Pair production of beyond the Standard Model Higgs bosons

Ramona Gröber | 11.11.2016
Motivation

Higgs pair production in the SM
  Can it be measured?

New Physics in Higgs pair production
  Can we observe new physics in Higgs pair production?

Higher order corrections to Higgs pair production
  MSSM and SM + dim 6 operators
Higgs potential:

\[ V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]

unitary gauge: \[ \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \]

\[ \implies V(H) = \frac{1}{2} \mu^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^4}{8v^2} H^4 \]

- In SM Higgs self-couplings fixed by Higgs mass.
- Trilinear coupling accessible in Higgs pair production.
- Quartic Higgs self-coupling can be neither measured at the LHC nor at ILC/CLIC.

[CLIC Physics working group; Plehn, Rauch ’05; Djouadi, Kilian, Mühlleitner, Zerwas ’99; Binoth, Karg, Kauer, Rückl ’06]
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Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12
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Can the process even be measured?
Consider only largest production process: Gluon fusion (at $\sqrt{s} = 14$ TeV)

Production cross section small $\rightarrow$ at least use one $H \rightarrow b \bar{b}$

- $HH \rightarrow b \bar{b}b \bar{b}$: Overwhelmed by large QCD background [Baur, Plehn, Rainwater ‘03]
  Newer analysis: Possible with jet substructure techniques [Ferreira de Lima, Papaefstathiou, Spannowsky ’14; Wardrope et al. ’14; Behr et al. ’15]

- $HH \rightarrow b \bar{b}W^+W^-$ and $W \rightarrow \ell\nu\ell$: difficult because mass reconstruction only possible for one $H$ [Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira ’12]
  If one $W$ decays hadronically, it can become possible [Papaefstathiou, Yang, Zurita ’12]

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**Can we measure \( HH \) pair production?**

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Feasibility studies for $\sqrt{s} = 14$ TeV and $\int \mathcal{L} = 3000$ fb$^{-1}$:

ATLAS: $1.3\sigma$ signal significance for $b\bar{b}\gamma\gamma$ final state.

CMS: $1.9\sigma$ combination of $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$. 

[ATLAS-PHYS-PUB-2014-019]
[CMS PAS FTR-15-002]
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However, limits are and will be set on non-resonant and resonant BSM $HH$ pair production:

- **Non-resonant production:** $\mathcal{O}(50 - 100 \sigma_{SM})$ excluded
- **Limits on resonant production** $\sigma(pp \rightarrow X)BR(X \rightarrow hh)$ are $\mathcal{O}(10 \text{ fb} - 10 \text{ pb})$

Higgs pair production in the SM

Ramona Gröber – Pair production of beyond the Standard Model Higgs bosons
New Physics in Higgs Pair Production
HOW CAN NEW PHYSICS MODIFY $HH$ 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; ...]
  Singlet extended SM [Dawson, Lewis ’15; ...]
  or non-minimal Composite Higgs Models

- **Additional particles in the loop.**
  E.g. in SUSY or Composite Higgs Models [Dawson, Ismail, Low ’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]

- **Exotic decays of the Higgs bosons**
  E.g. invisible decays [Banerjee, Batell, Spannowsky ’16]
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But could we see new physics for the first time in Higgs pair production?
This question has to be answered in concrete models.

Obviously for resonant production in $s$ channel, with new resonance predominantly decaying to Higgs bosons this will be the case.

Here other case:
No $s$ channel resonance, just coupling modifications and new couplings → Composite Higgs Models.
COMPOSITE HIGGS MODELS (CHM)

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elementary particles

| gluon g | photon γ | W±, Z |

light, since pseudo-Goldstone boson

spin 0: $H$, ...

spin 1/2: $T$, $B$, $X^{5/3}$, ...

spin 1: $\rho$, $a$, ...

strongly interacting sector

- 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
Parametrization of 4 Goldstone bosons

\[ \Sigma(x) = \Sigma_0 e^{-iT^a h^a \sqrt{2}/f}, \quad \Sigma_0 = (0, 0, 0, 0, 1) \]

Description by non-linear \( \sigma \)-model

\[ \mathcal{L} = \frac{f^2}{2} (D_\mu \Sigma)^T (D^\mu \Sigma), \quad \text{in unitary gauge: } \Sigma = (0, 0, 0, \sin H/f, \cos H/f) \]

Leads to

\[ \mathcal{L} = \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{f^2}{4} \sin^2 \left( \frac{H}{f} \right) \left[ g^2 W^\mu W_\mu + \frac{g^2}{\cos \theta_W} Z^\mu Z_\mu \right] + \ldots \]

\[ \xi = \frac{v^2}{f^2} = \sin^2 \left( \frac{\langle H \rangle}{f} \right) \]

Gauge boson-Higgs couplings:

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

hff, hh, ... couplings depend on fermion embedding
Consider three models here:

- Pure Higgs non-linearities

\[
\text{MCHM4: } g_{hf\bar{f}/hhh} = g^{SM}_{hf\bar{f}/hhh} \sqrt{1 - \xi}, \quad g_{hhf\bar{f}} = -\xi \frac{m_f}{v^2}
\]

\[
\text{MCHM5: } g_{hf\bar{f}/hhh} = g^{SM}_{hf\bar{f}/hhh} \frac{(1 - 2\xi)}{\sqrt{1 - \xi}}, \quad g_{hhf\bar{f}} = -4\xi \frac{m_f}{v^2}
\]

- Fermionic resonances
  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

- explicit breaking of global symmetry
- 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.
Indirect tests: EWPT, $|V_{tb}| > 0.92$

Higgs couplings: projected sensitivities

Direct searches: projected sensitivities for vector-like quarks

Valid points:
$S_{SM} \pm \beta \sqrt{S_{SM}} \leq S$

Consider two final states: $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$

EWPTs from [Gillioz, RG, Kapuvari, Mühlleitner '14]
Higgs coupling sensitivity from [Englert, Freitas, Mühlleitner et. al'14]
Vector-like quarks, projected sensitivities $m \lesssim 1.5 \text{ TeV}$
Let's look at yet another model with more freedom...

→ MCHM4:
we cannot expect to see any significant deviation in $HH$ production

→ MCHM5:
we will first see new physics in form of deviations in Higgs coupling measurements

New Physics in Higgs pair production
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MCHM10:
Both top- and bottom-partners in only one 10-plet.
Model has more freedom, since bottom partners introduce parameter dependence in $h \to b\bar{b}$, $h \to \gamma\gamma$ and $gg \to h$ rates.
**RESULTS**

[RG, Mühleitner, Spira '16]

New Physics in Higgs pair production

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Details of top-partner spectrum only show small effect on invariant Higgs mass distribution.
Higher Order Corrections to BSM Higgs Pair Production
Higher order corrections to the SM cross section

- LO cross section known exactly in full mass dependence
- NLO QCD corrections
  Difficulty: Multi-scale problem \( m_t^2, \hat{s}, \hat{t}, \hat{u}, m_h^2 \).
- LET: \( K = \sigma_{NLO}/\sigma_{LO} \approx 1.7 \)
  LET approximation \( \rightarrow \) small external momenta \( \hat{s}, \hat{t}, \hat{u}, m_h^2 \ll m_t^2 \)

\[
\frac{1}{(p + q_i)^2 - m_t^2} \approx \frac{1}{p^2 - m_t^2} \left( 1 + \frac{2p \cdot q_i + q_i^2}{p^2 - m_t^2} + \ldots \right)
\]
LO cross section known exactly in full mass dependence

NLO QCD corrections
Difficulty: Multi-scale problem $m_t^2$, $\hat{s}$, $\hat{t}$, $\hat{u}$, $m_h^2$.

LET: $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$
LET approximation $\rightarrow$ small external momenta $\hat{s}$, $\hat{t}$, $\hat{u}$, $m_h^2 \ll m_t^2$

At LO, however,
\[
\frac{1}{(p + q_i)^2 - m_t^2} \approx \frac{1}{p^2 - m_t^2} \left( 1 + \frac{2p \cdot q_i + q_i^2}{p^2 - m_t^2} + \ldots \right)
\]

Higher order corrections to BSM Higgs pair production

Ramona Gröber – Pair production of beyond the Standard Model Higgs bosons
Higher order corrections to the SM cross section

- LO cross section known exactly in full mass dependence
  [Glover, van der Bij ’88; Plehn, Spira, Zerwas ’95]
- NLO QCD corrections
  Difficulty: Multi-scale problem $m_t^2, \hat{s}, \hat{t}, \hat{u}, m_h^2$.
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  \[
  \frac{1}{(p + q_i)^2 - m_t^2} \approx \frac{1}{p^2 - m_t^2} \left( 1 + \frac{2p \cdot q_i + q_i^2}{p^2 - m_t^2} + \ldots \right)
  \]

**Born-improved HEFT:**
LO cross section in exact top-mass dependence is factored out
$\rightarrow$ Used for BSM NLO calculations.
Higher order corrections to the SM cross section

- LO cross section known exactly in full mass dependence
  [Glover, van der Bij '88; Plehn, Spira, Zerwas '95]
- NLO QCD corrections
  Difficulty: Multi-scale problem $m_t^2, \hat{s}, \hat{t}, \hat{u}, m_h^2$.
  [Dawson, Dittmaier, Spira '98]
- LET: $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$
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  \[
  \frac{1}{(p + q_i)^2 - m_t^2} \approx \frac{1}{p^2 - m_t^2} \left( 1 + \frac{2p \cdot q_i + q_i^2}{p^2 - m_t^2} + \ldots \right)
  \]
- Full NLO computation $\rightarrow$ top mass effects are $-14\%$
  [Bobrowka, et al.'16; Johannes talk in Dec]
  [de Florian, Mazzitelli '13; Grigo, Melnikov, Steinhauser '14; Grigo, Hoff, Steinhauser '15; de Florian, Mazzitelli '15; de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16]
- Lot of recent progress in NNLO QCD corrections (of $\mathcal{O}(20\%)$)
  based on expansion in small external momentum
  [de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16]
Higher order corrections to the SM cross section

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      \]

- Full NLO computation $\rightarrow$ top mass effects are $-14\%$

- Lot of recent progress in NNLO QCD corrections (of $O(20\%)$) based on expansion in small external momentum

BSM NLO corrections:
- 2HDM [Hespel, Lopez-Val, Vryonidou '14], SM + dimension 6 operators [RG, Mühlleitner, Spira, Streicher '15], scalar singlet [Dawson, Lewis '15], composite Higgs models with and without fermionic resonances [RG, Mühlleitner, Spira '16], MSSM [QCD: Dawson, Dittmaier, Spira '98, SQCD: Agostini, Degrassi, RG, Slavich '16] and NMSSM [Agostini, Degrassi, RG, Slavich '16]
Top-loop contributions given in [Dawson, Dittmaier, Spira '98]

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

box form factors for stop contributions need to be computed

**LET approximation:**

NLO form factors (for CP-even Higgs bosons) computed from derivatives of the field-dependent contributions of top and stops in the gluon self-energy at 2-loop

\[
M_{ij} \propto \frac{\partial \Pi^{g}(0)}{\partial H_i \partial H_j}
\]

with

\[
m_t = y_t H_u , \quad \sin \theta_t = \frac{2y_t(A_t H_u + \mu H_d)}{m^2_{t_1} - m^2_{t_2}},
\]

\[
m_{t_{1/2}}^2 = \frac{1}{2} \left( m_{Q_L}^2 + m_{Q_R}^2 + 2y_t^2 H_u^2 \pm \sqrt{(m_{Q_L}^2 - m_{Q_R}^2)^2 + 4y_t^2 (A_t H_u + \mu H_d)^2} \right)
\]

**Validity:** \( \hat{s}, \hat{t}, \hat{u}, m_{H}^2 \ll m_{\text{loop}}^2 \)
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]

$\rightarrow$ Computed as zeroth order coefficient of an asymptotic expansion for $m_b = 0$
Results

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[Agostini, Degrassi, RG, Slavich '16]
Higher order corrections to BSM Higgs pair production

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Non-linear effective Lagragian

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

- \( c_t \): 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
Computation 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 $\mathcal{O}$ (few %)
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: Stops have non-negligible effect for masses below the TeV scale

SM + dim-6 operators: $K$ factor of SM good approximation.
Higgs pair production not only interesting for a measurement of trilinear Higgs self-coupling but New Physics can modify it in many different ways.

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SQCD corrections in the MSSM: Stops have non-negligible effect for masses below the TeV scale.

SM + dim-6 operators: $K$ factor of SM good approximation.

Thanks for your attention!
Parameters defined as on-shell parameters.

\[
\tan \beta = 10, \quad m_A = 500 \text{ GeV}, \quad \mu = -400 \text{ GeV}, \quad M_3 = 1500 \text{ GeV},
\]
\[
X_t = 2 M_S, \quad m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} = M_S,
\]

Leads to \(324 \text{ GeV} < m_{\tilde{t}_1} < 1326 \text{ GeV}\)
Plot for MCHM5 (pure Higgs non-linearities)

- Vector-like quarks contribute to the gluon self-energy at 2-loop.
- They couple however in the same way to gluons than the top quark.
- Modification only in the reducible double-triangle contribution.