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

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## Central exclusive reactions processes

- Central exclusive reactions $p p \rightarrow p+X+p$ can be studied by measuring $X$ ( $X=\gamma \gamma, \ell \bar{\ell}, W^{+} W^{-}, Z Z$ ) in a general purpose detector (e.g., CMS, ATLAS) and the scattered intact protons $p p$ with forward proton detectors located at $\sim$ 210 m w.r.t. main interaction vertex. These can be due to $\gamma-\mathbb{P}, \mathbb{P}-\mathbb{P}$ 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 $\sigma_{E x c l}^{S M}$ is typically small for $m_{X}>600 \mathrm{GeV}$.
- Measure the proton fractional momentum loss $\xi=\Delta p / p$ with the forward proton detectors $\mathrm{w} /$ nominal acceptance $0.015<\xi_{1,2}<0.15$.
- Event selection criteria: Compute the diffractive mass $m_{p p}=\sqrt{\xi_{1} \xi_{2} s}$ and rapidity $y_{p p}=\frac{1}{2} \log \left(\xi_{1} / \xi_{2}\right)$ and compare with $m_{X}$ and $y_{X}$. Central exclusive processes yield $y_{p p}=y X, m_{p p}=m_{X}$.


## CMS-TOTEM Precision Proton Spectrometer (CT-PPS)



- 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 $p p \rightarrow p X p$ 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 $\xi)$.
- Observation of the $p p \rightarrow p^{*} \mu^{+} \mu^{-} p$ in CT-PPS CMS-PAS-PPS-17-001.

Standard candle measurement for central exclusive production in $p p$ 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 $S U(2) \times U(1)_{Y}$ 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 $p p$ collisions via photon-induced processes with leading intact protons in the final state, i.e., $p p \rightarrow p \gamma \gamma p$. [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: $\mathbf{V V}=\gamma \gamma, Z Z, W^{+} W^{-}, Z \gamma$.

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

Effective Field Theory assumption, $\Lambda_{N e w}$ 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 ,

$$
\begin{equation*}
\mathcal{L}_{4 \gamma}=\zeta_{1} F^{\mu \nu} F_{\mu \nu} F^{\rho \sigma} F_{\rho \sigma}+\zeta_{2} F_{\mu \nu} F^{\nu \rho} F_{\rho \lambda} F^{\lambda \mu} \tag{1}
\end{equation*}
$$

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,

$$
\begin{equation*}
\frac{\mathrm{d} \sigma_{\gamma \gamma \rightarrow \gamma \gamma}}{\mathrm{d} \Omega}=\frac{1}{16 \pi^{2} s}\left(s^{2}+t^{2}+s t\right)^{2}\left[48 \zeta_{1}^{2}+40 \zeta_{1} \zeta_{2}+11 \zeta_{2}^{2}\right] \tag{2}
\end{equation*}
$$

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

$$
\begin{equation*}
\zeta_{1}, \zeta_{2}<\left(10^{-12}-10^{-11}\right) \mathrm{GeV}^{-4} \tag{3}
\end{equation*}
$$

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

## 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,

$$
\begin{equation*}
\left(\zeta_{1}, \zeta_{2}\right)=\frac{1}{\left(f_{\phi}^{\gamma} m\right)^{2}}\left(d_{1, s}, d_{2, s}\right) \tag{4}
\end{equation*}
$$

Where $1 / f_{\phi}^{\gamma}$ is the tree-level coupling, $m$ its mass.
Loop of heavy charged can induce the $\zeta_{1}$, $\zeta_{2}$ couplings

$$
\begin{equation*}
\left(\zeta_{1}, \zeta_{2}\right)=\alpha_{e m}^{2} Q^{4} m^{-4} N\left(c_{1, s}, c_{2, s}\right) \tag{5}
\end{equation*}
$$

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 $\gamma \gamma\left(\sim 10^{-1} \mathrm{fb}\right.$ 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 $\xi_{\text {central }}$ and $\xi_{\text {forward }}$ )

## 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 $p_{T, \gamma, \text { lead }}\left(p_{T, \gamma, \text { sublead }}\right)>200(100) \mathrm{GeV}$ and $m_{\gamma \gamma}>600 \mathrm{GeV}$, 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).


## Forward proton detector $\xi_{1,2}$ measurement



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

- Exclusive processes peak on the $m_{p p} / m_{\gamma \gamma}$ and $\left|y_{p p}-y_{\gamma \gamma}\right|$ distributions. (Reminder: $m_{p p}=\sqrt{\xi_{1} \xi_{2} s}, y_{p p}=\frac{1}{2} \log \left(\xi_{1} / \xi_{2}\right)$ )
- 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 | $\begin{gathered} \text { Signal } \\ \text { (full) } \end{gathered}$ | Signal with (without) f.f (EFT) | Excl. | DPE | $\begin{gathered} \hline \text { DY, } \\ \text { di-jet } \\ +\quad \text { pile up } \\ \hline \end{gathered}$ | $\begin{gathered} \gamma \gamma \\ + \text { pile up } \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\begin{gathered} {\left[0.015<\xi_{1,2}<0.15,\right.} \\ \left.p_{\mathrm{T} 1,(2)}>200,(100) \mathrm{GeV}\right] \end{gathered}$ | 65 | 18 (187) | 0.13 | 0.2 | 1.6 | 2968 |
| $m_{\gamma \gamma}>600 \mathrm{GeV}$ | 64 | 17 (186) | 0.10 | 0 | 0.2 | 1023 |
| $\begin{aligned} & {\left[p_{\mathrm{T} 2} / p_{\mathrm{T} 1}>0.95,\right.} \\ & \|\Delta \phi\|>\pi-0.01] \end{aligned}$ | 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 |
| $\left\|y_{\gamma \gamma}-y_{p p}\right\|<0.03$ | 60 | 12 (169) | 0.09 | 0 | 0 | 0 |

- Event selection considers $\int \mathcal{L} \mathrm{d} t=300 \mathrm{fb} b^{-1}$ and $\langle\mu\rangle=50$ interactions per bunch crossing and fixed coupling value at $\sqrt{s}=14 \mathrm{TeV}$.
- 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.


## $\zeta_{1}, \zeta_{2}$ reach at CT-PPS/AFP

| Luminosity | $300 \mathrm{fb}^{-1}$ | $300 \mathrm{fb}^{-1}$ | $300 \mathrm{fb}^{-1}$ | $300 \mathrm{fb}^{-1}$ | $3000 \mathrm{fb}^{-1}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| pile up $(\mu)$ | 50 | 50 | 50 | 50 | 200 |
| coupling | $\geq 1$ conv. $\gamma$ | $\geq 1$ conv. $\gamma$ | all $\gamma$ | all $\gamma$ | all $\gamma$ |
| $\left(\mathrm{GeV}^{-4}\right)$ | $5 \sigma$ | $95 \% \mathrm{CL}$ | $5 \sigma$ | $95 \% \mathrm{CL}$ | $95 \% \mathrm{CL}$ |
| $\zeta_{1}$ f.f. | $1.5 \cdot 10^{-13}$ | $7.5 \cdot 10^{-14}$ | $6 \cdot 10^{-14}$ | $4 \cdot 10^{-14}$ | $3.5 \cdot 10^{-14}$ |
| $\zeta_{1}$ no f.f. | $3.5 \cdot 10^{-14}$ | $2.5 \cdot 10^{-14}$ | $2 \cdot 10^{-14}$ | $1 \cdot 10^{-14}$ | $1 \cdot 10^{-14}$ |
| $\zeta_{2}$ f.f. | $2.5 \cdot 10^{-13}$ | $1.5 \cdot 10^{-13}$ | $1.5 \cdot 10^{-13}$ | $8.5 \cdot 10^{-14}$ | $7 \cdot 10^{-14}$ |
| $\zeta_{2}$ 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 $\mathcal{O}\left(10^{-13}\right) \mathrm{GeV}^{-4}$ in $\zeta_{1}, \zeta_{2}$ at $95 \% \mathrm{CL}$ for $\int \mathcal{L} d t=300 \mathrm{fb}^{-1}$ at 14 TeV .

## Couplings reach at the LHC with the exclusive channel


$95 \%$ C.L., $3 \sigma$ and $5 \sigma$ reach in the anomalous couplings $\zeta_{1}, \zeta_{2}$ in red, grey and yellow respectively for $300 \mathrm{fb}^{-1}$ and $\mu=50$. Couplings for which $\sim 0$ after selection cuts in white.

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

Effective Field Theory assumption, $\Lambda_{N e w}$ 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,

$$
\begin{equation*}
\mathcal{L}_{\gamma \gamma \gamma}=\zeta^{Z \gamma} F^{\mu \nu} F_{\mu \nu} F^{\rho \sigma} Z_{\rho \sigma}+\tilde{\zeta}^{Z \gamma} F^{\mu \nu} \tilde{F}_{\mu \nu} F^{\rho \sigma} \tilde{Z}_{\rho \sigma} \tag{6}
\end{equation*}
$$

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. $\mathcal{B R}(Z \rightarrow q \bar{q})$ enhances sensitivity on $\zeta, \tilde{\zeta}$ considerably.

## Distribution of signal and background $Z_{\gamma}$



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


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



Figure : Left: Mass ratio $m_{p p} / m_{z \gamma}$. Right: Rapidity difference $\left|y_{p p}-y_{j j \gamma}\right|$. Signal in black.

- Signal peaks on the $m_{p p} / m_{Z_{\gamma}}$ and $\left|y_{p p}-y_{Z_{\gamma}}\right|$ 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 $\left(\mathrm{GeV}^{-4}\right)$ | $\zeta(\tilde{\zeta}=0)$ |  | $\zeta=\tilde{\zeta}$ |  |
| :---: | :---: | :---: | :---: | :---: |
| Luminosity | $300 \mathrm{fb}^{-1}$ |  | $300 \mathrm{fb}^{-1}$ |  |
| Pile-up $(\mu)$ | 50 |  | 50 |  |
| Channels | $5 \sigma$ | $95 \% \mathrm{CL}$ | $5 \sigma$ | $95 \% \mathrm{CL}$ |
| $\ell \bar{\ell} \gamma$ | $2.8 \cdot 10^{-13}$ | $1.8 \cdot 10^{-13}$ | $2.5 \cdot 10^{-13}$ | $1.5 \cdot 10^{-13}$ |
| $j j \gamma$ | $2.3 \cdot 10^{-13}$ | $1.5 \cdot 10^{-13}$ | $2 \cdot 10^{-13}$ | $1.3 \cdot 10^{-13}$ |
| $j j \gamma \bigoplus \ell \bar{\ell} \gamma$ | $1.93 \cdot 10^{-13}$ | $1.2 \cdot 10^{-13}$ | $1.7 \cdot 10^{-13}$ | $1 \cdot 10^{-13}$ |

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

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

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

## $\zeta-\tilde{\zeta}$ sensitivity plane


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

## 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 $\nu$. 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:

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

For instance, a $\delta t=30 p s$ yields $\delta z_{p p} \approx 6 \mathrm{~mm}$

## 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.
- Stay tuned for results with the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) and ATLAS Forward Physics (AFP)!

