Electroweak Higgs production in SMEFT at NLO in QCD

Ken Mimasu

Outline

• Motivation & brief intro to standard model effective field theory (SMEFT)

• EW Higgs production in SMEFT at the LHC

• Results from the implementation of operators affecting Higgs couplings to gauge bosons
  • Current constraints from global fits & resulting benchmark choices
  • FeynRules/NLOCT UFO model via MadGraph5_aMC@NLO
  • Differential distributions @ NLO in QCD
  • Validity of the EFT
  • Future sensitivity in WH production at HL-LHC
Going NLO

• The LHC is now in the precision era
  • No clear evidence for new physics as we approach the limits of the ‘energy frontier’
  • Fully complementary approach: search for deviations in SM processes
  • Require high precision theory input including higher order corrections

• EFT: theoretically consistent, model independent approach to deviations of interactions between SM fields
  • Active area of research that is moving towards NLO predictions
  • NLO important for capturing potentially large QCD K-factors in total rates → greater sensitivity
  • Verify stability of differential information beyond leading order
  • Consistent scale uncertainty estimates
SMEFT

- Parametrise new physics effects at experimental energy $E$
  - BSM states are ‘decoupled’ \( i.e. \) live at an energy $\Lambda >> E$
  - Generalised, gauge-invariant interactions between SM degrees of freedom

- Operator expansion:
  \[
  \mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_{D_i}^D}{\Lambda^{D-4}} \quad \text{more: fields derivatives}
  \]
  - Introduces higher-derivative operators to which we are sensitive via large momentum flows through vertices (tails of energy distributions)

- Dimension 6: 59 (76 real) - 2499 operators depending on assumptions regarding CP, flavour…
  \cite{BuchmullerWyler,Grzadkowski}
- Dimension 8: $\approx 895 \ (36971)$ operators!
  \cite{Lehman, Henning}

\[ \leq \]
\[ \leq \]
\[ \leq \]
EW Higgs production

- LHC can provide complementary information to existing fits to lower energy data, i.e. LEP

- Higgs comes with additional objects
  - We can construct kinematic observables probing the high energy regime
  - Higgs $p_T$, $M_{VH}$, leading lepton $p_T$, $\Delta\eta_{ij}$,…

- Look into the tails…

- Investigate validity of EFT expansion/interpretation given current constraints from global fits

- Consider future reach of HL-LHC to constrain relevant Wilson coefficients
D=6 operators

- **SMEFT**: Higgs-EW gauge boson operators in ‘SILH’ basis

\[
\mathcal{L}_{D6} = \frac{1}{\Lambda^2} \left[ \frac{g'^2}{4} \bar{c}_{BB} \Phi^\dagger \Phi B_{\mu\nu} B_{\mu\nu} + \frac{ig}{2} \bar{c}_W [\Phi^\dagger T_{2k} \overset{\leftrightarrow}{D^\mu} \Phi] D^\nu W^k_{\mu\nu} + \frac{ig'}{2} \bar{c}_B [\Phi^\dagger \overset{\leftrightarrow}{\partial^\mu} \Phi] \partial^\nu B_{\mu\nu} \\
+ ig \bar{c}_{HW} [D^\mu \Phi^\dagger T_{2k} D^\nu \Phi] W^k_{\mu\nu} + ig' \bar{c}_{HB} [D^\mu \Phi^\dagger D^\nu \Phi] B_{\mu\nu} \\
+ \frac{g'^2}{4} \bar{c}_{BB} \Phi^\dagger \Phi B_{\mu\nu} \tilde{B}_{\mu\nu} + ig \bar{c}_{HW} [D^\mu \Phi^\dagger T_{2k} D^\nu \Phi] \tilde{W}^k_{\mu\nu} + ig' \bar{c}_{HB} [D^\mu \Phi^\dagger D^\nu \Phi] \tilde{B}_{\mu\nu} \right]
\]

\[\Phi^\dagger \overset{\leftrightarrow}{D^\mu} \Phi \equiv (D^\mu \Phi)^\dagger \Phi - \Phi^\dagger (D^\mu \Phi)\]

- **Anomalous couplings**: new Lorentz structures (1) & (2):

\[
\mathcal{L}_{HAC} = -\frac{1}{4} g^{(1)}_{hzz} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{hzz} Z_\nu \partial_\mu Z^{\mu\nu} h + \frac{1}{2} g^{(3)}_{hzz} Z_\mu Z^{\mu\nu} h - \frac{1}{4} \tilde{g}_{hzz} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h
\]

\[\mathcal{-} \frac{1}{2} g^{(1)}_{hww} W_{\mu\nu} W^\dagger_{\mu\nu} h - \left[ g^{(2)}_{hww} W_\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right] + g^{(3)}_{hww} W_\mu W^\dagger_{\mu\nu} h - \frac{1}{2} \tilde{g}_{hww} W_{\mu\nu} \tilde{W}^\dagger_{\mu\nu} h \]

\[\mathcal{-} \frac{1}{2} g^{(1)}_{haz} Z_{\mu\nu} F^{\mu\nu} h - g^{(2)}_{haz} Z_\nu \partial_\mu F^{\mu\nu} h - \frac{1}{2} \tilde{g}_{haz} Z_{\mu\nu} \tilde{F}^{\mu\nu} h \]
Limits from global fits

- Many global fits to data constrain EFT Wilson coefficients
  - LHC, LEP & other low-energy experiments
- Marginalised constraints from EWPO + LHC Run 1 data on coefficients of interest

<table>
<thead>
<tr>
<th>Operator</th>
<th>Coefficient</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_W = \frac{ig}{2} \left( H^\dagger T_{2k} D^\mu H \right) D^\nu W^k_{\mu\nu}$</td>
<td>$\frac{m_W^2}{\Lambda^2} (\bar{c}_W/2 - \bar{c}_B)$</td>
<td>(-0.035, 0.005)</td>
</tr>
<tr>
<td>$O_B = \frac{ig'}{2} \left( H^\dagger D^\mu H \right) \partial^\nu B_{\mu\nu}$</td>
<td>$\frac{m_W^2}{\Lambda^2} (\bar{c}_W/2 + \bar{c}_B)$</td>
<td>(-0.0033, 0.0018)</td>
</tr>
<tr>
<td>$O_{HW} = ig(D^\mu H)^\dagger T_{2k}(D^\nu H)W^k_{\mu\nu}$</td>
<td>$\frac{m_W^2}{\Lambda^2} \bar{c}_{HW}$</td>
<td>(-0.07, 0.03)</td>
</tr>
<tr>
<td>$O_{HB} = ig'(D^\mu H)^\dagger (D^\nu H)B_{\mu\nu}$</td>
<td>$\frac{m_W^2}{\Lambda^2} \bar{c}_{HB}$</td>
<td>(-0.045, 0.075)</td>
</tr>
</tbody>
</table>

See also: [Falkowksi & Riva; JHEP 1502 (2015) 039], [Berthier & Trott; JHEP 1505 (2015) 024], [Corbett et al.; JHEP 1508 (2015) 156], [Englert et al.; EPJC 76 (2016) 7, 393]
EFT Benchmarks

- Select \((c_W, c_{HW})\) benchmarks that:
  - Approximately saturate global fit limits
  - Select new Lorentz structures in the new vertices
  - Tightly constrained direction in \((c_B, c_W)\) forces \(c_B \sim -c_W/2\)
  - Benchmarks that single out \(g^{(1)}\) & \(g^{(2)}\) structures

\[
\mathcal{L}_{\text{new}} = -\frac{1}{4} g^{(1)}_{hzz} V^{\mu\nu} V_{\mu\nu} h - g^{(2)}_{hzz} V^{\nu} \partial^\mu V_{\mu\nu} h
\]

- Pattern B is a feature of matching conditions that arise in a large class of UV completions, e.g. 2HDM

[\text{Gorbahn, No & Sanz; JHEP 1510 (2015) 036}]

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Selection of results

- WH, VBF differential distributions (MG5_aMC@NLO)
- Used PYTHIA8 for Higgs decay, PS and Hadronisation
  - Rescaled rates by eHDECAY BRs to capture EFT contributions
- Events were reconstructed using Fastjet thanks to MadAnalysis5 “reco” mode and analysed according to some realistic event selection procedure also in MA5
- Included a basic ‘fiducial’ event selection
- Theoretical uncertainties due to scale variation were quantified but not PDF uncertainties
  - Envelope of 9 combinations of $(1/2, 2) \times \mu_0$
HELatNLO
http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

- SMEFT implementation in FeynRules + NLOCT framework
  - Generate NLO UFO file & simulate with MG5_aMC@NLO ~ any process!
  - First results for VBF in SMEFT @ NLO in QCD

- Includes 5 operators affecting Higgs couplings to W/Z/γ
  - First step for EW Higgs production

- Builds upon previous LO implementation of full SILH basis

- Modification of EW parameters due to SILH operators taken into account in the \((m_Z, \alpha_S, G_F)\) input scheme
  [Alloul, Fuks & Sanz; JHEP 1404 (2014) 110]

- Validated WH & ZH against existing POWHEG-BOX/MCFM implementation
  [KM, Sanz & Williams.; JHEP 1608 (2016) 039]
**pp \rightarrow W^+ H \rightarrow l^+ \nu bb**

Flat K-factors (as expected) & consistent definition of scale uncertainty allows for more confident SM/EFT discrimination

\[ \delta = \frac{\text{TOT}}{\text{SM}} - 1 \]

NLO/LO

**Big effects**

**Small effects**


**Benchmark B** does not exhibit strong “EFT” features

→ The $g_{h\nu\nu}^{(2)}$ Lorentz structure is responsible for these
EFT validity

- Relative size of SM/EFT interference ($1/\Lambda^2$) and $|\text{EFT}|^2$ terms ($1/\Lambda^4$) is a naive measure of the EFT validity
  - We don’t (want to) include SM/D=8 interference

- Can be used to assess at which energy scales the expansion breaks down
  - Test how appropriate the EFT interpretation is given current constraints from global fits

- MG5_aMC@NLO provides this functionality (at LO)
  - Select only interference
Interference only (LO)

40-80% difference for our benchmarks…
A possible way to define an additional theory uncertainty?
Included “VBF” cuts on $M_{jj}$ and $\Delta \eta_{jj}$
Smaller effects (25-50%), sensitivity to benchmark B

K-factors not as flat
Correlating VH & VBF may help disentangle $g^{(2)}$ coupling structure
Interference only (LO)

Interference vs. square much more under control.

~10% difference
HL-LHC prospects in VH

- 8 & 13 TeV analyses searching for VH → llbb
  - Large fit to many signal & control regions with some floating backgrounds
  - 13 TeV uses multivariate methods = difficult to recast without further info
- Performed a naive projection of the LHC 8 TeV analysis
  - Conservative with respect to the more sophisticated methods that will likely be employed in future updates in this channel
- Signal region: PTV > 200 GeV overflow bin in the single lepton channel (WH)
  - Background: determine the change in acceptance x efficiency for the dominant ttbar background from 8 to 13 TeV
  - Rescale fitted background in 8 TeV analysis to estimate contribution at 13 TeV
HL-LHC prospects in VH

- Also considered +1 jet category where ttbar contribution is even more dominant
- Single overflow bin of a single signal region ~ per mille sensitivity to $c_{HW}, c_W$ with 3 ab$^{-1}$
Future

• Several separate implementations of SMEFT operators in different sectors now exist

• Working on a “merge” of these to obtain a complete SMEFT model at NLO in QCD
  • Full set of operators contributing to EW Higgs production processes
  • Validation of anomalous dimension matrix calculation

• Basis independent predictions will be accessible via Rosetta translation tool

• Ultimate goal is to incorporate NLO QCD corrections in a global fit to LHC + low energy data

http://rosetta.hepforge.org
SMEFT @ the LHC

- Higgs
- Top
- EW

- $HH$
- $ggF$
- $ttH$
- $VH/VBF$
- $t+H/Z$
- $tt$
- single-top
- $tt+V$
- FCNC
- TGC
- EW
- EWPO

+CPV, flavor,...
## EFT $\rightarrow$ AC map

<table>
<thead>
<tr>
<th>Coupling</th>
<th>HEL@NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{hzz}^{(1)}$</td>
<td>( \frac{e^2 v}{2 c_w^2 s_w^2} \frac{1}{\Lambda^2} \left[ \tilde{c}<em>w^2 \tilde{c}</em>{HW} + 2 \tilde{s}<em>w^2 \tilde{c}</em>{HB} - 2 \tilde{s}<em>w^4 \tilde{c}</em>{BB} \right] )</td>
</tr>
<tr>
<td>$g_{hzz}^{(2)}$</td>
<td>( \frac{e^2 v}{4 \tilde{s}<em>w^2 c_w^2 \Lambda^2} \left[ \tilde{c}<em>w^2 (\tilde{c}</em>{HW} + \tilde{c}</em>{W}) + 2 \tilde{s}<em>w^2 (\tilde{c}</em>{B} + \tilde{c}_{HB}) \right] )</td>
</tr>
<tr>
<td>$g_{hzz}^{(3)}$</td>
<td>( \frac{g^2 v}{2 c_w^2} \right) + \frac{e^3 v^3}{8 \tilde{s}_w^4 c_w^2 \Lambda^2} \left[ \tilde{c}_w^2 \tilde{c}_w + 2 \tilde{c}_B \right] )</td>
</tr>
<tr>
<td>$g_{haz}^{(1)}$</td>
<td>( \frac{e^2 v}{4 \tilde{s}<em>w^2 c_w \Lambda^2} \left[ \tilde{c}</em>{HW} - 2 \tilde{c}_{HB} + 4 \tilde{s}<em>w^2 \tilde{c}</em>{BB} \right] )</td>
</tr>
<tr>
<td>$g_{haz}^{(2)}$</td>
<td>( \frac{e^2 v}{4 \tilde{s}<em>w^2 c_w \Lambda^2} \left[ \tilde{c}</em>{HW} + \tilde{c}<em>{W} - 2(\tilde{c}</em>{B} + \tilde{c}_{BB}) \right] )</td>
</tr>
<tr>
<td>$g_{hww}^{(1)}$</td>
<td>( \frac{e^2 v}{2 \tilde{s}<em>w^2 \Lambda^2} \tilde{c}</em>{HW} )</td>
</tr>
<tr>
<td>$g_{hww}^{(2)}$</td>
<td>( \frac{v e^2}{4 \Lambda^2 \tilde{s}_w^2} \left[ \tilde{c}<em>W + \tilde{c}</em>{HW} \right] )</td>
</tr>
<tr>
<td>$g_{hww}^{(3)}$</td>
<td>( \frac{g^2 v}{2} )</td>
</tr>
</tbody>
</table>
SM inputs

\[ O_H = \frac{c_H}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \]
\[ = \frac{c_H}{\Lambda^2} \frac{v^2}{2} \partial_\mu h \partial^\mu h + O(h^3, h^2) \]
\[ h \to h(1 + \delta h), \quad \delta h = -\frac{c_H}{\Lambda^2} \frac{v^2}{4} \]

\[ O_W |_{\Phi = \langle \Phi \rangle} = \frac{i g}{2} \bar{c}_W \left[ \Phi^\dagger T_{2k} \leftrightarrow D^\mu \Phi \right] D^\nu W_{\mu \nu}^k |_{\Phi = \langle \Phi \rangle} \]
\[ = \frac{g v^2}{16} \bar{c}_W \left[ 2g W_{+\mu\nu} W_{-\mu\nu} + g (W_3^{\mu\nu} - g' B^{\mu\nu}) W_{3\mu\nu}^3 \right] + aGC \]

\[ W_\pm^\mu \to W_\pm^\mu [1 + \delta W] \]
\[ B^\mu \to B^\mu [1 + \delta B] + y W_3^\mu \]
\[ W_3^\mu \to W_3^\mu [1 + \delta W] + z B^\mu \]

- After EWSB, canonical mass eigenbasis, different from SM
  - Perform field & coupling redefinitions to fix their normalisation
  - Modifications of gauge bosons masses, interactions, e.g., Z \to ff
  - Modifications to the SM parameters as a function of EW inputs
  - Can also affect backgrounds!

- Not all tools take these into account
  - Various choices can be made that are all equivalent up to dimension-6
Feynman Rules

\[ Z^\mu(p) \]
\[ Z^\nu(q) \]
\[ W^\mu_+(p) \]
\[ W^\nu_-(q) \]
\[ A^\mu(p) \]
\[ Z^\nu(q) \]

\( H : \)

\[ i \left[ \eta^{\mu\nu} \left( \frac{g}{\cos \theta_W} M_Z + g_{hzz}^{(1)} p \cdot q + g_{hzz}^{(2)} (p^2 + q^2) \right) - \\ g_{hzz}^{(1)} q^\mu p^\nu - \tilde{g}_{hzz} \epsilon^{\mu\nu\rho\sigma} q_\rho p_\sigma - g_{hzz}^{(2)} (p^\mu p^\nu + q^\mu q^\nu) \right] \]

\( H : \)

\[ i \left[ \eta^{\mu\nu} \left( g_{WW}^{(1)} p \cdot q + g_{WW}^{(2)} (p^2 + q^2) \right) - \\ g_{WW}^{(1)} q^\mu p^\nu - \tilde{g}_{WW} \epsilon^{\mu\nu\rho\sigma} q_\rho p_\sigma - g_{WW}^{(2)} (p^\mu p^\nu + q^\mu q^\nu) \right] \]

\( H : \)

\[ i \left[ \eta^{\mu\nu} \left( g_{haz}^{(1)} p \cdot q + g_{haz}^{(2)} p^2 \right) - g_{haz}^{(1)} q^\mu p^\nu - \\ \tilde{g}_{haz} \epsilon^{\mu\nu\rho\sigma} q_\rho p_\sigma - g_{haz}^{(2)} p^\mu p^\nu \right] \]
POWHEG-BOX/MCFM

- Higgs associated production with a leptonically decaying W or Z at NLO in QCD matched to parton shower
  - Include EFT effects via a mapping to AC/HC (also CP violating)
- At NLO, the initial state current factorises from the final state, even when the Higgs decays to b’s
  - Drell-Yan-like NLO corrections which are well known
- Builds upon previous work in the SM matched to parton shower in the same framework as well as fixed order predictions including anomalous couplings
- Matrix elements based on MCFM code interfaced with POWHEG-BOX for which the SM process was already implemented
## Selection

| Process |
|-----------------|-----------------|
| $HZ \rightarrow bb\ell^+\ell^-$ | $HW \rightarrow bb\ell\nu$ |

<table>
<thead>
<tr>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_T$ algorithm: $\Delta R=0.4$, $p_T &gt; 25$ GeV &amp; $\eta_b &lt; 2.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 $b$-jets, $p_T &gt; 25$ GeV, $\eta_b &lt; 2.5$</td>
</tr>
<tr>
<td>1 lepton, $\ell^\pm$ ($e$ or $\mu$)</td>
</tr>
<tr>
<td>$p_T^\ell &lt; 25$ GeV, $</td>
</tr>
</tbody>
</table>

MA5 performs $b$-jet identification based on truth level jet information (presence of $b$-hadrons in jet)
\( gg \rightarrow Z H \rightarrow l^+l^- b\bar{b} \)

- \( gg \) initiated process (formally NNLO)
  - Gluon PDF plus kinematics of EFT searches warrant its inclusion
  - Well known to ‘mimic’ EFT effects if not properly taken into account
\[ \text{pp } \rightarrow \text{ Z H } \rightarrow \ell^+\ell^- \text{ bb} \]

Validity? (EFT) \( \leq 5\% \)

Benchmark II does not show "EFT-like" features

\[ g_{hzz}^{(1)} \propto \bar{c}_{HW}, \quad g_{hzz}^{(2)} \propto (\bar{c}_{HW} + \bar{c}_{W}) \]
pp → Z H → l⁺l⁻ bb

N_j exhibits some difference but stats too low to distinguish
K-factors

No significant difference between SM & EFT
Relatively flat

Higgs-Z invariant mass ($q\bar{q} \rightarrow HZ \rightarrow b\bar{b}\ell^+\ell^-$)

<table>
<thead>
<tr>
<th>$M_{VH}$ [GeV]</th>
<th>$\frac{d\sigma}{dm_{VH}}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>200</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>250</td>
<td>10^{-4}</td>
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<tr>
<td>300</td>
<td>10^{-5}</td>
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<tr>
<td>350</td>
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</tr>
<tr>
<td>400</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>450</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>500</td>
<td>10^{-9}</td>
</tr>
</tbody>
</table>

$\delta(\%) = \frac{\sigma_{EFT} - \sigma_{SM}}{\sigma_{SM}} \times 100$

$\delta_{W} = -0.004$, $\delta_{HW} = 0$. 

No significant difference between SM & EFT
Relatively flat
New EFT scale uncertainty

- NLO calculations use scale uncertainty to approximate missing higher orders in perturbative expansion
  - EFT description contains an additional source of scale dependence from the running/mixing of Wilson coefficients

- Proposal for a new scale uncertainty component
  - Take $c_i$ defined at scales $2\mu_0$ & $\mu_0/2$ and run back to the central scale

Does not cancel in e.g. cross section ratios for which traditional scale uncertainty drops out