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An Exploratory study of Higgs Pair Production

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Higgs Measurements

After LHC Run-1, the current data still shows large uncertainties.

The combined signal strength shows deviation from the SM value.
From the Higgs measurements, we understand the Higgs couplings information, i.e. Yukawa Coupling, Gauge Higgs Coupling.

How About the Higgs self coupling?
Higgs Boson Self Coupling : SM

Standard Model Higgs potential

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

\[ \text{EWSB} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\lambda}{2}} m_h h^3 + \frac{\lambda}{4} h^4 \]

\[ m_h = \frac{\lambda v^2}{2}, \quad v^2 = \frac{\mu^2}{\lambda} \]

\[ \lambda_{hh\bar{h}}^{(0,SM)} = \frac{3m_h^2}{v}, \quad \lambda_{hh\bar{h}h}^{(0,SM)} = \frac{3m_h^2}{v^2} \]
Higgs Boson Self Coupling : BSM

MSSM tree level Higgs Potential

\[ V^{(0, MSSM)} = m_1^2 |H_u|^2 + m_2^2 |H_d|^2 - B_\mu \epsilon_{\alpha \beta} (H_u^\alpha H_d^\beta + h.c.) \]
\[ + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 + \frac{g^2}{2} |H_u^+ H_d|^2, \]

Neutral CP-even Higgs h, H trilinear couplings at LO :

\[ \lambda_{hhh}^{(0, MSSM)} = \frac{3M_Z^2}{v} c_{2\alpha} s_{\alpha + \beta}, \quad \lambda_{hhh}^{(0, MSSM)} = \frac{M_Z^2}{v} [2s_{2\alpha} s_{\alpha + \beta} - c_{2\alpha} c_{\alpha + \beta}], \]

\[ \lambda_{HHH}^{(0, MSSM)} = \frac{3M_Z^2}{v} c_{2\alpha} c_{\alpha + \beta}, \quad \lambda_{HHH}^{(0, MSSM)} = -\frac{M_Z^2}{v} [2s_{2\alpha} c_{\alpha + \beta} + c_{2\alpha} s_{\alpha + \beta}]. \]

In the MSSM, the ratio of \( \lambda_{3h}^{MSSM} / \lambda_{3h}^{SM} \) has been tightly constrained by the LHC data, which can be only slightly smaller than 1 and minimally reach 97%. 
Higgs Boson Self Coupling : BSM

NMSSM tree level Higgs Potential

\[
V^{(0,NMSSM)} = (|\lambda S|^2 + m_{H_u}^2)H_{u}^\dagger H_{u} + (|\lambda S|^2 + m_{H_d}^2)H_{d}^\dagger H_{d} + m_S^2|S|^2 \\
+ \frac{1}{8}(g_1^2 + g_2^2)(H_{u}^\dagger H_{u} - H_{d}^\dagger H_{d})^2 + \frac{1}{2}g_2^2|H_{u}^\dagger H_{d}|^2 \\
+ [\epsilon^{\alpha\beta\lambda} H_{u}^\alpha H_{d}^\beta + \kappa S^2]^2 + [\epsilon^{\alpha\beta\lambda} A_{\alpha} H_{u}^\alpha H_{d}^\beta S + \frac{1}{3}\kappa A_{\kappa} S^3 + h.c.
\]

Neutral CP-even Higgs trilinear couplings at LO :

\[\lambda^{(0,NMSSM)}_{h_i h_j h_k} = \mathcal{O}_{i\alpha}\mathcal{O}_{j\beta}^{\dagger}\mathcal{O}_{k\gamma}^{\dagger}\lambda_{h_i h_j h_k}.\]
Higgs Boson Self Coupling : BSM

Littlest Higgs Model Coleman-Weinberg potential

\[ V_{CW} = \lambda_{\phi^2} f^2 \text{tr}(\phi^\dagger \phi) + i \lambda_{\phi h} f(h\phi^\dagger h^T - h^* \phi h^\dagger) - \mu^2 hh^\dagger + \lambda_{h^4}(hh^\dagger)^2 \]

Higgs trilinear couplings :

\[ g_{H^0 H^0 H^0} : -i \left( \frac{3m_{H^0}^2}{v} - \frac{33m_{H^0}^2 v}{4f^2} \frac{x^2}{1-x^2} \right), \]

\[ g_{H^0 \bar{t} t} : -i \frac{m_t}{v} \left[ 1 + \frac{xv^2}{2f^2} - \frac{x^2v^2}{4f^2} - \frac{2}{3} \frac{v^2}{f^2} \frac{\lambda_1^2}{\lambda_1^2 + \lambda_2^2} \left( 1 + \frac{\lambda_1^2}{\lambda_1^2 + \lambda_2^2} \right) \right]. \]

\[ \langle h^0 \rangle = v/\sqrt{2}, \langle i\phi^0 \rangle = v' \]

\[ x = 4fv'/v^2 \]
Higgs self coupling is important, the cross section of Higgs boson pair production which can probe the Higgs self coupling is very small in SM.

Top/Bottom Yukawa Coupling

Destructive interference

Higgs Self Coupling

\[ g g \rightarrow h h \]

\[ t/b g \rightarrow h \]

\[ h \]

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Significance of HH production at LHC

Cross section of HH production depends on HHHH coupling

LHC 14 TeV, 100 fb\(^{-1}\)
reach 2\(\sigma\) significance:

\[ \frac{\lambda}{\lambda_{SM}} \geq 4, \quad \frac{\lambda}{\lambda_{SM}} \leq 1 \]
Kinematics of HH production

Kinematic Distribution of HH production depends on HHH coupling

LHC 14 TeV

$\frac{\lambda_{hhh}/\lambda_{hhh}^{SM}}{} = 1, 2, 3$

$1/\sigma_{hh} \frac{d\sigma_{hh}}{dp_T(h)}$

$M_{hh}$ (GeV)
Higgcision

Model-Independent Higgs Precision Analysis

Followed CPsuperH notations for Higgs couplings to the SM particles
Assuming the Higgs boson is a generally CP-mixed state without carrying any definite CP-parity

Use these parameter to fit

\[
\Delta \Gamma_{tot} = \Delta S^g, \Delta S^\gamma ; \quad \Delta P^g, \Delta P^\gamma
\]

\[
C_u^S = g_{H \bar{u} u}^S, \quad C_d^S = g_{H \bar{d} d}^S, \quad C_l^S = g_{H \bar{l} l}^S; \quad C_v = g_{HV V};
\]

\[
C_u^P = g_{H \bar{u} u}^P, \quad C_d^P = g_{H \bar{d} d}^P, \quad C_l^S = g_{H \bar{l} l}^P
\]
Most constrained
$g_{hVV}/g_{hVV}^{SM} \ 0.93-1.00$ uncertainty 7%-12%

CPC case, top Yukawa more prefer positive
**Electric Dipole Moments**

2HDM framework
With no contributions from:
- other Higgs bosons,
- supersymmetric particles,
- other exotic particles

delicately cancel the current Higgs-mediated contributions

pseudoscalar Yukawa coupling $|C^P_u|$ less than about $10^{-2}$

varying scalar Yukawa couplings $C^S_u$, Higgs gauge couplings $C_v$ and the pseudo scalar Yukawa coupling $C^P_u$

K. Cheung, J. S. Lee, E. Senaha and P. Y. Tseng, Higcision
Formalism

Lagrangian involved for the Higgs Pair Production

\[-\mathcal{L} = \frac{1}{3!} \left( \frac{3M_H^2}{v} \right) \lambda_{3H} H^3 + \frac{m_t}{v} \bar{t} \left( g_t^S + i \gamma_5 g_t^P \right) t H + \frac{1}{2} \frac{m_t}{v^2} \bar{t} \left( g_{tt}^S + i \gamma_5 g_{tt}^P \right) t H^2 \]

In the SM, \( \lambda_{3H} = g_t^S = 1 \), \( g_t^P = 0 \) and \( g_t^S, g_{tt}^P = 0 \).
\[ \sigma(hh)/\sigma(hh)_{SM} \text{ v.s. } \lambda_{3H} \, g_t^S \, g_{tt}^S \]

Interferes constructively with the triangle diagram but destructively with the box diagram.

The dominance of the box diagram leads to the totally destructive interference.

\[ g_{tt}^S \approx 0.5 \]

\[ \lambda_{3H} \approx 2.5 \]

The interference term strongly cancels the triangle and box diagrams.
The current data cannot rule out pseudo-scalar Yukawa coupling. Can only give a constraints on:

\[ |g_t^S|^2 + |g_t^P|^2 \]

Cross section’s dependence on Higgs self coupling will shift by consider pseudo-scalar Top/Bottom Yukawa Coupling.
If we only consider SM contribution:
can’t determined size and sign of Higgs trilinear coupling from top Yukawa coupling.

Contact diagram contributes significantly to the cross section:

Shift more to negative $\lambda$ for positive $g_{st}^S$.

Shift more to positive $\lambda$ for negative $g_{st}^S$.
Formalism

Lagrangian involved for the Higgs Pair Production

\[-\mathcal{L} = \frac{1}{3!} \left( \frac{3M_H^2}{v} \right) \lambda_{3H} H^3 + \frac{m_t}{v} \bar{t} (g^S_t + i\gamma_5 g^P_t) t H + \frac{m_t}{2v^2} \bar{t} (g^{tt}_t + i\gamma_5 g^{tt}_t) t H^2\]

In the SM, \(\lambda_{3H} = g^S_t = 1, g^P_t = 0\) and \(g^{S,P}_{tt} = 0\).

The differential Cross section with the extended couplings

\[
\frac{d\hat{\sigma}(gg \rightarrow HH)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left\{ \left(\lambda_{3H} g^S_t D(\hat{s}) + g^S_t \right) F^S_\Delta + (g^S_t)^2 F^{SS}_\Delta + (g^P_t)^2 F^{PP}_\Delta \right\}^2 + \left| (g^S_t)^2 G^{SS}_\Delta + (g^P_t)^2 G^{PP}_\Delta \right|^2
\]

\[
D(\hat{s}) = \frac{3M_H^2}{\hat{s} - M_H^2 + iM_H \Gamma_H}
\]

\[
\left| (\lambda_{3H} g^P_t D(\hat{s}) + g^P_{tt}) F^P_\Delta + g^S_t g^P_t F^{SP}_\Delta \right|^2 + \left| g^S_t g^P_t G^{SP}_\Delta \right|^2 \right\}.
\]
The production cross section normalized to the corresponding SM cross section, with or without cuts, can be parameterized as follows:

\[
\frac{\sigma(gg \rightarrow HH)}{\sigma_{SM}(gg \rightarrow HH)} = \lambda_{3H}^2 \left[ c_1(s)(g^S_t)^2 + d_1(s)(g^P_t)^2 \right] + \lambda_{3H} g^S_t \left[ c_2(s)(g^S_t)^2 + d_2(s)(g^P_t)^2 \right] \\
+ \left[ c_3(s)(g^S_t)^4 + d_3(s)(g^S_t)^2(g^P_t)^2 + d_4(s)(g^P_t)^4 \right] \\
+ \lambda_{3H} \left[ e_1(s)g^S_t g^S_t + f_1(s)g^P_t g^P_t \right] + g^S_{tt} \left[ e_2(s)(g^S_t)^2 + f_2(s)(g^P_t)^2 \right] \\
+ \left[ e_3(s)(g^S_{tt})^2 + f_3(s)g^S_t g^P_t + f_4(s)(g^P_{tt})^2 \right]
\]

Where the numerical coefficients \( c_{1,2,3}(s) \), \( d_{1,2,3,4}(s) \), \( e_{1,2,3}(s) \), and \( f_{1,2,3,4}(s) \) depend on \( s \) and experimental selection cuts.

Here the coefficients \( c_1(s) \) and \( C_3(s) \) are for the SM contributions from the triangle and box diagrams, \( c_2(s) \) for the interference between them.

Once we have the coefficients \( c_i \), \( d_i \), \( e_i \), and \( f_i \)'s, the cross sections can be easily obtained for any combinations of couplings.

Upon our normalization, the ratio should be 1 when \( \lambda_{3H} = g^S_t = 1, g^P_t = 0 \) and \( g^{S,P}_{tt} = 0 \) or \( c_1(s) + c_3(s) + c_3(s) = 1 \).
Cross sections vs Energies

\[ \sigma/\sigma_{SM} \]

- triangle
- box
- ttHH

Variables:
- \( c_i(s) \) [functions of \( s \)]
- \( d_j(s) \) [functions of \( s \)]
- \( e_k(s) \)
- \( f_l(s) \)

Graphs show dependence on \( \sqrt{s} \) (TeV) with \( \sigma/\sigma_{SM} \) ranging from -6 to 25.
BSM CPC contribution

LHC-14, Detector Level-ATLAS, CPC, $\lambda_{3H}=g_t^{S=1}$

$\lambda, g^S_t, g^{S_{tt}}$
BSM CPV contribution

\( \lambda, g^s_t, g^p_t \)
What we do in this work,…

• We are trying to disentangle Higgs trilinear coupling from top/bottom Yukawa coupling and other BSM coupling in Higgs boson pair production.

• Map out the sensitivity regions of parameter space that can be probed at the LHC.

• Working assumption : BG can be estimated & extracted from data.

• Considered :
  1. SM BG
     (can be estimated with uncertainties less than the NNLO corrections. can be estimated with uncertainties less than the NNLO corrections. )
  2. the NLO corrections
     (the NLO and NNLO corrections can be as large as 100% with uncertainty of order 10–20%.)

• We therefore adopt an approach that the signal cross sections (after background subtraction) are measured with uncertainties of order 25–50%.
We consider the SM NLO HH cross section: $\sigma_{SM}(pp \to HH) \approx 34 \text{ fb}$

$p_T$ and $\eta$ dependent b-tagging efficiency

$\tau$ tagging efficiency as 0.5

mis-tagging $P_{j \to \tau} = 0.01$

$p_{T\gamma} > 10 \text{ GeV}, \quad p_{Tb} > 10 \text{ GeV}, \quad |\eta_\gamma| < 2.5, \quad |\eta_b| < 2.5, \quad \Delta R_{\gamma\gamma} > 0.4, \quad \Delta R_{bb} > 0.4,$

$|M_H - M_{\gamma\gamma}| < 15 \text{ GeV}, \quad |M_H - M_{bb}| < 25 \text{ GeV}, \quad |M_H - M_{\tau\tau}| < 25 \text{ GeV}.$

<table>
<thead>
<tr>
<th>Cuts</th>
<th>SM-14 (\gamma\gamma b\bar{b})</th>
<th>SM-100 (\gamma\gamma b\bar{b})</th>
<th>SM-14 (\tau^+\tau^- b\bar{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cuts</td>
<td>$8.92 \times 10^{-2}$</td>
<td>$3.73$</td>
<td>$2.41$</td>
</tr>
<tr>
<td>Basic Cuts</td>
<td>$5.1 \times 10^{-3}$</td>
<td>$2.05 \times 10^{-1}$</td>
<td>$3.53 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta R_{\gamma\gamma/\tau+\tau-} &gt; 2$</td>
<td>$1.34 \times 10^{-3}$</td>
<td>$4.34 \times 10^{-2}$</td>
<td>$6.43 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta R_{\gamma\gamma/\tau+\tau-} &lt; 2$</td>
<td>$3.76 \times 10^{-3}$</td>
<td>$1.61 \times 10^{-1}$</td>
<td>$2.89 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta R_{bb} &gt; 2$</td>
<td>$7.61 \times 10^{-4}$</td>
<td>$2.23 \times 10^{-2}$</td>
<td>$4.82 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta R_{bb} &lt; 2$</td>
<td>$4.34 \times 10^{-3}$</td>
<td>$1.83 \times 10^{-1}$</td>
<td>$3.05 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta R_{bb} &gt; 2 &amp; \Delta R_{\gamma\gamma/\tau+\tau-} &gt; 2$</td>
<td>$4.79 \times 10^{-4}$</td>
<td>$1.40 \times 10^{-2}$</td>
<td>$3.21 \times 10^{-4}$</td>
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<tr>
<td>$\Delta R_{bb} &lt; 2 &amp; \Delta R_{\gamma\gamma/\tau+\tau-} &lt; 2$</td>
<td>$3.48 \times 10^{-3}$</td>
<td>$1.53 \times 10^{-1}$</td>
<td>$2.73 \times 10^{-3}$</td>
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14 TeV with 3000 fb$^{-1}$ luminosity

It would be challenging to measure this size of cross section only in the bb\gamma\gamma mode and one may need to combine the measurements in different Higgs-decay channels.
Since the shape of the three bands are not exactly the same, we can make use of three simultaneous measurements in order to obtain more useful information for the couplings.
If the measured cross sections being multiples of the SM predictions.
LHC-8, LHC-14, LHC-100

### LHC-14 v.s. LHC-100

<table>
<thead>
<tr>
<th>$\sqrt{s}$: 14 TeV</th>
<th>$c_1(s)$</th>
<th>$c_2(s)$</th>
<th>$c_3(s)$</th>
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<tbody>
<tr>
<td>Cuts</td>
<td>$[\lambda_{3H}^2(g_t^S)^2]$</td>
<td>$[\lambda_{3H}(g_t^S)^3]$</td>
<td>$[(g_t^S)^4]$</td>
</tr>
<tr>
<td>No cuts</td>
<td>0.263</td>
<td>-1.310</td>
<td>2.047</td>
</tr>
<tr>
<td>Basic Cuts</td>
<td>0.221</td>
<td>-1.104</td>
<td>1.883</td>
</tr>
<tr>
<td>$\Delta R_{\gamma\gamma} &gt; 2$</td>
<td>0.470</td>
<td>-1.868</td>
<td>2.398</td>
</tr>
<tr>
<td>$\Delta R_{\gamma\gamma} &lt; 2$</td>
<td>0.133</td>
<td>-0.834</td>
<td>1.701</td>
</tr>
<tr>
<td>$\Delta R_{bb} &gt; 2$</td>
<td>0.666</td>
<td>-2.512</td>
<td>2.847</td>
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<tr>
<td>$\Delta R_{bb} &lt; 2$</td>
<td>0.143</td>
<td>-0.857</td>
<td>1.714</td>
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<tr>
<td>$\Delta R_{bb} &gt; 2$ &amp; $\Delta R_{\gamma\gamma} &gt; 2$</td>
<td>0.895</td>
<td>-3.150</td>
<td>3.255</td>
</tr>
<tr>
<td>$\Delta R_{bb} &lt; 2$ &amp; $\Delta R_{\gamma\gamma} &lt; 2$</td>
<td>0.121</td>
<td>-0.785</td>
<td>1.664</td>
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<th>$\sqrt{s}$: 100 TeV</th>
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<th>$c_2(s)$</th>
<th>$c_3(s)$</th>
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</thead>
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<td>Cuts</td>
<td>$[\lambda_{3H}^2(g_t^S)^2]$</td>
<td>$[\lambda_{3H}(g_t^S)^3]$</td>
<td>$[(g_t^S)^4]$</td>
</tr>
<tr>
<td>No cuts</td>
<td>0.208</td>
<td>-1.108</td>
<td>1.900</td>
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<tr>
<td>Basic Cuts</td>
<td>0.173</td>
<td>-1.032</td>
<td>1.860</td>
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<tr>
<td>$\Delta R_{\gamma\gamma} &gt; 2$</td>
<td>0.389</td>
<td>-1.904</td>
<td>2.515</td>
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<tr>
<td>$\Delta R_{\gamma\gamma} &lt; 2$</td>
<td>0.115</td>
<td>-0.798</td>
<td>1.683</td>
</tr>
<tr>
<td>$\Delta R_{bb} &gt; 2$</td>
<td>0.607</td>
<td>-2.419</td>
<td>2.813</td>
</tr>
<tr>
<td>$\Delta R_{bb} &lt; 2$</td>
<td>0.120</td>
<td>-0.863</td>
<td>1.743</td>
</tr>
<tr>
<td>$\Delta R_{bb} &gt; 2$ &amp; $\Delta R_{\gamma\gamma} &gt; 2$</td>
<td>0.753</td>
<td>-2.662</td>
<td>2.909</td>
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<tr>
<td>$\Delta R_{bb} &lt; 2$ &amp; $\Delta R_{\gamma\gamma} &lt; 2$</td>
<td>0.102</td>
<td>-0.733</td>
<td>1.632</td>
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</table>

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**LHC-14, Detector Level-ATLAS**

![Histogram for LHC-14](image1)

**LHC-100, Detector Level-ATLAS**

![Histogram for LHC-100](image2)
Conclusion

- **Triangle** diagram (contains an s-channel Higgs propagator) does not increase as much as the **Box** diagram or the **Contact** diagram with the center-of-mass energy.

- **Open angle** of Higgs decay product is **useful** to separate the triangle and box diagram, and helps to isolate the Higgs trilinear coupling.

- Contact diagram contains a dim-5 operator $\text{ttHH}$, which actually breaks the unitarity at about CM energy $\sim 17.6 \, \text{g}_{tt} \, \text{TeV}$. This implies that it could become dominant at high invariant mass.

- Suppose we take a **measurement of cross sections**, we can **map out** the possible region of **parameter space**. Since in **different kinematic regions** the regions of parameter space are mapped out differently, such that simultaneous measurements can map out the intersected regions. With measurement uncertainties less than 25% one can statistically show a nonzero value for the Higgs trilinear coupling, and also obtain the **sensitivity regions** of

$$\lambda_3 H: \quad 0.3 \lesssim |\lambda_3| \lesssim 2.6 \quad \text{for} \quad \sigma/\sigma_{\text{SM}} = 1$$
• We found that the behavior of the distributions of the invariant mass and angular separation at 14 TeV are very similar to those at 100 TeV. We can then use the same method as in 14 TeV to isolate the Higgs trilinear coupling.

• It is difficult, if not impossible, to determine the Higgs trilinear coupling uniquely at the LHC and 100 TeV pp machine even in the simplest case assuming very high luminosity and precise independent input for the top-Yukawa coupling. We suggest to combine the LHC results with information which can be obtained at a future e+e- linear collider.

• If the couplings deviate from their SM values, the Higgs-boson pair production cross section can easily increase by an order of magnitude.
LHC-13 ATLAS

Searches for Higgs boson pair production in the $hh \rightarrow b\bar{b}b\bar{b}$ channels with the ATLAS detector for LHC-13, luminosity : 3.2 fb$^{-1}$

For nonresonant production, the upper limit is 1.22 pb (at 95% CL).
Thanks for your Attention!
BackUp
Experiment Results
Searches for Higgs boson pair production in the \( hh \rightarrow yybb \) channels with the ATLAS detector for LHC-13, luminosity : 3.2 fb\(^{-1}\)

An upper limit of 3.9 pb on the cross-section for non-resonant production is extracted at the 95\% confidence level, while the expected limit is 5.4 pb. In the search for a narrow \( X \rightarrow hh \) resonance, the observed limit ranges between 7.0 pb and 4.0 pb for masses of the resonance between 275 and 400 GeV. The corresponding expected limit varies between 7.5 pb and 4.4 pb for the same mass range.
Resonant & Nonresonant

LHC-8 ATLAS

Searches for Higgs boson pair production in the $hh \rightarrow bb\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma bb$, $bbbb$ channels with the ATLAS detector for LHC-8, luminosity: $20.3 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\gamma\gamma bb$</th>
<th>$\gamma\gamma WW^*$</th>
<th>$bb\tau\tau$</th>
<th>$bbbb$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>1.0</td>
<td>6.7</td>
<td>1.3</td>
<td>0.62</td>
<td>0.47</td>
</tr>
<tr>
<td>Observed</td>
<td>2.2</td>
<td>11</td>
<td>1.6</td>
<td>0.62</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Upper limit on the cross section [pb]

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\gamma\gamma bb$</th>
<th>$\gamma\gamma WW^*$</th>
<th>$bb\tau\tau$</th>
<th>$bbbb$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>100</td>
<td>680</td>
<td>130</td>
<td>63</td>
<td>48</td>
</tr>
<tr>
<td>Observed</td>
<td>220</td>
<td>1150</td>
<td>160</td>
<td>63</td>
<td>70</td>
</tr>
</tbody>
</table>

Upper limit on the cross section relative to the SM prediction

An upper limit of 0.69 (0.47) pb on the nonresonant $hh$ production is observed (expected), corresponding to 70 (48) times the SM $gg \rightarrow hh$ cross section.

With two simplified scenarios of MSSM, they give the observed (expected) limits range depends on the heavy Higgs boson mass, from 2.1 (1.1) pb at 260 GeV to 0.011 (0.018) pb at 1000 GeV for the narrow resonance Higgs pair production.
(a) Bulk RS, $k/\bar{M}_{Pl} = 1$

(b) Bulk RS, $k/\bar{M}_{Pl} = 2$
Resonant Higgs boson pair production in the $\text{hh} \to \text{bbbb}$ channels with the CMS detector for LHC-8, luminosity : 20.3 fb$^{-1}$

No evidence is observed for such a signal. Upper limits obtained at 95% confidence level for the product of the production cross section and branching fraction $\sigma(gg \to X) \cdot B(X \to HH \to b\bar{b}b\bar{b})$ range from 10 to 1.5 fb for the mass of $X$ from 1.15 to 2.0 TeV, significantly extending previous searches. For a warped extra dimension theory with a mass scale $\Lambda_R = 1$ TeV, the data exclude radion scalar masses between 1.15 and 1.55 TeV.
## Searches for Higgs boson pair production in the $hh \rightarrow bb\tau\tau$ channels with the CMS detector for LHC-13, luminosity : $2.7 \text{ fb}^{-1}$

$k_\lambda = \lambda_{hhh}/\lambda_{hhh}^{SM} = 1$

<table>
<thead>
<tr>
<th>$k_\lambda$</th>
<th>$\text{bb}\mu\tau_h$ (Obs)</th>
<th>$\text{bb}\ell\tau_h$ (Obs)</th>
<th>$\text{bb}\tau_h\tau_h$ (Obs)</th>
<th>Combined (Obs)</th>
<th>$\text{Theoretical cross section [pb]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>59.6 (49.6)</td>
<td>53.9 (70.4)</td>
<td>20.9 (20.9)</td>
<td>19.8 (19.0)</td>
<td>5.5</td>
</tr>
<tr>
<td>-1</td>
<td>38.1 (30.4)</td>
<td>31.3 (42.7)</td>
<td>14.2 (12.8)</td>
<td>13.2 (11.6)</td>
<td>0.146</td>
</tr>
<tr>
<td>0</td>
<td>32.2 (25.5)</td>
<td>25.8 (35.4)</td>
<td>12.3 (10.6)</td>
<td>11.3 (9.6)</td>
<td>0.81</td>
</tr>
<tr>
<td>1</td>
<td>25.3 (19.6)</td>
<td>19.4 (26.9)</td>
<td>9.8 (8.1)</td>
<td>8.8 (7.2)</td>
<td>0.038</td>
</tr>
<tr>
<td>2</td>
<td>21.4 (15.9)</td>
<td>15.4 (21.7)</td>
<td>8.2 (6.5)</td>
<td>7.3 (5.7)</td>
<td>0.018</td>
</tr>
<tr>
<td>5</td>
<td>107 (82.7)</td>
<td>85.0 (111)</td>
<td>29.0 (30.1)</td>
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<tr>
<td>20</td>
<td>73.5 (62.3)</td>
<td>69.3 (89.0)</td>
<td>24.4 (25.9)</td>
<td>23.4 (23.7)</td>
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</tr>
<tr>
<td>30</td>
<td>88.2 (59.7)</td>
<td>85.3 (86.0)</td>
<td>23.7 (24.9)</td>
<td>22.7 (22.8)</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Nonresonant
For non-resonant Higgs boson pair production at $k_\lambda = 1$ the observed (expected) limit on $\sigma(pp \rightarrow hh)$ amounts to 8.8 (7.2) pb. These values correspond to approximately 200 times the SM prediction.
Searches for Higgs boson pair production in the \( hh \rightarrow bb\tau\tau \) channels with the CMS detector for LHC-13, luminosity : 2.7 fb\(^{-1}\)
BSM
effective Coupling
Effective Field Theory
with operator mass dimension 4-6

\[ \mathcal{L}_h = \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa \lambda \lambda_{SM} v h^3 - \frac{m_t}{v} (v + \kappa_t h + \frac{c_2}{v} h h) (t_L t_R + h.c.) \]
\[ + \frac{1}{4} \frac{\alpha_s}{3 \pi v} (c_g h - \frac{c_{2g}}{2v} h h) G^{\mu\nu} G_{\mu\nu}. \]

Composite Higgs Models i.e. strongly-interacting light Higgs (SILH)
Effective Field Theory

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\kappa_\lambda$</th>
<th>$\kappa_t$</th>
<th>$c_2$</th>
<th>$c_g$</th>
<th>$c_{2g}$</th>
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<td>1</td>
<td>7.5</td>
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<tr>
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<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Cluster 1

$N_{\text{samples}} = 20$

$m_{hh}$ (GeV/c$^2$)

Cluster 4

$N_{\text{samples}} = 446$

$m_{hh}$ (GeV/c$^2$)

Cluster 9

$N_{\text{samples}} = 187$

$m_{hh}$ (GeV/c$^2$)
<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\kappa_\lambda$</th>
<th>$\kappa_t$</th>
<th>$c_2$</th>
<th>$c_g$</th>
<th>$c_{2g}$</th>
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<td>0.6</td>
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<td>1.0</td>
<td>-1.5</td>
<td>0.0</td>
<td>-0.8</td>
</tr>
<tr>
<td>4</td>
<td>-3.5</td>
<td>1.5</td>
<td>-3.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>1</td>
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</tr>
<tr>
<td>12</td>
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<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Higgcision

Model-Independent Higgs Precision Analysis

Followed CPsuperH notations for Higgs couplings to the SM particles
Assuming the Higgs boson is a generally CP-mixed state without
carrying any definite CP-parity

Use these parameter to fit

\[ \Delta \Gamma_{tot} \]
\[ \Delta S^g, \Delta S^\gamma; \Delta P^g, \Delta P^\gamma \]

\[ C_u^S = g_{H \bar{u} u}, \quad C_d^S = g_{H \bar{d} d}, \quad C_l^S = g_{H \bar{l} l}^S; \quad C_v = g_{HVV}; \]
\[ C_u^P = g_{H \bar{u} u}^P, \quad C_d^P = g_{H \bar{d} d}^P, \quad C_l^P = g_{H \bar{l} l}^P \]
Most constrained
$g_{hVV}/g_{hVV}^{SM}$ 0.93-1.00 uncertainty 7%-12%

CPC case, top Yukawa more prefer positive
Electric Dipole Moments

2HDM framework
With no contributions from:
- other Higgs bosons,
- supersymmetric particles,
- other exotic particles

delicately cancel the current
Higgs-mediated contributions

pseudoscalar Yukawa coupling $|C^P_u|$ less than about $10^{-2}$

K. Cheung, J. S. Lee, E. Senaha and P. Y. Tseng, Higcision

Varying scalar Yukawa couplings $C^S_u$, Higgs gauge couplings $C_v$ and the pseudo scalar Yukawa coupling $C^P_u$ can't rule out $C^P_u$

Elliptical equation constraint
NLO Contribution
Higgs Pair Production at the LHC


Total cross sections at the NLO in QCD

LHC-14, cross section as function of $\lambda/\lambda_{SM}$

(a) gg double-Higgs fusion: \( gg \rightarrow HH \)

(b) WW/ZZ double-Higgs fusion: \( qq' \rightarrow HHqq' \)

(c) Double Higgs-strahlung: \( qq' \rightarrow ZHH/WHH \)

(d) Associated production with top-quarks: \( qq'/gg \rightarrow t\bar{t}HH \)

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\sqrt{s} [\text{TeV}] & \sigma_{gg \rightarrow HH}^{\text{NLO}} \text{[fb]} & \sigma_{qq' \rightarrow HHqq'}^{\text{NLO}} \text{[fb]} & \sigma_{qq' \rightarrow WHH}^{\text{NNLO}} \text{[fb]} & \sigma_{qq' \rightarrow ZHH}^{\text{NNLO}} \text{[fb]} & \sigma_{qq'/gg \rightarrow t\bar{t}HH}^{\text{LO}} \text{[fb]} \\
\hline
8 & 8.16 & 0.49 & 0.21 & 0.14 & 0.21 \\
14 & 33.89 & 2.01 & 0.57 & 0.42 & 1.02 \\
33 & 207.29 & 12.05 & 1.99 & 1.68 & 7.91 \\
100 & 1417.83 & 79.55 & 8.00 & 8.27 & 77.82 \\
\hline
\end{array}
\]
Our Results
CPC2

The dashed lines denoted by -50%, the solid line +50%.

\[(g_t^S, g_{tt}^S)\]

\[(\lambda_3H, g_{tt}^S)\]

\[(\lambda_3H, g_t^S)\]

The contact diagram contributes significantly to the cross section.

Same as SM

nontrivial correlation

the \(g_{tt}^S\) negatively correlates with \(\lambda_3H\)

shift more to

negative (positive) \(\lambda_3H\)

positive (negative) \(g_t^S\).
Bottom Yukawa interference & ttHH validity
Additional Destructive Interference from BSM physics

- Arises between the top and bottom–mediated loops, although the bottom quark effects are very small in the SM.

- For example: 2HDM.

- Sign–flipped bottom–quark Yukawa: the top and bottom–mediated triangles to interfere constructively. Slightly enhanced triangle amplitudes, which thus reinforce the interference with the boxes.

- O(20)% enhanced bottom Yukawa: reinforces the destructive interference between the top and bottom–mediated triangles. Slightly suppressed Higgs-self coupling to pull down triangle contribution. Reduced the triangle and box interference term. Slightly above SM expectation.
Examine the ttHH validity


projecting out the leading partial-wave coefficient for the scattering
At high energy, the amplitude

\[ i\mathcal{M}(t\bar{t} \to HH) \sim g_{tt}^S m_t \sqrt{\hat{s}} / v^2 \]

The leading partial-wave coefficient is given by

\[ a_0 = \frac{1}{64\pi} \int_{-1}^{1} d(\cos \theta) P_0(\cos \theta) (i\mathcal{M}) = g_{tt}^S m_t \sqrt{\hat{s}} / 32\pi v^2 \]

Requiring \(|a_0| < 1/2\) for unitary, we got:

\[ \sqrt{\hat{s}} \leq \frac{17.6}{g_{tt}^S} \text{ TeV} \]

Therefore, the anomalous ttHH contact term can be safely applied at the LHC for \(g_{tt}^S \lesssim 3 - 5\) as most of the collisions occur at \(\sqrt{\hat{s}} \lesssim\) a few TeV.
Top-Yukawa Coupling

SM top-Higgs interaction

\[ \mathcal{L}_{tth}^{SM} = -y_{tSM} \overline{Q}_{3L} t_R \bar{\phi} + \text{h.c.} \]

\[ y_{tSM} = \sqrt{2} m_t / v \]

New Physics model independent
dim-6 effective top-Higgs coupling

\[ \mathcal{L}_{\tilde{t}th}^6 = -\frac{C_{u\phi}^{33}}{\Lambda^2} (\phi^\dagger \phi) (\overline{Q}_{3L} t_R \bar{\phi}) + \text{h.c.} \]

After EWSB, the most general top Higgs interactions:
SM+dim-6 operator contributions

\[ \mathcal{L}_{\tilde{t}th} = -\frac{y_t}{\sqrt{2}} \bar{t} (\cos \theta + i \sin \theta \gamma^5) t h, \]

\[ y_t \cos \theta = y_{tSM} + \frac{v^2}{\Lambda^2} \text{Re} \ C_{u\phi}^{33}, \quad y_t \sin \theta = \frac{v^2}{\Lambda^2} \text{Im} \ C_{u\phi}^{33}. \]

\[ c_t = y_t \cos \theta / y_{tSM} \text{ and } \tilde{c}_t = y_t \sin \theta / y_{tSM} \]

The most relevant indirect constraint ggF and h\gamma\gamma,
Parameterized signal strength for hgg and h\gamma\gamma

\[ \mu_{hgg} \simeq c_t^2 + 2.6 \tilde{c}_t^2 + 0.11 c_t (c_t - 1), \]

\[ \mu_{h\gamma\gamma} \simeq (1.28 - 0.28 c_t)^2 + (0.43 \tilde{c}_t)^2 \]
ILC & photon collider
FIG. 5: The double Higgs boson production process $\gamma\gamma \to hh$ at the photon collider.
FIG. 6: The full cross section of $e^-e^- (\gamma(+)\gamma(+)) \rightarrow hh$ process as a function of $\sqrt{s_{ee}}$ for $m_h = 120$ GeV (left) and $m_h = 160$ GeV (right).

FIG. 7: The cross sections of $e^+e^- \rightarrow hh\nu\bar{\nu}$ process at the ILC as a function of collision energy $\sqrt{s}$ for $m_h = 120$ GeV (left) and $m_h = 160$ GeV (right).
BSM models
Higgs Sector in MSSM

Two Higgs doublet,
Same as 2HDM type II.
One couples to up type quark
One couples to down type quark
Physical Higgs : h, H, A, H+

tree level Higgs Potential

\[
V^{(0,\text{MSSM})} = m_1^2 |H_u|^2 + m_2^2 |H_d|^2 - B_\mu \epsilon_{\alpha\beta} (H_u^\alpha H_d^\beta + h.c.) + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 + \frac{g^2}{2} |H_u^\dagger H_d|^2,
\]

Neutral CP-even Higgs h, H
trilinear couplings, at LO

\[
\lambda^{(0,\text{MSSM})}_{hhh} = \frac{3M_Z^2}{v} c_{2\alpha} s_{\alpha + \beta}, \quad \lambda^{(0,\text{MSSM})}_{Hhh} = \frac{M_Z^2}{v} [2s_{2\alpha} s_{\alpha + \beta} - c_{2\alpha} c_{\alpha + \beta}],
\]

\[
\lambda^{(0,\text{MSSM})}_{HHH} = \frac{3M_Z^2}{v} c_{2\alpha} c_{\alpha + \beta}, \quad \lambda^{(0,\text{MSSM})}_{HHH} = -\frac{M_Z^2}{v} [2s_{2\alpha} c_{\alpha + \beta} + c_{2\alpha} s_{\alpha + \beta}].
\]

In the MSSM, either the lighter scalar h
or the heavier scalar H can be the SM-like Higgs boson.
\[ V^{(0, \text{MSSM})} = m_1^2 |H_u|^2 + m_2^2 |H_d|^2 - B_\mu \varepsilon_{\alpha \beta} (H^\alpha_u H^\beta_d + h.c.) \]
\[ + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 + \frac{g^2}{2} |H^\dagger_u H_d|^2 , \]

adds an additional singlet chiral superfield to the MSSM

\[ V^{(0, \text{NMSSM})} = (|\lambda S|^2 + m_{H_u}^2) H^\dagger_u H_u + (|\lambda S|^2 + m_{H_d}^2) H^\dagger_d H_d + m_S^2 |S|^2 \]
\[ + \frac{1}{8} (g_2^2 + g_1^2) (H^\dagger_u H_u - H^\dagger_d H_d)^2 + \frac{1}{2} g_2^2 |H^\dagger_u H_d|^2 \]
\[ + |\varepsilon^{\alpha \beta} \lambda H^\alpha_u H^\beta_d + \kappa S|^2 + [\varepsilon^{\alpha \beta} \lambda A_\lambda H^\alpha_u H^\beta_d S + \frac{1}{3} \kappa A_\kappa S^3 + h.c] , \]

\[ \lambda^{(0, \text{NMSSM})}_{h_i h_j h_k} = \mathcal{O}_{i \alpha} \mathcal{O}_{j \beta} \mathcal{O}_{k \gamma} \lambda_{h_\alpha h_\beta h_\gamma} . \]
L. Wu, J. M. Yang, C.P. Yuan, M. Zhang,
arXiv: 1504.06932v2[hep-ph]
Composite Higgs

Littlest Higgs Model with T-Parity

The amplitude of each diagram

Higgs Top quartic coupling

FIG. 2: Triangle contributions to Higgs boson pair production at LHC in a Little Higgs model.

\[ A_{\Box} \sim \alpha_s \frac{m_t^2}{v^2}, \]

\[ A_{\Delta} \sim c \alpha_s \frac{m_t^2}{v^2} \left( \frac{m_h^2}{s} \right) \left[ \log \left( \frac{m_t^2}{s} \right) + i\pi \right]^2, \]

\[ A_{\Delta nt} \sim c_2 \alpha_s \frac{m_t^2}{v^2} \left[ \log \left( \frac{m_t^2}{s} \right) + i\pi \right]^2, \]

\[ g_{Htt} = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \]

\[ g_{HT_{RL}} = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \]

\[ g_{HTT} = -\frac{\lambda_1 \lambda_2}{(\lambda_1^2 + \lambda_2^2)^{3/2}} \frac{v}{f}, \]

\[ g_{HHTT} = -\frac{1}{f} \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \]

\[ g_{HHtt} = \frac{m_t}{f^2} \frac{\lambda_1^2}{\lambda_1^2 + \lambda_2^2 - 4f v'/v^2}, \]

\[ g_{HT_{RL}} = -\frac{\lambda_1 \lambda_2^3}{(\lambda_1^2 + \lambda_2^2)^{3/2}} \frac{v}{f}, \]
$MSSM: \lambda_{hhh} = 3 \cos(2\alpha) \sin(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\cos^3 \alpha}{\sin \beta}$

$\lambda_{Hhh} = 2 \sin(2\alpha) \sin(\beta + \alpha) - \cos(2\alpha) \cos(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\sin \alpha \cos^2 \alpha}{\sin \beta}$

$\lambda_{HHh} = -2 \sin(2\alpha) \cos(\beta + \alpha) - \cos(2\alpha) \sin(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\sin^2 \alpha \cos \alpha}{\sin \beta}$

$\lambda_{HHH} = 3 \cos(2\alpha) \cos(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\sin^3 \alpha}{\sin \beta}$

$\lambda_{hAA} = \cos(2\beta) \sin(\beta + \alpha) + \frac{\epsilon}{M_Z^2} \frac{\cos \alpha \cos^2 \beta}{\sin \beta}$

$\lambda_{HAA} = -\cos(2\beta) \cos(\beta + \alpha) + \frac{\epsilon}{M_Z^2} \frac{\sin \alpha \cos^2 \beta}{\sin \beta}$
general 2HDM

\[ \lambda_{{h^0_{h^0_{h^0}}} } : \]
\[ - \frac{3}{\sin 2\beta} \left[ \frac{4 \cos(\alpha + \beta) \cos^2(\beta - \alpha) m^2_{12}}{\sin 2\beta} - m^2_{h^0} (2 \cos(\alpha + \beta) + \sin 2\alpha \sin(\beta - \alpha)) \right] \]
\[ = 3m^2_{h^0} + \xi^2 \left[ \frac{9m^2_{h^0}}{2} - \frac{12m^2_{12}}{\sin 2\beta} \right] + \mathcal{O}(\xi^3) \]

\[ \lambda_{{h^0_{h^0_{H^0}}} } : \]
\[ \frac{\cos(\beta - \alpha)}{\sin 2\beta} \left[ \sin 2\alpha \left( 2m^2_{h^0} + m^2_{H^0} \right) - \frac{2m^2_{12}}{\sin 2\beta} (3 \sin 2\alpha - \sin 2\beta) \right] \]
\[ = -\xi \left( 2m^2_{h^0} + m^2_{H^0} - \frac{8m^2_{12}}{\sin 2\beta} \right) - \frac{2\xi^2}{\tan 2\beta} \left( 2m^2_{h^0} + m^2_{H^0} - \frac{6m^2_{12}}{\sin 2\beta} \right) + \mathcal{O}(\xi^3) \]

\[ \lambda_{{H^0_{H^0_{h^0}}} } : \]
\[ - \frac{\sin(\beta - \alpha)}{\sin 2\beta} \left[ \sin 2\alpha \left( m^2_{h^0} + 2m^2_{H^0} \right) - \frac{2m^2_{12}}{\sin 2\beta} (3 \sin 2\alpha + \sin 2\beta) \right] \]
\[ = m^2_{h^0} + 2m^2_{H^0} - \frac{4m^2_{12}}{\sin 2\beta} + \frac{2\xi}{\tan 2\beta} \left( m^2_{h^0} + 2m^2_{H^0} - \frac{6m^2_{12}}{\sin 2\beta} \right) \]
\[ + \xi^2 \left( \frac{14m^2_{12}}{\sin 2\beta} - \frac{5}{2} (m^2_{h^0} + 2m^2_{H^0}) \right) + \mathcal{O}(\xi^3) \]

\[ \lambda_{{H^0_{H^0_{H^0}}} } : \]
\[ - \frac{3}{\sin 2\beta} \left[ \frac{m^2_{H^0} (\cos(\beta - \alpha) \sin 2\alpha - 2 \sin(\alpha + \beta)) + \frac{4m^2_{12} \sin(\alpha + \beta) \sin^2(\beta - \alpha)}{\sin 2\beta} }{\tan 2\beta} \right] \]
\[ = \frac{-6}{\tan 2\beta} \left[ \frac{m^2_{H^0} - 2m^2_{12}}{\sin 2\beta} \right] + \xi \left( m^2_{H^0} - \frac{12m^2_{12}}{\sin 2\beta} \right) \]
\[ + \frac{3\xi^2}{\tan 2\beta} \left( m^2_{H^0} - \frac{6m^2_{12}}{\sin 2\beta} \right) + \mathcal{O}(\xi^3) \]
1. Triangle topologies, which give rise to $\mathcal{O}(G_F \alpha_s \hat{g}_q)$ contributions through the s-channel exchange of (at least) one neutral Higgs boson. The Higgs boson couples to the gluons via the usual heavy-quark loops.

2. Box topologies, which contribute at $\mathcal{O}(G_F \alpha_s \hat{g}^2_q)$ through the virtual heavy quark exchange.

2HDM NLO Feynman Diagram example
\[
\lambda_{h^0h^0h^0} : - \frac{3}{\sin 2\beta} \left[ \frac{4 \cos(\alpha + \beta) \cos^2(\beta - \alpha) m_{12}^2}{\sin 2\beta} - m_{h^0}^2 (2 \cos(\alpha + \beta) + \sin 2\alpha \sin(\beta - \alpha)) \right] \\
= 3m_{h^0}^2 + \xi^2 \left[ \frac{9m_{h^0}^2}{2} - \frac{12m_{12}^2}{\sin 2\beta} \right] + \mathcal{O}(\xi^3)
\]

\[
\lambda_{h^0h^0H^0} : \frac{\cos(\beta - \alpha)}{\sin 2\beta} \left[ \sin 2\alpha \left( 2m_{h^0}^2 + m_{H^0}^2 \right) - \frac{2m_{12}^2}{\sin 2\beta} (3 \sin 2\alpha - \sin 2\beta) \right] \\
= -\xi \left( 2m_{h^0}^2 + m_{H^0}^2 - \frac{8m_{12}^2}{\sin 2\beta} \right) - \frac{2\xi^2}{\tan 2\beta} \left( 2m_{h^0}^2 + m_{H^0}^2 - \frac{6m_{12}^2}{\sin 2\beta} \right) + \mathcal{O}(\xi^3)
\]

\[
\lambda_{H^0H^0h^0} : - \frac{\sin(\beta - \alpha)}{\sin 2\beta} \left[ \sin 2\alpha \left( m_{h^0}^2 + 2m_{H^0}^2 \right) - \frac{2m_{12}^2}{\sin 2\beta} (3 \sin 2\alpha + \sin 2\beta) \right] \\
= m_{h^0}^2 + 2m_{H^0}^2 - \frac{4m_{12}^2}{\sin 2\beta} + \frac{2\xi}{\tan 2\beta} \left( m_{h^0}^2 + 2m_{H^0}^2 - \frac{6m_{12}^2}{\sin 2\beta} \right) \\
+ \xi^2 \left( \frac{14m_{12}^2}{\sin 2\beta} - \frac{5}{2} \left( m_{h^0}^2 + 2m_{H^0}^2 \right) \right) + \mathcal{O}(\xi^3)
\]

\[
\lambda_{H^0H^0H^0} : - \frac{3}{\sin 2\beta} \left[ \frac{m_{h^0}^2 \left( \cos(\beta - \alpha) \sin 2\alpha - 2 \sin(\alpha + \beta) \right) + \frac{4m_{12}^2 \sin(\alpha + \beta) \sin^2(\beta - \alpha)}{\sin 2\beta}}{\sin 2\beta} \right] \\
= -\frac{6}{\tan 2\beta} \left[ m_{h^0}^2 - \frac{2m_{12}^2}{\sin 2\beta} \right] + \xi \left( \frac{9m_{h^0}^2}{\sin 2\beta} - \frac{12m_{12}^2}{\sin 2\beta} \right) \\
+ \frac{3\xi^2}{\tan 2\beta} \left( 3m_{h^0}^2 - \frac{6m_{12}^2}{\sin 2\beta} \right) + \mathcal{O}(\xi^3)
\]
Higgs self coupling RG evolution at one loop

with various Top Yukawa coupling

\[ 16\pi^2 \frac{d\lambda}{d\ln \mu} = 24\lambda^2 + 12\lambda y_t^2 - 9\lambda(g^2 + \frac{1}{3}g'^2) \]

\[ - 6y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2. \]

\[ m_H = 125.7 \text{ GeV} \]

\[ M_h \approx \sqrt{2\lambda (\mu = M_h)v} \]
SM Higgs potential

\[
\lambda_{hh}^{(0,SM)} = \frac{3m_h^2}{v}, \quad \lambda_{hhh}^{(0,SM)} = \frac{3m_h^2}{v^2}
\]

\[
V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad \text{EWSB} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\lambda}{2}} m_h h^3 + \frac{\lambda}{4} h^4
\]

\[
m_h = \frac{\lambda v^2}{2}, v^2 = \frac{\mu^2}{\lambda}
\]

Study the Higgs self coupling
reveal the EWSB

General 2HDM Higgs potential

\[
V = \frac{1}{2} \mu_1^2 (\Phi_1^\dagger \Phi_1) - \mu_2 (\Phi_1^\dagger \Phi_2) - m_{12}^2 (\Phi_1^\dagger \Phi_2) - m_{12}^2 (\Phi_2^\dagger \Phi_1)
+ \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)
+ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \frac{\lambda_6}{2} (\Phi_2^\dagger \Phi_1)^2 + \lambda_6^* (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_6^* (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)
+ \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \lambda_7^* (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2)
\]

2HDM Higgs self coupling example

\[
\lambda_{h^0 h^0 h^0} : - \frac{3}{\sin 2\beta} \left[ \frac{4 \cos \alpha + \beta \cos^2(\beta - \alpha)m_{12}^2}{\sin 2\beta} - m_{h^0}^2 (2 \cos(\alpha + \beta) + \sin 2\alpha \sin(\beta - \alpha)) \right]
\]

Composite Higgs model Higgs potential example

\[
V(h) = \alpha \cos \frac{h}{f} - \beta \sin^2 \frac{h}{f} \quad \text{MCHM4}
\]

\[
V(H) = V(<h>) + \frac{1}{2} M_H^2 H^2 + \frac{1}{6} \sqrt{1 - \xi} \lambda_{H^3}^{SM} H^3 + \frac{1}{24} \left( 1 - \frac{7}{3} \xi \right) \lambda_{H^4}^{SM} H^4
\]

\[
M_H^2 = \frac{4\beta^2 - \alpha^2}{2\beta f^2}
\]

\[
V(h) = \sin^2 \frac{h}{f} (\alpha - \beta \cos^2 \frac{h}{f}) \quad \text{MCHM5}
\]

\[
V(H) = V(<h>) + \frac{1}{2} M_H^2 H^2 + \frac{1}{6} \left( \frac{1 - 2\xi}{\sqrt{1 - \xi}} \right) \lambda_{H^3}^{SM} H^3 + \frac{1}{24} \left( \frac{3 - 28\xi(1 - \xi)}{3(1 - \xi)} \right) \lambda_{H^4}^{SM} H^4
\]

\[
M_H^2 = \frac{2(\beta^2 - \alpha^2)}{\beta f^2}
\]

different SM fermion transform representations, spinorial and fundamental
BG of HH
HH Production at the LHC, pMSSM, H→hh

<table>
<thead>
<tr>
<th>Point</th>
<th>Input Parameters</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{	ilde{q}}$ (GeV)</td>
<td>$M_A$ (GeV)</td>
</tr>
<tr>
<td>BP1</td>
<td>4350</td>
<td>272</td>
</tr>
<tr>
<td>BP2</td>
<td>5820</td>
<td>338</td>
</tr>
<tr>
<td>BP3</td>
<td>4125</td>
<td>449</td>
</tr>
<tr>
<td>BP4</td>
<td>4275</td>
<td>498</td>
</tr>
<tr>
<td>BP5</td>
<td>4275</td>
<td>599</td>
</tr>
</tbody>
</table>

Graphs showing the relationship between $M_A$ and $\lambda_{hhh}/\lambda_{hhh}^{	ext{SM}}$ for $\tan\beta = 5$, $M_S = 4275$ GeV and $\tan\beta = 2$, $M_S = 6000$ GeV. Additionally, histograms display the invariant mass of hh for different scenarios.
Higgs Production, Signal & BG

J. Baglio, A. Djouadi, R. Grber, M. M. Mhlleitner, J. Quevillon and M. Spira,

Normalized signal and backgrounds distributions in the $b\bar{b}\gamma\gamma$ channel.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$HH$</th>
<th>$b\bar{b}\gamma\gamma$</th>
<th>$t\bar{t}\gamma\gamma$</th>
<th>$ZH$</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section NLO [fb]</td>
<td>$8.92 \times 10^{-2}$</td>
<td>$5.05 \times 10^{3}$</td>
<td>$1.39 \times 10^{-1}$</td>
<td>$3.33 \times 10^{-1}$</td>
<td>$1.77 \times 10^{-5}$</td>
<td>$6.87 \times 10^{-2}$</td>
</tr>
<tr>
<td>Reconstructed Higgs from $bs$</td>
<td>$4.37 \times 10^{-2}$</td>
<td>$4.01 \times 10^{2}$</td>
<td>$8.70 \times 10^{-2}$</td>
<td>$1.24 \times 10^{-3}$</td>
<td>$1.09 \times 10^{-4}$</td>
<td>$1.20 \times 10^{-1}$</td>
</tr>
<tr>
<td>Reconstructed Higgs from $\gamma s$</td>
<td>$3.05 \times 10^{-2}$</td>
<td>$1.78 \times 10^{-2}$</td>
<td>$2.48 \times 10^{-2}$</td>
<td>$3.73 \times 10^{-4}$</td>
<td>$1.69 \times 10^{-2}$</td>
<td>$1.24$</td>
</tr>
<tr>
<td>Cut on $M_{HH}$</td>
<td>$2.73 \times 10^{-2}$</td>
<td>$3.74 \times 10^{-2}$</td>
<td>$7.45 \times 10^{-3}$</td>
<td>$1.28 \times 10^{-4}$</td>
<td>$6.07 \times 10^{-1}$</td>
<td>$7.05$</td>
</tr>
<tr>
<td>Cut on $P_{T,H}$</td>
<td>$2.33 \times 10^{-2}$</td>
<td>$3.74 \times 10^{-2}$</td>
<td>$5.33 \times 10^{-3}$</td>
<td>$1.18 \times 10^{-4}$</td>
<td>$5.44 \times 10^{-1}$</td>
<td>$6.17$</td>
</tr>
<tr>
<td>Cut on $\eta_H$</td>
<td>$2.04 \times 10^{-2}$</td>
<td>$1.87 \times 10^{-2}$</td>
<td>$3.72 \times 10^{-3}$</td>
<td>$9.02 \times 10^{-5}$</td>
<td>$9.06 \times 10^{-1}$</td>
<td>$7.45$</td>
</tr>
<tr>
<td>Cut on $\Delta R(b, b)$</td>
<td>$1.71 \times 10^{-2}$</td>
<td>$0.00$</td>
<td>$3.21 \times 10^{-3}$</td>
<td>$7.44 \times 10^{-5}$</td>
<td>$5.21$</td>
<td>$16.34$</td>
</tr>
<tr>
<td>“Detector level”</td>
<td>$1.56 \times 10^{-2}$</td>
<td>$0.00$</td>
<td>$8.75 \times 10^{-3}$</td>
<td>$8.74 \times 10^{-3}$</td>
<td>$8.92 \times 10^{-1}$</td>
<td>$6.46$</td>
</tr>
</tbody>
</table>
Higgs Production, Signal & BG


Normalized signal and backgrounds distributions in the $b\bar{b}\tau\tau$ channel.

<table>
<thead>
<tr>
<th></th>
<th>$H H$</th>
<th>$b\bar{b}\tau\tau$</th>
<th>$b\bar{b}\tau\nu_\tau\bar{\nu}_\tau$</th>
<th>$Z H$</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section NLO [fb]</td>
<td>2.47</td>
<td>$2.99 \times 10^4$</td>
<td>$8.17 \times 10^3$</td>
<td>$2.46 \times 10^1$</td>
<td>$6.48 \times 10^{-5}$</td>
<td>$6.93 \times 10^{-1}$</td>
</tr>
<tr>
<td>Reconstructed Higgs from $\tau s$</td>
<td>$2.09 \times 10^{-1}$</td>
<td>$8.35 \times 10^1$</td>
<td>$1.58 \times 10^2$</td>
<td>$5.70 \times 10^{-1}$</td>
<td>$8.63 \times 10^{-4}$</td>
<td>$7.36 \times 10^{-1}$</td>
</tr>
<tr>
<td>Reconstructed Higgs from $bs$</td>
<td>$1.46 \times 10^{-1}$</td>
<td>$6.34 \times 10^{-1}$</td>
<td>$1.43 \times 10^1$</td>
<td>$3.75 \times 10^{-2}$</td>
<td>$9.75 \times 10^{-3}$</td>
<td>$2.07$</td>
</tr>
<tr>
<td>Cut on $M_{HH}$</td>
<td>$1.30 \times 10^{-1}$</td>
<td>$1.37 \times 10^{-1}$</td>
<td>$1.74$</td>
<td>$1.26 \times 10^{-2}$</td>
<td>$6.88 \times 10^{-2}$</td>
<td>$5.18$</td>
</tr>
<tr>
<td>Cut on $P_{T,H}$</td>
<td>$1.10 \times 10^{-1}$</td>
<td>$7.80 \times 10^{-2}$</td>
<td>$7.17 \times 10^{-1}$</td>
<td>$1.15 \times 10^{-2}$</td>
<td>$1.36 \times 10^{-1}$</td>
<td>$6.71$</td>
</tr>
</tbody>
</table>

With $112.5 \text{ GeV} < M_{\tau\tau} < 137.5 \text{ GeV}$ | $1.10 \times 10^{-1}$ | $3.41 \times 10^{-2}$ | $3.76 \times 10^{-1}$ | $3.15 \times 10^{-3}$ | $2.67 \times 10^{-1}$ | $9.37$ |
**Higgs Production, Signal & BG**

J. Baglio, A. Djouadi, R. Grber, M. M. Mhlleitner, J. Quevillon and M. Spira,

**Normalized signal and backgrounds distributions in the b$^-$bWW channel.**

![Graphs showing normalized distributions for signal and backgrounds](image)

<table>
<thead>
<tr>
<th></th>
<th>$HH$</th>
<th>$b\bar{b}l_1\nu_1l_2\nu_2$</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section NLO [fb]</td>
<td>$3.92 \times 10^{-1}$</td>
<td>$2.41 \times 10^4$</td>
<td>$1.63 \times 10^{-5}$</td>
<td>$1.38 \times 10^{-1}$</td>
</tr>
<tr>
<td>Reconstructed Higgs from $bs$</td>
<td>$6.18 \times 10^{-2}$</td>
<td>$1.89 \times 10^2$</td>
<td>$3.27 \times 10^{-4}$</td>
<td>$2.46 \times 10^{-1}$</td>
</tr>
<tr>
<td>Cut on $M_T$</td>
<td>$6.18 \times 10^{-2}$</td>
<td>$1.19 \times 10^2$</td>
<td>$5.19 \times 10^{-4}$</td>
<td>$3.10 \times 10^{-1}$</td>
</tr>
<tr>
<td>Cut on $\Delta\phi_{\ell_1\ell_2}$</td>
<td>$5.37 \times 10^{-2}$</td>
<td>$6.96 \times 10^1$</td>
<td>$7.72 \times 10^{-4}$</td>
<td>$3.53 \times 10^{-1}$</td>
</tr>
<tr>
<td>Cut on $\Delta\theta_{\ell_1\ell_2}$</td>
<td>$5.17 \times 10^{-2}$</td>
<td>$5.65 \times 10^1$</td>
<td>$9.15 \times 10^{-4}$</td>
<td>$3.77 \times 10^{-1}$</td>
</tr>
<tr>
<td>Cut on $E_T^{miss}$</td>
<td>$8.41 \times 10^{-3}$</td>
<td>$3.77 \times 10^{-1}$</td>
<td>$2.22 \times 10^{-2}$</td>
<td>$7.50 \times 10^{-1}$</td>
</tr>
<tr>
<td>Cut on $\hat{E}_T^{miss}$</td>
<td>$4.59 \times 10^{-3}$</td>
<td>$2.70 \times 10^{-2}$</td>
<td>$1.70 \times 10^{-1}$</td>
<td>$1.53$</td>
</tr>
</tbody>
</table>