Enhanced di-Higgs signals at hadron colliders probe singlet scalar, coupled to colored sector

Kenji Nishiwaki (KIAS)

based on collaboration with

Koji Nakamura (KEK & CERN), Kin-ya Oda (Osaka Univ.), Seong Chan Park (Yonsei Univ.), Yasuhiro Yamamoto (Yonsei Univ.)

the SM was “confirmed!”, BUT...

A 125 GeV scalar was discovered, which looks SM-like.

(Part of) gauge & Yukawa couplings were measured.
the SM was “confirmed!”, BUT...

**discovery of the SM-like Higgs**

[“5σ confirmation” on 4 July 2012, CERN]

A 125GeV scalar was discovered, which looks SM-like.

(Part of) gauge & Yukawa couplings were measured.

But, we know only few on Higgs potential yet!

**the curvature at the bottom = Higgs mass**
di-Higgs production @ LHC

\[ V = c_4(H^0)^4 + c_3(H^0)^3 + c_2(H^0)^2 + \cdots \]

- effective couplings
- the Higgs
- next target
- measured

\[
(c_3^{SM} = \lambda^{SM} v, \quad c_2^{SM} = 2\lambda^{SM} v^2) \quad v = 246 \text{ GeV}
\]

\[ \lambda^{SM} \sim 0.1 \]
How to address $c_3$ (in the SM) $\rightarrow$ di-Higgs production

- Cross section is not so large.
- A featured decay branch is $HH\rightarrow bb\gamma\gamma$ ($\text{Br}[HH\rightarrow bb\gamma\gamma] \sim 3 \times 10^{-3}$) is suppressed.
- Lots of data would be required...

**di-Higgs production @ LHC**

$$V = c_4(H^0)^4 + c_3(H^0)^3 + c_2(H^0)^2 + \ldots$$

$$\begin{align*}
(c_3^{SM} &= \lambda^{SM}v, \quad c_2^{SM} = 2\lambda^{SM}v^2) & v &= 246 \text{ GeV} \\
\lambda^{SM} &\sim 0.1
\end{align*}$$

**Effective couplings**

**The Higgs**

Effective coupling

**Next target**

**Measured**

$\lambda^{SM}$ is a measured and determined parameter of the standard model.

**[Baglio et al., arXiv:1212.5581]**

Figure 13: The sensitivity of the various Higgs pair production processes to the trilinear effective couplings $\lambda$. The precise measurement of $\lambda$ is important from the point of view of measuring the trilinear self-coupling of the Higgs boson.

$\lambda^{SM}$ is a measured and determined parameter of the standard model.
**di-Higgs production @ LHC**

Effective couplings to the Higgs

\[ V = c_4(H^0)^4 + c_3(H^0)^3 + c_2(H^0)^2 + \ldots \]

**The Higgs**

**Next target**

**Measured**

\[ v = 246 \text{ GeV} \]

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**Situation can be drastically changed if another scalar exists!**

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  \[ (\text{Br}[HH \rightarrow bb\gamma\gamma] \sim 3 \times 10^{-3}) \]
  \[ \rightarrow \text{suppressed} \]

Lots of data would be required...

**Figure 1**

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Lots of data would be required...

**Figure 3**

The sensitivity of the various Higgs pair production processes to the trilinear self-coupling of the Higgs boson is required to confirm the form of the scalar sector.

3 The top-Higgs anomalous coupling

- Effective couplings

\[ V = c_4(H^0)^4 + c_3(H^0)^3 + c_2(H^0)^2 + \ldots \]

- The Higgs

\[ v = 246 \text{ GeV} \]

\[ \lambda_{SM} \sim 0.1 \]

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Lots of data would be required...
Significant enhancement happens: $SU(2)_L$ singlet $s$ coupling to (new) colored sector

We consider both of them.

(e.g. top partner)

direct coupling

resonant enhancement!

(when $m_s \geq 2m_h = 250$ GeV)

We consider both of them.

e.g. [G.D.Kribs, A.Martin, arXiv:1207.4496]

e.g. [I.M.Lewis, M Sullivan, arXiv:1701.08774]

information on scalar potential!
Significant enhancement happens: $SU(2)_L$ singlet $s$ coupling to (new) colored sector

We consider both of them.

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$$g\,\, T\,\, \bar{T}\,\, s$$

Resonant enhancement!

(when $m_s \geq 2m_h = 250\,\, \text{GeV}$)

We have information on scalar potential!

We consider both of them.

[ Motivation for new colored particle ]

1. Addressing flavor anomaly (leptoquark) e.g. [B.Dumont, K.N., R.Watanabe, arXiv:1603.05248]
2. 1st order electroweak transition e.g. [I.M.Lewis, M Sullivan, arXiv:1701.08774]

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[ Motivation for singlet scalar ]

Short Summary

1 + 1 \gg 2

colored particle

singlet scalar

di-Higgs production
**Short Summary**

**I + I >> 2**

**di-Higgs production**

A resonant bump was reported in \( HH \rightarrow bb\gamma\gamma \) (5 events) around 300 GeV.

**A nice benchmark is:**

[ATLAS, arXiv:1406.5053]

- **σ_{SM}(pp \rightarrow HH)|_{8 TeV} = 9.2 fb,**
- **expected events:**
  - non-H BG: 1.3 ± 0.5,
  - single-H: 0.17 ± 0.04,
  - SM HH: 0.04,
- **3.5/0.04 \rightarrow 87.5-time larger,**
- **σ(pp \rightarrow HH) = 800 fb.**
- **still consistent with other branches**
  \[ \sigma(pp \rightarrow s \rightarrow hh)_{8 \text{ TeV}} < \begin{cases} 1.1 \text{ pb} & (b\bar{b}\gamma\gamma \text{ at CMS}), \\ 1.7 \text{ pb} & (b\bar{b}\tau\tau \text{ at ATLAS}), \end{cases} \]
Setup: SM + real singlet scalar + colored particle(s)

\[ \eta \left\{ \Delta b_g, \Delta b_\gamma \right\} \]

**[Effective interactions to 2g & 2\gamma]**

\[
\begin{align*}
\mathcal{L}_{\text{eff}}^{hgg} &= \frac{\alpha_s}{8\pi^2} \left( b_{g,\text{top}} \cos \theta - \Delta b_g \eta \sin \theta \right) h G^{a}_{\mu\nu} G^{a\mu\nu} \\
\mathcal{L}_{\text{eff}}^{ggg} &= \frac{\alpha_s}{8\pi^2} \left( \Delta b_g \eta \cos \theta + b_{g,\text{top}} \sin \theta \right) s G^{a}_{\mu\nu} G^{a\mu\nu} \\
\mathcal{L}_{\text{eff}}^{h\gamma\gamma} &= \frac{\alpha}{8\pi^2} \left( A_{SM} \cos \theta - \Delta b_\gamma \eta \sin \theta \right) h F_{\mu\nu} F^{\mu\nu} \\
\mathcal{L}_{\text{eff}}^{\gamma\gamma\gamma} &= \frac{\alpha}{8\pi^2} \left( \Delta b_\gamma \eta \cos \theta + A_{SM} \sin \theta \right) s F_{\mu\nu} F^{\mu\nu}
\end{align*}
\]

**Beta functions** factorized coupling to S

(showing loop effects)

**[Carena et al., arXiv:1206.1082]**

**[Abe et al., arXiv:1209.4544]**

\[
\eta_{LQ} = \kappa_{LQ} N_{LQ} \frac{f v}{M_{LQ}^2} \quad M_{LQ}^2 = m_{LQ}^2 + \frac{\kappa_{LQ}}{2} f^2
\]

**[Mixing angle]**

\[
H^0 = v + h \cos \theta + s \sin \theta
\]

**[SU(2)_L doublet]**

\[
S = f - h \sin \theta + s \cos \theta
\]

**[SU(2)_L singlet]**

\[
125 \text{GeV} \quad \geq 250 \text{GeV}
\]

**[the most generic potential]**

\[
V = V_S + V_H + V_{SHE}
\]

\[
V_S = \frac{m_S^2}{2} S^2 + \frac{\mu_S}{3!} S^3 + \frac{\lambda_S}{4!} S^4
\]

\[
V_H = m_H^2 |H|^2 + \lambda_H |H|^4
\]

\[
V_{SHE} = \mu S |H|^2 + \frac{\kappa}{2} S^2 |H|^2
\]

246 GeV
Setup: SM + real singlet scalar + colored particle(s)

\[ \eta, \{ \Delta b_g, \Delta b_\gamma \} \]

- **Effective interactions to 2g & 2\gamma**
  - \[ \mathcal{L}_{\text{eff}}^{hgg} = \frac{\alpha_s}{8\pi v} \left( b_g^{\text{top}} \cos \theta - \Delta b_g \eta \sin \theta \right) h G_{\mu\nu}^a G_{a\mu\nu} \]
  - \[ \mathcal{L}_{\text{eff}}^{sgg} = \frac{\alpha_s}{8\pi v} \left( \Delta b_\gamma \eta \cos \theta + b_g^{\text{top}} \sin \theta \right) s G_{\mu\nu}^a G_{a\mu\nu} \]
  - \[ \mathcal{L}_{\text{eff}}^{h\gamma\gamma} = \frac{\alpha}{8\pi v} \left( A_{\text{SM}} \cos \theta - \Delta b_\gamma \eta \sin \theta \right) h F_{\mu\nu} F_{\mu\nu} \]
  - \[ \mathcal{L}_{\text{eff}}^{s\gamma\gamma} = \frac{\alpha}{8\pi v} \left( \Delta b_\gamma \eta \cos \theta + A_{\text{SM}} \sin \theta \right) s F_{\mu\nu} F_{\mu\nu} \]

**Beta functions** factorized coupling to S (showing loop effects)

- **[Carena et al., arXiv:1206.1082]**
- **[Abe et al., arXiv:1209.4544]**

\[ \eta_{\text{LQ}} = \kappa_{\text{LQ}} N_{\text{LQ}} \frac{f v}{M_{\text{LQ}}^2} \]
\[ M_{\text{LQ}}^2 = m_{\text{LQ}}^2 + \frac{\kappa_{\text{LQ}}}{2} f^2 \]

**[the most generic potential]**
\[ V = V_S + V_H + V_{SH}. \]
\[ V_S = \frac{m_S^2}{2} S^2 + \frac{\mu_S}{3!} S^3 + \frac{\lambda_S}{4!} S^4 \]
\[ V_H = m_H^2 |H|^2 + \lambda_H |H|^4 \]
\[ V_{SH} = \mu S |H|^2 + \frac{\kappa}{2} S^2 |H|^2 \]

**[mixing angle]**
\[ H^0 = \frac{v + h \cos \theta + s \sin \theta}{\sqrt{2}} \]

**[SU(2)_L doublet]**
\[ S = f - h \sin \theta + s \cos \theta \]

**[SU(2)_L singlet]**
\[ 125\text{GeV} \geq 250\text{GeV} \]
**Results**

**huge enhancement:**

\[
|b_g| = \frac{\Delta b_g \, \nu}{2 \, m_s},
\]

\[
\Delta b_g = \frac{2}{3} \text{ (top/bottom partner)}
\]

![Graph showing cross section as a function of mass](image)

\[
\sigma(pp \to s)_{m_s=300 \text{ GeV}} \approx \left[ \frac{b_g}{-1/3} \right]^2 \left[ \frac{\alpha_s}{0.1} \right]^2 \left[ \frac{K}{1.6} \right] \times
\]

\[
\begin{align*}
1.0 \text{ pb} & \quad (\sqrt{s} = 8 \text{ TeV}), \\
3.2 \ (3.8) \text{ pb} & \quad (\sqrt{s} = 13 \ (14) \text{ TeV}), \\
15 \ (18) \text{ pb} & \quad (\sqrt{s} = 28 \ (33) \text{ TeV}), \\
130 \ (83) \text{ pb} & \quad (\sqrt{s} = 100 \ (75) \text{ TeV}).
\end{align*}
\]

**coupling to gluons scaled as like in vector-like quark for illustration**

\[
b_g = -\frac{1}{2} \left( \Delta b_g \eta \cos \theta + b_g^{\text{top}} \sin \theta \right) \quad \eta = y_T N_T \frac{\nu}{M_T}
\]
Results

**huge enhancement:**

\[ |b_g| = \frac{\Delta b_g}{2} \frac{v}{m_s}, \]

\[ \Delta b_g = \frac{2}{3} \text{ (top/bottom partner)} \]

**favored \( \mu_{\text{eff}} \) & \( \eta \)**

Leptoquark

\( m_s = 300 \text{ GeV} \)

- \( \sqrt{s} = 100 \text{ TeV} \)
- \( \sqrt{s} = 75 \text{ TeV} \)
- \( \sqrt{s} = 33 \text{ TeV} \)
- \( \sqrt{s} = 28 \text{ TeV} \)
- \( \sqrt{s} = 14 \text{ TeV} \)
- \( \sqrt{s} = 13 \text{ TeV} \)
- \( \sqrt{s} = 8 \text{ TeV} \)

Line preferred by 2.4\( \sigma \) excess

larger \( \text{Br}(s \to hh) \)

Excluded by \( \sigma(s \to ZZ \to 4l)_{13 \text{ TeV}} \)

larger \( \sigma(pp \to s) \)

\[ \eta_{\text{LQ}} = \kappa_{\text{LQ}} N_{\text{LQ}} \frac{f v}{M_{\text{LQ}}^2} \ \text{m}_{\text{LQ}} \leq 0.7 \sim 1.1 \text{ TeV} \]

\( 13 \text{ TeV LHC bound} \)

[ATLAS, arXiv:1605.06035]
The mass bound for the leptoquark respectively, depending on the possible decay channels.

\[ \Delta b_g = \frac{2}{3} \] (top/bottom partner)

\[ |b_g| = \frac{\Delta b_g \cdot \nu}{m_s}, \]

\[ \sigma(pp \rightarrow s \rightarrow \gamma\gamma)_{13 \text{ TeV}} \sim 7.4 \text{ fb} \]

\[ \left( \frac{b_g}{-1/3} \right)^2 \left( \frac{b_\gamma}{-8/9} \right)^2 \left( \frac{\alpha_s}{0.1} \right)^2 \left( \frac{\alpha}{1/129} \right)^2 \left( \frac{\mu_{\text{eff}}}{800 \text{ GeV}} \right)^{-2} \left( \frac{\sin \theta}{0.01} \right)^{-2} \]

\[ |\sin \theta| \geq 0.01 \]

\[ \sigma(pp \rightarrow s \rightarrow \gamma\gamma)_{13 \text{ TeV}} \leq 10 \text{ fb} \]

\[ \sqrt{s} = 100 \text{ TeV} \]
\[ \sqrt{s} = 75 \text{ TeV} \]
\[ \sqrt{s} = 33 \text{ TeV} \]
\[ \sqrt{s} = 28 \text{ TeV} \]
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\[ \sqrt{s} = 8 \text{ TeV} \]

\[ \text{Excluded by } \sigma(s \rightarrow ZZ \rightarrow 4\ell)_{13 \text{ TeV}} \]

\[ \mu_{\text{eff}} \text{ and } \eta \]

[ATLAS+CMS, arXiv:1606.02266]
A nice benchmark is:

\[ \frac{3.5}{0.04} \rightarrow 87.5 \text{-time larger}, \quad \sigma(pp \rightarrow HH) = 800 \text{fb}. \]

Color-boosted resonant one will be seen as a nice probe of the nature of Higgs potential.
A nice benchmark is:

\[ 3.5/0.04 \rightarrow 87.5\text{-time larger}, \quad \sigma(pp\rightarrow HH) = 800\text{fb}. \]

Color-boosted resonant one will be seen as a nice probe of the nature of Higgs.
BACKUP
### Possible choices of the colored particle(s) [SU(2)\textsubscript{L} singlets, assumed]:

<table>
<thead>
<tr>
<th>field</th>
<th>Dirac spinor</th>
<th>complex scalar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>top partner</td>
<td>bottom partner</td>
</tr>
<tr>
<td>SU(3)\textsubscript{C}</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Y</td>
<td>$\frac{2}{3}$</td>
<td>$-\frac{1}{3}$</td>
</tr>
<tr>
<td>$\Delta b_g$</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>$\Delta b_\gamma$</td>
<td>$\frac{16}{9}$</td>
<td>$\frac{4}{9}$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$y_T N_T \frac{v}{M_T}$</td>
<td>$y_B N_B \frac{v}{M_B}$</td>
</tr>
<tr>
<td>latest bound</td>
<td>$\geq 800$ GeV</td>
<td>$\geq 0.7$-1.1 TeV</td>
</tr>
</tbody>
</table>

[CMS, arXiv:1611.03568]

(note: they can decay into a pair of SM particles through mixings or Yukawa-type interactions.)
Branching ratios of $s$
Constraints via 125GeV Higgs signal strengths

Figure 4: Excluded regions from the signal strength of 125 GeV Higgs are shaded. The color represents the contribution from each channel; see Fig. 5 for details.
Figure 5: The 2\sigma-excluded regions from the signal strength of 125 GeV Higgs. The top-partner parameters are chosen as an illustration to present the contribution from each channel.

Figure 6: The 2\sigma-excluded regions from $s!ZZ!^4l\mu\varepsilon$ vs $m_s$ plane. The color is changed in increments of 0.1. The weakest bound starts existing from $b g = 0$. $K$-factor is set to be $K = 1$.6.
Yukawa interactions for decay

**Φ\textsubscript{3} (leptoquark):**

$$
\begin{align*}
(\phi_3)^* \frac{(q_L)^c}{(q_L)^c} \cdot l_L, & \quad (Q_\Phi = -1/3) \\
(\phi_3)^* \frac{(u_R)^c}{(u_R)^c} e_R, & \quad (Q_\Phi = -1/3) \\
(\phi_3)^* \frac{(d_R)^c}{(d_R)^c} e_R, & \quad (Q_\Phi = -4/3) \\
\epsilon^{abc} \epsilon^{ij} (\phi_3)_a \frac{(q_L)^c}{(q_L)^c} b_i (q_L)_{c_j}, & \quad (Q_\Phi = -1/3) \\
\epsilon^{abc} (\phi_3)_a \frac{(u_R)^c}{(u_R)^c} b_i (u_R)_{c}, & \quad (Q_\Phi = -4/3) \\
\epsilon^{abc} (\phi_3)_a \frac{(d_R)^c}{(d_R)^c} b_i (d_R)_{c}, & \quad (Q_\Phi = 2/3) \\
\epsilon^{abc} (\phi_3)_a \frac{(u_R)^c}{(u_R)^c} b_i (d_R)_{c}, & \quad (Q_\Phi = -1/3)
\end{align*}
$$

**Φ\textsubscript{6} (di-quark):**

$$
\begin{align*}
(\phi_6)^*ab \frac{(u_R)^c}{(u_R)^c} u_R, & \quad (Q_\Phi = 4/3) \\
(\phi_6)^*ab \frac{(u_R)^c}{(u_R)^c} u_R, & \quad (Q_\Phi = 1/3) \\
(\phi_6)^*ab \frac{(d_R)^c}{(d_R)^c} d_R, & \quad (Q_\Phi = -2/3) \\
(\phi_6)^*ab \frac{(q_L)^c}{(q_L)^c} q_L, & \quad (Q_\Phi = 1/3)
\end{align*}
$$

**Φ\textsubscript{8} (coloron):**

$$
\begin{align*}
\frac{1}{\Lambda} \frac{u_R}{u_R} (\phi_8)_a \frac{b}{b} (q_L)_{bi} \epsilon^{ij} H_j, & \quad (Q_\Phi = 0) \\
\frac{1}{\Lambda} \frac{u_R}{u_R} (\phi_8)_a \frac{b}{b} (q_L)_{bi} (H^*)^i, & \quad (Q_\Phi = -1) \\
\frac{1}{\Lambda} \frac{d_R}{d_R} (\phi_8)_a \frac{b}{b} (q_L)_{bi} \epsilon^{ij} H_j, & \quad (Q_\Phi = -1) \\
\frac{1}{\Lambda} \frac{d_R}{d_R} (\phi_8)_a \frac{b}{b} (q_L)_{bi} (H^*)^i, & \quad (Q_\Phi = 0)
\end{align*}
$$