Search for the rare decays of the Z and Higgs bosons to a J/ψ or ψ′ meson and a photon at CMS

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1. Introduction

CMS and ATLAS measurements of couplings to Higgs boson

- The couplings to the 3rd generation of fermions are measured and consistent with SM expectation
- **The focus is now on couplings to 2nd generation** and lighter quarks, in particular to charm quark
- **Discrepancies? ⇒ Hint to Physics Beyond the SM!**

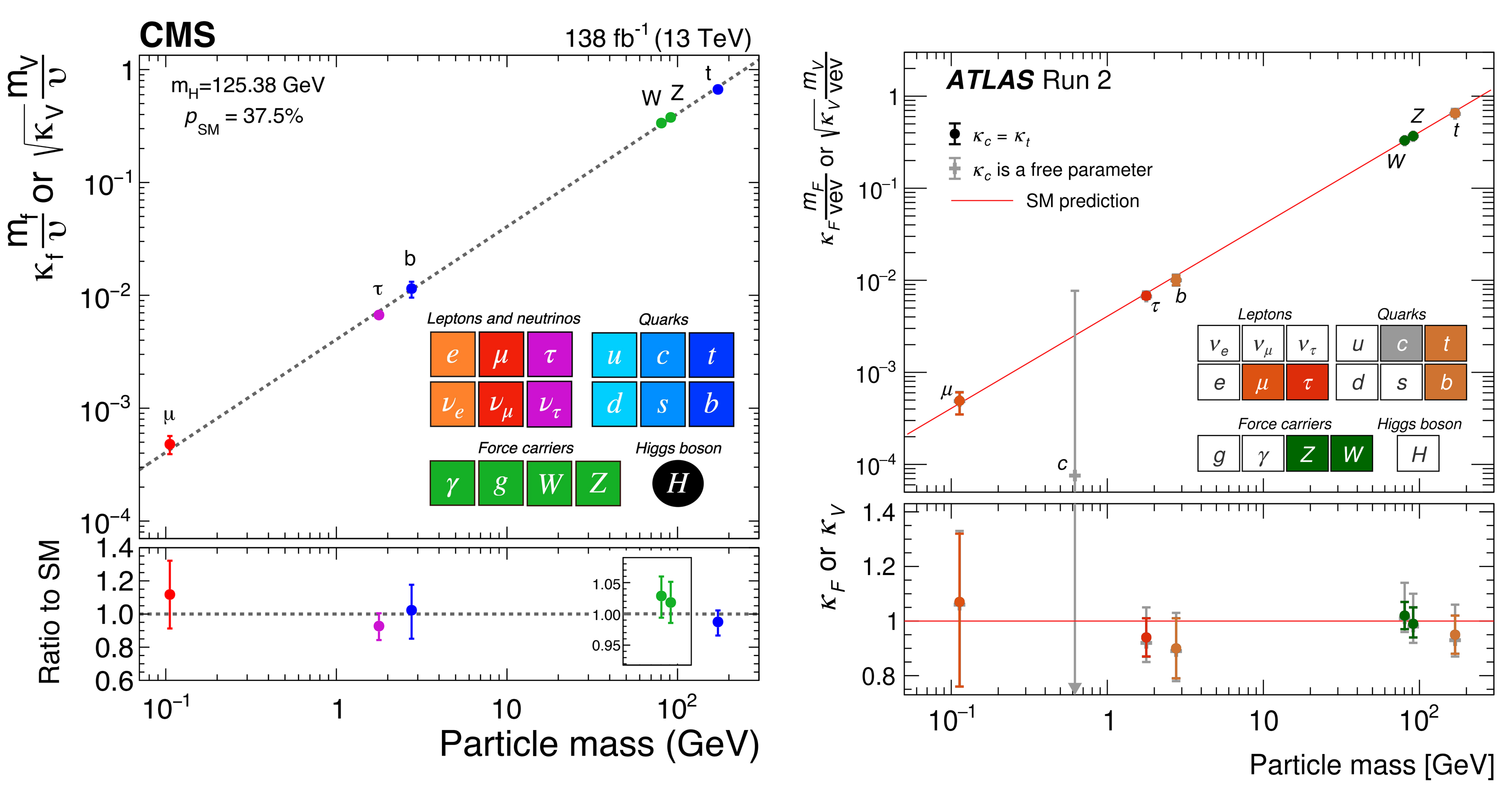

Figure 1: Higgs to fermions/gauge bosons coupling modifiers as a function of the fermion/gauge boson mass, measured by CMS [1] (left) and by ATLAS [2] (right) Collaborations.

2. Analysis overview

SM predicted Higgs boson rare decays to a charmed meson and a photon act as a probe

- $J/\psi \equiv \psi(1S)$, $\psi' \equiv \psi(2S)$
- $\mathcal{B}(Z \to \psi(1S)\gamma) = 8.96 \times 10^{-8}$, $\mathcal{B}(H \to \psi(1S)\gamma) = 2.99 \times 10^{-6}$ [3] ⇒ Never observed before
- **The direct decay goes through charm quark loop and is sensitive to Hcc coupling**
- The Z decay is a good benchmark for the theoretical prediction method validation
- Meson decay to a pair of muons: $\mathcal{B}(\psi(1S) \to \mu\mu) \approx 6\%$, $\mathcal{B}(\psi(2S) \to \mu\mu) \approx 0.8\%$
- **Very clean process, low SM background**

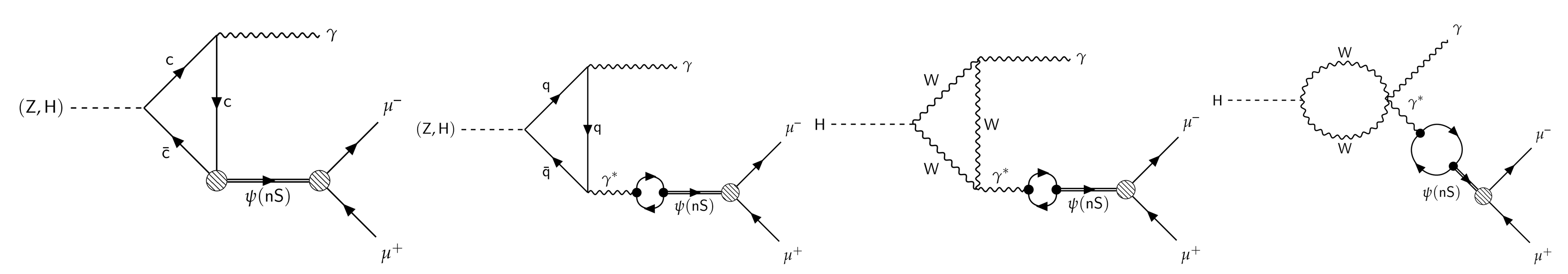

Figure 2: Leading-order Feynman diagrams of Z and Higgs boson rare decays to ψ(nS) and a photon.

Analysis performed using CMS Run-2 data set (123 fb^{-1}) and looking for μμγ final state [4]

- Excellent reconstruction performance of the final state particles
- **Signal is expected to appear with two resonances (Z/H and ψ(nS) meson)**
- Main background due to QCD processes with and without a ψ(nS) meson
- Resonant backgrounds from $Z \to \mu\mu\gamma$ Final State Radiation (FSR) and $H \to \mu\mu\gamma$ "Dalitz" decays
- The strategy consists in reconstructing the invariant mass distributions $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$, where the signal is expected to peak unlike the SM backgrounds

3. Event selection

Event preselection

- "Single muon + photon" trigger with p_T threshold of 17 (30) GeV on the muon (photon)
- Muons: $p_T(\mu_1) > 18$ GeV, $p_T(\mu_2) > 5$ GeV, "medium promt" identification and tight isolation from hadronic activity
- Photon: $p_T(\gamma) > 32$ GeV, multivariate identification at 80% efficiency + pixel seed veto
- ψ(nS) candidate as the one with pair of OS muons with closest angular distance ΔR

Signal and Control region definition

- **Signal Region 1 (SR1)**: $m_{\mu\mu} \in [3.0, 3.2]$ GeV ⇒ ψ(1S) mass window
- **Signal Region 2 (SR2)**: $m_{\mu\mu} \in [3.6, 3.75]$ GeV ⇒ ψ(2S) mass window
- **Control Region (CR)**: $m_{\mu\mu} \in [2.0, 3.0] \cup [3.2, 3.6] \cup [3.75, 8.0]$ GeV ⇒ $Z \to \mu\mu\gamma$ bkg modelling

Likelihood Discriminator (LD) for Z → ψ(1S)γ search

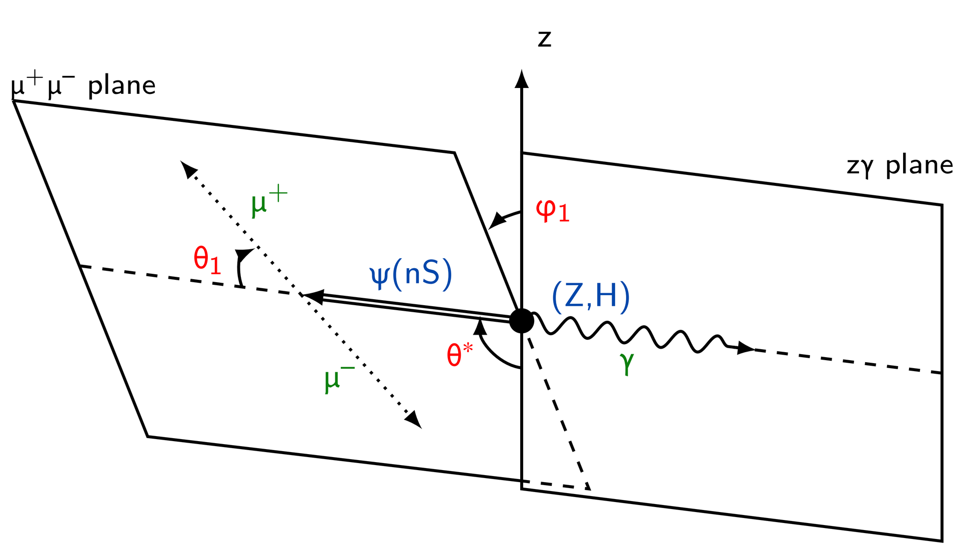

Figure 3: Main angular variables in the process.

- $\cos\theta^*$, $\cos\theta_1$, φ_1 main angular variables
- Fit their distributions after Preselection for observed data (in CR) and MC signals using a polynomial function f, and evaluate likelihood Ratio

$$\begin{cases} L_s = f_s(\cos\theta^*) \cdot f_s(\cos\theta_1) \cdot f_s(\varphi_1) \\ L_b = f_b(\cos\theta^*) \cdot f_b(\cos\theta_1) \cdot f_b(\varphi_1) \end{cases} \qquad LD = \frac{L_s}{L_s + L_b}$$

- Categorization on LD variable threshold
- **LD Low Purity (LP)**: LD < 0.5
- **LD High Purity (HP)**: LD > 0.5

Higgs boson production mode categorization for H → ψ(1S)γ search

- **Vector Boson Fusion (VBF)**: at least two forward jets with $m_{jj} > 350$ GeV
- **Heavy Flavour Lepton (HFL)**: at least a b-tag jet
- **ggF HP/LP**: not entering the previous categories, with High (Low) Purity for $|\cos\theta^*| > 0.5$ (< 0.5)

4. Event modelling

Signal and resonant backgrounds modelled from Monte Carlo samples

- Using Gaussian + Double-Sided Crystal Ball function (gaussian core and 2 power-law tails)
- Signal: normalization from theory, shape from Monte Carlo,
- **$Z \to \mu\mu\gamma$: normalization constrained by CR, shape from Monte Carlo**
- $H \to \mu\mu\gamma$: normalization and shape from Monte Carlo

Main QCD background is estimated directly from the data

- Power-laws, Exponentials and Bernstein polynomials function families are used in the fit
- The pptimal number of parameters for every family is chosen by the F-test
- **The uncertainty from the choice of family for QCD background modelling is handled as a discrete nuisance parameter with the discrete profiling method** [5]

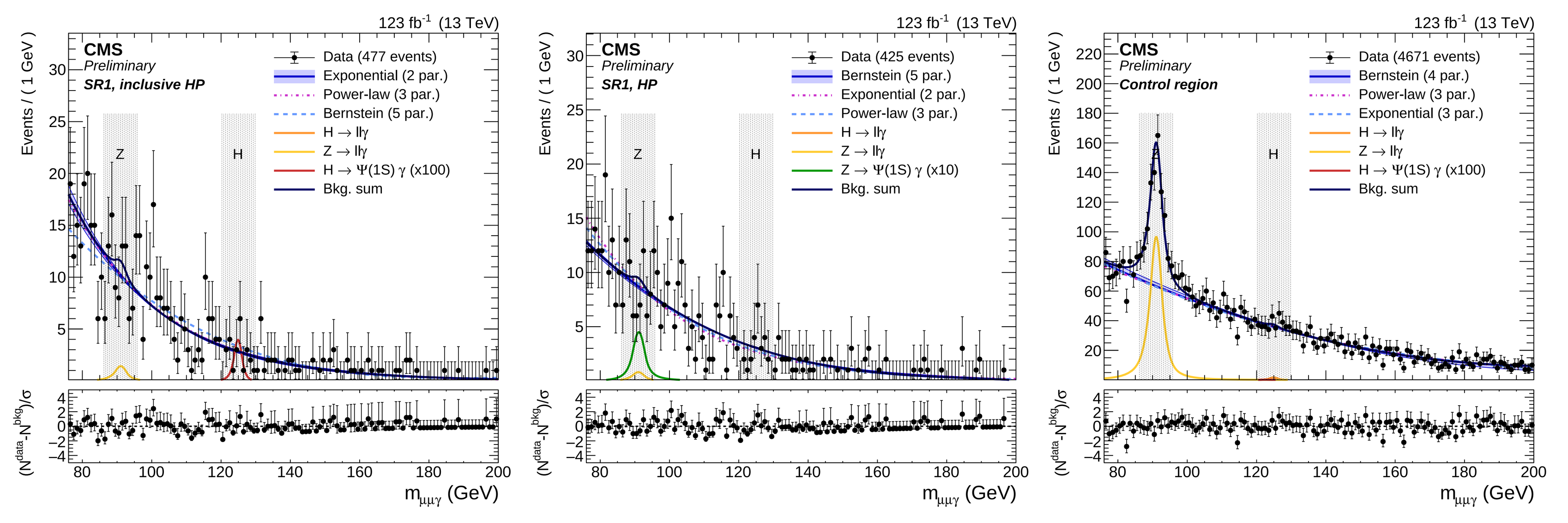

Figure 4: Background-only fits ranked according to the fit χ^2 [4]. Left: $H \to \psi(1S)\gamma$ ggF HP category. Center: $Z \to \psi(1S)\gamma$ HP category. Right: Control Region.

5. Results and Outlook

Systematic uncertainties to profile in the final fit

- Theory: $Z/H \to \psi(nS)\gamma$ branching ratio prediction, QCD and PDF scale, integrated luminosity
- Detector (normalization): trigger efficiency, identification and isolation of muons, identification of photon, pixel seed veto
- Detector (shape): muon momentum scale and resolution, photon and jet energy scale and resolution, trigger prefire
- QCD background function model choice: discrete profiling method

The final statistical analysis is performed using profile likelihood ratio test statistics

- A standalone fit, performed on the $Z \to \mu\mu\gamma$ signal strength in the CR alone, returns a value statistically compatible with the SM expectation

$$\mu(Z \to \mu\mu\gamma) = \sigma/\sigma^{SM} = 1.18 \pm 0.12$$

- **Upper limits at 95% Confidence Level are set on the signal $\sigma \times \mathcal{B}$**
- The limits are set using the CL_s method, with the asymptotic approximation
- **The results are interpreted within the κ-framework to constrain the c quark Yukawa coupling**, writing the partial $H \to \psi(1S)\gamma$ decay width in terms of both direct and indirect amplitudes

$$\frac{\mu(H \to \psi(1S)\gamma)}{\mu(H \to \gamma\gamma)} \approx \frac{\Gamma(H \to \psi(1S)\gamma)/\Gamma^{SM}(H \to \psi(1S)\gamma)}{\Gamma(H \to \gamma\gamma)/\Gamma^{SM}(H \to \gamma\gamma)} = \frac{|\mathcal{A}_{ind}\kappa_\gamma + \mathcal{A}_{dir}\kappa_c|^2}{\kappa_\gamma^2 \cdot \Gamma^{SM}(H \to \psi(1S)\gamma)} = \frac{|\mathcal{A}_{ind} + \mathcal{A}_{dir}\kappa_c/\kappa_\gamma|^2}{\Gamma^{SM}(H \to \psi(1S)\gamma)}$$

Process	This work (123 fb^{-1})			CMS (36 fb^{-1}) [6]	ATLAS (139 fb^{-1}) [7]
	$\mu_{obs}(\mu_{exp})$	$\sigma \times \mathcal{B}_{obs}(\sigma \times \mathcal{B}_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \psi(1S)\gamma$	$7.2\ \left(8.6^{+4.1}_{-2.7}\right)$	$3.8\ \left(4.4^{+1.9}_{-1.3}\right) \times 10^{-2}$	**$0.6\ \left(0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$**	$1.5\ \left(1.7^{+0.7}_{-0.5}\right) \times 10^{-6}$	$1.2\ \left(0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$
$Z \to \psi(2S)\gamma$	$29\ \left(68^{+36}_{-22}\right)$	$8\ \left(19^{+8}_{-6}\right) \times 10^{-2}$	**$1.3\ \left(3.1^{+1.4}_{-0.9}\right) \times 10^{-6}$**	—	$2.4\ \left(3.0^{+1.3}_{-0.8}\right) \times 10^{-6}$
$H \to \psi(1S)\gamma$	$88\ \left(62^{+30}_{-19}\right)$	$1.4\ \left(1.0^{+0.5}_{-0.3}\right) \times 10^{-2}$	**$2.6\ \left(1.8^{+0.9}_{-0.6}\right) \times 10^{-4}$**	$7.6\ \left(5.2^{+2.4}_{-1.6}\right) \times 10^{-4}$	$2.0\ \left(1.8^{+0.8}_{-0.5}\right) \times 10^{-4}$
$H \to \psi(2S)\gamma$	$970\ \left(781^{+417}_{-259}\right)$	$5.5\ \left(4.4^{+2.3}_{-1.5}\right) \times 10^{-2}$	**$9.9\ \left(8.0^{+4.2}_{-2.6}\right) \times 10^{-4}$**	—	$10.5\ \left(8.1^{+3.6}_{-2.3}\right) \times 10^{-4}$

Table 1: Observed (expected) upper limits at 95% CL on $\sigma \times \mathcal{B}$ and $\mu = \mathcal{B}/\mathcal{B}^{SM}$ of the $(H, Z) \to \psi(nS)\gamma$ processes.. The results are compared with previous ones [6, 7]

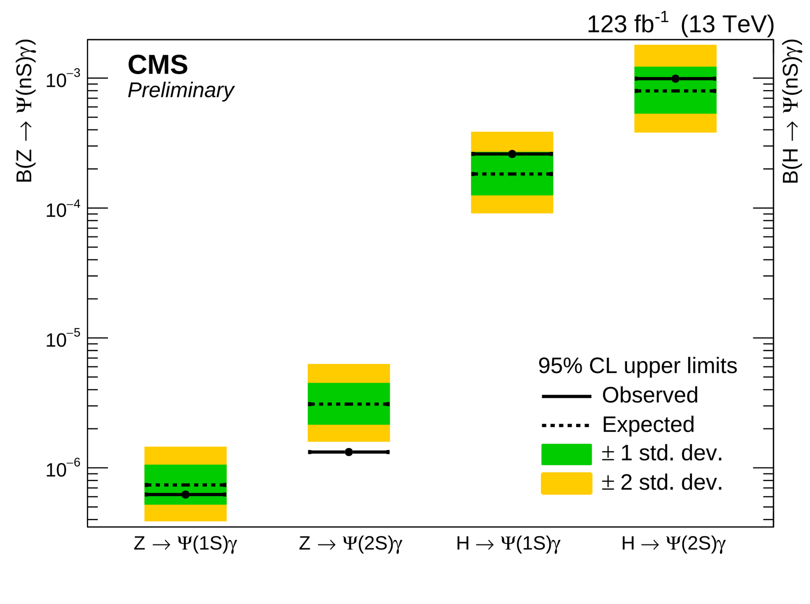

Figure 5: Observed/Expected exclusion limits on $\mathcal{B}$ [4].

Summary

- **Constraints on κ_c/κ_γ at 95% CL set to (−157, +199)** (not set in previous CMS search)
- **The sensitivity of this analysis shows an improvement that exceeds the expectations from a simple increase in the integrated luminosity**
- Optimization in event selection, improved categorization based on angular likelihood discriminator and Higgs production mode, discrete profiling method
- Run-3 data set will further improve the results

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