Double Higgs searches at CMS

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Outline

1. Introduction

2. Double Higgs searches in CMS:
   A. $b\bar{b}\gamma\gamma$
   B. $b\bar{b}b\bar{b}$
   C. $b\bar{b}W\bar{W}$
   D. $b\bar{b}\tau\tau$

3. Results from LHC Run2

4. Future possibilities and projections
Motivations: Resonant searches

**MSSM/2HDM:** Additional Higgs doublet → CP-even scalar H.
- We can probe the low $m_A$/low $\tan\beta$ region where BR($H \rightarrow h(125)h(125)$) is sizeable.

**Singlet model:** Additional Higgs singlet with an extra scalar H.
- Sizeable BR beyond $2m_{\text{top}}$, non negligible width at high $m_H$.

**Warped Extra Dimensions:**
- spin-2 (KK-graviton) and spin-0 (radion) resonances.
- Different phenomenology if SM particles are allowed (bulk RS) or not (RSI model) in the extra dimensional bulk.
Motivations: Non-resonant searches

The non-resonant double Higgs production allows to directly probe the Higgs trilinear coupling ($\lambda_{hhh}$).

Even if in Run2 we do not have full sensitivity to “measure” SM $\lambda_{hhh}$ → The BSM physics can be modelled in EFT adding dim-6 operators\(^2\) to the SM Lagrangian, and the physics can be described with 5 parameters: $\lambda_{hhh}$, $\gamma_t$, $c_2$, $c_{2g}$, $c_g$

- Non SM top Yukawa and $\lambda_{hhh}$ couplings
- New diagrams and couplings in the game

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\[\sigma_{SM_{hh}}(13\text{TeV}) = 33.45\text{fb}^{+4.3\%-6.0\%(scale\ unc.)} \pm 3.1\%(PDF+\alpha_s\ unc)[1]\]

The shape of the Higgs potential is determined by the self coupling value

\[V(\phi) = \mu^2(\phi^+\phi) + \lambda(\phi^+\phi)^2\]
CMS searches

4 main channels presented today:
- $b\bar{b}b\bar{b}$, $b\bar{b}WW$, $b\tau\bar{\tau}$, $b\gamma\gamma$

At least one $h \rightarrow b\bar{b}$ to have large enough BR

Rare processes, low $\sigma$, complex environment

Covering both resonant and non-resonant searches

- **Run2:**
  - $b\tau\bar{\tau}$ Resonant and non-resonant PLB 778 (2018) 101/PAS-B2G-17-006
  - $b\bar{b}WW$ Resonant and non-resonant JHEP01(2018)054
  - $b\gamma\gamma$ Resonant and non-resonant PAS-HIG-17-008
  - $b\bar{b}bb$ Resonant PAS-HIG-17-009/arXiv:1710.04960 non-resonant PAS-HIG-16-026

- **Run1:**
  - $b\gamma\gamma$ Resonant and Non-resonant: arxiv:1603.06896

Trade-off between BR and contamination, complementarity among channels
- **$b\bar{b}b\bar{b}$:** highest BR, high QCD/$t\bar{t}$ contamination
- **$b\bar{b}WW$:** high BR, large irreducible $t\bar{t}$ background
- **$b\tau\bar{\tau}$:** relatively low background and BR
- **$b\gamma\gamma$:** high purity, very low BR
35.9 fb⁻¹ (2016). Low BR in the 2l2ν final state (2.72%)
• 2 OS leptons (ee, eμ, μe, μμ)
• Focus on the bbWW channel, Invariant mass cut to remove Z(ll) contributions
• Large background contamination from tt, Z+jets (from MC)

Parametrised DNNs used to discriminate against background
• Resonant: mₓ, non-resonant kt, kλ
• Limit extraction from DNN shape in 3 mjj bins

Results
• SM σxBR<72fb
• Obs.(exp.): σ/σ_SM< 79 (89)
Non-resonant $b\bar{b}b\bar{b}$

2.3 fb$^{-1}$ (2015)
- Highest BR among HH searches
- 4 jets, 3/4 b-tagged jets
- Pairing: 2 pairs closest in mass

Large Multijet (and tt) backgrounds. We want reliable background estimation with large statistics → Hemisphere mixing
- Data events cut in 2 hemispheres
- Hemisphere library → recreate events
- Pairing: nearest neighbour (kinematics)
- Validated in BDT sideband
- Small bias → systematic on bkg.
- Cut on BDT

Signal extraction: 2D shape of leading vs. sub-leading $m_{jj}$

$\text{SM} \sigma \times \text{BR} < 3.9$ pb

Obs.(exp.): $\sigma / \sigma_{\text{SM}} < 342 (308)$

To be updated soon! Expect sensitivity close to $b\bar{b}\tau\tau$
Resonant resolved bbbb

35.9 fb⁻¹ (2016)

4 b-tagged jets, deepCSV algorithm

b-jet energy regression to improve resolution, Kinematic fit for $m_{HH}$

Low Mass Region ($m_H < 400$) and High Mass Region ($400 < m_H < 1200$) studied separately to exploit kinematic properties of the signal

Background shape estimation from data in LMR, HMR

Background estimation cross-checked

- In <4 b-tag side bands
- With alternate SR definitions
Resonant boosted bbbb

35.9 fb⁻¹ (2016)

• Search for a heavy (MX>800GeV) resonance
• 2 “fat” jets (R=0.8), with double b-tagging
• B-tag based categories (LL, TT)
• Use constituent jets properties (“soft-drop” mass, N-subjettiness)
• Signal extraction → reduced mass: \( M_{\text{red}} = m_{jj} - (m_{j1} - m_{H}) - (m_{j2} - m_{H}) \)

Multijet background estimation

\( M_{\text{red}} < 1200 \text{ GeV}: \) refined ABCD method
• \( m_{j1} \) and b-tag sidebands
• Interpolate dependence on \( m_{j1} \)

\( M_{\text{red}} > 1200 \text{ GeV}: \)
• Parametric fit
• Same shape SB & SR, yields from ABCD


### bbττ

35.9 fb⁻¹ (2016)

3 final states (eτ_H, μτ_H, τ_Hτ_H), covering 88% of the BR

3rd lepton veto

Kinematic fit (SVFit) to reconstruct m(ττ)

Main backgrounds: tt, Z+jets (from MC) DY, multijet (from data)

- BDTs (low/high mass) to reject tt in semileptonic categories

**Resolved analysis:**
- 2 categories (1 or 2 b-jets)
- Elliptical cut in m(ττ), m(jj)

**Boosted (bb) analysis**
- 1 (R=0.8 jet), subjet b-tagging
- cut in m(ττ), m(j)

**Discriminant variable:**
- Non-resonant: Stransverse mass M_{T2}
- Resonant: Kinematic Fit of m(jjττ)
Non-resonant limits:
• SM $\sigma \times BR < 75.4$ fb
• Obs.(exp.): $\sigma/\sigma_{SM} < 30$ (25)

hMSSM interpretation on top of narrow width resonant searches
Resonant boosted bbττ

35.9 fb⁻¹ (2016), search for heavy mass resonances

Boosted b-jet (anti-kT,R=0.8) and boosted ττ (lτ_H,τ_Hτ_H)

Kinematic fit to reconstruct 50<m_ττ<150GeV

>0 b-tagged sub-jet, 105<m_j<135 GeV

Main backgrounds: tt, t+X,V+jets

• tt, t+X: Shape from MC simulation, normalisation from CR
• V+jets: from mj sidebands, shape corrected with simulation

Search performed up to 4TeV, excludes narrow width radion up to 2.5TeV
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35.9 fb⁻¹ (2016)

Low BR (0.26%), excellent resolution, clear signature

2 photons, 2 b-tagged jets (R=0.4)

Reduced mass: \( M_{\tilde{X}} = m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma} + 250 \text{ GeV} \)

BDT x \( M_{\tilde{X}} \) categorization: medium/high BDT purity and low/high reduced mass \( M_{\tilde{X}} < 350 \text{ GeV} / M_{\tilde{X}} > 350 \text{ GeV} \)

Main backgrounds: multijet, fake photons, SM Higgs production

2D parametric fit in \( (m_{jj}, m_{\gamma\gamma}) \) for signal extraction
bbγγ - Results

Sensitivity to non-resonant production dominated by the high mass/high purity category

Most performant CMS channel:
- SM σxBR<1.67 fb
- Obs.(exp.): σ/σ_{SM}< 19.2 (16.5)

Preliminary CMS (13 TeV)
No evidence for either spin-0 or spin-2 resonance up to 4 TeV

Excluded cross-section ranges from $<1$ pb (300 GeV) to $\sim$4 fb (3 TeV)

Sensitivity to non-resonant at $\sim 20$ times the SM expectation

Anomalous Higgs trilinear coupling constrained in the region $-8.8 < \lambda / \lambda_{SM} < 15$
Double Higgs searches are an important physics case for HL (and HE) LHC. CMS will undergo relevant upgrades for the HL-LHC phase.

New all-silicon tracker, $|\eta|<4$, track-trigger

Barrel calorimeters: new electronics

New endcap calorimeter (high granularity)

Muon detectors to $|\eta|<2.8$

Trigger: L1 @ 750 kHz, HLT @ 7.5 kHz
Double Higgs at HL-LHC, Projections

Dedicated studies: PAS-FTR-15-002

**bbγγ, bbττ, bbVV(lvlv, lvjj) ~50% precision**

Extrapolations of 2015 analyses: PAS-FTR-16-002

**bbγγ, bbττ, bbbb, bbVV(lvlv)**

Poor stat. for projections

New studies with updated CMS simulations coming soon
Conclusions

Several competing analyses in different final states under study in CMS, providing excellent coverage in different decay modes.

Non resonant double Higgs production is the main way to measure Higgs self-coupling.
- At the moment, we can probe $O(10-100\times SM)$.
- More luminosity is needed to reach SM sensitivity, but we are starting to probe BSM and to constraint exotic BSM
- Outperforming Run1 (scaled) results and projections.

Resonant searches can already provide important constrain on BSM physics (MSSM, WED, heavy scalars).
- KK-graviton excluded below 800 GeV, $\Lambda_R=1$ TeV Radion excluded below 2.5 TeV
- Boosted categories enhance sensitivity to high mass resonances

Further improvement awaited from the combination of the results among all channels

Exciting prospects for double Higgs searches
BACKUP
Why measure HH?

- Measurement of HH gives access to the magnitude of the Higgs self-interaction:

\[ V = \lambda v^2 H^2 + \lambda v^3 H + \frac{\lambda}{4} H^4 \]

- Higgs trilinear coupling constant \( \lambda \) only depends on the Higgs field VEV and Higgs mass. Purely determined by EWSB (in the SM).

- Shape of the Higgs potential is determined by the self coupling value (EWPT).
### gg→hh parametrization

The relevant lagrangian terms of gg→HH production in D=6 EFT

\[ \mathcal{L}_{hh} = -\frac{m_h^2}{2v} \left( 1 - \frac{3}{2}c_H + c_6 \right) h^3 + \frac{\alpha_s c_g}{4\pi} \left( \frac{h}{v} + \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\mu\nu}_{\mu\nu} \]

\[ - \left[ \frac{m_t}{v} \left( 1 - \frac{c_H}{2} + c_t \right) \tilde{t}_L t_R h + \text{h.c.} \right] - \left[ \frac{m_t}{v^2} \left( \frac{3c_t}{2} - \frac{c_H}{2} \right) \tilde{t}_L t_R h^2 + \text{h.c.} \right] \]

arXiv:1410.3471

**SM diagrams**

- **ttHH non-linear interaction**
- **Higgs-gluon contact interactions**
An EFT implementation for hh

The double Higgs production cross section can be written as a function of the 5 EFT parameters: $\lambda_{hhh}, \gamma_t, c_2, c_{2g}, c_g$

$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = \frac{\sigma_{LO}}{\sigma_{LO}^{SM}} = A_1 c_1^4 + A_2 c_2^2 + (A_3 c_2^2 + A_4 c_g^2) c_3^2 + A_5 c_2 g + (A_6 c_2 + A_7 c_2 c_\lambda) c_3^2 + (A_8 c_2 c_\lambda + A_9 c_g c_\lambda) c_2 + A_{10} c_2 c_2 g + (A_{11} c_g c_\lambda + A_{12} c_g) c_1^2$$

$$+(A_{13} c_2 c_\lambda + A_{14} c_2 g) c_1 c_\lambda + A_{15} c_2 c_g c_\lambda$$

$2D (M_{HH}, \cos \theta^*)$ signal shapes from different points in the 5D EFT phase space are clustered together.

12 clusters are identified according to there kinematical properties

Inside each cluster, a representative shape is identified, as the one with the minimum distance (in the test statistics) from all other shapes in the cluster

Each point of the phase space can be mapped by means of its cross-section and representative shape
Shape benchmark

$\lambda_k$ SM

$\rightarrow$

(fb)

$\rightarrow$

(σ → HH) [fb]

95% CL upper limit on

$\sigma(gg \rightarrow HH)$ [fb]

CMS Preliminary

Assumes SM Higgs branching fractions

Observed

Median expected

95% expected

68% expected

bbττ (arXiv:1707.02909)

bbγγ (HIG-17-008)

Observed

Median expected

95% expected

68% expected

35.9 fb$^{-1}$ (13 TeV)

1

2

3

4

5

6

7

8

9

10

11

12

$\kappa = 0$ SM

Shape benchmark

Observed

68% expected

Median expected

95% expected

(13 TeV)

-1

$-35.9$ fb

branching fractions

Assumes SM Higgs

Preliminary

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DIS2018 - Kobe - 16-23/04/2018
Beyond HL-LHC: HH@FCC-hh

Delphes based study for hypothetical FCC-hh detector. Not a CMS projection