Anomalous couplings with proton tagging

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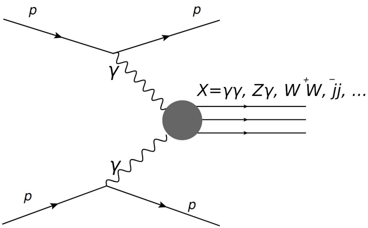
The LHC as a photon-photon collider



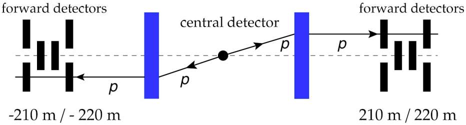
Most LHC studies are based on quark- and gluon-initiated processes, with sizable cross sections for new physics searches. This is the heart of the CERN LHC physics program.

In quasi-real photon exchange processes, we can have reactions like $pp \to pXp$ where $X = \gamma\gamma$, W^+W^-, ZZ, $Z\gamma$, jets, and the protons remain intact with a small fraction of beam-momentum loss $\xi \equiv \Delta p/p$. If we reconstruct X in ATLAS/CMS, and tag each of the scattered protons, we can reconstruct the complete final state "a la LEP".

Quasi-real photon exchange treated in the equivalent photon approximation (EM form factors) $\to$ Good theoretical control.

Absence of underlying event activity and QCD initial-state radiation effects in central exclusive production $\to$ Very clean final-state.

Forward proton detectors



LHC magnets (blue boxes) bend scattered protons out of the beam envelope.

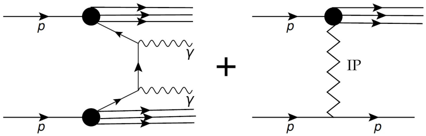
Central system X reconstructed with central detector (ATLAS, CMS), and intact protons are tagged with forward proton detectors (Roman Pot detectors). The latter detect protons at a few mm from the beam at 210 m from the interaction point.

ATLAS Forward Proton (**AFP**, `https://cds.cern.ch/record/2017378`) and CMS-TOTEM Precision Proton Spectrometer (**PPS**, `https://cds.cern.ch/record/1753795`) are two such systems that were brought online during Run-2. There is 115 fb^{-1} of data collected with these detectors, and these are planned to be running after shutdown (PPS).

Reconstruct fractional momentum loss of each proton, $\xi \equiv \Delta p/p$. The standard acceptance is of $0.015 < \xi < 0.15$. This translates to a mass acceptance of $0.3 \lesssim m_X \lesssim 2$ TeV ($m_X = \sqrt{\xi_1 \xi_2 s}$).

Photon physics at electroweak energy scale and beyond is a reality. First physics results by CMS and TOTEM JHEP 07 (2018) 153 by studying $pp \to p\ell^+\ell^-p^{(*)}$. See talk by Justin Williams today on PPS prospects.

Dominant background: pileup



Soft single- and central-diffraction ($pp \to pX$ and $pp \to pXp$) are produced copiously at the LHC ($\sigma = \mathcal{O}(10)$ mb at 13 TeV). With 30–50 interactions per bunch crossing, we tag protons from soft diffraction frequently.

This can mimick signal signature when we detect uncorrelated protons from pileup interactions + a hard scattering signature in central detector (standard high-p_T photons, jets, ...).

Can be largely suppressed by looking at kinematic correlations between the central system and forward system, since we have kinematic constraint set by the complete reconstruction of the final state (shown in a future slide).

Time-of-flight measurement

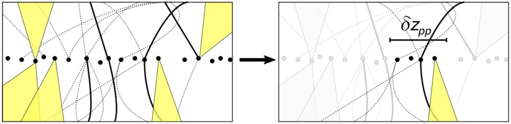


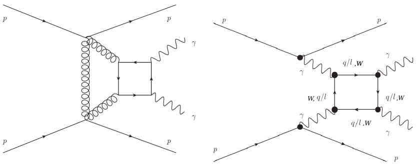
Fig. by L. Forthomme.

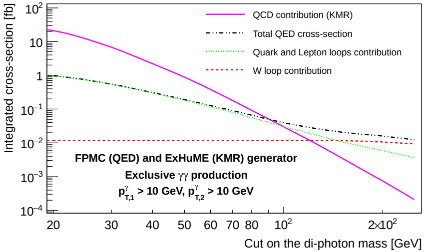
One can further measure the difference in time-of-flight of the scattered protons on both sides, and deduce the position of the interaction vertex. A timing precision of 20 ps corresponds to a vertex position determination of 2 mm.

One can further suppress pileup contributions by looking at the position of the reconstructed primary vertex with standard tracking techniques and that reconstructed independently with the proton time-of-flight measurement. One can have additional rejection factor of ≈ 40 on pileup backgrounds with this method.

Very important to suppress background in channels highly sensitive to pileup contributions (jet production, final states with missing transverse momentum).

High-mass exclusive production with intact protons





S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 02 (2015) 165

Cross section for SM exclusive $\gamma\gamma$ as a function of the $m_{\gamma\gamma}$ cut. Two-gluon exchange QCD contribution is highly suppressed at large invariant masses (Sudakov form factor). $W^{\pm}$ boson loops dominate at high $m_{\gamma\gamma}$ probed in the CT-PPS/AFP acceptance. SM $\gamma\gamma \to \gamma\gamma$ cross section is $\mathcal{O}(10^{-2})$ fb $\to$ Sensitive to new physics contributions.

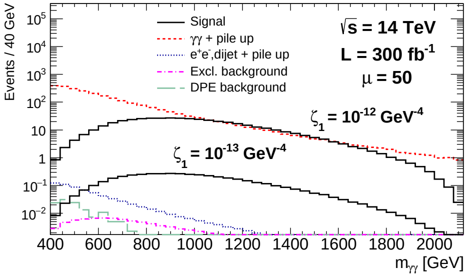
In a nutshell, high-mass two-proton tagged system $\to$ dominated by two-photon exchange over QCD color-singlet exchange.

Photon-exchange processes implemented in Forward Physics Monte Carlo (FPMC) generator. Similar implementations in Starlight and SuperChic3 generators.

Parametrize deviations from SM $\gamma\gamma \to \gamma\gamma$ in effective field theory approach, by integrating out new degrees of freedom assuming $\Lambda_{NP} \gg \sqrt{s_{\gamma\gamma}}$. The 4γ interaction coupling can be parametrized in the effective field theory framework via two dimension-8 operators:

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

where $\zeta_{1,2}$ are the 4γ anomalous couplings.



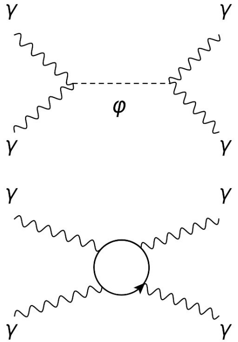
Diphoton invariant mass distribution (pre-selection level). Pileup background in red, SM exclusive $\gamma\gamma$ in magenta, and potential anomalous coupling contribution with $\zeta_1 = 10^{-13}$ and $\zeta_1 = 10^{-12}$ GeV^{-4}.

S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 02 (2015) 165

s-channel exchange of a neutral resonance. The effective coupling is (for $\Lambda_{NP} \gg m_{\gamma\gamma}$),

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

where $d_{1,s}, d_{2,s}$ are some numerical constants function of the spin of the neutral resonance, m is the mass of the particle, and f^γ the tree-level coupling.



Heavy electrically charged particles contribute directly to the scattering of light-by-light via loops,

$$\{\zeta_1, \zeta_2\} = \alpha_{\text{em}} Q^4 m^{-4} c_{1,s}, c_{2,s} \qquad (3)$$

where $d_{1,s}, d_{2,s}$ are some numerical constants function of the spin of the neutral resonance.

Standard analysis strategies

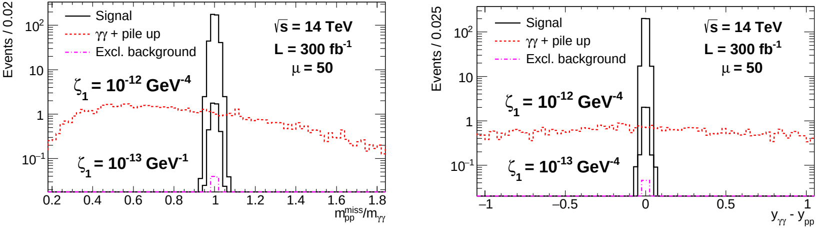
Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ GeV]	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	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

S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 02 (2015) 165

Selection requirements to suppress pileup background, exploiting topology of central exclusive production. End up with a nearly background-free probe of light-by-light scattering at high-mass.

Note that the mass matching and rapidity matching selection requirements are fundamental in the analysis, which directly exploit the kinematic constraint set by the proton tagging.

Rapidity and mass matching: key to suppress pileup background



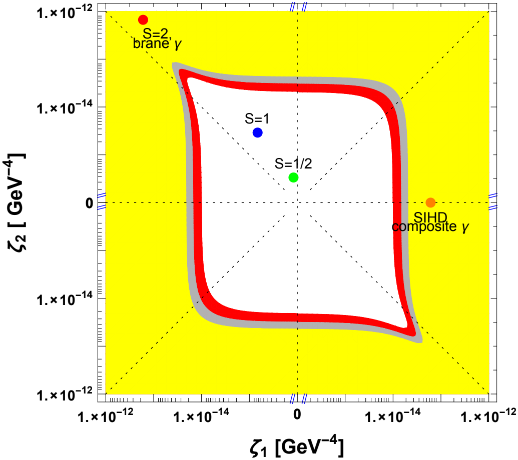
S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 02 (2015) 165

We can calculate the diphoton mass and the rapidity with the central detector information (ATLAS, CMS) or with $\xi_{1,2}$. By virtue of momentum conservation, we have the relations between diphoton and protons:

$$m_{\gamma\gamma} = \sqrt{\xi_1 \xi_2 s} \equiv m_{pp}$$

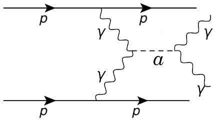
$$y_{\gamma\gamma} = \frac{1}{2} \log(\xi_1/\xi_2) \equiv y_{pp}$$

Pileup protons are uncorrelated with standard diphoton. Therefore, no correlations are expected when looking at $m_{pp}/m_{\gamma\gamma}$ and $y_{pp} - y_{\gamma\gamma}$. **A cut on these variables is absolutely necessary to suppress pileup!** Couplings can be probed at $\zeta_{1,2} \approx 10^{-14}$ GeV^{-4}.



95% CL, 3σ, and 5σ reach on anomalous couplings ζ_1, ζ_2 in red, grey, yellow regions respectively for 300 fb^{-1} and $\langle\mu\rangle = 50$ at $\sqrt{s} = 14$ TeV. (S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 02 (2015) 165). Couplings can be probed at $\zeta_{1,2} \approx 10^{-14}$ GeV^{-4}.

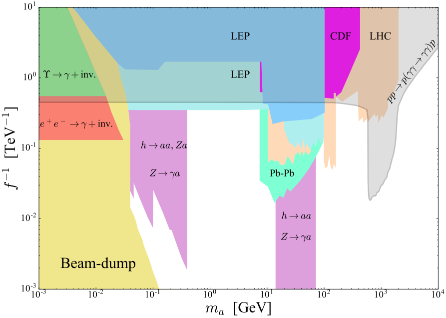
Pseudoscalars coupled to electromagnetic field. Large mass ALPs need to be constrained with collider probes → Challenging in collisions dominated by QCD interactions. Further constrains in central exclusive production of photon pairs.



Model ALP–hoton coupling via dimension-five operator

$$\mathcal{L}_{\text{int}} = \frac{1}{f} m_a a F \tilde{F}$$

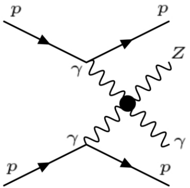
Where a is the ALP field, and $1/f$ and m_a the coupling parameter and ALP mass.

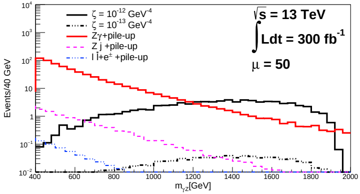


We can improve the sensitivity for ALP masses 0.6–2 TeV for coupling values of $1/f = 10^{-2}$ –10^{-1} TeV^{-1} at 300 fb^{-1} at 14 TeV.

Projections for 300 fb^{-1}. **CB, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 131**

Phase space complementary to that covered in PbPb ultraperipheral collisions.





CB, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142.

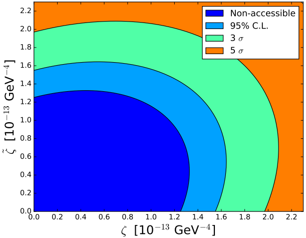
The presence of new particles charged under SU(2)$\times$ U$_Y$(1) induce anomalous $\gamma\gamma\gamma Z$ coupling via loop corrections. Effective dimension-8 field theory at low energies reads,

$$\mathcal{L}_{3\gamma Z} = \zeta F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \tilde{\zeta} F^{\mu\nu} \tilde{F}_{\mu\nu} F^{\rho\sigma} \tilde{Z}_{\rho\sigma} \quad (4)$$

where $\tilde{F}_{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$, and $\zeta, \tilde{\zeta}$ are the interaction couplings. The interaction can be probed in $\gamma\gamma \to \gamma Z$ scattering.

Z boson decays into charged lepton pair or hadronically, in association with an isolated photon. Similar selection requirements as in the exclusive diphoton production for the reconstructed Z boson and the photon.

Sensitivity to anomalous $\gamma\gamma\gamma Z$ coupling



CB, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142.

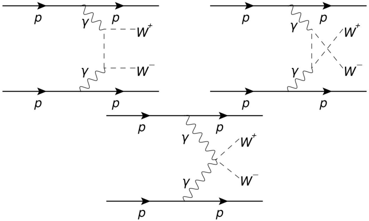
Existing bound at 95%CL set via measurement of $\mathcal{B}(Z \to \gamma\gamma\gamma) < 2.2 \times 10^{-6}$ at 8 TeV by the ATLAS Collaboration Eur. Phys. J. C 76(4), 1-26 (2016). This translates to an upperbound on the $3\gamma Z$ anomalous couplings,

$$\sqrt{\zeta^2 + \tilde{\zeta}^2 - \frac{2}{3}\zeta\tilde{\zeta}} \leq 1.3 \times 10^{-9}\ \text{GeV}^{-4} \tag{5}$$

Expected bound at 95% CL by studying reaction $pp \to pZ\gamma p$ at 300 fb^{-1} of data,

$$\sqrt{\zeta^2 + \tilde{\zeta}^2 - \frac{2}{3}\zeta\tilde{\zeta}} \leq 1.5 \times 10^{-13}\ \text{GeV}^{-4} \tag{6}$$

Central exclusive production of W^+W^-



Probe of $\gamma\gamma \to W^+W^-$ production. Unlike $\gamma\gamma \to Z\gamma$, $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to ZZ$, this process is induced at tree-level in the SM by virtue of non-abelian couplings between photons and W bosons. Thus, the cross section is larger $\sigma(pp \to pW^+W^-p) = 95$ fb and can be probed at the LHC.

Evidence for $\gamma\gamma \to W^+W^- \to \mu^\pm e^\mp$ compatible with SM expectations found by ATLAS and CMS with 7 and 8 TeV data with moderate pileup conditions based on rapidity gap method (CMS Coll. JHEP08 (2016) 119, ATLAS Coll. Phys.Rev. D94 (2016) 032011) with a significance of 3.4σ (CMS) and 3.0σ (ATLAS).

To further study this process, we have to use the proton tagging technique. Process can be used to further validate proton spectrometer calibration and proton reconstruction.

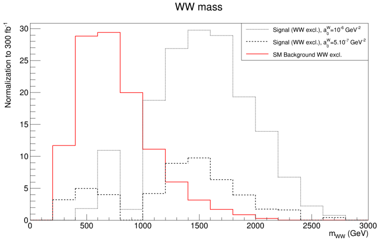
One can consider other decays of each W boson: two large-R jet, one large-R jet + one lepton, two leptons. Absence of underlying event activity + initial-state radiation effects $\rightarrow$ Cleaner W boson pair reconstruction.

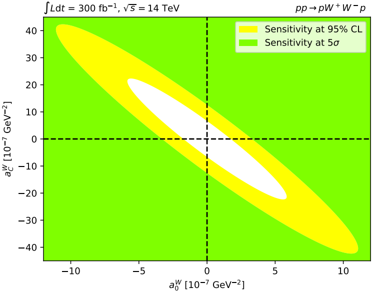
Possibility of excl. W^+W^- reconstruction in hadronic and semi-leptonic decays is being evaluated as part of the Snowmass process (CB, G. Biagi, G. Legras, C. Royon). W bosons reconstructed as large-R jets (anti-k_T $R = 0.8$ jets, with $p_T > 100$ GeV).

Selection requirements	Excl. W^+W^-	W^+W^-+pileup	$W^\pm Z$+pileup	ZZ+pileup	$W^\pm$j+pileup	Zj+pileup	$t\bar{t}$+pileup	tW+pileup	QCD jets	Total background
Preselection	990	1.37E+05	7.8E+4	2.6E+4	1.72E+07	7.27E+06	2.99E+06	7.85E+05	1.33E+10	1.33E+10
$70 < m_{j1} < 90$ GeV	591	4.10E+04	1.39E+4	5.99E+3	4.00E+06	1.23E+06	1.05E+06	1.26E+05	9.17E+08	9.23E+08
$65 < m_{j2} < 85$ GeV	274	1.50E+04	3.99E+3	2.1E+3	2.26E+05	5.03E+04	1.52E+05	5.22E+03	4.36E+07	4.41E+07
$\lvert\Delta\phi_{jj} - \pi\rvert < 0.01$	203	2.00E+03	521	265	5.37E+03	1.02E+03	4.23E+03	1.00E+02	1.22E+06	1.23E+06
$\lvert y_{WW} - y_{pp}\rvert < 0.2$	131	3.00E+02	70	40	4.28E+02	8.37E+01	7.76E+02	2.33E+01	1.92E+05	1.94E+05
$0.7 < m_{pp}/m_{WW} < 1.6$	125	1.65E+02	33	17	7.06E+01	6.01E+01	2.66E+02	1.27E+01	8.10E+04	8.16E+04
$\delta t = 20$ ps	120	12	0	0	0	0	6.7	0	3.84E+03	3.86E+03

Work in preparation.

Challenge is to suppress QCD jets + pileup. Cuts on N-subjettinness ratios or other jet substructure technique to further suppress this bkg by an additional factor of 6–10, together with precise proton time-of-flight measurement of 20 ps. Opportunity to study SM $\gamma\gamma \rightarrow W^+W^-$ at high-mass.





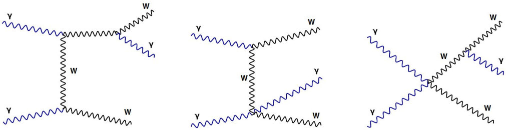
Anomalous coupling mostly at high-mass m_{WW} and high-p_T^W $\to$ Boosted topologies are favored, more likely to reconstruct a large-radius jet (anti-k_t $R = 0.8$ jets). Projections based on on dimension-6 $\gamma\gamma W^+W^-$ effective field theory:

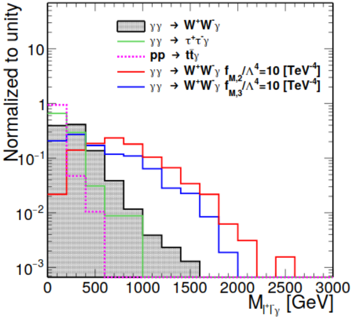
$$\mathcal{L}_6^{\text{eff}} = -\frac{e^2}{8} a_0^W F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_\alpha^- - \frac{e^2}{16} a_C^W F_{\mu\alpha} F^{\mu\beta} \left(W^{+\alpha} W_\beta^- + W^{-\alpha} W_\beta^+ \right) \quad (7)$$

We could probe couplings down to $\{|a_0^W|, |a_C^W|\} = 3 \times 10^{-7} (1 \times 10^{-6})$ GeV^{-2} at 95% CL with 300 fb^{-1} at $\sqrt{s} = 14$ TeV when combining the various decay channels. Existing ATLAS and CMS bounds are of $\{|a_0^W|, |a_C^W|\} = 1 \times 10^{-4} (3.5 \times 10^{-3})$ GeV^{-2}.

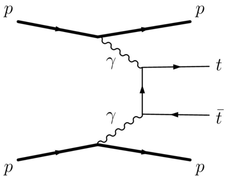
Central exclusive production of $W^+W^-\gamma$

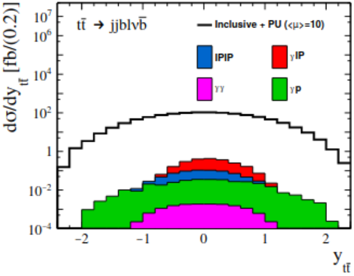
Recently proposed by S. Tizchang, S. M. Etesami, arXiv:2004.12203. In events with two charged leptons and an isolated photon, one can constrain anomalous coupling interactions and further probe the SM non-abelian couplings between photons and the W boson. Cross section is reduced, but greater sensitivity due to lower pileup backgrounds in this channel.





Central exclusive $t\bar{t}$ production



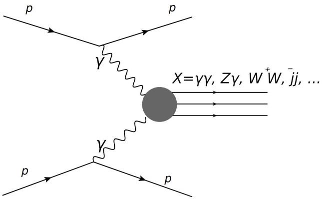


V. Goncalves, D. Martins, M. Rangel, M. Tasevsky, arXiv:2007.04565

Direct probe of top quark electromagnetic coupling. Cross section is very small $\mathcal{O}(1)$ fb, much smaller than inclusive $t\bar{t}$. Study is very challenging. Existing theory calculations by Sh. Fayazbakhsh, S. Taheri Monfared, M. M. Najafabadi Phys. Rev. D 92, 014006 (2015) and M. Luszczak, L. Forthomme, W. Schaefer, A. Szczurek JHEP02(2019)100. Recent study on exclusive SM $t\bar{t}$ phenomenology V. Goncalves, D. Martins, M. Rangel, M. Tasevsky, arXiv:2007.04565

A phenomenology study that incorporates detector reconstruction effects of exclusive $t\bar{t}$ to be part of the Snowmass process in standard LHC and High Luminosity LHC (CB, A. Bellora, S. Fichet, G. von Gersdorff, M. Pitt, C. Royon). New physics contributions to be studied in an effective field theory framework as part of Snowmass process.

Summary



- Great sensitivity to photon-photon interactions in central exclusive production processes.
- In particular, one can probe quartic gauge couplings of $\gamma\gamma VV$ $(V = W, Z, \gamma)$ in low-background scenarios.
- As part of Snowmass process:
  - Assessment of $\gamma\gamma \to W^+W^-$ in hadronic and semi-leptonic channel to enhance our sensitivity to BSM effects and a better understanding of non-abelian couplings in the SM (CB, G. Biagi, G. Legras, C. Royon).
  - Phenomenology study of $\gamma\gamma \to t\bar{t}$, study of hadronic, semi-leptonic channel (CB, A. Bellora, S. Fichet, G. von Gersdorff, M. Pitt, C. Royon).