PPS program at CMS: status/prospects

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on behalf of the CMS and TOTEM Collaborations

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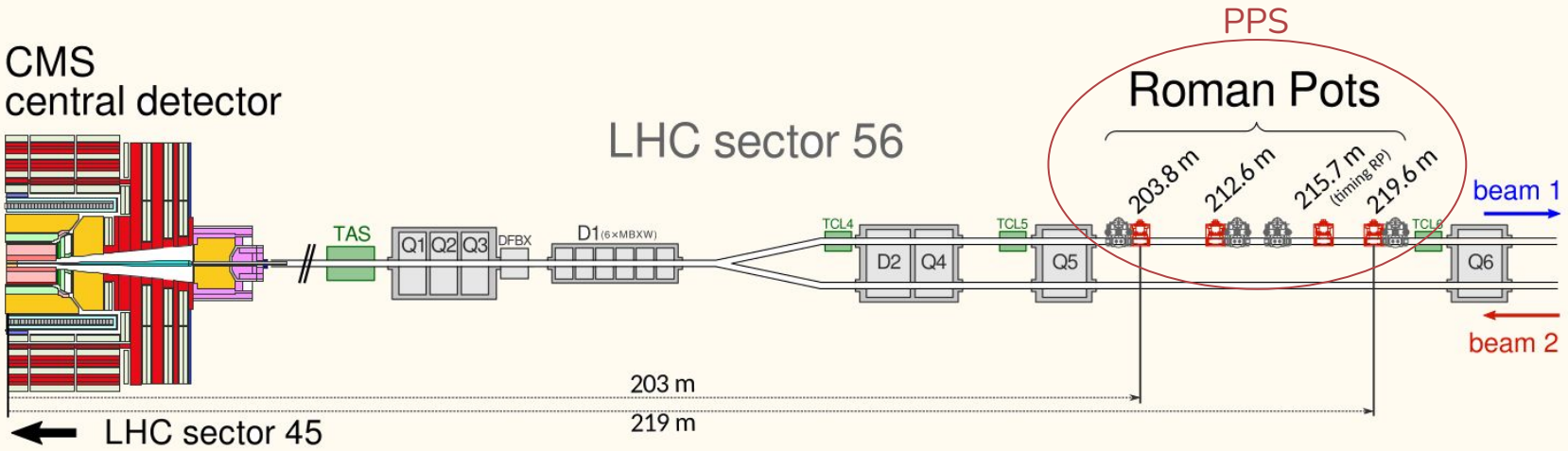
PPS

- Precision Proton Spectrometer (PPS): a CMS subdetector
- **Extends forward coverage of CMS** to outgoing protons scattered at small angles
- Commissioned in Run 2, ~130 fb^{-1} of data collected during regular, high lumi LHC runs
- ***The main measured variable is ξ -- fractional momentum loss of forward proton***



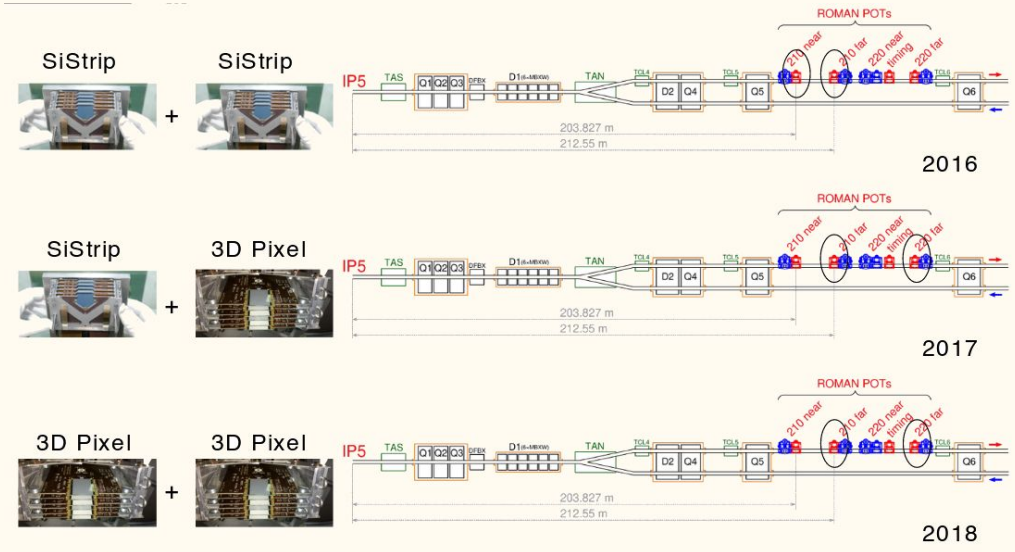
Detectors placed inside movable beam pipe insertions (Roman pots, RP), which approach the beam down to a few mm. Two tracking, one timing station per arm.

PPS detectors in Run 2

Reconstruction combining two tracking stations per arm: better resolution, more complete kinematics reconstruction

- 2016, 2017: Si strip detectors cannot resolve multiple tracks
- 2018+: upgrade with two pixel detectors allowed multitracking

Timing: diamond sensors

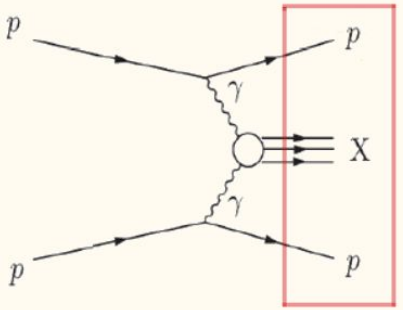


Timing: Diamonds in 2017-2018

different detector configurations each year!

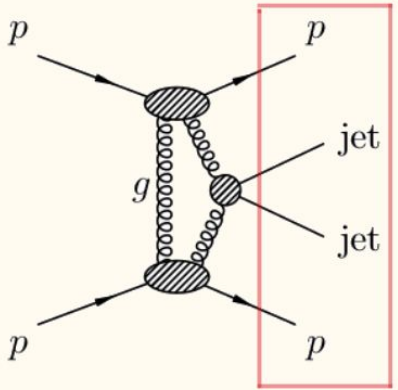
Physics with PPS

Primary goal: study central exclusive production in γγ or gg collisions



Proton tag advantages:

- **closure of event kinematics** (full center of mass energy reconstructed)
- effective background rejection
- reduced theory uncertainties related to proton dissociation



Opportunity to access a variety of topics: from diffraction to BSM physics

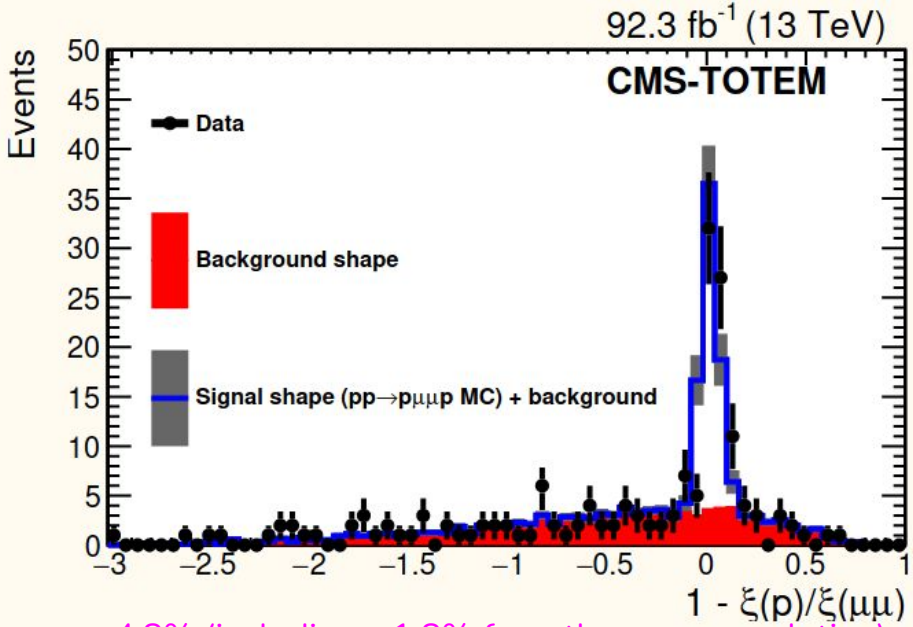
- anomalous couplings with high sensitivity
- new resonances in very clean final state
- rare SM processes

Resolution in data

JINST 18 (2023) P09009
arXiv:2210.05854

Multi-RP ξ resolution

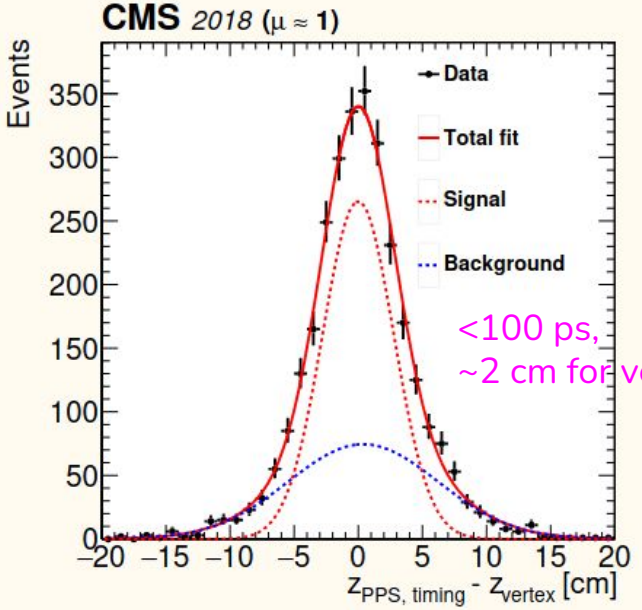
- Exclusive dimuon events sample, comparing ξ(PPS) to $\xi(\mu^+\mu^-) = \frac{1}{\sqrt{s}}\left[p_T(\mu^+)e^{\pm\eta(\mu^+)} + p_T(\mu^-)e^{\pm\eta(\mu^-)}\right]$



~ 4.8% (including ~ 1.8% from the muon resolution)

Timing resolution

- CMS vertex Z vs $z_{\mathrm{PPS,timing}} = \Delta t_{\mathrm{PPS}} \times \frac{c}{2}$
- Events with pileup ~1
- Double proton tagged (i.e. both PPS arms)



<100 ps,
~2 cm for vertex Z

arXiv:submit/516747
Submitted to JHEP

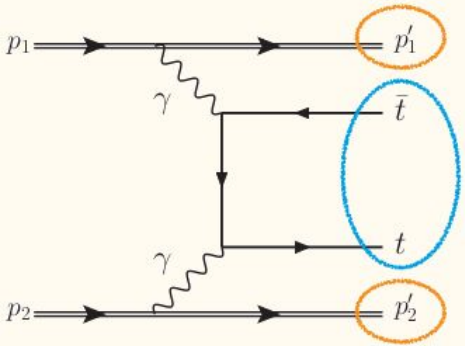
Exclusive top quark pairs

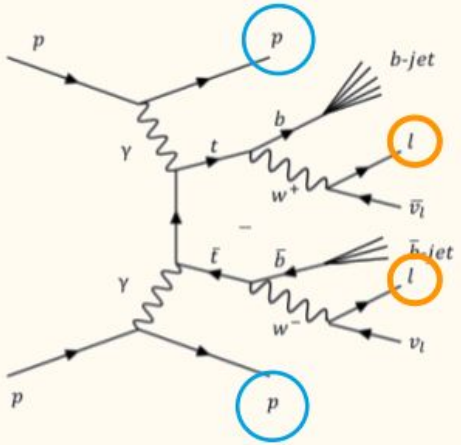
Production of top quark-antiquark pairs in pp scattering via the exchange of colourless particles, such as photons or pomerons

Predicted to occur at LHC with very low cross-section, which also suffers from substantial uncertainties; usually in the O(0.1 fb) range

Motivation:

- Sensitive to electroweak top-photon coupling
- **First-ever search for this process**

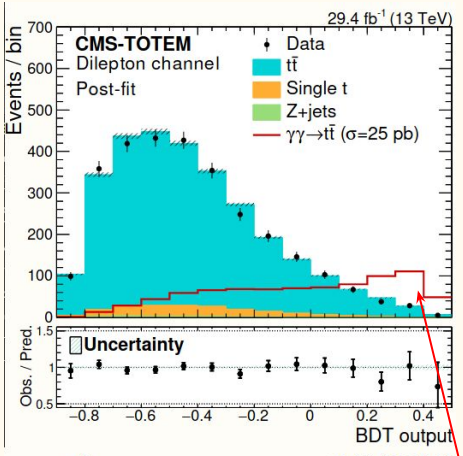




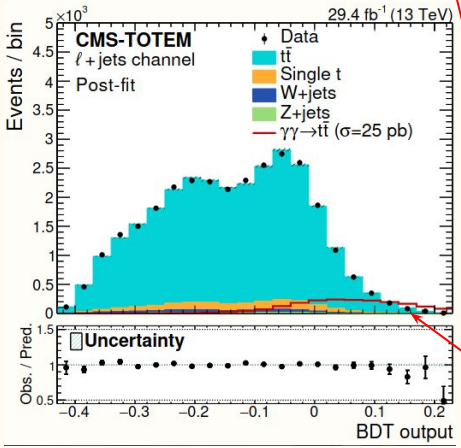
Results

arXiv:submit/516747
Submitted to JHEP

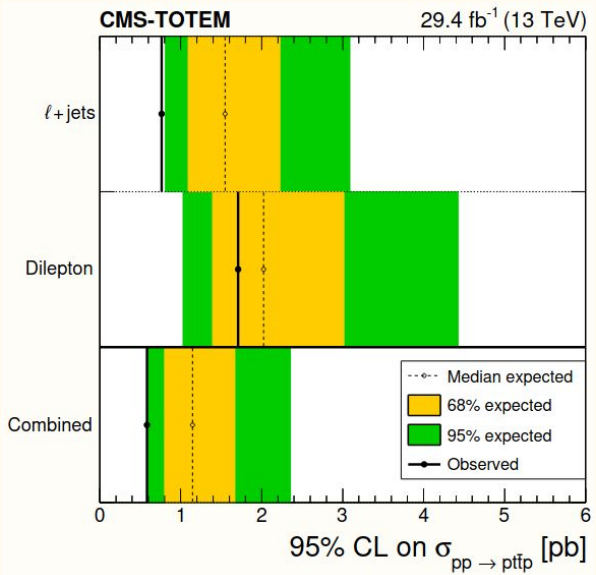
l+jets channel



Dilepton channel



Signal rescaled ~x10^5 SM prediction



First ever upper limit on production cross-section of exclusive tt̄, in the single lepton and dilepton channels:

Observed combined limit

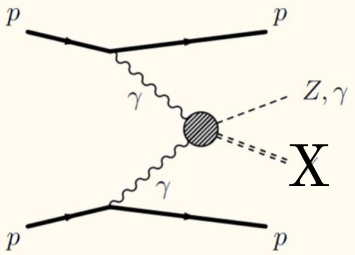
0.59 pb

Expected: 1.14 pb $^{+1.2}_{-0.6}$ at 95% CL

EPJC 83 (2023) 827
arXiv:2303.04596

Anomalous exclusive Z/γ + X

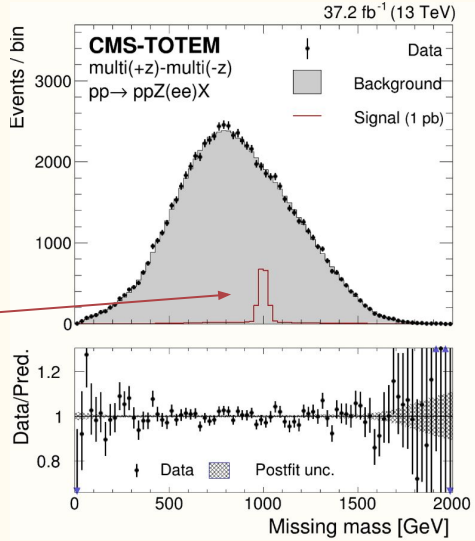
A generic search for production of a Z boson or a photon with an additional unspecified massive particle X in proton-tagged events



Main variable of interest is the so-called missing mass – first use of this technique at the LHC

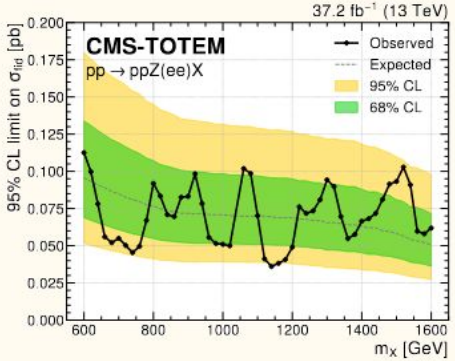
Motivation:

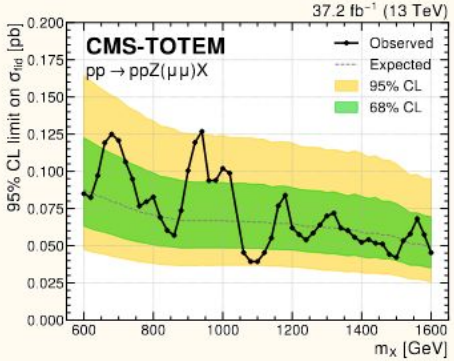
- Excellent (percent level) proton momentum reconstruction of PPS allows to search for missing mass signatures at high invariant mass
- EWK processes are enhanced relative to QCD-induced processes => look for weakly interacting BSM particle
- Relatively unknown region (600-1600 GeV) covered

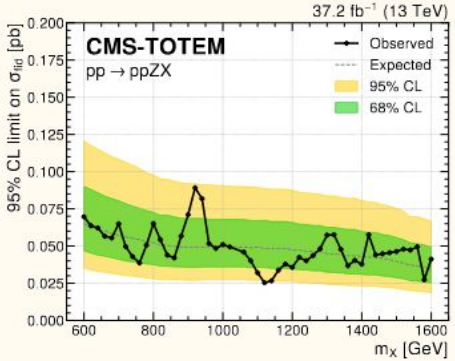


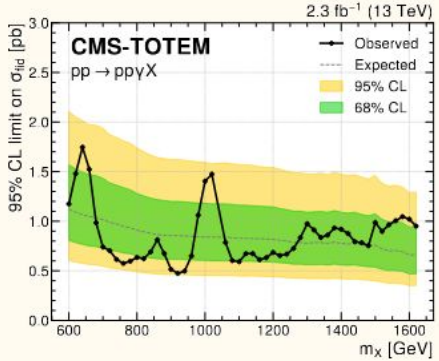
EPJC 83 (2023) 827
arXiv:2303.04596

Results







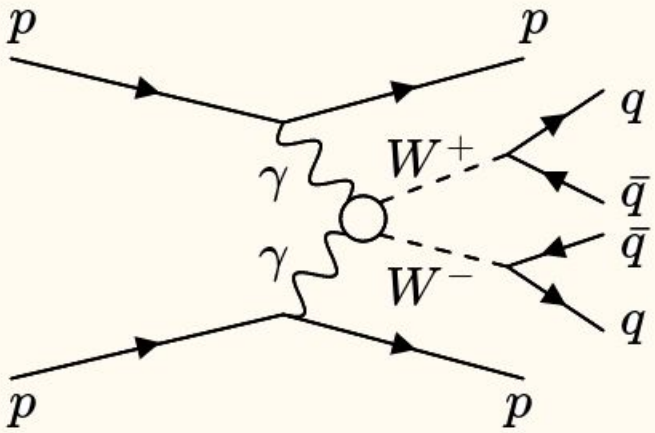


- No major local excess/deficit observed
- The new missing mass technique can be applied to other signatures

JHEP 07 (2023) 229
arXiv:2211.16320

Exclusive hadronic γγ → VV

Search for high-mass exclusive γγ→WW and γγ→ZZ with both V's decaying to boosted/merged quark jets and both protons remaining intact



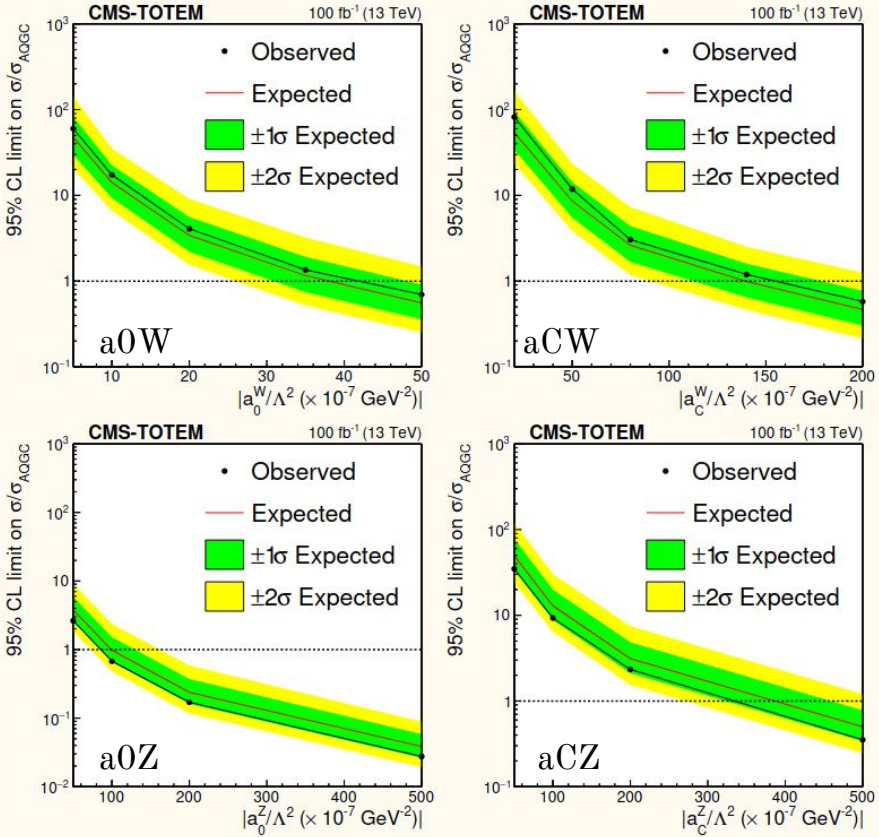
Due to extremely high inclusive QCD background, process can be accessed only with proton tagging

Physics goals:

- Probing gamma-gamma collisions at hadron collider
- **Search for non-resonant enhancements over the SM in high mass tails** (AQGC/EFT)
- SM production for WW allowed (ZZ ~ 0), but with the Run 2 HLT jet thresholds we have no sensitivity to it in the hadronic channel – PPS trigger for SM ready for Run 3

Results

JHEP 07 (2023) 229
arXiv:2211.16320



- No significant excess over the SM
- LEP-style **Dim-6 γγWW AQGC limits ~15 – 20x more stringent** than the unitarized limits obtained from the γγ → WW without proton tag in Run 1
- **Dim-8 limits close to CMS same-sign WW and WZ** scattering analyses at 13 TeV after unitarization
- **First γγZZ limits through the exclusive γγ → ZZ**
- New **limits on the fiducial cross section** for TeV-scale

Fiducial cross section limits:

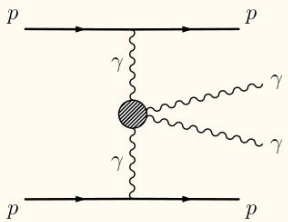
$$\sigma(pp \to pWWp)_{0.04<\xi<0.20, m>1000\ \text{GeV}} < 67(53^{+34}_{-19})\ \text{fb}$$

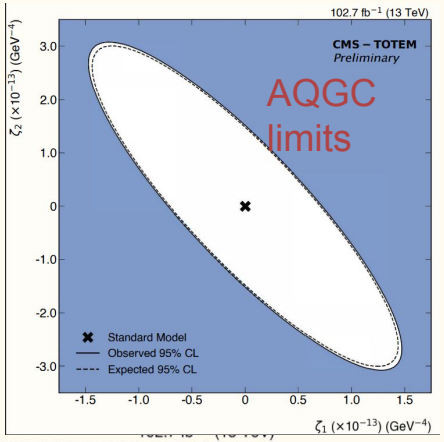
$$\sigma(pp \to pZZp)_{0.04<\xi<0.20, m>1000\ \text{GeV}} < 43(62^{+33}_{-20})\ \text{fb}$$

Exclusive γγ production

arXiv:2110.05916
Phys.Rev.Lett. 129 (2022)
CMS-PAS-EXO-21-007

Search for exclusive two-photon production via photon exchange in proton-proton collisions





Diphoton invariant mass above 350 GeV

Matching mass and rapidity between pp and γγ

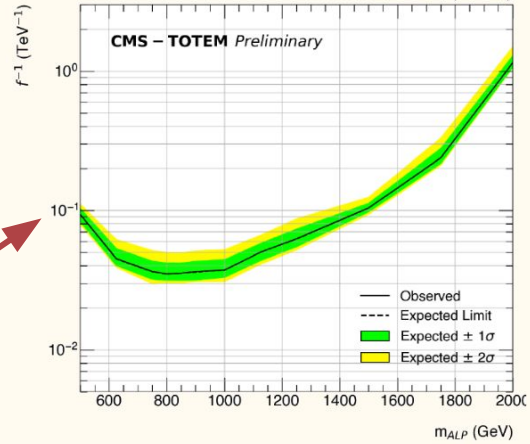
Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, axion-like particles

Main results:

- **New limits** on anomalous couplings for the four-photon interaction (updating Phys. Rev. Lett. 129 (2022))

$$|\zeta_1| < 7.3(7.1) \times 10^{-14}\ \text{GeV}^{-4} \quad (\zeta_2 = 0),$$
$$|\zeta_2| < 1.5(1.5) \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_1 = 0).$$

- **First limits on axion-like particles at high mass**



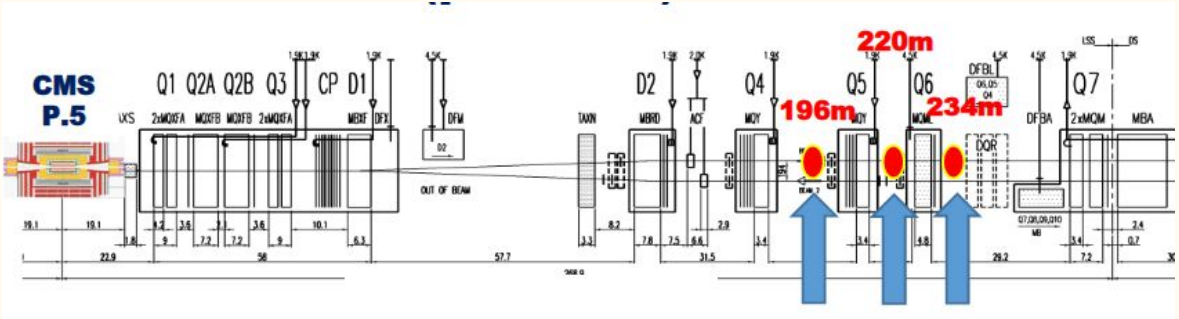
Run 3 and HL-LHC

- **Run 3** data-taking is **in progress**, possibility to double the Run 2 lumi
- With Run 3 data, expect almost all results to be limited by statistical uncertainties and/or upper limits on BSM processes

- The High Luminosity LHC: **more lumi (~3000/fb goal), higher energy range**
- **PPS2 for HL-LHC approved** by the CMS Collaboration Board and CERN
- Expression of interest published arXiv:2103.02752
- **Design and construction ramping up**

PPS2 for HL-LHC

- Re-install the PPS Roman Pots at locations 196m, 220m, and 234m from the CMS interaction point

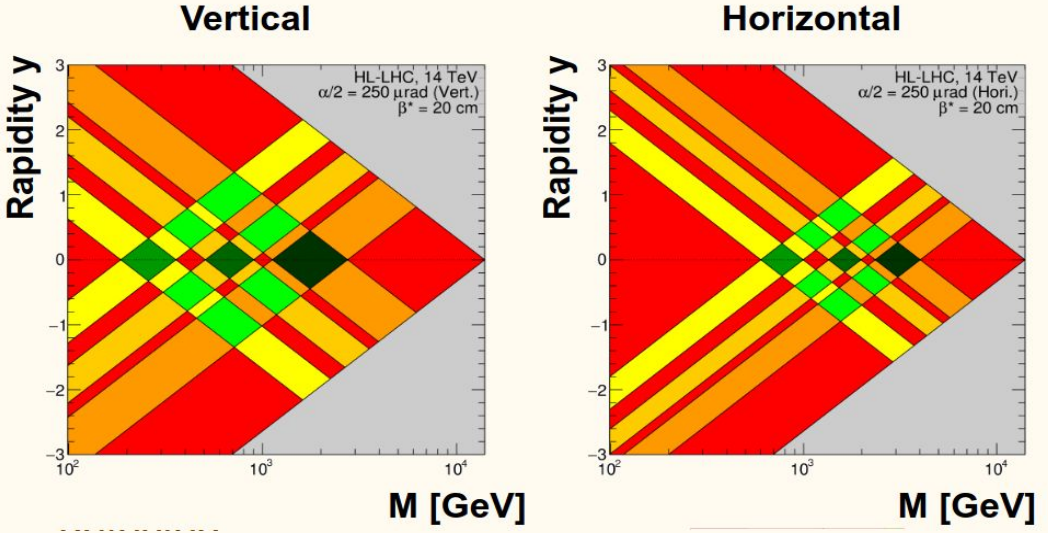


- Challenges: impedance heating, order of magnitude higher pileup (μ up to 200), new emittance profile with thinner beams, increased showers
- => upgrade 3D pixel sensors for tracking, new Low Gain Avalanche Detectors for timing
- The only forward proton detector @ HL-LHC

PPS2 mass and rapidity acceptance

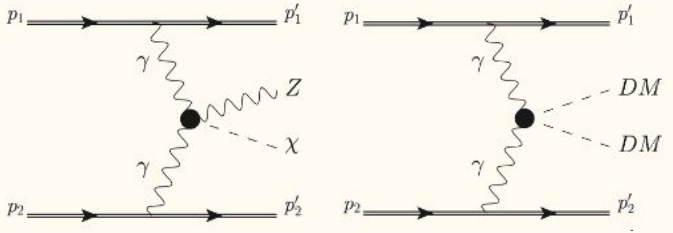
Assuming the latest HL-LHC optics and lumi levelling scenarios; precise values will slightly change during fill, from year to year etc

Currently expect vertical crossing angle in P5 for Run 4.



- Green diamonds: values of mass and rapidity of "X" (in pp→pXp events) where both protons can be detected
- Yellow/orange bands are regions where 1 of the 2 protons can be detected: extends acceptance to much lower masses

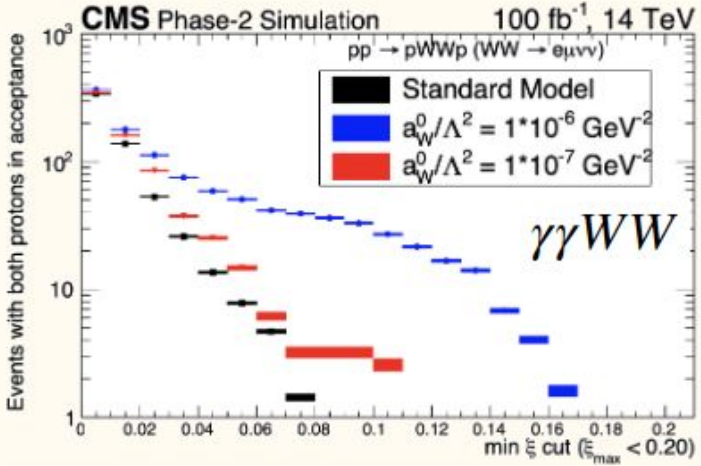
BSM searches



If BSM physics is below a few TeV, new particles could be directly produced with protons in PPS2

For “X” in pp→pXp events with both protons detected:
m(X) ~ 200-2800 GeV for vertical crossing

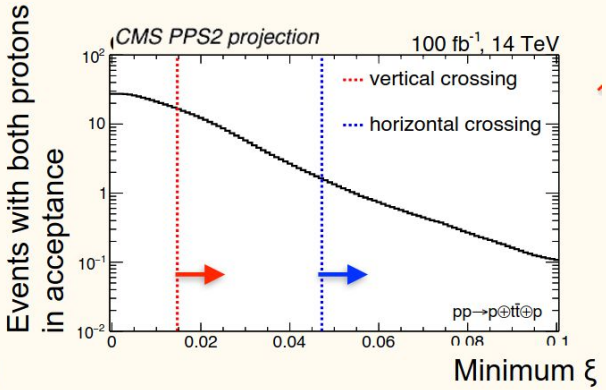
- s-channel resonances
- axion-like particles in γγ→a→γγ
- “missing mass” searches - new particles that do not leave any signature in the central detector
- γγ→γX, γγ→ZX, γγ→XX
- pair production: slepton/chargino, doubly charged particles, magnetic monopoles



Strong complementarity to indirect searches: CMS upgrades in the forward region (HGCAL, etc.) help turn CMS in to a “W/Z collider”, where VBS/VBF events are tagged by forward jets.
PPS2 adds a “γγ collider” mode, where VBS/VBF events are tagged by forward protons

SM searches

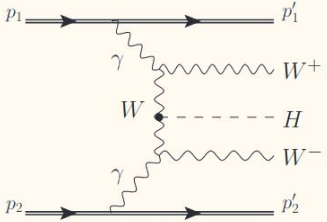
- Example of γγ->ttbar: large/steeply falling cross-section

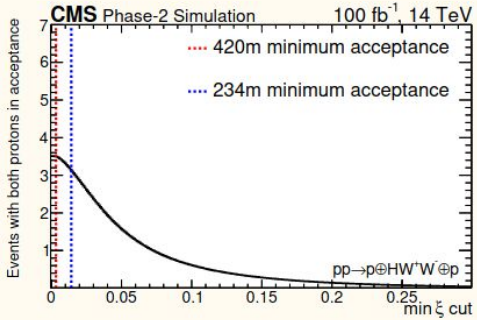


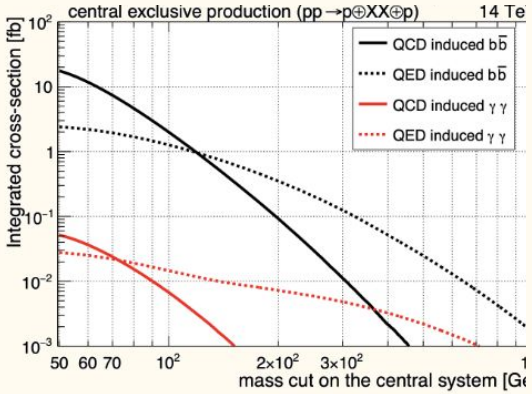
Two-arm fiducial cross sections		
Process	**Vertical crossing**	**Horizontal crossing**
γγ→μμ	1.6 fb	0.04 fb
Dijets	2.3 fb	0.06 fb
γγ→WW	27 fb	4.1 fb
γγ→$t\bar{t}$	0.18 fb	0.02 fb

- Dijet production provides information for theoretical modeling of survival factors (3% for IP, 90% for γγ).

- HW+W-: potential for probing the Higgs sector in central exclusive production







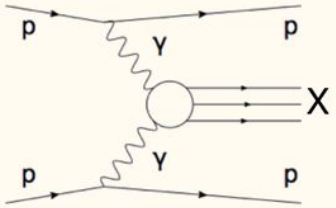
Summary

- PPS brought **proton tagging to regular, high-luminosity LHC runs**
- **New results in several domains of particle physics**: possibility of studying processes otherwise beyond reach and employ new analysis strategies

Future:

- Analysis of Run 2 data continues; Run 3 data-taking ongoing
- **PPS2 for HL-LHC: design and construction ramping up**
- **New collaborators very welcome: if interested get in touch!**

Kinematics matching in CEP



Proton kinematics:

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \quad M_X = \sqrt{s\xi_1\xi_2}$$

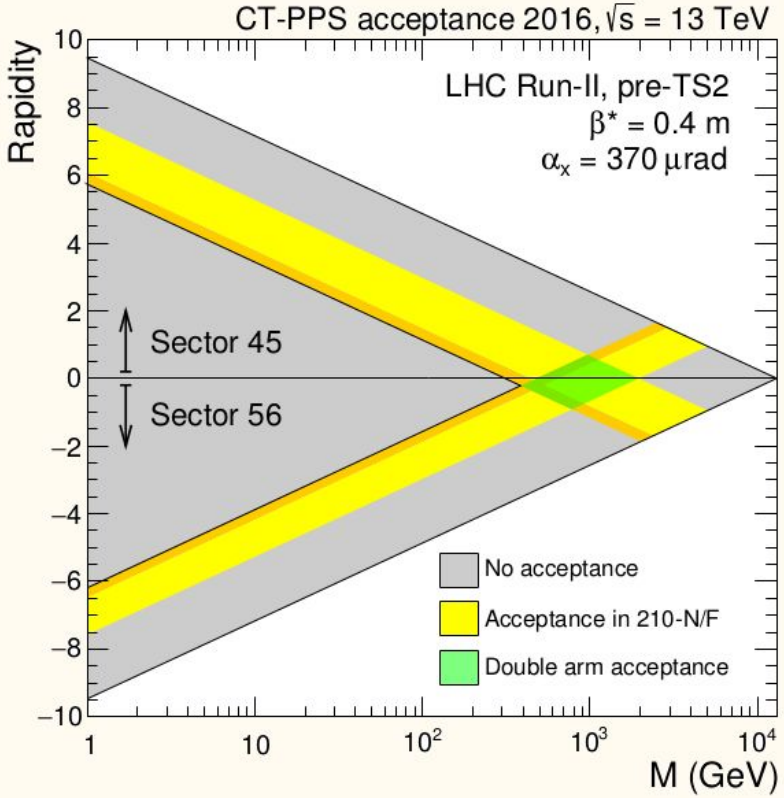
$$t = (p_f - p_i)^2 \quad y_X = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$$

For each event, the value of the fractional momentum loss of the scattered proton can be estimated from the centrally produced dilepton (dijet, VV ...) as:

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

where the two solutions for + and - correspond to the protons moving in the ±z direction. **The formula is exact for exclusive events, but is expected to hold also for the single-dissociation case**; in this case only one of the two possible solutions will correspond to the direction of the intact proton.

PPS acceptance illustration

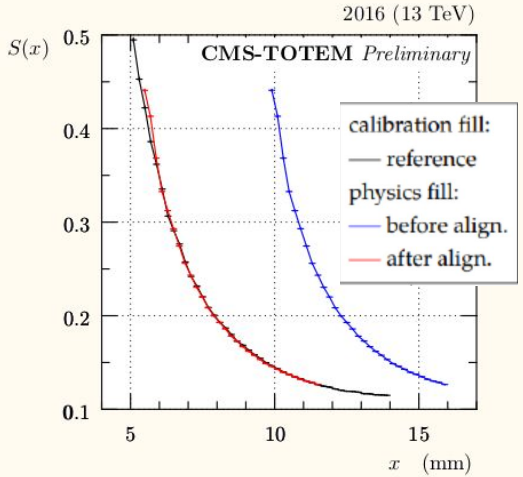


PPS calibration

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

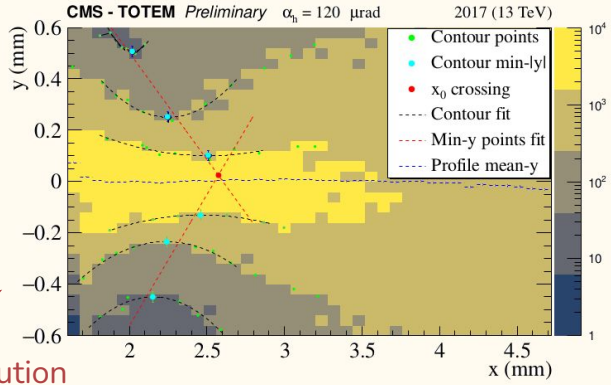
Alignment determines:

- Position of the sensors wrt each other inside a RP
- Relative position of the RPs
- Position of the spectrometer wrt the beam



Optics:

- Reconstruction of ξ from track impact point position x requires precise knowledge of the magnetic fields traversed
- Treat LHC magnets as a ‘system of optical lenses’, known as transport matrix
    - Constraints/calibrations from data features (focal points in proton hit distributions etc)



Proton hit x,y coordinates distribution