

# Recent results with the CMS Precision Proton Spectrometer

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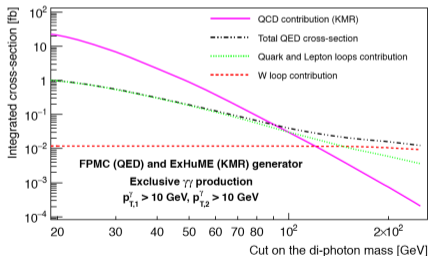
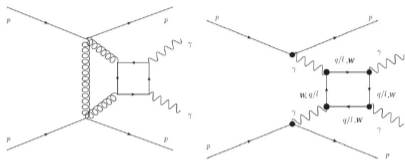


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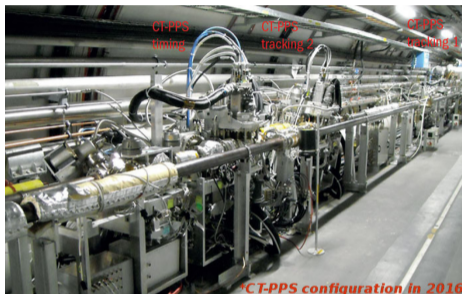
- Proton tagging at the LHC in CMS/TOTEM
- $\gamma\gamma\gamma$ ,  $\gamma\gamma Z$ ,  $\gamma\gamma WW$ ,  $\gamma\gamma ZZ$ ,  $\gamma\gamma t\bar{t}$  anomalous coupling studies
- Search for Axion-like particles
- Search for  $Z+X$  and  $\gamma+X$  events

# Photon-induced processes at the LHC

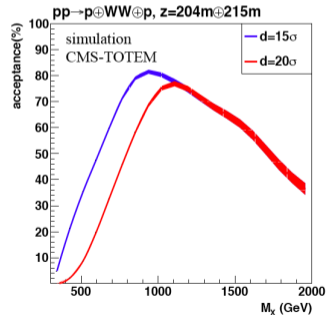
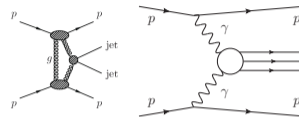


- Consider exclusive production of  $ee, \mu\mu, WW, \gamma\gamma$ , etc
- Dilepton production is a QED ( $\gamma$ -exchange) process
- In  $pp$  interactions, QCD production of  $\gamma\gamma$  dominates at low  $m_{\gamma\gamma}$ , QED at high  $m_{\gamma\gamma}$  (similar for  $WW, ZZ, Z\gamma, t\bar{t}$  production)
- At high masses, in  $pp$  interactions, possibility to select photon-induced events by tagging protons and by measuring high mass objects in CMS/ATLAS
- Pb Pb interactions:  $\gamma\gamma$  exchanges enhanced by  $Z^4$ , measure low mass exclusive  $\gamma$ -induced processes ( $\gamma\gamma$ )

# Roman pot detectors from PPS installed in the tunnel

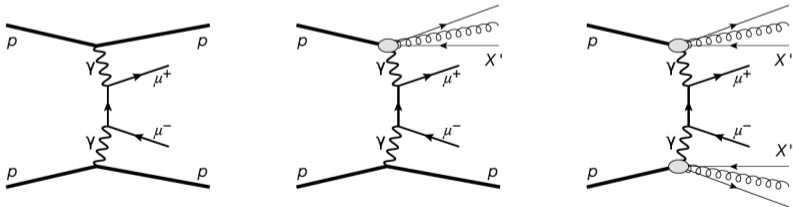


- Good acceptance at high mass in standard runs (PPS in CMS, TOTEM-TDR-003 ; CMS-TDR-13)
- $>100 \text{ fb}^{-1}$  collected in Run II



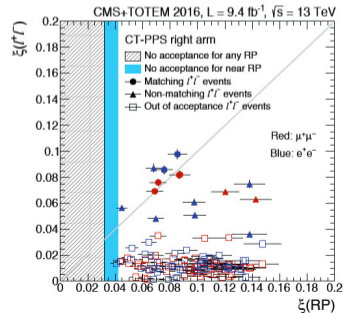
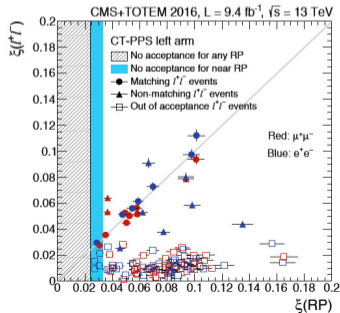
# Quasi-exclusive $\mu\mu$ and $ee$ production in CMS-TOTEM

- Turn the LHC into a  $\gamma\gamma$  collider at high luminosity: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons
- The dilepton mass acceptance of PPS/AFP starts at about  $\sim 400$  GeV  $\rightarrow$  expect very small number of double tagged events
- The two first diagrams are signal, the last one background



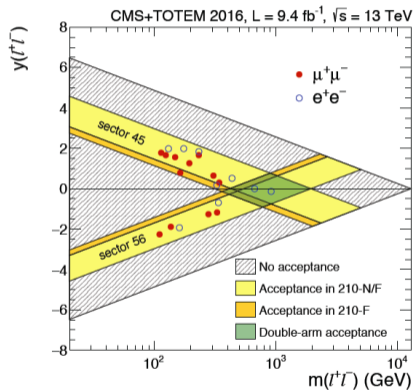
# Observed signal

- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (resp. 23) events are found with protons in the PPS acceptance and 12 (resp. 8)  $< 2\sigma$  matching in the  $\mu\mu$  (resp.  $ee$ ) 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  $ee$ )

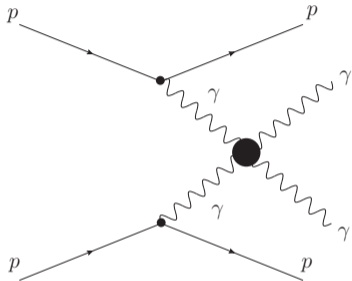


# Summary of 20 candidates properties

- 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
- JHEP 1807 (2018) 153



# Search for quartic $\gamma\gamma\gamma\gamma$ anomalous coupling



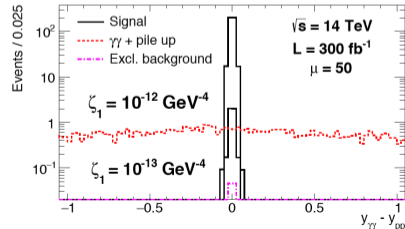
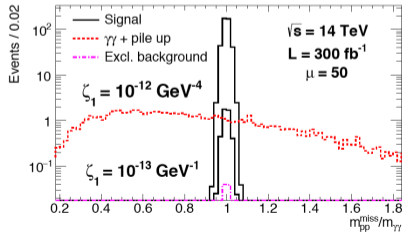
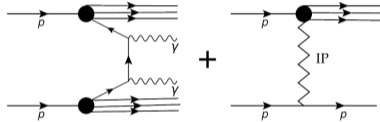
- Search for production of two photons and two intact protons in the final state:

$$pp \rightarrow p\gamma\gamma p$$

- Additional channels:  $WW$ ,  $ZZ$ ,  $\gamma Z$ ,  $t\bar{t}$
- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, axion-like particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons
- JHEP 1806 (2018) 131; JHEP 1502 (2015) 165; Phys.Rev. D89 (2014) 114004; Phys.Rev. D81 (2010) 074003; Phys.Rev. D78 (2008) 073005

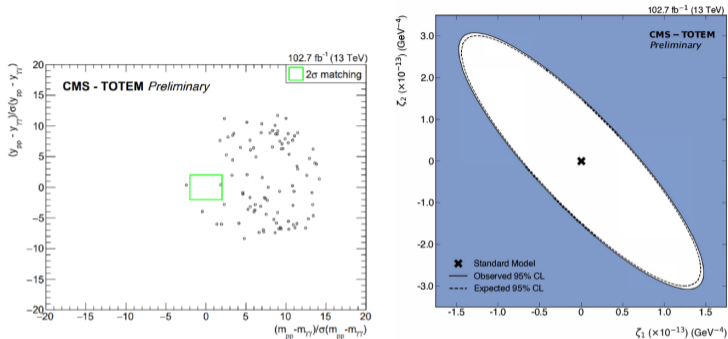
# Removing pile up at the LHC

- Advantage of tagging protons: negligible background after matching mass/rapidity of photon and proton systems (JHEP 1502 (2015) 165; Phys.Rev. D89 (2014) 114004)
- Possibility to use fast timing detectors to measure proton time of flights



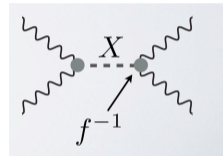
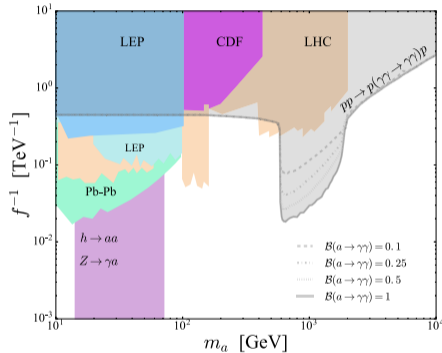
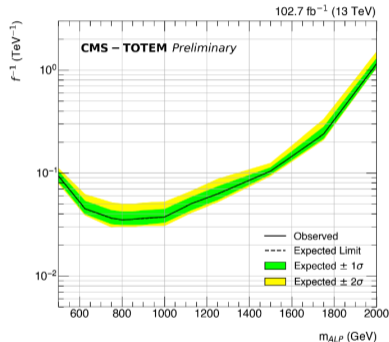


# First search for high mass exclusive $\gamma\gamma$ production



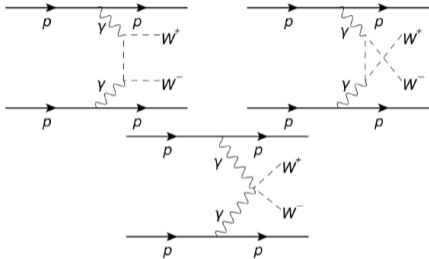
- Search for exclusive diphoton production: back-to-back, high diphoton mass ( $m_{\gamma\gamma} > 350$  GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings:  $|\zeta_1| < 2.9 \cdot 10^{-13} \text{ GeV}^{-4}$ ,  $|\zeta_2| < 6. \cdot 10^{-13} \text{ GeV}^{-4}$  with about  $10 \text{ fb}^{-1}$ , accepted by PRL (2110.05916)
- Limit updates with  $102.7 \text{ fb}^{-1}$ :  $|\zeta_1| < 7.3 \cdot 10^{-14} \text{ GeV}^{-4}$ ,  $|\zeta_2| < 1.5 \cdot 10^{-13} \text{ GeV}^{-4}$

# First search for high mass production of axion-like particles



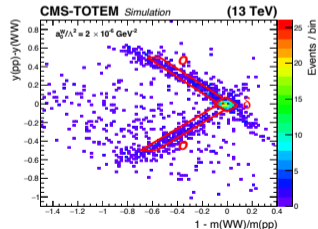
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb<sup>-1</sup> (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

# Exclusive production of $W$ boson pairs

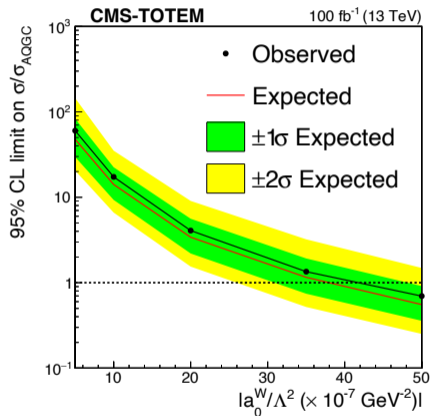


- Search with fully hadronic decays of  $W$  bosons: anomalous production of  $WW$  events dominates at high mass with a rather low cross section

- 2 “fat” jets (radius 0.8), jet  $p_T > 200$  GeV,  $1126 < m_{jj} < 2500$  GeV, jets back-to-back ( $|1 - \phi_{jj}/\pi| < 0.01$ )
- Signal region defined by the correlation between central  $WW$  system and proton information

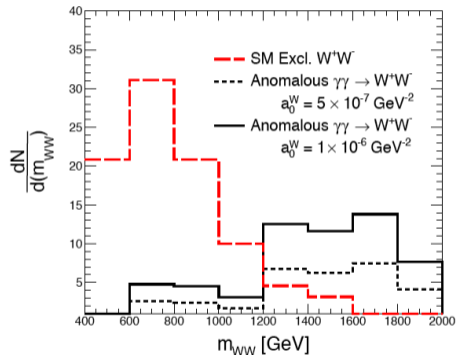


# WW and ZZ exclusive productions



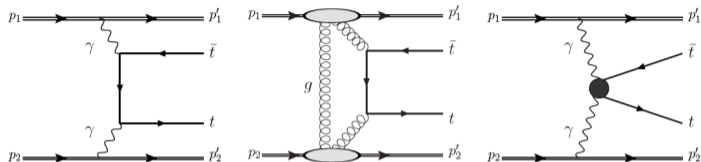
- Searches performed in full hadronic decays of  $W$  bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section  $\sigma_{WW} < 67 \text{ fb}$ ,  $\sigma_{ZZ} < 43 \text{ fb}$  for  $0.04 < \xi < 0.2$  (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings (events violating unitarity removed) :  $a_0^W/\Lambda^2 < 4.3 \cdot 10^{-6} \text{ GeV}^{-2}$ ,  
 $a_C^W/\Lambda^2 < 1.6 \cdot 10^{-5} \text{ GeV}^{-2}$ ,  
 $a_0^Z/\Lambda^2 < 0.9 \cdot 10^{-5} \text{ GeV}^{-2}$ ,  
 $a_C^Z/\Lambda^2 < 4. \cdot 10^{-5} \text{ GeV}^{-2}$  with  $52.9 \text{ fb}^{-1}$

# The future: Observation of exclusive $WW$ production



- SM contribution appears at lower  $WW$  masses compared to anomalous couplings
- Use purely leptonic channels for  $W$  decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive  $WW$  (leptonic decays) after selection: about 50 events for  $300 \text{ fb}^{-1}$  (2 background)
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.

# Exclusive $t\bar{t}$ production



**dilep channel ( $\bar{t}t \rightarrow lvb + lv\bar{b}$ )**

**Semilep channel ( $\bar{t}t \rightarrow lvb + jj\bar{b}$ )**

## Object selection

Leptons:  $p_T > 30(20)\text{GeV}$ ,  $|\eta| < 2.1$   
 Jets:  $p_T > 30\text{GeV}$ ,  $|\eta| < 2.4$ ,  $\Delta R(j,l) > 0.4$

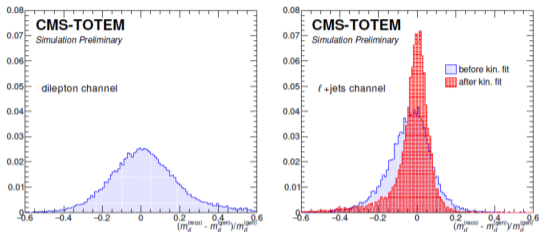
Leptons:  $p_T > 30\text{GeV}$ ,  $|\eta| < 2.1(2.4)$  for  $e(\mu)$   
 Jets:  $p_T > 25\text{GeV}$ ,  $|\eta| < 2.4$ ,  $\Delta R(j,l) > 0.4$

## Event selection

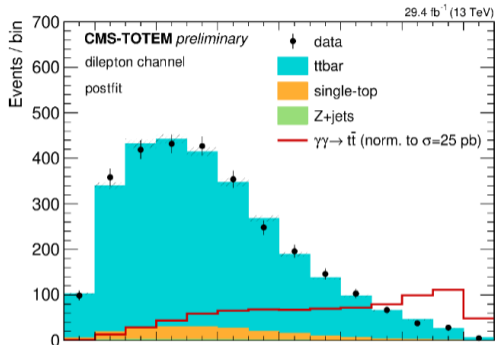
$\geq 2$  leptons (OS pair),  $|m(\text{ll}) - m(\text{Z})| > 15\text{GeV}$   
 $\geq 2$  b-jets  
 1 proton / side

= 1 lepton  
 $\geq 2$  b-jets,  $\geq 2$  non b-jets  
 1 proton / side

# Exclusive $t\bar{t}$ production

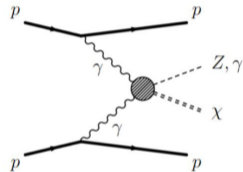
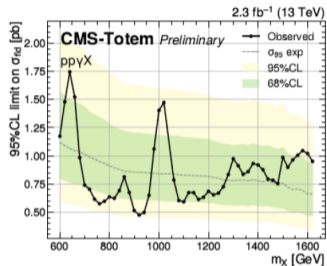
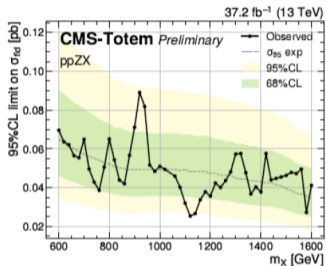


- Kinematic fitter based on  $W$  and  $t$  mass constraints to reduce background



- Search for exclusive  $t\bar{t}$  production in leptonic and semi-leptonic modes
- $\sigma_{t\bar{t}}^{\text{excl.}} < 0.59$  pb (CMS-PAS-TOP-21-007)

# $Z + X$ production (CMS/TOTEM)



- Search for  $Z + X$  events: use total mass reconstructed using intact protons, allows obtaining the mass of  $Z + X$ ,  $X$  might be not reconstructed, or decaying resonance
- No signal found but should be redone with higher lumi (CMS-PAS-EXO-21-009)

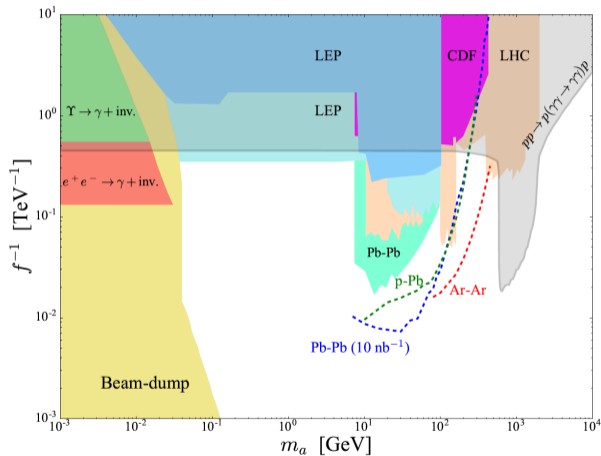


# Conclusion

- LHC can be seen as a  $\gamma\gamma$  collider! Lead to extremely clean events where all particles in the final state are measured, like at LEP
- First sensitivities to quartic  $\gamma\gamma\gamma\gamma$  anomalous couplings at high diphoton mass and to ALP production
- First sensitivities to  $\gamma\gamma ZZ$ ,  $\gamma\gamma WW$ ,  $\gamma\gamma t\bar{t}$  anomalous coupling and sensitivities expected to increase by more than one order of magnitude at Run III also using new detectors (timing detectors as an example) - SM observation possible in Run III
- $\gamma\gamma\gamma Z$  anomalous coupling studies to be performed in CMS: very clean events, easy triggers

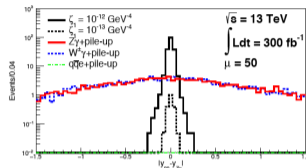
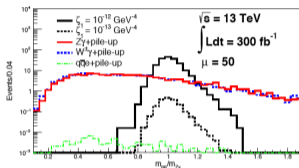
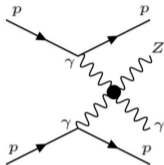


# Search for axion like particles: complementarity with heavy ion runs



- 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  $\gamma\gamma Z$  couplings in  $pp$  collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142

# $\gamma\gamma\gamma Z$ quartic anomalous coupling: leptonic and hadronic decays of $Z$ boson



Coupling ( $\text{GeV}^{-4}$ )	$\zeta$ ( $\tilde{\zeta} = 0$ )		$\zeta = \tilde{\zeta}$	
Luminosity	$300 \text{ fb}^{-1}$		$300 \text{ fb}^{-1}$	
Pile-up ( $\mu$ )	50		50	
Channels	$5 \sigma$	95% CL	$5 \sigma$	95% CL
$ll\gamma$	$2.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
$jj\gamma$	$2.3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$2 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
$jj\gamma \oplus ll\gamma$	$1.93 \cdot 10^{-13}$	$1.2 \cdot 10^{-13}$	$1.7 \cdot 10^{-13}$	$1 \cdot 10^{-13}$

- C. Baldenegro, S. Fichtel, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Sensitivity to wide/narrow resonances, loops of new particles

# Exclusive $t\bar{t}$ production: the future

- Search for  $\gamma\gamma t\bar{t}$  anomalous coupling in semi-leptonic decays with  $300 \text{ fb}^{-1}$
- Use similar selection: high  $t\bar{t}$  mass, matching between  $pp$  and  $t\bar{t}$  information
- Use fast timing detectors to suppress further the pile up background
- C. Baldenegro, A. Bellora, S. Fichet, G. von Gersdorff, M. Pitt, CR arXiv:2205.01173

Coupling [ $10^{-11} \text{ GeV}^{-4}$ ]	95% CL	$5\sigma$	95% CL (60 ps)	$5\sigma$ (60 ps)	95% CL (20 ps)	$5\sigma$ (20 ps)
$\zeta_1$	1.5	2.5	1.1	1.9	0.74	1.5
$\zeta_2$	1.4	2.4	1.0	1.7	0.70	1.4
$\zeta_3$	1.4	2.4	1.0	1.7	0.70	1.4
$\zeta_4$	1.5	2.5	1.0	1.8	0.73	1.4
$\zeta_5$	1.2	2.0	0.84	1.5	0.60	1.2
$\zeta_6$	1.3	2.2	0.92	1.6	0.66	1.3