Probing Non-Universal Theories Through Higgs Processes at Hadron Colliders

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Where are we now?

• Standard Model = Success*
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- Still need description of NP
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- Assume:

\[ SU(3) \times SU(2)_L \times U(1)_Y \subset G \]
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• Standard Model = Success*
• Still need description of NP
• Assume:
  \[ SU(3) \times SU(2)_L \times U(1)_Y \subseteq G \]
• IR limit of NP obeys SM gauge symmetries
SM-EFT

• Extend SM with all operators obeying SM-gauge symmetry

\[ \mathcal{L} = \mathcal{L}_\text{SM} + \sum_{d=5}^{\infty} \sum_i \frac{c_{d,i}}{\Lambda^{d-4}} \mathcal{O}_{d,i} \]
SM-EFT

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• In the Warsaw basis
  • \( d = 5 \) has 2 operators
  • \( d = 6 \) has 59 CP-even operators ← LO correction to SM
Probing EFT parameter space

• High $\Lambda$ suppression $\Rightarrow$ Needs precision measurements
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• Typically associated with EWPO

$\delta \lesssim \mathcal{O}(1\%)$
Probing EFT parameter space

• High $\Lambda$ suppression $\Rightarrow$ Needs precision measurements
• Typically associated with EWPO
  \[ \delta \lesssim O(1\%) \]
• But is this the only way?
Probing EFTs with hadron colliders

• Doable if

\[ \frac{S}{B} \propto E^n, \quad n \geq 1 \]
Probing EFTs with hadron colliders

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• Example: Diboson processes

\footnote{Figure from LT Wang}
Diboson at LHC

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Diboson at LHC

First generation only

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$\bar{d}_L d_L \rightarrow W_L W_L$ | $(c_L - c_L^{(3)})/\Lambda^2$ |

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Diboson at LHC

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$1$ R. Franceschini et al, [1712.01310](https://arxiv.org/abs/1712.01310)
Constraints from flavor

• This type of model contributes to FCNCs
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- For $\Delta C = 2$, 2 classes of processes:
Constraints from flavor (cont.)

• Contributes to 2 different $\Delta C = 2$, $d = 6$ operators:
  \[ \bar{c}_L u_R \bar{c}_R u_L \text{ and } \bar{c}_R \gamma_\mu u_R \bar{c}_R \gamma^\mu u_R \]
Constraints from flavor (cont.)

• Contributes to 2 different $\Delta C = 2, d = 6$ operators:
  \[ \bar{c}_L u_R \bar{c}_R u_L \text{ and } \bar{c}_R \gamma_\mu u_R \bar{c}_R \gamma^\mu u_R \]

• Parametrically, the corresponding Wilson coefficients are given by
  \[
  \frac{1}{16\pi^2} \frac{v^2}{M_Z^2} \frac{M_b^2}{M_W^2} \frac{c_{Hu}}{\Lambda^2} |V_{ub}||V_{cb}| \left( U_{R,uu}^\dagger U_{R,uc} \right) \lesssim 1.6 \times 10^{-7} \left( \frac{1}{1 \text{ TeV}} \right)^2
  \]
  \[
  3 \left| \frac{c_{Hu}}{\Lambda^2} v \left( U_{R,uu}^\dagger U_{R,uc} \right) \right|^2 \lesssim 5.7 \times 10^{-7} \left( \frac{1}{1 \text{ TeV}} \right)^2
  \]

1. O. Gedalia et al, 0906.1879
Constraints from flavor (cont.)

• Model dependent: Assume $|U_{R,uu}^\dagger U_{R,uc}| \sim |V_{ud}||V_{us}|$

  \[ \text{SM} - \text{EFT: } \frac{c_{Hu}}{\Lambda_{\text{TeV}}^2} \lesssim 48.0 \]

  \[ \text{EFT} - \text{EFT: } \frac{c_{Hu}}{\Lambda_{\text{TeV}}^2} \lesssim 8.86 \times 10^{-3} \]
Constraints from flavor (cont.)

• Consider 2 generation universal theories

\[ U_{R,uu}^\dagger U_{R,uc} \rightarrow U_{R,uu}^\dagger U_{R,uc} + U_{R,uc}^\dagger U_{R,cc} = -U_{R,ut}^\dagger U_{R,tc} \]
Constraints from flavor (cont.)

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\[ U_{R,uu}^+ U_{R,uc} \rightarrow U_{R,uu}^+ U_{R,uc} + U_{R,uc}^+ U_{R,cc} = -U_{R,ut}^+ U_{R,tc} \]

• Dominated by

\[ \frac{\Delta \Gamma(Z \rightarrow c\bar{c})}{\Gamma(Z \rightarrow c\bar{c})} \approx 1.6\% \]

\[ \rightarrow \frac{c_{Hu}}{\Lambda_{\text{TeV}}^2} \lesssim 0.163 \]

\(^1\) PDG, Phys.Rev.D\textit{98}, 030001
Analysis

• Implemented operator in MG5_aMC using a UFO file from FeynRules
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\(^1\) The ATLAS Collaboration, [1712.06518](https://arxiv.org/abs/1712.06518)
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• Generated $Zh$ events while scanning values of $c_{Hu}/\Lambda^2$
• Background estimated from 2017 ATLAS heavy resonance search$^1$
  • Extended range by fitting tail to exponential
• Cuts imposed to mimic the ATLAS study and scaled to match SM $Zh$

---

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Analysis

• Data binned by $M_{Zh}$ with bin sizes of 150 GeV
• Exclude regions with total significance of bins with $M_{Zh} < \Lambda$ greater than 2
Uncertainty estimates

- Assume a universal 5% systematic uncertainty
- Theoretical uncertainty from scale uncertainty → Assumed to be gaussian and folded in
Results

Projected Existing Collider Reach

Results (cont.)

Flavor Model Comparison

$\Lambda_{95\%}$ (TeV) vs $C_{H_u}$

- HL-LHC $pp \rightarrow Zh$
- HL-LHC $\gamma p \rightarrow AV$
- Benchmark theory 1
- Benchmark theory 2
Analysis (cont.)

• Repeated analysis for several potential future colliders:

<table>
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<th>$\sqrt{s}$</th>
<th>$\int L dt$</th>
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<tr>
<td>HE-LHC</td>
<td>27 TeV</td>
<td>15 ab$^{-1}$</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>37.5 TeV</td>
<td>30 ab$^{-1}$</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>100 TeV</td>
<td>30 ab$^{-1}$</td>
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• Estimated background via differential rescaling from parton luminosity ratios
Results

$^1$ Numbers from C Grojean et al
Results (cont.)
Complementarity with Higgs exotic decays
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Summary

• Explored existing constraints on flavor models
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• Projected reach for many hadron colliders
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• Explored existing constraints on flavor models
• Projected reach for many hadron colliders
• Higgs exotic decay searches at lepton colliders provide complementary information