IJCLab Irène Joliot-Curie · CNRS · Université Paris-Saclay · THE MORA PROJECT — MATTER'S ORIGIN FROM RADIOACTIVITY

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SMEFT and CP violation

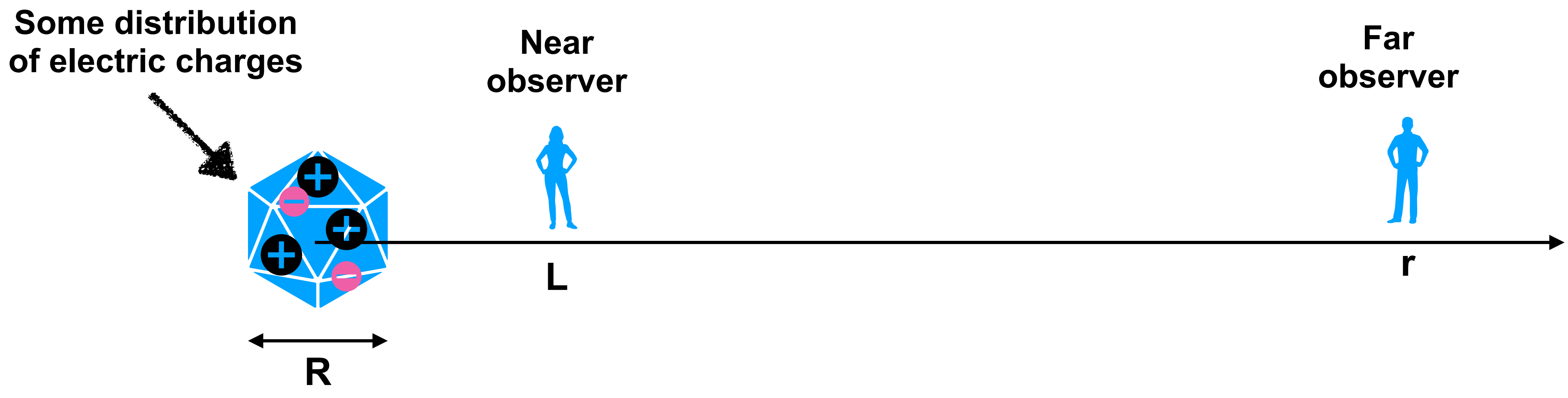
Lectures given at CP2023, International Workshop on the origin of matter-antimatter asymmetry

12-17 February 2023

Part 1

Brief Philosophy of EFT

Role of scale in physical problems



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

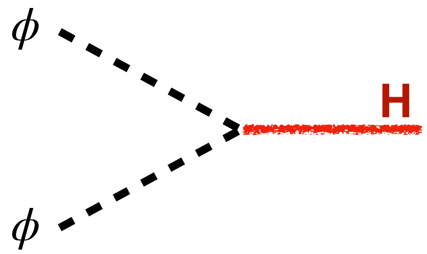
Far observer is able to describe electric field in his vicinity using just a few parameters:
the total electric charge Q, the dipole moment $\vec{d}$, eventually the quadrupole moment Q_{ij}, etc….

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

Far observer, like Molière's Mr. Jourdain,
discovers that he has been using EFT all his life

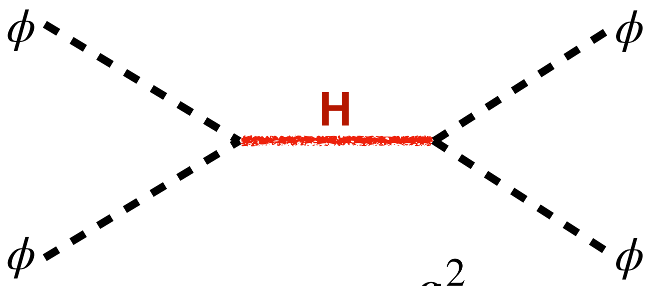
Role of scale in quantum field theory

Consider a theory of a light particle ϕ
interacting with a heavy particle H

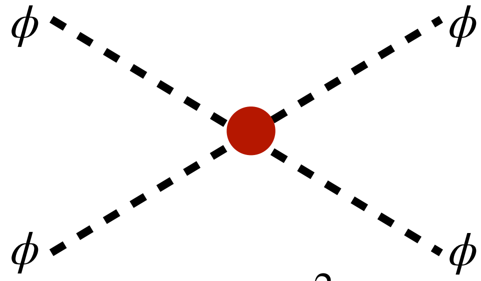


Heavy particle H propagator in momentum space:

$$P(p^2) = \frac{1}{p^2 - m_H^2 + i\epsilon} \approx \begin{cases} \dfrac{1}{p^2 + i\epsilon} & p^2 \gg m_H^2 \\ -\dfrac{1}{m_H^2} & p^2 \ll m_H^2 \end{cases}$$



$$\mathscr{M} \sim \frac{g^2}{p^2 + i\epsilon}$$



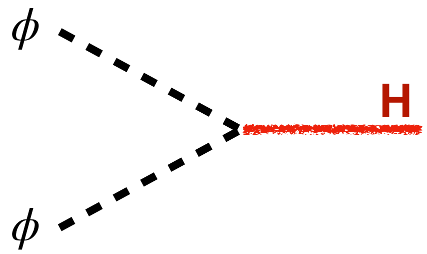
$$\mathscr{M} \sim \frac{g^2}{m_H^2}$$

At large momentum scales, $p^2 >> m_H^2$,
we see propagation of the heavy particle H.
Long range force acting between light particles ϕ

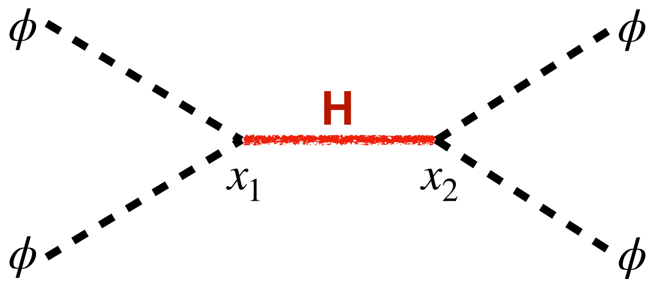
At small momentum scales, $p^2 << m_H^2$,
propagation of the heavy particle H
effectively leads to a contact interaction
between light particles ϕ

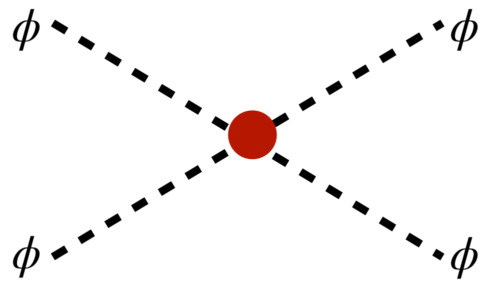
Role of scale in quantum field theory

Consider a theory of a light particle ϕ interacting with a heavy particle H



Heavy particle H propagator in coordinate space: $P(x_1, x_2) \sim \exp(-m_H |x_1 - x_2|)$





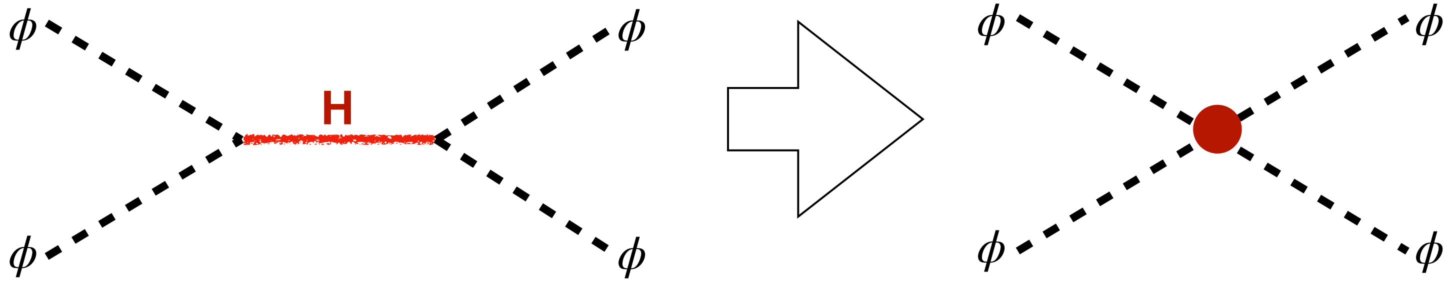
At small distance scales, $|x_1\text{-}x_2| << 1/m_H$, the heavy particle H propagates. Force acting between light particles ϕ

At large distance scales, $|x_1\text{-}x_2| >> 1/m_H$, propagation of the heavy particle H suppressed. Interaction looks like a delta function potential

$$m_H \sim \Delta E \ll \frac{1}{|x_1 - x_2|} \sim \frac{1}{\Delta t} \quad \Rightarrow \quad \Delta E \Delta t \ll 1$$

$$m_H \sim \Delta E \gg \frac{1}{|x_1 - x_2|} \sim \frac{1}{\Delta t} \quad \Rightarrow \quad \Delta E \Delta t \gg 1$$

Role of scale in quantum field theory



- Processes probing distance scales $L \gg m_H$, equivalently energy scales $E \ll m_H$, cannot resolve the propagation of H

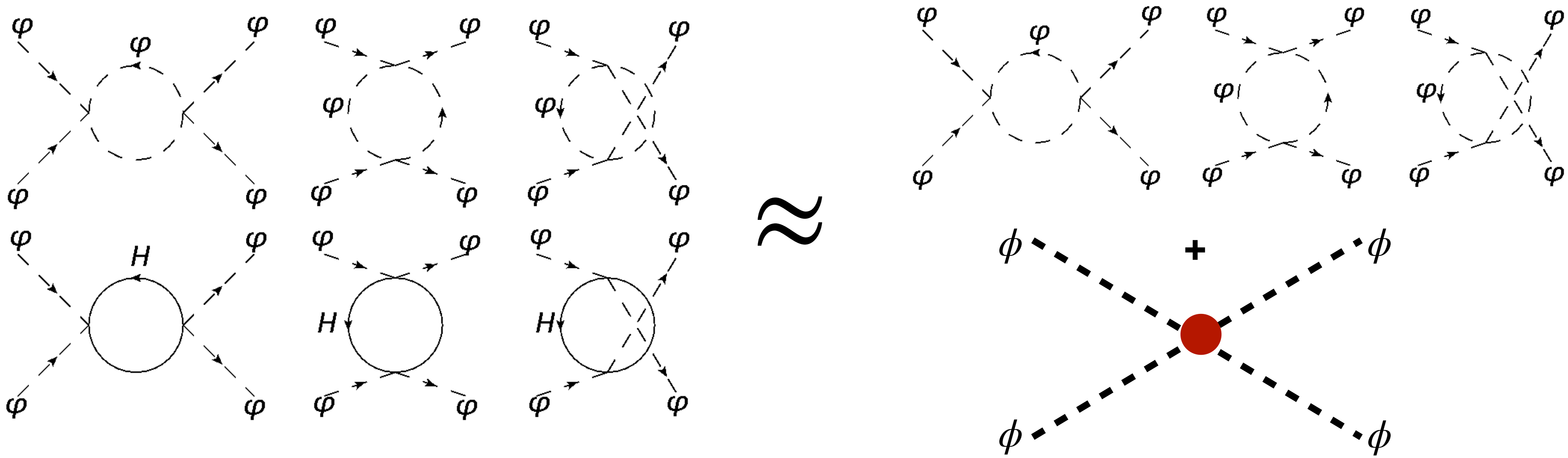
- Then, intuitively, exchange of heavy particle H between light particles ϕ should be indistinguishable from a contact interaction of ϕ

- In other words, the effective theory describing ϕ interactions should be well approximated by a local Lagrangian, that is, by a polynomial in ϕ and its derivatives

This is the generic way how the effective theory description arise in particle physics,

Role of scale in quantum field theory

Effective theory approach works beyond tree level



This works also for higher loops, and with both heavy and light particles in the loops

Effective field theory

How to build an EFT

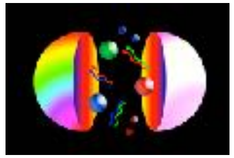
Bottom up

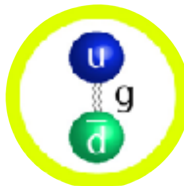
Top down

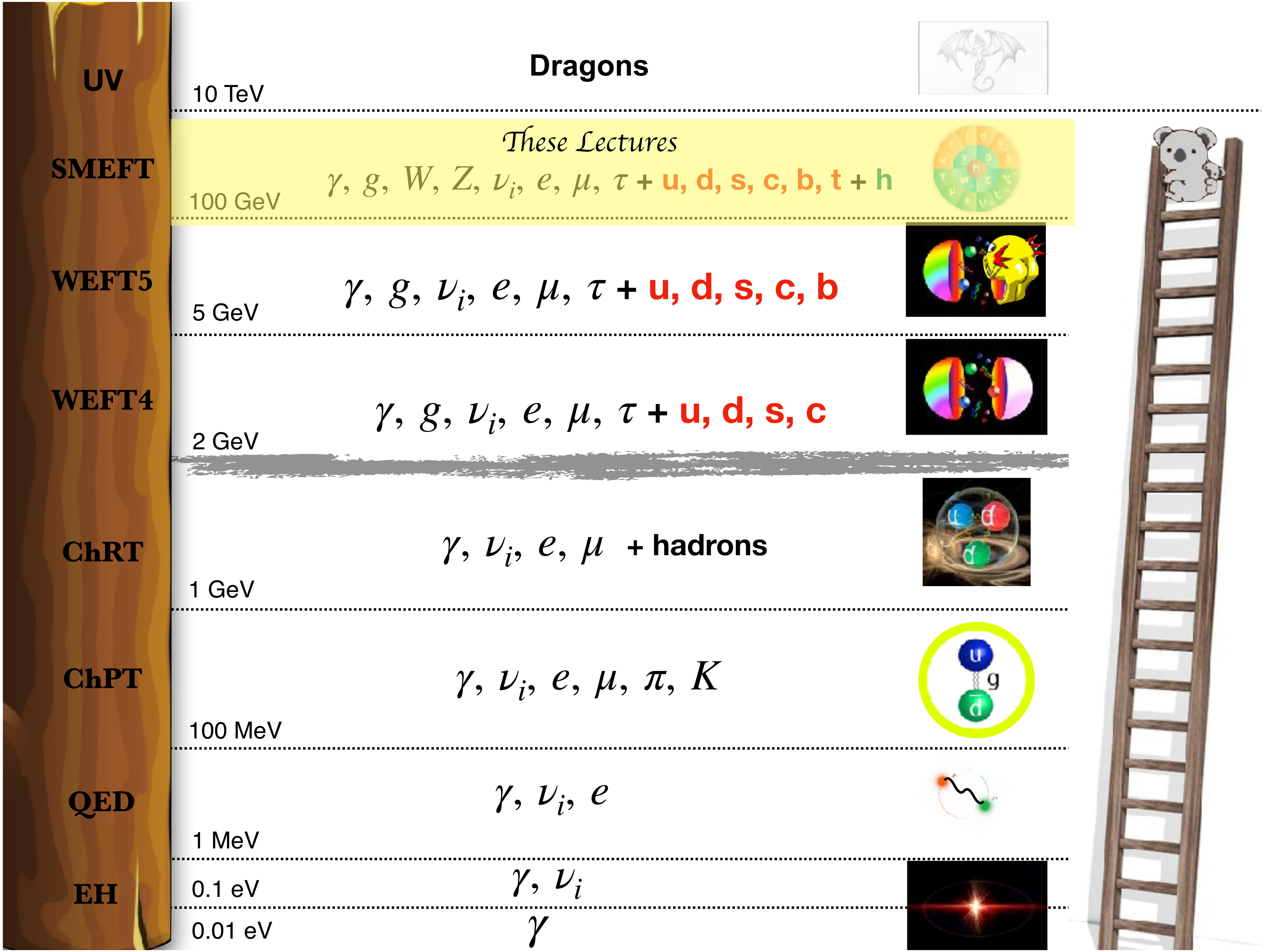
Starting with a set of particles
we build the Lagrangian
describing all their possible interactions
obeying a prescribed set of symmetries
and organised in a consistent expansion

Starting with a given theory
(effective or fundamental)
we integrate out degrees of freedom
heavier than some prescribed mass scale

UV	10 TeV	**Dragons**
SMEFT	100 GeV	$\gamma, g, W, Z, \nu_i, e, \mu, \tau$ + **u, d, s, c, b, t** + **h**
WEFT5	5 GeV	$\gamma, g, \nu_i, e, \mu, \tau$ + **u, d, s, c, b**
WEFT4	2 GeV	$\gamma, g, \nu_i, e, \mu, \tau$ + **u, d, s, c**
ChRT	1 GeV	γ, ν_i, e, μ + **hadrons**
ChPT	100 MeV	$\gamma, \nu_i, e, \mu, \pi, K$
QED	1 MeV	γ, ν_i, e
EH	0.01 eV	γ, ν_i γ





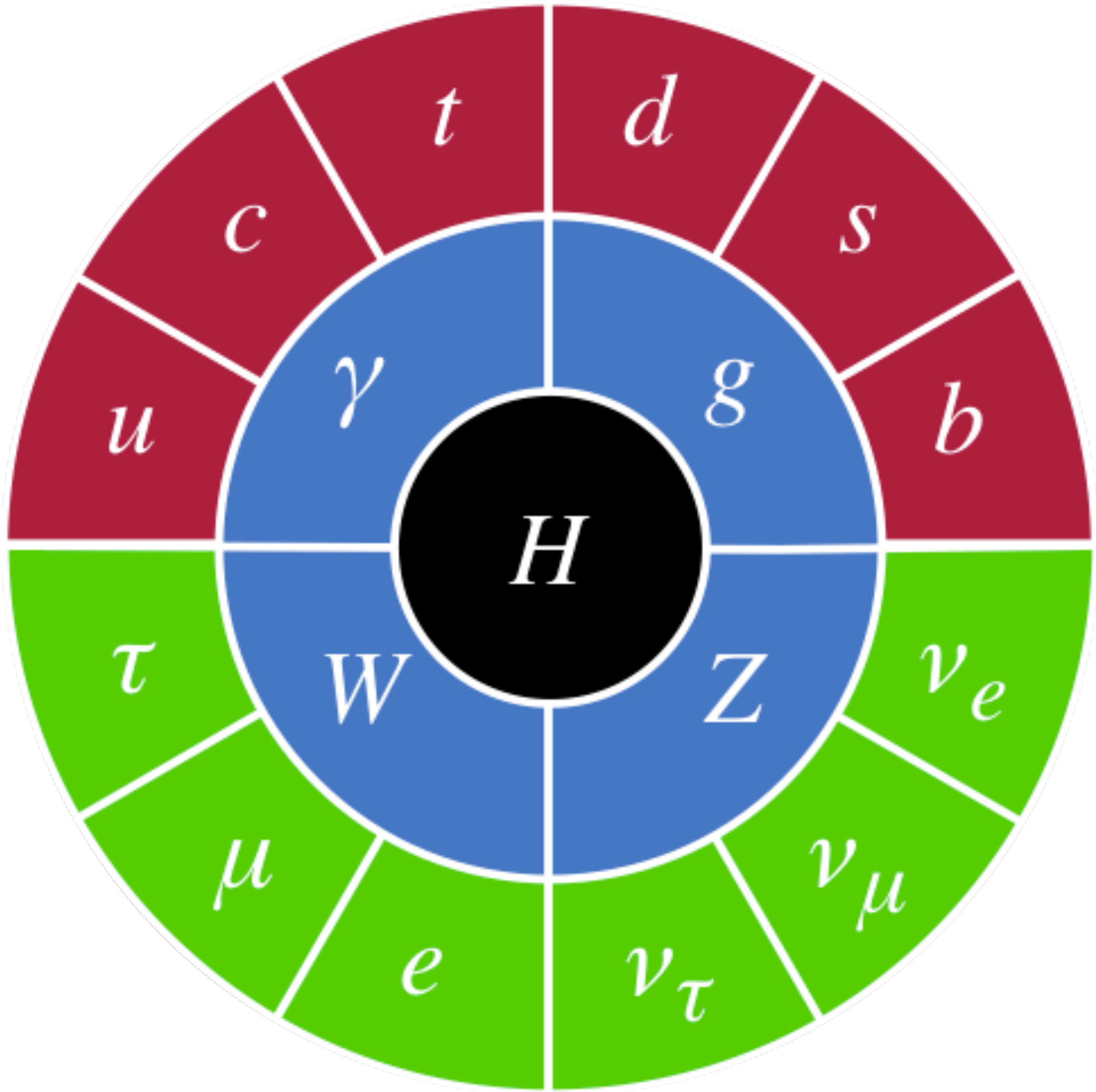


UV
Dragons
10 TeV
SMEFT
These Lectures
γ, g, W, Z, ν_i, e, μ, τ + u, d, s, c, b, t + h
100 GeV
WEFT5
γ, g, ν_i, e, μ, τ + u, d, s, c, b
5 GeV
WEFT4
γ, g, ν_i, e, μ, τ + u, d, s, c
2 GeV
ChRT
γ, ν_i, e, μ + hadrons
1 GeV
ChPT
γ, ν_i, e, μ, π, K
100 MeV
QED
γ, ν_i, e
1 MeV
EH
0.1 eV
γ, ν_i
0.01 eV
γ

Part 2

Introducing SMEFT

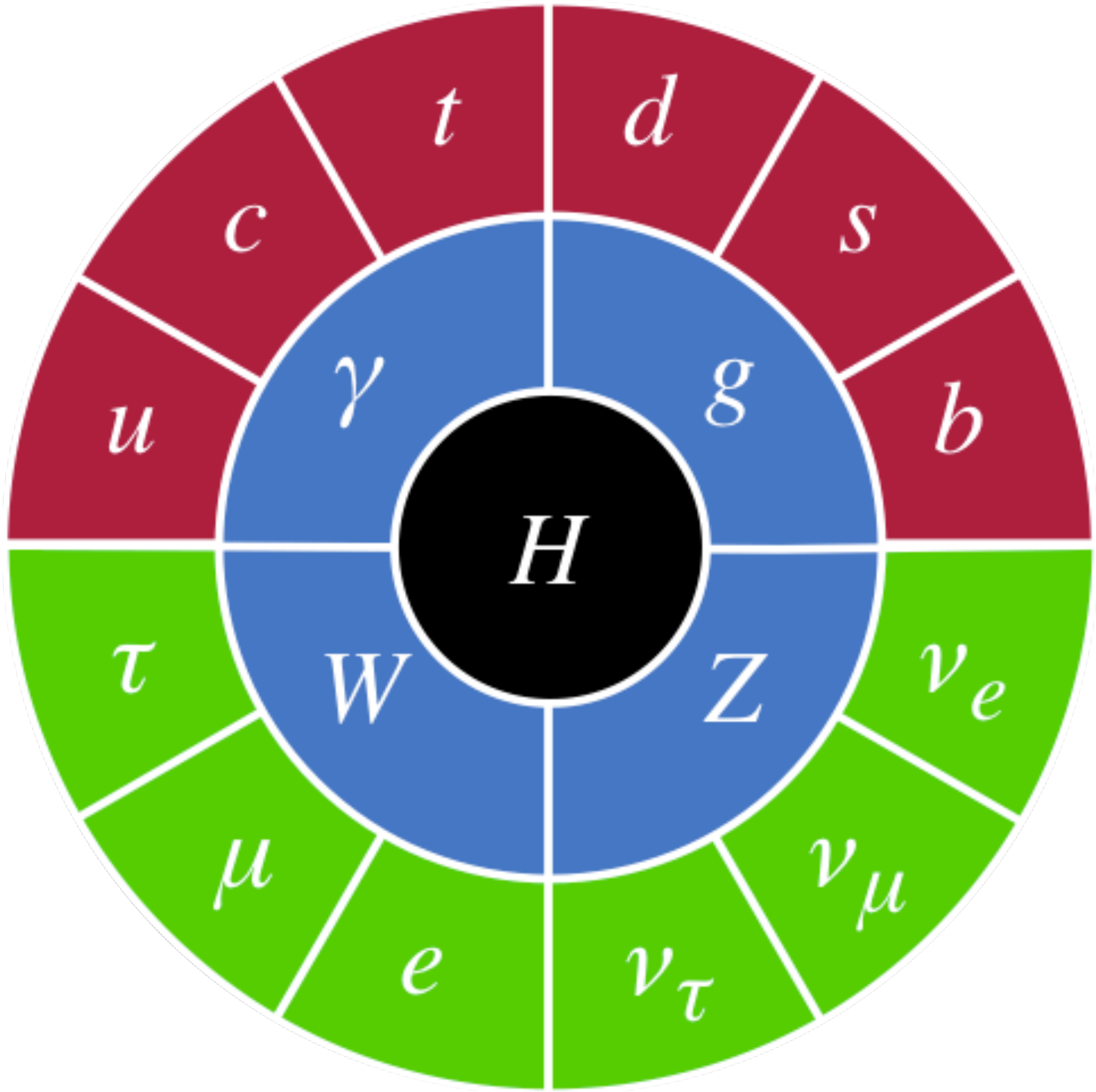
Elementary particles we know today



graviton

This set of particles are the propagating degrees of freedom (at least) right above the electroweak scale, that is at $E \sim$ 100 GeV - 1 TeV

Elementary particles we know today



In these lectures gravity is decoupled and ignored (good assumption in most of laboratory experiments). Otherwise the relevant EFT is called GRSMEFT.

SMEFT

SMEFT is an effective theory for these degrees of freedom:

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Name	Spin	Dimension
G^a_μ	$\mathbf{8}$	$\mathbf{1}$	0	Gluon	1	1
W^k_μ	$\mathbf{1}$	$\mathbf{3}$	0	Weak SU(2) bosons	1	1
B_μ	$\mathbf{1}$	$\mathbf{1}$	0	Hypercharge boson	1	1
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	Quark doublets	1/2	3/2
U^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	Up-type anti-quarks	1/2	3/2
D^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	Down-type anti-quarks	1/2	3/2
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	Lepton doublets	1/2	3/2
E^c	$\mathbf{1}$	$\mathbf{1}$	1	Charged anti-leptons	1/2	3/2
H	$\mathbf{1}$	$\mathbf{2}$	1/2	Higgs field	0	1

incorporating certain physical assumptions:

1. **Locality, unitarity, Poincaré symmetry**
2. **Mass gap: absence of non-SM degrees of freedom at or below the electroweak scale**
3. **Gauge symmetry: local SU(3)xSU(2)xU(1) symmetry strictly respected by all interactions and spontaneously broken to SU(3)xU(1) by a VEV of the Higgs field**

Note on fermion conventions

I am using the 2-component spinor formalism

A Dirac fermion is described by a pair of spinor fields f and $\bar{f}^c$ **with the kinetic and mass terms**

$$\mathscr{L} = i\bar{f}\bar{\sigma}^\mu D_\mu f + i f^c \sigma^\mu D_\mu \bar{f}^c - m f^c f - m \bar{f}\bar{f}^c$$

$$\sigma^\mu = (1, \boldsymbol{\sigma})$$
$$\bar{\sigma}^\mu = (1, -\boldsymbol{\sigma})$$
$$\bar{f} \equiv f^*$$

To translate to 4-component Dirac notation use

$$F = \begin{pmatrix} f \\ \bar{f}^c \end{pmatrix}, \qquad \bar{F} = \begin{pmatrix} f^c & \bar{f} \end{pmatrix}, \qquad \gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}$$

$$\bar{F} \equiv F^\dagger \gamma^0$$

For example

$$\bar{f}\bar{\sigma}^\mu \partial_\mu f = \bar{F}_L \gamma^\mu \partial_\mu F_L$$

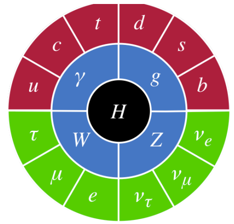
$$f^c \sigma^\mu \partial_\mu \bar{f}^c = \bar{F}_R \gamma^\mu \partial_\mu F_R$$

$$f^c f = \bar{F}_R F_L$$

$$\bar{f}\bar{f}^c = \bar{F}_L F_R$$

See the spinor bible [arXiv:0812.1594] for more details

SMEFT power counting



1. **Locality, unitarity, Poincaré symmetry**
2. **Mass gap: absence of non-SM degrees of freedom at or below the electroweak scale**
3. **Gauge symmetry: local SU(3)xSU(2)xU(1) symmetry strictly respected by all interactions**

We can organize the SMEFT Lagrangian in a dimensional expansion:

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Each $\mathscr{L}_D$ is a linear combination of SU(3)xSU(2)xU(1) invariant interaction terms (operators) where D is the sum of canonical dimensions of all the fields entering the interaction

Since Lagrangian has mass dimension $[\mathscr{L}] = 4$, by dimensional analysis the couplings (Wilson coefficients) of interactions in $\mathscr{L}_D$ have mass dimension $[C_D] = 4 - D$

Standard SMEFT power counting: $C_D \sim \dfrac{c_D}{\Lambda^{D-4}}$ where $c_D \sim 1$,

and Λ is identified with the mass scale of the UV completion of the SMEFT,

In the spirit of EFT, each $\mathscr{L}_D$ should include a complete and non-redundant set of interactions

SMEFT power counting

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

SM Lagrangian

Higher-dimensional $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant interactions added to the SM

At sufficiently high energies, such that we can ignore particle masses, amplitudes for physical processes take the form

$$\mathscr{M}_{\rm SMEFT} = \mathscr{M}_{\rm SM} + C_{D=5}E + C_{D=6}E^2 + C_{D=7}E^3 + C_{D=8}E^4 + \ldots$$

$$\sim \mathscr{M}_{\rm SM} + \frac{c_5 E}{\Lambda} + \frac{c_6 E^2}{\Lambda^2} + \frac{c_7 E^3}{\Lambda^3} + \frac{c_8 E^4}{\Lambda^4} + \ldots$$

Standard SMEFT power counting sets up the rules for expanding the amplitudes and observables in powers of the new physics scale Λ.
For $E \ll \Lambda$ expansion can be truncated at some D, depending on the desired precision

SMEFT

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Only a single D=2 operator can be build from the SM fields:

$$\mathscr{L}_{D=2} = \mu_H^2 H^\dagger H$$

Philosophy of EFT: $\mu_H \sim \Lambda \gtrsim 1\ \text{TeV}$

Experiment: $\mu_H \sim 100\ \text{GeV}$

Unsolved mystery why $\mu_H^2 \ll \Lambda^2$,
which is called the hierarchy problem

From the point of view of EFT, the hierarchy problem is a breakdown of dimensional analysis

SMEFT

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

$$\mathscr{L}_{D=3} = 0$$

Simply, no gauge invariant operators made of SM fields exist at canonical dimension D=3

The absence of D=3 operators is a feature of SMEFT, but not a law of nature. E.g. in νSMEFT, where one also has singlet neutrino, one can write down

$$\mathscr{L}_{D=3}^{\nu\text{SMEFT}} = \frac{1}{2}\nu^c M_\nu \nu^c + \text{h.c.}$$

SMEFT

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

D=4 is special because it doesn't contain an explicit scale (marginal interactions)

$$\mathscr{L}_{D=4} = -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \sum_{f\in Q,L} i\bar{f}\bar{\sigma}^\mu D_\mu f + \sum_{f\in U,D,E} if^c\sigma^\mu D_\mu \bar{f}^c$$
$$-\left(U^cY_u\tilde{H}^\dagger Q + D^cY_dH^\dagger Q + E^cY_eH^\dagger L + \text{h.c.}\right) + D_\mu H^\dagger D^\mu H - \lambda(H^\dagger H)^2$$
$$+\tilde{\theta}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu},$$

$$\tilde{H}_a = \epsilon^{ab}H^*_b$$
$$V^a_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu - gf^{abc}V^b_\mu V^c_\nu$$
$$D_\mu f = \partial_\mu f + ig_sG^a_\mu T^a f + ig_LW^i_\mu\frac{\sigma^i}{2}f + ig_YB_\mu Yf$$
$$\tilde{G}^a_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}G^{\alpha\beta\ a}$$

$$U^c = \begin{pmatrix} u^c \\ c^c \\ t^c \end{pmatrix} \quad D^c = \begin{pmatrix} d^c \\ s^c \\ b^c \end{pmatrix} \quad E^c = \begin{pmatrix} e^c \\ \mu^c \\ \tau^c \end{pmatrix}$$

$$Q = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \\ \begin{pmatrix} c \\ s \end{pmatrix} \\ \begin{pmatrix} t \\ b \end{pmatrix} \end{pmatrix} \quad L = \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix} \\ \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \\ \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \end{pmatrix}$$

Experiment: all these interactions at D=4 above have been observed, except for $\tilde{\theta}$

Strictly speaking, λ has not been observed directly. Its value is known within SM hypothesis, but not within SMEFT, without additional assumptions. Observation of double Higgs production (receiving contribution from cubic Higgs coupling) will be a direct proof that λ is there in the Lagrangian.

Note that $\theta_B B_{\mu\nu}\tilde{B}_{\mu\nu}$ has no physical consequences, while $\theta_W W^k_{\mu\nu}\tilde{W}^k_{\mu\nu}$ can be eliminated by chiral rotation

SMEFT at dimension-5

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Weinberg (1979)
Phys. Rev. Lett. 43, 1566

$$H \to \begin{pmatrix} 0 \\ \mathrm{v}/\sqrt{2} \end{pmatrix}$$

$$\mathscr{L}_{D=5} = (LH)C(LH) + \mathrm{h.c.} \to \frac{1}{2} \sum_{J,K=e,\mu,\tau} \mathrm{v}^2 C_{JK}(\nu_J \nu_K) + \mathrm{h.c.}$$

- At dimension 5, the only gauge-invariant operators one can construct are the so-called Weinberg operators, which break the lepton number

- After electroweak symmetry breaking they give rise to Majorana mass terms for the SM (left-handed) neutrinos with the mass matrix $M = -\mathrm{v}^2 C$

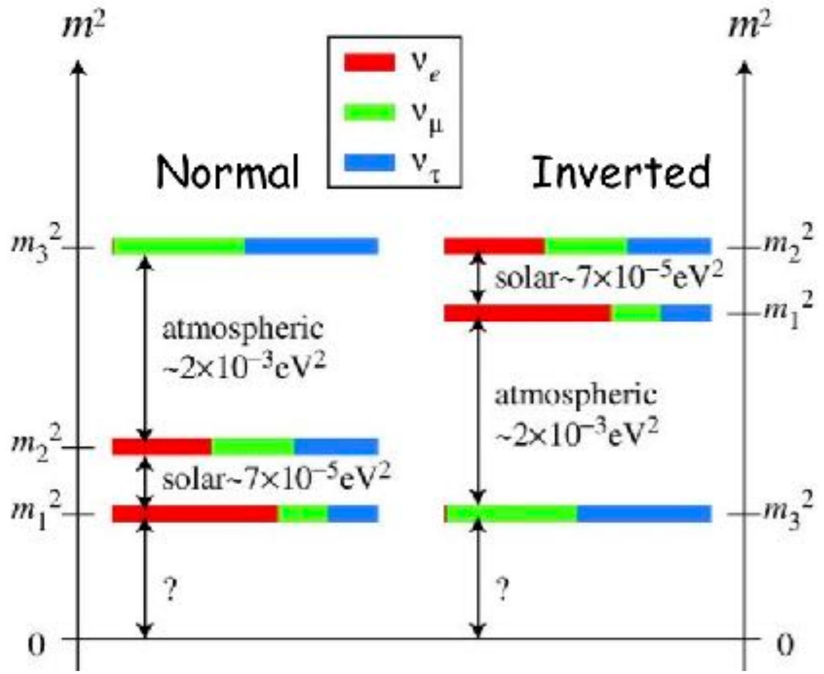
- Neutrino oscillation experiments strongly suggest that these operators are present (unless neutrino masses are of the Dirac type)

This is a huge success of the SMEFT paradigm:
corrections to the SM Lagrangian predicted at the next order in the EFT expansion, are indeed observed in experiment!

SMEFT at dimension-5

$$\mathscr{L}_{\mathrm{SMEFT}} \supset -\frac{1}{2}(\nu M \nu) + \mathrm{h.c.} \qquad M = -\mathrm{v}^2 C$$

Neutrino masses or most likely in the 0.01 eV - 0.1 eV ballpark (though the lightest neutrino may even be massless)

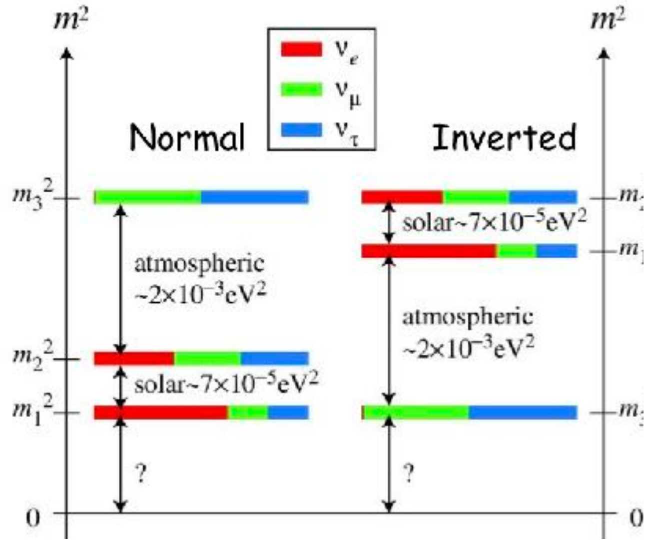


It follows that the dimension-5 Wilson coefficient is of order $C \sim \dfrac{1}{\Lambda}$ with $\Lambda \sim 10^{15}$ **GeV**

One one hand, that is perfect, because it suggests that the basic SMEFT assumption, $\Lambda \gg \mathrm{v}$, **is indeed satisfied**

SMEFT at dimension-5

$$\mathscr{L}_{\rm SMEFT} \supset -\frac{1}{2}(\nu M \nu) + \text{h.c.} \quad M = -\,\mathrm{v}^2 C$$



However, $\Lambda \sim 10^{15}$ **GeV leads to a *psychological* problem**

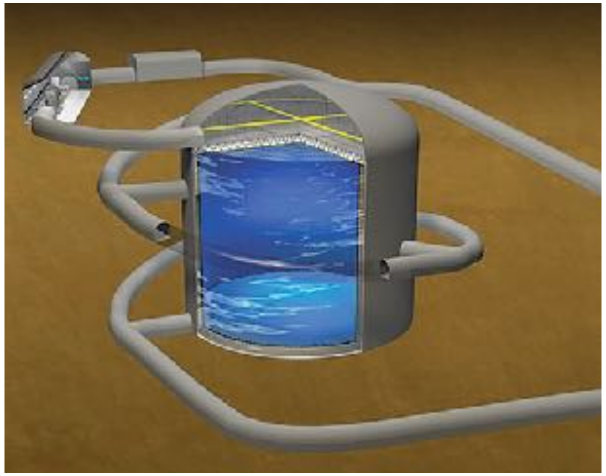
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

If $\mathscr{L}_{D=5} \sim \frac{1}{\Lambda}$ **then naive SMEFT counting suggest** $\mathscr{L}_{D=6} \sim \frac{1}{\Lambda^2}$ **,** $\mathscr{L}_{D=7} \sim \frac{1}{\Lambda^3}$**,**

and so on

If this is really the correct estimate, then we will never see any other effects of higher-dimensional operators, except possibly of the baryon-number violating ones :/

Career opportunities



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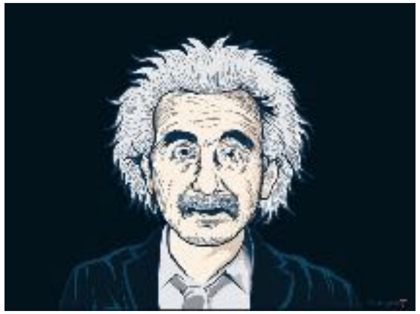
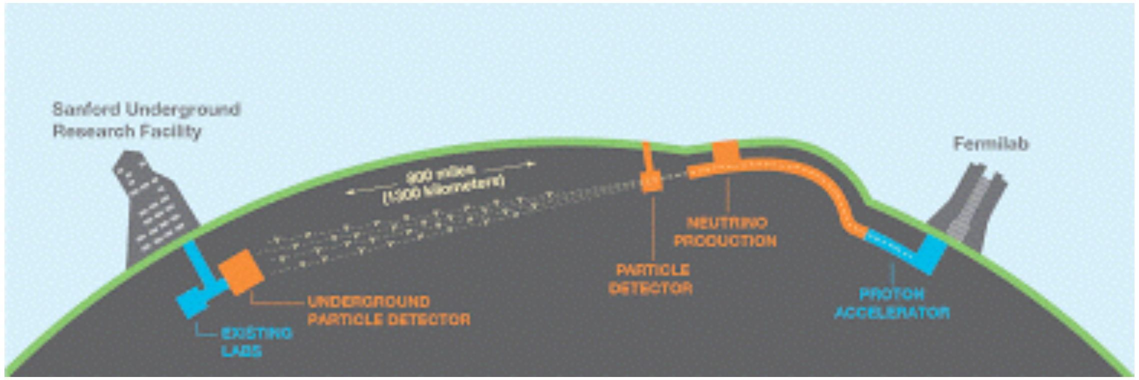
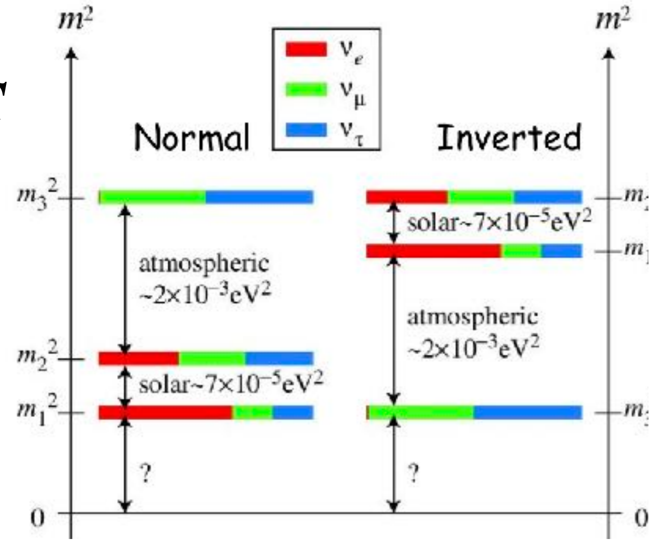




SMEFT at dimension-5

$$\mathscr{L}_{\text{SMEFT}} \supset -\frac{1}{2}(\nu M \nu) + \text{h.c.} \quad M = -\text{v}^2 C$$



$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

If $\mathscr{L}_{D=5} \sim \frac{1}{\Lambda}$ **then naive SMEFT counting suggest**

$$\mathscr{L}_{D=6} \sim \frac{1}{\Lambda^2}, \mathscr{L}_{D=7} \sim \frac{1}{\Lambda^3}, \ldots$$

However, this conclusion is not set in stone
It is possible that the true new physics scale is not far from TeV,
but its coupling to the lepton sector is very small

Alternatively, it is possible (and likely) that there is more than one mass scale of new physics

Dimension-5 interactions are special because they violate lepton number L.
More generally, all odd-dimension SMEFT operators violate B-L
If we assume that the mass scale of new particles with B-L-violating interactions is Λ_L**,**
and there is also B-L-conserving new physics at the scale $\Lambda \ll \Lambda_L$ **, then the estimate is**

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

SMEFT at dimension-6

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

Grządkowski et al
arXiv:1008.4884

At dimension-6 all hell breaks loose

$$\begin{aligned}
\mathscr{L}_{D=6} = {} & C_H (H^\dagger H)^3 + C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}|H^\dagger D_\mu H|^2 \\
& + C_{HWB} H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu} + C_{HG} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} + C_{HW} H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu} + C_{HB} H^\dagger H\, B_{\mu\nu} B_{\mu\nu} \\
& ++ C_W \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_G f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \\
& + C_{H\widetilde{G}} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu} + C_{H\widetilde{W}} H^\dagger H\, \widetilde{W}^k_{\mu\nu} W^k_{\mu\nu} + C_{H\widetilde{B}} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu} + C_{H\widetilde{W}B} H^\dagger \sigma^k H\, \widetilde{W}^k_{\mu\nu} B_{\mu\nu} \\
& + C_{\widetilde{W}} \epsilon^{klm} \widetilde{W}^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_{\widetilde{G}} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \\
& + H^\dagger H(\bar{L} H C_{eH} \bar{E}^c) + H^\dagger H(\bar{Q} \tilde{H} C_{uH} \bar{U}^c) + H^\dagger H(\bar{Q} H C_{dH} \bar{D}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(\bar{L} C^{(1)}_{Hl} \bar{\sigma}^\mu L) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{L} C^{(3)}_{Hl} \bar{\sigma}^\mu \sigma^k L) + iH^\dagger \overleftrightarrow{D}_\mu H(E^c C_{He} \sigma^\mu \bar{E}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(\bar{Q} C^{(1)}_{Hq} \bar{\sigma}^\mu Q) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{Q} C^{(3)}_{Hq} \bar{\sigma}^\mu \sigma^k Q) + iH^\dagger \overleftrightarrow{D}_\mu H(U^c C_{Hu} \sigma^\mu \bar{U}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(D^c C_{Hd} \sigma^\mu \bar{D}^c) + \Big\{ i\tilde{H}^\dagger D_\mu H(U^c C_{Hud} \sigma^\mu \bar{D}^c) \\
& + (\bar{Q} \sigma^k \tilde{H} C_{uW} \bar{\sigma}^{\mu\nu} \bar{U}^c) W^k_{\mu\nu} + (\bar{Q} \tilde{H} C_{uB} \bar{\sigma}^{\mu\nu} \bar{U}^c) B_{\mu\nu} + (\bar{Q} \tilde{H} C_{uG} T^a \bar{\sigma}^{\mu\nu} \bar{U}^c) G^a_{\mu\nu} \\
& + (\bar{Q} \sigma^k H C_{dW} \bar{\sigma}^{\mu\nu} \bar{D}^c) W^k_{\mu\nu} + (\bar{Q} H C_{dB} \bar{\sigma}^{\mu\nu} \bar{D}^c) B_{\mu\nu} + (\bar{Q} H C_{dG} T^a \bar{\sigma}^{\mu\nu} \bar{D}^c) G^a_{\mu\nu} \\
& + (\bar{L} \sigma^k H C_{eW} \bar{\sigma}^{\mu\nu} \bar{E}^c) W^k_{\mu\nu} + (\bar{L} H C_{eB} \bar{\sigma}^{\mu\nu} \bar{E}^c) B_{\mu\nu} + \mathrm{h.c.} \Big\} + \mathscr{L}^{4-\text{fermion}}_{D=6}
\end{aligned}$$

$|H|^2 B_{\mu\nu}\widetilde{B}_{\mu\nu}$
$|H|^2 G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu}$
$|H|^2 W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}$
$|H|^2 W^a_{\mu\nu}W^a_{\mu\nu}$
$|H|^2 B_{\mu\nu}B_{\mu\nu}$
$G^a_{\mu\nu}G^a_{\nu\rho}\widetilde{G}^a_{\rho\mu}$
$|H|^6$
$|H|^2 G^a_{\mu\nu}G^a_{\mu\nu}$

SMEFT at dimension-6

$$\mathscr{L}_{\mathrm{SMEFT}} \supset \sum_X C_X O_X$$

Bosonic CP-even operators

$$O_H = (H^\dagger H)^3$$

$$O_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)$$

$$O_{HD} = |H^\dagger D_\mu H|^2$$

$$O_{HG} = H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$$

$$O_{HW} = H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu}$$

$$O_{HB} = H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

SMEFT at dimension-6

Bosonic CP-even operators

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$$O_{HB} = H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

These affect single Higgs boson couplings to SM gauge bosons. For example

$$C_{HG} H^\dagger H G^a_{\mu\nu} G^a_{\mu\nu} = C_{HG} \frac{(\mathrm{v}+h)^2}{2} G^a_{\mu\nu} G^a_{\mu\nu} \to \mathrm{v} C_{HG} h G^a_{\mu\nu} G^a_{\mu\nu}$$

For operators inducing couplings to photons and gluons bounds of order $|C| \lesssim \frac{1}{(10\ \mathrm{TeV})^2}$ **, while** $|C_{HD}| \lesssim \frac{1}{(\mathrm{TeV})^2}$ **from Higgs physics alone**

SMEFT at dimension-6

Bosonic CP-even operators

$$O_H = (H^\dagger H)^3$$

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$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

Peculiar effect...

Contributes to the kinetic term of the Higgs boson

$$C_{H\Box}(H^\dagger H)\Box(H^\dagger H) \to -\mathrm{v}^2 C_{H\Box}(\partial_\mu h)^2$$

Together with the SM kinetic term:

$$\mathscr{L}_{\mathrm{SMEFT}} \supset \frac{1}{2}(\partial_\mu h)^2\left(1 - 2\mathrm{v}^2 C_{H\Box}\right)$$

To restore canonical normalization, we need to rescale the Higgs boson field:

$$h \to h\left(1 + \mathrm{v}^2 C_{H\Box}\right)$$

All Higgs boson couplings present in the SM are modified in a universal way!

$$\frac{h}{\mathrm{v}}\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right] \to \frac{h}{\mathrm{v}}\left(1 + \mathrm{v}^2 C_{H\Box}\right)\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$

$$\frac{h}{\mathrm{v}} m_f \bar{f} f \to \frac{h}{\mathrm{v}}\left(1 + \mathrm{v}^2 C_{H\Box}\right) m_f \bar{f} f$$

Bounds of order $|C_{H\Box}| \lesssim \frac{1}{(\mathrm{TeV})^2}$

SMEFT at dimension-6

Bosonic CP-even operators

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$$O_{HB} = H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

Affects cubic Higgs boson coupling

$$C_H (H^\dagger H)^3 = \frac{C_H}{8}(\mathrm{v} + h)^6 \rightarrow \frac{5\mathrm{v} C_H}{2} h^3$$

Currently weak bounds of order $|C_H| \lesssim \frac{1}{\mathrm{v}^2}$

SMEFT at dimension-6

Bosonic CP-even operators

$$O_H = (H^\dagger H)^3$$

$$O_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$O_{HD} = |H^\dagger D_\mu H|^2$$

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$$O_{HW} = H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu}$$

$$O_{HB} = H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

Induce anomalous triple gauge couplings
Bounds on the electroweak ones lead to

$$|C_W| \lesssim \frac{1}{(3\mathrm{TeV})^2},$$

bounds on the gluon ones much weaker

SMEFT at dimension-6

Bosonic CP-even operators

$$O_H = (H^\dagger H)^3$$

$$O_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$O_{HD} = |H^\dagger D_\mu H|^2$$

$$O_{HG} = H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$$

$$O_{HW} = H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu}$$

$$O_{HB} = H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

These affect electroweak precision observables (W boson mass, Z branching fractions), which are measured at per-mille level at LEP

Bounds of order $|C| \lesssim \frac{1}{(10\ \mathrm{TeV})^2}$

SMEFT at dimension-6

Bosonic CP-even operators

$$O_H = (H^\dagger H)^3$$

$$O_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$O_{HD} = |H^\dagger D_\mu H|^2$$

$$O_{HG} = H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$$

$$O_{HW} = H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu}$$

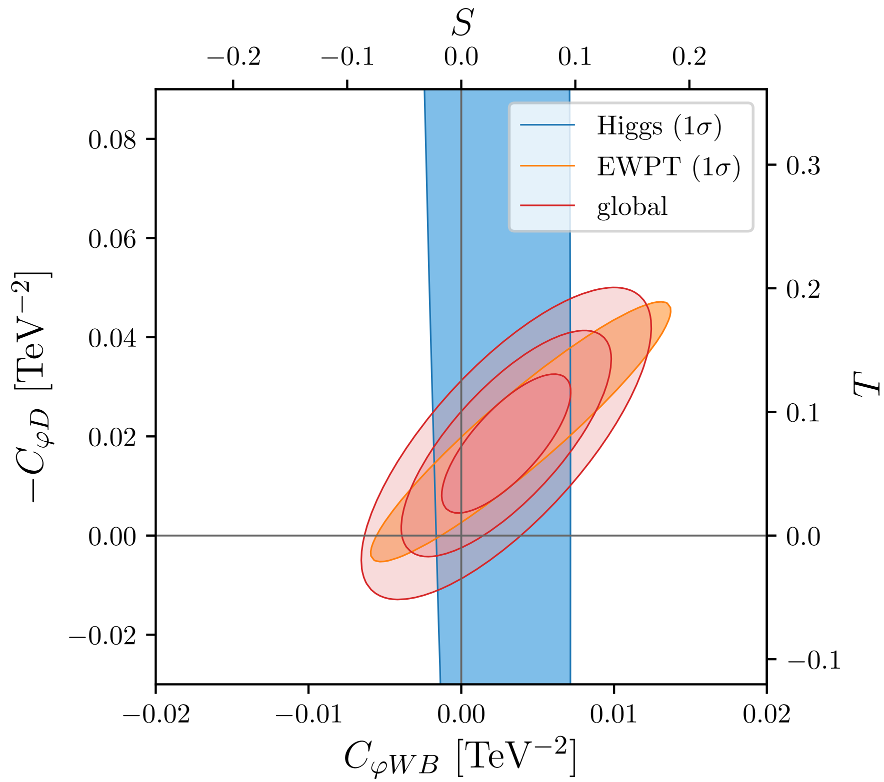
$$O_{HB} = H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$O_{HWB} = H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu}$$

$$O_W = \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu}$$

$$O_G = f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

Similar constraining power of Higgs and electroweak constraints on these particular operators Interesting synergy



SMEFT at dimension-6

$$+C_{H\widetilde{G}} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu} + C_{H\widetilde{W}} H^\dagger H\, \widetilde{W}^k_{\mu\nu} W^k_{\mu\nu} + C_{H\widetilde{B}} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$$

$$+C_{H\widetilde{W}B} H^\dagger \sigma^k H\, \widetilde{W}^k_{\mu\nu} B_{\mu\nu} + C_{\widetilde{W}} \epsilon^{klm} \widetilde{W}^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_{\widetilde{G}} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu},$$

These affect single Higgs boson couplings to SM gauge bosons, and triple gauge couplings But also, via loop effects other CP observables, such as e.g. electron EDMs

SMEFT at dimension-6

$$\mathscr{L}_{\rm SMEFT} \supset \sum_{I,J=1}^{3} [O_{fH}]_{IJ}[C_{fH}]_{IJ} + \mathrm{h.c.}$$

Yukawa-like operators

$$O_{eH} = H^\dagger H(\bar{L}H\bar{E}^c)$$

$$O_{uH} = H^\dagger H(\bar{Q}\tilde{H}\bar{U}^c)$$

$$O_{dH} = H^\dagger H(\bar{Q}H\bar{D}^c)$$

These affect single Higgs boson couplings to SM fermions. Bounds depends on the flavor but typically don't exceed $|C| \lesssim \frac{1}{(1\ \mathrm{TeV})^2}$

SMEFT at dimension-6

Vertex-like operators

$$O_{Hl}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H(\bar{L}\bar{\sigma}^\mu L)$$

$$O_{Hl}^{(3)} = iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{L}\bar{\sigma}^\mu \sigma^k L)$$

$$O_{He} = iH^\dagger \overleftrightarrow{D}_\mu H(E^c \sigma^\mu \bar{E}^c)$$

$$O_{Hq}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H(\bar{Q}\bar{\sigma}^\mu Q)$$

$$O_{Hq}^{(3)} = iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{Q}\bar{\sigma}^\mu \sigma^k Q)$$

$$O_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H(U^c \sigma^\mu \bar{U}^c)$$

$$O_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H(D^c \sigma^\mu \bar{D}^c)$$

$$O_{Hud} = i\tilde{H}^\dagger D_\mu H(U^c \sigma^\mu \bar{D}^c)$$

These affect electroweak precision observables (W boson mass, Z branching fractions), which are measured at per-mille level at LEP

Bounds of order $|C| \lesssim \frac{1}{(10\ \mathrm{TeV})^2}$

SMEFT at dimension-6

$$\begin{aligned}\mathcal{L}^{\text{dipole}}_{D=6} =&(\bar{Q}\sigma^k \tilde{H} C_{uW} \bar{\sigma}^{\mu\nu} \bar{U}^c) W^k_{\mu\nu} + (\bar{Q}\tilde{H} C_{uB} \bar{\sigma}^{\mu\nu} \bar{U}^c) B_{\mu\nu} + (\bar{Q}\tilde{H} C_{uG} T^a \bar{\sigma}^{\mu\nu} \bar{U}^c) G^a_{\mu\nu} \\ &+(\bar{Q}\sigma^k H C_{dW} \bar{\sigma}^{\mu\nu} \bar{D}^c) W^k_{\mu\nu} + (\bar{Q} H C_{dB} \bar{\sigma}^{\mu\nu} \bar{D}^c) B_{\mu\nu} + (\bar{Q} H C_{dG} T^a \bar{\sigma}^{\mu\nu} \bar{D}^c) G^a_{\mu\nu} \\ &+(\bar{L}\sigma^k H C_{eW} \bar{\sigma}^{\mu\nu} \bar{E}^c) W^k_{\mu\nu} + (\bar{L} H C_{eB} \bar{\sigma}^{\mu\nu} \bar{E}^c) B_{\mu\nu} + \text{h.c.} \qquad (\end{aligned}$$

These affect anomalous magnetic and electric moments of SM particles at tree level
Bounds depend on flavor and can be very strong, especially for the first generation

SMEFT at dimension-6

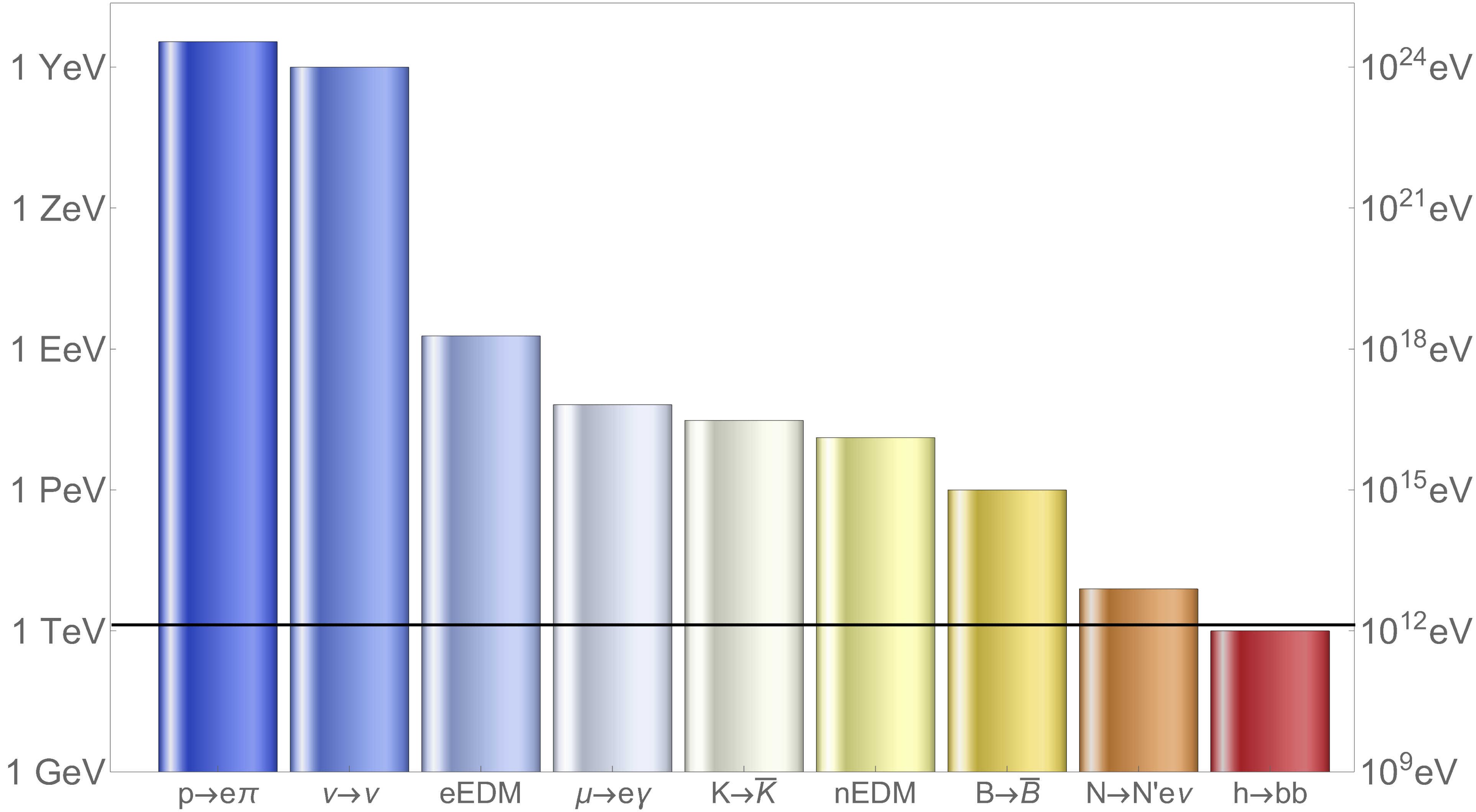
4-fermion operators

$$\mathscr{L}^{4-\text{fermion}}_{D=6} = (\bar{L}\bar{\sigma}^{\mu}L)C_{ll}(\bar{L}\bar{\sigma}_{\mu}L) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{ee}(E^{c}\sigma_{\mu}\bar{E}^{c}) + (\bar{L}\bar{\sigma}^{\mu}L)C_{le}(E^{c}\sigma_{\mu}\bar{E}^{c})$$
$$+(\bar{L}\bar{\sigma}^{\mu}L)C^{(1)}_{lq}(\bar{Q}\bar{\sigma}_{\mu}Q) + (\bar{L}\bar{\sigma}^{\mu}\sigma^{k}L)C^{(3)}_{lq}(\bar{Q}\bar{\sigma}_{\mu}\sigma^{k}Q)$$
$$+(E^{c}\sigma_{\mu}\bar{E}^{c})C_{eu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{ed}(D^{c}\sigma_{\mu}\bar{D}^{c})$$
$$+(\bar{L}\bar{\sigma}^{\mu}L)C_{lu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (\bar{L}\bar{\sigma}^{\mu}L)C_{ld}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{eq}(Q\bar{\sigma}_{\mu}Q)$$
$$+\left\{(\bar{L}\bar{E}^{c})C_{ledq}(D^{c}Q) + \epsilon^{kl}(\bar{L}^{k}\bar{E}^{c})C^{(1)}_{lequ}(\bar{Q}^{l}\bar{U}^{c}) + \epsilon^{kl}(\bar{L}^{k}\bar{\sigma}^{\mu\nu}\bar{E}^{c})C^{(3)}_{lequ}(\bar{Q}^{l}\bar{\sigma}^{\mu\nu}\bar{U}^{c}) + \text{h.c.}\right\}$$
$$+(\bar{Q}\bar{\sigma}^{\mu}Q)C^{(1)}_{qq}(\bar{Q}\bar{\sigma}_{\mu}Q) + (\bar{Q}\bar{\sigma}^{\mu}\sigma^{k}Q)C^{(3)}_{qq}(\bar{Q}\bar{\sigma}_{\mu}\sigma^{k}Q)$$
$$+(U^{c}\sigma_{\mu}\bar{U}^{c})C_{uu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (D^{c}\sigma_{\mu}\bar{D}^{c})C_{dd}(D^{c}\sigma_{\mu}\bar{D}^{c})$$
$$+(U^{c}\sigma_{\mu}\bar{U}^{c})C^{(1)}_{ud}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (U^{c}\sigma_{\mu}T^{a}\bar{U}^{c})C^{(8)}_{ud}(D^{c}\sigma_{\mu}T^{a}\bar{D}^{c})$$
$$+(Q^{c}\sigma_{\mu}\bar{Q}^{c})C^{(1)}_{qu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (Q^{c}\sigma_{\mu}T^{a}\bar{Q}^{c})C^{(8)}_{qu}(U^{c}\sigma_{\mu}T^{a}\bar{U}^{c})]$$
$$+(Q^{c}\sigma_{\mu}\bar{Q}^{c})C^{(1)}_{qd}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (Q^{c}\sigma_{\mu}T^{a}\bar{Q}^{c})C^{(8)}_{qd}(D^{c}\sigma_{\mu}T^{a}\bar{D}^{c})$$
$$+\left\{\epsilon^{kl}(\bar{Q}^{k}\bar{U}^{c})C^{(1)}_{quqd}(\bar{Q}^{l}\bar{D}^{c}) + \epsilon^{kl}(\bar{Q}^{k}T^{a}\bar{U}^{c})C^{(1)}_{quqd}(\bar{Q}^{l}T^{a}\bar{D}^{c}) + \text{h.c.}\right\}$$
$$+\left\{(D^{c}U^{c})C_{duq}(\bar{Q}\bar{L}) + (QQ)C_{qqu}(\bar{U}^{c}\bar{E}^{c}) + (QQ)C_{qqq}(QL) + (D^{c}U^{c})C_{duu}(U^{c}E^{c}) + \text{h.c.}\right\}.$$

These affect a wide range of physics.
Bounds can be very strong, especially for baryon-number violating operators and for certain flavor- or lepton-flavor-violating operators

SMEFT up to dimension-6

SMEFT Lagrangian up to dimension-6 provides a convenient framework for a bulk of precision physics happening today.
In particular, it allows one to quantify the strength of different observables



SMEFT up to dimension-6

SMEFT Lagrangian up to dimension-6 provides a convenient framework for a bulk of precision physics happening today.

Moreover, it leads to correlations between different observables, e.g. due to $SU(2)_W$ symmetry relating charged and neutral currents, and due to the interplay of tree- and loop-level contributions to observables

Importance of global fits collecting results from different types of experiments !

Global fits with SMEFT up to dimension-6

$$
\begin{pmatrix}
[\delta g_L^{Wl}]_{ee} \\
[\delta g_L^{Wl}]_{\mu\mu} \\
[\delta g_L^{Wl}]_{\tau\tau} \\
[\delta g_L^{Ze}]_{ee} \\
[\delta g_R^{Ze}]_{ee} \\
[\delta g_L^{Ze}]_{\mu\mu} \\
[\delta g_R^{Ze}]_{\mu\mu} \\
[\delta g_L^{Ze}]_{\tau\tau} \\
[\delta g_R^{Ze}]_{\tau\tau} \\
[\delta g_R^{Wq}]_{11} \\
[\delta g_L^{Zu}]_{11} \\
[\delta g_R^{Zu}]_{11} \\
[\delta g_L^{Zd}]_{11} \\
[\delta g_R^{Zd}]_{11} \\
[\delta g_L^{Zu}]_{22} \\
[\delta g_R^{Zu}]_{22} \\
[\delta g_L^{Zd}]_{22} \\
[\delta g_R^{Zd}]_{22} \\
[\delta g_L^{Zd}]_{33} \\
[\delta g_R^{Zd}]_{33}
\end{pmatrix}
=
\begin{pmatrix}
-1.8(2.6) \\
-0.6(2.2) \\
0.2(3.5) \\
-0.21(28) \\
-0.42(27) \\
0.2(1.2) \\
0.0(1.4) \\
-0.09(59) \\
0.61(62) \\
-3.8(8.1) \\
-7(22) \\
4(29) \\
-13(35) \\
10(120) \\
-1.5(3.6) \\
-3.3(5.3) \\
14(27) \\
34(46) \\
3.2(1.7) \\
22(8.8)
\end{pmatrix}
\times 10^{-3},
\qquad
\begin{pmatrix}
[c_{ll}]_{eeee} \\
[c_{le}]_{eeee} \\
[c_{ee}]_{eeee} \\
[c_{ll}]_{e\mu\mu e} \\
[c_{ll}]_{ee\mu\mu} \\
[c_{le}]_{e\mu\mu e} \\
[c_{le}]_{ee\mu\mu} \\
[c_{le}]_{\mu\mu ee} \\
[c_{ee}]_{ee\mu\mu} \\
[c_{ll}]_{e\tau\tau e} \\
[c_{ll}]_{ee\tau\tau} \\
[c_{le}]_{ee\tau\tau} \\
[c_{le}]_{\tau\tau ee} \\
[c_{ee}]_{ee\tau\tau} \\
[\hat{c}_{ll}]_{\mu\mu\mu\mu} \\
[c_{ll}]_{\mu\tau\tau\mu} \\
[c_{le}]_{\mu\tau\tau\mu}
\end{pmatrix}
=
\begin{pmatrix}
1.03(38) \\
-0.22(22) \\
0.19(38) \\
-0.56(80) \\
0.1(2.0) \\
11.4(6.8) \\
0.3(2.2) \\
-0.2(2.1) \\
0.2(2.3) \\
-0.60(68) \\
2(11) \\
-2.3(7.2) \\
1.7(7.2) \\
-1(12) \\
2(21) \\
1.5(1.9) \\
19(15)
\end{pmatrix}
\times 10^{-2},
$$

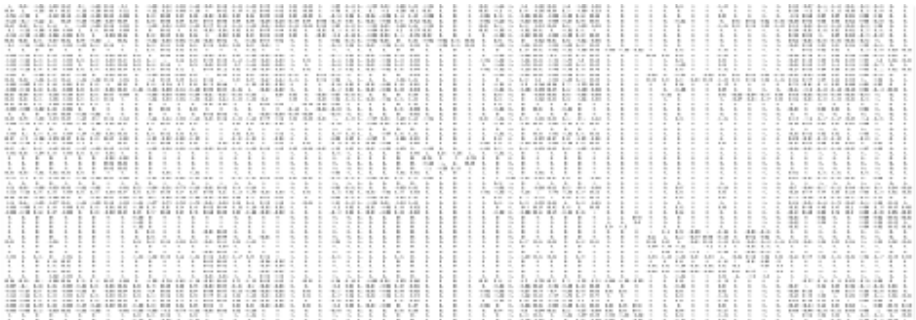
$$
\begin{pmatrix}
[c_{lq}^{(3)}]_{ee11} \\
[\hat{c}_{eq}]_{ee11} \\
[\hat{c}_{lu}]_{ee11} \\
[\hat{c}_{ld}]_{ee11} \\
[\hat{c}_{eu}]_{ee11} \\
[\hat{c}_{ed}]_{ee11} \\
[c_{lequ}^{(1)}]_{ee11} \\
[c_{ledq}]_{ee11} \\
[c_{lequ}^{(3)}]_{ee11} \\
[\hat{c}_{lq}^{(3)}]_{ee22} \\
[c_{lu}]_{ee22} \\
[\hat{c}_{ld}]_{ee22}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

Breso-Pla et al
arXiv:2301.07036

Ingredients

- e^+e^- collisions
- W boson mass and decays
- Drell-Yan at LHC and Tevatron
- Neutrino scattering on electrons
- Atomic parity violation
- Parity-violating electron scattering
- Nuclear beta decays
- Semi-leptonic decays of pions and kaons
- Trident muon production in ν scattering
- Leptonic and hadronic tau decays
- ν scattering on nuclei (coherent to not)

Correlation matrix



Only 65 dimension-6 Wilson coefficients simultaneously constrained in this fit. Can do better :)

SMEFT at higher dimensions

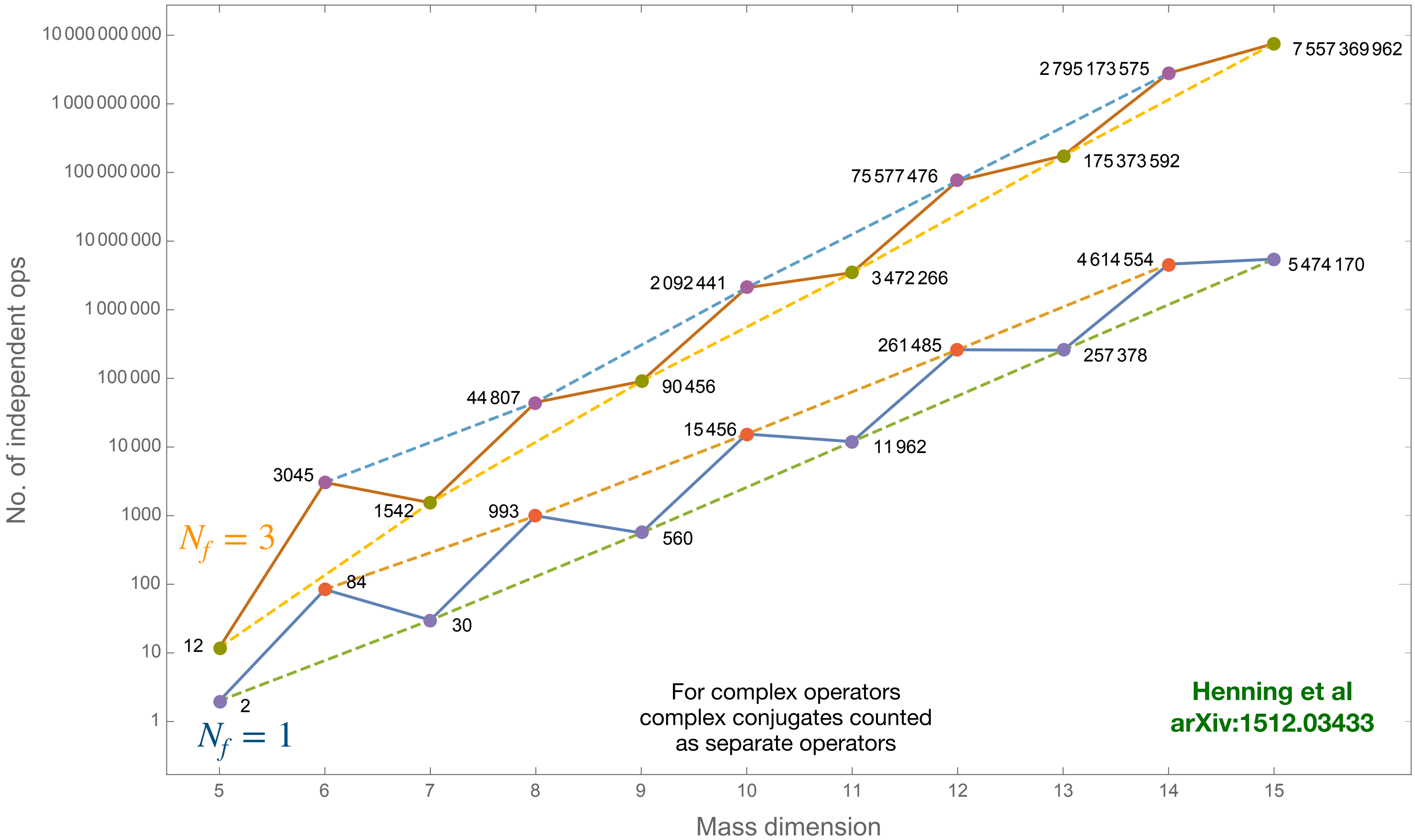
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Number of baryon-number-conserving operators as function of D and number of generations N_f

	N_f=0	N_f=1	N_f=2	N_f=3	...
Dimension-5	0	2	6	12	...
Dimension-6	15	76	582	2499	...
Dimension-7	0	22	212	948	...
Dimension-8	89	895	8251	36971	...
...	...	...	...	...	...

SMEFT at higher dimensions

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$



Exponential growth of the number of operators with the canonical dimension D

SMEFT at higher dimensions

SMEFT at dimension-5:	Weinberg (1979) Phys. Rev. Lett. 43, 1566
SMEFT at dimension-6:	Grzadkowski et al arXiv: 1008.4884
SMEFT at dimension-7:	Lehman arXiv: 1410.4193
SMEFT at dimension-8:	Li et al arXiv: 2005.00008
SMEFT at dimension-9:	Li et al arXiv: 2012.09188

Code to generate a basis at arbitrary dimension in SMEFT: Li et al arXiv:2201.04639

Beyond dimension-6

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

You need to be aware of the existence of higher-dimensional operators, whenever you need to argue validity of the EFT description

Moreover, a qualitatively new phenomenon may arise at higher dimensions

At tree level, light-by-light scattering receives contribution from dimension-8, which in some situations may compete with lower order loop contributions

$$\mathscr{L}_{D=8} \supset (B_{\mu\nu}B_{\mu\nu})^2 + \dots$$

Neutron-antineutron oscillations arise at dimension-9

$$\mathscr{L}_{D=9} \supset \epsilon_{abc}\epsilon_{def}(\bar{d}_a\bar{d}_d)(q_b q_e)(q_c q_f) + \dots$$

CP violating 3Z vertex in SMEFT from integrating out 2HDM arises via a dimension-12 operator!

$$\mathscr{L}_{D=12} \supset C_{12}[H^\dagger D^2(HH^\dagger H)]^2 + \mathrm{h.c.}$$

In all such cases however, you need to argue validity of your EFT and why you don't expect any larger effects of new physics from operators of lower dimensions

Beyond dimension-6

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

You need to be aware of the existence of higher-dimensional operators, whenever you need to argue validity of the EFT description

Moreover, a qualitatively new phenomenon may arise at higher dimensions

If experiment pinpoints a coefficient of some operators of dimension-6, then subleading dimension-8 operators will provide precious information

$$C_6 \sim \frac{g_*^2}{M^2} \qquad\qquad C_8 \sim \frac{g_*^2}{M^4}$$

Only determines coupling over mass scala of new physics

May allow disentangle coupling and mass