CMS and TOTEM results on diffraction and low x

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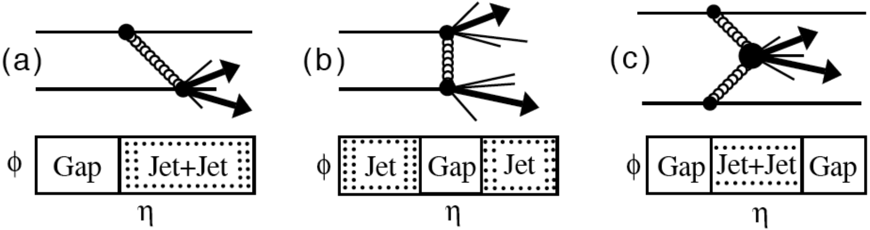
- Hard diffraction: diffractive jet cross section
- Gap between jets
- The LHC as a $\gamma\gamma$ collider

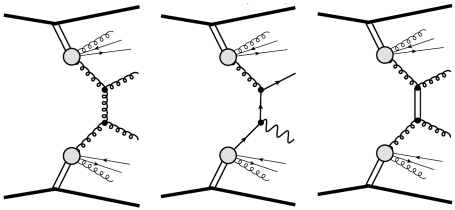
Diffraction at the LHC



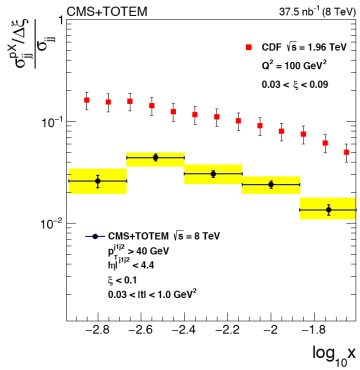
Kinematic variables

- t: 4-momentum transfer squared
- ξ_1, ξ_2: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken-x of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta\eta \sim \log 1/\xi_{1,2}$: rapidity gap

Hard diffraction at the LHC (CMS/TOTEM)

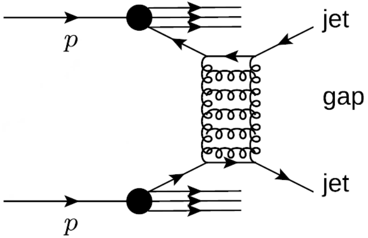


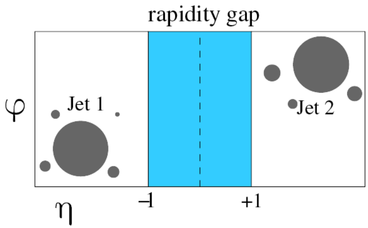
- Dijet production: dominated by gg exchanges
- γ+jet production and W production: dominated by qg exchanges
- Jet gap jet in diffraction: Probe BFKL



- SD dijet production further suppressed at the LHC compared to the Tevatron
- Eur.Phys.J.C 80 (2020) 12, 1164

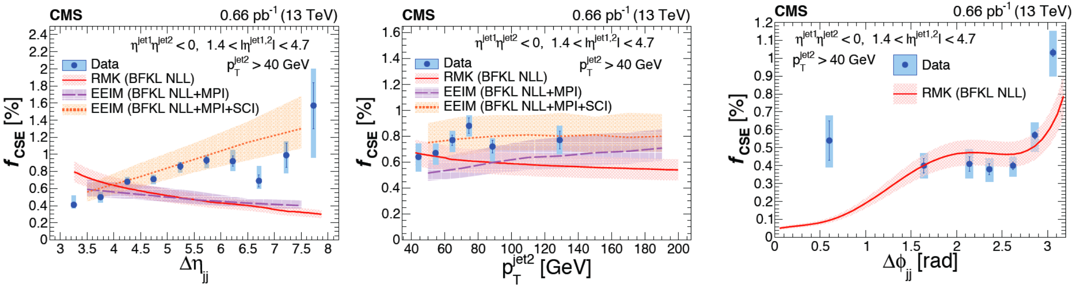
Gap between jets at the LHC



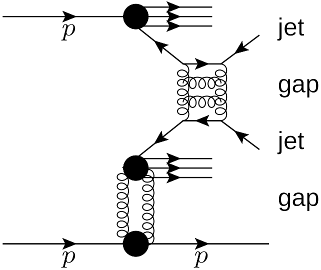


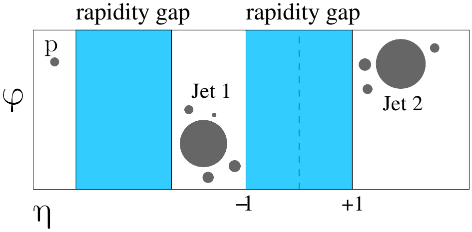
- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector (Phys.Rev.D 104 (2021) 032009)
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow

Jet gap jet fraction



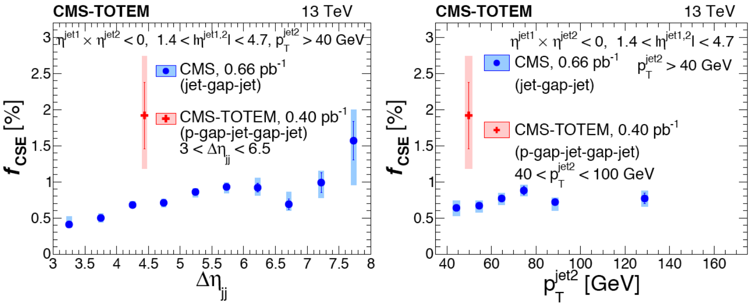
- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$
- Comparison with NLL BFKL (with LO impact factors) as implemented in PYTHIA, and soft color interaction based models (Ingelman et al.)
- Sensitivity to gap definition: see talk by Cristian
- Comparison with full BFKL NLL calculation in progress (F. Deganutti, D. Colferai)



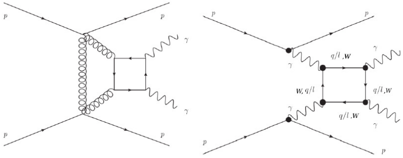


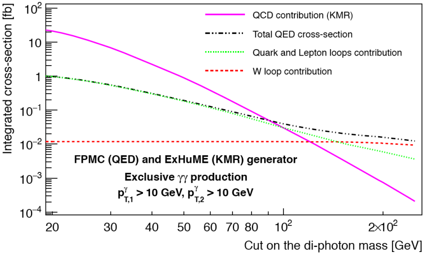
- Jet gap jet events: powerful test of BFKL resummation
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time by CMS!** (Phys.Rev.D 104 (2021) 032009)

First observation of jet gap jet events in diffraction



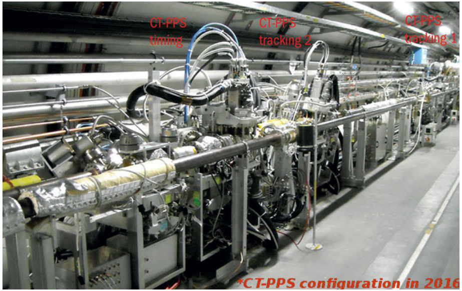
- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb^{-1} needed, 100 for DPE

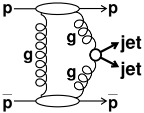


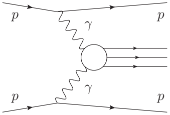


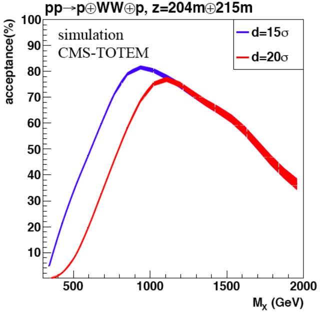
- Consider exclusive production of ee, $\mu\mu$ WW, $\gamma\gamma$, etc
- Dilepton production is a QED (γ-exchange) process
- In pp interactions, QCD production of $\gamma\gamma$ dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$ (similar for WW, ZZ, $Z\gamma$, $t\bar{t}$ production)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





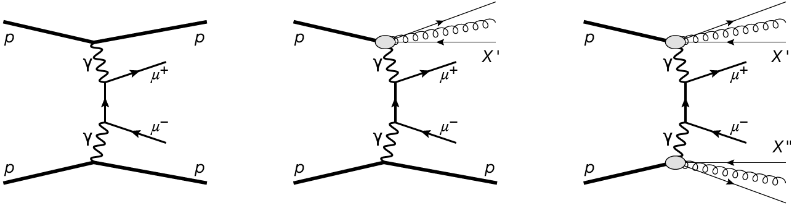




- Good acceptance at high mass in standard runs (PPS in CMS, AFP in ATLAS)
- >100 fb^{-1} collected in Run II

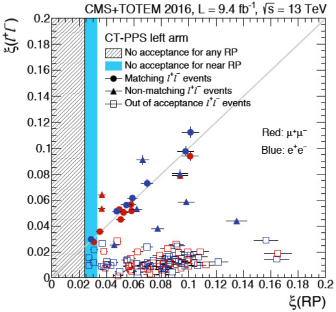
Quasi-exclusive $\mu\mu$ and *ee* production in CMS-TOTEM

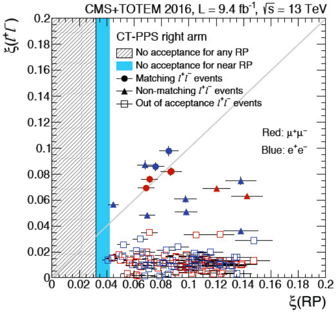
- Turn the LHC into a $\gamma\gamma$ collider at high luminosity: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons
- The dilepton mass acceptance of PPS/AFP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



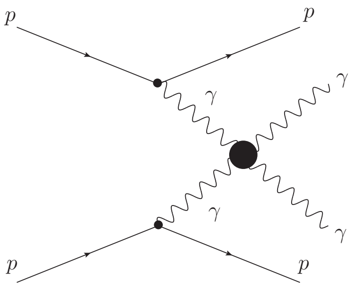
Observed signal of semi-exclusive dilepton

- 1st measurement of semi-exclusive dileptons with proton tag (JHEP 1807 (2018) 153)
- 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)





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

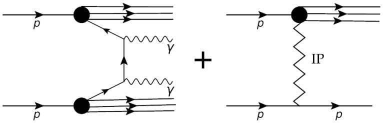


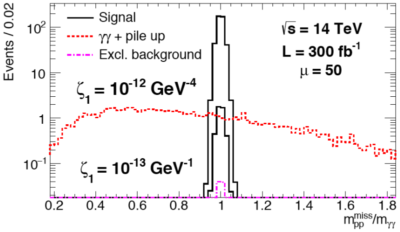
- Search for production of two photons and two intact protons in the final state: $pp \to p\gamma\gamma p$

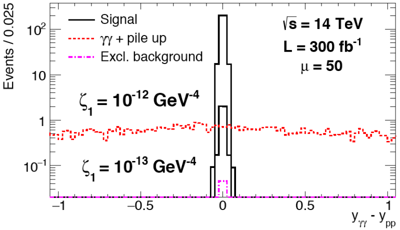
- Additional channels: WW, ZZ, γZ, $t\bar{t}$
- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, axion-like particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons
- JHEP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

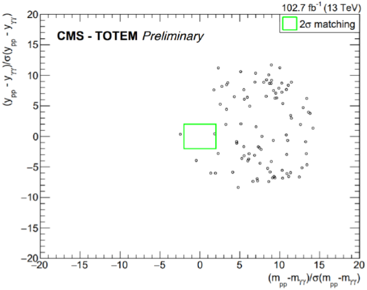
- Advantage of tagging protons: negligible background after matching mass/rapidity of photon and proton systems
- Use fast timing detectors in the case of *WW* production and *W*s decaying leptonically

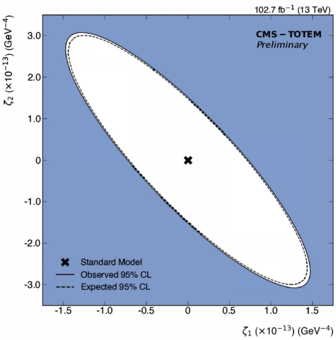






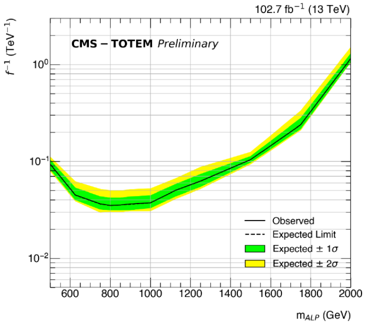
First search for high mass exclusive $\gamma\gamma$ production with tagged protons

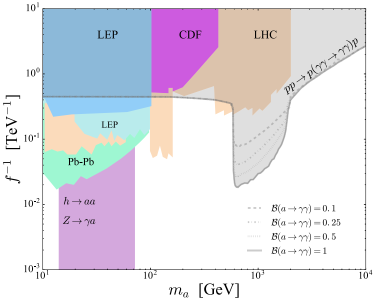


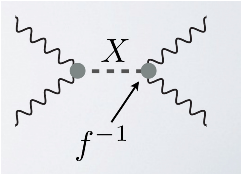


- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- Limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9\ 10^{-13}$ GeV^{-4}, $|\zeta_2| < 6.\ 10^{-13}$ GeV^{-4}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

First search for high mass production of axion-like particles with tagged protons

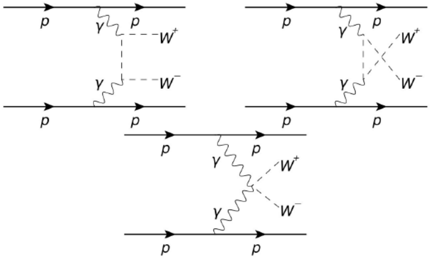






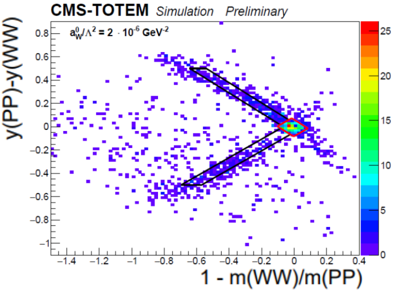
- Limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

Exclusive production of W boson pairs

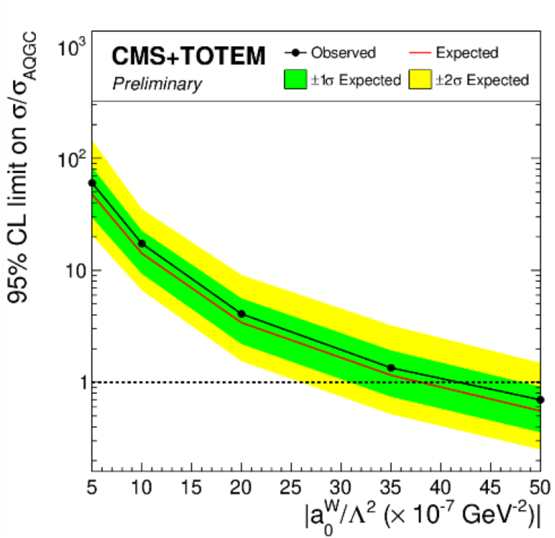


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 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

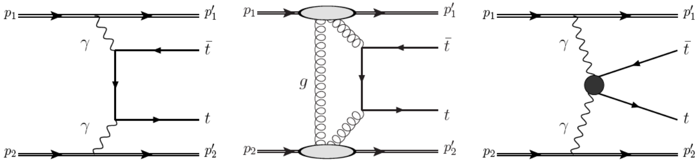


WW and *ZZ* exclusive productions



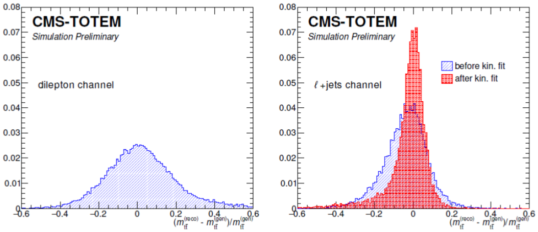
- Searches performed in full hadronic decays of *W* bosons with AK8 jets
- Limits on SM cross section $\sigma_{WW} < 67$fb, $\sigma_{ZZ} < 43$fb for $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings: $a_0^W/\Lambda^2 < 4.3\ 10^{-6}$ GeV^{-2}, $a_C^W/\Lambda^2 < 1.6\ 10^{-5}$ 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}
- Observation of SM production using leptonic channels: JHEP 2012 (2020) 165

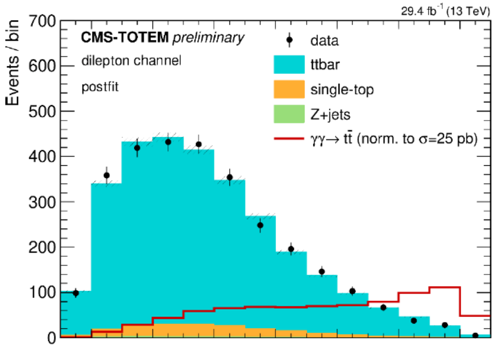
Exclusive $t\bar{t}$ production



dilep channel ($\bar{t}t \to l\nu b + l\nu\bar{b}$)	Semilep channel ($\bar{t}t \to l\nu b + jj\bar{b}$)
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

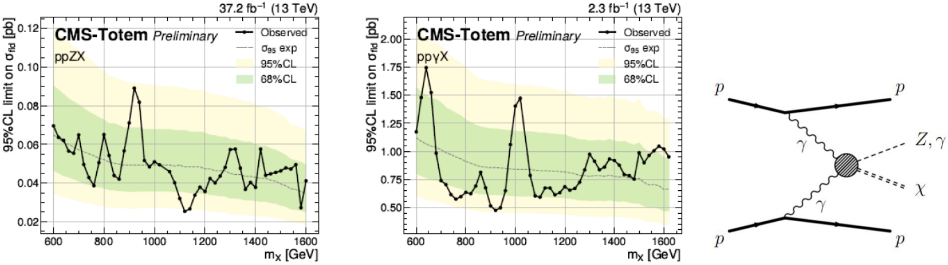




- Kinematic fitter based on W and t mass constraints to reduce background
- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes

- $\sigma_{t\bar{t}}^{excl.} < 0.6$ pb (CMS-PAS-TOP-21-007)
- Sensitivity to anomalous couplings with 300 fb^{-1}: JHEP 08 (2022) 021

$Z + X$ production



- 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-19-009)

Conclusion

- Measurement of hard diffractive events: Jet gap jet events observed for the first time with intact protons in CMS; BFKL calculation in agreement with measurement for strong gap definition
- Observation of quasi-exclusive di-lepton production by CMS/TOTEM (one proton tagged in PPS/AFP)
- Consider the LHC as a $\gamma\gamma$ collider: leads to very clean events (like at LEP) where we measure intact protons and produced particles in CMS/ATLAS
- Search for exclusive $\gamma\gamma$, ZZ, WW, $t\bar{t}$ at high luminosity at the LHC: Leads to best sensitivities to quartic anomalous couplings to date and also to the productions of axion-like particles at high mass