Search for low mass Higgs-boson like resonances with $m_h < 125$ GeV in the diphoton final state with the CMS experiment

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On behalf of CMS collaboration

July 29, 2019
• Introduction

• Motivations:
  ★ Observations
  ★ BSM models

• Results:
  ★ Result of 8 TeV data
  ★ Result of 13 TeV 2016 data
  ★ Combined Result

• Conclusions
Introduction

- Will include the results of 8 TeV dataset (19.7 fb$^{-1}$) and 13 TeV 2016 dataset (35.9 fb$^{-1}$)

- Documentations:
  - CMS-PAS-HIG-14-037 (PAS-Only)
Motivations

- Is the observed 125 GeV scalar at the LHC really the SM Higgs boson?

→ Still room for BSM!
• Some BSM theories predict **modified and extended** Higgs sectors, possibly with **additional low-mass** (< 125 GeV) scalars/pseudoscalars.

♣ **General Two Higgs Doublet Model (2HDM):**
  ✽ 2 Higgs doublets (h, H, a, $H^\pm$)
  ✽ 4 types of models ($\tan\beta$, $\alpha$)
  ✽ compatible with a 125 GeV SM-Like scalar (h or H) + a lighter Higgs Boson (a or h) in the ”alignment limit”.

♣ **Next-to-Minimal Supersymmetric Standard Model (NMSSM):**
  ✽ 2 Higgs doublets & 1 singlet superfields ($h_1$, $h_2$, $h_3$, $a_1$, $a_2$, $H^\pm$)
  ✽ solved the known ”$\mu$-problem” of MSSM;
  ✽ compatible with a 125 GeV SM-Like scalar ($h_1$ or $h_2$) & a mostly ”singlet-like” lighter Higgs Boson ($a_1$ or $h_1$).
The $H \rightarrow \gamma\gamma$ Decay Channel

**Higgs Production Modes**

- $pp \rightarrow H$ (NLO QCD + NLO EW)
- $pp \rightarrow q\bar{q}H$ (NLO QCD + NLO EW)
- $pp \rightarrow WH$ (NLO QCD + NLO EW)
- $pp \rightarrow ZH$ (NLO QCD + NLO EW)
- $pp \rightarrow t\bar{t}H$ (NLO QCD + NLO EW)
- $pp \rightarrow b\bar{b}H$ (NLO QCD + NLO EW)

$M(H) = 125$ GeV

**Higgs Decay Modes**

- $H \rightarrow \gamma\gamma$
- $H \rightarrow tW$
- $H \rightarrow Z\gamma$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \mu\mu$
- $H \rightarrow \tau\tau$
- $H \rightarrow c\bar{c}$
- $H \rightarrow g\gamma$
- $H \rightarrow b\bar{b}$

- **Clean signature with two isolated and highly energetic photons**
- **Final state fully reconstructed with excellent mass resolution**
- **Large background** from QCD ($\gamma\gamma, \gamma j, jj$)
Inherit analysis strategy from standard $H \rightarrow \gamma\gamma$ analysis.

- **Event categorization** on mass resolution and S/B
- Signal extracted from background by fitting the observed di-photon mass distributions in each category.

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

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**Event Categorization**

**IHEP Beijing, IPN-Lyon**
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 and EM shower width
- Smearing to the reconstructed photon energy in Mont Carlo to match the resolution in data
  ⇒ Z\to ee peak 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.  
  \[ \Rightarrow \text{negligible impact} \] 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  
  \[ \Rightarrow \text{used later for diphoton classification} \]

- Method validated with \( Z \rightarrow \mu\mu \) events, by refitting vertices ignoring the muon tracks

\[ \epsilon_{vtx} \sim 80\% \]

\[ \langle N_{vtx} \rangle \sim 18.5 \]
Photon Selection

- **Trigger selection:**
  - *double-photon 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
- **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
Untagged Events

- All the inclusive events are categorized according to the **photon kinematics**, per-event **mass resolution**, photon ID and **good vertex probability** by a **MultiVariate Classifier**
- The number of categories and their boundaries are **optimized** to maximize the **expected significance**
- Method validated with **Z → ee events**, where the electrons are reconstructed as photons
Signal and Background Model

**Signal**

Parametrized model of Higgs boson mass shape
- Obtained from *Simulation*
- MC tuning and data/MC efficiency scale factors applied

**Background**

Background model extracted from *data*
- Different functional forms used for each category
  - *Sum of polynomial* (chosen from 4 families) + *Double-sided Crystal Ball (DCB)* functions for relic $Z\rightarrow ee$ component;
  - Choice of function treated as a *discrete nuisance parameter*
- DCB: shape parameters from MC "double-fake" events, syst. uncertainty from "single-fake" events
Mass Spectrum

8 TeV

19.7 fb\(^{-1}\) (8 TeV)

13 TeV

35.9 fb\(^{-1}\) (13 TeV)

$H \to \gamma \gamma$

Data

Bkg fit

±1σ

±2σ

$H \to \gamma \gamma$ (m\(_H\) = 90 GeV) × 10

Data - best-fit model

m\(_{\gamma \gamma}\) (GeV)

m\(_{\gamma \gamma}\) (GeV)
\[ \rightarrow 8 \text{ TeV}: \text{Minimum (Maximum) limit on } \sigma \times Br: 31 (133) \text{ fb at } m_H = 102.8 (91.1) \text{ GeV} \]

\[ \rightarrow 13 \text{ TeV}: \text{Minimum (Maximum) limit on } \sigma \times Br: 26 (161) \text{ fb at } m_H = 103.0 (89.9) \text{ GeV} \]

• Production processes assumed in SM proportions.
Results

- Normalized **Upper limits on $\sigma \times Br$:**
  - $\rightarrow$ Minimum (Maximum) Limit:
    - $0.17 (1.13)$ at $m_H = 103.0 (90.0)$ GeV

- Expected and observed **local p-values:**
  - $\rightarrow 8 \text{ TeV}$: Excess with $\sim 2.0\sigma$ local significance at $m_H = 97.6$ GeV
  - $\rightarrow 13 \text{ TeV}$: Excess with $\sim 2.9\sigma$ local (1.47$\sigma$ global) significance at $m_H = 95.3$ GeV
  - $\rightarrow 8\text{TeV}+13 \text{ TeV}$: Excess with $\sim 2.8\sigma$ local (1.3$\sigma$ global) significance at $m_H = 95.3$ GeV

- ♣ More data are required to ascertain the origin of this excess.
Conclusions

• Results of the CMS low mass \( H \rightarrow \gamma\gamma \) analysis have been reported, using 35.9 (19.7) fb\(^{-1}\) of collision data collected in 2016 (2012) at 13 (8) TeV;

• No significant (>3\(\sigma\)) excess with respect to the expected number of background events is observed:
  - CMS Run I (8 TeV): Modest excess with maximum local significance 2.0\(\sigma\) at \(m_H = 97.6\)GeV;
  - CMS Run II (13 TeV 2016 data): Modest excess with maximum local significance 2.9\(\sigma\) at \(m_H = 95.3\)GeV;
  - Combination results (Run I and Run II): Modest excess with maximum local significance 2.8\(\sigma\) at \(m_H = 95.3\)GeV;

** Looking forward to the results of 13TeV 2017 data or full RunII data!**
BackUp
• MSSM:
  → 2 Higgs doublets (2 CP-even, 1 CP-odd and 2 charged Higgs bosons)
  → $\mu$ problem: There’s a mass term $\mu$ in the low energy Higgs which seems unrelated to the electroweak scale;

• Solution of $\mu$ problem in NMSSM:
  → NMSSM introduces a new gauge singlet superfield which only couples to the Higgs sector in a similar way as the Yukawa coupling and give rise to a effective $\mu$-term to solve the ”$\mu$ problem”;
  → The new singlet adds additional degrees of freedom to the NMSSM particle spectrum.
  → 2 Higgs doublets (3 CP-even, 2 CP-odd and 2 charged Higgs bosons).
Results: Upper limits on $\sigma \times Br$

- Per-process limits on $\sigma \times Br$ assuming 100% gluon-induced processes (ggH, ttbarH in SM proportions)
Results: Upper limits on $\sigma \times Br$

- Per-process limits on $\sigma \times Br$ assuming 100% fermion-induced processes (VBF, VH in SM proportions)