PROCEEDINGS OF SCIENCE

Searches for new physics in CMS in events with photons in the final state

Jyoti Babbar[a,*] **on behalf of the CMS Collaboration**

[a] *Istituto Nazionale di Fisica Nucleare (INFN), - Sezione di Trieste Galleria Padriciano, 99, 34149 Trieste, Italy*

E-mail: jyoti.babbar@cern.ch

Many new physics models such as compositeness, extra dimensions, extended Higgs sectors, supersymmetry, and dark sectors are expected to manifest themselves in the final states with photons. This talk presents searches in CMS for new phenomena in the final states that include photons, focusing on the recent results obtained using the full Run-II data-set collected by the CMS Experiment at the LHC.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

PoS(ICHEP2024)247

1. Introduction

Many extensions of Standard Model (SM) predict the existence of new resonant and non-resonant particles decaying to SM gauge bosons. In this note, I will summarize the recent resonant and non-resonant CMS searches with at least one photon in the final state. All the searches presented in this document utilize proton-proton collision data collected by the CMS experiment [1] in 2016-2018 at centre of mass energy $\sqrt{s}$ =13 TeV and correspond to a total integrated luminosity of 138 fb^{-1}.

2. Search for $X \rightarrow W\gamma$ resonances

A charged resonant particle X, decaying to a pair of SM gauge bosons, is predicted by various theoretical models such as unified field theories [2], two Higgs doublet models [3], and folded-supersymmetry models [4]. In a recent CMS search performed at $\sqrt{s}$ = 13 TeV, an excess over SM background was observed at 1.58 TeV in hadronic channel of Wγ analysis [5]. To conduct a complementary search, a similar analysis is performed for $X \rightarrow W\gamma$, where W decays leptonically into either an $e\nu$ or $\mu\nu$ final state. Additionally, this analysis presents combined results from both the hadronic and leptonic decays of the W boson.

The search considers signals of two different resonances widths i.e narrow resonance Γ_X/m_X = 0.01% (where Γ_X is the width and m_X is the mass) and broad resonance Γ_X/m_X = 5%. The analysis follows a bump hunt strategy over the falling transverse mass spectra ($m_{l\nu\gamma}$) of the final states, since the longitudinal component of the neutrinos cannot be measured. To ensure robust background modeling, the mass distribution ($m_{l\nu\gamma}$) from the data is fitted with various parametric functions.

No significant deviation from the background only expectation is observed, and thus 95% confidence level (CL) exclusion limits are calculated for both narrow and broad resonances on the production cross section of X multiplied by the decay branching ratio. The exclusion limit plots are shown in Figure 1 [6]. The local $p-$value significance of 2.8 (3.1) standard deviation observed for narrow (broad) resonances in the $W\gamma$ hadronic channel at mass 1.58 TeV, is reduced to 2.7 (2.5) standard deviations when combined with the leptonic channel.

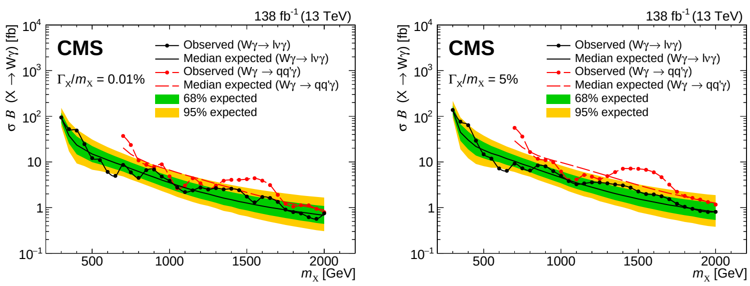

Figure 1: Expected and observed 95% CL limits on $\sigma B(X \rightarrow W\gamma)$ from events with leptonic W boson decays (solid black lines) are presented as a function of the X resonance mass for Γ_X/m_X = 0.01% (left) and for Γ_X/m_X = 5% (right). For comparison, the limits from hadronic W boson decays (dashed red lines), as reported in [5], are also included.

3. Search for $X \to \phi\phi \to \gamma\gamma\gamma\gamma$ resonances

A search is presented for an extended Higgs sector [7] featuring two new spin-0 particles X and ϕ, where $X \to \phi\phi \to \gamma\gamma\gamma\gamma$. The decay $X \to \phi\phi$ is possible, as long as $m_X > 2m_\phi$, with each ϕ boson subsequently decaying to a pair of photon. The analysis covers a wide range of m_X from 0.3 to 3 TeV, with the mass ratio α (defined as $\alpha = m_\phi/m_X$) varying between 0.5% and 2.5%. This results in Lorentz boosts of the ϕ bosons such that the two photons from each ϕ are highly collimated and appear to overlap. For such highly merged photons, the CMS photon reconstruction algorithm is not efficient and hence, a Convolutional Neural Network (CNN) is developed to identify the energy clusters in the electromagnetic calorimeter as coming from two overlapping photons (denoted Γ), hadronic activity, or a single photon. Once the events with two Γ candidates are selected, another CNN is trained to reconstruct the mass of these candidates. The analysis searches for localized excess in the falling background distribution of the paired reconstructed mass ($m_{\Gamma\Gamma}$), in different slices of the reconstructed mass ratio $\alpha_{\text{reco}} = \hat{m_\Gamma}/m_{\Gamma\Gamma}$, where $\hat{m_\Gamma}$ is the average reconstructed mass of the two Γ candidates. To further validate the signal efficiency of classification CNN, a control sample where η meson decays to a diphoton state is utilized and the m_Γ distribution is reconstructed using a CNN. The distribution of m_Γ, shown in Figure 2 (left), clearly differentiates η mesons from the background, highlighting the CNN's strong performance.

The $m_{\Gamma\Gamma}$ distribution from data is fitted across nine different α_{reco} bins ranging from 0.3% to 3% using the envelope method with different functional forms. While no significant deviation from the background is observed, the most prominent excess is found at $m_X \approx 720$ GeV with $\alpha = 0.7\%$ (and $m_\phi \approx 5$ GeV). This excess has a local significance of 3.57 standard deviations and a global significance of 1.07 standard deviations. As a result, 95% CL exclusion upper limits are set on the cross-section $\sigma(X \to \phi\phi \to \gamma\gamma\gamma\gamma)$ in the α-m_X plane and are shown in Figure 2 (right) [8].

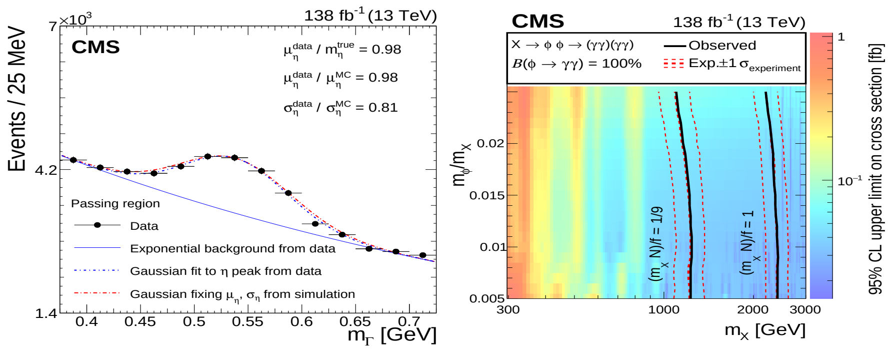

Figure 2: Left: The η meson peak reconstructed over the m_Γ distribution in data. Right: The 95% CL exclusion limits set on $\sigma(X \to \phi\phi \to \gamma\gamma\gamma\gamma$ in the $\alpha-$ m_X plane).

4. Search for resonant and non-resonant $X \to \gamma\gamma$

A search for high mass resonance X decaying to diphoton state is presented, based on several theoretical models that aim to address the hierarchy problem in the SM. The analysis utilizes two distinct background estimation methods. The first method, that is optimal for resonant searches, involves fitting a smoothly falling mass distribution from data. In this approach, the resonant excesses from the Randall-Sundrum (RS) [9] model with one warped extra dimension and heavy spin-0 resonances from extended Higgs sectors [7] are considered. The second method combines next-to-next-to-leading order (NNLO) quantum chromodynamics (QCD) calculations for the SM diphoton background with a fake-rate technique to estimate the contribution from jets misidentified as photons. This method is used for non-resonant searches arising from the Arkani-Hamed, Dimopoulos, and Dvali (ADD) [10] extra-dimensional model and the continuum clockwork (CW) model [11]. The ADD model is parametrized by the variable scale M_S, which represents the ultraviolet cutoff for the virtual graviton exchange process, according to the Giudice–Rattazzi–Wells (GRW) convention [12]. Additionally, alternate conventions such as Hewett [13] and Han–Lykken–Zhang (HLZ) [14] are also considered along with GRW.

For the resonant analysis, the reconstructed $m_{\gamma\gamma}$ distribution is fitted with a parametric function to localize the excess over the smoothly falling background. No statistically significant excess is observed, and thus the 95% CL upper cross-section limits are derived and presented as a function of RS graviton mass m_G (left) and heavy Higgs boson mass m_s (middle) in Figure 3 [15]. The largest excess over SM expectation is observed at 1.3 TeV for the resonance signal of width $\Gamma_X/m_X = 5.6 \times 10^{-2}$, where Γ_X is the natural width of the resonance, and m_X is the resonance mass.

In the case of non-resonant search, no event is observed beyond $m_{\gamma\gamma} > 3$ TeV. The 95% CL upper cross-section limits are set on the signal strength. They are translated into lower limits on the mass scale M_S for different conventions as reported in Table 1, and are found between 7.1 to 11.1 TeV depending on the convention. The exclusion limits on the clockwork model are set in the k-M_5 plane, as shown in Figure 3 (right), where values of M_5 lower than 8.0 TeV are excluded for k values in the range of 0.2 GeV to 2.0 TeV [15].

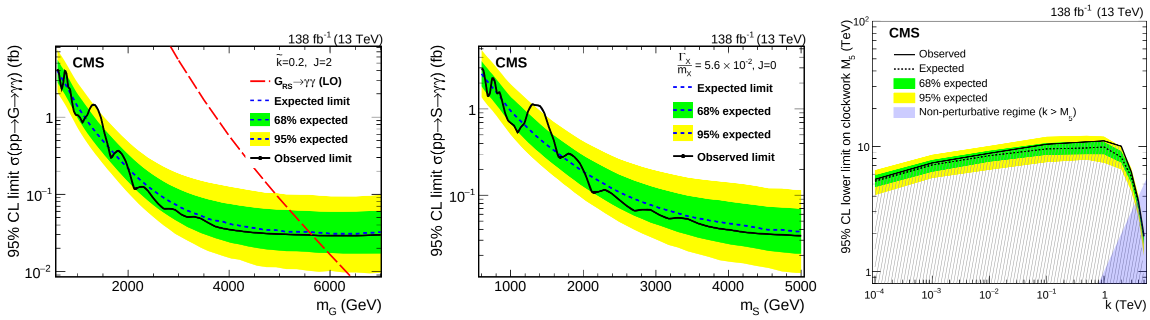

Figure 3: Expected and observed 95% CL upper limits on the product of the production cross section and branching fraction as a function of the RS graviton mass m_G (left), heavy Higgs boson mass m_S (middle) and for the clockwork model over the k–M_5 parameter space (right). The dotted red line in the left plot represents the leading order theoretical cross-section of the RS graviton.

5. Search for $\tau^\star \to \tau\gamma$ resonances

This analysis presents the search for an excited state of the heaviest charged lepton, $\tau^\star$, as a test of compositeness models [16]. The analysis targets a tau lepton τ and an excited tau lepton $\tau^\star$ produced via contact interactions, where $\tau^\star$ decay to ground state τ lepton and a photon. Consequently, the final state is characterized by a pair of τ leptons and a photon.

Signal:	GRW	Hewett		HLZ				
		negative	positive	n_{ED}=3	n_{ED}=4	n_{ED}=5	n_{ED}=6	n_{ED}=7
Expected:	$8.7^{+0.7}_{-0.6}$	$7.3^{+0.3}_{-0.3}$	$7.8^{+0.6}_{-0.5}$	$10.3^{+0.8}_{-0.7}$	$8.7^{+0.7}_{-0.6}$	$7.9^{+0.6}_{-0.5}$	$7.3^{+0.6}_{-0.5}$	$6.9^{+0.6}_{-0.5}$
Observed:	9.3	7.1	8.3	11.1	9.3	8.4	7.8	7.4

Table 1: The observed and expected lower limits on M_S in TeV at the 95% CL for different theoretical conventions of the ADD extra dimension model.

The reconstruction of τ lepton is a challenging task since it decays within the volume of the detector and neutrinos carries most of its energy. In this analysis, an approximation is used where the momentum of the undetected neutrinos is assumed to be aligned with the direction of the visible τ decay products. This "collinear approximation" provides the momentum of the initial tau lepton, enabling the precise reconstruction of the $\tau^\star$ mass by adding the contribution from the selected photon. Since, the final state has two τ leptons, there is a two-fold ambiguity for the correct pairing of the photon with a τ to reconstruct the $\tau^\star$ mass. As a solution, a 2-dimensional distribution is made for the mass of two pairs ordered as minimum and maximum mass for each event. This distribution is shown in Figure 4 (left), and the correct combinations lie in the inverted 'L' shape.

The SM processes such as Z boson production, diboson production and $t\bar{t}$ production are the background processes that contribute with real τ leptons. To estimate these backgrounds or those faked by e and μ, MC simulation is used, and for those coming from fake τ (mis-reconstructed jets), a data-driven ABCD method is used. No excess is observed over the SM background expectation and hence the upper limits on cross-section times branching ratio of the model are set as a function of the $\tau^\star$ mass. As shown in Figure 4 (right), for the compositeness scale Λ equal to the $\tau^\star$ mass, the $\tau^\star$ mass below 4700 GeV is excluded [17].

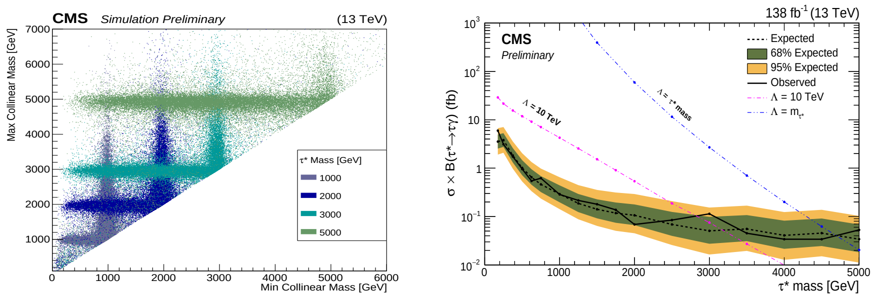

Figure 4: Left: 2-dimensional collinear mass distribution for signal mass points, with a visible inverted L shaped region. Right: Expected and observed upper limit exclusion plots as a function of the $\tau^\star$ mass, produced via a contact interaction. The green and yellow bands respectively, represents the 68% and 95% exclusion region.

References

[1] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004

[2] N. Arkani-Hamed, R. T. D'Agnolo, M. Low and D. Pinner, "Unification and New Particles at the LHC," JHEP **11** (2016), 082, doi:10.1007/JHEP11(2016)082

[3] H. E. Logan and Y. Wu, "Searching for the $W\gamma$ decay of a charged Higgs boson," JHEP **11** (2018), 121, doi:10.1007/JHEP11(2018)121

[4] G. Burdman, Z. Chacko, R. Harnik, L. de Lima and C. B. Verhaaren, "Colorless Top Partners, a 125 GeV Higgs, and the Limits on Naturalness," Phys. Rev. D **91** (2015) no.5, 055007 doi:10.1103/PhysRevD.91.055007

[5] CMS Collaboration, "Search for Wγ resonances in proton-proton collisions at $\sqrt{s}$ = 13 TeV using hadronic decays of Lorentz-boosted W bosons," Phys. Lett. B **826** (2022), 136888 doi:10.1016/j.physletb.2022.136888

[6] CMS Collaboration, "Search for a resonance decaying to a W boson and a photon in proton-proton collisions at $\sqrt{s}$ = 13 TeV using leptonic W boson decays," [arXiv:2406.05737 [hep-ex]].

[7] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, "Theory and phenomenology of two-Higgs-doublet models," Phys. Rept. **516** (2012), 1-102 doi:10.1016/j.physrep.2012.02.002

[8] CMS Collaboration, "Search for new resonances decaying to pairs of merged diphotons in proton-proton collisions at $\sqrt{s}$ = 13 TeV," [arXiv:2405.00834 [hep-ex]].

[9] L. Randall and R. Sundrum, "A Large mass hierarchy from a small extra dimension," Phys. Rev. Lett. **83** (1999), 3370-3373 doi:10.1103/PhysRevLett.83.3370

[10] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, "The Hierarchy problem and new dimensions at a millimeter," Phys. Lett. B **429** (1998), 263-272 doi:10.1016/S0370-2693(98)00466-3

[11] G. F. Giudice and M. McCullough, "A Clockwork Theory," JHEP **02** (2017), 036 doi:10.1007/JHEP02(2017)036

[12] G. F. Giudice, R. Rattazzi and J. D. Wells, "Quantum gravity and extra dimensions at high-energy colliders," Nucl. Phys. B **544** (1999), 3-38 doi:10.1016/S0550-3213(99)00044-9

[13] J. L. Hewett, "Indirect collider signals for extra dimensions," Phys. Rev. Lett. **82** (1999), 4765-4768 doi:10.1103/PhysRevLett.82.4765

[14] T. Han, J. D. Lykken and R. J. Zhang, "On Kaluza-Klein states from large extra dimensions," Phys. Rev. D **59** (1999), 105006 doi:10.1103/PhysRevD.59.105006

[15] CMS Collaboration, "Search for new physics in high-mass diphoton events from proton-proton collisions at $\sqrt{\mathrm{s}}$ = 13 TeV," JHEP **08**, 215 (2024) doi:10.1007/JHEP08(2024)215

[16] H. Harari, "Composite Models for Quarks and Leptons," Phys. Rept. **104** (1984), 159 doi:10.1016/0370-1573(84)90207-2

[17] CMS Collaboration, "Search for excited tau leptons in the $\tau\tau\gamma$ final state in pp collisions at $\sqrt{s}$ = 13 TeV," CMS-PAS-EXO-22-007.