The LHC as a $\gamma\gamma$ collider

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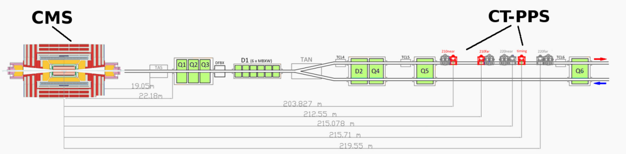
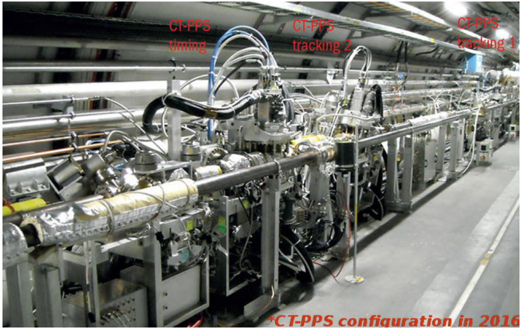
- Proton tagging at the LHC
- Possible observation of WW exclusive production
- $\gamma\gamma\gamma\gamma$, $\gamma\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$ anomalous coupling studies
- Triple gauge $\gamma\gamma W$ anomalous couplings
- Search for Axion-like particles

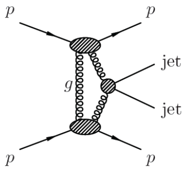
What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?

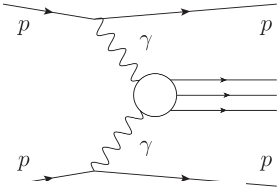


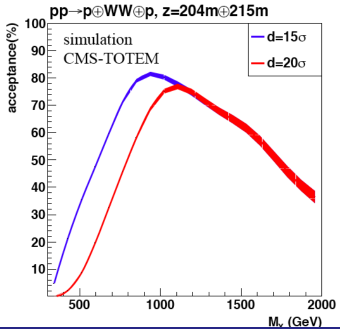


- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim$ 115 fb^{-1} of data collected
- Similar detectors: ATLAS Forward Proton (AFP)

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

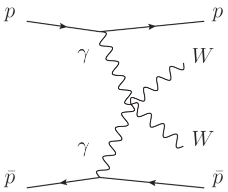


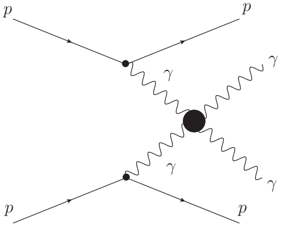




- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs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

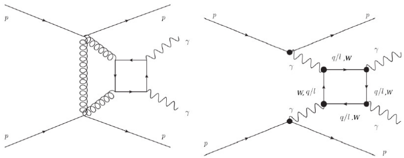
Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling

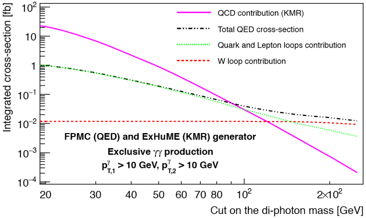




- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated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

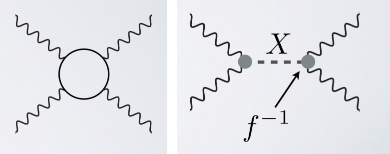
$\gamma\gamma$ exclusive production: SM contribution





- 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

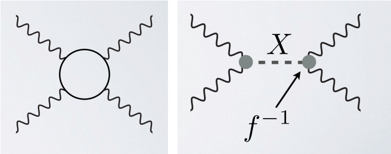


- Two effective operators at low energies

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

- $\gamma\gamma\gamma\gamma$ 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

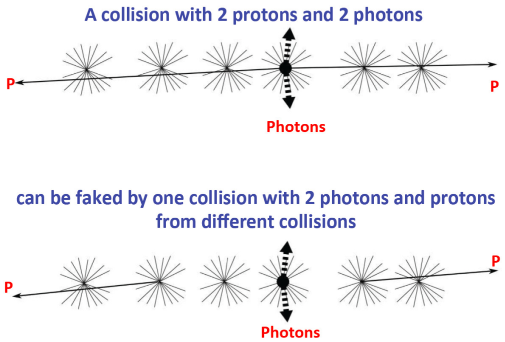


- Two effective operators at low energies

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

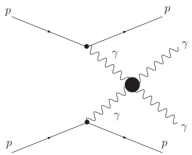
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$

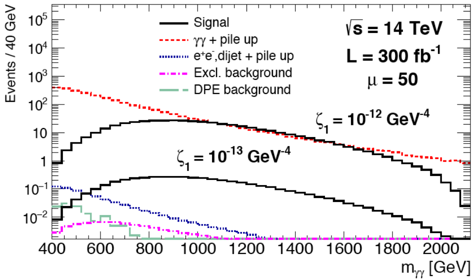
One aside: what is pile up at LHC?



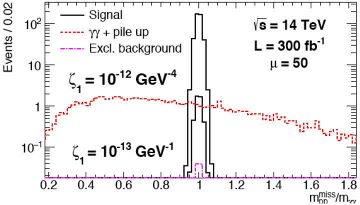
- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

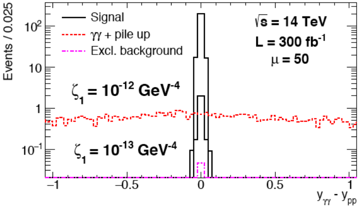
Search for quartic $\gamma\gamma$ anomalous couplings





- 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

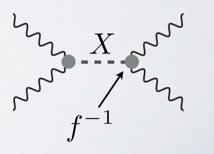


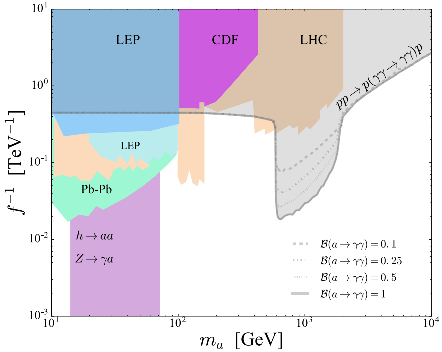


Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{\mathrm{T}1,(2)} > 200, (100)$ GeV$]$	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{\mathrm{T}2}/p_{\mathrm{T}1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	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
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	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})

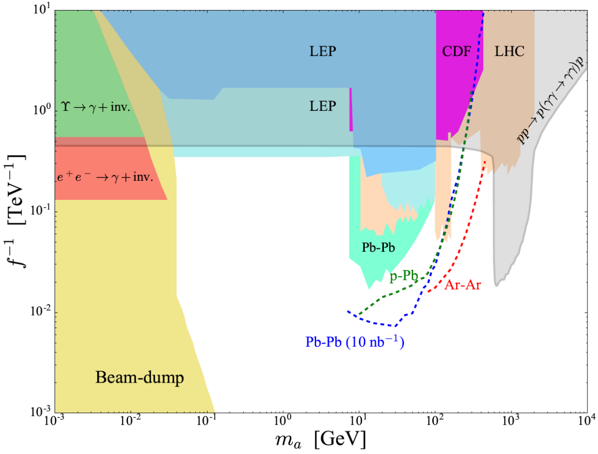
Search for axion like particles





- 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

Full $\gamma\gamma\gamma\gamma$ amplitude calculation

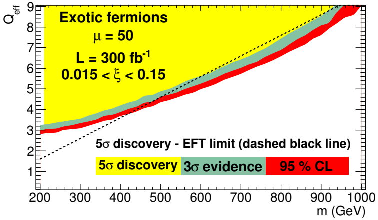
- Effective field theory valid if $S << 4m^2$, S smaller than the threshold production of real particles
- Since the maximum proton missing mass is $\sim$ 2 TeV at the 14 TeV LHC, the effective theory needs to be corrected for masses of particles below $\sim$ 1 TeV $\rightarrow$ use of form factor which 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 $Q_{eff} = QN^{1/4}$ where N is the multiplicity

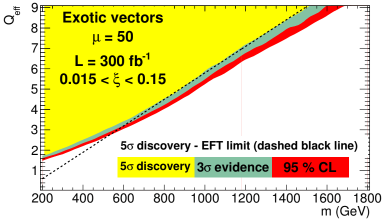
Full $\gamma\gamma\gamma\gamma$ amplitude calculation

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200, (100)$ GeV]	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\|\Delta\phi\| > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\|y_{\gamma\gamma} - y_{pp}\| < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

- 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 $S \sim m^2$

Fulll amplitude calculation



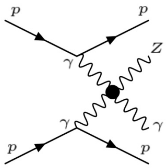


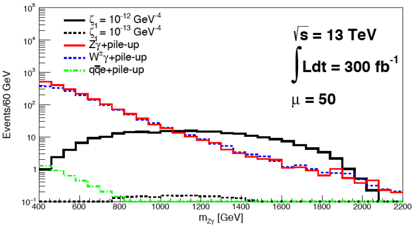
- 5 σ sensitivity for new charged fermions and vector bosons for 300 fb^{-1} and $\mu = 50$

Mass (GeV)	300	600	900	1200	1500
Q_{eff} (vector)	2.2	3.4	4.9	7.2	8.9
Q_{eff} (fermion)	3.6	5.7	8.6	-	-

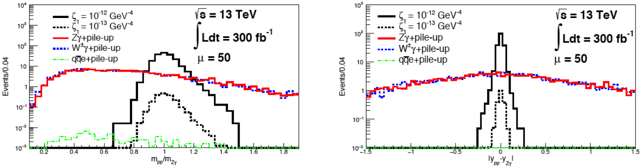
- Unprecedented sensitivites at hadronic colliders. We also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation
- For $Q_{Jeff} = 4$, we are sensitive to new vectors (fermions) up to 700 (370) GeV for a luminosity of 300 fb^{-1}

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





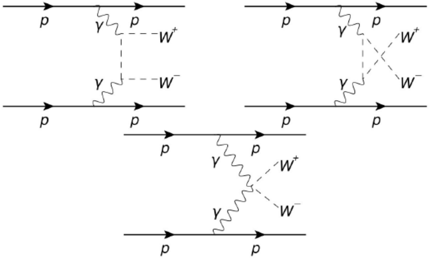
- Look for $Z\gamma$ anomalous production
- Z can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidiy matching technique allows us to look in both channels (very small background)
- Leads to a very good sensitivity to $\gamma\gamma\gamma Z$ couplings



Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8\cdot10^{-13}$	$1.8\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.5\cdot10^{-13}$
$jj\gamma$	$2.3\cdot10^{-13}$	$1.5\cdot10^{-13}$	$2\cdot10^{-13}$	$1.3\cdot10^{-13}$
$jj\gamma\bigoplus\ell\bar{\ell}\gamma$	$1.93\cdot10^{-13}$	$1.2\cdot10^{-13}$	$1.7\cdot10^{-13}$	$1\cdot10^{-13}$

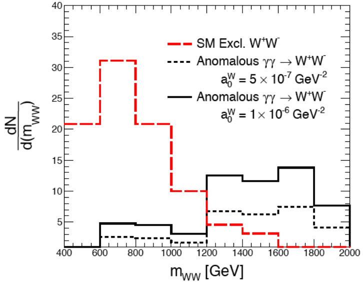
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a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

SM observation and anomalous couplings studies in WW events

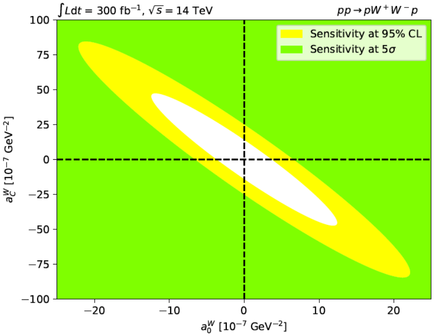


- Possible observation of WW exclusive production at high mass: study all decay channels, 2 "fat" jets, 1 lepton + 1 "fat" jet, 2 leptons

- 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

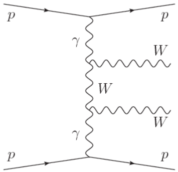


Quartic anomalous couplings studies in WW events



- 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 10^{-7} GeV^{-2} (present limits using exclusive production of WW at medium luminosity (low pile up) without proton tagging led to limits of $\sim 10^{-4}$ GeV^{-2})
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.

Trilinear γWW anomalous gauge couplings



- Search for anomalous $WW\gamma$ couplings
- References: O.Kepka, C. Royon, Phys. Rev. D 78 (2008) 073005; E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005

- Lagrangian with trilinear gauge $WW\gamma$ anomalous couplings λ^γ and $\Delta\kappa^\gamma$

$$\mathcal{L} \sim (W^\dagger_{\mu\nu} W^\mu A^\nu - W_{\mu\nu} W^{\dagger\mu} A^\nu) + (1 + \Delta\kappa^\gamma) W^\dagger_\mu W_\nu A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu A^{\nu\rho}$$

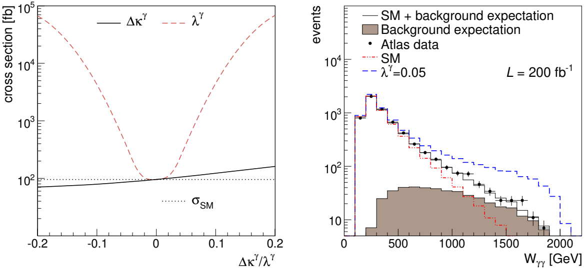
- Signal appears at high mass for λ^γ, and $\Delta\kappa^\gamma$ only modifies the normalisation and the low mass events have to be retained
  - for $\Delta\kappa^\gamma$:

$$p_T^{lep1} > 25 \text{ GeV} , \not{E}_T > 20 \text{ GeV} , W > 160 \text{ GeV} , \Delta\phi < 2.7, W < 500 \text{ GeV}$$

  - for λ^γ:

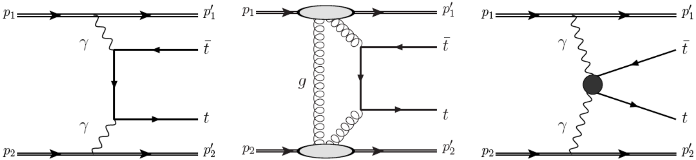
$$p_T^{lep1} > 160 \text{ GeV} , \not{E}_T > 20 \text{ GeV} , W > 800 \text{ GeV} , M_{ll} \notin \langle 80, 100 \rangle \, GeV, \Delta\phi < 3.13 rad$$

Trilinear γWW anomalous gauge couplings



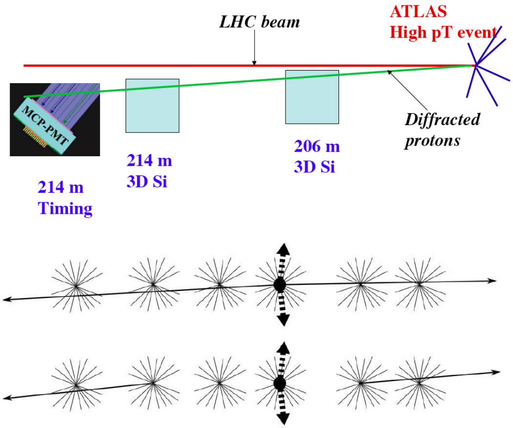
- Different behaviour of the cross section as a function of anomalous couplings
- Measurement of WW events at high luminosities at LHC, $2W$ events and protons tagged in forward detectors
- Reach on anomalous coupling at the LHC using a luminosity of 200 fb^{-1}
  - 5σ discovery: $-0.26 < \Delta\kappa^\gamma < 0.16$; $-0.053 < \lambda^\gamma < 0.049$
  - 95% CL limit: $-0.096 < \Delta\kappa^\gamma < 0.057$; $-0.023 < \lambda^\gamma < 0.027$,
- Best reaches before ILC, which can be improved using semi-leptonic decays of Ws

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

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 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

- 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 arXiv:2205.01173

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** $pp \to p\gamma\gamma p$ (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 probablity 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