Higgs property measurements for Run 2: kappa's and beyond

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LHC Higgs XS WG workshop, 12th June 2014
Higgs measurements from the experimental point of view

- Rate and coupling measurements
  - Indirect width measurement in high mass WW+ZZ
  - Direct width measurement
- Mass
- Separation of production modes
- Spin/CP hypothesis tests and CP measurements
- Measurements of differential distributions
Higgs measurements from the experimental point of view

- All these measurements tell us something about the observed Higgs (but also need some assumptions)
- Many measurements use the same data → this makes it difficult to extract the big picture
Higgs measurements from the experimental point of view

- All these measurements tell us something about the observed Higgs
- Many measurements use the same data → this makes it difficult to extract the big picture
- The same applies to beyond Higgs searches/measurements
Focus of the light mass sub-group so far

Rate and coupling measurements

... and the big picture: EFT

(Also other topics were discussed, but by far not as extensive as couplings, Spin/CP and EFT)
Focus of the light mass sub-group so far

- Define a common framework between the theory community and ATLAS+CMS on how to do Higgs coupling fits in Run 1.
  - Includes proposals for benchmark parameterizations for coupling measurements

- Discussion of Higgs Spin and CP hypothesis tests and CP measurements
  - Proposed benchmark parametrizations
  - Anomalous couplings vs. EFT discussion

- Start of the work for an EFT approach to Higgs (coupling) measurements in Run 2
  - EFT approach goes beyond the Higgs sector: Allows a consistent treatment of a wide range of measurements!
  - Can go beyond leading order and include EWK corrections
  - Naturally includes CP odd operators
  - But: several basis choices possible (all equivalent)
Couplings: $\kappa$-framework

- Define a framework in which to look for deviations from the SM in the Higgs coupling sector. Focus only on one Higgs!
- Make sure that the theory community understands exactly which definitions are used and how to interpret the results.
- Experimental precisions on observed rates are at best $O(20\%)$ in Run 1. Try to keep it simple:
  - Introduce one scale factor $\kappa$ per SM particle with observable “Higgs coupling” at the LHC: $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_\tau$, $\kappa_\mu$, $\kappa_\gamma$, $\kappa_g$, $\kappa_H$. 

![Diagram](image.png)
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Very "experimental" friendly definition:

- SM Higgs analysis can be used out-of-the-box after some $\kappa$-dependent rescaling of expected rates
- Natural evolution from simple to complicated fits
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- Use best available SM calculation for cross-section and BR $\rightarrow$ we want to look for deviations from the SM!

- Example:

$$\begin{aligned}
\sigma \cdot \text{BR} (gg \rightarrow H \rightarrow \gamma\gamma) &= \sigma_{\text{SM}} (gg \rightarrow H) \cdot \text{BR}_{\text{SM}} (H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \\
\end{aligned}$$

Include all higher order QCD and EW corrections! These corrections are also scaled with $\kappa$!
Couplings: $\kappa$-framework

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• Experimental precisions on observed rates are at best $O(20\%)$ in Run 1. Try to keep it simple:
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• Needs assumptions:
  • Only one low mass state ($m_H \sim 125$ GeV): no other “signals”
  • Zero/narrow width approximation
  • Only modification of scalar coupling strength: no change to production and decay kinematics of Higgs processes

• All simplifications/assumptions should be valid as long as all results agree with the SM expectations

→ the $\kappa$-framework does not give a true measurement!
NLO corrections are not treated properly. The known SM EWK corrections are just scaled with $\kappa$.

- EWK corrections are expected at the $\sim 10\%$ level → uncritical as long as experimental precision is $>>10\%$
- but we are getting close...

- Best cases $15-20\%$ uncertainty on $\kappa^2$ with Run 1
**κ-framework: known limitations**

- NLO corrections are not treated properly. The known SM EWK corrections are just scaled with κ
  - EWK corrections are expected at the ~10% level
    → uncritical as long as experimental precision is >>10%
    → but we are getting close...
  
- And expected to get to <10% with Run 2 and beyond

<table>
<thead>
<tr>
<th>S-LHC projections</th>
<th>$K_gK_z/\bar{K}_H$</th>
<th>$K_w/\bar{K}_Z$</th>
<th>$K_\nu/\bar{K}_Z$</th>
<th>$K_g/K_z$</th>
<th>$K_\nu/K_z$</th>
<th>$K_t/K_z$</th>
<th>$K_\mu/K_z$</th>
<th>$\kappa_{zy}/K_z$</th>
<th>$K_t/K_g$</th>
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<tbody>
<tr>
<td>300fb⁻¹ ATLAS</td>
<td>[3,6]</td>
<td>[4,5]</td>
<td>[5,11]</td>
<td>[11,12]</td>
<td>N/a</td>
<td>[11,13]</td>
<td>[20,22]</td>
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<td>[17,18]</td>
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<tr>
<td>CMS</td>
<td>[4,6]</td>
<td>[4,7]</td>
<td>[5,8]</td>
<td>[6,9]</td>
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<td>[6,9]</td>
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<td>[6,8]</td>
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</table>
\kappa\text{-framework: known limitations}

- NLO corrections are not treated properly. The known SM EWK corrections are just scaled with \kappa

- Changes to the W- and Z-couplings would likely also cause changes to event kinematics
  - Visible in H\rightarrow WW and H\rightarrow ZZ decays
  - Visible in VBF and VH production
→ \kappa\text{-framework is good for inclusive quantities}
→ but a coupling strength is not sufficient for distributions
NLO corrections are not treated properly. The known SM EWK corrections are just scaled with $\kappa$.

Changes to the W- and Z-couplings would likely also cause changes to event kinematics.

If several couplings contribute to a Higgs process, some kinematic dependence is expected. Examples:

- $gg\rightarrow H$ production:
  - At low $p_T$ the b-t-interference contributes with $\sim -7\%$
  - At high $p_T \sim 100\%$ t-loop in the SM. But would expect largest influence from heavy BSM particles here

- $tH$ production:
  - size of t-, W- and interference terms depends on event selection
So far the angular correlations in $H \to ZZ$, $H \to WW$ and $H \to \gamma\gamma$ are used to test alternative Spin/CP hypothesis.

Benchmarks/examples for 

<table>
<thead>
<tr>
<th>scenario</th>
<th>X production</th>
<th>$X \to VV$ decay</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_m$</td>
<td>$gg \to X$</td>
<td>$g_1^{(0)} \neq 0$ in Eq. (200)</td>
<td>SM Higgs boson scalar</td>
</tr>
<tr>
<td>$0^+_h$</td>
<td>$gg \to X$</td>
<td>$g_2^{(0)} \neq 0$ in Eq. (200)</td>
<td>scalar with higher-dim. operators</td>
</tr>
<tr>
<td>$0^-$</td>
<td>$gg \to X$</td>
<td>$g_4^{(0)} \neq 0$ in Eq. (200)</td>
<td>pseudo-scalar</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$\bar{q}q \to X$</td>
<td>$g_2^{(1)} \neq 0$ in Eq. (202)</td>
<td>exotic pseudo-vector</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$\bar{q}q \to X$</td>
<td>$g_1^{(1)} \neq 0$ in Eq. (202)</td>
<td>exotic vector</td>
</tr>
<tr>
<td>$2^+_m$</td>
<td>$g_1^{(2)} \neq 0$ in Eq. (203)</td>
<td>$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (203)</td>
<td>graviton-like tensor with min. couplings</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$g_4^{(2)} \neq 0$ in Eq. (203)</td>
<td>$g_4^{(2)} \neq 0$ in Eq. (203)</td>
<td>tensor with higher-dimension operators</td>
</tr>
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<td>$2^-_h$</td>
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<td>$g_8^{(2)} \neq 0$ in Eq. (203)</td>
<td>“pseudo-tensor”</td>
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documented in YR3 but mixings possible.
For Spin 0, CP measurements are a natural continuation of the $0^+$ and $0^-$ hypothesis tests.

Can be viewed in the amplitude (JHU) or EFT picture (MG5)
• So far the angular correlations in $H \rightarrow ZZ$, $H \rightarrow WW$ and $H \rightarrow \gamma\gamma$ are used to test alternative Spin/CP hypothesis

• The measurements do NOT use the observed rates, just decay correlations!
  • Results in some inconsistencies, e.g. tested Spin 2 models predict rates which are incompatible with the observation

• Ongoing discussion for Spin 2 models:
  • Additional (more consistent?) benchmarks
  • General measurements of helicity amplitudes

• For Spin 0 measurements:
  • Goal is to merge with the coupling measurements using a consistent EFT approach with CP odd operators
  • $H \rightarrow \tau\tau$ will be crucial, as it allows to probe CP in fermion couplings
EFT (Higgs) measurements

- Effective Lagrangian approach, obtained from integrating out heavy particles. Assumption: new physics appears at scale \( \Lambda \gg m_H \sim 125 \text{ GeV} \)
EFT (Higgs) measurements

- Systematic approach: expansion in inverse powers of $\Lambda$:

\[ \Delta \mathcal{L} = \sum_i \frac{a_i}{\Lambda^2} \mathcal{O}_{i}^{d=6} + \sum_j \frac{a_j}{\Lambda^4} \mathcal{O}_{j}^{d=8} + \ldots \]

- Minimal complete basis of dimension-6 operators has 59 independent operators (for one fermion family)
  - Allows to include (and calculate) higher order corrections
  - Allows consistent treatment of all measurements
  - SM precision observables
  - Higgs rate measurements
  - Higgs differential distributions and angular correlations (the coupling tensor structure is naturally included)
  - Anomalous non-Higgs coupling measurements
  - Systematic and coherent approach to organize the expansion in ratio of the momentum over the new physics scale $\Lambda$

- Basis choice is not unique $\rightarrow$ need “rotation” functions
EFT challenges

• What about light BSM particles?
  Complementary approach between
  • EFT measurements and
  • analysis in specific BSM benchmark models (e.g. MSSM) with light degrees of freedom
EFT challenges

- What about light BSM particles?

- EFT approach is “theory” friendly
  - Everything emerges from one Lagrangian
  - Experimental analysis will have to grow in order to take the full variability of the EFT approach into account:
    - simultaneous rate and differential measurements in several observables
  - A simple $\kappa$-like scaling of the SM analysis is not possible, as signal (and background) acceptances can change with modified kinematic distributions
EFT challenges

- What about light BSM particles?
- EFT approach is “theory” friendly
- Need to understand how to simplify EFT
  - Models need to be both
    - Sufficiently general and
    - Practically feasible to fit

\[ \mu = \kappa^2 \]
\[ \kappa_v, \kappa_F \]
\[ \kappa_g, \kappa_\gamma \]
\[ \lambda_{WZ} \]
\[ \lambda_{ud} \]
\[ \lambda_{lq} \]
Generic coupling models

\[ 8(EWPD) + 3(aTGC) + 8(\text{Higgs}) \text{?} \]
59 EFT dim-6 operators
EFT challenges

• What about light BSM particles?

• EFT approach is “theory” friendly

• Need to understand how to simplify EFT

• Full EFT aware theory tool chain will be needed
  • MC generators for signal AND background
    (e.g. MG5_aMC@NLO)
  • (N)NLO calculations for signal and background
    (e.g. HAWK, HIGLU)
  • BRs
    (e.g. eHDECAY)
  • “Rotations” between different EFT basis choices
  • Predictions should recover the best known SM predictions
    (including all higher order QCD and EWK corrections) in the
    SM limit
Summary

- $\kappa$-framework did good job for Run 1 for the searches for deviations in Higgs couplings
  - do we want to (can we?) do something similar for differential distributions?

- Spin/CP benchmarks allowed to characterize the observed particle to be very likely Spin 0

- For Run 2, the EFT approach offers the possibility of
  - Precision BSM measurements
  - Consistent treatment of observables, also outside the Higgs sector, within one BSM theory framework
  - Especially combination with electroweak precision data and aTGC measurements
    → need coherent approach with LHC EW WG

- And don't forget: theory systematics are crucial!
Many thanks to the theory conveners and theory colleagues of the LM group! Their inputs made the ATLAS+CMS Higgs property measurements possible!