Photon photon physics at the LHC

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Contents

- Proton tagging at the LHC
- $\gamma\gamma\gamma\gamma, \gamma\gamma\gamma Z, \gamma\gamma WW, \gamma\gamma ZZ$ anomalous coupling studies
- Search for Axion-like particles
- Possible observation of $WW$ exclusive production
What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?

- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few mm from the beam on both sides of CMS: 2016-2018, \(\sim 115 \text{ fb}^{-1}\) of data collected
- Similar detectors: ATLAS Forward Proton (AFP)
Detecting intact protons in ATLAS/CMS-TOTEM at the LHC

- Tag and measure protons at $\pm 210$ m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs at low luminosity (no pile up) and standard luminosity runs with pile up
Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling

- Study of the process: $pp \to ppWW$, $pp \to ppZZ$, $pp \to pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1 \text{TeV}) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$

Important to consider $W$ loops at high $m_{\gamma\gamma}$

At high masses (> 200 GeV), the photon-induced processes are dominant

**Conclusion:** Two photons and two tagged protons means photon-induced process
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charged particles $\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$ where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle. This leads to $\zeta_1$ of the order of $10^{-14}$-$10^{-13}$
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- $\zeta_1$ can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where $f_s$ is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$
One aside: what is pile up at LHC?

- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events
Search for quartic $\gamma\gamma$ anomalous couplings

- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...
- Anomalous coupling events appear at high di-photon masses
Search for quartic $\gamma \gamma$ anomalous couplings

- No background after cuts for 300 fb$^{-1}$: sensitivity up to a few $10^{-15}$, better by 2 orders of magnitude with respect to “standard” methods.

- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Cut / Process</th>
<th>Signal (full)</th>
<th>Signal with (without) f.f (EFT)</th>
<th>Excl.</th>
<th>DPE</th>
<th>DY, di-jet + pile up</th>
<th>$\gamma \gamma$ + pile up</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015 &lt; $\xi_{1,2}$ &lt; 0.15, $p_{T1,2} &gt; 200, (100)$ GeV</td>
<td>65</td>
<td>18 (187)</td>
<td>0.13</td>
<td>0.2</td>
<td>1.6</td>
<td>2968</td>
</tr>
<tr>
<td>$m_{\gamma \gamma} &gt; 600$ GeV</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
</tr>
<tr>
<td>$p_{T2}/p_{T1} &gt; 0.95$, $</td>
<td>\Delta \phi</td>
<td>&gt; \pi - 0.01$</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
</tr>
<tr>
<td>$\sqrt{\xi_1 \xi_2} = m_{\gamma \gamma}$ ± 3%</td>
<td>61</td>
<td>16 (175)</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
<td>2.8</td>
</tr>
<tr>
<td>$</td>
<td>y_{\gamma \gamma} - y_{pp}</td>
<td>&lt; 0.03$</td>
<td>60</td>
<td>12 (169)</td>
<td>0.09</td>
<td>0</td>
</tr>
</tbody>
</table>

Photon photon physics at the LHC
First search for high mass exclusive $\gamma\gamma$ production

- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9 \times 10^{-13}$ GeV$^{-4}$, $|\zeta_2| < 6.1 \times 10^{-13}$ GeV$^{-4}$ with about 10 fb$^{-1}$, accepted by PRL (2110.05916)
- Limit updates with 102.7 fb$^{-1}$: $|\zeta_1| < 7.3 \times 10^{-14}$ GeV$^{-4}$, $|\zeta_2| < 1.5 \times 10^{-13}$ GeV$^{-4}$
First search for high mass production of axion-like particles

- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb\(^{-1}\) (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)
Search for axion like particles: complementarity with heavy ion runs

- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to $pp$ running
Effective field theory valid if $S \ll 4m^2$, $S$ smaller than the threshold production of real particles

Since the maximum proton missing mass is $\sim 2$ TeV at the 14 TeV LHC, the effective theory needs to be corrected for masses of particles below $\sim 1$ TeV $\rightarrow$ use of form factor which creates an uncertainty on the results (depends on the exact value of form factors)

Solution: compute the full momentum dependence of the 4 photon amplitudes: computed for fermions and bosons

Full amplitude calculation for generic heavy charged fermion/vector contribution

Existence of new heavy charged particles enhances the $\gamma\gamma\gamma\gamma$ couplings in a model independant way

Enhancement parametrised with particle mass and effective charge $Q_{\text{eff}} = QN^{1/4}$ where $N$ is the multiplicity
**Full $\gamma\gamma\gamma$ amplitude calculation**

<table>
<thead>
<tr>
<th>Cut / Process</th>
<th>Signal (full)</th>
<th>Signal with (without) f.f (EFT)</th>
<th>Excl.</th>
<th>DPE</th>
<th>DY, di-jet + pile up</th>
<th>$\gamma\gamma + pile up$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[0.015 &lt; \xi_{1,2} &lt; 0.15,$ $p_{T1,(2)} &gt; 200, (100) GeV]$</td>
<td>130.8</td>
<td>36.9 (373.9)</td>
<td>0.25</td>
<td>0.2</td>
<td>1.6</td>
<td>2968</td>
</tr>
<tr>
<td>$m_{\gamma\gamma} &gt; 600 GeV$</td>
<td>128.3</td>
<td>34.9 (371.6)</td>
<td>0.20</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
</tr>
<tr>
<td>$[p_{T2}/p_{T1} &gt; 0.95,$ $</td>
<td>\Delta\phi</td>
<td>&gt; \pi - 0.01]$</td>
<td>128.3</td>
<td>34.9 (371.4)</td>
<td>0.19</td>
<td>0</td>
</tr>
<tr>
<td>$\sqrt{\xi_1\xi_2s} = m_{\gamma\gamma} \pm 3%$</td>
<td>122.0</td>
<td>32.9 (350.2)</td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td>2.8</td>
</tr>
<tr>
<td>$</td>
<td>y_{\gamma\gamma} - y_{pp}</td>
<td>&lt; 0.03$</td>
<td>119.1</td>
<td>31.8 (338.5)</td>
<td>0.18</td>
<td>0</td>
</tr>
</tbody>
</table>

- No background after cuts for 300 fb$^{-1}$ **without needing timing detector information**
- For signal: 119.1 events for $Q_{eff} = 4$, $m = 340$ GeV
- Results for full calculation lay between the effective field result with/without form factor as expected since effective calculation not valid in the region of $S \sim m^2$
5 σ sensitivity for new charged fermions and vector bosons for 300 fb$^{-1}$ and $\mu = 50$

Unprecedented sensitivities at hadronic colliders. We also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation.

For $Q_{eff} = 4$, we are sensitive to new vectors (fermions) up to 700 (370) GeV for a luminosity of 300 fb$^{-1}$

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>300</th>
<th>600</th>
<th>900</th>
<th>1200</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{eff}$ (vector)</td>
<td>2.2</td>
<td>3.4</td>
<td>4.9</td>
<td>7.2</td>
<td>8.9</td>
</tr>
<tr>
<td>$Q_{eff}$ (fermion)</td>
<td>3.6</td>
<td>5.7</td>
<td>8.6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Look for $Z\gamma$ anomalous production

$Z$ can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidity matching technique allows us to look in both channels (very small background)

Leads to a very good sensitivity to $\gamma\gamma\gamma Z$ couplings

Best expected reach at the LHC by about three orders of magnitude

Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a threshold effect
Exclusive production of $W$ boson pairs

- 2 “fat” jets (radius 0.8), jet $p_T > 200$ GeV, $1126 < m_{jj} < 2500$ GeV, jets back-to-back ($|1 - \phi_{jj}/\pi| < 0.01$)
- Signal region defined by the correlation between central $WW$ system and proton information

Search with fully hadronic decays of $W$ bosons: anomalous production of $WW$ events dominates at high mass with a rather low cross section
**WW and ZZ exclusive productions**

- Searches performed in full hadronic decays of $W$ bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section
  $$\sigma_{WW} < 67 \text{fb}, \quad \sigma_{ZZ} < 43 \text{fb} \quad \text{for} \quad 0.04 < \xi < 0.2 \quad \text{(CMS-PAS-EXO-21-014)}$$
- New limits on quartic anomalous couplings (events violating unitarity removed) :
  $$a^W_0 / \Lambda^2 < 4.3 \times 10^{-6} \text{ GeV}^{-2},$$
  $$a^W_C / \Lambda^2 < 1.6 \times 10^{-5} \text{ GeV}^{-2},$$
  $$a^Z_0 / \Lambda^2 < 0.9 \times 10^{-5} \text{ GeV}^{-2},$$
  $$a^Z_C / \Lambda^2 < 4. \times 10^{-5} \text{ GeV}^{-2} \quad \text{with} \quad 52.9 \text{ fb}^{-1}$$
The future: Observation of exclusive $WW$ production

- SM contribution appears at lower $WW$ masses compared to anomalous couplings
- Use purely leptonic channels for $W$ decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive $WW$ (leptonic decays) after selection: about 50 events for 300 fb$^{-1}$ (2 background)
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.
Search for exclusive $\bar{t}t$ anomalous coupling in leptonic and semi-leptonic decays

High background due to standard non-exclusive $\bar{t}t$ production and protons from pile up

**dilep channel ($\bar{t}t \rightarrow l\nu b + l\nu \bar{b}$)**

<table>
<thead>
<tr>
<th>Object selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons: $p_T &gt; 30(20)$ GeV, $</td>
</tr>
<tr>
<td>Jets: $p_T &gt; 30$ GeV, $</td>
</tr>
</tbody>
</table>

**Semilep channel ($\bar{t}t \rightarrow l\nu b + jj\bar{b}$)**

<table>
<thead>
<tr>
<th>Object selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons: $p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td>Jets: $p_T &gt; 25$ GeV, $</td>
</tr>
</tbody>
</table>

**Event selection**

<table>
<thead>
<tr>
<th>dilep channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 2$ leptons (OS pair), $</td>
</tr>
<tr>
<td>$\geq 2$ b-jets</td>
</tr>
<tr>
<td>1 proton / side</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semilep channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1$ lepton</td>
</tr>
<tr>
<td>$\geq 2$ b-jets, $\geq 2$ non b-jets</td>
</tr>
<tr>
<td>1 proton / side</td>
</tr>
</tbody>
</table>
Exclusive $t\bar{t}$ production

- Kinematic fitter based on $W$ and $t$ mass constraints to reduce background

- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes
  - $\sigma_{t\bar{t}}^{\text{excl.}} < 0.59$ pb (CMS-PAS-TOP-21-007)
Additional method to remove pile up: Measuring proton time-of-flight

- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon.
- Typical precision: 10 ps means 2.1 mm
- Idea: use diamond, quartz bar, ultra-fast Si Low Gain Avalanche Detectors (signal duration of ~few ns and possibility to use fast sampling to reconstruct full signal)
Exclusive $t\bar{t}$ production: the future

- Search for $\gamma\gamma t\bar{t}$ anomalous coupling in semi-leptonic decays with $300 \text{ fb}^{-1}$
- Use similar selection: high $t\bar{t}$ mass, matching between $pp$ and $t\bar{t}$ information
- Use fast timing detectors to suppress further the pile up background
- C. Baldenegro, A. Bellora, S. Fichet, G. von Gersdorff, M. Pitt, CR, JHEP 08 (2022) 021

<table>
<thead>
<tr>
<th>Coupling $[10^{-11} \text{ GeV}^{-4}]$</th>
<th>95% CL</th>
<th>$5\sigma$</th>
<th>95% CL (60 ps)</th>
<th>$5\sigma$ (60 ps)</th>
<th>95% CL (20 ps)</th>
<th>$5\sigma$ (20 ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\zeta_1$</td>
<td>1.5</td>
<td>2.5</td>
<td>1.1</td>
<td>1.9</td>
<td>0.74</td>
<td>1.5</td>
</tr>
<tr>
<td>$\zeta_2$</td>
<td>1.4</td>
<td>2.4</td>
<td>1.0</td>
<td>1.7</td>
<td>0.70</td>
<td>1.4</td>
</tr>
<tr>
<td>$\zeta_3$</td>
<td>1.4</td>
<td>2.4</td>
<td>1.0</td>
<td>1.7</td>
<td>0.70</td>
<td>1.4</td>
</tr>
<tr>
<td>$\zeta_4$</td>
<td>1.5</td>
<td>2.5</td>
<td>1.0</td>
<td>1.8</td>
<td>0.73</td>
<td>1.4</td>
</tr>
<tr>
<td>$\zeta_5$</td>
<td>1.2</td>
<td>2.0</td>
<td>0.84</td>
<td>1.5</td>
<td>0.60</td>
<td>1.2</td>
</tr>
<tr>
<td>$\zeta_6$</td>
<td>1.3</td>
<td>2.2</td>
<td>0.92</td>
<td>1.6</td>
<td>0.66</td>
<td>1.3</td>
</tr>
</tbody>
</table>
LHC can be seen as a $\gamma\gamma$ collider!

$\gamma\gamma\gamma\gamma, \gamma\gamma ZZ, \gamma\gamma WW, \gamma\gamma\gamma Z$ anomalous coupling studies and SM observation

- Exclusive process: **photon-induced processes** $pp \rightarrow p\gamma\gamma p$ (gluon exchanges suppressed at high masses)
- Theoretical calculation in better control (QED processes with intact protons), not sensitive to the photon structure function
- **“Background-free” experiment** and any observed event is signal
- NB: Survival probability in better control than in the QCD (gluon) case

CT-PPS/AFP allow to probe BSM diphoton production in a model independent way

Sensitivity to ALPs: Improvement by more than one order of magnitude

Complementarity between $pp$, $pA$, $AA$ runs