Latest CMS results on 
Higgs $\rightarrow$ $\gamma\gamma$

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Higgs Boson

Production @ 13 TeV

Production cross section increases by a factor of ~2 in 13 TeV in all production mechanisms.

$t\bar{t}H$ production increases by a factor of ~4.
Higgs Boson

*Decay to photons*

- No direct Higgs-Photon interaction
- Higgs decays to two photons via loops
- The Higgs → γγ branching-fraction is ~0.2%
  - Almost the least branching fraction for Higgs(MH=125GeV)
Higgs Boson

Decay to photons

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  - Almost the least branching fraction for Higgs($MH=125 GeV$)

Total number of $H \rightarrow \gamma\gamma$ in 35.9 fb$^{-1}$ of pp collisions at CMS in 2016: ~4.2K
Data and Simulation

- **35.9 fb\(^{-1}\) of pp collision recorded by CMS**

- **Online selection:**
  - Events with two photon candidate
  - Loose isolation and shower shape criteria
  - \(p_T^1 > 30\) GeV and \(p_T^2 > 18\) GeV

- **Simulation:**
  - Higgs signals are generated at NLO using **MG5_aMC@NLO**
  - Showkening and hadronization in **Pythia8**

- **Documented in**
  - CMS-HIG-16-040: Inclusive
  - CMS-HIG-17-015: Differential and Fiducial
Photon reconstruction in CMS

- ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL
  - No matched pixel detector hit
- Collection of complete energy of the photon in clustering
  - Contain the energy of converting photons
- The energy is corrected for the EM showers and energy loss of converted photons
  - Regression method trained in simulation
- Photon energy scale applied in data
  - Simulation is smeared to reproduce the energy resolution of data

- Validated in $Z \rightarrow ee$ events, where electron showers are reconstructed as photons
Photon Selection

Pre-selection

- $p_T^{1(2)} > 30(20)$ GeV
- $R_9$ and $\sigma_\eta\eta$
- H/E energy
- Electron Veto
- Isolation (photons, tracks, charged hadrons)

Efficiencies from $Z \rightarrow ee$ events in data and MC

For electron-veto: $Z \rightarrow \mu\mu$
Photon Identification

- Boosted Decision Tree (BDT) trained using $\gamma$+jet simulated events
- Input variables
  - All the variables used for selection
  - the median energy density per unit area in the event
Diphoton Vertex

\[ \Delta z_{\text{vertex}} < 1\text{cm} \quad \rightarrow \quad \text{Mass resolution dominated by photon energy resolution} \]

- **BDT** is trained to assign the photon-pair to the right vertex

- **Input variables:**
  - Observables related to tracks recoiling against the diphoton system
  - For photons with conversion tracks, information of the vertex of those tracks are also included

- Vertex assignment is validated using \( Z \rightarrow \mu\mu \) events

- The assigned vertex is within 1cm of the real one in 81% of cases

- \( \sum_i |p_T^i|^2, \)

- \( - \sum_i (p_T^i \cdot \frac{p_T^{\gamma\gamma}}{|p_T^{\gamma\gamma}|}) , \)

- \( (|\sum_i p_T^i| - p_T^{\gamma\gamma}) / (|\sum_i p_T^i| + p_T^{\gamma\gamma}) , \)
Diphoton identification

- **BDT** Trained to evaluate the di-photon mass resolution per-event
  - And select signal-like events

- **Input variables:**
  - $PT$ / Mass and $\eta$ of each photon
  - $\Delta\phi$ of the photons
  - Photon ID BDT scores
  - Mass resolution estimates
  - Probability of the correct vertex assignment

- **Validated** in $Z \rightarrow ee$ events

- Used for **categorization** of "untagged" events
## Event Categorization

### ttH
- A dedicated BDT is trained
  - Cut optimized along with $\gamma\gamma$ BDT ID
- Leptonic
  - At least one lepton, far enough from photons
  - At least 2 jets, one is tagged as b-jet
- Hadronic
  - No lepton
  - At least 3 jets, one is tagged as b-jet

### V (Z,W) H
- ZH-Leptonic
  - Two leptons with 70<\(M\)<110
- WH-Leptonic
  - At least one lepton, MET > 45 GeV
  - n Jets < 3
- VH-Leptonic Loose
  - Same as WHLeptonic, MET < 45 GeV
- VH-MET
  - MET > 85 GeV
  - $\Delta\varphi$(MET,\(\gamma\gamma\)) > 2.4
- VH-Hadronic
  - At least two jets, 60 < \(m(jj)\) < 120 GeV

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### Process Flow

1. **ttH**
   - Leptonic
   - Hadronic

2. **tVBF**
   - A dedicated BDT is trained
     - Forward jet kinematics
     - Optimize exp. significance in 3 categories
   - Two forward jets, \(m(jj)\) > 250

3. **3 VH**
   - Leptonic

4. **TTH**
   - Hadronic

5. **VBF 0-2**
   - MET

6. **VH**
   - Hadronic

7. **Untagged 0-3**
Selection Results

Yields in different categories for different Higgs production modes / Backgrounds
Search for the signal

- **Strategy:**
  - Search for the Higgs bump in the falling background

- **Modeling the signal shape:**
  - Separate for Wrong-Vertex and Right-Vertex events
  - Sum of n-Gaussians (n < 5)

- **Modeling the falling background:**
  - Fully data-driven, fitting across the full range
  - A large set of functions are fitted:
    - Exponentials, Bernstein polynomials, Laurent and power law functions
  - F-Test to determine the maximum order to be used
Results

\[ \hat{\mu} = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10} \text{ (stat.)}^{+0.09}_{-0.08} \text{ (syst.)}^{+0.06}_{-0.05} \text{ (theo.)} \]

Best Fit Mass:
\[ M_H = 125.4 \text{ (GeV)} \pm 0.15 \text{ (stat.)} \pm \sim 0.3 \text{ (syst.)} \]

Observed (Expected) Signal Strength for ttH: 3.3 (1.5) σ
Results on Higgs Couplings

$q = 35.6 \sim 5.6\sigma$ away from best fit
Differential/Fiducial cross section measurement

HIG-17-015
Categorization

Based on “Uncorrelated mass resolution” estimator

\[
y(\sigma_{m/m|m}) = \int_0^{\sigma_{m/m}} f(\sigma_{m/m'|m}) d\sigma_{m/m'}
\]

uniformly distributed, thus not correlated with mass

Make cumulative distribution functions

Constructed by sorting values of \(\sigma_{m/m}\) in bins of \(m\)

- Verified using \(Z \rightarrow ee\) events, with electrons reconstructed as photons
- 3 Categories enough to saturate the maximum achievable sensitivity
Results

- Data is unfolded to particle-level using a likelihood fit.
- Total fiducial cross section in $p_T^{1(2)}=m/3(4)$ and $|\eta|<2.5$ is measured.
- Differential fiducial cross section in $p_T^{\gamma\gamma}$ and nJets bins are reported.
Summary

- Higgs → γγ is (one of) the most precise channel to study the Higgs properties

- CMS has developed dedicated selection to tag photon pairs coming from Higgs decay
  - overall efficiency ~45%

- 2016 dataset has been analyzed by CMS and first results were presented
  - Some evidence of ttH production mode
  - Diff. results up to $p_{T}^{Higgs} \sim 2 \times m_{top}$ and $n_{Jets} > 3$ were presented

- Stay tuned for the most precise mass measurement in this channel using the 2016 dataset
BACKUP
The CMS detector

- Silicon pixel and strips trackers
  - Covering $|\eta|<2.5$

- lead-tungstate crystal electromagnetic calorimeter (ECAL)
  - Barrel extends to $|\eta|<1.48$
  - Endcap: $1.48<|\eta|<3.0$

- A lead/silicon-strip preshower detector in front of the ECAL-Endcap
Vertex assignment efficiency

**CMS Simulation Preliminary**

$H \rightarrow \gamma \gamma$ ($m_H = 125$ GeV)

Data PU scenario (35.9 fb$^{-1}$)

Fraction of $|Z_{\text{selected}} - Z_{\text{true}}| < 10$ mm

$E_{T}^{\gamma\gamma}$ (GeV)

Number of vertices

True vertex efficiency

Average vertex probability

Average vertex probability
Signal, Background, data
all categories summed
Differential: uncorrelated mass resolution
Differential Response matrices
\[ \mathcal{L}(\text{data}| \Delta \sigma, n_{\text{bkg}}^\sigma, \bar{\theta}_S, \bar{\theta}_B) = \]

\[
\prod_{i=1}^{n_{\text{cat}}} \prod_{j=1}^{n_b} \prod_{l=1}^{n_{m_{\gamma \gamma}}} \left( \sum_{k=1}^{n_b} L \Delta \sigma_k K_{k}^{ij}(\bar{\theta}_S) S_{k}^{ij}(m_{\gamma \gamma}|\bar{\theta}_S) + n_{\text{OOA}}^{ij} S_{\text{OOA}}^{ij}(m_{\gamma \gamma}|\bar{\theta}_S) + n_{\text{bkg}}^{ij} B_{ij}(m_{\gamma \gamma}|\bar{\theta}_B) \right)^{n_{\text{ev}}^{ij}}.
\]

\[ \text{Pois}(n_{\text{ev}}^{ij}|n_{\text{sig}}^{ij} + n_{\text{bkg}}^{ij}) \cdot Pd f(\bar{\theta}_S) Pd f(\bar{\theta}_B) \]

- \( L \) is the total integrated luminosity analyzed;
- \( \Delta \sigma = (\Delta \sigma_1...\Delta \sigma_{n_b}) \) is the vector of fiducial cross sections being measured;
- \( K_{k}^{ij} \) are the response matrices, which represent the probability that an event in the k-th kinematic bin at generator level is reconstructed in the ij-th reconstruction-level category (with the index i running on the \( \sigma_m/m|_{\text{decorr}} \) categories and the index j running on the kinematic bin);
- the functions \( S_{k}^{ij} \) and \( B_{ij} \) are the signal and background distributions in \( m_{\gamma \gamma} \), which will be described in the next section;
- \( n_{\text{ev}}^{ij}, n_{\text{sig}}^{ij}, n_{\text{bkg}}^{ij} \) are the number of observed, signal and background events in the ij-th reconstruction-level category respectively;
- the terms \( n_{\text{OOA}}^{ij} S_{\text{OOA}}^{ij} \) represent the contributions of the Higgs boson signal originating outside of the fiducial region. The contribution of the out of acceptance Higgs boson signal is estimated from simulations to be roughly 1% of the total expected SM signal;
- the parameters \( \bar{\theta}_S \) and \( \bar{\theta}_B \) are the nuisance parameters associated with the signal and background model respectively.