Search for rare Higgs decays and production of the di-Higgs boson at CMS

Chia Ming, Kuo
National Central University, Taiwan
Within the SM, the partial width ($\Gamma_{Z\gamma}$) for the $H \rightarrow Z\gamma$ decay channel is rather small, resulting in a BR between 0.11% and 0.25% in 120-160 GeV.

The measurement of $\Gamma_{Z\gamma}$ provides important information on the underlying dynamics of the Higgs sector because it is induced by loops of heavy charged particles, just as $H \rightarrow \gamma\gamma$. 

$BR(H \rightarrow Z\gamma) = 1.6 \times 10^{-3}$
$H \to Z\gamma$

- $\Gamma_{Z\gamma}$ is sensitive to physics beyond SM, and could be substantially modified by new charged particles without affecting the gluon-gluon fusion Higgs boson production cross section [1], such as derived from an extended Higgs sector [2], or by the presence of new scalars [3,4]

We look for \( H \rightarrow Z \gamma \) with the Z boson decaying into an electron or a muon pair.

- A clean final-state with good mass resolution (~1-3%)
- Leading/trailing lepton \( p_T > 20/10 \text{ GeV} \), \( p_T^\gamma > 15 \text{ GeV} \)
- \( |\eta^\gamma| < 2.5 \), but excluding the ECAL barrel-endcap transition region, \( |\eta^e| < 2.5 \) and \( |\eta^\mu| < 2.4 \)
- \( m_{ll} > 50 \text{ GeV}, \Delta R(l, \gamma) > 0.4 \)
- \( p_T^\gamma / m_{ll\gamma} > 15/110 \) to suppress Z+jets
- \( m_{ll} + m_{ll\gamma} > 185 \text{ GeV} \)
- \( p_T^{\text{jet}} > 30 \text{ GeV} \) and \( |\eta^{\text{jet}}| < 4.7 \)
- Zeppenfeld \( \eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2 \)
- \( \Delta \eta_{jj} > 3.5, \Delta \Phi(Z\gamma, jj) > 2.4 \)

**Table 1: Observed and expected event yields for a 125 GeV SM Higgs boson.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Integrated luminosity (fb(^{-1}))</th>
<th>Observed event yield for ( 100 &lt; m_{ll\gamma} &lt; 190 \text{ GeV} )</th>
<th>Expected number of signal events for ( m_H = 125 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 ee</td>
<td>5.0</td>
<td>2353</td>
<td>1.2</td>
</tr>
<tr>
<td>2011 ( \mu \mu )</td>
<td>5.1</td>
<td>2848</td>
<td>1.4</td>
</tr>
<tr>
<td>2012 ee</td>
<td>19.6</td>
<td>12899</td>
<td>6.3</td>
</tr>
<tr>
<td>2012 ( \mu \mu )</td>
<td>19.6</td>
<td>13860</td>
<td>7.0</td>
</tr>
</tbody>
</table>

VBF dijet tag

- Signal yield is similar to \( H \rightarrow ZZ \rightarrow 4l \) at 125 GeV
- Background processes:
  - SM Z+\( \gamma \) associated production
  - SM Z+jets where jet fakes photon
$H \rightarrow Z \gamma$ mass spectrum
$H \rightarrow Z \gamma$ Background and signal modeling
the observed and expected limits for $m_{ll\gamma}$ at 125 GeV are within one order of magnitude of the SM prediction

Future sensitivity of ATLAS: $2.3\sigma$ (300/fb), $3.9\sigma$ (3000/fb) [ATL-PHYS-PUB-2014-006]
**$H \rightarrow Z\gamma$ limits**

- Excludes models predicting $\sigma \times \text{BR}$ to be larger than one order of magnitude of the SM prediction for 125-157 GeV mass range.

- Models predicting significant enhancements for $\Gamma_{Z\gamma}$ with respect to the SM expectations due to a pseudoscalar admixture are now excluded.
• Search for a high mass scalar particle
$A \rightarrow Z\gamma$ limits

Broad resonance signal ($\Gamma_h^{SM}$)

Narrow resonance signal (1% Mx)
In analogy to $\pi^0 \rightarrow ee\gamma$ decays via an internal conversion of one of the photons, discovered by R. H. Dalitz, we call the $H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$ process Higgs Dalitz decay.

\[ \text{BR}(H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma) = 3.3 \times 10^{-5} \]

- an extra handle on the measurement of the Higgs’s couplings
- consists of non-trivial angular correlations that could result in a forward-backward asymmetry
- sensitive to new physics via loops
H → γ*γ → llγ : experimental challenges

μ: two close-by charged tracks

e: two close-by charged tracks
  + one merged energy cluster
  in electromagnetic calorimeter
$H \rightarrow \gamma^* \gamma \rightarrow ll\gamma$ : mass spectra
$H \rightarrow \gamma^* \gamma \rightarrow ll\gamma : \text{limits}$
$H \rightarrow J/\Psi + \gamma$

\[ \text{BR}(H \rightarrow J/\Psi + \gamma) = 2.8 \times 10^{-6} \]

- sensitive to the Higgs-charm coupling
$H \rightarrow J/\Psi + \gamma$

95% CL limit on $\text{BR}(H \rightarrow J/\Psi + \gamma) < 1.5 \times 10^{-3}$

could be possible at 3000/fb of data at LHC
HH production

- Non-resonant
  - need to determine the Higgs self-interaction potential responsible for EWSB → requiring a measurement of trilinear and quadrilinear self-coupling of the Higgs particle, as predicted by the SM
  - Quartic coupling out of each of LHC and HL-LHC
  - SM predicts $\sigma(gg\rightarrow HH) = 34$ fb at 13 TeV → not sensitive, but BSM can induce kinematic differences and cross section enhancement

- Resonant
  - Many BSM models predict resonances decaying into two Higgs bosons: WED, MSSM, 2HDM, etc.
  - Model independent search for spin-0 and spin-2 resonances decaying to HH with $M_x = [260, 1100]$ GeV → non-boosted regime
  - Benchmark model: Warped Extra Dimensions predicts spin-0 (radion) and spin-2 (KK graviton) new particles that couple to the Higgs bosons
$HH \rightarrow \gamma\gamma bb$

- $H \rightarrow bb$
  - high branching ratio
  - tag b-jet to obtain good $S/\sqrt{B}$
- $H \rightarrow \gamma\gamma$
  - high trigger efficiency and selection
  - good mass resolution
- $HH \rightarrow b\bar{b}\gamma\gamma$
  - low background
$X \rightarrow HH \rightarrow bb\gamma\gamma$

**CMS PAS HIG-13-032**

- **Low mass regime (260 - 400 GeV)**: Fit $m_{\gamma\gamma}$
- **High mass regime (400 - 1100 GeV)**: Fit $m_{\gamma\gamma\gamma\gamma}$ after kinematically constrain $m_{\gamma\gamma}$ and $m_{jj}$ to 125 GeV within energy resolutions.
$X \rightarrow HH \rightarrow bb\gamma\gamma$ results

- No significant deviation from expectations
- The radion with $\Lambda_R = 1$ TeV is excluded below 970 GeV. The RS1 KK-graviton is excluded from 340 to 400 GeV at a 95% CL
Combined Run I CMS HH results

- No significant deviation from expectations
- \( X \rightarrow HH \rightarrow bby\gamma \) and \( X \rightarrow HH \rightarrow bbbbb \) sensitivities cross. Complementary searches
- Resonant searches constrain BSM physics
Non-resonant $HH \rightarrow \gamma\gamma bb$ future study

• At $\sqrt{s} = 14$ TeV, expected 390 produced events in 3000/fb
• Parametrize object performance tuned to CMS Phase II detector at $<\text{PU}> = 140$
Non-resonant $HH\rightarrow\gamma\gamma bb$ future study

![Graph showing relative uncertainty on fitted signal yield vs. integrated luminosity and non-resonant background scale factor.](image)
Summary

- $H \rightarrow Z \gamma$: the observed limit at 125 GeV is within one order of magnitude of the SM prediction. No significant deviation from expectations is seen between 200 and 500 GeV.

- $H \rightarrow \gamma^* \gamma$: the observed limit at 125 GeV is about six times of the SM prediction.

- $H \rightarrow J/\Psi \gamma$: the observed limit on BR is 540 times higher than SM expectation.

- $HH \rightarrow b \bar{b} \gamma \gamma$: No appreciable excess has yet to be seen. However, upper limits place constraints on BSM models.

- Stay tuned with more data to come in 2016.