Effective Field Theories and Anomalous Gauge Couplings

— Multibosons At The Energy Frontier, Fermilab —

Claudius Krause

Fermi National Accelerator Laboratory

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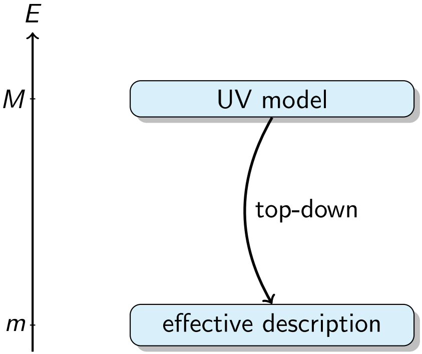
The top-down approach simplifies computations.



- At low energies, there are no heavy external states.

$\Rightarrow$ Heavy states are integrated-out.

- The effective low-energy description is given in terms of the light states only.

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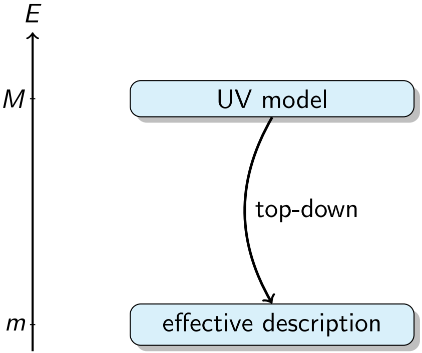

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⇒ Heavy states are integrated-out.

- The effective low-energy description is given in terms of the light states only.

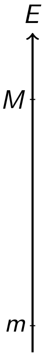
Examples:

- Fermi Theory at energies below m_W.

Sometimes, the degrees of freedom change completely:

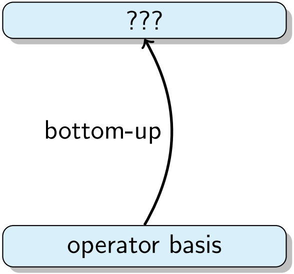
- Chiral Perturbation Theory (ChPT) as low-energy QCD.

We can use EFTs because we have a mass gap.



- We write down the most general set of interactions given the light states.

$\Rightarrow$ We can describe many different UV-models.



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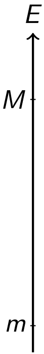

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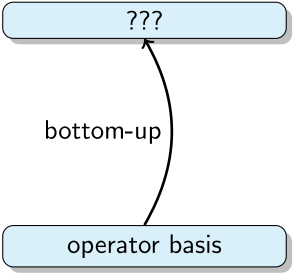
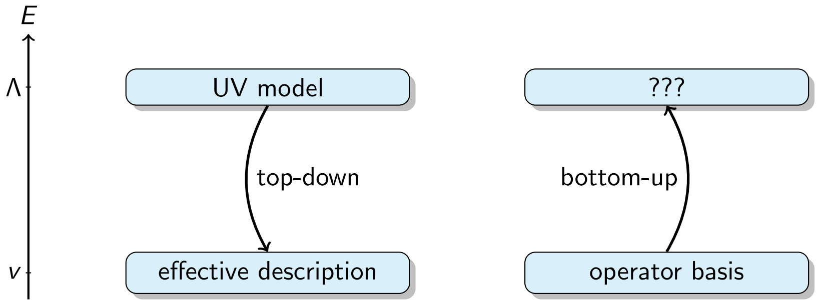


Advantages:

- We have a well-defined QFT (incl. gauge invariance etc.).
- We know how to include higher orders (in EFT and in QFT).
- There are almost no assumptions on the UV physics.

Both approaches are important.



For a model-independent analysis we use the bottom-up approach.

However, for a complete picture, we need both approaches:

- bottom-up: Tells us about deviations from the SM.
- top-down: Tells us about the UV-model causing them.

⇒ The bottom-up EFT should always be understood as low-energy approximation of a (so far unknown) UV completion!

We need 3 ingredients to construct a bottom-up EFT.

Ingredients:

- Particles: all SM particles (incl. 3 GBs for the $W^{\pm}/Z$ masses)
- Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$, $(B,\, L)$
- Power counting: depends on type of the EFT:

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non-decoupling (nonlinear) EFT:
– $EWCh\mathcal{L}$ –

- LO: Higgs-less chiral Lagrangian + generic scalar h
- expansion chiral dimensions (generalized momenta).

$\Rightarrow$ "testing the Higgs-hypothesis"

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$\Rightarrow$ "testing the Higgs-hypothesis"

decoupling (linear) EFT:
– SMEFT –

- LO: SM
- expansion in canonical dimensions

$\Rightarrow$ "testing physics beyond the (complete) Standard Model"

Effective Field Theories and Anomalous Gauge Couplings

Part I: Higgs-Electroweak Chiral Lagrangian

$\Rightarrow$ Understanding electroweak symmetry breaking

$\boxed{EWCh\mathcal{L}}$

$\boxed{\text{SMEFT}}$

Part II: Standard Model EFT

$\Rightarrow$ Understanding physics beyond the SM

$\mathcal{EWCh\mathcal{L}}$ I: The construction of the chiral Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\text{LO}} = & \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \ (1 + F_U(h)) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}(h) \\
& + i\bar{\psi}_f \not{D}\psi_f - (v\,\bar{\psi}_f U\, Y_f(h)\psi_f + \text{h.c.}) \\
& - \frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}
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In unitary gauge:

$$\frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle = \frac{g^2 v^2}{4} W^+_\mu W^{\mu -} + \frac{(g^2 + g'^2)v^2}{8} Z_\mu Z^\mu$$

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Properties:

- It has generalized Higgs-couplings compared to the SM.

  $\Rightarrow$ related to the κ-formalism at LO.
- There is a hierarchy to the operators that modify the EWPD.
- It captures the low-energy effects of strongly-coupled new physics (similar to ChPT).
- It is non-renormalizable at LO.

$\mathcal{EWChL}$ I: Current Higgs observables constrain a few c_i.

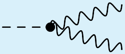
$$\mathcal{L}_{EWCh} = \mathcal{L}_{\text{kin}}^{h,\psi,\text{gauge}} + \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \; (1 + F_U(h)) - \mathcal{V}(h)$$
$$- (v\,\bar{\psi}_f U\, Y_f(h)\psi_f + \text{h.c.}) + \mathcal{L}_{\text{NLO}}$$

Buchalla/Catà/Celis/CK [1504.01707,NPB]

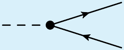
We focus on current observables.

Single h processes:

tree:

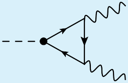


c_V



$c_{t,b,\tau,\mu,(c)}$

1-loop:



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$+$

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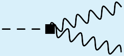

$c_{\gamma\gamma,gg,Z\gamma}$

$\mathcal{EWChL}$ I: Current Higgs observables constrain a few c_i.

$$\begin{aligned}\mathcal{L}_{\text{fit}} =&2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(\tfrac{h}{v}\right)\\ &- c_t y_t \bar{t}th - c_b y_b \bar{b}bh - c_c y_c \bar{c}ch - c_\tau y_\tau \bar{\tau}\tau h - c_\mu y_\mu \bar{\mu}\mu h\\ &+ \tfrac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \tfrac{h}{v} + \tfrac{e^2}{16\pi^2} c_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} \tfrac{h}{v} + \tfrac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu}\rangle \tfrac{h}{v}\end{aligned}$$

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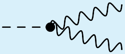

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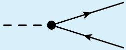

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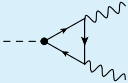

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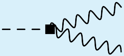

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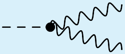

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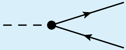


$c_{t,b,\tau,\mu,(c)}$

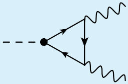
$$\kappa_i^2 = \Gamma^i / \Gamma^i_{\text{SM}}, \quad \kappa_i^2 = \sigma^i / \sigma^i_{\text{SM}}$$

LHCHXSWG [1209.0040,1307.1347]

$$\kappa_{V,t,b,\tau,\mu} \simeq c_{V,t,b,\tau,\mu}$$
$$\kappa_{\gamma\gamma,gg} \simeq f\left(c_V, c_t, c_b, c_\tau, c_\mu, c_{\gamma\gamma,gg}\right)$$

de Blas/Eberhardt/CK [1803.00939,JHEP]

1-loop:



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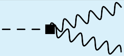
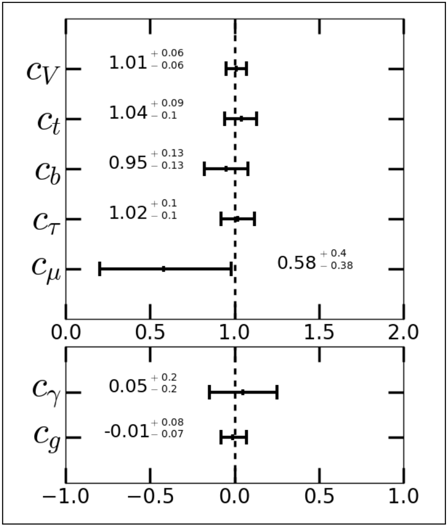


$c_{\gamma\gamma,gg,Z\gamma}$

$\mathcal{EWChL}$ I: The result is consistent with the SM.

- The likelihood has multiple maxima ($c_i \to -c_i$ symmetries).
- We use a prior to select the SM-like solution.
- More details about the choice of priors are in [1803.00939,JHEP].
- Consistent with SM, but $\mathcal{O}(10\%)$ deviations still possible.
- $c_{Z\gamma}$ and c_c are not constrained beyond prior.



data through Moriond '18
de Blas/Eberhardt/CK [1803.00939,JHEP]

$\mathcal{EWChL}$ I: Strong New Physics manifests itself in VBS.

If a strongly-coupled UV-completion triggers EWSB, Goldstone Bosons will couple strongly. Scattering of longitudinal gauge boson modes is therefore enhanced with respect to transverse modes.

$\Rightarrow$ Operators like

$$a_5 \,\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) \mathrm{Tr}\left(D_\nu U^\dagger D^\nu U\right) \quad \text{and} \quad a_4 \,\mathrm{Tr}\left(D_\mu U^\dagger D_\nu U\right) \mathrm{Tr}\left(D^\mu U^\dagger D^\nu U\right)$$

are NLO ($\mathcal{O}(p^4)$) in the *EWChL* but NNLO (dimension 8) in the SMEFT.

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- Non vanishing coefficients a_4 and a_5 imply resonances based on unitarity arguments. e.g. see Delgado et al. [1707.04580,JHEP]
- Such resonances will also show up in final states involving Higgs. Dobado et al. [1711.10310,JHEP]
- And through indirect (top-down EFT) effects. Krause et al. [1810.10544,JHEP]

Effective Field Theories and Anomalous Gauge Couplings

Part I: Higgs-Electroweak Chiral Lagrangian

$\Rightarrow$ Understanding electroweak symmetry breaking

$\boxed{EWCh\mathcal{L}}$

$\boxed{\text{SMEFT}}$

Part II: Standard Model EFT

$\Rightarrow$ Understanding physics beyond the SM

II: The construction of the SMEFT.

$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}} =& (D_\mu \Phi)^\dagger (D^\mu \Phi) + \mu^2 \Phi^\dagger \Phi - \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 + i \bar{\psi}_f \not{D} \psi_f \\
& - (\bar{\psi}_L Y_\psi \psi_R \Phi + \text{h.c.}) - \tfrac{1}{2} \langle G_{\mu\nu} G^{\mu\nu} \rangle - \tfrac{1}{2} \langle W_{\mu\nu} W^{\mu\nu} \rangle - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
& + \frac{c^{(5)}}{\Lambda} ((\widetilde{\Phi}^\dagger \ell)^T C (\widetilde{\Phi}^\dagger \ell) + \text{h.c.}) + \frac{c_i^{(6)}}{\Lambda^2} \mathcal{L}_{\text{dim-6}} + \ldots
\end{aligned}
$$

SMEFT II: The construction of the SMEFT.

$$\mathcal{L}_{\text{SMEFT}} = (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + i\bar{\psi}_f \not{D}\psi_f$$
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Properties:

- In the decoupling limit ($\Lambda \to \infty$) we recover the SM.
- Modifications to the gauge- and Higgs-sector enter at dimension 6.
- Field redefinitions and the use of equations of motion affect subleading orders.

$\Rightarrow$ There are different dimension 6 bases on the market:

Warsaw SILH (Higgs)

Codes like `Rosetta` (Falkowski et al. [1508.05895, EPJC]) and `DEFT` (Gripaios/Sutherland [1807.07546,JHEP]) translate between bases.

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$$-(\bar{\psi}_L Y \ldots \; W^{\mu\nu}\rangle - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

- Grzadkowski et al. [1008.4884, JHEP]
- uses operators with least number of derivatives
- most commonly used for computations (RGEs, processes at NLO)

Properti…

- In the decoupling … SM.
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SMEFT II: The construction of the SMEFT.

$$\mathcal{L}_{\text{SMEFT}} = (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + i\bar{\psi}_f \not{D}\psi_f$$
$$- (\bar{\psi}_L Y_\psi \psi_R \Phi + \text{h.c.}) - \tfrac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \tfrac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

- Contino et al. [1303.3876, JHEP]
- "nice" to associate certain operators with observables

Properties:

- In the decoupling limit ($\Lambda \to$ c... ...cover the SM.
- Modifications to the gauge- an... ...-sector enter at dimension 6.
- Field redefinitions and the use o... ...ations of motion affect subleading orders.

$\Rightarrow$ There are different dimension 6 ba...es on the market:

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- Falkowski [LHCHXSWG-INT-2015-001] / CERN Higgs YR 4 [1610.07922]
- gauge-dependent rotation of Warsaw to mass eigenstates
- see discussion of Trott/Passarino [1610.08356]

Prope

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SMEFT II: The number of free parameters is large.

At dimension 6, there are

- 76 parameters for 1 fermion generation.
- 2499 parameters for 3 fermion generations.

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Ways to reduce these numbers:

✓ by symmetries (MFV, CP, ...)

✓ by (classes of) UV-models, see dictionary of de Blas et al. [1711.10391,JHEP]

× by choice

⇒ Keep in mind the RGEs!

SMEFT II: There are direct and indirect contributions.

direct

Once the set of operators is fixed, the next steps are:

- rotate to physical mass eigenstates
- extract the Feynman rules and compute the matrix element of the process `FeynRules` implementation: Brivio et al. [1709.06492,JHEP]

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indirect

One should keep in mind that our Lagrangian is not $\mathcal{L}_{\mathrm{SM}}$, but $\mathcal{L}_{\mathrm{SMEFT}}$:

- The definition of input values like $\alpha_{ew}, m_Z, G_F, m_W$ depend on $c_i^{(6)}$.
- The same applies to the values of V_{CKM}. Brivio/Trott [1701.06424,JHEP];
- And the PDFs. Descotes-Genon et al. [1812.08163,JHEP]; Carrazza et al. [1905.05215]

SMEFT II: An example: anomalous gauge couplings.

Consider the process $\bar{\psi}\psi \rightarrow W^+W^-$, the following operators contribute directly: taken from Zhang [1610.01618,PRL], see also Grojean et al. [1810.05149,JHEP]

$$\mathcal{O}_{\Phi WB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_{\Phi D} = |\Phi^\dagger D_\mu \Phi|^2, \qquad \mathcal{O}_{\Phi\psi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{\psi}_R \gamma^\mu \psi_R)$$

$$\mathcal{O}^{(3)}_{\Phi\psi} = i(\Phi^\dagger \overleftrightarrow{D}^a_\mu \Phi)(\bar{\psi}_L \gamma^\mu \sigma^a \psi_L), \qquad \mathcal{O}^{(1)}_{\Phi\psi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{\psi}_L \gamma^\mu \psi_L), \qquad \mathcal{O}_{3W} = \epsilon^{abc} W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$$

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They contribute to the aGCs:

$$\mathcal{L}_{\text{TGC}} = ig \Big\{ (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) \left[(1 + \delta g_{1z})\, c_\theta Z^\nu + s_\theta A^\nu \right] + \frac{1}{2} W^+_{[\mu,} W^-_{\nu]} \left[(1 + \delta\kappa_z)\, c_\theta Z^{\mu\nu} + (1 + \delta\kappa_\gamma)\, s_\theta A^{\mu\nu} \right] + \frac{1}{m_W^2} W^{+\nu}_\mu W^{-\rho}_\nu (\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu) \Big\}$$

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But they also modify the gauge-fermion vertices:

$$\mathcal{L}_{\text{vertex}} = \sum_\psi \frac{g}{c_\theta} \left((T^3_\psi - Q_\psi s^2_\theta)\delta_{ij} + \left[\delta g^{Z\psi}_{L/R}\right]_{ij} \right) Z_\mu \bar{\psi}_i \gamma^\mu \psi_j$$
$$+ \frac{g}{\sqrt{2}} \left[\left(\delta_{ij} + \left[\delta g^{Wq}_L\right]_{ij}\right) W^+_\mu \bar{u}_{Li} \gamma^\mu (V_{\text{CKM}} d_L)_j + \left(\delta_{ij} + \left[\delta g^{Wl}_L\right]_{ij}\right) W^+_\mu \bar{\nu}_i \gamma^\mu e_{Lj} + \text{h.c.} \right]$$

SMEFT II: aGCs: Can we neglect the fermion vertices?

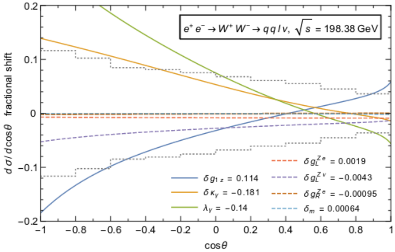

FIG. 1. Fractional shift in LEP2 $e^+e^- \to W^+W^- \to qq\ell\nu$ differential cross section induced by each of the anomalous couplings in Eq. (8), compared with experimental uncertainties (gray dotted) reported in [2]. Assuming lepton flavor universality, effects of the anomalous TGCs being constrained (solid) [27] are seen to dominate over those of Zff vertex and W mass corrections (dashed), even when the latter are set to maximum values allowed by EWPD [3, 26], providing justification for the conventional TGC analysis procedure.

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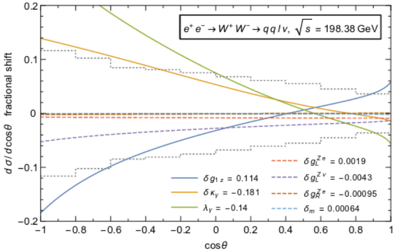

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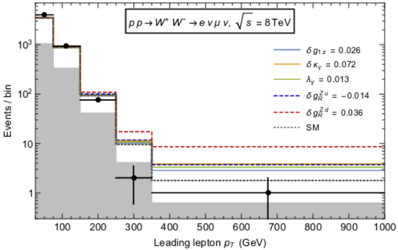

FIG. 2. Leading lepton p_T distribution of 8 TeV LHC W^+W^- events in the $e\mu$ channel when each anomalous coupling is turned on individually, compared with experimental data (dots with error bars) and SM predictions (gray dotted). The latter, together with non-WW backgrounds (gray shaded), are taken from [8]. Effects of anomalous TGCs being considered in recent TGC fits (solid) are clearly *not* dominant over those of δg_R^{Zu}, δg_R^{Zd} (dashed) consistent with EWPD, calling for extension of the conventional TGC analysis procedure.

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SMEFT II: Poles and tails are very different.

at LEP: $\sqrt{s} \leq 209$ GeV

- Poles and tails were always below Λ and the EFT approach was well justified.

$\Rightarrow$ $\boxed{p^2/\Lambda^2 \ll 1}$

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Biekötter et al. [1406.7320,PRD]
Contino et al. [1604.06444,JHEP]

- Is the EFT still valid there?

$\Rightarrow$ extracted limits become model-dependent.

- And on a related note, what happens to unitarity?

SMEFT II: What are the next steps?

Include one loop effects.

- For some observables, NLO QCD effects were already important at Run-1. Baglio et al. [1708.03332,PRD;1812.00214,PRD]
- Loop effects induce the running that is necessary to combine results from different scales. Alonso et al. [1308.2627,1310.4838,1312.2014,JHEP] Brivio/Trott [1706.08945,PR]
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Include dimension 8 operators.

- In many cases not feasable due to their large suppression ($1/\Lambda^4$) and their large number (895 & 36971). Henning et al. [1512.03433,JHEP]
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Towards a global SMEFT likelihood. `SMELLI` by Aebischer et al. [1810.07698,EPJC]

- Ideally, results from different sectors (Higgs, top, EWPD, . . .) should be combined to a global likelihood function.
- This requires a consistent treatment of the EFT in all analyses.

Effective Field Theories and Anomalous Gauge Couplings — Summary & Discussion—

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EWCh$\mathcal{L}$

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EWCh$\mathcal{L}$

SMEFT

Ideas for discussion:

- Where should we "meet"? At the level of EFT coefficients? Or Pseudo-observables? Or fiducial cross sections? Or . . . ?
- . . .