

Anomalous coupling studies with forward protons at the LHC

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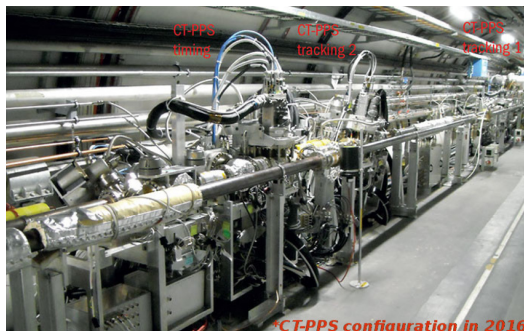
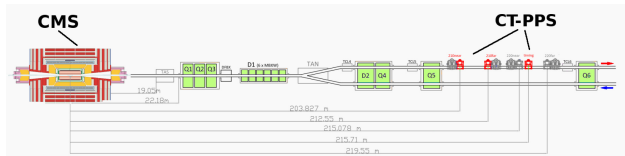


April 9, 2021

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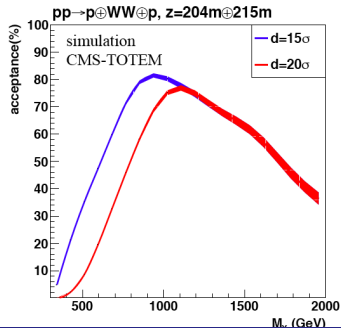
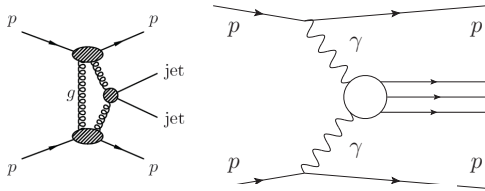
- Proton tagging at the LHC
- Possible observation of WW exclusive production
- $\gamma\gamma\gamma\gamma$, $\gamma\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$ anomalous coupling studies
- Search for Axion-like particles

What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?



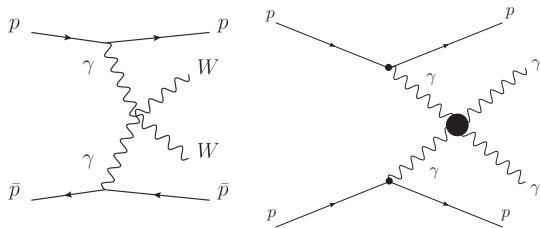
- Joint CMS and TOTEM project: <https://cds.cern.ch/record/1753795>
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim 115 \text{ fb}^{-1}$ of data collected
- Similar detectors: ATLAS Forward Proton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

Detecting intact protons in ATLAS/CMS-TOTEM at the LHC



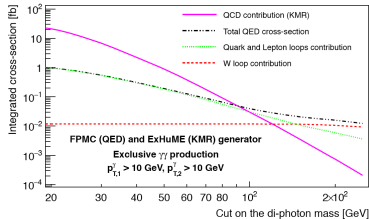
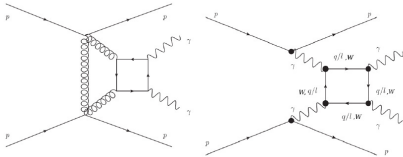
- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs 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



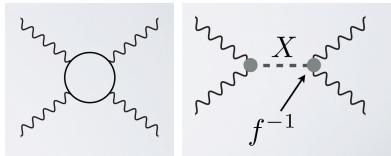
- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6 \text{ fb}$, $\sigma_{WW}(W = M_X > 1 \text{ TeV}) = 5.9 \text{ fb}$
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich $\gamma\gamma$ physics at LHC: see papers by C. Baldenegro, S. Fichet, M. Saimpert, G. Von Gersdorff, E. Chapon, O. Kepka, CR... Phys.Rev. D89 (2014) 114004 ; JHEP 1502 (2015) 165; Phys. Rev. Lett. 116 (2016) no 23, 231801; JHEP 1706 (2017) 142; JHEP 1806 (2018) 131

$\gamma\gamma$ exclusive production: SM contribution



- 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

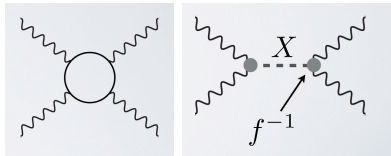


- Two effective operators at low energies

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

- $\gamma\gamma\gamma\gamma$ 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 ζ_1 of the order of 10^{-14} - 10^{-13}

Motivations to look for quartic $\gamma\gamma$ anomalous couplings



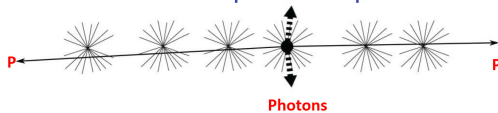
- Two effective operators at low energies

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

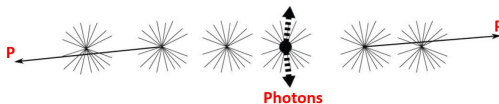
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on 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?

A collision with 2 protons and 2 photons

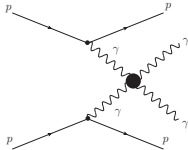


can be faked by one collision with 2 photons and protons from different collisions

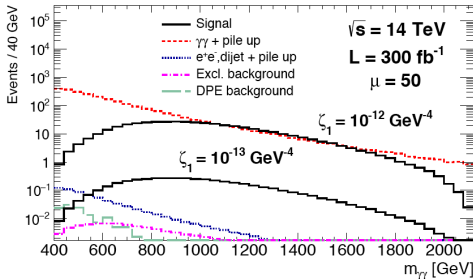


- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

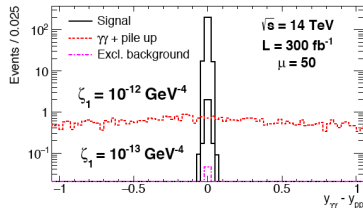
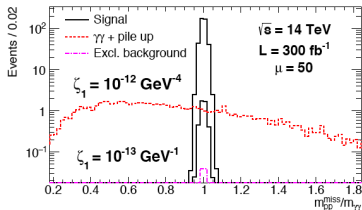
Search for quartic $\gamma\gamma$ anomalous couplings



- 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
- S. Fichet, G. von Gersdorff, B. Lenzi, C.R., M. Saimpert, JHEP 1502 (2015) 165



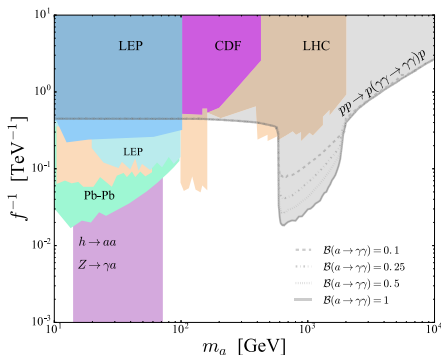
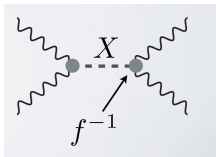
Search for quartic $\gamma\gamma$ anomalous couplings



Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100) \text{ GeV}]$	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $ \Delta\phi > \pi - 0.01]$	64	17 (186)	0.10	0	0	80.2
$\sqrt{\xi_1 \xi_2 s} = m_{\gamma\gamma} \pm 3\%$	61	16 (175)	0.09	0	0	2.8
$ y_{\gamma\gamma} - y_{pp} < 0.03$	60	12 (169)	0.09	0	0	0

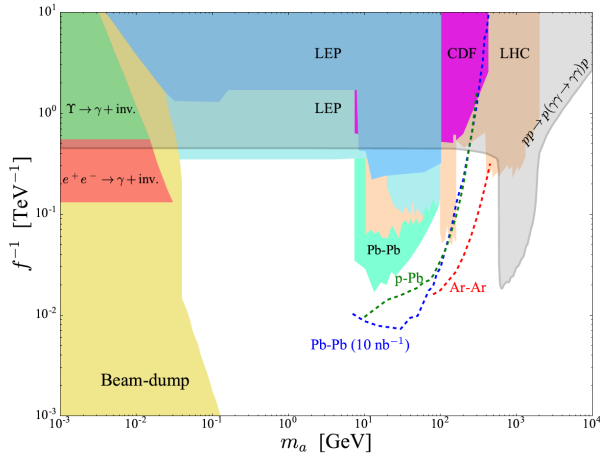
- No background after cuts for 300 fb^{-1} : sensitivity up to a few 10^{-15} , better by 2 orders of magnitude with respect to “standard” methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

Search for axion like particles



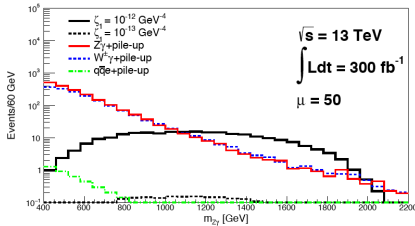
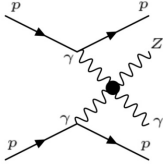
- Production of ALPs via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC (Z decays into 3 photons): sensitivity at high ALP mass, C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835, JHEP 1806 (2018) 131
- Complementarity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



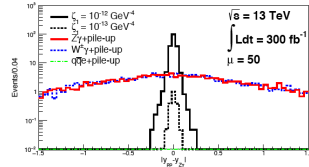
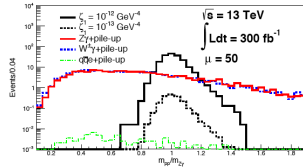
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to pp running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4 , C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for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

$\gamma\gamma\gamma Z$ quartic anomalous coupling



- 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

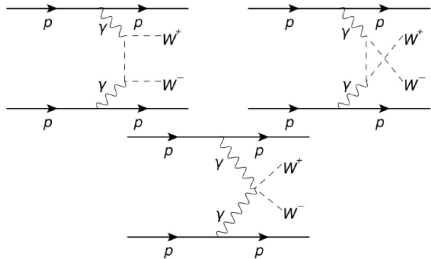
$\gamma\gamma\gamma Z$ quartic anomalous coupling



Coupling (GeV^{-4})	ζ ($\tilde{\zeta} = 0$)		$\zeta = \tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5σ	95% CL	5σ	95% CL
$\ell\ell\gamma$	$2.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
$jj\gamma$	$2.3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$2 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
$jj\gamma \oplus \ell\ell\gamma$	$1.93 \cdot 10^{-13}$	$1.2 \cdot 10^{-13}$	$1.7 \cdot 10^{-13}$	$1 \cdot 10^{-13}$

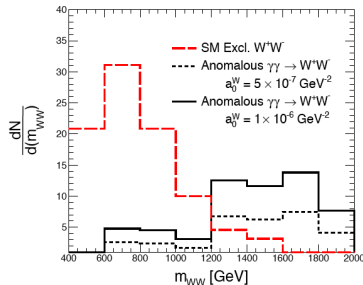
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a threshold effect

SM observation and anomalous couplings studies in WW events

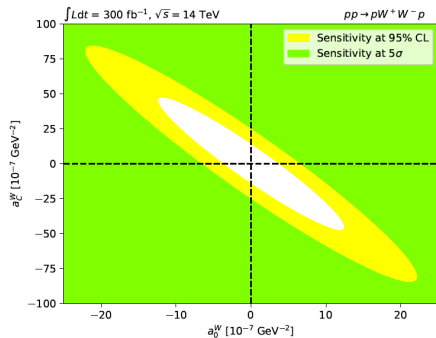


- Possible observation of WW exclusive production at high mass: study all decay channels, 2 “fat” jets, 1 lepton + 1 “fat” jet, 2 leptons

- SM prediction on exclusive WW (leptonic decays) after selection: about 50 events for 300 fb^{-1} (2 background)
- 1st possible observation at high mass
- Anomalous coupling: Use hadronic channels



Anomalous couplings studies in WW events



- For an anomalous coupling of 10^{-6} GeV^{-2} , we expect about 110 events for a background of 87 due to pile up events
- Sensitivity down to $3.7 \cdot 10^{-7} \text{ GeV}^{-2}$ (present limits using exclusive production of WW at medium luminosity (low pile up) without proton tagging led to limits of $\sim 10^{-4} \text{ GeV}^{-2}$)
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.

Conclusion

- 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 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...

