Recent results from the CMS PPS

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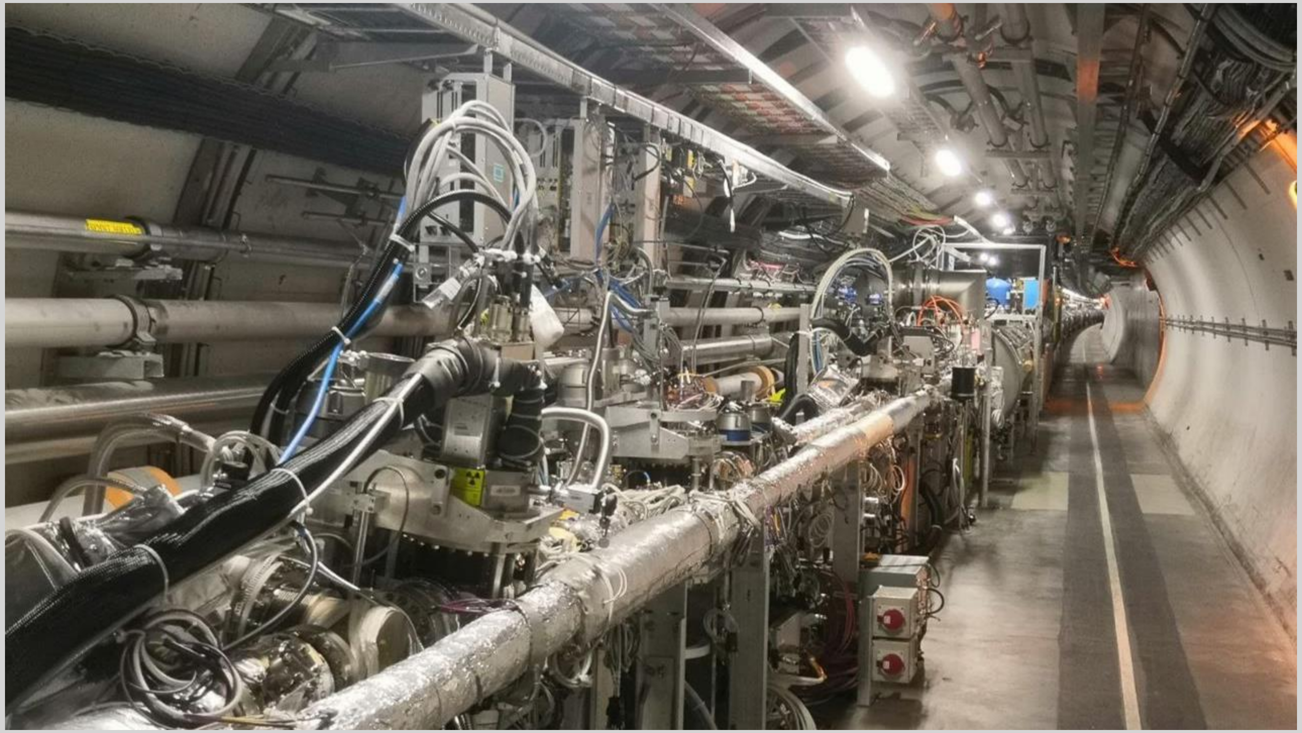
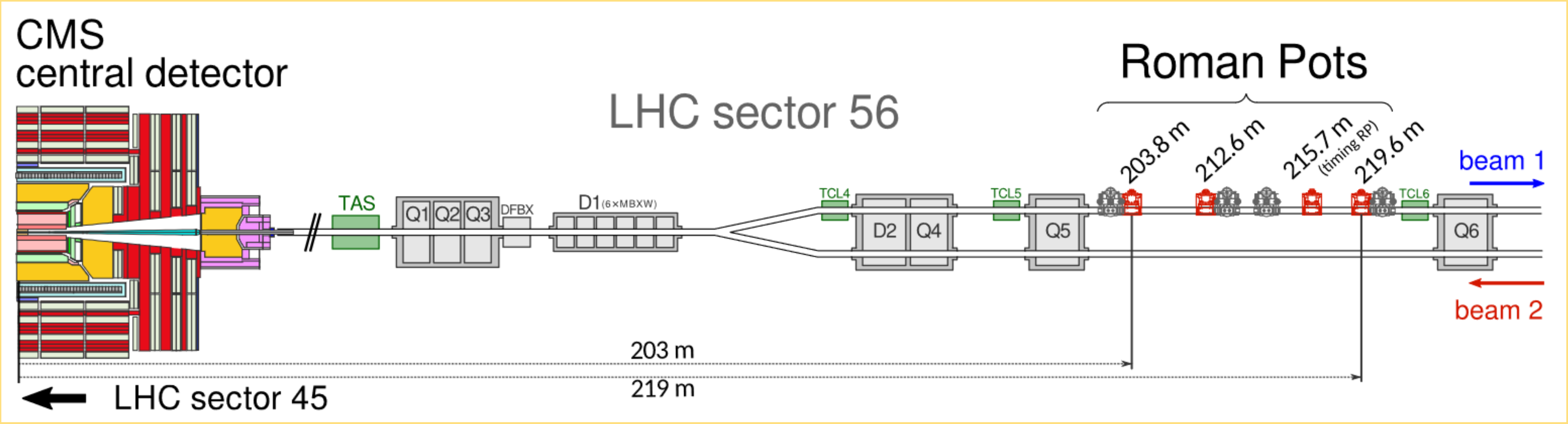
(on behalf of the CMS and TOTEM Collaborations)

Low-x 2023, Leros island, Greece

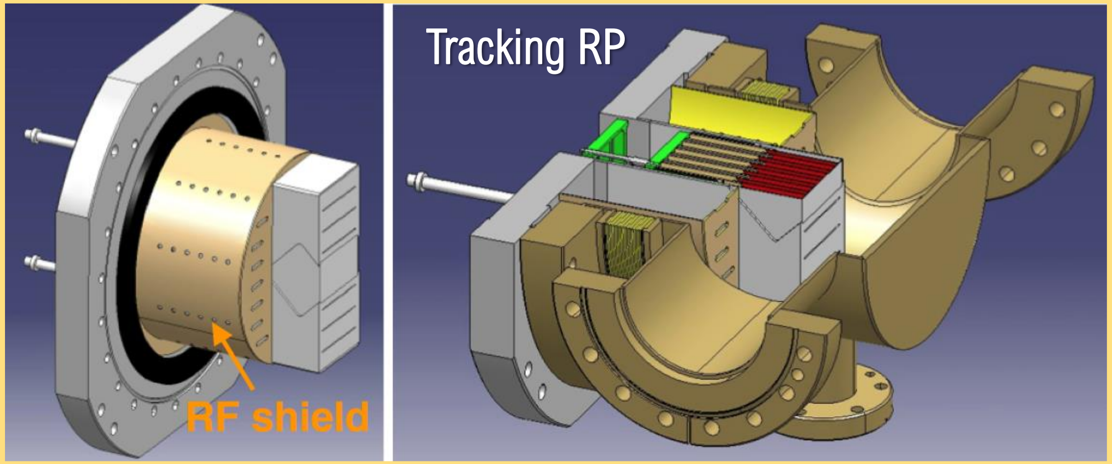


The Precision Proton Spectrometer



- LHC magnetic field bends protons that survived the interaction in CMS:
  - Tracking and timing detectors installed in Roman Pots (RPs), to measure:
    - Fraction of momentum lost by the proton (ξ) - tracking
    - Longitudinal coordinate of the primary vertex (z) – timing
- More than 100 fb^{-1} of data collected in Run 2
- Taking Run 3 data with CMS!

The Precision Proton Spectrometer

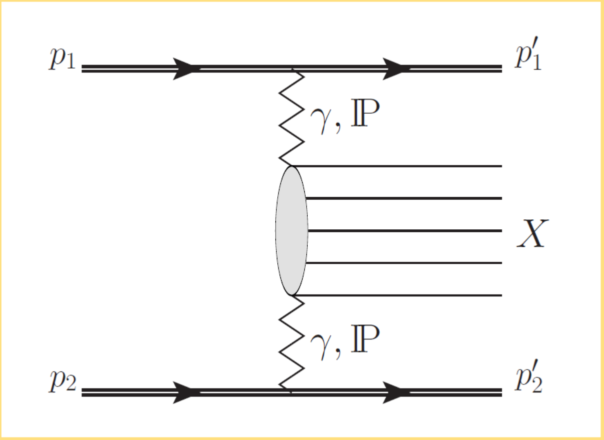


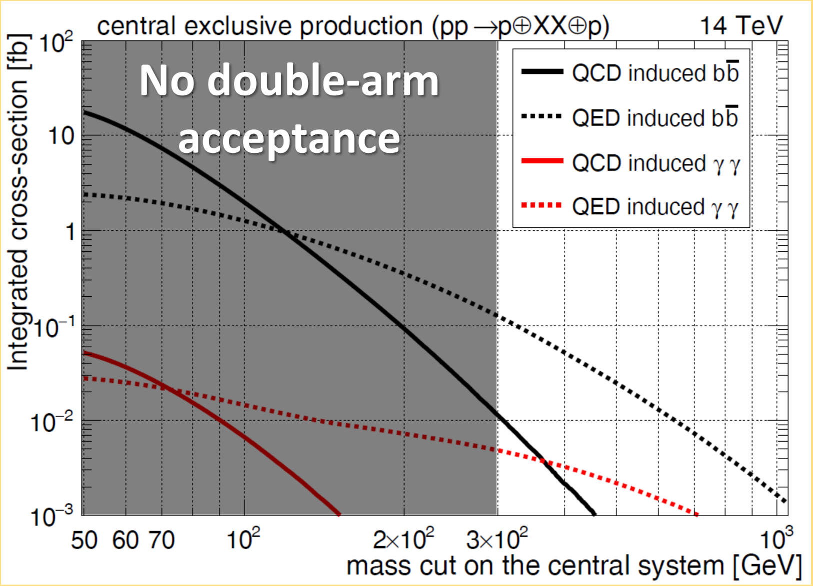
- ...ons that survived the interaction in CMS:
  - ...stalled in Roman Pots (RPs), to measure:
    - ...he proton (ξ) - tracking
    - ...rimary vertex (z) – timing
- ...ected in Run 2
- Taking data Run 3 data with CMS!

Beam pipe insertions that approach the LHC beam down to ~1.5 mm

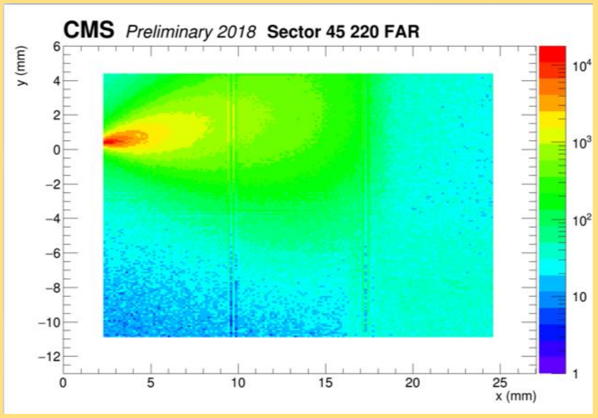
The PPS physics case

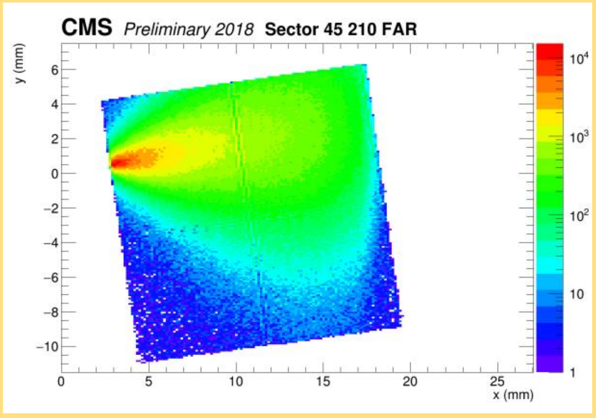
- Study central exclusive production (CEP) at the LHC
  - Double colourless exchange via QED (γ) or QCD ($I\!P$)
  - Protons remain intact
- Proton tagging provides:
  - Additional constraints on the final state
  - Strong background rejection
- Exploit LHC as a photon-photon collider:
  - Test QED processes (favoured at high mass)
  - Search for BSM physics:
    - Enhancements over high-mass tails
    - New resonances
    - High sensitivity to anomalous couplings

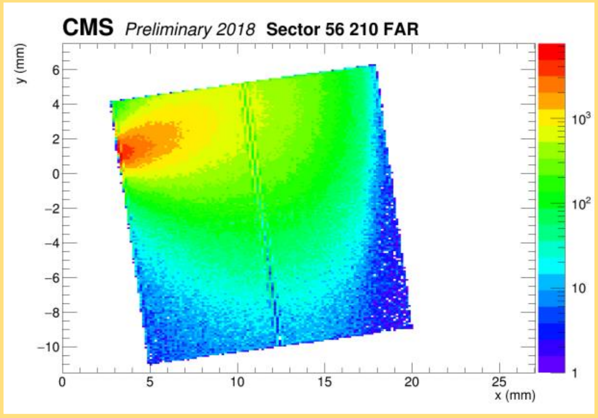


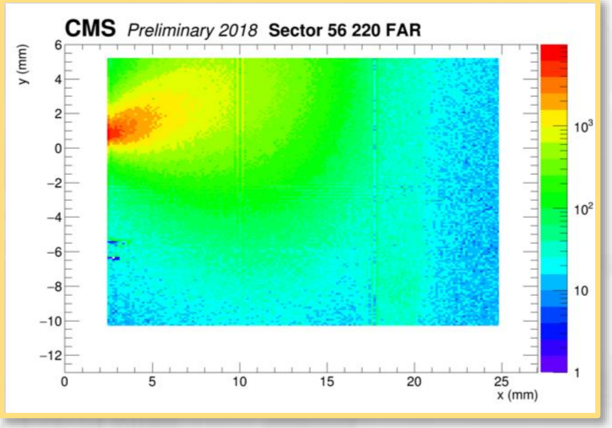


Proton reconstruction









LHC Sector 45 ← **IP5** → **LHC Sector 56**

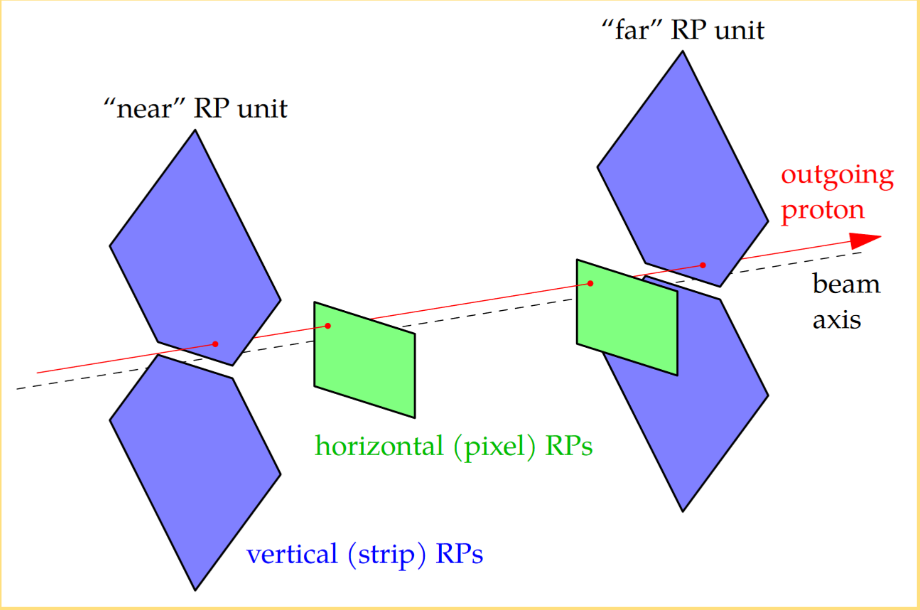
HITS FROM PPS TRACKER → RECONSTRUCTED TRACKS → PROTONS

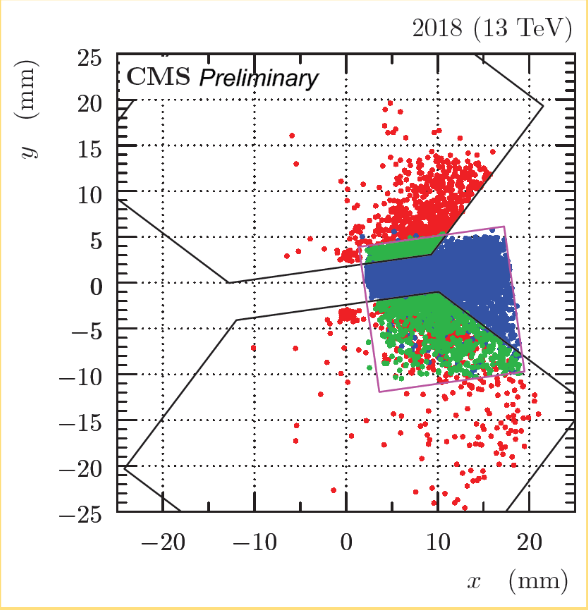
CONDITIONS
Alignment among detector planes

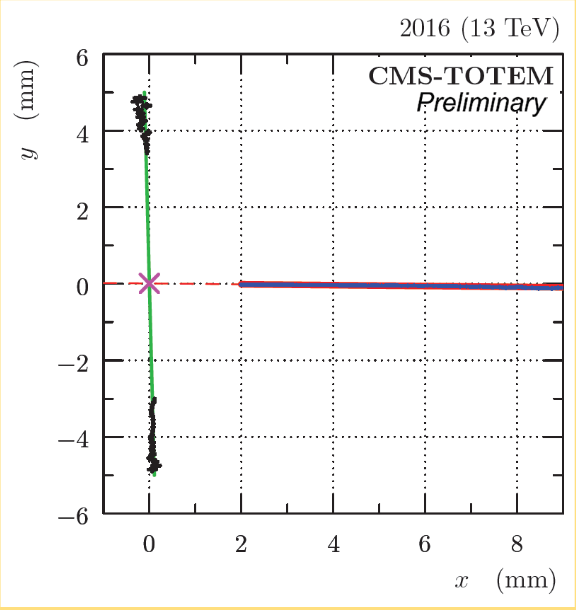
CONDITIONS
Alignment wrt. beam
Optics

arXiv:2210.05854

Detector alignment







Multi-step procedure: base measurement in dedicated LHC fill, then corrected fill-by-fill

- Alignment fill: determine the beam position and the relative detector positions
  - Low intensity (2-3 bunches), detectors closer to the beam, vertical RPs inserted
  - Data collected for each LHC setting that will be used during future data-taking
  - Elastic scattering kinematic properties used to find the beam center
- Corrections: match dedicated observables to their alignment fill counterpart

arXiv:2210.05854

Proton transport

- Reconstruct the proton kinematics at the IP (d^*) from the measurements at the RP positions (d)
- Propagation modelled via the transport matrix T, containing the optical functions: $d = T \cdot d^*$

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \\ \xi \end{pmatrix} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & D_y \\ 0 & 0 & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \theta^*_x \\ y^* \\ \theta^*_y \\ \xi \end{pmatrix}$$

- Simplified version with leading terms:

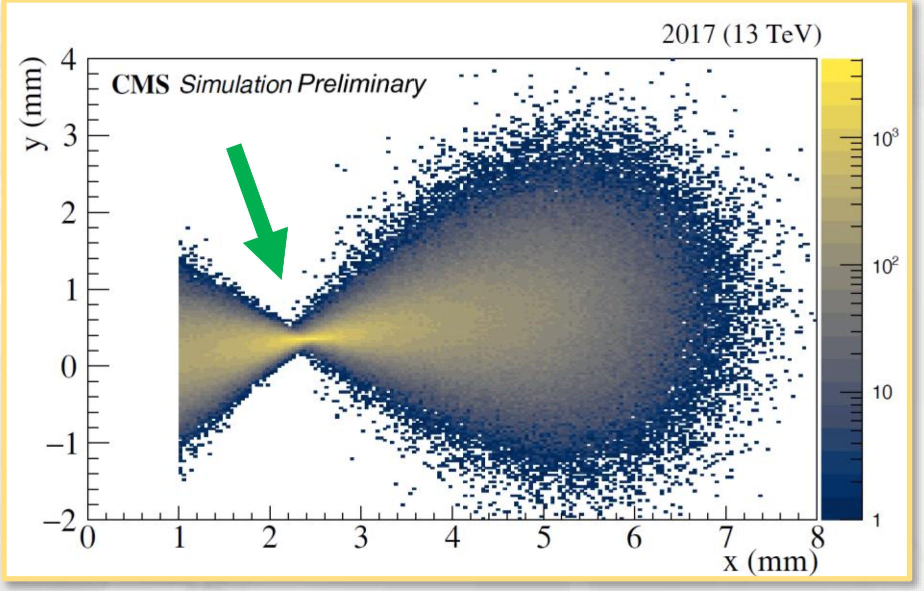
$$x = v_x(\xi) \cdot x^* + L_x(\xi) \cdot \theta^*_x + D_x(\xi) \cdot \xi$$
$$y = v_y(\xi) \cdot y^* + L_y(\xi) \cdot \theta^*_y + D_y(\xi) \cdot \xi$$

Magnifications — Effective lengths — Dispersions

arXiv:2210.05854

Optics calibration

- Precise knowledge of the LHC beam optics is needed for proper reconstruction
  - Nominal optics calculated with MAD-X (accelerator simulation based on LHC parameters)
- Further calibration with data:
  - L_y determined using elastic events in the alignment run
  - D_x derived with two methods:
    - Determination of the 'pinch' point ($L_y = 0$) in min-bias events
    - ξ comparison in (semi-)exclusive di-muon events $\xi_{\pm}(\mu^+\mu^-) = \frac{1}{\sqrt{s}}\left(p_T(\mu^+)e^{\pm\eta(\mu^+)} + p_T(\mu^-)e^{\pm\eta(\mu^-)}\right)$
- Optical functions vary with crossing angle
  - This means variable acceptance during data-taking!

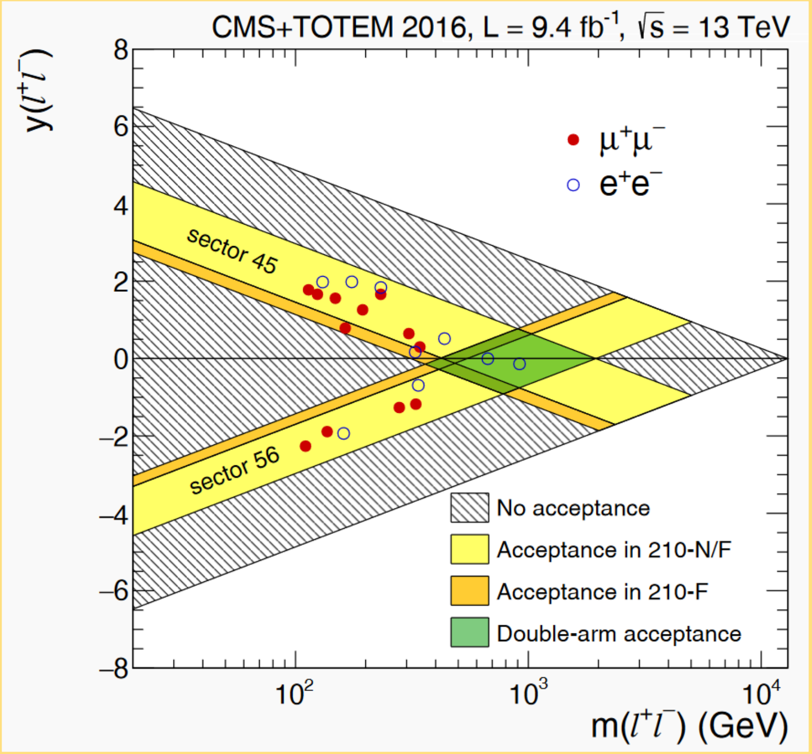


arXiv:2210.05854

Di-lepton CEP as a validation tool

- High-mass central (semi)exclusive production of lepton pairs at $\sqrt{s} = 13\ \mathrm{TeV}$
  - 5.1σ significance reached with 2016 data
  - First observation of proton-tagged $\gamma\gamma$ collisions at the EW scale
- Now an essential calibration handle:
  - Select high-mass muon pairs produced back-to-back
  - Use the correlation between di-muons and protons to validate the PPS proton reconstruction:

$$\xi(\mu^+\mu^-) = \frac{1}{\sqrt{s}}\left(p_T(\mu^+)e^{\pm\eta(\mu^+)} + p_T(\mu^-)e^{\pm\eta(\mu^-)}\right)$$

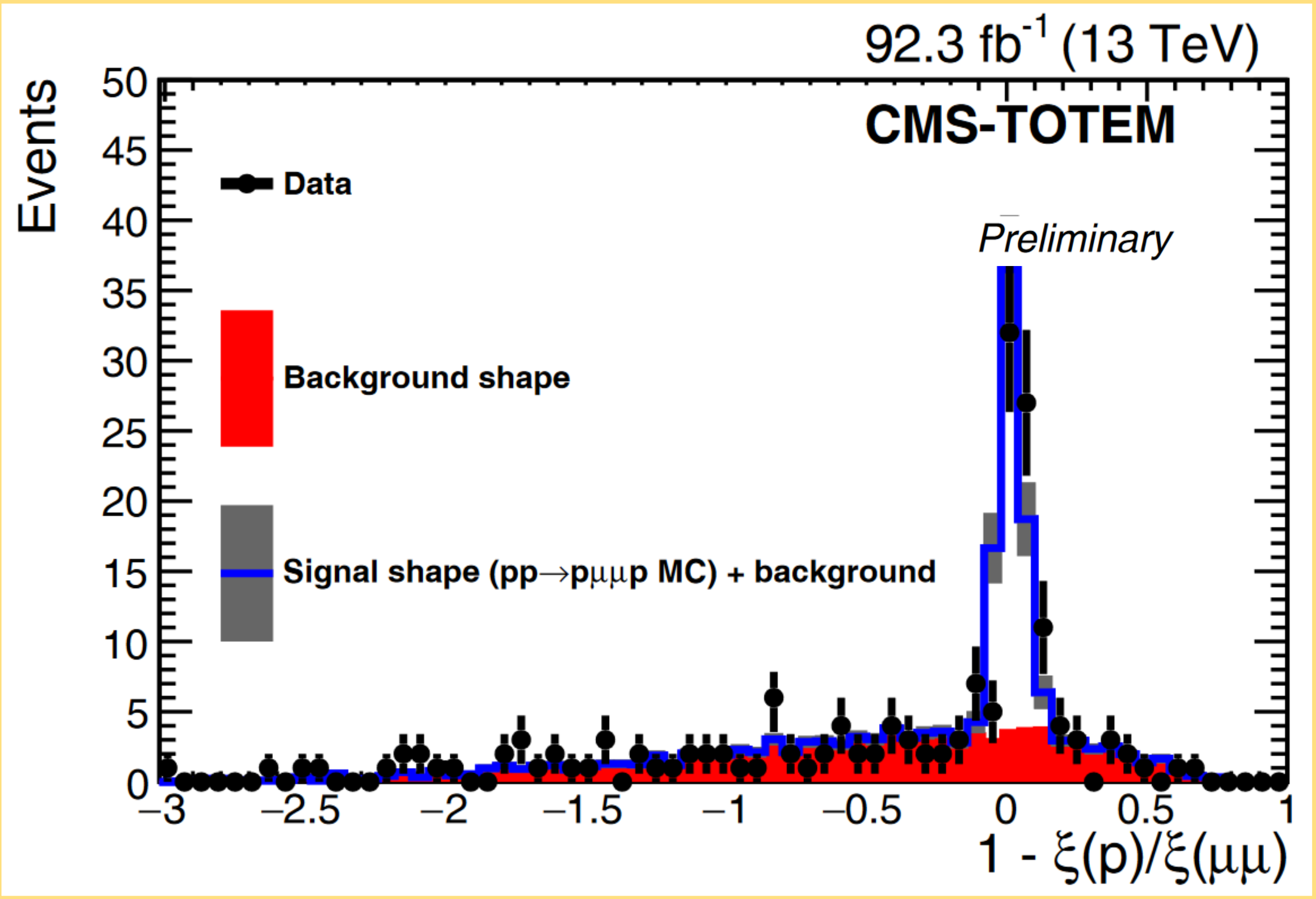


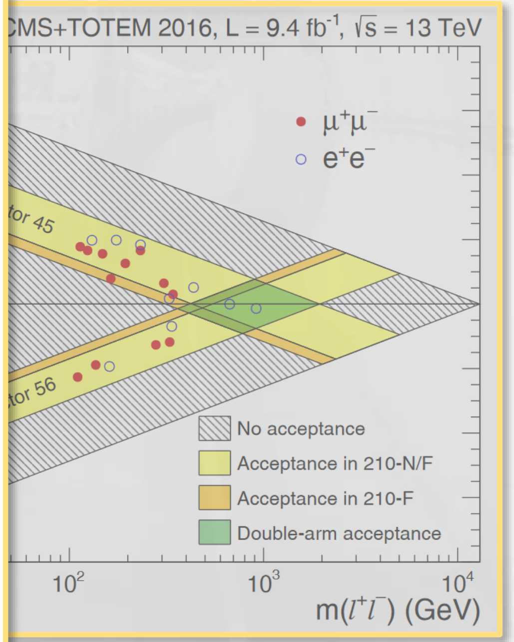
JHEP07(2018)153

Di-lepton CEP as a validation tool

- High-mass ce… $\sqrt{s} = 13$ TeV
  - 5.1σ signif…
  - First observ…
- Now an essen…
  - Select high…
  - Use the co… validate the…

$\xi($…

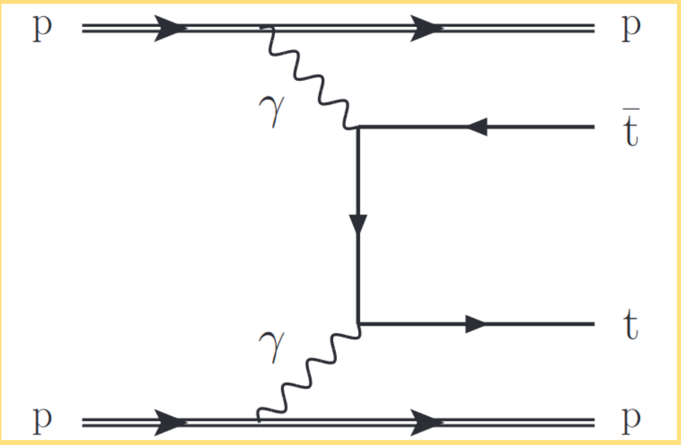




arXiv:2210.05854

CEP of top quark pairs

- First search for top quark-antiquark pair production with intact protons
- Low cross section - $\mathcal{O}$(0.3 fb) in the PPS acceptance
  - Signal concentrated at low $t\bar{t}$ mass, where BG is dominant
- 2017 dataset: 29.4 fb^{-1}
- Two $t\bar{t}$ decay channels studied: $\ell\ell$ and ℓ+jets



$\ell\ell$

Leptons:	Jets:
$p_T > 30/20$ GeV $\lvert\eta\rvert < 2.1$	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$ $\Delta R(j,\ell) > 0.4$ *tightLepVeto* jet ID, loose PU ID b-tagging Deep CSV medium

Selection:
- ≥ 2 leptons ($= 1$ OS pair), $m(\ell\ell) > 20\ GeV$
- $m(\ell\ell)$ off-Z (15 GeV) – only for $ee, \mu\mu$
- ≥ 2 b − jets
- $= 1$ proton on each side of PPS

ℓ + jets

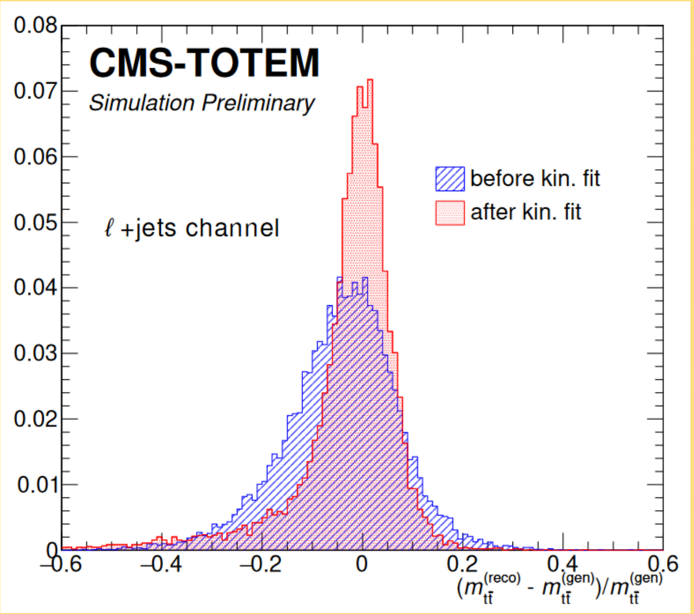
Leptons:	Jets:
$p_T > 30$ GeV $\lvert\eta\rvert < 2.1\ (e)$ $\lvert\eta\rvert < 2.4\ (\mu)$	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$ $\Delta R(j,\ell) > 0.4$ *tightLepVeto* jet ID, loose PU ID b-tagging Deep CSV medium

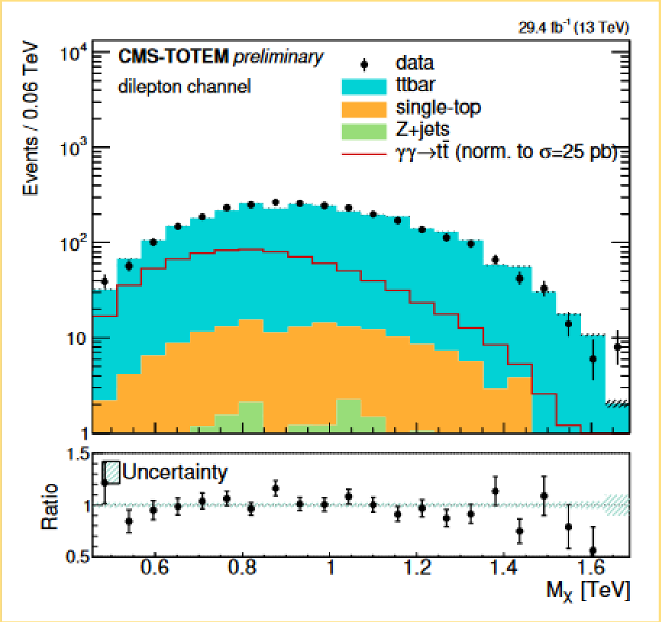
Selection:
- $= 1$ lepton
- ≥ 2 b − jets, ≥ 2 light jets
- $= 1$ proton on each side of PPS

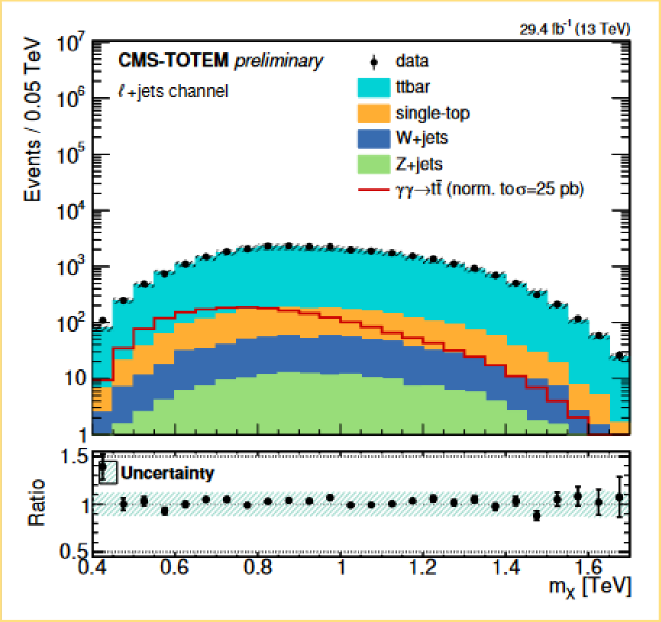
CMS-PAS-TOP-21-007
CERN-TOTEM-NOTE-2022-002

CEP of top quark pairs

- Background dominated by inclusive $t\bar{t}$ events in coincidence with pileup protons
- Proton matching criteria used as BDT inputs or kinematic fitting constraints



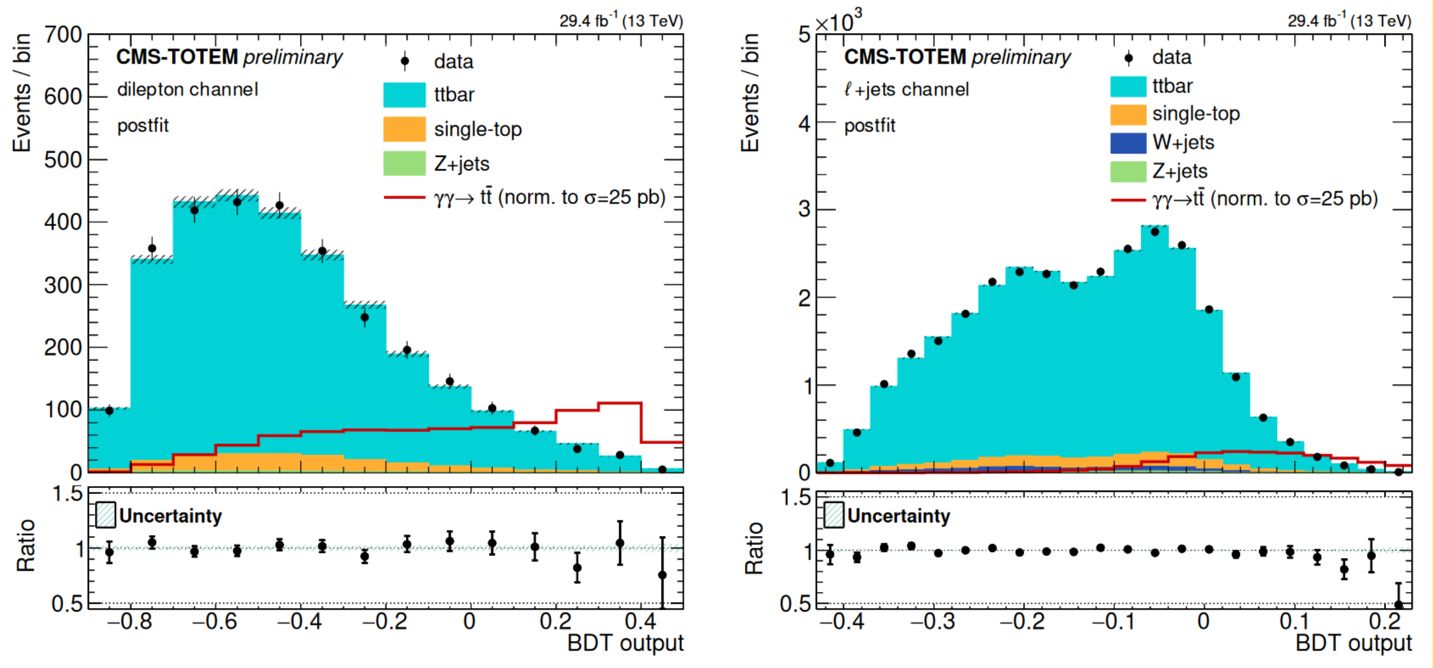


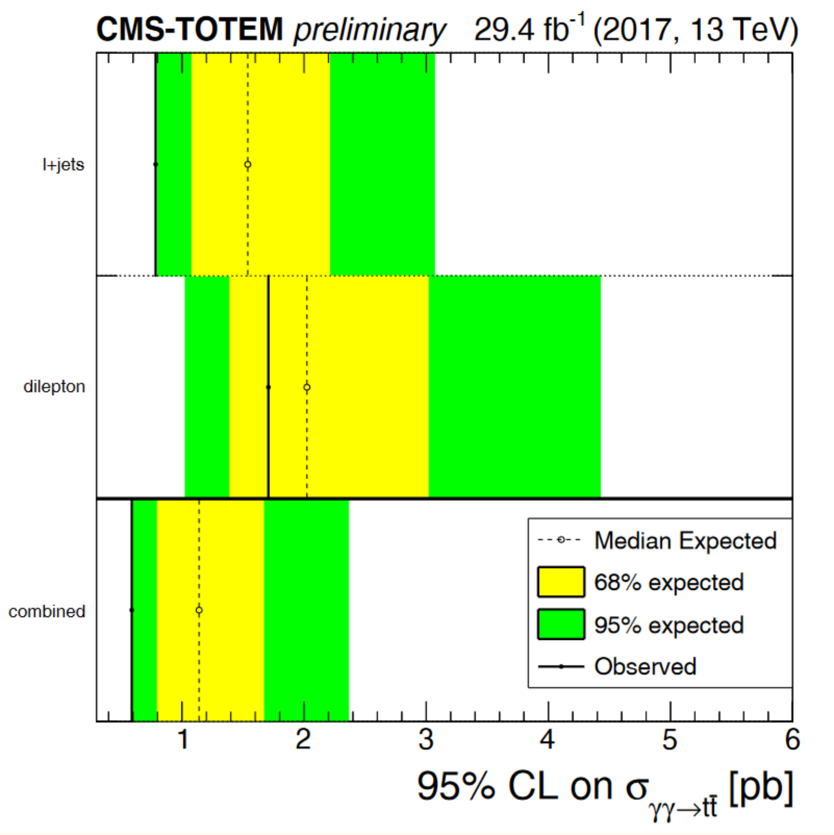


CMS-PAS-TOP-21-007
CERN-TOTEM-NOTE-2022-002

CEP of top quark pairs

- MVA approach used to tag exclusive $t\bar{t}$ events
- Cross section upper limits extracted from multivariate discriminant distributions:
  - Observed combined 95% CL limit: $\mathbf{0.59}$ pb ($\mathbf{1.14^{+1.2}_{-0.6}}$ expected)





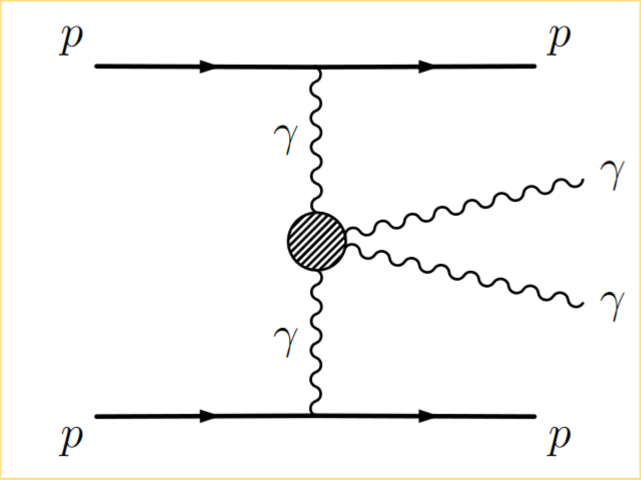
CMS-PAS-TOP-21-007
CERN-TOTEM-NOTE-2022-002

Exclusive $\gamma\gamma \to \gamma\gamma$

- Search for LbyL scattering with proton tagging
- Full Run 2 dataset, 102.7 fb^{-1}
  - Extending Phys. Rev. Lett. 129, 011801
- Matching requirement in the mass and rapidity between $\gamma\gamma$ and protons:

$$m_{\gamma\gamma} = \sqrt{s\xi_1\xi_2} \quad y_{\gamma\gamma} = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)$$

- Main background: inclusive $\gamma\gamma$ production + pileup
- One candidate observed:
  - BG prediction of 1.1 events with 2σ matching



Event selection:

- ≥ 2 isolated γ ($H/E < 0.10$)
- $|\eta(\gamma_1, \gamma_2)| < 2.5$
- $p_T(\gamma_1, \gamma_2) > 75$ GeV
  - 100 GeV for 2017/8
- $m(\gamma_1\gamma_2) > 350$ GeV
- $1 - |\Delta\phi(\gamma_1\gamma_2)/\pi| < 0.0025$
- 1 proton per side of PPS within acceptance

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

Exclusive $\gamma\gamma \to \gamma\gamma$

- Search for LbyL scattering with proton tag
- Full Run 2 dataset, 102.7 fb^{-1}

$$\mathcal{L}_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\nu}$$

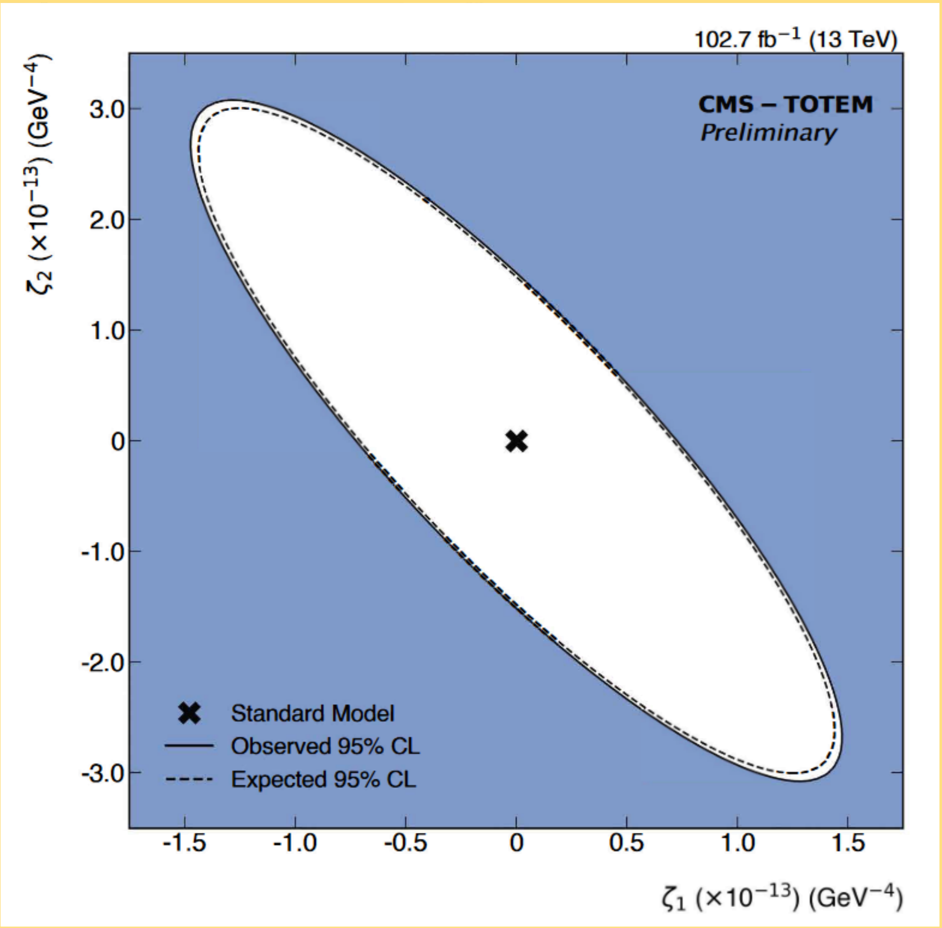
- Matching requirement in the mass and rap
  between $\gamma\gamma$ and protons:

~3-4x more stringent limits observed (expected) on 4γ coupling parameters:

$|\zeta_1| < 7.3\ (7.1) \times 10^{-14}$ GeV^{-4}

$|\zeta_2| < 1.5\ (1.5) \times 10^{-13}$ GeV^{-4}

- One candidate observed:
  - BG prediction of 1.1 events with 2σ matchin



within acceptance

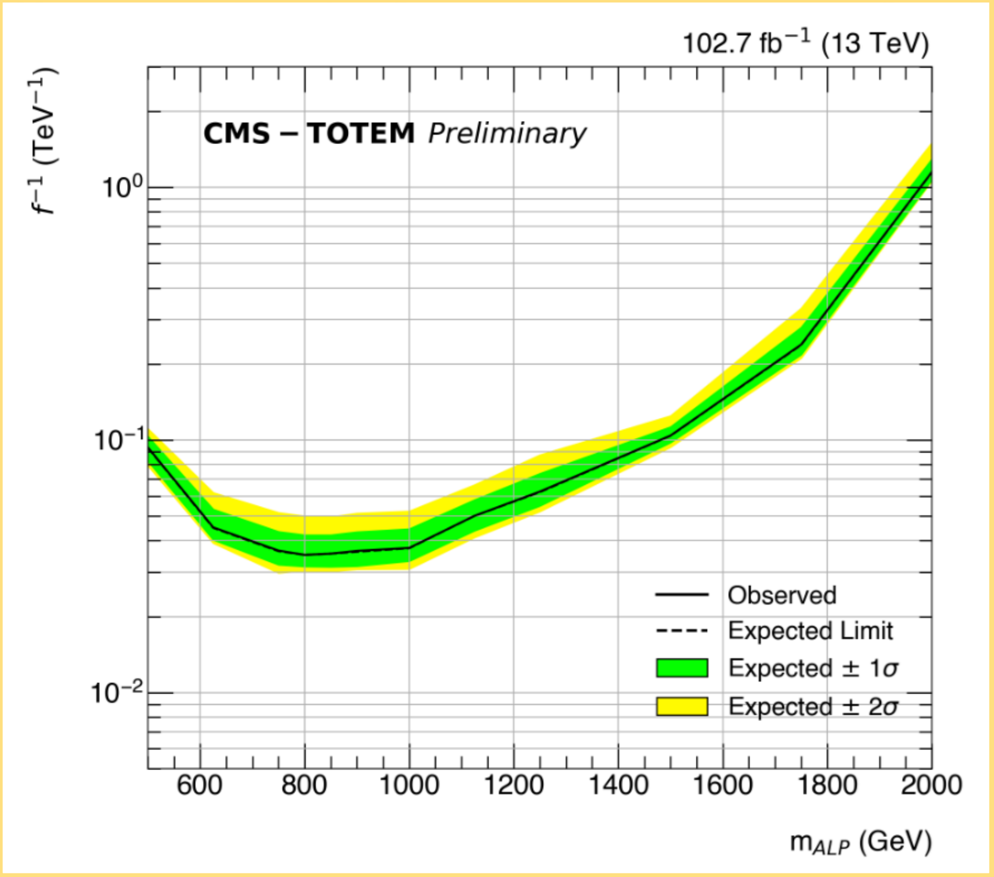
CMS-PAS-EXO-21-007
CERN-TOTEM-NOTE-2022-005

Exclusive $\gamma\gamma \to \gamma\gamma$

- Search for LbyL scattering with proton taggin[g]
- Full Run 2 dataset, 102.7 fb^{-1}
  - Extending Phys. Rev. Lett. 129, 011801
- Matching requirement in the mass and rapid[ity]

Limits also set for ALP production ($\gamma\gamma \to a \to \gamma\gamma$) as a function of m_{ALP} and its coupling f^{-1}: strongest limits in the 500-2000 GeV range

- Main background: inclusive $\gamma\gamma$ production -
- One candidate observed:
  - BG prediction of 1.1 events with 2σ matching



- 1 proton per side of PPS within acceptance

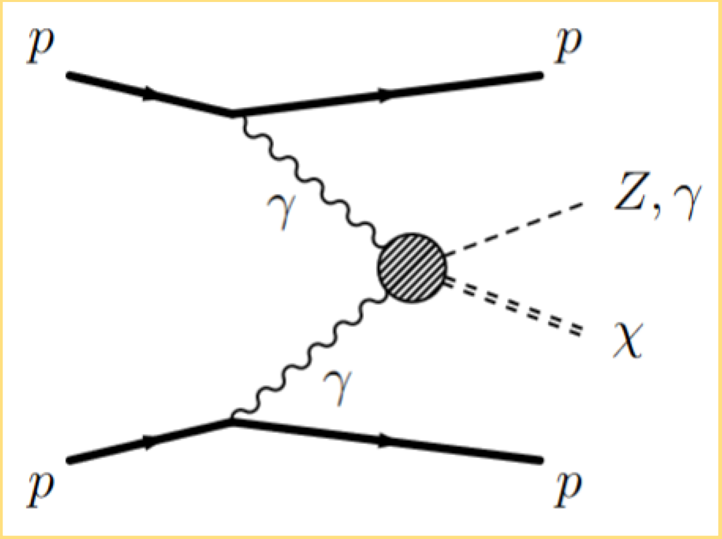
CMS-PAS-EXO-21-007
CERN-TOTEM-NOTE-2022-005

Searching for missing mass with Z/γ

- A novel technique to search for new particles at the LHC:
  - Use the so-called missing mass:

$$m_{miss}^2 = \left[\left(p_{p_2}^{in} + p_{p_2}^{in}\right) - \left(p_V + p_{p_1}^{out} + p_{p_2}^{out}\right)\right]^2$$

- Search for missing mass produced in association with a $\boldsymbol{Z}$ boson or photon in proton-tagged events
- Exploit the high-precision proton momentum measurement from PPS
- Search for weakly interacting BSM massive particles
  - QED interactions are favoured over QCD processes
  - Broad invariant mass spectrum explored (600-1600 GeV)



arXiv:2303.04596

Searching for missing mass with Z/γ

Event selection

$\boldsymbol{Z \to e^+e^- / Z \to \mu^+\mu^-}$

≥ 2 leptons (SF OS)

$p_T(\ell_1, \ell_2) > 30, 20$ GeV

$|\eta(\ell)| < 2.4$

$|m(\ell\ell) - m_Z| < 10$ GeV

$p_T(Z) > 40$ GeV

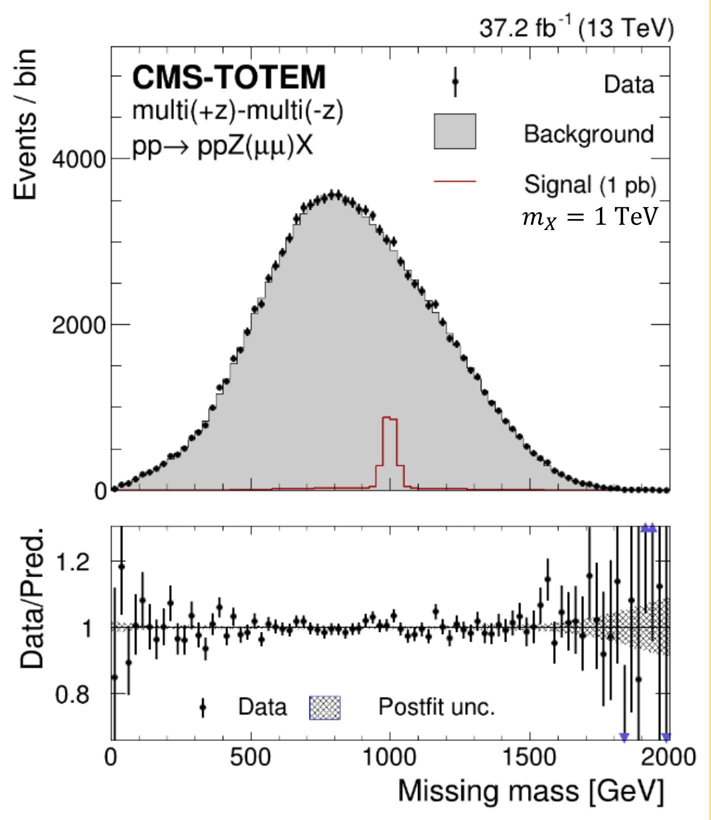
Photon

$= 1$ isolated photon

$p_T(\gamma) > 95$ GeV

$|\eta(\gamma)| < 1.48$ (CMS barrel)

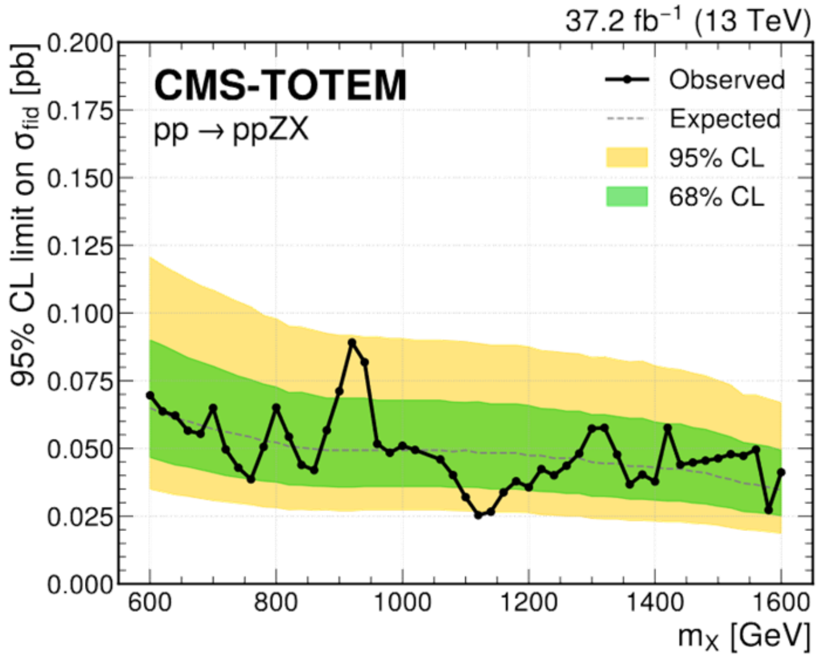
≥ 1 proton per side of PPS

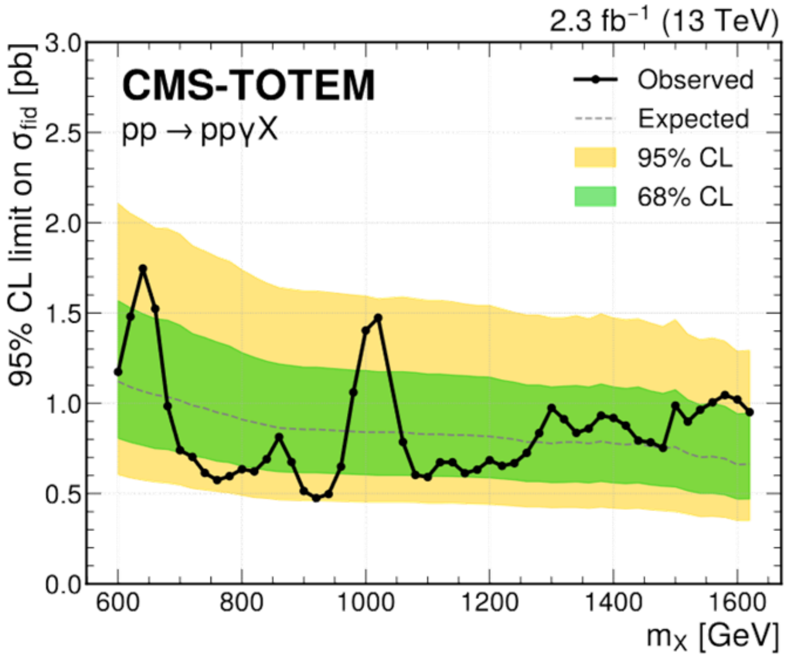


- 2017 data, 37.2 fb^{-1} integrated luminosity
- Signal modelled with a simplified dedicated MC generator
- Main background: non-exclusive Z/γ production + protons from pileup
  - Data-driven estimation by mixing uncorrelated protons with MC

arXiv:2303.04596

Searching for missing mass with Z/γ



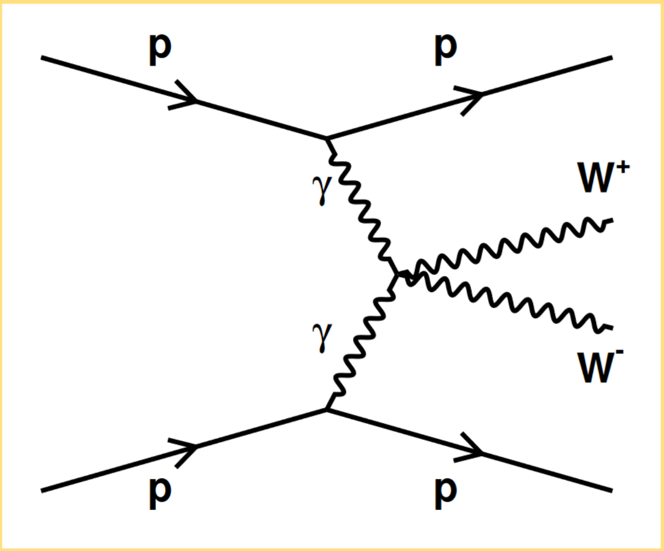


- Bump search over missing mass spectrum
  - No major local excess/deficit observed
  - Larger dataset will be analysed
- Setting 95% CL on fiducial cross section as a function of m_X

arXiv:2303.04596

Anomalous $\gamma\gamma \to VV$ into hadrons

- Search for anomalous $\boldsymbol{WW/ZZ}$ ($\boldsymbol{VV}$) exclusive production at high mass:
  - Exploring the hadronic decay channel (each V decaying into a boosted and merged jet)
  - Require intact protons on both sides
  - Look for non-resonant enhancements over high-mass tails (AQGC/EFT)
- SM production:
  - $\boldsymbol{ZZ}$ not allowed at tree level
  - $\boldsymbol{WW}$ exclusive production concentrated in the low mass region:
    - Higher QCD background
    - Out of reach with the Run 2 trigger thresholds on jets
    - Dedicated trigger prepared for Run 3



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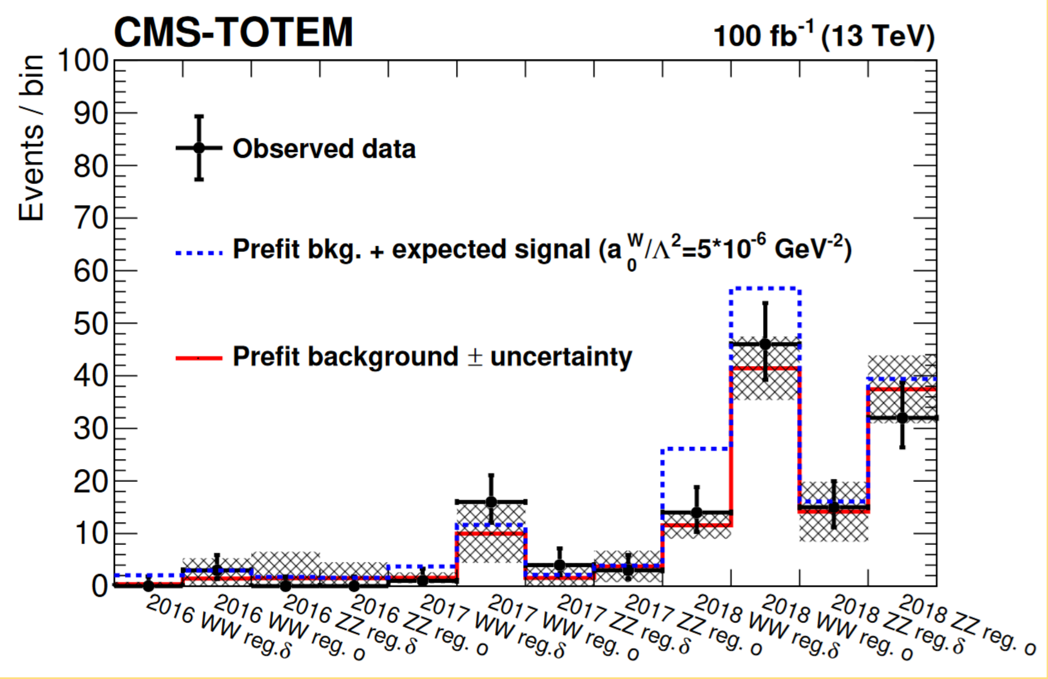
Anomalous $\gamma\gamma \rightarrow VV$ into hadrons

- Full Run 2 dataset, 100 fb^{-1}
- $\boldsymbol{WW/ZZ}$ separation based on $m(j_1)$ vs. $m(j_2)$
- Selection based on:
  - Mass match ratio
  - Rapidity difference
- Two signal regions:
  - $\boldsymbol{\delta}$: both protons from the interaction
  - $\boldsymbol{o}$: one proton mistakenly chosen from pileup
- Main background:
  - QCD di-jet production combined with pileup protons
  - Data-driven estimation with 'ABCD' method (sidebands)



Event selection:

- ≥ 2 V-tagged AK8 jets
- $|\eta(j_1, j_2)| < 2.5$
- $p_T(j_1, j_2) > 200$ GeV
- $|\eta(j_1) - \eta(j_2)| < 1.3$
- $p_T(j_1)/p_T(j_2) < 1.3$
- $|1 - \Delta\phi(j_1 j_2)/\pi| < 0.01$
- $1126 \text{ GeV} < m(j_1 j_2) < 2500$ GeV
- ≥ 1 proton per side of PPS

JHEP07(2023)229

Anomalous $\gamma\gamma \to VV$ into hadrons

- Full Run 2 dataset, 100 fb^{-1}
- $\boldsymbol{WW/ZZ}$ separation based on $m(j_1)$ vs. $m(j_2)$
- Selection based on:
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- Two signal regions:
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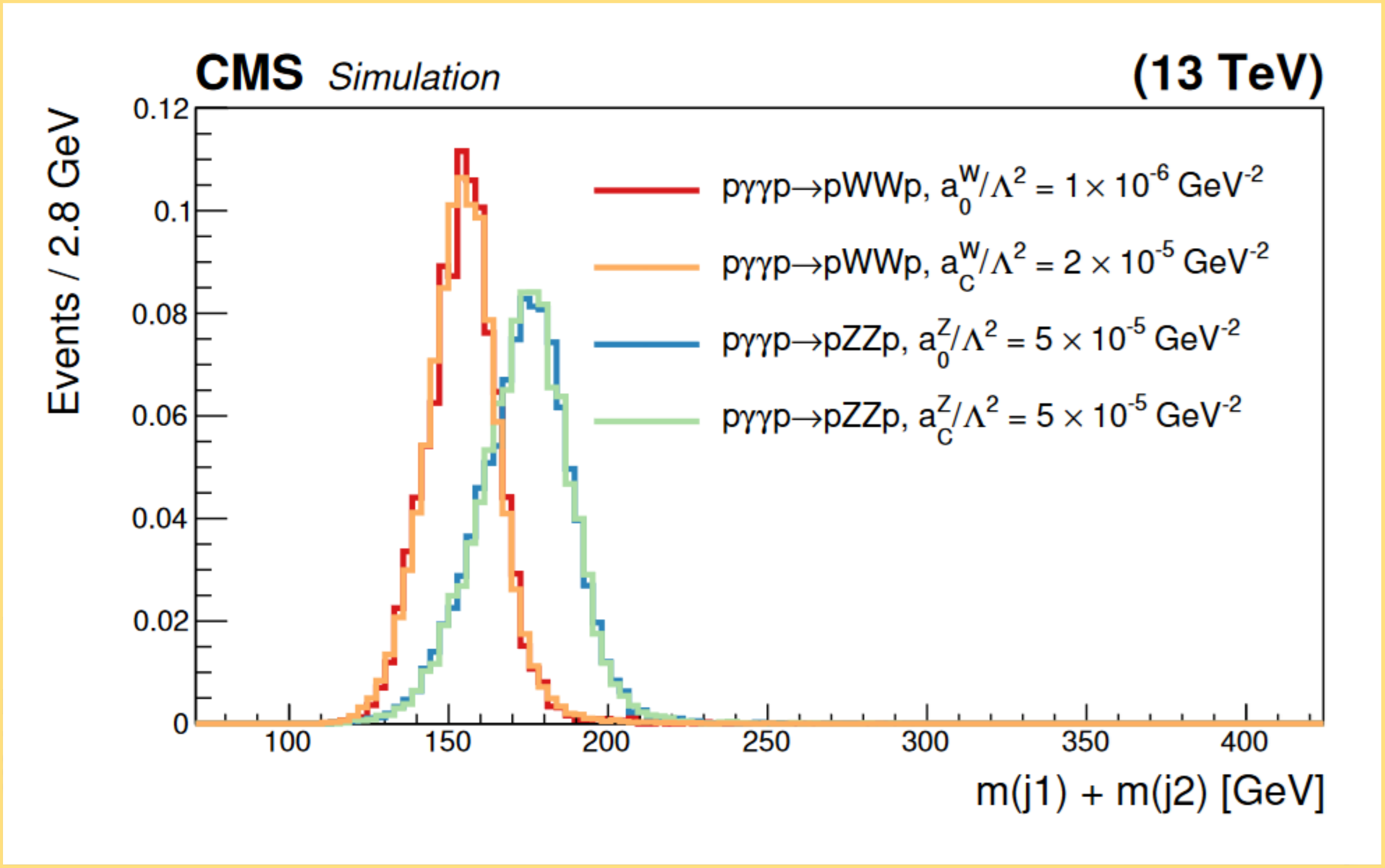

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- ≥ 1 proton per side of PPS

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Anomalous $\gamma\gamma \to VV$ into hadrons

- Full Run 2 dataset, 100 fb^{-1}

$|y(PP) - y(VV)|$

$y(pp) = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)$

$|1 - m(VV)/m(pp)|$

$m(pp) = \sqrt{s\xi_1\xi_2}$

- Selection based on:
  - Mass match ratio
  - Rapidity difference
- Two signal regions:
  - $\boldsymbol{\delta}$: both protons from the interaction
  - $\boldsymbol{o}$: one proton mistakenly chosen from pileup
- Main background:
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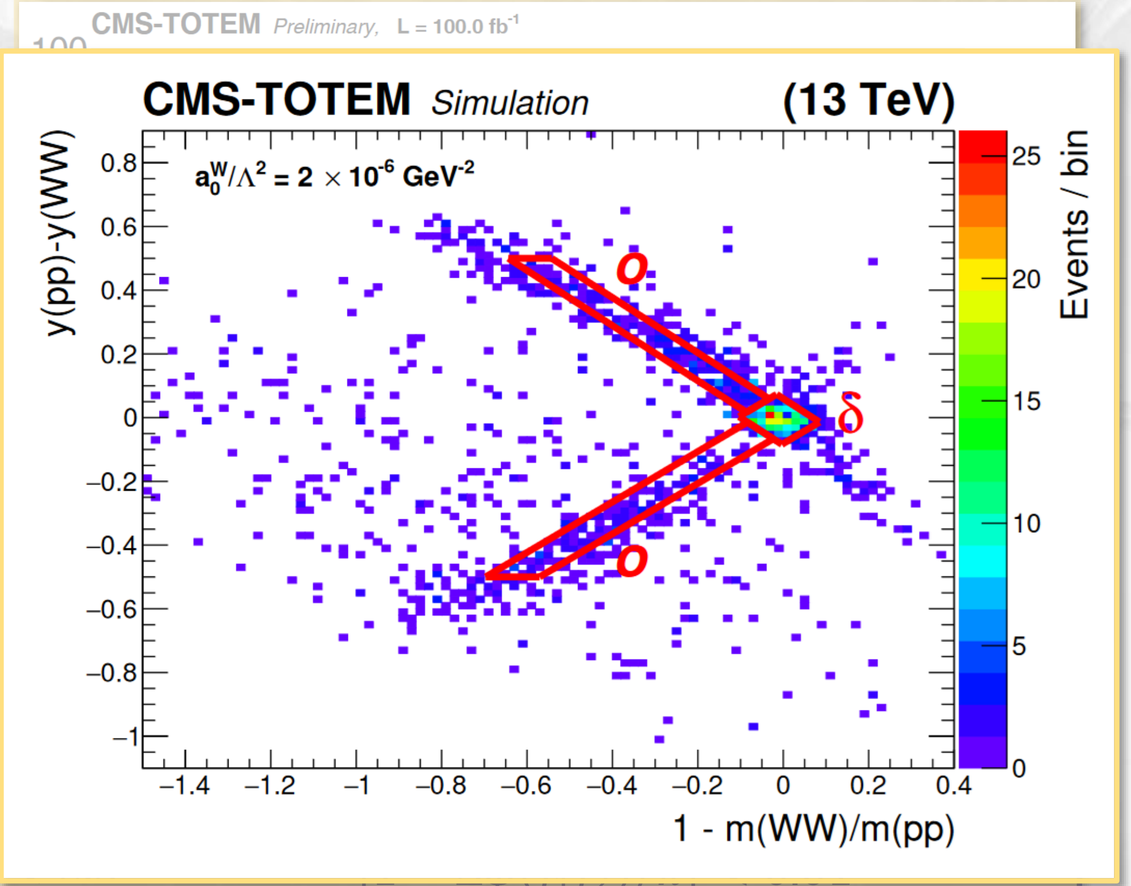
Event selecti

- ≥ 2 V-tag
- $|\eta(j_1, j_2)|$
- $p_T(j_1, j_2) > 200$ GeV
- $|\eta(j_1) - \eta(j_2)| < 1.3$
- $1126\ \text{GeV} < m(j_1 j_2) < 2500$ GeV
- ≥ 1 proton per side of PPS



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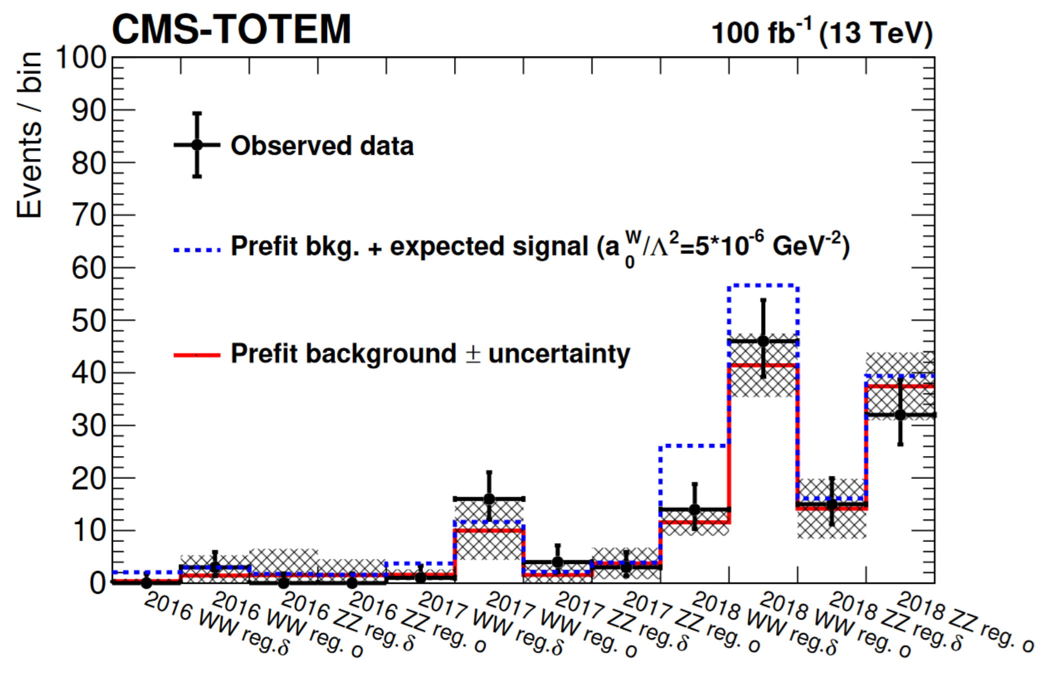

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- ≥ 2 V-tagged AK8 jets
- $|\eta(j_1, j_2)| < 2.5$
- $p_T(j_1, j_2) > 200$ GeV
- $|\eta(j_1) - \eta(j_2)| < 1.3$
- $p_T(j_1)/p_T(j_2) < 1.3$
- $|1 - \Delta\phi(j_1 j_2)/\pi| < 0.01$
- $1126 \text{ GeV} < m(j_1 j_2) < 2500$ GeV
- ≥ 1 proton per side of PPS

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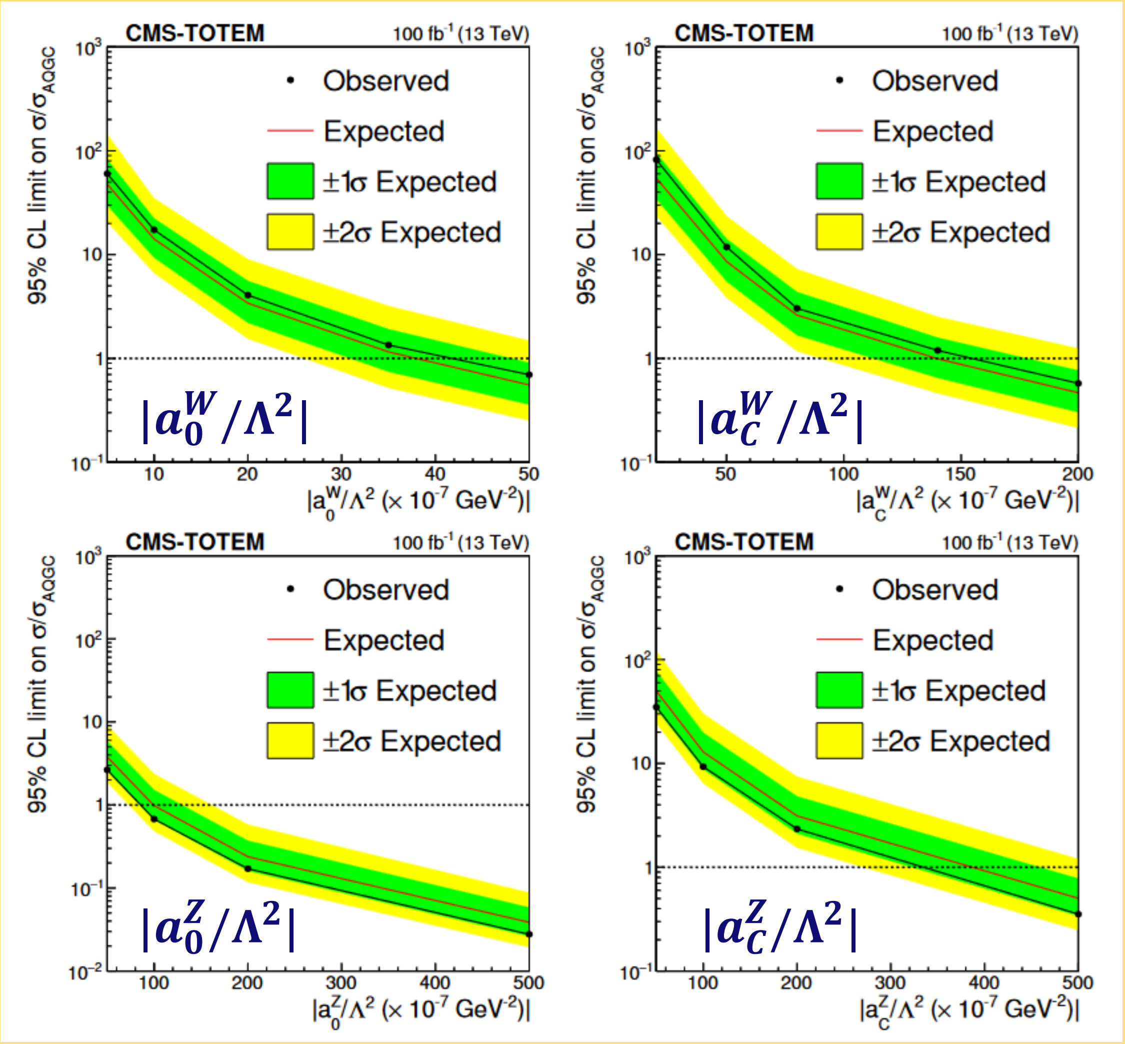
Anomalous $\gamma\gamma \to VV$ into hadrons

- No significant excess observed
- Factor ~15-20 tighter limits on dimension-6 $\gamma\gamma WW$ AQGC wrt. Run 1 analysis without protons
- Limits converted to dim-8 operators, close to CMS same-sign WW and WZ results at 13 TeV after unitarization
- First limits on $\gamma\gamma ZZ$ AQGC via exclusive $\gamma\gamma \to ZZ$
- Fiducial cross section limits:

$$\sigma(pp \to pWWp)_{0.04<\xi<0.2, m(WW)>1\ \text{TeV}} < 67(53^{+34}_{-19})\ \text{fb}$$
$$\sigma(pp \to pZZp)_{0.04<\xi<0.2, m(WW)>1\ \text{TeV}} < 43(62^{+33}_{-20})\ \text{fb}$$



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Summary

- The PPS proton tagging capabilities open up new analysis strategies for CMS
- Physics processes across multiple domains are now within reach

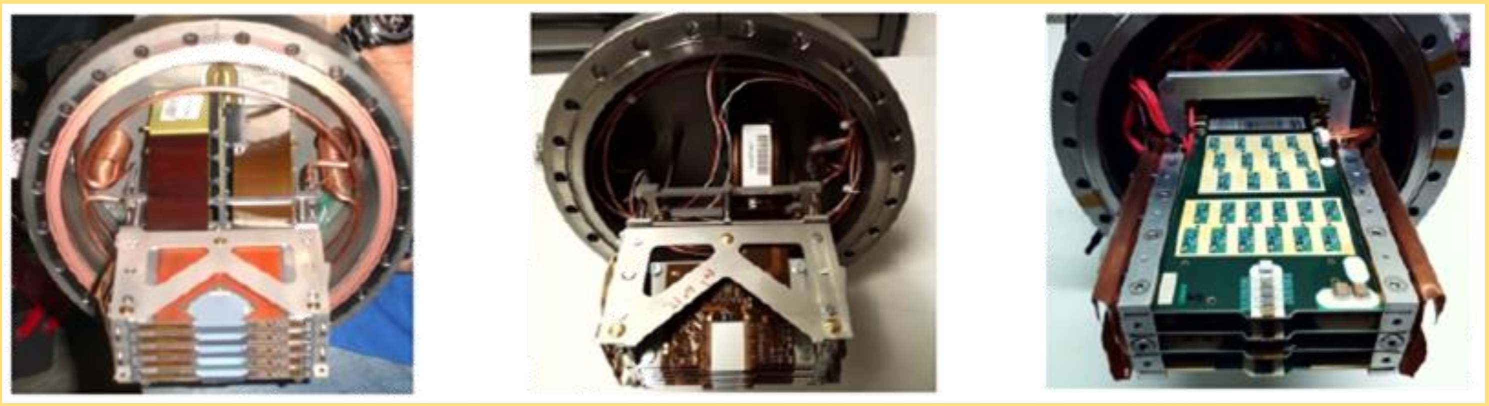
Looking forward:

- PPS is taking Run 3 data, stay tuned!
- PPS intends to take part in HL-LHC (arXiv:2103.02752)
  - A lot of interesting physics processes to explore!

Thank you!

BACKUP

PPS detector technologies



TOTEM si-strips | 3D pixels | scCVD (diamond)

- 2016 Detectors
  - Tracking: 2 stations of TOTEM Si-strips detectors (10 planes), 20 μm resolution. Limited radiation resistance ($\Phi_{max} \sim 5 \cdot 10^{14}$p/cm^2), no multi-track capability.
- 2017 Detectors
  - Tracking: 1 station of TOTEM si-strips, 1 station of silicon 3D pixels (6 planes with CMS Phase 1 tracker readout chips), $\sigma_x \sim 15\ \mu m$ and $\sigma_y \sim 30\ \mu m$, $\Phi_{max} \sim 5 \cdot 10^{15}$p/cm^2
  - Timing: 1 station with 3 planes of single-layer diamond with expected $\sigma_t = 80$ ps/plane and 1 plane of UFSD with expected $\sigma_t = 30$ ps/plane ($\Phi_{max} \sim 10^{14}$p/cm^2)
- 2018 Detectors
  - Tracking: two 3D pixels stations
  - Timing: 1 station of diamond detectors (2 single-layer + 2 double-layer)

Anomalous $\gamma\gamma \to VV$ into hadrons: 2D limits