Higgs self-coupling: *Experimental vision*

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on behalf of the ATLAS and CMS collaborations

Ultimate Precision at Hadron Colliders
2nd of December 2019
Higgs potential: $V(\Phi) = \frac{1}{2} \mu^2 \Phi^2 + \frac{1}{4} \lambda \Phi^4$

Approximation around the v.e.v:

$V(\Phi) \approx \lambda v^2 h^2 + \lambda vh^3 + \frac{1}{4} \lambda h^4$

mass term self-coupling terms

$\lambda$ known from v.e.v and Higgs mass: $\lambda = \frac{m_H^2}{2 \cdot v^2} \approx 0.13$

BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- no quartic terms considered here
Self-couplings through di-Higgs measurements
Di-Higgs production at hadronic colliders (1)

- Main production mode: ggF
- Rare process of the Standard Model
  - destructive interference between triangle and box diagrams
  - $\sigma(HH)/\sigma(H) = 0.1\%$

For those results, state of the art NNLO calculation with finite $m_t$ effects at NLO
  - -8% wrt Yellow Report 4, used in previous projections
Di-Higgs production at hadronic colliders (2)

♦ Self-couplings through
  - **total** HH cross section
  - **differential** cross section $d\sigma/dm_{HH}$

![Diagrams showing self-couplings through total and differential cross sections.](diagrams.png)

![Graphs showing HH production at 14 TeV LHC at (N)LO in QCD.](graphs.png)
Di-Higgs production at hadronic colliders (3)

- Sensitivity to $\kappa_\lambda$ directly related to the acceptance, so to the $m_{HH}$ shape

- NB: most analyses optimised for $\kappa_\lambda=1$
Many decay channels!

In practice consider channels with $b\bar{b}$ (BR = 59%) to maximise the rate.
Summary of channels/methods for HL-LHC studies:

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>extrapolation</td>
<td>parametric</td>
</tr>
<tr>
<td></td>
<td>Largest BR ☻</td>
<td>Large multijet and tt bkg ☹</td>
</tr>
<tr>
<td>bbττ</td>
<td>extrapolation</td>
<td>parametric</td>
</tr>
<tr>
<td></td>
<td>Sizeable BR ☻</td>
<td>Relatively small bkg ☻</td>
</tr>
<tr>
<td>bbγγ</td>
<td>smearing</td>
<td>parametric</td>
</tr>
<tr>
<td></td>
<td>Small BR ☹</td>
<td>Good diphoton resolution ☻ ☻</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relatively small bkg ☻</td>
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<tr>
<td>bbVV</td>
<td>parametric</td>
<td>parametric</td>
</tr>
<tr>
<td>(→ lνlν)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large BR ☻</td>
<td>Large bkg ☹</td>
</tr>
<tr>
<td>bbZZ</td>
<td>parametric</td>
<td>parametric</td>
</tr>
<tr>
<td>(→ 4l)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very small BR ☹</td>
<td>Very small bkg ☻</td>
</tr>
</tbody>
</table>

Benefit from **performance** work of Technical design reports

New analyses, either
- **extrapolations** from Run-2 analyses
- dedicated studies with **smeared/parametric detector response**, corresponding to pile-up of 200
Run-2 results

**ATLAS**

- $\sigma_{ggF}^{SM} (pp \to HH) = 33.5 \text{ fb}$
- Expected limit on $\sigma(HH)/\sigma(H) = HH)$: $10*SM$
  
  - $-5.0 < \kappa_\lambda < 12.0$ at 95% CL

**CMS**

- Expected limit on $\sigma(HH)$: $12.8*SM$
  
  - $-7.1 < \kappa_\lambda < 13.6$ at 95% CL
♦ **Upgrades** of ATLAS and CMS to cope with aging, pile-up, radiation
♦ **2017-2019:** >4500 pages of Technical Design Reports
♦ Outcome of TDRs: current resolutions/efficiencies could be kept at HL-LHC!
♦ Example for ATLAS HH $\rightarrow b\bar{b}\gamma\gamma$ analysis
  - Electromagnetic calorimeter
  - Inner Tracker

<table>
<thead>
<tr>
<th></th>
<th>significance [$\sigma$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip TDR</td>
<td>1.05</td>
</tr>
<tr>
<td>LAr TDR</td>
<td>1.29</td>
</tr>
<tr>
<td>Pixel TDR</td>
<td>1.51</td>
</tr>
</tbody>
</table>

♦ Systematic uncertainties: common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC stat uncertainties neglected
Di-Higgs search, methods

♦ General analysis strategy:
  - candidates mass consistent with SM Higgs boson
  - multivariate methods to reject background
  - use $m_{HH}$ when possible

♦ A few examples:

♦ NB: some inputs or systematics with large unknowns
  - multijet bkg modelling for $HH \rightarrow b\bar{b}b\bar{b}$
  - $\tau$ fake-rate
  - …

⇒ room for improvement
Extrapolation from Run-2 analysis
- fit of $m_{4j}$ distribution
- $p_T^{jet} > 40$ GeV, different thresholds tested

Systematics
- dominated by multijet data-driven model
- conservative assumption: Run-2 systematics used

Significance:
1.4/0.61σ without/with syst
SM signal + BSM benchmark points

Resolved and boosted b-jets

- boosted topologies more sensitive to BSM scenarios where high $m_{HH}$ is enhanced

Resolved:

- $p_T > 45$ GeV, different thresholds tested
- BDT against multijet bkg + $t\bar{t}$ and single-Higgs

Small uncertainty considered for multijet background

Significance:

1.2σ wo/syst

0.95σ w/ syst
♦ **Extrapolation** from Run-2 analysis

♦ Three signal regions:
  - $\tau_{\text{lep}} \tau_{\text{had}}$ (Single Lepton Trigger)
  - $\tau_{\text{lep}} \tau_{\text{had}}$ (Lepton Tau Trigger)
  - $\tau_{\text{had}} \tau_{\text{had}}$ (Single Tau Trigger and Di-Tau Trigger)

♦ **BDT output** used as final discriminant
  - binning adapted to higher statistics

♦ Limit on $\kappa_{\lambda}$: LTT category not included and dedicated BDT trained on $\kappa_{\lambda} = 20$

♦ **Different assumptions** for systematics
  - from current to baseline for HL-LHC

♦ **Significance:**
  - $2.5/2.1\sigma$ without/with syst
3 categories: $\mu h$, $e h$, $\tau h$

Use of a Deep Neural Network
- 27 basic + 21 reconstructed + 4 global features
- deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

Simultaneous fit of the NN output for the 3 decay channels
- discriminant binned per decay channel via adaptive binning

Significance: $1.6/1.4\sigma$ without/with syst
Dedicated analysis with smearing functions: upgraded detector geometry and performance functions
- $m_{\gamma\gamma}$ resolution $\sim 1.6$ GeV

Dedicated BDT trained to remove continuum background and main single-Higgs background ($ttH$)

Limit on $\kappa_\lambda$: use of the $m_{b\bar{b}\gamma\gamma}$ distribution for events with $123 < m_{\gamma\gamma} < 127$ GeV

Systematics: very small impact in general

Significance: $2.1/2.0\sigma$ without/with syst
Dedicated BDT to reject $t\bar{t}H$
- 75% reduction for 90% signal efficiency

Classification of events based on $M_x = m_{jj\gamma\gamma} - m_{\gamma\gamma} - m_{jj} + 250$ GeV into low and high mass categories

MVA event categorisation BDT to separate background and HH signal into medium (MP) and high (HP) purity

Fit of $m_{\gamma\gamma}$ x $m_{jj}$

Significance: 1.8/1.8σ without/with syst
- difference with ATLAS partly due to $m_{\gamma\gamma}$ resolution
Optimised on WW, but ZZ signal included for the results

Large irreducible backgrounds: \( \bar{t}t \), DY

**Neural Network** discriminant
- 9 input angular and mass variables
- signal extracted from the NN output (3 categories \( ee \), \( \mu\mu \), \( e\mu \))

**Results:** \( 0.6\sigma \) significance
Very rare but clean final state, yet unexplored at the LHC

Powerful $H \rightarrow 4\ell$ signature $\Rightarrow$ single Higgs dominant background

Select events with $m_{4\ell}$ compatible with $m_H$

Counting experiment with events around $m_H$

~1 signal event after selection
  - $S/B \sim 0.1$

Results: $0.4\sigma$ significance
Combined results (1)

- **Expected significance** (SM) with and without systematics at HL-LHC

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \to bbbb$</td>
<td>1.4</td>
<td>1.2</td>
<td>0.61</td>
<td>0.95</td>
</tr>
<tr>
<td>$HH \to b\bar{b}\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>$HH \to b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}VV(l\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}ZZ(4l)$</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>combined</td>
<td>3.5</td>
<td>2.8</td>
<td>3.0</td>
<td>2.6</td>
</tr>
</tbody>
</table>

- **4σ** expected with ATLAS+CMS!

- **Measurement of $\mu$ (SM signal injected):**
  - $\delta\mu/\mu \sim 25\%$ (30%) without (with) systematics

- **$\mu = 0$ (no SM HH signal) excluded at 95% CL**

- **Measurement of $\kappa$:**
  - 68% CI: [0.5; 1.5]
  - 2$^{nd}$ minimum excluded at 99.4% CL thanks to the $m_{HH}$ shape information
♦ Comparison of negative log-likelihood ratios:

- **ATLAS and CMS**

  - **3000 fb⁻¹ (14 TeV)**

  ![Graph showing -2ln(L) vs k_λ](image)

  - **HL-LHC prospects**
  - **-2ln(L)**
  - **k_λ**
  - **95%**
  - **68%**

  - **b±bb±**
  - **b±ττ**
  - **bbVV(lfv)**
  - **bbγγ**
  - **bbZZ⁺(4l)**
  - **ATLAS**
  - **CMS**

  - Difference on 2⁰ minimum mainly from the b±γγ channel:
  - 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6
  - (while this low-m_{HH} category has no effect around 1)

  - CMS slightly better below 1: b±bb± + other smaller channels
Combined results (3)

- 68% CI, channel by channel
- Dashed line = no ATLAS analysis, using value from CMS (as for Higgs couplings)

\[ \kappa \lambda \]

- Measured with a precision of 50%
♦ **Extrapolation** of ATLAS HL-LHC results to HE-LHC
  - scale cross-section to 27 TeV (*4) and luminosity to 15 ab⁻¹ (*5), **no systematic uncertainties**
  - $b\bar{b}\tau\tau$ channel: significance: 10.7σ, precision on $\kappa_\lambda$: 20%
  - $b\bar{b}\gamma\gamma$ channel: significance: 7.1σ, precision on $\kappa_\lambda$: 40%
    - pessimistic because analysis not optimised for measurement of $\kappa_\lambda$

♦ **Phenomenology study for $b\bar{b}\gamma\gamma$: 15% precision on $\kappa_\lambda**
  - realistic detector performance
  - no pile-up considered
    - ($\mu=800-1000$)

♦ **Combination of channels**: $\kappa_\lambda$ could be measured with a 68% CI of 10 to 20%
Possible improvements

♦ Analyses extrapolated from Run-2:
  – for the moment not aiming for $\kappa_\lambda$ measurement
    (eg no use of $m_{HH}$ categories)
♦ Dedicated HL-LHC analyses:
  – optimised for HH production, not always for $\kappa_\lambda$
  – eg ATLAS vs CMS HH $\rightarrow$ $b\bar{b}\gamma\gamma$
♦ Improvement of background modelling
  – eg ATLAS HH $\rightarrow$ $b\bar{b}b\bar{b}$, significance $1.4\sigma \rightarrow 0.61\sigma$
♦ Improvement of signal yields
  – object efficiencies
  – trigger
♦ Adding new variables and improved MVA techniques (DNN, ...)
Self-couplings through single-Higgs measurements
Single-Higgs, introduction

- Single-Higgs production: Higgs self-interaction only via one-loop corrections (ie two loop-level for ggF)
- $\kappa_\lambda$-dependent corrections to the tree-level cross-sections
  - valid for $|\kappa_\lambda| < 20$
  - production mode
    - eg for $\kappa_\lambda = 2 \sigma(pp\to t\bar{t}H)$ modified by 3%
  - kinematics properties of the event
    - eg $p_T^{Higgs}$ for $t\bar{t}H$ and VH
- Also effects Higgs boson decay BR
Run-2 result using coupling measurements

Combined fit result ($\kappa_\lambda$ only variation):

$$\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5} \text{ (stat.)}^{+1.2}_{-1.2} \text{ (exp.)}^{+0.7}_{-0.5} \text{ (sig. th.)}^{+0.6}_{-1.0} \text{ (bkg. th.)} \text{ [observed]}$$

$$\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0} \text{ (stat.)}^{+3.0}_{-1.7} \text{ (exp.)}^{+1.8}_{-1.2} \text{ (sig. th.)}^{+1.7}_{-1.1} \text{ (bkg. th.)} \text{ [expected]}$$

Similar sensitivity between single-Higgs and di-Higgs with the current luminosity
Method applied to $\bar{t}tH(\rightarrow \gamma\gamma)$ differential cross-section measurement:

- $68\%$ CI: $-1.9 < \kappa_\lambda < 5.3$ if only $\kappa_\lambda$ varied
- First test with experimental “data”, more channels to be added
Global fits of single-Higgs inclusive couplings and \(ttH\) differential measurements
- for HL-LHC and HE-LHC

Different BSM scenarios
- only \(\kappa_\lambda\) can be varied (dotted line)
- EFT framework (solid line)

Different scenarios for systematics (bands)

Biggest impact from diff. cross-section

Improvement of di-Higgs direct measurements for variations of \(\kappa_\lambda\) only

HL-LHC: 68% CI (optimistic systematics):
- \(-0.1 < \kappa_\lambda < 2.3\) if only \(\kappa_\lambda\) varied
- \(-2 < \kappa_\lambda < 3.9\) for global fit
Summary
Summary of HL(HE)-LHC prospects
Conclusion

♦ State-of-the art experimental studies on HH measurements
  - coherent results by ATLAS and CMS
  - went from ~2σ last year to a combined significance of 4σ!
    • first real measurements possible, eg precision on $\kappa_\lambda$: 50%
  - much room for improvement

♦ Nice developments on single-Higgs constrains
  - differential cross-sections, global fits

♦ Estimates of sensitivity at HE-LHC
  - experimental and phenomenology

♦ HL-LHC measurement of the Higgs self-coupling will remain the most precise until the high-energy phase of the next generation of Future Colliders around 2050

♦ More on the global interpretation in the talk by C. Grojean tomorrow
References

♦ Measurement prospects of the pair production and self-coupling of the Higgs boson with the ATLAS experiment at the HL-LHC, ATL-PHYS-PUB-2018-053
♦ Prospects for HH measurements at the HL-LHC, CMS-FTR-18-019
♦ Higgs Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-04
♦ Constraint of the Higgs boson self-coupling from Higgs boson differential production and decay measurements, ATL-PHYS-PUB-2019-009
♦ Constraints on the Higgs boson self-coupling from the combination of single-Higgs and double-Higgs production analyses performed with the ATLAS experiment, ATLAS-CONF-2019-049
♦ Expected performance of the ATLAS detector at the High-Luminosity LHC, ATL-PHYS-PUB-2019-005
♦ Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC, CMS-NOTE-2018-006
♦ Combination of searches for Higgs boson pairs in pp collisions at $s\sqrt{=}13$ TeV with the ATLAS detector HDBS-2018-58
♦ Combination of searches for Higgs boson pair production in proton-proton collisions at $\sqrt{s}= 13$ TeV HIG-17-030
Di-Higgs production

- Only ggF production considered at present
Single-Higgs couplings (1)

♦ Higgs self-interaction via one-loop corrections of the single-Higgs production
  - $\kappa_\lambda$-dependent corrections to the tree-level cross-sections

♦ pp colliders:

  ex. for $\kappa_\lambda = 2$:
  - $\sigma(pp \to t\bar{t}H)$ modified by 3%
  - $\sigma(ee \to ZH)$ modified by 1%
Single-Higgs couplings (2)

♦ More global view: SMEFT\textsubscript{ND}

♦ Deformation of the single-Higgs + EW processes:

\[
\text{SMEFT}_{\text{ND}} \equiv \left\{ \delta m, c_{gg}, \delta c_{\gamma \gamma}, c_{\gamma Z}, c_{ZZ}, c_{\square}, \delta y_t, \delta y_c, \delta y_b, \delta y_\tau, \delta y_\mu, \lambda_\gamma \right\} \\
+ \left\{ (\delta g_{\lambda}^{Z_u})_{q_i}, (\delta g_{\lambda}^{Z_d})_{q_i}, (\delta g_{\lambda}^{Z_\ell})_{\ell}, (\delta g_{\lambda}^{Z_{\ell \ell}})_{q_i}, (\delta g_{\lambda}^{Z_{\ell \ell}})_{\ell_i}, (\delta g_{\lambda}^{Z_{\ell \ell}})_{\ell} \right\} \quad q_1 \neq q_3, \ell = e, \mu, \tau
\]

+ correction to the trilinear Higgs self-coupling: \( \delta \kappa_\lambda = \kappa_\lambda - 1 \)

♦ Can also consider the effect of \( \delta \kappa_\lambda \) on the other parameters

- a few examples:

![Higgs couplings variation along the flat direction](1704.01953)

- could also affect EW precision observables at NNLO
Di-Higgs at Future Colliders

**Graph:**

- HL-LHC
- HE-LHC
- FCC-hh

**Legend:**

- $\sigma_{\text{HHC}}$ (fb)
- $\sqrt{s}$ [TeV]

**Axes:**

- $\sigma$ [fb]
- $\sqrt{s}$ [GeV]

**Points:**

- FCC-ee, ILC, CECP
- FCC-ee, ILC, CLIC
- CLIC

**Curves:**

- ZHH
- HH$\nu_e\bar{\nu}_e$
**Di-Higgs production: ee colliders**

- **Main production modes:** \(ZHH\) and \(\nu\bar{\nu}HH\)
  - \(ZHH\)
  - VBF \(\nu\bar{\nu}HH\)

- **Self-couplings through HH cross-section at different \(\sqrt{s}\) + production modes + \(m_{HH}\)**
  - \(ZHH\) stronger constraints for \(\kappa_\lambda > 1\)
  - \(\nu\bar{\nu}HH\) stronger constraints for \(\kappa_\lambda < 1\)
HL-LHC, ‘alternative’ methods

- HH→b¯bWW(→lllv):
  Introduce two new variables
  - Topness (T): degree of consistency with di-lepton tt production
  - Higgsness (H): compatibility with Higgs and W masses

- HH→b¯bγγ:
  Bayesian optimisation and BDT compared to cut-based

- Could enhance the significance from 0.6 to 1.4-3.0σ
  - effect of pile-up on those variables?

- No pile-up included, but shows the potential of sophisticated techniques: could achieve up to 4σ
  - illustrated in the YR with ATLAS and CMS using MVA techniques
6 HOW TO APPROACH SYSTEMATICS

* The large HL-LHC dataset will enable accurate measurements and unprecedented sensitivity to very rare phenomena.

* In several analyses **systematic uncertainties will become a limiting factor**

* Several sources of systematics to consider:
  - Detector driven
  - Data statistics in control regions
  - Theory normalization and modeling
  - Luminosity
  - Method uncertainties
  - MC statistics

* Synergy of ATLAS and CMS in many physics projections and complexity of the problem required development of a **common set of guidelines**

  * Focus on experimental systematics that are most important for the projection studies we need (can't be comprehensive!)
    * Jet Energy Scale/Resolution, MET, B-tagging, Tau-ID, and many more...

* Evaluation of theory uncertainties improvement
7 COMMON GUIDING PRINCIPLES FOR YR18

* Statistics-driven sources: data $\rightarrow \sqrt{E}$, simulation $\rightarrow 0$
  * account for larger data sample statistics available
  * to better understand full potential of HL-LHC
* Theory uncertainties typically halved
  * applies to both normalization (x-sec) and modeling
  * due to higher-order calculation and PDF improvements
* Uncertainties on methods kept as latest published results
  * Trigger thresholds same or better(lower) than current
  * assumption that pile-up effects are compensated by detector upgrades improvement and algorithmic developments
* Intrinsic detector limitations stay ~constant
  * usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
  * detector understanding and operational experience may compensate for e.g. detector aging
  * harmonized definition of « floor » values for experimental systematics
* Luminosity uncertainty 1%
Whenever feasible present results as

\[ \text{value} \pm \text{stat} \pm \text{syst}\_\text{exp} \pm \text{syst}\_\text{theory} \pm \text{syst}\_\text{lumi} \]

Baseline scenario defined as:

* **YR18(S2):** based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

### Summary (simplified) table of some values of experimental systematics harmonized between ATLAS & CMS

<table>
<thead>
<tr>
<th>Object</th>
<th>WP</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>reco+ID(+ISO)</td>
<td>0.1%(0.5%)</td>
</tr>
<tr>
<td>Electrons</td>
<td>reco+ID+ISO</td>
<td>0.5%</td>
</tr>
<tr>
<td>Taus</td>
<td>reco+ID+ISO</td>
<td>5%(as in Run2)</td>
</tr>
<tr>
<td>B-jet tag</td>
<td>30&lt;pt&lt;300GeV (pt&gt;300GeV)</td>
<td>~1%(2-6%)</td>
</tr>
<tr>
<td>c-jet tag</td>
<td></td>
<td>~2%</td>
</tr>
<tr>
<td>Light jets</td>
<td>L/M/T WP</td>
<td>5/10/15%</td>
</tr>
<tr>
<td>JES</td>
<td>abs/rel scale</td>
<td>0.1-0.2%(0.1-0.5%)</td>
</tr>
<tr>
<td>JEC</td>
<td>Pile-Up</td>
<td>0-2%</td>
</tr>
<tr>
<td>JEC</td>
<td>Flavor</td>
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<tr>
<td>Integrated Luminosity</td>
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<td>1%</td>
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