Search for a new Higgs boson-like low-mass resonance in the diphoton final state at $\sqrt{s} = 8$ TeV in pp collisions at CMS

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Theoretical Motivations

Is the new particle discovered in 2012 by the CMS and ATLAS Collaborations at a mass of 125 GeV really the Standard Model Higgs boson?

Some **BSM theories** predict **modified** and **extended Higgs sectors**:

- **General Two Higgs Doublet Model (2HDM)**
  - 2 Higgs Doublets → 5 Higgs bosons: $h, H, a, H^\pm$
- **Next-to-Minimal Supersymmetric Standard Model (NMSSM)**
  - 2 Higgs Doublets + 1 singlet → 7 Higgs bosons: $h_1, h_2, h_3, a_1, a_2, H^\pm$

- **The Higgs boson at 125 GeV** can be identified as the **next-to-lightest scalar**, allowing to focus on a possible lighter particle

- **Strong interest** from the **theoretical community**

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**G. Cacciapagia et al., JHEP 1612 (2016) 068**
Experimental Motivations

- Small excess of events (≈2σ) at LEP observed by 3 of the 4 experiments in $bb/\tau\tau$ channels

- During LHC Run I, the standard $H \rightarrow \gamma\gamma$ search range was [110,150] GeV
- Clean signature with two isolated and highly energetic photons
- Final state fully reconstructed with excellent mass resolution
- Background from QCD ($\gamma\gamma \rightarrow \gamma j \rightarrow jj$) large enough to be evaluated directly on data

![LEP Signal Plot](image)

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The $H \to \gamma\gamma$ Decay Channel at Low Mass

**STANDARD $H \to \gamma\gamma$ ANALYSIS**

**LOW-MASS $H \to \gamma\gamma$ ANALYSIS**

NARROW SIGNAL PEAK

LARGE FALLING BACKGROUND
The $H \rightarrow \gamma\gamma$ Decay Channel at Low Mass

MAIN CHALLENGES:

- Difficulty to extend the range to very low mass values (mainly for the trigger)
- Lower limit at 80 GeV
The $H\rightarrow\gamma\gamma$ Decay Channel at Low Mass

MAIN CHALLENGES:

• Additional Drell-Yan background $Z\rightarrow ee$, with electrons misidentified as photons
  
  Loss of sensitivity around 90 GeV

STANDARD $H\rightarrow\gamma\gamma$ ANALYSIS

LOW-MASS $H\rightarrow\gamma\gamma$ ANALYSIS

Analysis Strategy

- Select two "good quality" photons
- Measure photon energy precisely
- Find the primary vertex of the decay

- Very similar to the standard $H \rightarrow \gamma \gamma$ analysis (see Michael’s talk yesterday)
- Event categorization defined to maximize S/B
- Signal extracted from background by fitting the observed diphoton mass distributions in each category

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos \theta)}$$

Photon Energy

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

- Photon energy reconstructed by building clusters of energy deposits in the electromagnetic calorimeter.

- Energy and its uncertainty corrected for local and global shower containment regression technique:
  - corrects photons’ energies
  - provides an estimate of energy resolution

- Energy scale in data corrected as a function of data taking epochs, pseudorapidity, EM shower width and transverse energy

- Smearing to the reconstructed photon energy in MC to match the resolution in data \( Z \rightarrow ee \) peak used as reference
Vertex Identification

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

- **Vertex assignment** considered as correct within 1 cm of the diphoton interaction point
  - negligible impact on mass resolution
- **Multi-variate approach:**
  - Observables related to tracks recoiling against the diphoton system
  - direction of conversion tracks
- **Second MVA discriminant** to estimate the probability for the vertex assignment to be within 1 cm
  - used for diphoton classification
- Method validated on \( Z \rightarrow \mu\mu \) events, by refitting vertices ignoring the muon tracks

\[ \varepsilon_{\text{vtx}} \sim 80\% \]

Photon Selection

- **Trigger selection:**
  Trigger paths based on transverse energy, H/E, electromagnetic shower shapes and isolation variables, $m_{\gamma\gamma}$

- **Preselection:**
  - Similar to trigger requirements, but more stringent
  - Specific cuts for the low-mass analysis
  - Electron veto based on pixel detector

- **Photon Identification:**
  - Multi-Variate approach to reject fake photon candidates (mainly from $\pi^0$ mesons produced in jets)
  - Shower shape and isolation observables, median energy density ($\rho$)
  - BDT output provides an estimate of the per-photon quality

Event Categorization

• To gain sensitivity, events are split into classes according to their expected signal/background ratio
• Events are categorized according to the photon kinematics, per-event mass resolution, photon ID and good vertex probability by a multivariate classifier (same as the standard $H \rightarrow \gamma\gamma$ analysis)
• Number of classes limited by MC DY statistics (4 classes, no exclusive classes tagging production modes like in standard analysis)
Signal Model

- $H\rightarrow\gamma\gamma$ MC samples with $m_H$ from **80 to 110 GeV** are used (5 GeV steps)
- The model is **interpolated between the mass points**
- The **signal shape** corresponds to a **standard Higgs boson**
- The signal is fitted by a **sum of Gaussian distributions** in each event class (then combined together)
Background Model

CONTINUUM BACKGROUND
• Modeled with Bernstein polynomials (order chosen with a p-value test)

DRELL-YAN CONTRIBUTION
• Modeled with a double-sided Crystal Ball (DCB) distribution
• Shape parameters extracted by fitting MC Z → ee events passing the whole analysis selection (double-fake events)
• Data/MC systematic uncertainty estimated from single-fake Z → ee events

FINAL BACKGROUND MODEL
Bernstein polynomial + double-sided Crystal Ball
• Fitted to the data
• DCB fraction let floating
Results

- No significant excess is observed
- Maximum significance of 1.9 $\sigma$ (no Look-Elsewhere Effect) at 97.5 GeV, about the same value observed at LEP
- Worse sensitivity around the $Z$ boson mass
Conclusions

• The search for a **Higgs boson at low mass** values is strongly motivated by **theoretical predictions** (2HDM, NMSSM)

• The **standard \( H \rightarrow yy \)** analysis has been **extended** to the mass range \([80, 110] \text{ GeV}\), analyzing Run I data collected by CMS

• The low-mass analysis has **specific features**, in particular the Drell-Yan contribution

• **No evidence for new particle** has been observed

Looking forward to seeing the results at 13 TeV!
Backup
Mass Resolution

![Graphs showing mass resolution with CMS EGM-14-001]
Mass Spectra

**CLASS 0**

![Mass Spectrum Class 0](image1)

**CLASS 1**

![Mass Spectrum Class 1](image2)

**CLASS 2**

![Mass Spectrum Class 2](image3)

**CLASS 3**

![Mass Spectrum Class 3](image4)
Results – ggH + ttH Production Modes
Results – VBF + VH Production Modes
Production Modes

4 PRODUCTION MECHANISMS
Decay Modes

5 MAIN DECAY MODES EXPLOITED:

- $H \rightarrow bb$ (~58%)
- $H \rightarrow WW \rightarrow 2l2\nu$ (~22%)
- $H \rightarrow gg$ (~8.5%)
- $H \rightarrow \tau\tau$ (~6%)
- $H \rightarrow ZZ \rightarrow 4l$ (~3%)
- $H \rightarrow \gamma\gamma$ (~0.2%)