The SMEFT program at the LHC: status and prospects

Ilaria Brivio

Institut für Theoretische Physik,
Universität Heidelberg
What’s an Effective Field Theory?

A field theory valid in a regime $\delta \ll 1$

Taylor expansion in $\delta$
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A field theory valid in a regime $\delta \ll 1$

Taylor expansion in $\delta$

Classic example: **Fermi’s interaction** for $\beta$-decays

Diagram:
- $n$ to $p$
- $W^-$
- $e^-$
- $\bar{\nu}_e$
What’s an Effective Field Theory?

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Taylor expansion in $\delta$

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$\delta = \frac{E}{m_W}$
What's an Effective Field Theory?

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Classic example: **Fermi's interaction** for $\beta$-decays

$\delta = \frac{E}{m_W}$

$\propto G_F \sim \frac{1}{m^2_W}$

$+ \mathcal{O} \left( \frac{E^4}{m^4_W} \right)$

Irrelevant / not needed
EFTs for unknown UV sectors: bottom-up

main strength: can be constructed order-by-order in $\delta$

without knowing the underlying physics

$\rightarrow$ free parameters to be fixed from data

Fermi theory: the expansion parameter is a scale separation $\delta = \frac{E}{\Lambda} \ll 1$

$\Lambda$ scale of a physics sector

$E$ energy of the measurement(s) where the physical impact is observed
EFTs for unknown UV sectors: bottom-up

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→ free parameters to be fixed from data

Fermi theory: the expansion parameter is a scale separation $\delta = \frac{E}{\Lambda} \ll 1$

unknown $\rightarrow \Lambda$

assuming $\Lambda \gg E$, define dynamical fields + symmetries
construct all allowed terms up to some power in $E/\Lambda$
EFTs for unknown UV sectors: bottom-up

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unknown $\rightarrow \Lambda$

$E$ assuming $\Lambda \gg E$, define dynamical fields + symmetries

construct all allowed terms up to some power in $E/\Lambda$

infer properties of underlying physics

measure EFT parameters

$1/\sqrt{G_F} \sim 300$ GeV
LH currents, CP...

$G_F$
SMEFT: Standard Model Effective Field Theory

The EFT constructed with Standard Model field & symmetries

→ expansion in canonical dimensions $d$ (Taylor series in $\nu/\Lambda$ or $E/\Lambda$)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \ldots$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

$C_i =$ Wilson coefficients

$\mathcal{O}_i^{(d)} =$ gauge-invariant operators

At each order, $\mathcal{O}_i^{(d)}$ form a complete, non-redundant basis

SMEFT describes $\sim$ any beyond-SM physics living at $\Lambda \gg \nu$

(nearly decoupled)
### $\mathcal{L}_6$: the Warsaw basis

<table>
<thead>
<tr>
<th>$X^3$</th>
<th>$\varphi^6$ and $\varphi^4D^2$</th>
<th>$\psi^2\varphi^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_G$</td>
<td>$f^{ABC} G^{A\mu}<em>\nu G^{B\rho}</em>\nu G^{C\mu}_\rho$</td>
<td>$Q_\varphi$</td>
</tr>
<tr>
<td>$Q_{\tilde{G}}$</td>
<td>$f^{ABC} \tilde{G}^{A\mu}<em>\nu G^{B\rho}</em>\nu G^{C\mu}_\rho$</td>
<td>$Q_{\varphi \Box}$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$\epsilon^{IJK} W^I_\mu W^J_\nu W^K_\rho$</td>
<td>$Q_{\varphi \Box}$</td>
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<tr>
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<th>$\psi^2X\varphi$</th>
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<tr>
<td>$Q_{\varphi G}$</td>
<td>$\varphi^\dagger \varphi G^{A\mu}<em>\nu G^{A\mu}</em>\nu$</td>
<td>$Q_{eW}$</td>
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<tr>
<td>$Q_{\varphi \tilde{G}}$</td>
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<td>$Q_{eB}$</td>
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<td>$\varphi^\dagger \varphi W^I_\mu W^I_\mu$</td>
<td>$Q_{uG}$</td>
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<td>$Q_{dG}$</td>
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<tr>
<td>$Q_{\varphi W B}$</td>
<td>$\varphi^\dagger \tau^I \varphi W^I_\mu B^\mu$</td>
<td>$Q_{dW}$</td>
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<tr>
<td>$Q_{\varphi \tilde{W} B}$</td>
<td>$\varphi^\dagger \tau^I \varphi \tilde{W}^I_\mu B^\mu$</td>
<td>$Q_{dB}$</td>
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</table>
$L_6$: the Warsaw basis

<table>
<thead>
<tr>
<th>$Q_{ll}$</th>
<th>$(\bar{L}L)(\bar{L}L)$</th>
<th>$Q_{ee}$</th>
<th>$(\bar{R}R)(\bar{R}R)$</th>
<th>$Q_{le}$</th>
<th>$(\bar{L}L)(\bar{R}R)$</th>
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<tr>
<td>$Q_{qq}$</td>
<td>$(\bar{L}<em>p \gamma</em>\mu l_r)(\bar{L}<em>s \gamma</em>\mu l_t)$</td>
<td>$(\bar{L}<em>p \gamma</em>\mu l_r)(\bar{L}<em>s \gamma</em>\mu l_t)$</td>
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<td>$Q^{(1)}_{qq}$</td>
<td>$(\bar{q}<em>p \gamma</em>\mu q_r)(\bar{q}<em>s \gamma</em>\mu q_t)$</td>
<td>$(\bar{u}<em>p \gamma</em>\mu u_r)(\bar{u}<em>s \gamma</em>\mu u_t)$</td>
<td>$(\bar{L}<em>p \gamma</em>\mu l_r)(\bar{L}<em>s \gamma</em>\mu u_t)$</td>
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<td></td>
</tr>
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<td>$(\bar{q}<em>p \gamma</em>\mu T^I q_r)(\bar{q}<em>s \gamma</em>\mu T^I q_t)$</td>
<td>$(\bar{d}<em>p \gamma</em>\mu d_r)(\bar{d}<em>s \gamma</em>\mu d_t)$</td>
<td>$(\bar{L}<em>p \gamma</em>\mu l_r)(\bar{L}<em>s \gamma</em>\mu d_t)$</td>
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<td>$Q_{lq}$</td>
<td>$(\bar{L}<em>p \gamma</em>\mu l_r)(\bar{q}<em>s \gamma</em>\mu q_t)$</td>
<td>$(\bar{e}<em>p \gamma</em>\mu e_r)(\bar{e}<em>s \gamma</em>\mu e_t)$</td>
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<tr>
<td>$Q^{(8)}_{ud}$</td>
<td>$(\bar{u}<em>p \gamma</em>\mu u_r)(\bar{d}<em>s \gamma</em>\mu d_t)$</td>
<td>$(\bar{q}_p \gamma_μ T^A q_r)(\bar{u}_s \gamma_μ T^A u_t)$</td>
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<tr>
<td>$Q^{(1)}_{qu}$</td>
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<tr>
<td>$Q^{(8)}_{quad}$</td>
<td>$(\bar{L}<em>p \gamma</em>\mu u_r)(\bar{d}<em>s \gamma</em>\mu d_t)$</td>
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$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$

<table>
<thead>
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<th>$B$-violating</th>
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<tr>
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<tr>
<td>$Q^{(3)}_{lequ}$</td>
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\[\varepsilon^{\alpha\beta}\gamma^{\epsilon j k} \left[(d_p^{\alpha})^T C u_r^{\beta}\right] \left[(q_s^{\gamma})^T C l_t^{k}\right] \]
\[\varepsilon^{\alpha\beta}\gamma^{\epsilon j k} \left[(q_p^{\alpha})^T C q_r^{\beta k}\right] \left[(u_s^{\gamma})^T C e_t^{k}\right] \]
\[\varepsilon^{\alpha\beta}\gamma^{\epsilon j k} \left[(q_p^{\alpha})^T C q_r^{\beta k}\right] \left[(q_s^{\gamma})^T C l_t^{k}\right] \]
\[\varepsilon^{\alpha\beta}\gamma^{\epsilon j k} \left[(d_p^{\alpha})^T C u_r^{\beta}\right] \left[(u_s^{\gamma})^T C e_t^{k}\right] \]
new physics seems indeed nearly decoupled
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collider physics is entering a precision era
new physics seems indeed nearly decoupled

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indirect searches more and more competitive with direct ones
SMEFT for indirect searches at LHC

new physics seems indeed nearly decoupled

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SMEFT-based searches at the LHC are crucial

+ a proper QFT:
  renormalizable order by order, well-defined radiative corrections and RGE
+ minimal commitment to a specific UV
+ systematically includes all BSM effects, compatible with assumptions
+ universal language for data interpretation: can connect to other experiments
Challenges

1. being **sensitive** to indirect BSM effects → needs uncertainty reduction

\[ \text{in bulk } \sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}. \quad g_{UV} \approx 1, \quad M \approx 2 \text{ TeV} \rightarrow 1.5\% \]

\[ \text{on tails } \sim \frac{E^2}{\Lambda^2} \approx \frac{E^2 g_{UV}}{M^2} \quad E \approx 1 \text{ TeV}, \quad M \approx 3 \text{ TeV} \rightarrow 10\% \]
Challenges

1. being sensitive to indirect BSM effects → needs uncertainty reduction

\[ \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}. \]

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\[ \frac{E^2}{\Lambda^2} \approx \frac{E^2 g_{UV}}{M^2} \quad E \approx 1 \text{ TeV}, \quad M \approx 3 \text{ TeV} \rightarrow 10\% \]

2. making sure that, if we observe one, we interpret it correctly. needs:

- retaining all relevant contributions: all operators, NLO corrections...
  - handling many parameters in predictions and fits
  - understanding the theory structure

- correct understanding of uncertainties and correlations

- systematic mapping to BSM models
Combine, combine, combine

2499 parameters in the most general case can be reduced

- assuming symmetries: flavor, CP
- taking advantage of kinematic suppressions

beyond this combining different measurements is necessary

- to access as many operators as we can
- to avoid bias in interpretation i.e. miss a potential deviation or assign it to the wrong op.
SMEFT fits @LHC
Example: SMEFT for EW and Higgs sectors

leading Warsaw basis operators in Higgs and EW processes: \( \sim 20 \)

\[
Q_{HWB} \quad Q_{ll} \quad Q_{HD} \quad Q_{Hl}^{(3)}
\]

input parameters

Higgs decays

VBS

diboson

Higgs production

+ CP odd + flavor indices + others entering through loop corrections \ldots
SMEFT in Higgs production

$ggF$  $VBF$  $VH$  $ttH$

Diagrams of various Higgs production processes at the LHC, including $ggF$, $VBF$, $VH$, and $ttH$.
SMEFT in Higgs production

- \( ggF \)
- \( VBF \)
- \( VH \)
- \( ttH \)
SMEFT in Higgs production

\[ |A_{\text{SMEFT}}|^2 = \left[ |A_{\text{SM}}|^2 + \sum_i \frac{C_i}{\Lambda^2} A_i A_{SM}^\dagger + \sum_{ij} \frac{C_i C_j^*}{\Lambda^2} A_i A_j^\dagger \right] \times K_{\text{SM}} \]
Higgs combinations:

\[ n_k = \mathcal{L}_k \sum_{i,f} (\sigma_i \cdot B_f) (\varepsilon \cdot A)_{if} \]

fit to \( n_k \rightarrow (\sigma_i \cdot B_f) \) for defined \( i, f \) categories.

STXS define production categories:
unfolded XS organized in “macro-bins” → minimize selection cuts + modeling bias better reproducibility

- defined in stages: finer and finer bins
- include \( f = \{ \gamma\gamma, 4\ell, 2\ell2\nu, \tau\tau, b\bar{b} \} \)
Higgs + EW fit results

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates (STXS)

HISZ basis

Hagiwara et al PRD48(1993)2182
Higgs + EW fit results

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates (STXS)

Warsaw basis Grzadkowski et al 1008.4884
Extensive literature, covering many sectors

- **Higgs + EW**
  - Alves et al 1211.4580, 1805.11108, Butter et al 1604.03105
  - Corbett et al 1509.01585, de Blas et al 1608.01509, 1710.05402, 1910.14012
  - Ellis, Murphy, Sanz, You 1803.03252, Biekötter, Corbett, Plehn 1812.07587
  - da Silva Almeida et al 1812.01009, 2108.04828
  - Dawson, Homiller, Lane 2007.01296, Dawson, Giardino 2201.09887

- **top**
  - Englert et al 1506.08845, 1512.05560, 1901.03164 + ICHEP2020 proc.
  - Cirigliano, Dekens, de Vries, Mereghetti 1605.04311 Hartland et al 1901.05965
  - Durieux, Irles, Miralles, Peñuelas, Pöschl 1907.10619, IB et al 1910.0306
  - Miralles et al 2107.13917

- **Higgs + EW + top**
  - Ellis, Madigan, Mimasu, Sanz, You 2012.02779
  - Ethier, Maltoni, Mantani, Nocera, Rojo 2105.00006

- **top + B physics**
  - Bruggisser, Schäfer, Westhoff, VanDyk 2101.07273

- **diboson (+ VBS)**
  - Baglio, Dawson, Homiller, (Lane, Lewis) 1812.00214, 1909.11576, 2003.07862
  - Ethier, Gomez-Ambrosio, Magni, Rojo 2101.03180
  - Bellan, Boldrini, Brambilla, Brusa, IB et al 2108.03199

- references list incomplete!
Some general features

- currently up to 20 – 30 parameters simultaneously

- most often: frequentist likelihood ($\chi^2$) analysis
  
  replica models / toys also used

  moving to bayesian inference for many parameters

- most SMEFT predictions are at tree level
  
  NLO QCD most used for top physics and $gg \rightarrow h$.
  
  available also for diboson processes, automated in MG5.

  NLO EW harder. not automated.
  
  available only for EWPO and most Higgs decays

- results typically reported in multiple setups: linear/quadratic, LO/NLO …

- information geometry (Fisher information matrix), Partial Component Analysis used to show multi-dimensional information, determine impact of individual constraints
Top + EW + Higgs

Higgs
- $C_{HB}$
- $C_{bH}$
- $C_{HW}$
- $C_{\tau H}$
- $C_{HG}$
- $C_{H\Box}$

EW
- $C_{Hl}$
- $C_{He}$
- $C_{H\ell}$
- $C_{Hu}$

Top
- $C_{tH}$
- $C_{tG}$

$\approx 50$ parameters @ LO interference

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Combining Higgs and top

1. **top operators → Higgs / EW processes**
   - $gg \rightarrow h$
   - $t\bar{t}h$
   - $h \rightarrow \gamma\gamma$

2. **non-top operators → top processes**
   - $C_{tH}$ operator $\rightarrow t\bar{t}H$ vertex
   - $C_{tG} \rightarrow t\bar{t}G + t\bar{t}GG + t\bar{t}GH + t\bar{t}GGH$
   - $C_{tW}, C_{tB}, C_{HQ}^{(3)}, C_{HQ}^{(1)}, C_{Ht} \rightarrow t\bar{t}V + t\bar{t}VH$

Grazzini, Ilnicka, Spira, (Wiesemann) 1612.00283, 1806.08832, (Maltoni), Vryonidou, Zhang 1607.05330, 1804.09766 Deutschmann, Duhr, Maltoni, Vryonidou 1708.00460
Combining Higgs and top

1. **top operators → Higgs / EW processes**

2. **non-top operators → top processes**

\[ gg \rightarrow h \]

\[ t\bar{t}h \]

\[ h \rightarrow \gamma\gamma \]

\[ \leftrightarrow \quad t\bar{t} \]

\[ t\bar{t}V, \quad \text{single-}t \]

- **\( C_{tH} \)** operator → \( t\bar{t}H \) vertex
- **\( C_{tG} \)** → \( t\bar{t}G + t\bar{t}GG + t\bar{t}GH + t\bar{t}GGH \)
- **\( C_{tW}, C_{tB}, C_{HQ}^{(3)}, C_{HQ}^{(1)}, C_{Ht} \)** → \( t\bar{t}V + t\bar{t}VH \)

Grazzini, Ilnicka, Spira, (Wiesemann) 1612.00283, 1806.08832, (Maltoni), Vryonidou, Zhang 1607.05330, 1804.09766
Deutschmann, Duhr, Maltoni, Vryonidou 1708.00460
Example: complementarities in top + Higgs
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Ellis, Madigan, Mimasu, Sanz, You 2012.02779

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Example: complementarities in top + Higgs

Ellis, Madigan, Mimasu, Sanz, You 2012.02779
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The SMEFT program at the LHC: status and prospects

16/37
Top + EW + Higgs: global results

34 param, linear, LO + ggH

Ilaria Brivio (ITP Heidelberg)
Top + EW + Higgs: global results

50 param (36 indep.), linear+quadratic, NLO QCD
Where is this going?
EFT parameterisations for LHC measurements are here to stay, independently of observation of new resonances. Will become a standard analysis procedure, to be brought to future colliders too.

- the best parameterisation of non-resonant BSM effects in shapes
- allows SM tests at differential level
- can be easily simulated, is theoretically consistent
  (≠ anomalous couplings, form-factors / pseudo-observables)

- will serve as book-keeping → LHC legacy results easily reinterpretable

- will enable combinations of LHC and non-LHC data (e.g. flavor)
  → one “universal map” of constraints on heavy-BSM
In practice: (near) future directions

1. **More refined SMEFT predictions**
   higher orders in loops and in EFT \((d \geq 8)\), EFT in backgrounds, improved technology for predictions (Monte Carlo, ML...)

2. **Larger global fits**
   more complex processes, complementary to usual ones, bring sensitivity to new parameters (e.g. VBS, tWZ, CP violation, flavor...)

3. **Higher-quality constraints**
   more precise measurements and SM predictions, more differential measurements

4. **Better uncertainties and correlations treatment**
   better understanding of PDF/scale dependence in EFT predictions, ATLAS, CMS to provide more information and do combined analyses directly

5. **More and more working in (simplified) model setups**
   “make the ends meet” in top-down vs bottom-up approaches

6. **Should we move to HEFT?**

7. **What if we see an anomaly (e.g. \(m_W\))? What if we discover a particle?**
Increasing complexity & interplay

Ex.: including more processes / loop corrections increases top-Higgs interplay

\[
\begin{align*}
  gg & \rightarrow tZj \\
  gg & \rightarrow thj \\
  gg & \rightarrow hg \\
  gg & \rightarrow ZZ, \gamma\gamma \\
  gg & \rightarrow Zh \\
  gg & \rightarrow hh
\end{align*}
\]
More differential information

- more statistics ➔ finer binning
- higher-dim. histograms ➔ better shape analyses
- interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!
More differential information

- more statistics \(\rightarrow\) finer binning
- higher-dim. histograms \(\rightarrow\) better shape analyses
- interplay of kin. variables

one of the most important improvements for future runs. not fully accounted for in current projections!

- extract **more information** from each measurement

![Graph showing differential information](brehmer-dawson-homiller-kling-plehn_1908_06980)
More differential information

- more statistics → finer binning higher-dim. histograms → better shape analyses interplay of kin. variables

one of the most important improvements for future runs. not fully accounted for in current projections!

- extract **more information** from each measurement
- more discriminating power between different shapes → operators
More differential information

- more statistics \rightarrow \text{finer binning}\newline\text{higher-dim. histograms} \rightarrow \text{better shape analyses interplay of kin. variables}

one of the most important improvements for future runs. not fully accounted for in current projections!

- extract \textbf{more information} from each measurement
- more discriminating power between different shapes \rightarrow \text{operators}
- access to CP properties

Biektötter, Gregg, Krauss, Schönherr 2102.01115
More differential information

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- interplay of kin. variables

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- access to polarizations $\rightarrow$ crucial for VBS, diboson
  $\rightarrow$ single out Goldstone boson contributions
  $\rightarrow$ more direct access to EWSB
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- ...

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The SMEFT program at the LHC: status and prospects
interesting from SMEFT point of view because

- gives access to $VV \rightarrow VV$ scattering, crucial probe of EWSB dynamics
- probes simultaneously $qqqq$, $HVV$ and TGC/QGC operators
- comes in several $V_1 V_2 = \{W^\pm, Z, \gamma\}$ channels $\rightarrow$ discrimination power
- bound to improve significantly at next Runs
interesting from SMEFT point of view because

- gives access to $VV \rightarrow VV$ scattering, crucial probe of EWSB dynamics
- probes simultaneously $qqqq$, $HVV$ and TGC/QGC operators
- comes in several $V_1 V_2 = \{W^\pm, Z, \gamma\}$ channels $\rightarrow$ discrimination power
- bound to improve significantly at next Runs
SMEFT corrections to VBS at $d = 6$

- representative set of 14 operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{Hl}^{(1)}$</td>
<td>$(H^\dagger i\bar{D}^i H)(\bar{I}_p \gamma^\mu I_p)$</td>
</tr>
<tr>
<td>$Q_{Hq}^{(1)}$</td>
<td>$(H^\dagger i\bar{D}^i H)(\bar{Q}_p \gamma^\mu q_p)$</td>
</tr>
<tr>
<td>$Q_{qq}^{(1)}$</td>
<td>$(\bar{Q}<em>p \gamma</em>\mu q_p)(\bar{Q}_r \gamma^\mu q_r)$</td>
</tr>
<tr>
<td>$Q_{qq}^{(3)}$</td>
<td>$(\bar{Q}<em>p \gamma</em>\mu \sigma^i q_p)(\bar{Q}_r \gamma^\mu \sigma^i q_r)$</td>
</tr>
<tr>
<td>$Q_{HD}$</td>
<td>$(H^\dagger D_\mu H)(H^\dagger D^\mu H)$</td>
</tr>
<tr>
<td>$Q_{HWB}$</td>
<td>$(H^\dagger \sigma^i H)W^i_{\mu\nu}B^{\mu\nu}$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$\varepsilon^{ijk} W^{i\mu}<em>{\mu} W^{j\nu}</em>{\nu} W^{k\mu}_{\rho}$</td>
</tr>
<tr>
<td>$Q_{Hl}^{(3)}$</td>
<td>$(H^\dagger i\bar{D}^i H)(\bar{I}_p \sigma^i \gamma^\mu I_p)$</td>
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</tr>
<tr>
<td>$Q_{qq}^{(1,1)}$</td>
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</tr>
<tr>
<td>$Q_{qq}^{(3,1)}$</td>
<td>$(\bar{Q}<em>p \gamma</em>\mu \sigma^i q_p)(\bar{Q}_r \gamma^\mu \sigma^i q_p)$</td>
</tr>
<tr>
<td>$Q_{H\Box}$</td>
<td>$(H^\dagger H) \Box (H^\dagger H)$</td>
</tr>
<tr>
<td>$Q_{HW}$</td>
<td>$(H^\dagger H)W^i_{\mu\nu} W^{i\mu\nu}$</td>
</tr>
<tr>
<td>$Q_{ll}^{(1)}$</td>
<td>$(\bar{I}<em>p \gamma</em>\mu I_r)(\bar{I}_r \gamma^\mu I_p)$</td>
</tr>
</tbody>
</table>

- 4 VBS→ $\ell$ processes ($W^\pm W^\pm$, $W^+ W^-$, $W^\pm Z$, $ZZ$)
- + 1 VBS→ $\ell J$ process ($VZ$, $V = Z, W$)
- + 1 diboson process ($qq \rightarrow W^+ W^-$)

- simulated full 2 → 6(4) processes, incl. non-resonant diagrams

- parton level analysis: only expected limits, no comparison to data yet

similar studies: Gomez-Ambrosio 1809.04189, Dedes Kozow, Szleper 2011.07367, Ethier et al 2101.03180
VBS constrains the most 4-quark operators and $Q_W$
all these are dominated by $ssWW$
SMEFT in VBS: main results

- VBS constrains the most 4-quark operators and $Q_W$
  all these are dominated by $s\bar{s}WW$
- VBS competitive with diboson for “input” operators: $Q_{HWB}, Q_{HD}, Q_{Hl}^{(3)}, Q_{ll}'$

![Graph showing constraints with different experimental samples and theoretical expectations for SM EW corrections.](image)
VBS constrains the most 4-quark operators and $Q_W$
all these are dominated by $ssWW$

VBS competitive with diboson for “input” operators: $Q_{HWB}, Q_{HD}, Q_{Hl}^{(3)}, Q_{ll}'$

for several operators, constraints are dominated by linear terms → “safe”
SMEFT in VBS: main results

- VBS constrains the most 4-quark operators and $Q_W$
  all these are dominated by $s_s W W$

- VBS competitive with diboson for "input" operators: $Q_{HWB}, Q_{HD}, Q_{HL}^{(3)}, Q_{Il}^{'}$

- for several operators, constraints are dominated by linear terms $\rightarrow$ "safe"

- adding SMEFT corrections to QCD backgrounds never worsens the results
Matching to UV models

E

UV model
$(g_i, M_i)$

Q

matching scale

EFT
$(C_i, \Lambda)$

imposing all matrix elements are equal at $\mu = Q$

$C_i, \Lambda$ as function of $(g_i, M_i)$
Matching to UV models

UV model \((g_i, M_i)\)

EFT \((C_i, \Lambda)\)

matching scale \(Q\)

done efficiently up to 1-loop in UV model via functional methods:

- Covariant Derivative Expansion
- Universal One-Loop Effective Action

\[ S_{\text{eff}}[\phi] = S[\Phi_0] + \frac{i}{2} \text{Tr} \log \left( -\frac{\delta^2 S}{\delta \Phi^2} \right|_{\Phi_0} \right) \]

light fields

heavy fields. \(\Phi = \Phi_0 + \eta\)

Henning, Lu, Murayama, deAguila, Santiago, Ellis, Quevillon, You, Fuentes-Martin, Cohen, Lu, Zhang, Krämer, Summ, Voigt, Dittmaier, Passarino. . .
A case study: SM + Heavy Vector Triplet

\[ \mathcal{L}_{HVT} = -\frac{1}{4} V^i_{\mu\nu} V^{i\mu\nu} - \frac{g_M}{2} V^i_{\mu\nu} W^{i\mu\nu} + \frac{m^2_V}{2} V^i_{\mu} V^{i\mu} + \frac{g_H}{2} V^i_{\mu} (H^\dagger i \overleftrightarrow{D}^{i\mu}_\mu H) \\
+ \frac{g_l}{2} V^i_{\mu} \ell \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V^i_{\mu} \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V^i_{\mu} V^{i\mu} \]

\( V_i \rightarrow W'^\pm, Z' \)
A case study: SM + Heavy Vector Triplet

\[
\mathcal{L}_{HVT} = -\frac{1}{4} V^i_{\mu \nu} V^i_{\mu \nu} - \frac{g_M}{2} V^i_{\mu \nu} W^i_{\mu \nu} + \frac{m_V^2}{2} V^i_{\mu} V^i_{\mu} + \frac{g_H}{2} V^i_{\mu} (H^\dagger i \not{D}^{i \mu} H)
\]

\[
+ \frac{g_l}{2} V^i_{\mu} \bar{\ell} \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V^i_{\mu} \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V^i_{\mu} V^i_{\mu}
\]

Constraints on model

Observables
\[ O = f \left( \frac{C_i}{\Lambda^2} \right) \]

Matching
\[ (C_i/\Lambda^2) = h_i(g_i, m_V) \]

Fit to \((g_i, m_V)\)

Similar approach in: daSilva Almeida, Alves, Éboli, González-García 2108.04828
A case study: SM + Heavy Vector Triplet

\[ \mathcal{L}_{HVT} = -\frac{1}{4} \, V^{i}_{\mu \nu} \, V^{i \mu \nu} - \frac{g_M}{2} \, V^{i}_{\mu \nu} \, W^{i \mu \nu} + \frac{m_{V}^{2}}{2} \, V^{i}_{\mu} \, V^{i \mu} + \frac{g_{H}}{2} \, V^{i}_{\mu} \left( H^{\dagger} \, i \, \not{D}^{i \mu} \, H \right) \]
\[ + \frac{g_{l}}{2} \, V^{i}_{\mu} \, \not{\ell} \, \gamma^{\mu} \sigma^{i} \, \ell + \frac{g_{q}}{2} \, V^{i}_{\mu} \, \not{q} \, \gamma^{\mu} \sigma^{i} \, q + \frac{g_{VH}}{2} \left( H^{\dagger} \, H \right) \, V^{i}_{\mu} \, V^{i \mu} \]

\[ \left( C_{H}^{(3)} \right)_{ij} = -\frac{g_{l} g_{H}}{4 m_{V}^{2}} \delta_{ij} \]
A case study: SM + Heavy Vector Triplet

\[ \mathcal{L}_{HVT} = -\frac{1}{4} V_{i\mu} V_{i\mu}^\dagger - \frac{g_M}{2} V_{i\mu} W_{i\mu}^\dagger + \frac{m_V^2}{2} V_{i\mu} V_{i\mu}^\dagger + \frac{g_H}{2} V_{i\mu} (H^\dagger i \overleftrightarrow{D} i H) \\
+ \frac{g_L}{2} V_{i\mu} \overline{\gamma}^\mu \sigma^i \ell + \frac{g_q}{2} V_{i\mu} \overline{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V_{i\mu} V_{i\mu} \]

\[
(C_{Hi}^{(3)})_{ij} = -\frac{g_L g_H}{4m_V^2} \delta_{ij} + \frac{1}{36864\pi^2 m_V^2} \frac{\delta_{ij}}{1 - g_M^2} \left[ g_w^4 (288 + 1531g_M^2 + 2989g_M^4) \\
+ g_w^3 (2642g_H g_M + 2340g_L g_M + 7942g_H g_M^3 + 6732g_L g_M^3) \\
+ g_w^2 (g_L^2 (-102 + 3054g_M^2) + g_H^2 (49 + 5711g_M^2)) \\
+ g_w g_M (1080g_H^3 + 5400g_H^2 g_L + 2304g_H g_L^2 + 432g_L^3 + 1440h_H g_{VH} + 1440g_L g_{VH}) \\
+ g_H g_L (1080g_H^2 - 360g_H g_L + 432g_L^2 + 1440g_{VH} + (1 + g_w^2)(2160 + 12600g_M^2)) \\
+ 1440g_M^2 g_{VH} \right] + \frac{3}{3032\pi^2 m_V^2} (g_L - g_H)(g_L + g_W g_M)(Y_e Y_e^\dagger)_{ij}
\]
Heavy vector triplet: tree vs loop matching

$m_V = 4 \text{ TeV}$

contours
$\Delta \chi^2 = 2.3, 5.991$

tree matching
1-loop matching $Q = m_V$
1-loop matching $m_Z \leq Q \leq m_V$
Heavy vector triplet: tree vs loop matching

\[ m_V = 4 \text{ TeV} \]

contours

\[ \Delta \chi^2 = 2.3, 5.991 \]

tree matching

1-loop matching \( Q = m_V \)

1-loop matching \( m_Z \leq Q \leq m_V \)

profiling over \( Q \) worsens \( g_H \) bound by a factor 2
Heavy vector triplet: tree vs loop matching

\[ m_V = 4 \text{ TeV} \]

contours
\[ \Delta \chi^2 = 2.3, 5.991 \]

- Red: tree matching
- Orange: 1-loop matching \( Q = m_V \)
- Blue: 1-loop matching \( m_Z \leq Q \leq m_V \)

Profiling over \( Q \) worsens \( g_H \) bound by a factor 2.
extra “leaves” around lines where \( f_{\phi 2} \approx 0 \approx f_{u \phi} \)

\[
f_{\phi 2} \left( \frac{1}{\text{TeV}^2} \right) - f_{u \phi} \text{ similar}
\]

\[
f_{\phi 2} \approx 0.04 \ g_H^2 \left( 1 + 0.1 \log \frac{m_V}{Q} \right) + 10^{-3} \ g_H^4 \left( 1 - 2.4 \log \frac{m_V}{Q} \right)
\]

flips sign for \( Q \lesssim m_V / 1.52 \)

→ we treated this as a new systematic error. currently poorly understood
SMEFT vs direct searches: WW case

$m_{Z'} = m_V = 4 \text{ TeV}$

ATLAS 2004.14636

Ilaria Brivio (ITP Heidelberg)
SMEFT vs direct searches: $WW$ case

$m_{Z'} = m_V = 4$ TeV

bound from $WW$ resonance search

resonance s. only valid for narrow $Z'$
SMEFT vs direct searches: WW case

\[ m_{Z'} = m_V = 4 \text{ TeV} \]

ATLAS 2004.14636

bound from EFT fit to WW spectrum

bound from EFT fit to all obs.
(incl. EWPO, Higgs)

Ilaria Brivio (ITP Heidelberg)
SMEFT vs direct searches: WW case

$m_{Z'} = m_V = 4 \text{ TeV}$

point excluded by resonance s.
but allowed by EFT

Ilaria Brivio (ITP Heidelberg)

The SMEFT program at the LHC: status and prospects
SMEFT vs direct searches: $WW$ case

\[ m_{Z'} = m_V = 4 \text{ TeV} \]

best EFT sensitivity to this peak: bins with smallest uncertainties!

point excluded by resonance s. but allowed by EFT
Impact of $d \geqslant 8$ operators

EFT obtained from matching to full model

$p p \to V h$ (T4)

adapted from Brehmer, Freitas, López-Val, Plehn 1510.03443

adapted from Lang, Liebler, Schaef-Siebert, Zeppenfeld 2103.16517

Ilaria Brivio (ITP Heidelberg)

The SMEFT program at the LHC: status and prospects
Impact of $d \geq 8$ operators

EFT obtained from matching to full model

$d \geq 8$ breaks down

$p p \rightarrow V h$ (T4)

$d = 6$ breaks down
Impact of $d \geq 8$ operators

EFT obtained from matching to full model

**top-down:** $C_i$ fixed by matching
$\rightarrow$ EFT not valid in high-E region

**bottom-up:** fit $C_i$ to data
tends to make EFT match full result
$\rightarrow$ find wrong values of $C_i$

how to keep this into account?

sliding upper cut:
Contino,Falkowski,Goertz,
Grojean,Riva 1604.06444

uncertainty band:
Trott et al 1508.05060,2007.00565,2106.13794,
Hays,Martin,Sanz,Setford 1808.00442
Shepherd et al 1812.07575,1907.13160

compute at $d=8$
Boughezal,Mereghetti,Petriello
2106.05337
safe scenarios $\leftrightarrow$ no energy growth $\leftrightarrow$ small effects

typical cases where $d = 6$ works well across the whole visible spectrum:

- observables w/o E dependence (1 $\to$ 2 decays)
- BSM scenarios with very narrow and/or heavy states

adapted from
Brehmer, Freitas, López-Val, Plehn 1510.03443

Brivio, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, Plehn, Summ 2108.01094

price to pay: $\%$ effects only
$\to$ most sensitivity from lowest error region ($\sim$ bulk)
SMEFT or HEFT?

A component of the $d = 6$ vs model discrepancy can be removed by reabsorbing higher powers of $v$ within $d = 6$ coefficients instead of leaving them to $d \geq 8$

conceptually similar to using HEFT instead

which EFT is most convenient?
Higgs EFT

Feruglio 9301281, Grinstein, Trott 0704.1505, Buchalla, Catà 1203.6510, Alonso et al 1212.3305...

\[ H \rightarrow v + \frac{h}{\sqrt{2}} U, \quad U = \exp \left( \frac{i \vec{\sigma} \cdot \vec{\pi}}{v} \right) \]

- less restrictive symmetry assumptions → more parameters

- separate couplings with different \# of Higgs legs

\[ D_\mu \Phi^\dagger D^\mu \Phi \rightarrow \text{Tr}(D_\mu U^\dagger D^\mu U) \left( 1 + a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

- enhanced anomalous interactions among Goldstones = $W_L, Z_L$

- there are BSM theories that admit HEFT but not SMEFT:
  - with BSM sources of EWSB
  - with BSM particles that take $>1/2$ of their mass from EWSB

- more convergent than SMEFT

- only consistent if $\Lambda \leq 4\pi v$ (unitarity violation)
What if...
...an anomaly shows up?

as for B-anomalies: dedicated studies focused on interesting parameters/models

nonzero values of effective operators

\[ O_9^\ell = (\bar{s}_L \gamma^\mu b_L)(\bar{\ell} \gamma_\mu \ell) \]
\[ O_{10}^\ell = (\bar{s}_L \gamma^\mu b_L)(\bar{\ell} \gamma_\mu \gamma_5 \ell) \]

combine with constraints from Drell-Yan, \( B_s - \bar{B}_s \) mixing etc

leptoquarks as preferred (combined) explanation

Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert 2103.16658
what about the CDF $m_W$ measurement then?

⚠️ CDF II measurement is in tension with previous ones at LEP and at ATLAS!

干嘛as we assume there is an actual deviation there: mostly $T$ parameter ($C_{HD}$)

Ilaria Brivio (ITP Heidelberg) The SMEFT program at the LHC: status and prospects 35/37
what about the CDF $m_W$ measurement then?

⚠️ CDF II measurement is in tension with previous ones at LEP and at ATLAS!

⚠️ if we *assume* there is an actual deviation there: mostly $T$ parameter ($C_{HD}$)

![Graphs showing correlation between $C_{HD}$ and $C_{Hl}$, $C_{HD}$ and $C_{HWB}$, and $C_{Hl}$ and $C_{HWB}$.

similar: Strumia 2204.04191, deBlas et al 2204.04204, diLuzio,Gröber,Paradisi 2204.05284, Fan,Li,Liu,Lyu 2204.04805, Asadi et al 2204.05283, daSilva Almeida et al 2204.10130 ...
we discover a new particle?

new particles hardly come alone. need sectors / multiplet partners

- extend EFT field content

- gauge invariance: observation in one channel $\Rightarrow$ other predicted signals

- restrict EFT parameter space to coefficients motivated by extensions containing the new particle $\rightarrow$ more efficient searches

- use matching knowledge to get quickly a comprehensive map of the new particle’s **effects at lower E** $\rightarrow$ everything consistent?

$\rightarrow$ lots of examples from 750GeV literature (2016)
SMEFT is the best framework for indirect searches of new physics at LHC

- current direct bounds consistent with $(v/\Lambda_{BSM}) \ll 1$
- collider physics entering **precision era**

Combining different measurements is key to constraining as many coefficients as possible and avoiding bias

Studies in EW, Higgs and top sectors are theoretically advanced but more improvements are needed for this to become standard business

- **a lot to stay tuned for** in the next years!
  - more precise measurements: fits entering relevant regime
  - more exp info available (differential meas, new processes, correlations…)
  - streamline mapping to models for better interpretation
  - better predictions and fitting technology
  …