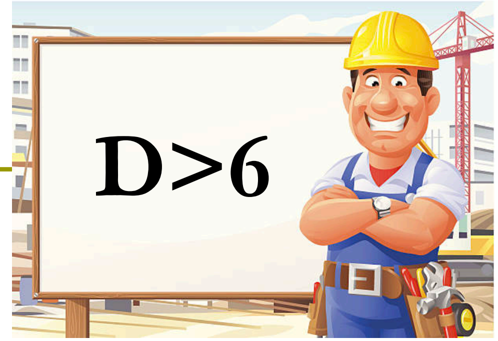
Lehman'14

Li et al.'20

Li et al.'21

Li et al'22
(Code valid at any dimension)

Building the SMEFT

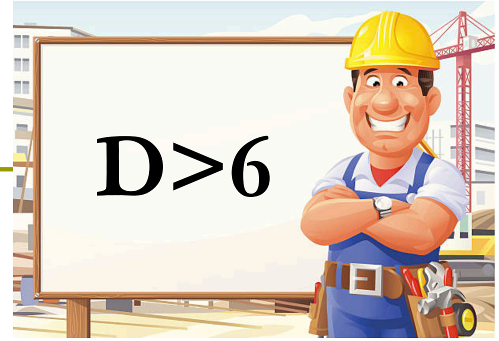


$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- At dim-6 is where all the fun starts, but it's also where it ends
  - Really too many operators
  - For D=7, 9, … the effect is expected to be tiny
  - For D=8, 10, … not easy to imagine situations where terms that are so suppressed (if the EFT works) give measurable effects in observable X whereas all D=6 terms do not give measurable effects in so many other observables.

- A few processes receive their first tree-level correction at D>6:
  light-by-light scattering (dim-8), neutron-antineutron oscillation (dim-9), …
  Depending on the mass gap, they could compete w/ loop effects from lower-dim. operators.

Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- It's crucial to keep in mind that these operators exist.
  E.g. (dim-6)^2 vs dim-8 contributions (validity of the EFT expansion)

- Let's think in a (non-forbidden) low-E process (E<<v):

$$\mathscr{M} = \mathscr{M}_{SM}\left(1 \;+\; c_6\,\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \;+\; c_8\,\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) \;+\; \ldots\right)$$

$$|\mathscr{M}|^2 = |\mathscr{M}_{SM}|^2\left(1 \;+\; c_6\,\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \;+\; c_6^2\,\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) \;+\; c_8\,\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) \;+\; \ldots\right)$$

- One should *not* include quadratic terms
  (equivalently: results should not depend strongly on quadratic terms)

- The reasoning is the same for E~v or higher energies.

Building the SMEFT

$$\mathscr{L} = \mathscr{L}_{SM} + \text{Majorana neutrino masses} + \sum \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \ldots$$

Down the EFT stairs

Top down

Known theory at high-E

↓

EFT at low-E

Bottom up

EFT that includes high-E effects

SMEFT

↑

Low-E symmetries & fields

Down the EFT stairs

Top down

Known theory at high-E

SMEFT

↓

EFT at low-E

Low-energy (~GeV) EFT (LEFT)

Bottom up

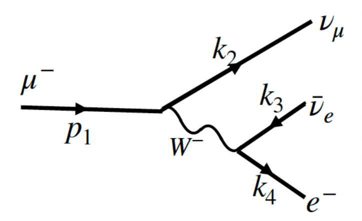
EFT that includes high-E effects

SMEFT

↑

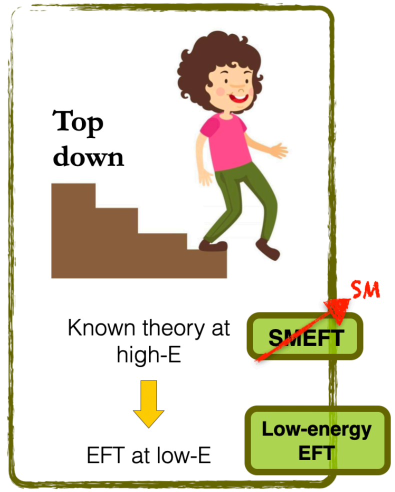
Low-E symmetries & fields

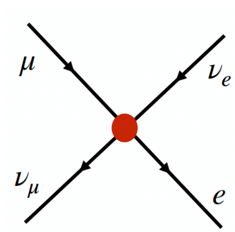
Down the EFT stairs



~ 100 GeV

$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$





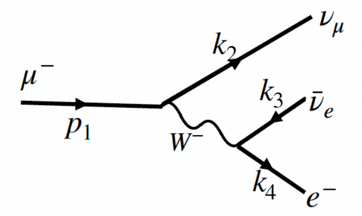
$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2}$$

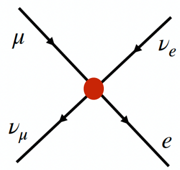
~ GeV

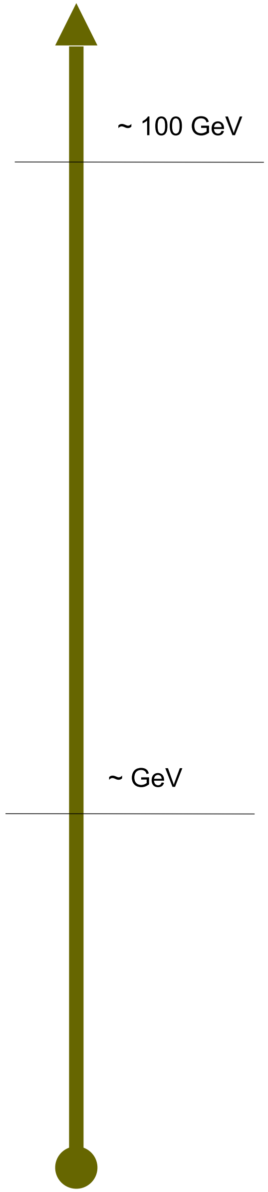
$$\mathscr{L}_{eff} = -\frac{4G_F}{\sqrt{2}} \bar{e}\, \gamma_\mu (1-\gamma_5)\, \nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\, \mu$$

+ higher-dim terms

Down the EFT stairs

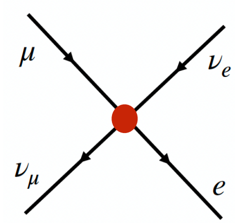






$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$

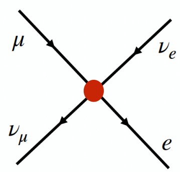
$$+ \frac{c_5}{\Lambda}\mathcal{O}_5 + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \ldots$$



$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2} + f\left(\frac{c_6^i}{\Lambda^2}\right)$$

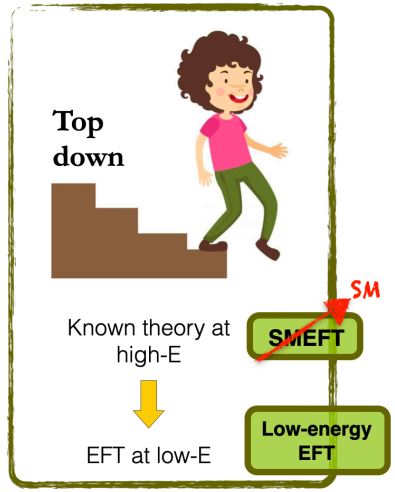
$$\mathscr{L}_{eff} = -\frac{4 G_F}{\sqrt{2}} \bar{e}\,\gamma_\mu (1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\,\mu$$

+ *higher-dim terms*

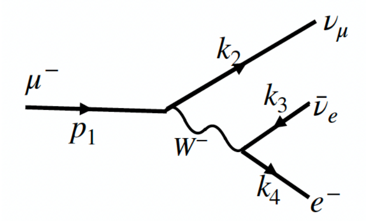


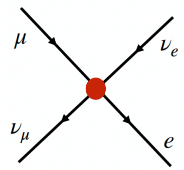
$$+ \frac{4\epsilon}{\sqrt{2}} \bar{e}\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu (1+\gamma_5)\,\mu$$

$$\epsilon = g\left(\frac{c_6^i}{\Lambda^2}\right)$$



Down the EFT stairs





~ 100 GeV

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{c_5}{\Lambda}\mathcal{O}_5 + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \dots$$

$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2} + f\left(\frac{c_6^i}{\Lambda^2}\right)$$

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

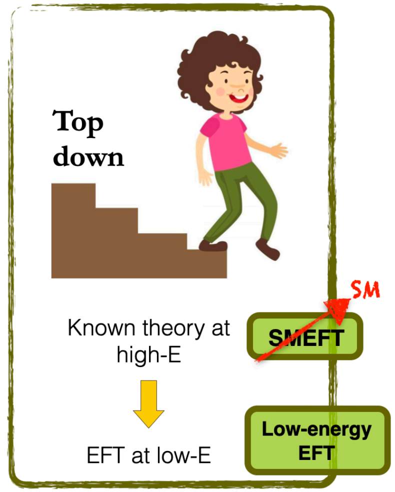
+ *higher-dim terms*

$$+\frac{4\epsilon}{\sqrt{2}}\bar{e}\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu (1+\gamma_5)\,\mu$$

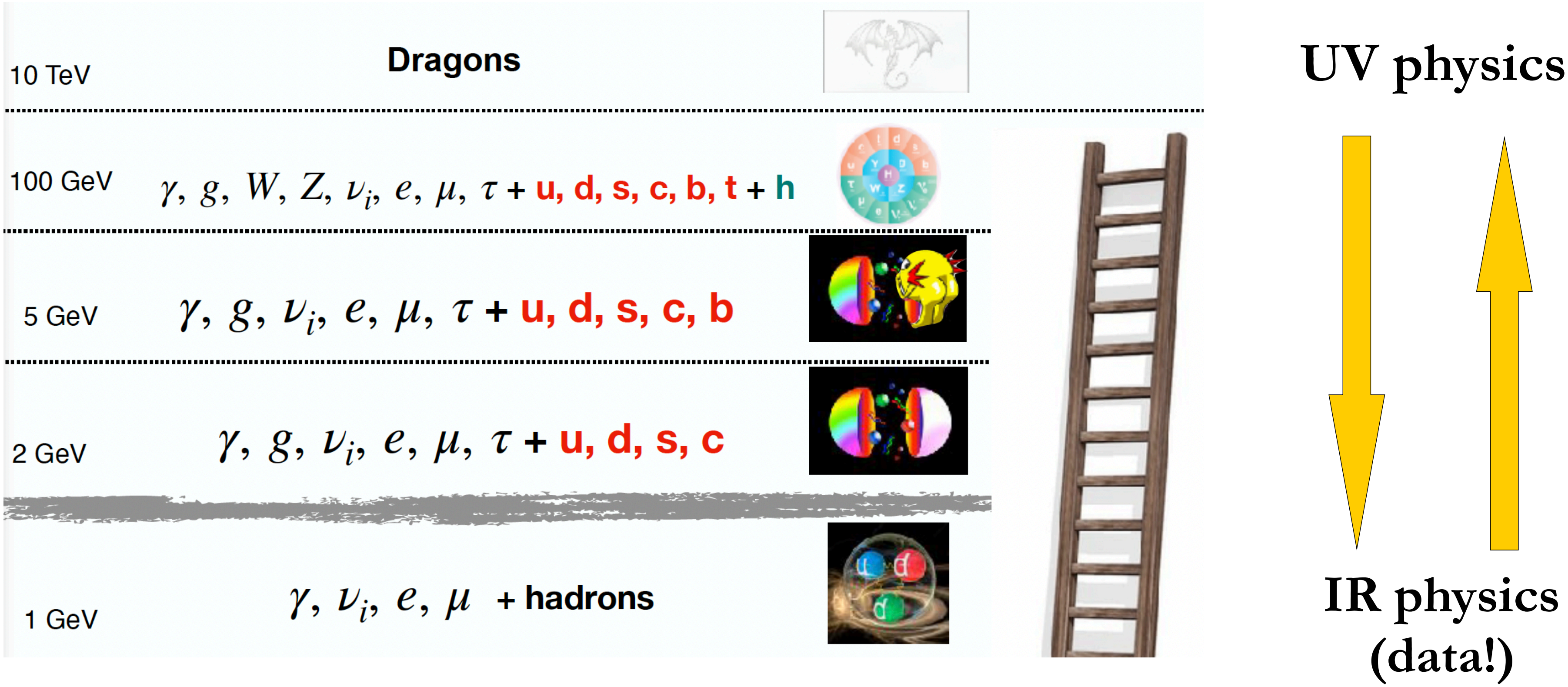
$$\epsilon = g\left(\frac{c_6^i}{\Lambda^2}\right)$$

The SMEFT has ~3K coefficients, but it generates only one new term to the muon decay low-energy EFT Lagrangian.

- Moreover this term can be neglected in most cases (contributions $\sim m_e/m_\mu$)



SMEFT → Low-energy EFT

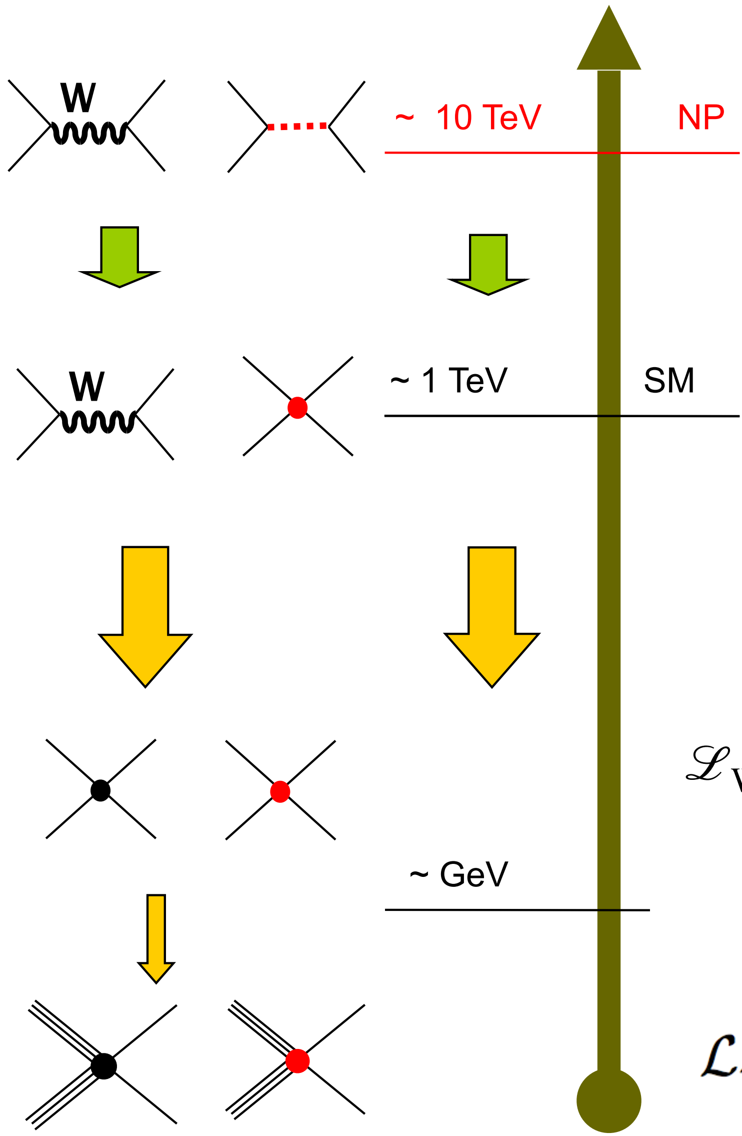


- Various names: LEFT, WEFT, WET, …
  - Variants: LEFT-5, LEFT-4, …

- In any case, the full LEFT (generated by the SMEFT) has of course many many terms. The matching between LEFT & SMEFT is known at 1-loop [Jenkins et al., 1709.04486; Dekens & Stoffer, 1908.05295].

- For concreteness, I'll focus on beta decays ($d \to ue\bar{\nu}$).

SMEFT → Beta-decay LEFT



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

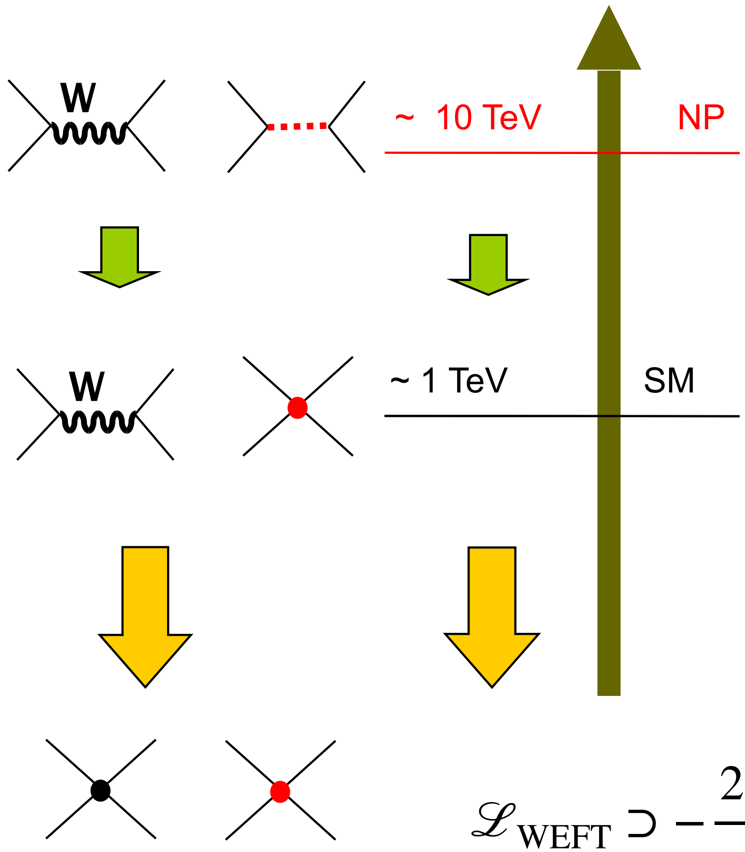
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathscr{O}_6^i + \ldots$$

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

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

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

SMEFT → Beta-decay LEFT



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

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

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\Big\},$$

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

SMEFT → Beta-decay LEFT

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

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$
$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$
$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\}\,,$$

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

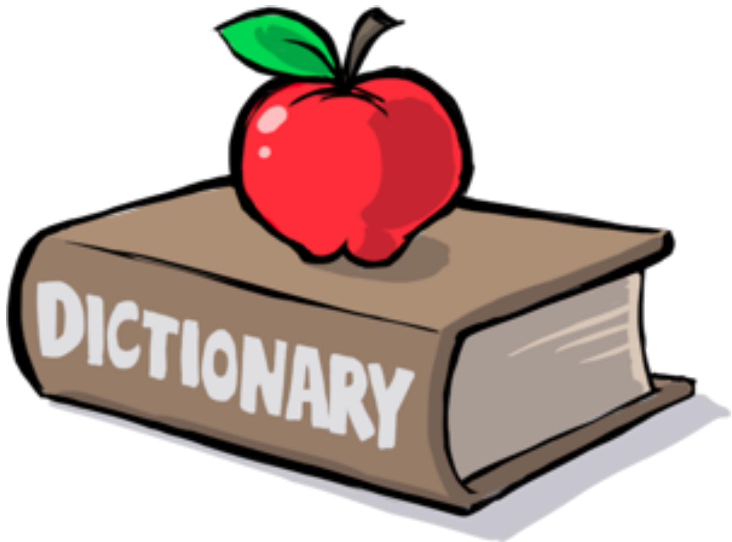
$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1}\,,$$

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



SMEFT → Beta-decay LEFT

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

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$
$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$
$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\Big\},$$

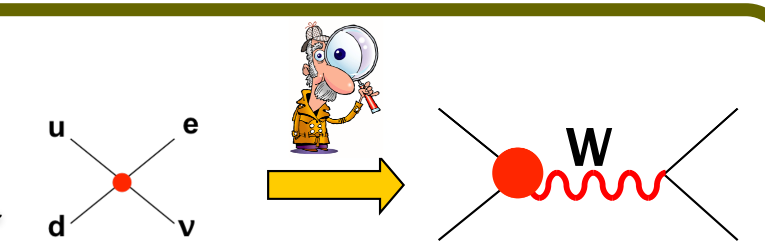
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\Big(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\Big),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\Big(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\Big),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\Big(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\Big),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]^*_{11j1},$$



$$\bar{e}_L\gamma_\mu\nu_L \cdot \bar{u}_R\gamma^\mu d_R \qquad i(\varphi^T\epsilon D_\mu\varphi)(\bar{u}\gamma^\mu d)$$

(V-A) x (V+A)

→ RH currents are lepton flavor universal! (SMEFT prediction)

SMEFT → Beta-decay LEFT

Reminder:

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

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

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$
$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$
$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\Big\},$$

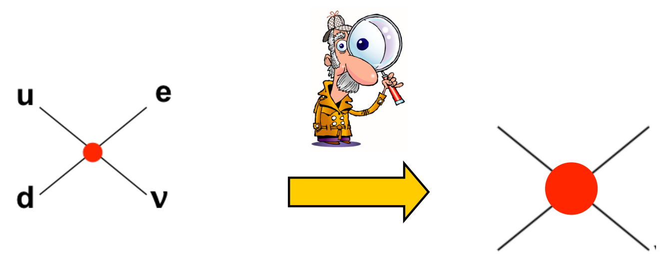
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

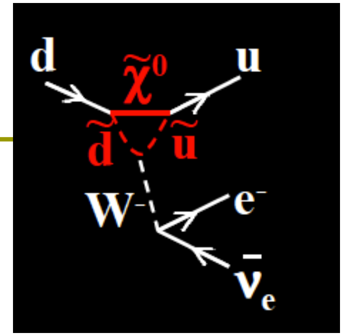
$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1},$$



S, P, T

$$(\bar{\ell}e)(\bar{d}q)$$
$$(\bar{\ell}_a e)\epsilon^{ab}(\bar{q}_b u)$$
$$(\bar{\ell}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u)$$

SMEFT → Beta-decay LEFT



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

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\{(1+\epsilon_L)(\bar u\gamma^\mu P_L d)(\bar e\gamma_\mu P_L\nu_e) + \epsilon_R(\bar u\gamma^\mu P_R d)(\bar e\gamma_\mu P_L\nu_e) + \frac{1}{2}\epsilon_S(\bar u d)(\bar e P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar u\gamma_5 d)(\bar e P_L\nu_e) + \frac{1}{4}\epsilon_T(\bar u\sigma^{\mu\nu}P_L d)(\bar e\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\}$$

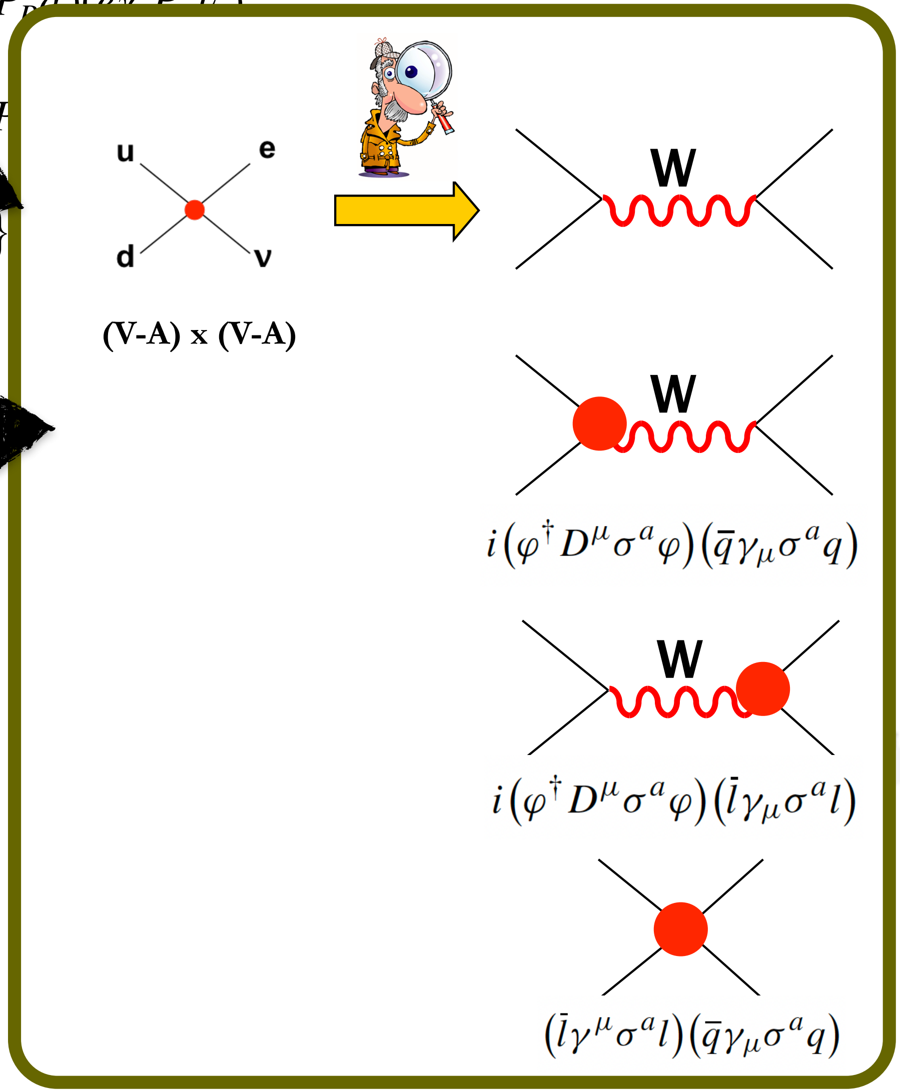
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

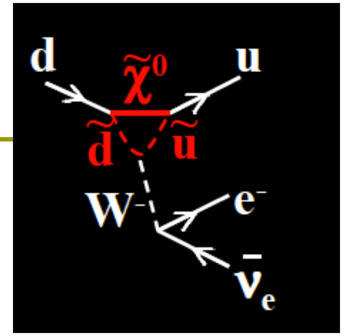
$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1}\ ,$$



SMEFT → Beta-decay LEFT



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

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar u\gamma^\mu P_L d)(\bar e\gamma_\mu P_L\nu_e) + \epsilon_R(\bar u\gamma^\mu P_R d)(\bar e\gamma_\mu P_L \nu_e)$$

$$+\frac{1}{2}\epsilon_S(\bar u d)(\bar e P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar u\gamma_5 d)(\bar e P \ldots$$

$$+\frac{1}{4}\epsilon_T(\bar u\sigma^{\mu\nu}P_L d)(\bar e\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\}$$

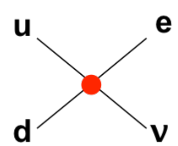
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\right),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

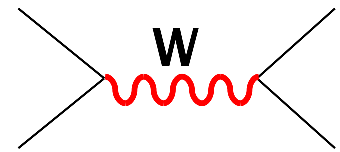
$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

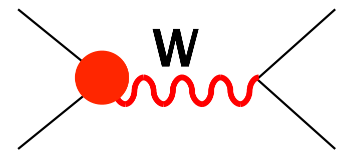
$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11\ldots} - [c_{\ldots}]^* \ldots\right)$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]^*_{11j\ldots}$$

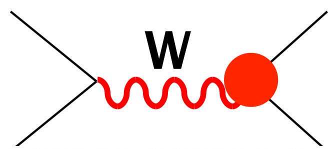


(V-A) x (V-A)

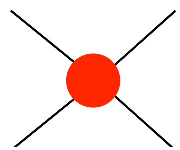




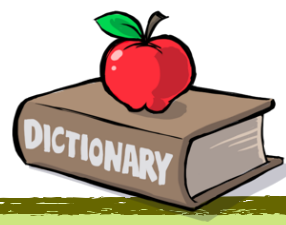
$i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar q\gamma_\mu\sigma^a q)$



$i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar l\gamma_\mu\sigma^a l)$



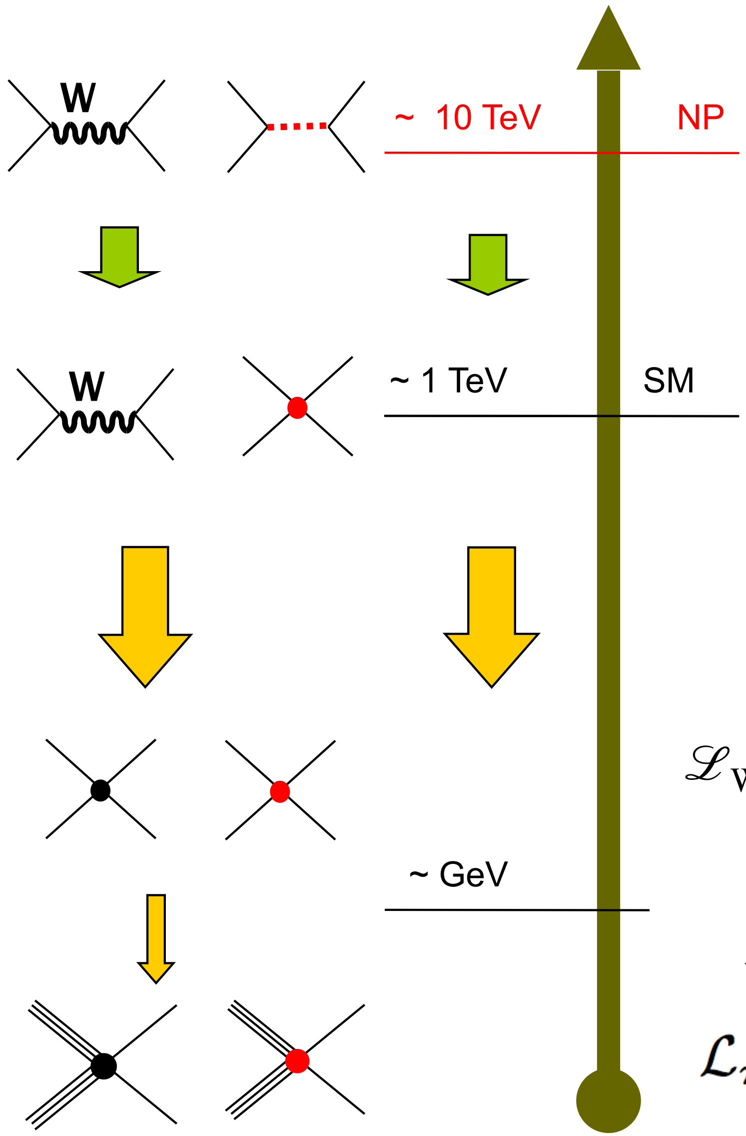
$(\bar l\gamma^\mu\sigma^a l)(\bar q\gamma_\mu\sigma^a q)$



This dictionary shows the interplay between:

- low-E and high-E searches
- CC ($d \to u e\bar\nu$) & NC ($e\,d \to e\,d$) low-E searches

LEFT from SMEFT



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

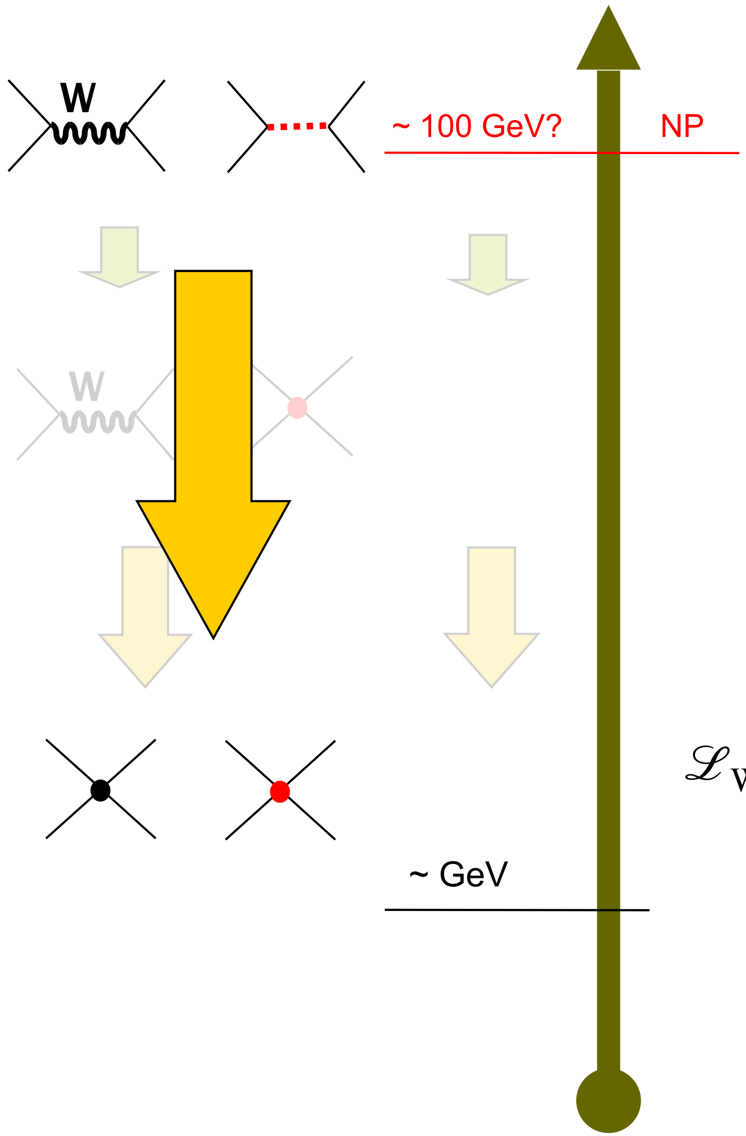
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathscr{O}_6^i + \ldots$$

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

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

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

LEFT ~~from~~ without SMEFT



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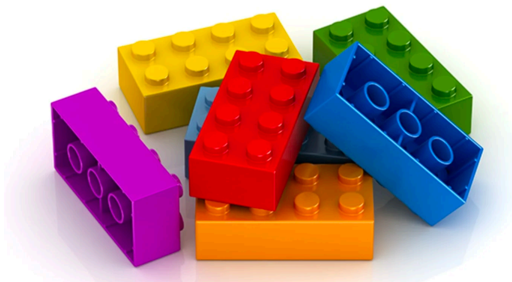
Building the LEFT

Building blocks:

$G^a_\mu\ ,\ A_\mu\ ,\ q^i_L\ ,\ q^i_R\ ,\ e^i_L\ ,\ e^i_R\ ,\ \nu^i_L$



Rules

$SU(3)c \times U(1)_{em}$

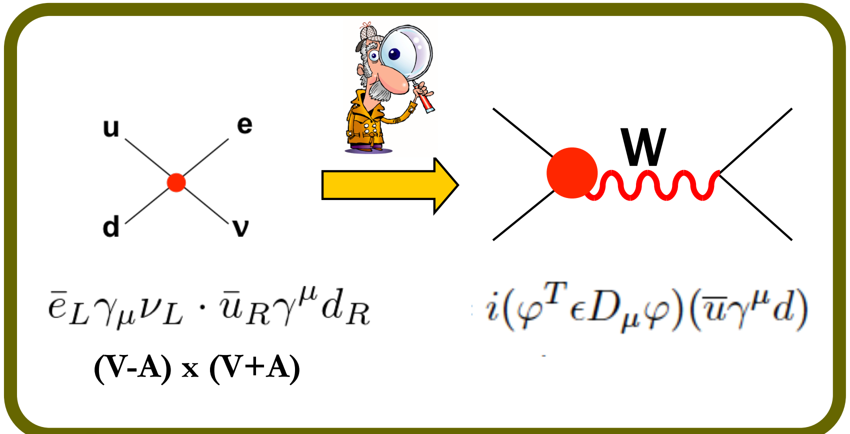
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

[Jenkins et al., 1709.04486]

Beta-decay LEFT (not necessarily from SMEFT)

$$
\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) \; + \; \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)
+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) \; - \; \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)
+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\} \, ,
$$

No new operators (SMEFT generates them all)*

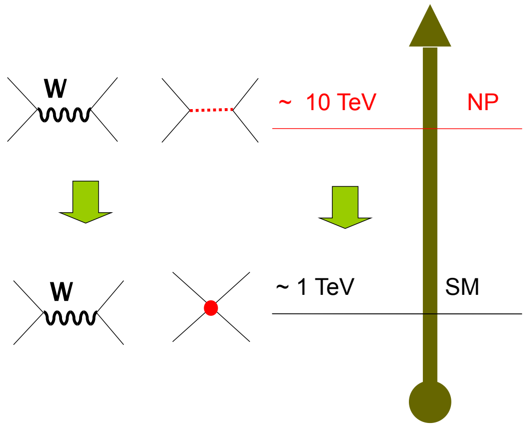


Not necessarily true anymore

~~*RH currents are lepton flavor universal!*~~
(SMEFT prediction)

*Not always the case. E.g., in b → s e⁺e⁻ some structures are forbidden!
[Alonso, Grinstein & Camalich'2014]

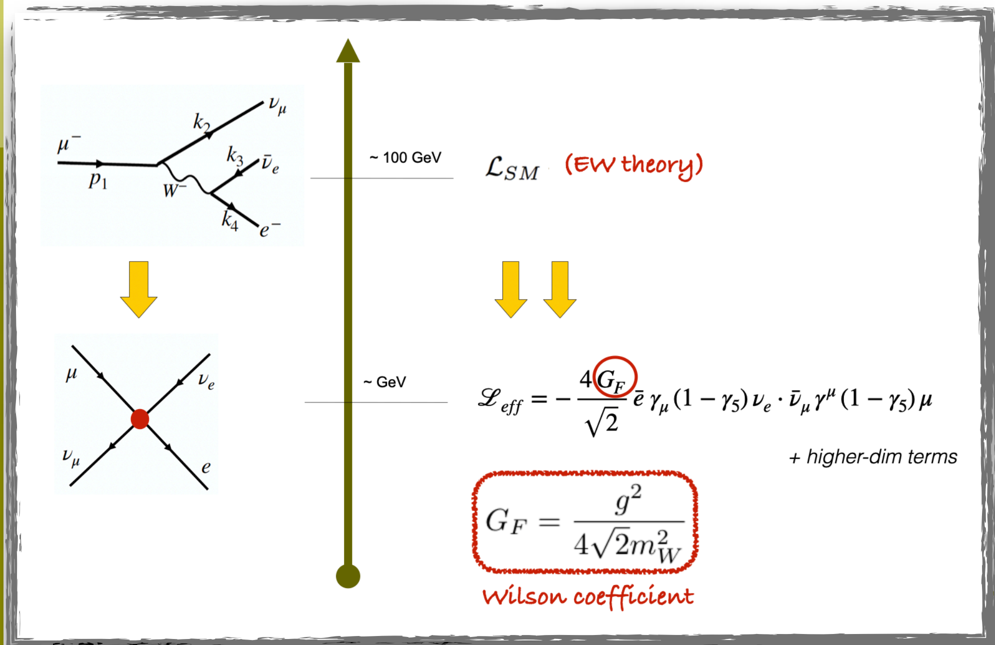
Matching to NP models

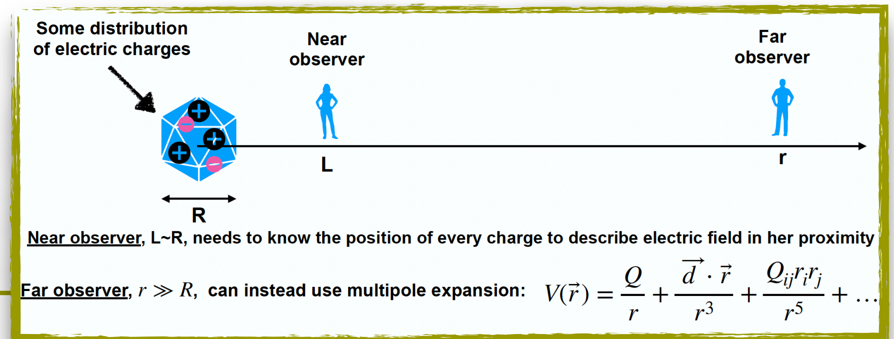


$$\mathscr{L}_{multi-TeV} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum C_6^i \mathcal{O}_6^i + \ldots$$

$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$





(SM)EFT phenomenology

(SM)EFT phenomenology

- First step: calculate observable X in the (SM)EFT:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i C_6^i O_6^i + \ldots \longrightarrow X = X_{SM} + \sum_i \alpha_i C_6^i + \ldots$$

- Sometimes it's trivial.
  Sometimes it's not:

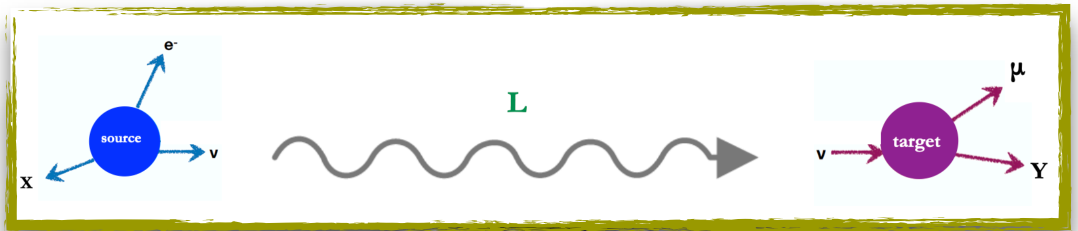
  - New quark currents? Hadrons? Nuclei?

  - "Indirect" BSM effects: $X = X_{SM}(V_{ud}) + 3C_6^{(13)}$
    One can't just take the value of V_{ud} from the PDG.
    More generally: $V_{ud} \rightarrow$ CKM, PMNS, FFs (FLAG), …

  - PDFs, cuts, correlations, FFs, EFT at 1 loop, consistent EFT expansion, …

  - Was the SM assumed to hold in the experimental analysis?

  - Other complications…



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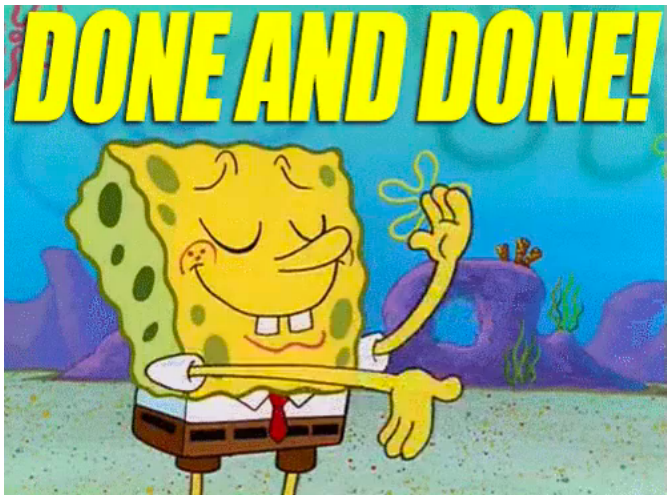
- Sometimes it's trivial.
  Sometimes it's not.

- But once it's done, it's done.
  (you don't have to do it for each model)



(SM)EFT phenomenology

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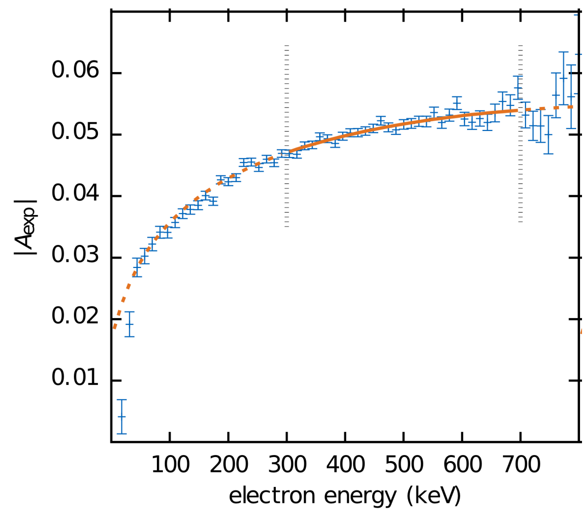
$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i C_6^i O_6^i + \ldots \longrightarrow X = X_{SM} + \sum_i \alpha_i C_6^i + \ldots$$

- Sometimes it's trivial.
  Sometimes it's not.

$$X_j = X_{j,SM} + \sum_i \alpha_{ij} C_6^i + \ldots$$



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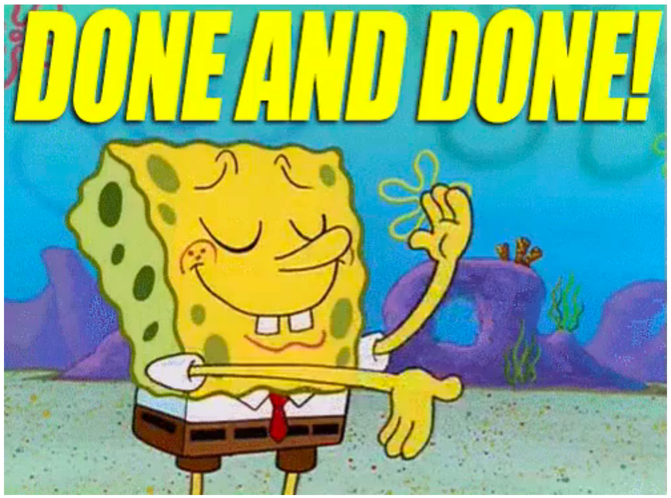
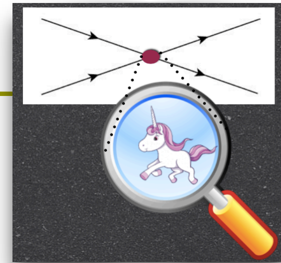


This approach gives us a model-indep. parametrization for the observable X

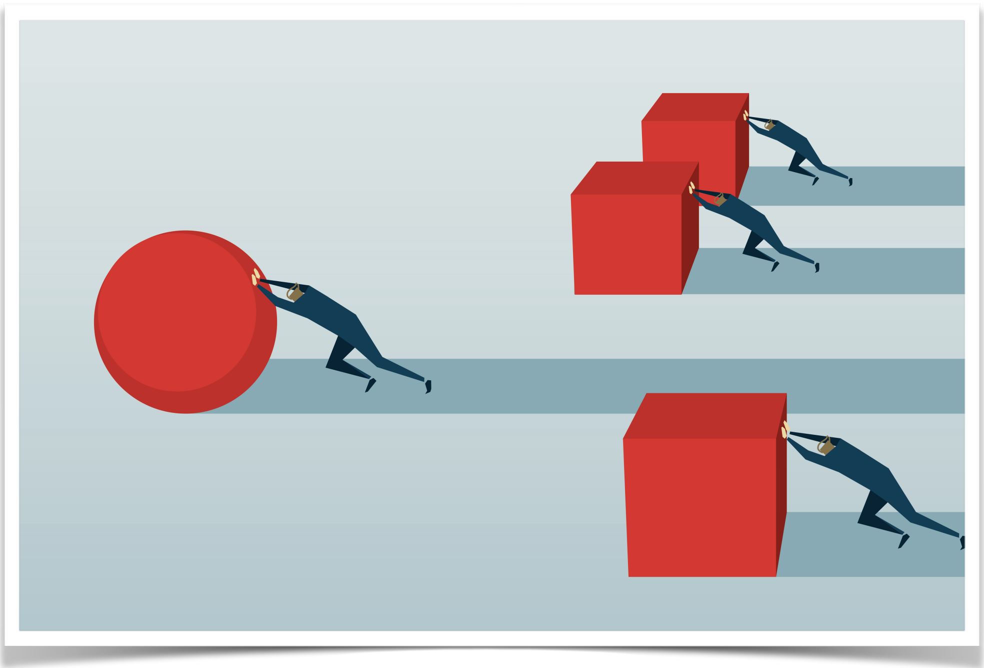
$$\frac{dX}{dE} = \left(\frac{dX}{dE}\right)_{SM} (1 + 2C_6^{13}) + \frac{m_e}{E_e} C_6^4$$

(SM)EFT phenomenology

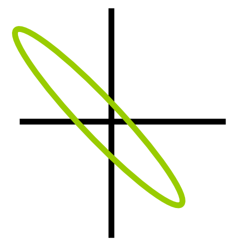


Measurement → **(Correlated) bounds on the EFT Wilson Coefficents** → **Matching with a specific NP model**

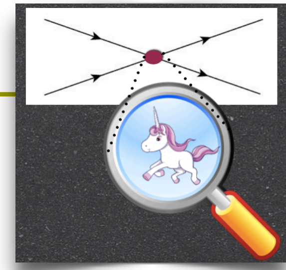
$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$



- Useful especially if…
  - Global analysis
  - Final likelihood public (correlation matrix!)
  - Avoid additional assumptions
- Valid also if NP is found!



(SM)EFT phenomenology



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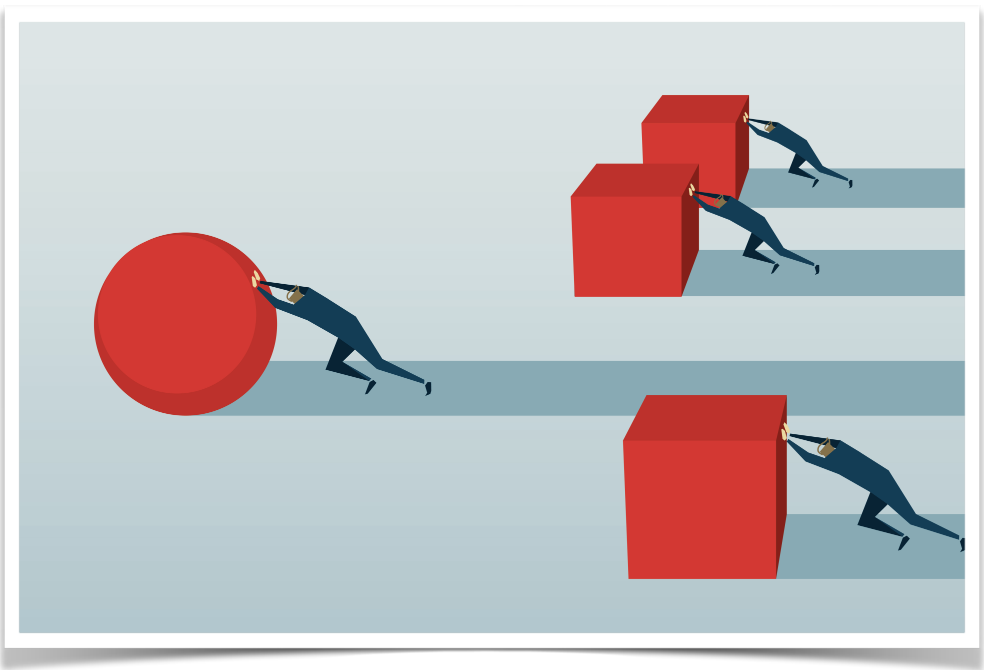
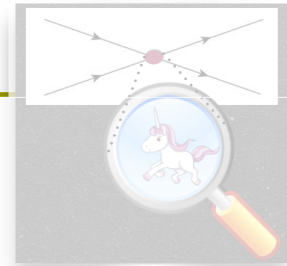


The EFT setup allows us to…

- Obtain results that can be applied to any given model later;
- Assess the interplay between processes (related by symmetries) in a general setup;

(SM)EFT phenomenology



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

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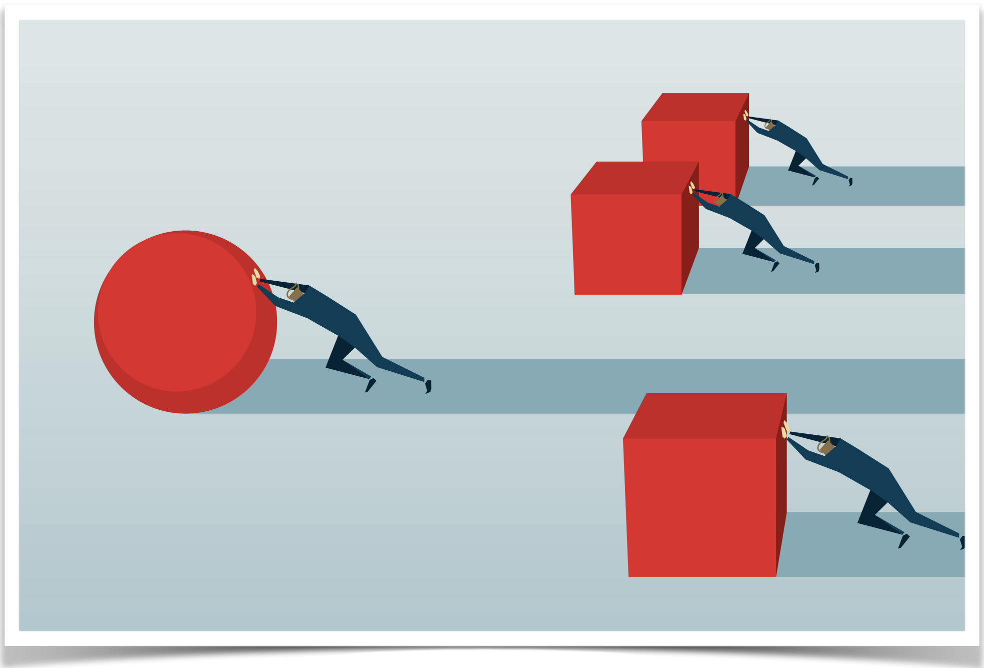


The EFT setup allows us to…

- Obtain results that can be applied to any given model later;
- Assess the interplay between processes (related by symmetries) in a general setup;

Comparing different probes

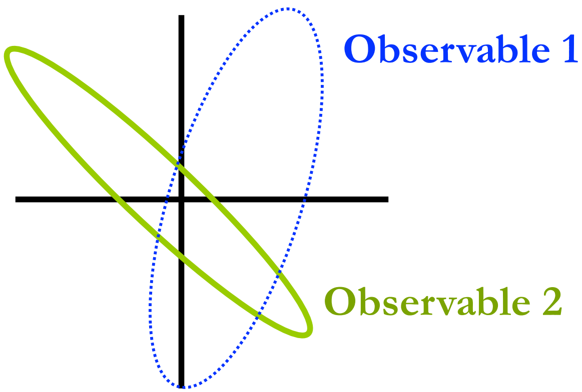
- Choose an operator basis $\{O_1, O_2, \ldots, O_n\}$, *e.g. the Warsaw basis*
  $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma\, C_i\, O_i$

- Calculate the observable you like in the EFT, *e.g.* $O = O_{SM} + 3C_1 - C_6$

- What are the known limits on the Wilson coeff.? *e.g. from LEP… C_1 =0.001(3), C_2=…, …*
  More precisely: χ^2 with (*LEP*) measurements gives you central values and error matrix.

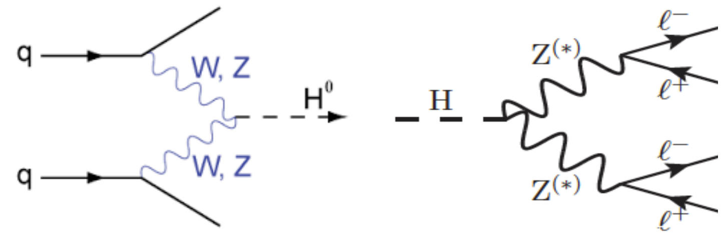
- Implications for your observable? *e.g. error matrix →* $3C_1 - C_6 = 0.02(4)$
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - If your sensitivity is better than that, you are exploring new SMEFT territory and your measurement should be added to the big fit.
  - A deviation larger than that indicates some wrong assumptions in your EFT!

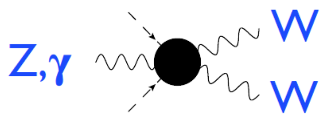
- Often we have a dataset (instead of a single data point O). The same logic applies, but it's often better to look at the (C_1 , C_6) space → example.



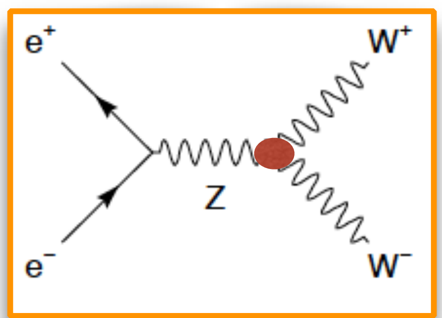
Comparing different probes

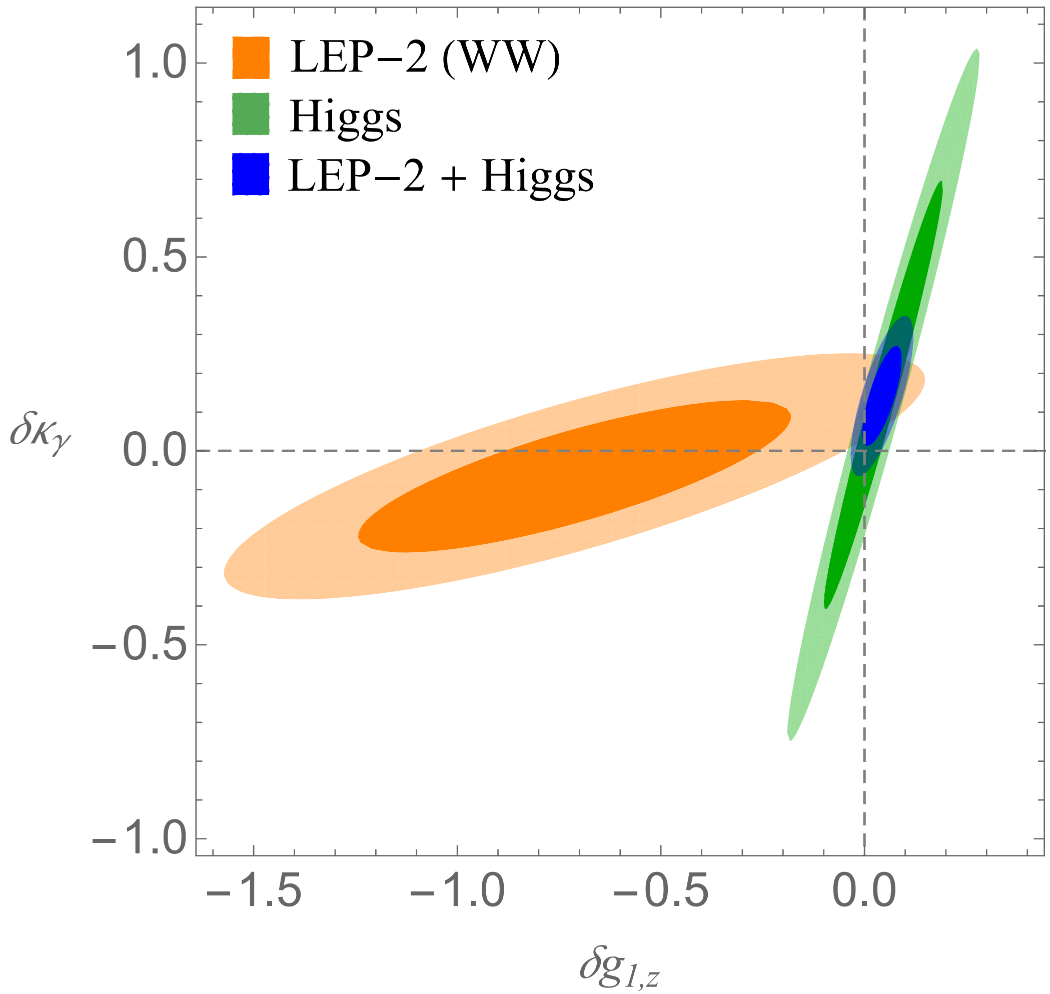
$$(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$





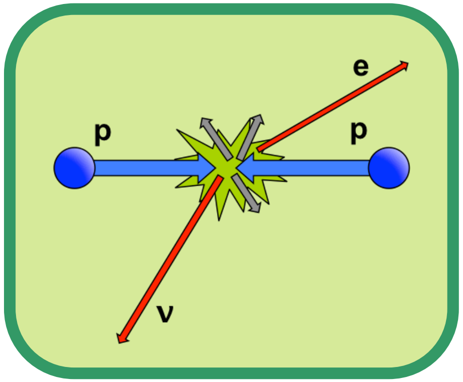
$e^+e^- \to W^+W^-$ (LEP2)

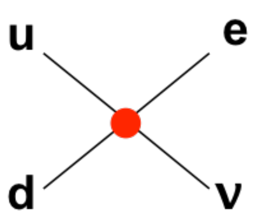


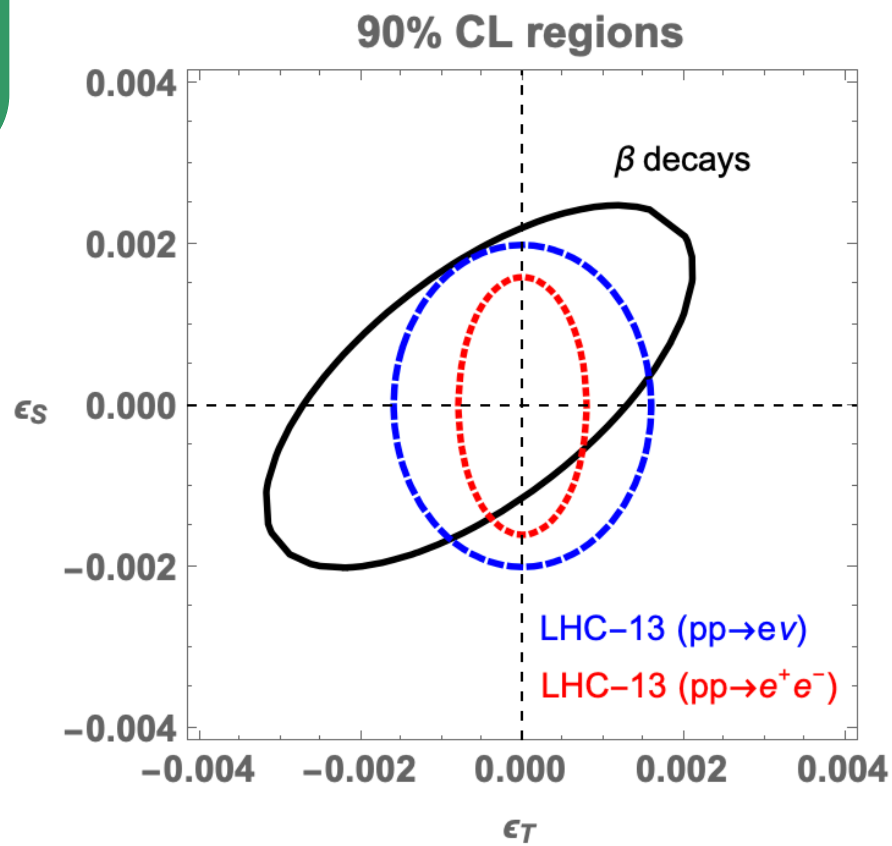


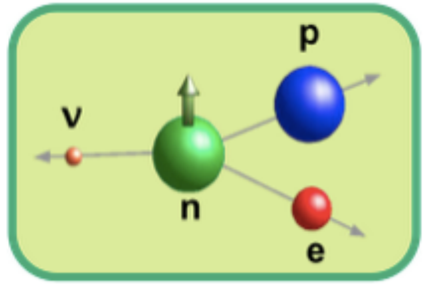
[Falkowski et al., 1508.00581]

Comparing different probes









[Falkowski et al, JHEP 04 (2021) 126]

[Gupta et al., PRD98 (2018)]

[Gupta et al., PRD98 (2018)]

[Cirigliano et al., 1210.4553]

Fitting room: global analyses

Measurement 1

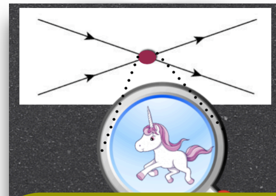
Measurement 2

…

Measurement N

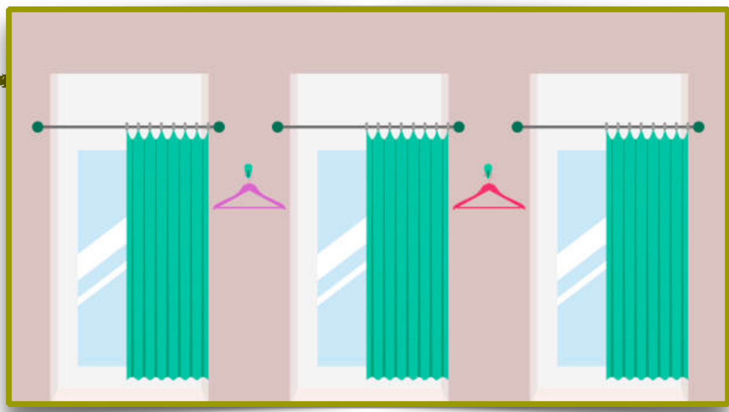
→ $\chi^2 = \chi^2(C_6^i)$

→ **(Correlated) bounds on the EFT Wilson Coefficients**

→ 

Specific NP model

$C_6^i = f\left(g_{NP}, M_{NP}\right)$

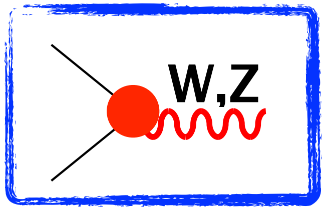


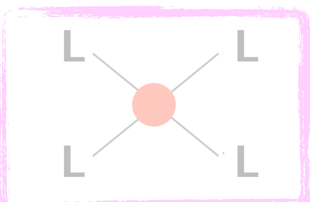
EFT fitting room

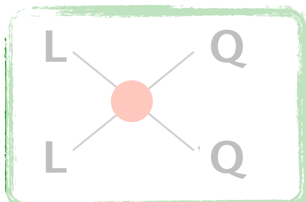
EWPO fit *in the flavorful SMEFT*

$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)$$

- 264 experimental input
  - Z- & W-pole data
  - [e⁺e⁻⟶l⁺l⁻, qq]
  - Low-energy processes:
    - hadron decays (d⟶ulν)
    - neutrino scattering
    - PV in atoms and in scattering
    - Leptonic tau decays
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]







		$\times 10^{-2}$
δg_L^{We}	-1.00 ± 0.64	
$\delta g_L^{W\mu}$	-1.36 ± 0.59	
$\delta g_L^{W\tau}$	1.95 ± 0.79	
δg_L^{Ze}	-0.023 ± 0.028	
$\delta g_L^{Z\mu}$	0.01 ± 0.12	
$\delta g_L^{Z\tau}$	0.018 ± 0.059	
δg_R^{Ze}	-0.033 ± 0.027	
$\delta g_R^{Z\mu}$	0.00 ± 0.14	
$\delta g_R^{Z\tau}$	0.042 ± 0.062	
δg_L^{Zu}	-0.8 ± 3.1	
δg_L^{Zc}	-0.15 ± 0.36	
δg_L^{Zt}	-0.3 ± 3.8	
δg_R^{Zu}	1.4 ± 5.1	
δg_R^{Zc}	-0.35 ± 0.53	
δg_L^{Zd}	-0.9 ± 4.4	
δg_L^{Zs}	0.9 ± 2.8	
δg_L^{Zb}	0.33 ± 0.17	
δg_R^{Zd}	3 ± 16	
δg_R^{Zs}	3.4 ± 4.9	
δg_R^{Zb}	2.30 ± 0.88	
δg_R^{Wq}	1.3 ± 1.7	
$[c_{\ell\ell}]_{1111}$	1.01 ± 0.38	
$[c_{\ell e}]_{1111}$	-0.22 ± 0.22	
$[c_{ee}]_{1111}$	0.20 ± 0.38	
$[c_{\ell\ell}]_{1221}$	-4.8 ± 1.6	
$[c_{\ell\ell}]_{1122}$	1.5 ± 2.1	
$[c_{\ell e}]_{1122}$	1.5 ± 2.2	
$[c_{\ell e}]_{2211}$	-1.4 ± 2.2	
$[c_{ee}]_{1122}$	3.4 ± 2.6	
$[c_{\ell\ell}]_{1331}$	1.5 ± 1.3	
$[c_{\ell\ell}]_{1133}$	0 ± 11	
$[c_{\ell e}]_{1133}$	-2.3 ± 7.2	
$[c_{\ell e}]_{3311}$	1.7 ± 7.2	
$[c_{ee}]_{1133}$	-1 ± 12	
$[\hat{c}_{\ell\ell}]_{2222}$	-2 ± 21	
[illegible]	3.0 ± 2.3	

		$\times 10^{-2}$
$[c_{\ell q}^{(3)}]_{1111}$	-2.2 ± 3.2	
$[\hat{c}_{eq}]_{1111}$	100 ± 180	
$[\hat{c}_{\ell u}]_{1111}$	-5 ± 11	
$[\hat{c}_{\ell d}]_{1111}$	-5 ± 23	
$[\hat{c}_{eu}]_{1111}$	-1 ± 12	
$[\hat{c}_{ed}]_{1111}$	-4 ± 21	
$[\hat{c}_{\ell q}^{(3)}]_{1122}$	-61 ± 32	
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$[c_{\ell d}]_{2211}$	25 ± 34	
$[\hat{c}_{eq}]_{2211}$	4 ± 41	
$[c_{\ell equ}]_{1111}$	-0.080 ± 0.075	
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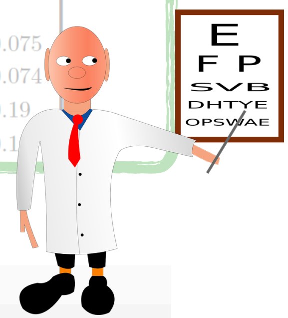

[Efrati et al., 2015]
[Falkowski & Mimouni, 2015]

EWPO fit in the flavorful SMEFT

$$O = O_{SM} + O(c_1, c_2, \ldots, c_{80}) \longrightarrow \chi^2 = \chi^2(c_i)$$

- 264 experimental input
  - Z- & W-pole data
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  - Low-energy processes:
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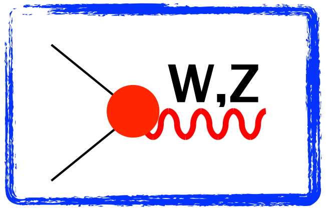
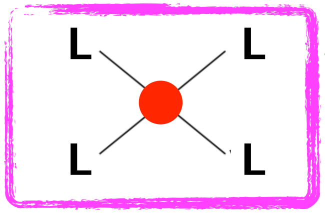
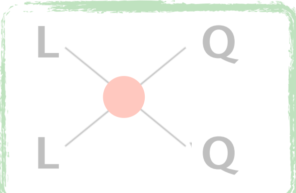
    - PV in atoms and in scattering
    - Leptonic tau decays
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]







	$\times 10^{-2}$
δg_L^{We}	-1.00 ± 0.64
$\delta g_L^{W\mu}$	-1.36 ± 0.59
$\delta g_L^{W\tau}$	1.95 ± 0.79
δg_L^{Ze}	-0.023 ± 0.028
$\delta g_L^{Z\mu}$	0.01 ± 0.12
$\delta g_L^{Z\tau}$	0.018 ± 0.059
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$\delta g_R^{Z\mu}$	0.00 ± 0.14
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δg_L^{Zu}	-0.8 ± 3.1
δg_L^{Zc}	-0.15 ± 0.36
δg_L^{Zt}	-0.3 ± 3.8
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δg_R^{Zc}	-0.35 ± 0.53
δg_L^{Zd}	-0.9 ± 4.4
δg_L^{Zs}	0.9 ± 2.8
δg_L^{Zb}	0.33 ± 0.17
δg_R^{Zd}	3 ± 16
δg_R^{Zs}	3.4 ± 4.9
δg_R^{Zb}	2.30 ± 0.88
$[c_{\ell\ell}]_{1111}$	1.01 ± 0.38
$[c_{\ell e}]_{1111}$	-0.22 ± 0.22
$[c_{ee}]_{1111}$	0.20 ± 0.38
$[c_{\ell\ell}]_{1221}$	-4.8 ± 1.6
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$[c_{ee}]_{1133}$	-1 ± 12
$[\hat{c}_{\ell\ell}]_{2222}$	-2 ± 21

	$\times 10^{-2}$
$[c^{(3)}_{\ell q}]_{1111}$	-2.2 ± 3.2
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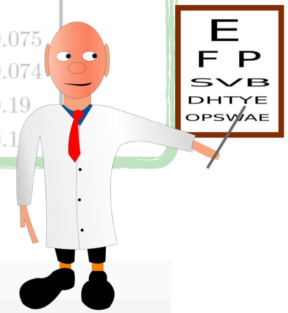

EWPO fit *in the flavorful SMEFT*

[Efrati et al., 2015]
[Falkowski & Mimouni, 2015]
[Falkowski, MGA & Mimouni, 2017]

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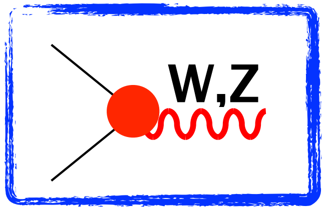

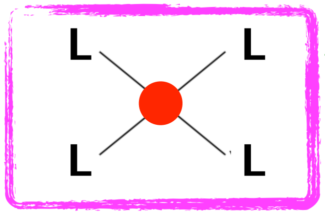

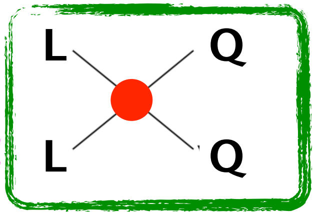

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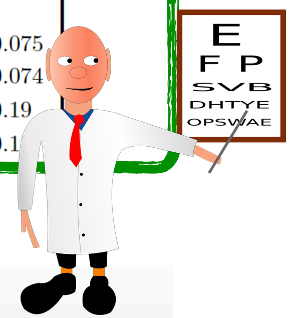
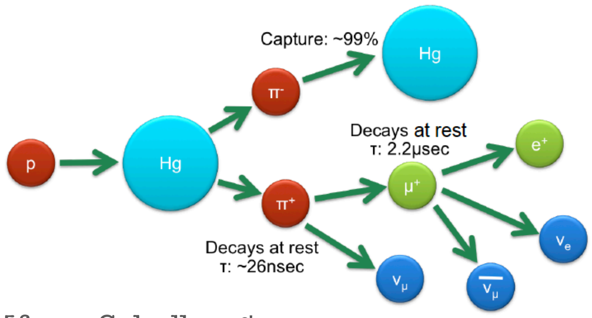


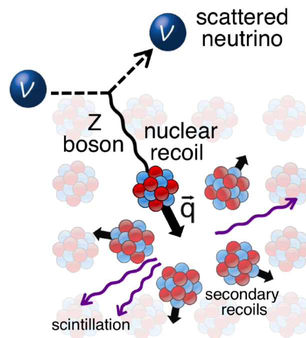
A new low-energy observable:

the COHERENT experiment

EFT analysis of NP at COHERENT



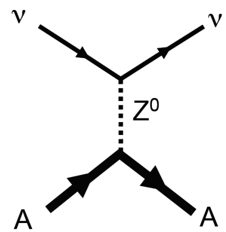
[from Scholberg's talk at IPA18]



[from COHERENT coll.]

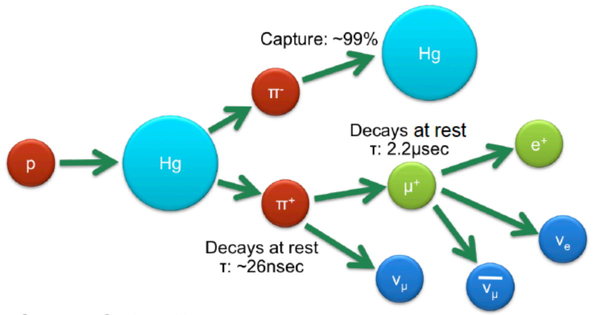
$\pi^+ \rightarrow \mu^+ \, \nu_\mu$ (prompt)

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



- COHERENT observed for the first time CEνNS (Coherent Elastic Neutrino-Nucleus Scattering): νN → νN
- It occurs for E_ν small enough so that the neutrino does not resolve the nucleus
  → CEνNS cross section enhanced by N^2.
  Theoretically known since the 70's [Freedman'74; Kopeliovich & Frankfurt'74]
- Extremely challenging experimentally (very small nuclear recoil)

EFT analysis of NP at COHERENT



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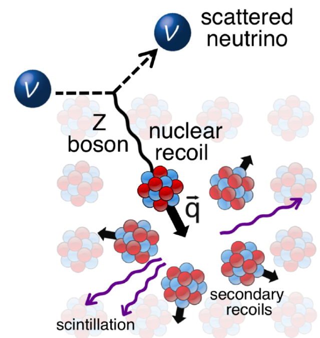

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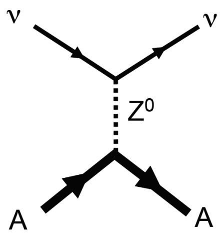
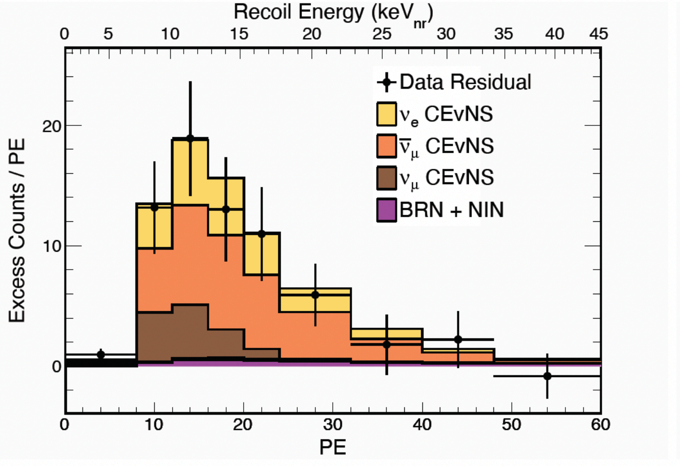
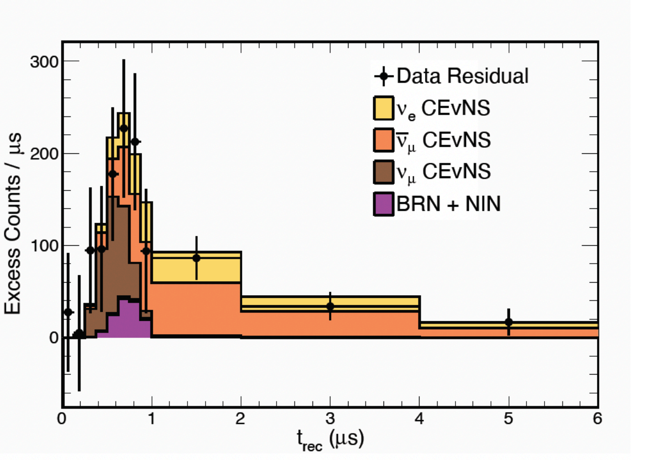




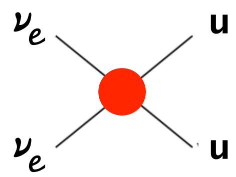


[Breso-Pla et al., 2301.07036]

EFT analysis of NP at COHERENT

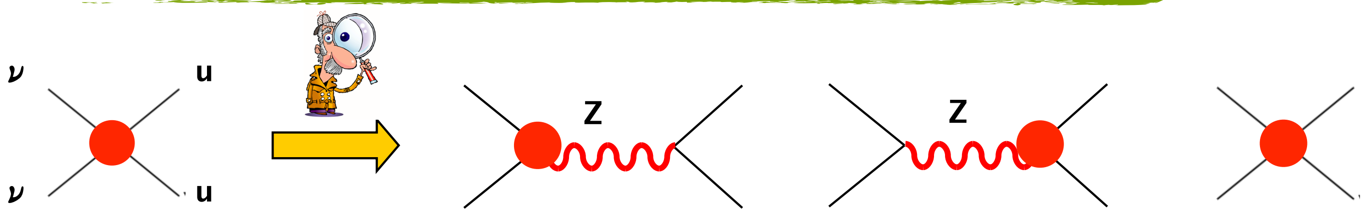
- COHERENT data (LAr + CsI, recoil & time distribution: 664 data, 13 nuisance parameters) give:

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



$$\epsilon_u = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8s_\theta^2}{3}\right)\delta g_L^{Z\nu} - \frac{1}{2}\left(c_{lq}^{(1)} + c_{lq}^{(3)} + c_{lu}\right)$$
$$\epsilon_d = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu} - \frac{1}{2}\left(c_{lq}^{(1)} - c_{lq}^{(3)} + c_{ld}\right)$$

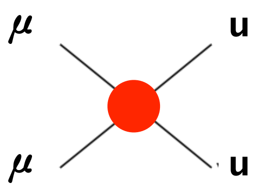
WEFT/SMEFT Matching

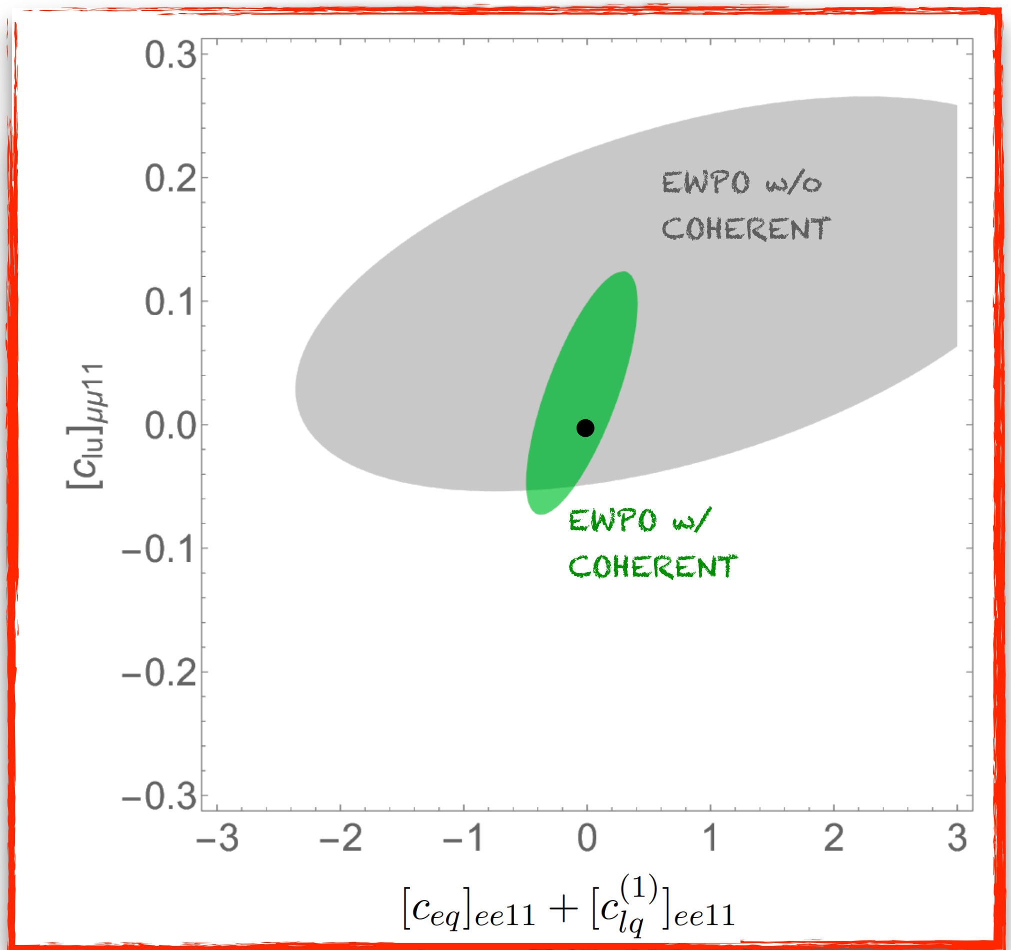


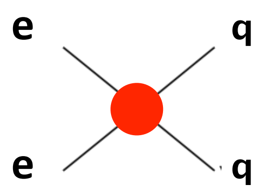
- Is COHERENT probing a new region in the SMEFT parameter space?
  These operators are constrained by many EWPO: LEP1, LEP2, APV, … → Global fit needed!

[Breso-Pla et al., 2301.07036]

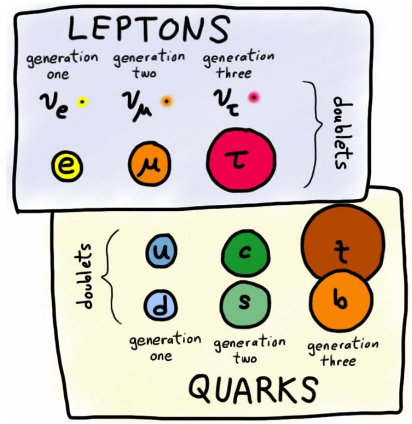
COHERENT in the SMEFT







~~Outline~~ → Summary



- Intro: SM → BSM
- Classes of low-energy BSM searches
  → Plenty of activity!
- Effective Field Theories
  → A natural theory setup to study low-E probes with minimal assumptions (plenty of theory activity)
- EFT Phenomenology
  → Efficient & model-independent (plenty of theory activity)
  → Forbidden processes probe huge scales
  → Precision low-E measurements probe TeV scales (interplay with high-E!)

EFT!!