

# Anomalous coupling studies with intact protons at the LHC

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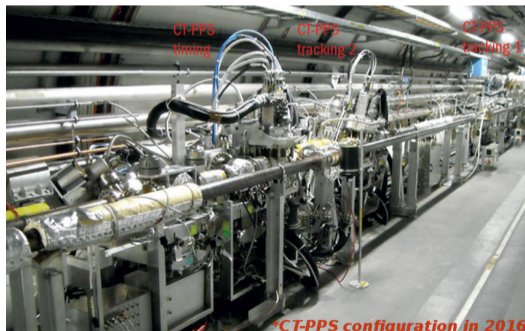
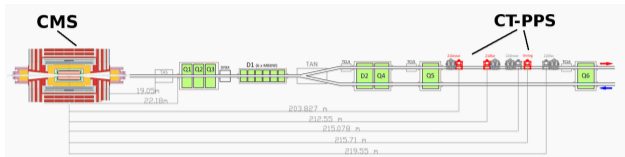


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## Contents

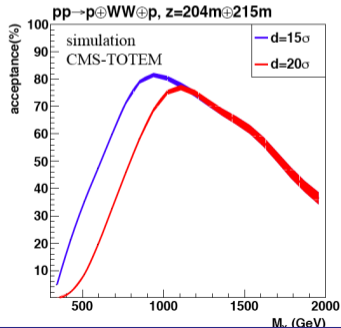
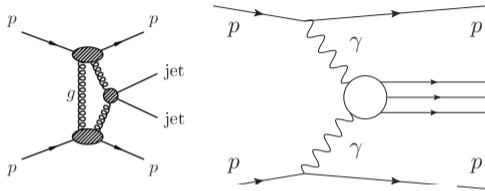
- Proton tagging at the LHC
- Possible observation of  $WW$  exclusive production
- $\gamma\gamma\gamma$ ,  $\gamma\gamma Z$ ,  $\gamma WW$ ,  $\gamma ZZ$  anomalous coupling studies
- Search for Axion-like particles

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



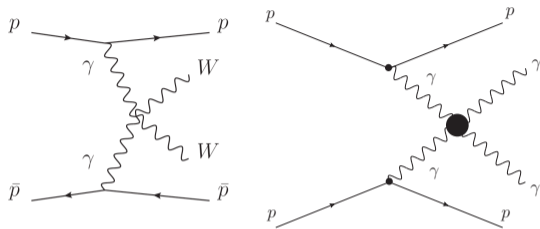
- Joint CMS and TOTEM project: <https://cds.cern.ch/record/1753795>
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018,  $\sim 115 \text{ fb}^{-1}$  of data collected
- Similar detectors: ATLAS Forward Proton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

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



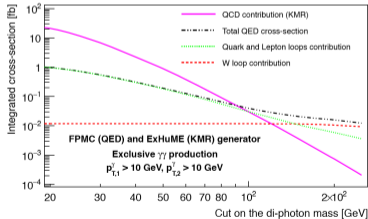
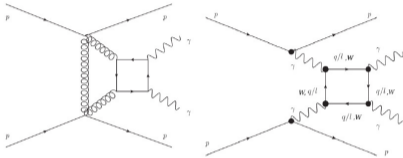
- Tag and measure protons at  $\pm 210$  m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special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



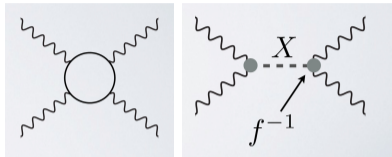
- Study of the process:  $pp \rightarrow ppWW$ ,  $pp \rightarrow ppZZ$ ,  $pp \rightarrow pp\gamma\gamma$
- Standard Model:  $\sigma_{WW} = 95.6 \text{ fb}$ ,  $\sigma_{WW}(W = M_X > 1 \text{ TeV}) = 5.9 \text{ fb}$
- Process sensitive to anomalous couplings:  $\gamma\gamma WW$ ,  $\gamma\gamma ZZ$ ,  $\gamma\gamma\gamma\gamma$ ; 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 ( $> 200 \text{ GeV}$ ), 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

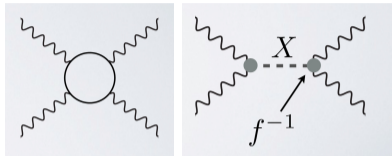


- Two effective operators at low energies

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

- $\gamma\gamma\gamma\gamma$  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

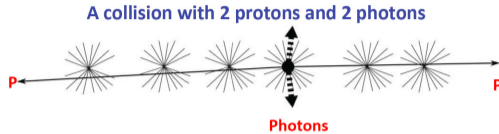


- Two effective operators at low energies

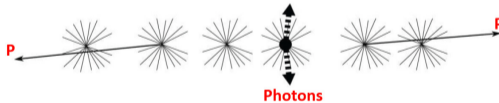
$$\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- $\zeta_1$  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?



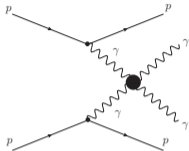
can be faked by one collision with 2 photons and protons from different collisions



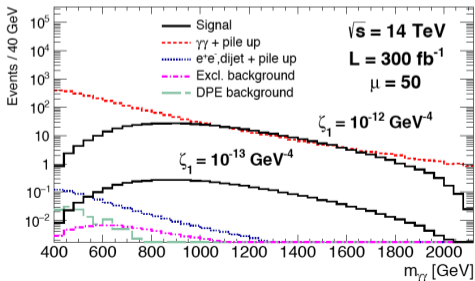
- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events



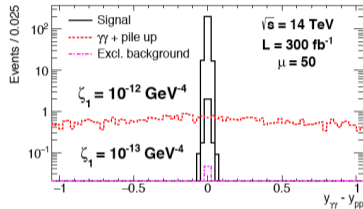
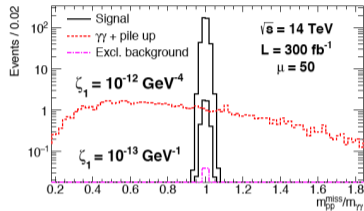
# Search for quartic $\gamma\gamma$ anomalous couplings



- 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



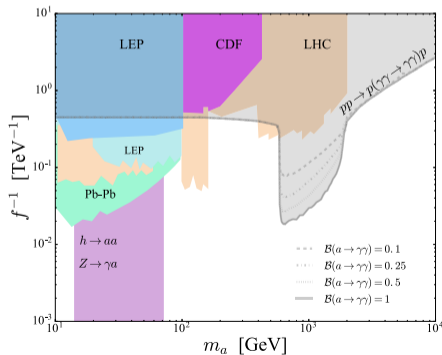
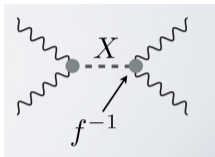
# Search for quartic $\gamma\gamma$ anomalous couplings



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

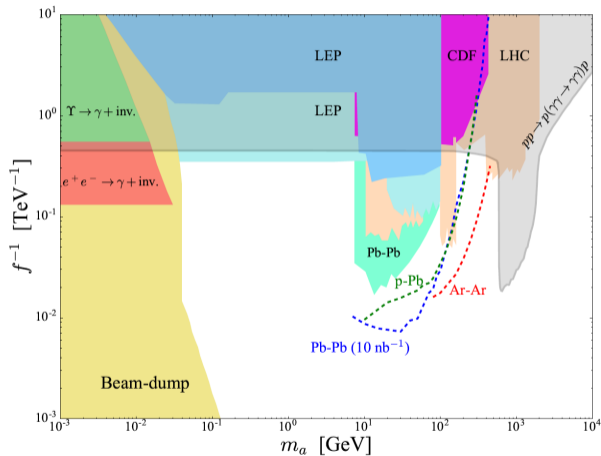
- No background after cuts for  $300 \text{ fb}^{-1}$ : sensitivity up to a few  $10^{-15}$ , better by 2 orders of magnitude with respect to “standard” methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for  $300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

# Search for axion like particles



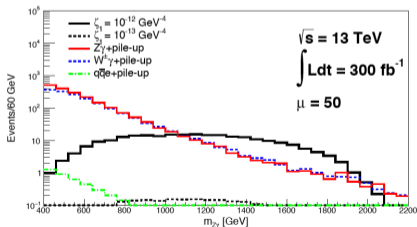
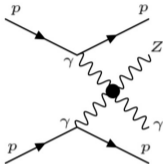
- Production of ALPs via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC ( $Z$  decays into 3 photons): sensitivity at high ALP mass, C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835, JHEP 1806 (2018) 131
- Complementarity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



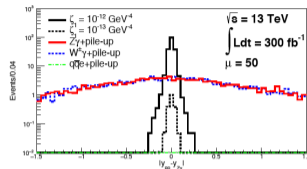
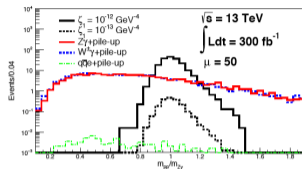
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to  $pp$  running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by  $Z^4$ , C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity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

# $\gamma\gamma Z$ 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  $\gamma\gamma Z$  couplings

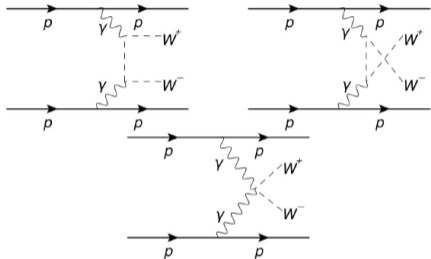
# $\gamma\gamma Z$ quartic anomalous coupling



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

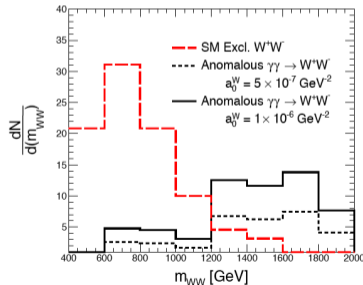
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a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

# SM observation and anomalous couplings studies in $WW$ events

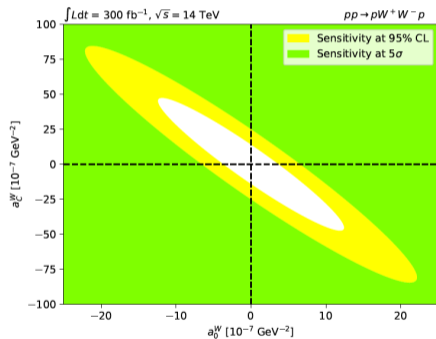


- Possible observation of  $WW$  exclusive production at high mass: study all decay channels, 2 “fat” jets, 1 lepton + 1 “fat” jet, 2 leptons

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



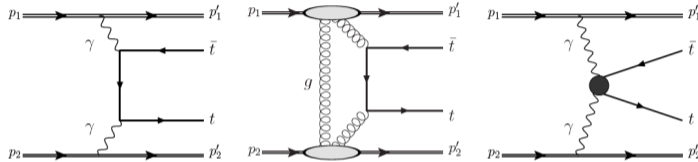
# Anomalous couplings studies in $WW$ events



- For an anomalous coupling of  $10^{-6} \text{ GeV}^{-2}$ , 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.



# Exclusive $t\bar{t}$ production



- Search for  $\gamma\gamma t\bar{t}$  anomalous coupling in leptonic and semi-leptonic decays (the QCD diagram in the middle does not contribute)
- High background due to standard non exclusive  $t\bar{t}$  production and protons from pile up
- C. Baldenegro, A. Bellora, S. Fichet, G. von Gersdorff, M. Pitt, CR arXiv:2205.01173

# Exclusive $t\bar{t}$ production

- 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 arXiv:2205.01173

Coupling [ $10^{-11} \text{ GeV}^{-4}$ ]	95% CL	$5\sigma$	95% CL (60 ps)	$5\sigma$ (60 ps)	95% CL (20 ps)	$5\sigma$ (20 ps)
$\zeta_1$	1.5	2.5	1.1	1.9	0.74	1.5
$\zeta_2$	1.4	2.4	1.0	1.7	0.70	1.4
$\zeta_3$	1.4	2.4	1.0	1.7	0.70	1.4
$\zeta_4$	1.5	2.5	1.0	1.8	0.73	1.4
$\zeta_5$	1.2	2.0	0.84	1.5	0.60	1.2
$\zeta_6$	1.3	2.2	0.92	1.6	0.66	1.3

# Conclusion

- LHC can be seen as a  $\gamma\gamma$  collider!
- $\gamma\gamma\gamma$ ,  $\gamma\gamma ZZ$ ,  $\gamma\gamma WW$ ,  $\gamma\gamma Z$  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

