A Search for the Higgs Boson in the $H \rightarrow \gamma\gamma$ Channel with CMS

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9 August 2011
$H \rightarrow \gamma\gamma$ in a Nutshell

- Sharp signal peak
  - need great resolution
- Smoothly declining background
  - Irreducible - 2 real $\gamma$'s
  - Reducible - 1,2 fake $\gamma$'s
    - Electrons faking $\gamma$'s ($Z \rightarrow e^+ e^-$)
    - Jets faking $\gamma$'s ($\pi_0 \rightarrow \gamma\gamma$)

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![Graph showing signal and background distributions](image)

**Standard Model**

![Graph showing branching ratios](image)

**Fermiophobic**

![Graph showing branching ratios](image)

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General purpose detector
Searching for Higgs, SUSY and more
Reconstructing photons ($\gamma$’s), electrons, hadronic jets and muons ($\mu$’s)
CMS - Electromagnetic Calorimeter (ECAL)

- \( \sim 76K \) PbWO\(_4\) crystals in barrel (\(|\eta| < 1.48\)) and endcap (\(1.48 < |\eta| < 3.\))
- Design resolution \( \sim 0.5\% \) for unconverted \( \gamma \)'s with energy > 100 GeV
- Critical resolution issues
  - Calibration
    - Crystal inter-calibration - \( \pi_0 \rightarrow \gamma\gamma \)
    - Energy scale calibration - \( Z \rightarrow e^+ e^- \)
  - Transparency corrections for radiation damage
    - An integrated laser system measures the transparency of crystals
Photon Selection in Categories

- Photon Identification
  - Isolation
    - $\Sigma P_T, \text{Tracks} + \text{ECAL}$ energy + HCAL energy in hollow cone around $\gamma$
  - Cluster shape
    - Spread in $\eta$ rejects $\pi_0 \rightarrow \gamma\gamma$
  - Electron veto
- Cuts are optimized in 4 photon categories
  - Barrels/endcap
  - Unconverted/converted
  - Indicated by a measure of the spread of $\gamma$'s shower

- Photon Transverse Momentum ($P_T$)
  - $P_T^{\gamma_1} > 40$ GeV/c
  - $P_T^{\gamma_2} > 30$ GeV/c

Efficiencies vs. $\eta_\gamma$

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CMS Simulation Preliminary

$H \rightarrow \gamma\gamma$ with CMS

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Vertex Selection

- The Pile-Up (PU) problem
  - $<N_{PU}> \sim 5.6$ vertices in our $1.09 \text{ fb}^{-1}$
  - Wrong vertex, wrong $\gamma\gamma$ invariant mass $\rightarrow$ resolution loss

- Determine vertex using
  - $\sum P_T^2$ Tracks
  - Projection of tracks onto $\gamma\gamma$
  - Balance between $\gamma\gamma$ and vertex’s tracks
  - For converted $\gamma$’s use conversion-tracks to point back to vertex

- Efficiency of correct selection (within 1 cm) $\sim 83\%$ with nearly 100% efficiency at high $P_T^{\gamma\gamma}$

- From just using beamspot resolution improves by $\sim 16\%$ overall
Selection Efficiency in Data

\[ Z \rightarrow e^+ e^- \] Tag and Probe
- Assume that electrons and photons have similar shower properties
- Tag with tight electron ID
- Probe with high \( E_T \) reconstructed electron
- Use associated reconstructed \( \gamma \) and apply \( \gamma \) selection

\[ Z \rightarrow \mu\mu\gamma \]
- Select \( \mu \)'s and \( \gamma \) that make \( Z \)-mass
- Use to measure electron veto efficiency

### Trigger Efficiencies from \( Z \rightarrow e^+ e^- \)

<table>
<thead>
<tr>
<th></th>
<th>Both photons in barrel</th>
<th>One or more in endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Unconverted</td>
<td>1,2 Converted</td>
</tr>
<tr>
<td>100.00±0.00%</td>
<td>99.53±0.04%</td>
<td>100.00±0.00%</td>
</tr>
</tbody>
</table>

### Selection Efficiencies from Data

<table>
<thead>
<tr>
<th>Category</th>
<th>( \epsilon_{data} ) (%)</th>
<th>( \epsilon_{MC} ) (%)</th>
<th>( \epsilon_{data}/\epsilon_{MC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>All cuts except electron rejection (from ( Z \rightarrow e^+ e^- ))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>91.77±0.14</td>
<td>92.43±0.07</td>
<td>0.993±0.002</td>
</tr>
<tr>
<td>2</td>
<td>72.67±0.43</td>
<td>71.89±0.08</td>
<td>1.011±0.007</td>
</tr>
<tr>
<td>3</td>
<td>80.33±0.47</td>
<td>80.04±0.18</td>
<td>1.004±0.008</td>
</tr>
<tr>
<td>4</td>
<td>57.80±1.26</td>
<td>55.09±0.15</td>
<td>1.049±0.025</td>
</tr>
<tr>
<td>Electron rejection cut (from ( Z \rightarrow \mu\mu\gamma ))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>99.78±0.13</td>
<td>99.59±0.13</td>
<td>1.002±0.002</td>
</tr>
<tr>
<td>2</td>
<td>98.77±0.59</td>
<td>97.70±0.32</td>
<td>1.011±0.007</td>
</tr>
<tr>
<td>3</td>
<td>99.32±0.51</td>
<td>99.29±0.30</td>
<td>1.000±0.006</td>
</tr>
<tr>
<td>4</td>
<td>93.0±2.1</td>
<td>93.34±0.79</td>
<td>0.996±0.024</td>
</tr>
</tbody>
</table>
Resolution from $Z \rightarrow e^+ e^-$

- ECAL resolution measured from $Z \rightarrow e^+ e^-$ is applied to simulated Higgs' $\gamma$'s.
- The simulated Higgs' $\gamma$'s with data resolution are used in signal modeling for CL limits.

Suboptimal transparency loss corrections are primarily responsible for degraded resolution.
Event Classes Used for CL Evaluation

2 $\eta$ Classes
- 2 $\gamma$’s in the barrel
- 1 or 2 $\gamma$’s in the endcap

2 Conversion Classes
- 2 Unconverted $\gamma$’s ($R_9 > 0.94$)
- 1 or 2 Converted $\gamma$’s ($R_9 < 0.94$)

2 $P_T^\gamma\gamma$ Classes
- $P_T^\gamma\gamma > 40$ GeV/c
- $P_T^\gamma\gamma < 40$ GeV/c

Fraction of selected signal and background expected in each event class.

<table>
<thead>
<tr>
<th>$P_T^\gamma\gamma$</th>
<th>Both $\gamma$’s in barrel</th>
<th>One or more in endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Unconverted</td>
<td>1,2 Converted</td>
</tr>
<tr>
<td>$P_T^\gamma\gamma &lt; 40$ GeV/c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>0.209</td>
<td>0.271</td>
</tr>
<tr>
<td>Background</td>
<td>0.167</td>
<td>0.263</td>
</tr>
<tr>
<td>Signal $\sigma_{\text{effective}}$ (GeV/c$^2$)</td>
<td>1.58</td>
<td>2.33</td>
</tr>
<tr>
<td>$P_T^\gamma\gamma &gt; 40$ GeV/c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>0.102</td>
<td>0.122</td>
</tr>
<tr>
<td>Background</td>
<td>0.043</td>
<td>0.079</td>
</tr>
<tr>
<td>Signal $\sigma_{\text{effective}}$ (GeV/c$^2$)</td>
<td>1.37</td>
<td>2.12</td>
</tr>
</tbody>
</table>
Background Modeling

Background from data fit to 2nd order polynomial

\((100 < M_{\gamma\gamma} < 150 \text{ GeV/c}^2)\)

High \(P_T^{\gamma\gamma}\), both high \(R_9\), barrel-barrel

Low \(P_T^{\gamma\gamma}\), both high \(R_9\), barrel-barrel
### Systematic Errors on the Signal

**Source** | **Systematics**
--- | ---
Photon identification efficiency | 1.0% ± 4.0%
R9 cut efficiency | 4.0% ± 6.5%
Energy resolution | 0.2% ± 0.5%
Energy scale | 0.05% ± 0.34%

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**applicable to individual photons**

**Source** | **Systematics**
--- | ---
Integrated luminosity | 6.0%
Trigger efficiency | 1.0%
Vertex finding efficiency | 0.5%
pT>40GeV cut efficiency | 6.0%

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**cross sections and branching ratios**

**Source** | **Systematics**
--- | ---
Gluon-gluon cross section | 12.5%(scale) 7.9%(PDF)
Fermiophobic: scale | 0.5%(VBF) 0.8%(WH) 1.6%(ZH)
Fermiophobic: PDF | 3.1%
Fermiophobic: BR | 5.0%
SM Exclusion at 95% CL

- Limits determined in two ways with consistent results
  - Modified frequentist approach (CLs) using profile likelihood
  - Bayesian method with flat prior
- Excluding between 0.06 and 0.26 pb

![Graph showing CMS preliminary $\sqrt{s} = 7$ TeV $L = 1.09$ fb$^{-1}$ results for $H \rightarrow \gamma\gamma$ with CMS]
SM Exclusion Relative to $\sigma_{SM}$

- Excluding between 1.9 and 7.0 $\sigma_{SM}$
Fermiophobic Exclusion at 95% CL

- Excluding between 0.04 and 0.18 pb
- Constraining $M_{\text{Fermiophobic}} > 111$ GeV/c$^2$
Conclusions

- \( H \rightarrow \gamma\gamma \) Analysis
  - Photon selection in categories
  - Vertex selection (from conversions and event topology) improves resolution
  - Resolution measured from \( Z \rightarrow e^+e^- \)

- Limits
  - CL evaluation in event classes \( \rightarrow \) greater sensitivity
  - Becoming sensitive to SM Higgs (2-6 times \( \sigma_{SM}\times BR \) in 110-135 GeV range)
  - Already quite sensitive to Fermiophobic Higgs (\( M_{Fermiophobic} > 111 \) GeV)

- Outlook
  - More data!
  - Improved CMS \( \gamma\gamma \) resolution
BACKUP
Vertex ID: $P^\text{Asym}_T$ and $P^\text{Bal}_T$

$P^\text{Asym}_T = \left( \frac{\sum_{\text{Tracks}} P_T - P^\gamma_\gamma}{\sum_{\text{Tracks}} P_T + P^\gamma_\gamma} \right)$

$P^\text{Bal}_T = -\left( \frac{\sum_{\text{Tracks}} P_T \cdot \frac{P^\gamma_\gamma}{|P^\gamma_\gamma|}}{\sum_{\text{Tracks}} P_T} \right)$

Simulated Mass Resolution

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Re-weighting applied on the number of in-time pile-up events according to the number of expected number of interactions in data.
$P_T^\gamma > 40$ Fits in Data

2 high $R_9\gamma$’s

1 or 2 low $R_9\gamma$’s

2 barrel $\gamma$’s

1 or 2 endcap $\gamma$’s

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$P_T^{\gamma\gamma} < 40$ Fits in Data

2 high $R_9\gamma$’s

1 or 2 low $R_9\gamma$’s

2 barrel $\gamma$’s

1 or 2 endcap $\gamma$’s

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Combined Fits from Data

CMS preliminary
$\sqrt{s} = 7$ TeV $L = 1.09$ fb$^{-1}$

All Categories Combined

- Data
- Bkg Model
- $\pm 1 \sigma$
- $\pm 2 \sigma$

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$P_T > 40$ Resolution with Smearing

2 high $R_9\gamma$'s

1 or 2 low $R_9\gamma$'s

2 barrel $\gamma$'s

1 or 2 endcap $\gamma$'s
$P_T^{\gamma\gamma} < 40$ Resolution with Smearing

2 high $R_\gamma\gamma$'s

<table>
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<td>Simulation</td>
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<td>Parametric Model</td>
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</table>

CMS preliminary Simulation

- $p_T^{\gamma\gamma} < 40$ GeV
- Max(|$\eta$|) < 1.5
- Min($R_\gamma$) > 0.94

$\sigma_{eff} = 1.58$ GeV/c$^2$

FWHM = 2.97 GeV/c$^2$

1 or 2 low $R_\gamma\gamma$'s

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CMS preliminary Simulation

- $p_T^{\gamma\gamma} < 40$ GeV
- Max(|$\eta$|) < 1.5
- Min($R_\gamma$) > 0.94

$\sigma_{eff} = 2.33$ GeV/c$^2$

FWHM = 4.72 GeV/c$^2$

2 barrel $\gamma$'s

1 or 2 endcap $\gamma$'s
Combined Resolution with Smearing

Simulation

Parametric Model

$\sigma_{\text{eff}} = 2.40 \text{ GeV}/c^2$

FWHM = 4.23 GeV/c$^2$

CMS preliminary

Simulation

Combined

All Categories

Events / (0.35 GeV/c$^2$)
Limits Relative to Fermiophobic Cross Section

\[ \sqrt{s} = 7 \text{ TeV} \quad L = 1.09 \text{ fb}^{-1} \]

- Observed CLs Limit
- Observed Bayesian Limit
- Median Expected CLs Limit
- ±1σ Expected CLs
- ±2σ Expected CLs

\[ \sigma(H \rightarrow \gamma\gamma)_{CL} \]

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\[ H \rightarrow \gamma\gamma \text{ with CMS} \]

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P-Values (SM)

![Graph showing P-values for H → γγ with CMS]

- CMS preliminary
- √s = 7 TeV, L = 1.09 fb⁻¹
- LEE Not Included (~12)
- Observed
- 1xSM Higgs Median Expected
- 1xSM Higgs Single Mass 119 GeV

Graph shows the p-value (Profile Likelihood) vs. m_H (GeV/c²) with observed and expected distributions.
P-Values (Fermiophobic)

LEE Not Included (~12)  
CMS preliminary  
$\sqrt{s} = 7$ TeV $L = 1.09$ fb$^{-1}$

$p$-value (Profile Likelihood)

- Observed
- 1xFP Higgs Median Expected
- 1xFP Higgs Single Mass 113.5 GeV

$m_H$ (GeV/c$^2$)
CMS PAS HIG-11-010 ($H \rightarrow \gamma\gamma$ PAS)
cdsweb.cern.ch/record/1369553/files/HIG-11-010-pas.pdf

CMS PAS HIG-11-011 (Higgs combination PAS)
cdsweb.cern.ch/record/1370076/files/HIG-11-011-pas.pdf

Other public plots
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11010TWiki