Waiting for discoveries/deviations a paradigm shift?

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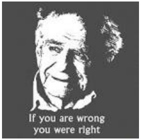

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Synopsis

Practices that define hep at this point in time

A set of constructs, definitions, and propositions that present a systematic view of SMEFT[1]

… while attempting to provide a consistency proof[2] of quasi-renormalization in SMEFT

Theory deals with the well founded theoretical results obtained from first principles, while phenomenology deals with not so well founded effective models with a smaller domain of application.

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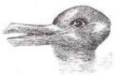
[1] how the influence of higher energy processes is localizable in a few structural properties which can be captured by a handful of Wilson coefficients

[2] Not only power counting, but a proof that proves that there are enough Wilson coefficients

Mathematics suffers from some of the same inherent difficulties as theoretical physics: great successes during the 20th century, increasing difficulties to do better, as the easier problems get solved[3].

- ✓ **Conventional vision**: some very different physics occurs at Plank scale, SM is just an effective field theory. What about the next SM? A new weakly coupled renormalizable model? A tower of EFTs?
- ✓ **A different vision**: is the SM close to a fundamental theory?

[3] The lesson of experiments 1973 - today: extremely difficult to find a flaw in the SM: maybe the SM includes elements of a truly fundamental theory. But then how can one hope to make progress without experimental guidance? One should pay close attention to what we don't understand precisely about the SM even if the standard prejudice is
"that's a hard technical problem, and solving it won't change anything"
Should we try to better understand links between SM and mathematics?



- ☛ The naive version: for a theory or hypothesis to count as *scientific* it ought to be falsifiable in principle
  - ✓ SM is in. The reason is that SM has withstood *risky* tests that it could have easily failed
- ☛ The *non-empirical confirmation*, where the value of a theory is judged in conjunction with empirical confirmation elsewhere in the same field, assuming that a long term perspective of empirical confirmation exists for the given theory[4]

[4] A mature science, according to Kuhn, experiences alternating phases of normal science and revolutions. In normal science the key theories, instruments and values that comprise the disciplinary matrix are kept fixed, permitting the cumulative generation of puzzle-solutions, whereas in a scientific revolution the disciplinary matrix undergoes revision, in order to permit the solution of the more serious anomalous puzzles that disturbed the preceding period of normal science

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One-loop divergencies in the theory of gravitation

par

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ABSTRACT. — All one-loop divergencies of pure gravity and all those of gravitation interacting with a scalar particle are calculated. In the case of pure gravity, no physically relevant divergencies remain; they can all be absorbed in a field renormalization. In case of gravitation interacting with scalar particles, divergencies in physical quantities remain, even when employing the socalled improved energy-momentum tensor.

1. INTRODUCTION

The recent advances in the understanding of gauge theories make a fresh approach to the quantum theory of gravitation possible. First, we now know precisely how to obtain Feynman rules for a gauge theory [*1*]; secondly, the dimensional regularization scheme provides a powerful tool to handle divergencies [*2*]. In fact, several authors have already published work using these methods [*3*], [*4*].

One may ask why one would be interested in quantum gravity. The foremost reason is that gravitation undeniably exists; but in addition we may hope that study of this gauge theory, apparently realized in nature, gives insight that can be useful in other areas of field theory. Of course, one may entertain all kinds of speculative ideas about the role of gravitation in elementary particle physics, and several authors have amused themselves imagining elementary particles as little black holes etc. It may well be true that gravitation functions as a cut-off for other interactions; in view of the fact that it seems possible to formulate all known

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It is possible that at some very large energy scale, all nonrenormalizable interactions disappear. This seems unlikely, given the difficulty with gravity. It is possible that the rules change drastically, it may even be possible that there is no end, simply more and more scales (Georgi).

This prompts the important question whether there is a last fundamental theory in this tower of EFTs which supersede each other with rising energies. Some people conjecture that this deeper theory could be a string theory, i.e. a theory which is not a field theory any more. Or should one ultimately expect from physics theories that they are only valid as approximations and in a limited domain? (Hartmann, Castellani)

Or ... one should not resort to arguments involving gravity: let us banish further thoughts about gravity and the damage it could do to the weak scale (J. D. Wells)

? spin partners

45 spin 1/2

13 spin 1

1 spin 0 ?

more ? Hierarchy of VEVs?

↙

serious fine-tuning

↘

small mixings

accidental?
systematic (i.e. symmetry)?

banishing scalars?
extra dimensions?
warped extra dimensions?

Thinking UV …

Back to the "more and more scales" scenario. Let's undergo revision (SMEFT) but it is an error to believe that rigour is the enemy of simplicity. On the contrary we find it confirmed by numerous examples that the rigorous method is at the same time the simpler and the more easily comprehended.

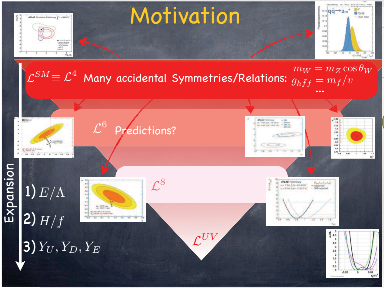
> *The very effort for rigor forces us to find out simpler methods of proof*
>
> *D. Hilbert*

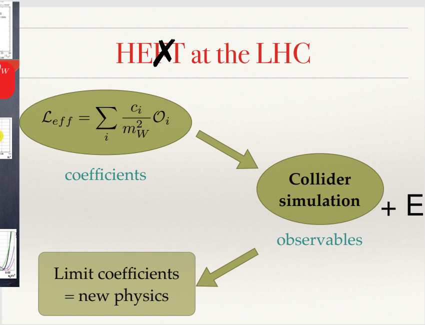
Executive summary (so far)

After the LHC Run 1, the SM has been completed, raising its status to that of a full theory. Despite its successes, this SM has shortcomings vis-à-vis cosmological observations. At the same time, there is presently a lack of direct evidence for new physics phenomena at the accelerator energy frontier. From this state of affairs arises the need for a consistent theoretical framework in which deviations from the SM predictions can be calculated. Such a framework should be applicable to comprehensively describe measurements in all sectors of particle physics: LHC Higgs measurements, past electroweak precision data, etc.

By simultaneously describing all existing measurements, this framework then becomes an intermediate step toward the next SM, hopefully revealing the underlying symmetries

SMEFT *is needed*





+ EWPD

It is manifestly of interest to formulate joint analysis where all of the data is fit simultaneously

❶ SM augmented with the inclusion of higher dimensional operators ($\mathbf{T_1}$); not strictly renormalizable. Although workable to all orders, $\mathbf{T_1}$ fails above a certain scale, $\mathbf{\Lambda_1}$.

❷ Consider any BSM model that is strictly renormalizable and respects unitarity ($\mathbf{T_2}$); its parameters can be fixed by comparison with data, while masses of heavy states are presently unknown. $\mathbf{T_1} \neq \mathbf{T_2}$ in the UV but must have the same IR behavior.

❸ Consider now the whole set of data below $\mathbf{\Lambda_1}$.

> $\mathbf{T_1}$ should be able to explain them by fitting Wilson coefficients,
>
> $\mathbf{T_2}$ adjusting the masses of heavy states (as SM did with the Higgs mass at LEP) should be able to explain the data.

Goodness of both explanations are crucial in understanding how well they match and how reasonable is to use $\mathbf{T_1}$ instead of the full $\mathbf{T_2}$

❹ Does $\mathbf{T_2}$ explain everything? Certainly not, but it should be able to explain something more than $\mathbf{T_1}$.

❺ We could now define $\mathbf{T_3}$ as $\mathbf{T_2}$ augmented with (its own) higher dimensional operators; it is valid up to a scale $\mathbf{\Lambda_2}$.

❻ ......

SMEFT rulebook

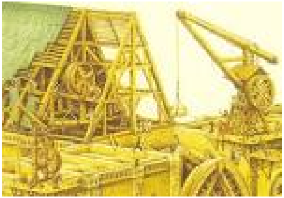
❶ The construction of the SMEFT, to all orders, is not based on assumptions on the size of the Wilson coefficients of the higher dimensional operators

❷ Restricting to a particular UV case is not an integral part of a general SMEFT treatment and various cases can be chosen once the general calculation is performed.

❸ If the value of Wilson coefficients in broad UV scenarios could be inferred in general this would be of significant scientific value.

Despite Wightman Axioms QFT is full of assumptions but, once you accept them, QFT is a non flexible working environment: you cannot work with the theory (pretending to get meaningful results) before constructing it

What can be said at all can be said clearly and whereof one cannot speak thereof one must be silent L. Wittgenstein

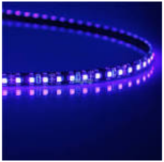


$\cdots$ constructing SMEFT

Experiments occur at finite energy and measure $\mathbf{S^{eff}(\Lambda)}$

Whatever QFT should give low energy $\mathbf{S^{eff}(\Lambda)}$, $\forall \Lambda < \infty$

There is no fundamenta scale above which $\mathbf{S^{eff}(\Lambda)}$ is not defined (K. Costello)



The UV connection

$$\mathscr{A} = \sum_{n=N}^{\infty} g^n \mathscr{A}_n^{(4)} + \sum_{n=N_6}^{\infty} \sum_{l=1}^{n} \sum_{k=1}^{\infty} g^n g^l{}_{4+2k} \mathscr{A}_{nlk}^{(4+2k)}$$

where g is the $SU(2)$ coupling constant and $g_{4+2k} = 1/(\sqrt{2}\, G_F \Lambda^2)^k = g_6^k$, where G_F is the Fermi coupling constant and Λ is the scale around which new physics (NP) must be resolved. For each process N defines the $\dim = 4$ LO (e.g. $N = 1$ for $H \to VV$ etc. but $N = 3$ for $H \to \gamma\gamma$). $N_6 = N$ for tree initiated processes and $N - 2$ for loop initiated ones. Here we consider single insertions of $\dim = 6$ operators, which defines NLO SMEFT.

Ex: HAA (tree) vertex generated by $\mathscr{O}^{(6)}_{\phi W} = \left(\Phi^\dagger \Phi\right) F^{a\mu\nu} F^a_{\mu\nu}$, by $\mathscr{O}^{(8)}_{\phi W} = \Phi^\dagger F^{a\mu\nu} F^a_{\mu\rho} D^\rho D_\nu \Phi$ etc.

SMEFT ordertable for tree initiated $1 \to 2$ processes

$$
\begin{array}{llll}
g\,/\,\mathrm{dim} & \longrightarrow & & \\
\downarrow & g\,\mathscr{A}^{(4)}_{1} & +\,g\,g_6\,\mathscr{A}^{(6)}_{1,1,1} & +\,g\,g_8\,\mathscr{A}^{(8)}_{1,1,2} \\
 & g^3\,\mathscr{A}^{(4)}_{3} & +\,g^3\,g_6\,\mathscr{A}^{(6)}_{3,1,1} & +\,g^3\,g_6^2\,\mathscr{A}^{(6)}_{3,2,1} \\
 & \cdots\cdots & \cdots\cdots & \cdots\cdots
\end{array}
$$

- $g\,g_6\,\mathscr{A}^{(6)}_{1,1,1}$ LO SMEFT. There is also RG-improved LO (arXiv:1308.2627) and MHOU for LO SMEFT (arXiv:1508.05060)
- $g^3\,g_6\,\mathscr{A}^{(6)}_{3,1,1}$ (arXiv:1505.03706) NLO SMEFT
- $g\,g_8\,\mathscr{A}^{(8)}_{1,1,2}$ (arXiv:1510.00372), $g^3\,g_6^2\,\mathscr{A}^{(6)}_{3,2,1}$ MHOU for NLO SMEFT

N.B. g_8 denotes a single $\mathscr{O}^{(8)}$ insertion, g_6^2 denotes two, distinct, $\mathscr{O}^{(6)}$ insertions

$\mathrm{CT}_{4,6} + \mathrm{Mix}$

$$\mathrm{A} = g^{N}\, \mathrm{A}^{(4)}_{\mathrm{LO}}(\{p\}) + g^{N}\, g_6\, \mathrm{A}^{(6)}_{\mathrm{LO}}(\{p\}) + \frac{1}{16\,\pi^2}\, g^{N+2}\, \mathrm{A}^{(4)}_{\mathrm{NLO}}(\{p\}\,,\,\{a\}) + \frac{1}{16\,\pi^2}\, g^{N+2}\, g_6\, \mathrm{A}^{(6)}_{\mathrm{NLO}}(\{p\}\,,\,\{a\})$$

CT_4

$\{p\} = \{g\,,\, \sin\theta_{\mathrm{W}}\,,\, M\,,\, M_{\mathrm{H}}\,,\, M_{\mathrm{f}}\} \in$ SM

$\{a\} =$ Wilson coeff. $\in$ Warsaw basis

$$\{p\}\,,\,\{a\} \longrightarrow \{p_{\mathrm{ren}}\}\,,\,\{a_{\mathrm{ren}}\} \longrightarrow \mathrm{IPS}\,,\,\{a_{\mathrm{ren}}(\mu_R)\}$$

$$\underbrace{\mathrm{G}_F\,,\, M_{\mathrm{W}}\,,\, M_{\mathrm{Z}}\,,\, M_{\mathrm{H}}}_{\nearrow\ \mathrm{IPS}}$$

CT = counterterm

Physics could be made much easier if

1. Each statement/equation/data is transformed into a table of rules
2. Interpretation is left to a Turing machine
3. The degree of complexity of a theory could be measured by comparing the CPU time needed to

input data (+ cuts + ...)	run TM	output ascii file
input theory	run TM	output ascii file

☛ 01100001 00100000 01100010 01100001 01110011 01101001 01110011 00100000 01101001 01110011 00100000 01100011 01101100 01101111 01110011 01100101 01100100 00100000 01110101 01101110 01100100 01100101 01110010 00100000 01110010 01100101 01101110 01101111 01110010 01101101 01100001 01101100 01101001 01111010 01100001 01110100 01101001 01101111 01101110

The role of $\mathrm{H} \to$ VEV

$$\mathscr{O} = \Lambda^{-n}\, M^{l}\, \partial^{c}\, \overbrace{\overline{\psi}^{a}\, \psi^{b}\, \underbrace{\overbrace{\left(\Phi^{\dagger}\right)^{d}\, \Phi^{e}\, \mathrm{A}^{f}}^{\mathrm{N_F}}}_{\mathrm{codim}}}^{\mathrm{dim}}$$

$$\frac{3}{2}\,(a+b)+c+d+e+f+l+n=4$$

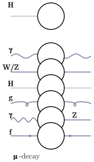
one loop renormalization is controlled by:

$$\boxed{\mathrm{dim}=6 \quad \mathrm{codim}=4 \quad \mathrm{N_F}>2 \quad \text{(Jargon: LO SMEFT)}}$$

The hearth of the problem: a large number of operators implodes into a small number of coefficients

$$\boxed{\text{92 SM vertices} \Longleftrightarrow \text{28 CP even operators (1 flavor, } \mathrm{N}_{\psi}=0,2)}$$

Self-energies



$$S_{\rm HH} = \frac{g^2}{16\,\pi^2}\,\Sigma_{\rm HH} = \frac{g^2}{16\,\pi^2}\,\Bigl(\Sigma^{(4)}_{\rm HH} + g_6\,\Sigma^{(6)}_{\rm HH}\Bigr)$$

$$S^{\mu\nu}_{\rm AA} = \frac{g^2}{16\,\pi^2}\,\Sigma^{\mu\nu}_{\rm AA} \qquad \Sigma^{\mu\nu}_{\rm AA} = \Pi_{\rm AA}\,{\rm T}^{\mu\nu}$$

$$S^{\mu\nu}_{\rm VV} = \frac{g^2}{16\,\pi^2}\,\Sigma^{\mu\nu}_{\rm VV} \qquad \Sigma^{\mu\nu}_{\rm VV} = {\rm D}_{\rm VV}\,\delta^{\mu\nu} + {\rm P}_{\rm VV}\,p^\mu\,p^\nu$$

$${\rm D}_{\rm VV} = {\rm D}^{(4)}_{\rm VV} + g_6\,{\rm D}^{(6)}_{\rm VV} \qquad {\rm P}_{\rm VV} = {\rm P}^{(4)}_{\rm VV} + g_6\,{\rm P}^{(6)}_{\rm VV}$$

$$S^{\mu\nu}_{\rm ZA} = \frac{g^2}{16\,\pi^2}\,\Sigma^{\mu\nu}_{\rm ZA} + g_6\,{\rm T}^{\mu\nu}\,a_{\rm AZ} \qquad \Sigma^{\mu\nu}_{\rm ZA} = \Pi_{\rm ZA}\,{\rm T}^{\mu\nu} + {\rm P}_{\rm ZA}\,p^\mu\,p^\nu$$

$$S_{\rm f} = \frac{g^2}{16\,\pi^2}\,\Bigl[\Delta_{\rm f} + \bigl({\rm V}_{\rm f} - {\rm A}_{\rm f}\,\gamma^5\bigr)\,i\not{p}\Bigr]$$

Counterterms

$\Delta_{\rm UV} = \frac{2}{4-n} - \gamma - \ln\pi - \ln\frac{\mu_{\rm R}^2}{\mu^2}$
n is space-time dimension
loop measure $\mu^{4-n}\, d^n q$

$\mu_{\rm R}$ ren. scale

$$\mathrm{Z}_i \;=\; 1 + \frac{g^2}{16\,\pi^2}\left(d\mathrm{Z}_i^{(4)} + g_6\, d\mathrm{Z}_i^{(6)}\right)\Delta_{\rm UV}$$

With field/parameter counterterms we can make

$\mathbf{S_{HH}}, \mathbf{\Pi_{AA}}, \mathbf{D_{VV}}, \mathbf{\Pi_{ZA}}, \mathbf{V_f}, \mathbf{A_f}$ and the corresponding Dyson resummed propagators UV finite at $\mathscr{O}(g^2\, g_6)$ (Q.E.D.)

which is enough when working under the assumption that gauge bosons couple to conserved currents

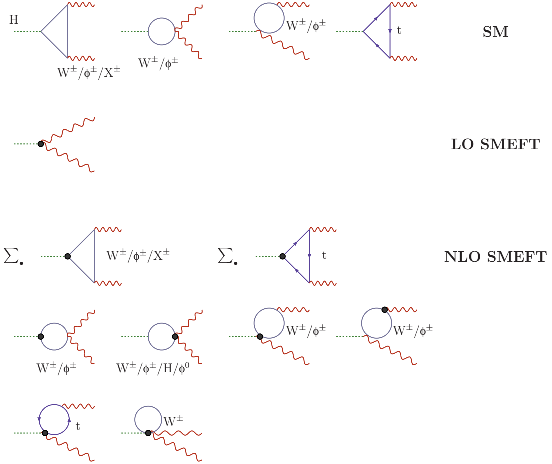
Mixing

Field/parameter counterterms are not enough to make UV finite the Green's functions with more than two legs. A mixing matrix among Wilson coefficients is needed:

$$a_i = \sum_j \mathrm{Z}^{\mathrm{w}}_{ij}\, a^{\mathrm{ren}}_j \qquad \mathrm{Z}^{\mathrm{w}}_{ij} = \delta_{ij} + \frac{g^2}{16\,\pi^2}\, d\mathrm{Z}^{\mathrm{w}}_{ij}\, \Delta_{\mathrm{UV}}$$

$$|\, g^{\mathrm{N}}\, \mathscr{A}^{(4)}_{\mathrm{N}} + g^{\mathrm{K}}\, g_6\, \mathscr{A}^{(6)}_{\mathrm{K},1,1}\,|^2 \quad \rightsquigarrow \quad |\, g^{\mathrm{N}}\, \mathscr{A}^{(4)}_{\mathrm{N}}\,|^2 + 2\, g^{\mathrm{N}+\mathrm{K}}\, g_6\, \mathrm{Re}\left[\mathscr{A}^{(4)}_{\mathrm{N}}\right]^{\dagger} \mathscr{A}^{(6)}_{\mathrm{K},1,1}$$

Remark negative bin entries judge the validity of the $\mathrm{dim} = 6$ "linear" approach (arXiv:1511.05170)



Diagrams contributing to the amplitude for $\mathbf{H} \to \gamma\gamma$ in the $\mathbf{R}_\xi$ -gauge: SM (first row), LO SMEFT (second row), and NLO SMEFT. Black circles denote the insertion of one $\mathbf{dim} = \mathbf{6}$ operator. $\Sigma_\bullet$ implies summing over all insertions in the diagram (vertex by vertex). For triangles with internal charge flow ($\mathbf{t}, \mathbf{W}^\pm, \phi^\pm, \mathbf{X}^\pm$) only the clockwise orientation is shown. Non-equivalent diagrams obtained by the exchange of the two photon lines are not shown. Higgs and photon wave-function factors are not included. The Fadeev-Popov ghost fields are denoted by $\mathbf{X}$.

❶ 

Define the following combinations of Wilson coefficients (where $s_\theta\,(c_\theta)$ denotes the sine(cosine) of the renormalized weak-mixing angle.

$$
\begin{aligned}
a_{\rm ZZ} &= s^2_\theta\, a_{\phi\rm B} + c^2_\theta\, a_{\phi\rm W} - s_\theta\, c_\theta\, a_{\phi\rm WB} \\
a_{\rm AA} &= c^2_\theta\, a_{\phi\rm B} + s^2_\theta\, a_{\phi\rm W} + s_\theta\, c_\theta\, a_{\phi\rm WB} \\
a_{\rm AZ} &= 2\, c_\theta\, s_\theta\, \left(a_{\phi\rm W} - a_{\phi\rm B}\right) + \left(2\, c^2_\theta - 1\right)\, a_{\phi\rm WB}
\end{aligned}
$$

and compute the (on-shell) decay $\mathrm{H}(P) \to \mathrm{A}_\mu(p_1)\mathrm{A}_\nu(p_2)$ where the amplitude is

$$
\mathrm{A}^{\mu\nu}_{\rm HAA} = \mathscr{T}_{\rm HAA}\, T^{\mu\nu} \qquad M^2_{\rm H}\, T^{\mu\nu} = p^\mu_2\, p^\nu_1 - p_1 \cdot p_2\, \delta^{\mu\nu}
$$

Remark The amplitude is made UV finite by mixing $a_{\rm AA}$ with $a_{\rm AA}, a_{\rm AZ}, a_{\rm ZZ}$ and $a_{\rm QW}$ Q.E.D.

go

❷ 

Compute the (on-shell) decay $\mathrm{H}(P) \to \mathrm{A}_\mu(p_1)\mathrm{Z}_\nu(p_2)$. After adding 1PI and 1PR components we obtain

$$\mathrm{A}^{\mu\nu}_{\mathrm{HAZ}} = \mathscr{T}_{\mathrm{HAZ}}\, T^{\mu\nu} \qquad M^2_{\mathrm{H}}\, T^{\mu\nu} = p_2^\mu\, p_1^\nu - p_1 \cdot p_2\, \delta^{\mu\nu}$$

Remark The amplitude is made UV finite by mixing a_{AZ} with $a_{\mathrm{AA}}, a_{\mathrm{AZ}}, a_{\mathrm{ZZ}}$ and a_{QW} Q.E.D.

❸ 

Compute the (on-shell) decay $\mathrm{H}(P) \to \mathrm{Z}_\mu(p_1)\mathrm{Z}_\nu(p_2)$. The amplitude contains

- a $\mathscr{D}_{\mathrm{HZZ}}$ part proportional to $\delta^{\mu\nu}$ and
- a $\mathscr{P}_{\mathrm{HZZ}}$ part proportional to $p_2^\mu\, p_1^\nu$.

Remark Mixing of a_{ZZ} with other Wilson coefficients makes $\mathscr{P}_{\mathrm{HZZ}}$ UV finite, while the mixing of $a_{\phi\Box}$ makes $\mathscr{D}_{\mathrm{HZZ}}$ UV finite Q.E.D.

❹ 

Compute the (on-shell) decay $\mathbf{H}(P) \to \mathbf{W}^{-}{}_{\mu}(p_1)\mathbf{W}^{+}{}_{\nu}(p_2)$. This process follows the same decomposition of $\mathbf{H} \to \mathbf{ZZ}$ and it is UV finite in the $\mathbf{dim} = \mathbf{4}$ part. However, for the $\mathbf{dim} = \mathbf{6}$ one, there are no Wilson coefficients left free in $\mathscr{P}_{\mathbf{HWW}}$ so that its UV finiteness follows from gauge cancellations

($\mathrm{H} \to \mathrm{AA}, \mathrm{AZ}, \mathrm{ZZ}, \mathrm{WW} = 6$ Lorentz structures controlled by 5 coefficients)

Proposition

This is the first part in proving closure of NLO SMEFT under renormalization Q.E.D.

Remark Mixing of $a_{\phi \mathrm{D}}$ makes $\mathscr{D}_{\mathbf{HWW}}$ UV finite Q.E.D.

❺ 

Compute the (on-shell) decay $\mathbf{H}(P) \to \mathbf{b}(p_1)\bar{\mathbf{b}}(p_2)$.

Remark

- It is $\mathbf{dim} = 4$ UV finite and
- mixing of $a_{\mathbf{d}\phi}$ makes it UV finite also at $\mathbf{dim} = 6$ Q.E.D.

❻ 

Compute the (on-shell) decay $Z(P) \to f(p_1)\bar{f}(p_2)$. It is $\dim = 4$ UV finite and we introduce

$$
\begin{aligned}
a_{l\,W} &= s_\theta\, a_{l\,WB} + c_\theta\, a_{l\,BW} & a_{l\,B} &= s_\theta\, a_{l\,BW} - c_\theta\, a_{l\,WB} \\
a_{d\,W} &= s_\theta\, a_{d\,WB} + c_\theta\, a_{d\,BW} & a_{d\,B} &= s_\theta\, a_{d\,BW} - c_\theta\, a_{d\,WB} \\
a_{u\,W} &= s_\theta\, a_{u\,WB} + c_\theta\, a_{u\,BW} & a_{u\,B} &= c_\theta\, a_{u\,WB} - s_\theta\, a_{u\,BW}
\end{aligned}
$$

$$
\begin{aligned}
a^{(3)}_{\phi l} - a^{(1)}_{\phi l} &= \frac{1}{2}\,(a_{\phi l\,V} + a_{\phi l\,A}) & a_{\phi l} &= \frac{1}{2}\,(a_{\phi l\,A} - a_{\phi l\,V}) \\
a_{\phi u\,V} &= a^{(3)}_{\phi q} + a_{\phi u} + a^{(1)}_{\phi q} & a_{\phi u\,A} &= a^{(3)}_{\phi q} - a_{\phi u} + a^{(1)}_{\phi q} \\
a_{\phi d\,V} &= a^{(3)}_{\phi q} - a_{\phi d} - a^{(1)}_{\phi q} & a_{\phi d\,A} &= a^{(3)}_{\phi q} + a_{\phi d} - a^{(1)}_{\phi q}
\end{aligned}
$$

and obtain that (Q.E.D.)

$Z \to \bar{l}l$ requires mixing of $a_{l\,BW}, a_{\phi l\,A}$ and $a_{\phi l\,V}$ with other coefficients,

$Z \to \bar{u}u$ requires mixing of $a_{u\,BW}, a_{\phi u\,A}$ and $a_{\phi u\,V}$ with other coefficients,

$Z \to \bar{d}d$ requires mixing of $a_{d\,BW}, a_{\phi d\,A}$ and $a_{\phi d\,V}$ with other coefficients,

$Z \to \bar{\nu}\nu$ requires mixing of $a_{\phi\nu} = 2\,(a^{(1)}_{\phi l} + a^{(3)}_{\phi l})$ with other coefficients.

❼ 

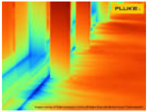
At this point we are left with the universality of the electric charge. In QED there is a Ward identity telling us that e is renormalized in terms of vacuum polarization and Ward-Slavnov-Taylor identities allow us to generalize the argument to the full SM.

We can give a quantitative meaning to the the previous statement by saying that the contribution from vertices (at zero momentum transfer) exactly cancel those from (fermion) wave function renormalization factors. Therefore,

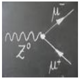
Compute the vertex $\mathbf{A}\bar{\mathbf{f}}\mathbf{f}$ (at $q^2 = 0$) and the $\mathbf{f}$ wave function factor in SMEFT, proving that the WST identity can be extended to $\mathbf{dim} = 6$; this is non trivial since there are no free Wilson coefficients in these terms (after the previous steps); (non-trivial) finiteness of $\mathbf{e}^+\mathbf{e}^- \to \bar{\mathbf{f}}\mathbf{f}$ follows.

Proposition

This is the second part in proving closure of NLO SMEFT under renormalization Q.E.D.



The IR connection (e.g. $Z \to \bar{l}l$)



$$= \rho_Z^f \gamma^\mu \left[\left(I_f^{(3)} + i\, a_L \right) \gamma_+ - 2\, Q_f\, \kappa_Z^f \sin^2\theta + i\, a_Q \right]$$

$$\mathscr{A}_\mu^{\text{tree}} \quad = \quad g\, \mathscr{A}_{1\,\mu}^{(4)} + g\, g_6\, \mathscr{A}_{1\,\mu}^{(6)}$$

$$\mathscr{A}_{1\,\mu}^{(4)} = \frac{1}{4\, c_\theta}\, \gamma_\mu \left(v_L + \gamma^5 \right) \qquad\qquad \mathscr{A}_{1\,\mu}^{(6)} = \frac{1}{4}\, \gamma_\mu \left(V_l + A_l\, \gamma^5 \right)$$

$$\begin{aligned} V_l \quad &= \quad \frac{s_\theta^2}{c_\theta} \left(4\, s_\theta^2 - 7 \right) a_{AA} + c_\theta \left(1 + 4\, s_\theta^2 \right) a_{ZZ} + s_\theta \left(4\, s_\theta^2 - 3 \right) a_{AZ} \\ &+ \quad \frac{1}{4\, c_\theta} \left(7 - s_\theta^2 \right) a_{\phi D} + \frac{2}{c_\theta}\, a_{\phi 1 V} \\ A_l \quad &= \quad \frac{s_\theta^2}{c_\theta}\, a_{AA} + c_\theta\, a_{ZZ} + s_\theta\, a_{AZ} - \frac{1}{4\, c_\theta}\, a_{\phi D} + \frac{2}{c_\theta}\, a_{\phi L A} \end{aligned}$$

After UV renormalization, i.e. after counterterms and mixing have been introduced, we perform analytic continuation in n (space-time dimension), $n = 4 + \varepsilon$ with ε positive.

$$\mathscr{A}^{\text{tree},\,1\text{L}} = \overline{u}_1\, \mathscr{A}_{\mu}^{\text{tree},\,1\text{L}}\, v_2\, e^{\mu}(\lambda\,,\,P)$$

$$\Gamma\left(\mathrm{Z} \to \bar{\mathrm{l}} + \mathrm{l}\right)\big|_{\text{div}} = \frac{2}{3}\,\frac{1}{(2\,\pi)^2}\,\sum_{\text{spin}}\int d\Phi_{1\to 2}\,\mathrm{Re}\left[\mathscr{A}^{\text{tree}}\right]^{\dagger}\mathscr{A}^{1\text{L}}\big|_{\text{div}}$$

$\boldsymbol{(\varepsilon\,,\,m_{\mathrm{f}})}$ -scheme for (IR , collinear) singularities

$$\frac{1}{\hat{\varepsilon}} = \frac{2}{\varepsilon} + \overline{\gamma} - \ln\frac{M_{\mathrm{W}}^2}{\mu^2} \quad \mathrm{L}_{c\mathrm{W}} = \ln\frac{m_{\mathrm{l}}^2}{M_{\mathrm{W}}^2} \quad \mathrm{L}_{c\mathrm{Z}} = \ln\frac{m_{\mathrm{l}}^2}{M_{\mathrm{Z}}^2}$$

$$\overline{\gamma} = \gamma + \ln\pi \quad \mathrm{L} = \ln\frac{M_{\mathrm{Z}}^2}{M_{\mathrm{W}}^2}$$

IR /collinear divergent factor

$$\mathscr{F}^{\rm virt} = -2\left(\frac{1}{\hat{\varepsilon}}+\overline{\gamma}\right)(1+\mathrm{L}_{\rm cZ})-\mathrm{L}^2_{\rm cZ}-4\,\mathrm{L}_{\rm cZ}\,\mathrm{L}+3\,\mathrm{L}_{\rm cZ}-4\,\mathrm{L}$$
$$-\quad 2\ln\frac{M^2_{\rm W}}{\mu^2}(1+\mathrm{L}_{\rm cZ})+2-8\,\zeta(2)$$

Sub-amplitudes

$$\Gamma^{(4)}_0 = \frac{1}{2}\left(1-4\,s^2_\theta+8\,s^4_\theta\right)\frac{1}{c^2_\theta}=\frac{1}{4}\left(1+v^2_{\rm l}\right)\frac{1}{c^2_\theta}$$

$$\Gamma^{(4)}_{0\,\rm A} = 2\left(1-4\,s^2_\theta\right)\frac{s_\theta}{c_\theta}=2\,v_{\rm l}\,\frac{s_\theta}{c_\theta}$$

$$\Gamma^{(6)}_0 = -\left(3-16\,s^2_\theta+8\,s^4_\theta\right)\frac{s^2_\theta}{c^2_\theta}\,a_{\rm AA}+\left(1-8\,s^4_\theta\right)a_{\rm ZZ}-\left(1-8\,s^2_\theta+8\,s^4_\theta\right)\frac{s_\theta}{c_\theta}\,a_{\rm AZ}$$
$$+\quad\frac{1}{4}\left(3-16\,s^2_\theta+8\,s^4_\theta\right)\frac{1}{c^2_\theta}\,a_{\phi\,\rm D}+\frac{1}{c^2_\theta}\,a_{\phi\,1\,\rm A}+\left(1-4\,s^2_\theta\right)\frac{1}{c^2_\theta}\,a_{\phi\,1\,\rm V}$$

Proposition

The infrared/collinear part of the one-loop virtual corrections shows double factorization.

$$\Gamma\left(\mathrm{Z} \to \bar{\mathrm{l}} + \mathrm{l}\right)\Big|_{\mathrm{div}} = -\frac{g^4}{384\,\pi^3}\, M_{\mathrm{Z}}\, s_\theta^2\, \mathscr{F}^{\mathrm{virt}} \left[\Gamma_0^{(4)}\,\left(1 + g_6\,\Delta\Gamma\right) + g_6\,\Gamma_0^{(6)}\right]$$

$$\Delta\Gamma = 2\left(2 - s_\theta^2\right) a_{\mathrm{AA}} + 2\, s_\theta^2\, a_{\mathrm{ZZ}} + 2\,\frac{c_\theta^3}{s_\theta}\, a_{\mathrm{AZ}} - \frac{1}{2}\,\frac{1}{s_\theta^2\, c_\theta^2}\, a_{\phi\mathrm{D}}$$

Next we compute $\mathrm{Z}(P) \to \mathrm{l}(p_1) + \bar{\mathrm{l}}(p_2) + \gamma(k)$, obtaining

$$\Gamma\left(\mathrm{Z} \to \bar{\mathrm{l}} + \mathrm{l} + \gamma\right) \quad = \quad \frac{1}{3}\,\frac{1}{(2\,\pi)^5}\,\sum_{\text{spin}} \int d\Phi_{1\to 3}\;|\,\mathscr{A}^{\text{real}}\,|^2$$

$$\mathscr{A}^{\text{real}} \quad = \quad \overline{u}_1\,\mathscr{A}^{\text{real}}_{\mu\nu}\,v_2\,e^{\mu}(\lambda\,,P)\,e^{\nu}(\sigma\,,k)$$

We split the total into

- "approximated", $n \neq 4$, approximated phase-space, reproducing the exact structure of singularities
- "remainder", $n = 4$, finite

After expanding in $\varepsilon = n - 4$ we obtain an overall infrared/collinear (real) factor

$$\mathscr{F}^{\text{real}} = -2\left(\frac{1}{\hat{\varepsilon}} + \overline{\gamma}\right)(1 + \mathrm{L}_{cZ}) - \mathrm{L}_{cZ}^2 - 2\,\mathrm{L}_{cZ}\,\mathrm{L} + 3\,\mathrm{L}_{cZ} - 2\,\mathrm{L}$$
$$- \; 2\ln\frac{M_Z^2}{\mu^2}(1 + \mathrm{L}_{cZ}) + 1 - 4\,\zeta(2)$$

and a partial width integrated over the whole photon phase space

$$\Gamma^{\text{app}}(Z \to \bar{l} + l + (\gamma)) = \frac{g^4}{384\,\pi^3} M_Z\, s_\theta^2\, \mathscr{F}^{\text{real}} \left[\Gamma_0^{(4)}(1 + g_6\,\Delta\Gamma) + g_6\,\Gamma_0^{(6)}\right]$$

Proposition

The infrared/collinear part of the real corrections shows double factorization. The total = virtual + real is IR /collinear finite at $\mathscr{O}(g^4\, g_6)$ (Q.E.D.).

Assembling everything gives

$$\Gamma^{\mathrm{l}}_{\mathrm{QED}} = \frac{3}{4}\,\Gamma^{\mathrm{l}}_{0}\,\frac{\alpha}{\pi}\,\left(1 + g_6\,\Delta^{(6)}_{\mathrm{QED}}\right) \qquad \Gamma^{\mathrm{l}}_{0} = \frac{G_{\mathrm{F}}\,M^3_{\mathrm{Z}}}{24\,\sqrt{2}\,\pi}\,\left(v^2_{\mathrm{l}} + 1\right)$$

$$\begin{aligned} \Delta^{(6)}_{\mathrm{QED}} &= 2\,\left(2 - s^2_\theta\right)\,a_{\mathrm{AA}} + 2\,s^2_\theta\,a_{\mathrm{ZZ}} + 2\,\left(\frac{c^3_\theta}{s_\theta} + \frac{512}{26}\,\frac{v_{\mathrm{L}}}{v^2_{\mathrm{L}} + 1}\right)\,a_{\mathrm{AZ}} \\ &- \frac{1}{2}\,\frac{c^2_\theta}{s^2_\theta}\,a_{\phi\,\mathrm{D}} + \frac{1}{v^2_{\mathrm{L}} + 1}\,\delta^{(6)}_{\mathrm{QED}} \\ \delta^{(6)}_{\mathrm{QED}} &= \left(1 - 6\,v_{\mathrm{l}} - v^2_{\mathrm{l}}\right)\,\frac{1}{c^2_\theta}\,\left(s_\theta\,a_{\mathrm{AA}} - \frac{1}{4}\,a_{\phi\,\mathrm{D}}\right) \\ &+ \left(1 + 2\,v_{\mathrm{l}} - v^2_{\mathrm{l}}\right)\,\left(a_{\mathrm{ZZ}} + \frac{s_\theta}{c_\theta}\,a_{\mathrm{AZ}}\right) \\ &+ \frac{2}{c^2_\theta}\,\left(a_{\phi\,\mathrm{l\,A}} + v_{\mathrm{l}}\,a_{\phi\,\mathrm{l\,V}}\right) \end{aligned}$$

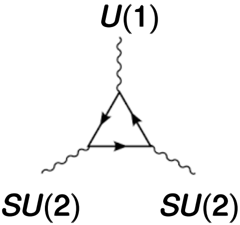
W-decay: solvable problems expected 

 Triple/quadrupole gauge couplings,

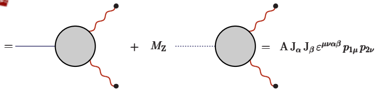
last stop before renormalizability?

Gauge anomalies, anomaly cancellation; d'Hoker-Farhi (Wess-Zumino) terms? Extra simmetry? Etc: severe problems expected

(perhaps, a deeper understanding of SMEFT) 



etc.



Proposition

✗ *SMEFT anomalies are UV finite[a] and local[b]*

It's another tiny step forward

---

[a] It's good for renormalizability

[b] It's good for unitarity

- ✔ EFT is traditionally a very successful paradigm to use to interpret the data because it is implemented as a well defined field theory
- ✔ Standard EFTs can be systematically improved from LO to NLO as they avoid ad-hoc and ill defined assumptions

Ideas that require people to reorganize their picture of the world provoke hostility

To conclude, the journey to the next SM may require crossing narrow straits of precision physics. If that is what nature has in store for us, we must equip ourselves with both a range of concrete BSM models as well as a general SMEFT. Both will be indispensable tools in navigating an ocean of future experimental results.

Each paradigm will be shown to satisfy more or less the criteria that it dictates for itself and to fall short of a few of those dictated by its opponent

T. S. Kuhn

Thank you for your attention


Backup Slides

NLO SMEFT for Higgs and EW precision data

No NP yet?

A study of $\mathcal{SM}$-deviations: here the reference process is $\mathbf{gg \to H}$

✓ κ-approach: write the amplitude as

$$\mathbf{A^{gg}} = \sum_{\mathbf{q=t,b}} \kappa^{\mathbf{gg}}_{\mathbf{q}} \mathscr{A}^{\mathbf{gg}}_{\mathbf{q}} + \kappa^{\mathbf{gg}}_{c}$$

$\mathscr{A}^{\mathbf{gg}}_{\mathbf{t}}$ being the SM t-loop etc. The contact term (which is the LO SMEFT) is given by $\kappa^{\mathbf{gg}}_{c}$. Furthermore

$$\kappa^{\mathbf{gg}}_{\mathbf{q}} = 1 + \Delta\kappa^{\mathbf{gg}}_{\mathbf{q}}$$

Compute

$$\mathbf{R} = \sigma\left(\kappa_{\mathbf{q}}^{gg}, \kappa_{C}^{gg}\right)/\sigma_{SM} - 1 \quad [\%]$$

❶ In LO SMEFT κ_C is non-zero and $\kappa_{\mathbf{q}} = 1$. [5] You measure a deviation and you get a value for κ_C

❷ However, at NLO $\Delta\kappa_{\mathbf{q}}$ is non zero and you get a degeneracy

❸ The interpretation in terms of κ_C^{LO} or in terms of $\{\kappa_C^{NLO}, \Delta\kappa_{\mathbf{q}}^{NLO}\}$ could be rather different.

[5] Certainly true in the linear realization

Going interpretational

$$\mathrm{A}^{\mathrm{gg}}_{\mathrm{SMEFT}} = \frac{g\, g_S^2}{\pi^2} \sum_{\mathrm{q=t,b}} \kappa^{\mathrm{gg}}_{\mathrm{q}}\, \mathscr{A}^{\mathrm{gg}}_{\mathrm{q}}$$

$$+ \; 2\, g_S\, g_6\, \frac{s}{M_W^2}\, a_{\phi \mathrm{g}} + \frac{g\, g_S^2\, g_6}{\pi^2} \sum_{\mathrm{q=t,b}} \mathscr{A}^{\mathrm{NF;gg}}_{\mathrm{q}}\, a_{\mathrm{qg}}$$

Remark use arXiv:1505.03706, adopt Warsaw basis (arXiv:1008.4884), eventually work in the Einhorn-Wudka PTG scenario (arXiv:1307.0478)

① LO SMEFT: $\kappa_{\mathrm{q}} = 1$ and $a_{\phi \mathrm{g}}$ is scaled by $1/16\,\pi^2$ being LG (blue color)

② NLO PTG-SMEFT: $\kappa_{\mathrm{q}} \neq 1$ but only PTG operators inserted in loops (non-factorizable terms absent), $a_{\phi \mathrm{g}}$ scaled as above

③ NLO full-SMEFT: $\kappa_{\mathrm{q}} \neq 1$ LG/PTG operators inserted in loops (non-factorizable terms present), LG coefficients scaled as above

At NLO, $\Delta\kappa = g_6\, \rho$

Warsaw basis

$$g_6^{-1} = \sqrt{2}\, G_F\, \Lambda^2$$

$$4\,\pi\,\alpha_s = g_S^2$$

$$\rho_t^{gg} = a_{\phi W} + a_{t\phi} + 2\,a_{\phi\Box} - \frac{1}{2}\,a_{\phi D}$$

$$\rho_b^{gg} = a_{\phi W} - a_{b\phi} + 2\,a_{\phi\Box} - \frac{1}{2}\,a_{\phi D}$$

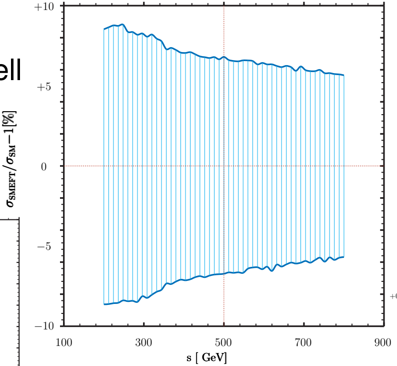
Relaxing the PTG assumption introduces non-factorizable sub-amplitudes proportional to a_{tg}, a_{bg} with a mixing among $\{a_{\phi g}, a_{tg}, a_{bg}\}$. Meanwhile, renormalization has made one-loop SMEFT finite, e.g. in the G_F -scheme, with a residual μ_R -dependence.

What are POs? Experimenters collapse some “primordial quantities” (say number of observed events in some pre-defined set-up) into some “secondary quantities” which we feel closer to the theoretical description of the phenomena.

Residues of resonant poles, κ-parameters and Wilson coefficients are different layers of POs

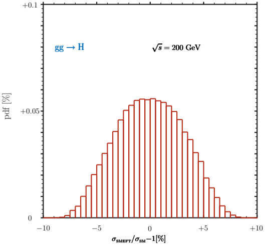
support $|a_i| \in [-1,+1]$

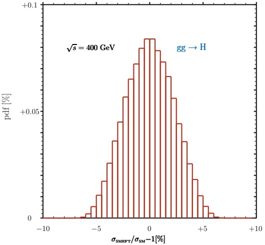
$\mathbf{gg \to H}$ off-shell

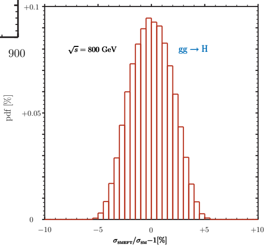


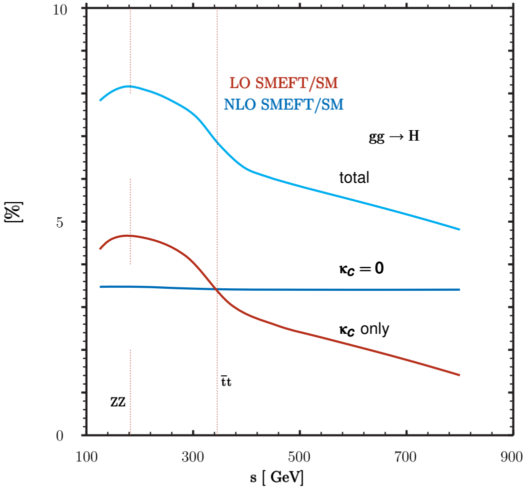
unif$(-1,1)$

$\Lambda = 3$ ***TeV***









Another reason to go NLO

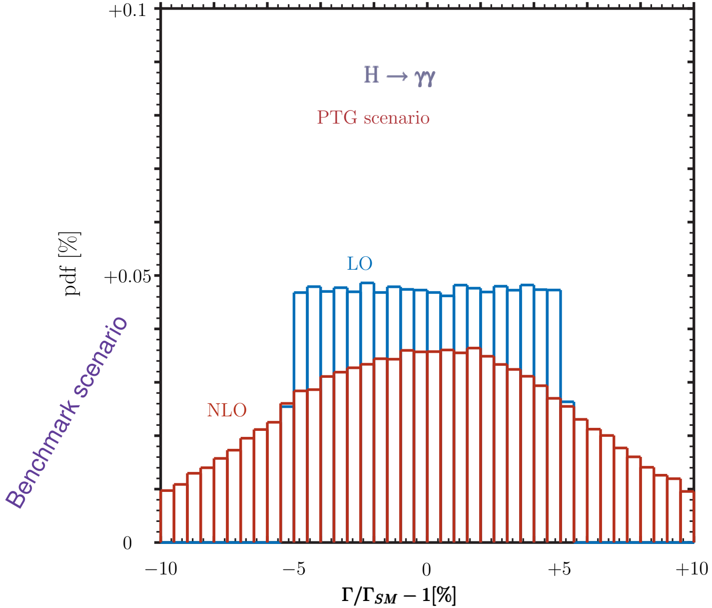
The contact term is real ... $\kappa_c^{gg} \in \mathbb{R}$

$\frac{g\, g_S^2\, g_6}{\pi^2} \sum_{q=t,b} \left[\Delta\kappa_q^{gg}\, \mathscr{A}_q^{gg} + \mathscr{A}_q^{NF;gg}\, a_{qg} \right] \in \mathbb{C}$

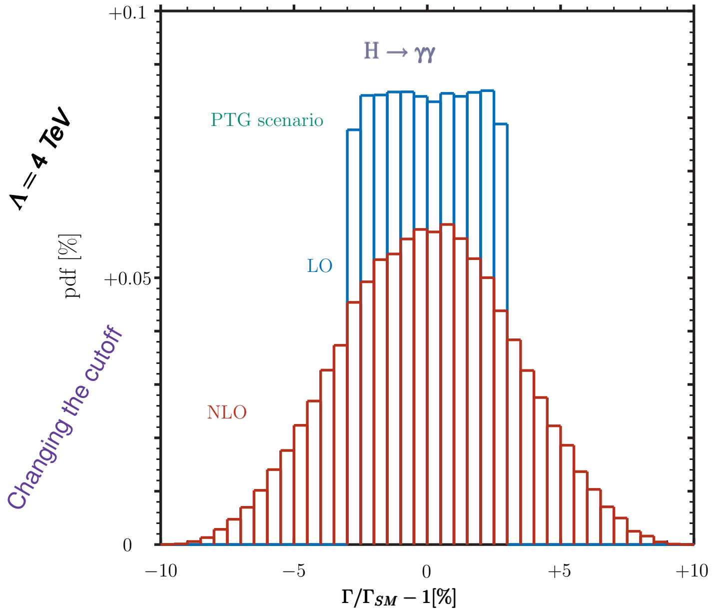
$2\, g_S\, g_6\, \frac{s}{M_W^2}\, a_{\phi g} \in \mathbb{R}$

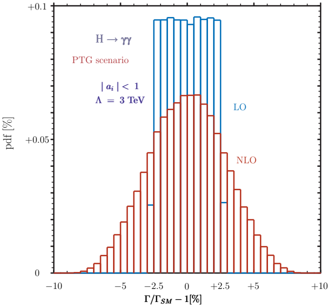
$a_i = 1,\ \forall i$

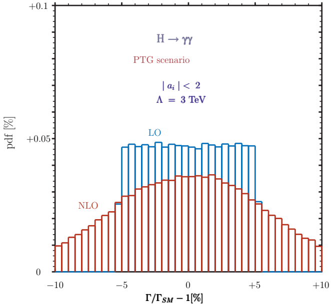
$\Lambda = 3\ TeV$

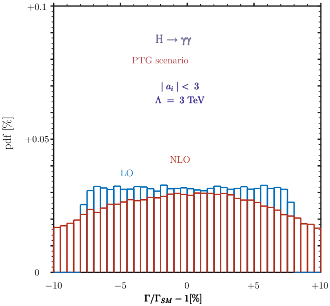


H → γγ
PTG scenario
LO
NLO
Benchmark scenario
pdf [%]
+0.1
+0.05
0
−10
−5
0
+5
+10
Γ/Γ_SM − 1[%]


$\Lambda = 4$ TeV
Changing the cutoff
$H \to \gamma\gamma$
PTG scenario
LO
NLO
pdf [%]
+0.1
+0.05
0
−10
−5
0
+5
+10
$\Gamma/\Gamma_{SM} - 1[\%]$







Changing the interval

Appendix C. Dimension-Six Basis Operators for the SM[22].

X^3 **(LG)**		φ^6 and $\varphi^4 D^2$ **(PTG)**		$\psi^2\varphi^3$ **(PTG)**	
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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$ **(LG)**		$\psi^2 X\varphi$ **(LG)**		$\psi^2\varphi^2 D$ **(PTG)**	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	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 C.1: Dimension-six operators other than the four-fermion ones.

[22] These tables are taken from [5], by permission of the authors.