Looking forward:
Photon-induced processes with tagged protons at CMS

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on behalf of the CMS and TOTEM Collaborations

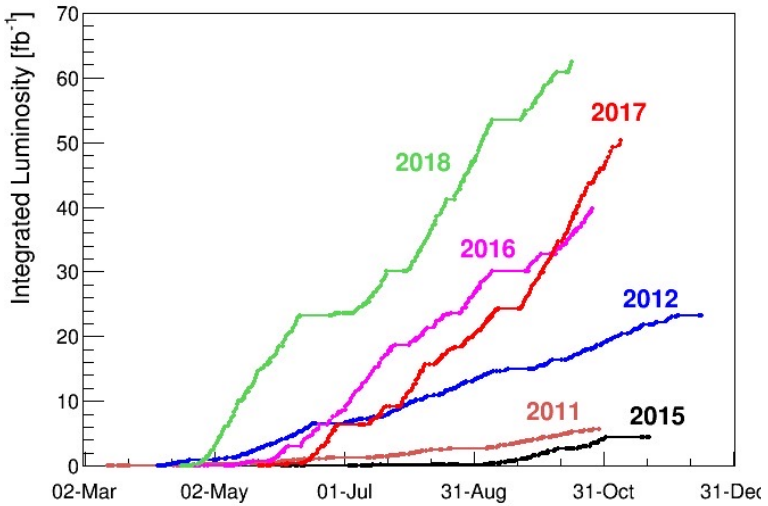
September 28, 2022

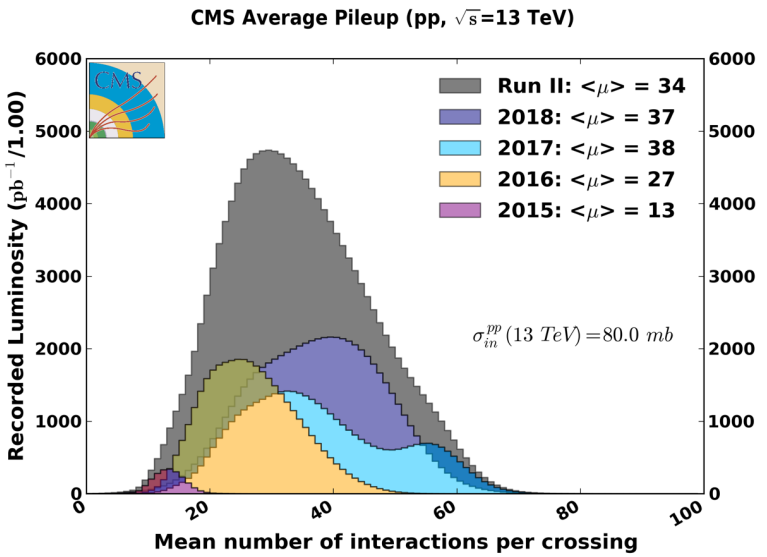
- ✓ Overview
- ✓ Physics motivations
- ✓ Tracking and timing detectors
- ✓ Exclusive dileptons, WW, and prospects
- ✓ Summary

CERN-LHC-2014-021

LHC: from searches to precision

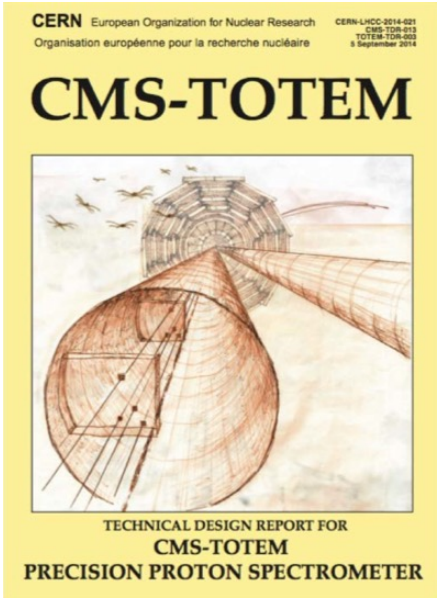
- A hadron collider at full throttle
  - Reaching the energy limit
  - Large datasets
- Moving from searches to precision measurements and rare processes
  - Top quarks and rare decays
  - Higgs couplings and rare decays
  - Anomalous couplings etc.
- Preparing for High-Luminosity (2028 and beyond) with improved detectors
  - Several technological challenges ahead as complexity increases



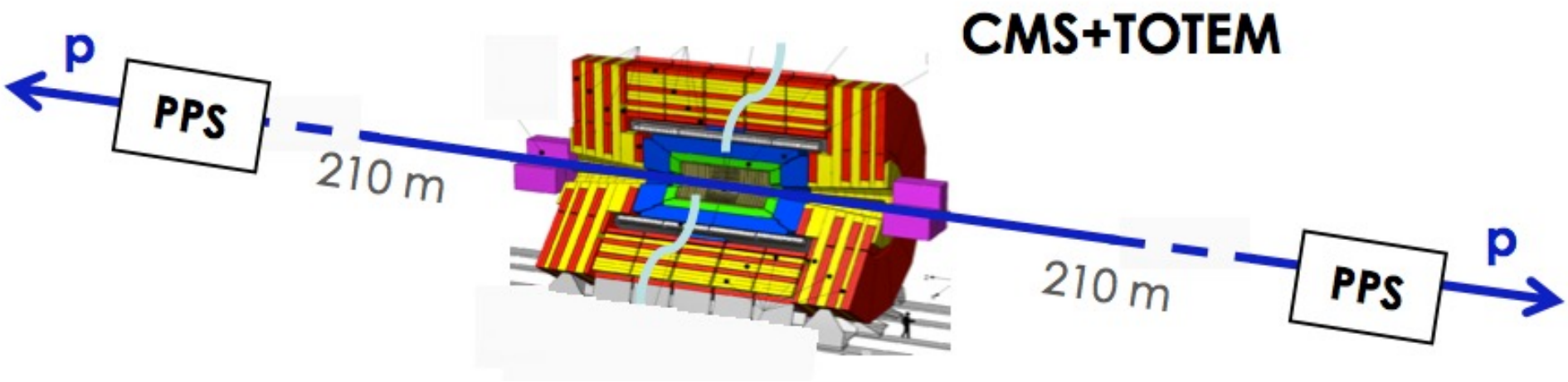


Precision Proton Spectrometer

- It is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Approved (2014), exploratory phase in 2015, data taking started in 2016, pixels installed from 2017, full detectors in 2018

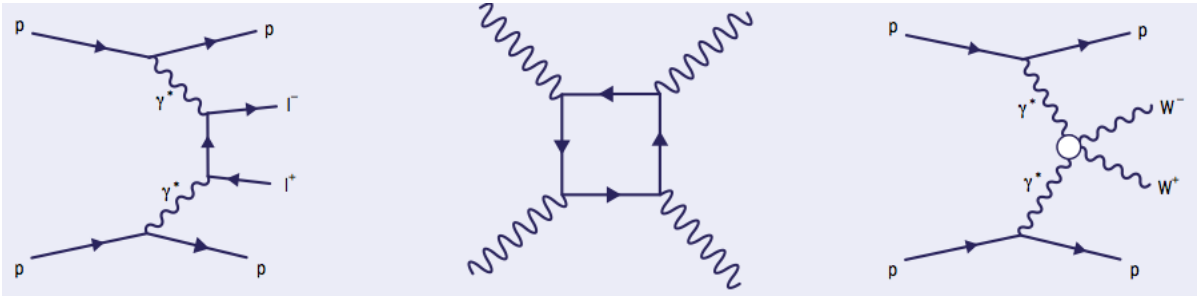


CERN-LHC-2014-021



Physics motivations

- Central Exclusive Production
  - photon-photon collisions
  - gluon-gluon fusion in color singlet, $J^{PC}=0^{++}$
- High-mass system in central detector, together with very forward protons in PPS
  - momentum balance between central system and forward protons, provides strong kinematical constraints
  - Mass of central system measured by momentum loss of the two leading protons
- Gauge boson production by photon-photon fusion and anomalous couplings ($\gamma\gamma WW$, $\gamma\gamma ZZ$, and $\gamma\gamma\gamma\gamma$)
- Search for new BSM resonances
- Study of QCD in a new domain

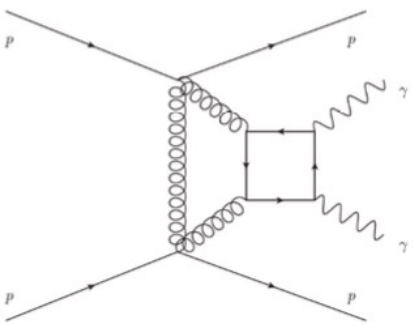


Photon-induced processes

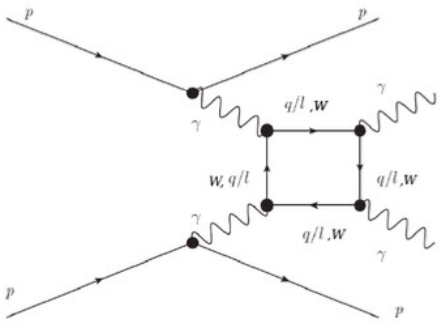
JHEP02(2015)165

Not all exclusive processes are photon-induced (QED)

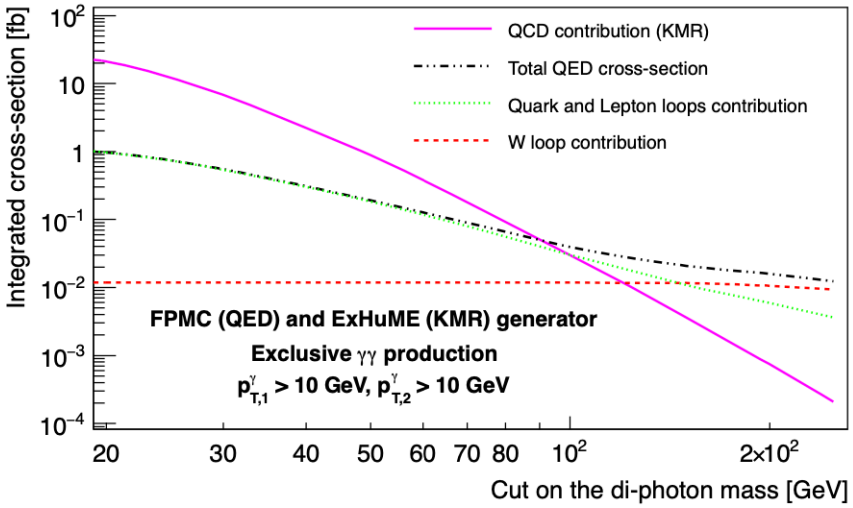
- Exclusive dilepton production a purely QED process
- Exclusive $\gamma\gamma$ is:
  - QCD-dominated at low mass
  - QED-dominated at high mass



QCD

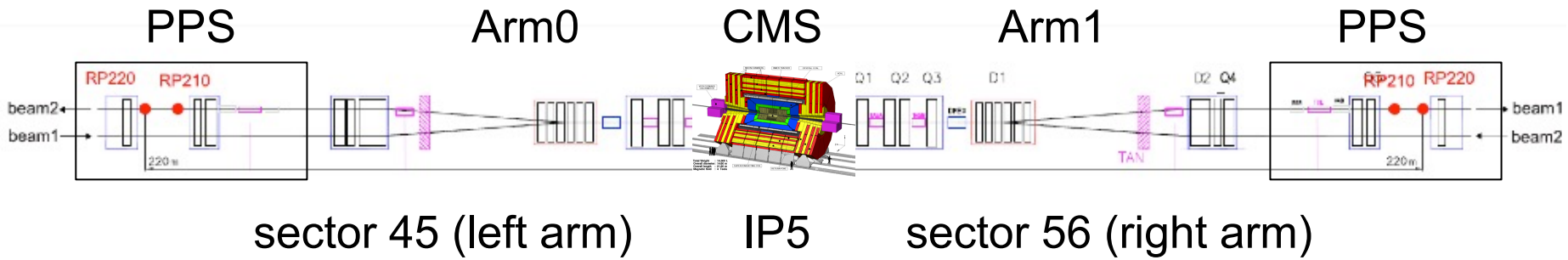


QED



Experimental challenges

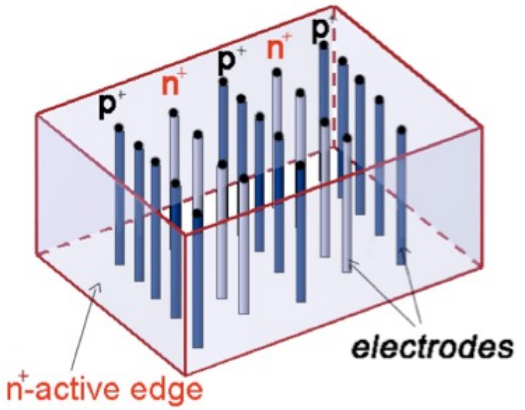
- Ability to operate the detectors close to the beam (15-20σ, i.e. ~1-3 mm) to maximize acceptance for low momentum loss (ξ) protons
- Limit impedance introduced by beam pockets
- Sustain high radiation levels
- Reject background in the high-pileup (μ=50) of normal LHC running



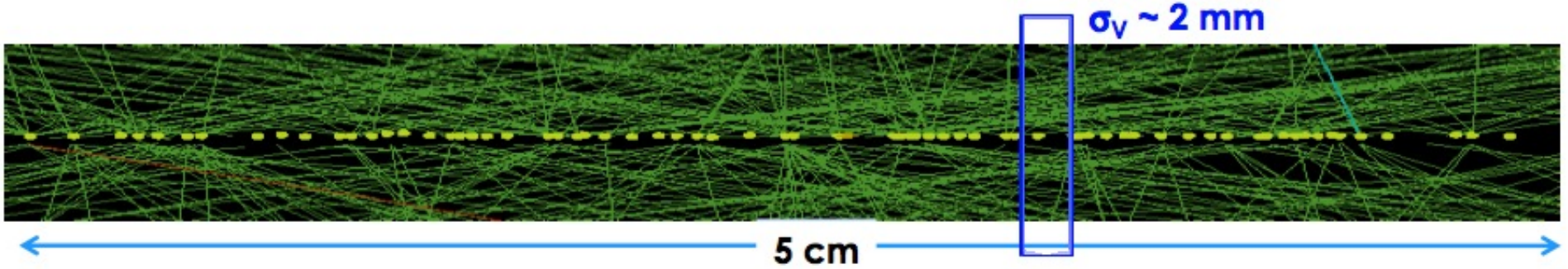
Detectors

- Tracking detectors
  - Goal: measure proton momentum
  - Technology: silicon 3D pixels

"3D" pixel sensors with columnar electrodes



- Timing detectors
  - Goal: identify primary vertex, reject "pileup"
  - σ_{time}~10ps ⇒ σ_z~2mm
  - Technology: silicon/diamond



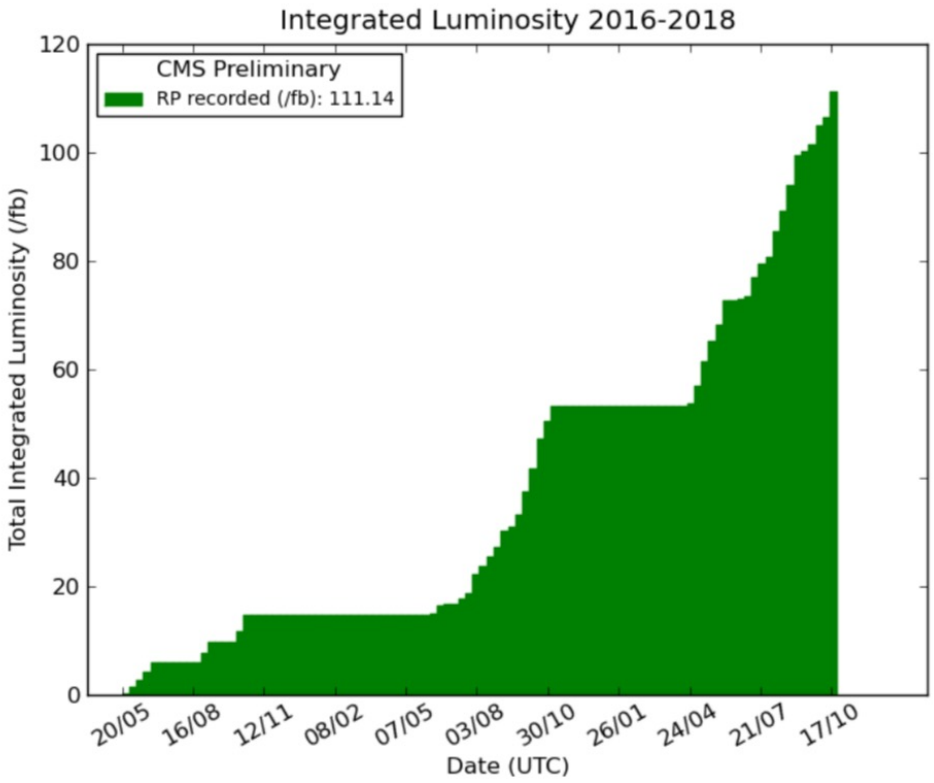
Data taking

- Successful RP insertions in 2016 at 15σ
- Regular near-beam operation in high-luminosity fills

2016 – collected ~15/fb
  - Silicon strips+diamond

2017 – collected ~40/fb
  - Tracking: silicon strips + 3D silicon pixels (first installation in CMS)
  - Timing: diamond+UFSD
  - Detectors fully integrated in central DAQ from first fill

2018 – collected ~60/fb
  - full scope with Si pixels+diamonds



Good detector stability ⇒ integrated luminosity in Run2 ~115 fb^{-1}

Proton reconstruction

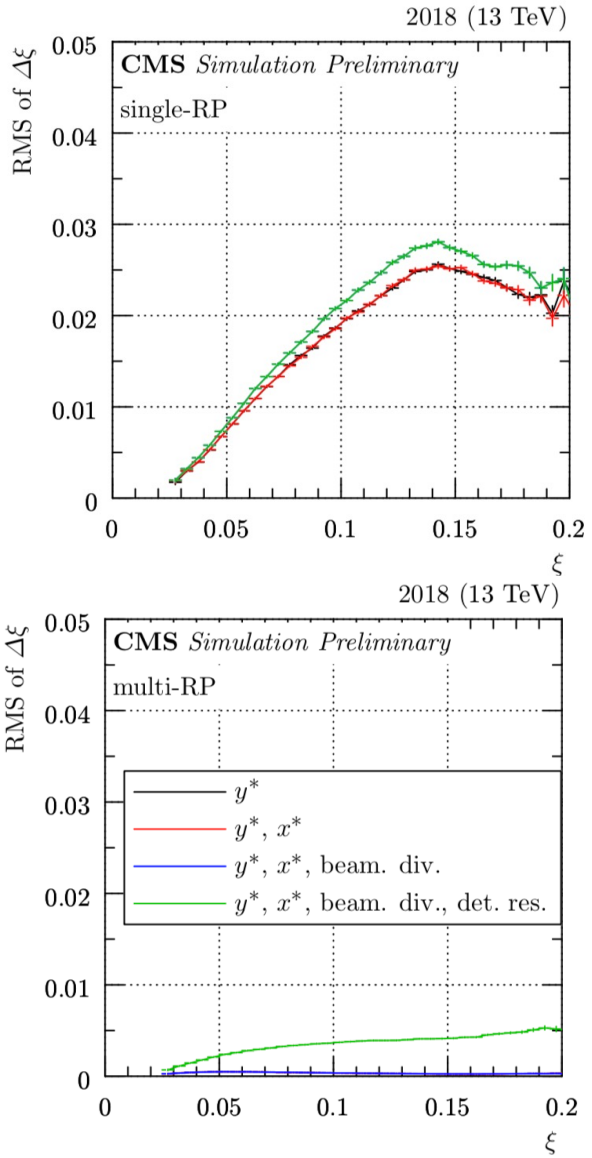
CMS-PRO-21-001

Single-RP: treats each tracking RP as a separate detector

- Relatively poor resolution but maximizes acceptance/efficiency

Multi-RP: combines measurements of both tracking RPs.

- Result is a global track.
- Significantly improves resolution $\sigma(\xi)$ and uncertainties
- Some loss of efficiency
- Ultimate performance, baseline
- significantly smaller bias, better resolution and comparable systematics



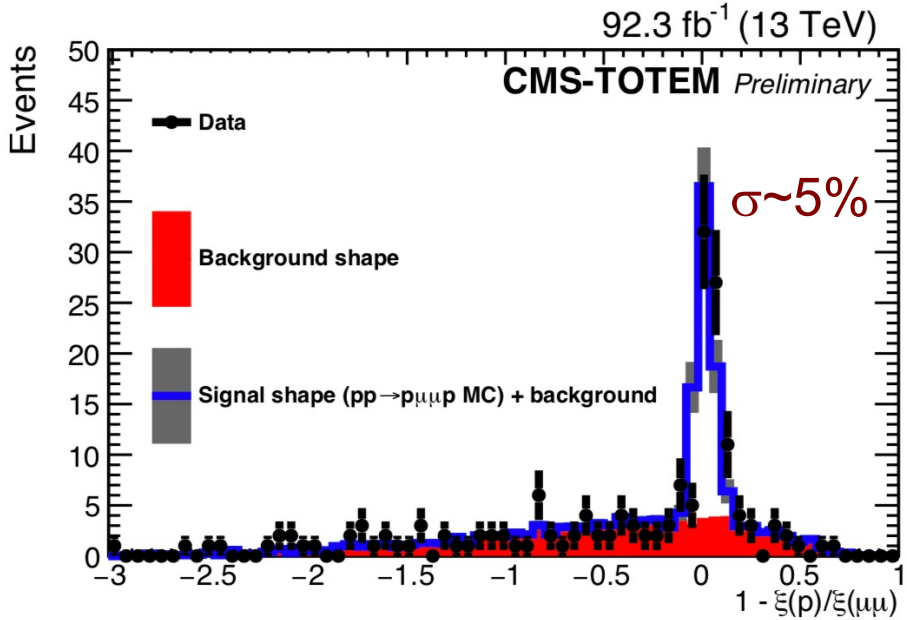
Resolution

CMS-PRO-21-001

Multi-RP ξ resolution

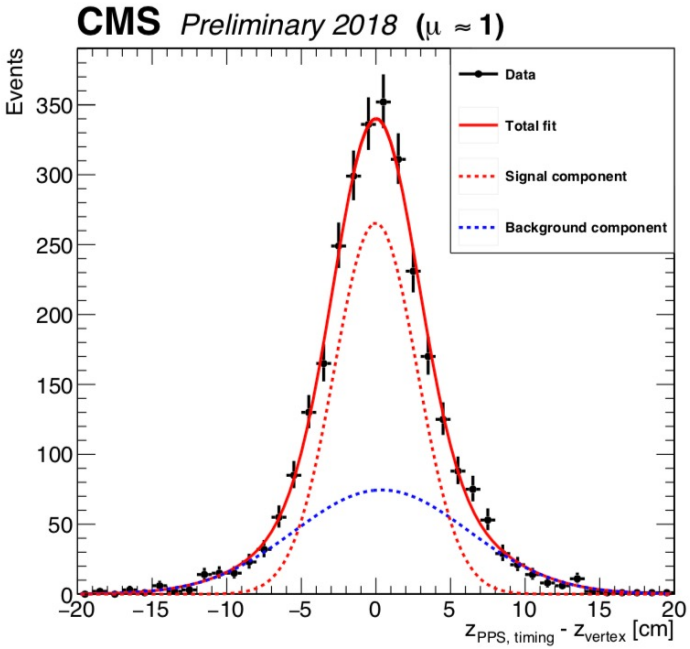
- Exclusive dimuon events
- One-dimensional projections of the correlation between ξ(p) and $\xi(\mu^+\mu^-)$

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



Timing resolution

- z_{vertex} vs $z_{PPS,timing} = \Delta t_{PPS} \times \frac{c}{2}$
- Pileup ~1
- Tagged on both PPS arms

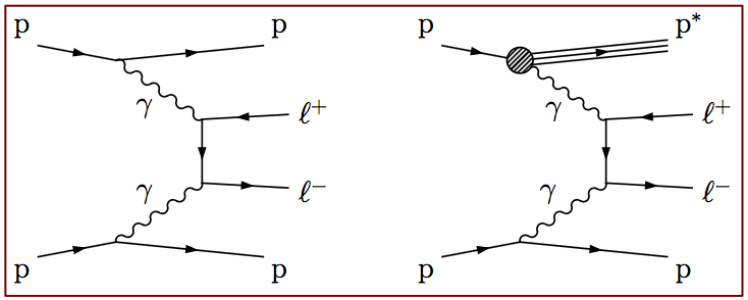


Exclusive dilepton production

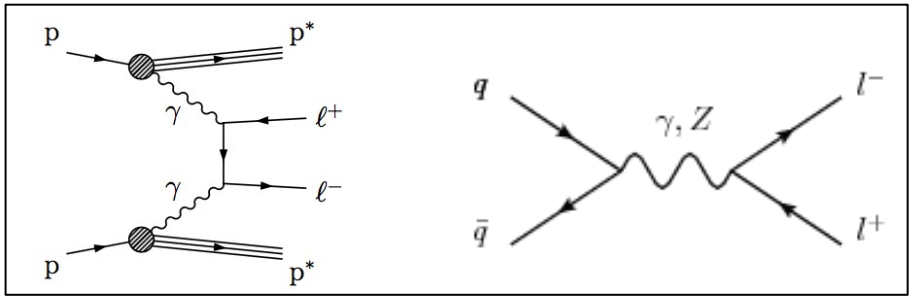
arXiv:1803.04496

- Exclusive processes at the EWK scale
- Study SM candle process: $\gamma\gamma \to \ell\ell$
- Observation of $\gamma\gamma$ interaction with proton tag
  - Single arm selection to enhance statistics at low m($\ell\ell$)
  - Signal includes both exclusive and SD production

signal

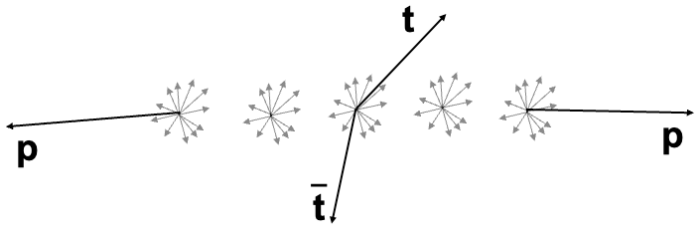


bkg: overlapping with PU protons or beam bkg



Pileup: Background determination

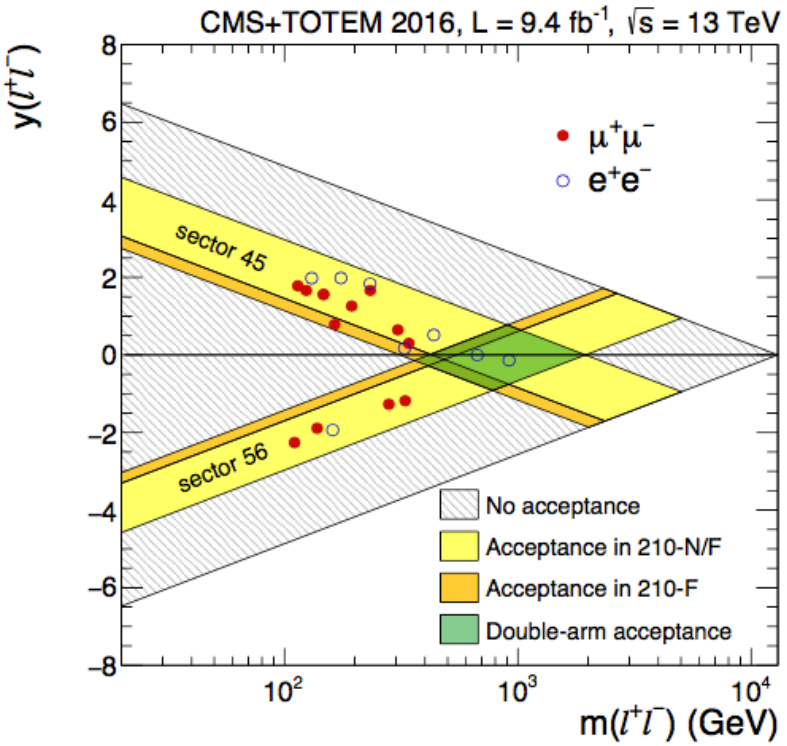
- Main background from superimposition of inclusive process+PU protons
  - Modeling of PU protons not reliable in MC samples ⇒ use data
- Use signal sample (with relaxed selection) from data
- Superimpose data control sample & MC
- Weigh events depending on time interval (“era”), PU, crossing angle

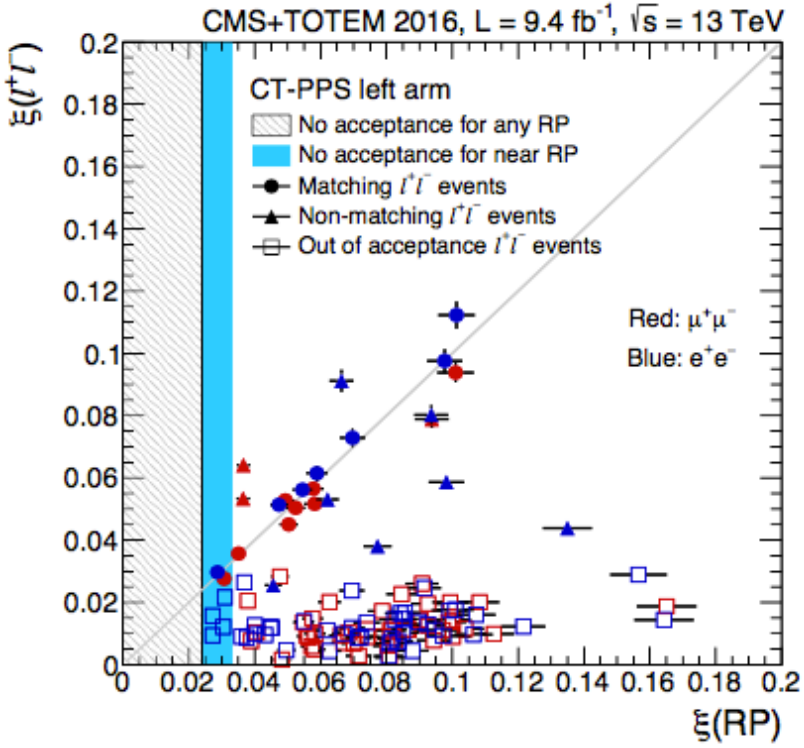


Exclusive dilepton production

JHEP 07(2018)153

- Correlation between the ξ values in central system vs PPS
- 12 $\mu\mu$, 8 ee candidates observed (>5σ over expected bkg)
  - Mass and rapidity distribution consistent with single-arm acceptance
  - Highest mass candidate >900 GeV

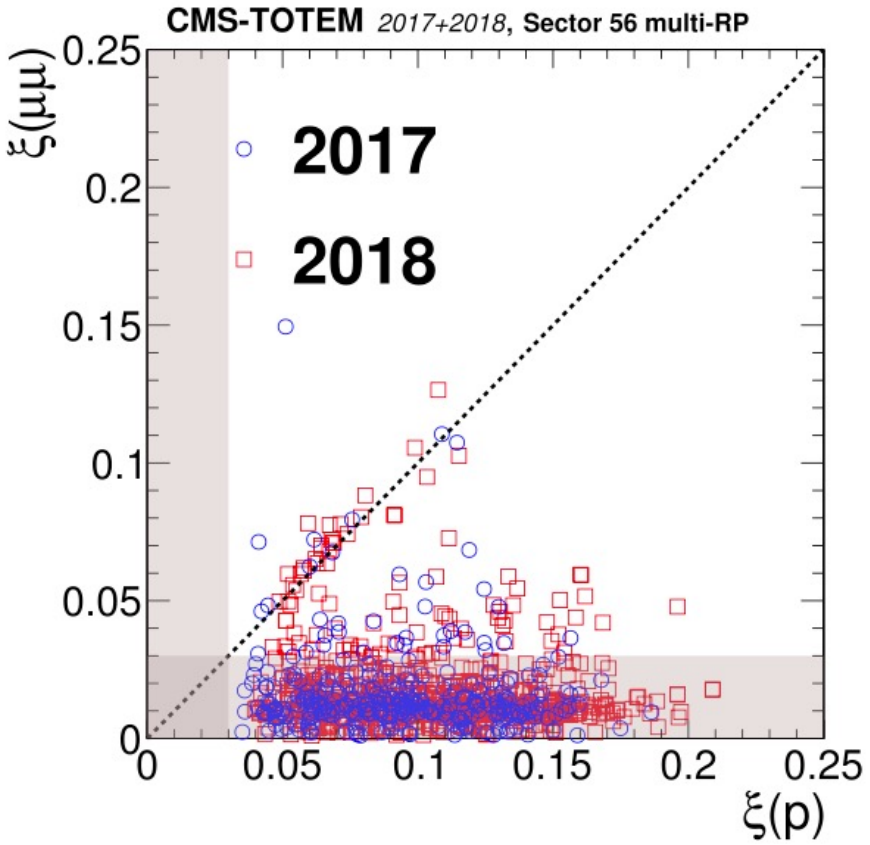




Exclusive μμ events

CMS-PRO-21-001

- Sample of $\gamma\gamma \rightarrow \mu\mu$ events with at least one intact proton
  - using ~100fb^{-1} of data
- Clear cluster of events along the diagonal
- Extend to ξ~0.12

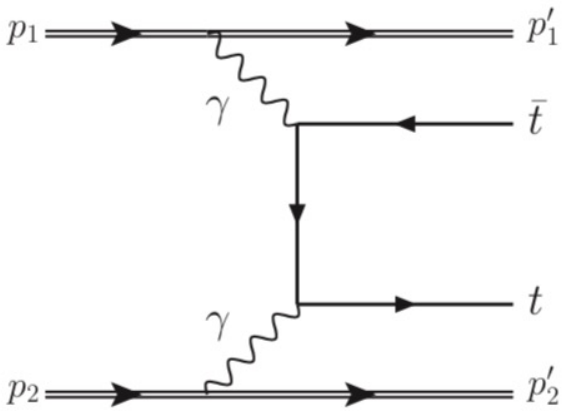


Exclusive top quark pairs

CMS-TOP-21-007

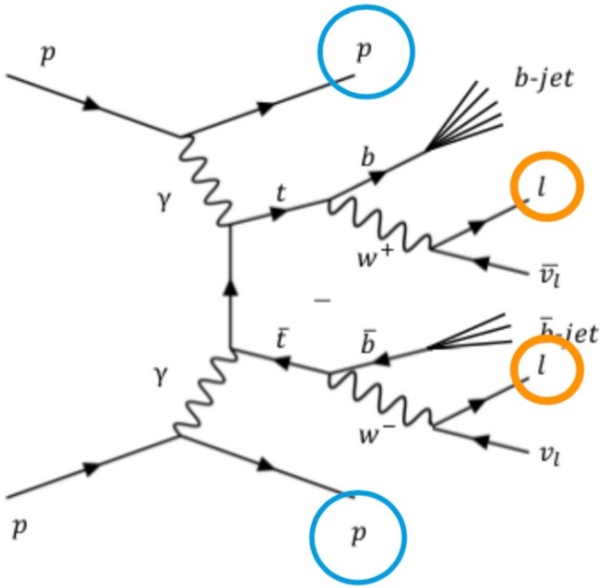
Top quark pair production in $\gamma\gamma$ interaction

- Small x-section O(1fb)
- Sensitive to top-photon coupling
- First search of this process



Strategy

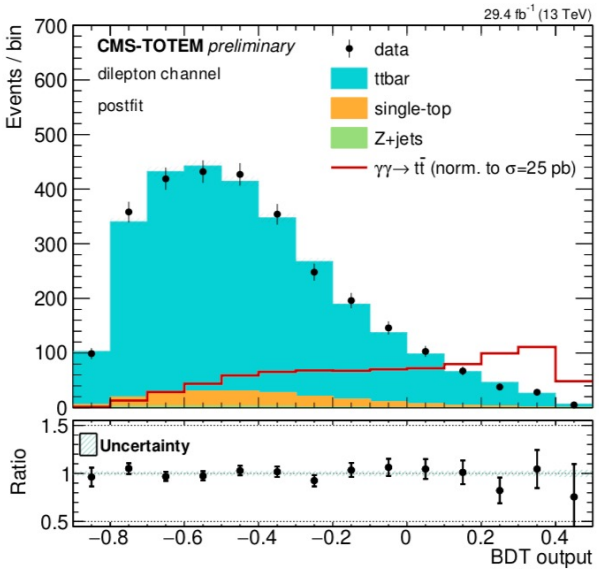
- Use dilepton and ℓ+jet channels
- Tag protons and measure fraction of momentum lost
- Can measure protons that lost ~2-20% of their momentum
- Measure ttbar system in central detector

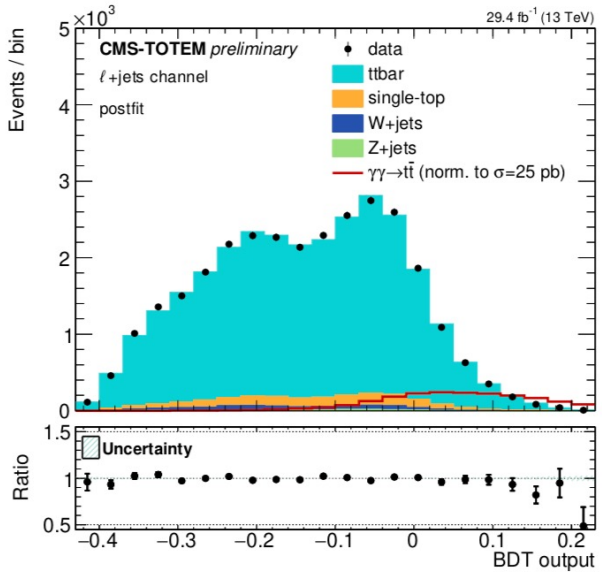


$$\xi_i = \frac{|\vec{p_f}| - |\vec{p_i}|}{|\vec{p_i}|} \qquad M_X = \sqrt{s\xi_1\xi_2}$$

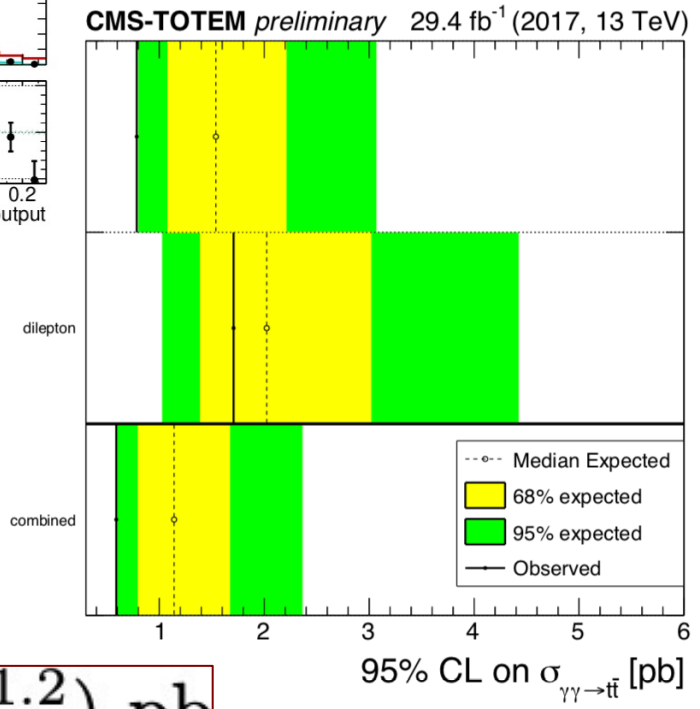
Exclusive top quark pairs (cont.)

CMS-TOP-21-007





- BDT: proton & event kinematics
- Extract limits & combine



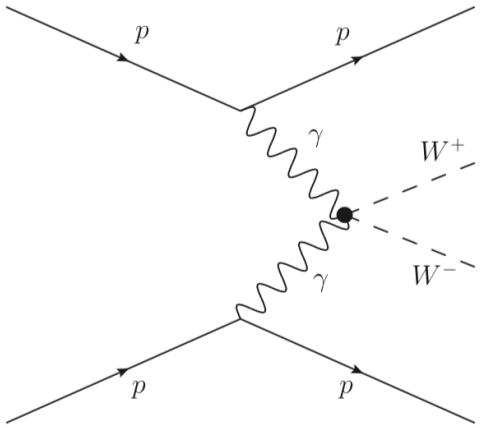
- Results dominated by stat. unc.
- Main systematics (FSR, JER, ttbar normalization, b-tag, proton reco)
- Set upper limits:

$$\text{observed (expected)} : 0.59\ (1.14^{+1.2}_{-0.6})\ \text{pb}$$

Exclusive VV (V=W,Z)

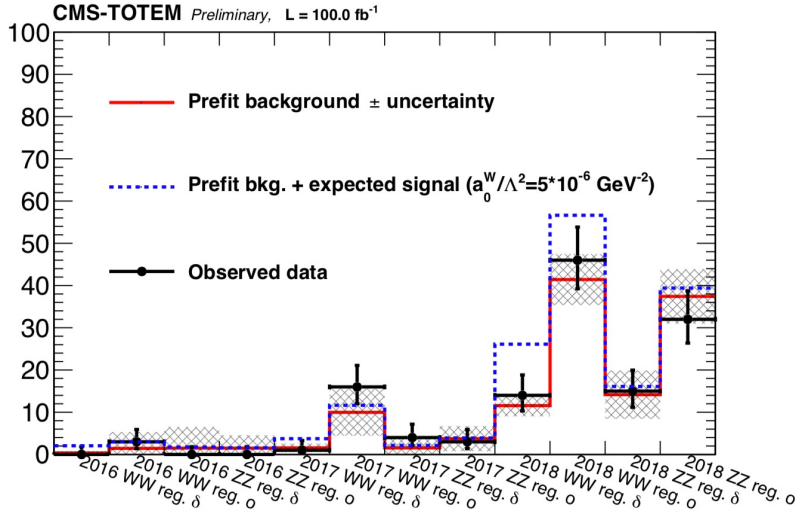
CMS-SMP-21-014

- Search for anomalous high-mass $\gamma\gamma \longrightarrow VV$ with forward protons
  - Search for non-resonant excess in high-mass tails (AQGC/EFT)
  - Small expected SM production
- Study ZZ and WW final states
  - Fully hadronic final state
  - Boosted/merged quark jets
  - Both tagged protons
  - Large multi-jet background
  - compute mass match ratio and rapidity difference



$$1 - m_{VV}/m_{pp}, \text{ where : } m_{pp} = \sqrt{s \cdot \xi_1 \xi_2}$$

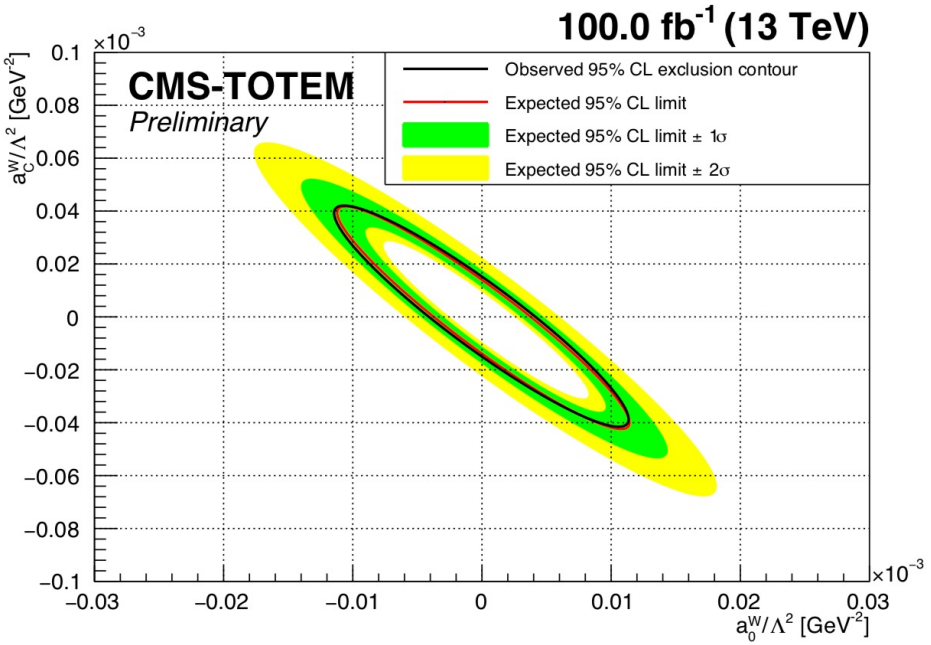
$$y_{VV} - y_{pp}, \text{ where : } y_{pp} = 1/2 \log(\xi_1/\xi_2)$$



Exclusive VV (cont.)

CMS-SMP-21-014

- No significant excess over SM expectations
  - Set upper limits Dim-6 $\gamma\gamma$WW AQGCs (x15-20 better than results w/o leading protons)
  - Dim-8 limits close to ssWW and ssWZ scattering analyses
- First $\gamma\gamma$ZZ limits



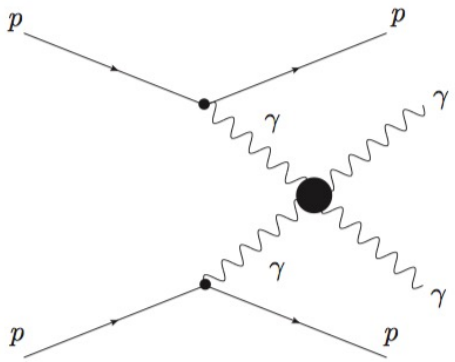
$$\sigma(pp \to pWWp)_{0.04<\xi<0.20, m>1000\ \text{GeV}} < 67(53^{+34}_{-19})\ \text{fb},$$

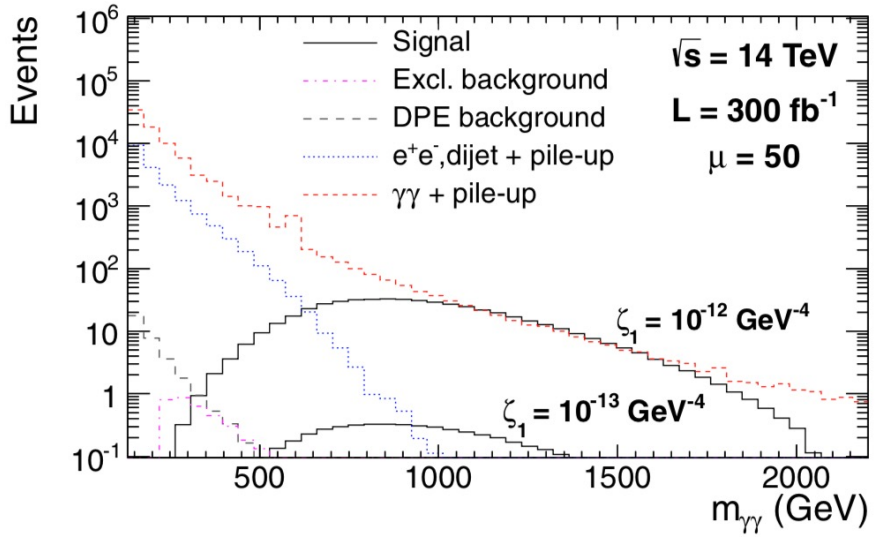
$$\sigma(pp \to pZZp)_{0.04<\xi<0.20, m>1000\ \text{GeV}} < 43(62^{+33}_{-20})\ \text{fb},$$

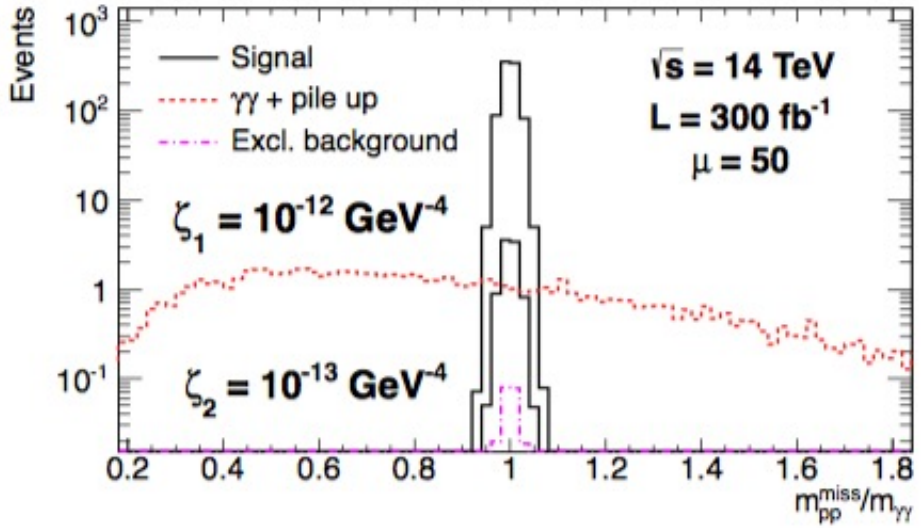
$\gamma\gamma \rightarrow \gamma\gamma$: light-by-light scattering

PRD 89(2014)114004

- Indirect search: neutral quartic gauge couplings (forbidden in SM) in $\gamma\gamma \rightarrow \gamma\gamma$
- Expect to provide best sensitivity at LHC
- Sensitive to axion-like particles





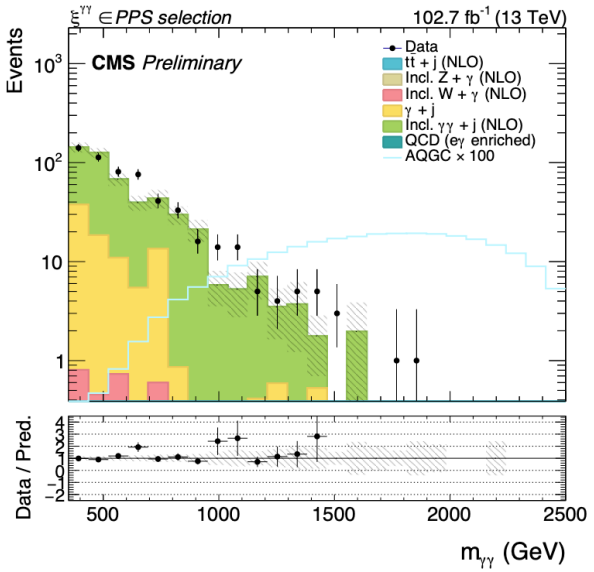


Exclusive $\gamma\gamma$ production

PRL 129(2022)011801, CMS-EXO-21-007

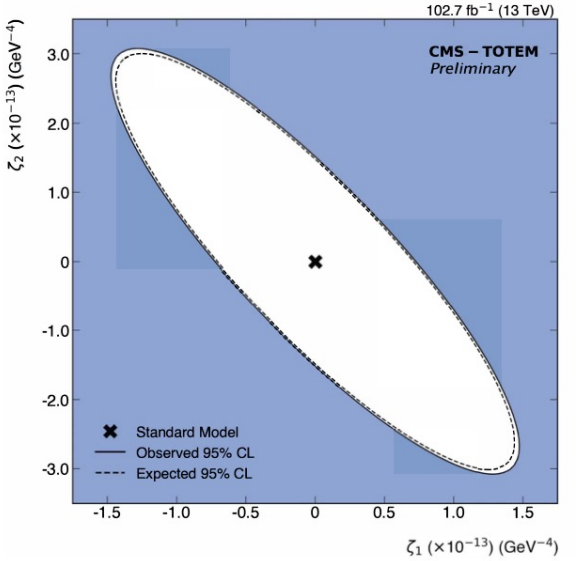
- Light-by-light scattering
  - Study $m_{\gamma\gamma} > 350$ GeV
  - Matching mass & rapidity: pp vs $\gamma\gamma$
  - 1 events observed (1.1 expected)

$$\sigma(pp \to p\gamma\gamma p | \xi_p \in \xi^{\mathrm{PPS}}) < 0.61 \text{ fb}$$



- Set limits on $\gamma\gamma$ scattering
  - Direct limits on anomalous couplings (four-photon interation):

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



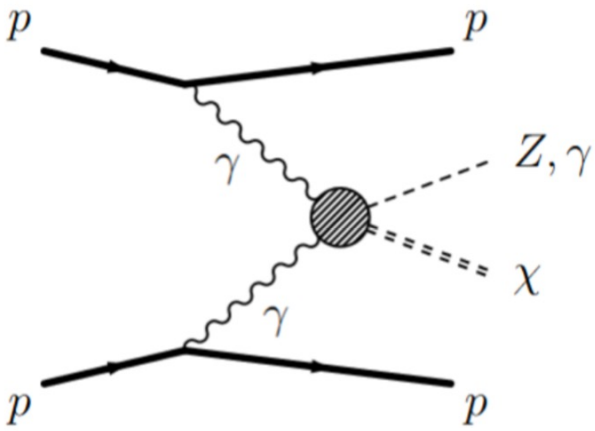
Exclusive Z/γ+X

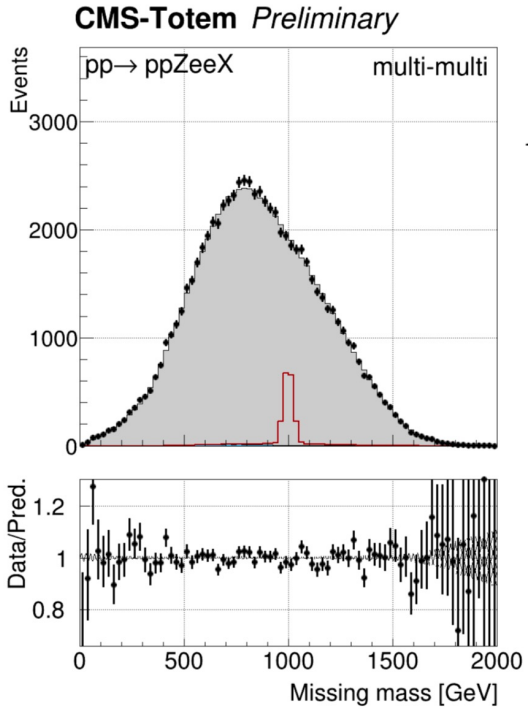
CMS-EXO-19-009

- Generic search for Z/γ+X production
  - X is an unspecified massive particle
  - Main variable of interest: missing mass (M_{miss}) from boson+final state protons

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

  - Look for weakly-interacting BSM particle
  - Relatively unknown region (600-1600GeV)
- Use Z leptonic decay or photon
  - Background mostly from random coincidence with PU protons
  - Use different proton categories (multi-multi, multi-single, single-multi and single-single methods)

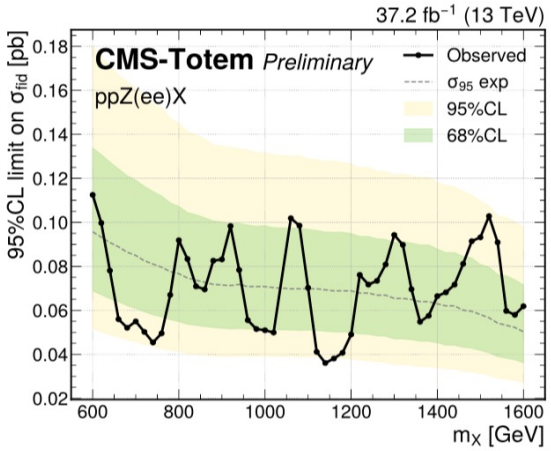


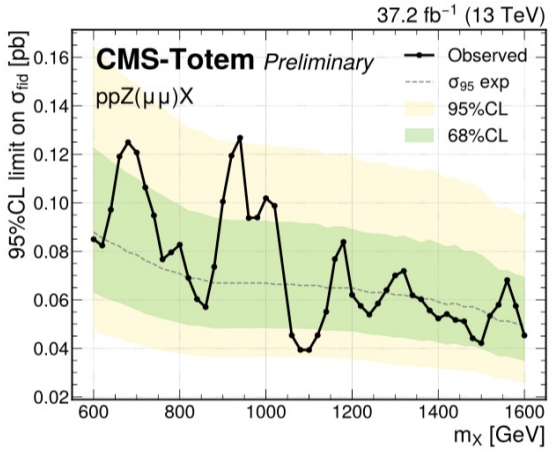


Exclusive Z/γ+X (cont.)

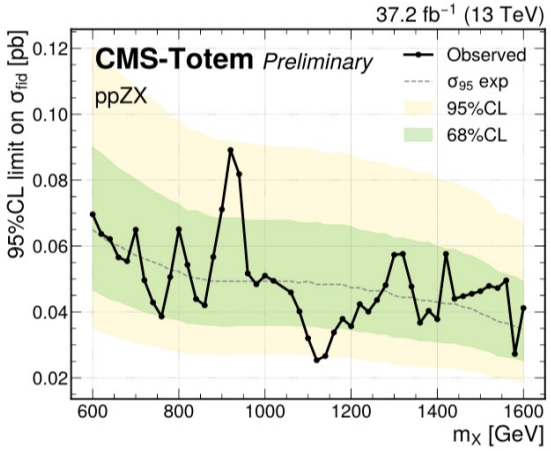
CMS-EXO-19-009

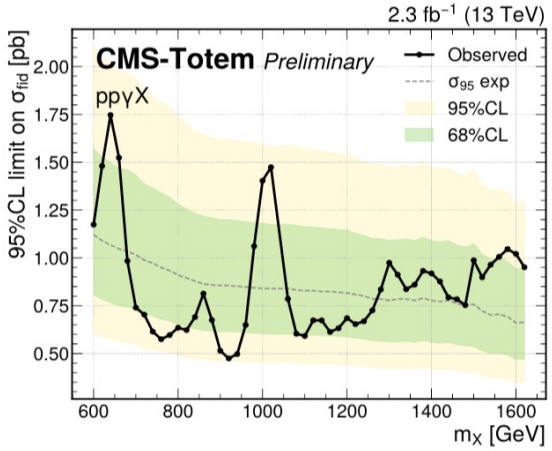
Z+X ⇒





γ+X ⇒

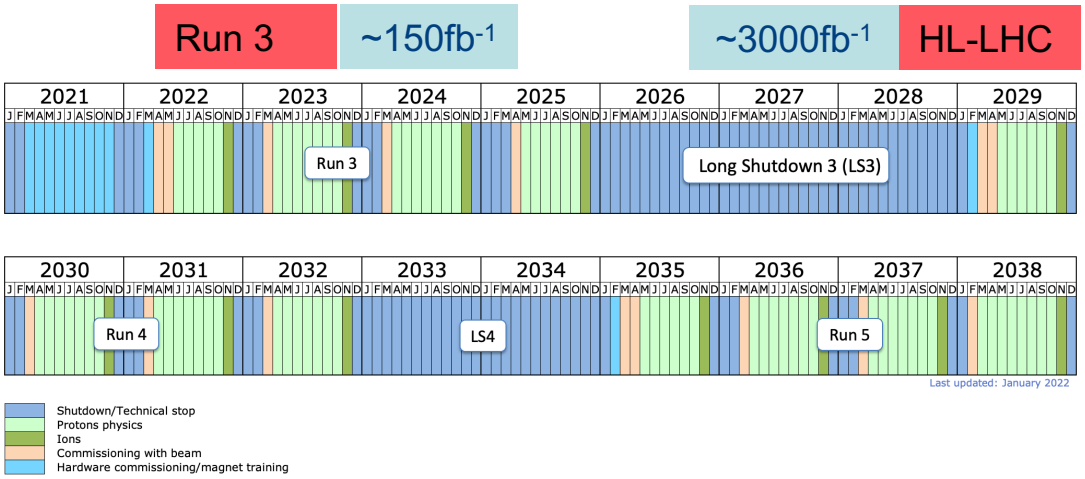


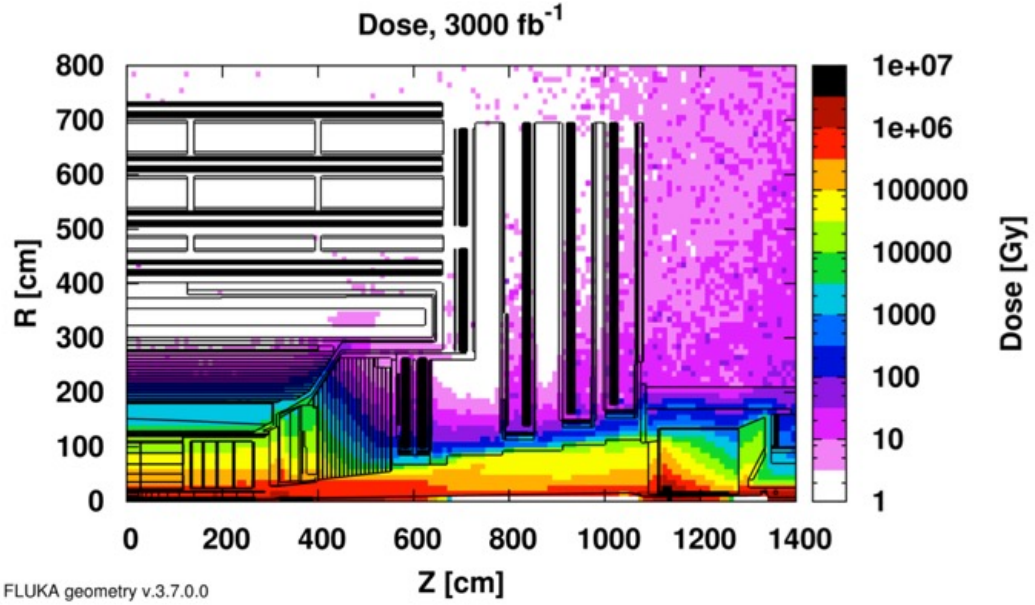


- No significant local excess/deficit of events observed

Prospects for Run3 and beyond

- More luminosity in a more challenging environment
- Will enhance the mass reach in the search for new particles
- Need to meet experimental challenges
  - Aging of detector, improve/adapt capability
  - Integrated luminosity: 300-3000/fb
  - peak luminosity of $2x10^{35}cm^{-2}s^{-1}$
  - PU ~150 or higher (Phase2)
  - large radiation doses



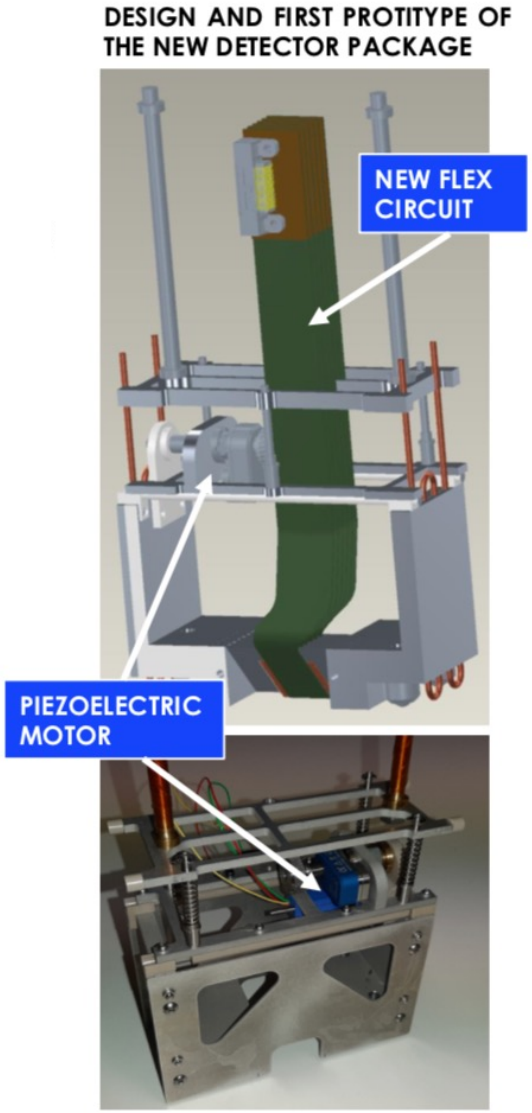


Run3: Tracking

PPS will operate in Run3 (2022-2025)

Tracker system in Run3

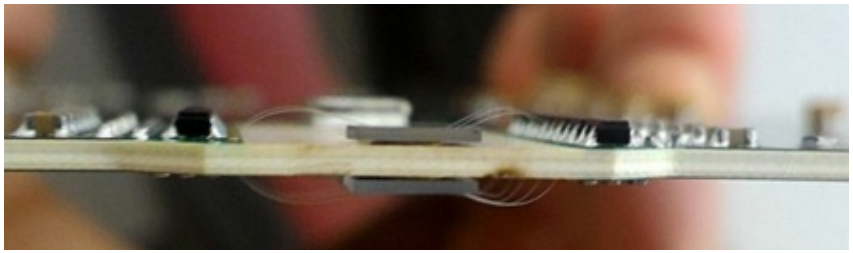
- 2 RPs per side at 210 m and 220 m
  - 6 detector planes per RP (as in 2018)
- New 3D silicon pixel sensors
  - Single side technology
  - 2x2 sensor geometry
  - 150um thick
  - 2E electrode configuration
- ROC: same as layer 1 of CMS pixel detector
- New detector package with internal movement system
  - 12 positions spaced by 500 um to handle radiation damage (more than 50/fb with minimal efficiency loss)

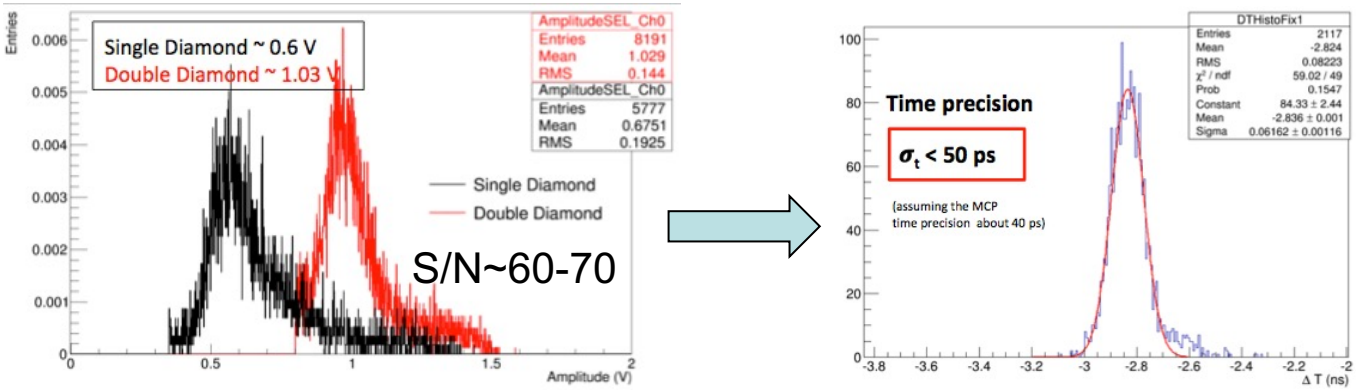


Run3: Timing

JINST12(2017)P03026

- Optimize timing measurement in Run3
  - Aim at 50ps/plane (8 planes/arm)
  - Install and instrument a 2nd timing RP (only one/side for now)
  - “Double Diamond” (DD) sensors
  - Revised electronics with improved performance

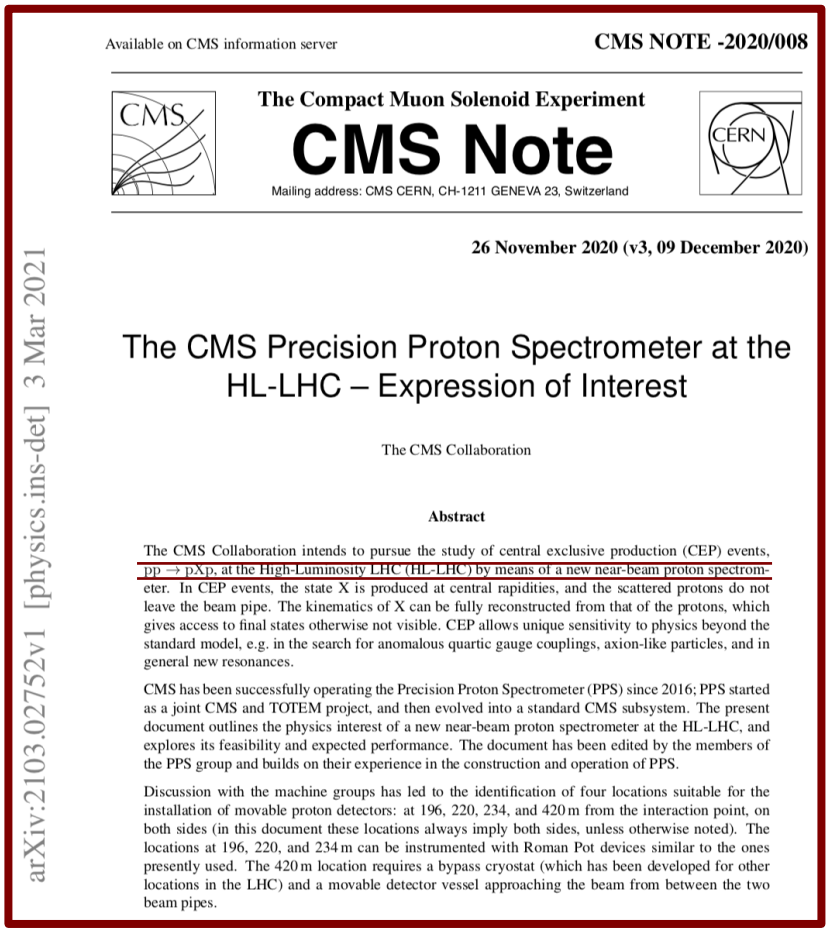




PPS @ HL-LHC

arXiv:2103.02752

- HL-LHC studies detailed in EoI
- Re-install PPS-like spectrometer for HL-LHC approved by the CMS collaboration
- 4 locations identified: near 200m (current location) and 420m (new technology)
- Expanded physics program
- Synergies with other future detector upgrades



Available on CMS information server

CMS NOTE -2020/008

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2020 (v3, 09 December 2020)

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

The CMS Collaboration

Abstract

The CMS Collaboration intends to pursue the study of central exclusive production (CEP) events, $pp \to pXp$, at the High-Luminosity LHC (HL-LHC) by means of a new near-beam proton spectrometer. In CEP events, the state X is produced at central rapidities, and the scattered protons do not leave the beam pipe. The kinematics of X can be fully reconstructed from that of the protons, which gives access to final states otherwise not visible. CEP allows unique sensitivity to physics beyond the standard model, e.g. in the search for anomalous quartic gauge couplings, axion-like particles, and in general new resonances.

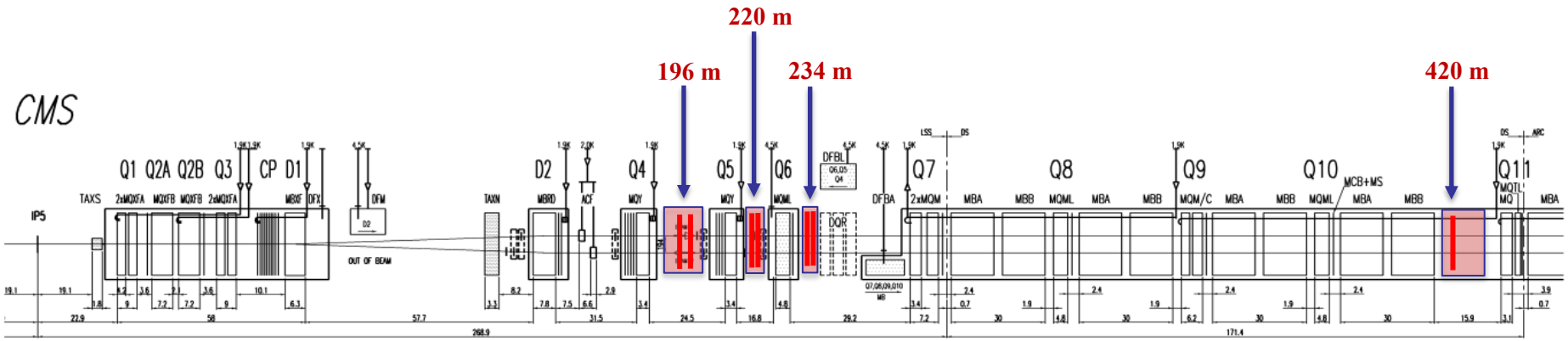
CMS has been successfully operating the Precision Proton Spectrometer (PPS) since 2016; PPS started as a joint CMS and TOTEM project, and then evolved into a standard CMS subsystem. The present document outlines the physics interest of a new near-beam proton spectrometer at the HL-LHC, and explores its feasibility and expected performance. The document has been edited by the members of the PPS group and builds on their experience in the construction and operation of PPS.

Discussion with the machine groups has led to the identification of four locations suitable for the installation of movable proton detectors: at 196, 220, 234, and 420 m from the interaction point, on both sides (in this document these locations always imply both sides, unless otherwise noted). The locations at 196, 220, and 234 m can be instrumented with Roman Pot devices similar to the ones presently used. The 420 m location requires a bypass cryostat (which has been developed for other locations in the LHC) and a movable detector vessel approaching the beam from between the two beam pipes.

arXiv:2103.02752v1 [physics.ins-det] 3 Mar 2021

PPS@HL-LHC: Run4 and beyond

- After Run3 all RPs must be removed to allow reconfiguration of HL-LHC
- Layout of proposed RP stations:
- Extended mass range:
  - 133 GeV - 2.7 TeV (first 3 stations)
  - 43 GeV - 2.7 TeV (all stations)

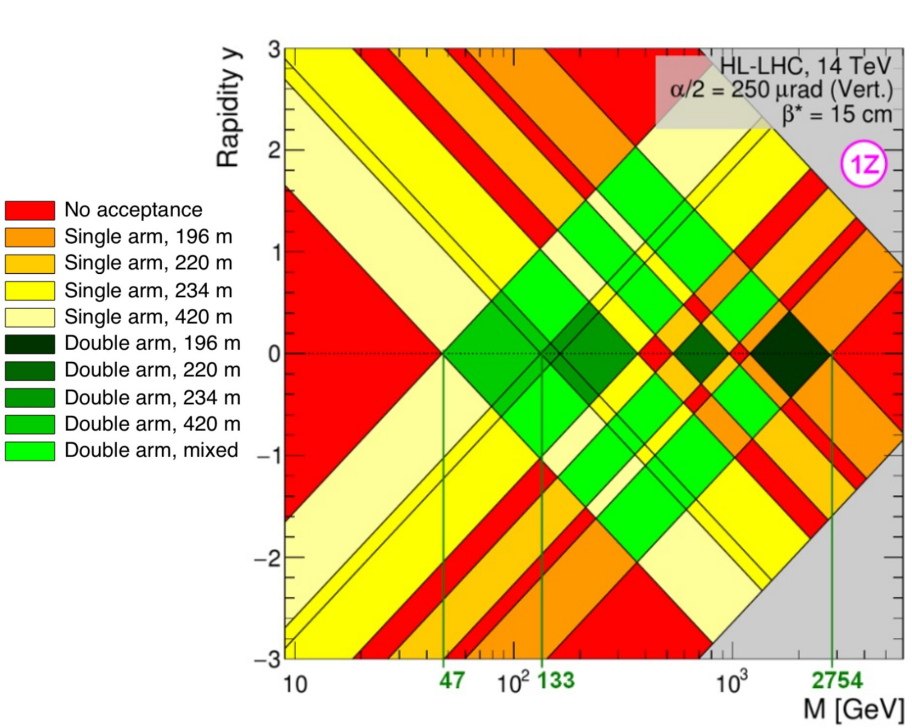


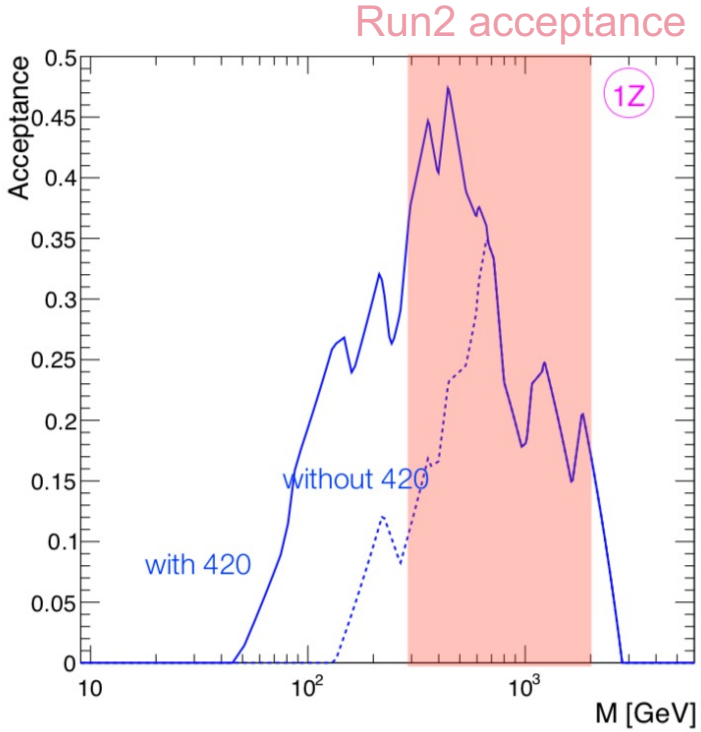
Suitable for standard RP technology

New developments needed (new cryogenic bypass)

Extend current LHC physics program (WW, top, ALPs, SUSY, etc.)

Acceptance: HL-LHC vs Run2/3

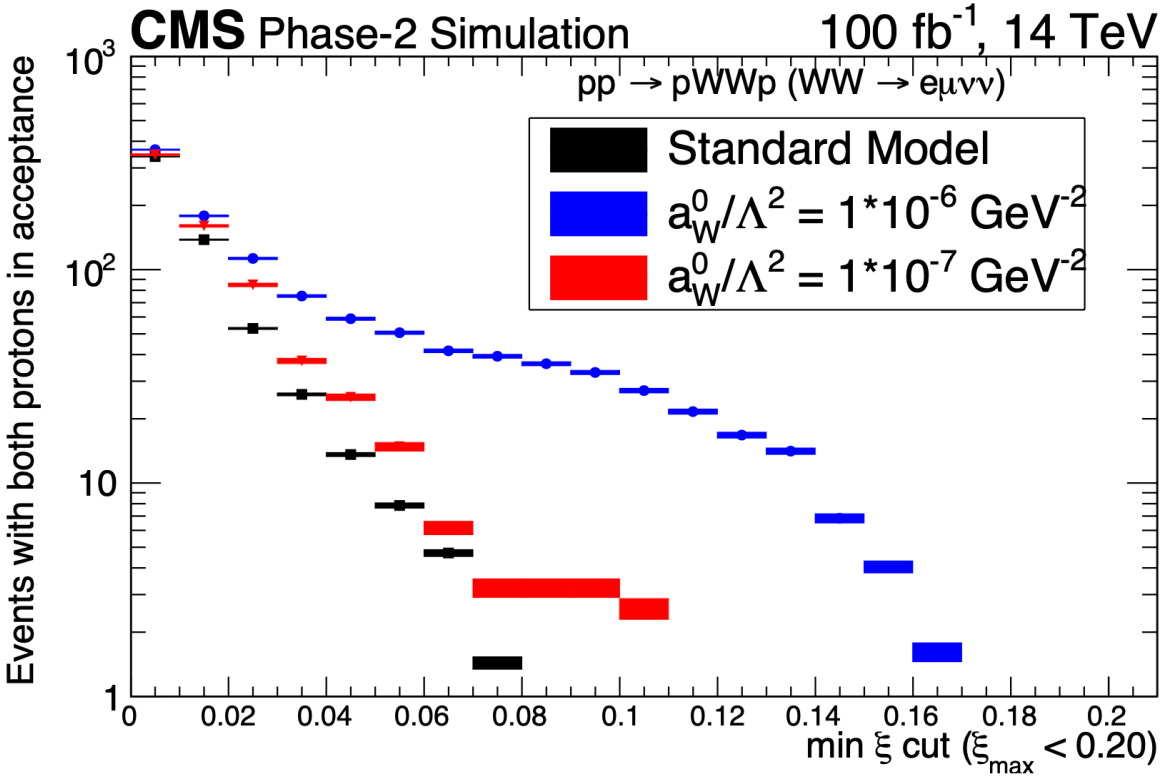




- Green diamonds: both protons in detector acceptance
- Improved acceptance over Run2/3:
  - almost continuous coverage in range 50-2700GeV

Impact on physics

- All physics processes will benefit from increased luminosity and/or increased acceptance
- Example: $\gamma\gamma \longrightarrow WW$

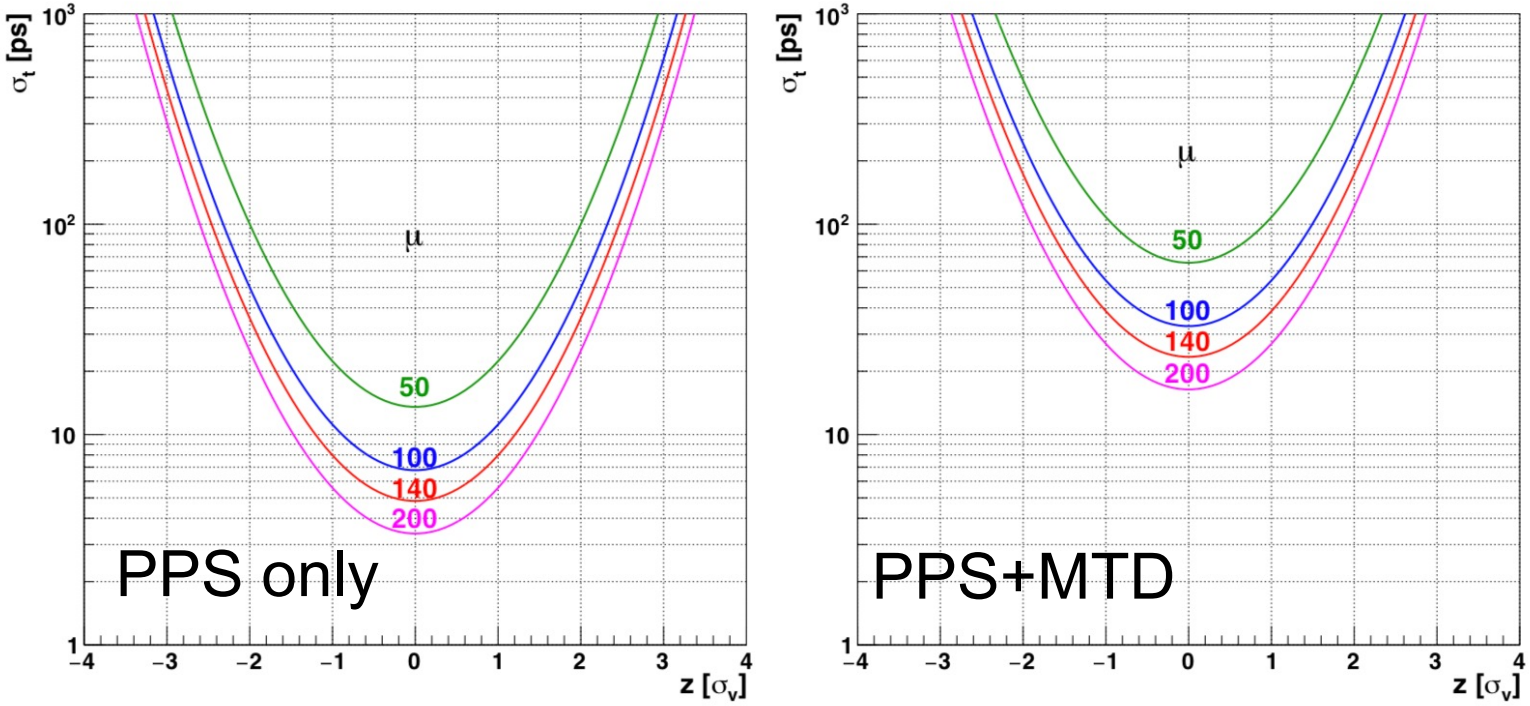


Low ξ: increase acceptance for SM processes

High ξ: increase acceptance for BSM processes

Detectors

- Synergies with central CMS upgrades
  - Tracking: pixel detectors are aligned with Phase-II tracker upgrade
  - Timing: several options investigated Diamond, LGADs (as in MTD-ETL)



Time resolution required per arm to resolve the vertex distance at a position z

Summary

- LHC as a $\gamma\gamma$ collider
- PPS extends coverage to very forward regions
  - Exclusive processes at the EWK scale
  - Additional sensitivity to NP searches
  - Collected ~115/fb
- Regularly taking data in high-luminosity fills
- Preparing improved detectors and extending sensitivity for Run3 and for HL-LHC phase (EoI)

backup

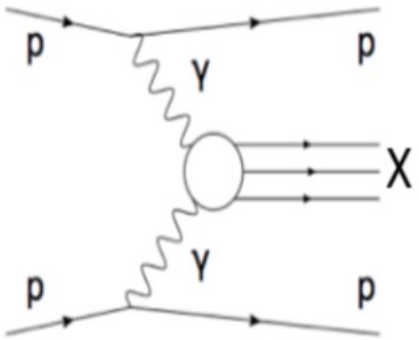
Proton reconstruction

- In a special class of LHC collisions, the protons stay intact and scatter in the far forward direction
- If protons can be detected, powerful tool to study very high energy $\gamma\gamma$ or multiple-gluon ("Pomeron") exchanges
- Small detectors placed far from the central CMS detector (~200m)
- Movable RP used to move the detectors to a few mm from LHC beams

Proton kinematics:

$$\xi = 1 - \frac{p_f}{p_i}; \quad M_X = \sqrt{s \cdot \xi_1 \xi_2}$$

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



- Measure protons that lost ~2-20% of their initial momentum
- Acceptance starts at M_X~300 GeV

Detector acceptance