Prospects for anomalous quartic $\gamma\gamma\gamma Z$ coupling at the LHC with proton tagging

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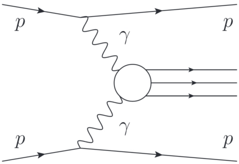
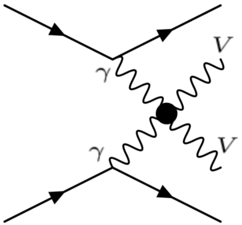
Anomalous couplings at CT-PPS/AFP

- Study of the central exclusive process $pp \rightarrow p + X + p$ with forward proton tagging.
- Measure the proton fractional momentum loss $\xi = \Delta p/p$ with the forward proton detectors; $0.015 < \xi_{1,2} < 0.15$.
- 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.



Anomalous quartic gauge couplings at the LHC

It has been discussed before the feasibility of studying BSM gauge interactions $\gamma\gamma\gamma\gamma$, $\gamma\gamma W^+W^-$ with the forward proton detector technology. [1],[2],[3].
The proton taggers will be available soon in both CT-PPS (Currently installed) and AFP (See Maciej's talk). It's important to address the discovery potential for 4-boson interactions in the exclusive channel.



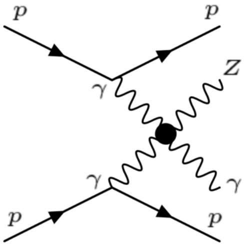
Anomalous quartic coupling $\gamma\gamma\gamma Z$

Motivated by New Physics extensions (Warped extra-dimensions, Kaluza-Klein graviton, composite Higgs). $\Lambda \gg \sqrt{s_{Z\gamma}}$, Effective Field Theory assumption,

$$\mathcal{L}_{\gamma\gamma\gamma Z} = \zeta^{Z\gamma} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \tilde{\zeta}^{Z\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu} F^{\rho\sigma} \tilde{Z}_{\rho\sigma} \quad (1)$$

We use a form factor at the amplitude level to restore unitarity.

$$f.f. = 1/(1 + (s_{Z\gamma}/\Lambda)^2) \quad (2)$$



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

The unpolarized differential cross section reads,

$$\frac{\mathrm{d}\sigma_{\gamma\gamma\to Z\gamma}}{\mathrm{d}\Omega} = \frac{\beta}{16\pi^2 s}\Big[(3\zeta^2 + 3\tilde{\zeta}^2 - 2\zeta\tilde{\zeta})(st+tu+us)^2 \\ -4(\zeta^2+\tilde{\zeta}^2-\zeta\tilde{\zeta})^2 m_Z^2 stu\Big], \quad (3)$$

Symmetric under ζ, $\tilde{\zeta}$ exchange. Imposing unitarity on the S-wave from the EFT amplitudes, we get

$$\zeta, \tilde{\zeta} < (10^{-12} - 10^{-11})\mathrm{GeV}^{-4} \quad (4)$$

We quote sensitivities $10^2 - 10^3$ lower than this bounds.

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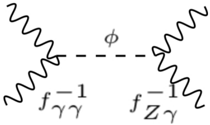
New Physics contributions to $3\gamma Z$ coupling

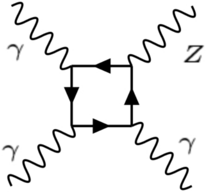
***s*-channel exchange** Induced by exchange of a neutral resonance on the *s*-channel. The effective coupling is,

$$(\zeta, \tilde{\zeta}) = \frac{1}{f_s^{\gamma\gamma} f_s^{Z\gamma}\, m^2}(d_s, \tilde{d}_s) \quad (5)$$

Loop of heavy charged can induce the ζ, $\tilde{\zeta}$ couplings

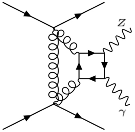
$$(\zeta\tilde{\zeta}) = \alpha_{\rm em}^2 Q^4\, m^{-4}\, N\, c_s(\tilde{c}_s) \quad (6)$$



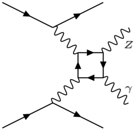


Background in the exclusive $pZ\gamma p$ channel

Exclusive background

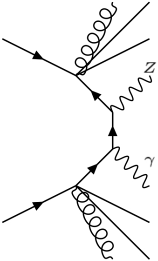


Khoze Martin Ryskin $Z\gamma$ prod. (Negligible at high mass).



Photon-induced $Z\gamma$ (Small at high mass).

$Z\gamma$ final state + pile-up



Reducible by exploiting exclusivity cuts set by proton taggers $\xi_{1,2}$ measurement. This constitutes the dominant background, which is the focus of our study.

Background contributions to $pp \to pZ\gamma p$

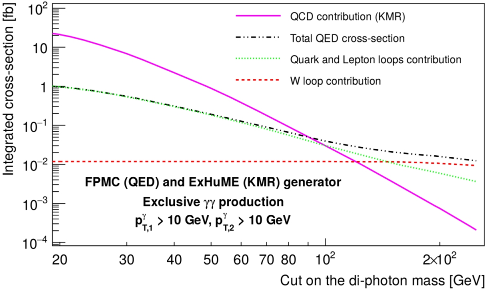


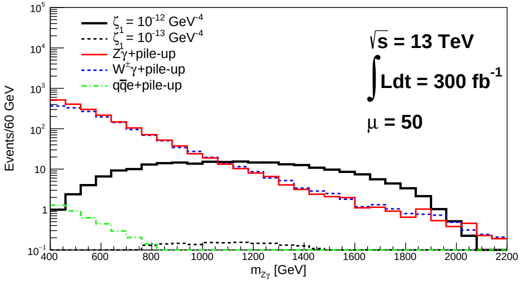
Figure: Integrated cross-section for exclusive SM $\gamma\gamma$ production for different $m_{\gamma\gamma}$ cuts.

A similar behavior is expected for the exclusive $Z\gamma$ channel (Same diagrams). We make the assumption that this background is ~ 0 after all selection cuts.

Signal and background generation

- The $pp \to pZ\gamma p$ process was implemented in the Forward Physics Monte Carlo. The Equivalent Photon Approximation (EPA) is used to take into account the coherent photon flux from the interacting protons. Intact protons lie within the nominal acceptance $0.015 < \xi_{1,2} < 0.15$.
- Non-exclusive events (PYTHIA8) in association with pile-up with protons within acceptance.
- Smearing on η, ϕ, p_T, E on photons, leptons and hadrons to simulate the effects of the detector. We apply an smearing of 15% on the energy of the reconstructed jet. We reconstruct jets with anti-kt clustering algorithm.

Distribution of signal and background $Z\gamma$ ($jj\gamma$ channel)



- 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.
- p_T ratio, and asking $Z\gamma$ system back-to-back in the final selection cut (Exclusive process).

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

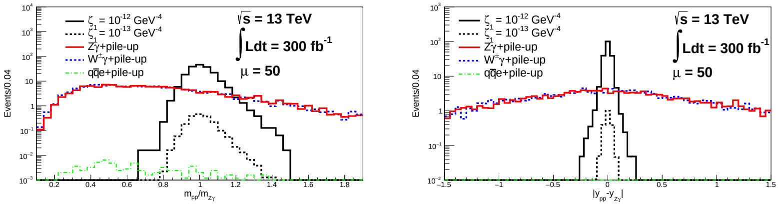


Figure: Left: Mass ratio $m_{pp}/m_{Z\gamma}$. Right: Rapidity difference $|y_{pp} - y_{jj\gamma}|$.

- 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 poor energy resolution on the reconstructed jets energy $\sim 15\%$.

Event selection (Hadronic channel)

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	$Z\gamma$ +pile-up	$W^{\pm}\gamma$ +pile-up	$jje^{\pm}$ +pile-up
$0.015 < \xi_{1,2} < 0.15$, $p_{T,\gamma} > 150$ GeV $p_{T,jj} > 100$ GeV]	38.6(8.6)	51.4 (11.5)	1951.8	1631	8.47
$m_{Z\gamma} > 700$ GeV	37 (7.4)	49.5 (9.9)	349.8	358.9	1.3
$p_{T,\gamma}/p_{T,jj} > 0.90$, $\|\Delta\phi - \pi\| < 0.02$	33.8 (6.4)	45.1 (8.6)	144.7	145.4	0.54
$\sqrt{\xi_1\xi_2 s} = m_{Z\gamma} \pm 10\%$	28.2 (5.4)	37.9 (7.2)	19.7	19.3	0.1
$\|y_{pp} - y_{Z\gamma}\| < 0.05$	26 (5)	34.7 (6.5)	1.5	1.6	0

- Event selection considers 300 fb^{-1} and $\mu = 50$ and a coupling value of $\zeta = 4 \times 10^{-13}\mathrm{GeV}^{-4}$ at $\sqrt{s} = 13$ TeV. Final state hadrons are reconstructed with anti-kt clustering algorithm with R=0.5.
- About 3 background events remain after selection cuts.
- Timing detector technology to resolve exclusive event vertices in this channel with milimetric precision ($\sim$ 15 ps resolution).

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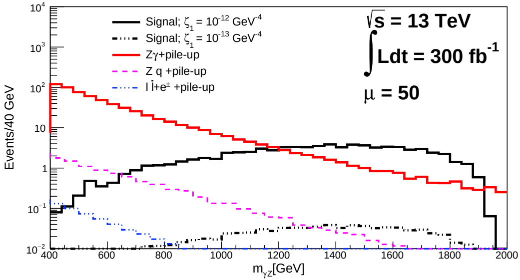
Event selection $Z\gamma$ (Leptonic channel)



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

Forward proton detector $\xi_{1,2}$ measurement (Leptons)

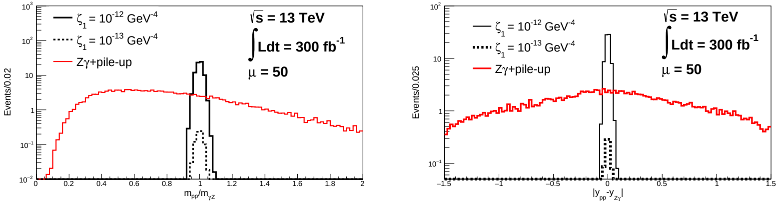


Figure: Left: Missing diproton mass m_{pp} to $m_{Z\gamma}$ ratio. Right: Rapidity difference $|y_{pp} - y_{\ell\bar{\ell}\gamma}$

- Signal peaks on the $m_{pp}/m_{Z\gamma}$ and $|y_{pp} - y_{Z\gamma}|$ distributions. Criteria for exclusive event selection.
- Widths for the signal are due to the smearing on ξ_i due to detector effects (2% smearing).
- Missing proton mass $\sqrt{\xi_1 \xi_2 s}$ matches $m_{Z\gamma}$ for the signal

Event selection ($\ell\bar{\ell}\gamma$)

Cut/Process	Signal ζ ($\tilde{\zeta} = 0$)	Signal $\zeta = \tilde{\zeta}$	$Z\gamma$ +pile-up	$\ell\bar{\ell}$ +pile-up	$\ell\bar{\ell}e^{\pm}$ +pile-up
[$0.015 < \xi_{1,2} < 0.15$, $p_{T,\gamma} > 100$ GeV $p_{T,\ell\bar{\ell}} > 100$ GeV]	13.2 (1.7)	17.4 (2.1)	2239.2	64.5	1.2
$m_{Z\gamma} > 600$ GeV	12.9 (1.5)	17.1 (1.9)	227	3.8	0.2
$p_{T,\gamma}/p_{T,\ell\bar{\ell}} > 0.95$, $\lvert\Delta\phi - \pi\rvert < 0.02$	12.6 (1.4)	16.7 (1.8)	175	0	0
$\sqrt{\xi_1\xi_2 s} = m_{Z\gamma} \pm 5\%$	12.2 (1.4)	16.4 (1.8)	12.7	0	0
$\lvert y_{pp} - y_{Z\gamma}\rvert < 0.03$	10 (1.2)	13.7 (1.5)	0.6	0	0

- Event selection considers $= 300\ fb^{-1}$ and $\mu = 50$ and a coupling value of $\zeta = 4 \times 10^{-13}\mathrm{GeV}^{-4}$ at $\sqrt{s} = 13$ TeV.
- Background free measurement for the $\ell\bar{\ell}\gamma$ final state. The selection yields signal efficiency of $\approx 75\%$ in this channel.
- No need for timing detectors to reject pile-up background in this channel. Asking for exclusivity is enough.

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

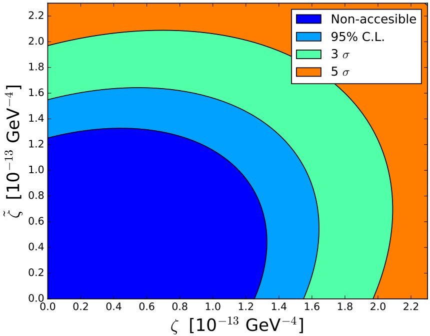
Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\ell\gamma$	3.2×10^{-13}	2×10^{-13}	2.6×10^{-13}	1.7×10^{-13}
$\ell\ell\gamma$(f.f.)	7.2×10^{-13}	4.8×10^{-13}	6.2×10^{-13}	4.1×10^{-13}
$jj\gamma$	2.4×10^{-13}	1.52×10^{-13}	2×10^{-13}	1.3×10^{-13}
$jj\gamma$ (f.f)	6×10^{-13}	3.6×10^{-13}	5×10^{-13}	2.9×10^{-13}
Combined	1.97×10^{-13}	1.32×10^{-13}	1.6×10^{-13}	1.2×10^{-13}
Combined (f.f.)	5.3×10^{-13}	3.3×10^{-13}	4.4×10^{-13}	2.8×10^{-13}

Sensitivities down to $2.8\times10^{-14}\mathrm{GeV}^{-4}$ in ζ, $\tilde{\zeta}$ at 95 % CL.
The branching ratio for $Z\to\gamma\gamma\gamma$ has been constrained by ATLAS.
This translates to the limit,

$$\sqrt{\zeta^2+\tilde{\zeta}^2-\frac{\zeta\tilde{\zeta}}{2}}<1.3\cdot10^{-9}\ \mathrm{GeV}^{-4}\quad(95\%\mathrm{CL}) \tag{7}$$

Our sensitivity at 300 fb^{-1} provides a more stringent constraint on ζ, $\tilde{\zeta}$ by a factor of $\sim10^4$.

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 $0.015 < \xi_{1,2} < 0.15$).

Search at the High Luminosity LHC

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	$Z\gamma$ +pile-up	$\ell\bar{\ell}$ +pile-up	$\ell\bar{\ell}e^{\pm}$ +pile-up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T,\gamma} > 200$ GeV $p_{T,\ell\bar{\ell}} > 200$ GeV$]$	99.5 (12.2)	132.8 (14.5)	6403.6	1207.3	30.1
$m_{Z\gamma} > 1100$ GeV	77.2 (3.1)	105.5 (4.2)	550.4	106.3	5.3
$p_{T,\gamma}/p_{T,\ell\bar{\ell}} > 0.95$, $\lvert\Delta\phi-\pi\rvert < 0.01$	76.4 (3.1)	104.8 (4.2)	458.2	19.2	0.5
$\sqrt{\xi_1\xi_2 s} = m_{Z\gamma} \pm 3\%$	62.2 (2.4)	85 (3.3)	16.4	1.2	0
$\lvert y_{pp} - y_{Z\gamma}\rvert < 0.025$	46.2 (2.1)	72 (3)	1.8	0	0

- Event selection considers 3000 fb^{-1} and $\mu = 200$ and a coupling value of $\zeta = 4 \times 10^{-13}\mathrm{GeV}^{-4}$ at $\sqrt{s} = 13$ TeV. Selection cuts are optimized in this scenario.
- After selection cuts, ~ 2 background events remain. Selection yields signal efficiency of $\approx 50\%$.
- Timing detectors could allow to relax the selection cuts in this configuration.

ζ, $\tilde{\zeta}$ at the High Luminosity LHC

Coupling	ζ ($\tilde{\zeta} = 0$)		$\zeta = \tilde{\zeta}$	
Luminosity	$3000\,\mathrm{fb}^{-1}$		$3000\,\mathrm{fb}^{-1}$	
Pile-up	200		200	
Channel	5σ	95 % C.L.	5σ	95% C.L.
$\ell\ell\gamma$	1.6×10^{-13}	8×10^{-14}	1.4×10^{-13}	6.9×10^{-14}
$\ell\ell\gamma$ (f.f.)	6.4×10^{-13}	1.3×10^{-13}	5.5×10^{-13}	1.1×10^{-13}

- Measurement in the $\ell\bar{\ell}\gamma$ channel is feasible at $\mu = 200$ and $3000\,\mathrm{fb}^{-1}$. However, we don't gain much reach in the search for the anomalous $Z\gamma$ production.

Conclusions & Outlook

- CT-PPS/AFP provide a unique opportunity to study the anomalous quartic gauge boson couplings.
- In this talk, we discussed specifically the $Z\gamma\gamma\gamma$ coupling via photo-induced processes with proton tagging at the LHC in a model independent way.
- $Z\gamma$ exclusive channel: $\ell\bar{\ell}\gamma$ proves to be clean.
- We provide sensitivities for 300 fb^{-1} and moderate pile-up $\mu = 50$.

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