HH Production in the $bb\gamma\gamma$ Final State with 13 TeV data @ CMS

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UNDERSTANDING THE STANDARD MODEL

Probing the nature of the Electroweak Symmetry Breaking mechanism

What we know today:
- $\mu$ measured directly: $M_H = \sqrt{2|\mu|} = 125$ GeV
- $\lambda$ measured indirectly: $\lambda = (\mu/v)^2 \sim 0.13$
  - $v$: electroweak vacuum expectation value = 246 GeV

What we want to know:
- Is the Higgs vacuum stable?
- Is the Higgs potential the one predicted by the SM?
- Are there more fields involved in the EWSB mechanism?

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

Credits: Flip Tanedo

Higgs Mass
Higgs Self-Coupling
NONRESONANT HH

The Standard Model hh production
Mainly produced via gluon fusion (as for single h)
Access to the self-coupling \( \lambda \)
Scalar potential structure
Key property measurement of h(125)
Major setback: very low production cross-section
\[ \sigma = 33.45 \text{ fb} \] @ 13 TeV
Strong destructive interference of the two main diagrams:
by (lack of) chance SM is almost the most destructive case...

Carvalho et al, LHCHXSWG-2016-001

Not expected to be sensitive to SM HH @ LHC
But:
(1) BSM can increase \( \sigma(HH) \)
\[ [\kappa_\lambda = 10 \rightarrow \sigma_{\text{BSM}} = 10 \times \sigma_{\text{SM}}] \]
(2) Important to test the reach of current analysis for projecting HL-LHC sensitivity

Destructive interference between diagrams almost maximal for SM

| \( \kappa_\lambda = 1 \), \( c_2 = c_g = c_2 g = 0 \) |
|---|---|---|
| NNLL+NNLO (\( M_h = 125 \text{ GeV} \)) | 8 TeV | 13 TeV | 14 TeV |
| SM HH Cross Section | 10.16 fb | 33.45 fb | 39.56 fb |

LHCHXSWG Yellow Report 4
Many different BSM models predict HH resonances

Experimental solution: model independent results on narrow width resonances

**Low tanβ MSSM**

Djouadi & Quevillon, arXiv:1304.1787

Branching ratio of MSSM heavy H with $\tan\beta = 2.5$ and $M_h = 126$ GeV

**Warped Extra Dimensions**

Carvalho, arXiv:1404.0102

Radion (spin-0) branching ratios on RS1 and Bulk scenarios

**Neutral Naturalness**

See N. Craig’s talk on Wednesday

Heavy Twin Higgs decays to SM particles unconstrained

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**bbγγ FINAL STATE**

**Br(HH→XXYY)**

- **μμ**: 2.5e-04, 9.4e-05, 3.8e-05, 2.8e-05, 1.3e-05, 1.2e-05, 1.0e-06, 6.7e-07, 1.1e-07, 4.8e-08
- **ss**: 2.8e-04, 1.1e-04, 4.2e-05, 3.1e-05, 1.4e-05, 1.3e-05, 1.1e-06, 7.6e-07, 6.1e-08
- **Zγ**: 1.8e-03, 6.6e-04, 2.6e-04, 1.9e-04, 9.0e-05, 8.1e-05, 7.0e-06, 2.4e-06
- **γγ**: 2.6e-03, 9.8e-04, 3.9e-04, 2.9e-04, 1.1e-04, 4.5e-05, 3.3e-05, 1.5e-05, 7.0e-06
- **ZZ**: 3.0e-02, 1.1e-02, 4.5e-03, 3.3e-03, 1.5e-03, 7.0e-04
- **cc**: 3.4e-02, 1.3e-02, 5.0e-03, 3.7e-03, 8.5e-04
- **ττ**: 7.3e-02, 2.7e-02, 1.1e-02, 4.0e-03
- **gg**: 9.9e-02, 3.7e-02, 7.3e-03
- **WW**: 2.5e-01, 4.6e-02
- **b̅b**: 3.3e-01

**Good mass resolution**

**μμ**

**ss**

**Zγ**

**γγ**

**ZZ**

**cc**

**ττ**

**gg**

**WW**

**b̅b**

**High branching ratio**

**bbγγ FINAL STATE**

- **bbγγ**: Low background + All objects are reconstructed - Br(HH→bbγγ) = 0.26%

**Expected to be the most sensitive channel to non-resonant SM HH production**

\[ \sigma(pp \rightarrow HH \rightarrow bb\gamma\gamma)_{\text{NNLO}+\text{NNLL}} = 0.087 \text{ fb} @ 13 \text{ TeV} \]
**RUN I NONRESONANT RESULTS**

**CMS**

\[
\sigma(pp \to HH \to \gamma \gamma b\bar{b})
\]

- Observed 95% CL upper limits
- Expected 95% CL upper limits

- \(\kappa_1 = 1.0, c_2 = 0\), assuming SM H decays
- Expected limit ± 1 std. deviation
- Expected limit ± 2 std. deviations

**SM result**: limit observed \(\sim 74 \times \) SM

**For details, see O. Bondu earlier in this session**


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**Experimental constraints**

- \(\lambda \) predicted but (loosely) constrained experimentally
- \(\kappa \lambda = \lambda / \lambda_{SM} \), \(\kappa t = y_t / y_{t_{SM}} \)

**There exists other couplings in BSM scenarios:**

- \(c_2, c_g, c_{2g} \)

**There exists alternatives**

- \(1607.05330 \)

**Cross-section can vary sensibly**: \([10^{-1}, 10^4] \times \sigma(pp \to hh)_{SM}\)

**Signal shape can be significantly different from SM**

**Model builders manage to accommodate deviations of O(1)... we need to do better!**
RUN I RESONANT RESULTS

CMS

Supplementary
Assumes SM Higgs BR
and narrow width for X

95% CL limit on σ(pp → X → HH) (fb)

WED: gg → X, kl = 35
no radion/H mixing

17.9-19.7 fb⁻¹ (8 TeV)

σ(pp → X → HH) (fb)

m_X^{spin-0} (GeV)

Most sensitive analysis in low mass region

CMS

WED: kl = 35, k/M_p = 0.2, elementary top, no r/H mixing

- radion (Λ_R = 3 TeV)
- radion (Λ_R = 1 TeV)
- RS1 KK-graviton
- Bulk KK-graviton

Observed 95% upper limit
Expected 95% upper limit
Expected limit ± 1 std. deviation
Expected limit ± 2 std. deviation

Observed
Expected

19.7 fb⁻¹ (8 TeV)

Low mass (PLB 749 (2015) 560)
Low mass (PLB 755 (2016) 217)
Mid. mass (CMS-PAS-HIG-15-013)
High mass (CMS-PAS-EXO-15-008)
High mass (CMS-PAS-HIG-15-013)

Observed 95% upper limit
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Assumes SM Higgs BR
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**Resonant Low Mass Strategy** \([M_X < 500 \text{ GeV}]\)
- According to signal hypothesis, select mass window in \(M(jj\gamma\gamma)\) around resonance mass
- Two categories based on b-tagging

**Resonant High Mass Strategy** \([M_X > 500 \text{ GeV}]\)
- Same strategy as Resonant Low Mass
- But single b-tagging category (looser) \(M_X < 900 \text{ GeV}\) for spatially resolved objects

**Nonresonant Strategy**
- No mass window in \(M(jj\gamma\gamma)\), cut on \(M(jj\gamma\gamma) > 350 \text{ GeV}\)
- Two b-tagging categories

**Signal Extraction:** 2D unbinned fit in \(M(jj)\) and \(M(\gamma\gamma)\)
PHOTONS & JETS

Photons selection ~ SM H→γγ

- Online: $E_T$, $M(γγ)$, shower shape and isolation
- Offline:
  - $E_T(γ_1,2) > 30, 20$ GeV and $> M(γγ)/3, M(γγ)/4$, $|η(γ's)| < 2.5$,
  - $100 < M(γγ) < 180$ GeV
  - MVA Photon ID (~90% signal efficiency working point)

Jets selection

- $ΔR(\text{jet,γ's}) > 0.4$, $p_T(\text{jets}) > 25$ GeV, $|η(\text{jets})| < 2.4$
- $80 < M(jj) < 200$ GeV
- jj candidate: two jets with highest b-tagging score
  - b-tagging MVA (secondary vertex information) used for categorization
- Jet energy regression based on jets constituents developed to improve jet energy resolution and scale

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**SM Higgs Contribution**

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**EFFICIENCIES**

**CMS Simulation Preliminary** 13 TeV

\[ gg \rightarrow X \rightarrow HH \rightarrow \gamma\gamma bb \]
- jets \( \geq 2+n \geq 2 \)
- \( \gamma \) kin. sel.
- jet presel.
- btag

\[ \gamma \text{ Id.} \]

\[ \text{Trigger} \]

\[ \text{Id.} \]

\[ \text{di-jet sel.} \]

btag: efficiency of selecting at least one medium b-tagged jet

medium b-tagging working point \( \sim ~ 80\% \) efficiency
$\tilde{M}_X = M(jj\gamma\gamma) - M(jj) + 125$ GeV

$M(jj\gamma\gamma) \rightarrow \tilde{M}_X$: resonance width improved

13 TeV

$\tilde{M}_X,$

Radion, $M_X = 250$ GeV
Radion, $M_X = 300$ GeV
Radion, $M_X = 350$ GeV
Radion, $M_X = 400$ GeV
Radion, $M_X = 500$ GeV
Radion, $M_X = 600$ GeV
Radion, $M_X = 700$ GeV
Radion, $M_X = 800$ GeV
Radion, $M_X = 900$ GeV
Radion, $M_X = 1000$ GeV

CMS Simulation Preliminary

Events/(30.0 GeV)

Events/(10.0 GeV)
In the resonant analysis, mass windows around the mass hypotheses are constructed in the $M(\gamma \gamma):\tilde{M}_X$ plane

- Avoids performing the analysis in unphysical regions of kinematic phase space

\[
\tilde{M}_X < M(\gamma \gamma) - 125 \text{ GeV} + \Delta W/2, \quad \tilde{M}_X > M(\gamma \gamma) - 125 \text{ GeV} - \Delta W/2
\]

- $\Delta W/2$ intervals defined ensuring 90% signal efficiency
**B-TAGGING BASED CATEGORIZATION**

- B-tagging as a tool to create signal-enriched and background-enriched regions
- Categorization strategy dictated by S/B and by expected number of background events (for parametric background estimation)
- Tight: \(~60\%\) efficiency for signal jets
- Medium: \(~80\%\) efficiency for signal jets
- Loose: \(~90\%\) efficiency for signal jets

### Res. Low Mass

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<thead>
<tr>
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<th>Subleading Jet btagging</th>
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### Nonresonant

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**HPC:** High purity category  
**MPC:** Medium purity category  
**JCR:** Light jets control region  
**SR:** Signal Region
PARAMETRIZED SIGNAL

2D Signal shape: \( f_{\gamma\gamma}[M(\gamma\gamma)] \times f_{jj}[M(jj)] \)

- \( f_{\gamma\gamma} \) and \( f_{jj} \) are modeled as a sum of a gaussian and a Crystal-Ball function

Signal shape is parametrized separately for each individual category and signal mass point

Example fits from the SM Nonresonant signal sample
PARAMETRIZED BACKGROUND

2D Background shape: $f_{\gamma\gamma}[M(\gamma\gamma)] \times f_{jj}[M(jj)]$

- $f_{\gamma\gamma}$ and $f_{jj}$ are modeled as a Bernstein polynomials of order 2 if number of events in signal region > 10, or 1 otherwise

Cross checks performed on fake photon control region:

- Choice of PDF for background modeling was found to be unbiased, within statistical precision
- Background correlation between $M(\gamma\gamma)$ and $M(jj)$ was found statistically negligible in data

Example fits from the SM Nonresonant selection
Analysis Uncertainties

- Largest analysis uncertainty is statistical - < 10% impact from systematical uncertainties
- Main systematical uncertainties coming from jet energy scale and resolution, and b-tagging

Nonresonant results:

- $\sigma(pp\rightarrow HH\rightarrow bb\gamma\gamma) < 7.90$ fb (7.85 fb expected) ~ $91 \times$ SM
Large fluctuations in expected and observed limits due to mass window requirement - limits are obtained in separate datasets
SUMMARY

- HH$\rightarrow$bb$\gamma\gamma$ searches performed with the 2015 dataset recorded by CMS at 13 TeV
- Observed limits are consistent with the expected by the null hypothesis
- HH$\rightarrow$bb$\gamma\gamma$ is currently the most sensitive final state to the SM nonresonant HH production at CMS
- For resonant searches, it is the most sensitive in the low mass region ($M_X < 400$ GeV) and competitive up to 900 GeV

For details, see S. Das earlier in this session
Backup
B-TAGGING CATEGORIES EXPLAINED

The b-tagging categorization ↔ amount of background in individual analysis categories

Goal: improve analysis sensitivity while maintaining enough events in individual categories for robust parametric background estimation

Nonresonant analysis:
- No mass window: b-tagging requirement tighter than in the other analysis categories.

Resonant analyses:
- Mass window (efficient at background mitigation) → b-tagging must be loose
- Background(Low Mass) >> Background(High Mass) → b-tagging requirements must be looser at high mass. than in low mass

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