New results with the CMS Precision Proton Spectrometer (PPS)

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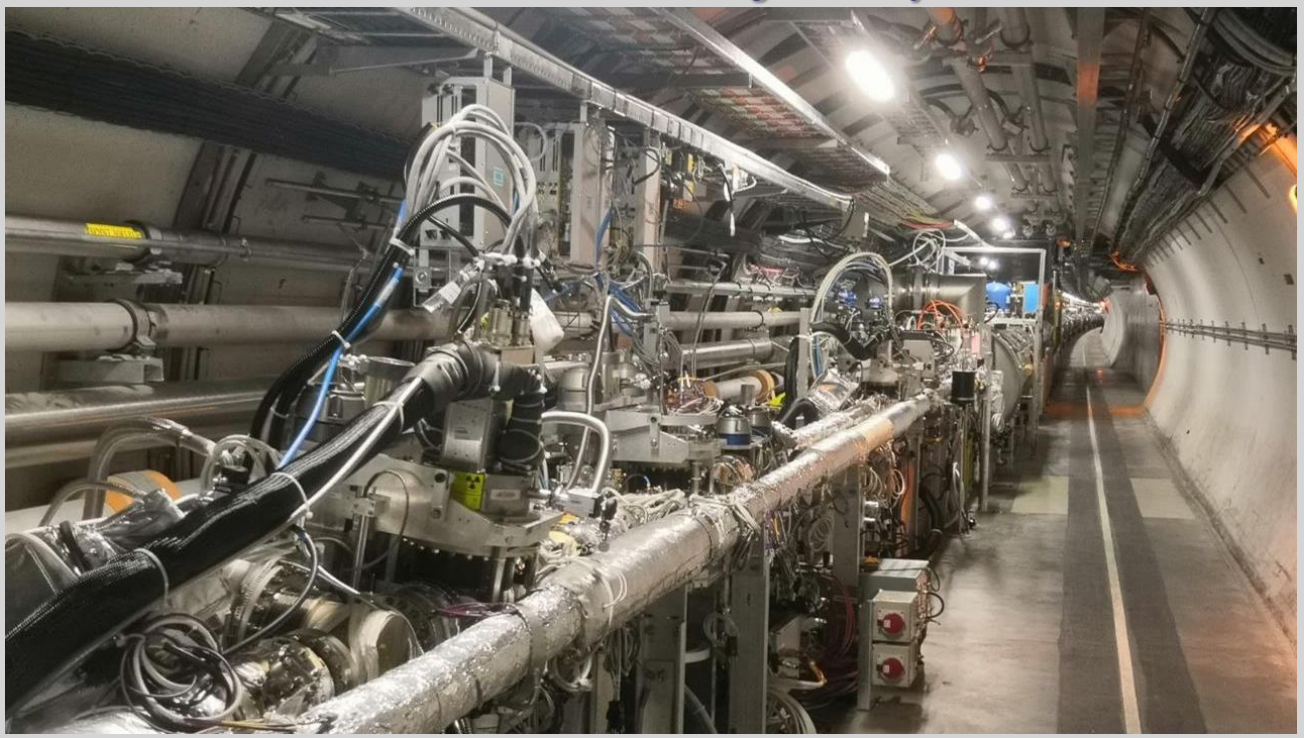
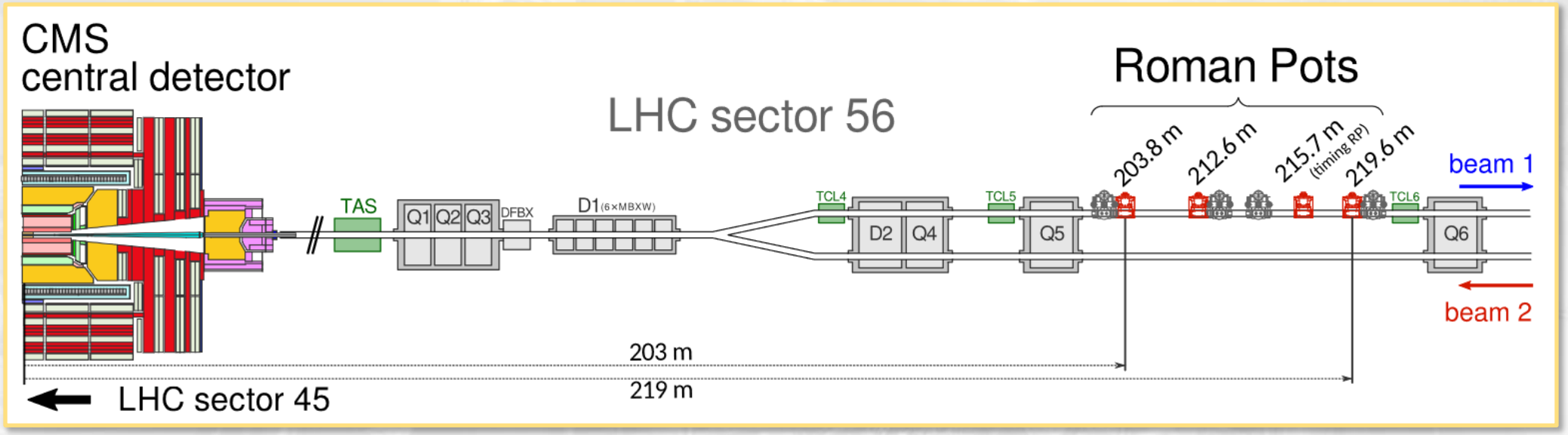
(on behalf of the CMS and TOTEM Collaborations)

ICHEP 2022, Bologna, Italy



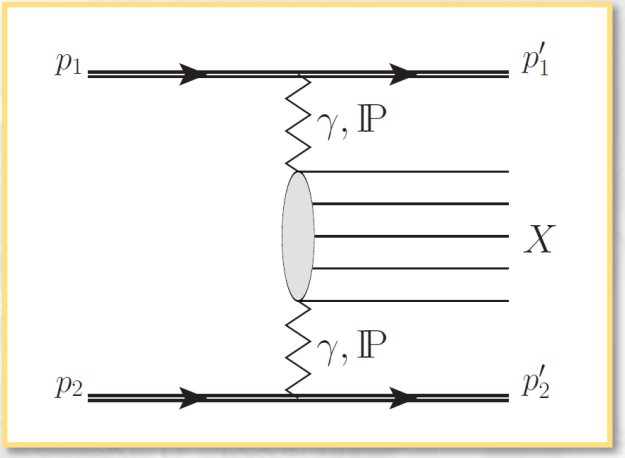
The Precision Proton Spectrometer

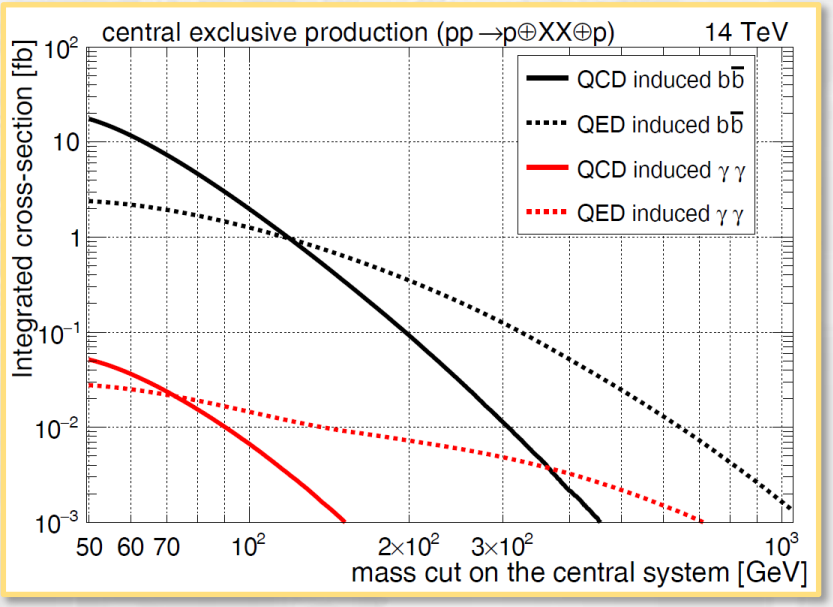


- LHC magnetic field bends **protons that survived the interaction in CMS**:
  - **Tracking and timing** detectors installed in Roman Pots (RPs), to measure:
    - **Fraction of momentum lost** by the proton (ξ) - tracking
    - Longitudinal coordinate of the primary vertex (z) – timing
- More than 100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

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:
  - **Full reconstruction** of 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



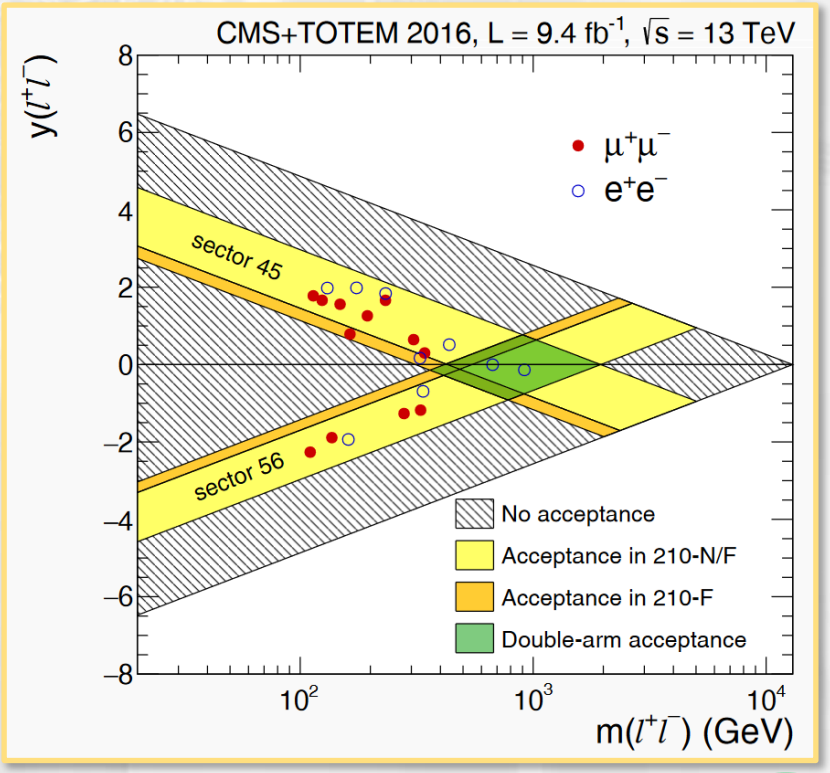


Di-lepton CEP as a validation tool

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

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

- Proton reconstruction presented in M. Obertino's talk



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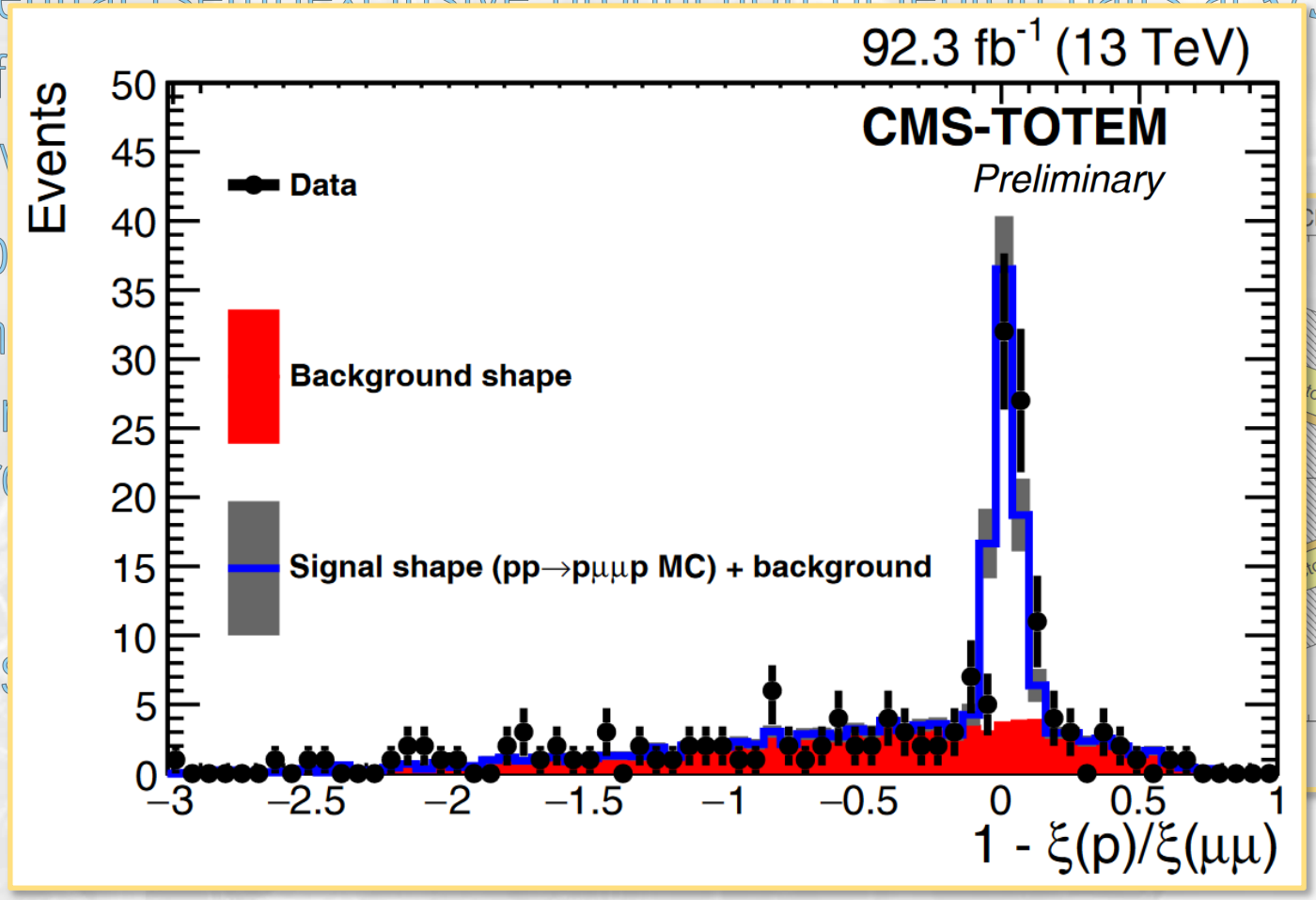
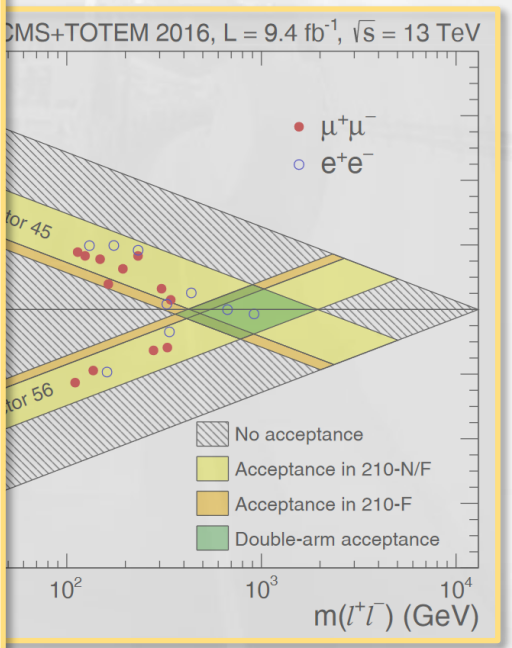
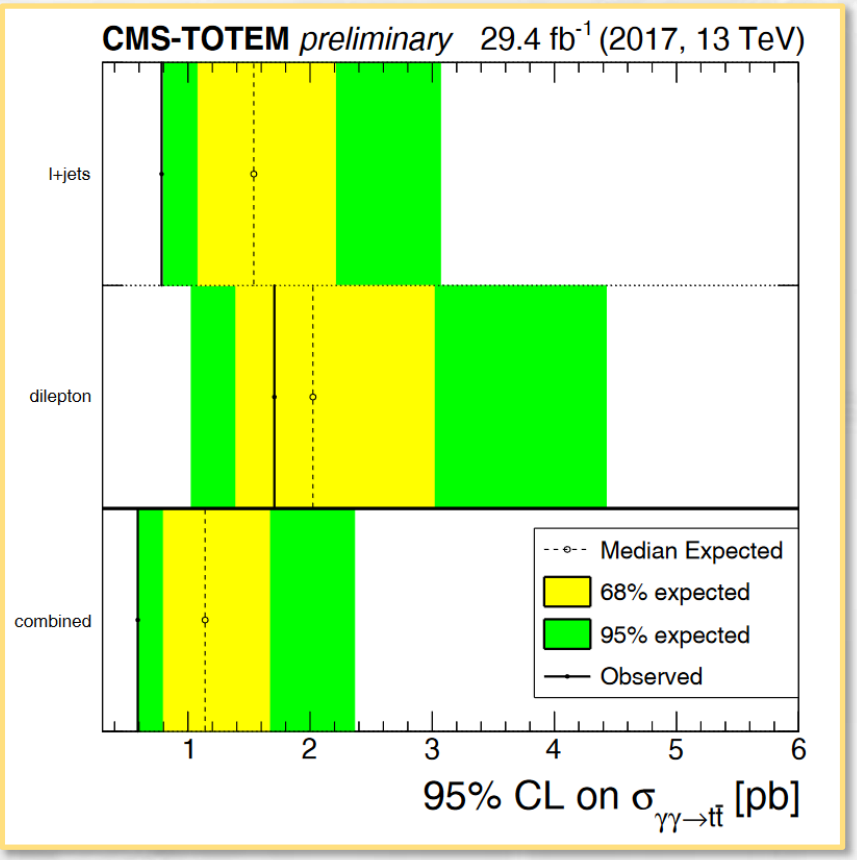




CMS-PAS-PRO-21-001
CERN-TOTEM-NOTE-2022-001

CEP of top quark pairs

- First search for **top quark-antiquark pair production with intact protons**
- **Low cross section** – $\mathcal{O}(0.3\ \text{fb})$ 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
- **Proton matching** criteria used as **BDT inputs** or kinematic **fitting constraints**
- **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

CEP of top quark pairs

- First search of top quark-antiquark pair production with intact protons
- Low cross section – $\mathcal{O}$(0.3 fb) in the PPS acc
  - Signal concentrated at low $t\bar{t}$ mass
- 2017 dataset: 29.4 fb
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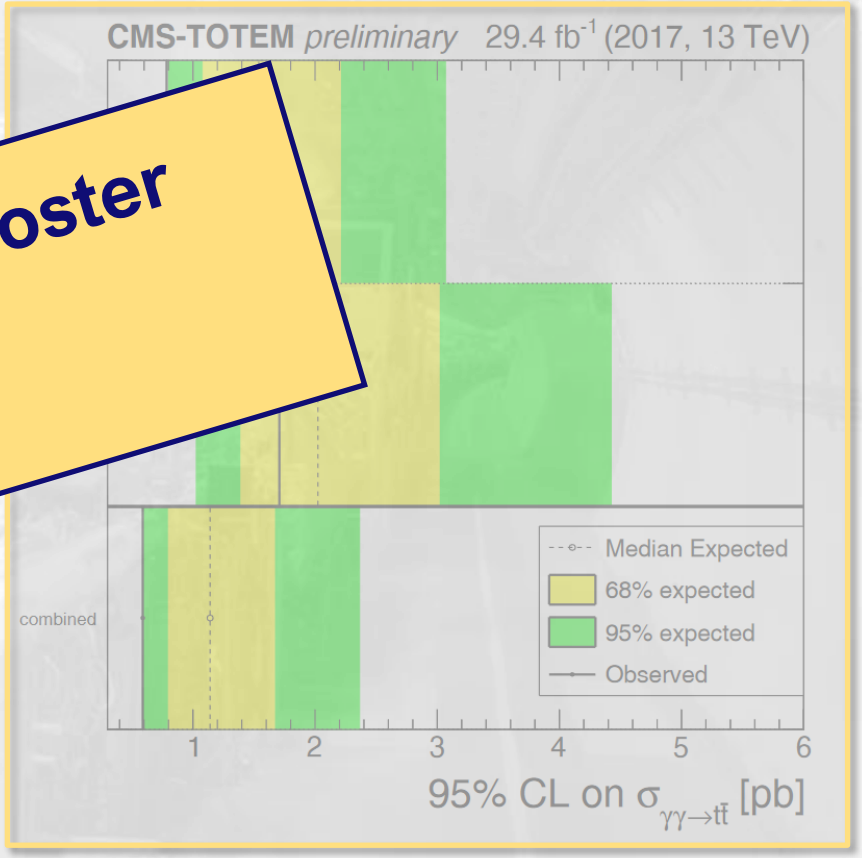
Check out B. Ribeiro Lopes' poster and D. Muller's talk!



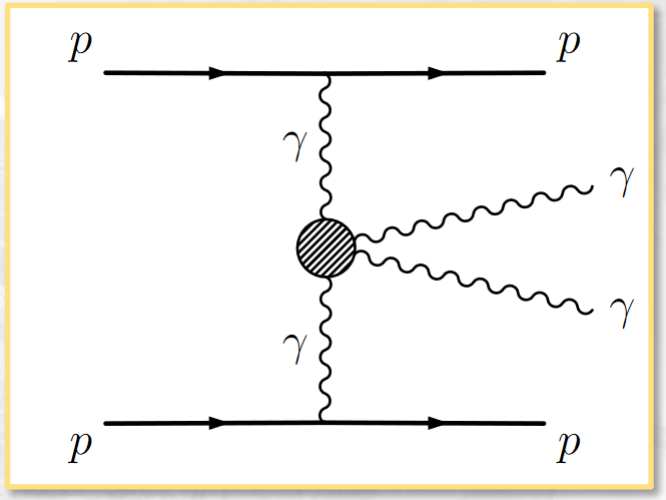
CMS-PAS-TOP-21-007
CERN-TOTEM-NOTE-2022-002

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

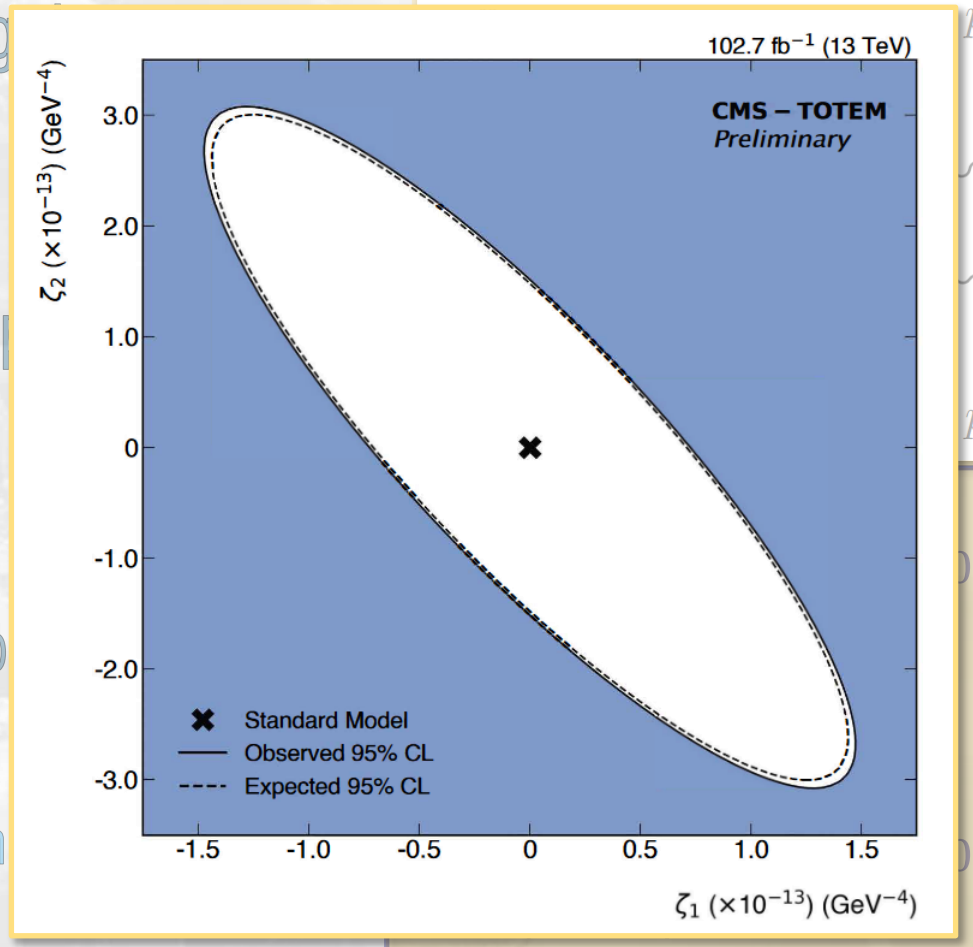
- Search for LbyL scattering with proton tag
- Full Run 2 dataset, 102.7 fb^{-1}
  - Extending Phys. Rev. Lett. 129, 011801
- Matching requirement in the mass and rapidity between $\gamma\gamma$ and protons:
- Production
- One candidate observed:
  - BG prediction of 1.1 events with 2σ matching

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

~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}



within acceptance

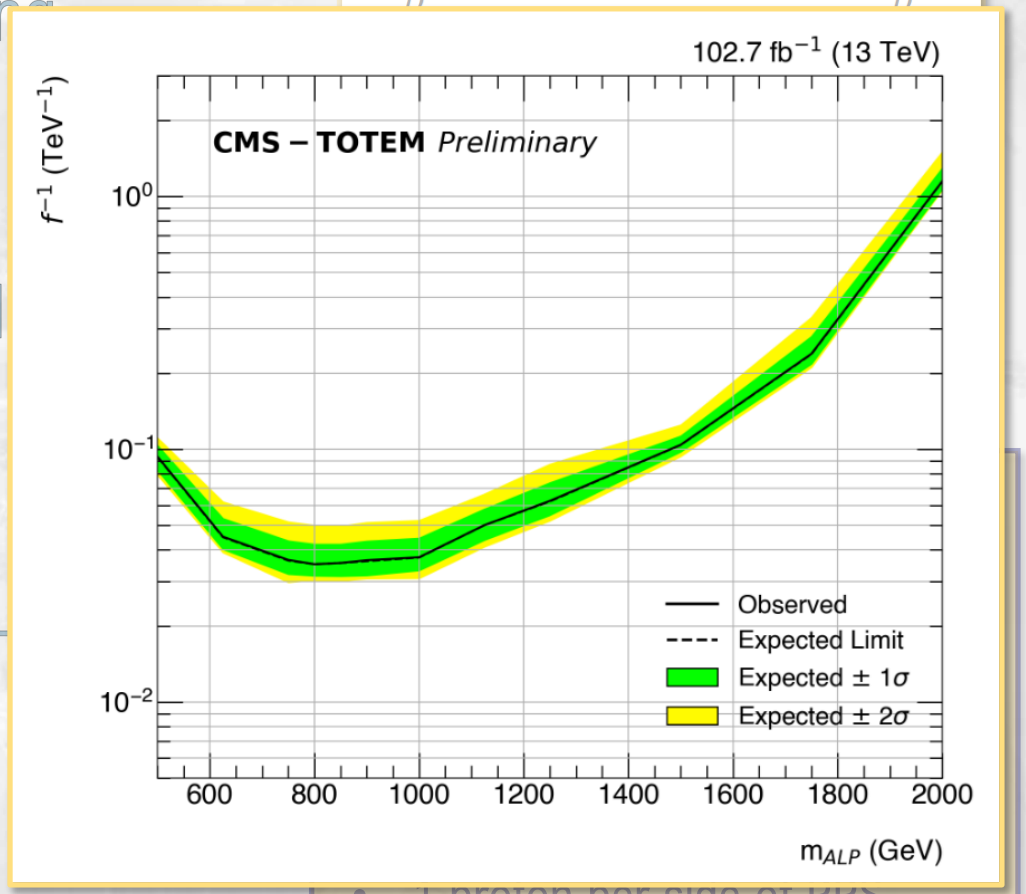
CMS-PAS-EXO-21-007
CERN-TOTEM-NOTE-2022-005

Exclusive $\gamma\gamma \rightarrow \gamma\gamma$

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

Limits also set for ALP production ($\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$) 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

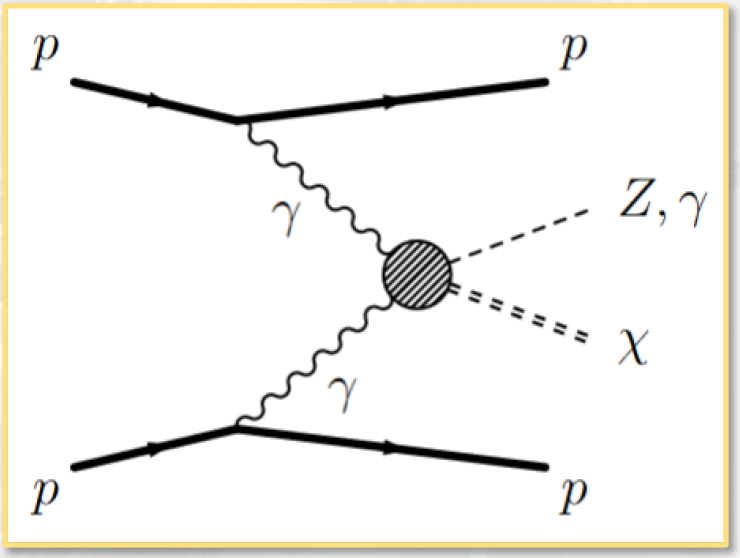
CMS-PAS-EXO-21-007
CERN-TOTEM-NOTE-2022-005

Searching for missing mass with Z/γ

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

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

- Search for **missing mass produced in association** with a 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)



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

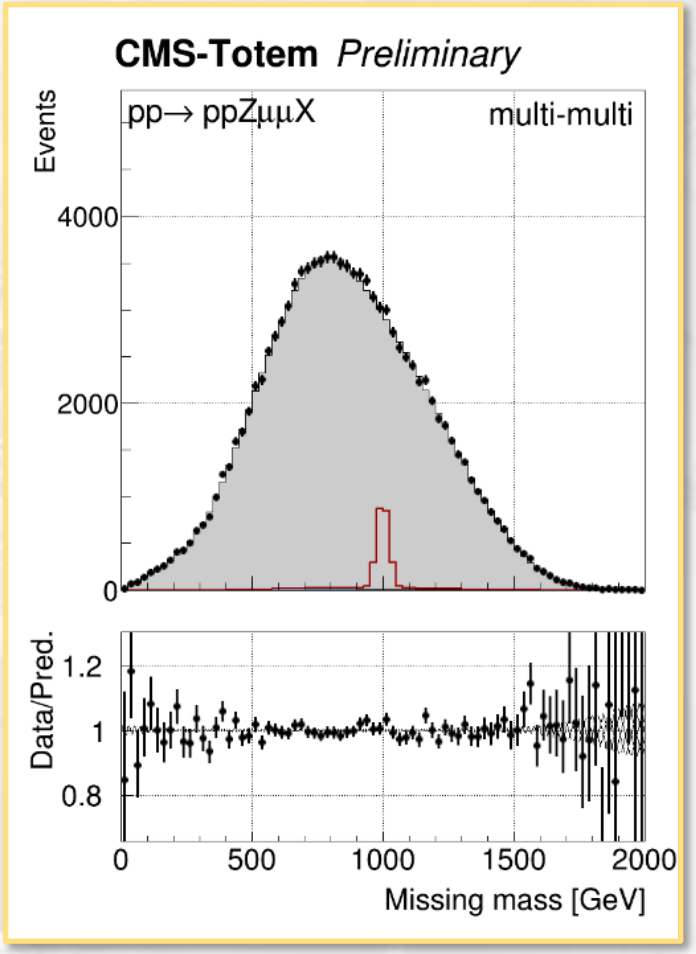
Searching for missing mass with Z/γ

Event selection

$Z \to e^+e^- / Z \to \mu^+\mu^-$
≥ 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)

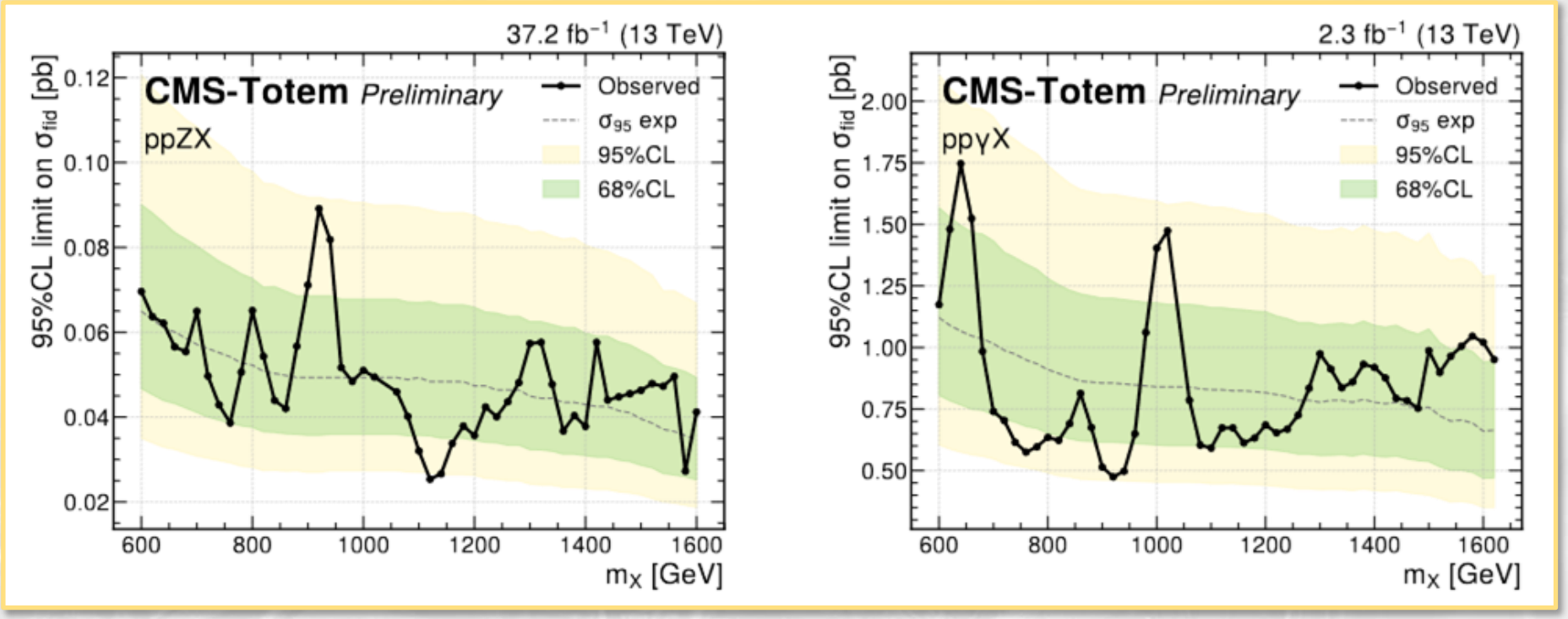
≥ 1 proton per side of PPS



- 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

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

Searching for missing mass with Z/γ

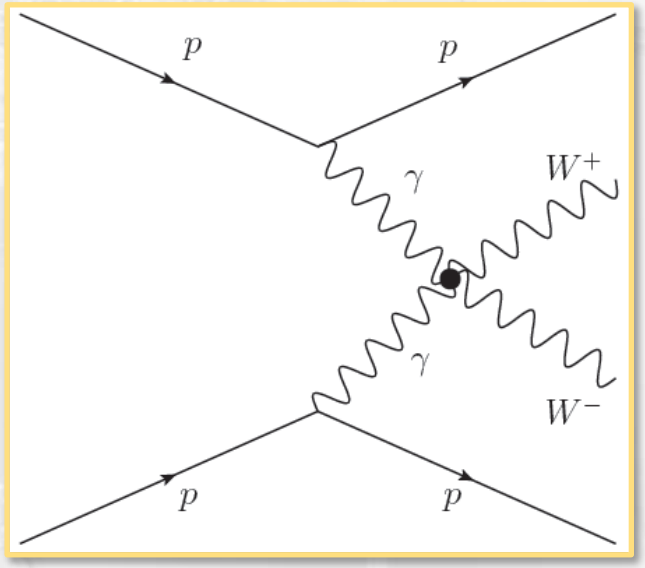


- Bump search over missing mass spectrum
  - **No major local excess/deficit observed**
  - Larger dataset will be analysed
- Setting **95% CL on fiducial cross section** as a function of m_X

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

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

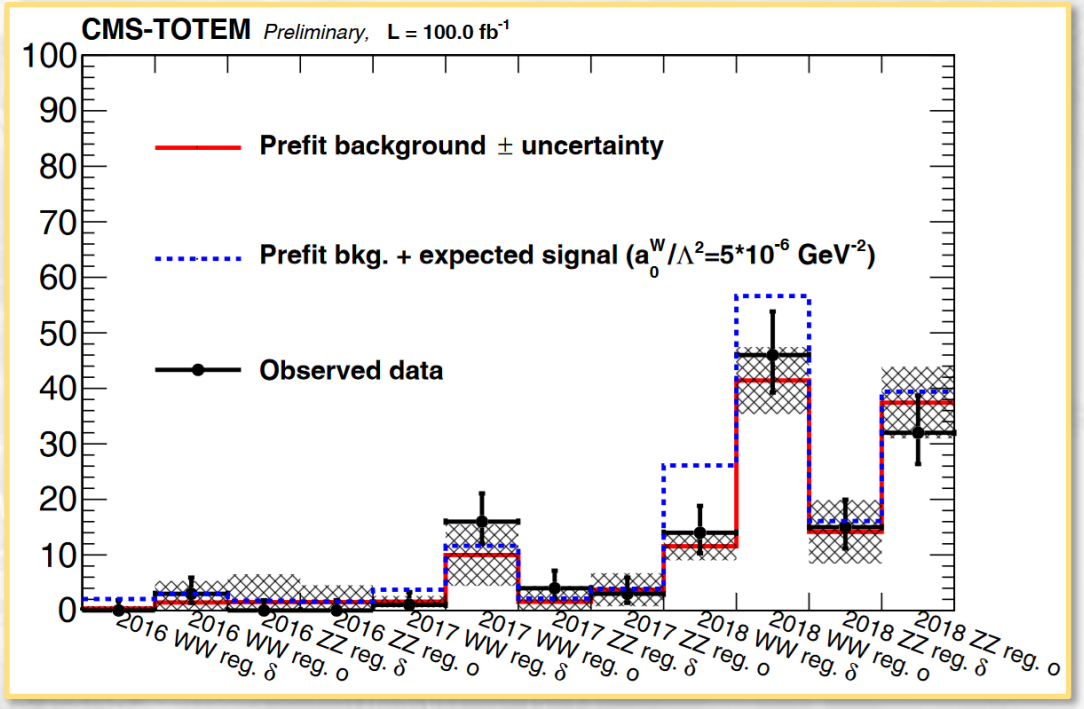
- Search for **anomalous WW/ZZ (VV) exclusive production** at high mass:
  - Exploring the **hadronic decay channel** (each V decaying into a boosted and merged jet)
  - Require **intact protons on both sides**
  - Look for **non-resonant enhancements** over high-mass tails (AQGC/EFT)
- SM production:
  - **ZZ not allowed** at tree level
  - **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



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

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:
  - **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
- $|\eta(j_1) - \eta(j_2)| < 1.3$
- $p_T(j_1)/p_T(j_2) < 1.3$
- $|1 - \Delta\phi(j_1 j_2)/\pi| < 0.01$
- $1126\ \text{GeV} < m(j_1 j_2) < 2500\ \text{GeV}$
- ≥ 1 proton per side of PPS

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

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

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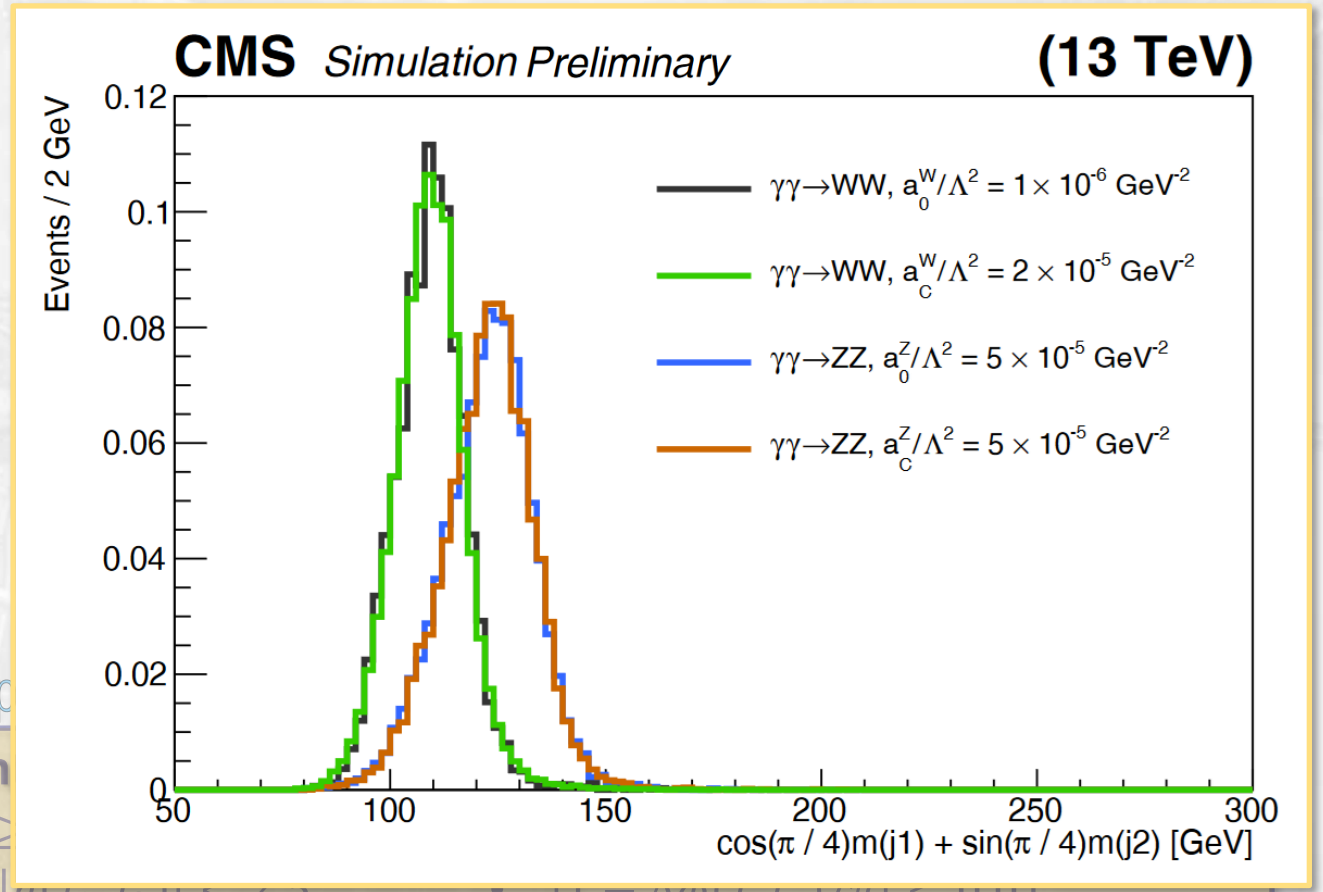
  - Rapidity difference
- Two signal regions:
  - δ: both protons from the interaction
  - o: one proton mistakenly chosen from p
- Main background:
  - QCD di-jet production combined with pileup protons
  - Data-driven estimation with 'ABCD' method (sidebands)



Even

- $|\eta(j_1, j_2)| < 2.5$
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CMS-PAS-SMP-21-014
CERN-TOTEM-NOTE-2022-004

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

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- Selection based on:
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- Two signal regions:
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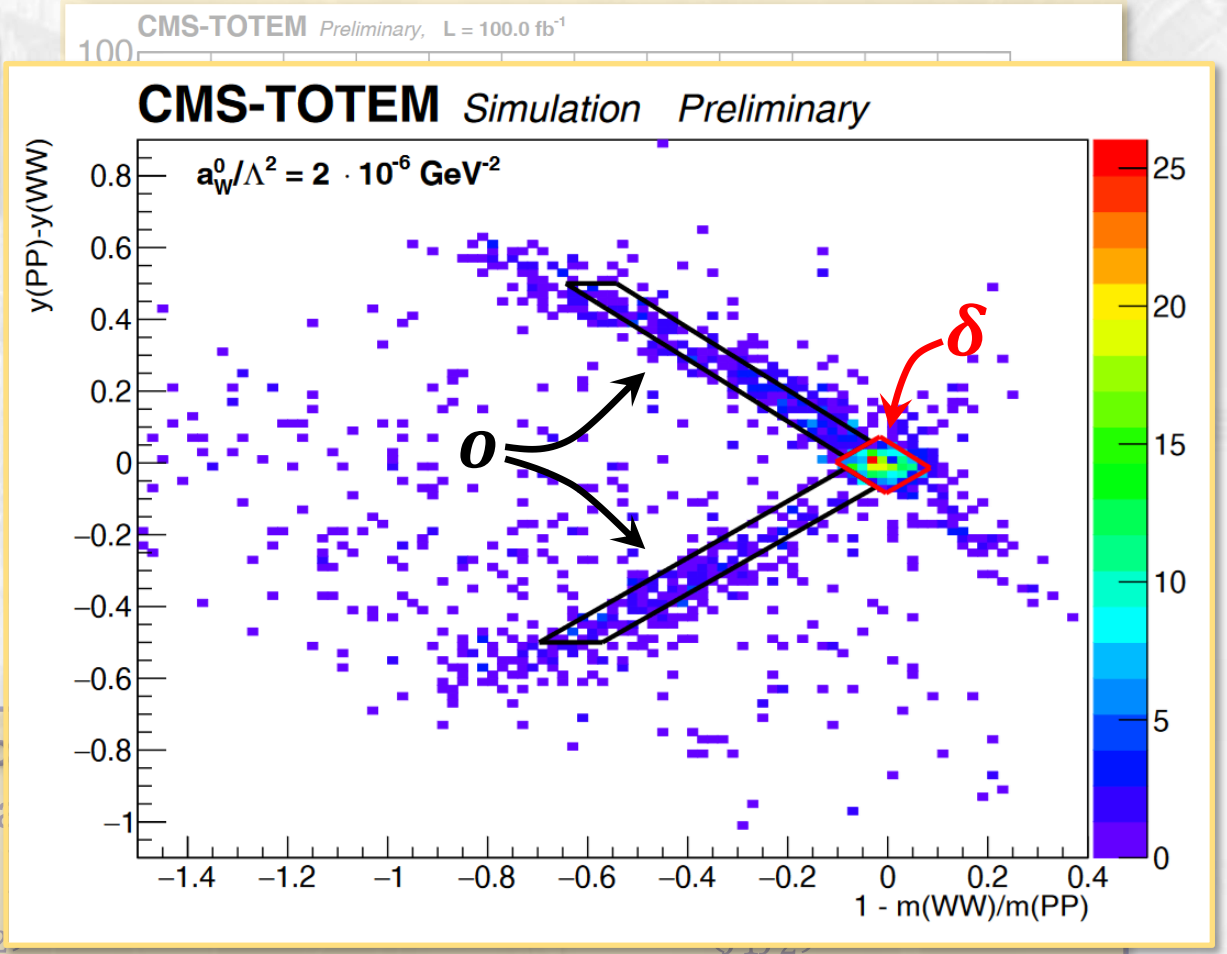
- Main background:
  - QCD di-jet production combined with pileup protons
  - Data-driven estimation with 'ABCD' method (sidebands)

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

$$|1 - m(VV)/m(pp)|$$
$$m(pp) = \sqrt{s\xi_1\xi_2}$$



Event selec

- ≥ 2 V-t
- $|\eta(j_1, j_2$
- $p_T(j_1, j_2$
- $|\eta(j_1) - \eta(j_2)| < 1.3$
- ≥ 1 proton per side of PPS

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

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

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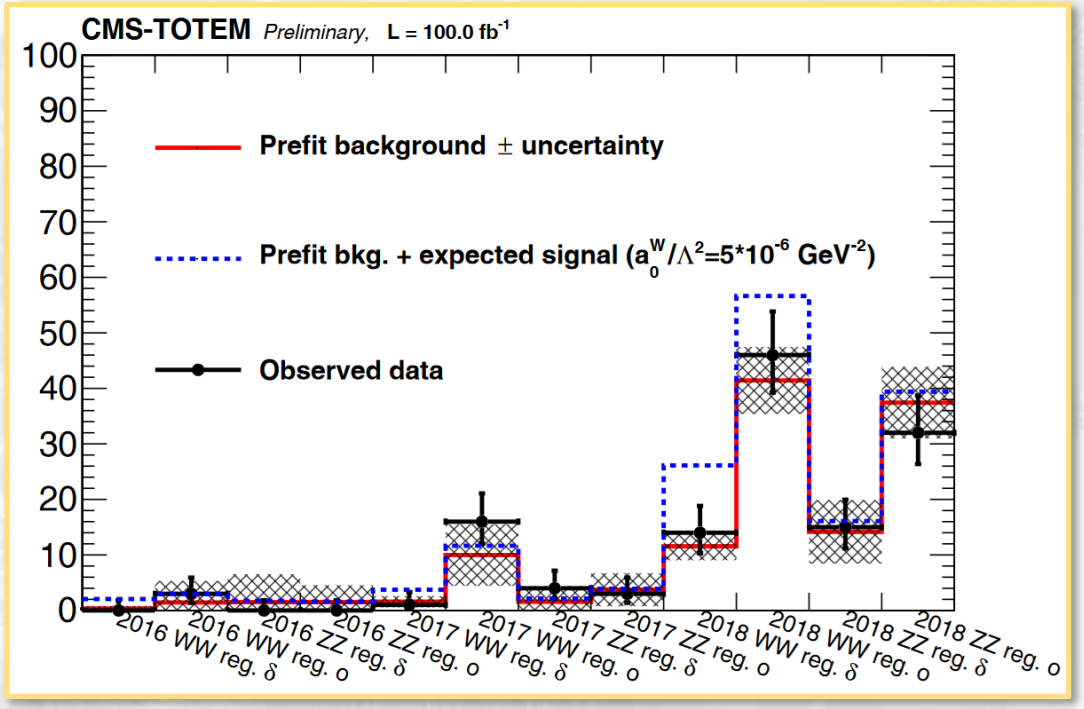

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- $p_T(j_1)/p_T(j_2) < 1.3$
- $|1 - \Delta\phi(j_1 j_2)/\pi| < 0.01$
- $1126\ \text{GeV} < m(j_1 j_2) < 2500\ \text{GeV}$
- ≥ 1 proton per side of PPS

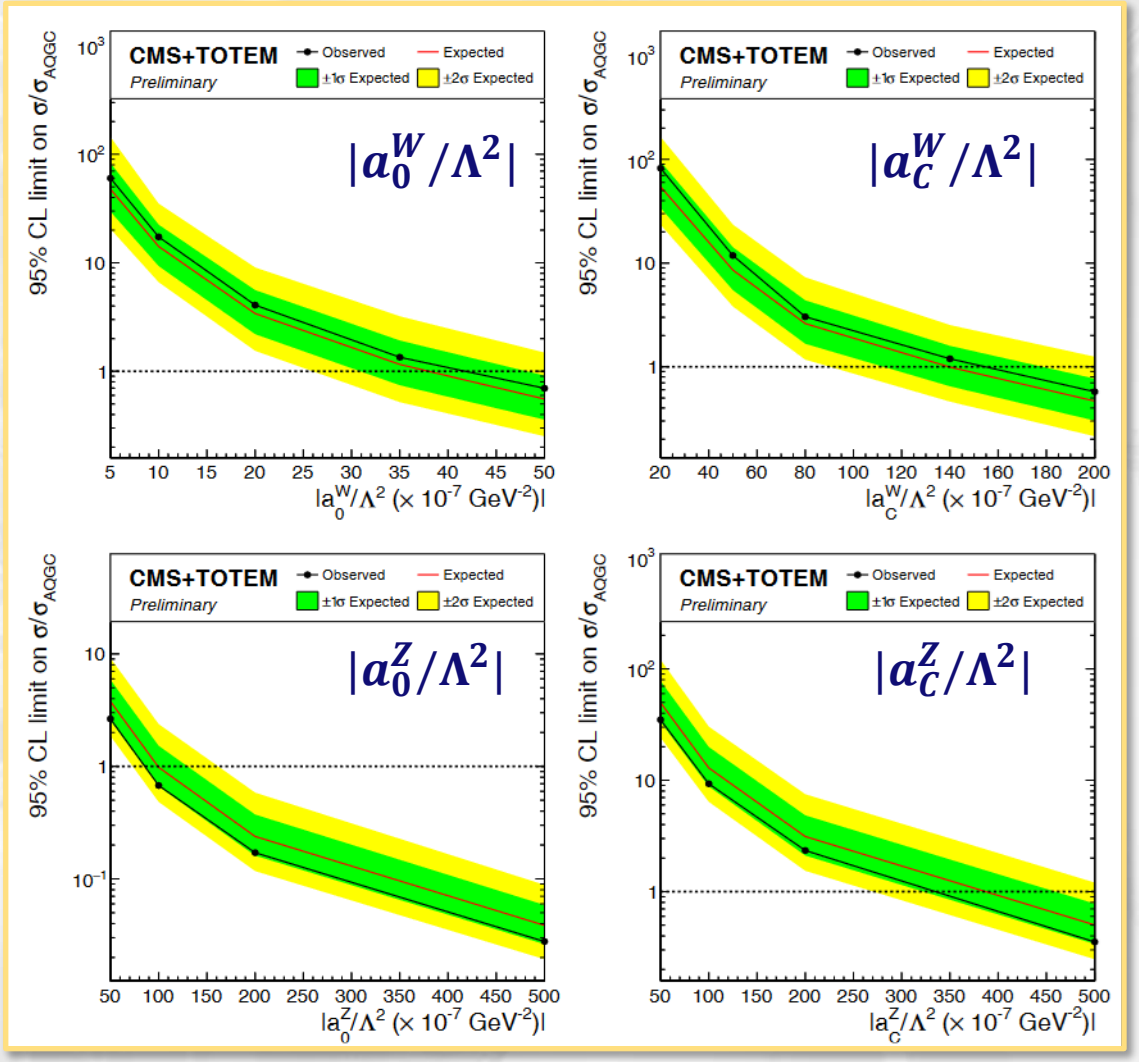
CMS-PAS-SMP-21-014
CERN-TOTEM-NOTE-2022-004

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 $\boldsymbol{WW}$ and $\boldsymbol{WZ}$ results at 13 TeV after unitarization
- First limits on $\boldsymbol{\gamma\gamma ZZ}$ AQGC via exclusive $\boldsymbol{\gamma\gamma \to ZZ}$
- Fiducial cross section limits:

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

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



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

Summary

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

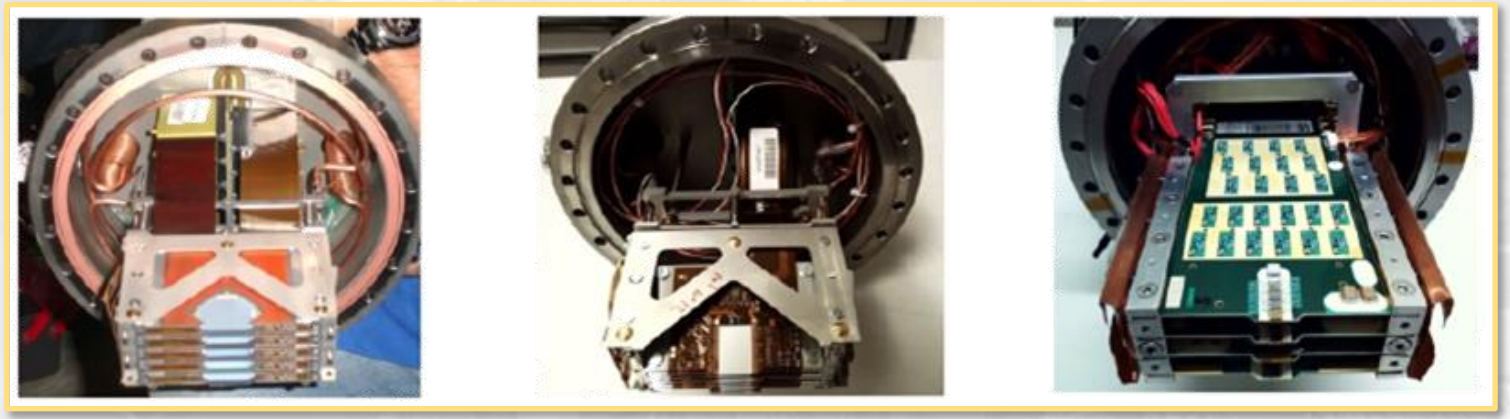
Looking forward:

- PPS is **now ready for Run 3** and starting data-taking
- **Extensions** of the present analyses and **new ones** are ongoing!
- PPS intends to **take part in HL-LHC** (arXiv:2103.02752)
  - A lot of interesting physics processes to explore!
  - **Check out G. Gil Da Silveira's poster!**

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), $\sigma_x \sim 15$ µm and $\sigma_y \sim 30$ µm, $\Phi_{max} \sim 5 \cdot 10^{15}$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