The CMS Precision Proton Spectrometer: recent results and status

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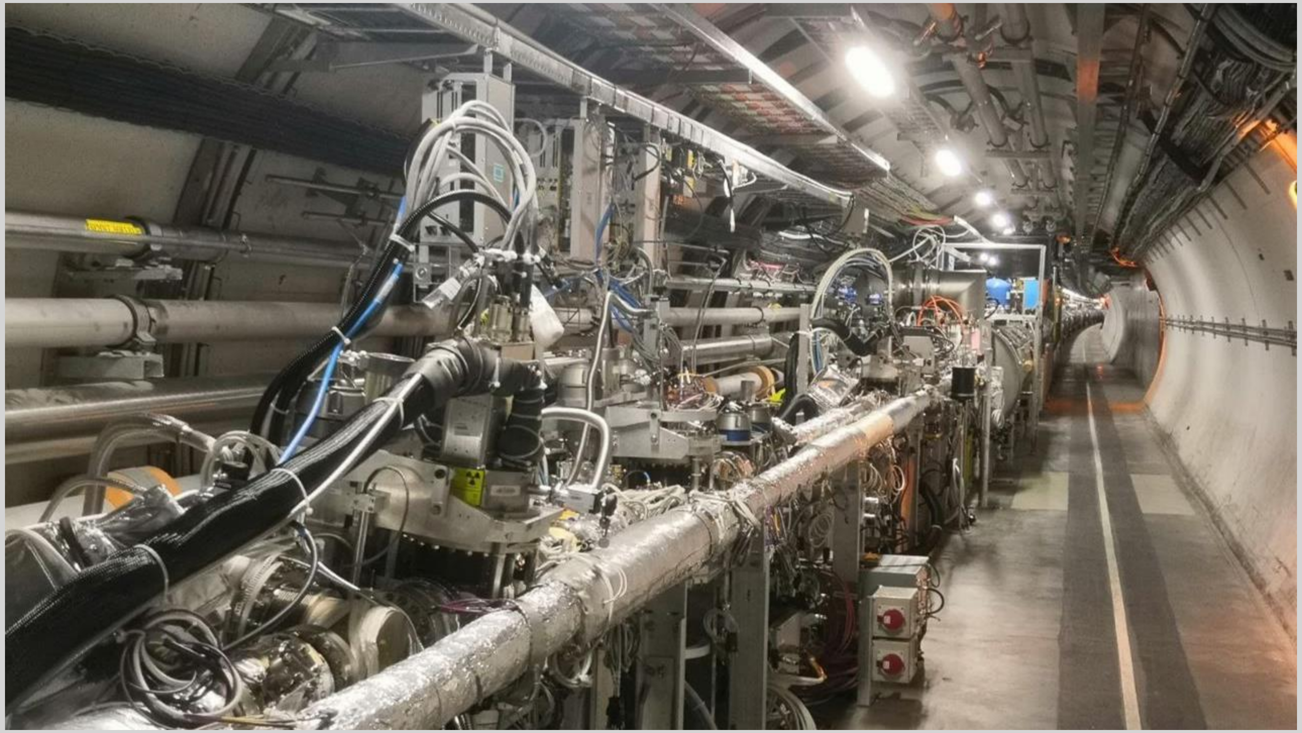
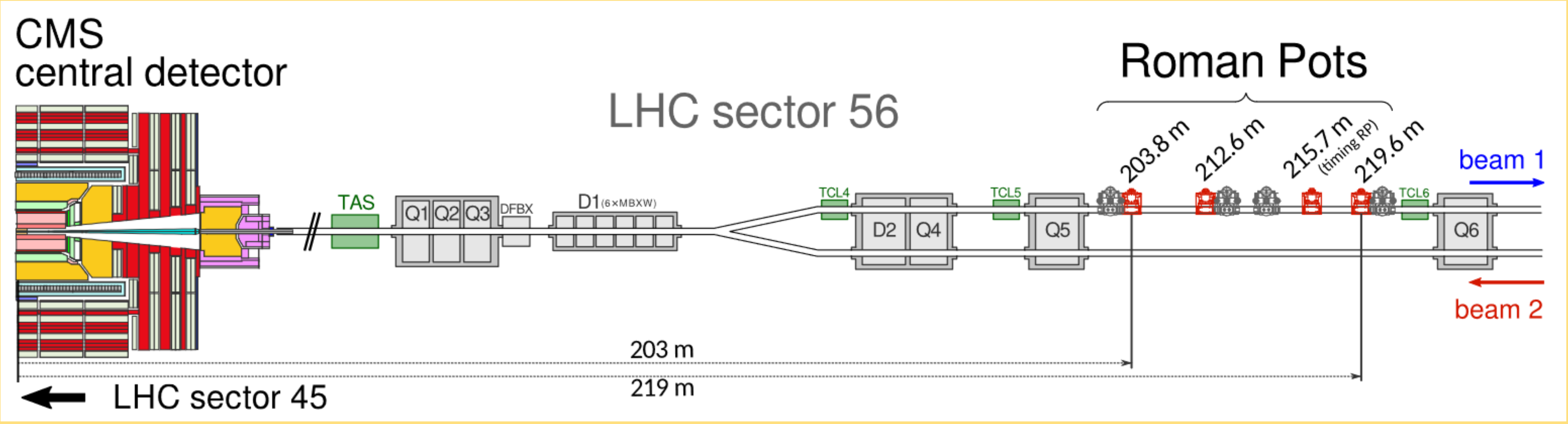
(on behalf of the CMS and TOTEM Collaborations)

Forward Physics and QCD at the LHC and EIC (WE-Heraeus-Seminar)

25th Oct. 2023, Bad Honnef, Germany

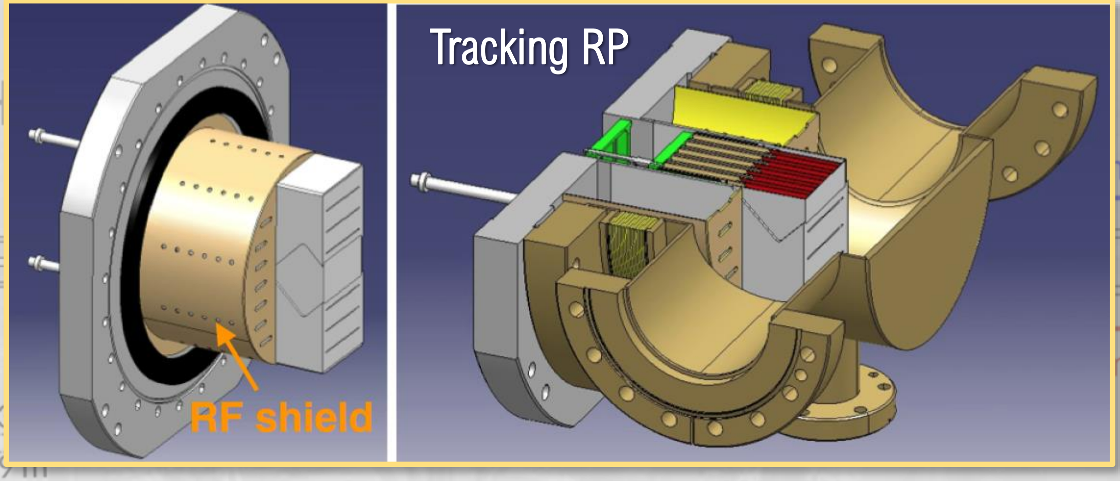


The Precision Proton Spectrometer



- 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

The Precision Proton Spectrometer

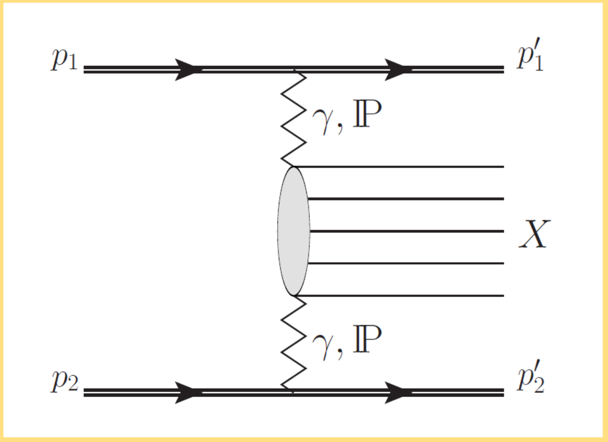


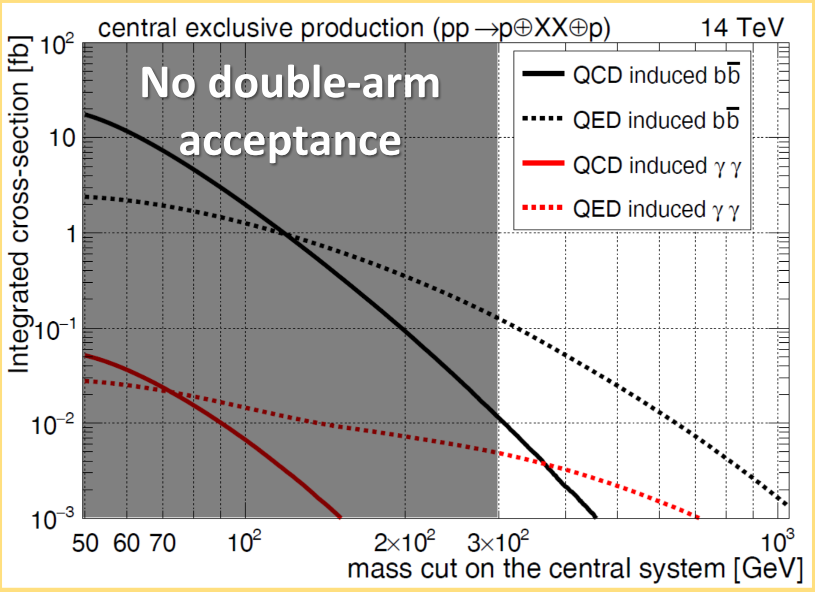
- …otons that survived the interaction in CMS:
  - …s installed in Roman Pots (R…
    - … the proton (ξ) - tracking
    - … primary vertex (z) – timing
- …ollected in Run 2

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

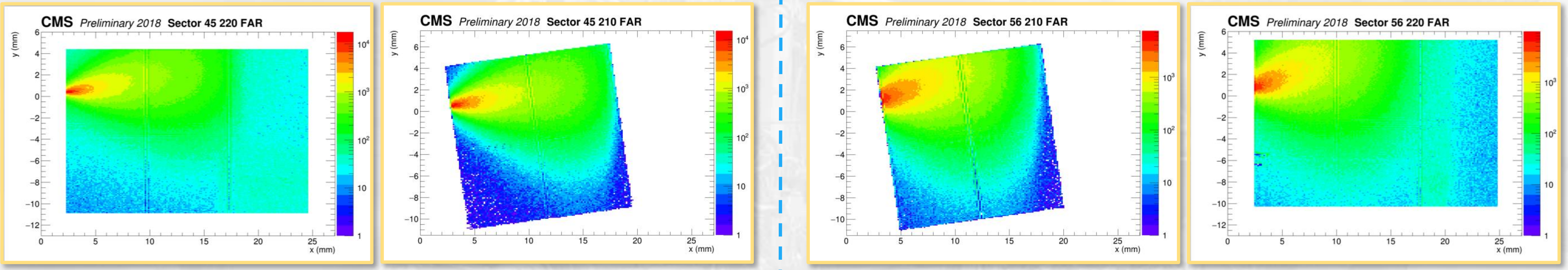
The PPS physics case

- 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
Proton transport

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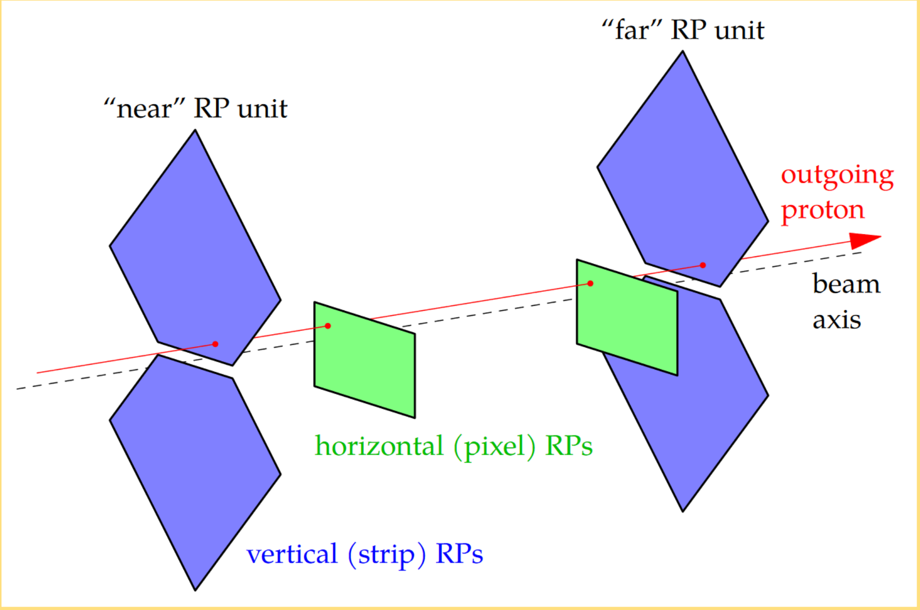
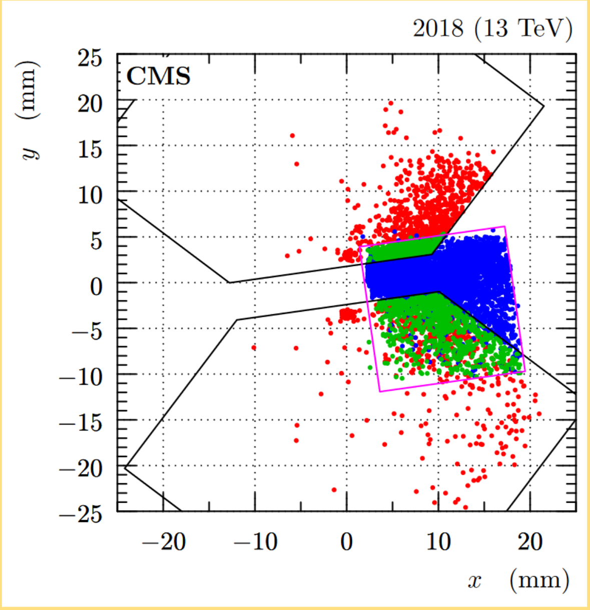
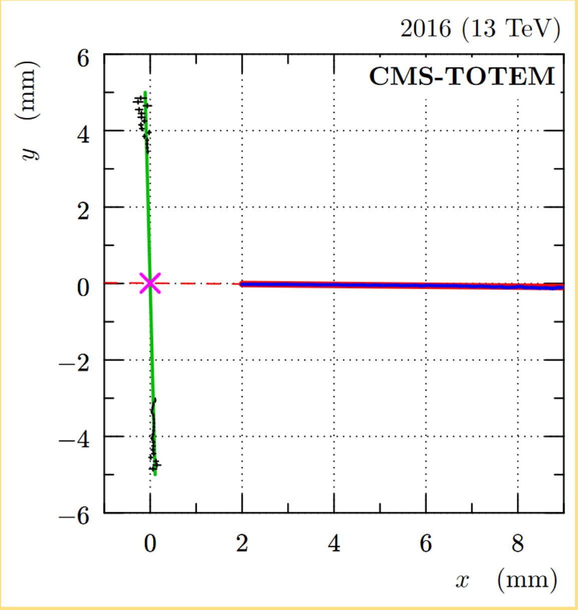
Detector alignment







Multi-step procedure: base measurement in dedicated LHC fill → corrected every LHC fill

- Alignment run: 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 (β^*/ beam crossing angle) 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

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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

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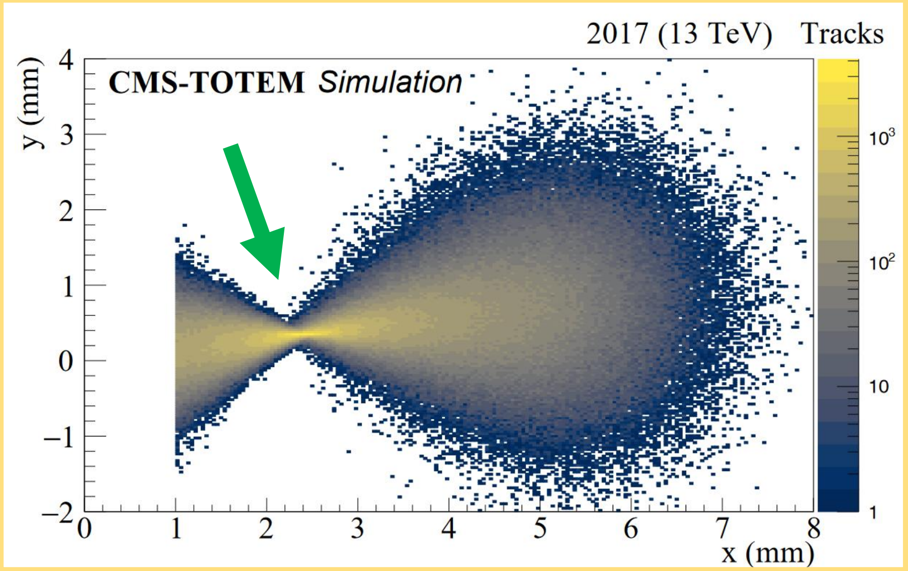
Optics calibration

- 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 the beam crossing angle
  - This means variable acceptance during data-taking!



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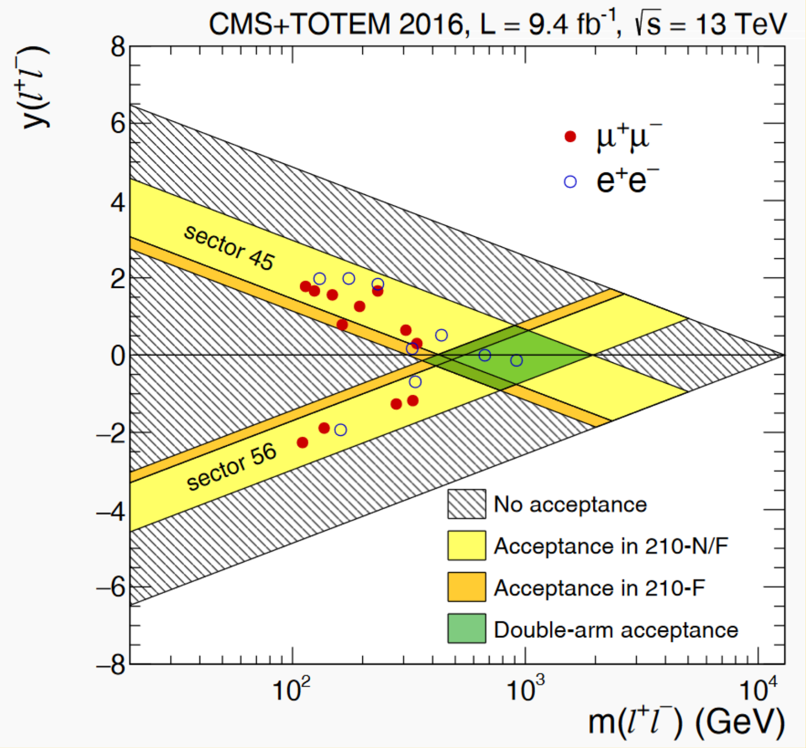
Di-lepton CEP as a validation tool

- 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 handle:
  - Select high-mass muon pairs produced back-to-back
  - Use the correlation between di-muons and protons to validate the PPS proton reconstruction:

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



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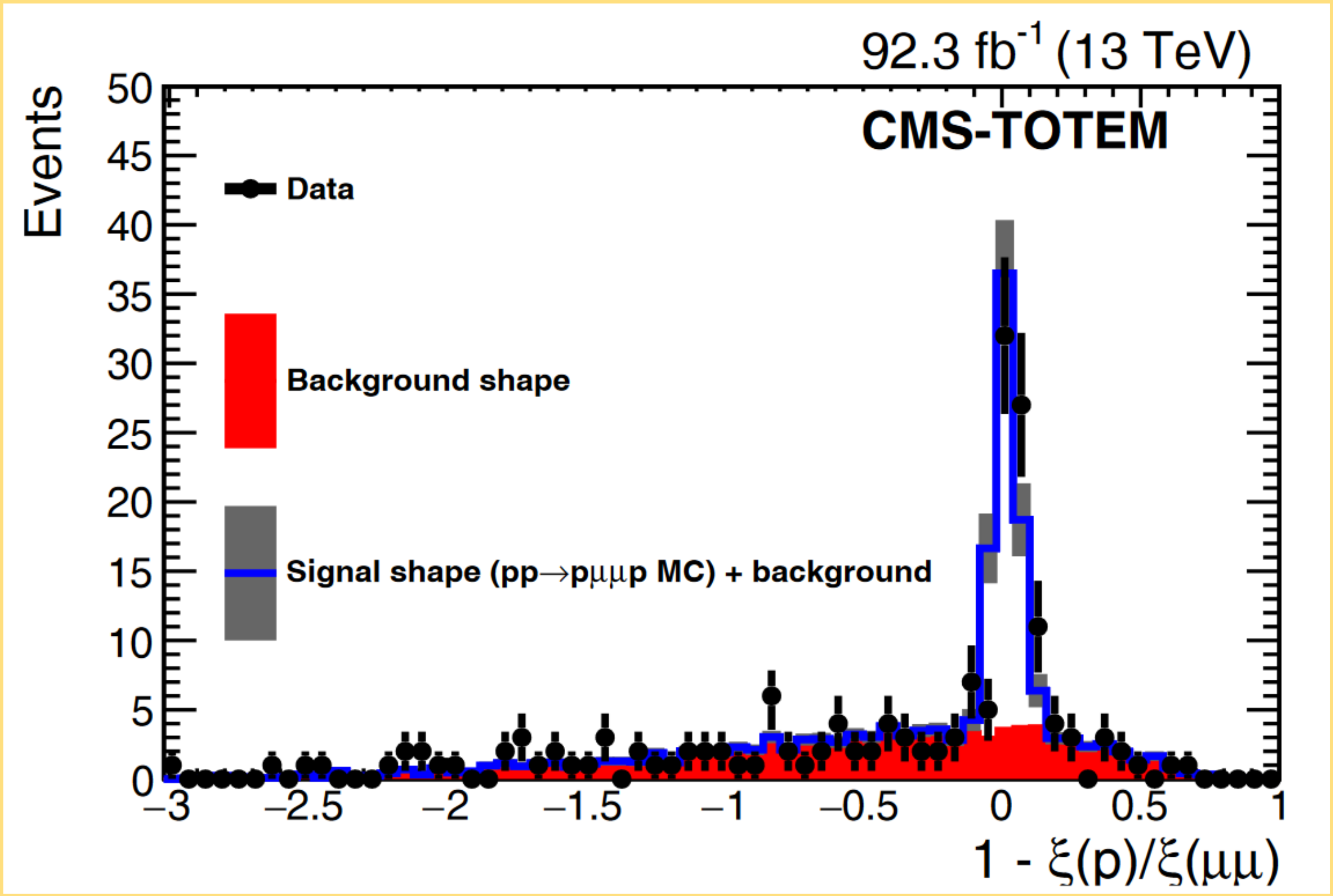
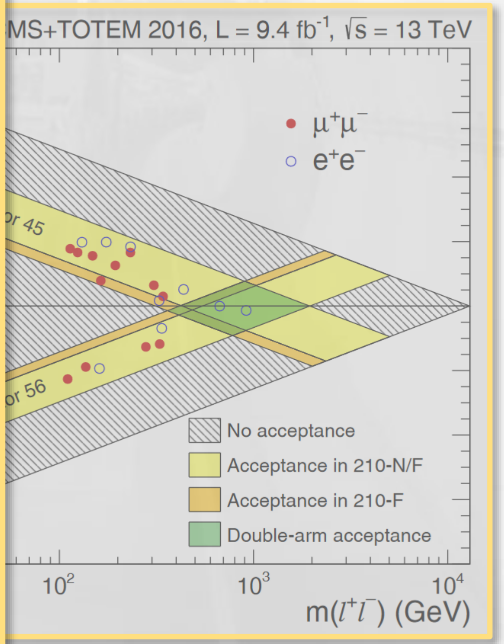
Di-lepton CEP as a validation tool

- High-mass c... $\sqrt{s} = 13$ TeV
  - 5.1σ signi...
  - First obser...
- Now an esse...
  - Select high...
  - Use the co... validate the...





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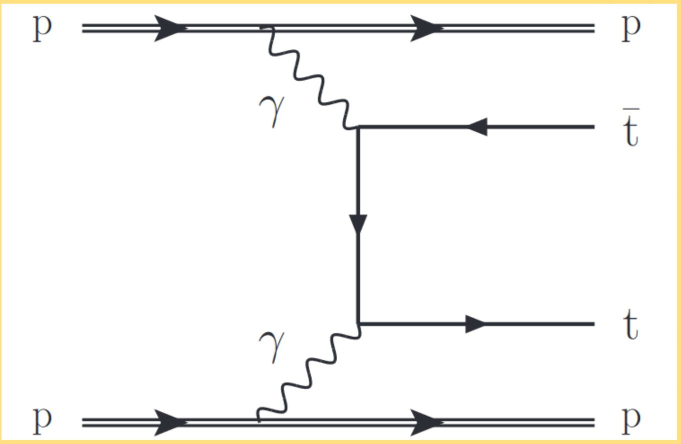
CEP of top quark pairs

- First search for exclusive 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: $p_T > 30/20$ GeV, $\lvert\eta\rvert < 2.1$	**Jets:** $p_T > 30$ 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

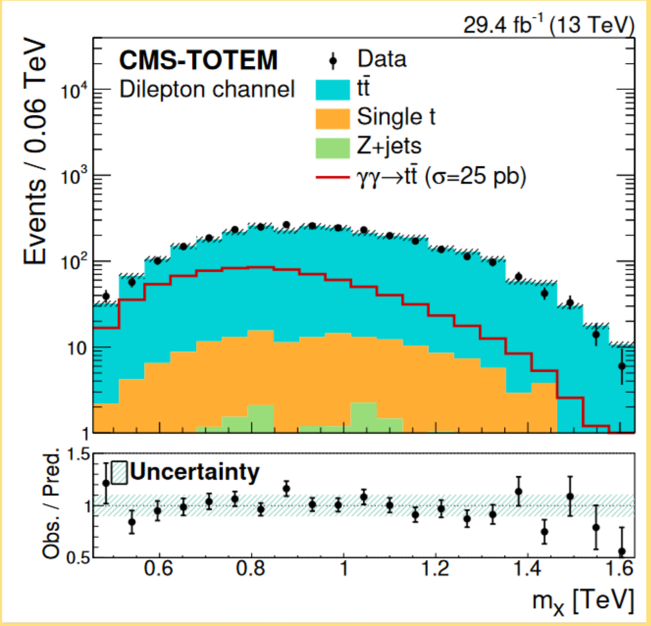
Leptons: $p_T > 30$ GeV; $\lvert\eta\rvert < 2.1$ (e); $\lvert\eta\rvert < 2.4$ (μ)	**Jets:** $p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$; $\Delta R(j,\ell) > 0.4$; *tightLepVeto* jet ID, loose PU ID; b-tagging Deep CSV medium

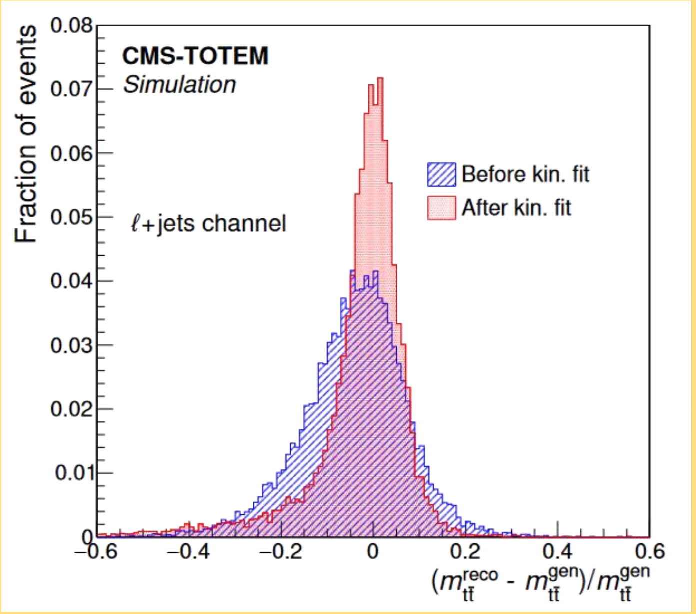
Selection:
- $= 1$ lepton
- ≥ 2 b − jets, ≥ 2 light jets
- $= 1$ proton on each side of PPS

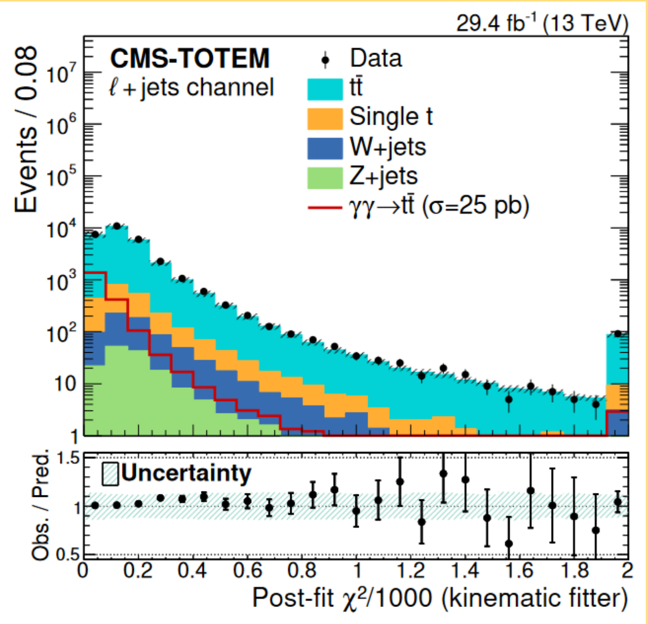
arXiv:2310.11231

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



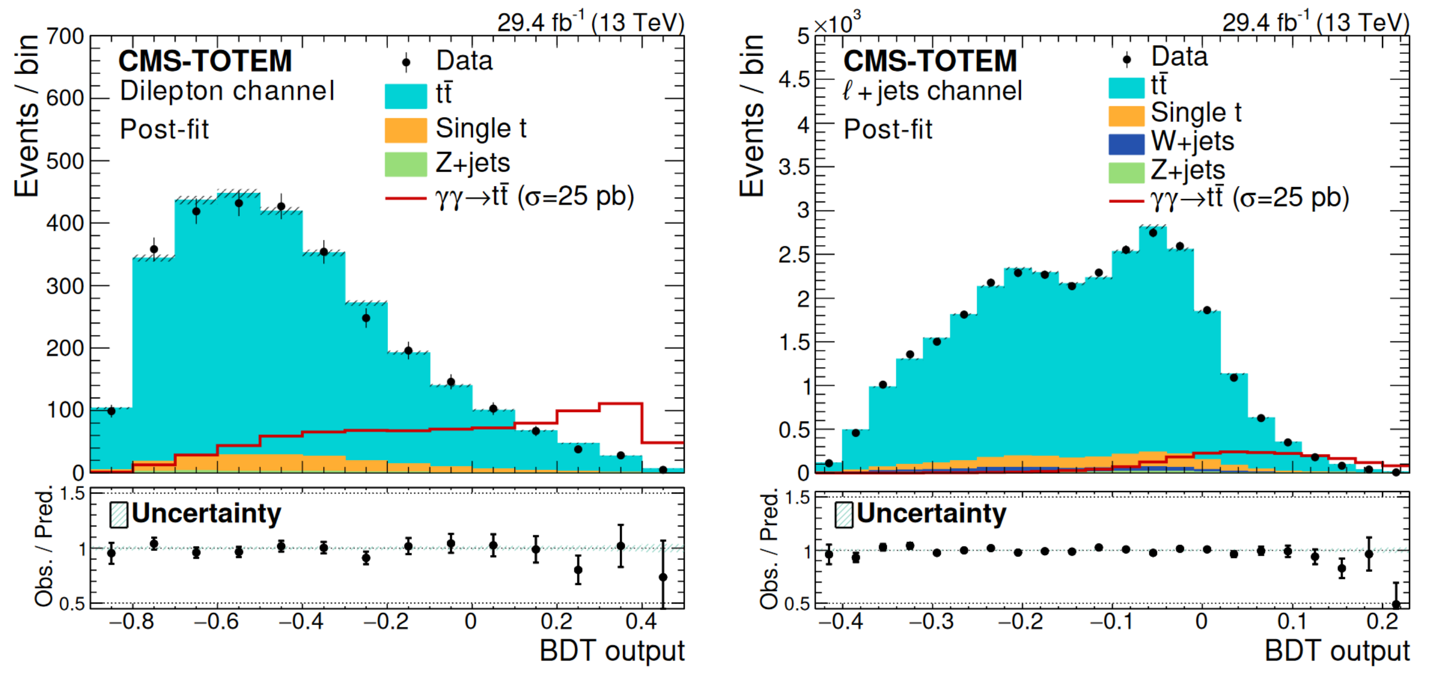


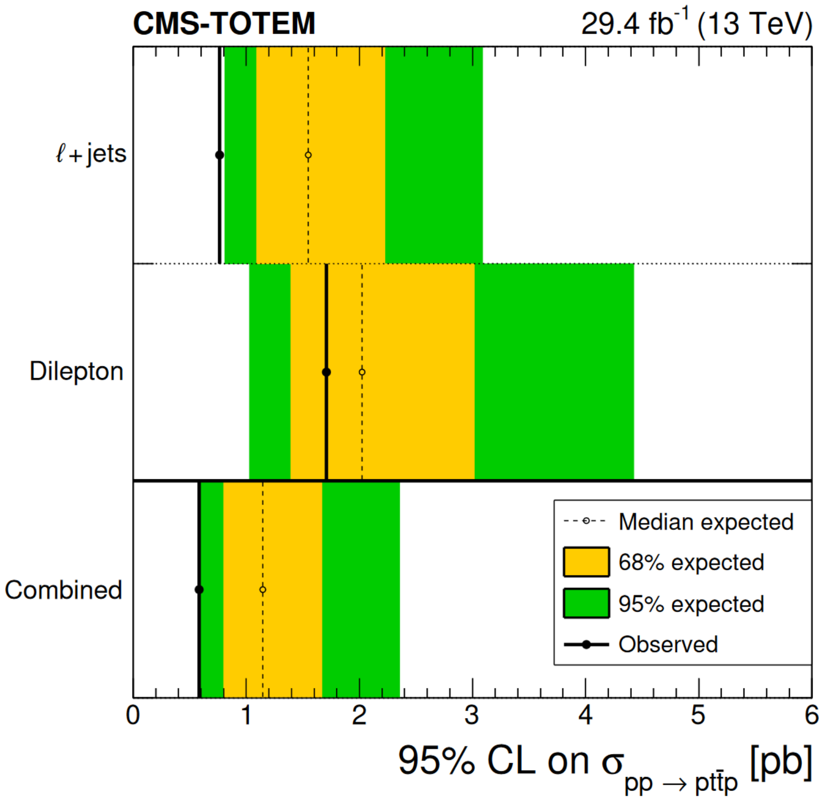


arXiv:2310.11231

CEP of top quark pairs

- MVA approach used for signal/background separation
- 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)





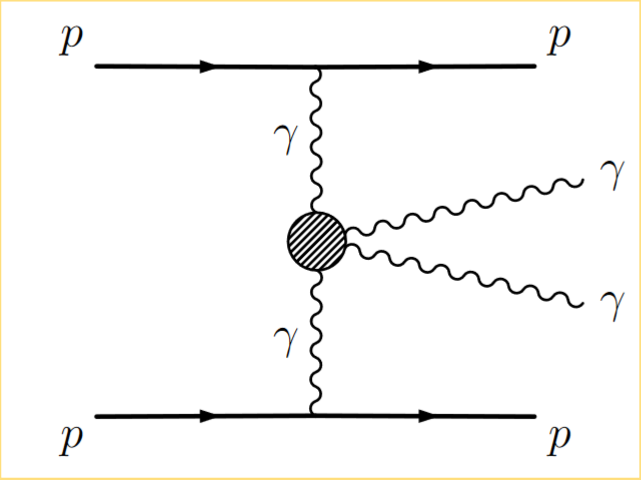
arXiv:2310.11231

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

- Search for LbyL scattering with proton tagging
- Full Run 2 dataset, 102.7 fb^{-1}
  - Extending Phys. Rev. Lett. 129, 011801
  - Improved photon ID
- 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 $\gamma\gamma \rightarrow \gamma\gamma$

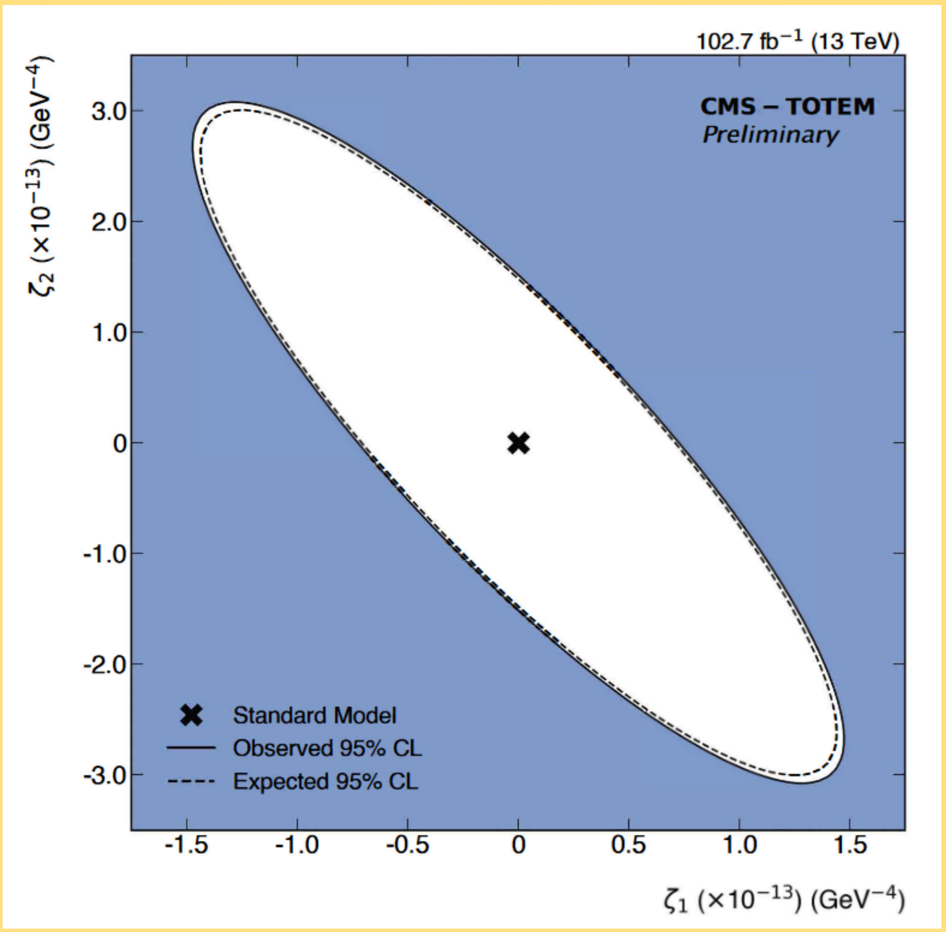
- Search for LbyL scattering with proton tag
- Full Run 2 dataset, 102.7 fb^{-1}
- Matching requirement in the mass and ra
between $\gamma\gamma$ and protons:
- One candidate observed:
  - BG prediction of 1.1 events with 2σ matchin

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

Best 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}



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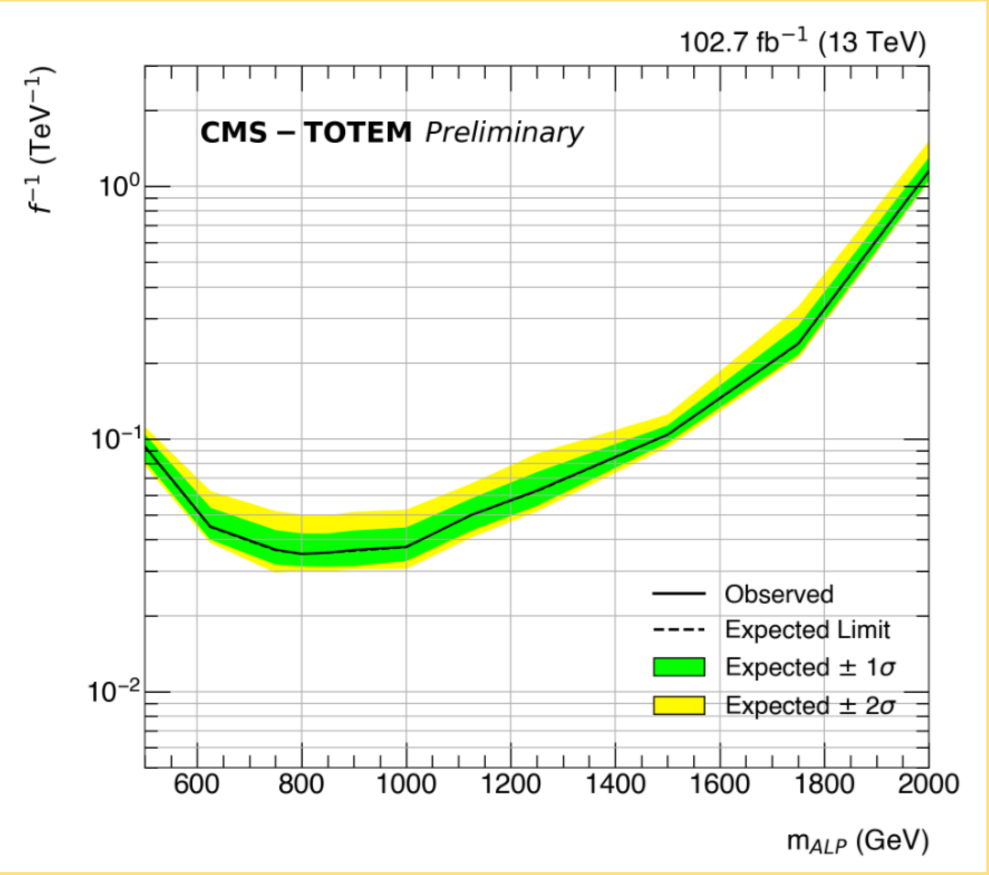
within acceptance

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

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

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

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



1 proton per side of PPS within acceptance

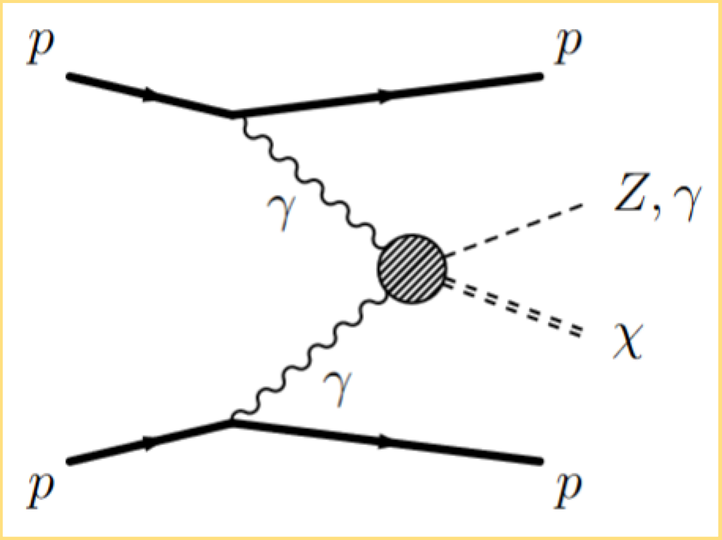
CMS-PAS-EXO-21-007
CERN-TOTEM-NOTE-2022-005

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 $\boldsymbol{Z}$ 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)



EPJC 83 827 (2023)

Searching for missing mass with Z/γ

Event selection

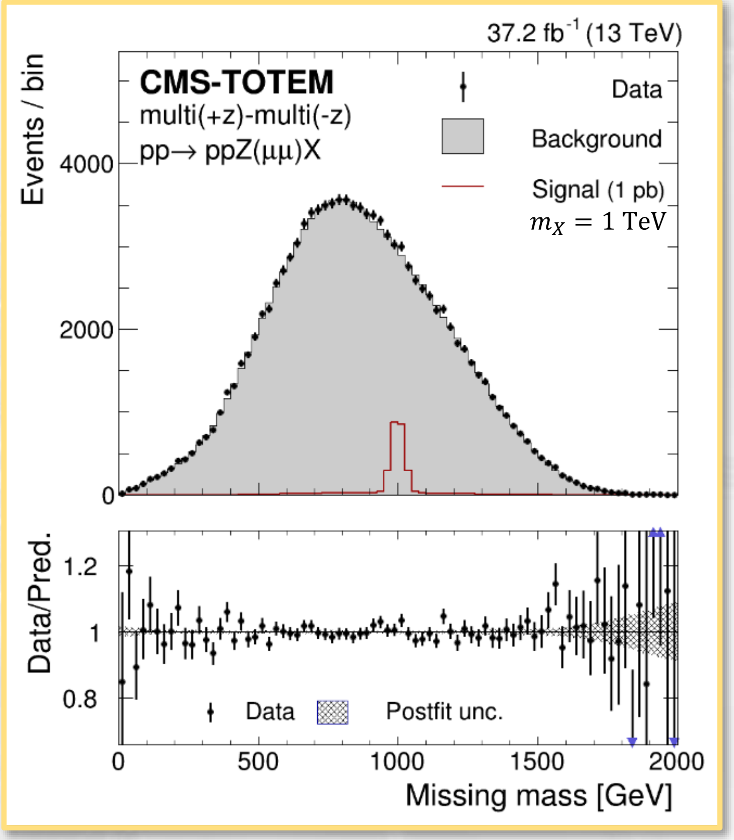
$Z \to e^+e^- / Z \to \mu^+\mu^-$

$\geq$ 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)

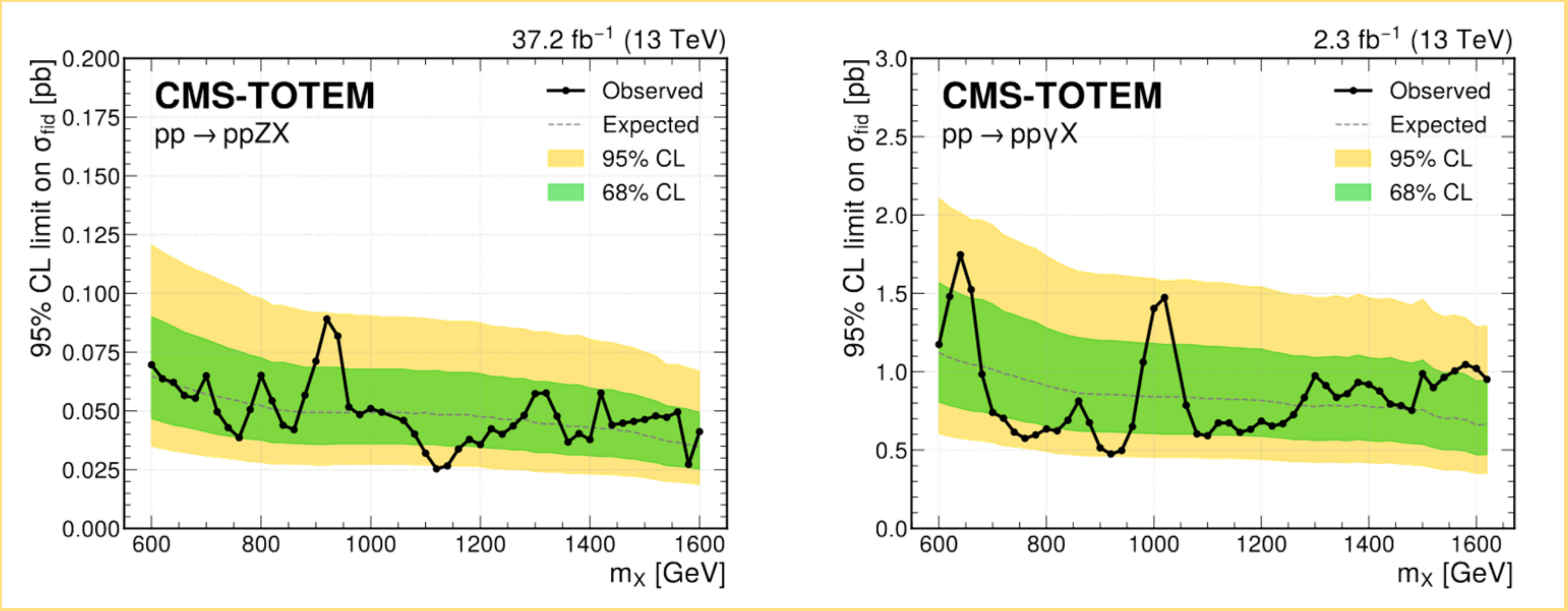
$\geq$ 1 proton per side of PPS



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

EPJC 83 827 (2023)

Searching for missing mass with Z/γ

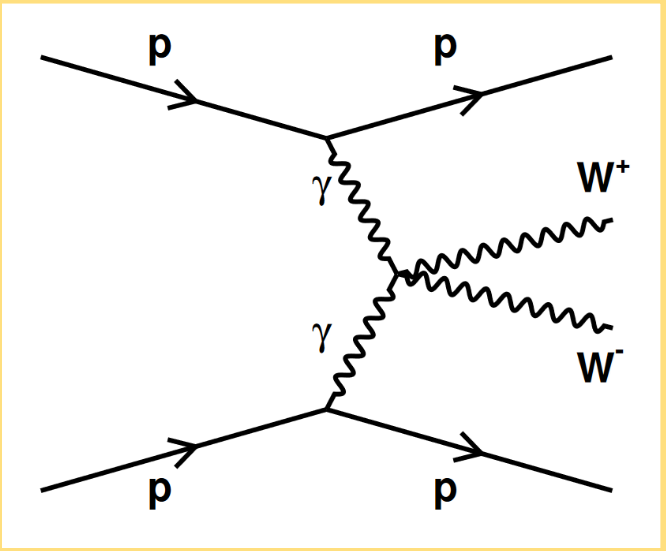


- Bump search over missing mass spectrum
  - No major local excess/deficit observed
- Setting 95% CL on fiducial cross section as a function of m_X

EPJC 83 827 (2023)

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

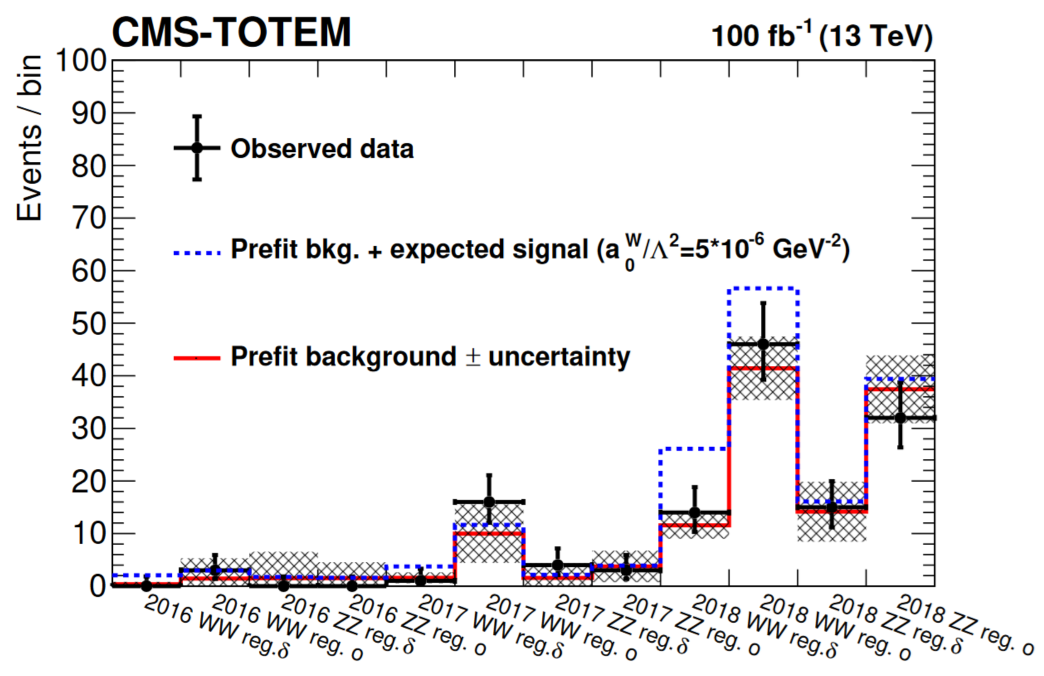
- Search for anomalous WW/ZZ (VV) exclusive production at high mass:
  - Exploring the hadronic decay channel (each V decaying into a boosted and merged jet)
  - Require intact protons on both sides
  - Look for non-resonant enhancements over high-mass tails (AQGC/EFT)
- SM production:
  - ZZ not allowed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



JHEP07(2023)229

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

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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:
  - Mass match ratio
  - Rapidity difference
- Two signal regions:
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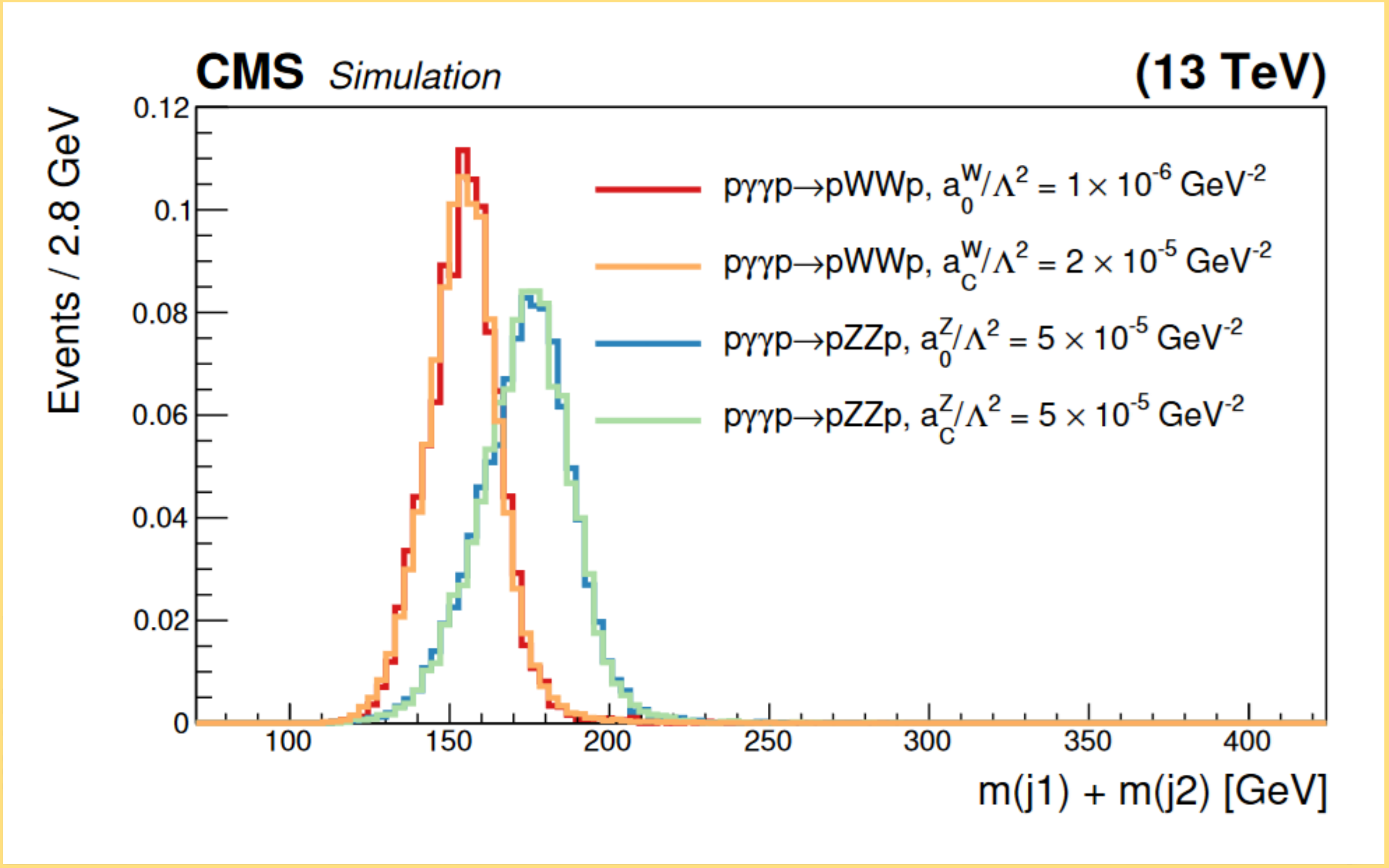

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- ≥ 1 proton per side of PPS

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

- Full Run 2 dataset, 100 fb^{-1} ... set, ... rat ... $_2)$

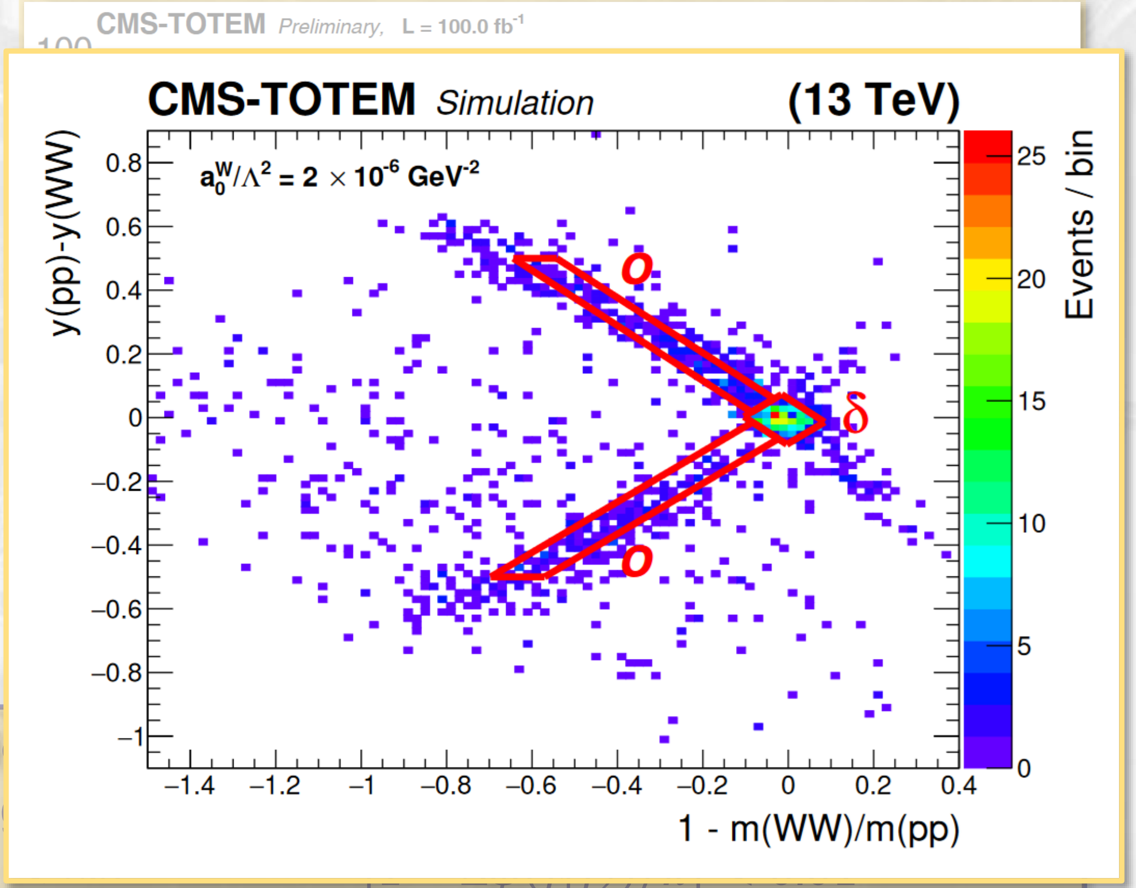
$|y(PP) - y(VV)|$

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

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

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

- 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:
  - QCD di-jet production combined with pileup protons
  - Data-driven estimation with 'ABCD' method (sidebands)



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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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
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- Two signal regions:
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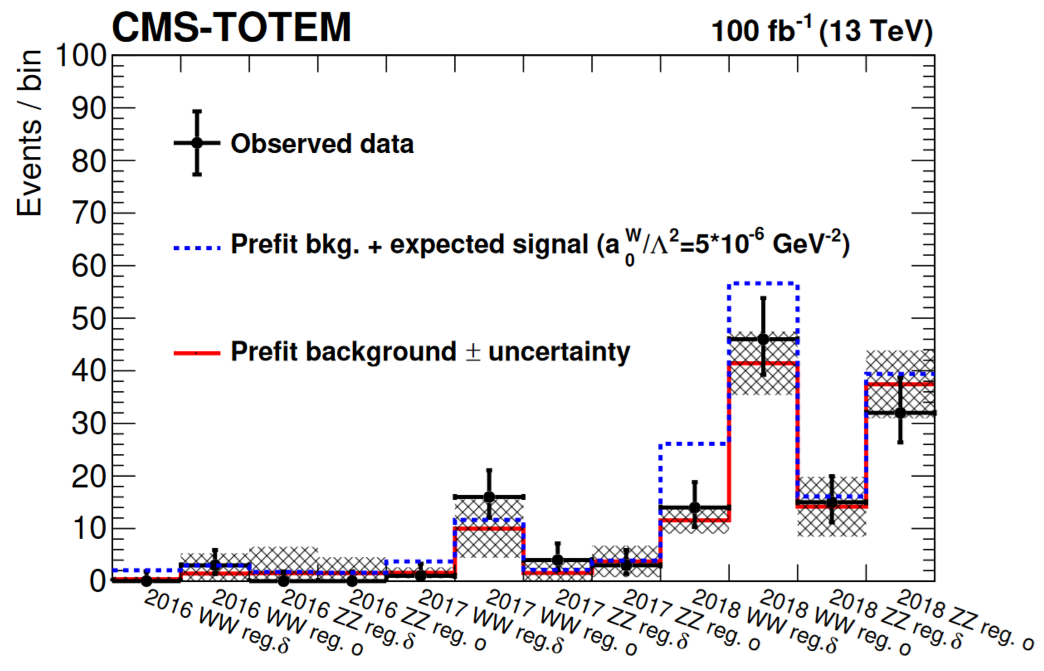

Event selection:

- ≥ 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 GeV $< m(j_1 j_2) < 2500$ GeV
- ≥ 1 proton per side of PPS

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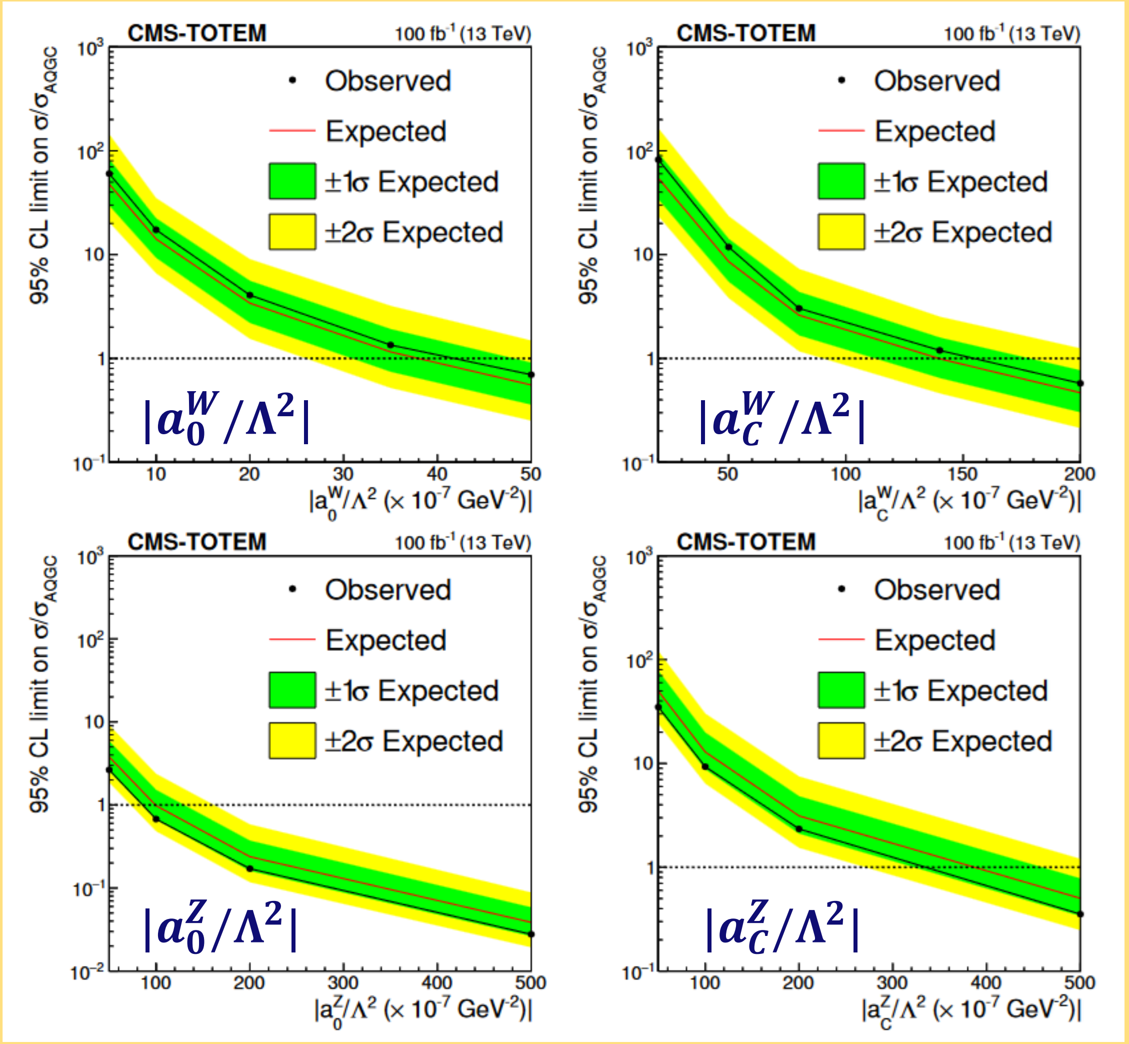
Anomalous $\gamma\gamma \rightarrow VV$ into hadrons

- 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 $\boldsymbol{\gamma\gamma \rightarrow ZZ}$
- Fiducial cross section limits:

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

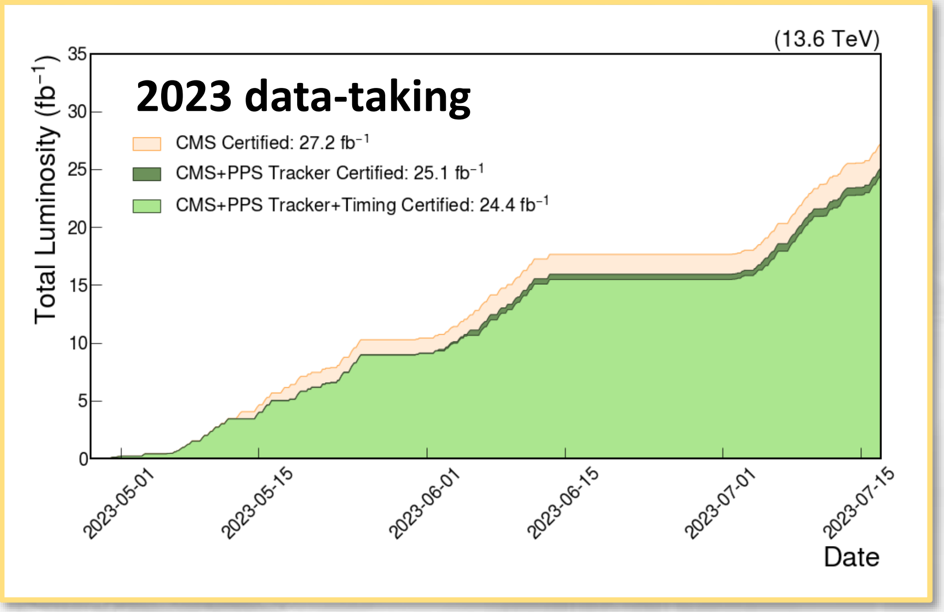


JHEP07(2023)229

PPS in Run 3: status

Run 3 is ongoing:

- We are taking data with CMS!
- Performance results are coming: stay tuned!



Highlights:

- Updated tracking detectors:
  - 150 μm-thick silicon 3D pixel sensors + PROC600 (CMS Pixel Layer 1)
  - Vertical movement system to better sustain radiation damage
- One additional timing station:
  - All stations equipped with scCVD double-diamond sensors
  - Revised electronics for improved timing resolution

PPS2 at HL-LHC formally approved by the CERN Research Board

After approval by CMS Collaboration Board and HL-LHC Executive Committee

APPROVED

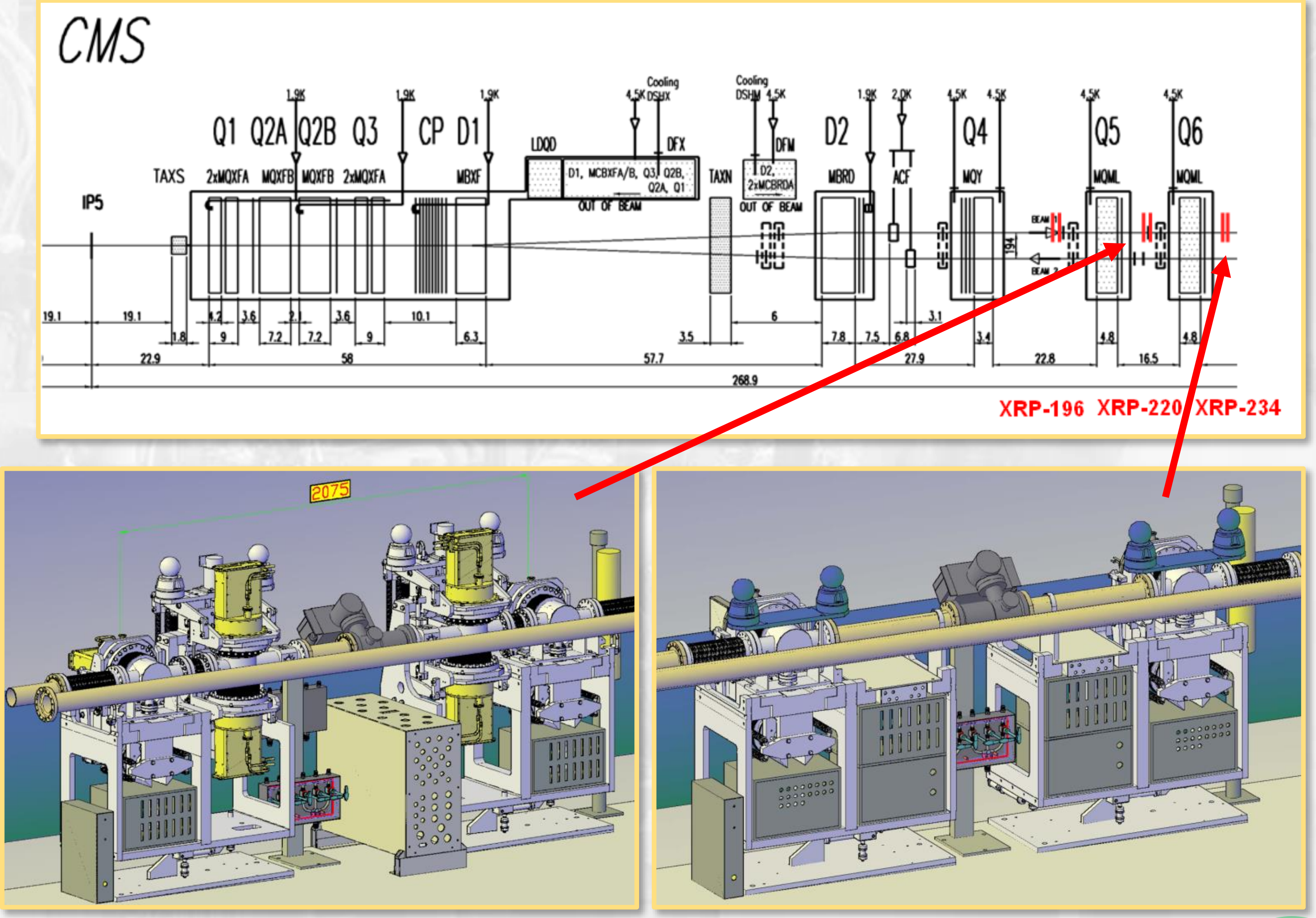
PPS2@HL-LHC: experimental setup

PPS2 setup (per CMS side)

- Re-use Run3 RP mechanics
- Choose best RP locations to exploit the new optics at HL-LHC
- 3 stations: 196, 220, 234 m
  - 2 horizontal RPs per station for data-taking
    - Tracking and timing
  - 2 vertical RP pairs at 220 m for alignment

Engineering Change Request prepared in Summer 2023

- Technical review ongoing



PPS2@HL-LHC: features

Higher integrated luminosity

- Current results using PPS are based on $\lesssim$100 fb^{-1} of Run 2 data
- Most results will remain statistically limited even with Run 3 data

Larger central system mass acceptance range

- Current PPS double-arm acceptance: ~350 GeV – 2 TeV
- HL-LHC will add acceptance up to 4 TeV
- With vertical crossing angles (Run 4), reach lower masses ~200 GeV

PPS2@HL-LHC: acceptance

Geometrical acceptance using the latest HL-LHC optics and leveling scenarios

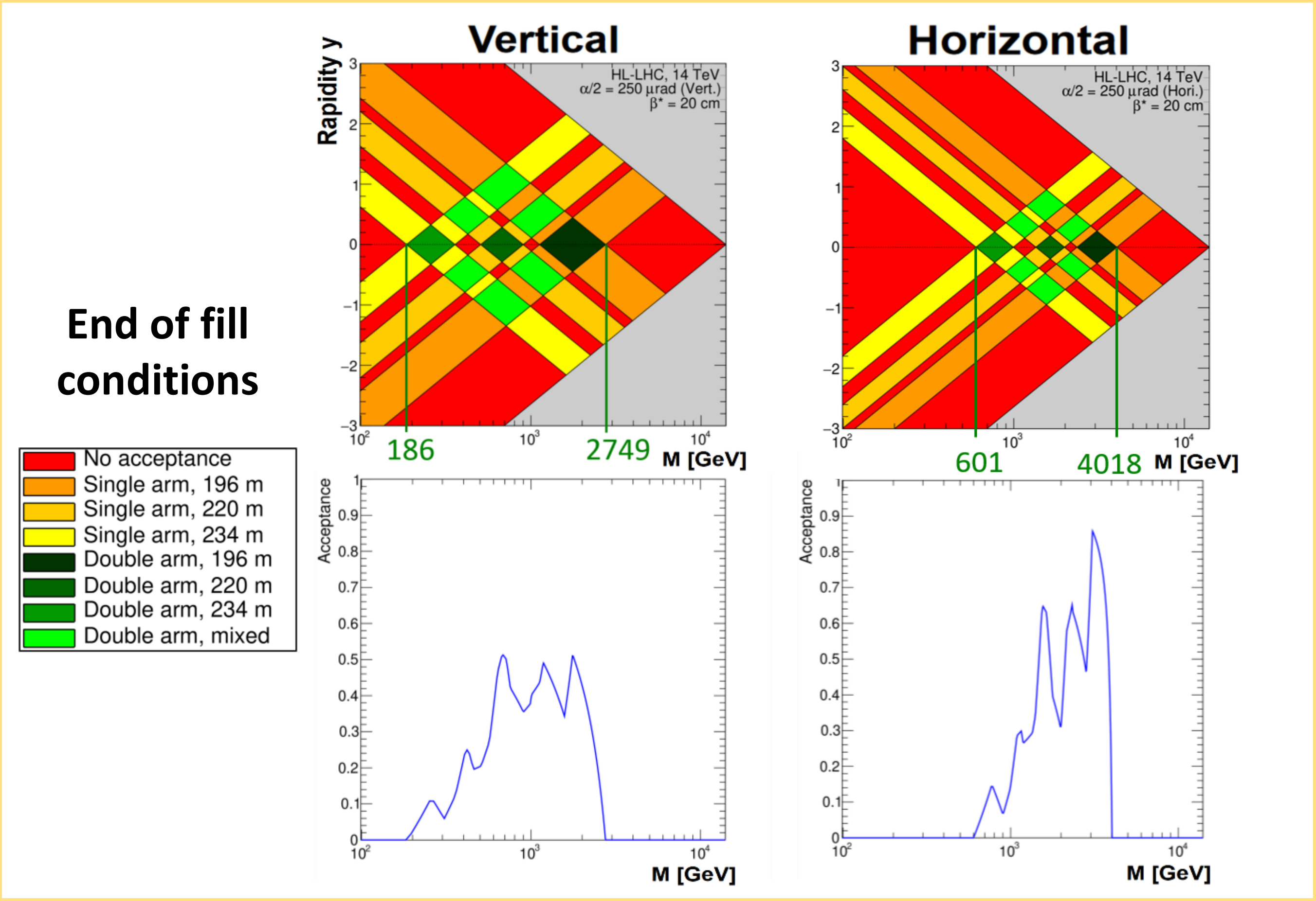
Acceptance values change during the fill because of the β^*/ crossing angle levelling

- Also depends on the crossing plane (ver./hor.)

Upper: mass and rapidity acceptance

- **Green diamonds:** kinematic regions with protons in acceptance for more than one RP

Lower: acceptance vs. mass



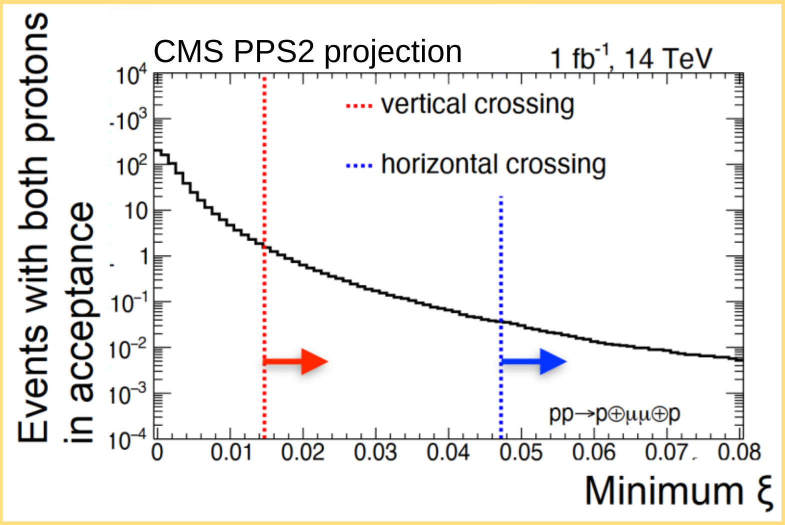
PPS2@HL-LHC: physics potential

PPS2 is an extraordinary opportunity at HL-LHC for CMS:
- No other equivalent detector (e.g. AFP) will be present
- Provides a unique extension to the CMS VBS/VBF physics program

Main reasons why PPS2 was approved!

Acceptance at low mass:
→ essential for SM measurements and spectrometer calibration
- Highly dependent on the minimum ξ selection

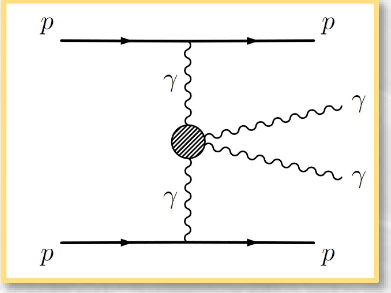
- Many CEP channels to be studied:
  - QCD physics: $pp \rightarrow p + jj + p$
  - EWK physics: $pp \rightarrow p + WW/\ell^+\ell^- + p$
  - Top physics: $pp \rightarrow p + t\bar{t} + p$
  - Higgs physics: $pp \rightarrow p + HWW + p$

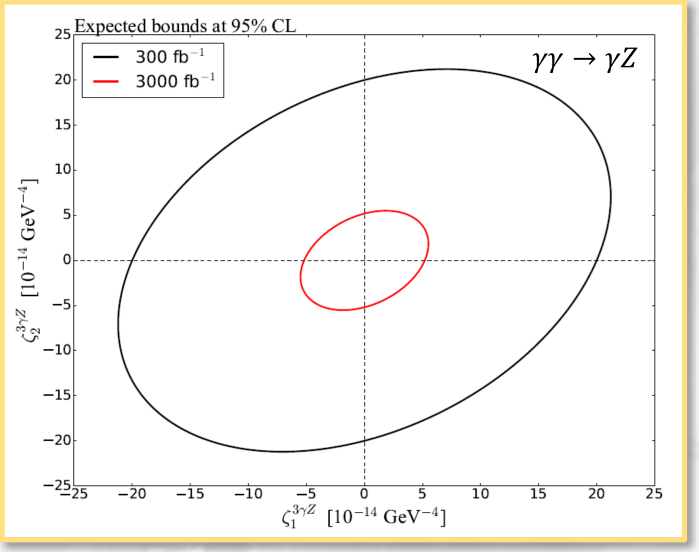


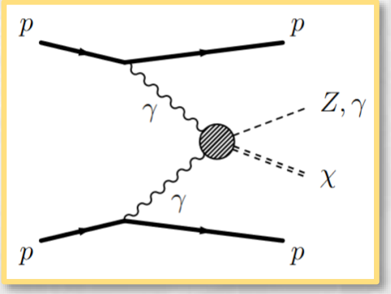
PPS2@HL-LHC: physics potential

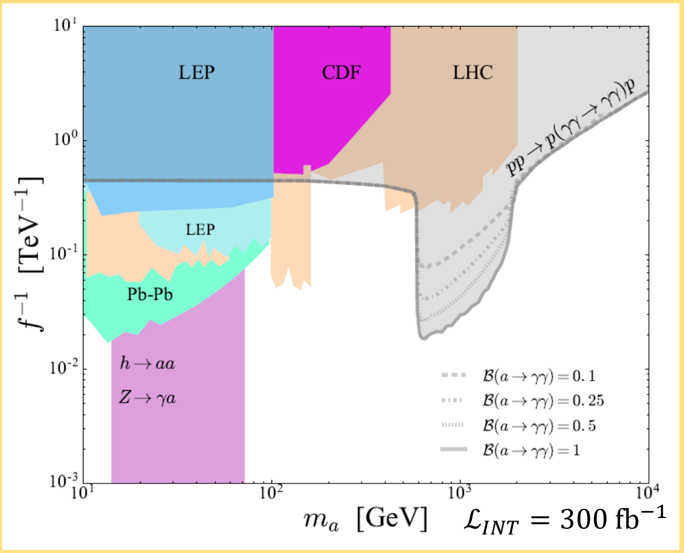
Acceptance at high mass

- Key for BSM searches
- Indirect searches:
  - $\gamma\gamma \to \gamma\gamma, \gamma\gamma \to WW, \gamma\gamma \to ZZ, \gamma\gamma \to \gamma Z$
  - Look for enhancements at high mass (AQGC)
- Direct searches:
  - Very good sensitivity to ALPs ($\gamma\gamma \to X \to \gamma\gamma$)
  - Search for invisible particles via the so-called '**missing mass technique**'









Summary

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

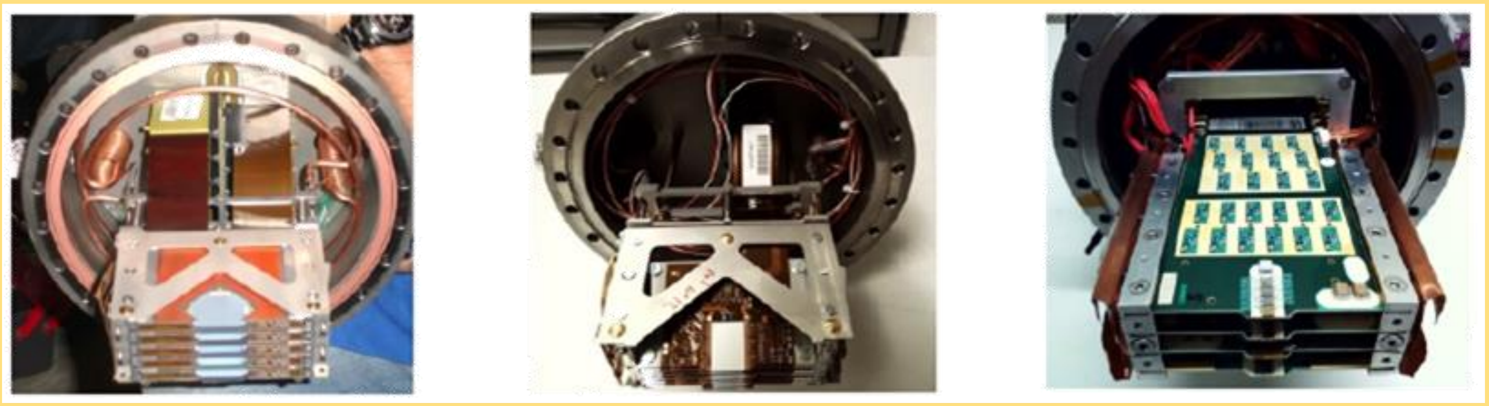
Looking forward:

- PPS is taking Run 3 data, stay tuned!
- PPS will take part in HL-LHC
  - A lot of physics potential to exploit
  - A unique opportunity at HL-LHC!

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