(Inverse) Higgs Phenomenology at LHC

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“LHC Inverse Problem” workshop @ Ann Arbor

This talk is based on collaborations and discussions with Alexander Belyaev, Chuan-Ren Chen, Daisuke Nomura and C.-P. Yuan
Introduction

LHC experiments have the great potential to discover a Higgs boson in various channels.
In physics beyond the SM (SUSY, Little Higgs etc), we expect some non-SM Higgs couplings.

Can we extract any information on new physics from Higgs data?

Expected relative error on the determination of $\sigma \times \text{BR}$ for various Higgs search channels at the LHC with 200 fb$^{-1}$ of data

Zeppenfeld hep-ph/0203123
Zeppenfeld et al, hep-ph/0002036
Duhrssen et al, hep-ph/0406323
Outline

✦ Introduction

✦ Higgs interactions in new physics (NP) models
  
  MSSM, Littlest Higgs model with T-parity

✦ Constraint on NP parameters from Higgs data
  
  $\chi^2$ analysis using Higgs $\sigma \times BR$ data
  
  • Littlest Higgs model with T-parity
    
    new particle mass scale $f$

  • MSSM $\beta, \alpha, \cdots$

✦ Summary (very preliminary)
Higgs interactions in new physics models

- Solution to “naturalness problem” of Higgs mass

If there is “new physics” which cancels the $\Lambda^2$ induced by top,

\[ \langle h \rangle \]

the “new Physics” can affect gluon fusion process.

MSSM --- light stop (gluophobic scenario)

Little Higgs --- fermionic partner of top etc

It can affect the SM like Higgs boson search at LHC
Note: SM Higgs production at LHC

Gluon fusion

Weak boson fusion

\( \sigma(pp \rightarrow H+X) \)
\( \sqrt{s} = 14 \text{ TeV} \)
\( m_t = 175 \text{ GeV} \)
CTEQ4M
• Higgs sector can be modified

**MSSM ---- two Higgs doublet model**

tree level couplings of the lightest Higgs is modified

e.g. \( \frac{g_{hdd}}{g_{hdd}^{SM}} = -\frac{\sin \alpha}{\cos \beta} \) it can be larger one

\( g_{hdd}/g_{hdd}^{SM} \approx 1.5 \) for \( m_h \) max scenario

Higgs production and decay can be very different from the SM prediction

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**Higgs interactions**

gauge bosons and fermions

\( \mathcal{L}_{eff} = -g_{hVV} h V_{\mu}^{\dagger} V^{\mu} - g_{hf\bar{f}} h \bar{f} f \)

\( g_{hVV}/g_{hVV}^{SM} = \gamma_V (A, B, \cdots), \quad g_{hf\bar{f}}/g_{hf\bar{f}}^{SM} = \gamma_f (A, B, \cdots) \)

 gluon and photon

\( \Gamma_{gg}/\Gamma_{gg}^{SM} = 1 + \delta_{gg} (A, B, \cdots), \quad \Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}^{SM} = 1 + \delta_{\gamma\gamma} (A, B, \cdots) \)

A, B, ... are parameters of the new physics model

Higgs production and decay data constrain (hopefully measure)
the parameters of the theory (A, B, ...)
Example 1: MSSM

MSSM lightest Higgs boson couplings

• gauge boson

\[
\frac{g_{hVV}^{SM}}{g_{hVV}} = \sin(\beta - \alpha) \quad \text{for} \quad V = W, Z
\]

\[\tan \beta = \frac{v_u}{v_d}\]

\[\alpha : \text{Higgs mixing angle}\]

• fermion

\[
\frac{g_{h\nu\nu}}{g_{h\nu\nu}^{SM}} = \frac{\cos \alpha}{\sin \beta} \quad \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{SM}} = -\frac{\sin \alpha}{\cos \beta}
\]

\[
\frac{g_{hbb}}{g_{hbb}^{SM}} = -\frac{\sin \alpha}{\cos \beta} (1 + \delta_b) \quad \text{for bottom} \quad (b \rightarrow \tau \text{ for tau})
\]

\[
\frac{g_{htt}}{g_{htt}^{SM}} = \frac{\cos \alpha}{\sin \beta} (1 + \delta_t) \quad \text{for top}
\]

• gluon and photon

\[
\Gamma_{gg}^{\gamma} = \frac{\sigma_{gg}^{\gamma}}{\sigma_{gg}^{\gamma}^{SM}} = 1 + \delta_{gg}
\]

Similarly, photon-Higgs coupling is parametrized

\[\alpha, \beta, \delta_p \quad (p = b, t, \tau, gg \text{ and } \gamma\gamma) \quad \text{are (effective) parameters for Higgs couplings}\]
Example 2: Littlest Higgs model with T-parity

• SU(5)/SO(5) non-linear sigma model

\[ SU(5) \xrightarrow{f} SO(5) \]

\[ [SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2 \rightarrow SU(2) \times U(1) \]

• Collective symmetry breaking mechanism

Large SM one-loop quadratic divergences in Higgs mass are canceled by new particles

• T-parity

\[ SU(2)_1 \times U(1)_1 \leftrightarrow SU(2)_2 \times U(1)_2 \]

SM particles \( \rightarrow \) +SM particles

\( (W_H, Z_H, A_H, \Phi) \rightarrow -(W_H, Z_H, A_H, \Phi) \) (heavy gauge bosons and Higgs)

\( q_- \rightarrow -q_- \) (T-odd doublet fermions)

✴ Contributions to EW observables are loop suppressed. The new particle scale \( f \) can be much lower than 1 TeV.

✴ The lightest T-odd particle can be a good dark matter candidate
Gluon fusion process in Littlest Higgs model with T-parity

Top sector

The large quadratic divergence induced by top is canceled by the heavy fermionic partner of the top-quark, T

\[ \frac{\delta \sigma_{gg \to h} (\text{top sector})}{\sigma_{gg \to h} (\text{top in SM})} \approx -\frac{3}{2} \frac{v_{SM}^2}{f^2} \]

Han, Logan, McElrath, Wang hep-ph/0302188

T-odd doublet quark sector

Interaction which generates T-odd doublet quarks induces the Higgs interaction

\[ \frac{\delta \sigma_{gg \to h} (\text{T odd fermions})}{\sigma_{gg \to h} (\text{top in SM})} \approx -\frac{3}{2} \frac{v_{SM}^2}{f^2} \]

Chen, Tobe, Yuan, hep-ph/0602211

Higgs couplings in Littlest Higgs model with T-parity

- gauge boson (V=W, Z)

\[
\frac{g_{hVV}}{g_{hVV}^{SM}} \approx 1 - \frac{3}{4} \frac{v_{SM}^2}{f^2} \approx \begin{cases} 
0.97 & \text{for } f = 700 \text{ GeV}, \\
0.98 & \text{for } f = 1000 \text{ GeV}.
\end{cases}
\]

- fermion

\[
\frac{g_{h\nu\nu}}{g_{h\nu\nu}^{SM}} \approx 1 - \frac{3}{4} \frac{v_{SM}^2}{f^2} \approx \begin{cases} 
0.90 & \text{for } f = 700 \text{ GeV}, \\
0.95 & \text{for } f = 1000 \text{ GeV}.
\end{cases}
\]

\[
\frac{g_{h\tau\tau}}{g_{h\tau\tau}^{SM}} \approx 1 - \frac{1}{2} \frac{v_{SM}^2}{f^2} \approx \begin{cases} 
0.94 & \text{for } f = 700 \text{ GeV}, \\
0.97 & \text{for } f = 1000 \text{ GeV}.
\end{cases}
\]

\[
\frac{g_{hdd}}{g_{hdd}^{SM}} \approx 1 - \frac{5}{4} \frac{v_{SM}^2}{f^2} \approx \begin{cases} 
0.84 & \text{for } f = 700 \text{ GeV}, \\
0.92 & \text{for } f = 1000 \text{ GeV},
\end{cases}
\]

(We consider the same Yukawa structures in lepton sector, as in quark sector.)

Higgs couplings are function of the scale “f”
\[
R_\sigma(X) = \frac{\sigma^{\text{LH}}(X)}{\sigma^{\text{SM}}(X)} \quad R_{\text{BR}}(Y) = \frac{\text{BR}^{\text{LH}}(Y)}{\text{BR}^{\text{SM}}(Y)}
\]

\[R_\sigma(X) \times R_{\text{BR}}(Y) \quad \text{for } f = (600, 700, 1000) \text{ GeV}\]

<table>
<thead>
<tr>
<th>(m_h = 120 \text{ GeV})</th>
<th>(R_{\text{BR}}(\gamma\gamma))</th>
<th>(R_{\text{BR}}(\tau\tau))</th>
<th>(R_{\text{BR}}(b\bar{b}))</th>
<th>(R_{\text{BR}}(VV))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_\sigma(gg)) (Case A)</td>
<td>0.57, 0.68, 0.84</td>
<td>0.56, 0.67, 0.83</td>
<td>–</td>
<td>0.55, 0.66, 0.83</td>
</tr>
<tr>
<td>(Case B)</td>
<td>0.81, 0.86, 0.93</td>
<td>0.51, 0.63, 0.81</td>
<td>–</td>
<td>0.78, 0.84, 0.92</td>
</tr>
<tr>
<td>(R_\sigma(VV)) (Case A)</td>
<td>0.97, 0.98, 0.99</td>
<td>0.95, 0.96, 0.98</td>
<td>–</td>
<td>0.94, 0.96, 0.98</td>
</tr>
<tr>
<td>(Case B)</td>
<td>1.34, 1.22, 1.09</td>
<td>0.84, 0.89, 0.95</td>
<td>–</td>
<td>1.30, 1.19, 1.08</td>
</tr>
<tr>
<td>(R_\sigma(t\bar{t}h)) (Case A)</td>
<td>–</td>
<td>0.87, 0.90, 0.95</td>
<td>0.87, 0.90, 0.95</td>
<td>–</td>
</tr>
<tr>
<td>(Case B)</td>
<td>–</td>
<td>0.77, 0.83, 0.92</td>
<td>0.77, 0.83, 0.92</td>
<td>–</td>
</tr>
<tr>
<td>(R_\sigma(Vh)) (Case A)</td>
<td>0.97, 0.98, 0.99</td>
<td>–</td>
<td>0.95, 0.96, 0.98</td>
<td>–</td>
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<th>(m_h = 200 \text{ GeV})</th>
<th>(R_{\text{BR}}(\gamma\gamma))</th>
<th>(R_{\text{BR}}(\tau\tau))</th>
<th>(R_{\text{BR}}(b\bar{b}))</th>
<th>(R_{\text{BR}}(VV))</th>
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<td>(R_\sigma(gg)) (Case A)</td>
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<tr>
<td>(R_\sigma(VV)) (Case A)</td>
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<td>–</td>
<td>0.90, 0.94, 0.97</td>
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<td>(Case B)</td>
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<td>–</td>
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- Higgs production via gluon fusion is suppressed.
- \(\gamma\gamma, \, VV\) decay modes via weak boson fusion can be enhanced in small Higgs mass region in Case B.
Constraint on NP parameters from Higgs data (preliminary)

• Suppose LHC experiments find a Higgs in various channels and measure $\sigma \times BR$
• The following errors on the determination of $\sigma_h = \sigma \times BR$ for various Higgs search channels are assumed:  

<table>
<thead>
<tr>
<th>$\Delta \sigma_h/\sigma_h(%)$</th>
<th>$\gamma\gamma$ (decay)</th>
<th>$\tau\tau$</th>
<th>$bb$</th>
<th>$VV$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg$ (production)</td>
<td>9.9, 9.4</td>
<td>-</td>
<td>-</td>
<td>23.1, 12.4 (ZZ*)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42.1, 26.0 (WW*)</td>
</tr>
<tr>
<td>$qqh$</td>
<td>12.0, 11.9</td>
<td>8.8, 9.9</td>
<td>-</td>
<td>7.1, 4.3 (WW*)</td>
</tr>
<tr>
<td>$tth$</td>
<td>-</td>
<td>17.0, 23.3</td>
<td>11.4, 14.3</td>
<td>-, 42.0 (WW*)</td>
</tr>
<tr>
<td>$Wh$</td>
<td>-</td>
<td>-</td>
<td>19.0, 25.0</td>
<td></td>
</tr>
</tbody>
</table>

for $m_h = 120$ and $130$ GeV, respectively

Theoretical QCD and PDF uncertainties on the various Higgs production channels.

$\chi^2$ analysis on $\sigma_h = \sigma \times BR$

• Constraints on parameters of the models

Duhrssen et al, hep-ph/0406323
Anastasiou et al, hep-ph/0509014
Littlest Higgs model with T-parity

\[ m_h = 120 \text{ GeV} \]

\[ \Delta \chi^2 \]

LH signal : Littlest Higgs in Case A with \( f = 700 \text{ GeV} \)
For simplicity,
\[ \delta_b = \delta_t = \delta_{gg} = \delta_{\gamma\gamma} = 0 \]

MSSM signal: \[ mh \text{ max scenario with } \tan \beta = 8 \text{ and } m_A = 250 \text{ GeV} \]
Table 1: $\sigma \times \text{BR}/(\sigma \times \text{BR})_{SM}$ in $m_h \text{ max scenario with } tan\beta = 8$ and $m_A = 250$ GeV.
It's difficult to constrain $\tan \beta$ and $\alpha$ more fundamental parameters?
• LHC experiments have the great potential to discover a Higgs in various channels.
• We expect non-SM Higgs interaction in interesting new physics model (MSSM, Little Higgs etc).
• Higgs production and decay data might provide interesting information on new physics models.

Higgs physics at the LHC can be indirect search for new physics