PROCEEDINGS OF SCIENCE

Measurements of photon-induced processes with the CMS detector

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Recent studies of photon-induced processes in ultraperipheral Pb–Pb and proton–proton collisions with the CMS detector play an important role in testing the Standard Model and probing potential new physics. The analysis of $\gamma\gamma \to \tau^+\tau^-$ production enables CMS to set the most stringent limits to date on the anomalous magnetic moment of the τ lepton. Using the $\gamma\gamma \to W^+W^-$ process, CMS has obtained stringent limits on anomalous quartic gauge couplings.

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1. Introduction

The analysis of photon-induced processes offers a unique window to a wide range of physical phenomena. The production of lepton pairs via photon-photon fusion draws significant interest since it is a pure quantum electrodynamics (QED) process at leading order. The photon-fusion channel has long been proposed to probe the $\gamma - \tau$ coupling at colliders, because the short τ lepton lifetime makes other measurements difficult. The anomalous magnetic moment of the electron (a_e) has been measured to agree with the Standard Model (SM) with an impressive precision of twelve significant digits, while the measurement of a_μ reaches a precision of ten significant digits. If Beyond-the-SM (BSM) effects scale with the squared lepton mass, the deviation of a_τ would be more than two orders of magnitude larger than that for a_μ.

In the SM, the photon fusion production of a pair of W bosons proceeds through interactions that involve trilinear and quartic gauge boson couplings. The measurement of this process can be used to constrain dimension-8 effective field theory (EFT) operators related to anomalous quartic gauge boson interactions.

The CMS apparatus is a multipurpose, nearly hermetic detector, designed to trigger on and identify electrons, muons, photons, and (charged and neutral) hadrons. The results presented here are based on Pb-Pb collision data and proton-proton collision data collected in Run 2 period, corresponding to integrated luminosities of 1.70 nb^{-1}[1] and 138 fb^{-1}[2, 3], respectively.

2. $\gamma\gamma \to \tau^+\tau^-$ and τ anomalous magnetic moments constrains

The most general form of photon-lepton coupling ($ie\Gamma^\mu$) satisfying Lorentz invariance is:

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu}}{2m}[iF_2(q^2) + F_3(q^2)\gamma_5],$$

where $\sigma^{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$ is the spin tensor proportional to the commutator of the gamma matrices, q is the momentum transfer between incoming and outgoing leptons of mass m, and $F_i(q^2)$ (i=1,2,3) are form factors that contain the complete information about the electric and magnetic couplings of the lepton. Beyond serving as a sensitive test of QED interactions, the photon-photon production process also offers insights into the anomalous electromagnetic moments of the lepton ($l = e, \mu, \tau$),$F_2(0) = a_l \equiv (g_l - 2)/2$ and $F_3(0) = -2md_l/e$, and is a powerful probe of BSM physics. In this expression, the gyromagnetic ratio g_l is a constant term that relates the magnetic moment of the lepton to its spin, and d_l is the lepton anomalous electric dipole moment[2]. The one-loop contribution to a_l is equal to the so-called 'Schwinger term', which is common to all leptons:

$$a_l = \frac{\alpha}{2\pi} \simeq 0.00116,$$

where α is the fine-structure constant.

The photon-fusion production of a pair of τ leptons probes the $\tau\tau\gamma$ vertex and can be used to measure a_τ, which is predicted to be $a_\tau = 1.17721 \pm 0.00005 \times 10^{-3}$ in the SM. This same process can also be studied to constrain d_τ, which is predicted to have a nonzero but tiny value.

2.1 $\gamma\gamma \to \tau^+\tau^-$ in Pb-Pb collisions at $\sqrt{s}$ = 5.02 TeV with integrated luminosity of 1.7 nb^{-1}

The measurement of a_τ from photo-produced τ lepton pairs benefits from the factor of Z^4 cross section enhancement in PbPb interactions (Z = 82 for Pb ions) as compared to proton-proton or electron-positron collisions. Photoproduction is prominent in ultraperipheral collisions (UPCs), which occur when the impact parameter of the passing Pb ions is larger than twice their radius. In the $PbPb \to Pb^{(*)}(\gamma\gamma \to \tau^+\tau^-)Pb^{(*)}$ process, quasireal photons ($q^2 \to 0$) emitted by the Pb ions interact via photon-photon fusion, producing a pair of τ leptons with an almost back-to-back topology in the transverse plane. Variations of a_τ in the $\gamma\tau^+\tau^-$ vertices modify both the rate of di-τ production and the kinematics of the τ leptons, and can therefore be used to constrain a_τ.

This analysis includes $\tau^+\tau^-$ decay modes with final states of μ+1prong, μ+3prong, e+3prong, and μ+e, in which "prong" refers to the charged pions in τ lepton decay.

Photoproduction in UPC events is distinguished from nuclear interactions by the low number of measured tracks and no activity above noise level in the forward detectors. Events are selected online by requiring a single muon for the three channels with a muon in the final state and an electron for the e+3prong decay channel. Offline, events are selected to have exactly the number of muons, electrons, and charged pions expected for each decay channel, each having a "high-purity" track, and all within the acceptance of the CMS detector.

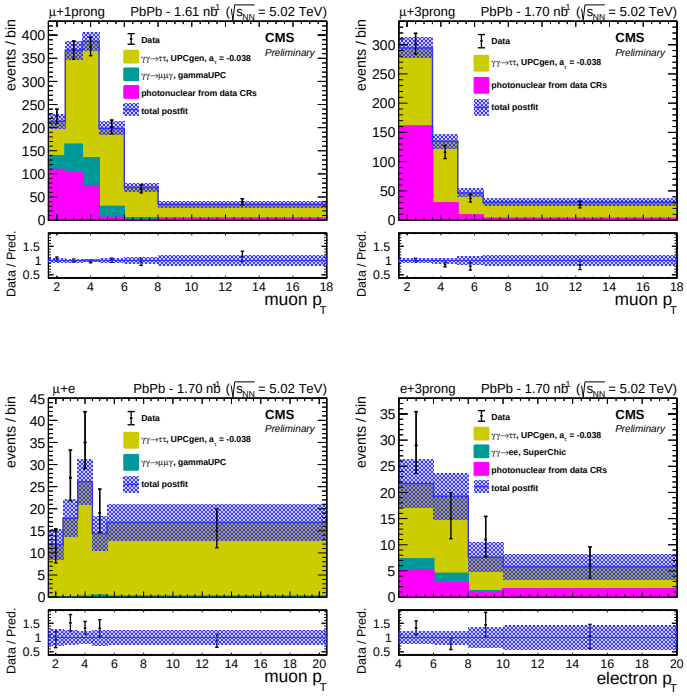

Figure 1: Postfit distributions of lepton p_T for the μ+1prong (upper left), μ+3prong (upper right), μ+e (lower left), and e+3prong (lower right) channels. Signal distributions are stacked on top of the background model, consisting of $\gamma\gamma \to \mu^+\mu^-\gamma$,$\gamma\gamma \to e^+e^-$, and/or the inclusive background predicted by the ABCD method. The stacked distributions are compared with data (black points).

In all distributions, it is observed that the the simulated signal distribution stacked on top of the background model consisting of the data-driven ABCD background, the simulated $\gamma\gamma \to \mu^+\mu^-\gamma$

exclusive background, and/or the $\gamma\gamma \to e^+e^-$ exclusive backgrounds is in agreement with data, as seen in Figure 1 for the lepton p_T distributions, which were determined to provide the most sensitivity to a_τ variations.

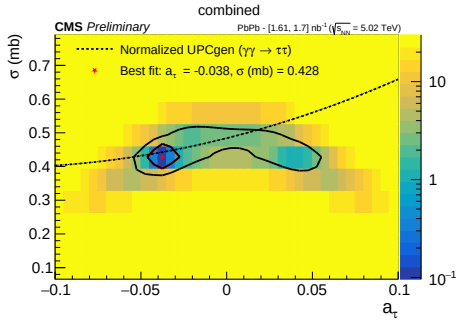

Figure 2: Limits on a_τ, using the sensitivity of both cross section and lepton p_T to a_τ.

The negative log likelihood of the fit of the distribution of the signal plus background to data is calculated in a range of a_τ values and fiducial cross sections as shown in Figure 2, while allowing for the variation of the systematic uncertainties. The fiducial phase space is $\tau p_T < 1$ GeV and $\tau|\eta| < 3$. Black 2D contours mark 1 σ and 2 σ limits on a_τ and the cross section. The measured a_τ is $-35^{+18}_{-10}(\text{stat} + \text{sys}) \times 10^{-3}$.

2.2 $\gamma\gamma \to \tau^+\tau^-$ in pp collisions at $\sqrt{s}$ = 13 TeV with integrated luminosity of 138 fb^-1

The production of a pair of τ leptons via photon-photon fusion, $\gamma\gamma \to \tau^+\tau^-$, is observed for the first time in proton-proton collisions, with a significance of 5.3 standard deviations. Events with a pair of τ leptons produced via photon-photon fusion are selected by requiring them to be back-to-back in the azimuthal direction and to have a minimum number of charged hadrons associated with their production vertex. The τ leptons are reconstructed in their leptonic and hadronic decay modes. Hadronic τ lepton decays (τ_h) are reconstructed from jets, using the hadrons-plus-strips algorithm, which combines 1 or 3 tracks with energy deposits in the calorimeters clustered as strips. The significance of the $\gamma\gamma \to \tau^+\tau^-$ process, as well as the constraints on a_τ and d_τ, are extracted with a binned maximum likelihood fit from the m_{vis} distributions in the four final states ($e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$) and two N_{tracks} bins, $N_{\text{tracks}} = 0$ and $N_{\text{tracks}} = 1$. N_{tracks} is the number of tracks that have a z coordinate with a 0.1 cm wide window centered around the dilepton vertex, removing the tracks that were used to build the lepton candidates. The m_{vis} distributions of the four final states for events with N_{tracks}=0 is shown in Figure 3.

Constraints are set on the contributions to a_τ and d_τ originating from potential effects of new physics on the $\gamma\tau\tau$ vertex: $a_\tau = 0.0009^{+0.0032}_{-0.0031}$ and $|d_\tau| < 2.9 \times 10^{-17} e$cm (95% confidence level), consistent with the SM as shown in Figure 4.

3. $\gamma\gamma \to W^+W^-$ in pp collisions at $\sqrt{s}$ = 13 TeV with integrated luminosity of 138 fb^{-1}

The total cross section of the W^+W^- production in photon fusion is measured using the proton-proton collision data collected with the CMS detector in 2016-2018. The signal in this analysis is

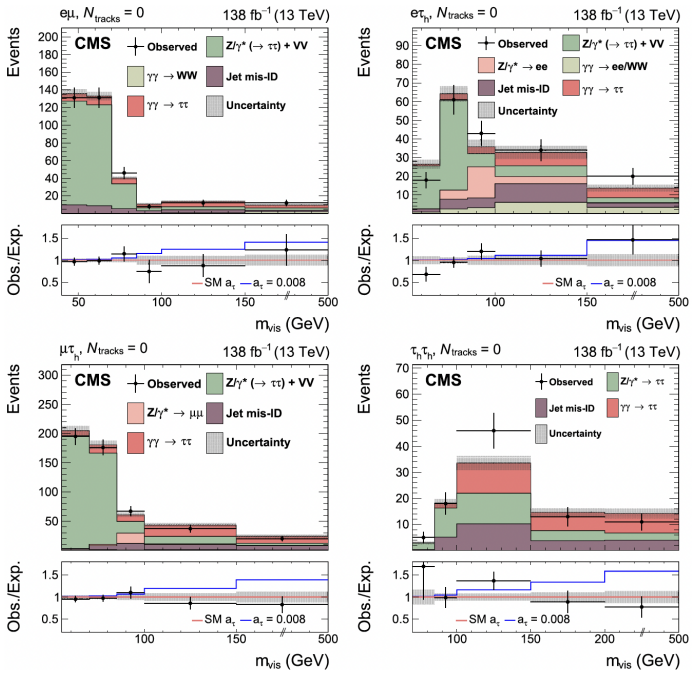

Figure 3: Observed and predicted m_{vis} distributions in the $e\mu$ (upper left), $e\tau_h$ (upper right), $\mu\tau_h$ (lower left), and $\tau_h\tau_h$ (lower right) final states for events with $N_{\text{tracks}} = 0$, the lower panel showing the observed/expected ratio. The observed data and their associated Poissonian statistical uncertainty are shown with black markers with vertical error bars. The predicted background distributions correspond to the result of the global fit. The signal distribution is normalized to its best fit signal strength.

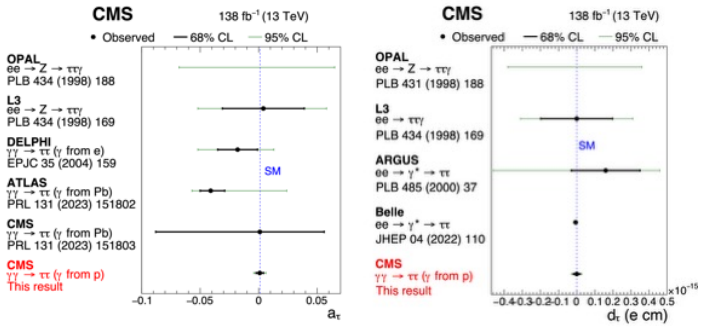

Figure 4: Expected and observed negative log-likelihood as a function of a_τ (left) and d_τ (right), for the combination of all Signal Regions (SR) with the data collected in Run 2 period.

$pp \xrightarrow{\gamma\gamma} p^{(*)}W^+W^-p^{(*)}$, where $p^{(*)}$ denotes a final-state proton that either stays intact or dissociates after the photon emission. Events are selected in the final state with one isolated electron and one isolated muon, and no additional tracks associated with the $e\mu$ production vertex. The N_{tracks} is the track multiplicity of the $e\mu$ vertex, it is calculated considering tracks with $|d_z|$ less than 0.05 cm with respect to the $e\mu$ vertex, $p_T > 0.5$ GeV, and $|\eta| < 2.5$, and discarding the tracks used to build the selected electron and muon candidates. In the SR, N_{tracks} is required to be zero. In the Control Region (CR), N_{tracks} is required to be between 1 and 5, which provides a CR enriched in inclusive backgrounds. An upper requirement of $N_{\text{tracks}} = 5$ is imposed to select events with a

similar topology as the SR and reduce extrapolation biases from the CR to the SR.

The results of the analysis are extracted with a binned maximum likelihood fit of the $p_T^{e\mu}$ distribution in the SR and CR, where $p_T^{e\mu}$ is defined as the magnitude of the vectorial p_T sum of the selected electron and muon. The inclusive and fiducial cross sections of the $\gamma\gamma \to W^+W^-$ process are extracted using the $p_T^{e\mu}$ distributions in the SR and CR shown in Figure 5. The fiducial selections in summarized in Table 1. The inclusive cross section for $\gamma\gamma \to W^+W^-$ is measured to be 659^{+82}_{-78} fb, while the measured fiducial cross section is $\sigma^{fid} = 4.1 \pm 0.5$ fb.

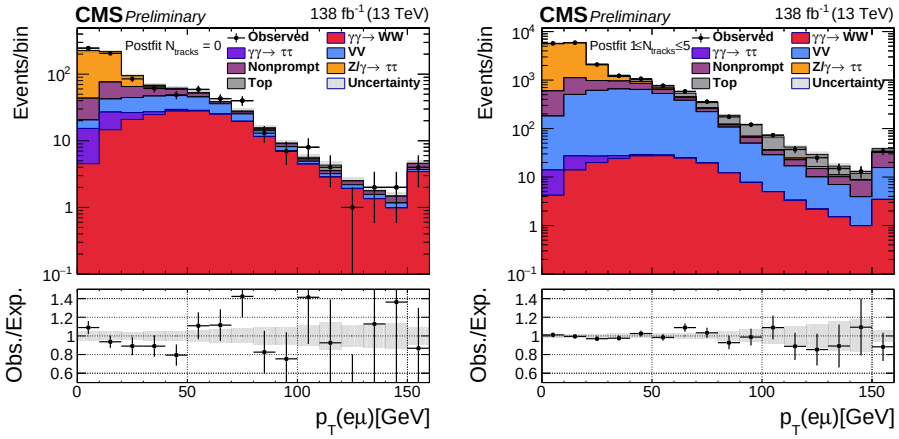

Figure 5: Observed and predicted $p_T^{e\mu}$ distributions for events with $N_{\text{tracks}} = 0$ (SR, left) and $1 \leq N_{\text{tracks}} \leq 5$ (CR, right), using 2016-2018 data. The distributions are shown after the maximum likelihood fit to the data. The last bin includes the overflow. The lower panels show the ratio of data to sum of signal and background contributions.

Table 1: Selection criteria of the fiducial region considered in this analysis. The two p_T values for the electron and muon correspond to the requirements for the leading and subleading leptons.

Requirement
OS $e\mu$ from W boson decays (or from τ decays from W boson decays)
No other stable charged particle with $p_T > 0.5$ GeV and $\lvert\eta\rvert < 2.5$
$1 - \frac{\lvert\Delta\phi_{e\mu}\rvert}{\pi} > 0.015$
$\Delta R > 0.5$
$p_T^e > 15/24$ GeV
$\lvert\eta^e\rvert < 2.5$
$p_T^\mu > 24/15$ GeV
$\lvert\eta^\mu\rvert < 2.4$

The $\gamma\gamma \to W^+W^-$ process is primarily sensitive to anomalous quartic gauge coupling (aQGC) and thus probes various dimension-8 operators with the EFT framework. The selected CP-even operators are bi-quadratic in the Higgs and gauge field strengths (denoted f_M) or quartic in the gauge field strength (denoted f_T). Constraints on a series of operators are competitive with other measurements by the CMS Collaboration in different final states. Figure 6 shows the comparison

of the observed limits on f_M and f_T with those from other measurements. In addition, limits are also set on the CP-odd operators.

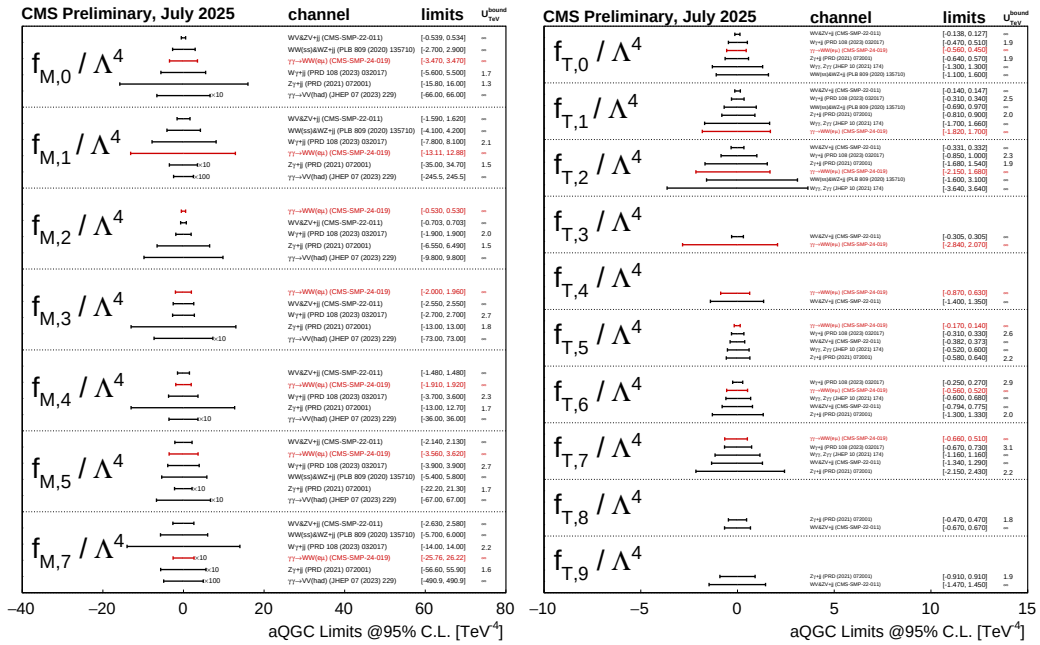

Figure 6: Summary of observed limits on the f_M (left) and f_T (right) Wilson coefficients for this analysis and previous results by the CMS Collaboration. The limits are arranged from most sensitive to least sensitive in descending order, with the current result highlighted in red. In some cases, limits on the Wilson coefficients are shown under the assumption of unitarity bounds, as indicated in the right-most column.

4. Conclusions

The CMS Collaboration has performed comprehensive studies of photon-induced processes in both heavy-ion and proton–proton collisions, achieving several important milestones. In ultraperipheral Pb–Pb collisions, the measurement of $\gamma\gamma \to \tau^+\tau^-$ provides the world-leading constraint on the a_τ. In proton–proton collisions, CMS has achieved the first observation of $\gamma\gamma \to \tau^+\tau^-$ with over 5 σ significance, yielding the most precise limits to date on both the a_τ and d_τ. The first CMS observation of $\gamma\gamma \to W^+W^-$ with more than 5σ significance enables a precise measurement of the inclusive cross section and sets the constraints on aQGC. These results significantly advance the precision frontier of photon-induced processes at the LHC and provide strong sensitivity to potential BSM physics.

References

[1] CMS Collaboration, *Measurement of the tau g-2 factor in ultraperipheral PbPb collisions recorded by the CMS experiment*, CERN, CMS-PAS-HIN-24-011, Geneva (2024). Available at: https://cds.cern.ch/record/2912969.

[2] CMS Collaboration, *Observation of $\gamma\gamma \to \tau\tau$ in proton–proton collisions and limits on the anomalous electromagnetic moments of the τ lepton*, Reports on Progress in Physics **87** (2024) 107801, doi:10.1088/1361-6633/ad6fcb.

[3] CMS Collaboration, *Measurement of the photon-fusion production cross section of a pair of W bosons*, CERN, CMS-PAS-SMP-24-019, Geneva (2025). Available at: https://cds.cern.ch/record/2938216.