Probing anomalous quartic couplings at the Large Hadron Collider with proton tagging

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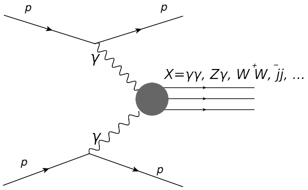
Central exclusive reactions processes

- Central exclusive reactions $pp \to p + X + p$ can be studied by measuring X ($X = \gamma\gamma, \ell\bar{\ell}, W^+W^-, ZZ$) in a general purpose detector (e.g., CMS, ATLAS) and the scattered intact protons pp with forward proton detectors located at $\sim$ 210 m w.r.t. main interaction vertex. These can be due to γ-$\mathbb{P}$, $\mathbb{P} - \mathbb{P}$ and $\gamma - \gamma$ exchanges. The final state can be reconstructed in its totality.



- The exclusive channel allows us to probe pure gauge interactions with unprecedented sensitivity, since σ^{SM}_{Excl} is typically small for $m_X > 600$ GeV.
- Measure the proton fractional momentum loss $\xi = \Delta p/p$ with the forward proton detectors w/ nominal acceptance $0.015 < \xi_{1,2} < 0.15$.
- Event selection criteria: Compute the diffractive mass $m_{pp} = \sqrt{\xi_1 \xi_2 s}$ and rapidity $y_{pp} = \frac{1}{2}\log(\xi_1/\xi_2)$ and compare with m_X and y_X. Central exclusive processes yield $y_{pp} = y_X$, $m_{pp} = m_X$.

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

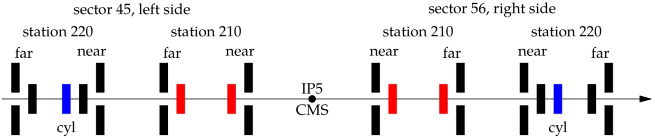


Figure : Forward detector stations at about $\sim$ 210 m w.r.t. IP5. (Figure not in scale)

- Joint project between the CMS and TOTEM collaborations. (Combine central and forward information to study central exclusive production). Operating since Summer 2016.
- Intact protons from $pp \to pXp$ reactions are detected with tracking sensors hosted in *roman pots*. Tracking + information of the accelerator magnetic lattice to reconstruct intact protons kinematics (e.g., fractional momentum loss ξ).
- Observation of the $pp \to p^{*}\mu^{+}\mu^{-}p$ in CT-PPS CMS-PAS-PPS-17-001. Standard candle measurement for central exclusive production in pp at the LHC nominal luminosity.
- ATLAS Forward Physics aims for a similar physics programme for central exclusive production. Operating with both arms since Summer 2017.

Anomalous quartic gauge couplings at the LHC

It has been discussed before the possibility of studying BSM pure gauge interactions $\gamma\gamma\gamma\gamma$, $\gamma\gamma W^+W^-$, $\gamma\gamma\gamma Z$ in the exclusive channel. If there exists a quartic gauge coupling, due to $SU(2) \times U(1)_Y$ we would expect quartic couplings with other combinations of vector bosons.

As a proof of principle, we will discuss the prospects of anomalous $\gamma\gamma\gamma\gamma$ coupling reach at the LHC in pp collisions via photon-induced processes with leading intact protons in the final state, i.e., $pp \to p\gamma\gamma p$. [S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, 10.1007/JHEP02(2015)] and the $\gamma\gamma\gamma Z$ anomalous coupling prospects in central exclusive production. [C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017)]

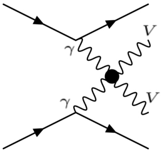


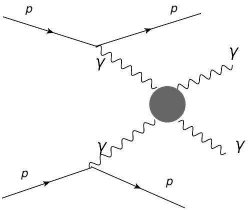
Figure : VV = $\gamma\gamma$, ZZ, W^+W^-, $Z\gamma$.

Anomalous quartic coupling $\gamma\gamma\gamma\gamma$

Effective Field Theory assumption, $\Lambda_{New\ Physics} \gg \sqrt{s_{\gamma\gamma}}$. Couplings can be related to parameters of BSM extension of choice (e.g., warped extra-dimensions, composite Higgs, new particles). The $\gamma\gamma\gamma\gamma$ interaction * is induced by two dimension 8 operators ,

$$\mathcal{L}_{4\gamma} = \zeta_1 F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu} \quad (1)$$

Amplitudes $\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4}$ induced by the EFT operators are implemented in the Forward Physics Monte Carlo.



* Exciting result from ATLAS on Light-by-light scattering at low masses $m_{\gamma\gamma}$ in PbPb collisions. [Nature Physics 13, 852858 (2017)]

Anomalous quartic coupling $\gamma\gamma\gamma\gamma$

The unpolarized differential cross section induced by the EFT Lagrangian reads,

$$\frac{\mathrm{d}\sigma_{\gamma\gamma\to\gamma\gamma}}{\mathrm{d}\Omega} = \frac{1}{16\pi^2 s}(s^2+t^2+st)^2\left[48\zeta_1^2+40\zeta_1\zeta_2+11\zeta_2^2\right] \tag{2}$$

Imposing unitarity on the S-wave from the EFT amplitudes, we find the bound

$$\zeta_1, \zeta_2 < (10^{-12} - 10^{-11})\mathrm{GeV}^{-4} \tag{3}$$

The quoted sensitivities are several orders of magnitude lower than this bound; form factor is not necessary within the mass acceptance ($m_{\gamma\gamma} \in$ [300 GeV, 2 TeV])

New Physics contributions to $\gamma\gamma\gamma\gamma$ coupling

s-channel exchange Induced by exchange of a neutral resonance on the s-channel. The effective coupling is,

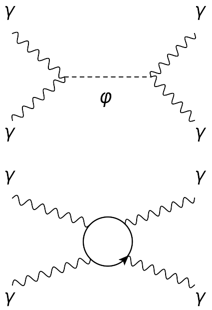
$$(\zeta_1, \zeta_2) = \frac{1}{(f_\phi^\gamma\ m)^2}(d_{1,s}, d_{2,s}) \qquad (4)$$

Where $1/f_\phi^\gamma$ is the tree-level coupling, m its mass.

Loop of heavy charged can induce the ζ_1, ζ_2 couplings

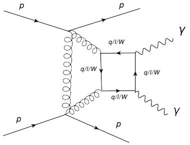
$$(\zeta_1, \zeta_2) = \alpha_{em}^2 Q^4\ m^{-4}\ N(\ c_{1,s}, c_{2,s}) \qquad (5)$$

Where Q is the charge, m mass, N number of copies.

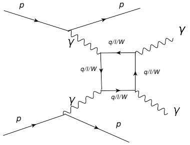


Background in the exclusive $p\gamma\gamma p$ channel

Exclusive background

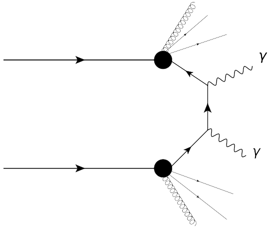


Khoze-Martin-Ryskin-like $\gamma\gamma$ (Highly suppressed at high mass due to Sudakov factor for central exclusive processes).



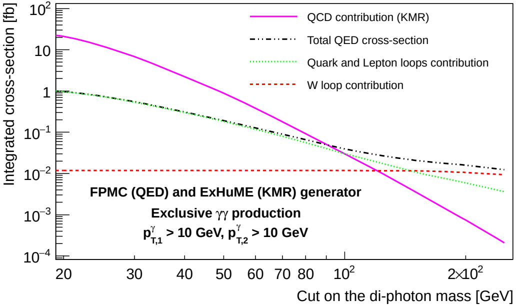
Photon-induced $\gamma\gamma$ ($\sim 10^{-1}$ fb after acceptance cuts)

$\gamma\gamma$ **overlapped with pileup interactions**



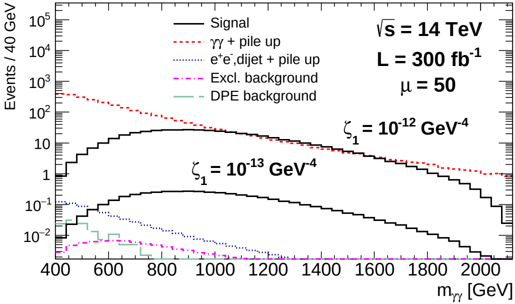
$\gamma\gamma$ + protons from secondary interactions (pile-up). Reducible by exploiting exclusivity cuts set by proton taggers $\xi_{1,2}$ measurement (i.e., compare ξ_{central} and ξ_{forward})

Exclusive background



Cross-section for SM exclusive reactions in $\gamma\gamma$ as a function of the $m_{\gamma\gamma}$ cut. QCD contribution is highly suppressed at high invariant masses compared to QED one. $W^{\pm}$ loops dominate at high $m_{\gamma\gamma}$ probed in the CT-PPS/AFP acceptance.

Event selection $\gamma\gamma$



- $0.015 < \xi < 0.15$ (Forward proton detector acceptance).
- By requesting $p_{T,\gamma,lead}(p_{T,\gamma,sublead}) > 200(100)$ GeV and $m_{\gamma\gamma} > 600$ GeV, practically only the signal and the $\gamma\gamma$+pile-up background remain.
- p_T ratio, and asking $\gamma\gamma$ system back-to-back in the final selection cut (Topology for central exclusive processes).

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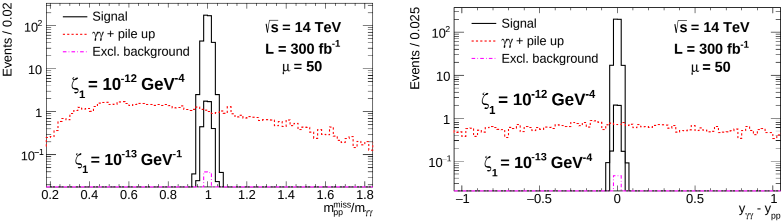


Figure : Left: Missing diproton mass m_{pp} to $m_{\gamma\gamma}$ ratio. Right: Rapidity difference $|y_{pp} - y_{\gamma\gamma}|$. Signal in **black**.

- Exclusive processes peak on the $m_{pp}/m_{\gamma\gamma}$ and $|y_{pp} - y_{\gamma\gamma}|$ distributions. (Reminder: $m_{pp} = \sqrt{\xi_1 \xi_2 s}$, $y_{pp} = \frac{1}{2}\log(\xi_1/\xi_2)$)
- Widths for the signal are due to the smearing on $\xi_{1,2}$ due to detector effects (3% smearing).
- Missing proton mass $\sqrt{\xi_1 \xi_2 s}$ matches $m_{\gamma\gamma}$ for the signal within 5% resolution.

Event selection

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$]$	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01]$	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

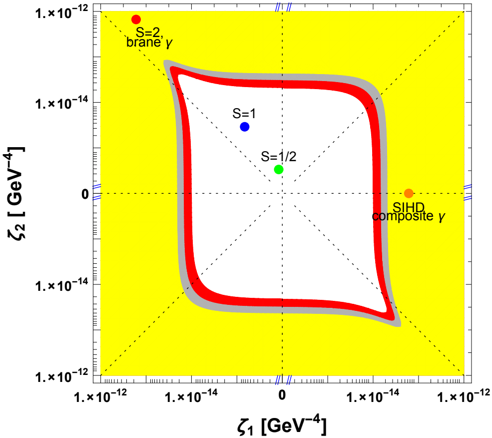
- Event selection considers $\int \mathcal{L}\mathrm{d}t = 300\ fb^{-1}$ and $\langle\mu\rangle = 50$ interactions per bunch crossing and fixed coupling value at $\sqrt{s} = 14$ TeV.
- Background free measurement for the $\gamma\gamma$ final state. The selection yields signal efficiency of $\sim 80\%$ in this channel after all selections.
- No need for time-of-flight measurement to reject pile-up background in this channel. Asking for exclusivity (four-momentum conservation) is enough.

ζ_1, ζ_2 reach at CT-PPS/AFP

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile up (μ)	50	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 5 σ	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1.5 \cdot 10^{-13}$	$7.5 \cdot 10^{-14}$	$6 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$3.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$	$1 \cdot 10^{-14}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8.5 \cdot 10^{-14}$	$7 \cdot 10^{-14}$
ζ_2 no f.f.	$7.5 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$

Sensitivities down to $\mathcal{O}(10^{-13})\,\mathrm{GeV}^{-4}$ in ζ_1, ζ_2 at 95 % CL for $\int \mathcal{L}dt = 300$ fb $^{-1}$ at 14 TeV.

Couplings reach at the LHC with the exclusive channel



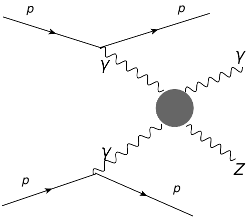
95% C.L., 3 σ and 5σ reach in the anomalous couplings ζ_1, ζ_2 in red, grey and yellow respectively for 300 fb^{-1} and $\mu = 50$. Couplings for which ~ 0 after selection cuts in white.

Anomalous quartic coupling $\gamma\gamma\gamma Z$

Effective Field Theory assumption, $\Lambda_{New\ Physics} \gg \sqrt{s_{Z\gamma}}$. Couplings can be related to parameters of BSM extension. The EFT $\gamma\gamma\gamma Z$ coupling is induced by two dimension-8 operators,

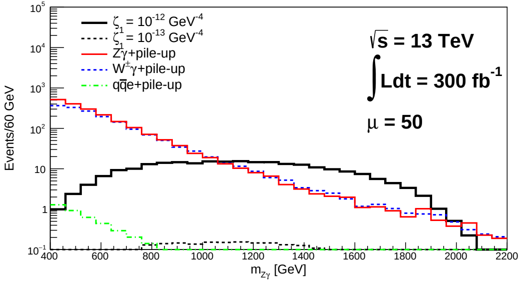
$$\mathcal{L}_{\gamma\gamma\gamma Z} = \zeta^{Z\gamma} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \tilde{\zeta}^{Z\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu} F^{\rho\sigma} \tilde{Z}_{\rho\sigma} \quad (6)$$

With $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$.



Possibility to study Z decay in $\ell\bar{\ell}$ and jets in exclusive channel. $\mathcal{BR}(Z \to q\bar{q})$ enhances sensitivity on ζ, $\tilde{\zeta}$ considerably.

Distribution of signal and background $Z\gamma$



- Implemented signal in the Forward Physics Monte Carlo. Background is simulated with PYTHIA8.
- For 300 fb^{-1} and $\mu = 50$ pile-up interactions at $\sqrt{s} = 13$ TeV.
- Protons within the nominal acceptance $0.015 < \xi_{1,2} < 0.15$.
- $p_{T,\gamma}(p_{T,jj}) > 150(100)$ GeV and $m_{Z\gamma} > 700$ GeV.
- Dijet and photon balanced in momentum (Similar p_T and back-to-back).

Forward proton detector $\xi_{1,2}$ measurement (Excl. $jj\gamma$)

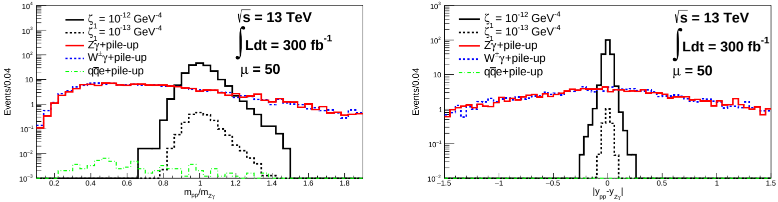


Figure : Left: Mass ratio $m_{pp}/m_{Z\gamma}$. Right: Rapidity difference $|y_{pp} - y_{jj\gamma}|$. Signal in **black**.

- Signal peaks on the $m_{pp}/m_{Z\gamma}$ and $|y_{pp} - y_{Z\gamma}|$ distributions. Criteria for exclusive event selection.
- Width for the signal are due to smearing on $\xi_{1,2}$ of 2% and the large smearing on the reconstructed jets energy.
- About $3 - 4$ background events remain after applying selection cuts. Still, better sensitivity than in $\ell\bar{\ell}\gamma$ channel due to the larger

$\zeta^{Z\gamma}$, $\tilde{\zeta}^{Z\gamma}$ reach at CT-PPS/AFP

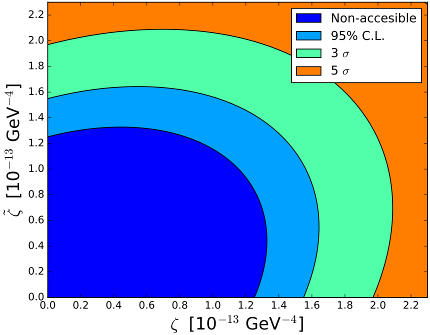
Coupling (GeV^{-4})	ζ ($\tilde{\zeta} = 0$)		$\zeta = \tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
$jj\gamma$	$2.3 \cdot 10^{-13}$	$1.5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

Sensitivities down to $1.3 \times 10^{-13}\mathrm{GeV}^{-4}$ in ζ, $\tilde{\zeta}$ at 95 % CL.
The branching ratio $\mathcal{BR}(Z \to \gamma\gamma\gamma)$ has been constrained by ATLAS [Eur. Phys. J. C 76(4)]. This translates to the bound,

$$\sqrt{\zeta^2 + \tilde{\zeta}^2 - \frac{\zeta\tilde{\zeta}}{2}} < 1.3 \cdot 10^{-9}\ \mathrm{GeV}^{-4} \quad (95\%\mathrm{CL}) \tag{7}$$

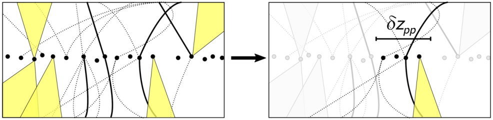
Our sensitivity at 300 fb^{-1} provides a stronger constraint on ζ, $\tilde{\zeta}$ by a factor of $\sim 10^3$.

ζ-$\tilde{\zeta}$ sensitivity plane



95% C.L., 3 σ and 5σ reach to the anomalous couplings ζ, $\tilde{\zeta}$ for 300 fb^{-1}, $\mu = 50$. Couplings for which ~ 0 after selection cuts in dark blue. (Including $0.015 < \xi_{1,2} < 0.15$).

Further removal of pile-up interactions



Time-of-flight measurement necessary for studying other interesting final states, e.g., exclusive W^+W^-, where we can't apply the same kinematic constraints due to the missing energy carried by ν. Not strictly necessary for measurable final states, but helps reduce even further the pile-up background.
Direct relation between timing resolution and longitudinal two-proton vertex resolution:

$$\delta z_{pp} = \frac{c}{\sqrt{2}} \delta t$$

For instance, a $\delta t = 30ps$ yields $\delta z_{pp} \approx 6$ mm

Summary

- We addressed the discovery potential for the anomalous quartic gauge couplings via photon-induced processes in *pp* collisions with leading intact protons at the LHC.
- Great background rejection pileup events by imposing four-momentum conservation. The irreducible SM contribution in this channel has a very low cross-section at high masses, which increases our reach in the anomalous quartic gauge couplings.
- Interesting studies on the way: Reach on semi-leptonic W^+W^- in the exclusive channel, low-mass resonances signatures at high invariant masses accessible to CT-PPS/AFP, Z -flux off protons which may allow to reach $4Z$ couplings...
- Stay tuned for results with the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) and ATLAS Forward Physics (AFP)!