

Recent results from PPS and prospects

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LHC Forward Physics WG meeting, CERN

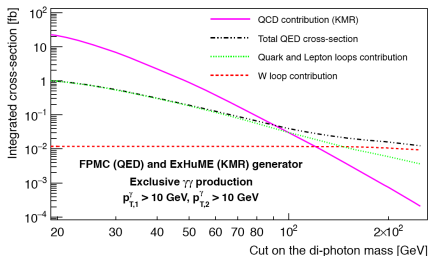
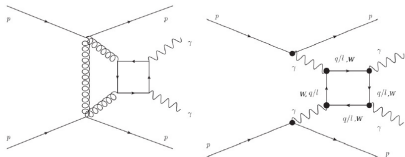


October 24-25 2022

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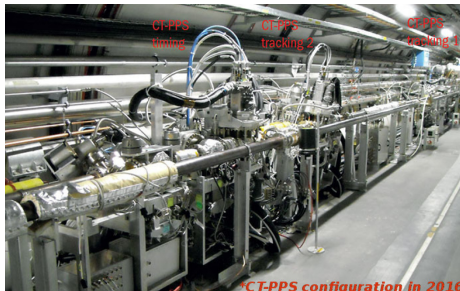
- Proton tagging at the LHC in CMS/TOTEM
- Quasi-exclusive dilepton production
- $\gamma\gamma\gamma\gamma$, $\gamma\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$ anomalous coupling studies
- Search for Axion-like particles

Photon-induced processes at the LHC

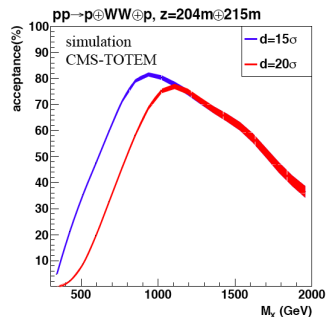
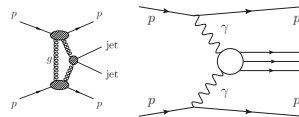


- Consider exclusive production of ee , $\mu\mu$, WW , $\gamma\gamma$, etc
- Dilepton production is a QED (γ -exchange) process
- In pp interactions, QCD production of $\gamma\gamma$ dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$ (similar for WW , ZZ , $Z\gamma$, $t\bar{t}$ production)
- 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 γ -induced processes ($\gamma\gamma$)

Roman pot detectors from PPS installed in the tunnel

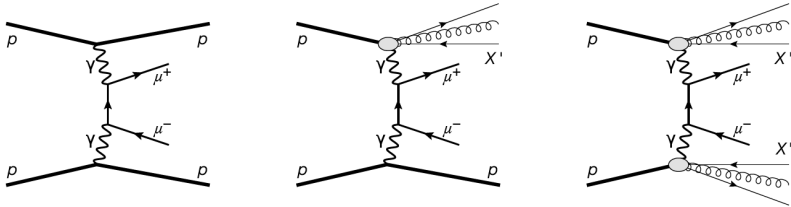


- Good acceptance at high mass in standard runs (PPS in CMS, AFP in ATLAS)
- $>100 \text{ fb}^{-1}$ collected in Run II



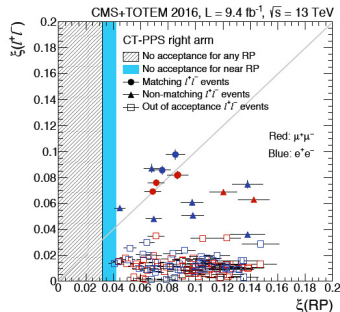
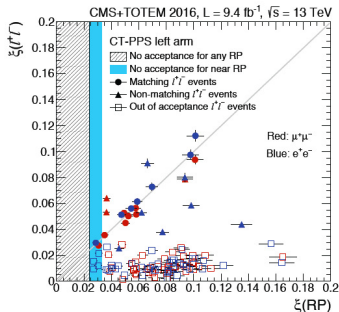
Quasi-exclusive $\mu\mu$ and ee production in CMS-TOTEM

- 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 ~ 400 GeV \rightarrow expect very small number of double tagged events
- The two first diagrams are signal, the last one background



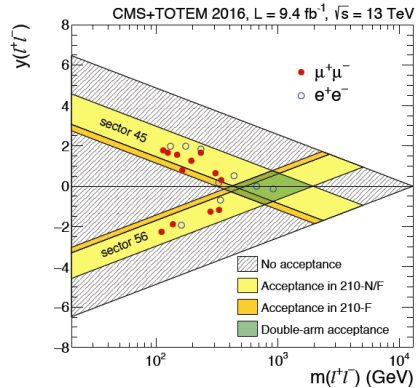
Observed signal (CMS)

- 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)

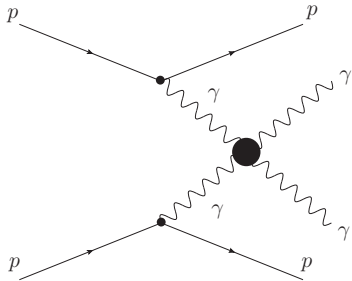


Summary of 20 candidates properties (CMS)

- 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

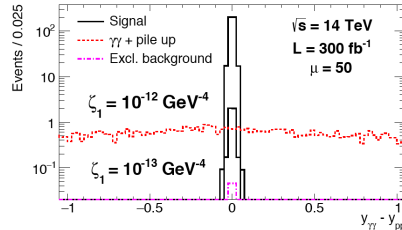
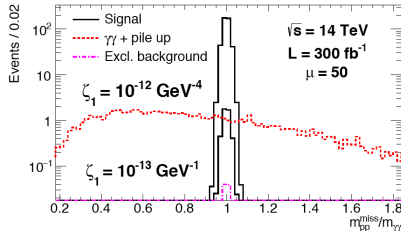
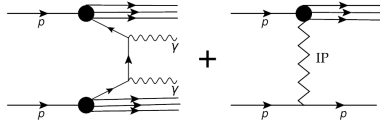


- Search for production of two photons and two intact protons in the final state:
 $pp \rightarrow p\gamma\gamma p$

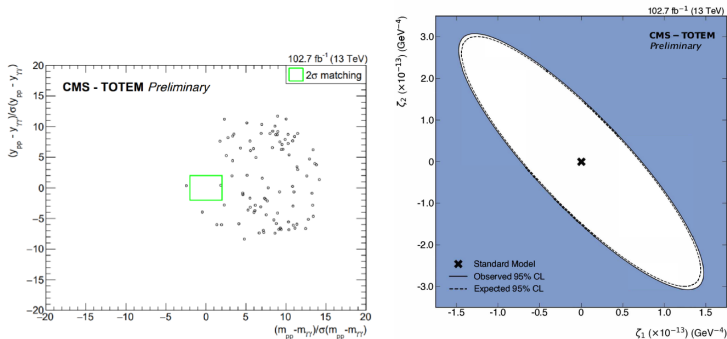
- Additional channels: WW , ZZ , γZ , $t\bar{t}$
- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, axion-like particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons
- JHEP 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

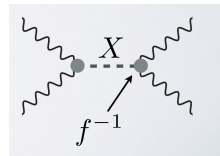
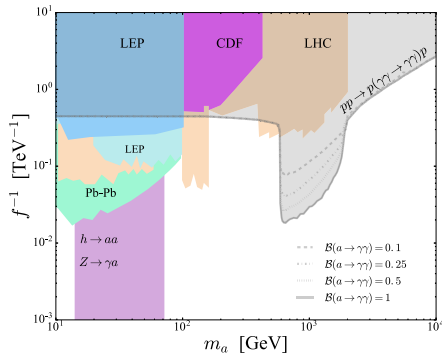
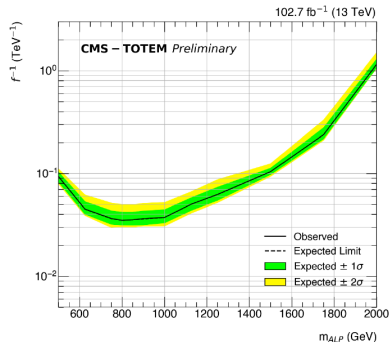


First search for high mass exclusive $\gamma\gamma$ production (CMS/TOTEM)



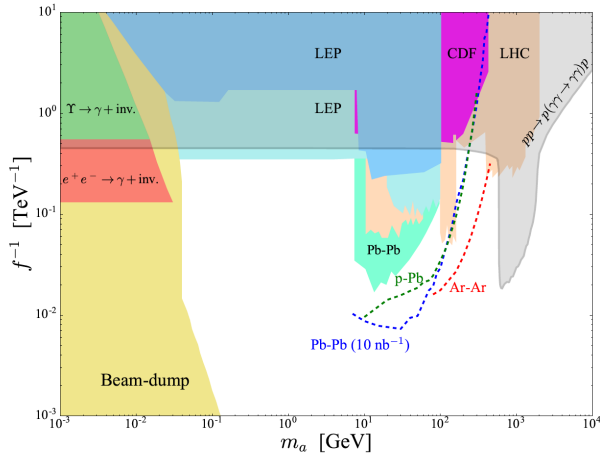
- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9 \cdot 10^{-13} \text{ GeV}^{-4}$, $|\zeta_2| < 6 \cdot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



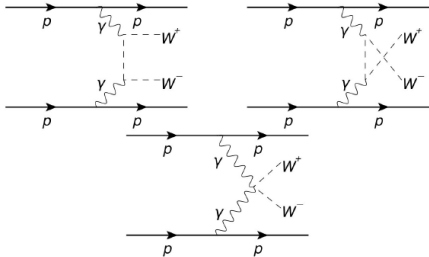
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensivities projected with 300 fb⁻¹ (C. Baldenegro, S. Fichtel, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

Search for axion like particles: complementarity with heavy ion runs



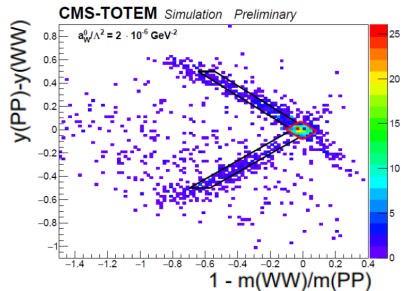
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to pp running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4 , C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for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

Exclusive production of W boson pairs (CMS/TOTEM)

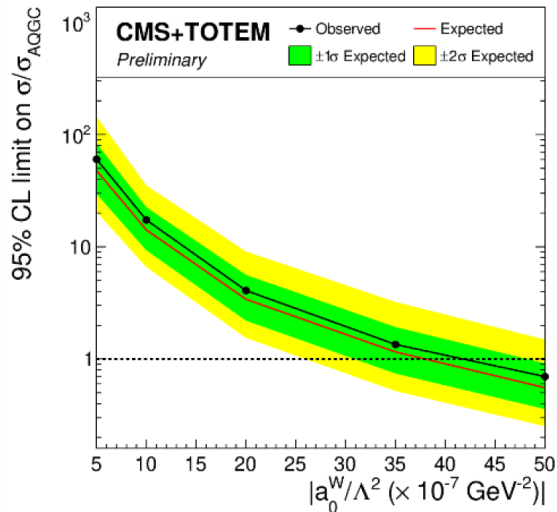


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 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

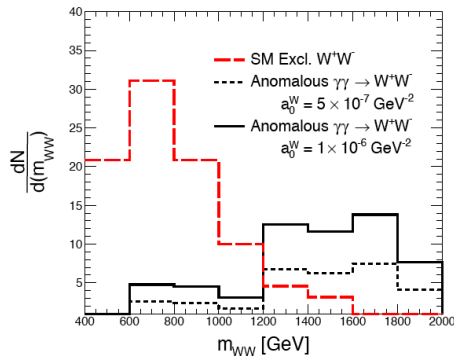


WW and ZZ exclusive productions (CMS/TOTEM)



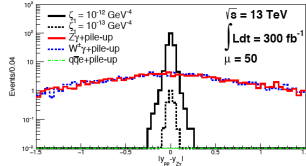
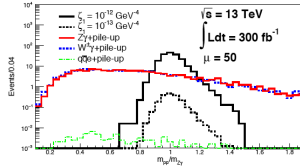
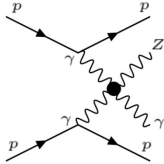
- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section
 $\sigma_{WW} < 67\text{fb}$, $\sigma_{ZZ} < 43\text{fb}$ for
 $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings:
 $a_0^W/\Lambda^2 < 4.3 \cdot 10^{-6} \text{ GeV}^{-2}$,
 $a_C^W/\Lambda^2 < 1.6 \cdot 10^{-5} \text{ GeV}^{-2}$,
 $a_0^Z/\Lambda^2 < 0.9 \cdot 10^{-5} \text{ GeV}^{-2}$,
 $a_C^Z/\Lambda^2 < 4. \cdot 10^{-5} \text{ GeV}^{-2}$ with 52.9 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 fb^{-1} (2 background)
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.

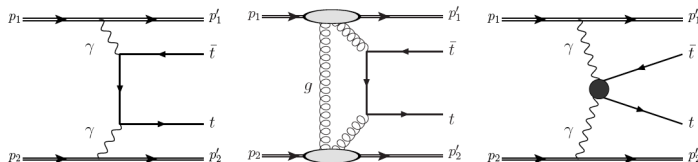
$\gamma\gamma\gamma Z$ quartic anomalous coupling: leptonic and hadronic decays of Z boson



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

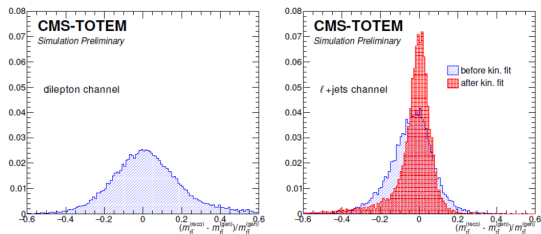
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Sensitivity to wide/narrow resonances, loops of new particles

Exclusive $t\bar{t}$ production (CMS/TOTEM)

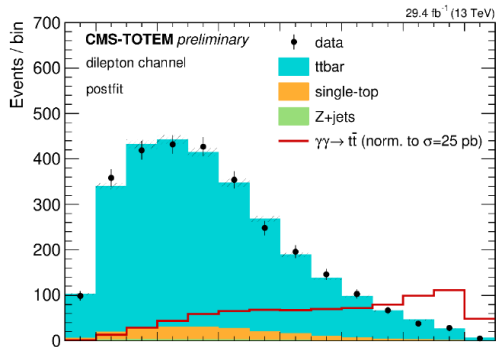


dilep channel ($\bar{t}t \rightarrow lvb + lv\bar{b}$)	Semilep channel ($\bar{t}t \rightarrow lvb + jj\bar{b}$)
Object selection	
Leptons: $p_T > 30(20)\text{GeV}$, $ \eta < 2.1$ Jets: $p_T > 30\text{GeV}$, $ \eta < 2.4$, $\Delta R(j,l) > 0.4$	Leptons: $p_T > 30\text{GeV}$, $ \eta < 2.1(2.4)$ for $e(\mu)$ Jets: $p_T > 25\text{GeV}$, $ \eta < 2.4$, $\Delta R(j,l) > 0.4$
Event selection	
≥ 2 leptons (OS pair), $ m(l\bar{l}) - m(Z) > 15\text{GeV}$ ≥ 2 b-jets 1 proton / side	$= 1$ lepton ≥ 2 b-jets, ≥ 2 non b-jets 1 proton / side

Exclusive $t\bar{t}$ production (CMS/TOTEM)



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



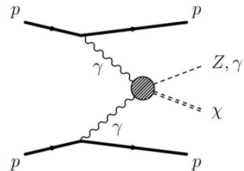
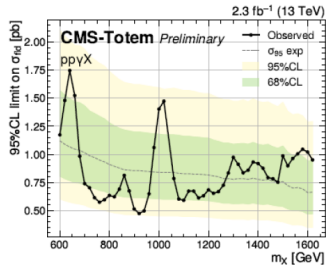
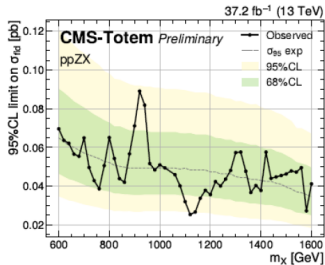
- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes
- $\sigma_{t\bar{t}}^{excl.} < 0.6$ pb (CMS-PAS-TOP-21-007)

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

- Search for $\gamma\gamma t\bar{t}$ anomalous coupling in semi-leptonic decays with 300 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	5σ	95% CL (60 ps)	5σ (60 ps)	95% CL (20 ps)	5σ (20 ps)
ζ_1	1.5	2.5	1.1	1.9	0.74	1.5
ζ_2	1.4	2.4	1.0	1.7	0.70	1.4
ζ_3	1.4	2.4	1.0	1.7	0.70	1.4
ζ_4	1.5	2.5	1.0	1.8	0.73	1.4
ζ_5	1.2	2.0	0.84	1.5	0.60	1.2
ζ_6	1.3	2.2	0.92	1.6	0.66	1.3

$Z + X$ 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

