Probing the anomalous $\gamma\gamma\gamma Z$ coupling at the LHC with proton tagging

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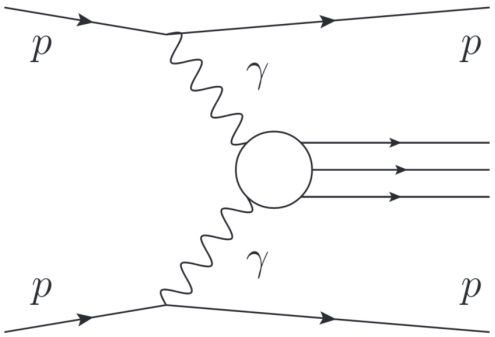
Exclusive processes at CT-PPS/AFP

- Exclusive reactions $pp \to p + X + p$ can be studied by measuring X in a general purpose detector (e.g., CMS, ATLAS) and the scattered intact protons 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 exclusive channel allows us to probe pure gauge interactions with unprecedented sensitivity, since σ^{SM}_{Excl} is typically small for $m_X > 500$ 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. Exclusive processes yield $y_{pp} = y_X$, $m_{pp} = m_X$.



Anomalous quartic gauge couplings at the LHC

It has been discussed before the possibility of studying BSM pure gauge interactions $\gamma\gamma\gamma\gamma$, $\gamma\gamma W^+W^-$ in the exclusive channel. [1],[2],[3]. 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.
We address the anomalous $\gamma\gamma\gamma Z$ coupling reach at the LHC in pp collisions via photon-induced $Z\gamma$ with leading intact protons in the final state, i.e., $pp \to pjj\gamma p$, $pp \to p\ell\bar{\ell}\gamma p$.

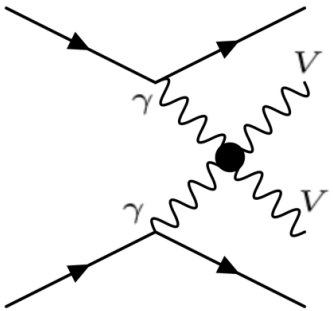


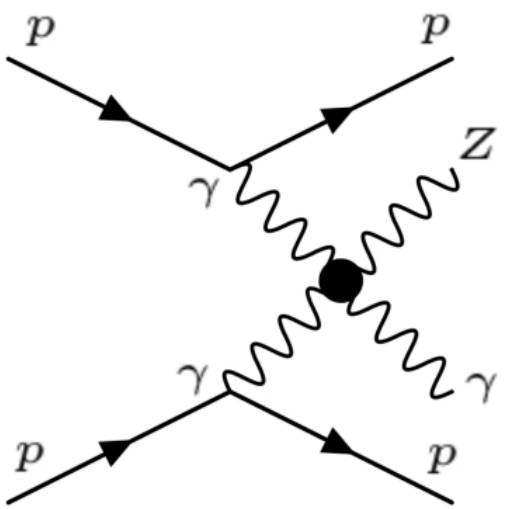
Figure : VV $= \gamma\gamma$, ZZ, W^+W^-, $Z\gamma$.

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 of choice (e.g., warped extra-dimensions, composite Higgs, new particles). The $\gamma\gamma\gamma Z$ coupling is induced by two dimension-8 operators,

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

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



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

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

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

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

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

Our sensitivities are about 10^2 lower than this bound; form factor is not necessary within the mass acceptance in CT-PPS/AFP ($m_{Z\gamma} \in$ [200 GeV,1.9 TeV])

New Physics contributions to $3\gamma Z$ coupling

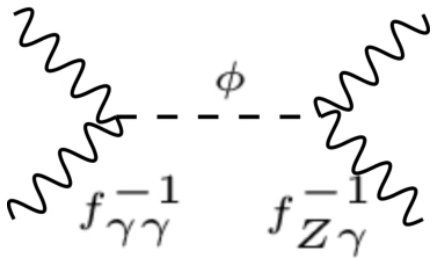
***s*-channel exchange** Induced by exchange of a neutral resonance on the *s*-channel. The effective coupling is,

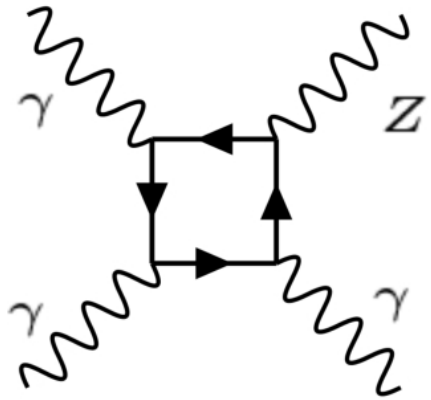
$$(\zeta, \tilde{\zeta}) = \frac{1}{f_s^{\gamma\gamma} f_s^{Z\gamma}\, m^2} (d_s, \tilde{d}_s) \qquad (4)$$

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

$$(\zeta, \tilde{\zeta}) \propto Y^4\, m^{-4}\, (\, c_s, \tilde{c}_s) \qquad (5)$$

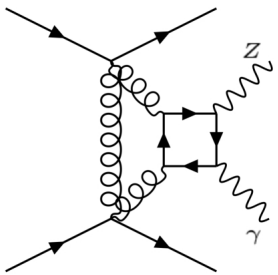
(See arXiv:1703.10600 for full expression)



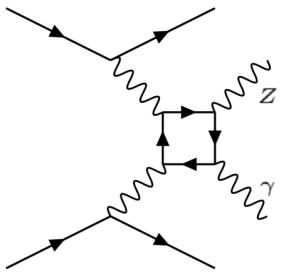


Background in the exclusive $pZ\gamma p$ channel

Exclusive background

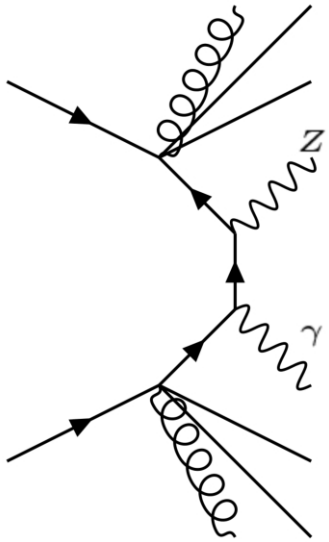


Khoze Martin Ryskin-like $Z\gamma$ (Highly suppressed at high mass due to Sudakov factor).



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

$Z\gamma$ final state + pile-up

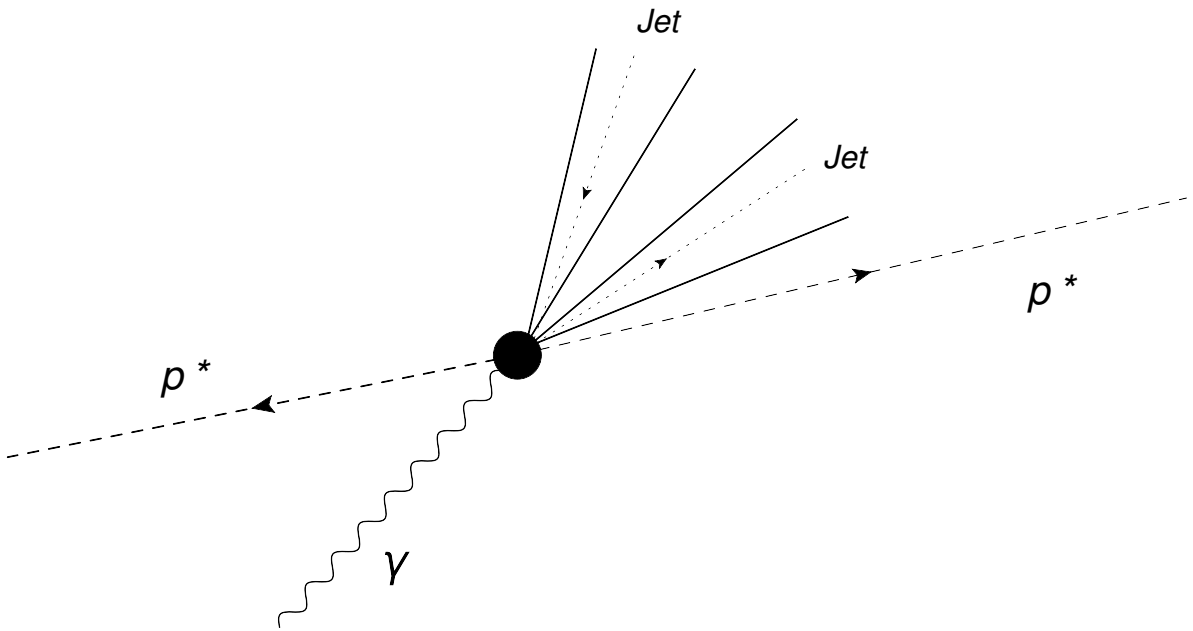


$Z\gamma$ + protons from pile-up interactions. Reducible by exploiting exclusivity cuts set by proton taggers $\xi_{1,2}$ measurement. This constitutes the dominant background, which is the focus of our study.

Signal and background generation

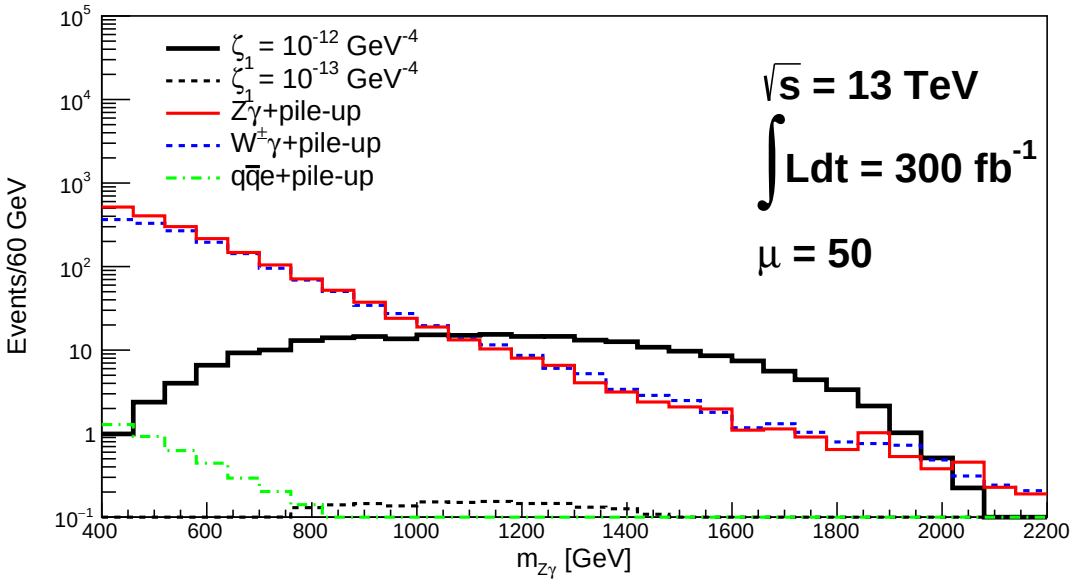
- The anomalous $pp \to pZ\gamma p$ process was implemented in the Forward Physics Monte Carlo. The Equivalent Photon Approximation is used to take into account the coherent photon flux from the interacting protons. Intact protons lie within the nominal acceptance $0.015 < \xi_{1,2} < 0.15$ of the proton taggers.
- Non-exclusive hard scattering events (PYTHIA8) in association with protons arising from pile-up interactions.
- Smearing on η, ϕ, p_T, E on photons, leptons and hadrons to simulate the effects of the detector, as well as acceptance cuts. We apply an smearing of 15% on the energy of the reconstructed jet. We reconstruct jets with *anti-kt* clustering algorithm with $R = 0.4$ w/ FastJet library.

$Z\gamma \rightarrow$jjγ channel



Proton tagging allows us to study the exclusive $Z\gamma$ production in the $jj\gamma$ channel. Dijet and photon are back-to-back, leading protons are detected in forward detectors.

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.
- Dijet and photon balanced in momentum (Similar p_T and back-to-back).

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

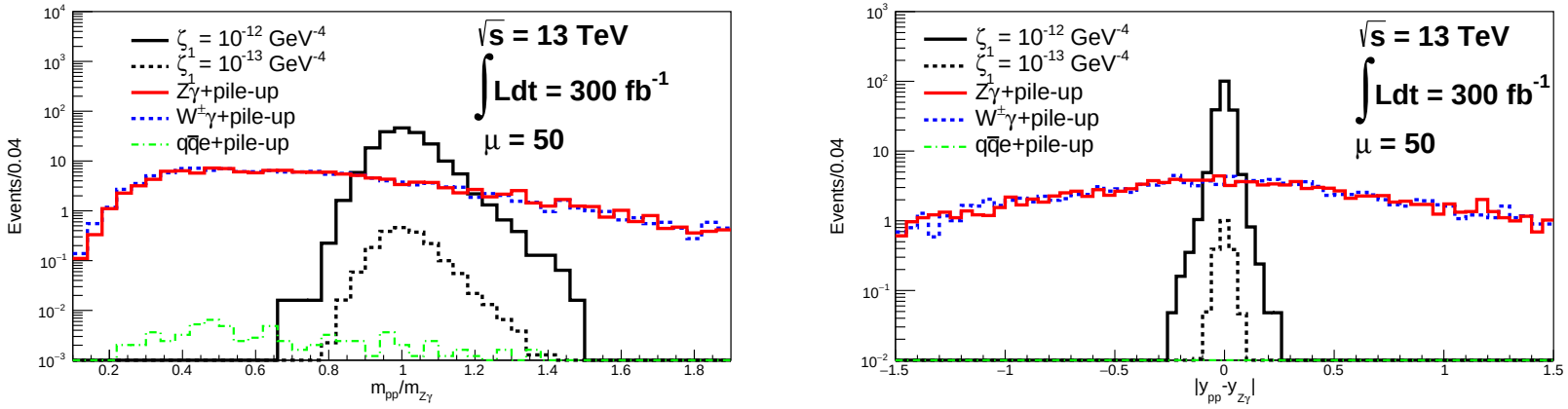


Figure : Left: Mass ratio $m_{pp}/m_{Z\gamma}$. Right: Rapidity difference $|y_{pp} - y_{jj\gamma}|$.

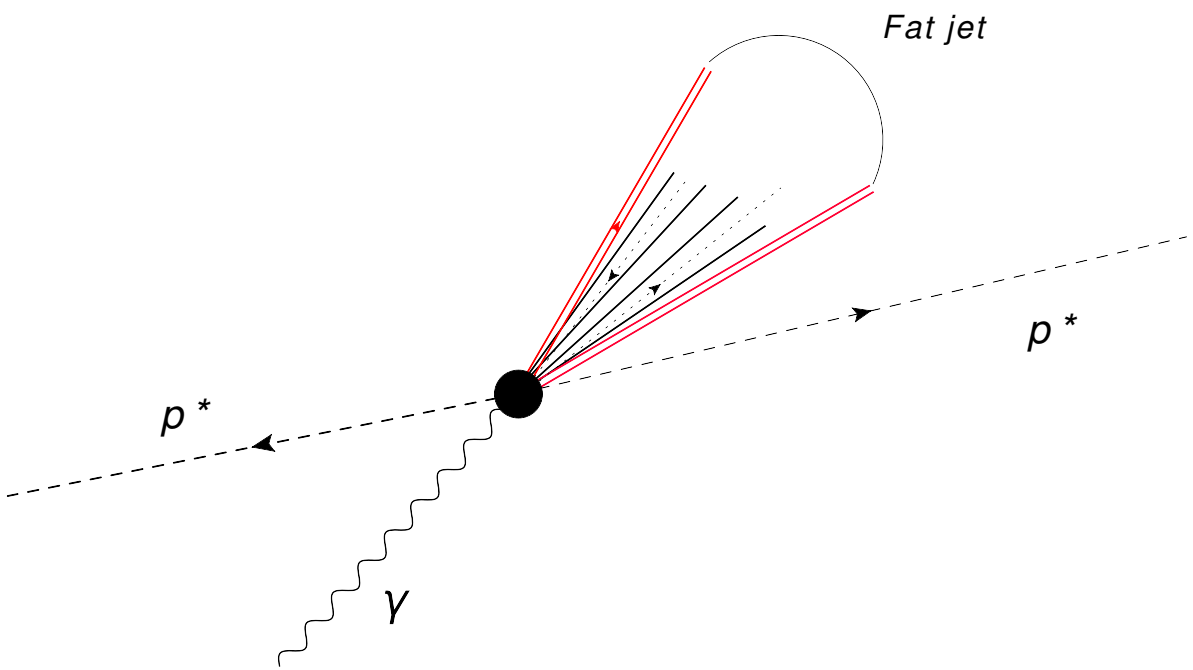
- Signal peaks on the $m_{pp}/m_{Z\gamma}$ and $|y_{pp} - y_{Z\gamma}|$ distributions. Criteria for exclusive event selection.
- Width for the signal are due to smearing on $\xi_{1,2}$ of 2% and the large energy resolution on the reconstructed jets energy $\sim$ 15%.

Event selection (Hadronic channel)

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	γZ +pile-up	$W^{\pm}\gamma$ +pile-up	$jje^{\pm}$ +pile-up
$0.015 < \xi_{1,2} < 0.15$, $p_{T\gamma} > 150$ GeV $p_{Tjj} > 100$ GeV]	38.6	51.4	1951.8	1631	8.47
$m_{\gamma Z} > 700$ GeV	37	49.5	349.8	358.9	1.3
$p_{T\gamma}/p_{Tjj} > 0.90$, $\lvert\Delta\phi - \pi\rvert < 0.02$	33.8	45.1	144.7	145.4	0.54
$\sqrt{\xi_1\xi_2 s} = m_{\gamma Z} \pm 10\%$	28.2	35.7	19.7	19.3	0.1
$\lvert y_{pp} - y_{\gamma Z}\rvert < 0.05$	25.5	32.7	1.5	1.6	0

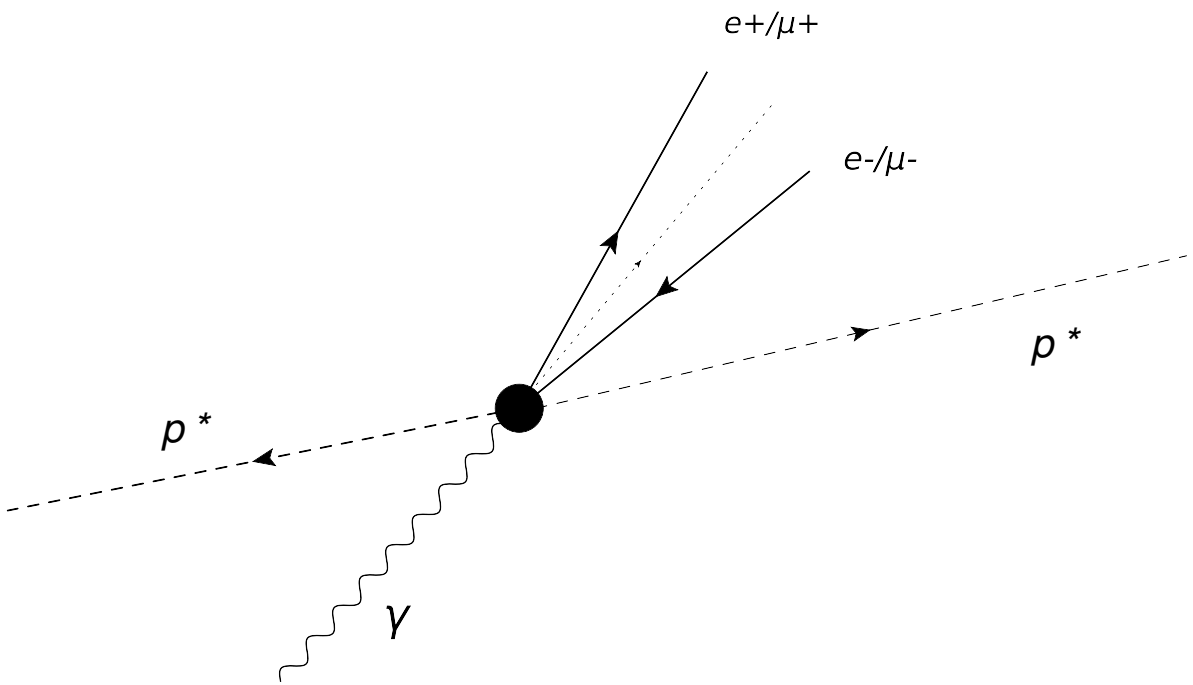
- Event selection considers 300 fb^{-1} and $\mu = 50$ and a coupling value of $\zeta = 4 \times 10^{-13}\mathrm{GeV}^{-4}$ at $\sqrt{s} = 13$ TeV. Final state hadrons are reconstructed with anti-kt clustering algorithm with $R = 0.4$.
- About three background events remain after selection cuts.
- Timing detector technology to resolve exclusive event vertices would enhance the sensitivity.

$Z\gamma \rightarrow$ Large radius jet + γ channel



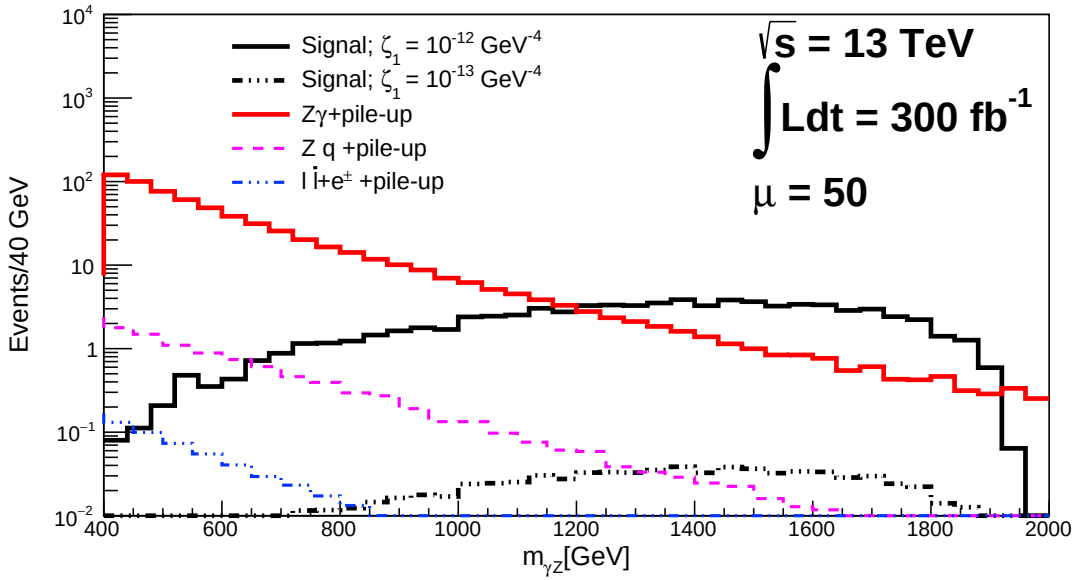
About 55% of the jets coming from the Z (For the anomalous signal) are reconstructed as large radius jets. Out of the scope of this study, but we could increase our reach on ζ, $\tilde{\zeta}$ by, in addition, looking at $pJ\gamma p$ final states.

$Z\gamma \to \ell\bar{\ell}\gamma$ channel



Proton tagging allows us to study the exclusive $Z\gamma$ production in the $\ell\bar{\ell}\gamma$ channel.

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 (Topology).

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

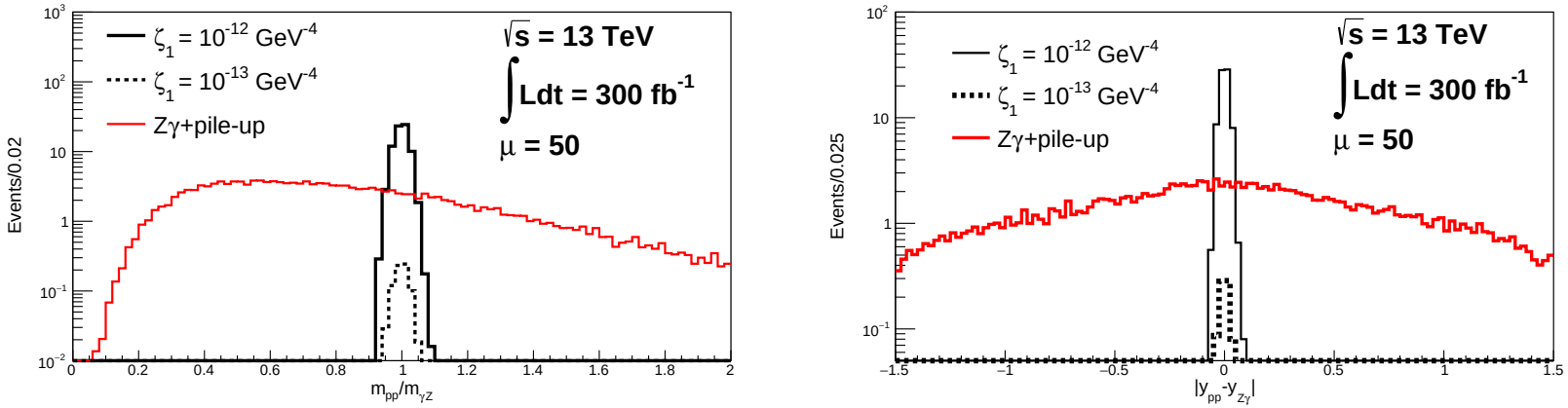


Figure : Left: Missing diproton mass m_{pp} to $m_{Z\gamma}$ ratio. Right: Rapidity difference $|y_{pp} - y_{\ell\bar{\ell}\gamma}|$

- Signal peaks on the $m_{pp}/m_{Z\gamma}$ and $|y_{pp} - y_{Z\gamma}|$ distributions. Criteria for exclusive event selection. ($m_{pp} = \sqrt{\xi_1\xi_2 s}$, $y_{pp} = \frac{1}{2}\log(\xi_1/\xi_2)$)
- Widths for the signal are due to the smearing on $\xi_{1,2}$ due to detector effects (2% smearing).

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

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	γZ +pile-up	$\ell\bar{\ell}j$ +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	17.4	2239.2	64.5	1.2
$m_{\gamma Z} > 600$ GeV	12.9	17.1	227	3.8	0.2
$p_{T\gamma}/p_{T\ell\bar{\ell}} > 0.95$, $\lvert\Delta\phi - \pi\rvert < 0.02$	12.6	16.7	175	0	0
$\sqrt{\xi_1\xi_2 s} = m_{\gamma Z} \pm 5\%$	12.2	16.4	12.7	0	0
$\lvert y_{pp} - y_{\gamma Z}\rvert < 0.03$	10	13.7	0.6	0	0

- Event selection considers $= 300\ fb^{-1}$ and $\mu = 50$ and a coupling value of $\zeta = 4 \times 10^{-13}\mathrm{GeV}^{-4}$ ($\sigma_{\gamma Z} \sim 1fb$) 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

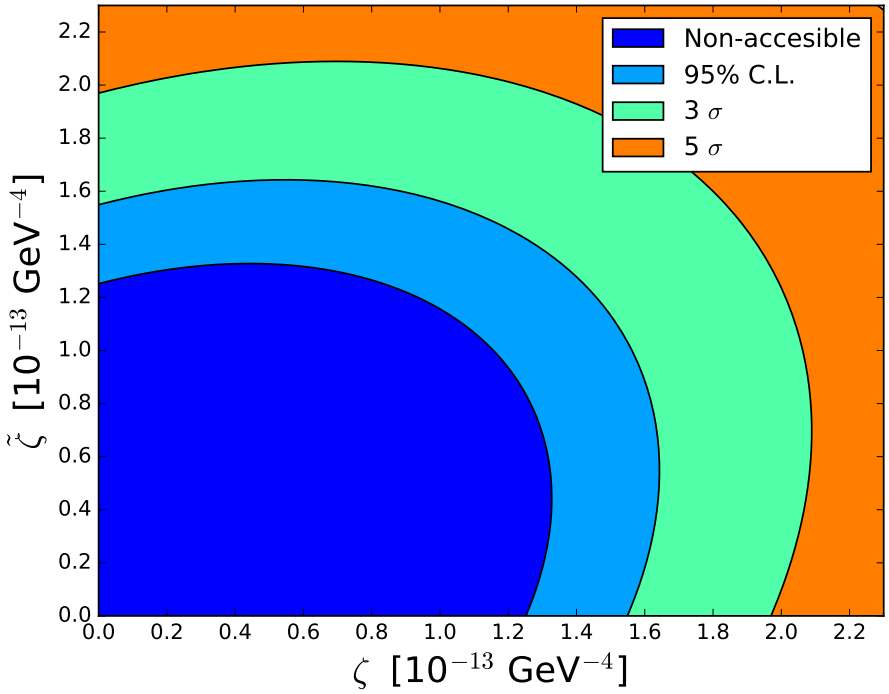
Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8\cdot10^{-13}$	$1.8\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.5\cdot10^{-13}$
$jj\gamma$	$2.3\cdot10^{-13}$	$1.5\cdot10^{-13}$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

Sensitivities down to $1.3\times10^{-13}\mathrm{GeV}^{-4}$ 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,

$$\sqrt{\zeta^2+\tilde{\zeta}^2-\frac{\zeta\tilde{\zeta}}{2}}<1.3\cdot10^{-9}\ \mathrm{GeV}^{-4}\quad(95\%\mathrm{CL}) \tag{6}$$

Our sensitivity at 300 fb^{-1} provides a stronger constraint on ζ, $\tilde{\zeta}$ by a factor of $\sim10^3$.

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

Search at the High Luminosity LHC

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	γZ +pile-up	$\ell\bar{\ell}j$ +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	132.8	6403.6	1207.3	30.1
$m_{\gamma Z} > 1100$ GeV	77.2	105.5	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	104.8	458.2	19.2	0.5
$\sqrt{\xi_1\xi_2 s} = m_{\gamma Z} \pm 3\%$	62.2	85	16.4	1.2	0
$\lvert y_{pp} - y_{\gamma Z}\rvert < 0.025$	46.2	72	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.
$\ell\bar{\ell}\gamma$	$1.8 \cdot 10^{-13}$	$1.1 \cdot 10^{-13}$	$1.25 \cdot 10^{-13}$	$7.8 \cdot 10^{-14}$

- 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

- We addressed the discovery potential for the anomalous $Z\gamma\gamma\gamma$ coupling via photo-induced $Z\gamma$ with leading intact protons at the LHC. For this, we
- Background rejection in the exclusive channel allows to consider hadronic final states in addition to the leptonic ones, which increases our reach in the $\zeta, \tilde{\zeta}$ couplings.
- We provide sensitivities for $300\,\mathrm{fb}^{-1}$ and at moderate pile-up $\mu = 50$ at $\sqrt{s} = 13$ TeV.
- The exclusive channel could provide stronger bounds on $\zeta_{\gamma Z}$ and $\tilde{z}eta_{\gamma Z}$ than the measurement $\mathcal{BR}(Z \to \gamma\gamma\gamma)$.

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