Higgs to gamma gamma at CMS
Higgs Hunting Orsay 2013

Matthew Kenzie
On Behalf of the CMS Collaboration
Introduction

- Low BR ~0.2%
- Clean final state
- Can reconstruct mass with good precision

\[ m_{\gamma\gamma} = \sqrt{2E_1 E_2(1 - \cos \alpha)} \]
Overview

- Main result as presented at Moriond - **CMS-PAS-HIG-13-001**
  - Multivariate (MVA) approach
  - Cut-based approach
- Properties and spin analysis - **CMS-PAS HIG-13-016**
  - Uses the cut-based selection
- ttH specific analysis – **CMS-PAG-HIG-13-015**
- H→Zγ analysis – **CMS-PAG-HIG-13-006**
- Use full dataset available 2011 (5.1fb⁻¹) + 2012 (19.6fb⁻¹)
  - Spin analysis uses just 2012
- Legacy paper towards end of the year

**Background composition**

- prompt-prompt (irreducible) pp→γγ ~70%
- prompt-fake (reducible) pp→γ+jet ~30%
- fake-fake (reducible) pp→jet+jet <1%

**Looking for a small peaking signal on a large falling background**

- MC only used for cut and MVA optimisation
- Background for analysis is data driven
Analysis Strategy

- Select events with two high energy, isolated photons
- Separate events into non-overlapping categories with different S/B and different resolution
- Particular exclusive tagged categories
  - Improve S/B in certain categories
  - Separate production modes for coupling measurements
- Background estimated in data
  - Fit $\gamma\gamma$ invariant mass distribution to data
- Two analyses
  - Multivariate approach $\rightarrow$ main result, couplings, second Higgs
  - Cut based approach $\rightarrow$ cross check, spin analysis
**Photon Energy**

\[ m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos \alpha)} \]

- **Single Crystal**
  - Energy calibration ([CMS-PAS-EGM-11-001](#))
  - Transparency loss correction
  - Inter-calibration -> uniform \( \eta-\phi \) response
- **SuperClustering (SC)**
  - Some photons convert in tracker
  - \( R_9 = \frac{E_{3x3}}{E_{SC}} \) (>0.94 is unconverted)
- **Energy regression correction**
  - BDT target = \( \frac{E_{raw}}{E_{true}} \)
  - Input variables: SC position, shower shape variables, median energy density per event (\( \rho \))
    - Improve \( \sigma_{eff} \) by \( \sim 30\% \)
- **Also provide per photon energy resolution estimate**
- **Monitored with \( Z \rightarrow ee \)**
  - Resolution stable with time
**Vertex Identification**

\[ m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\alpha)} \]

- Pileup (PU)
  - multiple collisions per event
  - \(<\text{PU}>_{2012} = 20\)

- Use a Boosted Decision Tree (BDT)
  - \(\Sigma p_T^2\) of all tracks
  - Track recoil/imbalance with respect to \(p_T(\gamma\gamma)\)
  - Pointing from conversion tracks

- Control samples for validation
  - \(Z\rightarrow\mu\mu\) for unconverted photons
  - \(\gamma^*\text{jet}\) for converted photons

- Also have an additional BDT which provides, per-event, the correct vertex probability

**Vertex efficiency** \(<\text{eff}> = 80\%\)

**Data/MC ratio**

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Photon ID BDT

- **Used to reject fakes**
  - Neutral mesons (mainly $\pi^0$) decay into two ~collinear photons (look similar to single high $E_T\gamma$)

- **Input variables**
  - Several shower shape variables (MC corrected to match data)
  - Isolation
    - Particle-flow energy around photon candidate
  - Average energy density per event ($\rho$)
    - Correlated to PU
  - Photon position $\eta$ (to exploit correlations)

- **Output**
  - Validated with $Z\rightarrow ee$ and $Z\rightarrow \mu\mu\gamma$
  - Shape corrections derived with $Z\rightarrow ee$

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ECAL clusters

Photon energy

Vertex ID

**Photon ID**

Diphoton Selection + Cats

Statistical analysis

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**Diphoton BDT**

- Produces a single discriminant (BDT) from
  - Event kinematics
    - $p_T(\gamma_1)/m_{\gamma\gamma}$, $p_T(\gamma_2)/m_{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$
  - Event resolution
    - mass resolution (right vertex), mass resolution (wrong vertex), vertex probability
  - Photon quality
    - photon ID MVA output for each $\gamma$

- Mass blind!
- Optimise four category boundaries to increase signal sensitivity
- Validated with $Z\rightarrow ee$
  - systematics propagated through

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**Event classes**

**Signal MC**

**Data & Bkg MC**

**Output of the BDT in $Z\rightarrow ee$**

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Cut Based Analysis

- Photon selection is optimised in four categories
  - photon in barrel (EB) or endcap (EE) - $|\eta|<1.444$
  - photon is flagged as converted or unconverted - $R_9>0.94$

- Efficiency corrections derived from $Z\rightarrow ee$ events in data/MC

- Split diphoton events into 4 natural categories with
  - Cat0 - both photons in barrel AND both photons unconverted
  - Cat1 - both photons in barrel AND at least one conversion
  - Cat2 - at least one photon in endcap AND both photons unconverted
  - Cat3 - at least one photon in endcap AND at least one conversion
• Tagging leptonic decays of associated W, Z or top in Higgs production

• 3 additional analysis categories for 2012 only
  - muon, electron, MET

• On top of standard diphoton selection:
  - require high energy electron or muon ($p_T > 20$ GeV)
  - or large MET (>70 GeV)

• High S/B but very low yield
Dijet tag

- PU ID rejects jets from PU
- Additional analysis categories
  - 2011 - 1 additional category
  - 2012 - 2 additional categories (tight and loose dijet selection)
- High S/B but considerable gluon fusion contamination
- MVA analysis uses a BDT for categorisation
- Cut-based analysis uses a cut based selection

- Tagging two high $p_T$ jets with characteristic topology from VBF Higgs production
  - Two forward high $p_T$ jets
  - Large $m_{jj}$
  - high $\Delta\eta(jj)$
  - $\Delta\phi(jj-\gamma\gamma)$
**Signal and Background Models**

- **Background** - 3\textsuperscript{rd}-5\textsuperscript{th} order polynomial in each cat
  - Chosen such that systematic is negligible
- **Signal** - sum of Gaussians in each category for each process
  - $\sigma/m$ for all events $\sim1.6\%$
  - $\sigma/m$ for best events $\sim1\%$

### Expected signal and estimated background

<table>
<thead>
<tr>
<th>Event classes</th>
<th>SM Higgs boson expected signal ($m_H=125$ GeV)</th>
<th>Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>$ggH$</td>
</tr>
<tr>
<td>Unagged 0</td>
<td>3.2</td>
<td>61.4%</td>
</tr>
<tr>
<td>Unagged 1</td>
<td>16.3</td>
<td>87.6%</td>
</tr>
<tr>
<td>Unagged 2</td>
<td>21.5</td>
<td>91.3%</td>
</tr>
<tr>
<td>Unagged 3</td>
<td>32.8</td>
<td>91.3%</td>
</tr>
<tr>
<td>Dijet tag</td>
<td>2.9</td>
<td>26.8%</td>
</tr>
<tr>
<td>Unagged 0</td>
<td>17.0</td>
<td>72.9%</td>
</tr>
<tr>
<td>Unagged 1</td>
<td>37.8</td>
<td>83.5%</td>
</tr>
<tr>
<td>Unagged 2</td>
<td>150.2</td>
<td>91.6%</td>
</tr>
<tr>
<td>Unagged 3</td>
<td>159.9</td>
<td>92.5%</td>
</tr>
<tr>
<td>Dijet tight</td>
<td>9.2</td>
<td>20.7%</td>
</tr>
<tr>
<td>Dijet loose</td>
<td>11.5</td>
<td>47.0%</td>
</tr>
<tr>
<td>Muon tag</td>
<td>1.4</td>
<td>0.0%</td>
</tr>
<tr>
<td>Electron tag</td>
<td>0.9</td>
<td>1.1%</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ tag</td>
<td>1.7</td>
<td>22.0%</td>
</tr>
</tbody>
</table>
Invariant Mass Spectra

- ECAL clusters
- Photon energy
- Vertex ID
- Photon ID
- Diphoton Selection + Cats
- Statistical analysis

MVA

Cut Based

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ECAL clusters → MVA
Photon energy → MVA
Vertex ID → MVA
Photon ID → MVA
Diphoton Selection + Cats → Cut Based

Statistical analysis

Results I

$$m_H = 125 \text{ GeV}$$

$$m_H = 124.5 \text{ GeV}$$

Compatible within 1.5σ (when correlations are taken into account)
Results II

MVA analysis

ECAL clusters
→ Photon energy
→ Vertex ID
→ Photon ID
→ Diphoton Selection + Cats
→ Statistical analysis

\( \sigma / \sigma_{SM} = 0.78 \)
\( m_H = 125.2 \)
Use MVA analysis with additional terms in the likelihood

Upper limit on natural width

- Observed <6.9 GeV at 95%CL
- Expected <5.9 GeV at 95% CL

Limit on second SM-like Higgs

- Assume state at 125 is SM like and is part of the background
- Set limit on second SM like state elsewhere
- Local p-value of excess at 136.5 GeV ~ 2.9σ
Results IV - Properties

- Limit on two degenerate Higgs
  - both have SM couplings
  - assume signal lower in mass contains fraction of the signal, $x$

**Expected**

**Observed**

- ECAL clusters
- Photon energy
- Vertex ID
- Photon ID
- Diphoton Selection + Cats
- Statistical analysis
Results V - Spin

- Uses cut-based analysis selection
  - No exclusive mode tags, 4 inclusive categories kept
  - 5 additional categories in $\cos(\theta_{CS}) = 20$ categories total
- Use spin-$2_m^+$ model - graviton with minimal couplings
  - Produced by gluon fusion (gg) and quark-antiquark annihilation (qq)

1. Extract signal yield in bins of $\cos(\theta_{CS})$
2. Fit all 20 categories together and plot likelihood ratio of spin2/spin0 varying spin-2 production from qq
Summary

- Results from the H$\rightarrow\gamma\gamma$ search at CMS have been presented
  - Excess with an observed significance of $3.2\sigma$ (expected $4.2\sigma$)
  - Best fit signal strength (at $m_H=125$GeV) $\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$
  - Mass measurement: $m_H = 125.4\pm0.5{(\text{stat})}\pm0.6{(\text{syst})}$
  - Couplings measurement: compatible with SM at $<1\sigma$

- Properties of the new state investigated
  - Exclusion limits set on second Higgs
  - Upper limit on natural width
  - Spin analysis
    - Unable to exclude spin-2 graviton with minimal couplings
  - $t\bar{t}H$ specific analysis
    - Observed (expected) upper limit at 95% $5.4 (5.3) \times SM$
Diphoton triggers:
- $E_T(\gamma_1) > 22$, $E_T(\gamma_2) > 18$ GeV
- $E_T(\gamma_1) > 28$, $E_T(\gamma_2) > 26$ GeV
- Loose isolation
- Loose shower shape

Trigger efficiency ~99.5%
SuperClustering

- ECAL-barrel = “Hybrid algorithm”

- ECAL-endcap = “Multi-5x5”

A crystal included in the nth cluster which can seed other clusters

A crystal included in a cluster which cannot seed other clusters

The seed crystal of the nth cluster
SuperClustering II

Barrel

Endcap

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Tracker material

- About 40% of photons convert in tracker
  - \(\sim\frac{2}{3}\) of diphoton events contain at least one conversion
Pileup (PU)

- Beam condition yield multiple collisions per event
  - $<\text{PU}_{2012}> = 20$
  - Beam spot with $\sim 6\text{cm}$
Event classification

• Separate events into classes to improve sensitivity
• Tag exclusive modes in this order:

  tag muon \rightarrow TTH
  tag electron \rightarrow VH
  tag dijets \rightarrow VBF
  tag MET \rightarrow GGH
  untagged

• Unagged events
  o use diphoton MVA to classify further into 4 categories
  o use cut based selection and classify in $\eta$, $R_9$
Energy scale

- Important input to mass measurement
- Use $Z \rightarrow ee$ where electrons are reconstructed *exactly* the same as photons
- Add fully correlated error which considers:
  - imperfect MC simulations of the difference between electrons and photons
  - the need to extrapolate the scale from $m_Z$ to $m_H$

![Graphs showing electron-photon ratio](image)
Jackknife resampling

• Given an estimator (an observable – in this case \( \mu \)) of a dataset you can obtain the expected variance of the estimator

• Cut (jackknife) the sample into multiple exclusive subsets and re-evaluate the estimator

• If you start with \( n \) events you remove exclusive sets of \( d \) events

• Thus you have \( g=n/d \) samples of \( n-d \) events on which you re-calculate \( \mu \)

• Analogous to the familiar undergraduate method of splitting a sample in two to estimate the statistical uncertainty
Jackknife resampling

- The **estimator** properties can be extracted from the jackknife histogram

\[
\begin{align*}
\mu^{(1)} & = \mu_x (1) \\
\vdots & \\
\mu^{(g)} & = \mu_x (g)
\end{align*}
\]

- For example the variance:

\[
\text{var}_J (\mu) := \frac{g-1}{g} \sum (\mu(j) - \bar{\mu}_d)^2 = \frac{(g-1)^2}{g} \text{var}(\mu(j))
\]

**NOTE:** \( g=2 \) recovers the familiar formula

\[
\bar{\mu}_d = \frac{1}{g} \sum \mu(j)
\]
Jackknife resampling

Given two analyses there are three datasets

- Events selected by Analysis A (CutBased)
- Events selected by Analysis B (MVA)
- Events selected by either A or B (i.e. $A \cup B$) of which the majority are in common

Use the jackknife to estimate

- $\sigma(\mu_A)$, $\sigma(\mu_B)$ and $\sigma(\delta \mu) = \sigma(\mu_A - \mu_B)$

\[
\begin{align*}
\text{var}(\mu_A) &= \left( \sigma(\mu_A)^2 + r \sigma(\mu_A) \sigma(\mu_B) \right) \\
\text{var}(\mu_{A-B}) &= \left( r \sigma(\mu_A) \sigma(\mu_B) \right) \\
\text{var}(\mu_B) &= \sigma(\mu_B)^2
\end{align*}
\]
Estimate the best fit of the signal strength modifier of the Hgg analysis:
method 1: $0.78 \pm 0.28 ^{+0.28}_{-0.26}$
method 2: $1.1 \pm 0.32 ^{+0.32}_{-0.30}$

One sample of data, two methods to extract one parameter. The results are correlated because they share the same dataset. Are the two results compatible?

\[
\rho_{X,Y} = \text{corr}(X, Y) = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} = \frac{E[(X - \mu_X)(Y - \mu_Y)]}{\sigma_X \sigma_Y},
\]

1) Get the correlation coefficient:
   i.e. calculate the variance of the first and the second measurement and the variance of the overlapping events
2) Calculate the difference between the two results using

\[
\sigma_x^2 + \sigma_y^2 - 2\rho \sigma_x \sigma_y
\]

Use resampling techniques (in this case a Jackknife) to get the variances
Remove one (or N) point from the sample distribution

and calculate the new sample average:

\[ \bar{x}(i) = \frac{n\bar{x} - x_i}{n - 1} = \frac{1}{n - 1} \sum_{j \neq i} x_j \]

dot notation

\[ \bar{x}(.) = \frac{1}{n} \sum_{i=1}^{n} \frac{x(i)}{n} \]

(on the sample at hand)

The jackknife estimate of the standard error is defined as:

\[ \bar{\sigma}_J = \left[ \frac{n - 1}{n} \sum_{i=1}^{n} \left( \bar{x}(i) - \bar{x}(.) \right)^2 \right]^{1/2} \]

\[ \hat{\sigma} = \bar{\sigma}_J \]
### Jack-knife Resampling III

<table>
<thead>
<tr>
<th></th>
<th>MVA analysis</th>
<th>Cut-based analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(at $m_H=125$ GeV)</td>
<td>(at $m_H=124.5$ GeV)</td>
</tr>
<tr>
<td>7 TeV</td>
<td>1.69$^{+0.65}_{-0.59}$</td>
<td>2.27$^{+0.80}_{-0.74}$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>0.55$^{+0.29}_{-0.27}$</td>
<td>0.93$^{+0.34}_{-0.32}$</td>
</tr>
<tr>
<td>7 + 8 TeV</td>
<td>0.78$^{+0.28}_{-0.26}$</td>
<td>1.11$^{+0.32}_{-0.30}$</td>
</tr>
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![Diagram](image)
Diphoton MVA Validation

- Inputs are validated with
  - $Z\rightarrow ee$ (electrons reconstructed as photons)
  - $Z\rightarrow \mu\mu\gamma$
- Empirical corrections derived for inputs
  - Use Drell-Yan data/MC comparison
  - Correct resolution and photonID
- Systematic uncertainties propagated through BDT
  - Resolution and photonID
  - Implemented as category migration
MVA-CiC comparison

- MVA output for data events which pass CiC selection
• Events which pass MVA selection
  ○ Events which also pass CiC are shaded
Background Model Choice

• For each category fit with different functional forms
  o exponentials sums, power laws, laurent series, polynomials

• Choose the lowest order of each which fits the data well
  o G.O.F test with unbinned like F-test - p(N+1)<0.05
  o Determines “truth” functions

• Throw toy MC from the truth functions

• Choose the lowest order functional form such that
  o bias on signal strength < 20% statistical uncertainty on background
  o neglect any systematics on background
  o choices are 3rd-5th order polynomials
Signal Strength

**MVA**

CMS preliminary
\[ \sqrt{s} = 7 \text{ TeV} \; L = 5.1 \text{ fb}^{-1} \; (\text{MVA}) \]
\[ \sqrt{s} = 8 \text{ TeV} \; L = 19.6 \text{ fb}^{-1} \; (\text{MVA}) \]

**Cut Based**

CMS preliminary
\[ \sqrt{s} = 7 \text{ TeV} \; L = 5.1 \text{ fb}^{-1} \; (\text{CIC}) \]
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Channel Compatibility

MVA

Cut Based

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\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)
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- Event Class
- Combined
- \( m_H = 125.0 \text{ GeV} \)
- \( \sigma/\sigma_{\text{SM}} = 0.78 \pm 0.29 - 0.26 \)

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- Event Class
- Combined
- \( m_H = 124.5 \text{ GeV} \)
- \( \sigma/\sigma_{\text{SM}} = 1.11 \pm 0.32 - 0.30 \)

MET
Electron
Muon
Di-jet loose
Di-jet tight
Untagged 3
Untagged 2
Untagged 1
Untagged 0
Di-jet
Untagged 3
Untagged 2
Untagged 1
Untagged 0

Best Fit \( \sigma/\sigma_{\text{SM}} \)

8TeV

7TeV

Imperial College London

Matthew Kenzie

24/07/2013

42
Second Higgs

Second Higgs has ggH and ttH coupling only

Second Higgs has qqH and VH coupling only
Two Higgs

Expected

Observed

CMS Preliminary

Observed

CMS Preliminary

γS=7TeV L=5.1fb⁻¹
γS=8TeV L=19.6fb⁻¹

γS=7TeV L=5.1fb⁻¹
γS=8TeV L=19.6fb⁻¹

Imperial College London
The limits on the production cross section times branching ratio of a Higgs boson decaying to two photons relative to the SM expectation, are shown in Figure 4, for the leptonic (left) and hadronic (right) channels. The expected limit is shown as a dotted black line, and the bands corresponding to 68% (green) and 95% (yellow) probability are added. The observed limit is limited with the current statistics, the expected limit being about 6% more stringent if systematic uncertainties are neglected. The observed and expected 95% upper limits are summarized in Table 2:

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<thead>
<tr>
<th>Channel</th>
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<th>Expected Limit</th>
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<tbody>
<tr>
<td>Leptonic</td>
<td></td>
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</tr>
<tr>
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<td></td>
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Statistical uncertainties are neglected. The observed and expected 95% upper limits are summarized in Table 2:

The signal strength modifier is evaluated using a data-mc comparison.

Hadronic Channel

The expected limit neglecting systematic uncertainties are given for the hadronic channel, the leptonic channel.

Numerical factors by one standard deviation of their uncertainty. The simulated signal yield changes by 1.3% in the leptonic channel and 1.1% in the hadronic channel.

This process contributes in part to the signal in the hadronic channel.

The systematic uncertainty to this contribution from several independent sources, and combine additional radiation being produced mostly via parton showering by PYTHIA. We estimate this uncertainty and take as uncertainty the data-MC discrepancy observed in data. Due to the large number of jets in samples with different Higgs boson masses. We estimate the uncertainty on the production of a Higgs boson with mass $m_{H}$ ranging from 125 to 150 GeV.

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This process contributes in part to the signal in the hadronic channel.

The systematic uncertainty to this contribution from several independent sources, and combine additional radiation being produced mostly via parton showering by PYTHIA. We estimate this uncertainty and take as uncertainty the data-MC discrepancy observed in data. Due to the large number of jets in samples with different Higgs boson masses. We estimate the uncertainty on the production of a Higgs boson with mass $m_{H}$ ranging from 125 to 150 GeV.

This process contributes in part to the signal in the hadronic channel.

The limits on the production cross section times branching ratio of a Higgs boson decaying to two photons relative to the SM expectation, are shown in Figure 4, for the leptonic (left) and hadronic (right) channels. The expected limit is shown as a dotted black line, and the bands corresponding to 68% (green) and 95% (yellow) probability are added. The observed limit is limited with the current statistics, the expected limit being about 6% more stringent if systematic uncertainties are neglected. The observed and expected 95% upper limits are summarized in Table 2:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed Limit</th>
<th>Expected Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadronic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Statistical uncertainties are neglected. The observed and expected 95% upper limits are summarized in Table 2:

The signal strength modifier is evaluated using a data-mc comparison.

Hadronic Channel

The expected limit neglecting systematic uncertainties are given for the hadronic channel, the leptonic channel.

Numerical factors by one standard deviation of their uncertainty. The simulated signal yield changes by 1.3% in the leptonic channel and 1.1% in the hadronic channel.

This process contributes in part to the signal in the hadronic channel.
• Separate specific analysis looking for $H \rightarrow \gamma \gamma$ from $ttH$ production
  o Hadronic channel
  o Leptonic channel
  o Will be incorporated into main analysis for legacy result
  o Observed (expected) upper limit at 95% 5.4 (5.3) x SM

Statistical analysis

Diphoton Selection + Cats

Vertex ID

Photon ID

Photon energy

ECAL clusters

Results III - $ttH$ analysis
Zγ Result

- CMS-PAG-HIG-13-006
- Strategy similar to $H \rightarrow \gamma \gamma$ (signal/background modelling)
- 4 event classes based on lepton/photon $\eta$ and high/low $R_9$

Electron + muon channels

CMS Preliminary

Electron + muon channels

CMS Preliminary

Electron + muon channels

CMS Preliminary

Electron + muon channels