Searching for new physics in the Higgs, Top and Electroweak sectors in EFT frameworks

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why EFT?
- the basic idea
- general theoretical and experimental considerations

the status of efforts to constrain new physics in EFT
- a selection of Higgs, Top and Electroweak experimental results
  - focusing on 13 TeV measurements including EFT interpretation
  - also highlight some results that could be reinterpreted

outlook
the search for new physics

- no new BSM light particles observed at the LHC so far...
- **why?** is the NP scale ($\Lambda_{NP}$) far larger than the LHC scale?
- extend the SM Lagrangian with higher-order operators to model NP @ $\Lambda_{NP}$

famous example of Fermi theory of Beta decay

\[ \mathcal{L}^{(6)}_{SM} = \mathcal{L}^{(4)}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots \]

LHC example - $O_{tG}$ affecting rate and kinematics of $tt$ production

modified $g_{tt}$ vertices

arXiv:1505.08841

new $gg_{tt}$ vertex

searching for new particles $\Rightarrow$ searching for new interactions

bump-hunting $\Rightarrow$ determining $c_i$
why EFT?

- well-defined parameterisation of array of new physics
- model-independent
- but for EFT to make sense, *all* operators must be considered together
- **long term goal**: (semi) **global analyses** to simultaneously constrain many $c_i$ using multiple measurements

- **theory considerations**
  - NLO vs LO
  - what operators to consider?
  - how to estimate theory uncertainties

- **sensitivity**
- detector level fit

- **scalability**
- unfold to particle-level

**experiment-theory collaboration is crucial**
EFT in the Higgs sector

- rich Higgs phenomenology at the LHC
  - multiple production and decay modes
  - diverse experimental signatures
- many observables to measure
  - inclusive cross sections, fiducial rates,
  - rates by production mode, decay mode
- large statistics $\Rightarrow$ detailed studies
  - (double) differential cross sections
  - jet activity in higgs production
  - rare production modes accessible - ttH
- observables affected by EFT operators
  - rescaling of rates
  - deformations of distribution shapes

example
- operator modifies the top loop in gg Higgs production mode
ttH observation

• observation of ttH @ 7 + 8 + 13 TeV
• significance across H decay channels and COM energies:
  – $5.2 \sigma$ (obs.), $4.2 \sigma$ (exp.)
• signal strength (relative to SM) $\mu = 1.26^{+0.31}_{-0.26}$
• signal strength in all decay channels consistent with SM
• important milestone – paves the way for more detailed measurements

consequences for EFT
• dim-6 operators $O_{hg}$, $O_{HG}$, $O_{H}$, $O_{Hy}$ contribute to ttH production at tree-level
• $O_{H}$, $O_{Hy}$ affect ttH rate,
  • can already be constrained
• $O_{hg}$, $O_{HG}$ alter distribution shapes
  • can be constrained with more detailed future measurements
$H \rightarrow \gamma \gamma$

- $H \rightarrow \gamma \gamma$ @ 13 TeV with 36.1 fb$^{-1}$
- large stats allow detailed measurements
- signal strength $\mu = 0.99^{+0.15}_{-0.14}$
- diff. results agree with SM

**EFT reinterpretation**

- dim-6 operators
  - $O_g$, $\tilde{O}_g \Rightarrow$ ggH interactions
  - $O_{HW}$, $\tilde{O}_{HW} \Rightarrow$ HWW, HZZ, HZ $\gamma$ interactions
    - shape + rate changes
  - $O_{HB}$, $\tilde{O}_{HB} \Rightarrow$ HZZ, HZ $\gamma$ interactions
- diff. distributions constrain associated $c_i$

NEW arXiv:1802.04146
EFT in the electroweak sector

- Large stats. @ LHC allow EW studies in great detail
- Rare EW processes measured e.g. EW V+jets, EW ZZ, same sign WW
- Sufficient stats for differential measurements in some cases
- Subtle effects of NP in multiboson events

**Triple-Gauge-Couplings (TGC)**

- Fixed in SM
- $\alpha_{TGC}$ in EFT increases cross section especially at large energy scales
- Diboson and Higgs production are related in EFT

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ZZ production

- inclusive and differential ZZ cross sections at 13 TeV with 36.1 fb$^{-1}$
- 4l final state
- differential cross sections for a range of observables

EFT reinterpretation

- aTGC vertex forbidden in SM
  - enhanced in BSM @ large energy scales
- leading $Z P_T$ distribution constrains aTGC
- data consistent with no aTGC

<table>
<thead>
<tr>
<th>EFT parameter</th>
<th>Expected 95% CL [TeV$^{-4}$]</th>
<th>Observed 95% CL [TeV$^{-4}$]</th>
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</thead>
<tbody>
<tr>
<td>$C_{BW}/\Lambda^4$</td>
<td>$-8.1, 8.1$</td>
<td>$-5.9, 5.9$</td>
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<tr>
<td>$C_{WW}/\Lambda^4$</td>
<td>$-4.0, 4.0$</td>
<td>$-3.0, 3.0$</td>
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<td>$C_{BB}/\Lambda^4$</td>
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<td>$C_{BB}/\Lambda^4$</td>
<td>$-3.7, 3.7$</td>
<td>$-2.7, 2.8$</td>
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</tbody>
</table>

EFT coefficients constrained individually

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EW ZZ production

- measurement of EW production of ZZ+2jets @ 13 TeV with 35.9 fb⁻¹
  - four lepton + 2jet final state
  - BDT discriminant distinguishes QCD and EW processes
  - signal extracted with 2.7 σ significance
  - fiducial cross section result consistent with SM

EFT reinterpretation

- $m_{ZZ}$ distribution used to constrain EFT parameters $f_{T_i}/\Lambda^4$ describing aQGC

- coefficients constrained individually
  - most precise constraints to date
- first results on EW ZZ production
EW Z+2jet

- EW Z+2jet @ 13 TeV with 35.9 fb$^{-1}$
  - 2 lepton + 2 jet final state
  - BDT discriminant distinguishes Drell-Yan and signal
  - cross section extracted from fit to BDT
  - result consistent with SM

**EFT reinterpretation**

- $P_{Tz}$ distribution used to constrain EFT parameters $c_{WWW}/\Lambda^2$, $c_{W}/\Lambda^2$
- results consistent with SM
- parameters constrained individually and in pair
same sign WW

- measurement of same-sign WW @ 13 TeV with 35.9 fb\(^{-1}\)
  - 2 SS lepton + 2 jet + MET
  - signal extracted with 5.5 \(\sigma\)
  - result consistent with SM
  - first observation of SS WW

EFT reinterpretation
- \(m_{ll}\) distribution used to constrain dim-8 EFT operators
- independently constrain 9 \(c_i\)
- bounds improved by up to factor of 6 on previous results

<table>
<thead>
<tr>
<th>Observed limits ((\text{TeV}^{-4}))</th>
<th>Expected limits ((\text{TeV}^{-4}))</th>
<th>Previously observed limits ((\text{TeV}^{-4}))</th>
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</table>
**WWγ, WZγ**

- search for WWγ WZγ production @ 8TeV with 20.2fb⁻¹
  - e, mu, γ, 2 jet, MET
  - fiducial region defined to be optimal wrt aQGC effects
  - backgrounds determined from control regions
  - upper limit placed on cross sections in optimal fiducial region for BSM

**EFT reinterpretation**
- upper limit used to constrain dim-8 EFT
- aQGC affect fiducial rates
- independently constrain 14 cᵢ describing anomalous WWZγ and WWγγ
- results consistent with SM

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EFT in the top sector

- **top observables at the LHC**
  - $t\bar{t} \rightarrow$ precision regime: percent level incl. cross section, multi-differential, jet spectra, charge asymmetries, spin correlations
  - **single-top** $\rightarrow$ detailed diff measurements: $t$-channel, $tW$, $tZq$ channels,
  - $t\bar{t}V \rightarrow$ observed, first inclusive measurements
  - $t\bar{t}t\bar{t} \rightarrow$ approaching observation
  - **FCNC decays** $\rightarrow$ upper limits at the $10^{-5}$ level

- **EFT in top**
  - many top observables modified in EFT
  - both rate increase and shape deformations
  - interplay with Higgs sector in $t\bar{t}H$, $t\bar{t}t\bar{t}$ and FCNC
  - NLO QCD EFT predictions for many observables already available
  - suggested “common standards” from theory experts

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**limits on FCNC branching ratios @ 8TeV**

- $t \rightarrow Hc$
- $t \rightarrow Hu$
- $t \rightarrow \gamma c$
- $t \rightarrow \gamma u$
- $t \rightarrow gc$
- $t \rightarrow gu$
- $t \rightarrow Zc$
- $t \rightarrow Zu$

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- $t \rightarrow Hc$
- $t \rightarrow Hu$
- $t \rightarrow \gamma c$
- $t \rightarrow \gamma u$
- $t \rightarrow gc$
- $t \rightarrow gu$
- $t \rightarrow Zc$
- $t \rightarrow Zu$

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- **BSM alters $t\bar{t}t\bar{t}$ rate in EFT**
- **dim-6 operator in $ttZ$ production**
- **BSM loop modifying $\text{Br(FCNC)}$ in EFT**

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top FCNC decays

- $t\rightarrow uZ$, $t\rightarrow cZ$ decays @ 13 TeV with 36.1 fb$^{-1}$
- anomalous $t\rightarrow uZ$, $t\rightarrow cZ$ branching ratios is a feature of BSM scenarios

- strategy
  - $tt$ events where one top decays to $uZ$, or $cZ$
  - require 3 leptons, 2 jets, 1 b-tag and MET
  - kin. reco. to find $t\rightarrow uZ$ or $t\rightarrow cZ$ decays
  - binned likelihood fit to kinematic distributions

result - no evidence of $t\rightarrow uZ$, $t\rightarrow cZ$ decays
- upper limits on branching ratios @ 95% CL
  - $\text{Br}(t\rightarrow uZ) < 1.7 \times 10^{-4}$
  - $\text{Br}(t\rightarrow cZ) < 2.4 \times 10^{-4}$

interpretation in TopFCNC EFT model
- assume only one operator has non-zero value

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**tt + V**

- measurement of $tt+Z$ and $tt+W$ cross sections at 13 TeV with 35.9 fb$^{-1}$
- $tt + V$ rates increased in NP scenarios
  - same-sign dileptons $\rightarrow$ optimal for $tt+W$
  - 3, 4 leptons $\rightarrow$ optimal for $tt+Z$
  - BDT discriminator in same-sign dilepton

- 8 $c_i$ independently constrained
- results consistent with SM

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summary and outlook

- EFT provides a model-independent framework in which to search for subtle hints of new physics at the LHC
- facilitates the simultaneous usage of Top, Higgs and EW data in global analysis
- global analysis becoming more feasible with wealth of Higgs, EW and Top measurements
- many analyses from ATLAS and CMS appearing with stand-alone EFT reinterpretations
  - so far no hints of new physics
- particle-level, fiducial measurements crucial to move towards desired global analysis