Higgs fits to new physics

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Challenges ahead
The LHC

The LHC is in a mature stage, already providing precision tests for the SM in most channels (excl the Higgs)

Precise tests of the full structure of the SM, based on QFT, symmetries (global/gauge) and consistent ways to break them
non-trivial tests of perturb.-non-perturb. QCD

Absence of excesses: interpreted as new physics exclusions

exclusions: rather impressive, many at the TeV
searches: outstanding coverage of possible topologies
any hints: (like in flavor) extremely tempting
This is just the beginning

HL-LHC (High-Luminosity) LHC approved, to deliver 3000 inverse fb of data. Funding ensured until 2035.

Plus other collider experiments testing SM at high precision e.g. *super-B factory*
So here we are finding our path through SYMMETRIES & DYNAMICS aiming for a UNIFIED FRAMEWORK

Light Higgs
Matter/Antimatter
Dark Energy
Inflation
fermion puzzles
CP QCD
Neutrinos
Unification
Dark Matter
Quantum Gravity

SM+GR
So here we are again, post-LHC Run 1

Light Higgs
Matter/Antimatter
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fermion puzzles
CP QCD
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Quantum Gravity

the normal process for an empirical science prediction, test & exclusion or discovery
The Higgs as a key to new physics
A cosmological Higgs

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales. Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile
The Higgs at the LHC
The Higgs is produced in ggF, VBF, VH and ttH decays to channels with photons, leptons (e, mu), missing energy, tagged b’s and taus.

- easy to difficult diphotons
- ZZ to 4L
- WW to 2L
- di-taus
- bb

mass=125 GeV
LHC Higgs in a nutshell (II)

QUANTUM NUMBERS

using kinematic distributions in ZZ, WW, …
determine the spin and parity as well as possible CP admixtures

kinematics

hypothesis discrimination
SM Higgs

Run1 (and now Run2) indicates a SM-like Higgs

\[ \delta \equiv \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}} \]

\[ \mu_{\text{ttH}} = -0.25^{+1.25}_{-0.99} \]
\[ \mu_{\text{VH}} = 0.23^{+1.27}_{-1.05} \]
\[ \mu_{\text{VBF}} = 2.24^{+0.80}_{-0.71} \]
\[ \mu_{\text{ggH}} = 0.59^{+0.29}_{-0.28} \]

\[ \mu_{\text{Run-2}} = 0.85^{+0.22}_{-0.20} \]
\[ \mu_{\text{Run-1}} = 1.17^{+0.28}_{-0.26} \]

but precision is poor (20-30%)
The low-hanging fruits: SUSY and Composite Higgs
SUSY Higgs: loop corrections compete with gluon fusion and Higgs to diphotons
Main effect *stop contributions*
ESPINOSA, GROJEAN, VS, TROTT. 1207.7355

\[ \kappa_g \simeq 1 + 0.3 \frac{m_{\tilde{t}}}{m_t} \]

indirect searches for stops

BANFI, BOND, MARTIN, VS. 1708.xxxx
Higgs data vs direct searches for stops
Composite Higgs (I)

Usual paradigm:
potential generated via Coleman-Weinberg contributions

e.g. GAUGE

Georgi-Kaplan (80’s)
gauge-top does not trigger EWSB
need new fermionic resonances
TOP-PARTNERS

\[ m_h^2 \sim \frac{N_c y_t^2}{16 \pi^2} \frac{v^2}{f^2} m_T^2 \]

pheno: New, light (below TeV) techni-baryons should couple to the Higgs, W, Z
Composite Higgs (II)

Panico et al. 2016

typical distribution of top-partners

\[ \Delta m^2 \sim y_{LA}^2 v^2 \]
\[ \Delta m^2 \sim y_{LA}^2 f^2 \]
\[ \Delta m^2 = 0 \]

\[ m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2 \]

resonances below \( \sim 800 \text{ GeV} \) are excluded

tuning in the Higgs potential severe
Composite Higgs after Run2

Composite Higgs models
Many realizations,
but some common features

Boson couplings

\[ \kappa_V = \sqrt{1 - \xi} \approx 1 - \frac{1}{2} \xi \]

Fermion couplings

\[ \kappa_F^A = \sqrt{1 - \xi} \]

\[ \kappa_F^H = \frac{1 - 2\xi}{\sqrt{1 - \xi}} \]

Models

- \( SO(5)/SO(4) \) - [8, 9]
- \( SO(6)/SO(4) \times SO(2) \) - [12, 13]
- \( SU(5)/SU(4) \) - [14]
- \( SO(8)/SO(7) \) - [18, 19]
- \( SO(5)/SO(4) \) - [9, 11, 17]
- \( SU(4)/Sp(4) \) - [3]
- \( SU(5)/SO(5) \) - [4]
- \( SO(6)/SO(4) \times SO(2) \) - [12, 13]
The EFT approach

Looking for small deviations from the SM
EFT approach

Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_{i}^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_{i}^{d=8} + \ldots \]

BSM effects \quad SM particles

**example:**

2HDM

\[ \frac{ig}{2m_W^2} \bar{c}_W \left[ \Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi \right] D_\nu W^{k,\mu\nu} \]

where \[ \bar{c}_W = \frac{m_W^2 (2 \tilde{\lambda}_3 + \tilde{\lambda}_4)}{192 \pi^2 \tilde{\mu}_2^2} \]
Beyond the kappa formalism

Kappa-formalism is useful when new physics effects are very simple
Just change the overall rates

<table>
<thead>
<tr>
<th>Squarks</th>
<th>Non-linear, CHM singlet mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\gamma$, $\kappa_g$</td>
<td>$\kappa_f$, $\kappa_V$</td>
</tr>
</tbody>
</table>

Models offer richer kinematics, and EFT approach captures them

$$
- \frac{1}{4} h g^{(1)}_{VV} V_{\mu\nu} V^{\mu\nu} - h g^{(2)}_{VV} V_{\nu} \partial_{\mu} V^{\mu\nu} - \frac{1}{4} h \tilde{g}_{VV} V_{\mu\nu} \tilde{V}^{\mu\nu}
$$

$$
\eta_{\mu\nu} \left( g^{(1)}_{VV} \left( \frac{s}{2} - m^2_v \right) + 2 g^{(2)}_{VV} m^2_v \right)
$$

$$
- ig^{(1)}_{VV} p_3^\mu p_2^\nu - i \tilde{g}_{VV} \epsilon^{\mu\nu\alpha\beta} p_2,\alpha p_3,\beta
$$

+ off-shell pieces
EFT approach

**THEORY**

Model-independent parametrization deformations respect to the SM

Well-defined theory can be improved order by order in momentum expansion

consistent addition of higher-order QCD and EW corrections

Connection to models is straightforward

**EXPERIMENT**

Beyond kappa-formalism: Allows for a richer and generic set of kinematic features

Higher-order precision in QCD/EW

The way to combine all Higgs channels and EW production
EFT: Matching with UV theories
Extended Higgs sectors

To combine direct/indirect and evaluate the validity of the EFT approximation, matching of the EFT with a UV model is required

We did the matching to UV theories with extended Higgs sectors

<table>
<thead>
<tr>
<th>Model</th>
<th>$c_H$</th>
<th>$c_6$</th>
<th>$c_T$</th>
<th>$c_W$</th>
<th>$c_B$</th>
<th>$c_{HW}$</th>
<th>$c_{HB}$</th>
<th>$c_{3W}$</th>
<th>$c_\gamma$</th>
<th>$c_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs Portal (G)</td>
<td>L</td>
<td>L</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Higgs Portal (Spontaneous G)</td>
<td>T</td>
<td>L</td>
<td>RG</td>
<td>RG</td>
<td>RG</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Higgs Portal (Explicit G)</td>
<td>T</td>
<td>T</td>
<td>RG</td>
<td>RG</td>
<td>RG</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2HDM Benchmark A ($c_{\beta-\alpha} = 0$)</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>X</td>
</tr>
<tr>
<td>2HDM Benchmark B ($c_{\beta-\alpha} \neq 0$)</td>
<td>T</td>
<td>T</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>X</td>
</tr>
<tr>
<td>Radion/Dilaton</td>
<td>T</td>
<td>T</td>
<td>RG</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>L</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>

combined EWPTs, direct searches and Higgs limits from the EFT

50 pages of gory details…
Matching procedure

Example: 2HDM

Matching EFT: unbroken phase

\[
\begin{align*}
\bar{c}_H &= - \left[ -4 \tilde{\lambda}_3 \tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4 \tilde{\lambda}_3^2 \right] \frac{v^2}{192 \pi^2 \tilde{\mu}_2^2} \\
\bar{c}_6 &= - \left( \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 \right) \frac{v^2}{192 \pi^2 \tilde{\mu}_2^2} \\
\bar{c}_T &= (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2) \frac{v^2}{192 \pi^2 \tilde{\mu}_2^2} \\
\bar{c}_\gamma &= \frac{m_W^2 \tilde{\lambda}_3}{256 \pi^2 \tilde{\mu}_2^2} \\
\bar{c}_W &= - \bar{c}_{HW} = \frac{m_W^2 (2 \tilde{\lambda}_3 + \tilde{\lambda}_4)}{192 \pi^2 \tilde{\mu}_2^2} = \frac{8}{3} \bar{c}_\gamma + \frac{m_W^2 \tilde{\lambda}_4}{192 \pi^2 \tilde{\mu}_2^2} \\
\bar{c}_B &= - \bar{c}_{HB} = \frac{m_W^2 (-2 \tilde{\lambda}_3 + \tilde{\lambda}_4)}{192 \pi^2 \tilde{\mu}_2^2} = -\frac{8}{3} \bar{c}_\gamma + \frac{m_W^2 \tilde{\lambda}_4}{192 \pi^2 \tilde{\mu}_2^2} \\
\bar{c}_3W &= \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440 \pi^2 \tilde{\mu}_2^2}
\end{align*}
\]

Also matching with the broken phase obtained EFT limits, dimension-6 and dimension-8 and EWPTs
Matching to UV theories

Within the EFT, connection to models is straightforward

EFT

\[ \bar{c}_H = -\left[ -4\lambda_3\lambda_4 + \lambda_4^2 + \frac{\lambda_3^2}{3} - 4\lambda_3^2 \right] \frac{v^2}{192 \pi^2 \mu_2^2} \]

\[ \bar{c}_6 = -\left( \lambda_4^2 + \lambda_3^2 \right) \frac{v^2}{192 \pi^2 \mu_2^2} \]

\[ \bar{c}_T = (\lambda_4^2 - \lambda_3^2) \frac{v^2}{192 \pi^2 \mu_2^2} \]

\[ \bar{c}_\gamma = \frac{m_W^2 \lambda_3}{256 \pi^2 \mu_2^2} \]

\[ \bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2 (2\lambda_3 + \lambda_4)}{192 \pi^2 \mu_2^2} = \frac{8}{3} \bar{c}_\gamma + \frac{m_W^2 \lambda_4}{192 \pi^2 \mu_2^2} \]

\[ \bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2 (-2\lambda_3 + \lambda_4)}{192 \pi^2 \mu_2^2} = -\frac{8}{3} \bar{c}_\gamma + \frac{m_W^2 \lambda_4}{192 \pi^2 \mu_2^2} \]

\[ \bar{c}_{3W} = \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440 \pi^2 \mu_2^2} \]
EFT: Global analyses
Global analyses using EFTs

EFTs induce effects in many channels
ideal framework for combination

### $L_{3h}$ Couplings vs $SU(2)_L \times U(1)_Y$ ($D \leq 6$) Wilson Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{hh}\gamma$</td>
<td>$g_{hh}(1) = 1 + \frac{5}{2} \bar{c}_6$</td>
</tr>
<tr>
<td>$g_{hh}\gamma$</td>
<td>$g_{hh}(2) = \frac{g}{m_W} \bar{c}_H$</td>
</tr>
<tr>
<td>$g_{h\gamma\gamma}$</td>
<td>$g_{h\gamma\gamma} = \frac{g^{\text{SM}}}{m_W} - \frac{4g^2 v \bar{c}_g}{m_W}$</td>
</tr>
<tr>
<td>$g_{h\gamma\gamma}$</td>
<td>$g_{h\gamma\gamma} = \frac{g^{\text{SM}}}{m_W} - \frac{8 g v^2 \bar{c}_g}{m_W}$</td>
</tr>
<tr>
<td>$g_{h_{WZZ}}$</td>
<td>$g_{h_{WZZ}} = \frac{2g}{m_W} \bar{c}_{WW}$</td>
</tr>
<tr>
<td>$g_{h_{zzz}}$</td>
<td>$g_{h_{zzz}} = g_{h_{WZZ}}(1) + \frac{2g}{c_W m_W} \left[ \bar{c}<em>{HB} s</em>{WW}^2 - 4 \bar{c}<em>\gamma s</em>{WW}^4 \right]$</td>
</tr>
<tr>
<td>$g_{h_{WZZ}}$</td>
<td>$g_{h_{WZZ}}(2) = \frac{g}{2 m_W} \left[ \bar{c}<em>W + \bar{c}</em>{WW} \right]$</td>
</tr>
<tr>
<td>$g_{h_{zzz}}$</td>
<td>$g_{h_{zzz}}(3) = \frac{g_{h_{WZZ}}}{c_W} (1 - 2 \bar{c}_T)$</td>
</tr>
<tr>
<td>$g_{h_{WZ\gamma}}$</td>
<td>$g_{h_{WZ\gamma}}(1) = \frac{g s_{WW}}{c_W m_W} \left[ \bar{c}<em>{WW} - c</em>{HB} + 8 \bar{c}<em>\gamma s</em>{WW}^2 \right]$</td>
</tr>
<tr>
<td>$g_{h_{WZ\gamma}}$</td>
<td>$g_{h_{WZ\gamma}}(2) = \frac{g s_{WW}}{c_W m_W} \left[ \bar{c}<em>{WW} - c</em>{HB} - c_B + c_W \right]$</td>
</tr>
</tbody>
</table>

### $L_{4h}$ Couplings vs $SU(2)_L \times U(1)_Y$ ($D \leq 6$) Wilson Coefficients

<table>
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</thead>
<tbody>
<tr>
<td>$g_{hh}\gamma$</td>
<td>$g_{hh}(1) = 1 + \frac{15}{2} \bar{c}_6$</td>
</tr>
<tr>
<td>$g_{hh}\gamma$</td>
<td>$g_{hh}(2) = \frac{g^2}{4 m_W^2} \bar{c}_H$</td>
</tr>
<tr>
<td>$g_{h\gamma\gamma}$</td>
<td>$g_{h\gamma\gamma} = -\frac{4g^2 v \bar{c}_g}{m_W}$</td>
</tr>
<tr>
<td>$g_{h\gamma\gamma}$</td>
<td>$g_{h\gamma\gamma} = -\frac{4g^2 v^2 \bar{c}_g}{m_W^2}$</td>
</tr>
<tr>
<td>$g_{h_{X\gamma}}$</td>
<td>$g_{h_{X\gamma}}(1,2) = \frac{g}{2 m_W} g_{h_{WZ\gamma}}(1,2)$</td>
</tr>
<tr>
<td>$g_{h_{zzz}}$</td>
<td>$g_{h_{zzz}}(3) = \frac{g}{2}$</td>
</tr>
<tr>
<td>$g_{h_{zzz}}$</td>
<td>$g_{h_{zzz}} = \frac{g_{h_{WZZ}}}{c_W} (1 - 6 \bar{c}_T)$</td>
</tr>
<tr>
<td>$g_{h_{WZWZ}}$</td>
<td>$g_{h_{WZWZ}}(1) = \frac{g s_{WW}}{m_W} \left[ 2 \bar{c}<em>W + \bar{c}</em>{WW} + \bar{c}_{HB} \right]$</td>
</tr>
<tr>
<td>$g_{h_{WZWZ}}$</td>
<td>$g_{h_{WZWZ}}(1) = \frac{g^2}{c_W m_W} \left[ \bar{c}<em>{WW} \bar{c}</em>{WW} - s_{WW}^2 \bar{c}<em>{HB} + (3 - 2 s</em>{WW}^2) \bar{c}_W \right]$</td>
</tr>
<tr>
<td>$g_{h_{WZWZ}}$</td>
<td>$g_{h_{WZWZ}}(2) = \frac{2g^2 s_{WW}}{m_W} \bar{c}_W$</td>
</tr>
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<td>$g_{h_{WZWZ}}$</td>
<td>$g_{h_{WZWZ}}(2) = \frac{g^2}{c_W m_W} \left[ \bar{c}<em>{WW} + (3 - 2 s</em>{WW}^2) \bar{c}_W \right]$</td>
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ALLOUL, FUKS, VS. 1310.5150
GORBANNO, NO, VS. 1502.07352
Global analyses using EFTs

EFTs induce effects in many channels
ideal framework for combination

TGCs, QGCs

\[ \mathcal{L}_{3V} \text{ Couplings vs } SU(2)_L \times U(1)_Y \text{ (} D \leq 6 \text{)} \text{ Wilson Coefficients} \]

\[
g_1^z = 1 - \frac{1}{c_w} \left[ \bar{c}_{hw} - (2s_w^2 - 3)\bar{c}_w \right], \quad \kappa_Z = 1 - \frac{1}{c_w} \left[ c_w^2 \bar{c}_{hw} - s_w^2 \bar{c}_{hb} - (2s_w^2 - 3)\bar{c}_w \right] \\
g_1^\gamma = 1, \quad \kappa_\gamma = 1 - 2\bar{c}_w - \bar{c}_{hw} - \bar{c}_{hb}, \quad \lambda_\gamma = \lambda_Z = 3g^2\bar{c}_w \\
\]

\[ \mathcal{L}_{4V} \text{ Couplings vs } SU(2)_L \times U(1)_Y \text{ (} D \leq 6 \text{)} \text{ Wilson Coefficients} \]

\[
g_2^w = 1 - 2c_{hw} - 4\bar{c}_w, \quad g_2^z = 1 - \frac{1}{c_w} \left[ 2c_{hw} + 2(2 - s_w^2)\bar{c}_w \right] \\
g_2^\gamma = 1, \quad g_2^{\gamma^2} = 1 - \frac{1}{c_w} \left[ \bar{c}_{hw} + (3 - 2s_w^2)\bar{c}_w \right] \\
\lambda_w = \lambda_\gamma w = \lambda_\gamma z = \lambda_{wz} = 6g^2\bar{c}_w \]
Global analyses using EFTs

Although the EFT has many parameters, the LHC is sensitive to a handful of them.

State of the art:
Global fit

ELLIS, VS, YOU. 1410.0773

LEP and LHC Run1 data

green: one-by-one
black: global fit
Global analyses using EFTs

sensitivity relies on combination of channels and on use of differential information

**WW production**

Dependence on EFT

Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for EFT

theorists are working closely with the experiments to bring this to higher precision in the 13 TeV runs
EFT: Precision
Precision in the EFT

Within the EFT approach
- incorporate higher-order QCD and EW effects
- higher-order EFT effects (dimension-8)
- check validity of the approach

Need to exploit differential information
simulate cuts and detector effects in analysis
MC tools should match the level of SM BGs

we started incorporating the EFT at QCD NLO
NLO EW & dim-8 underway
Monte Carlo EFT@NLO QCD

At LO there are a handful of EFT implementations, incl SM NLO
\textbf{WHIZARD, JHU, VBFNLO, AMC@NLO, POWHEG}

Largest collection of EFT operators in one MC (39 operators)
\textbf{ALLOUL, FUKS, VS. 1310.5150}

written in the SILH basis, we link to \textit{Rosetta} for change of basis
\textbf{MIMASU, VS ET AL. 1508.05895}

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\textbf{Comparison}

\textbf{Leading b-jet }p_T

\textit{W^+H; H → bb, W → l^+ l^-}
\textit{LHC 13 TeV, NLO+PS}

\textit{MG5.aMC}
\textit{POWHEG/MCFM}
\textit{\tilde{c}_{HW} = 0.03, \tilde{c}_W = \tilde{c}_B = 0.}
\textit{\tilde{c}_{HW} = -\tilde{c}_W = 0.03, \tilde{c}_B = 0.015}

\textbf{POWHEG-BOX}
\textbf{MIMASU, VS, WILLIAMS. 1512.02572. JHEP}

\textbf{aMC@NLO}
\textbf{DEGRANDE, FUKS, MAWATARI, MIMASU, VS. 1609.04833. EPJC}
Conclusions

- The Higgs may be the key to discover new physics: lightness and association with the origin of mass

- The discovery of the Higgs in 2012 opened a new way to look for new physics via quantum effects (indirect). With Run2 at 13 TeV, the LHC is approaching a precision stage for Higgs measurements

- The EFT approach to interpret Higgs data is a theorist-friendly procedure and with a well-defined procedure for systematic improvement. It is motivated by the absence of excesses in direct searches

- To reach the precision needed for discovery, theorists are developing NLO MC tools to facilitate the communication with experimentalists. Expect to reach scales into the TeV