Update on Higgs Pair Production
at the LC and (S)LHC

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4. Conclusions

Ulrich Baur
State University of New York at Buffalo
1 – Introduction

- If it exists, the Standard Model (SM) Higgs boson will be discovered at the Tevatron or LHC
  - at the Tevatron if $m_H < 180$ GeV and $> 15$ fb$^{-1}$ can be accumulated
  - at the LHC over the entire range $115$ GeV < $m_H$ < 1 TeV
- The LHC promises complete coverage of Higgs decay scenarios
- Quantitatively at the LHC: measure
  - $M_H$ to 0.1%
  - $\Gamma_H$ to $\leq 10\%$
  - $\sigma \times Br$ to 10\%
what remains to be done: determine Higgs potential

\[ V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4, \]

\( \eta_H \): physical Higgs field, \( v = (\sqrt{2} G_F)^{-1/2} \),

SM: \( \tilde{\lambda} = \lambda = \lambda_{SM} = m_H^2/(2v^2) \)

\( \lambda \) and \( \tilde{\lambda} \) are per se free parameters

to measure \( \lambda \) (\( \tilde{\lambda} \)), experiments must observe \( HH \) (\( HHH \)) production

\( HHH \) cross sections too small to probe \( \tilde{\lambda} \) at any machine considered so far

concentrate on \( \lambda \) in the following

radiative corrections to \( HHH \) coupling:

SM: \(-4\% \cdots -11\%\) for \( 120 \text{ GeV} < M_H < 200 \text{ GeV} \) (Yuan et al.)

can be up to \(100\%\) in general 2HDM

MSSM: up to \(8\%\) for light stop squarks (Hollik et al.)
Higgs Pair Production at Hadron Colliders

- $HH$ production mechanism at hadron colliders:
  - one-loop process $gg \to HH$ dominates
  
  - cross section for $qq \to qqHH$ and $WHH$, $ZHH$ and $t\bar{t}HH$ production are a factor $10 \sim 30$ smaller

- for $m_H > 140$ GeV, $H \to W^+W^-$ dominates
  - most channels swamped by background
  - most promising: $HH \to 4W \to (jj\ell^\pm\nu)(jj\ell'^\pm\nu)$ (A. Blondel et al., UB, T. Plehn, D. Rainwater)
• for $m_H < 140$ GeV, $H \to b\bar{b}$ dominates
  
  ✿ previously shown: $HH \to 4b$ and $HH \to b\bar{b}\tau^+\tau^-$ are overwhelmed by background
  ✿ so is $HH \to b\bar{b}\mu^+\mu^-$

• more promising for $m_H < 140$ GeV at hadron colliders:
  ✿ $HH \to b\bar{b}\gamma\gamma$

• calculation of the $HH \to b\bar{b}\gamma\gamma$ signal:
  ✿ use exact $gg \to HH$ one-loop matrix elements
  ✿ QCD corrections:
    → known only in $m_t \to \infty$ limit
    → and only for total cross section
    → $k = 1.65$ at LHC
    → to approximately take into account QCD corrections we use these $k$-factors
• basic kinematic acceptance cuts:

\[ p_T(b) > 45 \text{ GeV} , \quad |\eta(b)| < 2.5 , \quad \Delta R(b,b) > 0.4 , \]
\[ m_H - 20 \text{ GeV} < m_{b\bar{b}} < m_H + 20 \text{ GeV} , \]
\[ p_T(\gamma) > 20 \text{ GeV} , \quad |\eta(\gamma)| < 2.5 , \quad \Delta R(\gamma,\gamma) > 0.4 , \]
\[ m_H - 2.3 \text{ GeV} < m_{\gamma\gamma} < m_H + 2.3 \text{ GeV} , \]
\[ \Delta R(\gamma,b) > 0.4 , \]

☞ good \( \gamma\gamma \) mass resolution (~ 2 GeV) reduces background

• backgrounds

☞ irreducible: \( b\bar{b}\gamma\gamma \), \( H(\rightarrow \gamma\gamma)b\bar{b} \) and \( H(\rightarrow b\bar{b})\gamma\gamma \)

☞ reducible: multi-jet and jet(s)+photon(s) production, \( Hjj \) production, where jets are misidentified as \( b \)-quarks or photons

➞ use \( P_{c\rightarrow b} = 1/13, \quad P_{j\rightarrow b} = 1/140 \) (1/23) LHC (SLHC),
\[ P_{j\rightarrow \gamma} = 1/2500 \ldots 1/1600 \]
(SLHC: \( \mathcal{L} = 10^{35} \text{ cm}^{-2} \text{ s}^{-1} = 10 \times \mathcal{L}_{LHC} \))
• backgrounds depend on whether one or two $b$’s are required to be tagged
  ☐ one tag: signal a factor $(2/\epsilon_b - 1) = 3$ (for $\epsilon_b = 0.5$) larger than for 2 tags
  ☐ but significantly increased reducible background
  ☐ at LHC the small signal rate requires a single $b$-tag to have an observable signal
  ☐ at SLHC at large $P_{j \rightarrow b}$ leads to an increase in the bgd which more than compensates the gain in the signal for single $b$-tag
  → require double $b$-tag at SLHC
• reduction of background
  - photons tend to be collinear to $b$’s and back-to-back in background processes
  - but not in signal
  - requiring

$$\Delta R(\gamma, b) > 1.0, \quad \Delta R(\gamma, \gamma) < 2.0.$$ 

reduces bgd by factor $\sim 10$ and signal by $< 30\%$
• can achieve $S/B \approx 1/2$ at LHC, and $S/B \approx 1/1$ at SLHC
• if $\gamma$-jet and $b$-jet miss-id. probabilities can be independently measured, it may be possible to subtract large parts of the background
• expect $1 \: HH \rightarrow b\bar{b}\gamma\gamma$ event/100 fb$^{-1}$ at LHC
• use visible invariant mass to discriminate signal and bgd

![Graphs showing the distribution of visible invariant mass for different model parameters.](image)
• derive bounds on $HHH$ coupling from $\chi^2$ test of $m_{vis}$ distribution
  ➕ assume 10% normalization uncertainty of SM cross section
• 68.3% CL limits for $\Delta \lambda_{HHH} = \lambda/\lambda_{SM} - 1$

<table>
<thead>
<tr>
<th>machine</th>
<th>$m_H = 120$ GeV</th>
<th>$m_H = 140$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int \mathcal{L} dt$</td>
<td>norm</td>
<td>B sub</td>
</tr>
<tr>
<td>LHC 600 fb$^{-1}$</td>
<td>$+1.6$</td>
<td>$+0.94$</td>
</tr>
<tr>
<td>SLHC 6000 fb$^{-1}$</td>
<td>$+0.74$</td>
<td>$+0.52$</td>
</tr>
<tr>
<td></td>
<td>$-0.62$</td>
<td>$-0.46$</td>
</tr>
</tbody>
</table>
• to achieve 10% normalization uncertainty need
  ☞ NNLO QCD corrections to $gg \rightarrow HH$ signal cross section
  ☞ determine background normalization from data using sideband analysis

• bounds which can be achieved for a 30% normalization uncertainty
  are about a factor 2 weaker than those listed above
• comparison with LC bounds:
  ☞ for $\sqrt{s} = 500$ GeV, 1 ab$^{-1}$, can determine $\lambda$ with a precision of $\sim 20\%$ ($\sim 50\%$) for $m_H = 120$ GeV ($m_H = 140$ GeV) in $e^+e^- \rightarrow ZHH$
  → LHC will only be able to provide a first rough measurement for $m_H = 120$ GeV
  → SLHC will do better, but limits for $m_H = 120$ GeV ($m_H = 140$ GeV) will be a factor $2 - 4$ ($1.2 - 3$) weaker than those achievable at LC
  ☞ nevertheless, measurement is interesting, if luminosity upgraded LHC operates before LC
3 – Higgs Pair Production at Linear Colliders

- previously found: LHC/SLHC have a better chance to measure $H H H$ coupling for $m_H > 140$ GeV than a LC with $\sqrt{s} \leq 1$ TeV
- new analysis for $e^+ e^- \rightarrow H H \nu \nu$ for $120$ GeV $\leq m_H \leq 240$ GeV and $1.5$ TeV $\leq \sqrt{s} \leq 5$ TeV
  - results provided by Battaglia, DeRoeck for 2003 Les Houches workshop
- consider
  - $H H \rightarrow 4b$ for $m_H < 140$ GeV
  - $H H \rightarrow 4W$ for $m_H > 140$ GeV
  - and assume 5 ab$^{-1}$
• cross section: (plots from Albert DeRoeck’s talk at WIN03)

- red: \( m_H = 120 \text{ GeV} \)
- blue: \( m_H = 140 \text{ GeV} \)
- green: \( m_H = 180 \text{ GeV} \)
- black: \( m_H = 240 \text{ GeV} \)
- sensitivity limits:

\[ \Delta \lambda / \lambda / 5 \text{ ab}^{-1} \]

\[ \sqrt{s} \text{ (TeV)} \]

- for \( \sqrt{s} > 3 \text{ TeV} \), limits hardly improve
- can measure \( \lambda \) with a precision of \( \sim 30\% \) for a heavy Higgs (\( m_H = 240 \text{ GeV} \)) at a 1.5 TeV machine
big difference between a 1 TeV and a 1.5 TeV machine:

- $\sigma(ZHH)$ falls with $\sqrt{s}$
- $\sigma(HH\bar{\nu}\nu)$ rapidly increases with $\sqrt{s}$
- for $\sqrt{s} < 1.5$ TeV $ZHH$ production dominates, and cross sections are too small to do a measurement of $HHH$ coupling for $m_H > 140$ GeV

compare for $m_H = 180$ GeV:

- LC, $\sqrt{s} = 1.5$ TeV, 5 ab$^{-1}$: $\delta\lambda \approx 0.22$
- SLHC, 3000 fb$^{-1}$: $\delta\lambda \approx 0.15$

→ SLHC has some advantage

→ however, for $m_H \geq 200$ GeV, SLHC limits degrade rapidly, and LC might have advantage (no calculation of $HH$ production at SLHC in this mass range yet)
4 – Conclusions

LC and (S)LHC are complementary

- for $m_H < 140$ GeV the Higgs boson self-coupling can be measured at the (S)LHC in the $b\bar{b}\gamma\gamma$ final state with $S/B \sim \mathcal{O}(1)$
  - measurement is completely limited by rate
  - limits from $e^+e^- \rightarrow ZHH$ are up to a factor 4 better than those from $HH \rightarrow b\bar{b}\gamma\gamma$ at SLHC
- for $m_H > 140$ GeV, the LHC – in particular if a luminosity upgrade can be realized – appears to have a clear advantage over a LC with $\sqrt{s} \leq 1$ TeV
- to probe the $HHH$ coupling at a LC for $m_H > 140$ GeV, need $\sqrt{s} \geq 1.5$ TeV (Battaglia et al.)
  - for $m_H > 200$ GeV, a 1.5 TeV LC might be competitive with SLHC (more work needed)