(A very brief & focused introduction to…)

Effective Field Theories

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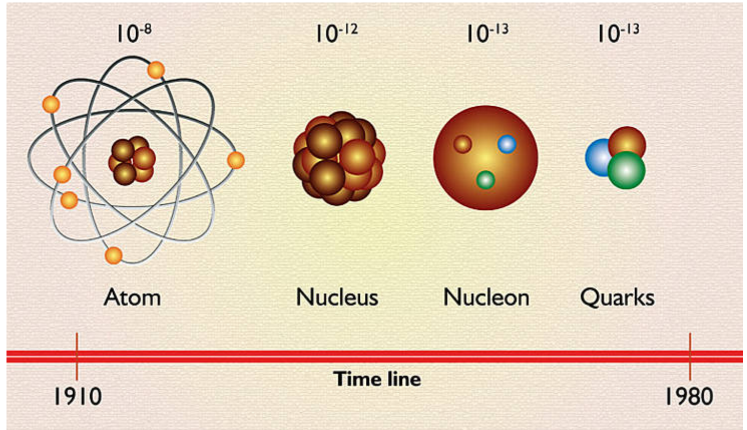
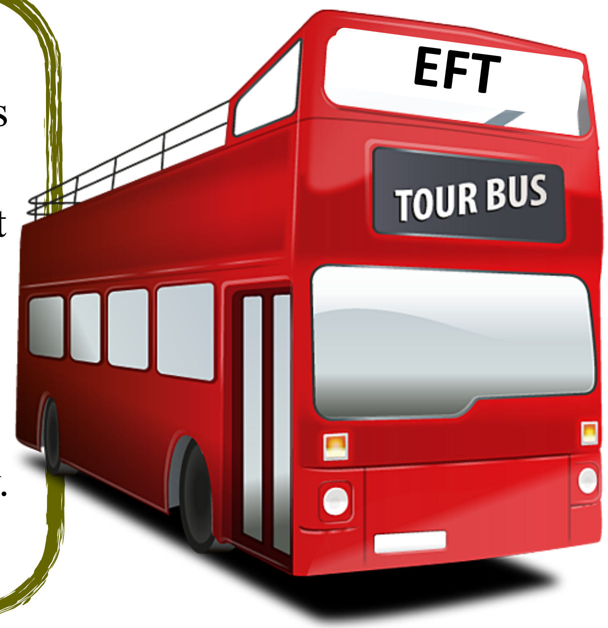
Outline

- Intro
- EFT at the ~100 GeV scale: SMEFT
- EFT at E << 100 GeV: LEFT
- EFT phenomenology
- Conclusions



Disclaimers:

- EFT is a wide field → we'll focus on its application to heavy New Physics
- I don't think a technical 2h presentation would be very useful. Instead I'll give a qualitative (personal) overview, hopefully conveying some important ideas, & giving you the motivation to read a real EFT work
- Many many good refs: EFT (Manohar'97, Pich'98, Rothstein'03, Kaplan'05, Skiba'10, Cohen'19, Burgess'20, ...), SMEFT (**Falkowski'23**, Isidori-Wilsch-Wyler'23, ...), recorded lectures, …
- Occasionally I went slightly outside my strict comfort zone. Fun but risky.
- It's OK if we don't go over all the slides. Stop me if you get lost.



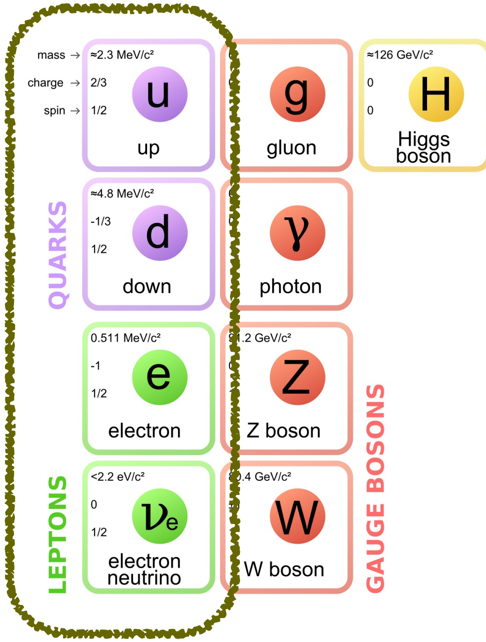
Motivation. 1- The Standard Model

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

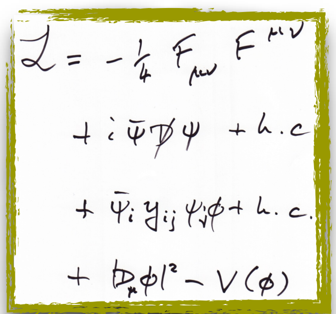
- It's the ultimate result of reductionism & unification
  [electromagnetism (→ chemistry), radioactivity, nuclear physics, …]
  Our periodic table.

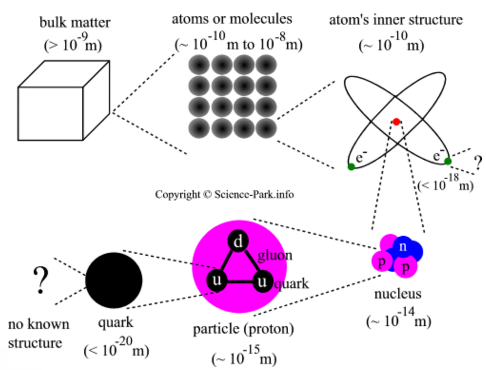
- ~50 years old, spectacularly confirmed
  [All particles have been observed (Higgs @CERN, 2012)]

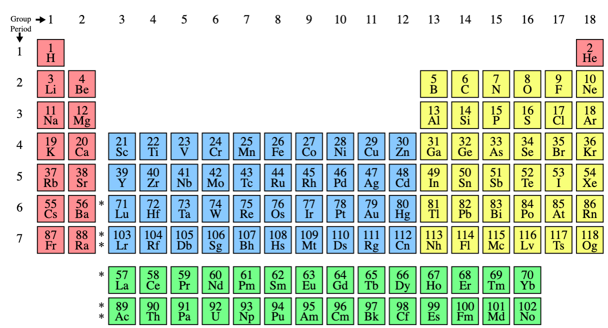
- Whatever [future experiments] find, SM has proven to be valid as an effective theory for E < TeV



x 3 !?

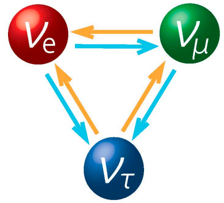


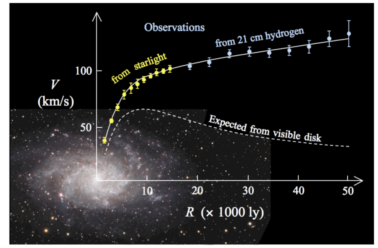




Motivation. 2- The SM is not enough*

- Neutrinos oscillate → they have a mass!



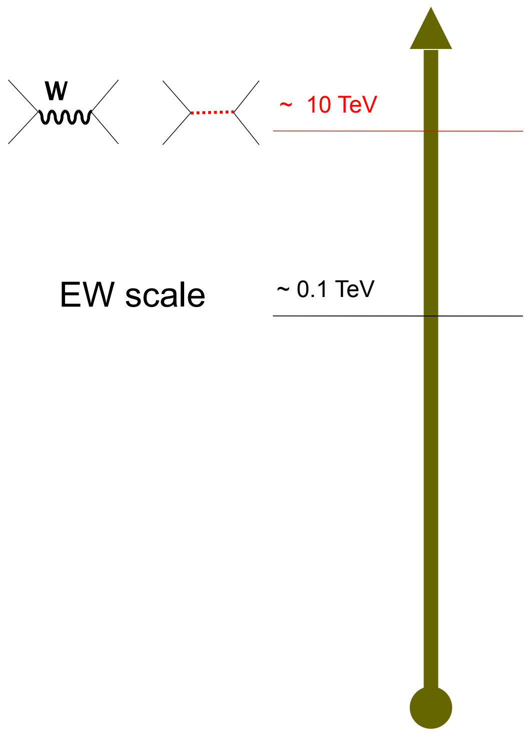


- What lies under the SM periodic table?
- Dark matter, matter-antimatter asymmetry, strong CP problem, hierarchy problem, dark energy, quantum gravity, cosmological problems, …
- All SM problems are theoretical or astrophysical/cosmological, except for neutrino masses.
- Many BSM theories around (often not very convincing)
- The SM works too well (quite curious crisis).
  We need new hints. Physics = EXP + TH

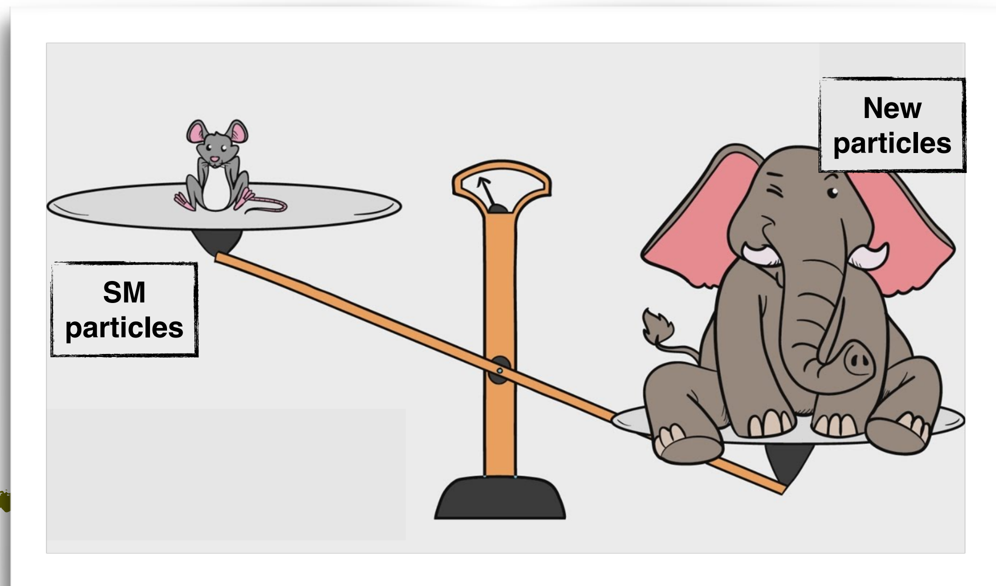
*Fortunately for us.

Motivation. 3- Going beyond the SM

Theory?



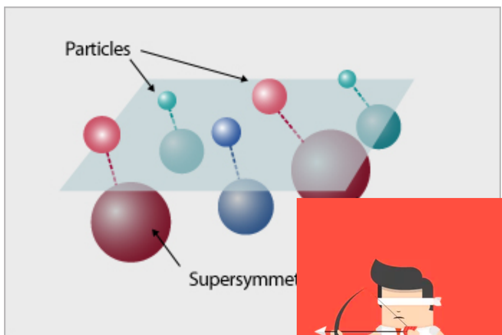
$$\mathscr{L}_{UV}(x) = \mathscr{L}(\varphi_{SM}, \Phi_{NP})$$

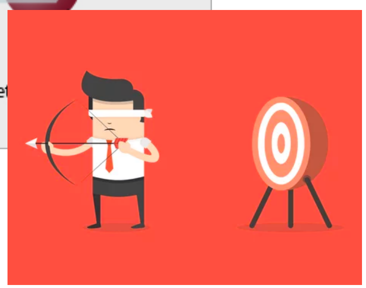


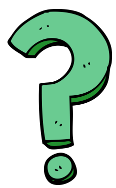
Motivation. 3- Going beyond the SM

Specific BSM model

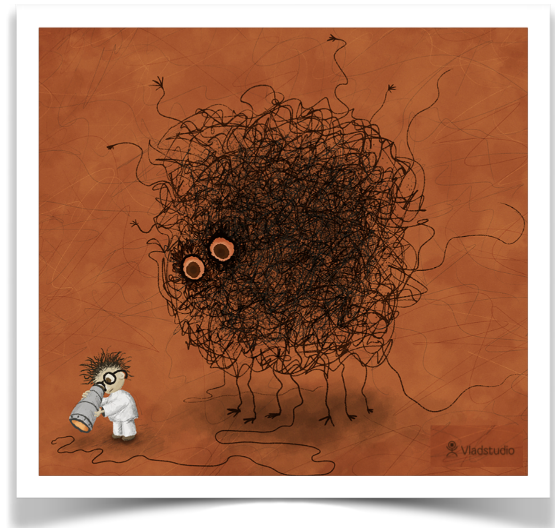
$$\mathscr{L}_{BSM} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$



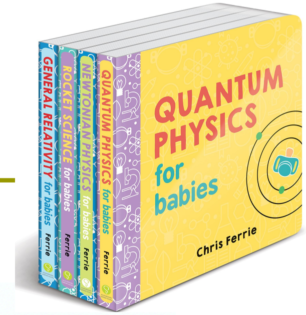


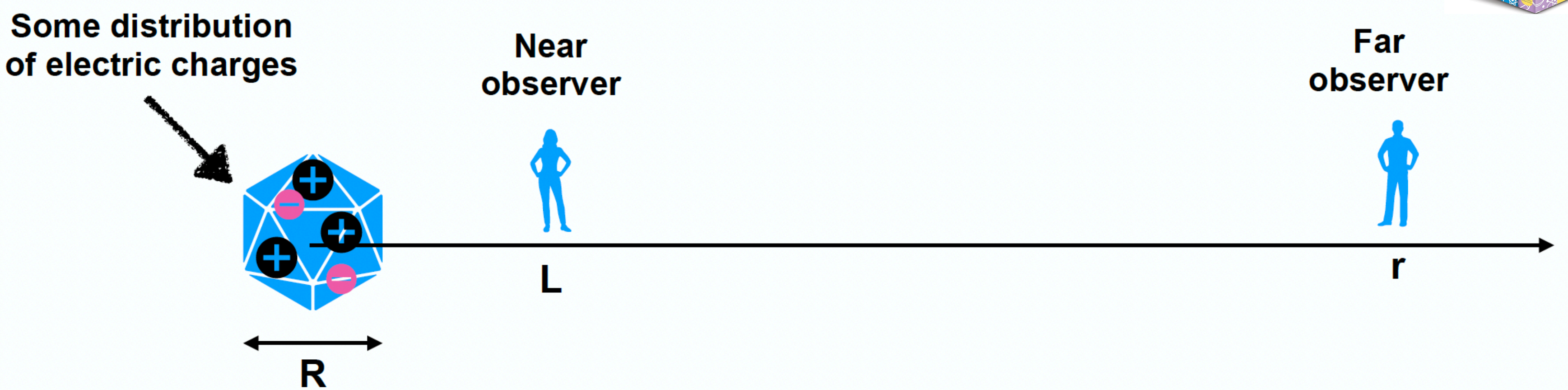


Effective Field Theory (EFT) approach



Far vs near





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

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

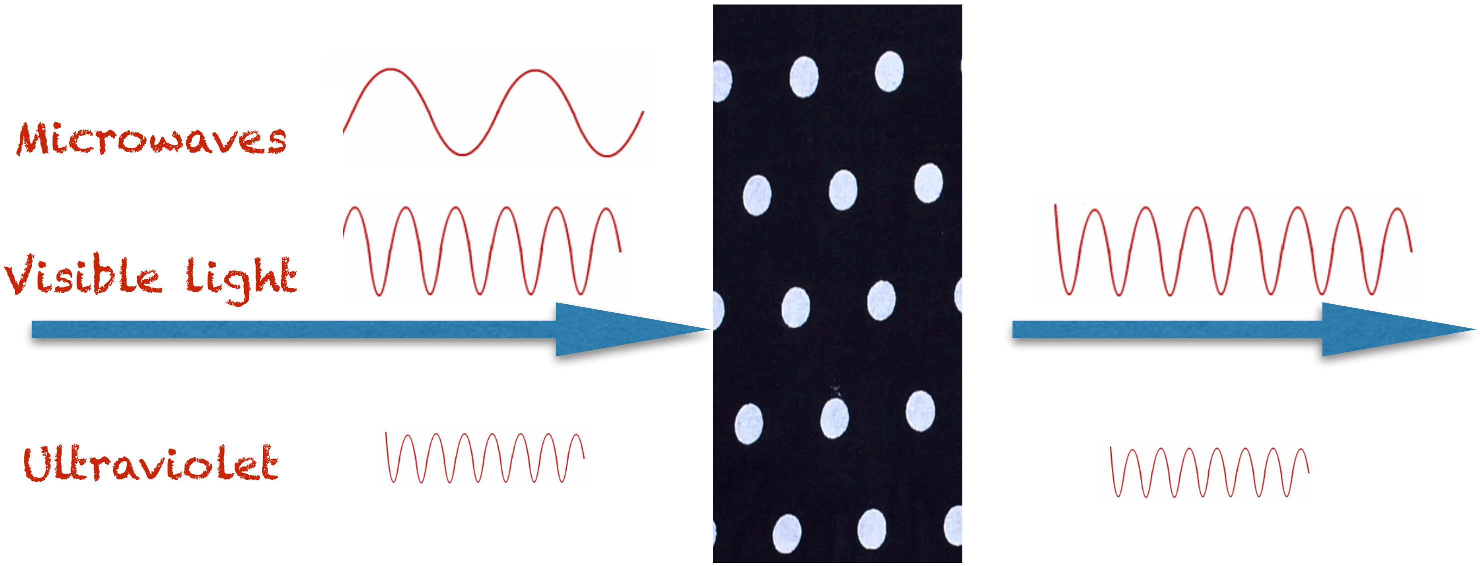
Higher order terms in the multipole expansion are suppressed by powers of the small parameter (R/r). One can truncate the expansion at some order depending on the value of (R/r) and experimental precision

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

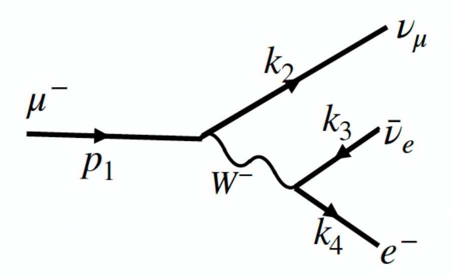
[A. Falkowski's CP2023 lectures]

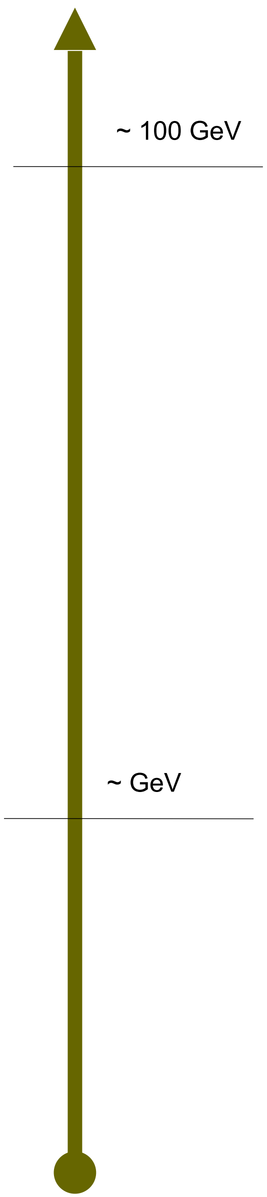
High-E = small distances



$E \sim 1/\lambda$

EFT in QFT (example)





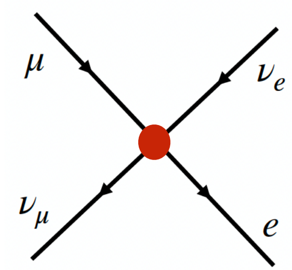
$\mathcal{L}_{SM}$ (EW theory)

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

$q = p_1 - k_2$

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

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

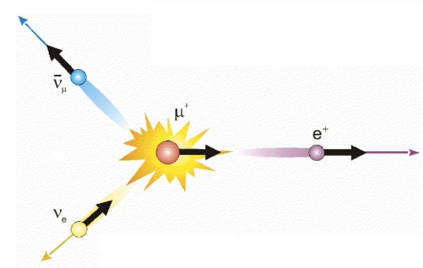


$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu\,(1-\gamma_5)\,\mu$$

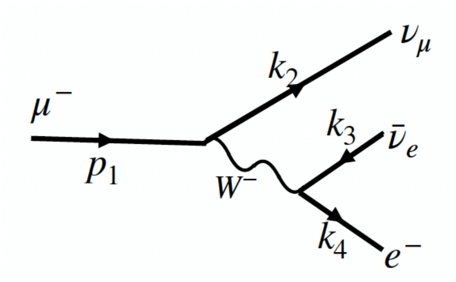
+ higher-dim terms

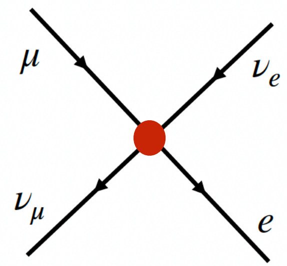
$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



EFT in QFT (example)





Historically the logic was quite different:

- Data → Fermi EFT → SM

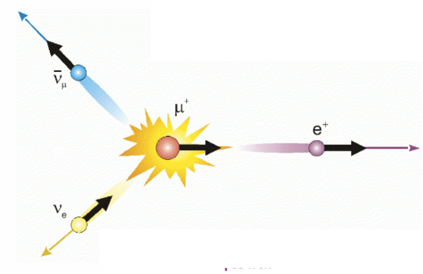
The EFT idea works beyond tree-level:

- The EFT is not renormalizable
- However, for a finite precision (= at a given order in the EFT *power counting*: E^2/m_W^2), the EFT is renormalizable.
- Couplings become renormalization scheme and scale (μ) dependent. They "run" → $\log(\mu/m_W)$. Renormalization group equations (RGEs) tell us how to calculate this *running*. Observables are μ indep.
- The UV/IR *matching* can be done at any given order. Typically done at $\mu = m_w$
- Running + matching + running: important to connect measurements (LHC measurement at ~300 GeV vs muon decay lifetime)

+ *higher-dim terms*

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

Wilson coefficient



EFT in QFT

Top down

Known theory at high-E

↓

EFT at low-E

Bottom up

EFT that includes high-E effects

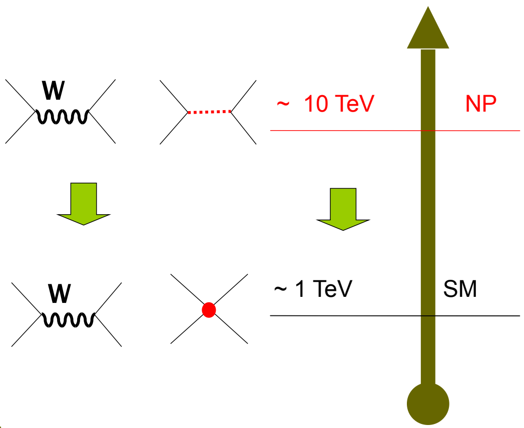
↑

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

EFT at the EW scale: SM → SMEFT

[S. Weinberg, 1979-1980;
Buchmuller-Wyler, 1986; ...]



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

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

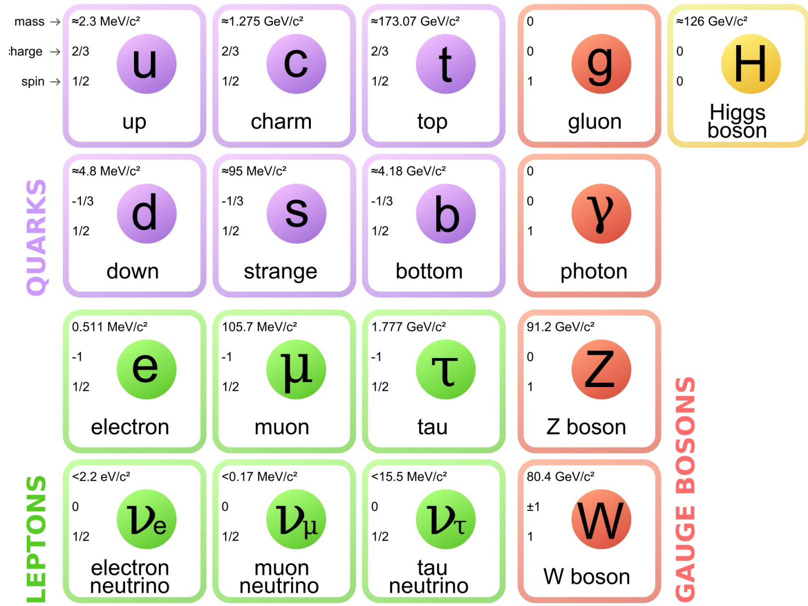
Given a set of low-E fields & symmetries, one builds an EFT Lagrangian putting all possible interactions and following a power counting

C_i: **Wilson coefficients (UV physics)**

EFT = Model-independent approach ≠ Assumption independent

SMEFT: assumptions

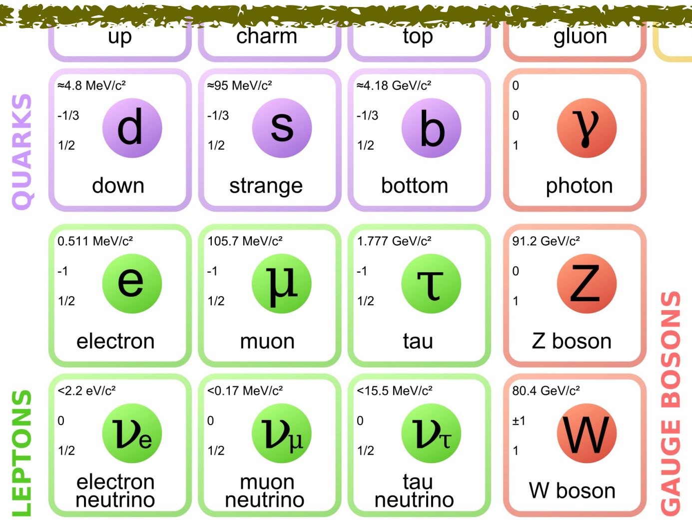
Known elementary particles
(masses < 173 GeV)



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

SMEFT: assumptions

Physics above the EW scale is described by a manifestly Poincaré-invariant local quantum theory.
Safe assumption.



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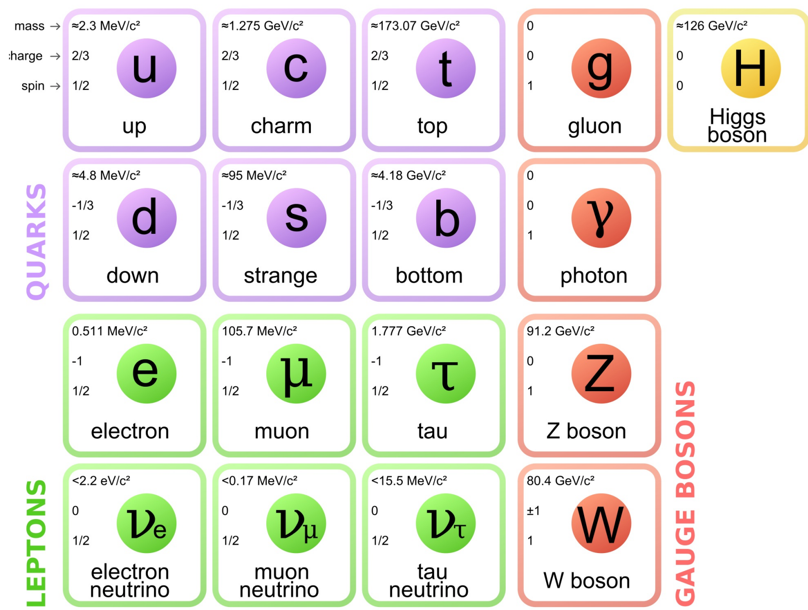

1. QFT

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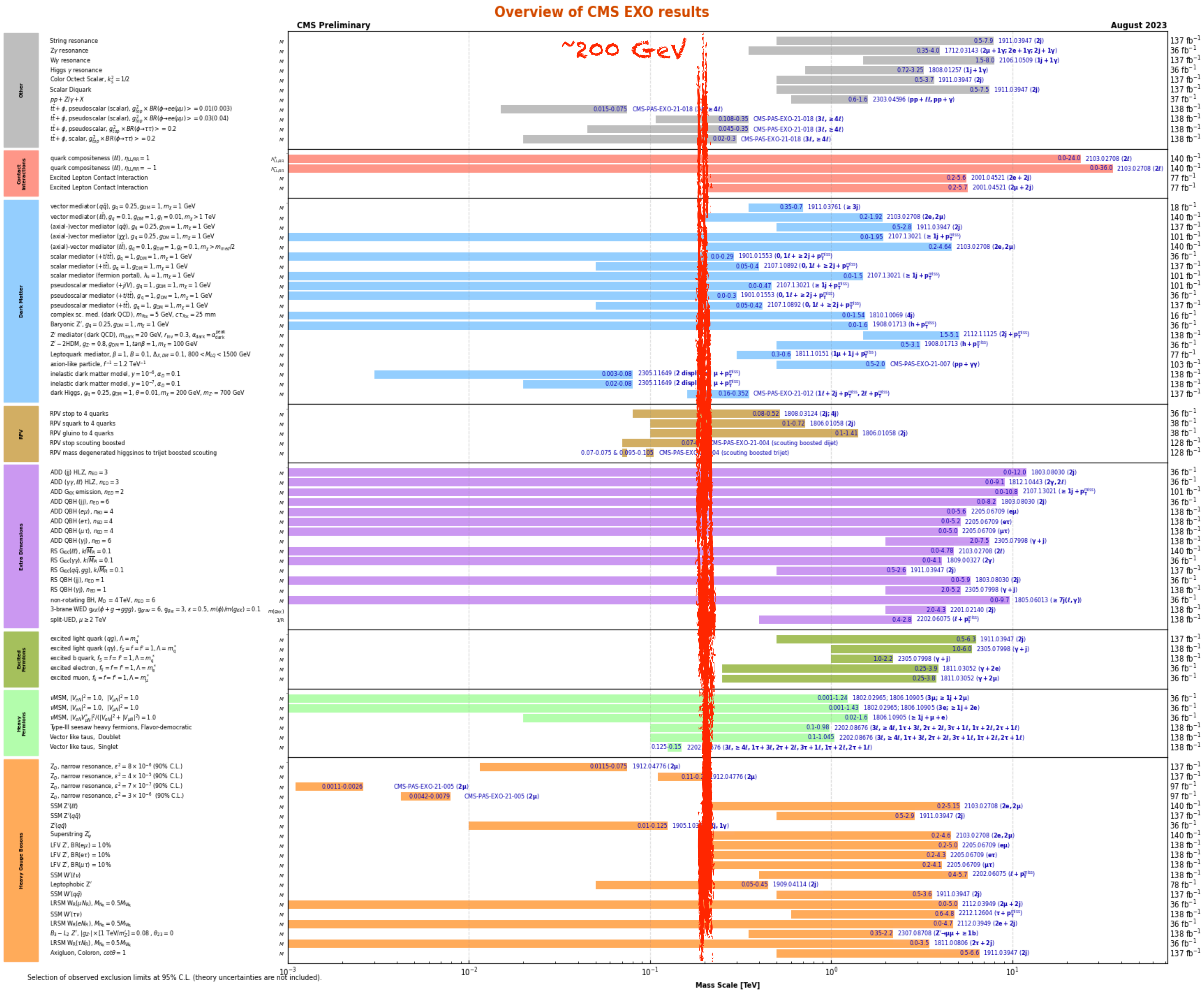

Overview of CMS EXO results
CMS Preliminary
August 2023
~200 GeV
Other
Contact Interactions
Dark Matter
RPV
Extra Dimensions
Excited Fermions
Heavy Fermions
Heavy Gauge Bosons
Mass Scale [TeV]
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

SMEFT: assumptions

Known elementary particles
(masses < 173 GeV)

- Reasonable assumption.
- But it could easily be wrong:
  - new O(100 GeV) particles somehow evading LHC searches;
  - light RH neutrinos (→ R-SMEFT), axions (→ALP-SMEFT), light dark matter, …
- In fact it's wrong (graviton!) but unlikely to be relevant for EW physics (→ GRSMEFT).

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

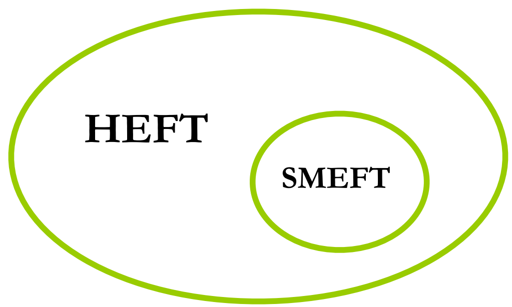
SMEFT: assumptions

- One could follow a different approach, where the higgs field h(x) transforms as a singlet (and the Goldstone bosons transform non-linearly). This takes us to a different EFT called **HEFT.**
- SMEFT ⊂ HEFT.
- HEFT \ SMEFT → non-decoupling BSM models (where the masses of new particles vanish in the limit v→0) [Falkowski-Rattazzi, 1902.05936; Cohen+, 2108.03240; …]. Example: a 4th SM family.
  - HEFT validity regime $\lesssim 4\pi v \sim 3$ TeV → mass gap! (Assumption #2)
- **SMEFT** describes BSM theories that can be parametrically decoupled, i.e., the mass scale of new particles depends on a free parameter that can be taken to infinity.
- Reasonable assumption, given the apparent mass gap.

1. QFT
2. SM fields + gap:
   NP scale >> EW scale.
3. Gauge symmetry: local SU(3)xSU(2)xU(1) symmetry
   [spontaneously broken to SU(3)xU(1) by a VEV of the Higgs field]

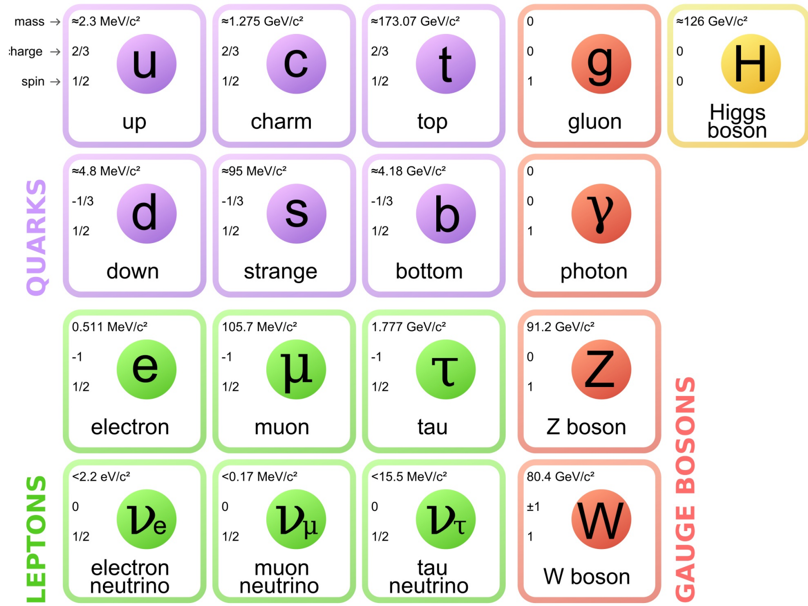
$$\varphi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \rightarrow \exp\left(i\vec{\sigma}\cdot\frac{\vec{\theta}}{v}\right)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

Unitarity gauge



SMEFT: assumptions

Known elementary particles
(masses < 173 GeV)



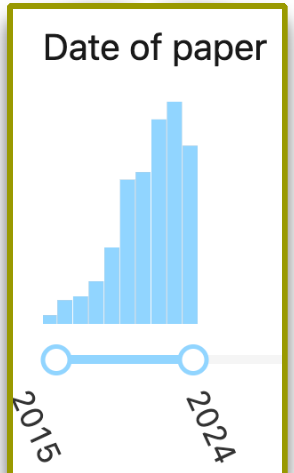
1. QFT

2. SM fields + gap:
   NP scale >> EW scale.

3. Gauge symmetry: local
   SU(3)xSU(2)xU(1) symmetry

SMEFT is the result of very conservative & parsimonious assumptions

(→ Extremely active field the last ~10 years)



F t SMEFT
(Use with caution:
the field is much older!)

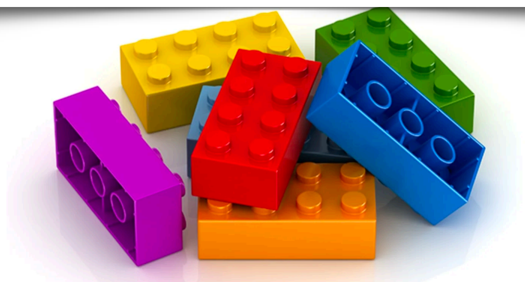
Building the SMEFT

Building the SMEFT

Building blocks:

$G_\mu^a\ ,\ W_\mu^k\ ,\ B_\mu\ ,\ q\ ,\ u\ ,\ d\ ,\ \ell\ ,\ e\ ,\ \varphi$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Spin
G_μ^a	**8**	**1**	0	1
W_μ^k	**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

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

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

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.

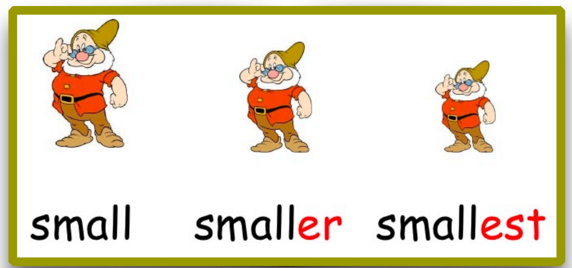
- Since $[\mathscr{L}] = E^4 \;\; \rightarrow \;\; \mathscr{L} \supset C_D\,\mathcal{O}_D$ where $[C_D] \sim c_D\,/\,\Lambda^{4-D}$

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

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

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

- 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
  (Generic key EFT feature)

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

Building the SMEFT

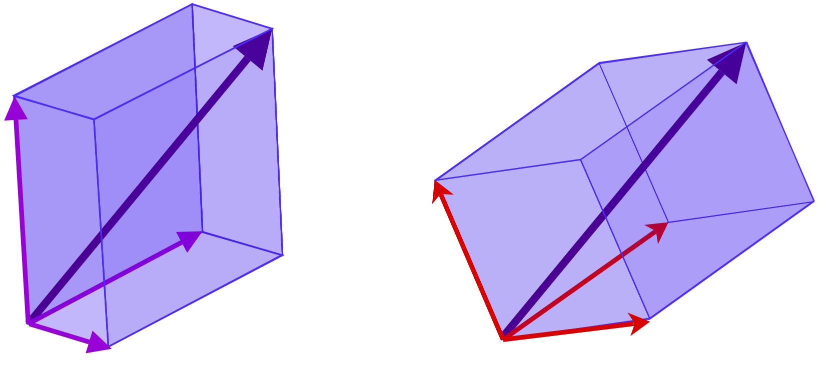
$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

$$\sum_i C_6^i \mathcal{O}_6^i$$

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.



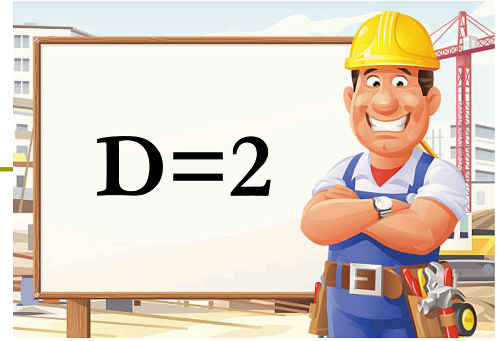
Building the SMEFT

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

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, $\frac{1}{\Lambda^2} \to \frac{E^2}{\Lambda^2}, \frac{v^2}{\Lambda^2}, \frac{v\,E}{\Lambda^2}$.
- Wilson Coefficients "run" → RGEs
  - Important to do precise analyses connecting experimental searches at different scales, & also with the UV scale (matching)
  - Operators mix under running

Building the SMEFT

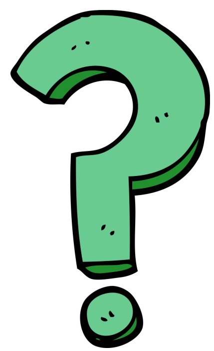


$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots$$

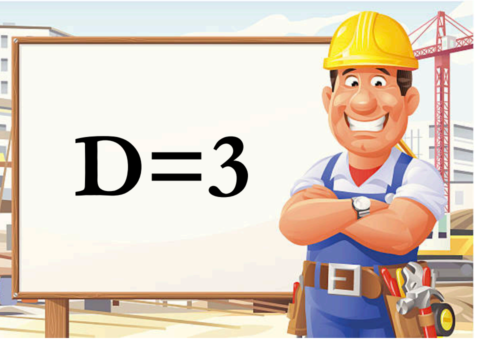
- The first contribution appears at D=2, where we find only one operator:

$$\mathcal{L}_2 = \mu^2 \varphi^\dagger \varphi$$

- From the EFT point of view one expects μ of order Λ >> EW scale (at least ~1 TeV)
- Data tell us that μ ~ 100 GeV
  (In the SM: $M_h = \mu\sqrt{2}$)
- → **"Hierarchy problem"**.
- The EFT (dimensional analysis!) "failed" us on the first try.



Building the SMEFT



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

- There are no operators.

- PS: There's nothing fundamental about this.
  If one adds RH neutrinos, a D=3 term is possible (Majorana mass).

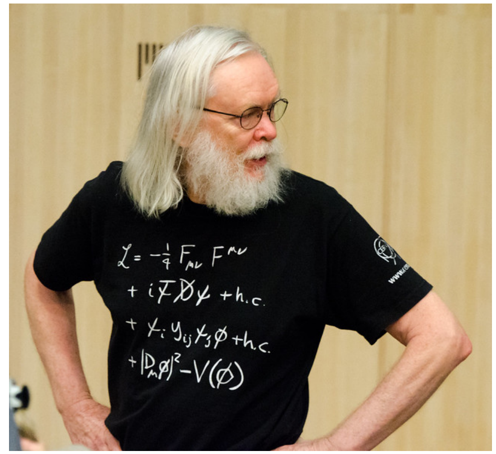
$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_R^c \nu_R + h.c.\,, \qquad \nu^c \equiv C\bar{\nu}^T$$

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 D=4 we find the rest of the SM

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

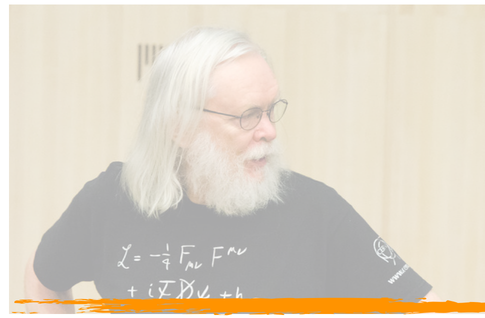


$$\begin{aligned}
W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\, \epsilon^{ijk}\, W^j_\mu\, W^k_\nu \\
D_\mu X &= \partial_\mu X + i g_s G^a_\mu T^a X + i g_L W^i_\mu \frac{\sigma^i}{2} X + i g_Y B_\mu Y_x X
\end{aligned}$$

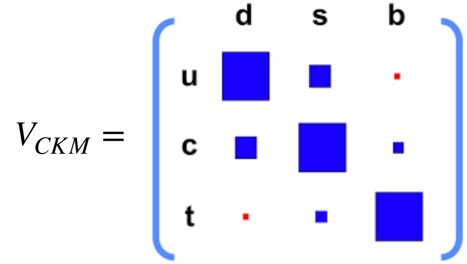
Building the SMEFT

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

- At D=4 we find the rest of the SM

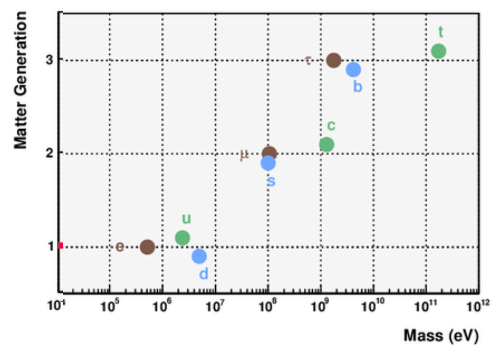


$$\mathscr{L}_{SM} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{k\mu\nu}W^k_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$
$$+ i\sum_f \bar{f} D_\mu \gamma^\mu f$$
$$-\left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\, \varphi\, Y_d\, d + \bar{q}\,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



- All coefficients have been measured…
  except the theta term → "strong CP problem"

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



Building the SMEFT

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

- Only one operator (Weinberg'79)

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

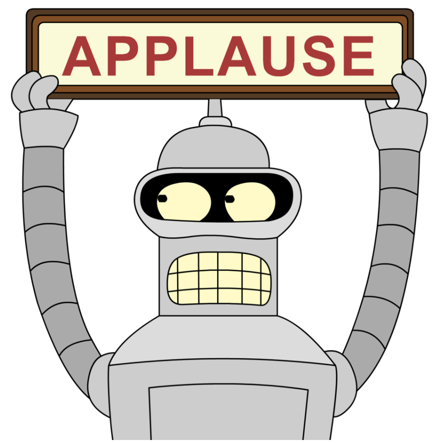
$$\tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix} \to \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix}$$

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

- 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

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

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

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

- The mass gap is certainly OK

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

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

Building the SMEFT

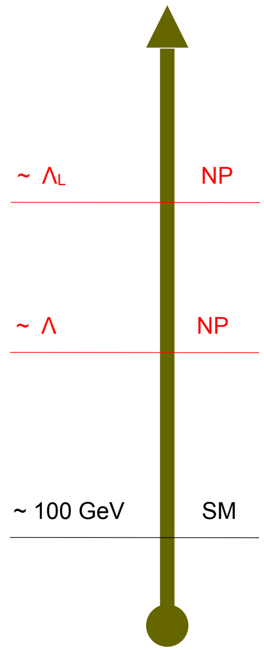
$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda}\left(\tilde{\varphi}^\dagger \ell_p\right)^T C\left(\tilde{\varphi}^\dagger \ell_r\right) + h.c. \quad \rightarrow \quad m_\nu \sim 2\, c_5\, v^2/\Lambda$$

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

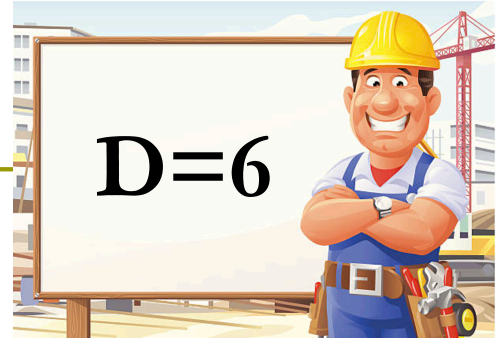
- Alternative:
  It's possible (and even natural) that there's more than one NP scale.
  This is not arbitrary since D=5 is "special": it violates B-L
  - A very high scale Λ_L associated to B-L violating physics (D=5, 7, …)
  - A (hopefully) not so high scale, Λ, associated to B-L conserving physics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

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

- 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



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

- 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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

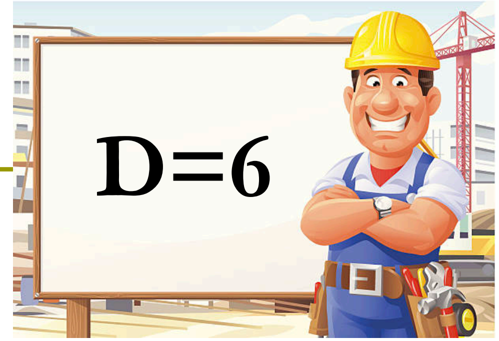
Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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.

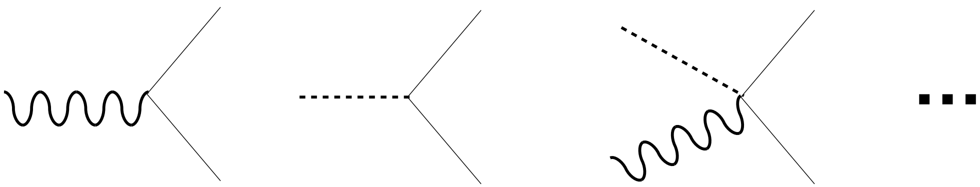
Building the SMEFT

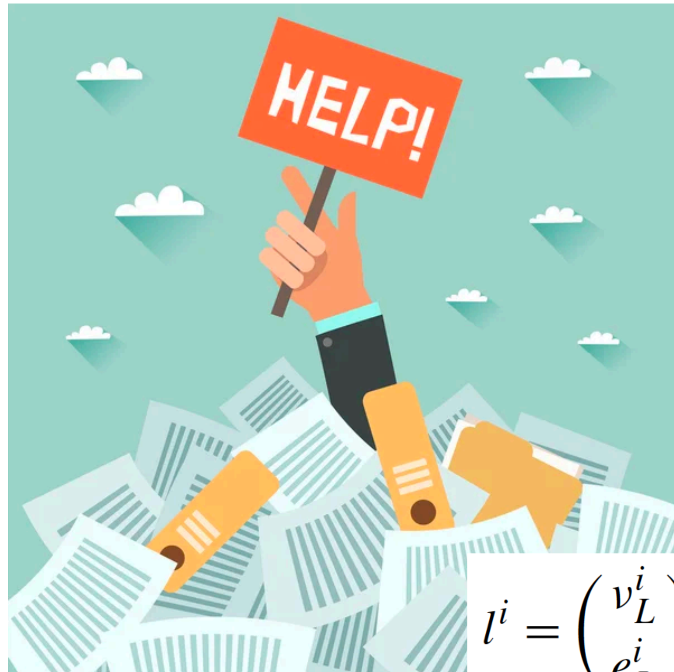


$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

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

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



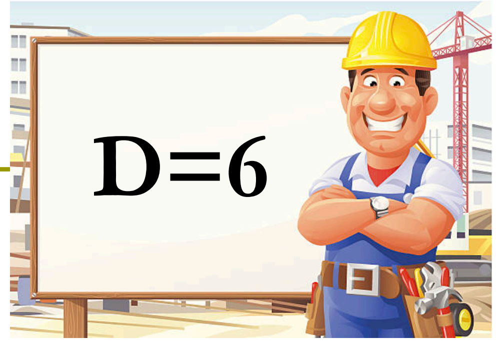


$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

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

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

Building the SMEFT



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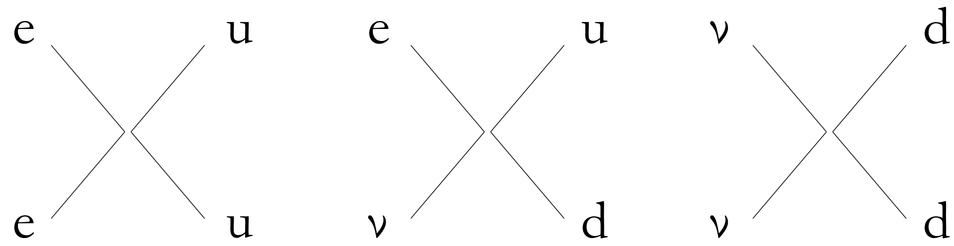
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

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



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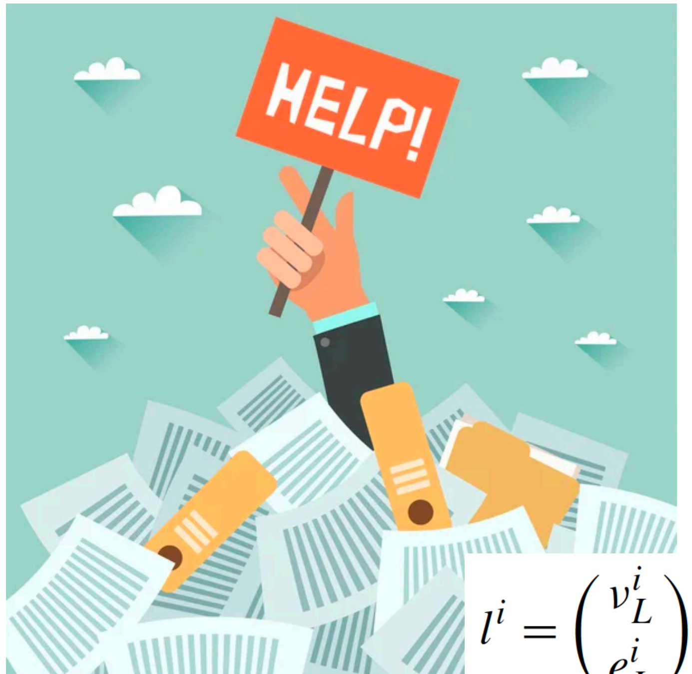

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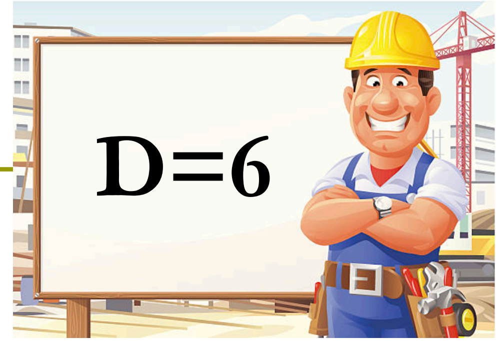
Building the SMEFT



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

- First B-L conserving corrections to the SM.

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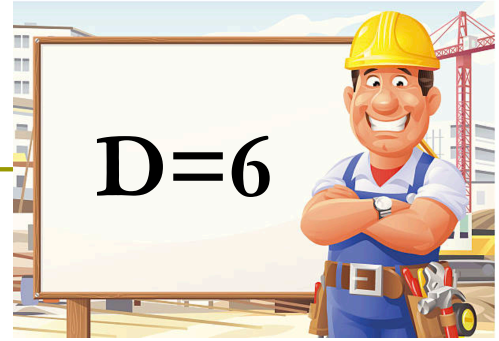
  Flavor structure → 3045 coefficients

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

- All results compatible with zero → Bounds on Λ

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

Building the SMEFT



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

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

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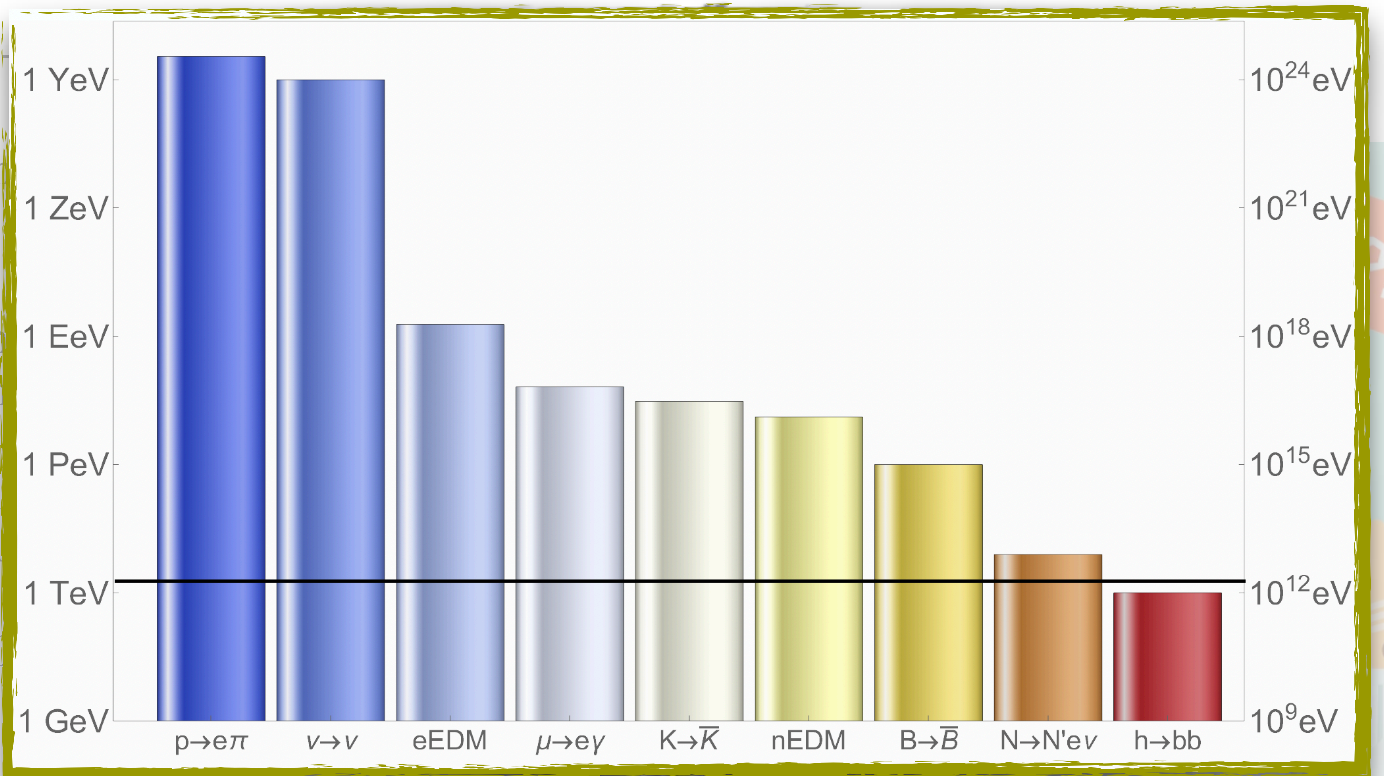
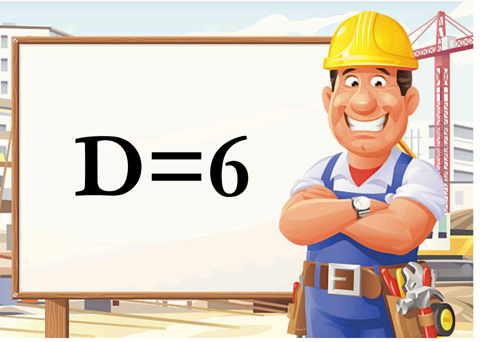


- All results compatible with zero → Bounds on Λ

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

Building the SMEFT



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

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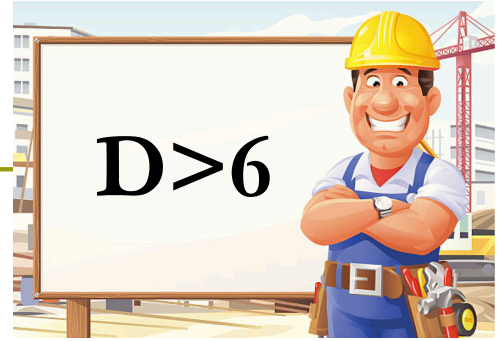
- Extremely rich phenomenology:
  colliders,
  flavor,
  low-energy searches (beta decay!),
  neutrino physics,
  proton decay,
  CP violation (EDMs!),
  …

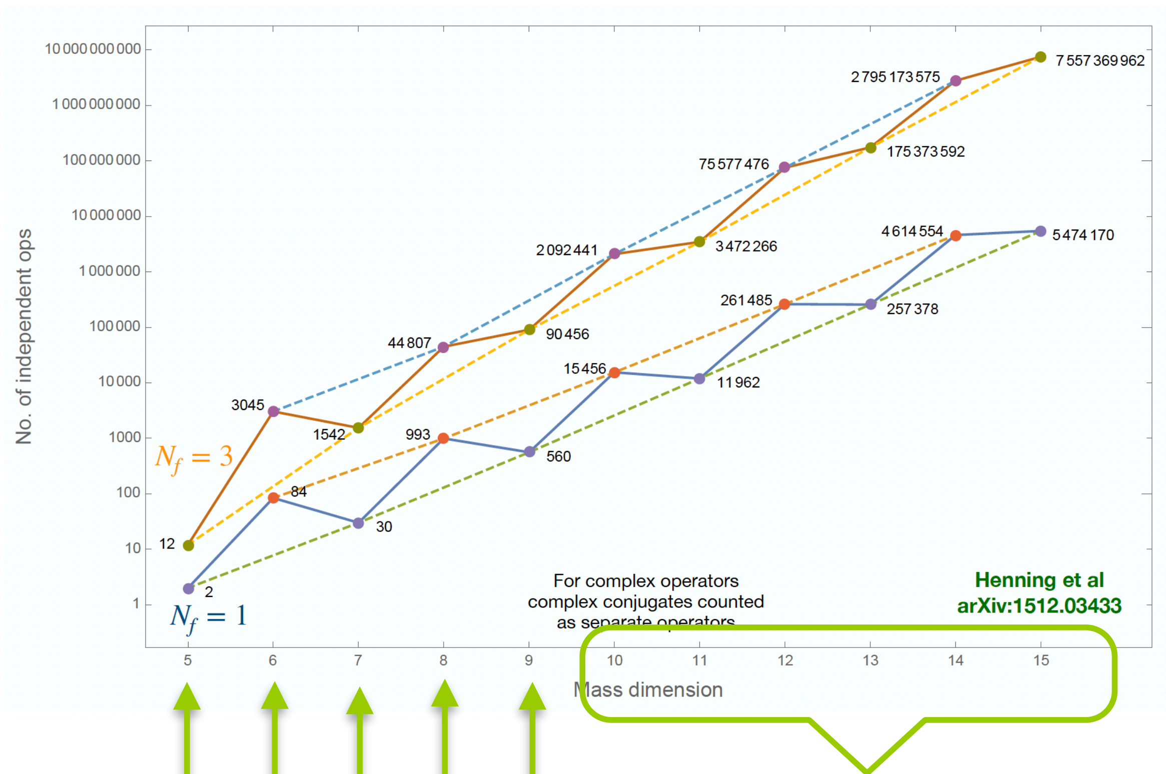
- All results compatible with zero → Bounds on Λ
- Dim-6 RGEs known at 1 loop
  [Jenkins et al., 1308.2627 & 1310.4838; Alonso et al., 1312.2014]

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)

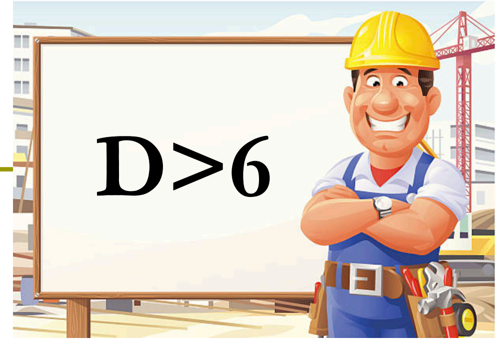
Building the SMEFT

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

- 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.

*In specific models: (dim-8) > (dim-6)^2.

Building the SMEFT

$$\mathscr{L} = \mathscr{L}_{SM} + \begin{array}{l}\textbf{Majorana}\\ \textbf{neutrino}\\ \textbf{masses}\end{array} + \sum \frac{c_6^i}{\Lambda^2} \mathscr{O}_6^i + \ldots$$

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

↓

EFT at low-E

SMEFT

Low-energy (~GeV) EFT (LEFT)

Bottom up

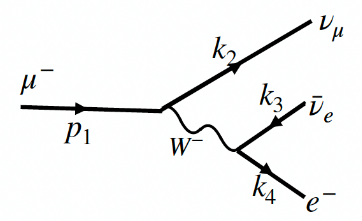
EFT that includes high-E effects

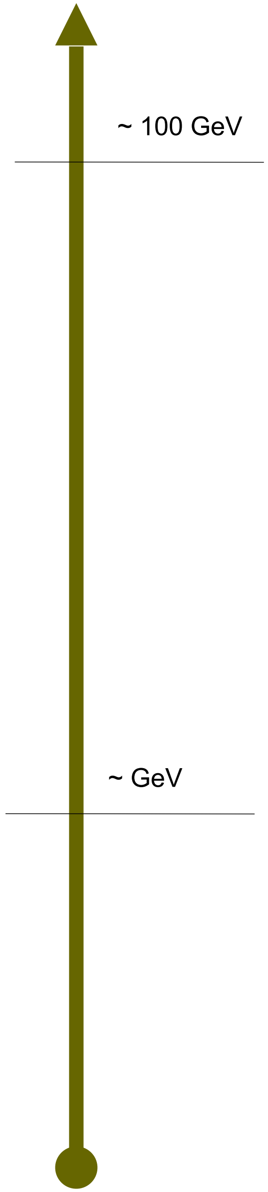
↑

Low-E symmetries & fields

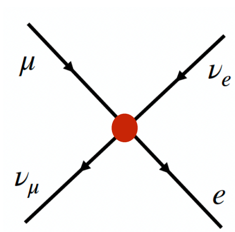
SMEFT

Down the EFT stairs





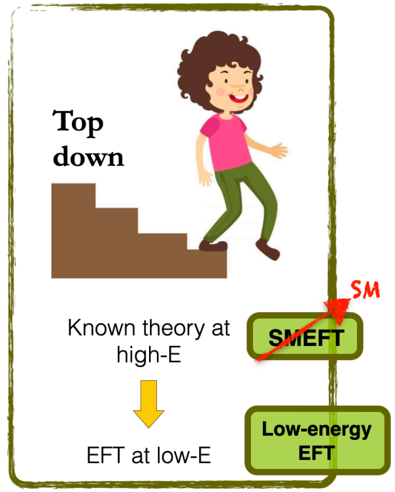
$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$



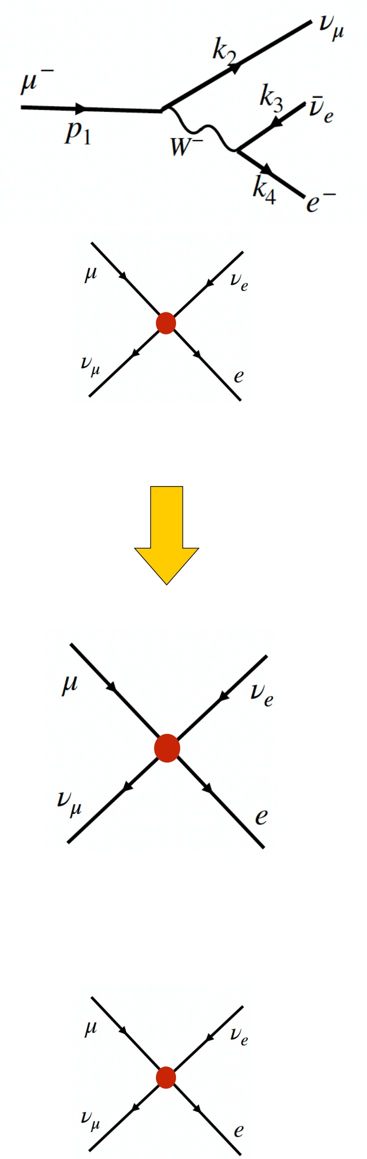
$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2}$$

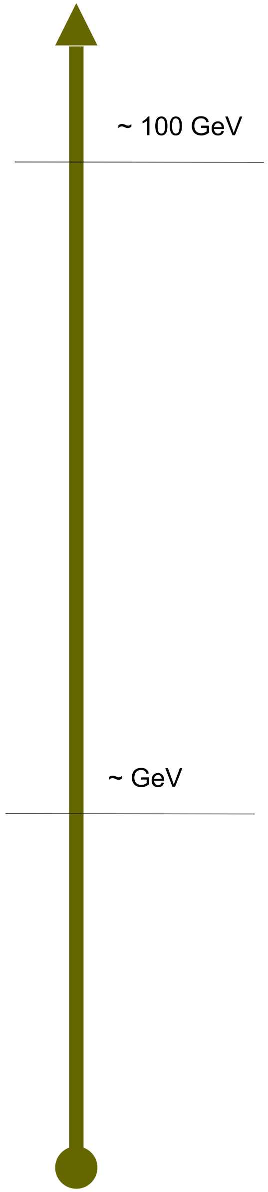
$$\mathscr{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu\,(1-\gamma_5)\,\mu$$

+ higher-dim terms



Down the EFT stairs





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

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

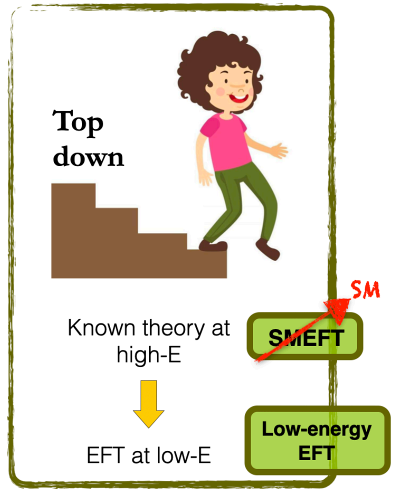
$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2} + f\left(\frac{c_6^i}{\Lambda^2}\right)$$

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

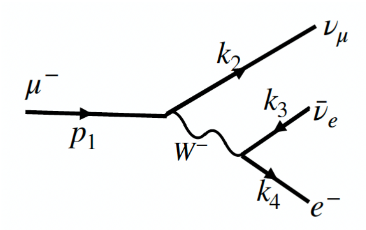
+ higher-dim terms

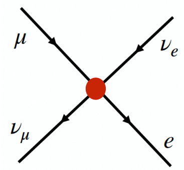
$$+\frac{4\epsilon}{\sqrt{2}}\bar{e}\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,(1+\gamma_5)\,\mu$$

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



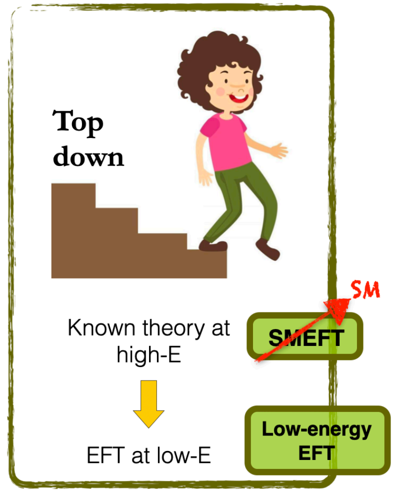
Down the EFT stairs





~ 100 GeV

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



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

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

+ *higher-dim terms*

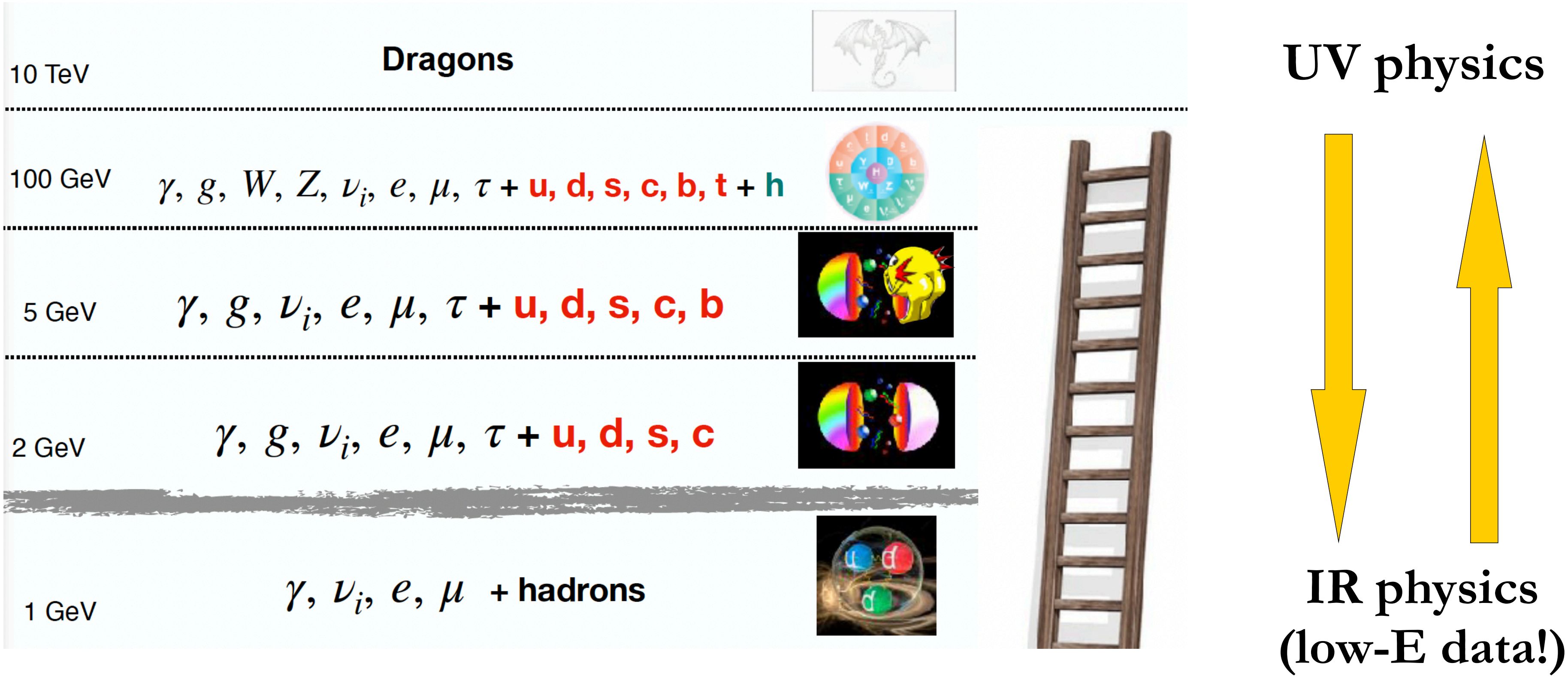
$$+\frac{4\epsilon}{\sqrt{2}}\bar{e}\,(1-\gamma_5)\,\nu_e\cdot\bar{\nu}_\mu\,(1+\gamma_5)\,\mu$$

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

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

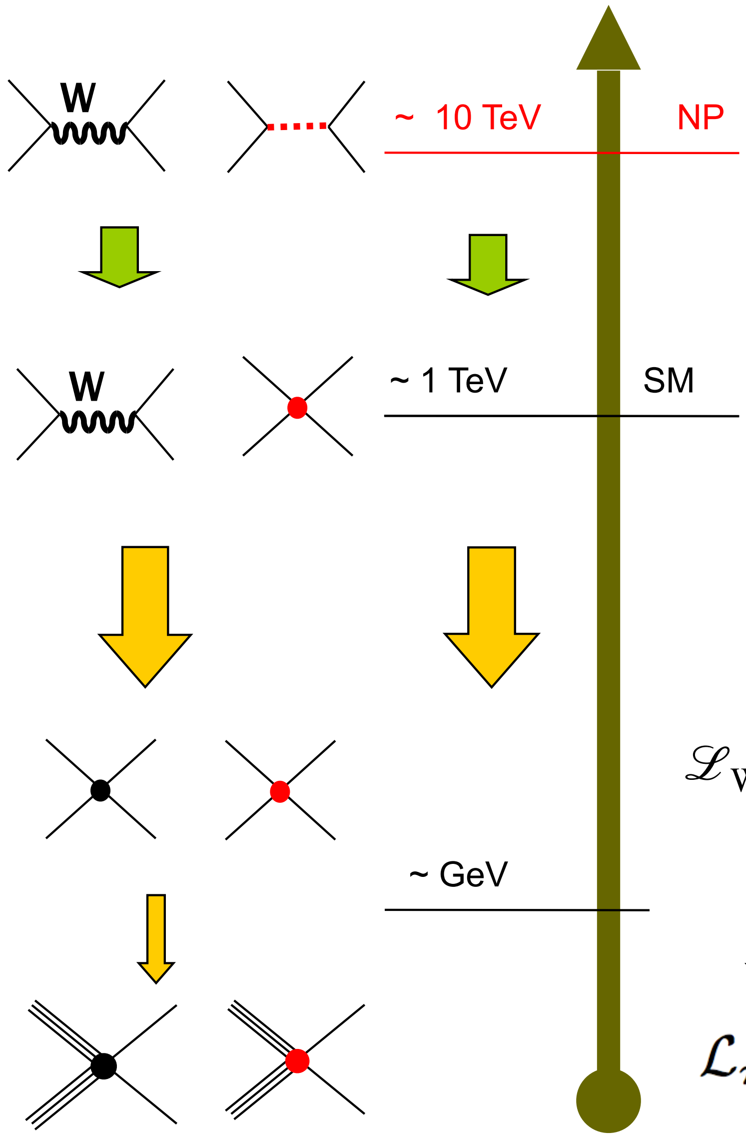


- Various names: LEFT, WEFT, WET, …
  - Variants: LEFT-5, LEFT-4, …

- In any case, the full LEFT (generated by the SMEFT) has of course many many terms. The LEFT running, and LEFT/SMEFT matching are known at 1-loop [Jenkins et al., 1709.04486 & 1711.05270; Dekens & Stoffer, 1908.05295].

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

SMEFT → Beta-decay LEFT



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

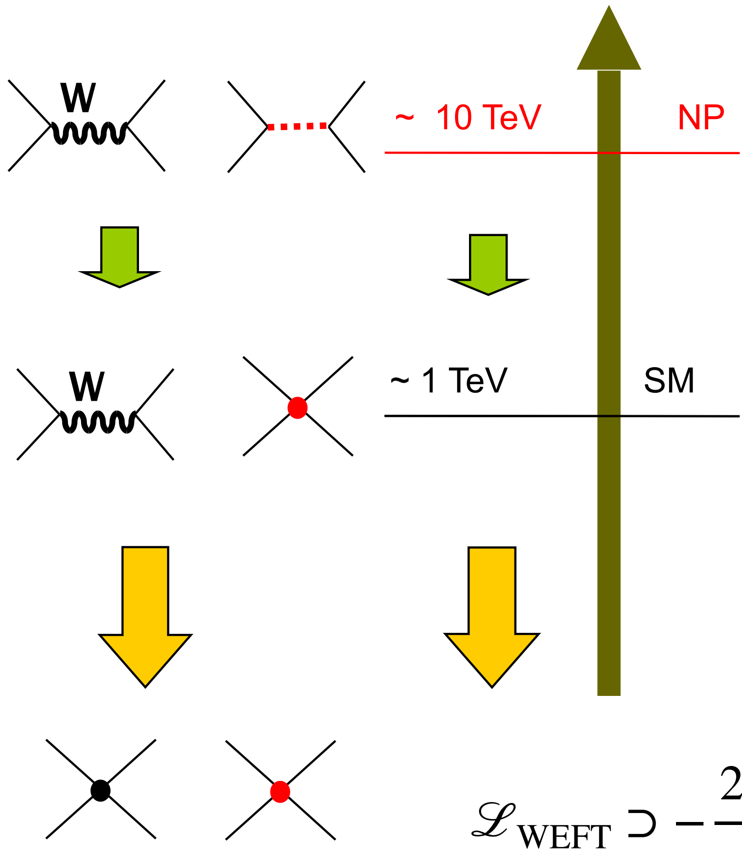
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathscr{O}_6^i + \ldots$$

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

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

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

SMEFT → Beta-decay LEFT



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

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

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

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

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

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

SMEFT $\longrightarrow$ Beta-decay LEFT

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

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

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

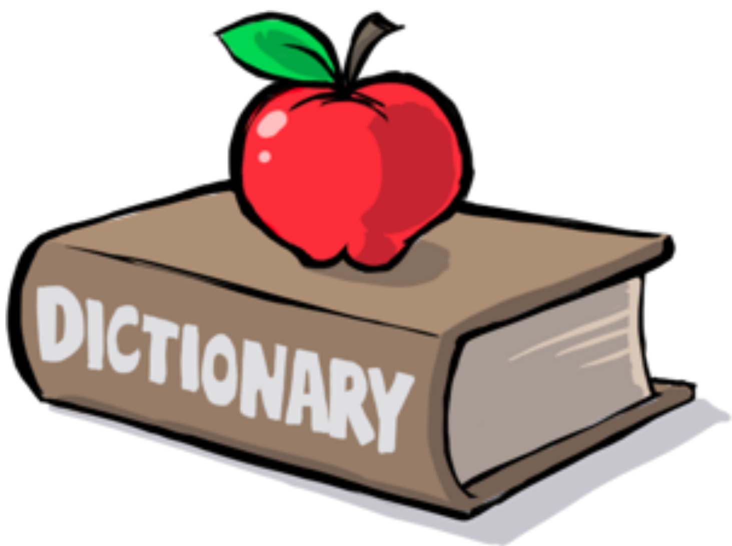
$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

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

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

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

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



SMEFT → Beta-decay LEFT

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

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

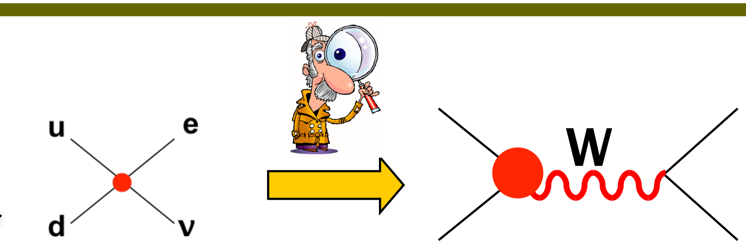
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

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

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

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

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



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

(V-A) x (V+A)

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

SMEFT → Beta-decay LEFT

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

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

Reminder:

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

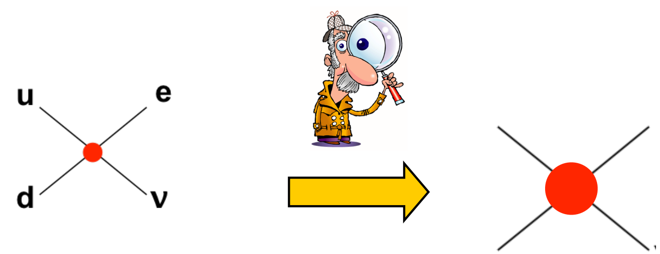
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\right),$$

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

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

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

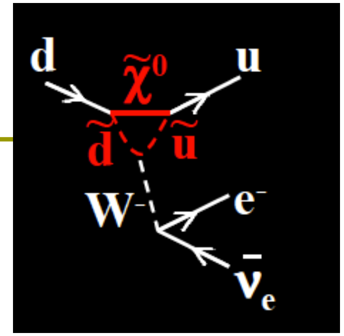
$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]^*_{11j1},$$



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

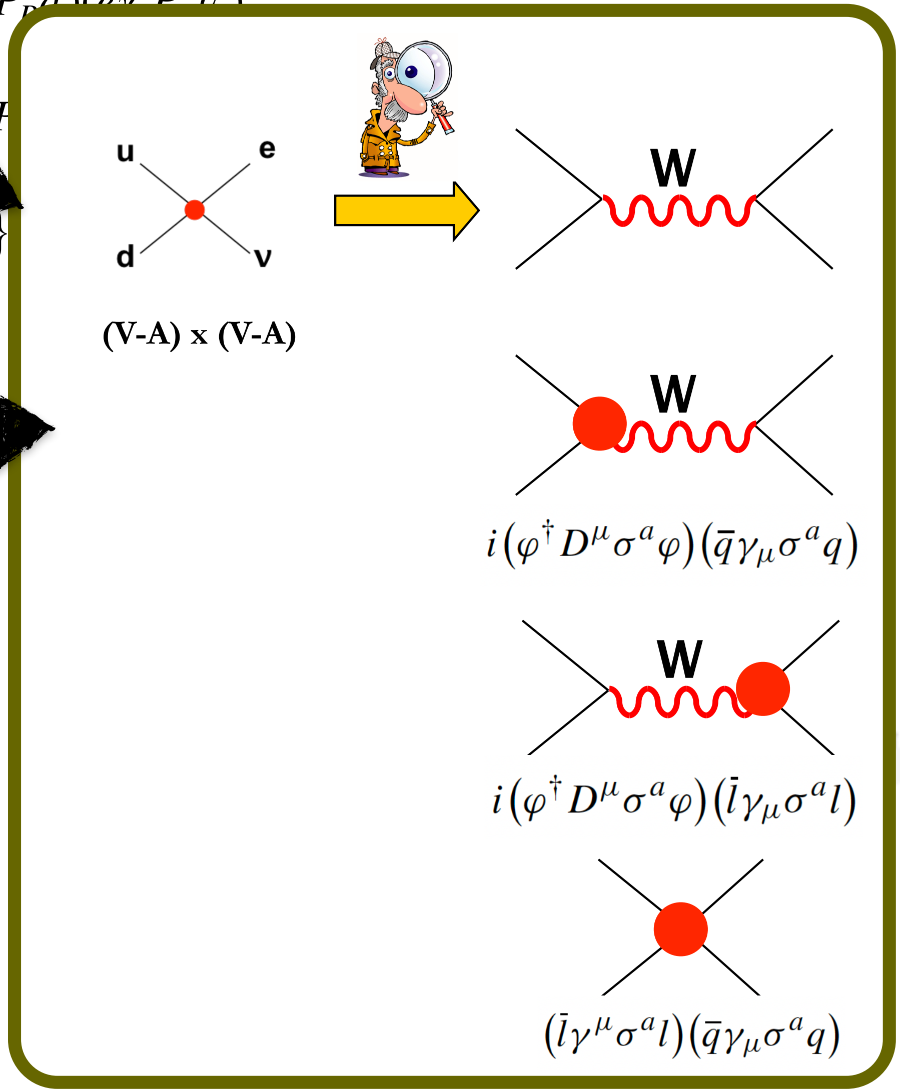


$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \ldots$$

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

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

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



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

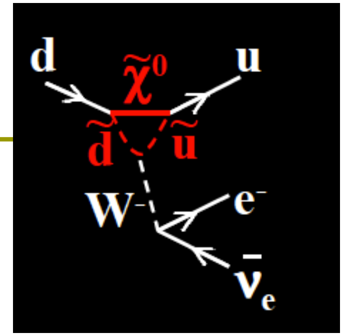
$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

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

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

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

SMEFT → Beta-decay LEFT

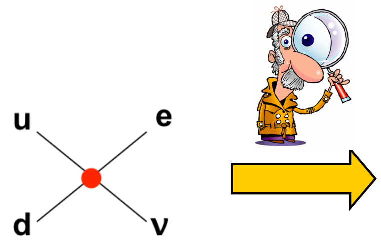


$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \ldots$$

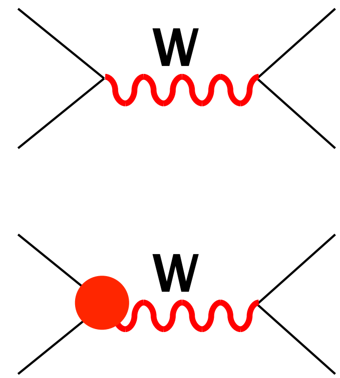
$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

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

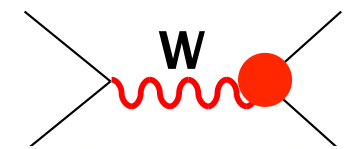
$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\}$$



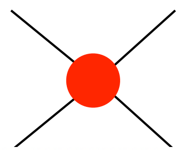
(V-A) x (V-A)



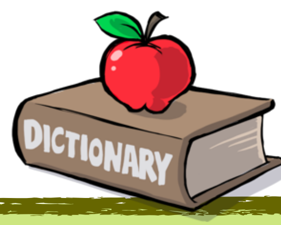
$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q)$



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



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



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

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

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

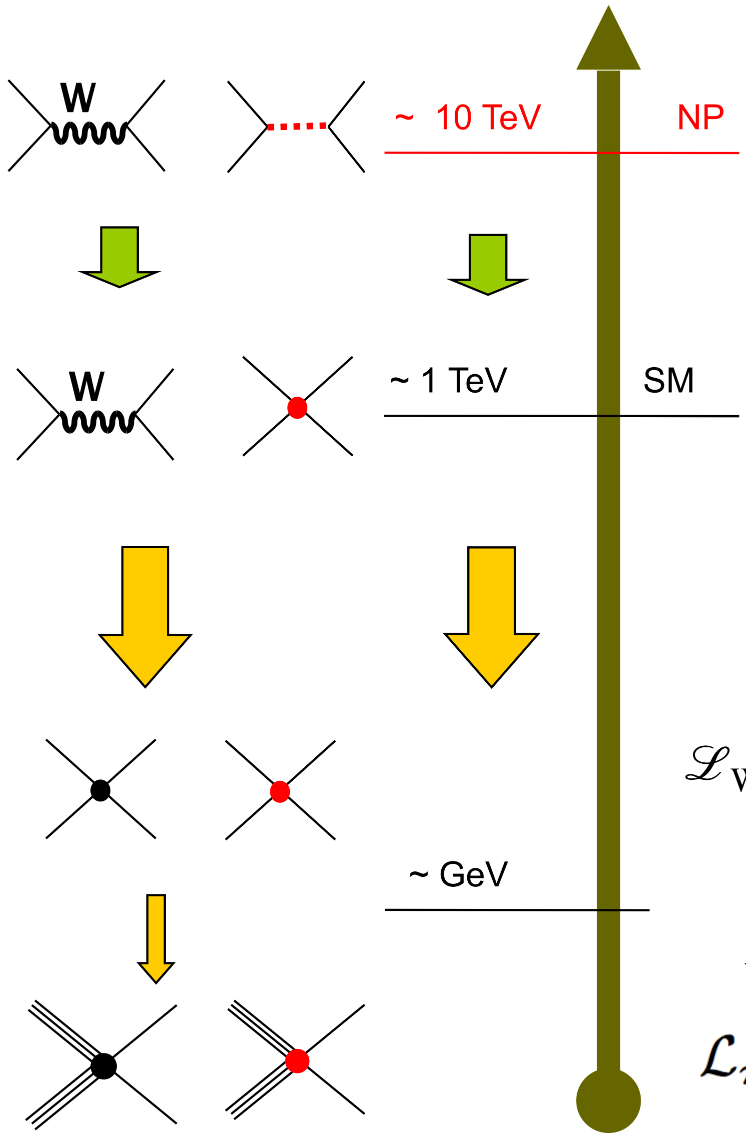
$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11\ldots} - [c_{\ldots}]^*\ldots\right)$$

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

This dictionary shows the interplay between:

- low-E and high-E searches (w/ & w/o Higgs)
- CC ($d \to u e \bar{\nu}$) & NC ($e\, d \to e\, d$) low-E searches

LEFT from SMEFT



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

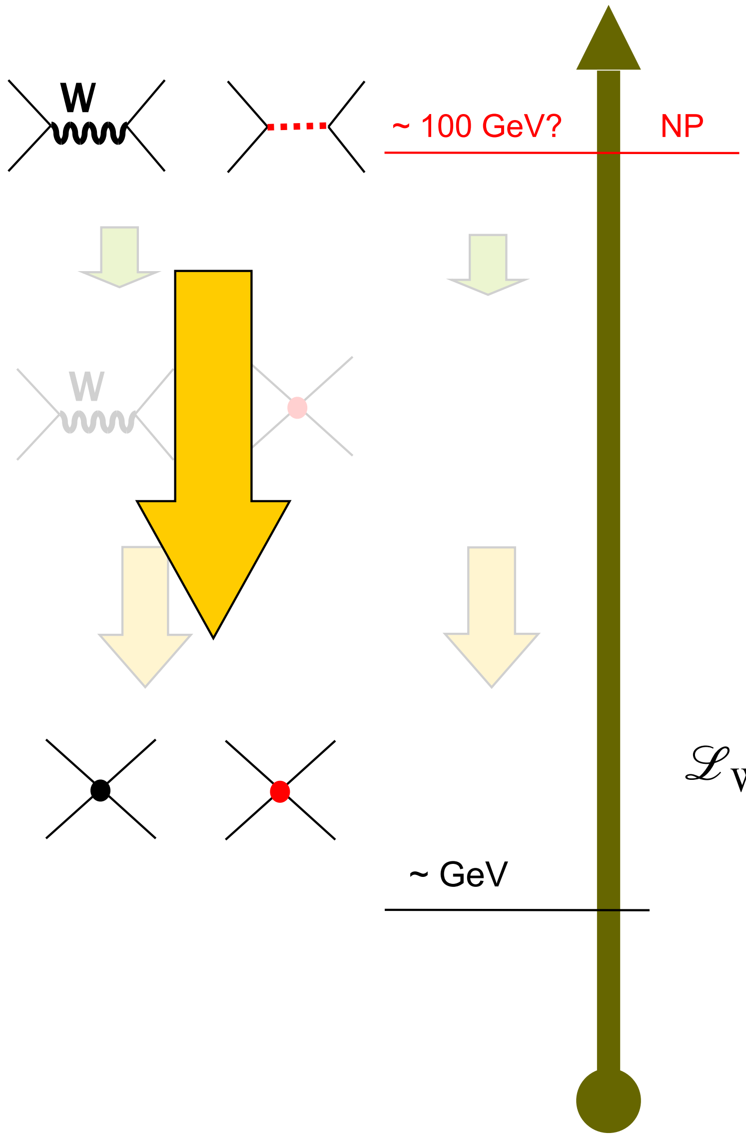
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \dots$$

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

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

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

LEFT ~~from~~ without SMEFT



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

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

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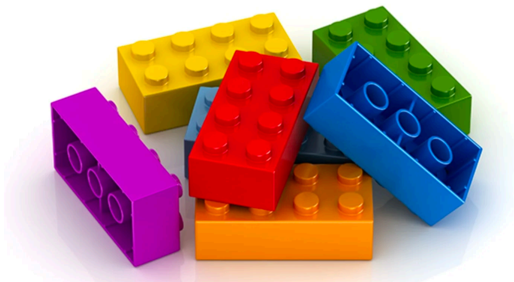
Building the LEFT

Building blocks:

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



Rules

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

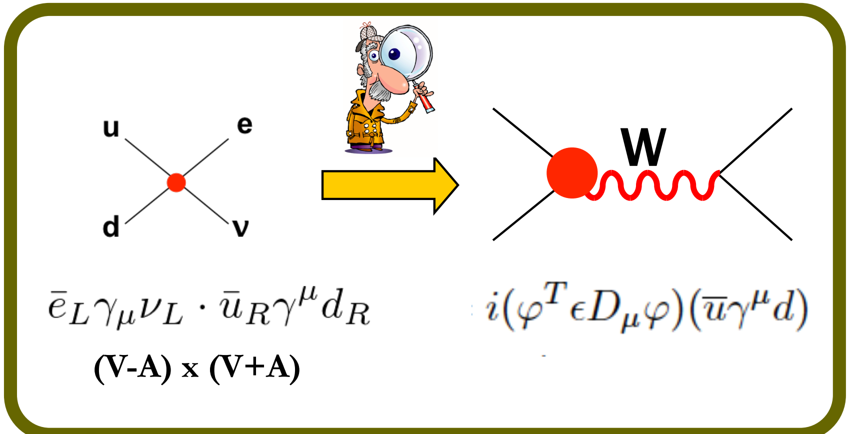
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

[Jenkins et al., 1709.04486]

Beta-decay LEFT (not necessarily from SMEFT)

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

No new operators (SMEFT generates them all)*



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

Not necessarily true anymore

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

Beta-decay LEFT (not necessarily from SMEFT)

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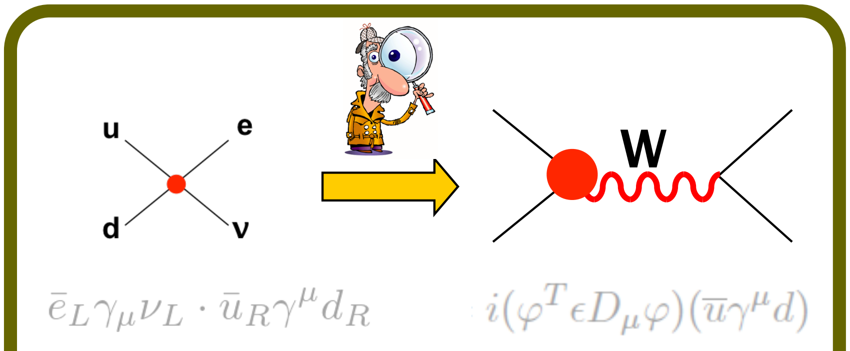
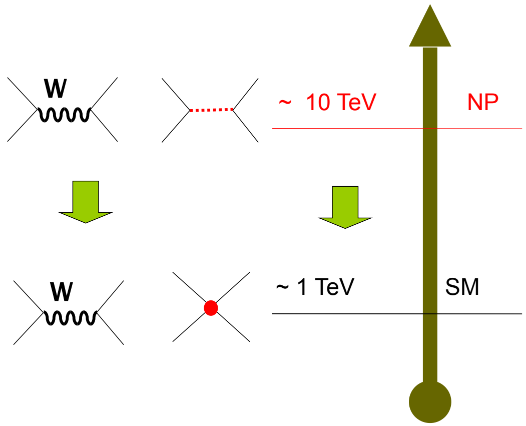


Correlations are lost in the LEFT (w/o SMEFT)

- CC ($d \to u e \bar{\nu}$) vs NC ($e\, d \to e\, d$) low-E searches
- Higgs vs Higgsless processes
- Low-E vs high-E (since the latter are not covered by the LEFT)

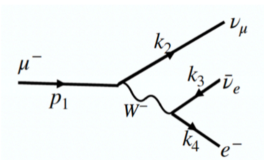
Matching to NP models

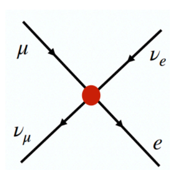


$$\mathscr{L}_{multi-TeV} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$

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

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





~ 100 GeV $\mathcal{L}_{SM}$ (EW theory)

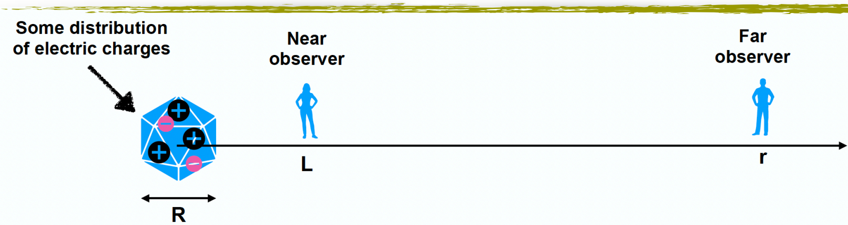
~ GeV

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

+ higher-dim terms

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

Wilson coefficient



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

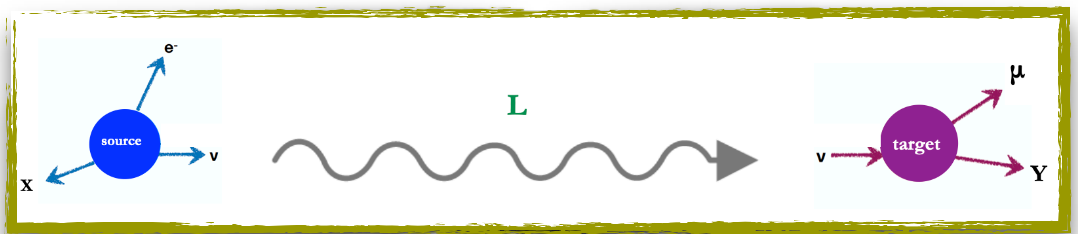
(SM)EFT phenomenology

(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: $X = X_{SM}(V_{ud}) + 3\,C_6$
    One can't just take the value of V_{ud} from the PDG.
    More generally: $V_{ud} \to$ 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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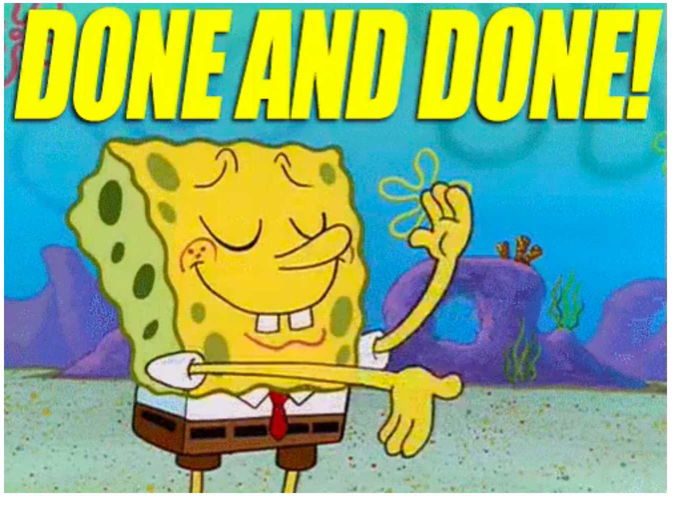
- But once it's done, it's done.
  (you don't have to do it for each model)



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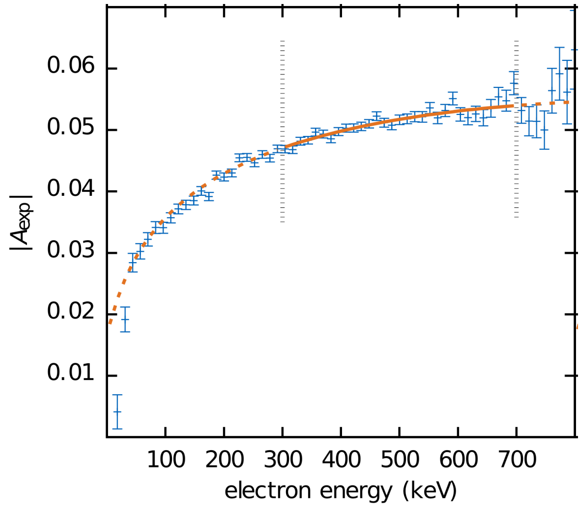
$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i C_6^i O_6^i + \dots \longrightarrow X = X_{SM} + \sum_i \alpha_i C_6^i + \dots$$

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

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



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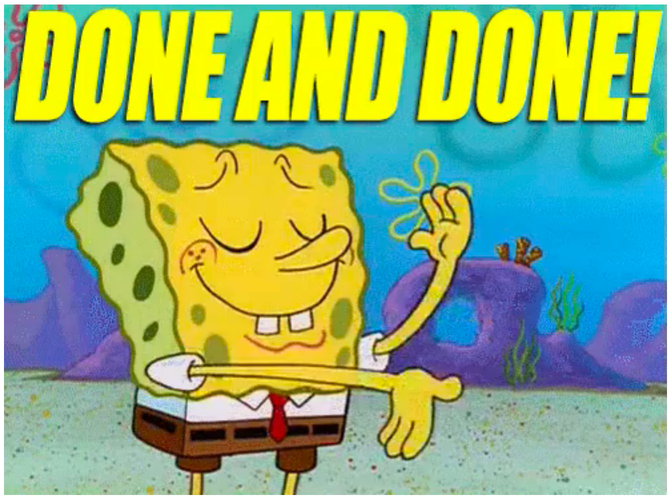
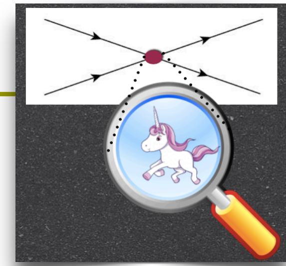


This approach gives us a model-indep. parametrization for the observable X

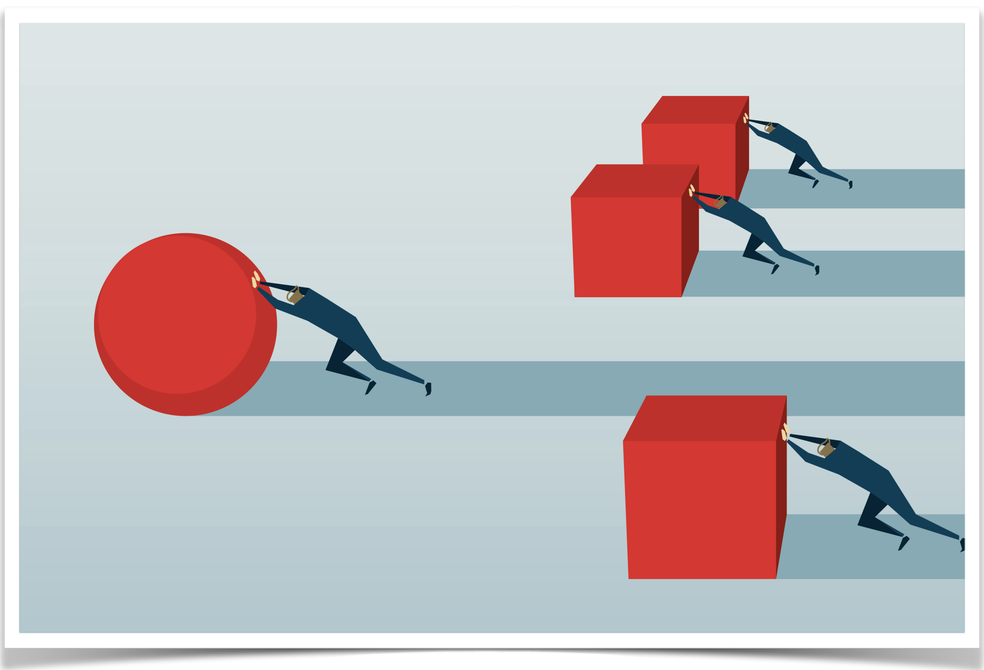
$$\frac{dX}{dE} = \left(\frac{dX}{dE}\right)_{SM} (1 + 2C_6^{13}) + \frac{m_e}{E_e} C_6^4$$

(SM)EFT phenomenology

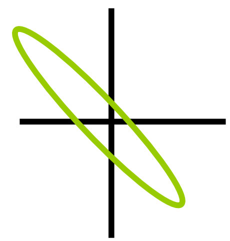


Measurement → **(Correlated) bounds on the EFT Wilson Coefficients** → **Matching with a specific NP model**

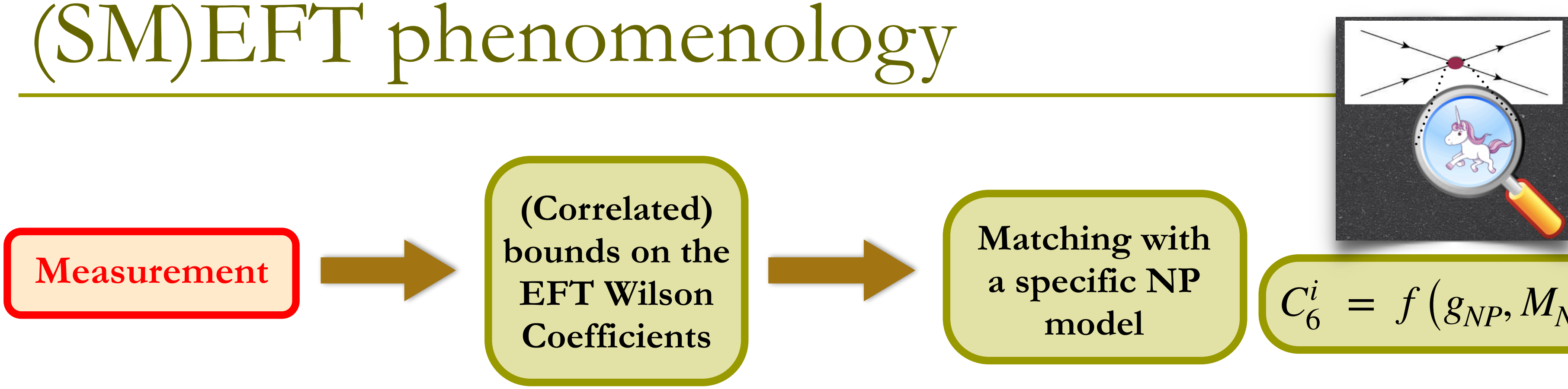
$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$



- 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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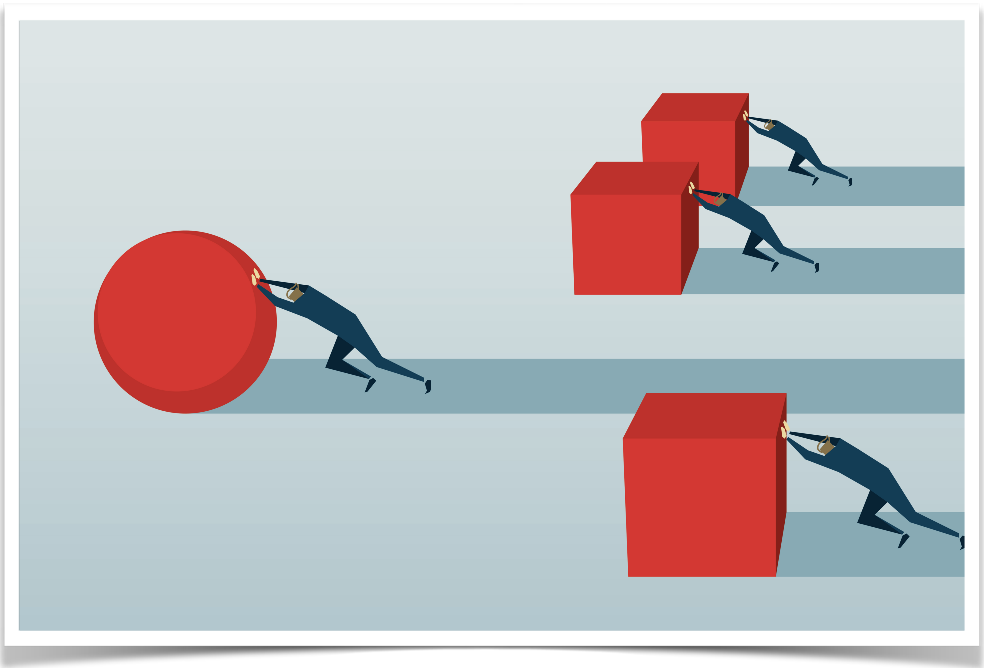
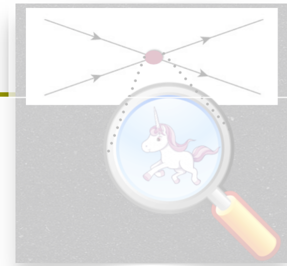


The EFT setup allows us to…

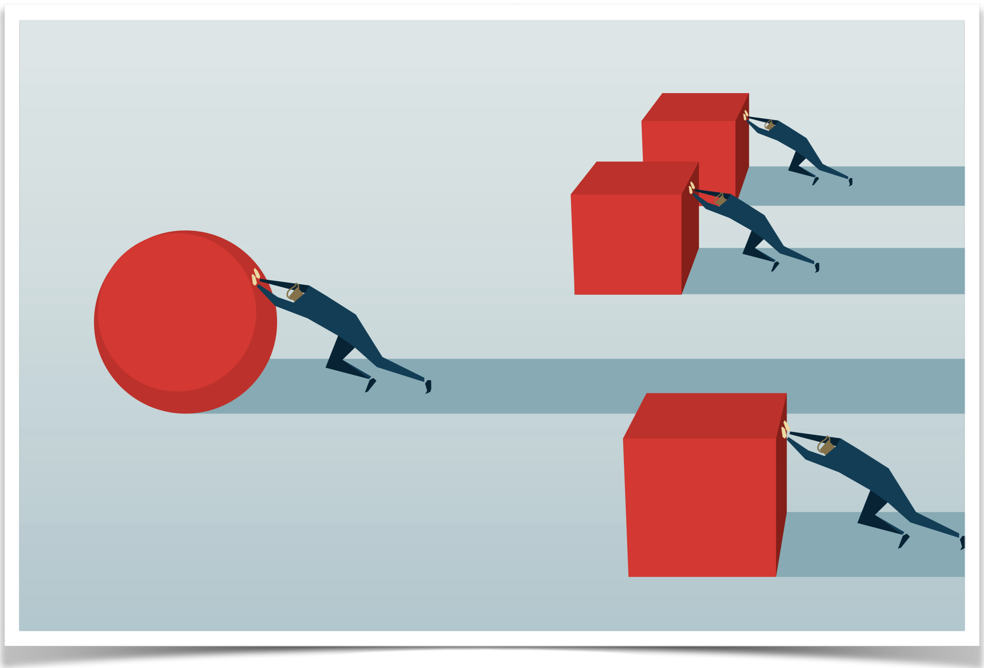
- Obtain results that can be applied to any given model later;
- Assess the interplay between processes (related by symmetries) in a general setup;

(SM)EFT phenomenology



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

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



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

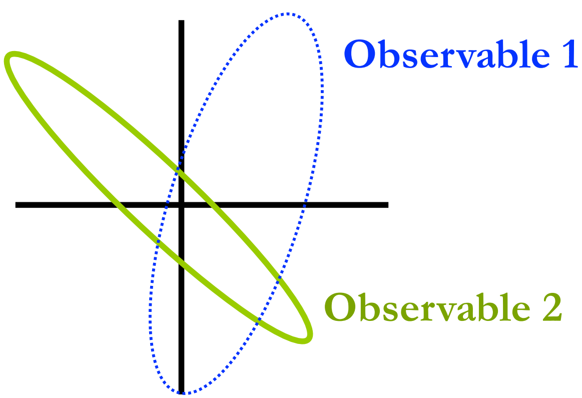
- Choose an operator basis $\{O_1, O_2, \ldots, O_n\}$, *e.g. the Warsaw basis*
  $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma\, C_i\, O_i$

- 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…* $C_1 = 0.001(3)$, $C_2 = \ldots, \ldots$
  More precisely: χ^2 with (*LEP*) measurements gives you central values and error matrix.

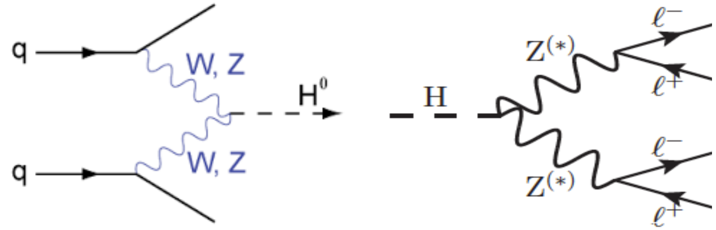
- Implications for your observable? *e.g. error matrix* $\rightarrow 3C_1 - C_6 = 0.02(4)$
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - If your sensitivity is better than that, you are exploring new SMEFT territory and your measurement should be added to the big fit.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

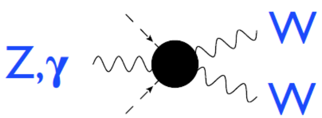
- Often we have a dataset (instead of a single data point O).
  The same logic applies, but it's often better to look at the (C_1, C_6) space → example.



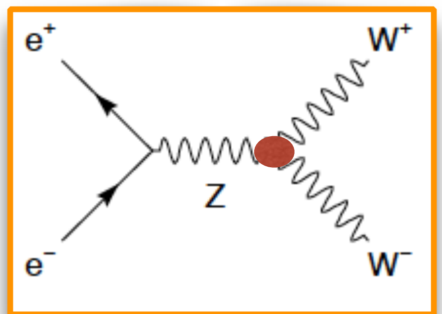
Comparing different probes

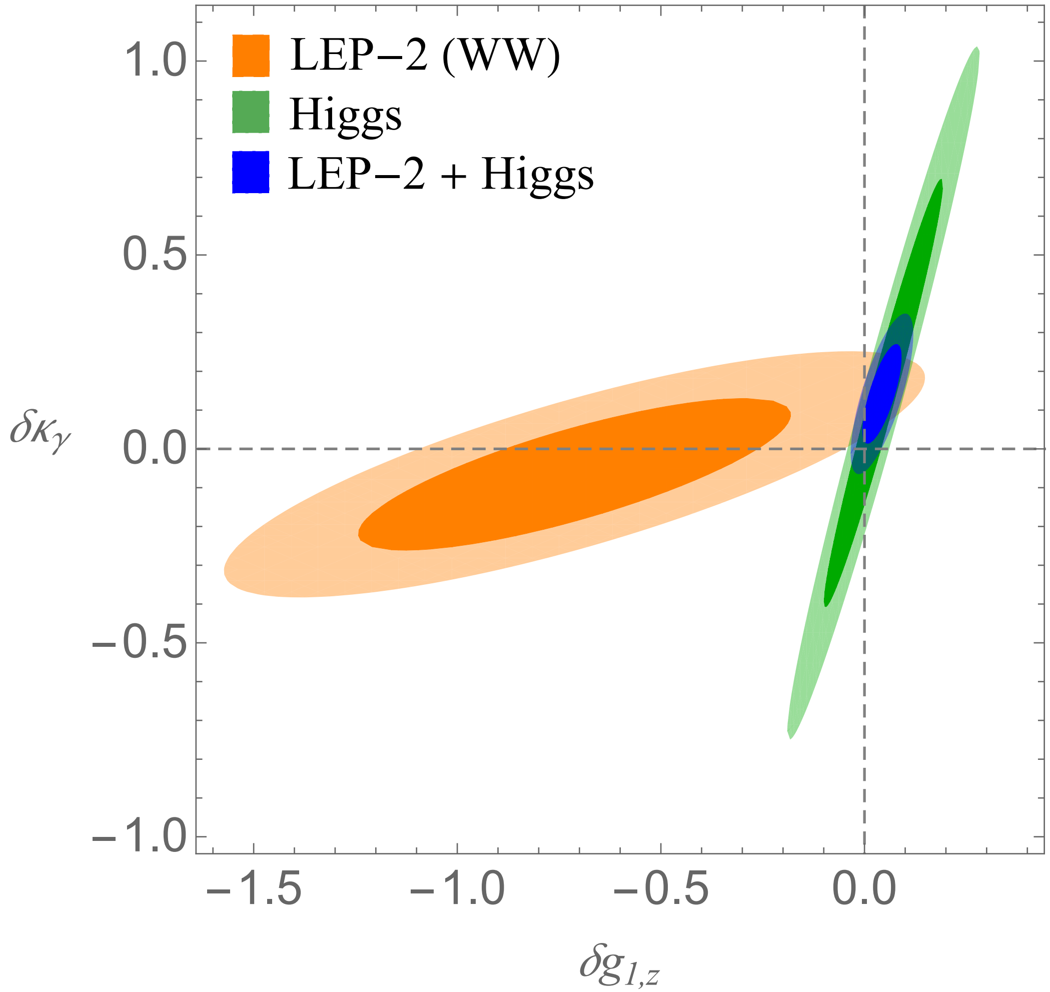
$$(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$





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





[Falkowski et al., 1508.00581]

Fitting room: global analyses

Measurement 1

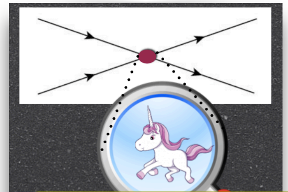
Measurement 2

…

Measurement N

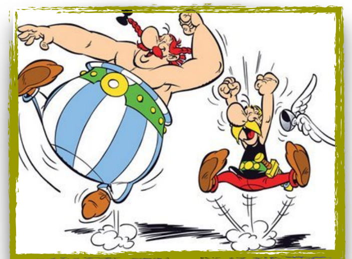
$$\chi^2 = \chi^2(C_6^i)$$

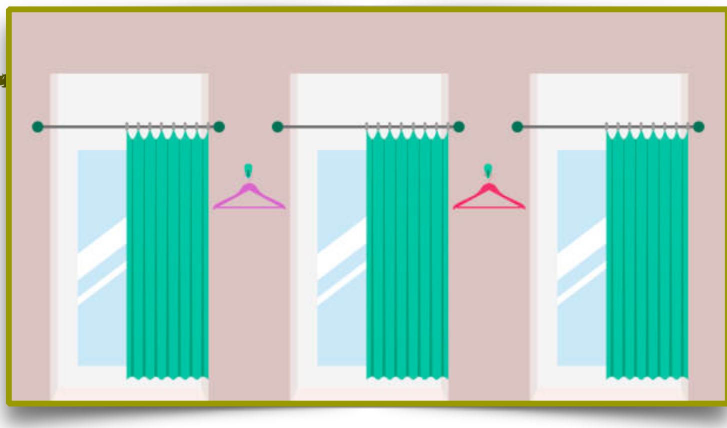
(Correlated) bounds on the EFT Wilson Coefficients



Specific NP model

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





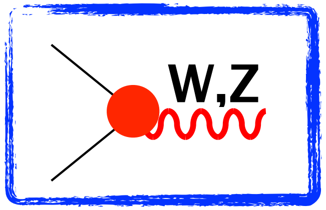
EFT fitting room

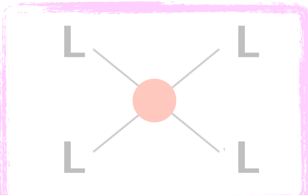
[Efrati et al., 2015]

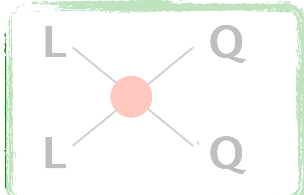
EWPO fit in the flavorful SMEFT

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

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





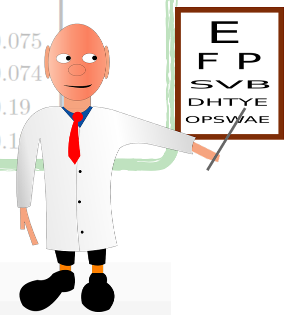


δg_L^{We}	=	-1.00 ± 0.64
$\delta g_L^{W\mu}$		-1.36 ± 0.59
$\delta g_L^{W\tau}$		1.95 ± 0.79
δg_L^{Ze}		-0.023 ± 0.028
$\delta g_L^{Z\mu}$		0.01 ± 0.12
$\delta g_L^{Z\tau}$		0.018 ± 0.059
δg_R^{Ze}		-0.033 ± 0.027
$\delta g_R^{Z\mu}$		0.00 ± 0.14
$\delta g_R^{Z\tau}$		0.042 ± 0.062
δg_L^{Zu}		-0.8 ± 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
$[c_{\ell\ell}]_{1111}$		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

$\times 10^{-2}$,

$[c_{\ell q}^{(3)}]_{1111}$	=	-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
$[c_{\ell u}]_{1122}$		2.4 ± 8.0
$[\hat{c}_{\ell d}]_{1122}$		-310 ± 130
$[c_{eq}]_{1122}$		-21 ± 28
$[c_{eu}]_{1122}$		-87 ± 46
$[\hat{c}_{ed}]_{1122}$		270 ± 140
$[\hat{c}_{\ell q}^{(3)}]_{1133}$		-8.6 ± 8.0
$[c_{\ell d}]_{1133}$		-1.4 ± 10
$[c_{eq}]_{1133}$		-3.2 ± 5.1
$[c_{ed}]_{1133}$		18 ± 20
$[c_{\ell q}^{(3)}]_{2211}$		-1.2 ± 3.9
$[c_{\ell q}]_{2211}$		1.3 ± 7.6
$[c_{\ell u}]_{2211}$		15 ± 12
$[c_{\ell d}]_{2211}$		25 ± 34
$[\hat{c}_{eq}]_{2211}$		4 ± 41
$[c_{\ell equ}]_{1111}$		-0.080 ± 0.075
$[c_{\ell edq}]_{1111}$		-0.079 ± 0.074
$[c_{\ell equ}^{(3)}]_{1111}$		-0.02 ± 0.19
$\epsilon_P^{d\mu}(2\ \mathrm{GeV})$		-0.02 ± 0.1

$\times 10^{-2}$.



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

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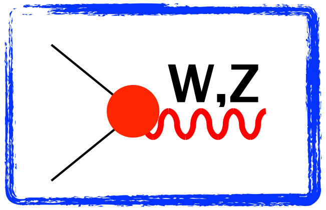

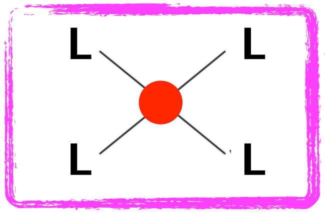

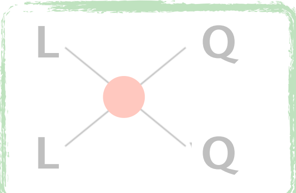

Values $\times 10^{-2}$:

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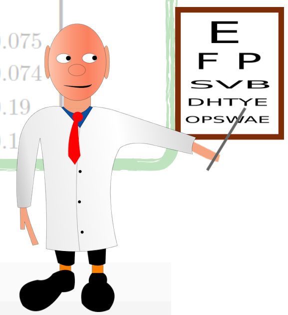
$[c_{\ell e}]_{3311}$	1.7 ± 7.2
$[c_{ee}]_{1133}$	-1 ± 12
$[\hat{c}_{\ell\ell}]_{2222}$	-2 ± 21
[illegible]	3.0 ± 2.3

Values $\times 10^{-2}$:

$[c^{(3)}_{\ell q}]_{1111}$	-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
$[\hat{c}^{(3)}_{\ell q}]_{1122}$	-61 ± 32
$[c_{\ell u}]_{1122}$	2.4 ± 8.0
$[\hat{c}_{\ell d}]_{1122}$	-310 ± 130
$[c_{eq}]_{1122}$	-21 ± 28
$[c_{eu}]_{1122}$	-87 ± 46
$[\hat{c}_{ed}]_{1122}$	270 ± 140
$[\hat{c}^{(3)}_{\ell q}]_{1133}$	-8.6 ± 8.0
$[c_{\ell d}]_{1133}$	-1.4 ± 10
$[c_{eq}]_{1133}$	-3.2 ± 5.1
$[c_{ed}]_{1133}$	18 ± 20
$[c^{(3)}_{\ell q}]_{2211}$	-1.2 ± 3.9
$[c_{\ell q}]_{2211}$	1.3 ± 7.6
$[c_{\ell u}]_{2211}$	15 ± 12
$[c_{\ell d}]_{2211}$	25 ± 34
$[\hat{c}_{eq}]_{2211}$	4 ± 41
$[c_{\ell equ}]_{1111}$	-0.080 ± 0.075
$[c_{\ell edq}]_{1111}$	-0.079 ± 0.074
$[c^{(3)}_{\ell equ}]_{1111}$	-0.02 ± 0.19
$\epsilon_P^{d\mu}(2\ \mathrm{GeV})$	-0.02 ± 0.1



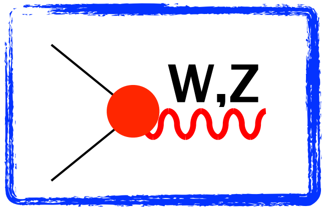
EWPO fit *in the flavorful SMEFT*

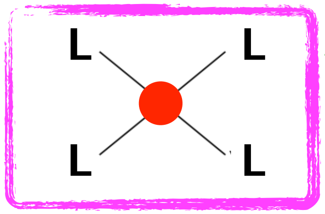
[Efrati et al., 2015]
[Falkowski & Mimouni, 2015]
[Falkowski, MGA & Mimouni, 2017]

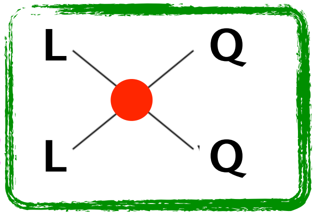
$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \longrightarrow \chi^2 = \chi^2\,(c_i)$$

- 264 experimental input
  - Z- & W-pole data
  - [$e^+e^- \to l^+l^-$, qq]
  - Low-energy processes:
    - hadron decays ($d \to u l \nu$)
    - 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
[illegible]	[illegible]
$[c_{\ell\ell}]_{1111}$	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]	[illegible]

	$\times 10^{-2}$
$[c^{(3)}_{\ell q}]_{1111}$	-2.2 ± 3.2
$[\hat{c}_{eq}]_{1111}$	100 ± 180
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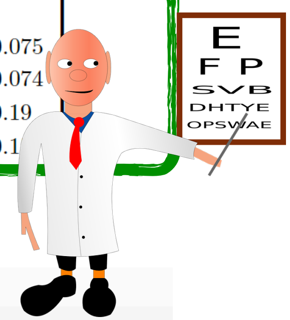
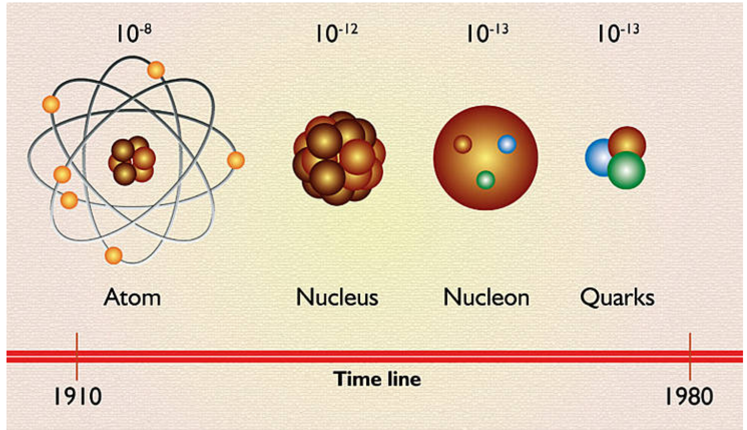
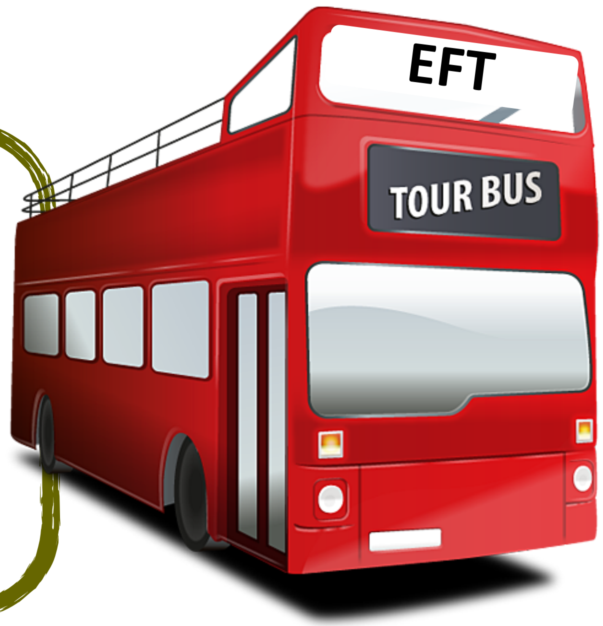


~~Outline~~ Summary

- Intro
- EFT at the ~100 GeV scale: SMEFT
- EFT at E << 100 GeV: LEFT
- EFT phenomenology

Plenty of recent activity!





Disclaimers:

- EFT is a wide field → we'll focus on its application to heavy New Physics
- I don't think a technical 2h presentation would be very useful. Instead I'll give a qualitative (personal) overview, hopefully conveying some important ideas, & giving you the motivation to read a real EFT work
- Many many good refs: EFT (Manohar'97, Pich'98, Rothstein'03, Kaplan'05, Skiba'10, Cohen'19, Burgess'20, ...), SMEFT (**Falkowski'23**, Isidori-Wilsch-Wyler'23, ...), recorded lectures, …