Central exclusive physics with PPS

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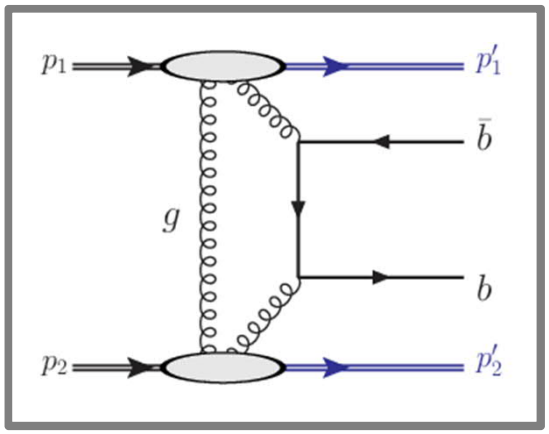
Content:

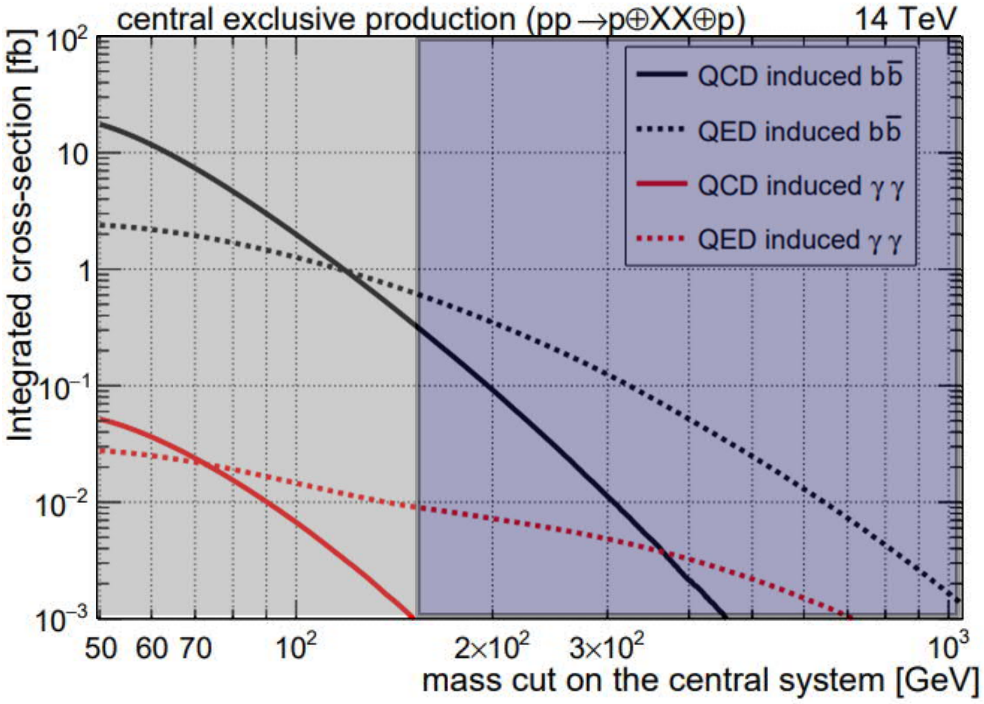
- Central exclusive processes (CEP)
- Proton Precision Spectrometer (PPS)
- Recent Run 2 physics results using PPS
- Run 3 & TALESMAN project

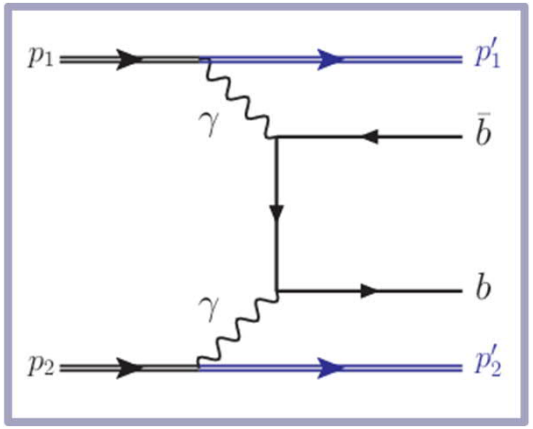
Central exclusive processes

Central exclusive processes

- Protons remain intact (tagged by PPS)
- Low activity due to colour neutral exchange via QCD ($\mathbb{P}$) or QED (γ)



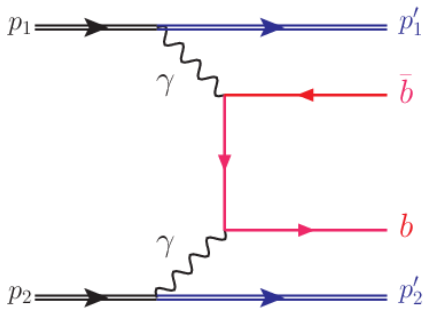




High mass range is dominated by photon-photon interactions

Central exclusive processes

- Photon-Photon fusion in pp collisions
  - In Central Exclusive production (CEP) processes, all beam energy is transferred to protons, and centrally produced event
  - For given proton momentum loss $\xi = \Delta p / p$:



Proton kinematics can be inferred from the central system:

$$\xi_{\pm} = \frac{\sum E \pm p_Z}{\sqrt{s}}$$

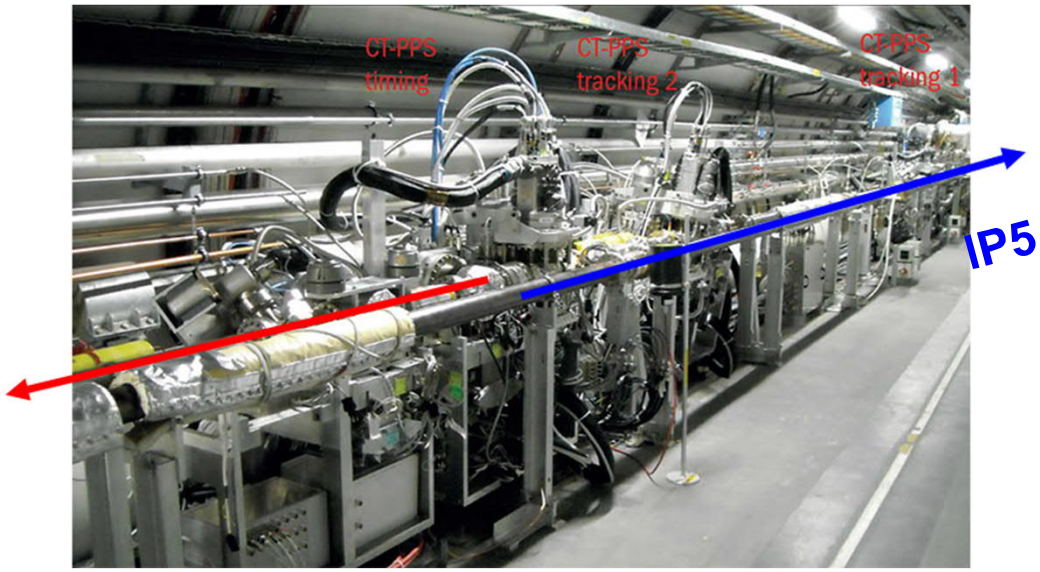
Central system kinematics can be inferred from the protons:

$$m = \sqrt{s\xi_+\xi_-}$$

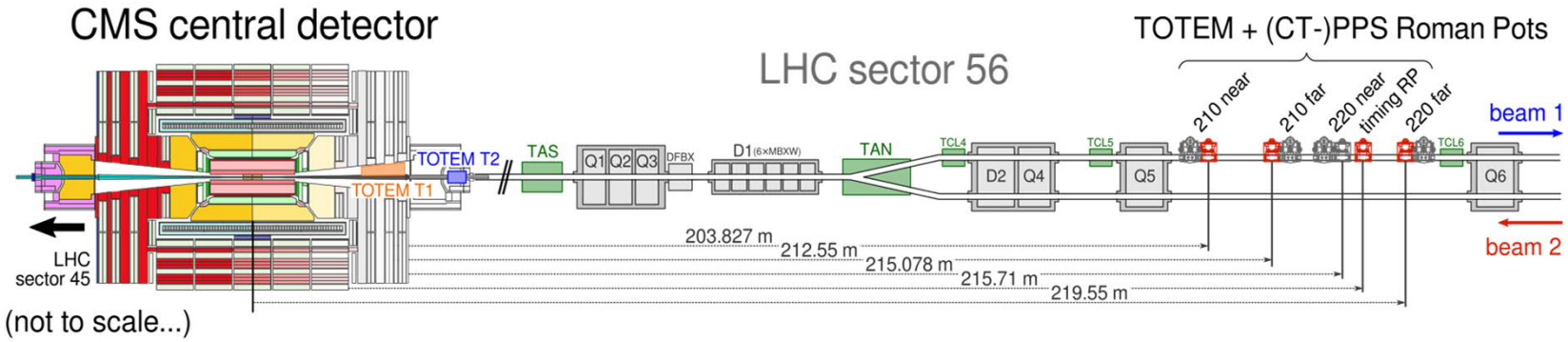
$$Y = \frac{1}{2} log\left(\frac{\xi_+}{\xi_-}\right)$$

Proton Precision Spectrometer (PPS)

- Built by combined TOTEM+CMS expertise
- Operated in standard LHC runs since 2016
- Located ~ 200m from CMS IP in both arms, equipped with tracking/timing detectors
- A set of near-beam detectors that approach outgoing beam to a few mm

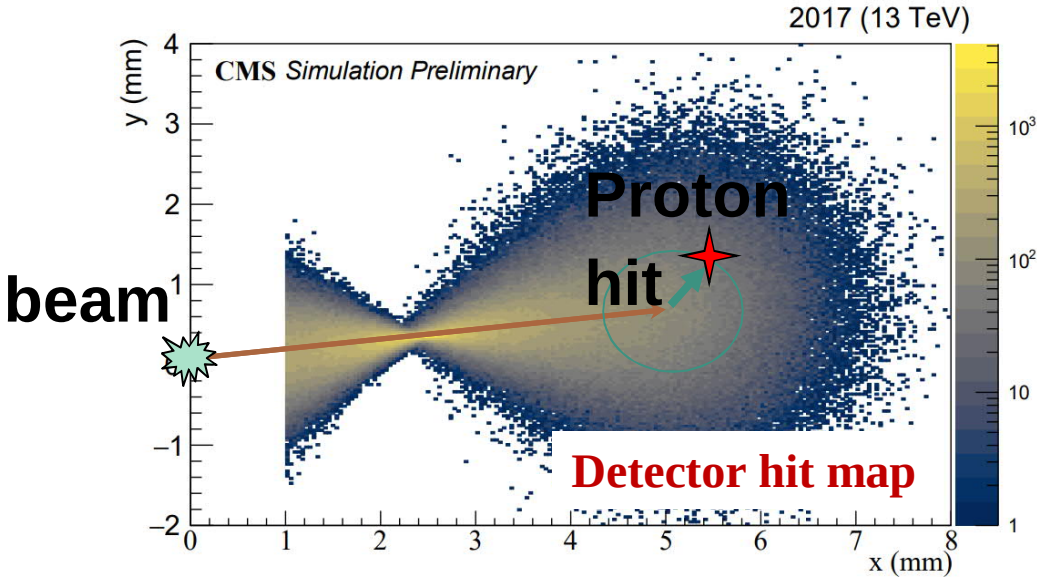


PPS farthest and, at the same time, closest CMS subsystem



PPS - tracking

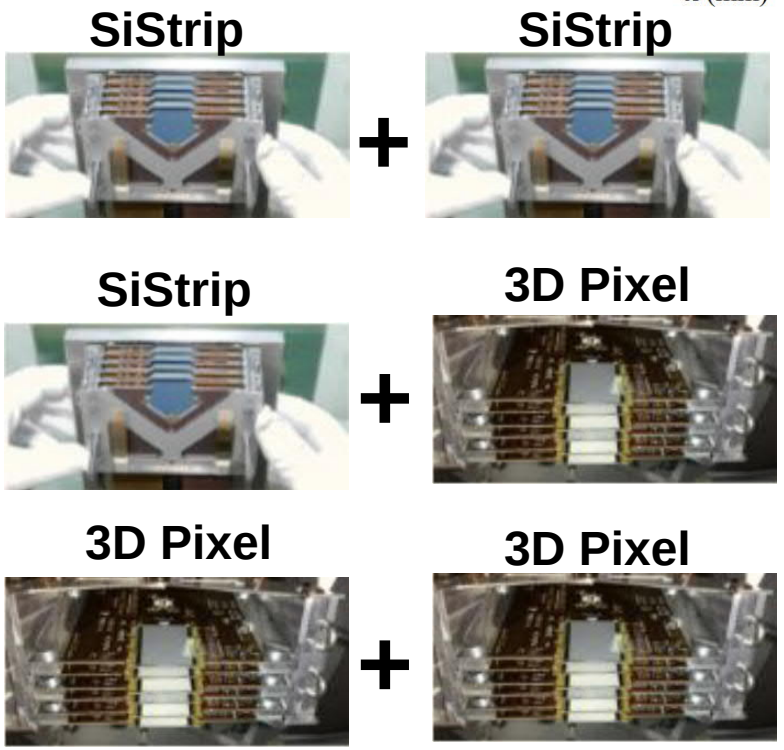
Determine proton momentum loss ξ from horizontal deviation of proton by LHC magnets



2016: PPS Inherit from TOTEM Silicon strip tracker (used in special runs, cannot resolve multiple tracks): ~ 15 fb^{-1}

2017: 3D Silicon pixels - a suitable detector technology was developed, and half of the stations were upgraded: ~ 37 fb^{-1}

2018: Both stations per arm are equipped with 3D pixel detectors: ~ 56 fb^{-1}



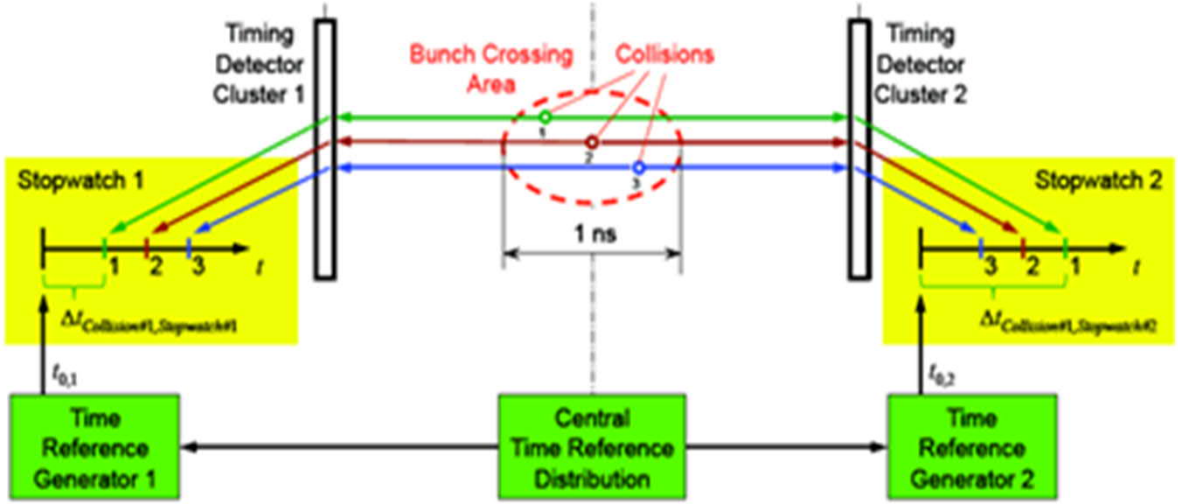
PPS - timing

- Vertex reconstruction using Time-of-Flight (TOF)
  - Vertex coordinate

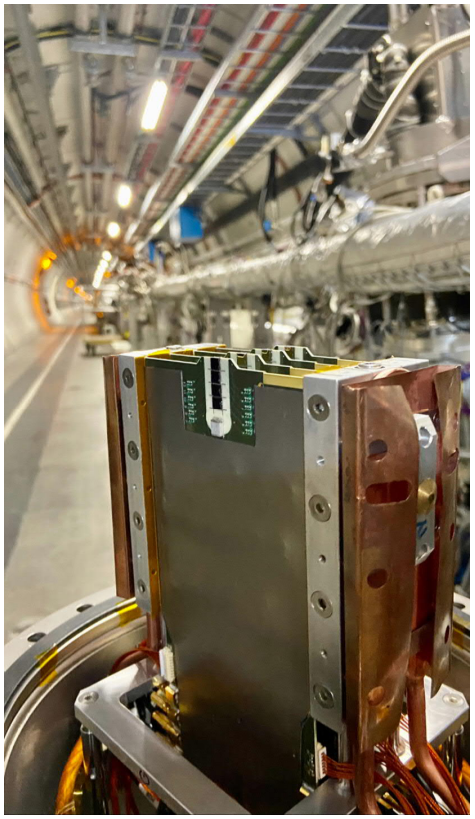
$$V_{Z,PPS} = \frac{c}{2}(t_{PPS\,1} - t_{PPS\,2})$$

  - Vertex time

$$V_{t,PPS} = \frac{1}{2}(t_{PPS\,1} + t_{PPS\,2}) - \frac{Z_{PPS}}{c}$$



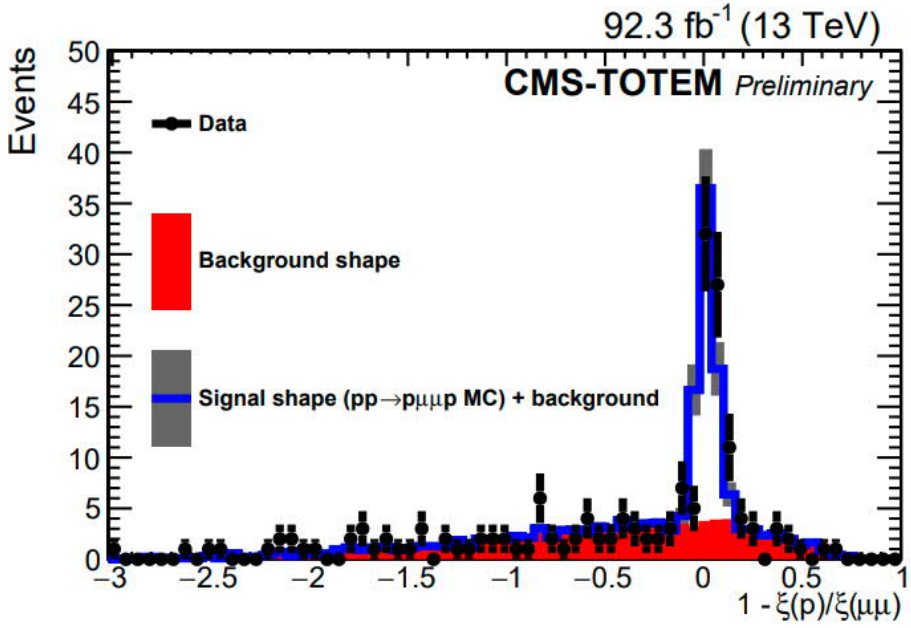
- Diamond detectors used in 2018
- 2 Single- and 2 Double-Diamond detector planes per station



PPS - performance

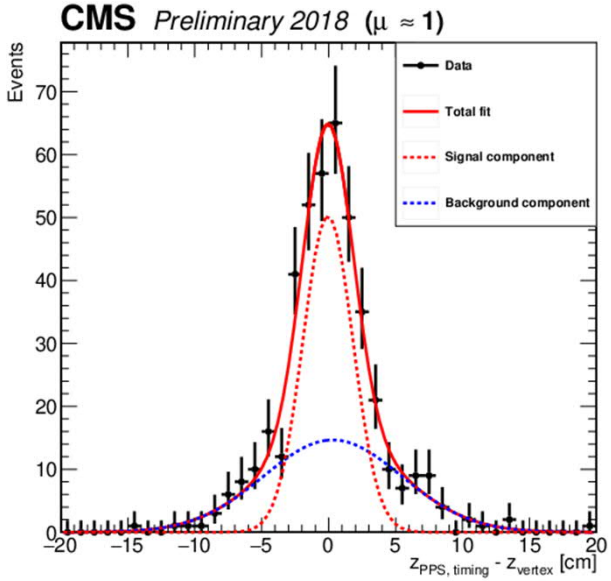
arXiv:2210.05854; submitted to JINST

- Tracking:
  - Using exclusive di-muon sample
  - Compare ξ(CMS) vs ξ(PPS)
  - **Few-% mass resolution(!!!)**



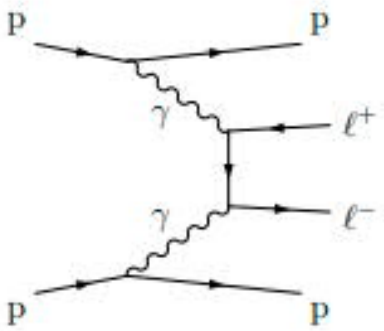
- Timing:
  - Using central diffractive events in μ~1 sample
  - Compare Z(PV) vs Z(PPS)
  - **All track resolution:**

$$\sigma_z = 2.77 \pm 0.17 cm$$



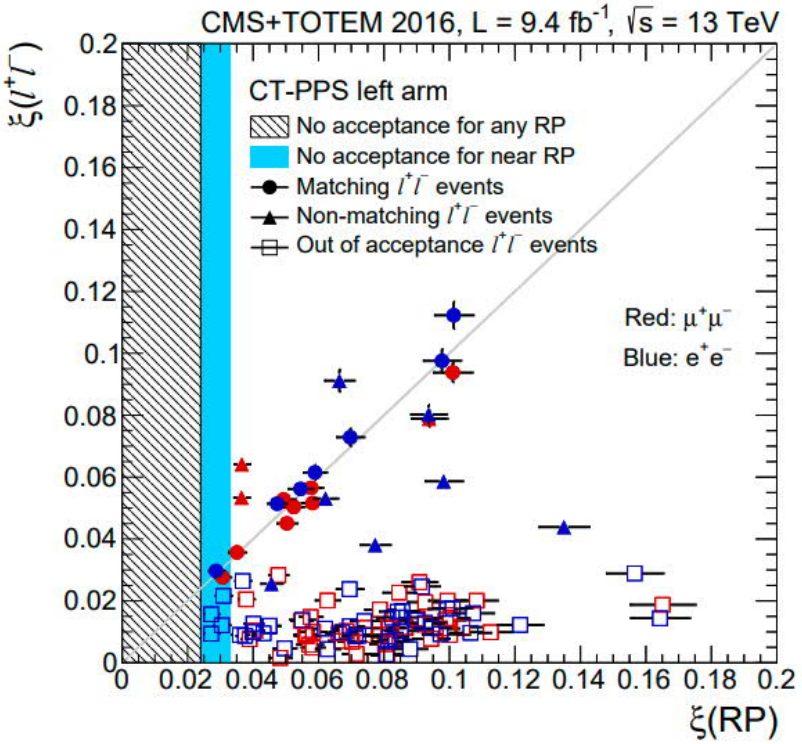
Exclusive di-lepton

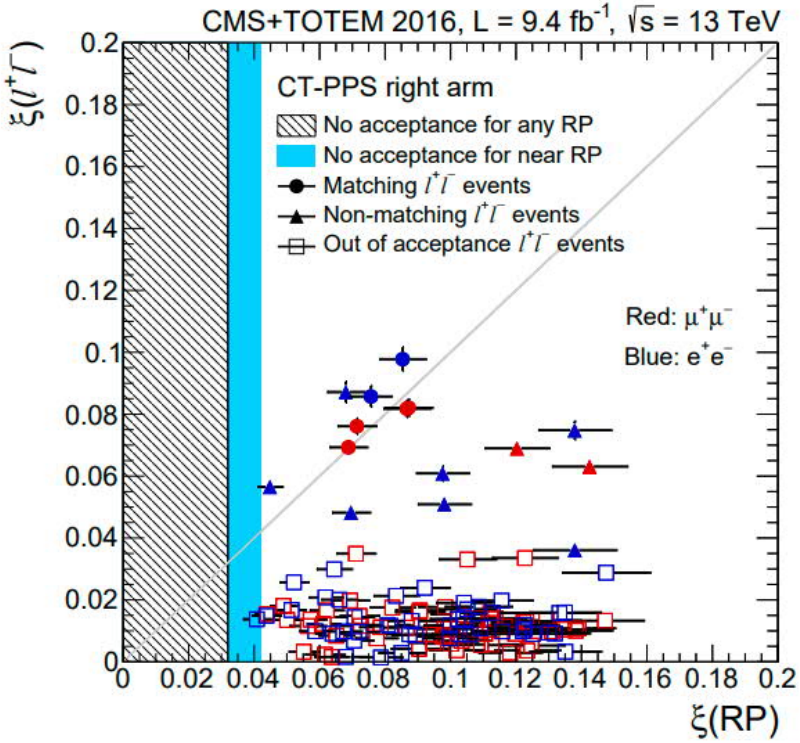
JHEP 07 (2018) 153



- Observation of (semi)-exclusive dilepton production
- Exclusive di-lepton production is the cleanest (sufficient to tag only one out-going proton) and most common CEP process
- Analysis based on 9.4fb^{-1} (2016 data), 5.1σ excess reported

Exclusive candidates are on the diagonal ($\xi(l^+l^-) = \xi(RP)$)

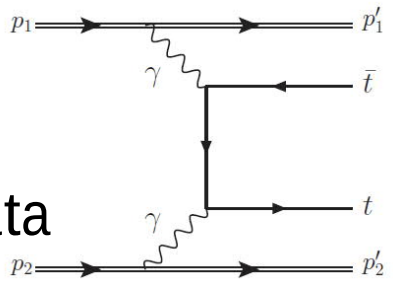




Exclusive di-muon used to calibrate PPS performance

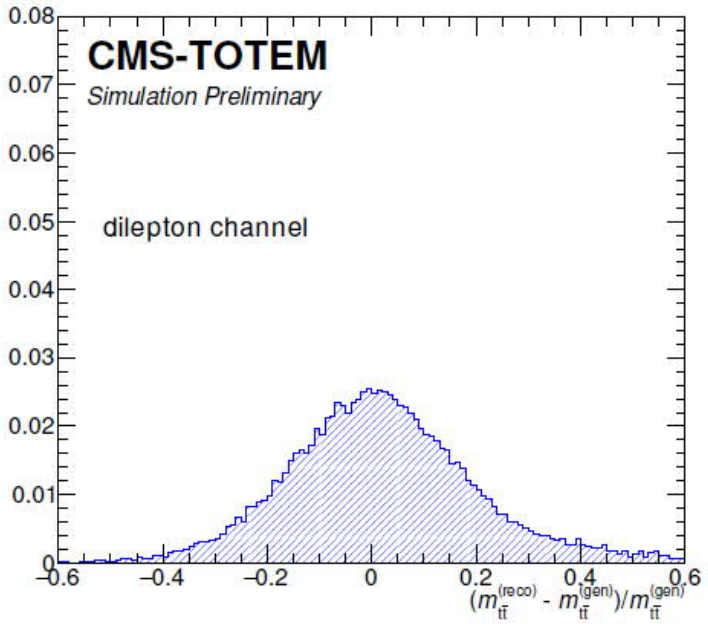
Exclusive $t\bar{t}$

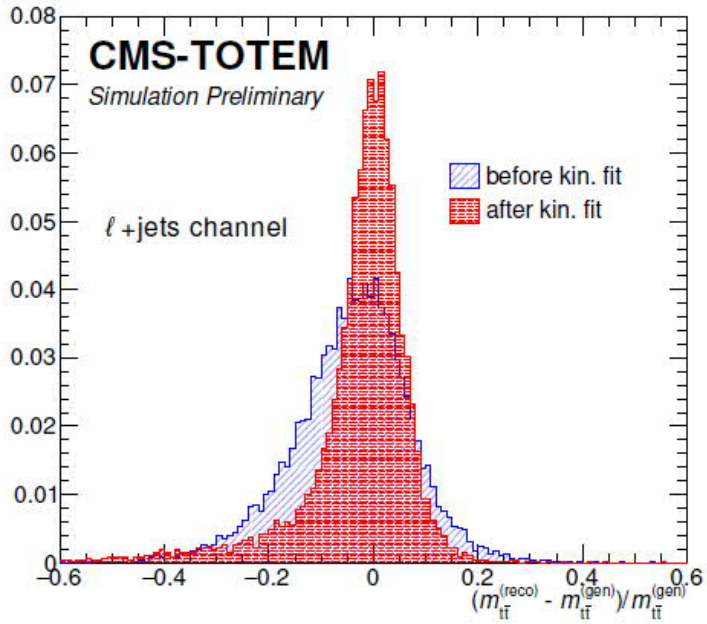
CMS-PAS-TOP-21-007; TOTEM-NOTE-2022-002



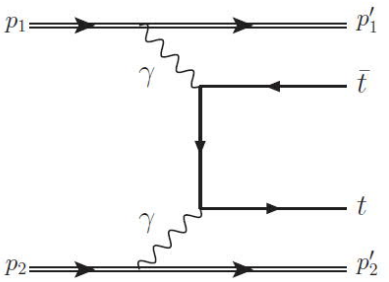
Search of xclusive production of top quark pairs in 2017 PPS data

- Searched in di-lepton and lepton + jets $t\bar{t}$ decay mode.
- Challenging due to high jet multiplicities - exclusivity condition not efficient
- Lepton + jets analysis relies on kinematic-fitter:
  - Use mass constrains to minimize $\chi^2 = \sum_{i=1}^{6} \frac{p_{x,i} - p_{x,i,initial}}{\sigma_{x,i}} + \sum_{i=1}^{6} \frac{p_{y,i} - p_{y,i,initial}}{\sigma_{y,i}} + \sum_{i=1}^{6} \frac{p_{z,i} - p_{z,i,initial}}{\sigma_{z,i}} + \sum_{j=1}^{2} \frac{\xi_j - \xi_{j,initial}}{\sigma_{\xi,j}}$
  - Protons used to improve the $t\bar{t}$ mass resolution





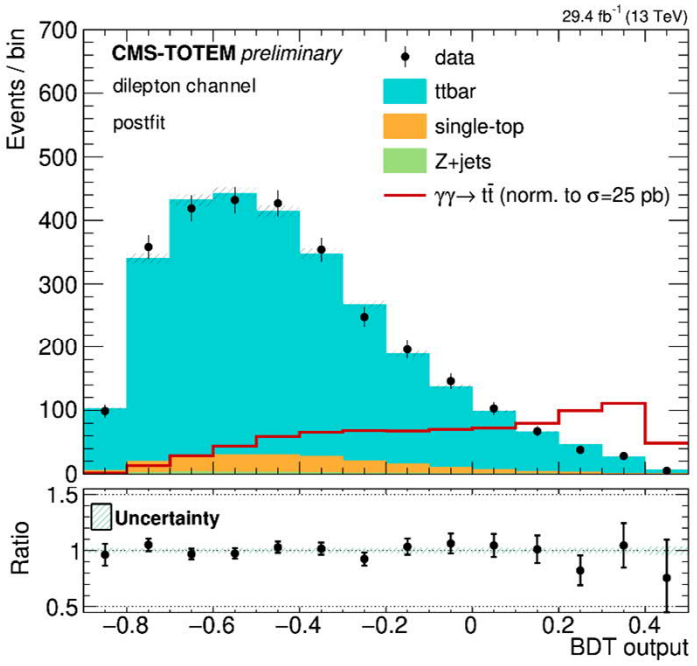
Exclusive $t\bar{t}$

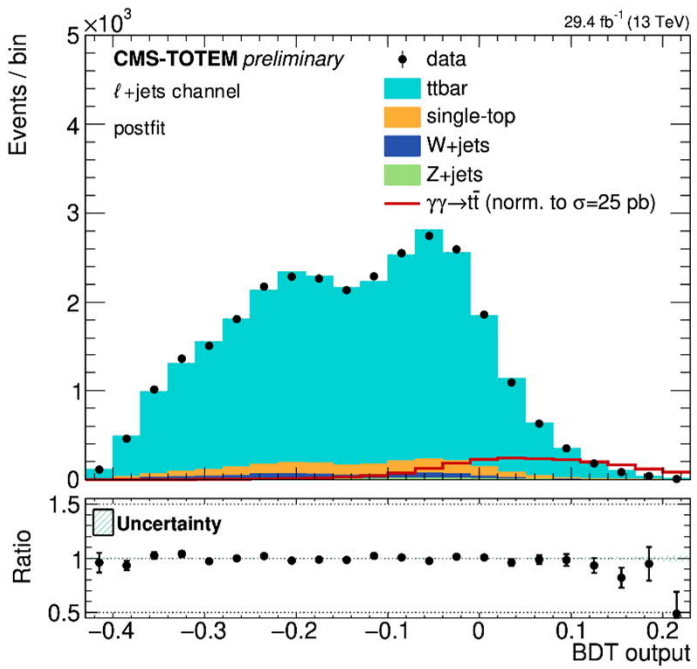


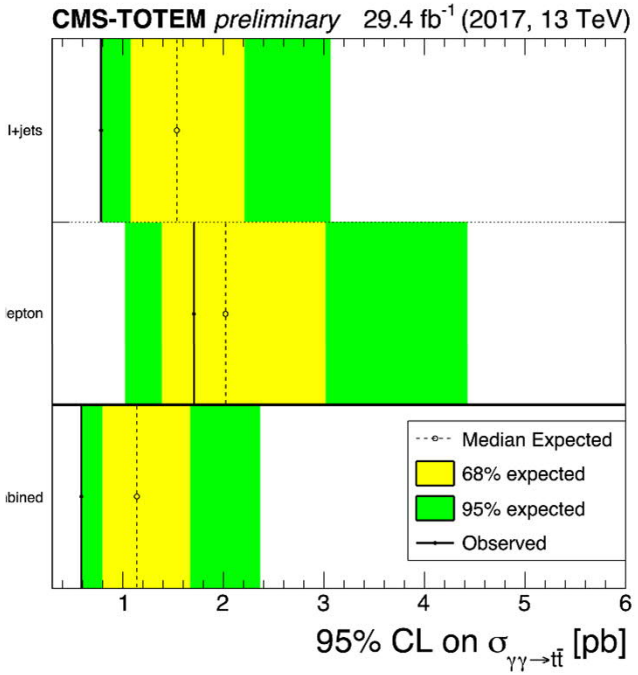
CMS-PAS-TOP-21-007; TOTEM-NOTE-2022-002

Exclusive production of top quark pairs

- Multivariate analysis based on kinematical variables to tag exclusive events
- Results interpreted as an upper limit of central exclusive production of top quark pairs (SM expectation: $\mathcal{O}(0.1\ \text{fb})$)







$$\sigma\ (pp\ \longrightarrow p +\ t\bar{t} + p) < 0.6\ \text{pb}$$

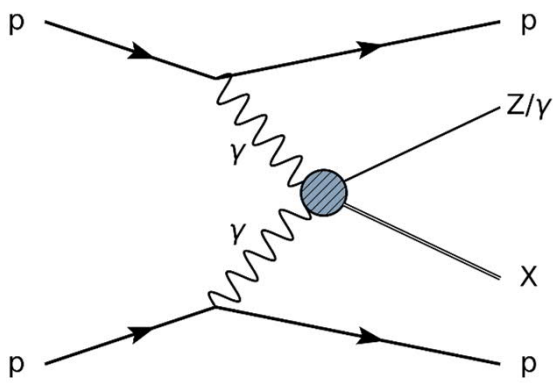
Missing mass (Z/γ + X)

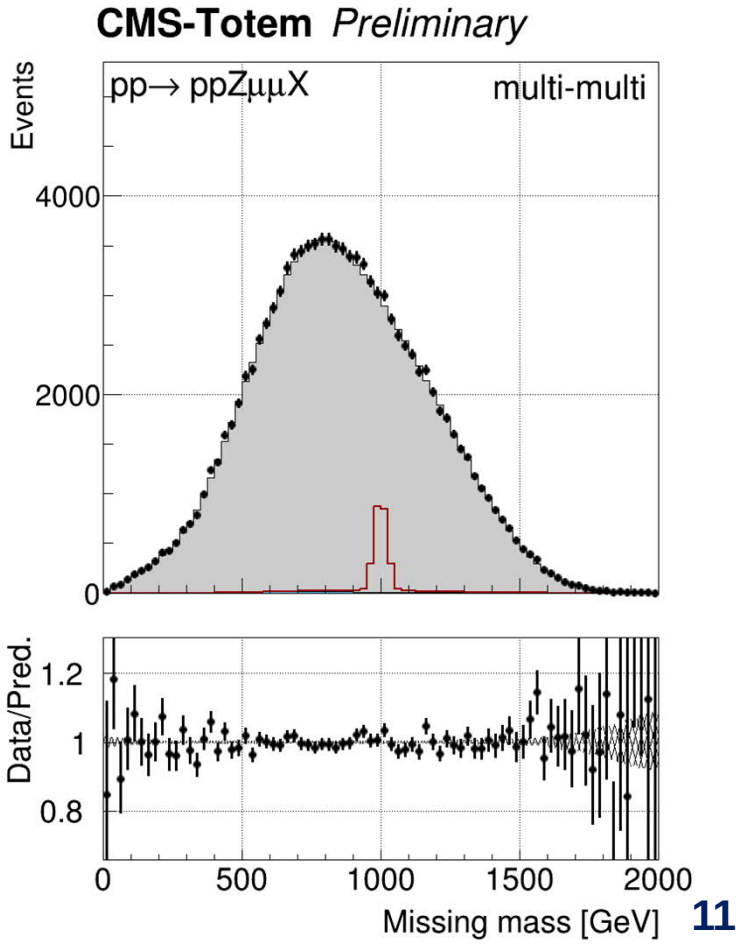
CMS-PAS-EXO-19-009; TOTEM-NOTE-2022-003

Searching for unknown particle using missing mass technique using 2017 PPS data

- Based on complete event reconstruction, first time at a hadron collider
- 4-vector of unknown state X determined from measured protons and boson
- Drell-Yan + pileup protons main background

$$m^2_{\text{miss}} = \left[(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2}) - (P_V + P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}) \right]^2$$





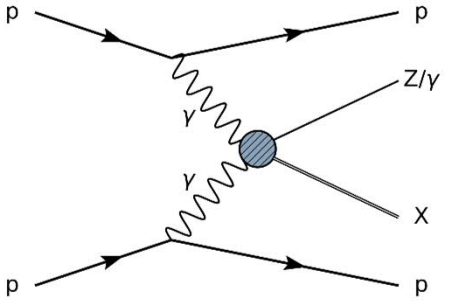
- Exploiting excellent mass resolution of PPS (2 % → 7 %) → bump hunt made in Z + X and γ + X channels

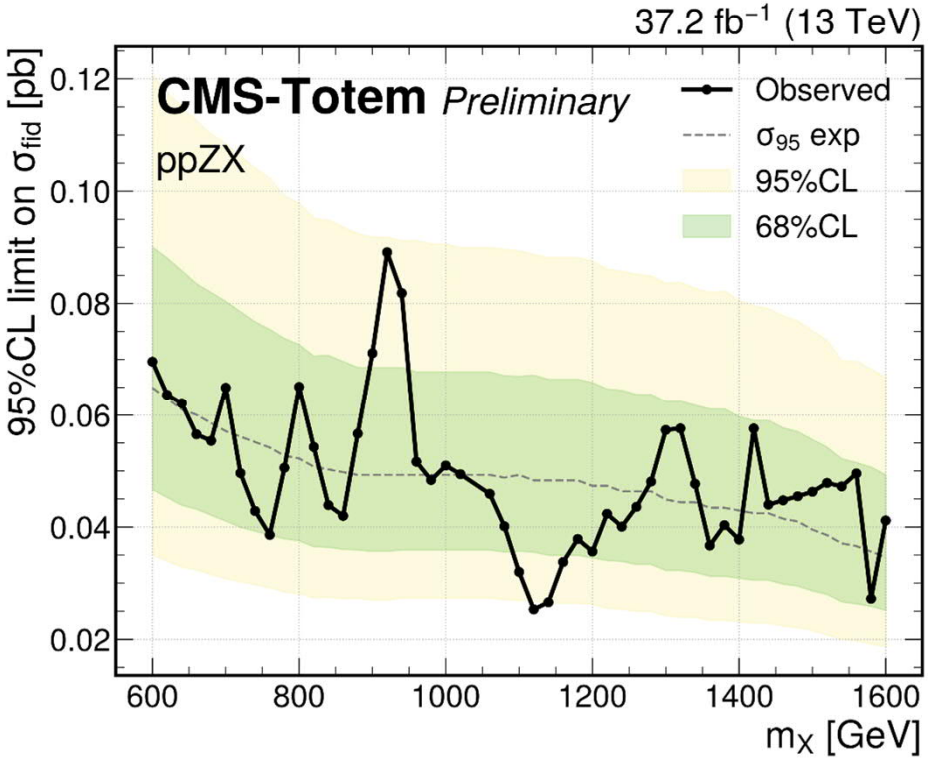
Missing mass (Z/γ + X)

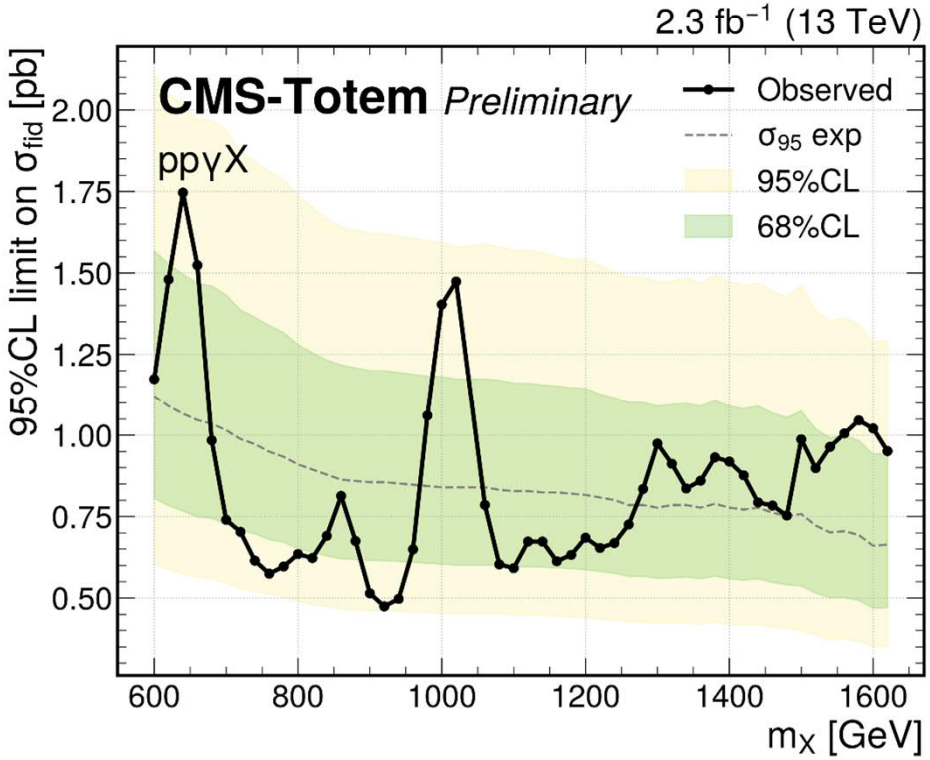
CMS-PAS-EXO-19-009; TOTEM-NOTE-2022-003

Searching for unknown particle using missing mass technique

- Data agree with background-only model, limits of central exclusive production cross-section of $Z/\gamma + X$ vs X mass derived







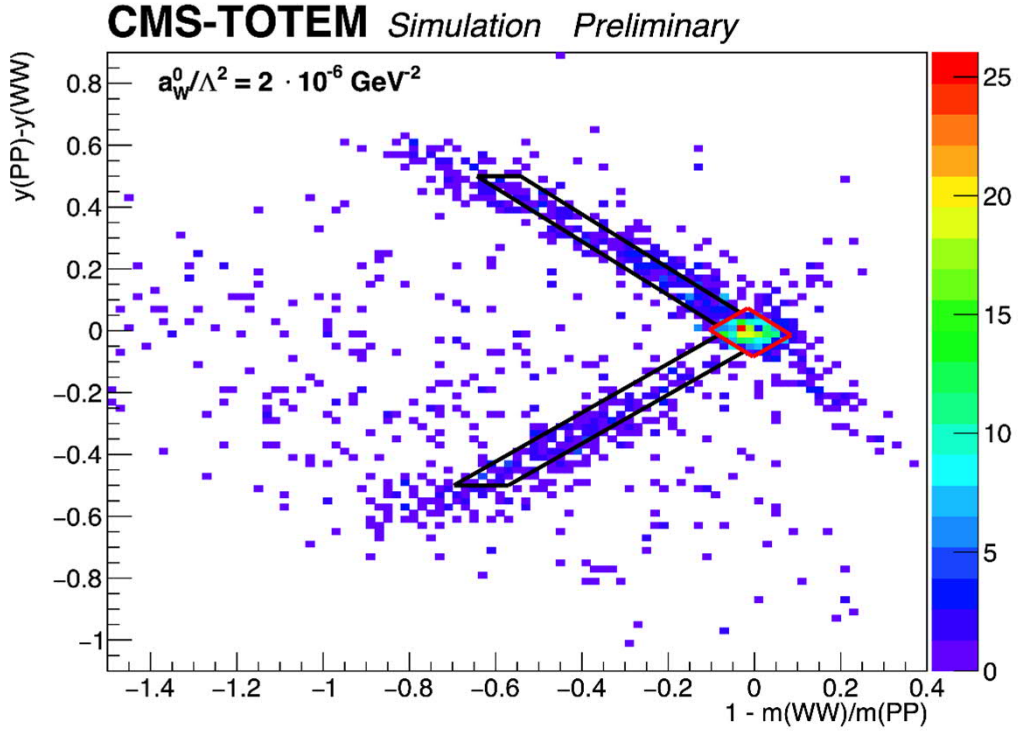
Exclusive WW & ZZ

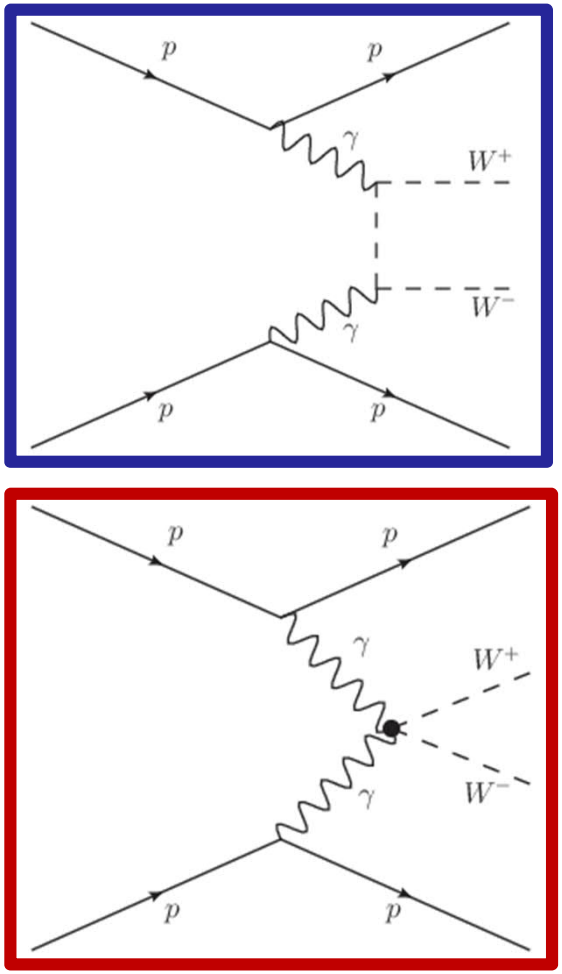
CMS-PAS-SMP-21-014; TOTEM-NOTE-2022-004

Exclusive production of weak bosons (WW/ZZ)

- Exclusive WW sensitive to both Triple (TGC) & Quartic Gauge Couplings (QGC)
- QGC enhance high masses
- Search for fully hadronic weak boson decays with protons using full Run2 data set

Signal region defined from the correlation between the central system & protons





Exclusive WW & ZZ

CMS-PAS-SMP-21-014; TOTEM-NOTE-2022-004

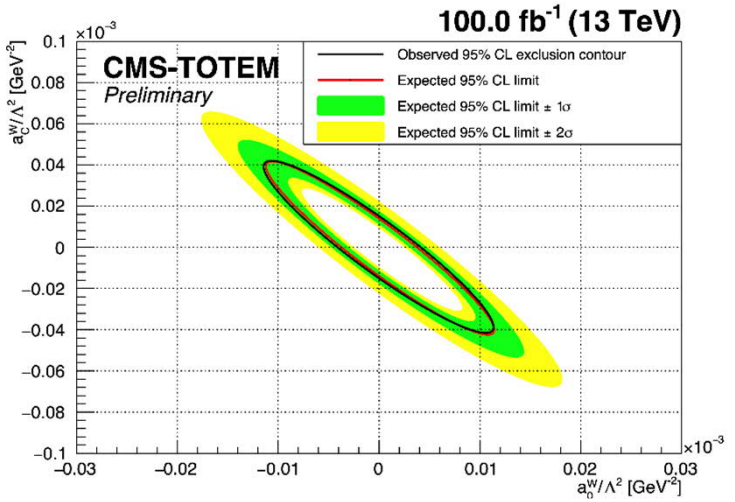
Exclusive production of weak bosons (WW/ZZ)

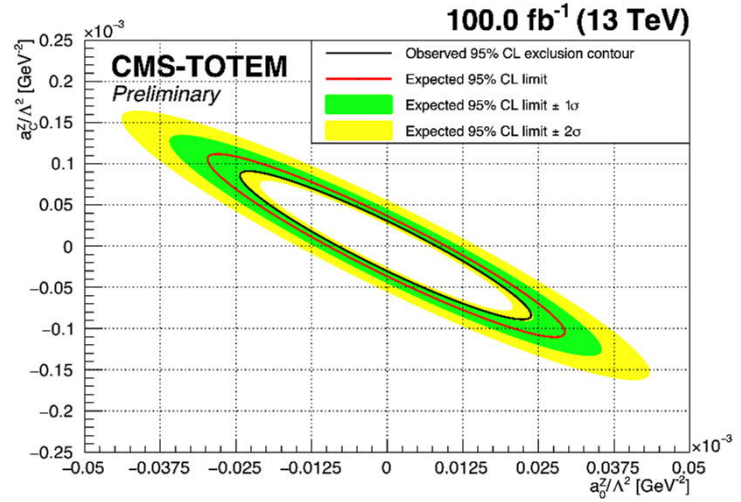
- Inclusive dijets + pileup protons main background
- Acceptance limited by dijet trigger (m_{jj} > 1.1 TeV)
- At high mass, SM cross-sections very small.
- Limit on SM fiducial cross-section obtained:

$$\sigma\,(pp \longrightarrow p + \mathrm{WW} + p \,|\, m_{pp} > 1\ \mathrm{TeV}) < 67\ \mathrm{fb}$$
$$\sigma\,(pp \longrightarrow p + \mathrm{ZZ} + p \,|\, m_{pp} > 1\ \mathrm{TeV}) < 43\ \mathrm{fb}$$

- Also limits on EFT operators extracted

$$\left|a_0^W/\Lambda^2\right| < 4.3 \cdot 10^{-6}\ \mathrm{GeV}^{-2}$$
$$\left|a_C^W/\Lambda^2\right| < 1.6 \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$
$$\left|a_0^Z/\Lambda^2\right| < 0.9 \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$
$$\left|a_C^Z/\Lambda^2\right| < 4.0 \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$

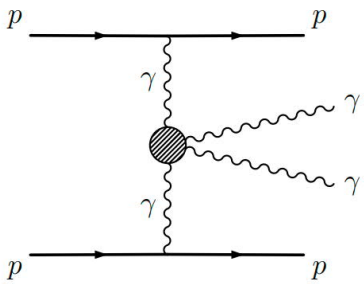




- limits competitive with VBS searches
- $\gamma\gamma WW$ limits 15-20 times more stringent than limits from Run 1
- first limits on the $\gamma\gamma ZZ$ coupling

Exclusive diphoton

Phys. Rev. Lett. 129 (2022) 011801



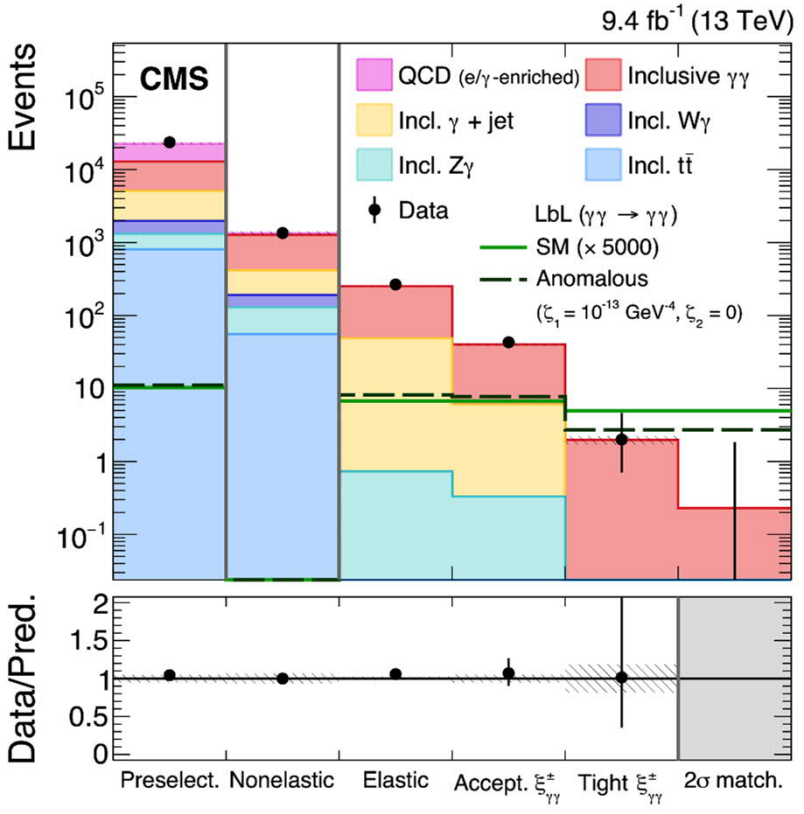
Light-by-light scattering

- Searching for anomalous 4-photon coupling & high mass axion-like particles
- Almost background free (0 candidate / 0.23 expected) after requiring mass & rapidity matching between diphoton & diproton systems
  $m_{\gamma\gamma} = m_{pp}$ & $y_{\gamma\gamma} = y_{pp}$

Measurement with 2016 data (~ 9.4 fb^{-1}) to extract first limits on 4-photon coupling:

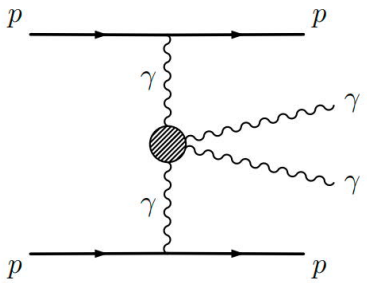
$|\zeta_1| < 2.9 \cdot 10^{-13}$ GeV^{-4} ($\zeta_2 = 0$)
$|\zeta_2| < 6.0 \cdot 10^{-13}$ GeV^{-4} ($\zeta_1 = 0$)

$\sigma\,(pp \longrightarrow p + \gamma\gamma + p|\xi_p \in \xi_{PPS}) < 2.1$ fb

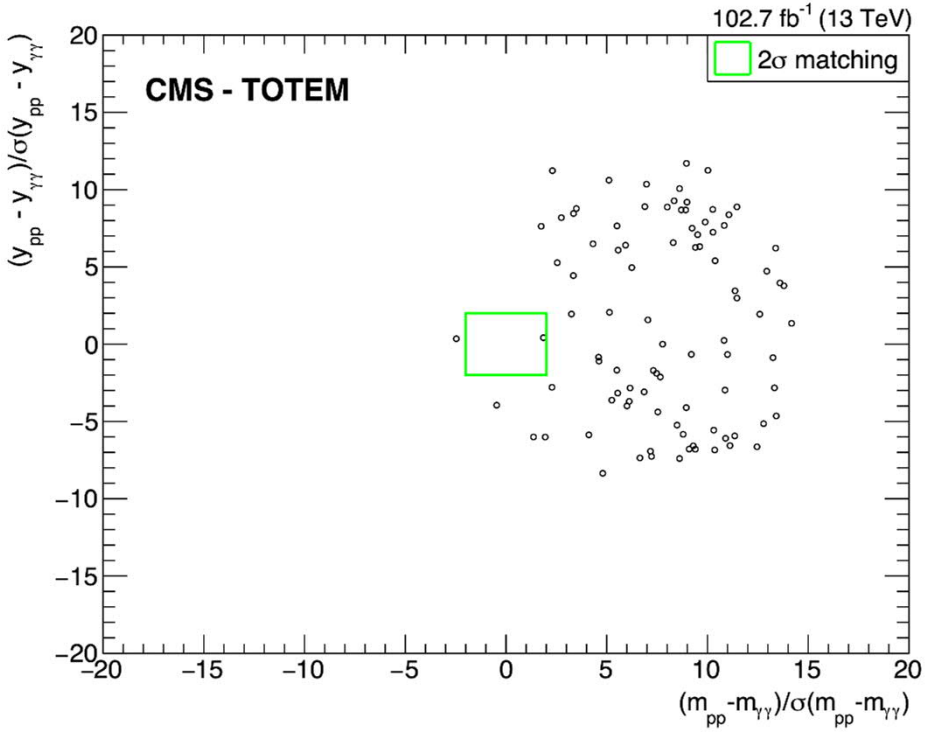


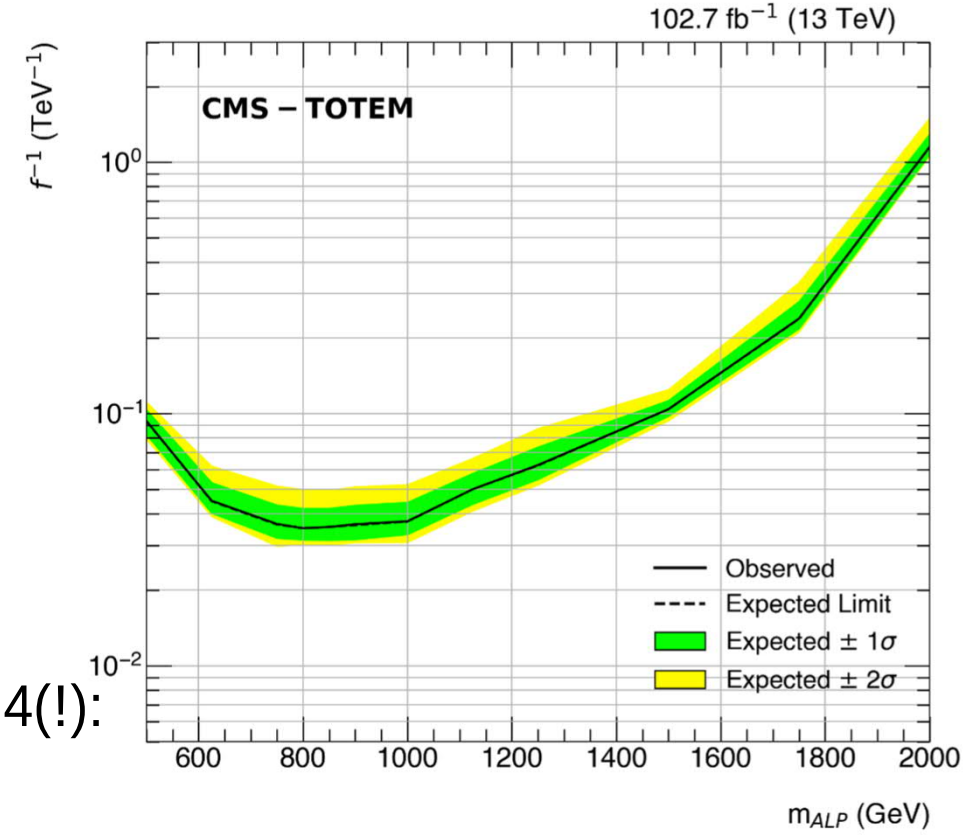
Exclusive diphoton

CMS-PAS-EXO-21-007; TOTEM-NOTE-2022-005



Light-by-light scattering: improved analysis repeated on full Run 2 data set: 1 candidate (background: 1.1 expected)





4-photon coupling limits improved by factor 4(!):

$|\zeta_1| < 7.3 \cdot 10^{-14}$ GeV^{-4} ($\zeta_2 = 0$)
$|\zeta_2| < 1.5 \cdot 10^{-13}$ GeV^{-4} ($\zeta_1 = 0$)

$\sigma\,(pp \longrightarrow p + \gamma\gamma + p|\xi_p \in \xi_{PPS}) < 0.6$ fb

First axion-like particles search in 500-2000 GeV mass range!

Run 3

Upgrading the PPS detectors: replacing the pixel detectors with new ones and doubling the diamonds (+ improving electronics & operating conditions) → similar ξ performance + improving TOF by a factor 3-4

TALESMAN project (S. Lehti & K. Österberg):
combining tau lepton tagging & PPS proton tagging to search for leptoquarks (LQ), exclusive tau pair production & inclusive + exclusive doubly-charged Higgs pair production