PPS results and prospects from CMS/TOTEM

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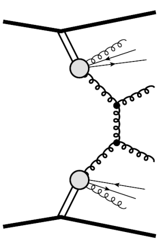
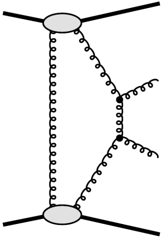
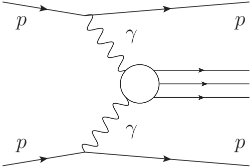
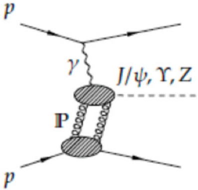
- What is PPS?
- Exclusive dilepton production
- Prospects: exclusive di-photons, $Z\gamma$, WW, ZZ...

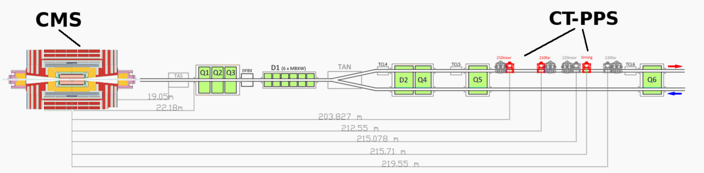
What do we call Exclusive Diffraction / γ exchange events?



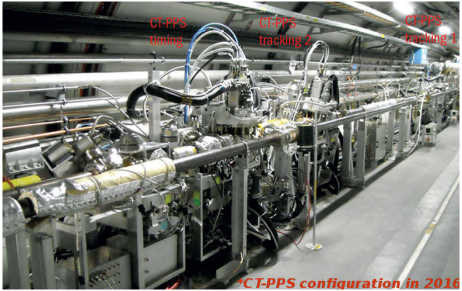
- Left diagram: Double Pomeron Exchange: some energy is “lost” in Pomeron remnants
- Next three diagrams: Exclusive production: the full energy is used to produce dijets, vector mesons, no energy loss
  - Dijet production via gluon exchange, QCD process (Khoze Martin Ryskin)
  - Photon exchange
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Central exclusive production is a potential channel for BSM physics: sensitivity to high masses up to 1.8 TeV

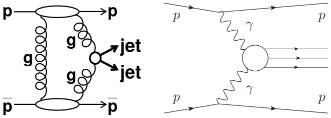
Proton detectors in CMS-TOTEM: Running at high luminosity

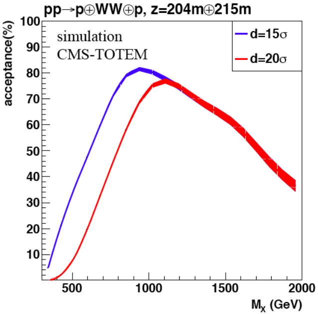


- Tag and measure protons at ±210 m CMS-TOTEM Precision Proton Spectrometer (PPS)
- Detectors: measure proton position (3D pixel or strip Silicon detectors) and time-of-flight (Ultrafast Si, diamond detectors)
- About 110 fb^{-1} of data have been accumulated
- Many analyses in progress
- Observation of semi-exclusive dileptons already published (PPS: JHEP 1807 (2018) 153)

Roman pot detectors from CMS-TOTEM (PPS) installed in the tunnel



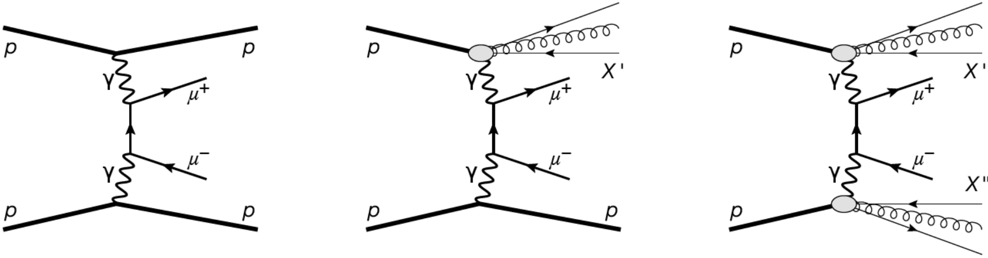




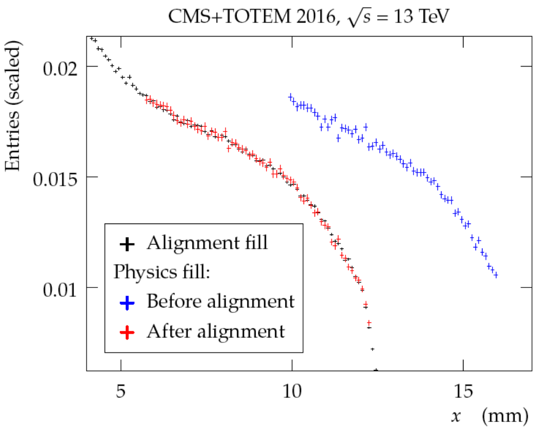
- Good acceptance at high mass
- Roman pots inserted routinely in every store without issues

Exclusive $\mu\mu/ee$ production in PPS

- Turn the LHC into a $\gamma\gamma$ collider: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- Observation of exclusive dimuon/dielectron production in PPS
- First time a near-beam detector operates at a hadron collider at high luminosity
- Request only one proton tagged (<1 event expected for double tagged events due to acceptance)
- Data-driven background estimate



PPS alignment



- Step 1 - Absolute alignment: Use elastic $pp \to pp$ events in a special alignment run where both horizontal and vertical roman pots get very close to the beam Alignment of roman pots with respect to each other using inclusive events
- Step 2 - Relative alignment: Use inclusive sample of protons triggered by CMS in standard runs and match distribution of proton track position to that of alignment runs

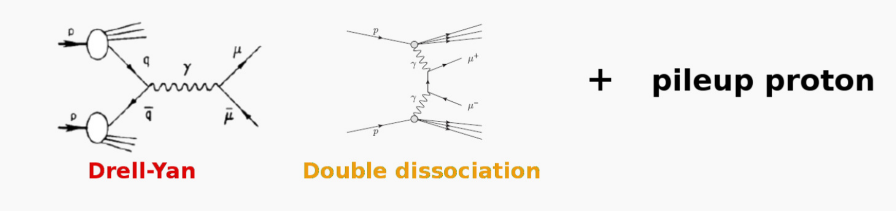
Observation of semi-exclusive $\mu\mu/ee$ production in PPS: Strategy

- In order to select exclusive events: Look for correlation between direct proton ξ measurement using PPS and using the dimuon/dielectron system in CMS:

$$\xi^{\pm} = \frac{1}{\sqrt{s}}(p_T^{\mu_1} e^{\pm\eta^{\mu_1}} + p_T^{\mu_2} e^{\pm\eta^{\mu_2}})$$

($\pm\eta$ solutions correspond to the protons in the $+z$ and $-z$ direction)

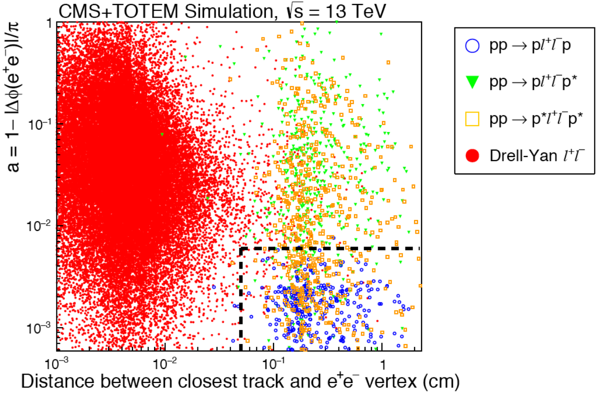
- Expected backgrounds:



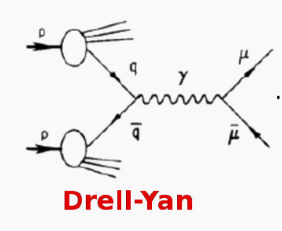
will fake signal (overlap with pile up or beam halo protons)

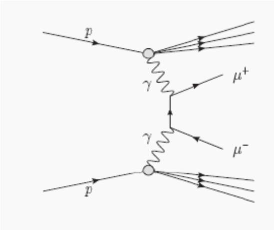
Event selection: dimuons and dielectrons

- Request pair of opposite sign muons or electrons with $p_T > 50$ GeV and $M_{ll} > 110$ GeV above the Z boson peak
- To suppress background: Veto additional tracks around dimuon/dielectron vertex (within 0.5 mm) and require back-to-back muons/electrons $|1 - \Delta\Phi/\pi| < 0.006$ for electrons (0.009 for muons)



Data driven background estimate

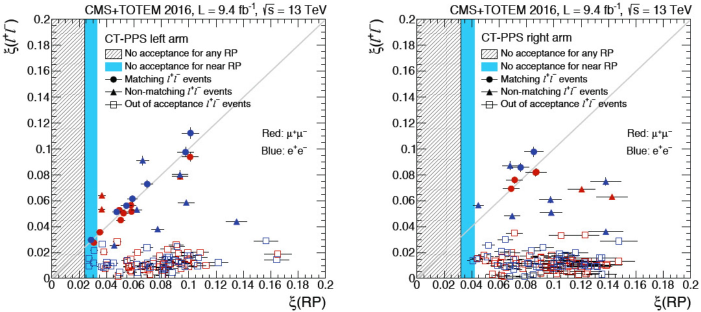




- Use sample of background protons from Z-peak events (data)
- Drell-Yan contribution: Count number of Z-peak events with $\xi(\mu\mu/ee)$ and ξ(proton) correlated within 2σ and use MC to extrapolate from Z-peak region to signal region
- Double dissociative contribution: Mix double dissociative simulated events (LPAIR) and protons from data to derive number of matching events
- Total number of expected matching background events: $1.49 \pm 0.07(stat) \pm 0.53(syst)$ for muons and $2.36 \pm 0.09(stat) \pm 0.47(syst)$ for electrons

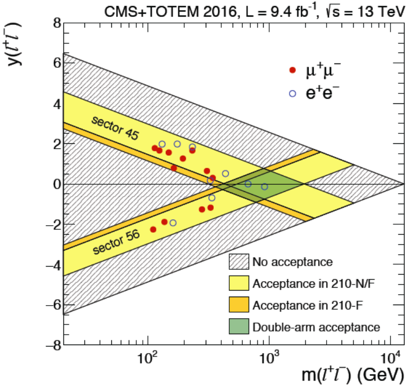
Observed signal

- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (res. 23) events are found with protons in the PPS acceptance and 12 (resp. 8) $< 2\sigma$ matching in the $\mu\mu$ (res. ee) channel
- Significance $> 5\sigma$ for observing 20 events for a background of 3.85 $(1.49 \pm 0.07(stat) \pm 0.53(syst)$ for $\mu\mu$ and $2.36 \pm 0.09(stat) \pm 0.47(syst)$ for ee)

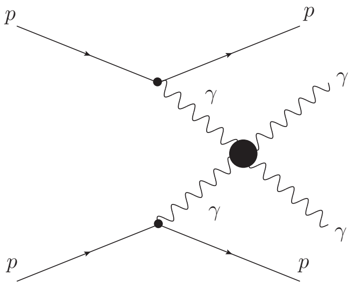


Summary of 20 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that are double tagged: The two dielectron events in the acceptance region are compatible with pile up contamination (2.36 events expected)
- Highest mass event: 917 GeV



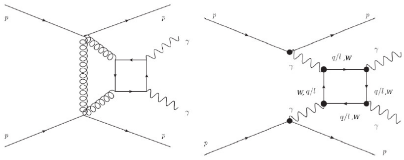
Search for extra dimensions in the universe using γ induced processes

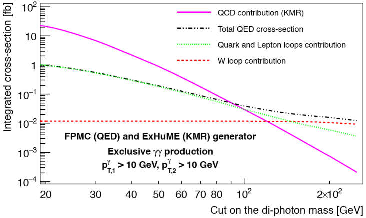


- Additional channels: WW, ZZ, γZ, dilepton production ($\gamma\gamma$ described in more detail as an example)

- Search for production of two photons and two intact protons in the final state: $pp \to p\gamma\gamma p$
- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, dark matter particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons

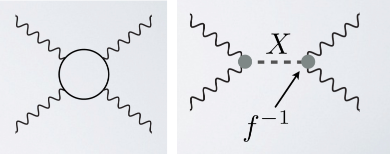
$\gamma\gamma$ exclusive production: SM contribution





- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses ($>$ 200 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

Motivations to look for quartic $\gamma\gamma$ anomalous couplings



- Two effective operators at low energies

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

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charged particles $\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$ where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle This leads to ζ_1 of the order of 10^{-14}-10^{-13}

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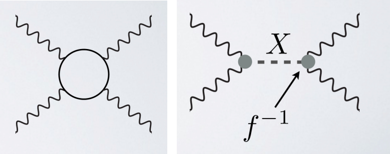

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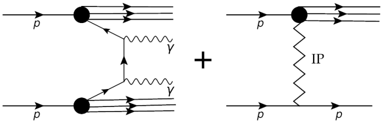
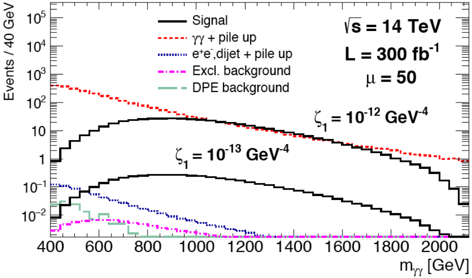
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$

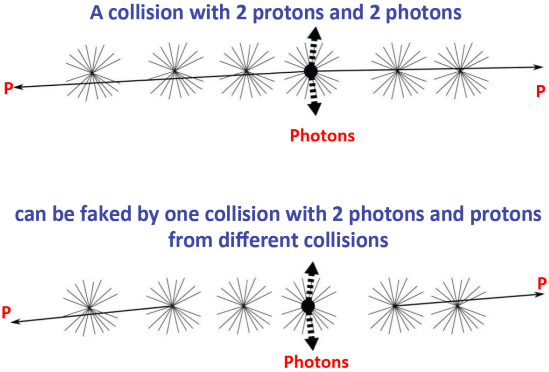
SM background





- SM exclusive diphoton production negligible at high diphoton mass
- γ selection: High p_T photon ($>$150 GeV), back-to-back, high mass di-photon (above 500 GeV)
- Proton selection: in the acceptance of the forward proton detectors (mass above 400 GeV)
- **Only background remaining after cuts: pile up**

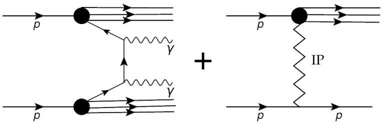
One aside: what is pile up at LHC?

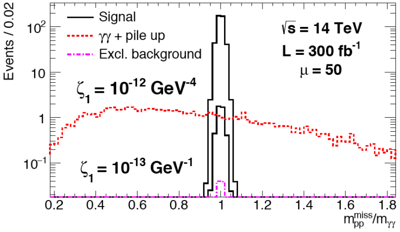


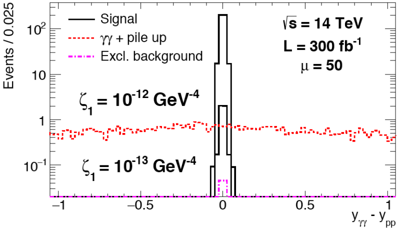
- Due to high number of protons in one packet, there can be more than one *pp* interaction when the packets collide
- Typically up to 50 pile up events in Run II (about 25-30 for 2016-2018 data)
- Analyses at high luminosity because of lower production cross section (exclusive WW, $\gamma\gamma$...): need to fight pile up!

Removing pile up at the LHC

- **Negligible background** after matching invariant mass and rapidity of diphoton system to prediction from protons (S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert. JHEP 1502 (2015) 165)
- Use fast timing detectors in the case of Ws decaying leptonically







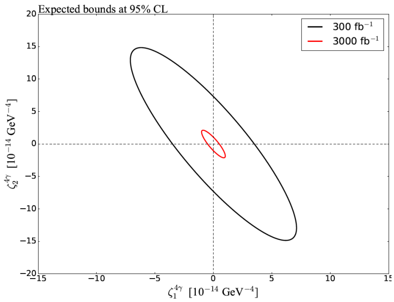
Search for quartic $\gamma\gamma$ anomalous couplings

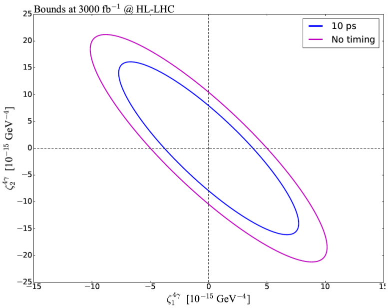
Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200, (100)$ GeV]	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert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

- No background after cuts for 300 fb^{-1}: sensitivity up to a few 10^{-15}, better by 2 orders of magnitude with respect to "standard" methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

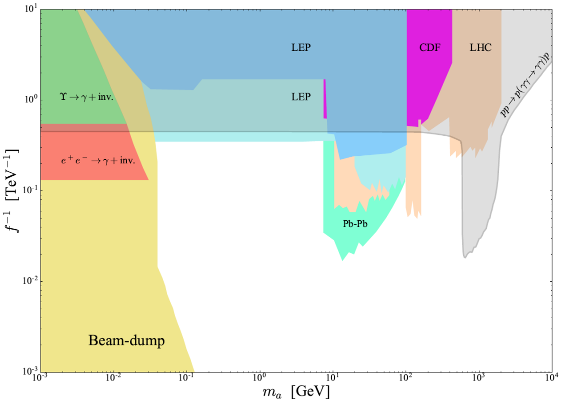
Sensitivity to anomalous couplings at medium and high lumi LHC

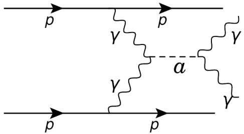
- With 300 fb^{-1} (Run III), gain of sensitivity by more than 2 orders of magnitude with respect to "usual" LHC sensitivity (similar for γZ, ZZ and WW)
- Run 4 (HL-LHC):Assuming similar proton acceptance as in Run 3, sensitivity further increased by about one order of magnitude with $\sim$ 3000 fb^{-1} (CERN-LPCC-2018-03)
- For exclusive diphoton production, timing detectors are not crucial





Application of exclusive $\gamma\gamma$: Looking for Axion Like Particles (ALPs)

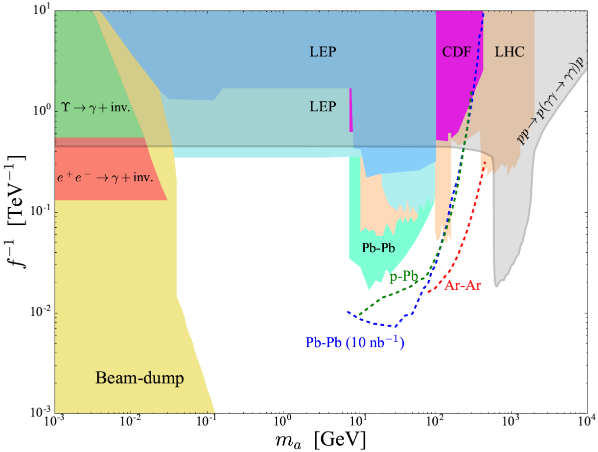




- Same analysis: two photons and two intact protons: sensitivity improved by 2 (resp. 3) orders of magnitude with 300 (resp. 3000) fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 131)
- Searching for high mass ALPs coupling to γ without PPS: Difficult to perform, usually combines couplings to gluons, quarks, leptons, γ

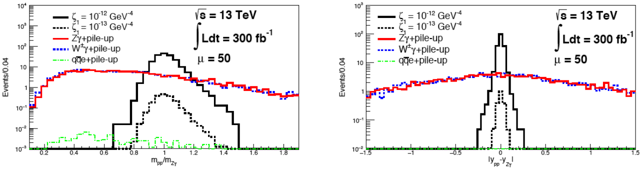
- ALPs decaying into two γs

Search for axion like particles: complementarity with heavy ion runs



- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to *pp* running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4, C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma\gamma Z$ couplings in *pp* collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142

$\gamma\gamma\gamma Z$ quartic anomalous coupling



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
$\ell\bar{\ell}\gamma$	$2.8\cdot10^{-13}$	$1.8\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.5\cdot10^{-13}$
$jj\gamma$	$2.3\cdot10^{-13}$	$1.5\cdot10^{-13}$	$2\cdot10^{-13}$	$1.3\cdot10^{-13}$
$jj\gamma\bigoplus\ell\bar{\ell}\gamma$	$1.93\cdot10^{-13}$	$1.2\cdot10^{-13}$	$1.7\cdot10^{-13}$	$1\cdot10^{-13}$

- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a threshold effect

Conclusion

- Exclusive dilepton production: First observation of high-mass exclusive dilepton production: $> 5\sigma$ significance for observing 20 events for a background of 3.85 ($1.49 \pm 0.07(stat) \pm 0.53(syst)$ for dimuons and $2.36 \pm 0.09(stat) \pm 0.47(syst)$ for dielectrons)
- $\gamma\gamma\gamma\gamma$ couplings: Nice prospects for PPS, highest possible sensitivities to $\gamma\gamma\gamma\gamma$, $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma Z$ anomalous couplings due to new resonances, extra-dim. axion-like particles, or composite Higgs...
- First results on anomalous couplings expected to come out soon

We need to look everywhere! For instance using intact protons...