Scalar boson self-coupling

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Mainly based on:
Andreas Papaefstathiou, Li Lin Yang, JZ: PRD 87 (2013) 011301 [arXiv 1209.1489]
Florian Goertz, Andreas Papaefstathiou, Li Lin Yang, JZ:

Scalar boson (H) potential: self couplings

After EWSB: \[ V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4. \]
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- Single boson:  
  \[ M_H \approx 125 \text{ GeV} \]  
  Is it the SM Higgs? Need to measure its properties.
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- HHH prod. very difficult @ HC \[ \sigma_{HHH} = 0.06(9.5) \text{ fb} \text{ 14 TeV LHC (200 TeV VLHC).} \]

  Plehn, Rauch, Phys. Rev D 72, 053008.

Linear Collider? TESLA TDR (hep-ph/0106315) \( \sim 1000 \text{ fb}^{-1} \) for 20% accuracy.
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- **Linear Collider?** TESLA TDR (hep-ph/0106315) \( \sim 1000 \) fb\(^{-1}\) for 20% accuracy.

- **Trilinear coupling (double scalar boson production): this talk!**
  - In the SM: \( \lambda^{SM}_{HHH} = \lambda^{SM}_{HHHH} = (M_H^2/2v^2) \approx 0.13 \) \( \rightarrow \) We want to verify it!
  - Throughout the talk: \( \lambda = \lambda^{SM}_{HHH}/\lambda^{SM}_{HHHH} \) and \( y_t = g_{Htt}/g_{Htt}^{SM} \).

**Disclaimer:** No BSM in this talk! (rather active field in the recent past, incomplete list below)

Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer [1205.5444]; Gillioz, Grober, Grojean, Muhlleitner, Salvioni [1206.7120]; Kribs, Martin [1207.4496]; Dawson, Furlan, Lewis [1210.6663]; Dolan, Englert, Spannowsky [1210.8166]; Englert, Re, Spannowsky [1302.6506]; Goutzevich, Oliveira, Rojo, Rosenfeld, Salam, Sanz [1303.3663]; Craig, Galloway, Thomas, [1303.2424]; Killick, Kumar, Logan, [1305.7236]; Gupta, Rzhak, Wells, [1305.6397]; Nhung, Muhlleitner, Streicher, Walz [1306.3926]; Choi, Englert, Zerwas [1308.784]; Nishiwaku, Noyogi, Shivaji [1309.6907]; Liu, Wang, Zhu [1310.3634]; Ramsey-Musolf, No [1310.6035]; Enkhbat [1311.4445]; Heng, Shang, Zhang, Zhu [312.4260], Hespel, Lopez-Val, Vryonidou [1407.0281], Bhattacharkee, Choudhury [1407.6866] + many others
Scalar boson pairs: 
production and decay
Cross sections, events and decay rates @ 14 TeV LHC

**Cross sections**
- Gluon fusion is dominant (> 90%) in 120-130 GeV, VBF also interesting.
- K-fac ~ 2 (2.3) LO (NLO), th. unc. 30 (20) [8] % @ LO (NLO) [NNLO].

<table>
<thead>
<tr>
<th>LO</th>
<th>NLO</th>
</tr>
</thead>
</table>

**NLO exp. top mass**: Grigo, Hoff, Melnikov and Steinhauser, 1305.7340
**NNLL+NLO**: D. Shao, C. Li, H. Li, J. Wang, 1301.1245.
**NNLO heavy top**: De Florian, Mazzitelli, 1305.5206, 1309.6594

**Event generation**
- Events can be generated with MG5 and Herwig++ (public).
- Matching to PS @ NLO:
  - **MG5_aMC@NLO**: Frederix et al, 1401.7340.
  - **Open Loops + Herwig++**: Maierhöfer, Papaefstathiou, 1401.0007

**Total rates**
- Hadronic decays dominate.
- Total rate for $b\bar{b}\tau^+\tau^-$ and $b\bar{b}l\nu jj$ ~2.4 fb. $b\bar{b}\gamma\gamma$ ~ 0.087 fb.

A. Papaefstathiou, L. L. Yang, JZ, PRD 87 (2013) 011301
Dissecting HH cross section

2 topologies, each with 2 Lorentz structures (1 and 2):

\[ \sigma_{LO} = |\alpha_1 C_{tri}^{(1)} + \beta_1 C_{box}^{(1)}|^2 + \gamma_1^2 |C_{box}^{(2)}|^2 \]

SM: \[ \alpha_1 = y_t \lambda \]
\[ \beta_1 = \gamma_1 = y_t^2 \]

Our fit: \[ \sigma_{HH}^{NLO}[fb] = 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(\lambda y_b y_t^2) . \]

(MSTW2008) Goertz, Papaefstathiou, Yang, JZ (arXiv: 1301.3492)

• Triangle diagram subdominant due to off-shell s-channel Higgs boson.
• Minimum for \( \lambda \sim 2.4 \ y_t \).
• Cross section is very sensitive to actual value of \( y_t \).
• Bottom loop effects 0.2 % in the SM (up to 2% for currently allowed ranges).
Final states @ 14 TeV LHC

<table>
<thead>
<tr>
<th>Process</th>
<th>S (600 fb⁻¹)</th>
<th>B (600 fb⁻¹)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbτ⁺τ⁻</td>
<td>50</td>
<td>104</td>
<td>4.5</td>
</tr>
<tr>
<td>bbW⁺W⁻</td>
<td>12</td>
<td>8</td>
<td>4.1</td>
</tr>
<tr>
<td>bbγγ</td>
<td>9</td>
<td>11</td>
<td>2.4</td>
</tr>
<tr>
<td>bbγγ</td>
<td>6</td>
<td>12.5</td>
<td>1.5</td>
</tr>
<tr>
<td>bbbb</td>
<td>50</td>
<td>2500</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Benefits from new techniques in jet physics:
  \[ \bar{b}b\tau^+\tau^-, \bar{b}bW^+W^- \] exploit jet substructure.
  \[ \bar{b}\bar{b}\bar{b}\bar{b} \] based on shower deconstruction.

- What if we combine channels?

<table>
<thead>
<tr>
<th>Channel</th>
<th>Evidence</th>
<th>Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbτ⁺τ⁻</td>
<td>270 fb⁻¹</td>
<td>730 fb⁻¹</td>
</tr>
<tr>
<td>Combination</td>
<td>140 fb⁻¹</td>
<td>350 fb⁻¹</td>
</tr>
</tbody>
</table>

Goertz, Papaefstathiou, Yang, JZ, in progress

Dolan, Englert, Spannowsky, 1206.5001
Papaefstathiou, L. L. Yang, JZ, 1209.1489.
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira:1212.5581.
Ferreira de Lima, Papaefstathiou, Spannowsky:1404.7139.

Soper, Spannowsky, 1102.3480.
Double to single scalar boson cross section ratio
Cross section ratio

\[ C_{HH} = \frac{\sigma(gg \to HH)}{\sigma(gg \to H)} \equiv \frac{\sigma_{HH}}{\sigma_H} \]

Djouadi, arXiv 1208.3436

- The bulk of the QCD corrections for both processes comes from real radiation from initial state gluons, hence we expect the ratio to be more stable against higher order corrections.

- Moreover, common systematic uncertainties will cancel out (i.e. luminosity).

\[ \sqrt{s} = 14 \text{ TeV}, \ 0.5 \mu_0 < \mu < 2.0 \mu_0, \ LO \ (MSTW2008lo68cl) \]

\[ \sigma_H \quad 20 \% \ (\text{scale}) \]

\[ \sigma_{HH} \quad 25 \% \ (\text{scale}) \]

\[ C_{HH} \quad 9 \% \ (\text{scale}) \text{ 2-3\% (PDF)} \]

\[ \sqrt{s} = 14 \text{ TeV}, \ 0.5 \mu_0 < \mu < 2.0 \mu_0, \ NLO \ (MSTW2008nlo68cl) \]

\[ \sigma_H \quad 16 \% \ (\text{scale}) \]

\[ \sigma_{HH} \quad 17 \% \ (\text{scale}) \]

\[ C_{HH} \quad 1.5 \% \ (\text{scale}) \text{ 2 \% (PDF)} \]

F. Goertz, A. Papaefstathiou, L. L. Yang, JZ (arXiv: 1301.3492)
Scalar boson self coupling at the LHC
Measuring the scalar boson self coupling

1 - Traditional method: fitting a distribution

![Graph showing the visible invariant mass distribution, \( m_{\text{vis}} \), in \( pp \to b\bar{b}\gamma\gamma \), LHC with \( m_H = 120 \text{ GeV} \).]

- A few events in a few bins: poor statistics.

(see also Chen, Low, 1405.7040)

2- Alternative: event count (more “shape-independent”)

- We measure N events, and we expected B background events.
- Assuming Gaussian distribution, \( S = N - B \), \( \Delta S = \sqrt{N + B} \).
- We draw 1 and 2\( \sigma \) exclusion contours (68 % and 95 % C.L).
Exploiting the ratio

\[
\begin{align*}
\sigma_{HH}^{b\bar{b}xx} & \equiv \sigma_{HH} \times 2 \times \text{BR}(b\bar{b}) \times \text{BR}(xx) \\
\sigma_{H}^{b\bar{b}} & \equiv \sigma_{H} \times \text{BR}(b\bar{b})
\end{align*}
\]

\[
C_{HH}^{\text{exp.}} = \left. \frac{\sigma_{HH}^{b\bar{b}xx}}{2 \times \sigma_{H}^{b\bar{b}} \times \text{BR}(xx)} \right|_{\exp.}
\]

- Uncertainties assumed:
  
  \(y_t \sim 20\%\) after 300/fb at 14 TeV LHC.
  
  \(h \rightarrow (\tau^+\tau^-, W^+W^-, \gamma\gamma) = (12, 12, 16)\%\)

- Assume no further improvement beyond 300/fb (conservative).

- Combine all errors in quadrature:

\[
\left( \frac{\Delta C_{HH}}{C_{HH}} \right)^2 = \left( \frac{\Delta \sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}} \right)^2 + \left( \frac{\Delta \text{BR}(xx)}{\text{BR}(xx)} \right)^2 + \left( \frac{\Delta \sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}} \right)^2 + \text{("theory" errors)}^2.
\]

CMS collaboration,

“CMS at the High Energy Frontier”

(Contribution to the Update of the European Strategy for Particle Physics, Aug 2012)
Constraining the self-coupling

• Given an assumption for the “true” value of the self-coupling ($\lambda_{\text{true}}$) what is the constraint we can impose on $\lambda$?

1σ : $\lambda \in (0.57 - 1.64)$

2σ : $\lambda \in (0.22 - 4.70)$

1σ : $\lambda \in (0.54 - 1.78)$

2σ : $\lambda \in (0.17 - 4.75)$
Exclusion intervals

<table>
<thead>
<tr>
<th>Process</th>
<th>600 fb$^{-1}$ (2$\sigma$)</th>
<th>600 fb$^{-1}$ (1$\sigma$)</th>
<th>3000 fb$^{-1}$ 2$\sigma$</th>
<th>3000 fb$^{-1}$ 1$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb\tau^+\tau^-$</td>
<td>(0.22, 4.70)</td>
<td>(0.57, 1.64)</td>
<td>(0.42, 2.13)</td>
<td>(0.69, 1.40)</td>
</tr>
<tr>
<td>$bbW^+W^-$</td>
<td>(0.04, 4.88)</td>
<td>(0.46, 1.95)</td>
<td>(0.36, 4.56)</td>
<td>(0.65, 1.46)</td>
</tr>
<tr>
<td>$bb\gamma\gamma$</td>
<td>(-0.56, 5.48)</td>
<td>(0.09, 4.83)</td>
<td>(0.08, 4.84)</td>
<td>(0.48, 1.87)</td>
</tr>
</tbody>
</table>

Table 1: The expected limits at 1$\sigma$ and 2$\sigma$ confidence levels, provided that $\lambda_{true}$ and $y_{t, true}$ have their SM values: $\lambda_{true} = 1$, $y_{t, true} = 1$. The results have been derived using $C_{HH}$ and are shown for 600 fb$^{-1}$ and 3000 fb$^{-1}$.

Naive combination, $\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$, gives $\pm 20\%$. (adding 4$b$ channel, not shown here)

• Compare to:

LHC: (0.26-1.94) $\sqrt{s} = 14$ TeV, 600 fb$^{-1}$ (1$\sigma$) Baur, Plehn, Rainwater, Phys.Rev. D69 (2004) 053004

ILC: (0.76-1.24) $\sqrt{s} = 1$ TeV, 1000 fb$^{-1}$

Varying Yukawa top

$\bar{b}b\tau^+\tau^-$ channel, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

\begin{align*}
y_t &= 0.85 \quad \lambda \in (0.2 - 1.1) \\
y_t &= 1.15 \quad \lambda \in (1.1 - 2.5)
\end{align*}

No overlap!

F. Goertz, A. Papaefstathiou, L. L. Yang, JZ (arXiv: 1301.3492)
Scalar boson pair production in Effective Field Theory (HEFT)
Lagrangean and couplings

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\bar{c}_H}{2v^2}(\partial^\mu |H|^2)^2 - \frac{\bar{c}_6}{v^2}v|H|^6 + \left\{ -\frac{\bar{c}_u}{v^2}y_u |H|^2 \bar{Q}_L H c_R - \frac{\bar{c}_d}{v^2}y_d |H|^2 \bar{Q}_L H d_R - \frac{\bar{c}_l}{v^2}y_l |H|^2 \bar{L}_L H e_R + \text{h.c.} \right\} \]

\[ + \frac{\alpha_s \bar{c}_g}{4\pi v^2} |H|^2 G^a_{\mu\nu} G^a_{\mu\nu} + \frac{g'^2}{v^2} |H|^2 B_{\mu\nu} B^{\mu\nu} + \frac{ig \bar{c}_{HW}}{v^2} (D^\mu H)^\dagger \sigma_k (D^\nu H) W^k_{\mu\nu} \]

\[ + \frac{ig'}{v^2} (D^\mu H)^\dagger (D^{\nu} H) B_{\mu\nu} + \frac{ig}{2v^2} (H^\dagger \sigma_k \rightarrow D^\mu H) D^{\nu} W^k_{\mu\nu} + \frac{ig'}{2v^2} (H^\dagger \rightarrow \bar{D}^\mu H) \partial^{\nu} B_{\mu\nu} \]

See (recent) e.g: Passarino (1209.5538), Buchalla, Cata, Krause (1307.5017), Alloul, Fuks, Sanz (1310.5150) and refs therein.

\[ \bar{c}_{HB} = -\bar{c}_{HW} = \bar{c}_W = -\bar{c}_B \quad \text{Elias-Miro, Espinosa, Masso, Pomarol (1308.1879).} \]

“Extended kappa framework” for double scalar boson production:

\[ \mathcal{L} \supset - \frac{m^2_h}{2v} \kappa_h h^3 - \frac{m^2_h}{8v^2} \kappa_{hh} h^4 + \left( \kappa_g \frac{h}{v} + \kappa_{2g} \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^a_{\mu\nu} - \sum_{f=b,t,\tau,...} \frac{m_f}{v} \bar{f}_L f_R \left( \kappa_f \frac{h}{v} + \kappa_{2f} \frac{h^2}{v^2} \right) \]

<table>
<thead>
<tr>
<th>Process</th>
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</tr>
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<tbody>
<tr>
<td>( h \rightarrow bb )</td>
<td>( \bar{c}_H, \bar{c}_d )</td>
</tr>
<tr>
<td>( h \rightarrow \tau\tau )</td>
<td>( \bar{c}_H, \bar{c}_l )</td>
</tr>
<tr>
<td>( h \rightarrow \gamma\gamma )</td>
<td>( \bar{c}_\gamma )</td>
</tr>
<tr>
<td>( h \rightarrow WW )</td>
<td>( \bar{c}<em>H, \bar{c}</em>{HW}, \bar{c}_W )</td>
</tr>
<tr>
<td>( gg \rightarrow h )</td>
<td>( \bar{c}_H, \bar{c}_g, \bar{c}_t )</td>
</tr>
<tr>
<td>( gg \rightarrow hh )</td>
<td>( \bar{c}_H, \bar{c}_g, \bar{c}_t, \bar{c}_6 )</td>
</tr>
</tbody>
</table>

Only place where \( \bar{c}_6 \) shows up!

Varying the trilinear coupling only is consistent with the EFT framework
BRs computed with eHDECAY Contino, Ghezzi, Grojean, Mühlleitner, Spira, 1303.3876, 1403.3381.

Compatibility with scalar boson data using HiggsBounds and HiggsSignals Bechtle et al, 1311.0055, 1305.1933.

EFT analysis

Our fit (MSTW)

\[
\frac{\sigma(gg \to hh)}{\sigma(gg \to hh)_{SM}} = 2.1\kappa_t^4 - 1.4\kappa_t^3\kappa_\lambda + 0.3\kappa_t^2\kappa_\lambda^2 + \kappa_g(0.05\kappa_\lambda^2 - 0.03\kappa_\lambda + 24.4) - 8.3\kappa_g\kappa_t^2
\]

\[+ \kappa_g\kappa_\lambda(2.8\kappa_t^2 - 0.5\kappa_\lambda\kappa_t + 1.5\kappa_t - 2.2\kappa_2t) + \kappa_2t(21.7\kappa_g + 3.1\kappa_\lambda\kappa_t - 8.8\kappa_t^2 + 8.9\kappa_2t)\]

Linearizing:

\[
\frac{\sigma(gg \to hh)}{\sigma(gg \to hh)_{SM}} = 1 + 1.6c_h - 0.8c_6 - 4.5c_g - 3.7c_t + \mathcal{O}(c_i^2)
\]

Large variations in the cross section still allowed by current SB data

Still a lot of room for surprises!

Goertz, Papaefstathiou, Yang, JZ, in preparation.
Conclusions

• We have considered the double to single scalar boson cross section ratio, $C_{HH}$, at the 14 TeV LHC, including scale and PDF uncertainties.

• The ratio is very stable under scale variation (1.5 % @ NLO), while the cross section itself has a 20 % theory uncertainty.

• We have derived exclusion limits for the trilinear scalar boson self coupling using the available channels, obtaining a 20% accuracy for the SM case.

• To measure it is crucial to know $y_t$ with a high accuracy.

• The channels used here have to be studied in more realistic environment (including detector simulation, underlying event, pile up, efficiencies, etc...)

• We have shown preliminary results for the EFT analysis, large effects still allowed in spite of a “SM-look-alike” scalar boson.