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 $H \to ZZ \to 4l$ 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 [hep-ex]

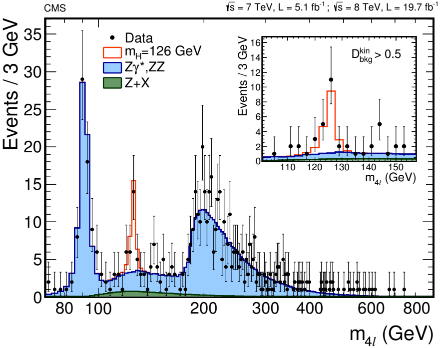
Event Reconstruction and Selection

- We consider isolated muons and electrons coming from the primary vertex

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

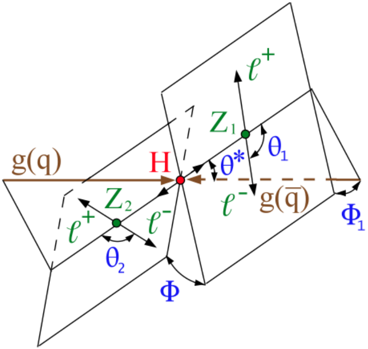
FSR If the inclusion of an FSR photon brings a Z candidates mass closer to nominal, keep it. ≤ 1 photon may be assigned to a Z candidate.



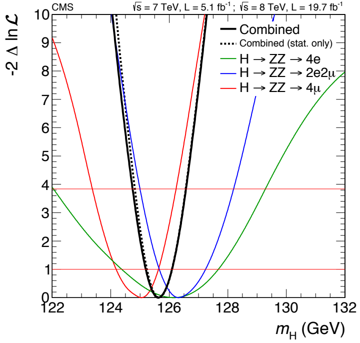
- Require that the leptons have a relative isolation of < 0.4 with an isolation cone of $\Delta R < 0.4$
- Require $m(ll) > 4$ GeV on opposite-sign lepton pairs for QCD suppression
- Require $40 < m_{Z_1} < 120$ GeV and $12 < m_{Z_2} < 120$ GeV
- At least one lepton should have $p_T > 20$ GeV and another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

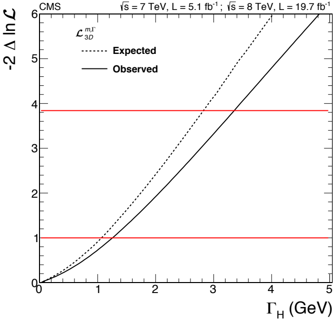
Observables

- 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 Zs



Mass and Width Measurements





- Above are the scans of the negative log-likelihood $-2\Delta \ln \mathcal{L}$ versus the mass m_H and width Γ_H
- Combined mass measurement:

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

- Upper limit of 3.4 GeV at 95% CL, with an expected upper limit of 2.8 GeV
- Measured width:

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

Spin-Parity Measurement Strategy

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

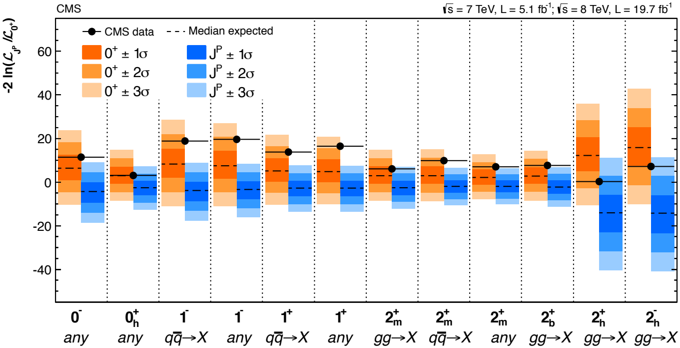
J^P	J^P Production	J^P	J^P Production
0^-	Any	2^+_m	$gg \to X$
0^+_h	Any	2^+_m	$q\bar{q} \to X$
1^-	$q\bar{q} \to X$	2^+_m	Any
1^-	Any	2^+_b	$gg \to X$
1^+	$q\bar{q} \to X$	2^+_h	$gg \to X$
1^+	Any	2^-_h	$gg \to X$

- 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

$$q = -2\ln\left[\frac{\mathcal{L}_{J^P}}{\mathcal{L}_{0^+}}\right] \qquad (1)$$

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

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 $m_H = 125.6$ 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^-	$q\bar{q} \to X$	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^+	$q\bar{q} \to X$	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^+	$gg \to X$	1.7σ (1.8σ)	-0.8σ	$+2.6\sigma$	1.9%
2_m^+	$q\bar{q} \to X$	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^+	$gg \to X$	1.6σ (1.8σ)	-1.2σ	$+3.1\sigma$	0.9%
2_h^+	$gg \to X$	3.7σ (4.0σ)	$+1.8\sigma$	$+1.9\sigma$	3.1%
2_h^-	$gg \to X$	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

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

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

Backup Slides

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 $p_T > 7$ 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 $p_T > 5$ 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 $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

Mass and Width Measurement Strategy

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

$$\mathcal{L}_{3D}^{m,\Gamma}\left(m_{4l},\mathcal{D}_m,\mathcal{D}_{bkg}^{kin}\right)=\mathcal{P}(m_{4l}|m_H,\Gamma,\mathcal{D}_m)\mathcal{P}(\mathcal{D}_m|m_{4l})\times\mathcal{P}(\mathcal{D}_{bkg}^{kin}|m_{4l}) \quad (2)$$

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

$$\mathcal{D}_{bkg}^{kin}=\frac{\mathcal{P}_{0^+}^{kin}}{\mathcal{P}_{0^+}^{kin}+\mathcal{P}_{bkg}^{kin}}=\left[1+\frac{\mathcal{P}_{bkg}^{kin}(m_{Z_1},m_{Z_2},\vec{\Omega}|m_{4l})}{\mathcal{P}_{0^+}^{kin}(m_{Z_1},m_{Z_2},\vec{\Omega}|m_{4l})}\right]^{-1} \quad (3)$$

- 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}

- General decay amplitude for spin-0 boson to two vectors (v is the SM VEV)

$$A(H \to ZZ) = v^{-1}\left(a_1 \cdot m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 \cdot f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 \cdot f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$f^{(i),\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu$$

$$\tilde{f}_{\mu\nu}^{(i)} = 1/2 \epsilon_{\mu\nu\alpha\beta} f^{(i),\alpha\beta} = \epsilon_{\mu\nu\alpha\beta} \epsilon_i^\alpha q_i^\beta$$

J^P	Description
0^+	SM pure scalar (a_1 dominates)
0^-	Pseudoscalar (a_3 dominates)
0_h^+	Non-SM scalar with higher-dimension operators (a_2 dominates)
1^+	Pseudovector
1^-	Vector
2_m^+	Graviton-like with minimal couplings
2_b^+	Graviton-like where SM fields propogate in the bulk of extra dimensions
2_h^+	Tensor with higher-dimension operators
2_h^-	Pseudotensor with higher-dimension operators

Spin-Parity Discriminants

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

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

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

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

- 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

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

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

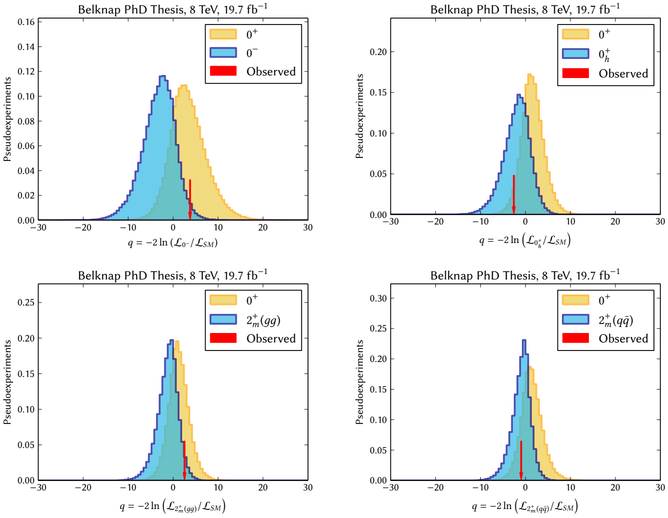
Angles-Only Spin-Parity Analysis

- 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-liklihood ratio test statistic as before, with a 3D liklihood

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

- 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]
- 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_h^+	Any	1.33σ	$+1.73\sigma$	-0.30σ	65%
2_m^+	$gg \to X$	1.11σ	-0.62σ	$+1.77\sigma$	14%
2_m^+	$q\bar{q} \to X$	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