

Properties of a Higgs Boson in the $H \rightarrow ZZ \rightarrow 4l$ Channel at CMS

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Introduction

- ▶ Since CMS and ATLAS announced its discovery in 2012, the focus has been measuring the properties of the Higgs boson
- ▶ Presented here are property measurements performed in the $H \rightarrow ZZ \rightarrow 4l$ channel at CMS
- ▶ We consider the final states 4μ , $4e$, and $2e2\mu$
- ▶ Measurements of the mass, width, and spin-parity will be shown
- ▶ These measurements use the full dataset recorded by CMS of LHC pp collisions
 - ▶ $\mathcal{L}_{int} = 5.1 \text{ fb}^{-1}$ at 7 TeV and $\mathcal{L}_{int} = 19.7 \text{ fb}^{-1}$ at 8 TeV
- ▶ CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state*, CMS-HIG-13-002, Submitted to Phys. Rev. D, [arXiv:1312.5353](https://arxiv.org/abs/1312.5353) [hep-ex]

Preselection and Physics Objects

► Triggers and Datasets

- Dimuon, Dielectron, and Muon + Electron datasets from the 7 and 8 TeV LHC run periods
- Corresponds to 5.1 fb^{-1} at 7 TeV, and 19.7 fb^{-1} at 8 TeV
- We use Double Muon, Double Electron, Triple Electron, and Electron + Muon high-level triggers

► Electrons

- Required to have $p_T > 7 \text{ GeV}$ and $|\eta| < 2.5$
- Includes identification using a multivariate method, and energy corrections/calibrations
- Required to come from the primary vertex

► Muons

- Required to have $p_T > 5 \text{ GeV}$ and $|\eta| < 2.4$
- Includes energy corrections/calibrations
- Required to come from the primary vertex

► Final State Radiation (FSR)

- The decay of a Z boson can be associated with final-state radiation photons ($Z \rightarrow l^+ l^- \gamma$), and we wish to recover the energy from the radiated photon
- Isolated photons are selected, and assigned to their closest preselected lepton by
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

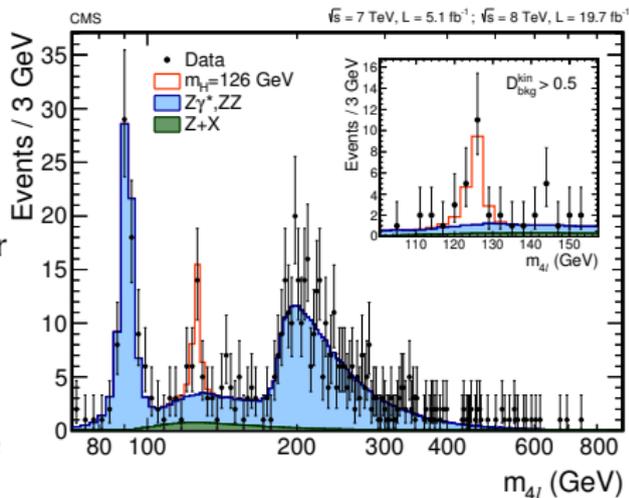
Event Reconstruction and Selection

Z_1 Select the opposite-sign same-flavor lepton pair that is closest to the nominal Z mass

Z_2 Of the remaining leptons, select the opposite-sign same-flavor lepton pair with the highest p_T scalar sum

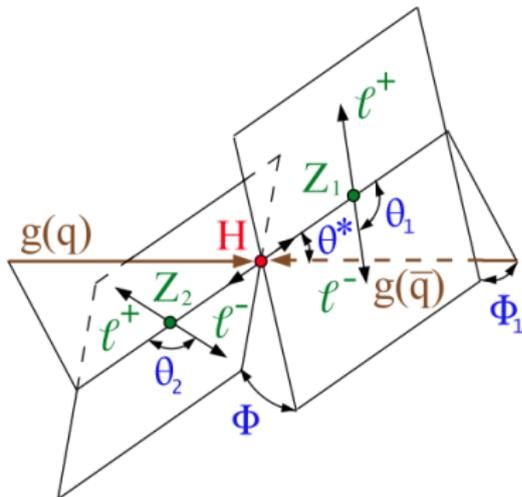
FSR If the inclusion of an FSR photon brings a Z candidates mass closer to nominal, keep it. ≤ 1 photon may be assigned to a Z candidate.

- ▶ Require that the leptons have a relative isolation of < 0.4 with an isolation cone of $\Delta R < 0.4$
- ▶ Require $m(ll) > 4$ GeV on opposite-sign lepton pairs for QCD suppression
- ▶ Require $40 < m_{Z_1} < 120$ GeV and $12 < m_{Z_2} < 120$ GeV
- ▶ At least one lepton should have $p_T > 20$ GeV and another $p_T > 10$ GeV



Observables

- ▶ The following quantities are measured from the $4l$ events, and higher-level observables/discriminants can be built from them
- ▶ Masses: m_{Z_1} , m_{Z_2} , m_{4l}
- ▶ Event-by-event mass uncertainties
 - ▶ The momentum uncertainties from the four leptons are propagated into the four-lepton mass
 - ▶ $\mathcal{D}_m = \sigma_{m_{4l}}/m_{4l}$
- ▶ Kinematic Angles
 - θ^* Angle between Z_1 's trajectory and the beam axis
 - Φ_1 Angle between the Z_1 decay plane and the X decay plane
 - $\theta_{1,2}$ Angle between the negative lepton trajectory and the trajectory of its parent Z
 - Φ Angle between the decay planes of the two Z s



Mass and Width Measurement Strategy



- ▶ The mass and width measurements are performed using a likelihood fit with a 3D p.d.f.

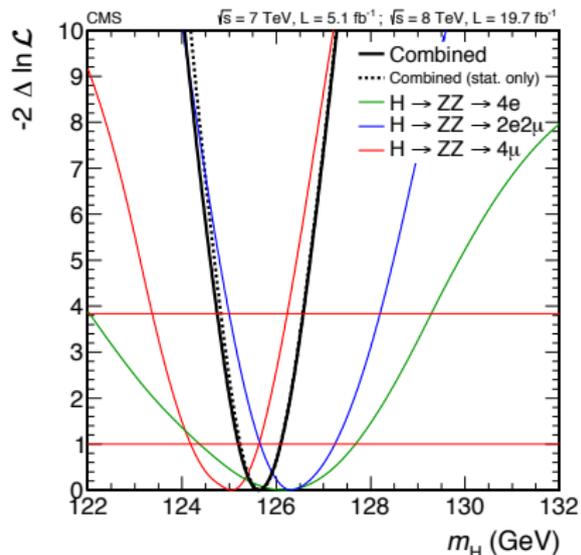
$$\mathcal{L}_{3D}^{m,\Gamma} (m_{4l}, \mathcal{D}_m, \mathcal{D}_{bkg}^{kin}) = \mathcal{P}(m_{4l}|m_H, \Gamma, \mathcal{D}_m) \mathcal{P}(\mathcal{D}_m|m_{4l}) \times \mathcal{P}(\mathcal{D}_{bkg}^{kin}|m_{4l}) \quad (1)$$

- ▶ We use a kinematic discriminant \mathcal{D}_{bkg}^{kin} to discriminate against the background

$$\mathcal{D}_{bkg}^{kin} = \frac{\mathcal{P}_{0^+}^{kin}}{\mathcal{P}_{0^+}^{kin} + \mathcal{P}_{bkg}^{kin}} = \left[1 + \frac{\mathcal{P}_{bkg}^{kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4l})}{\mathcal{P}_{0^+}^{kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4l})} \right]^{-1} \quad (2)$$

- ▶ Where $\vec{\Omega} = \{\theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$, and \mathcal{D}_{bkg}^{kin} does not carry discrimination power based on m_{4l}

Mass Measurement

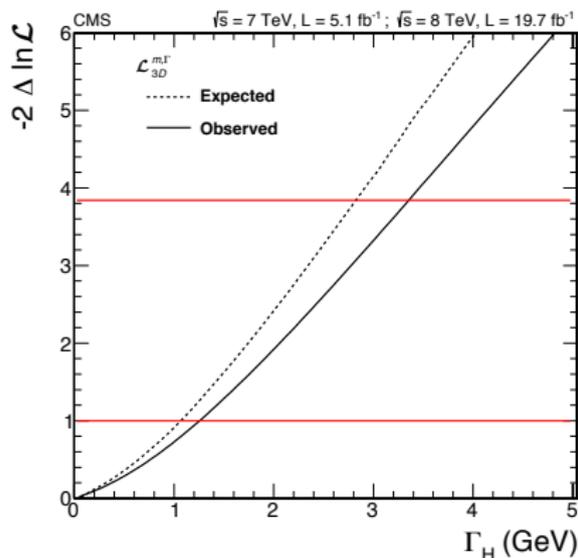


Channel	Measured Mass (GeV)
$4e$	$126.2^{+1.5}_{-1.8}$
$2e2\mu$	$126.3^{+0.9}_{-0.7}$
4μ	$125.1^{+0.6}_{-0.9}$

- ▶ Above is the scan of the negative log-likelihood $-2\Delta \ln \mathcal{L}$ versus the mass m_H
- ▶ The three channels are shown separately, as well as the combined result
- ▶ Combined mass measurement:

$$m_H = 125.6 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.) GeV}$$

Width Measurement



- ▶ To the left is a scan of the average expected and observed negative log-likelihood $-2\Delta \ln \mathcal{L}$ versus the width Γ_H
- ▶ Upper limit of 3.4 GeV at 95% CL, with an expected upper limit of 2.8 GeV
- ▶ Measured width:

$$\Gamma_H = 0.0_{-0.0}^{+1.3} \text{ GeV}$$

Spin-Parity Measurement Strategy



- The standard model $J^P = 0^+$ hypothesis is tested against twelve alternate hypotheses

J^P	J^P Production	J^P	J^P Production
0^-	Any	2_m^+	$gg \rightarrow X$
0_h^+	Any	2_m^+	$q\bar{q} \rightarrow X$
1^-	$q\bar{q} \rightarrow X$	2_m^+	Any
1^-	Any	2_b^+	$gg \rightarrow X$
1^+	$q\bar{q} \rightarrow X$	2_h^+	$gg \rightarrow X$
1^+	Any	2_h^-	$gg \rightarrow X$

- We use a mass window of $106 < m_{4l} < 141$ GeV for the spin-parity analysis
- A 2D log-likelihood ratio test statistic is used to separate the hypotheses

$$q = -2 \ln \left[\frac{\mathcal{L}^{J^P}}{\mathcal{L}^{0^+}} \right] \quad (3)$$

- Where $\mathcal{L}_{2D}^{J^P} \equiv \mathcal{L}_{2D}(\mathcal{D}_{bkg}, \mathcal{D}_{J^P})$
- The discriminants are discussed on the next slide



Spin-Parity Discriminants

- ▶ We build a kinematic discriminant to separate the signal from background, which includes the discrimination power of m_{4l}

$$\mathcal{D}_{bkg} = \left[1 + \frac{\mathcal{P}_{bkg}^{kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4l}) \times \mathcal{P}_{bkg}^{mass}(m_{4l})}{\mathcal{P}_{0^+}^{kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4l}) \times \mathcal{P}_{sig}^{mass}(m_{4l} | m_{0^+})} \right]^{-1} \quad (4)$$

- ▶ We build a similar discriminant to separate the different signal hypotheses

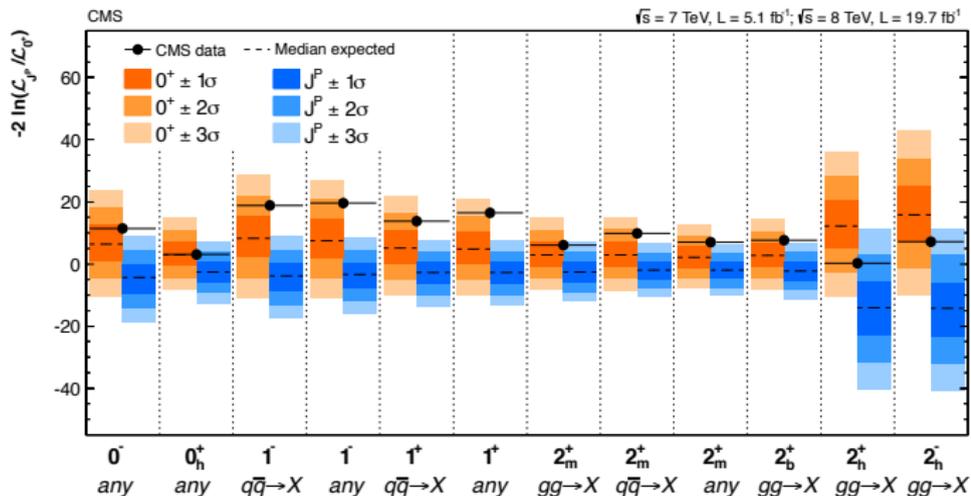
$$\mathcal{D}_{J^p} = \left[1 + \frac{\mathcal{P}_{J^p}^{kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4l})}{\mathcal{P}_{0^+}^{kin}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4l})} \right]^{-1} \quad (5)$$

- ▶ For spin-1 and spin-2 hypotheses, the angles $\cos \theta^*$ and Φ_1 depend on the production mode
- ▶ To remove this dependence, we integrate out those angles, and make the following replacements in the discriminants

$$\mathcal{P}_{bkg}^{kin} \rightarrow \frac{1}{4\pi} \int d\Phi_1 d \cos \theta^* \mathcal{P}_{bkg}^{kin} \quad (6)$$

$$\mathcal{P}_{J^p}^{kin} \rightarrow \frac{1}{4\pi} \int d\Phi_1 d \cos \theta^* \mathcal{P}_{J^p}^{kin} \quad (7)$$

Spin-Parity Hypothesis Separation



- ▶ The values of q are shown for the **standard model** and the **alternate J^P hypotheses**
- ▶ The expected distributions are created by generating MC toys assuming $m_H = 125.6 \text{ GeV}$
- ▶ The observed value is indicated by a black point

Spin-Parity Hypothesis Separation



J^P	J^P Production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	CL_s
0^-	Any	2.4σ (2.7σ)	-0.9σ	$+3.6\sigma$	0.09%
0^+_h	Any	1.7σ (1.9σ)	-0.0σ	$+1.8\sigma$	7.1%
1^-	$q\bar{q} \rightarrow X$	2.6σ (2.7σ)	-1.4σ	$+4.8\sigma$	0.001%
1^-	Any	2.6σ (2.6σ)	-1.7σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \rightarrow X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.03%
1^+	Any	2.0σ (2.1σ)	-1.9σ	$+4.5\sigma$	0.01%
2^+_m	$gg \rightarrow X$	1.7σ (1.8σ)	-0.8σ	$+2.6\sigma$	1.9%
2^+_m	$q\bar{q} \rightarrow X$	1.6σ (1.7σ)	-1.6σ	$+3.6\sigma$	0.03%
2^+_m	Any	1.5σ (1.5σ)	-1.3σ	$+3.0\sigma$	1.4%
2^+_b	$gg \rightarrow X$	1.6σ (1.8σ)	-1.2σ	$+3.1\sigma$	0.9%
2^+_h	$gg \rightarrow X$	3.7σ (4.0σ)	$+1.8\sigma$	$+1.9\sigma$	3.1%
2^-_h	$gg \rightarrow X$	4.0σ (4.5σ)	$+1.0\sigma$	$+3.0\sigma$	1.7%

- ▶ The expected separation is shown when the signal strength is calculated from data, and when it is fixed to 1
- ▶ The observed values reflect the consistency with the 0^+ or J^P models where the signal strength is allowed to float
- ▶ All cases are consistent with the standard model hypothesis



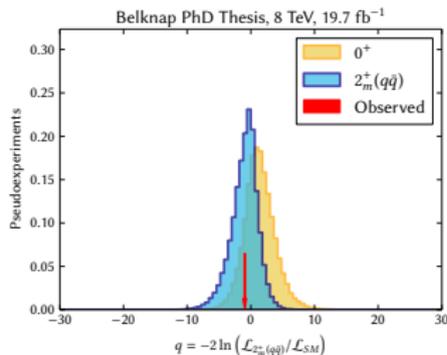
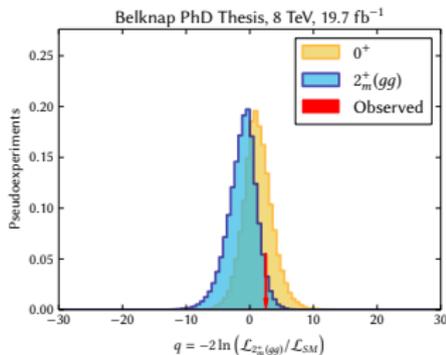
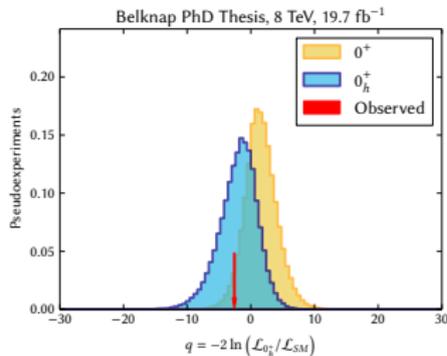
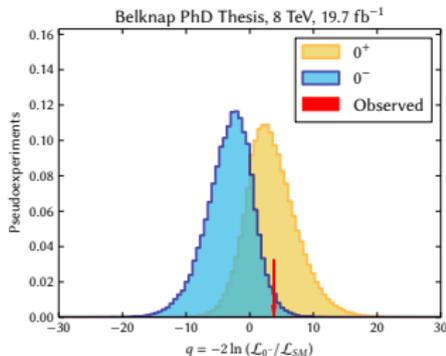
Angles-Only Spin-Parity Analysis

- ▶ As an alternate cross-check, the spin-parity analysis can also be performed using only a subset of the kinematic angles (CMS-approved D.A.B. PhD thesis analysis)
- ▶ We build a log-likelihood ratio test statistic as before, with a 3D likelihood

$$\mathcal{L}_{3D} \equiv \mathcal{L}_{3D}(P_2(\cos \theta_1), P_2(\cos \theta_2), \cos(2\Phi)) \quad (8)$$

- ▶ The choice of angles is outlined in: Modak, Sahoo, Sinha, and Cheng, *Inferring the nature of the boson at 125-126 GeV*, [arXiv:1301.5404 \[hep-ph\]](https://arxiv.org/abs/1301.5404)
- ▶ The 3D p.d.f. used to compute the likelihood is an $8 \times 8 \times 8$ template populated by Monte Carlo simulation for both signal and background (assuming $m_H = 126$ GeV)
- ▶ Since the m_{4l} shape is not used here, a smaller mass window is utilized: $121.5 < m_{4l} < 130.5$ GeV
- ▶ Hypotheses tested: 0^- , 0_h^+ , $2_m^+(gg)$, and $2_m^+(q\bar{q})$
- ▶ Uses 19.7 fb^{-1} of 8 TeV data only

Angles-Only Spin-Parity Analysis Results



The values of q are shown for the **standard model** and the **alternate hypothesis**, and the arrow indicates the **observed value**

Angles-Only Spin-Parity Analysis Results



J^P	J^P Production	Expected	Obs. 0^+	Obs. J^P	CL_s
0^-	Any	1.83σ	-0.17σ	$+2.04\sigma$	4.8%
0^+	Any	1.33σ	$+1.73\sigma$	-0.30σ	65%
2_m^+	$gg \rightarrow X$	1.11σ	-0.62σ	$+1.77\sigma$	14%
2_m^+	$q\bar{q} \rightarrow X$	1.10σ	$+1.08\sigma$	-0.11σ	63%

(Belknap Ph.D. Thesis)

- ▶ The expected separation is shown when the signal strength is calculated from data
- ▶ The observed values reflect the consistency with the 0^+ or J^P models where the signal strength is allowed to float
- ▶ Using only three of the angles is not nearly as powerful as using all five angles with the masses
- ▶ Results are consistent with the previous spin-parity results



Summary

- ▶ Presented are the CMS measurements of mass, width, and spin-parity in $H \rightarrow ZZ \rightarrow 4l$ (CMS-HIG-13-002)
- ▶ Utilizing 5.1 fb^{-1} of 7 TeV and 19.7 fb^{-1} of 8 TeV CMS data
- ▶ **Mass**
 - ▶ $m_H = 125.6 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.) GeV}$
- ▶ **Width**
 - ▶ $\Gamma_H = 0.0_{-0.0}^{+1.3} \text{ GeV}$
 - ▶ Upper limit of 3.4 GeV at 95% CL (2.8 GeV expected)
- ▶ **Spin-Parity**
 - ▶ For all hypotheses tested, the CMS data are consistent with the standard model pure scalar hypothesis
 - ▶ Pseudoscalar and spin-1 hypotheses tested are excluded at 99% CL or higher
 - ▶ All spin-2 hypotheses tested are excluded at 95% CL or higher
 - ▶ Results consistent with the angles-only cross-check

The production and decay properties of the observed boson in the $4l$ final state are consistent with the standard model expectations