

Photon photon physics at the LHC

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EMMI workshop on saturation

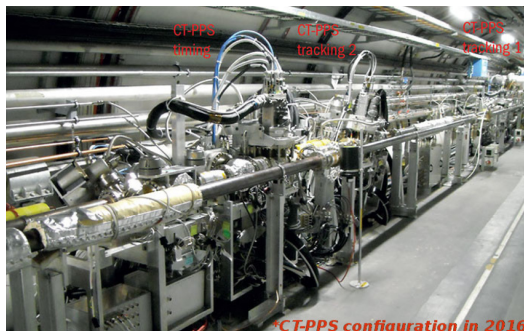
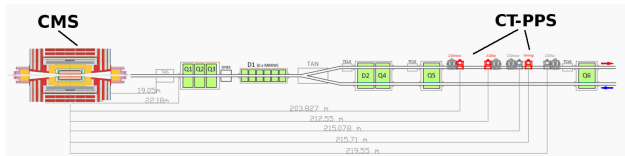


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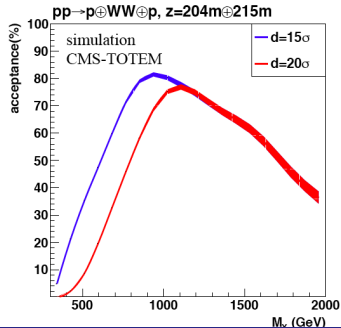
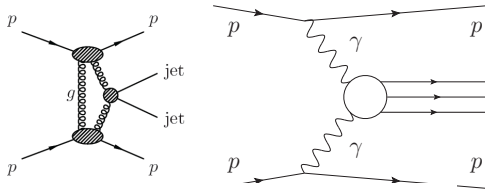
- Proton tagging at the LHC
- $\gamma\gamma\gamma\gamma$, $\gamma\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$ anomalous coupling studies
- Search for Axion-like particles
- Possible observation of WW exclusive production

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



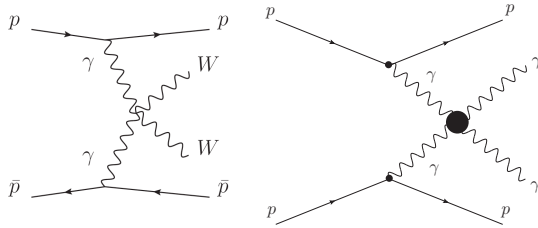
- Joint CMS and TOTEM project: <https://cds.cern.ch/record/1753795>
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim 115 \text{ fb}^{-1}$ of data collected
- Similar detectors: ATLAS Forward Proton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

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



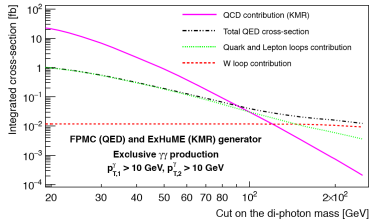
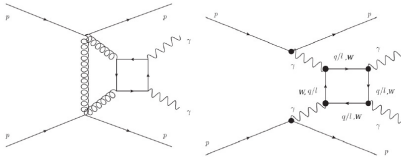
- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs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



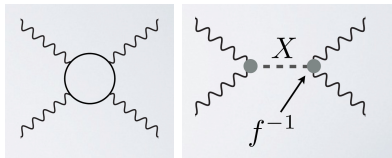
- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6 \text{ fb}$, $\sigma_{WW}(W = M_X > 1 \text{ TeV}) = 5.9 \text{ fb}$
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$;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

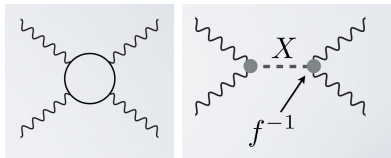


- Two effective operators at low energies

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

- $\gamma\gamma\gamma\gamma$ 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

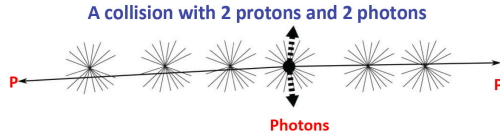


- Two effective operators at low energies

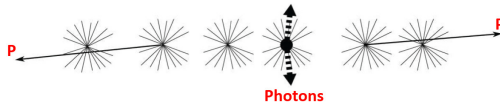
$$\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- 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?

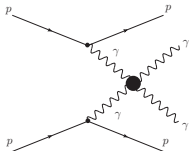


can be faked by one collision with 2 photons and protons from different collisions

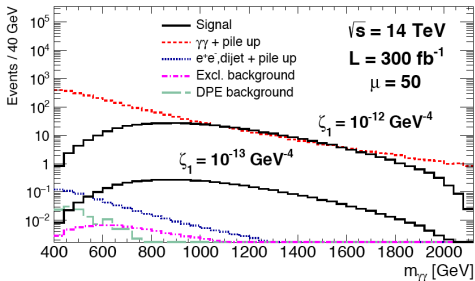


- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

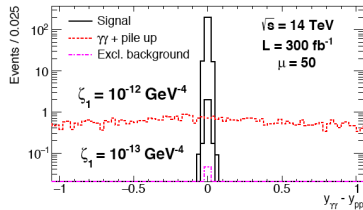
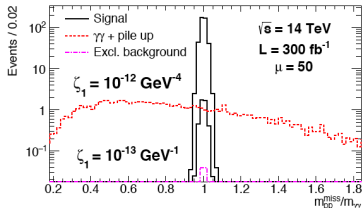
Search for quartic $\gamma\gamma$ anomalous couplings



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



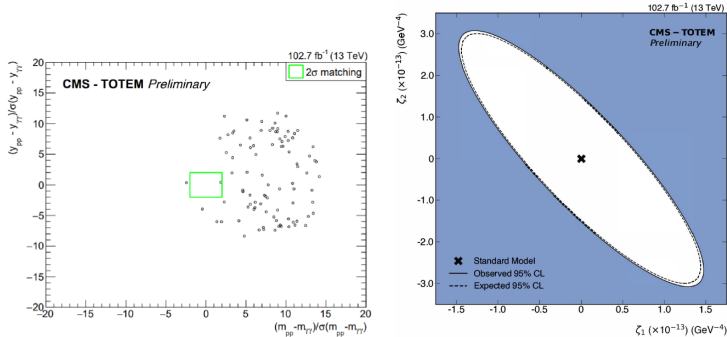
Search for quartic $\gamma\gamma$ anomalous couplings



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

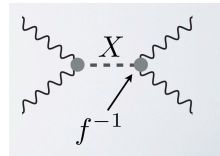
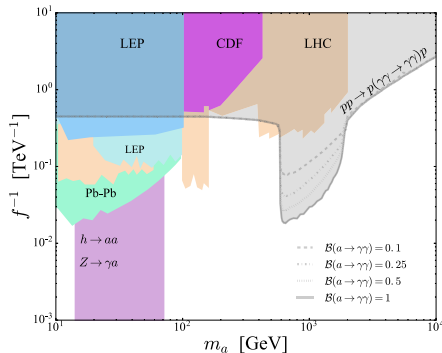
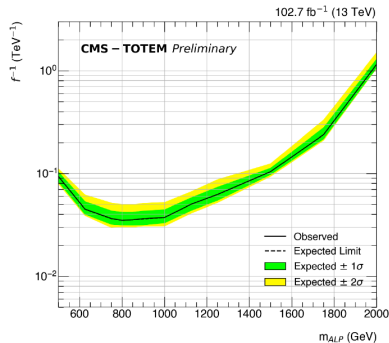
- No background after cuts for 300 fb^{-1} : sensitivity up to a few 10^{-15} , better by 2 orders of magnitude with respect to “standard” methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

First search for high mass exclusive $\gamma\gamma$ production



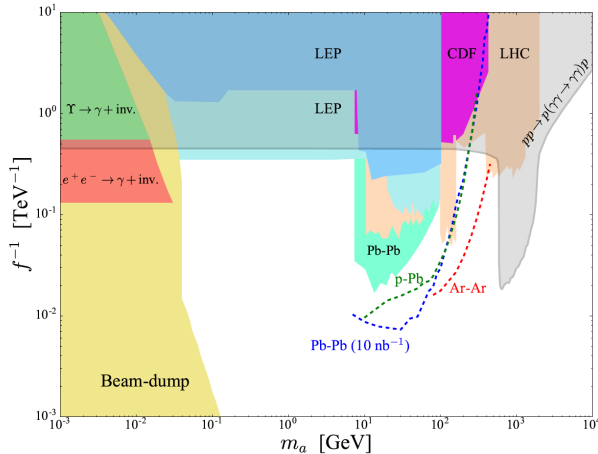
- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9 \cdot 10^{-13} \text{ GeV}^{-4}$, $|\zeta_2| < 6 \cdot 10^{-13} \text{ GeV}^{-4}$ with about 10 fb⁻¹, accepted by PRL (2110.05916)
- Limit updates with 102.7 fb⁻¹: $|\zeta_1| < 7.3 \cdot 10^{-14} \text{ GeV}^{-4}$, $|\zeta_2| < 1.5 \cdot 10^{-13} \text{ GeV}^{-4}$

First search for high mass production of axion-like particles



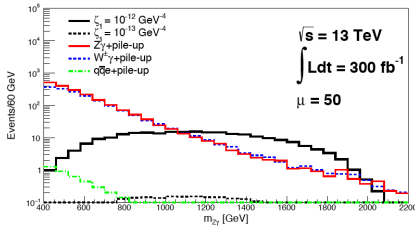
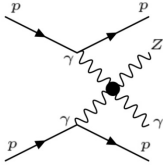
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb⁻¹ (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

Search for axion like particles: complementarity with heavy ion runs



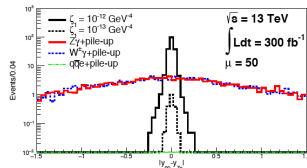
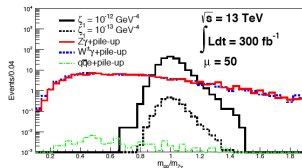
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to pp running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4 , C. Baldenegro, S. Hassani, C.R., L. Schoeffel, Phys. Lett. B795 (2019) 339; D. d'Enterria et al., PRL 111 (2013) 080405

$\gamma\gamma\gamma Z$ 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

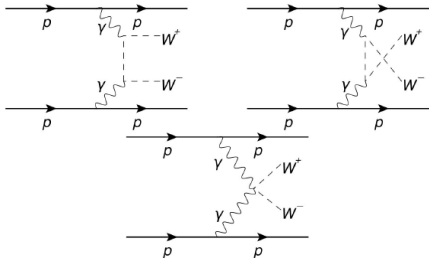
$\gamma\gamma\gamma Z$ quartic anomalous coupling



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
$\ell\bar{\ell}\gamma$	$2.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
$j\bar{j}\gamma$	$2.3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$2 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
$j\bar{j}\gamma \oplus \ell\bar{\ell}\gamma$	$1.93 \cdot 10^{-13}$	$1.2 \cdot 10^{-13}$	$1.7 \cdot 10^{-13}$	$1 \cdot 10^{-13}$

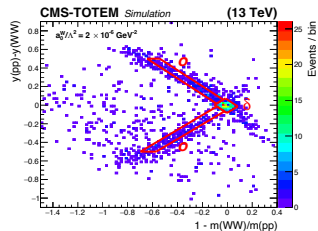
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a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

Exclusive production of W boson pairs

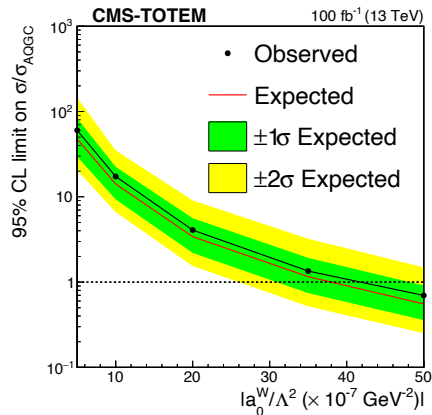


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 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

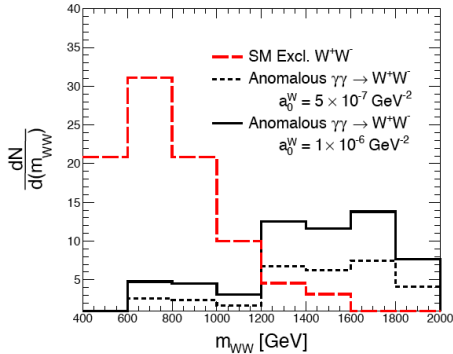


WW and ZZ exclusive productions



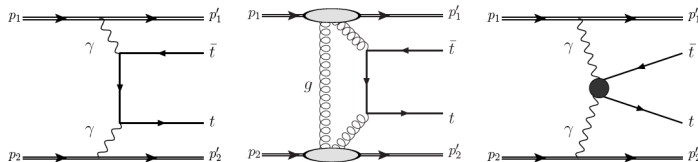
- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section
 $\sigma_{WW} < 67\text{fb}$, $\sigma_{ZZ} < 43\text{fb}$ for
 $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings (events violating unitarity removed) : $a_0^W/\Lambda^2 < 4.3 \cdot 10^{-6} \text{ GeV}^{-2}$,
 $a_C^W/\Lambda^2 < 1.6 \cdot 10^{-5} \text{ GeV}^{-2}$,
 $a_0^Z/\Lambda^2 < 0.9 \cdot 10^{-5} \text{ GeV}^{-2}$,
 $a_C^Z/\Lambda^2 < 4. \cdot 10^{-5} \text{ GeV}^{-2}$ with 52.9 fb⁻¹

The future: Observation of exclusive WW production



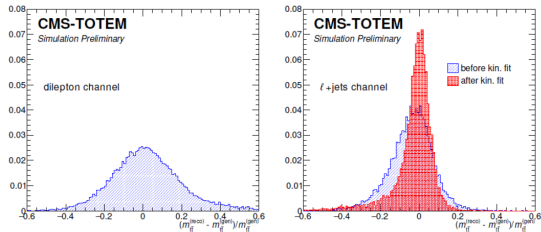
- SM contribution appears at lower WW masses compared to anomalous couplings
- Use purely leptonic channels for W decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive WW (leptonic decays) after selection: about 50 events for 300 fb^{-1} (2 background)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

Exclusive $t\bar{t}$ production

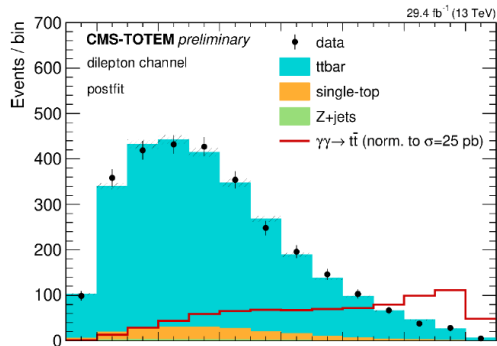


dilep channel ($\bar{t}t \rightarrow lvb + lv\bar{b}$)	Semilep channel ($\bar{t}t \rightarrow lvb + jj\bar{b}$)
Object selection	
Leptons: $p_T > 30(20)\text{GeV}$, $ \eta < 2.1$ Jets: $p_T > 30\text{GeV}$, $ \eta < 2.4$, $\Delta R(j,l) > 0.4$	Leptons: $p_T > 30\text{GeV}$, $ \eta < 2.1(2.4)$ for $e(\mu)$ Jets: $p_T > 25\text{GeV}$, $ \eta < 2.4$, $\Delta R(j,l) > 0.4$
Event selection	
≥ 2 leptons (OS pair), $ m(l\bar{l}) - m(Z) > 15\text{GeV}$ ≥ 2 b-jets 1 proton / side	$= 1$ lepton ≥ 2 b-jets, ≥ 2 non b-jets 1 proton / side

Exclusive $t\bar{t}$ production

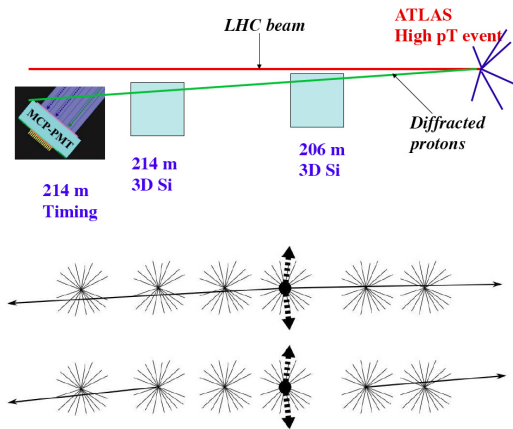


- Kinematic fitter based on W and t mass constraints to reduce background



- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes
- $\sigma_{t\bar{t}}^{excl.} < 0.59$ 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 $\sim$ 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 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

Coupling [$10^{-11} \text{ GeV}^{-4}$]	95% CL	5σ	95% CL (60 ps)	5σ (60 ps)	95% CL (20 ps)	5σ (20 ps)
ζ_1	1.5	2.5	1.1	1.9	0.74	1.5
ζ_2	1.4	2.4	1.0	1.7	0.70	1.4
ζ_3	1.4	2.4	1.0	1.7	0.70	1.4
ζ_4	1.5	2.5	1.0	1.8	0.73	1.4
ζ_5	1.2	2.0	0.84	1.5	0.60	1.2
ζ_6	1.3	2.2	0.92	1.6	0.66	1.3

Conclusion

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

