Search for the Higgs boson in the gamma gamma channel in CMS

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On behalf of the CMS Collaboration
Higgs Hunting 2012, Orsay-France
Overview

- Searches of 2 Higgs hypothesis are included:
  - the **Standard Model** (SM) Higgs $\rightarrow \gamma\gamma$
  - the **Fermiophobic** (FP) Higgs $\rightarrow \gamma\gamma$

- Results based on 2011 & 2012 data collected by CMS
  - 5.1 fb$^{-1}$ 2011 data at $\sqrt{s} = 7$ TeV
  - 5.3 fb$^{-1}$ 2012 data at $\sqrt{s} = 8$ TeV

- Search $m_H$ window: [110-150] GeV

- Blind analysis in 2012

- 3 independent analysis used in SM search
  - **Mass fit Multi-Variate Analysis (MVA)**
  - Mass Sideband Background MVA
  - Cut-based analysis

- Analysis used in FP search
  - Basically consistent with SM cut-based analysis
  - Additional modifications based on the FP topology
CERN-LHC and the CMS Detector

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
A discovery channel at low masses
- decay involves virtual loops
- low signal branching ratio
- clean signature
- identified as a narrow $m_{\gamma\gamma}$ peak on the top of continuous background

Published 2011 result,
- Observe 3.1σ local (1.8σ-global) excess at 124 GeV

The 2011 result here is reloaded
- improved detector calibration

Signal production procedures:
- $ggH$
- $ttH$
- $VH$
- $VBF$
- $W, Z$ bremsstrahlung
- vector boson fusion

Introduction
Main analysis uses Multi-Variate Analysis (MVA) technique to identify and to classify events:

- improvement in expected limit about 15% with respect to the cut-based analysis

Cross-checked with (independent) cut-based and mass sideband background MVA model

Background model derived from data

Final results extracted by fitting to the $m_{\gamma\gamma}$ distribution in 6 event classes

Mass resolution and signal to background ratio are crucial
Energy Corrections

- Estimated energy in the ECAL:
  \[ E_{\gamma,\gamma} = F \times \sum_{\text{clusters}} G c_i A_i \]

- Energy correction scheme
  - \( F = 1 \) for 5x5 crystal sum for the energy of unconverted photons
  - \( c_i \) - intercalibration constants (\( \pi^0 \))
  - transparency correction with laser monitoring (LM)

- ECAL cluster energies corrected using an MC trained multivariate regression
  - performed after individual crystal transparency correction and inter-calibration
  - also provides per photon energy resolution estimate
**Vertex Selection and $m_{\gamma\gamma}$ Reconstruction**

- **Signal $m_{\gamma\gamma}$ resolution**
  - The opening angle between photon pair affects the mass and resolution
  - Depend on the correct position of the primary vertex and correct reconstructed photon energy

- **Vertex identification**
  - Use MVA Boosted Decision Tree (BDT) method
  - Input information from tracks and photons

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**Validation by $Z \rightarrow \mu\mu$ data & MC**
- High correct selection rate

**Reconstructed mass using $Z \rightarrow ee$ data & MC**
- Higgs MC
  - $m_H = 120$ GeV
  - $\sigma_{\text{eff}} = 1.34$ GeV

**Events / (0.5 GeV)**
- Simulation
- Parametric Model
- $\sigma_{\text{eff}} = 1.34$ GeV
- FWHM = 2.85 GeV
Event Selection

- MVA Photon ID separates prompt photons from $\pi^0$ emerged from jets
  - MVA BDT input variables based on:
    - Shower Topology
    - Particle Isolation
    - The median energy density per solid angle
    - Supercluster pseudorapidity
- Form Higgs candidate from two isolated leading photons
  - $p_T^{\text{lead}}/m_{\gamma\gamma} > 1/3$, $p_T^{\text{sub-lead}}/m_{\gamma\gamma} > 1/4$
- Event selection based on diphoton MVA output
  - photon-like kinematic characteristics
  - signal-like kinematic characteristics
    - predominantly giving high score to high $p_T^{\gamma\gamma}$
  - good diphoton mass resolution
- Diphoton MVA input variables are designed to be $m_{\gamma\gamma}$ independent

Higgs Hunting 2012 Search for the Higgs boson in the $\gamma\gamma$ channel in CMS
Event Categorization

- To improve the analysis sensitivity
- Event with 6 categories:
  - 4 diphoton MVA categories
    - Boundaries optimized to give the best expected limit
  - 2 dijet-tagged categories
- Exclusive selection of di-photon events with VBF-like topology:
  - two high $p_T$ jets with wide separated in $\eta$
  - Higher S/B
- Use 2 categories based on $m_{jj}$ and jet $p_T$ in 2012 analysis
Result of the Search for the SM H $\rightarrow \gamma\gamma$
Background modeling: polynomial shape with order from 3 to 5

Potential bias from background model is negligible

\[ \leq 20\% \text{ of statistical uncertainty} \]
Large range with expected exclusion below $\sigma_{SM}$

Largest excess at 125 GeV

Cross-checked with (independent) cut-based and sideband background model:

- give similar results within experimental uncertainties
Minimum local p-value at 125 GeV with a local significance 4.1 \sigma

New state around 125 GeV is observed

Appears consistently in 2011 and 2012 data

3.2 \sigma global significance in the full search range (110-150 GeV)
Combined best fit signal strength at 125 GeV:
\[ \frac{\sigma}{\sigma_{SM}} = 1.56 \pm 0.43 \]

In agreement with the SM expectation within uncertainties.
Sum of mass distributions for each event class, weighted by S/B
To reduce model dependence
- allow for free signal strength in the MVA and dijet-tagged categories and fit for the common mass $m_X$.

The dominant systematic uncertainty
- Energy scale (0.47% correlates between categories)

$m_X = 125.1 \pm 0.4\text{(stat)} \pm 0.6\text{(syst)} \text{ GeV}$
The result in the context of FP model with alternative EWSB mechanism
In the Fermiophobic interpretation the Higgs boson couples at tree level only with W and Z.

- Decay modes: WW, ZZ, Zγ and γγ

- Testing beyond the SM scenario of EWSB (2 HDM)
  - suppressed fermion couplings
    - enhance $B(H \rightarrow γγ)$
  - the Fermiophobic model is extreme case
  - part of a couplings measurement program

Cut-based photon ID selection
VBF and VH production only
  boosted kinematics
  possibility to tag on recoil objects
  Mutually exclusive sub-channels:
    (S/B at $m_H = 120$ GeV)
      2 dijet-tagged sub-channels (VBF), S/B $\sim 1$
      2 lepton-tagged sub-channels (VH), S/B $\geq 1$
      1 MET-tagged sub-channels (VH), S/B $< 1$
      4 untagged sub-channels, S/B $\ll 1$

Use 1D $m_{\gamma\gamma}$ fit for tagged sub-channels
Use 2D ($m_{\gamma\gamma}$, $\pi_T^{VV}$) fit for untagged sub-channels
  $\pi_T^{VV} = \frac{p_T^{VV}}{m_{\gamma\gamma}}$

Example of $\pi_T^{VV}$ distribution

[arXiv:1201.3084]
Background modeling:
- Polynomial shape with order from 3 to 4 for dijet and MET tagged sub-channels
- Power law for lepton tagged sub-channels
- Potential bias from background model is negligible
8 TeV Mass Distribution in Untagged Sub-channels

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} L = 5.3 \text{ fb}^{-1} \)

Max(\(|H|\))<1.5, Min(\(R_g\))>0.94

\(1\times\text{FP} m_h=125 \text{ GeV} \)

Events / (1 GeV)

\(m_{\gamma\gamma} \) (GeV)

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} L = 5.3 \text{ fb}^{-1} \)

Max(\(|H|\))>1.5, Min(\(R_g\))>0.94

\(1\times\text{FP} m_h=125 \text{ GeV} \)

Events / (1 GeV)

\(m_{\gamma\gamma} \) (GeV)
The exclusion range of FP $H \rightarrow \gamma\gamma$ at 95% C.L. is $[110-147]$ GeV.

At 99% C.L. we exclude the FP $H \rightarrow \gamma\gamma$ in the range $[110-134]$ GeV.

The new state at 125 GeV observed in SM is at 99% C.L. excluded as FP
Largest excess at 125.5 GeV with a local significance 3.2 $\sigma$

The observed signal strength at 125.5 GeV:

$\sigma/\sigma_{FP} = 0.49 \pm 0.18$

The deviation is too weak to be consistent with the Fermiophobic hypothesis.
The results of the search of $H \rightarrow \gamma\gamma$ in CMS have been presented:
- In contexts of both the Standard Model and the Fermiophobic interpretation.
- Using 5.1 fb$^{-1}$ 7 TeV and 5.3 fb$^{-1}$ 8TeV pp collision data collected by CMS.
- We have reached the expected sensitivity in the low mass range.

The Standard Model $H \rightarrow \gamma\gamma$:
- Evidence of a new resonance decaying into two photons and appears consistently in 2011 and 2012 data with a mass of $125.1 \pm 0.7$ GeV is observed at $4.1 \sigma$ significance.
- Observed massive state is compatible with a Standard Model Higgs hypothesis within experimental uncertainties.

The Fermiophobic $H \rightarrow \gamma\gamma$:
- The FP Higgs boson is excluded at 95% C.L. in the interval [110-147] GeV.
- At 99% C.L. the largest excess at 125.5 GeV is excluded as a pure FP Higgs.
Backup
Higgs production cross sections

$\sqrt{s}=7 \text{ TeV}$

$\sqrt{s}=8 \text{ TeV}$

Higgs Hunting 2012  Search for the Higgs boson in the $\gamma\gamma$ channel in CMS
Increasing pile-up environment in 2012 data taking
- mean pile-up (PU) 19 events (MC reweighting)

Particle Flow (PF) algorithm:
- provides a global event description in form of list of particles
- improvements in jet, $\tau$ and $E_T^{\text{miss}}$ measurement
- Improves reconstruction performance at high PU
**ECAL Calibration**

- Dedicated calibration scheme:
  - inter-crystal calibration: $\pi^0$, $\eta$
  - crystal transparency correction (laser monitoring system)

- The energy scale stability after the response corrections:
  - barrel: 0.12% (2.5% loss)
  - endcap: 0.45% (10% loss)

- Exploit $W \rightarrow e\nu$ ($E/p$) and $Z^0 \rightarrow ee$ control samples to derive energy scale and resolution systematics
**Vertex Location**

- **Signal $m_{\gamma\gamma}$ resolution**
  - The opening angle between photon pair affects the invariant mass and resolution
  - Depend on the correct position of the primary vertex

- **Vertex identification**
  - Use MVA Boosted Decision Tree method
  - Input information from tracks and photon pair

- **High efficiency for the boosted Higgs:**
  - presence of hard recoil objects
  - efficiency falls down with PU

- **Correct vertex finding probability also estimated using a diphoton BDT**
MVA Photon ID

- MVA Photon ID separates prompt photons from $\pi^0$ emerged from jets
  - MVA BDT inputs
  - Shower Topology Variables (preshower shape in endcaps)
  - Isolation Variables
  - The median energy density per solid angle
  - Supercluster pseudorapidity

![CMS preliminary results for photon ID in CMS with electron veto inverted](image1)

![CMS preliminary results for photon ID in CMS with electron veto inverted](image2)
Event Categorization (MVA)

- The MVA classifies with a high score events with:
  - signal-like kinematic characteristics
  - predominantly giving high score to high $p_T^{\gamma\gamma}$
  - good diphoton mass resolution
  - photon-like values from the photon identification BDT
- MVA input variables are designed to be mass independent
- Fit $m_{\gamma\gamma}$ in each of 6 categories:
  - 4 diphoton MVA categories
  - 2 dijet-tagged categories
- MVA categories based on diphoton MVA output
- Boundaries optimized to give the best expected limit using MC background
**Signal Model & Mass Resolution**

### Event classes

<table>
<thead>
<tr>
<th>Event classes</th>
<th>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>$\sigma_{\text{eff}}$ (GeV)</td>
</tr>
<tr>
<td>8 TeV 5.3 fb$^{-1}$</td>
<td>Untagged 0</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>Untagged 1</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>Untagged 2</td>
<td>30.2</td>
</tr>
<tr>
<td></td>
<td>Untagged 3</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td>Dijet tight</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Dijet loose</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- **Simulation**
- **Parametric Model**

**CMS preliminary Simulation**

- $\sigma_{\text{eff}} = 1.34$ GeV
- FWHM = 2.85 GeV
- BDT >= 0.88

- $\sigma_{\text{eff}} = 2.02$ GeV
- FWHM = 3.67 GeV
- BDT >= -0.05 Tight VBF
Potential bias from background model is negligible

\[ \leq 20\% \text{ of statistical uncertainty} \]
95% C.L. Exclusion Limit (SM $H \rightarrow \gamma\gamma$ MVA)
Signal Strength at 136 GeV

Di-jet loose
Di-jet tight
Untagged 3
Untagged 2
Untagged 1
Untagged 0
Di-jet
Untagged 3
Untagged 2
Untagged 1
Untagged 0

CMS preliminary
\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

- Event Class
- Combined
- \( m_h = 136.0 \text{ GeV} \)
- \( \sigma / \sigma_{SM} = 0.90 \pm 0.43 \)

Best Fit \( \sigma / \sigma_{SM} \)
$P$-values per Class (SM $H \rightarrow \gamma\gamma$ MVA)

Interpretation Requires LLE

$\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

CMS preliminary

Combined
Untagged 0
Untagged 1
Untagged 2
Untagged 3
Di-jet tight
Di-jet loose
Results of SM $H \rightarrow \gamma\gamma$ Mass Sideband Background MVA
Results of SM $H \rightarrow \gamma\gamma$ Cut-based Analysis

Cut-based (Asymptotic CLs)
- Observed
- Expected (combined)
  - $\sigma = 7$ TeV $L = 5.1$ fb$^{-1}$ (2011)
  - $\sigma = 8$ TeV $L = 5.3$ fb$^{-1}$ (2012)
- Expected ($\sigma = 7$ TeV $L = 5.1$ fb$^{-1}$)
- Expected ($\sigma = 8$ TeV $L = 5.3$ fb$^{-1}$)

CMS preliminary

Local p-value

CMS preliminary
- $\sigma = 7$ TeV $L = 5.1$ fb$^{-1}$
- $\sigma = 8$ TeV $L = 5.35$ fb$^{-1}$

Best Fit $\sigma/\sigma_{SM}$

CMS preliminary
- $\sigma = 7$ TeV $L = 5.1$ fb$^{-1}$
- $\sigma = 8$ TeV $L = 5.3$ fb$^{-1}$

68% CL Bend
**Fermiophobic Higgs**

- In the Fermiophobic interpretation the Higgs boson couples at tree level only with W and Z.
- Decay modes: WW, ZZ, Zγ and γγ
- Testing beyond the SM scenario of EWSB (2 HDM)
  - suppressed fermion couplings
    - enhance B(H → γγ)
  - the Fermiophobic model is extreme case
  - part of a couplings measurement program
- LEP, Tevatron and ATLAS excluded at 95% C.L. a Fermiophobic Higgs boson lighter than 121 GeV.
Analysis Strategy of FP Higgs $\rightarrow \gamma\gamma$

- Cut-based analysis
- VBF and VH production
  - boosted kinematics
  - possibility to tag on recoil objects
- Mutually exclusive sub-channels:
  (S/B at $m_H = 120$ GeV)
  - 2 dijet-tagged classes (VBF)
    - $S/B \sim 1$
  - 2 lepton-tagged classes (VH)
    - $S/B \geq 1$
  - 1 MET-tagged classes (VH)
    - $S/B < 1$
  - 4 untagged classes based on pseudorapidity and shower shape
    - $S/B \ll 1$

The order of event tagging:
muon $\rightarrow$ electron $\rightarrow$ di-jet $\rightarrow$ MET $\rightarrow$ untagged

<table>
<thead>
<tr>
<th>channel</th>
<th>leading photon</th>
<th>trailing photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>dijet-tag</td>
<td>$p_T/m &gt; 60/120$</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>lepton-tag</td>
<td>$p_T/m &gt; 45/120$</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>MET-tag</td>
<td>$p_T/m &gt; 45/120$</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>untagged</td>
<td>$p_T/m &gt; 40/120$</td>
<td>$p_T/m &gt; 30/120$</td>
</tr>
</tbody>
</table>

[arXiv:1201.3084]
Di-jet tag
- The same selection as cut-based di-jet selection in SM analysis
- 1 category in 2011 and 2 categories in 2012 analysis

Lepton tag
- CMS Standard cut-based lepton ID updated in 2012 analysis to cope with new data taking conditions
- $\Delta R(l, \gamma) > 1$. (reject FSR $\gamma$), $|\Delta M(e\gamma, Z)| > 5$ GeV (reject $Z\gamma$)

MET tag (only 2012 analysis)
- $\gamma$ in the endcap are not considered due to negligible contribution
- $\text{MET} > 70$ GeV

<table>
<thead>
<tr>
<th></th>
<th>$E_T^{\text{miss}}$ tag</th>
<th>Dijet high $m_{jj}$</th>
<th>Dijet low $m_{jj}$</th>
<th>Lepton tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal ($m_H = 120$ GeV)</td>
<td>3.8</td>
<td>21.5</td>
<td>15.3</td>
<td>5.7</td>
</tr>
<tr>
<td>Data ($115 &lt; m_{\gamma\gamma} &lt; 125$ GeV)</td>
<td>4</td>
<td>20</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Data ($100 &lt; m_{\gamma\gamma} &lt; 180$ GeV)</td>
<td>41</td>
<td>84</td>
<td>271</td>
<td>30</td>
</tr>
<tr>
<td>$\sigma_{\text{eff}}$ (GeV)</td>
<td>1.91</td>
<td>1.98</td>
<td>2.02</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Event classification based on $\eta_{SC}$ and shower shape properties of photons

Exploit harder VBF, VH $p_T^{\gamma\gamma}$ spectrum:

$\pi_T^{\gamma\gamma} (= p_T^{\gamma\gamma} / m_{\gamma\gamma}) > 0.1$

In the untagged class a 2D model is constructed by using $(m_{\gamma\gamma}, \pi_T^{\gamma\gamma})$:

$\mathcal{L}(m|\vec{\theta}) = \frac{e^{-\mu_s n_s + n_b}}{N!} \prod_{i=1}^N (\mu_s n_s \mathcal{P}_s^i(m|\vec{\theta}_1) + n_b \mathcal{P}_b^i(m|\vec{\theta}_2))$

$\mathcal{P}_s^i = \mathcal{M}_s^i(m^{\gamma\gamma}|\vec{\theta}) \times \mathcal{K}_s^i(\pi_T^{\gamma\gamma}|\vec{\theta})$

$\mathcal{P}_b^i = \mathcal{M}_b^i(m^{\gamma\gamma}, \pi_T^{\gamma\gamma}|\vec{\theta}) \times \mathcal{K}_b^i(\pi_T^{\gamma\gamma}|\vec{\theta})$

$\mathcal{M}_s(m^{\gamma\gamma}|m_0, \sigma_{CB}, \alpha, n, f_G, \sigma_G) = (1 - f_G)\mathcal{C}(m^{\gamma\gamma}|m_0, \sigma_{CB}, \alpha, n) + f_G \mathcal{G}(m^{\gamma\gamma}|m_0, \sigma_G)$

$\mathcal{K}_s(\pi_T^{\gamma\gamma}|\mu_c, \sigma_c, f_c, \mu_o, \sigma_L, \sigma_R) = f_c \mathcal{G}(\pi_T^{\gamma\gamma}|\mu_c, \sigma_c) + (1 - f_c)\mathcal{B}(\pi_T^{\gamma\gamma}|\mu_o, \sigma_L, \sigma_R)$

$\mathcal{M}_b(m, \pi_T|a_0, a_1) = m^{a_0 + a_1 \pi_T}$

$\mathcal{K}_b(\pi_T^{\gamma\gamma}|\tau_B, f_d, \sigma_G) = f_d \mathcal{E}(\pi_T^{\gamma\gamma}|\tau_B) + (1 - f_d)\mathcal{G}(\pi_T^{\gamma\gamma}|0, \sigma_G)$

<table>
<thead>
<tr>
<th>Untagged</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal ($m_H = 120$ GeV)</td>
<td>29.2</td>
<td>37.9</td>
<td>18.5</td>
<td>22.0</td>
</tr>
<tr>
<td>Data (115 &lt; $m_{\gamma\gamma}$ &lt; 125 GeV)</td>
<td>683</td>
<td>1712</td>
<td>902</td>
<td>1755</td>
</tr>
<tr>
<td>Data (100 &lt; $m_{\gamma\gamma}$ &lt; 180 GeV)</td>
<td>4992</td>
<td>9546</td>
<td>5105</td>
<td>8574</td>
</tr>
<tr>
<td>$\sigma_{eff}$ (GeV)</td>
<td>1.44</td>
<td>2.00</td>
<td>3.72</td>
<td>3.76</td>
</tr>
</tbody>
</table>
### 2012 Cut-based Photon Selection

<table>
<thead>
<tr>
<th></th>
<th>barrel</th>
<th>endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_9 &gt; 0.94$</td>
<td>$R_9 &lt; 0.94$</td>
</tr>
<tr>
<td>PF isolation sum, chosen vertex</td>
<td>6</td>
<td>4.7</td>
</tr>
<tr>
<td>PF isolation sum worst vertex</td>
<td>10</td>
<td>6.5</td>
</tr>
<tr>
<td>Charged PF isolation sum</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$</td>
<td>0.0108</td>
<td>0.0102</td>
</tr>
<tr>
<td>H/E</td>
<td>0.124</td>
<td>0.092</td>
</tr>
<tr>
<td>$R_9$</td>
<td>0.94</td>
<td>0.298</td>
</tr>
</tbody>
</table>

- CiC4PF Photon ID cuts
- Use PF Isolation to improve performance at 2012 high PU
**Selection Cuts for FP Exclusive Sub-channels**

### Electron ID cuts

<table>
<thead>
<tr>
<th></th>
<th>loose WP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrel</td>
<td>Endcap</td>
</tr>
<tr>
<td>$\sigma_{\text{inj}}$</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{in}}$</td>
<td>0.015</td>
<td>0.010</td>
</tr>
<tr>
<td>$\Delta \eta$</td>
<td>0.007</td>
<td>0.009</td>
</tr>
<tr>
<td>$\sigma_{\text{inj}}$</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>$H/E$</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>$d_0$ w.r.t. selected vertex</td>
<td>$&lt; 0.02$ cm</td>
<td></td>
</tr>
<tr>
<td>$d_z$ w.r.t. selected vertex</td>
<td>$&lt; 0.2$ cm</td>
<td></td>
</tr>
<tr>
<td>$1/E - 1/p$</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Combined relative PF isolation</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>vertex fit probability (conv. rej)</td>
<td>$10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>missing hits (conv. rej.)</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### Muon ID cuts

<table>
<thead>
<tr>
<th>Description</th>
<th>criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pixel hits</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>$\chi^2$/n.d.f</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>Number of muon hits</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>Number of matched muon stations</td>
<td>$&gt; 1$</td>
</tr>
<tr>
<td>Number of tracker layers</td>
<td>$&gt; 5$</td>
</tr>
<tr>
<td>$d_0$ w.r.t. selected vertex</td>
<td>$&lt; 0.02$ cm</td>
</tr>
<tr>
<td>$d_z$ w.r.t. selected vertex</td>
<td>$&lt; 0.05$ cm</td>
</tr>
<tr>
<td>Combined relative PF isolation</td>
<td>$&lt; 0.2$</td>
</tr>
</tbody>
</table>

### Jet ID cuts

<table>
<thead>
<tr>
<th>jet$\eta$</th>
<th>$\beta^*$</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta &lt; 2.5$</td>
<td>$&lt; 0.2 \log N_{\text{vtx}} - 0.64$</td>
<td>$&lt; 0.06$</td>
</tr>
<tr>
<td>$2.5 &lt; \eta &lt; 2.75$</td>
<td>$&lt; 0.3 \log N_{\text{vtx}} - 0.64$</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>$2.75 &lt; \eta &lt; 3$</td>
<td>-</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>$3 &lt; \eta &lt; 4.7$</td>
<td>-</td>
<td>$&lt; 0.055$</td>
</tr>
</tbody>
</table>

### Di-jet event selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>cut VBF cat1</th>
<th>VBF cat2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\gamma_1} / m_{\gamma \gamma}$</td>
<td>$&gt; 0.5$</td>
<td>$&gt; 0.5$</td>
</tr>
<tr>
<td>$p_T^{\gamma_2}$</td>
<td>$&gt; 25$ GeV</td>
<td>$&gt; 25$ GeV</td>
</tr>
<tr>
<td>$p_T^{1}$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$p_T^{2}$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>Z</td>
<td>$</td>
</tr>
<tr>
<td>$M_{jj\gamma}$</td>
<td>$&gt; 500$ GeV</td>
<td>$&gt; 250$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi(jj, \gamma \gamma)</td>
<td>$</td>
</tr>
</tbody>
</table>
8 TeV $\pi_T^{\gamma\gamma}$ Distribution in Untagged Sub-channels
2011 & 2012 Results of FP \( H \to \gamma \gamma \)