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- Proton tagging at the LHC
- $\gamma\gamma\gamma, \gamma\gamma Z, \gamma\gamma WW, \gamma\gamma ZZ$ anomalous coupling studies
- Search for Axion-like particles
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, first data taking (∼ 15 fb⁻¹)
- 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: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1$ 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 $\zeta_1 \sim 10^{-13}$
Warped Extra Dimensions solve hierarchy problem of SM

× 5th dimension bounded by two branes

× SM on the visible (or TeV) brane

× The Kaluza Klein modes of the graviton couple with TeV strength

\[ \mathcal{L}_{\gamma\gamma h} = f^{-2} h_{\mu\nu}^{KK} (\frac{1}{4} \eta_{\mu\nu} F_{\rho\alpha}^2 - F_{\mu\rho} F_{\rho\nu}) \]

\[ f \sim \text{TeV} \quad m_{KK} \sim \text{few TeV} \]

× Effective 4-photon couplings \( \zeta_i \sim 10^{-14} - 10^{-13} \text{ GeV}^{-2} \) possible

× The radion can produce similar effective couplings

- Which models/theories are we sensitive to using AFP/CT-PPS
- Beyond standard models predict anomalous couplings of \( \sim 10^{-14} - 10^{-13} \)
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.

**Anomalous coupling studies with proton tagging at the LHC**

<table>
<thead>
<tr>
<th>Cut / Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
</tr>
<tr>
<td>$m_{\gamma\gamma} &gt; 600$ GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$\sqrt{\xi_1\xi_2} = m_{\gamma\gamma} \pm 3%$</td>
</tr>
<tr>
<td>$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<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>65</td>
<td>18 (187)</td>
<td>0.13</td>
<td>0.2</td>
<td>1.6</td>
<td>2968</td>
</tr>
<tr>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
</tr>
<tr>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>80.2</td>
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<tr>
<td>61</td>
<td>16 (175)</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>60</td>
<td>12 (169)</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Search for axion like particles

- Production of ALPs via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC ($Z$ decays into 3 photons): sensitivity at high ALP mass, C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835, JHEP 1806 (2018) 131

- Complementarity with Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by $Z^4$
Search for axion like particles: complementarity with heavy ion runs

- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to \( pp \) running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by \( Z^4 \), C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for \( \gamma\gamma Z \) couplings in \( pp \) collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142
- 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)

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
Anomalous couplings studies in $WW$ events

- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile-up effects; only leptonic decays of $W$s are considered.
- Signal appears at high lepton $p_T$ and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors).
- Cut on the number of tracks fitted to the primary vertex: very efficient to remove remaining pile-up after requesting a high mass object to be produced (for signal, we have two leptons coming from the $W$ decays and nothing else).

![Graphs showing event distribution and track number](image)

Anomalous coupling studies with proton tagging at the LHC
Effective anomalous couplings correspond to loops of charged particles, Reaches the values expected for extradim models (C. Grojean, J. Wells)

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Top</th>
<th>Dibosons</th>
<th>Drell-Yan</th>
<th>W/Z+jet</th>
<th>Diff.</th>
<th>$\alpha_W^+/\Lambda^2 = 5 \cdot 10^{-6}$ GeV$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>timing &lt; 10 ps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{lep1} &gt; 150$ GeV</td>
<td>5198</td>
<td>601</td>
<td>20093</td>
<td>1820</td>
<td>190</td>
<td>282</td>
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<tr>
<td>$p_T^{lep2} &gt; 20$ GeV</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M(ll)&gt;300$ GeV</td>
<td>1650</td>
<td>176</td>
<td>2512</td>
<td>7.7</td>
<td>176</td>
<td>248</td>
</tr>
<tr>
<td>nTracks $\leq$ 3</td>
<td>2.8</td>
<td>2.1</td>
<td>78</td>
<td>0</td>
<td>51</td>
<td>71</td>
</tr>
<tr>
<td>$\Delta \phi &lt; 3.1$</td>
<td>2.5</td>
<td>1.7</td>
<td>29</td>
<td>0</td>
<td>2.5</td>
<td>56</td>
</tr>
<tr>
<td>$m_V &gt; 800$ GeV</td>
<td>0.6</td>
<td>0.4</td>
<td>7.3</td>
<td>0</td>
<td>1.1</td>
<td>50</td>
</tr>
<tr>
<td>$p_T^{lep1} &gt; 300$ GeV</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>35</td>
</tr>
</tbody>
</table>

**Table 9.5.** Number of expected signal and background events for 300 fb$^{-1}$ at pile-up $\mu = 46$. A time resolution of 10 ps has been assumed for background rejection. The diffractive background comprises production of QED diboson, QED dilepton, diffractive WW, double pomeron exchange WW.

Improvement of “standard” LHC methods by studying $pp \rightarrow l^{\pm} \nu \gamma \gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb$^{-1}$ at LHC (Reach up to $1.3 \cdot 10^{-6}$)
LHC can be seen as a $\gamma\gamma$ collider!

$\gamma\gamma\gamma$, $\gamma\gamma ZZ$, $\gamma\gamma WW$, $\gamma\gamma\gamma Z$ anomalous coupling studies

- 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 allows to probe BSM diphoton production in a model independent way: sensitivities to values predicted by extradim or composite Higgs models

- Sensitivity to ALPs: Improvement by more than one order of magnitude
- Complementarity between $pp$, $pA$, $AA$ runs
We need to look everywhere! For instance using intact protons...