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Three avenues for Higgs phenomenology

Particle Physics Seminar
Warwick
17/01/2019
Overview

- *Improving the expected: SM-like Higgs couplings*
  - lifting degeneracies in coupling space for expected uncertainties with adversarial machine learning
  - ......
Overview

- **Improving the expected: SM-like Higgs couplings**
  - lifting degeneracies in coupling space for expected uncertainties with adversarial machine learning

- ..... 

- **Constraining/observing the unexpected:**
  - Higgs sector CP violation

- .....
Overview

- Improving the expected: SM-like Higgs couplings
  - lifting degeneracies in coupling space for expected uncertainties with adversarial machine learning
  - ....

- Constraining/observing the unexpected:
  - Higgs sector CP violation
  - ....

- Closing in on new physics in the Higgs sector
  - di-Higgs production as a probe of new physics
  - ....
W$\!\!\!\!\!\!\!\!\!\!\!'s$ and Z$\!\!\!\!\!\!\!\!\!\!\!\!\!'s$ in 1983 at UA1/UA2

\[ m_W \approx 80.42 \text{ GeV} \]
\[ m_Z \approx 91.19 \text{ GeV} \]

How do you accommodate this in QFT?
“Yang–Mills theories had to be right”

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"spontaneous" symmetry breaking

- massive gauge bosons, but no ghost problems at small distances

renormalizability, probability conservation
The Standard Model: taking stock

"What's next at the LHC?"

[Coleman, Mandula '67]
Status of LHC measurements

 everything is consistent with the SM Higgs hypothesis (so far) but what are the implications for new physics?
The SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

Fingerprinting the lack of new physics

Effective Field Theory

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots \]

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosick `10]

59 B-conserving operators $\otimes$ flavor $\otimes$ h.c., $d=6$
2499 parameters (reduces to 76 with $N_f=1$)
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coupling/scale
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the SM is flawed

no evidence for exotics

concrete models

- extended SMEFT
- \((\mathbb{C})\) Higgs portals
- 2HDMs
- \((N)\)MSSM
- compositeness….
Effective theory
Effective theory

Weak decay
Weak decay

\[ \frac{1}{t - m_W^2} = \frac{1}{m_W^2} - \frac{t}{m_W^4} + \ldots \]

\[ m_\mu^2 \sim |t| \ll m_W^2 \]
Effective theory

Weak decay

$$\frac{1}{t - m_W^2} = -\frac{1}{m_W^2} - \frac{t}{m_W^4} + \ldots$$

$\begin{array}{c}
\mu \\
\nu_{\mu} \\
W \\
\bar{\nu}_e \\
e
\end{array}$

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Effective theory

Weak decay

\[
\frac{1}{t - m_W^2} = - \frac{1}{m_W^2} - \frac{t}{m_W^4} + \ldots
\]

Effective theory below \( m_W \)
SM-like couplings

- large number of unconstrained EFT parameters lead to phenomenological degeneracies = “blind directions”
- one of the most prominent and relevant for Higgs physics

\[ m_t \to \infty \quad \subset \quad \frac{\alpha_s}{12\pi} G^{a\mu\nu} T^a_{\mu\nu} \frac{H}{v} \]

contact ggH interactions mask top Yukawa measurements

- way out: resolve C_0 function for \( p_T(H) \gtrsim m_t \) with one or more jets

[Banfi, Martin, Sanz ‘13] [Grojean, Salvioni, Schallfner, Weiler ‘13]
[Schallfner et al.’14] [Buschmann et al. ‘14] [Buschmann et al. ‘14]
way out: resolve $C_0$ function for $p_T(H) \gtrsim m_t$ with one or more jets

[Banfi, Martin, Sanz `13] [Grojean, Salvioni, Schaller, Weiler `13]
[Schaller et al.`14] [Buschmann et al. `14] [Buschmann et al. `14]
• comparably small impact of tail uncertainties (lin vs log ~ 35% different shape uncertainty at 150 GeV $p_T$)

• decoupled (non-resonant) new physics perturbatively constrained at relatively low transverse momentum

steer $p_T(H)$ shape uncertainty

Role of uncertainties

large stats!
more kinematic information for H+2j, which is particularly promising, unfortunately $m_t = \infty$ SM limit accidentally good

$PP \rightarrow Hjj$

SM, $\sqrt{s} = 13$ TeV

$cg = 0.1$, $ct = 0.2$

expected uncertainty “good” scale choices

competing new physics effects

[CE, Galler, Harris, Spannowsky `18]
SM-like couplings

- more kinematic information for H+2j, which is particularly promising, unfortunately $m_t=\infty$ SM limit accidentally good

**neural net learns** regions that are sensitive to uncertainty....

[CE, Galler, Harris, Spannowsky `18] [Goodfellow et al. `14] [Louppe, Kagan, Cranmer `16] ...
SM-like couplings

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... and can be forced to avoid them $\rightarrow$ **most robust constraints**

[Goodfellow et al. `14] [Louppe, Kagan, Cranmer `16] ...
more kinematic information for H+2j, which is particularly promising, unfortunately m_t=∞ SM limit accidentally good

... and can be forced to avoid them → most robust constraints
CP violation

- a repeating point of argument is inclusion of \((\text{dim} \, 6)^2\) as there is no clear right or wrong:

\[
\frac{d\sigma}{d^4 p} \sim |M_{\text{SM}}|^2 + 2 \text{Re}\{M_{\text{SM}}M_{d6}^*\} + |M_{d6}|^2
\]

\[
\sim \Lambda^0 \quad \sim \Lambda^{-2} \quad \sim \Lambda^{-4}
\]

unitarity…

MC perturbativity

matching...
CP violation

- a repeating point of argument is inclusion of $(\text{dim 6})^2$ as there is no clear right or wrong matching, MC perturbativity, unitarity…

- in practice this is (often) not a huge problem for large data samples
CP violation

- A repeating point of argument is inclusion of \((\text{dim } 6)^2\) as there is no clear right or wrong matching.

- In practice this is (often) not a huge problem for large data samples.

- Qualitatively different for CP-violation:
  - Only genuinely CP-sensitive observables carry information.
    - Signed \(\Delta \phi_{jj}\), asymmetries, etc.
    - [Figy, Hankele, Klämke, Zeppenfeld '06]...

  - Every CP-even observable carries information.
    - Cross sections, widths, \(p_T\) spectra...
The linearised upshot

\[ O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu} \tilde{G}^a_{\mu\nu}, \]
\[ O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu} \tilde{W}^a_{\mu\nu}, \]
\[ O_{H\tilde{B}} = H^\dagger H B^{\mu\nu} \tilde{B}_{\mu\nu}, \]
\[ O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu} \tilde{W}^{a\mu\nu} \]

• fit uses ATLAS results for 4 leptons, \( \gamma\gamma \)

[ATLAS 1708.02810; 1802.04146]

• small stats/observables = blind directions for decay vs production

• non-significant asymmetry \( 0.3 \pm 0.2 \)
\textbf{CP violation}

- the linearised upshot

\begin{align*}
O_{HG} &= H^\dagger H G^{\alpha\mu\nu} \tilde{G}_{\mu\nu}^\alpha, \\
O_{HW} &= H^\dagger H W^{\alpha\mu\nu} \tilde{W}_{\mu\nu}^\alpha, \\
O_{HB} &= H^\dagger H B^{\mu\nu} \tilde{B}_{\mu\nu}^\alpha, \\
O_{HWB} &= H^\dagger \tau^a H B_{\mu\nu} \tilde{W}^{\alpha\mu\nu}
\end{align*}

\begin{align*}
\sim \frac{\alpha_s}{8\pi v} G_{\mu\nu}^a \tilde{G}^{\alpha\mu\nu} h. = \tilde{O}_G
\end{align*}

...ignore them for now...

- can already narrow this down with 36/fb by using
  - GF vs VBF selections
  - lepton decay plane angles

[Bernlochner, CE, Hays, Lohwasser, Mildner, Pilkington, Price, Spannowsky ‘18]
CP violation

- the linearised upshot

\[
O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu} \tilde{G}^a_{\mu\nu}, \\
O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu} \tilde{W}^a_{\mu\nu}, \\
O_{H\tilde{B}} = H^\dagger H B^{\mu\nu} \tilde{B}_{\mu\nu}, \\
O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu} \tilde{W}^{a\mu\nu}
\]

\[\sim \frac{\alpha_s}{8\pi\mu} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} h. = \tilde{O}_G\]

Yukawa phases

...ignore them for now...

LHC and HL-LHC extrapolations

- Table IV: Expected sum of the moduli of the positive and negative interference contributions from CP-odd operators is a central task of the Large Hadron Collider (LHC) and the future high-luminosity LHC (HL-LHC).

For instance, Sakharov's criteria provide us a hint where anti-matter asymmetry can originate. These operators could originate from complex phases in the Standard Model (SM) and extend to the SMEFT as a theoretical framework.

- The top quark production cross-section and decay modes are the SU(2) generators. Fields with a tilde are the Higgs sector interactions for our analysis. They are closed under RGE and 100, respectively.

- The Higgs sector. Gluon fusion in association with 2 jets and 100, respectively.

- The modulus is taken to avoid cancellation that would otherwise strain CP-violating complex phases in the EFT operators. Given the lack of further information that could constrain the modulus, we can separate CP-odd Higgs interactions from the SM.

- These operators consider the four CP-odd operators that cause anomalous effects on top of the CP-violating sources in the SM, or a top-antitop pair (left) and with (right) marginalisation over other CP-odd coefficients, we can separate CP-odd Higgs interactions from the SM.

- Any kinematic information such as transverse momentum distributions are instead used to constrain CP-odd operators.

- The effective field theory (EFT) approach where only interference contributions with the SM are considered, the number of degeneracies in the multi-dimensional coupling space.

- The upshot of this analysis is a wealth of opportunities to connect the Higgs sector to the SM and produce a CP-even event.

- The constraints further. For example, all the constraints improve the combination of observables becomes relativistically meaningful constraints can be obtained in the positive and negative interference contributions from CP-odd operators.

- The top quark with CP-odd couplings with Yukawa coupling size following we will denote \( \tilde{O}_G \) for any CP-even observable. This, in particular, is a significant effect of interfering the SM.
CP violation

- lifting top-specific blind directions

\[ O_{H\tilde{G}} = H^\dagger H G^{a,\mu\nu} \tilde{G}^a_{\mu\nu} + \]

[Del Duca et al. '03]

- \( m_t = \infty \) SM limit accidentally good

- split GF selection into \( m_t \)-related Higgs \( p_T \) threshold \( \sim 150 \text{ GeV} \)

[CE, Galler, Pilkington, Spannowsky in prep.]

top quark

\[ \sim \frac{\alpha_s}{8\pi\nu} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} h. = \tilde{O}_G \]

top Yukawa phase

large stats / kin.
coverage necessary
CP violation

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\[ \top \text{ quark} \sim \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}_\mu^a \nu h = \tilde{O}_G \]

\[ \text{top Yukawa phase} \]

**Graphs:**
- \( hjj(h \to \gamma\gamma), \text{inclusive}, \sqrt{s} = 27 \text{ TeV}, \mathcal{L} = 6000.0/\text{fb} \)
- \( c_g = 2.5, \ c_t = -2.5 \)

- \( hjj(h \to \gamma\gamma), p_T,h \geq 150 \) GeV, \( \sqrt{s} = 27 \text{ TeV}, \mathcal{L} = 6000.0/\text{fb} \)
- \( c_g = 2.5, \ c_t = -2.5 \)
\begin{itemize}
  \item lifting top-specific blind directions
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\[ \text{top quark} \]
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HH pheno

- dimension 6 deformations of the Higgs potential

\[ V(H^* H)_6 \supset c_6 / \Lambda^2 (H^* H)^3 \]

modify Higgs self-interactions. Large top-threshold interference.

[Giudice, Grojean, Pomarol, Rattazzi '07]

LHC blind spots: Higgs potential

Other studies of Higgs pair production in the same final state at the LHC can be found in Refs. [28] and [29].

[Frederix et al '14]

HH production at 14 TeV LHC at (N)LO in QCD

-MH=125 GeV

-MSTW2008 (N)LO pdf (68%cl)

[MADGRAPH v5.2.3]

5.2.1 Dependence of total cross sections on the Higgs trilinear coupling at NNLL order is still 

\[ \lambda = 0 \]

\[ \lambda = 2 \lambda_{\text{SM}} \]

\[ \lambda = \lambda_{\text{SM}} \]

Variation at NNLL order is still [30, 31].

1% 4% 8% 26% 68% CL interval on the Higgs trilinear and

[LO set [Giudice, Grojean, Pomarol, Rattazzi '07], interfaced

[Frederix et al '14]]
### HH pheno

**LHC blind spots: Higgs potential**

#### CMS Projection \( \sqrt{s} = 13 \) TeV

<table>
<thead>
<tr>
<th>SM gg → HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECFA16 S2</td>
</tr>
<tr>
<td>Stat. Only</td>
</tr>
</tbody>
</table>

| \( \mu_{\gamma\gamma bb}^{(S2+)} \) |
| \( \mu_{\tau\tau bb} \)  |
| \( \mu_{VV bb} \)  |
| \( \mu_{bb bb} \)  |

**Expected uncertainty**

-2  -1  0  1  2  3  4  5

**Significance**

-2 \( 10^{-1} \)

**Total luminosity** [fb⁻¹]

-2 \( 10^{2} \)  \( 10^{3} \)

**CMS projection (13 TeV)**

- **gg→HH→\( \tau\tau bb \) channel**
- **scaled syst. + theory/2**
- **unchanged syst.**

- **ECFA16 S1**
- **ECFA16 S2**
- **Stat. error only**
\* however...

LHC blind spots: Higgs potential

- correlated with on-shell Higgs phenomenology
HH pheno

- however...

- easy to arrange EFT coefficients in a way to get spectacular rates, but can doubt physical relevance of such limits (→ matching)

LHC blind spots: Higgs potential

correlated with on-shell Higgs phenomenology broken by \( \sim \bar{t}th^2 / \Lambda \)....

[Gröber, Mühlleitner `10]
However... correlated with on-shell Higgs phenomenology broken by $\sim \bar{t}th^2/\Lambda$.

- Easy to arrange EFT coefficients in a way to get spectacular rates, but can doubt physical relevance of such limits (→ matching)

- Bit what about concrete Higgs sector extensions?
  - Extrapolate 125 GeV signal strengths
  - Extrapolate exotic Higgs searches
  - Additional constraints (electron EDMs, flavor, perturbativity, ...)

LHC blind spots: Higgs potential

Fig. 60: Diagrams contributing to the Higgs pair production process through gluon fusion (an additional diagram obtained by crossing the box one is not shown).

[Gröber, Mühlleitner `10]
However...

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bit what about concrete Higgs sector extensions?

extrapolate 125 GeV signal strengths

extrapolate exotic Higgs searches

additional constraints (electron EDMs, flavor, perturbativity, ...)

correlated with on-shell Higgs phenomenology broken by $\sim \bar{t}th^2/\Lambda$....
SM-like measurements can show a plethora resonant anomalies
diHiggs final states important for BSM discovery

...diHiggs final states quickly lose relevance when approaching EFT limit
**HH pheno**

**above Higgs pair threshold**
- (multi) resonant diHiggs production (hh, hH,...)

**opportunity for diHiggs**

Higgs interactions dominant

**exotics with large couplings to tops**

**above top pair threshold**
- tt final states preferred
- analysis highly model-dependent due to dedicated S-B interference

**below top pair threshold**
- compressed spectra
- single Higgs competitive except b-final states
  (>trigger etc...)

**opportunity for diHiggs**
Higgs in the SM and beyond

Summary

- *Advances have been extremely rapid*
  - good understanding of EFT
  - simulation
  - limit setting - machine learning

- *Opportunity to link the Higgs sector to new physics*
  - cure SM shortcomings (CP violation...)
  - multi-Higgs production as a chance for BSM
  - LHC probably not be enough to achieve this in full glory