Exclusive production processes in CMS and TOTEM

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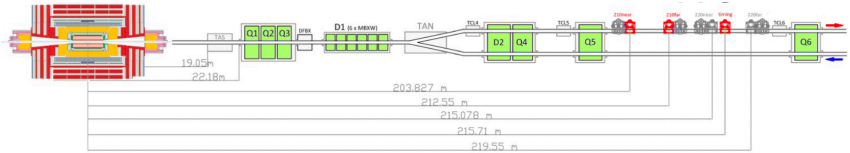
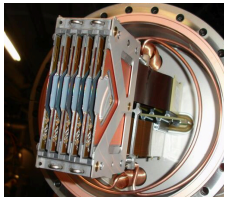
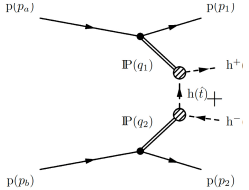
- Proton tagging at the LHC
- Central-exclusive non resonant production of pions at low mass
- Quasi-exclusive di-lepton production
- Observation of $\gamma\gamma \to \tau\tau$
- Search for $\gamma\gamma WW$, $\gamma\gamma ZZ$, Z/γ+X, $t\bar{t}$ production (see also Andrea and Gustavo's talks)

What are the CMS-TOTEM roman pot detectors?



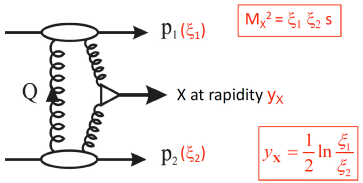


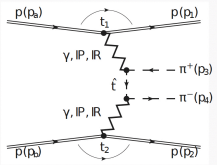


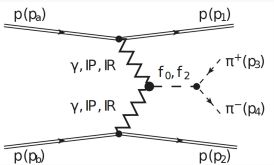
- Two sets of TOTEM roman pots on each side of CMS at 213 and 220 m

- CMS+TOTEM dataset, $\beta^* = 90$ m (2018), about 80 million events with two scattered protons and only two reconstructed central tracks, at low diffractive masses
- Allows to measure double pomeron exchange (DPE), exclusive diffraction (two particle production such as $\pi\pi$ production)

Central exclusive production

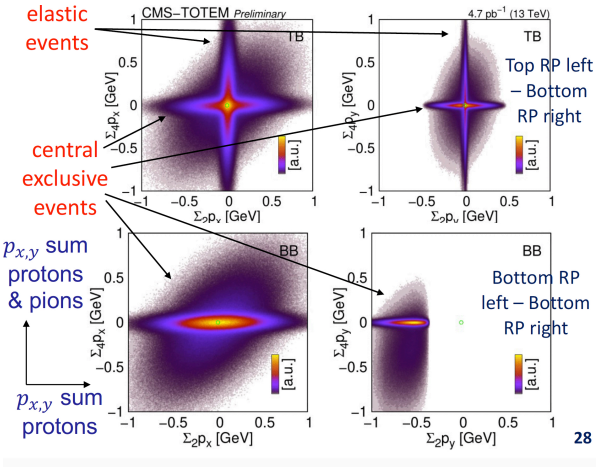






- Measurement of central exclusive production of pair of particles
- Measure both intact protons in TOTEM and pions in ATLAS/CMS
- Background can be controlled by matching the proton and CMS/ATLAS measurements: $M_{pp} = M_{central}$, $y_{pp} = y_{central}$
- Phys.Rev.D 109 (2024) 11

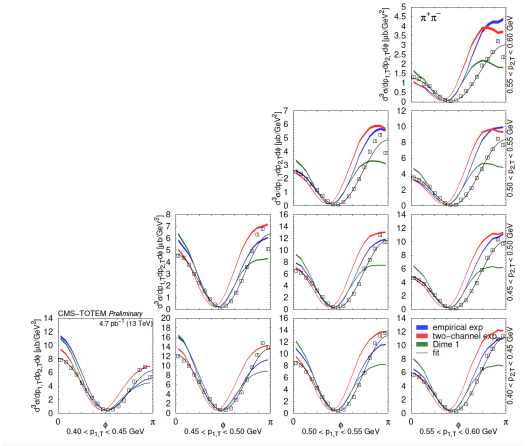
Non-resonant exclusive dipion production (CMS/TOTEM)



- Non-resonant exclusive di-pion production: Very clean events, 2 pions measured in CMS and 2 protons in TOTEM
- $pp \to p\pi\pi p$
- Sum of proton transverse momentum ($p_{X,Y}^{TOTEM}$) versus sum of charged particles in tracker ($p_{X,Y}^{CMS}$)
- Allows to select very pure sample
- Require diproton and dipion p_x and p_y to match ($\Sigma_4 p_x \sim 0$ and $\Sigma_4 p_y \sim 0$)
- Main background: elastic with inelastic pileup

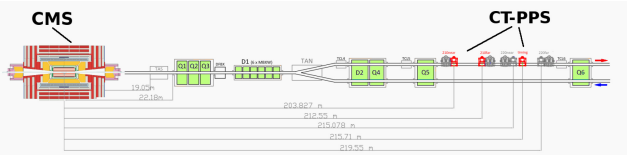
CMS-PAS-SMP-21-004 ; TOTEM-NOTE-2023-001

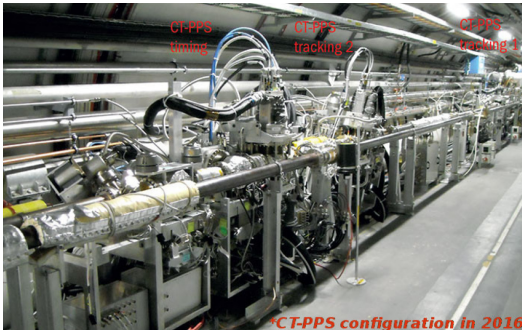
Non-resonant exclusive dipion production (CMS/TOTEM)



- Variables studied: $m_{\pi^+\pi^-}$, proton p_T and ϕ (2-proton azimuthal angle difference)
- Focus on non-resonant region: $0.35 < m_{\pi\pi} < 0.65$ GeV
- First observation of parabolic minimum in ϕ
- Study nucleon-pomeron and meson-pomeron couplings in different models with different form factors
- Two channel model favored
- Remarkable agreement with DIME model

What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?

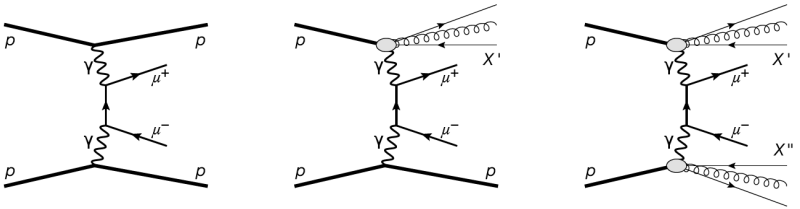




- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim$ 115 fb^{-1} of data collected
- Acceptance for two tagged protons starts at $\sim$450 GeV

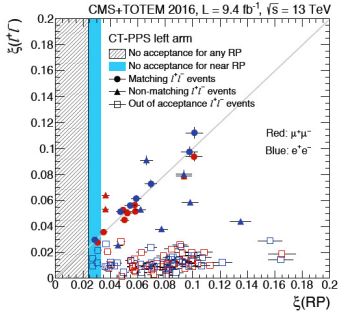
Quasi-exclusive $\mu\mu$ and ee production in PPS/AFP

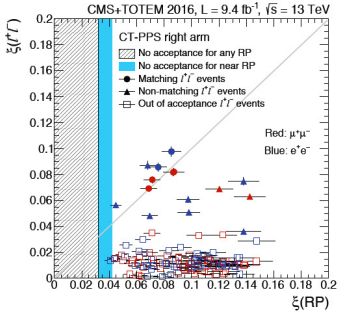
- Turn the LHC into a $\gamma\gamma$ collider at high luminosity: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons
- The dilepton mass acceptance of PPS/AFP 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



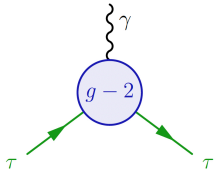
Observed signal

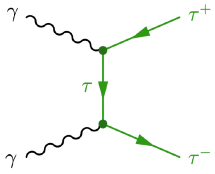
- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (resp. 23) events are found with protons in the PPS acceptance and 12 (resp. 8) $< 2\sigma$ matching in the $\mu\mu$ (resp. ee) channel (JHEP 1807 (2018) 153)
- 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)





τ electromagnetic moments from $\gamma\gamma \to \tau\tau$ events

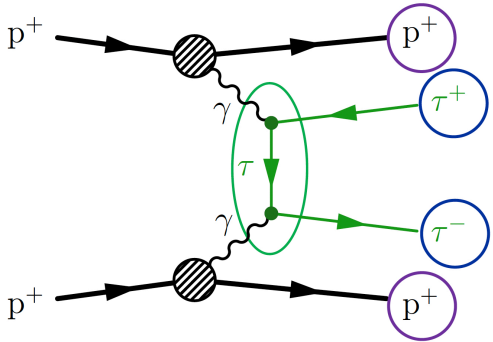




- τ (g-2) and electric dipole moment d_τ can be probed from $\gamma\tau\tau$ vertex
- $\gamma\gamma \to \tau\tau$ process includes two $\gamma\tau\tau$ vertex
- Constraints on d_τ from form factor or SMEFT approach
- In the SM, d_τ is very small but can be enhanced in BSM models
- CMS-PAS-SMP-23-005

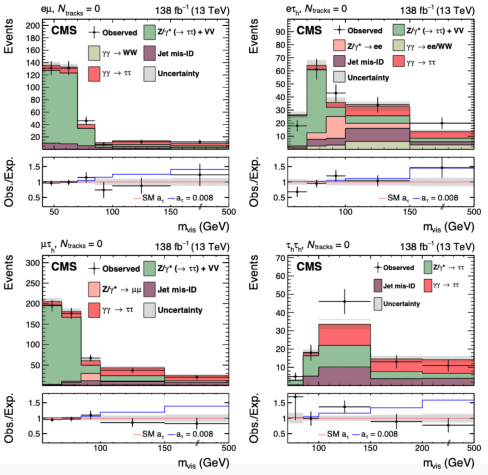
Event signature

- 2 diffracted protons: not reconstructed
- 2 back-to-back opposite side τ leptons: acoplanarity < 0.015
- Define *Ntracks* as the number of tracks with $p_T > 0.5$ GeV and $|\eta| < 2.5$ within a window of 0.1 cm around the di-τ vertex, excluding tracks from tau leptons
- No hadronic activity close to the di-τ vertex: $Ntracks = 0$



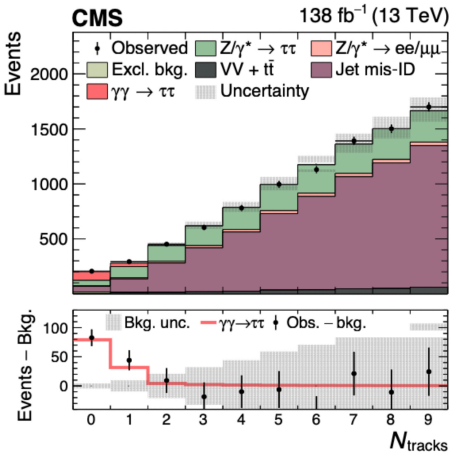
Final states and strategy

- We consider the following decays of $\tau\tau$: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- In each di-tau final state, 2 signal regions: $N_{tracks} = 0$ or 1
  - $N_{tracks} = 0$: $\sim$ 50% of the signal, inclusive backgrounds reduced by o(10^3)
  - $N_{tracks} = 1$: $\sim$ 25% of the signal, larger background
- Dimuon control region to derive corrections to the simulations
- In each of the categories, fit visible invariant mass of tau pair: signal appears at high mass



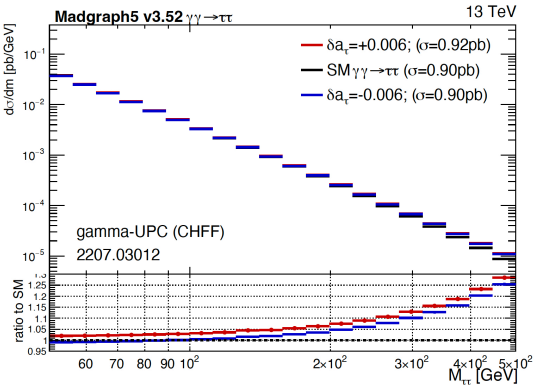
Observation of $\gamma\gamma \to \tau\tau$

- Inclusive background (Drell-Yan, etc): shape from data with $2 < N_{tracks} < 8$ $\to$ negligible contributions ; Normalized to Z peak in events with $N_{tracks} = 0, 1$
- Elastic $\gamma\gamma \to \mu\mu, WW$ estimated from gammaUPC, rescaled with linear $m_{\mu\mu}$ function to match data
- 5.3σ observed, 6.5σ expected ; First observation of $\gamma\gamma \to \tau\tau$ in pp runs



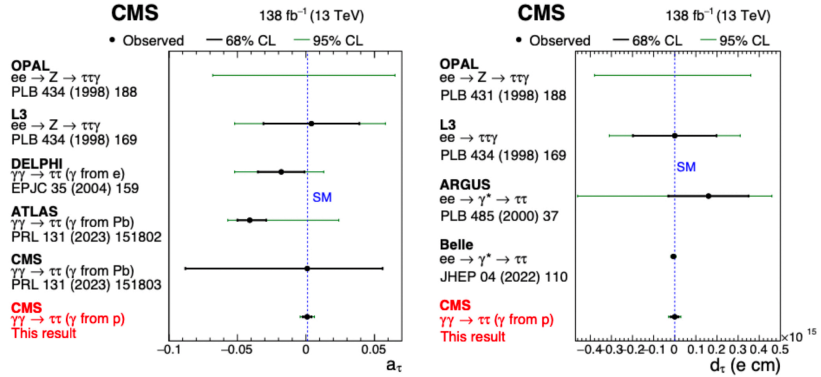
How does BSM physics in a_τ affect $\gamma\gamma \to \tau\tau$

- At large $m_{\tau\tau}$, ,$\gamma\gamma \to \tau\tau$ cross section increases with both positive and negative variations to a_τ
- Effect grows with $m_{\tau\tau}$
- a_τ can be constrained by looking at the yield and $m_{\tau\tau}$ distribution
- Expect better BSM sensitivity than with Pb-Pb runs because of higher $m_{\tau\tau}$ range probed

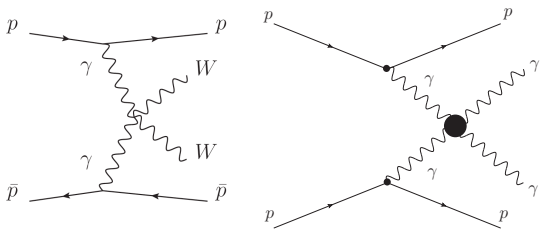


Comparison with previous results

- Constraint on the τ electromagnetic moments with an EFT approach: $a_\tau = 0.0009^{+0.0032}_{-0.0031}$ at 68% CL, $-0.0042 < a_\tau < 0.0062$ at 95% CL (Improving previous constraints by a factor of $\sim$5

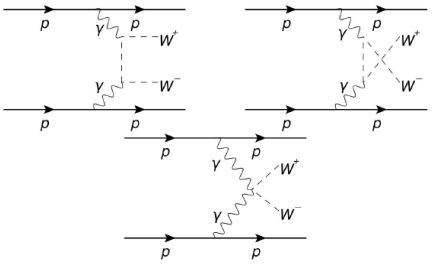


Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling



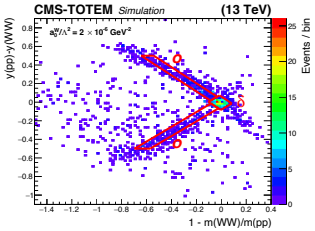
- Study of the process: $pp \to ppWW$, $pp \to ppZZ$, $pp \to pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1\,TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich $\gamma\gamma$ physics at LHC: see Phys.Rev. D89 (2014) 114004 ; JHEP 1502 (2015) 165; Phys. Rev. Lett. 116 (2016) 231801; JHEP 1706 (2017) 142; JHEP 1806 (2018) 131, etc
- See PPS talks by Andrea and Michael

Exclusive production of W boson pairs

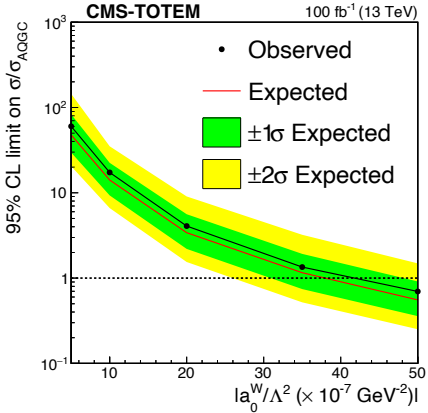


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 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

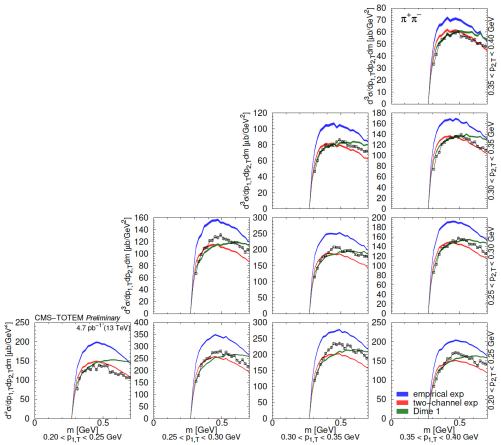


- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section $\sigma_{WW} < 67$fb, $\sigma_{ZZ} < 43$fb for $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings (events violating unitarity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

Conclusion

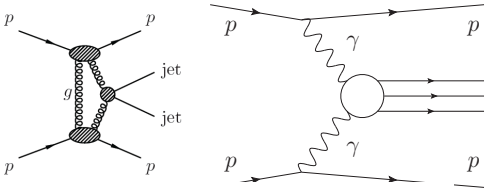
- Observation of quasi-exclusive dilepton production
- Central-exclusive non resonant production of pions at low mass
- Observation of $\gamma\gamma \to \tau\tau$ in pp runs
- Constraint on the τ electromagnetic moments with an EFT approach: $a_\tau = 0.0009^{+0.0032}_{-0.0031}$ at 68% CL, $-0.0042 < a_\tau < 0.0062$ at 95% CL (Improving previous constraints by a factor of $\sim$5
- Best sensitivities to $\gamma\gamma WW$, $\gamma\gamma ZZ$ couplings

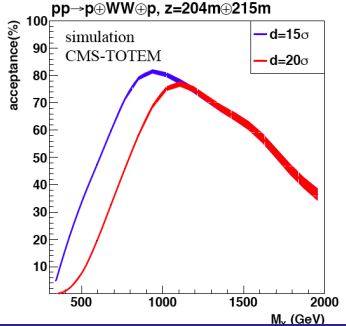
Non-resonant exclusive dipion production (CMS/TOTEM)



- Invariant mass spectrum of the central two hadron system
- Remarkable agreement with DIME model
- Data can be used to tune further MCs and also survival probabilities
- Similar study in the resonant region in progress

Detecting intact protons in ATLAS/CMS-TOTEM at high luminosity

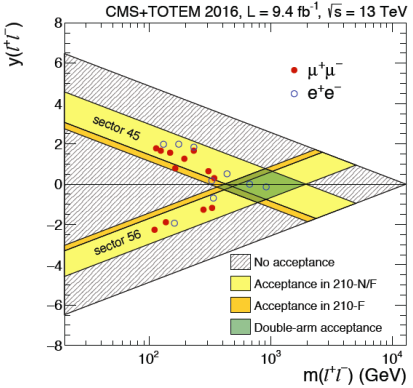




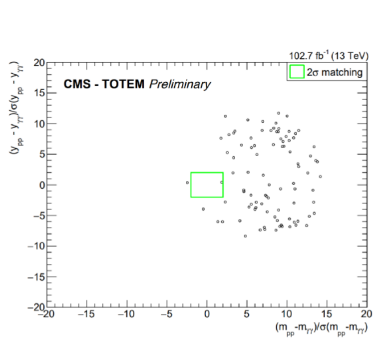
- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs at low luminosity (no pile up) and standard luminosity runs with pile up

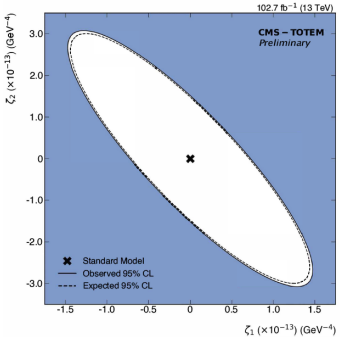
Summary of 20 candidates properties

- 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



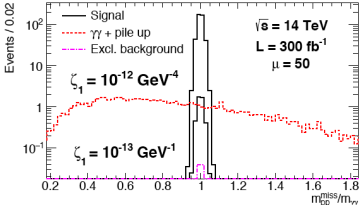
First search for high mass exclusive $\gamma\gamma$ production

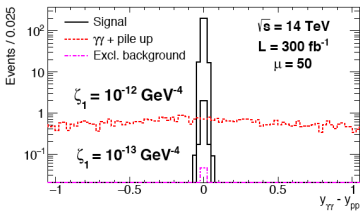




- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9\ 10^{-13}$ GeV^{-4}, $|\zeta_2| < 6.\ 10^{-13}$ GeV^{-4} with about 10 fb^{-1}, PRL 129 (2022) 011801
- Limit updates with 102.7 fb^{-1}: $|\zeta_1| < 7.3\ 10^{-14}$ GeV^{-4}, $|\zeta_2| < 1.5\ 10^{-13}$ GeV^{-4}

Search for quartic $\gamma\gamma$ anomalous couplings

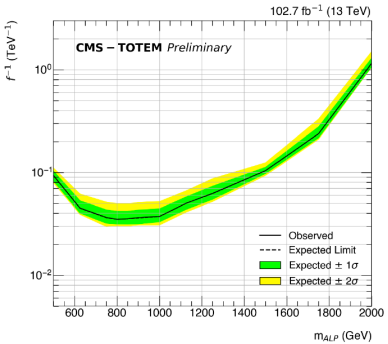


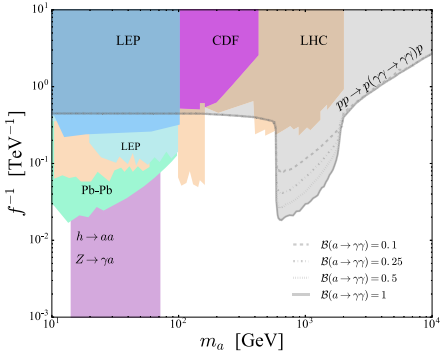


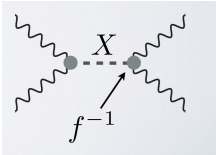
Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200,(100)$ GeV]	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert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

First search for high mass production of axion-like particles

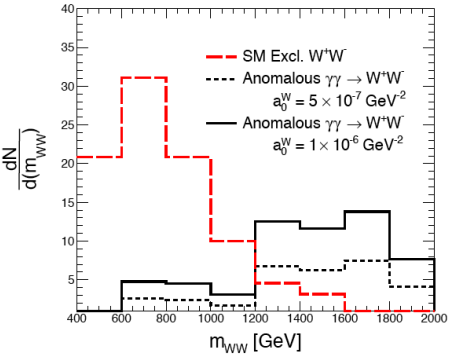






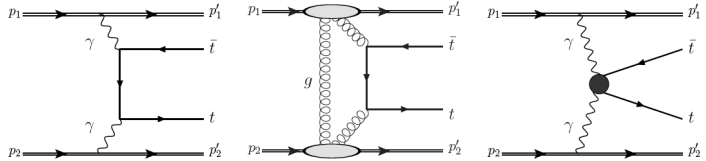
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 131)

The future: Observation of exclusive WW production



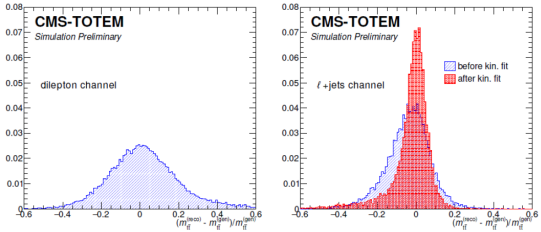
- SM contribution appears at lower WW masses compared to anomalous couplings
- Use purely leptonic channels for W decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive WW (leptonic decays) after selection: about 50 events for 300 fb^{-1} (2 background)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

Exclusive $t\bar{t}$ production

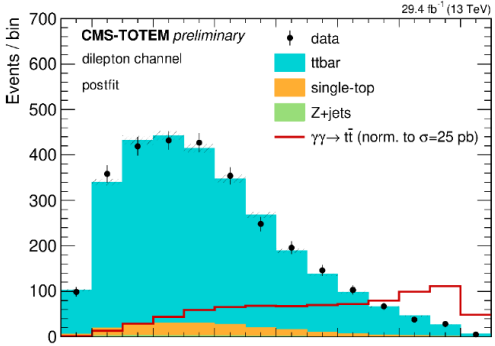


dilep channel ($\bar{t}t \to lvb + lv\bar{b}$)	**Semilep channel** ($\bar{t}t \to lvb + jj\bar{b}$)
Object selection	
Leptons: pT>30(20)GeV, |η|<2.1 Jets: pT>30GeV, |η|<2.4, ΔR(j,l)>0.4	Leptons: pT>30GeV, |η|<2.1(2.4) for e(μ) Jets: pT>25GeV, |η|<2.4, ΔR(j,l)>0.4
Event selection	
≥2 leptons (OS pair),|m(ll)-m(Z)|>15GeV ≥2 b-jets 1 proton / side	=1 lepton ≥2 b-jets, ≥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
- $\sigma_{t\bar{t}}^{excl.} < 0.59$ pb (JHEP 2406 (2024) 187)