Probing New Physics of Cubic Higgs Interaction

Jing Ren
University of Toronto

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Based on H.J. He (Tsinghua), JR, W. Yao (LBNL), 1506.03302
Outline

- Motivation

- New physics v.s. Higgs self-interactions
  - Strong first order electroweak phase transition (SFOEWPT)
  - Higgs non-minimal gravitational interaction

- Probing new cubic Higgs interactions on hadron collider
  - Effective theory with dim=6 operators
  - Higgs pair production on hadron collider
Higgs Discovery

- We now have the 125GeV SM-like Higgs with LHC Run I
- But no convincing evidence from new physics search
Higgs Discovery

- We now have the 125GeV SM-like Higgs with LHC Run I
- But no convincing evidence from new physics search
- Higgs as the window for new physics
Less Known Higgs Potential

SM Higgs potential

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- EWSB: $\mu^2, \lambda$ fixed by $v = 246\text{GeV}, M_h = 125\text{GeV}$
- EWPT: far from first order, (~cross-over)
- Self-couplings: $\lambda_3 = 3M_h^2/v, \lambda_4 = 3M_h^2/v^2$

Higgs self-couplings measurement

- Dihiggs production to probe $\lambda_3$
  - ~ 27% accuracy on ILC @500GeV [arXiv:1506.05992] [See Jianming Qian’s talk]
  - ~ 35% accuracy on CEPC5 (careful!) [McCullough, arXiv:1312.3322]

- TriHiggs production to probe $\lambda_4$: much more challenging [Plehn, Rauch, PRD 72 (2005) 053008]

Higgs self-interactions as the window to new physics
New Physics v.s. Higgs Self-Interactions
Strong first order EWPT (SFOEWPT)

- Correlation between SFOEWPT and cubic Higgs coupling

“Quantum” >20%

“Non-renormalizable” can be both >0 & <0

“Singlet”

[See M. Perelstein’s talk]  [See C. Wagner’s talk]  [See P. Winslow's talk]
Strong first order EWPT (SFOEWPT)

- Correlation between SFOEWPT and cubic Higgs coupling

- Resonance dihiggs production

[See M. Perelstein’s talk]
[See C. Wagner’s talk]
[See P. Winslow’s talk]
[See C. Chen’s talk]
Higgs non-minimal gravitational interaction

Joint effective action for SM and GR: \( S = S_{GR} + S_{SM} + S_{NMC} \)
Higgs non-minimal gravitational interaction

Joint effective action for SM and GR: \( S = S_{\text{GR}} + S_{\text{SM}} + \xi_h R H^\dagger H \)

\[
L \xrightarrow{\text{Einstein frame transformation}} \frac{3\xi_h^2}{M_{\text{Pl}}^2 \Omega^4} (\partial_\mu H^\dagger H)^2 + \frac{1}{\Omega^2} (D^\mu H)^\dagger (D_\mu H) - \frac{1}{\Omega^4} V(H) \quad \Omega^2 = 1 + \frac{2\xi_h H^\dagger H}{M_{\text{Pl}}^2}
\]

\[
\Delta L_6 = \frac{3\lambda}{\Lambda_{\xi_1}^2} (\partial_\mu H^\dagger H)^2 + \frac{4}{\Lambda_{\xi_2}^2} [\lambda (H^\dagger H)^3 + \cdots], \quad \Lambda_{\xi_1} = \frac{M_{\text{Pl}}}{\xi_h} \ll \Lambda_{\xi_2} = \frac{M_{\text{Pl}}}{\sqrt{\xi_h}}, \text{ if } \xi_h \gg 1
\]
Higgs non-minimal gravitational interaction

Joint effective action for SM and GR:

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\[ \Omega^2 = 1 + \frac{2\xi_h H^\dagger H}{M_{Pl}^2} \]

\[ \Delta L_6 = \frac{3\lambda}{\Lambda_{\xi_1}^2} (\partial_\mu H^\dagger H)^2 + \frac{4}{\Lambda_{\xi_2}^2} \left[ \lambda (H^\dagger H)^3 + \cdots \right], \quad \Lambda_{\xi_1} = \frac{M_{Pl}}{\xi_h} \ll \Lambda_{\xi_2} = \frac{M_{Pl}}{\sqrt{\xi_h}}, \quad \text{if } \xi_h \gg 1 \]

- Higgs rescaling induced by graviton-Higgs kinetic mixing

\[ \frac{6v^2}{\Lambda_{\xi_1}^2} \lesssim O(0.1) \Rightarrow |\xi_h| \lesssim 10^{15} \quad \text{(LHC bound)} \quad \Lambda_{UV} \lesssim \Lambda_{\xi_1} \quad \text{(Unitarity bound)} \]

- New derivative Higgs self-couplings: \( h\partial_\mu h\partial^\mu h \)

- Higgs inflation: extreme flat potential at large field

Slow roll:

\[ n_s \approx 1 - 2/N, \quad r_s \approx 12/N^2 \]

If \( \lambda \sim O(0.1), \ |\xi_h| \sim 10^4, \ \Lambda_{\text{INF}} \sim M_{Pl}/\sqrt{\xi_h} \sim 10^{16}\text{GeV} \]

Probing New Cubic Higgs Interactions
EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions:

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \]

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

\[ \mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger HH^\dagger (D_\mu H), \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H), \]

\[ \mathcal{O}_{\Phi,3} = \frac{1}{3} (H^\dagger H)^3, \quad \mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H). \]
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\[ \mathcal{O}_{\Phi,1} = (D^\mu H)^+ HH^+(D_\mu H), \]
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Violate custodial symmetry, negligible for collider study
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- Violate custodial symmetry, negligible for collider study
- Eliminated by EOM

- The 2d Parameter Space: \( (x_2, x_3) \)
  - Higgs-SM couplings rescaled by \( \zeta = (1 + x_2)^{-1/2} \)
  - Cubic Higgs coupling \( \lambda_3 = -i \frac{\zeta}{v} \left[ 3 (1 + \hat{r}) M_h^2 - \hat{x} (p_1^2 + p_2^2 + p_3^2) \right] \)

\[ \hat{r} \equiv -x_3 \frac{\zeta^2}{3M_h} \frac{2v^2}{M_h^2}, \quad \hat{x} \equiv x_2 \zeta^2 \]
EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions:
  \[ \mathcal{L}_{\text{eff}} = \sum_{n} \frac{f_n}{\Lambda^2} \mathcal{O}_n \]
  [Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

- \[ \mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H), \]
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  - Higgs-SM couplings rescaled by \(\zeta = (1 + x_2)^{-1/2}\)
  - Cubic Higgs coupling \(\lambda_3 = -\frac{i}{v} \left[ 3 (1 + \hat{r}) M_h^2 - \hat{x} \left( p_1^2 + p_2^2 + p_3^2 \right) \right] \)

- Treat \(\hat{r}, \hat{x}\) as two free inputs
  - Accidental cancelation with other operators in single higgs measurement
  - Nonlinear realization: “quadratic” & “cubic” correlation broken down
Dihiggs Production on Hadron Collider

Gluon fusion production

Vector boson fusion production

Top-pair associated production


NLO cross section in unit of fb

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$pp \rightarrow HH$</th>
<th>$pp \rightarrow HHjj$</th>
<th>$pp \rightarrow \bar{t}tHH$</th>
<th>$pp \rightarrow WHH$</th>
<th>$pp \rightarrow ZHH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>8.73</td>
<td>0.479</td>
<td>0.177</td>
<td>0.214</td>
<td>0.130</td>
</tr>
<tr>
<td>14</td>
<td>34.8</td>
<td>2.017</td>
<td>0.981</td>
<td>0.565</td>
<td>0.356</td>
</tr>
<tr>
<td>100</td>
<td>1186</td>
<td>79.6</td>
<td>87.8</td>
<td>7.90</td>
<td>5.18</td>
</tr>
</tbody>
</table>
Dihiggs Production on Hadron Collider

- **$gg \rightarrow hh$**
  \[
  \frac{\sigma}{\sigma_{\text{sm}}} \bigg|_{100\text{TeV}} = (1 - \hat{x})^2 \left( 1 - 0.72 \hat{r} + 3.6 \hat{x} + 0.22 \hat{r}^2 + 4.3 \hat{x}^2 - 1.7 \hat{r} \hat{x} \right)
  \]

- **$pp \rightarrow hhjj$**
  \[
  \frac{\sigma}{\sigma_{\text{sm}}} \bigg|_{100\text{TeV}} = (1 - \hat{x})^2 \left( 1 - 0.47 \hat{r} + 4.6 \hat{x} + 0.42 \hat{r}^2 + 38 \hat{x}^2 - 4.1 \hat{r} \hat{x} \right)
  \]

- **$pp \rightarrow t\bar{t}hh$**
  \[
  \frac{\sigma}{\sigma_{\text{sm}}} \bigg|_{100\text{TeV}} = (1 - \hat{x})^2 \left( 1 + 0.23 \hat{r} - 0.80 \hat{x} + 0.07 \hat{r}^2 + 2.2 \hat{x}^2 - 0.54 \hat{r} \hat{x} \right)
  \]

(dash, solid, dot) for $\hat{r} = (-1, 0, 1)$
Kinematic distributions @100 TeV

$gg \rightarrow hh$

$M_{hh}$ (GeV)

$pp \rightarrow t\bar{t}hh$

$M_{hh}$ (GeV)

$pp \rightarrow hhjj$ (VBF)
# Dihiggs Decay Channels

<table>
<thead>
<tr>
<th>Decay</th>
<th>Issues</th>
<th>Expectation 3000 ifb</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>• Signal small &lt;br&gt; • BKG large &amp; difficult to asses &lt;br&gt; • Simple reconst.</td>
<td>$S/B \simeq 1/3$&lt;br&gt;$S/\sqrt{B} \simeq 2.5$</td>
<td>[Baur, Plehn, Rainwater]&lt;br&gt;[Yao 1308.6302]&lt;br&gt;[Baglio et al. JHEP 1304]</td>
</tr>
<tr>
<td></td>
<td>(0.26%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>• tau rec tough &lt;br&gt; • largest bkg tt &lt;br&gt; • Boost+MT2 might help</td>
<td>differ a lot &lt;br&gt;$S/B \simeq 1/5$&lt;br&gt;$S/\sqrt{B} \simeq 5$</td>
<td>[Dolan, Englert, MS]&lt;br&gt;[Barr, Dolan, Englert, MS]&lt;br&gt;[Baglio et al. JHEP 1304]</td>
</tr>
<tr>
<td></td>
<td>(7.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b\bar{b}W^+W^-$</td>
<td>• looks like tt &lt;br&gt; • Need semilep. W to rec. two H &lt;br&gt; • Boost + BDT proposed</td>
<td>differ a lot &lt;br&gt;best case: &lt;br&gt;$S/B \simeq 1.5$&lt;br&gt;$S/\sqrt{B} \simeq 8.2$</td>
<td>[Dolan, Englert, MS]&lt;br&gt;[Baglio et al. JHEP 1304]&lt;br&gt;[Papaefstathiou, Yang, Zurita 1209.1489]</td>
</tr>
<tr>
<td></td>
<td>(25%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>• Trigger issue (high pT kill signal) &lt;br&gt; • 4b background large difficult with MC &lt;br&gt; • Subjets might help</td>
<td>$S/B \simeq 0.02$&lt;br&gt;$S/\sqrt{B} \leq 2.0$</td>
<td>[Dolan, Englert, MS]&lt;br&gt;[Ferreira de Lima, Papaefstathiou, MS]&lt;br&gt;[Wardrope et al, 1410.2794]</td>
</tr>
<tr>
<td></td>
<td>(33%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW^<em>WW^</em>$</td>
<td>• Many taus/W not clear if 2 Higgs &lt;br&gt; • Zs, photons no rate</td>
<td>$S/\sqrt{B} \sim 1.5\sigma$&lt;br&gt;(3l3vjj)</td>
<td>[Li, Li, Yan, Zhao, 1503.07611]&lt;br&gt;[Baur, Plehn, Rainwater, PRL 89, 151801 (2002)]</td>
</tr>
<tr>
<td></td>
<td>(3l3vjj, 2l±2v4j)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4.7%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**HL-LHC with 3ab$^{-1}$**<br>$S/\sqrt{B} = 1.3\sigma$<br>[ATL-PHYS-PUB-2014-019]**

Search in **tthh** and **VBF** channel,<br>[Liu, Zhang, 1410.1855]<br>[Dolan et al., 1506.08008]
Fast Simulation of $b\bar{b}\gamma\gamma@100\text{TeV}$

Events generation: Madgraph5, Pythia 6.2, Delphes 3

- Signal: include finite mt effect
- Background: include up to one extra parton with MLM matching
- Detector simulation based on ATLAS responses
  - Use anti-$k_T$ for jets with $\Delta R = 0.5$
  - $b$-tagging efficiency: 75%, 18.8%, and 1% for bottom, charm, and light favor jets in the central region
  - Photon identification efficiency: roughly 80% for photons with $E_T > 50\text{GeV}$ and $|\eta| < 2.5$ (HL-LHC: $E_T > 80\text{GeV}$)
  - Jet-faking-photon background: a faking probability of $f_j = 0.0093\exp(-E_T/27)$ as a function of jet $E_T$ in GeV, and scale the jet energy by $0.75 \pm 0.12$ as the photon energy
Fast Simulation of $b\bar{b}\gamma\gamma$ @100 TeV

- **Background:** $b\bar{b}\gamma\gamma$, $b\bar{b}h(\gamma\gamma)$, $Z(b\bar{b})h(\gamma\gamma)$, $\bar{t}th(\gamma\gamma)$, $jj\gamma$ (mis-tagging $b$ or $\bar{b}$)
  - $\bar{t}t\gamma\gamma$, $b\bar{b}j\gamma$, $b\bar{b}jj$, $\bar{t}t\gamma$ (jet-faking-photon)

- **Events selection**  
  - 2 bjets and b photon
    - $E_T > 25 \text{ GeV}$  
    - $|\eta| < 2.5$
    - $122 \text{ GeV} < M_{\gamma\gamma} < 128 \text{ GeV}$
    - $85 \text{ GeV} < M_{bb} < 135 \text{ GeV}$

- **Kinematic cuts**
  - $M_{bb\gamma\gamma} > 300 \text{ GeV}$
  - $\Delta R_{\gamma\gamma} < 2.5$, $\Delta R_{bb} < 2.0$
  - $p_T^{\gamma}, p_T^b > 35 \text{ GeV}$, $p_T^{\gamma}, p_T^{bb} > 100 \text{ GeV}$
  - $|\cos \theta_h| < 0.8$ (Higgs decay angle)
  - $\Sigma(njets + nphos + nleps + nmet) < 7$
Results

Signal and background at pp(100 TeV) with $L = 3 ab^{-1}$

<table>
<thead>
<tr>
<th>Samples</th>
<th>$\sigma \times$ BR (fb)</th>
<th>Generated Evt</th>
<th>Selected Evt</th>
<th>Accept</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h(bb)h(\gamma\gamma)$ (SM)</td>
<td>3.53</td>
<td>100000</td>
<td>3955</td>
<td>0.040</td>
<td>418.8 ± 6.6</td>
</tr>
<tr>
<td>$bbh(\gamma\gamma)$</td>
<td>50.49</td>
<td>99611</td>
<td>78</td>
<td>0.00078</td>
<td>118.6 ± 13.4</td>
</tr>
<tr>
<td>$Z(bb)h(\gamma\gamma)$</td>
<td>0.8756</td>
<td>68585</td>
<td>378</td>
<td>0.0055</td>
<td>14.5 ± 0.7</td>
</tr>
<tr>
<td>$tt\gamma(\gamma\gamma)$</td>
<td>37.26</td>
<td>63904</td>
<td>67</td>
<td>0.0010</td>
<td>117.2 ± 14.3</td>
</tr>
<tr>
<td>$tt\gamma$</td>
<td>335.8</td>
<td>150654</td>
<td>1</td>
<td>6.6e-06</td>
<td>6.75 ± 6.7</td>
</tr>
<tr>
<td>$tt\gamma$</td>
<td>108400</td>
<td>285787</td>
<td>0.013</td>
<td>4.7e-08</td>
<td>15.2 ± 3.2</td>
</tr>
<tr>
<td>$bb\gamma\gamma$</td>
<td>5037</td>
<td>763962</td>
<td>11</td>
<td>1.4e-05</td>
<td>217.6 ± 65.6</td>
</tr>
<tr>
<td>$bb\gamma\gamma$</td>
<td>8960000</td>
<td>1119406</td>
<td>0.0051</td>
<td>4.6e-09</td>
<td>123.6 ± 31.9</td>
</tr>
<tr>
<td>$jj\gamma\gamma$</td>
<td>164200</td>
<td>813797</td>
<td>0.056</td>
<td>6.9e-08</td>
<td>33.9 ± 3.8</td>
</tr>
<tr>
<td>Total background</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>647.3 ± 76.0</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Comparison:

Discrimination of Two Operators

- Utilize distribution in reconstructed $M_{hh}$ bins

$M_{hh}$ bins (GeV): [300, 500], [500, 700], [700, 900], [900, 1100]

<table>
<thead>
<tr>
<th>$M_{hh}$ bins (GeV)</th>
<th>[300, 500]</th>
<th>[500, 700]</th>
<th>[700, 900]</th>
<th>[900, 1100]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h(b\bar{b})h(\gamma\gamma)$ (SM)</td>
<td>200</td>
<td>170</td>
<td>52.5</td>
<td>11.1</td>
</tr>
<tr>
<td>$b\bar{b}h(\gamma\gamma)$</td>
<td>67.1</td>
<td>31.9</td>
<td>15.8</td>
<td>3.81</td>
</tr>
<tr>
<td>$Z(b\bar{b})h(\gamma\gamma)$</td>
<td>11.2</td>
<td>2.77</td>
<td>0.46</td>
<td>0.04</td>
</tr>
<tr>
<td>$t\bar{t}h(\gamma\gamma)$</td>
<td>97.5</td>
<td>15.9</td>
<td>3.22</td>
<td>0.58</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$</td>
<td>5.41</td>
<td>1.1</td>
<td>0.24</td>
<td>0.0</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$</td>
<td>13.9</td>
<td>1.09</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>188</td>
<td>23.7</td>
<td>5.25</td>
<td>0.32</td>
</tr>
<tr>
<td>$b\bar{b}\gamma$</td>
<td>107</td>
<td>11.8</td>
<td>3.44</td>
<td>1.32</td>
</tr>
<tr>
<td>$j\bar{j}\gamma$</td>
<td>30.3</td>
<td>2.58</td>
<td>0.82</td>
<td>0.24</td>
</tr>
<tr>
<td>Total Backgrounds</td>
<td>521</td>
<td>90.8</td>
<td>29.4</td>
<td>6.37</td>
</tr>
</tbody>
</table>

$$
\frac{\sigma}{\sigma_{sm}}_{\text{bin } 1} = (1 - \tilde{x})^2 (1 - 0.82 \tilde{r} + 3.4 \tilde{x} + 0.17 \tilde{r}^2 + 3.3 \tilde{x}^2 - 1.5 \tilde{r} \tilde{x}), \\
\frac{\sigma}{\sigma_{sm}}_{\text{bin } 2} = (1 - \tilde{x})^2 (1 - 0.42 \tilde{r} + 3.3 \tilde{x} + 0.06 \tilde{r}^2 + 3.8 \tilde{x}^2 - 0.95 \tilde{r} \tilde{x}), \\
\frac{\sigma}{\sigma_{sm}}_{\text{bin } 3} = (1 - \tilde{x})^2 (1 - 0.14 \tilde{r} + 3.5 \tilde{x} + 0.04 \tilde{r}^2 + 5.6 \tilde{x}^2 - 0.85 \tilde{r} \tilde{x}), \\
\frac{\sigma}{\sigma_{sm}}_{\text{bin } 4} = (1 - \tilde{x})^2 (1 - 0.03 \tilde{r} + 4.0 \tilde{x} + 0.03 \tilde{r}^2 + 8.6 \tilde{x}^2 - 0.65 \tilde{r} \tilde{x}).
$$
Sensitivity on \((\hat{r}, \hat{x})\) Plane: SM

- \((\hat{r}, \hat{x}) = (0,0)\)
- Degenerate direction around origin
- Exclusive analysis breaks degenerate direction
- 1d sensitivity: \(\delta \hat{r} \sim 13\% (4\%)\), \(\delta \hat{x} \sim 5\% (1.6\%)\)
- The weakest 2d sensitivity: \(\delta \hat{r} \sim 25\% (8\%)\), \(\delta \hat{x} \sim 10\% (3\%)\)

Dihiggs measurements alone can probe both \((\hat{r}, \hat{x})\) to a good accuracy
Sensitivity on \((\hat{r}, \hat{x})\) Plane: SM

- Exclusive analysis translated as probe of the effective cutoffs
- Tow cases: \(x_2 x_3 > 0\) (red), \(x_2 x_3 < 0\) (blue)
- 1d sensitivity: \(\tilde{\Lambda}_2, \tilde{\Lambda}_3 \gtrsim 1(2)\) TeV
- Weakest 2d sensitivity: \(\tilde{\Lambda}_2, \tilde{\Lambda}_3 \gtrsim 0.75(1.4)\) TeV
Sensitivity for Generic $(\hat{r}, \hat{x})$

- Sensitivity contours qualitatively different
  - **Benchmark B**: non-minimal gravitational coupling. 
    $(\hat{r}, \hat{x}) = (0, 0.2)$ (B1), $(\hat{r}, \hat{x}) = (0, 0.5)$ (B2), sensitivity contour and degenerate direction strongly depend on the explicit $\hat{x}$.
  - **Benchmark C**: CW potential in classical scale invariant model. 
    $(\hat{r}, \hat{x}) = (2/3, 0)$, similar to the SM.
Higgs self-interactions as the window for new physics, important for big questions: EWPT, EWSB, Higgs gravitational interaction…

Probing new physics of Higgs self-couplings based on effective theory with dim=6 operators. For dihiggs production on hadron collider, discriminate deviation couplings from the SM one by using $M_{hh}$ bins.

Dihiggs production alone can probe both cubic Higgs couplings to a good accuracy on 100TeV. Sensitivity qualitatively different for various benchmark points.
Thank You!
Perturbative Unitarity Bound

- Goldstone boson equivalence theorem: $\xi_h R H^\dagger H$ is gauge invariant

- Coupled channel analysis: $2 \rightarrow 2$ scattering
  \[ E^2 < \frac{16\pi v^2}{(1 - \zeta^2)(1 + \sqrt{1 + 3\zeta^4})} \]

- Unitarity analysis for Higgs inflation
  - **Puzzle**: $\Lambda_{\text{INF}} \sim M_{\text{Pl}}/\sqrt{|\xi_h|}$ go beyond cutoff $M_{\text{Pl}}/|\xi_h|$ for $|\xi_h| > 1$
  - Unitarity bound depends on background field
  - The strongest bound from $\pi^+\pi^- \rightarrow \pi^0\pi^0$
Other Dim=6 Operators

For different dihiggs production, some other operators contribute as well

- Top-pair associated production
  \[ \text{dim=6: } H^\dagger H \overline{q}_L H^c t_R + \text{h.c.} \]

- Gluon fusion production
  \[ \text{dim=6: } H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} \]

- Vector fusion production
  \[ \text{dim=6: } H^\dagger H W^a_{\mu\nu} W^a_{\mu\nu}, \quad H^\dagger H (D^\mu H)^\dagger (D^\mu H) \]
Higgs Mass Reconstruction

When one of the reconstructed mass consistent with the Higgs mass