Rare H and Z decays to quarkonia with CMS

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Abstract

Searches for SM Higgs and Z bosons decaying to a $J/\psi$ and a photon, with subsequent decay of the $J/\psi$ to $\mu^+\mu^-$ and the Z boson rare decay to a $\psi$ meson and two oppositely charged same-flavour leptons, $\ell^+\ell^-$, where $\psi$ represents contributions from direct $J/\psi$ and $\psi(2S) \rightarrow J/\psi X$, and $\ell = \mu, e$ are presented. The analyses are performed using data recorded by the CMS detector from proton-proton collisions at center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 35.9 $fb^{-1}$. The observed (expected) upper limit on the branching fraction for $H \rightarrow J/\psi \gamma$ with $m_H = 125$ GeV is $7.6(5.2) \times 10^{-4}$, 260 (170) times larger than the standard model prediction, at 95% confidence level. The observed (expected) upper limit on the $Z \rightarrow J/\psi \gamma$ branching fraction is $1.4(1.6) \times 10^{-6}$, 15 (18) times larger than the standard model prediction, at 95% confidence level. The signal of the Z boson rare decay to a $\psi$ meson and two oppositely charged same-flavour leptons, $\ell^+\ell^-$, is observed with a significance in excess of 5 standard deviations. After removing the contributions from $\psi(2S)$ decays to $J/\psi$, the ratio of the branching fraction of the $Z \rightarrow J/\psi \ell^+\ell^-$, to the decay $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ within a fiducial phase space is measured to be

$$\frac{B(Z \rightarrow J/\psi \ell^+\ell^-)}{B(Z \rightarrow \mu^+\mu^-\mu^+\mu^-)} = 0.70 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst).}$$

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Rare H and Z decays to quarkonia with CMS

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Abstract. Searches for SM Higgs and Z bosons decaying to a J/ψ and a photon, with subsequent decay of the J/ψ to μ⁺μ⁻ and the Z boson rare decay to a ψ meson and two oppositely charged same-flavour leptons, ℓ⁺ℓ⁻, where ψ represents contributions from direct J/ψ and ψ(2S) → J/ψX, and ℓ = μ, e are presented. The analyses are performed using data recorded by the CMS detector from proton-proton collisions at center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 35.9 fb⁻¹. The observed (expected) upper limit on the branching fraction for H → J/ψγ with m_H = 125 GeV is 7.6(5.2) × 10⁻⁴, 260 (170) times larger than the standard model prediction, at 95% confidence level. The observed (expected) upper limit on the Z → J/ψγ branching fraction is 1.4(1.6) × 10⁻⁶, 15 (18) times larger than the standard model prediction, at 95% confidence level. The signal of the Z boson rare decay to a ψ meson and two oppositely charged same-flavour leptons, ℓ⁺ℓ⁻, is observed with a significance in excess of 5 standard deviations. After removing the contributions from ψ(2S) decays to J/ψ, the ratio of the branching fraction of the Z → J/ψ ℓ⁺ℓ⁻, to the decay Z → μ⁺μ⁻μ⁺μ⁻ within a fiducial phase space is measured to be

\[ \frac{B(Z \rightarrow J/ψ ℓ⁺ℓ⁻)}{B(Z \rightarrow μ⁺μ⁻μ⁺μ⁻)} = 0.70 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)}. \]

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1. Introduction
The rare decays of the Higgs boson [1, 2] to a quarkonium state and a photon provide a unique sensitivity to the magnitude of the Yukawa couplings of the Higgs boson to quarks [3, 4, 5]. These couplings are difficult to access in hadronic collisions through direct decay of the Higgs boson into quark-antiquark pairs, due to the immense QCD background [6].

Among the channels available to explore Yukawa’s couplings of light quarks are those with heavy quarkonia. In addition, the rare decay modes of the Z boson have attracted attention as an alternative environment to investigate the Yukawa couplings and for their sensitivity to New Physics [7].

Owing to the high luminosity integrated by the LHC [8], CMS has collected a large sample of Z bosons. The large dataset allows to carry out searches for very rare decay channels. Recent standard model (SM) estimates for the branching fraction of the vector bosons decay into a vector meson plus a photon yield values of the order of 10⁻⁸. These are compatible with the limits recently published by the ATLAS collaboration [9, 10].
In addition, the decay \( Z \rightarrow Z \ell^+ \ell^- \) has been studied by various theory groups \([11, 12, 13]\) during the LEP period, yielding a branching fraction in the range \((6.7 - 7.7) \times 10^{-7}\). The leading Feynman diagrams contributing to both processes are illustrated in Figs. 1, 2.

**Figure 1.** Leading-order diagram for the \( H(Z) \rightarrow J/\psi \gamma \) process. The diagram shows the direct contribution for the decay modes of the \( H(Z) \rightarrow J/\psi \gamma \) processes.

**Figure 2.** Leading-order diagram for the \( Z \rightarrow J/\psi \ell^+ \ell^- \) process. The diagram shows the dominant production mechanism for the \( Z \rightarrow J/\psi \ell^+ \ell^- \) decay.

### 2. Selections and Results

The event selection for \( H(Z) \rightarrow J/\psi \gamma \) is divided in the following steps: at the beginning, a set of cuts related to trigger and object selection is applied. For the events that pass this selection, another set of cuts is applied, this time focusing on kinematic (phase space) event selection. After full selection, three exclusive categories are defined, based on the photon’s \( \eta \) region and its energy spread shape within the ECAL (R9). The selection criteria for the \( H(Z) \rightarrow J/\psi \gamma \) analyses are summarized in Table 1.

| Muon-Photon trigger with: \( p_T^{\mu} (E_T^\gamma) > 17 \text{(30)} \) GeV |
|-----------------------------|
| \( |p_T^{\gamma}| < 2.4, p_T^{\mu_1} > 20 \text{ GeV} \) and \( p_T^{\mu_2} > 4 \text{ GeV} \) |
| Isolation requirements |
| \( |\eta| < 2.5 \) (excluding ECAL Barrel-Endcap intersection), \( p_T^{\gamma} > 33 \text{ GeV} \) |
| \( \Delta R(\mu, \gamma) > 1, \Delta R(\mu_1, \mu_2, \gamma) > 2, |\Delta \phi(\mu, \gamma)| > 1.5, 3.0 < m_{\mu\mu} < 3.2 \text{ GeV} \) |
| \( Z(H) \rightarrow J/\psi \gamma): \ p_T^{\mu}, E_T^\gamma/m_{\mu\gamma} > 35/91.2(35/125) \) |

The \( Z \rightarrow J/\psi \ell^+ \ell^- \) result follows the trigger and offline selection criteria of the previous analysis of \( Z \rightarrow \ell^+ \ell^- \ell^+ \ell^- \) decay \([14]\). A set of high-\( p_T \) single, dilepton and lower-\( p_T \) three-lepton triggers is used.

An extended 2D unbinned maximum likelihood fit is used to determine the signal yield in the \( m_{Z \rightarrow \psi \mu^+ \mu^-} \) and \( m_{Z \rightarrow \psi e^+ e^-} \) variables. Figure 3 shows the one-dimensional projections of the fit. The signal yields found are \( N_{Z \rightarrow \psi \mu^+ \mu^-} = 13.0 \pm 3.9 \) and \( N_{Z \rightarrow \psi e^+ e^-} = 11.2 \pm 3.4 \).

The signal significance for the \( Z \rightarrow \psi \mu^+ \mu^- \) and \( Z \rightarrow \psi e^+ e^- \) decay channels is 4.0 \( \sigma \) and 4.3 \( \sigma \), respectively. The combined significance is 5.7 \( \sigma \). From the signal yield a ratio of branching fractions was computed over the fiducial phase space of the measurement defined in Table 2.
Figure 3. Invariant mass distributions for the ψ muon pairs (left) and for \( Z \to \psi \ell^+ \ell^- \) (right), for \( Z \to \psi \mu^+ \mu^- \) (top) and \( Z \to \psi e^+ e^- \) (bottom) candidates from Ref. [15]. Data are represented with filled circles, the solid blue line is the overall fit to the data, the green filled region corresponds to the signal yield, while the dashed blue lines are the ψ signal from the Z background (left) and the Z signal extracted from the ψ background (right).

The fiducial branching fraction of \( Z \to J/\psi \mu^+ \mu^- \) relative to the \( Z \to \mu^+ \mu^- \mu^+ \mu^- \) decay mode is calculated as:

\[
R_{J/\psi \ell^+ \ell^-} \equiv \frac{B(Z \to J/\psi \ell^+ \ell^-)}{B(Z \to \mu^+ \mu^- \mu^+ \mu^-)} = \sum_{\ell} \left( \frac{1}{2} \frac{N_{Z \to J/\psi \ell^+ \ell^-}}{N_{Z \to \mu^+ \mu^- \mu^+ \mu^-}} \frac{\epsilon_{Z \to \mu^+ \mu^- \mu^+ \mu^-}}{\epsilon_{Z \to J/\psi \ell^+ \ell^-}} \right) \frac{1}{B(J/\psi \to \mu^+ \mu^-)}, \quad \ell = \mu, e,
\]

where \( N_{Z \to J/\psi \ell^+ \ell^-} \) is the number of \( Z \to J/\psi \ell^+ \ell^- \) events, after removing ψ(2S) → J/ψ X contributions. The branching fraction ratio \( B[Z \to J/\psi \ell^+ \ell^-]/B[Z \to \psi(2S) \ell^+ \ell^-] \) from reference [12] is used, 1.9 events from \( N_{Z \to \mu^+ \mu^-} \) and 1.7 events from \( N_{Z \to e^+ e^-} \) are subtracted, resulting in 11.1 \( N_{Z \to J/\psi \mu^+ \mu^-} \) and 9.5 \( N_{Z \to J/\psi e^+ e^-} \) signal events.

The experimental efficiencies for reconstructed events within the fiducial phase space are determined from simulation; including the trigger, these are about 80%. The resulting branching fraction ratio for the phase-space region defined in Table 2 is measured to be: \( R_{J/\psi \ell^+ \ell^-} = 0.67 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)} \).
Table 2. The fiducial region for signal ($Z \rightarrow \psi \ell^+ \ell^-$) and reference ($Z \rightarrow \ell^+ \ell^- \ell^+ \ell^-$) channels.

| Condition                                                                 |
|----------------------------------------------------------------------------|
| Signal (reference) sample: 0 (40) $< m_{\ell^+ \ell^-} < 80$ GeV           |
| Reference channel: 4 $< m_{\mu^+ \mu^-} < 80$ GeV                        |
| $| m_{\mu^+ \mu^- \ell^+ \ell^-} - 91.2$ GeV $| < 25$ GeV                |
| $| \eta$(electrons) $| < 2.5$, $| \eta$(muons) $| < 2.4$                                    |
| $p_T(\ell_1, \ell_2, \mu_3, \mu_4) > (30, 15, 3.5, 3.5)$ GeV           |
| Signal: $p_T^{J/\psi} > 8.5$ GeV                                        |

Figure 4. Non-resonant background fits with the lowest order unbiased functions to the three-body invariant mass $m_{\mu\mu\gamma}$ distributions in data for $Z \rightarrow J/\psi \gamma$ in EB-HighR9 category (top), EB-LowR9 category (middle left), EE category (middle right), and $H \rightarrow J/\psi \gamma$ (bottom) from Ref. [16].
Considering the factors needed to extrapolate the signal and reference channels branching fractions to the full phase space cancel in the ratio, the measured value of \( B(Z \rightarrow \mu^+\mu^-\mu^+\mu^-) = (1.20 \pm 0.08) \times 10^{-6} \) for \( m_{\mu\mu} > 4 \) GeV [14] is used to obtain an estimate for \( B(Z \rightarrow J/\psi \ell^+\ell^-) \approx 8 \times 10^{-7} \), which is in accordance with \( (6.7 \pm 0.7) \times 10^{-7} \) and \( 7.7 \times 10^{-7} \) calculated in Refs. [11, 12].

In regard to Higgs and Z boson decays the continuum background for each category for both the Z and Higgs boson is estimated and modeled from data by fitting a parametric function to the \( m_{\mu\mu\gamma} \) distribution. An unbinned maximum likelihood fit is performed over the range \( 70 \) (100) < \( m_{\mu\mu\gamma} \) < 120 (150) GeV for the \( \text{H(Z)} \rightarrow J/\psi\gamma \) decays. An order-three polynomial function is used for each category in the Z boson search, and in the Higgs boson search an order-two polynomial function is used. Figure 4 shows \( m_{\mu\mu\gamma} \) distribution and background model for each category.

An unbinned maximum likelihood fit to the \( m_{\mu\mu\gamma} \) distributions of signal simulated events is used to obtain the signal model for each case. A Crystal Ball function plus a Gaussian with the same mean value is used in the Higgs boson search, and in the Z boson case, a double-sided Crystal Ball function is used.

The observed (expected) upper limit on the branching fraction of \( \text{Z} \rightarrow J/\psi\gamma \) is \( 1.4 \) (1.6) \( \times 10^{-6} \), which correspond to 15 (18) times the SM prediction. The observed (expected) upper limit on the branching fraction of \( \text{H} \rightarrow J/\psi\gamma \) is \( 7.6 \) (5.2) \( \times 10^{-4} \) corresponding to 260 (170) times the SM prediction.

3. Summary
The CMS experiment is taking advantage of the large datasets accumulated to search for increasingly rarer processes. This contribution summarizes recent results obtained in the search for rare decays of the Higgs and Z bosons into final states involving quarkonia and a photon or a lepton pair. The decay of the Z boson into a \( \psi \) meson plus a lepton pair (\( \mu\mu \) or \( ee \)) has been observed for the first time. The rarer decays \( \text{H(Z)} \rightarrow J/\psi\gamma \) have been also explored and stringent upper limits set. These sensitive channels will continue to be explored with the larger datasets that are being accumulated.

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