New Physics in Higgs Pair Production

Ramona Gröber in collaboration with M. Mühleitner and M. Spira, arXiv: 1602.05851
and A. Agostini, G. Degrassi and P. Slavich, arXiv: 1601.03671

10.05.16
Can we see New Physics for the first time in $HH$ production?

Higher order corrections to MSSM $HH$ production
HIGGS PAIR PRODUCTION

- Higgs pair production gives access to trilinear Higgs self-coupling
- Small cross sections, hence high luminosities are required
- Gluon fusion is dominant process → in the rest of my talk I will only refer to it

Ramona Gröber – New Physics in Higgs Pair Production
Shift in the trilinear Higgs coupling.
In most models: also shift in the other couplings.
Exception e.g. singlet with zero VEV [ew baryogenesis scenario, see e.g. Curtin, Meade, Yu ’14]

Shift in the other Higgs boson couplings.

Additional Higgs bosons.
E.g. in SUSY, [MSSM: Djouadi, Kilian, Mühlleitner, Zerwas ’99; ... NMSSM: Ellwanger ’13; Nhung, Mühlleitner, Streicher, Walz ’13]

Two Higgs Doublet Model [Baglio, Eberhardt, Nierste, Wiebusch ’14; Arhrib, Benbrik, Chen, Guedes, Santos ’09; ...]
or non-minimal Composite Higgs Models

Additional particles in the loop.
E.g. in SUSY or Composite Higgs Models [Dawson, Ismail, Low ’15; MSSM: Batell, McCullough, Stolarski, Verhaaren ’15, ... CHM: Gillioz, RG, Grojean, Mühlleitner, Salvioni ’12; Dolan, Englert, Spannowsky ’12]

Novel couplings.
E.g. in Composite Higgs Models and Little Higgs Models [CHM: RG, Mühlleitner ’10; Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer ’12; LHM: Dib, Rosenfeld, Zerwekh ’05]

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HOW CAN NEW PHYSICS MODIFY $HH$ PRODUCTION?

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But could we see new physics for the first time in Higgs pair production?
This question can of course only be answered in concrete models.

Resonant production in $s$ channel: If new resonance predominantly decaying to Higgs bosons
$\rightarrow$ large increase of cross section
$\rightarrow$ distinction from SM possible

Here other case: No $s$ channel resonance, just coupling modifications and new couplings
$\rightarrow$ Composite Higgs Models.
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Model:

- Higgs boson as pseudo-Goldstone boson of $SO(5)/SO(4)$
- MCHM10 with vector-like top and bottom partners transforming in one (10) representation
- Parameter $\xi \in [0, 1]$ ($\xi = v^2/f^2$ with global symmetry breaking scale $f$) describes departure from SM
Consider two final states: \( b\bar{b}\tau^+\tau^- \) and \( b\bar{b}\gamma\gamma \)

**Indirect tests:**
EWPT, \(|V_{tb}| > 0.92\)

**Higgs couplings:**
projected sensitivities

**Direct searches:**
projected sensitivities for vector-like quarks

**Valid points:**
\[ S_{SM} \pm \beta \sqrt{S_{SM}} \leq S \]

**S** = \( \sigma \) \( BR \) \( \mathcal{L} \) \( A \)

Can we see New Physics for the first time in \( HH \) production?
Can we see New Physics for the first time in $HH$ production?

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Higher Order Corrections to BSM Higgs Pair Production
SM:
- NLO QCD corrections to gluon fusion process are large $K = \frac{\sigma_{NLO}}{\sigma_{LO}} \sim 1.7$
- Many new developments in the recent years

BSM:
NLO QCD corrections available in
- Higgs singlet model
- 2-Higgs doublet model
- SM with dim-6 operators
- Composite Higgs Models
- MSSM: top loops
- **MSSM** and NMSSM: top, stop and sbottom loops

Plots for NLO QCD corrections of Composite Higgs Model and SM with dim-6 operators in backup
**MSSM SQCD CORRECTIONS**

**LET approximation:**
Useful tool for higher order corrections → Loop-induced gluon fusion process can be replaced by effective coupling.
Corresponds to zeroth order coefficient in expansion in small external momenta.

**Meaning:** Valid for $\hat{s}, \hat{t}, \hat{u}, m_H^2 \ll m_{\text{loop}}^2$!
→ Can be applied as long as stop masses are not very light!

Triangle form factors can be borrowed from single Higgs production [Anastasiou et al '06, Aglietti et al '06, Mühlleitner, Spira '06, Bonciani, Degrassi, Vicini '07]

NLO box form factors computed from derivatives of the field-dependent contributions of top and stops in the gluon self-energy at 2-loop

$$\mathcal{M}_{ij} \propto \frac{\partial \Pi^g_t(0)}{\partial H_i \partial H_j}$$

with e.g.

$$m_t = y_t H_u, \quad m_{t_{1/2}}^2 = \frac{1}{2} \left( m_{Q_L}^2 + m_{t_R}^2 + 2y_t^2 H_u^2 \pm \sqrt{(m_{Q_L}^2 - m_{t_R}^2)^2 + 4y_t^2 (A_t H_u + \mu H_d)^2} \right),$$

$$\sin \theta_t = \frac{2y_t (A_t H_u + \mu H_d)}{m_{t_{1/2}}^2 - m_{t_{1/2}}^2}.$$
For $m_b = 0$, contribute only via $D$-terms.

Cannot be computed via LET since there are diagrams containing sbottom, gluinos and bottoms. [Degrassi, Slavich '10]

→ Computed as zeroth order coefficient of an asymptotic expansion for $m_b = 0$
RESULTS

[Agostini, Degrassi, RG, Slavich '16]

Higher order corrections to MSSM HH production

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CONCLUSION

- Higgs pair production not only interesting for a measurement of trilinear Higgs self-coupling but New Physics can modify it in many different ways.
- In certain models New Physics might even be seen for the first time in Higgs pair production.
- SQCD corrections in the MSSM: Non-negligible effect for stop masses below TeV scale.
Higgs pair production not only interesting for a measurement of trilinear Higgs self-coupling but New Physics can modify it in many different ways.

In certain models New Physics might even be seen for the first time in Higgs pair production.

SQCD corrections in the MSSM: Non-negligible effect for stop masses below TeV scale.

Thanks for your attention!
Top quark $t$ can mix with fermionic resonances of the strongly-interacting sector ("top partner" $T$)

- Higgs boson is pseudo-Goldstone boson of spontaneous symmetry breaking of global symmetry at scale $f$
  Here: $SO(5) \times U(1)/SO(4) \times U(1)$

- global symmetry explicitly broken $\rightarrow$ Higgs potential generated by quantum corrections
Vector boson couplings to Higgs boson modified by $\xi = \frac{v^2}{f^2}$

$$g_{hVV} = g_{hVV}^{SM} \sqrt{1 - \xi}, \quad g_{hhVV} = g_{hhVV}^{SM} (1 - 2\xi)$$

Fermion couplings and Higgs self-couplings depend on embedding of fermions.

Consider three models here:

- **Pure Higgs non-linearities**

  MCHM4: $g_{hf\bar{f}/hhh} = g_{hf\bar{f}/hhh}^{SM} \sqrt{1 - \xi}$, $g_{hhf\bar{f}} = -\xi \frac{m_f}{v^2}$

  MCHM5: $g_{hf\bar{f}/hhh} = g_{hf\bar{f}/hhh}^{SM} \frac{(1 - 2\xi)}{\sqrt{1 - \xi}}$, $g_{hhf\bar{f}} = -4\xi \frac{m_f}{v^2}$

- **Fermionic resonances**

  Explicit breaking of global symmetry by linear couplings of SM fermions to strong sector

  $$\mathcal{L} = \left( \lambda_L \bar{q}_L Q_R + \lambda_R \bar{T}_L t_R \right)$$

  Leads to mixing of elementary quark with strong sector, mass generation for the top quark.

- **Fermions of strong sector in full multiplet $\psi$ of $SO(5)$, e.g. 4, 5, 10, 14 -plets**

  MCHM10: Antisymmetric representation (10) contains both bottom and top partner.
### Model with Pure Higgs Non-linearities: Results

<table>
<thead>
<tr>
<th>Model</th>
<th>$\xi$ Value</th>
<th>$\sigma_{b\bar{b}\gamma\gamma}$ [fb]</th>
<th>$\Delta_{3\sigma}$</th>
<th>$\sigma_{b\bar{b}\tau+\tau-}$ [fb]</th>
<th>$\Delta_{3\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCHM4</td>
<td>$\xi = 0.12$ (LHC20.3)</td>
<td>0.119</td>
<td>no</td>
<td>3.26</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>$\xi = 0.076$ (LHC300)</td>
<td>0.114</td>
<td>no</td>
<td>3.13</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>$\xi = 0.051$ (LHC3000)</td>
<td>0.112</td>
<td>no</td>
<td>3.07</td>
<td>no</td>
</tr>
<tr>
<td>MCHM5</td>
<td>$\xi = 0.15$ (LHC20.3)</td>
<td>0.315</td>
<td>yes</td>
<td>5.35</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>$\xi = 0.068$ (LHC300)</td>
<td>0.175</td>
<td>no</td>
<td>3.96</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>$\xi = 0.015$ (LHC3000)</td>
<td>0.119</td>
<td>no</td>
<td>3.14</td>
<td>no</td>
</tr>
</tbody>
</table>

$\rightarrow$ MCHM4:

we cannot expect to see any significant deviation in $HH$ production

$\rightarrow$ MCHM5:

we will first see new physics in form of deviations in Higgs coupling measurements
Feynman diagrams for Higgs pair production in Composite Higgs Models.
Details of top-partner spectrum only show small effect on invariant Higgs mass distribution.
**Higher Order Corrections**

**Gluon fusion:**
- LO cross section known exactly in full mass dependence
- NLO QCD corrections known in the LET approximation \( \sqrt{s} \ll m_t \): \( K = \sigma_{NLO}/\sigma_{LO} \sim 1.7 \)
- Estimation of finite mass effects: \( \mathcal{O}(10\%) \)
- Real contributions in full top mass dependence
- Full NLO computation \( \rightarrow \) top mass effects are \(-14\%\)
- Threshold resummation at NNLL point to \( M_{HH}/2 \) as optimal scale
- NNLO QCD corrections in LET: increase of \( \mathcal{O}(20\%) \)
- Top mass effects of NNLO QCD corrections are \( \mathcal{O}(5\%) \)

**BSM extensions:**
- Singlet-extended SM [Dawson, Lewis '15], 2-Higgs Doublet Model [Hespel, Lopez-Val, Vryonidou '14], SM with dimension six operators [RG, Mühlleitner, Spira, Streicher '15], MSSM [Dawson, Dittmaier, Spira '98; Agostini, Degrassi, RG, Slavich'16] and NMSSM [Agostini, Degrassi, RG, Slavich'16], Composite Higgs Model (with vector-like quarks) [RG, Mühlleitner, Spira'16]
- All at NLO QCD in the LET approximation (2-Higgs doublet model with exact real emission)
Parameters defined as on-shell parameters.

\[\tan \beta = 10, \quad m_A = 500 \text{ GeV}, \quad \mu = -400 \text{ GeV}, \quad M_3 = 1500 \text{ GeV},\]

\[X_t = 2 M_S, \quad m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} = M_S,\]
SQCD CORRECTIONS: BOX FORM FACTOR

[Agostini, Degrassi, RG, Slavich '16]

\[ F^{hh} \]

\[ M_S \ [\text{GeV}] \]

1-loop, top only

1-loop, top+SUSY

2-loop, top only

2-loop, top+SUSY
Non-linear effective Lagrangian

\[ \mathcal{L} = -m_t \bar{t} t \left( c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \frac{3M_h^2}{v} h^3 + \frac{\alpha_s}{\pi} G^{a \mu \nu} G^{a \mu \nu} \left( c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right) \]

- \( c_t \): Parameterizes deviations in the top-Yukawa coupling
- \( c_{tt} \): Effective coupling of two top quarks to two Higgs bosons
- \( c_3 \): Shift in Higgs self-coupling
- \( c_g \): Higgs gluon gluon coupling
- \( c_{gg} \): Higgs Higgs gluon gluon coupling
Computed in LET approximation.

- **Real corrections**: LO cross section factors out. Can be taken over from SM.
- **Virtual corrections**: Third diagram needs to be re-evaluated. At NLO in the matching condition no factorization of LO cross section for non-zero $c_g$ and $c_{gg}$.
- Results implemented in HPAIR [M. Spira's website], also for SILH Lagrangian (linearized)
Effect of dim-6 contributions on $K$-factor is $O($few%)
$K(pp \rightarrow hh + X)$
$\sqrt{s} = 14$ TeV
MCHM5

Plot for MCHM5 (pure Higgs non-linearities)