Looking forward:
The Precision Proton Spectrometer

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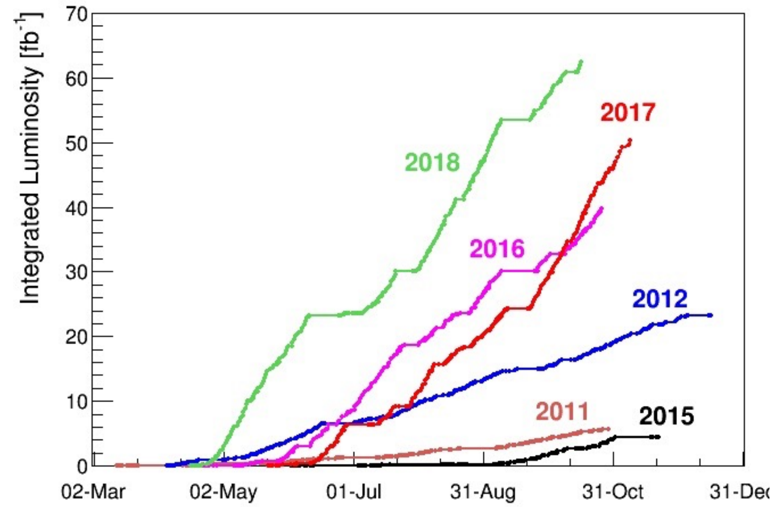
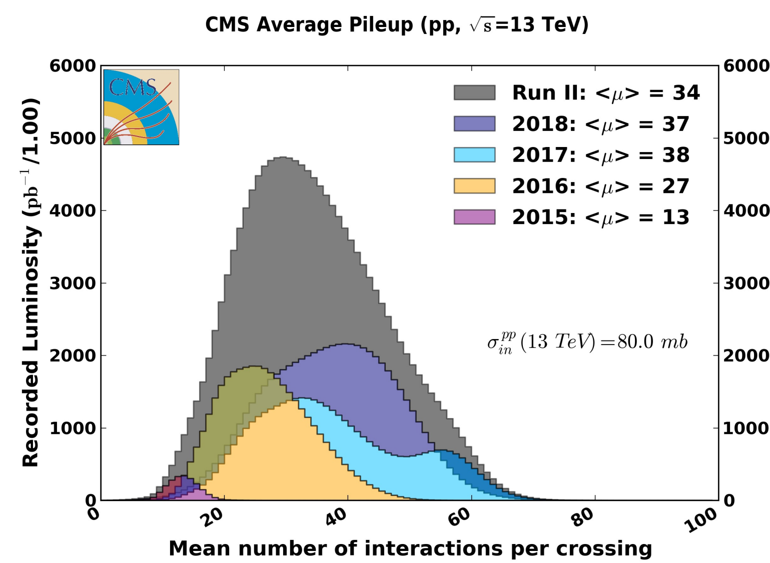
- ✓ Overview
- ✓ Physics motivations
- ✓ Tracking and timing detectors
- ✓ Exclusive dileptons, WW, and prospects
- ✓ Summary

CERN-LHC-2014-021

LHC: from searches to precision

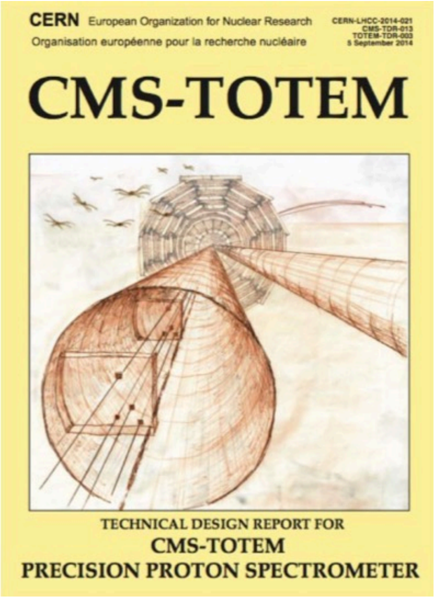
- A hadron collider at full throttle
  - Reaching the energy limit
  - Large datasets
- Moving from searches to precision measurements and rare processes
  - Top quarks and rare decays
  - Higgs couplings and rare decays
  - Anomalous couplings etc.
- Preparing for High-Luminosity (2028 and beyond) with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



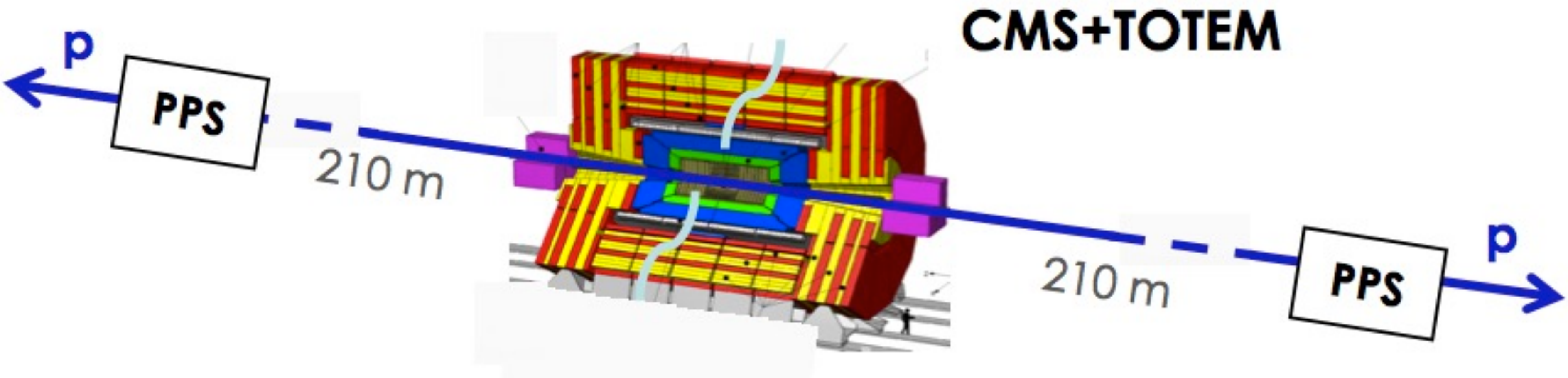


Overview

- 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



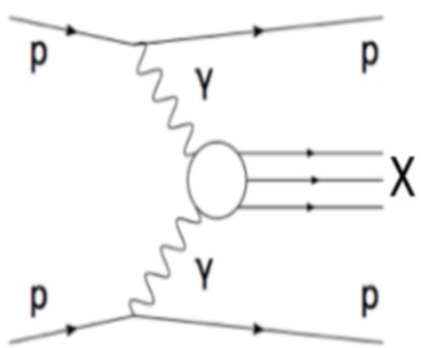
Proton reconstruction

- 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
- Requires small detectors placed far from the central CMS detector (~200m)
- Movable “Roman Pots” used to move the detectors to a few mm from LHC beams

Proton kinematics:

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

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



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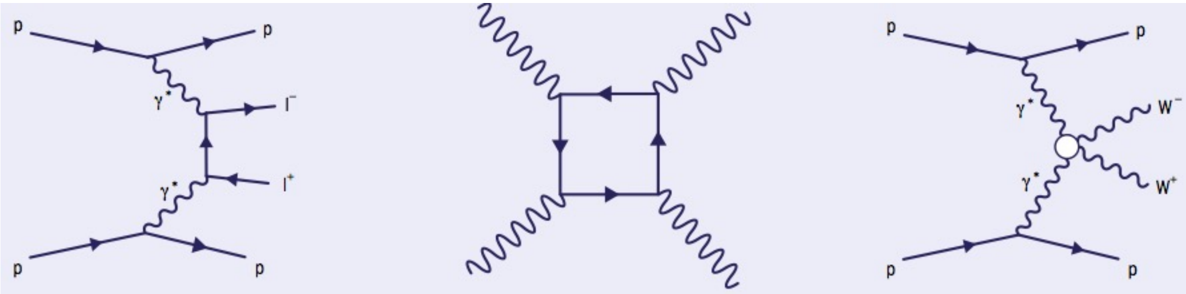
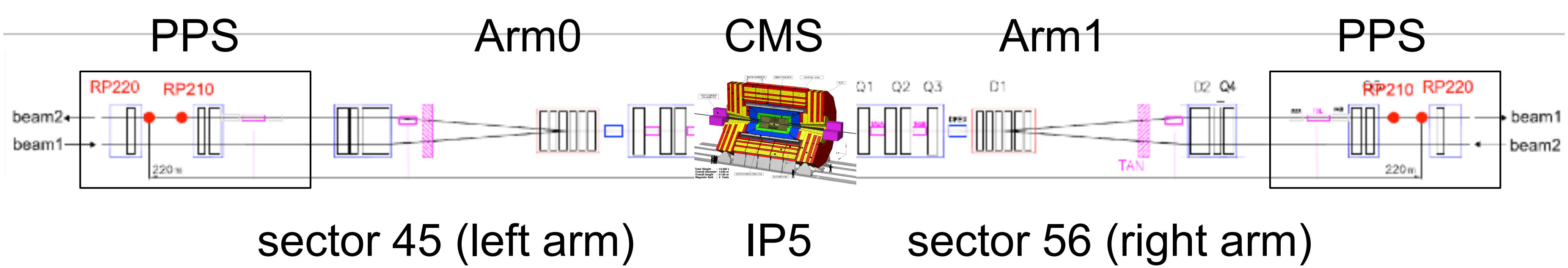
Physics motivations

- 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



Experimental challenges

- Ability to operate the detectors close to beam (15-20σ, i.e. ~1-3 mm) to maximize acceptance for low momentum loss (ξ) protons
- Limit impedance introduced by beam pockets
  – improved RF shielding of RPs
- Sustain high radiation levels
  – For 100/fb, proton flux up to $5\mathrm{x}10^{15}\mathrm{cm}^{-2}$ in tracking detectors, $10^{12} n_{eq}/\mathrm{cm}^2$ and 100Gy in photosensors and readout electronics
- Reject background in the high-pileup (μ=50) of normal LHC running



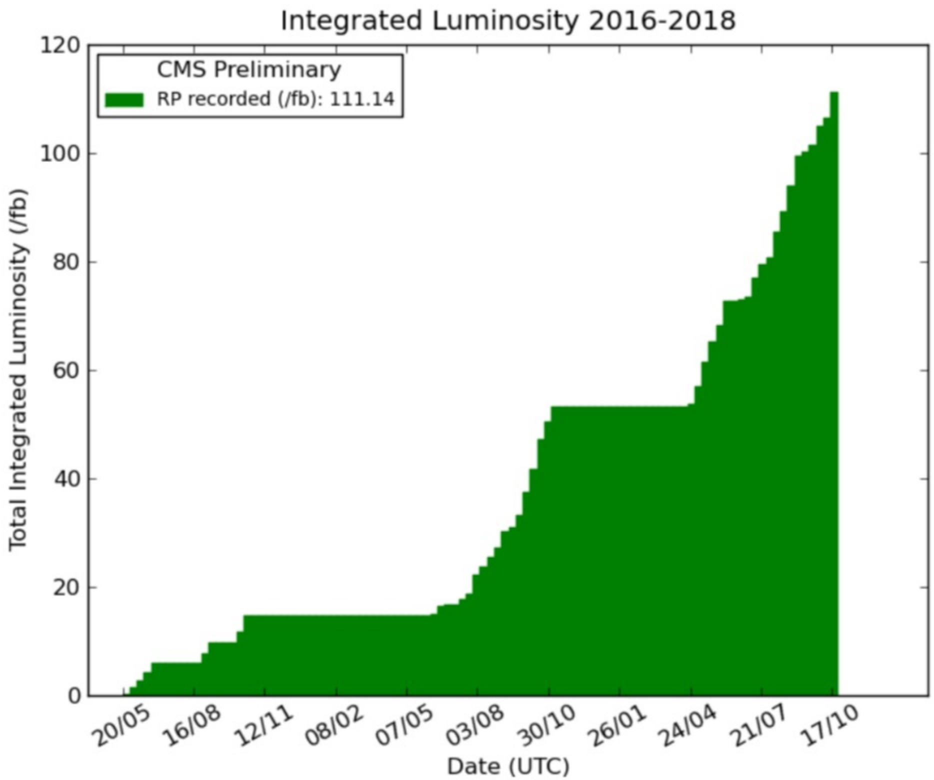
Data taking

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

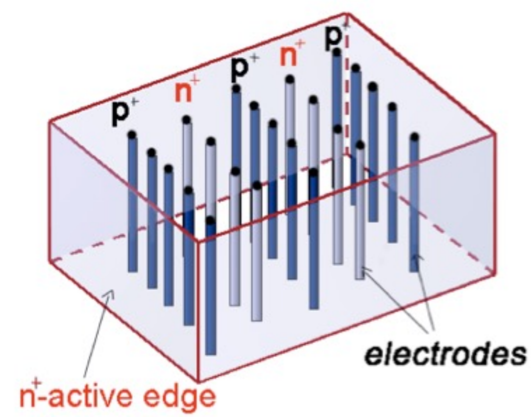


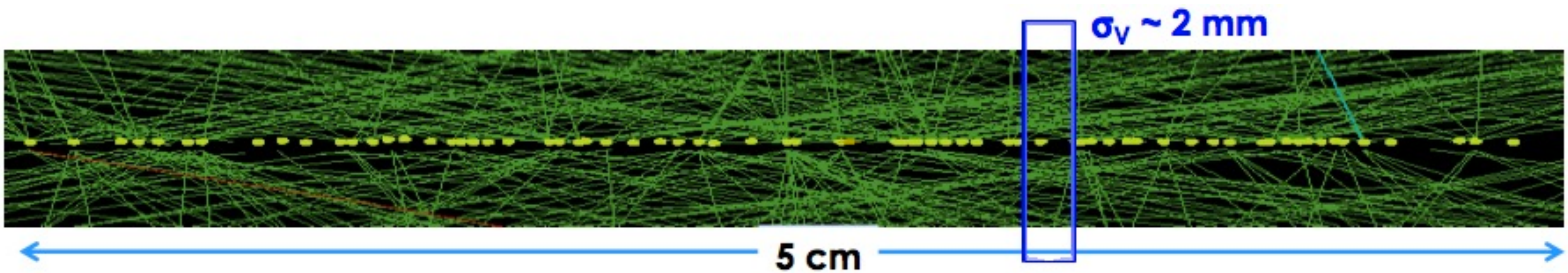
Good detector stability ⇒ integrated luminosity in Run2 ~115 fb^{-1}

Detectors

- Tracking detectors
  - Goal: measure proton momentum
  - Technology: silicon 3D pixels
- Timing detectors
  - Goal: identify primary vertex, reject “pileup”
  - σ_{time}~10ps $\Rightarrow$ σ_z~2mm
  - Technology: silicon/diamond

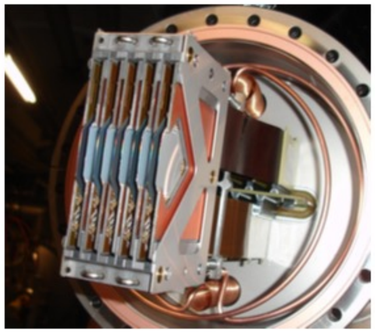
“3D” pixel sensors with columnar electrodes

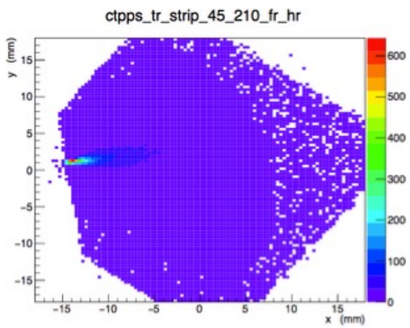




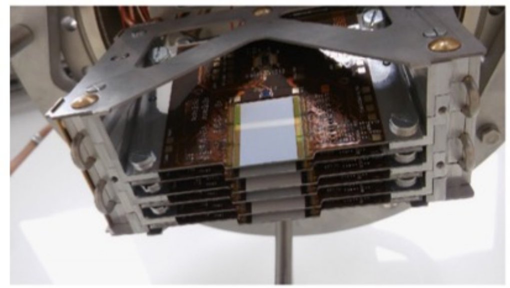
Tracking detectors

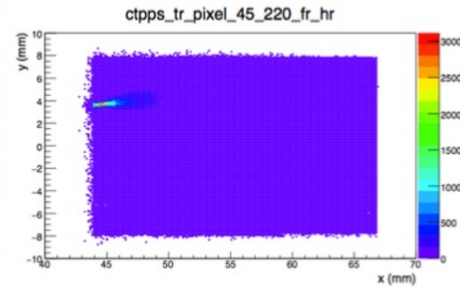
Silicon strips





Silicon pixels



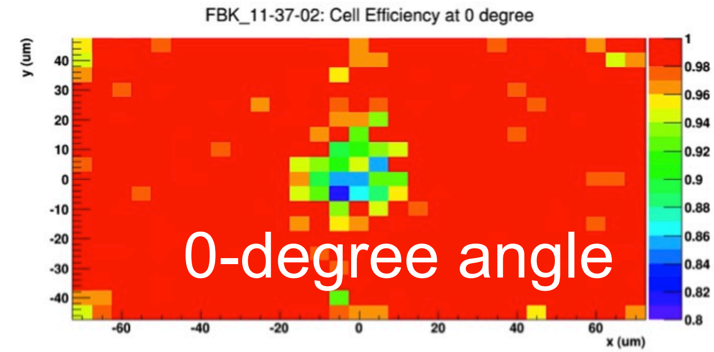


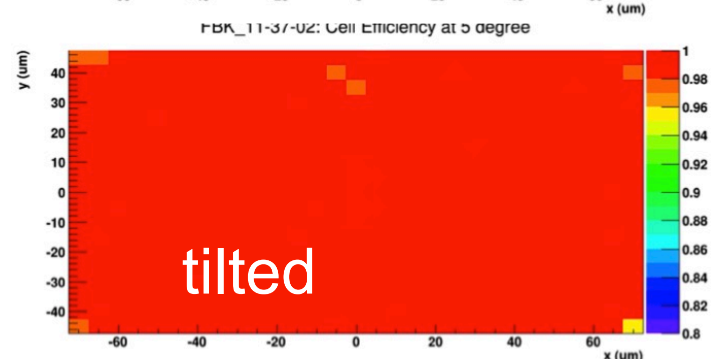
- 10 planes per station of “edgeless” silicon strip detectors (5U+5V)
- Pitch 66μm; track resolution ~12μm
- Designed for low-lumi running
- Used in 2016 and 2017

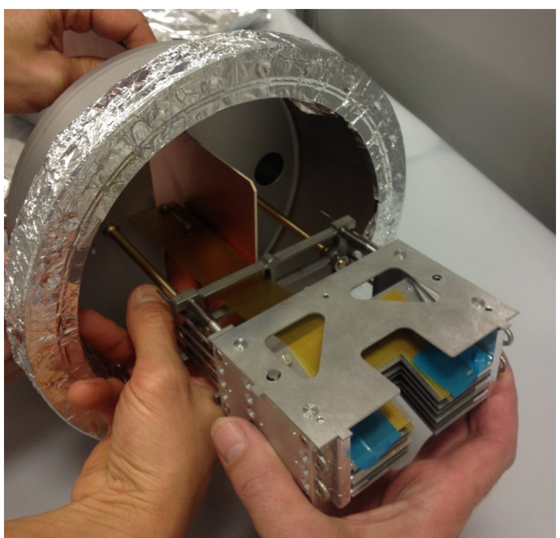
- 6 planes per station of “slim-edge” tilted silicon 3D pixel detectors
- Pixel size 100μm x 150μm; track resolution ~20μm
- Designed for high-lumi running
- Multi-track capability

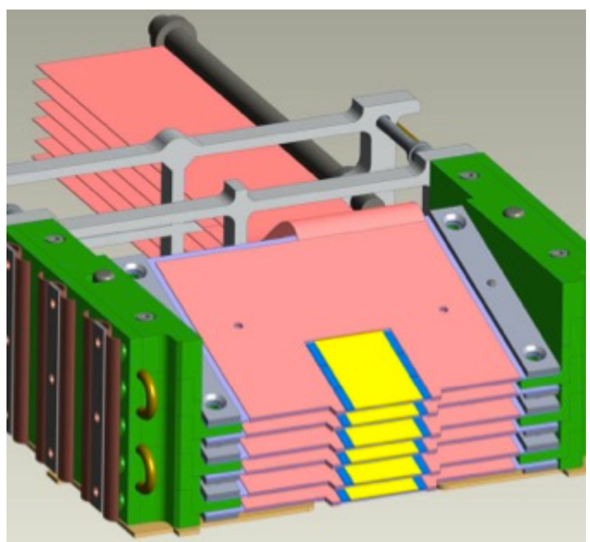
Tracking detectors

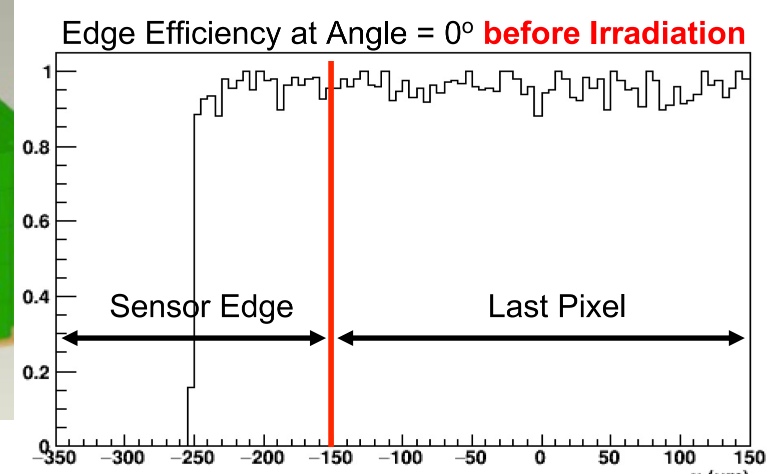
- 3D silicon pixel detectors
- 2 stations per side, 6 detector planes each RP
- Planes tilted to optimize efficiency and resolution
- Thin design studied to minimize impact on beam, insertion in pot, approach to beam
- Designed for high-luminosity running
- Multi-track capability



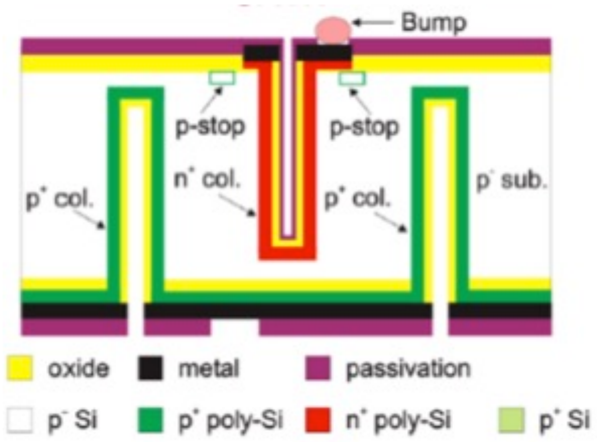






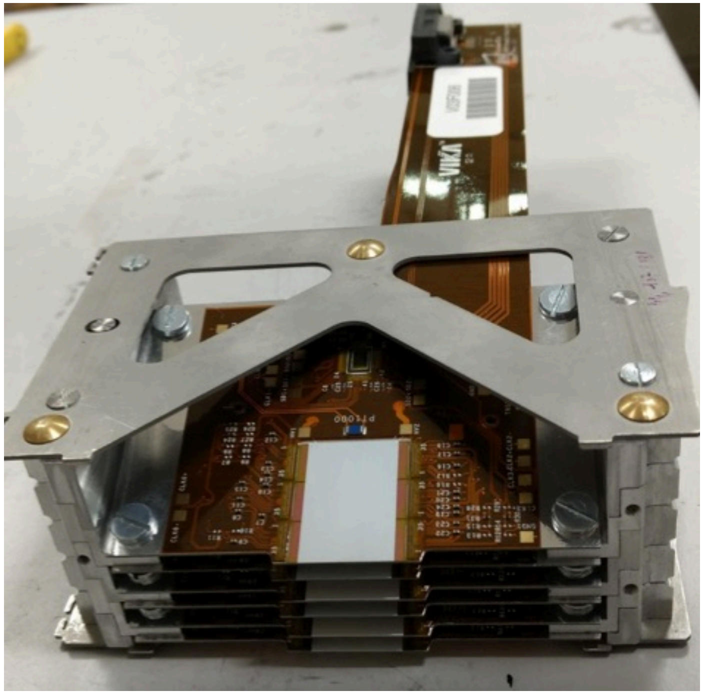


Tracking detectors (cont.)



Sensors:

- 3D sensor technology
- Intrinsic radiation hardness (to withstand overall integrated flux of 5×10^{15} protons/cm^2
- Pixel size 100μm x150μm
- 150μm slim edges (small dead edge to approach beam as close as possible)
- Spatial resolution <30μm



Front-end:

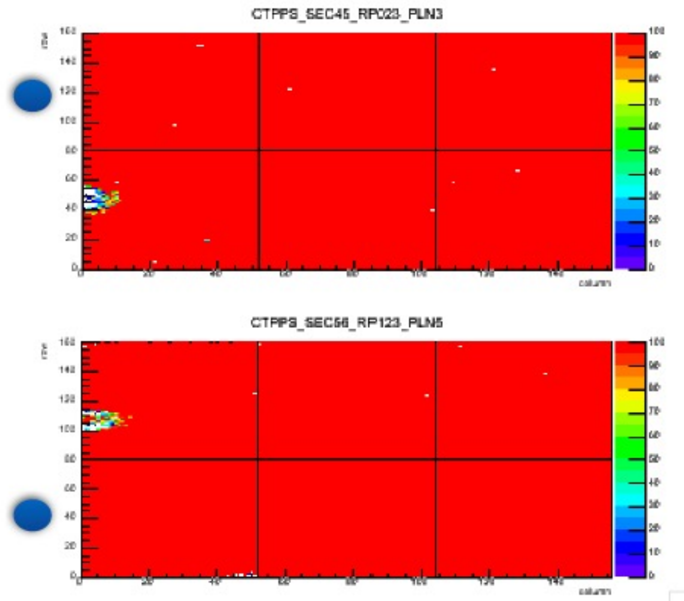
- PSI46dig, same as CMS Pixel Phase 1 upgrade
- Phase 1 DAQ components

Tracking: status and performance

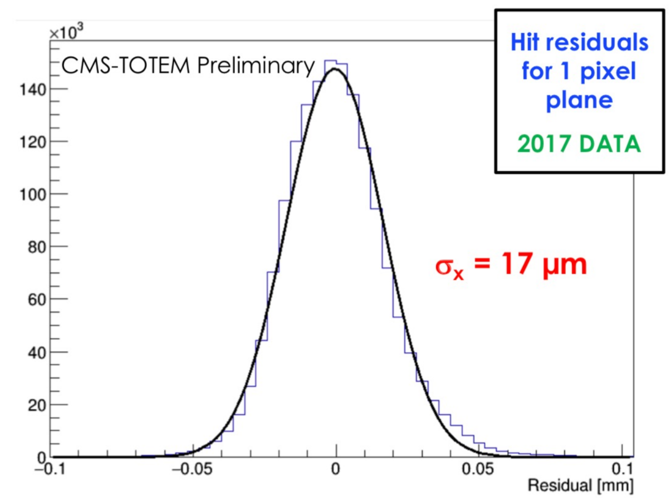
- Excellent performance of pixel detectors in 2017/2018
  - Track resolutions compatible with expectations
  - Average efficiency above 99%
  - Less than 0.05% bad/noisy pixels
- RP movement and BX shift to cope with radiation
- New detectors installed in 2018 (replacing strip detectors)
- Detector packages swapped btw 45 and 56 to minimize inefficiency

Beam in SEC45

Beam in SEC56

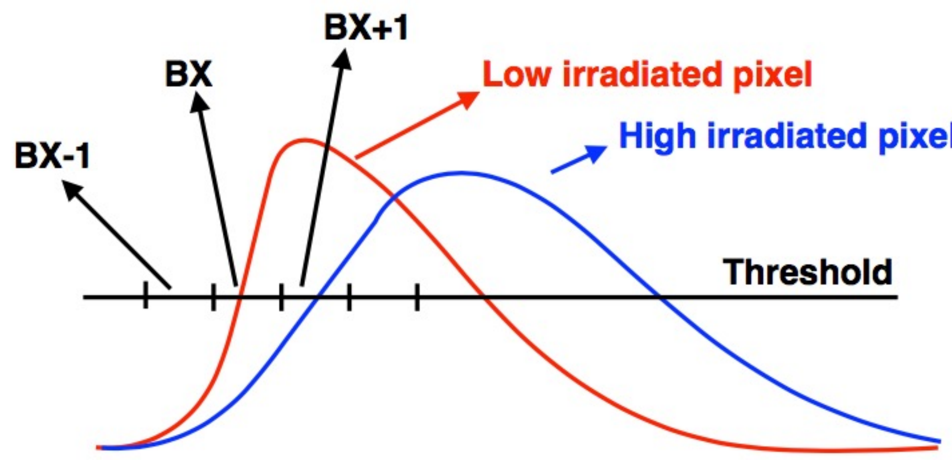


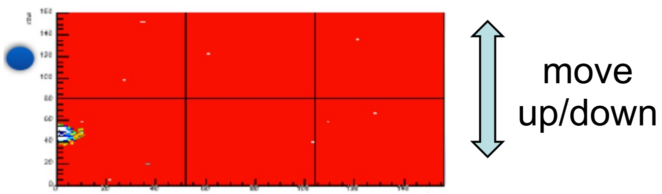
- Excellent spatial resolution, consistent with beam tests
- Single track events ~40%

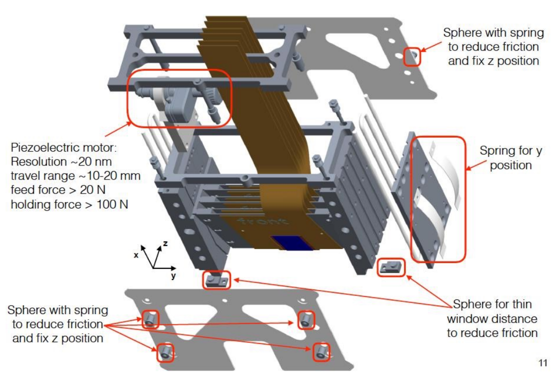


Tracking: Radiation

- Non-uniform irradiation
- Pixels not responding in same BX
- Effect due to readout chip





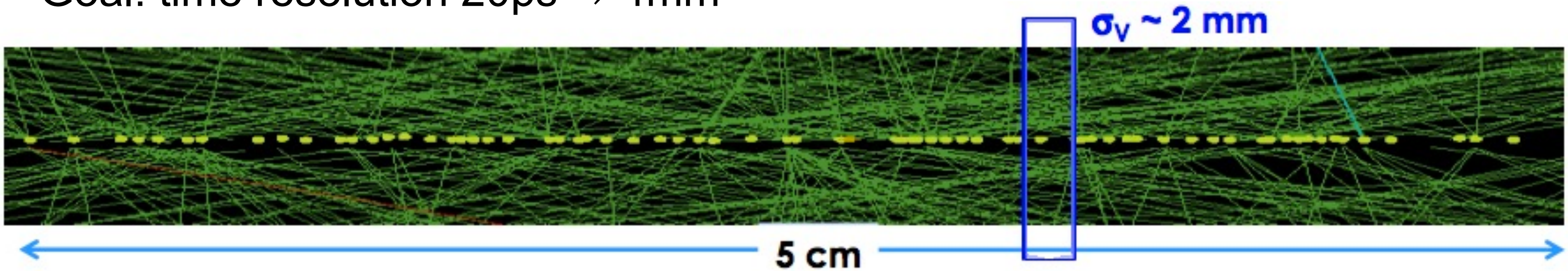


- Localized radiation damage near beam spot after ~10/fb
- Shift detector package to cope with radiation
- New stations with piezoelectric motor connected to detector package

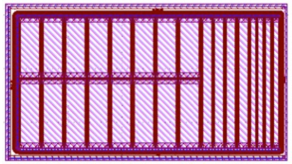
Timing detectors

Time-of-flight measurement to reject pileup bkg (uncorrelated proton tracks)

- Goal: time resolution 20ps ⇒ 4mm

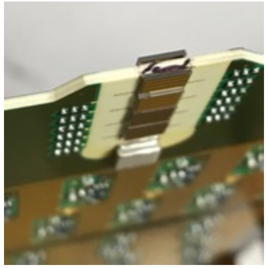


LGAD Silicon



- 1 plane (in 2017) per station
- Pixels of different sizes
- From test beam: single plane resolution ~30ps
- R&D to improve radiation hardness

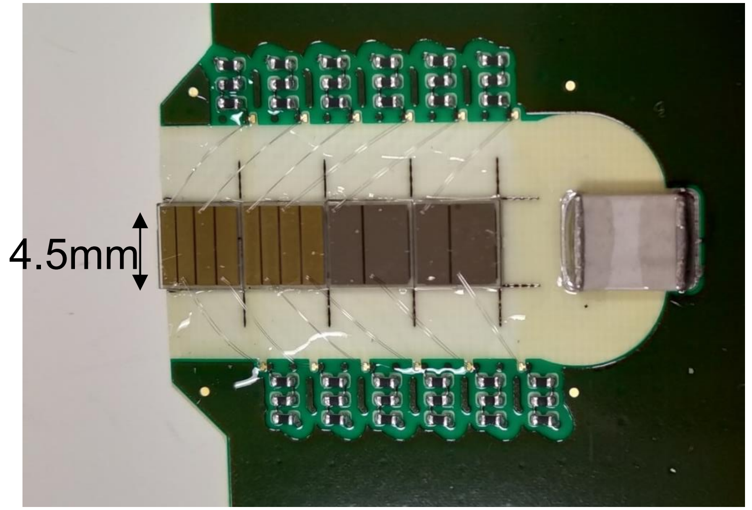
Diamonds

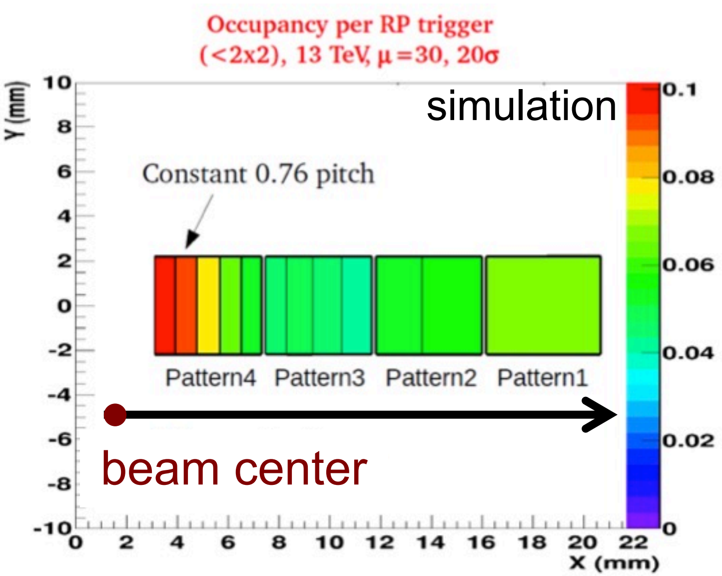


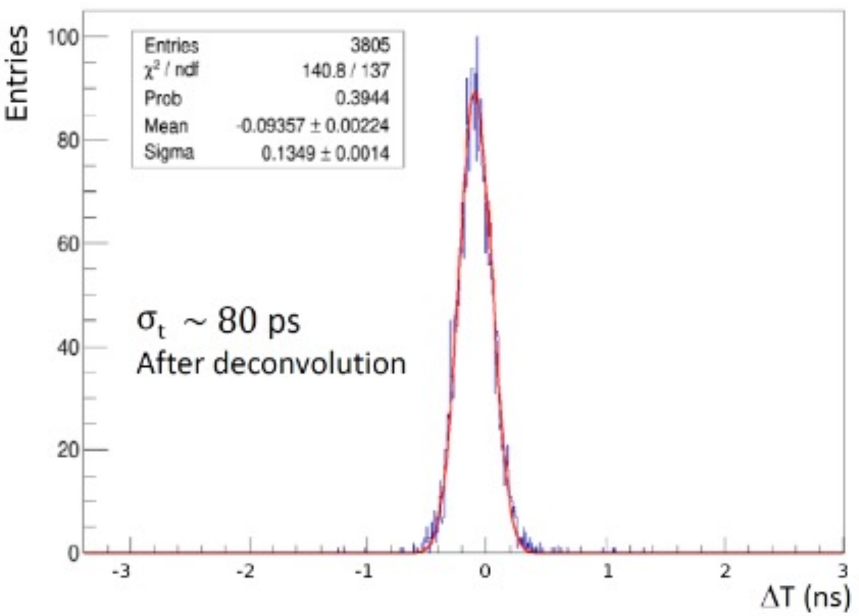
- 4 planes per station
- Pixels of different sizes
- Single plane resolution ~80ps
- Radiation hard

Diamond detectors

- Diamond detectors
  - Sensors based on single crystal CVD diamonds
  - σ_T~80ps per plane, i.e. ~50ps with 4 planes
  - Four 4x4mm^2 sensors per plane
  - Variable pad dimensions to optimize occupancy
- Custom-made readout electronics
- Intrinsic radiation hardness



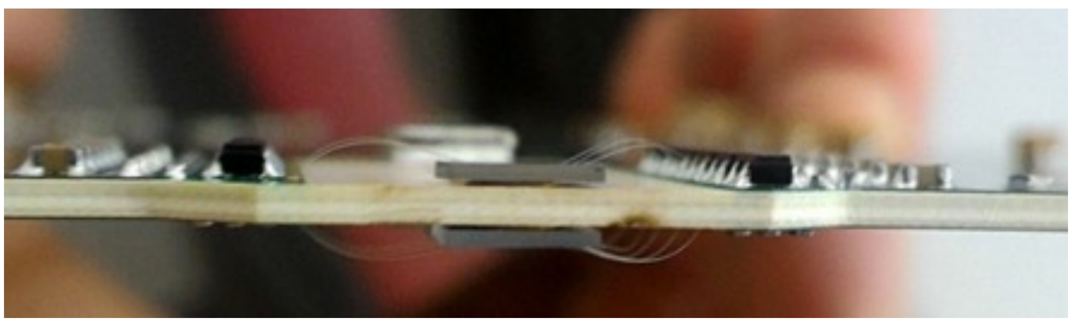


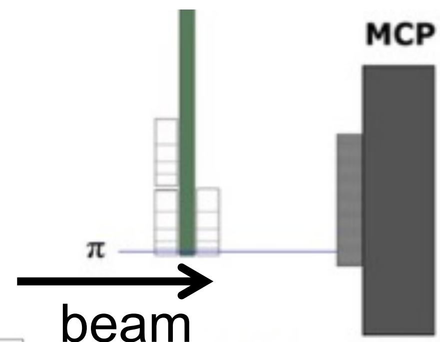


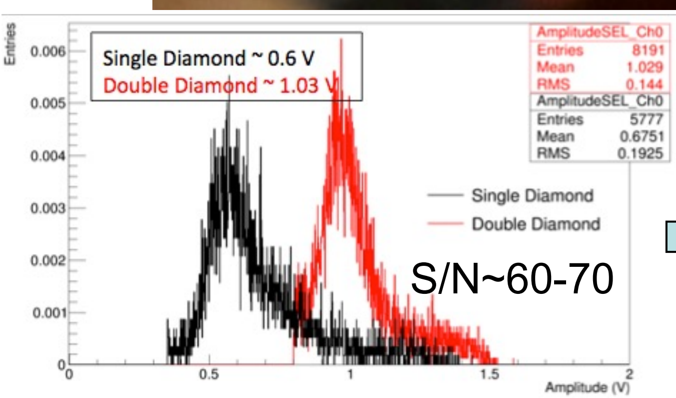
Double diamond layer

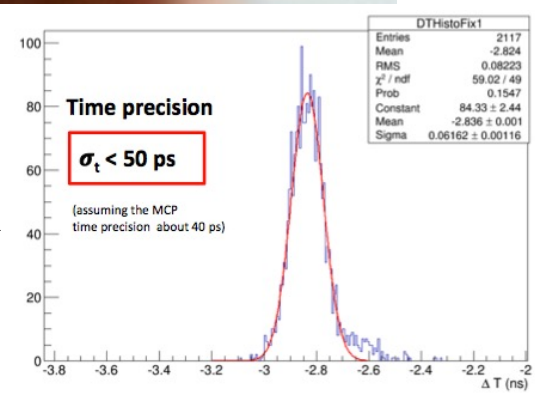
JINST12(2017)P03026

- Connected “sandwich” with two diamond sensors
- Beam tests in 2016/2017
- Performance improved (a factor of 1.7 wrt SD)
  - Larger signal amplitude dominant over extra capacitance
- With 4 diamond sandwich-planes could reach 25 ps



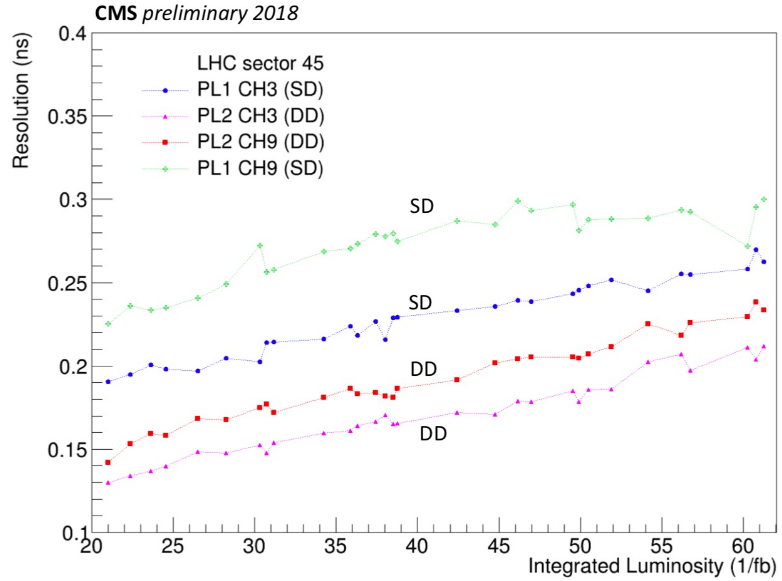


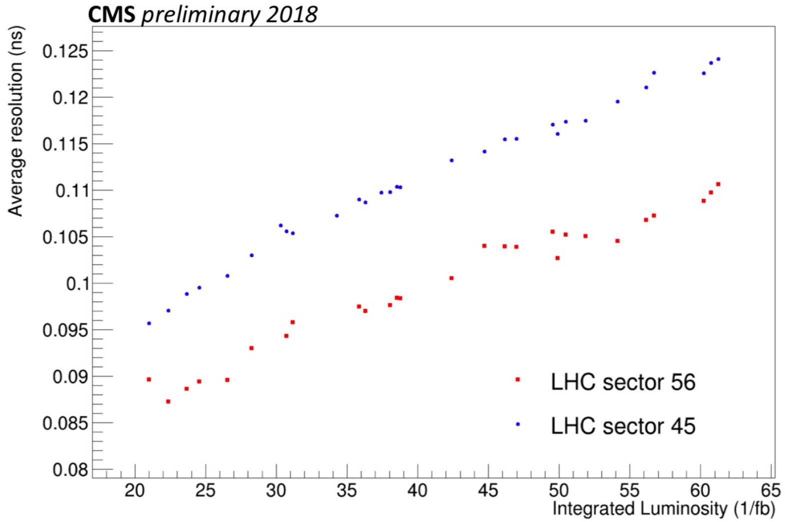




Timing: operation & calibration

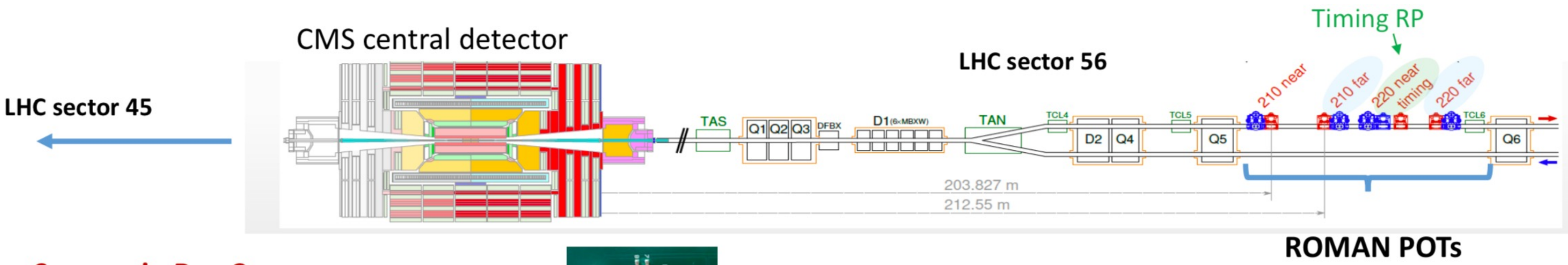
- Timing detectors installed in late 2016
  - Integrated luminosity in Run2 with timing ~100/fb
- Calibration
  - Correction of measured arrival time wrt ToT for each channel, independently
- Two types of degradation identified
  - due to radiation damage on sensors and electronics (pre-amp stage) close to beam
  - Localized damage on sensor in the most irradiated area (~1mm^2)
  - Can recover by raising LV on pre-amp stage (remote)
- Better resolution of DD by a factor of 1.7





The PPS detector

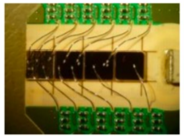
Symmetric experimental setup wrt interaction point

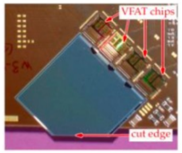


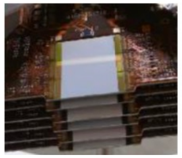
Sensors in Run 2

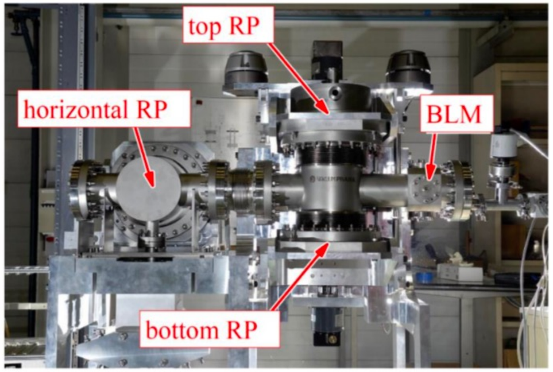
Timing
2016: 4 single diamond planes(SD)
2017: 3 single diamond and
1 UFSD planes
2018: 2 single and 2 double (DD) diamond planes

Tracking
2016: 2 TOTEM strip detector stations
2017: 1 strip and 1 3D pixel stations
2018: 2 3D pixel stations



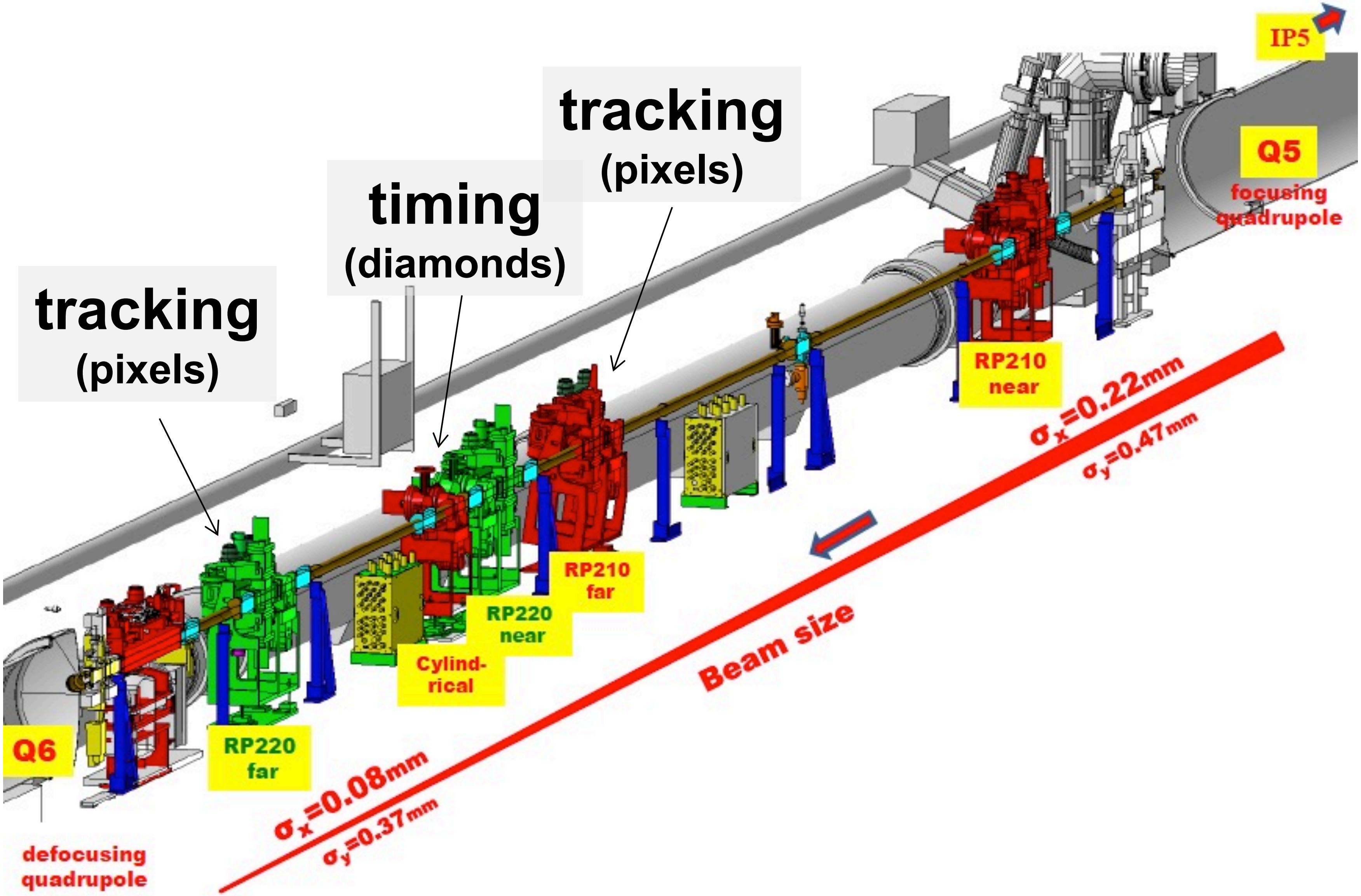




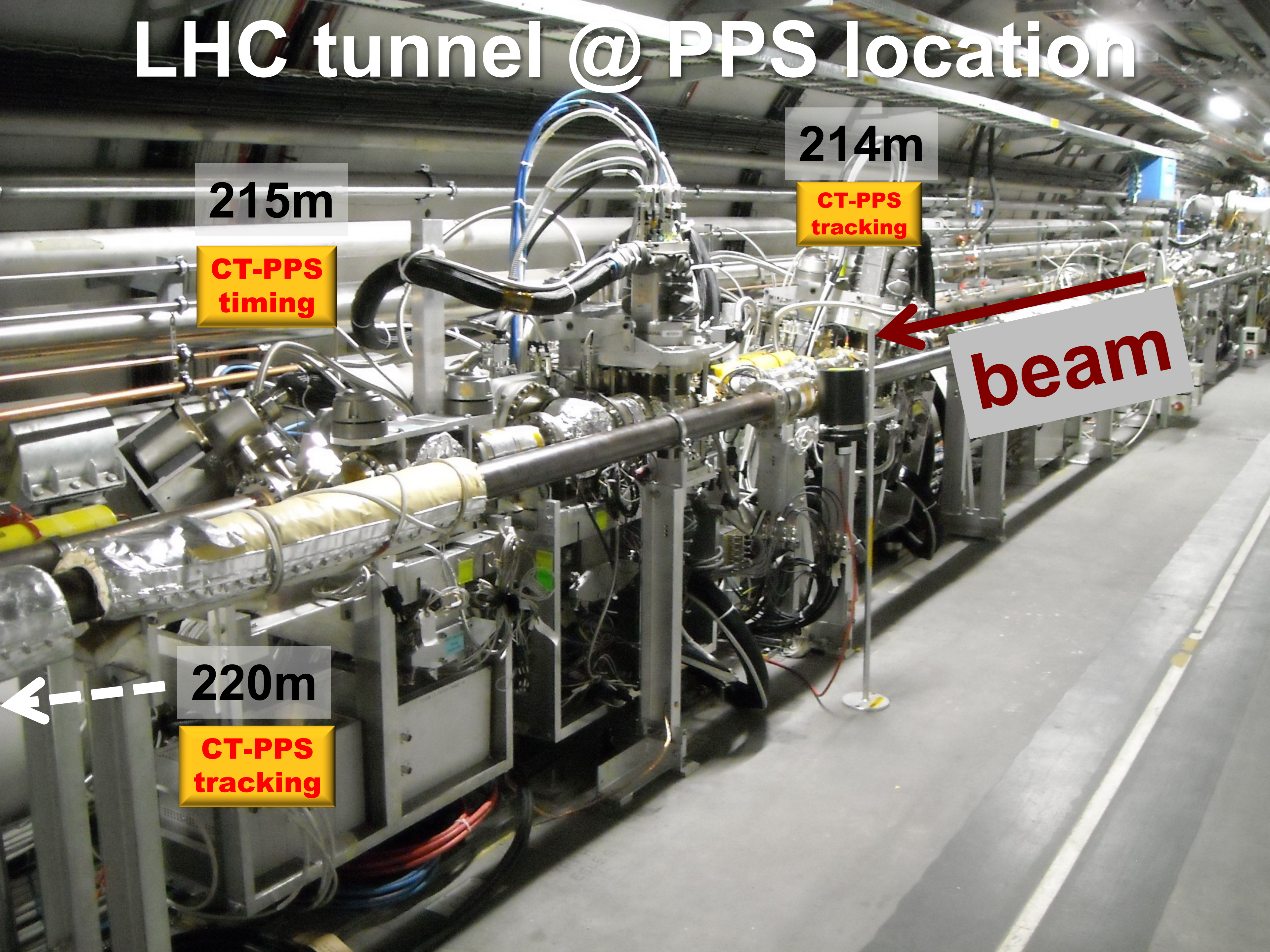


RP: Vacuum vessel entering the beam pipe, can be equipped with many types of detectors. Hosted detectors brought to few mm from LHC beam center.

PPS in 2018

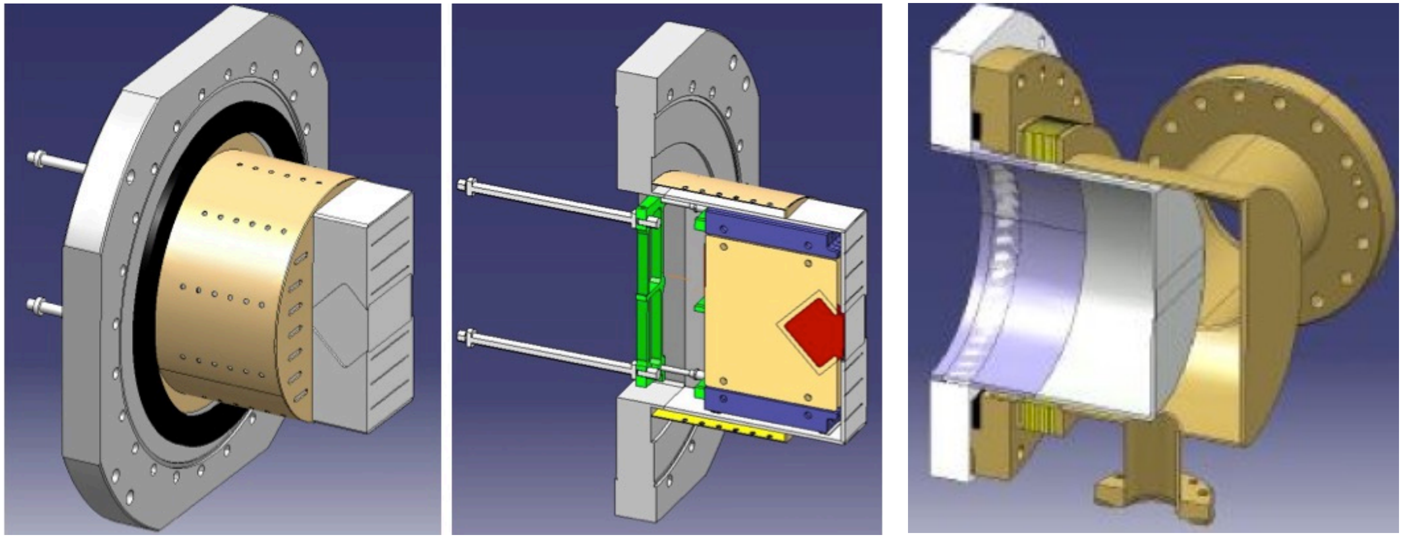

tracking
(pixels)
timing
(diamonds)
tracking
(pixels)
IP5
Q5
focusing
quadrupole
RP210
near
σ_x=0.22mm
σ_y=0.47mm
RP210
far
RP220
near
Cylind-
rical
Beam size
Q6
RP220
far
σ_x=0.08mm
σ_y=0.37mm
defocusing
quadrupole

LHC tunnel @ PPS location

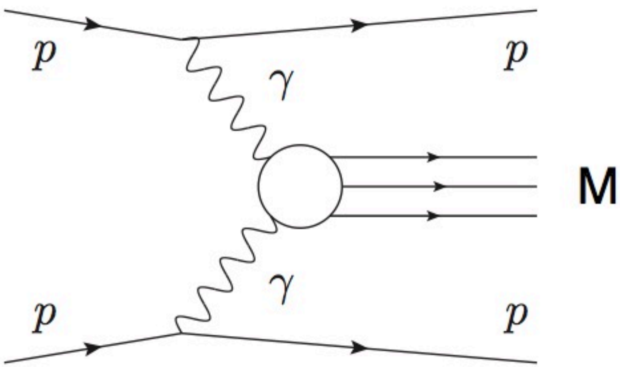


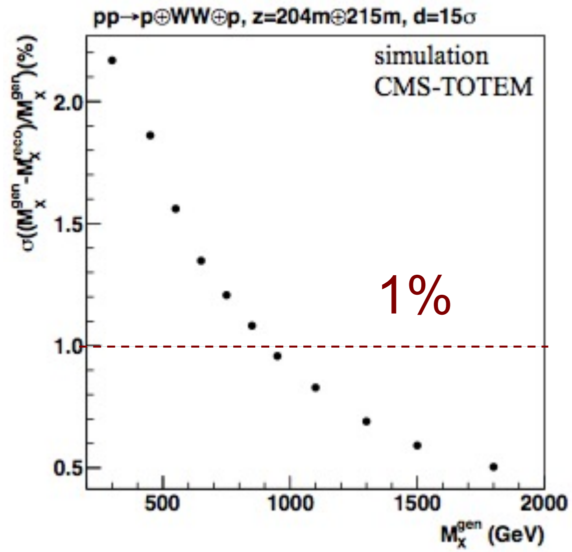
Roman Pot insertion

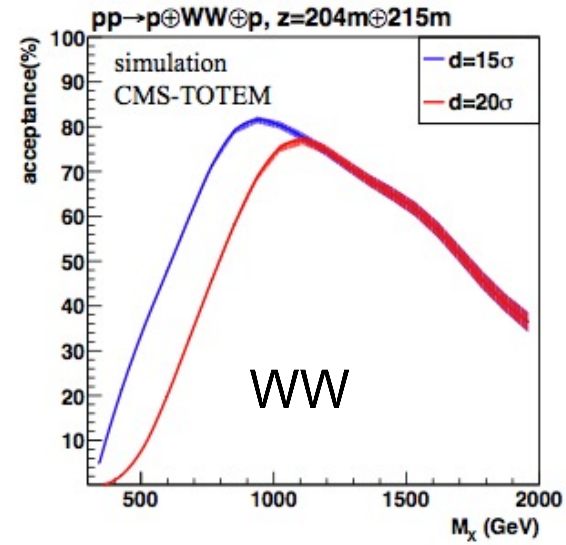
- Insertion procedure validated in 2016 by the LHC
  - Improvements carried out wrt earlier versions (RF shielding, cylindrical pots, ferrite, copper coating)
- Minimum distance of approach dramatically affects detector acceptance and physics reach
- A few mm ($\sim 15\sigma$) from beam in nominal high-luminosity runs
  - Monitor beam losses, showers, interplay with collimators, beam impedance (heating, vacuum and beam orbit stability)

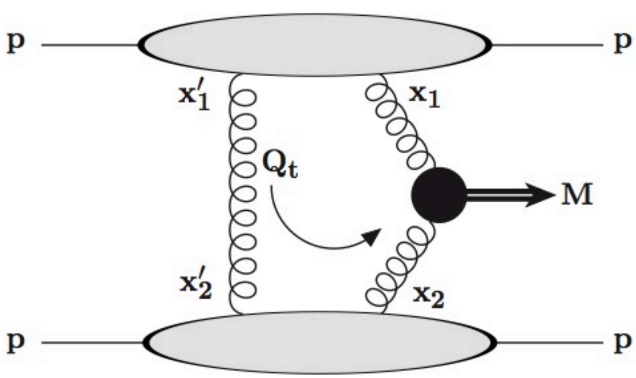


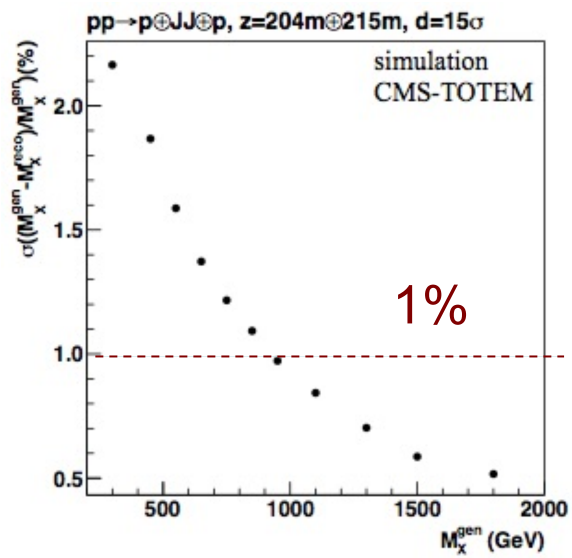
Mass acceptance and resolution

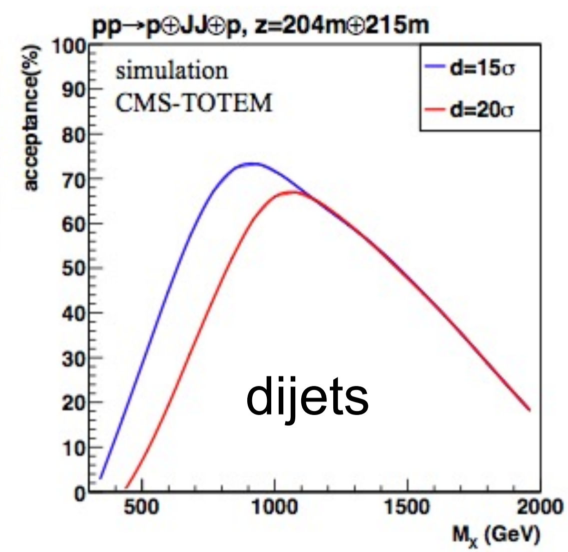




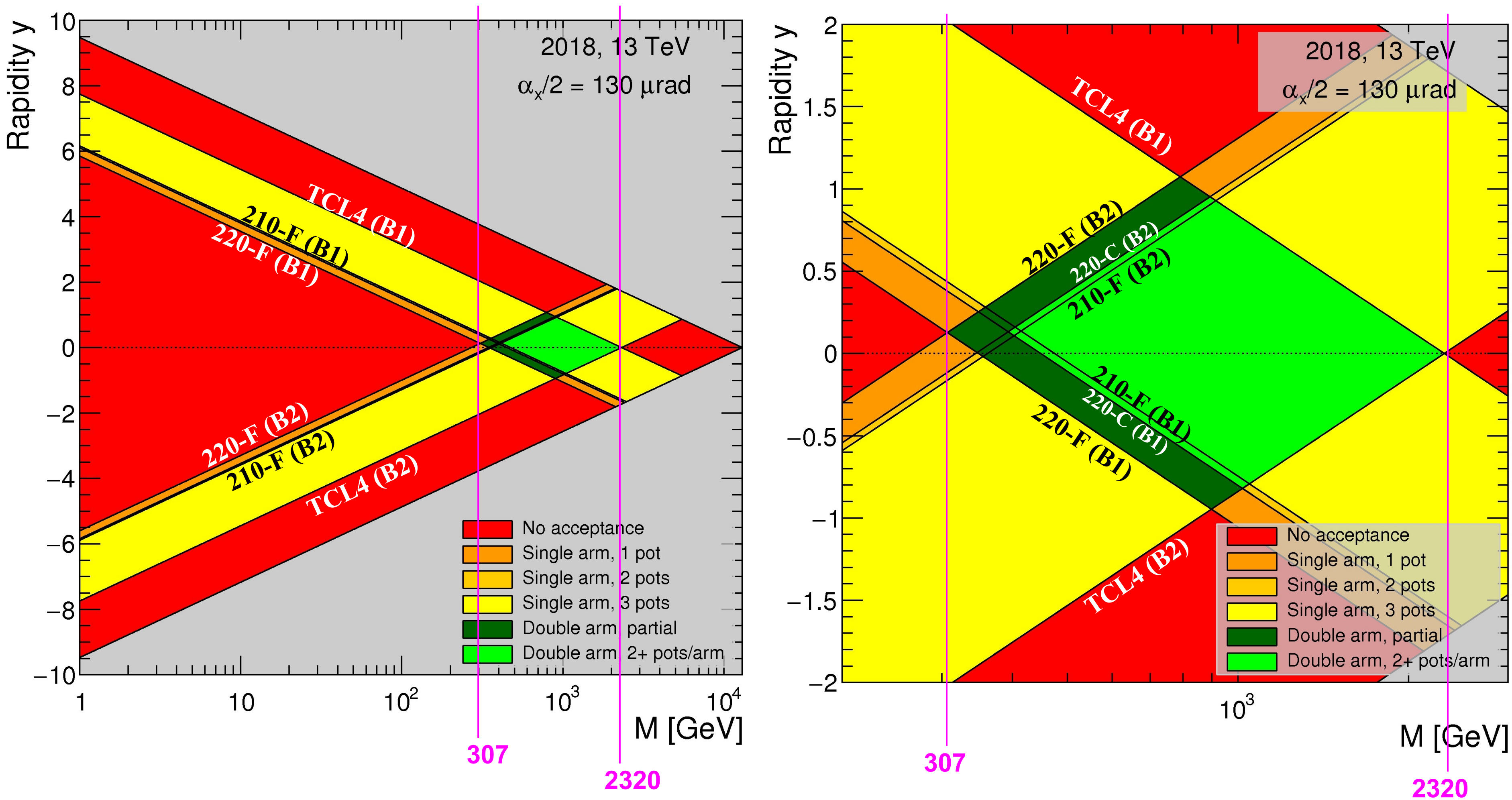






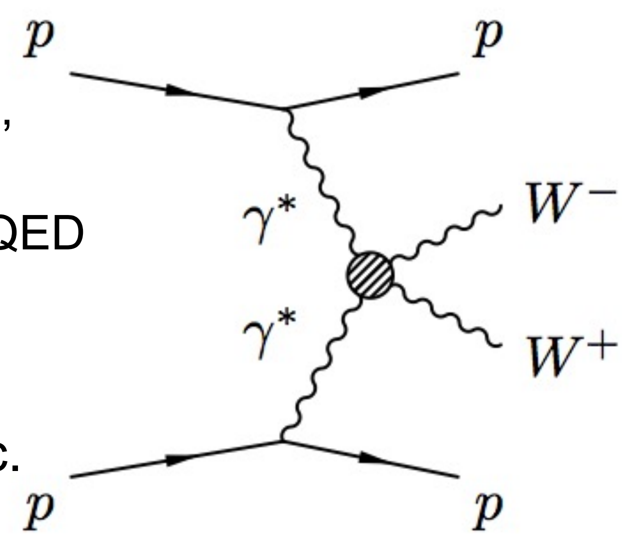


RP Acceptance in 2018

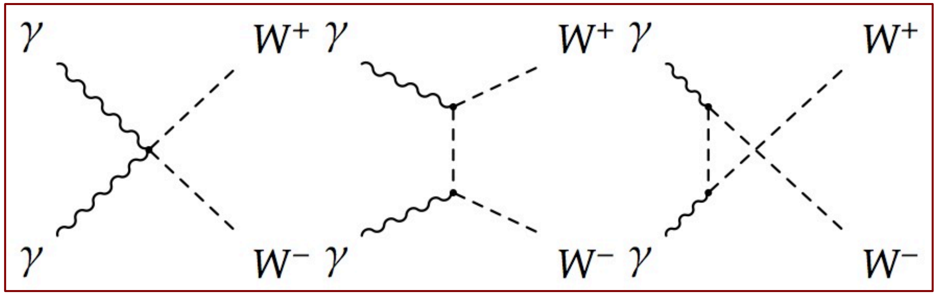


Prospects: WW production

- pp→pWWp
  - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known



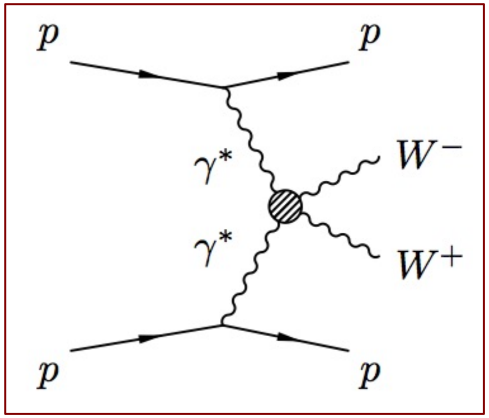
- Backgrounds:
  - inclusive WW, $\tau\tau$, exclusive two-photon $\gamma\gamma\rightarrow \ell\ell$, etc.
- Events:
  - WW pair in central detector, leading protons in PPS
- SM observation of WW events
- Anomalous couplings
  - predicted in BSM theories
  - parameters: a_0^W/Λ^2, a_C^W/Λ^2

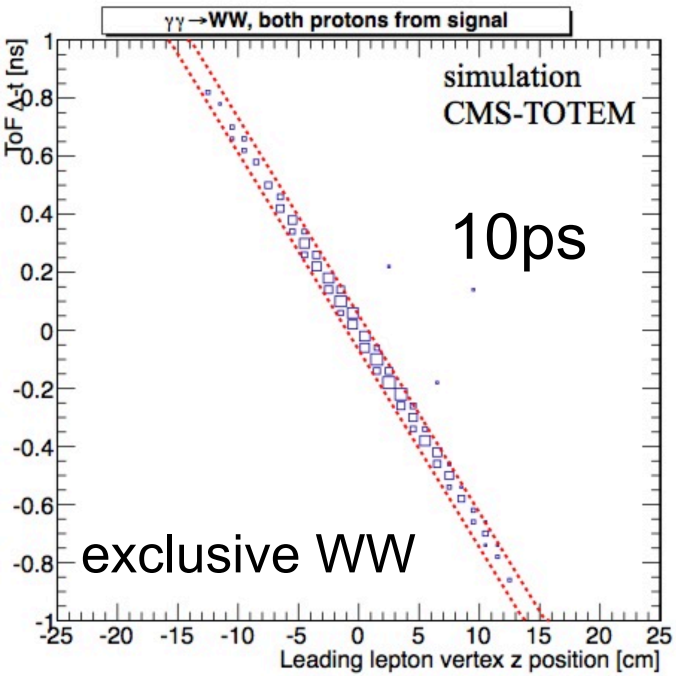


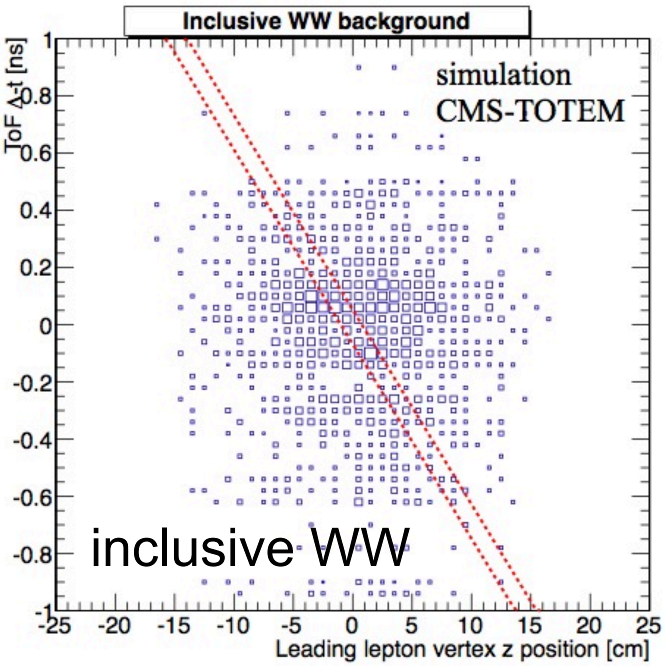
- Deviations from SM can be large

Prospects: anomalous couplings

- Allowed in SM via charged triple and quartic gauge couplings
- Sensitive to BSM contributions in high-mass tails







- Leptonic channels cleanest, but neutrinos prevent clear mass/rapidity matching
- time difference of two protons correlated with vertex position

Proton reconstruction

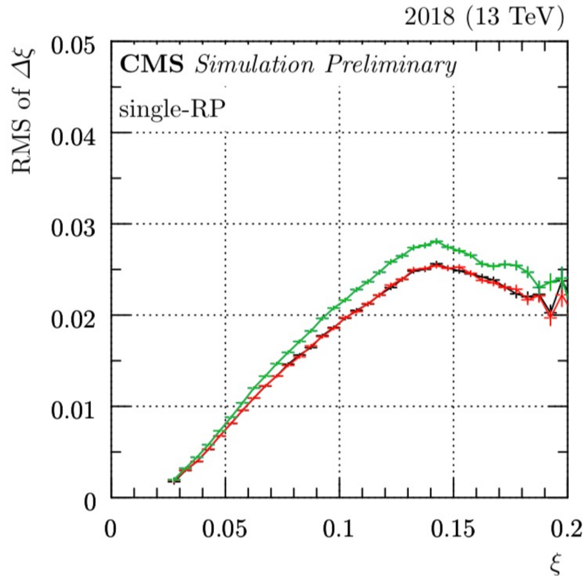
CMS-PRO-21-001

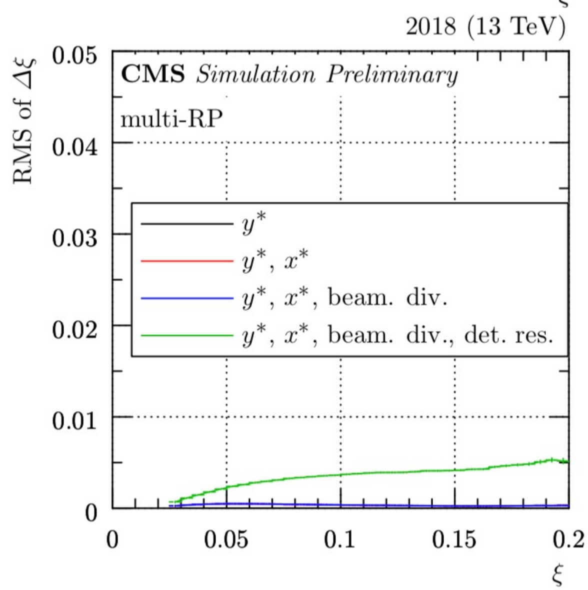
Single-RP: treats each tracking RP as a separate detector

- 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





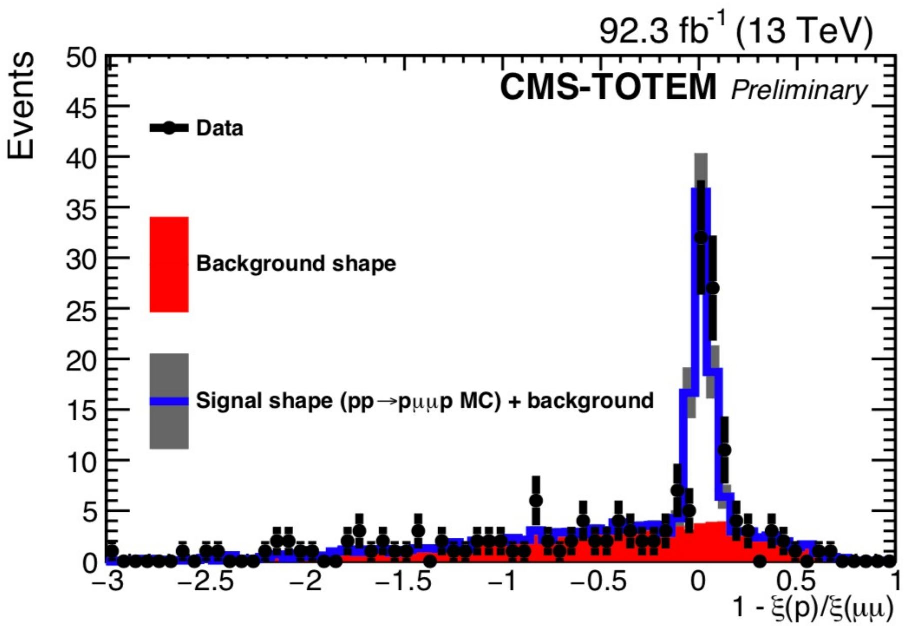
Resolution

CMS-PRO-21-001

Multi-RP ξ resolution

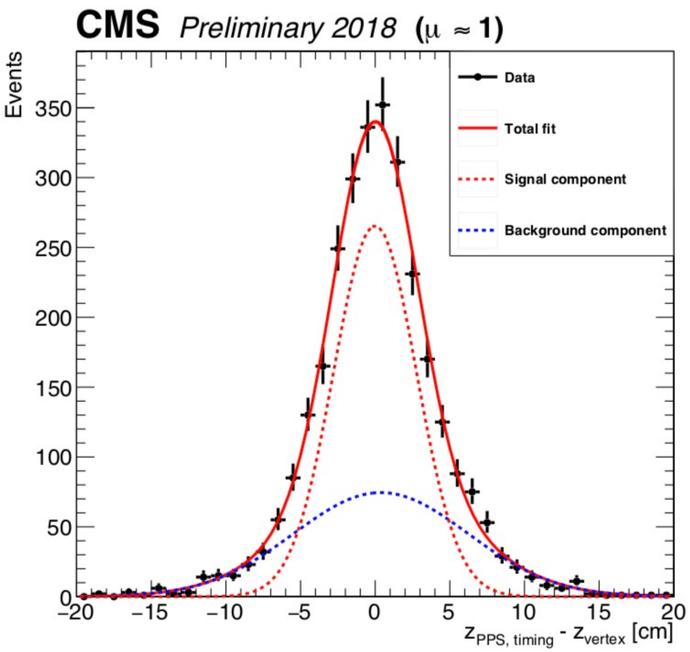
- Exclusive dimuon events
- One-dimensional projections of the correlation between ξ(p) and $\xi(\mu+\mu-)$

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

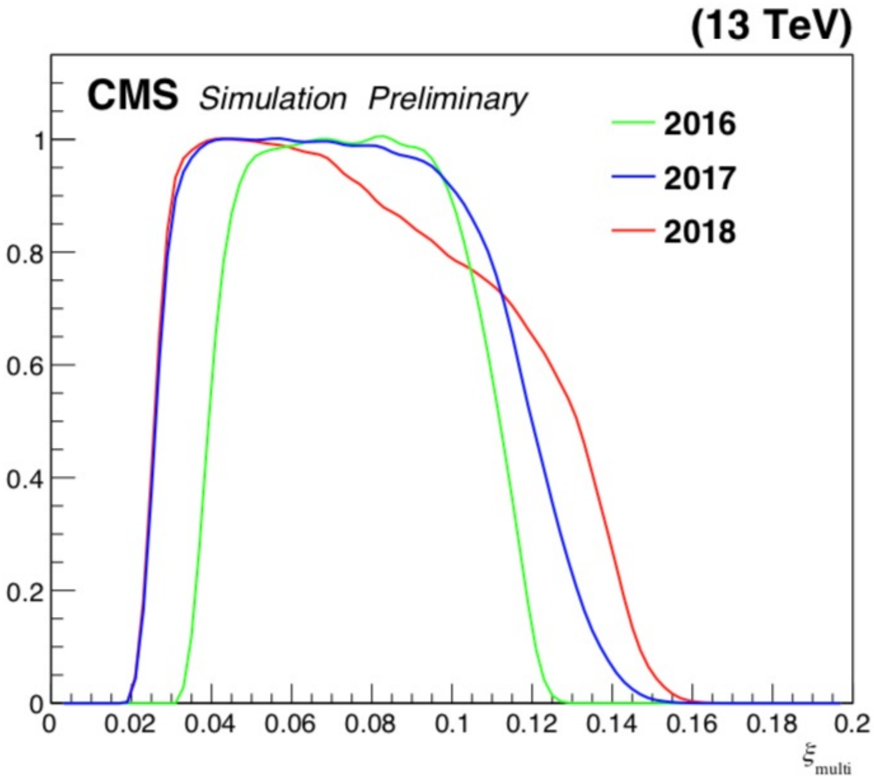


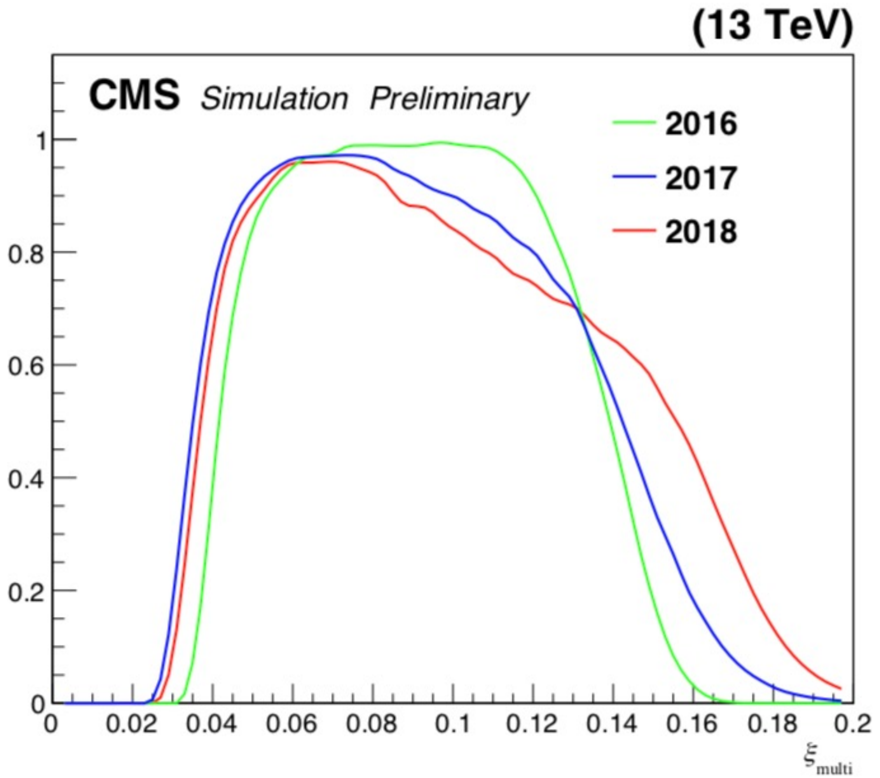
Timing resolution

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



Detector acceptance



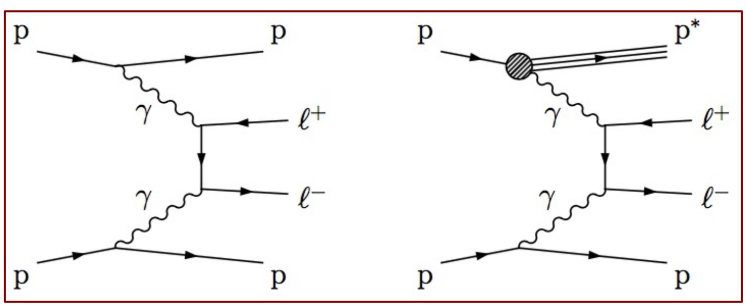


Exclusive dilepton production

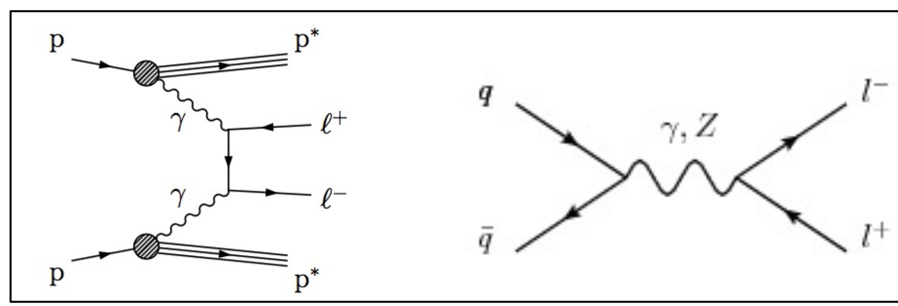
arXiv:1803.04496

- Exclusive processes at the EWK scale
- Study SM candle process: $\gamma\gamma \rightarrow \ell\ell$
- 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



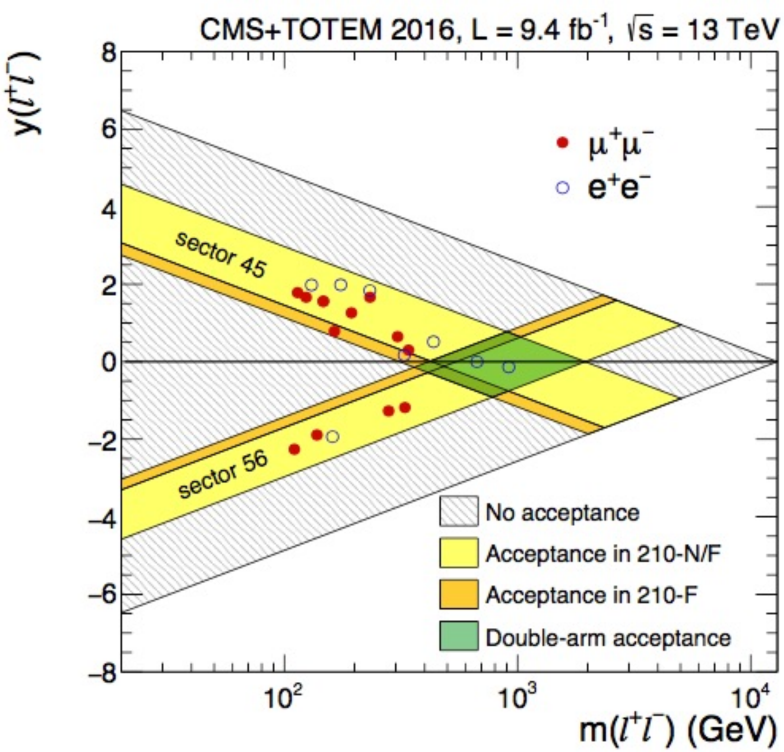
bkg: overlapping with PU protons or beam bkg

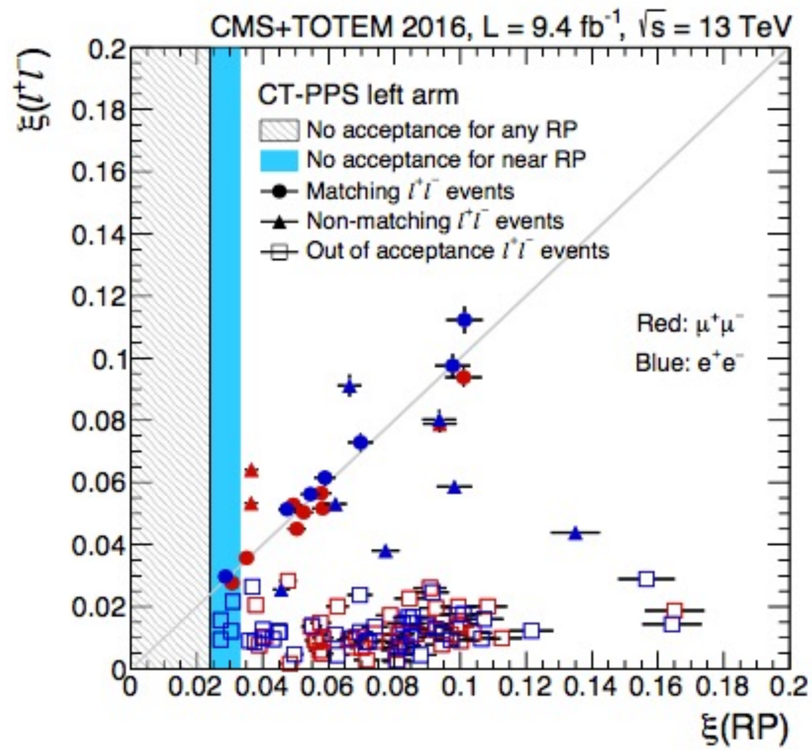


Exclusive dilepton production

arXiv:1803.04496

- 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



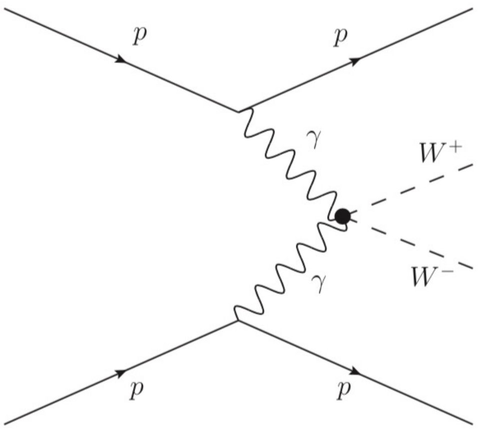


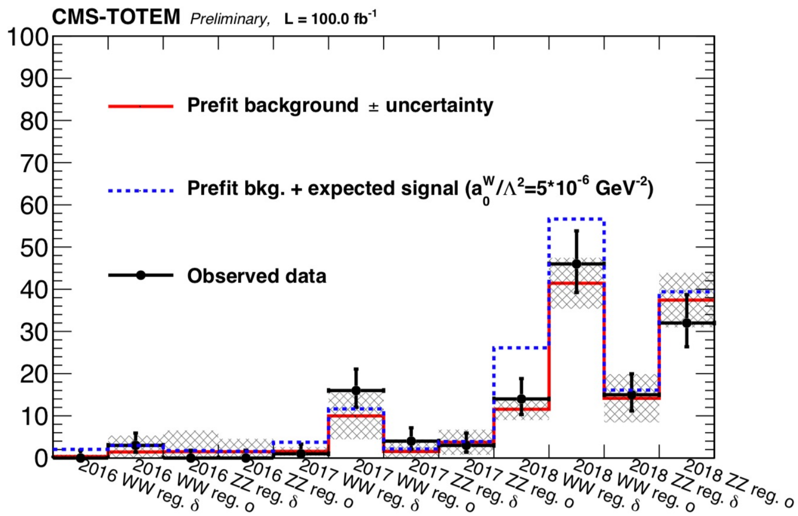
Exclusive VV (V=W,Z)

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
  - Boosted/merged quark jets
  - Both tagged protons
  - Large multi-jet background
  - compute mass match ratio and rapidity difference

$$1 - m_{VV}/m_{pp}, \text{ where : } m_{pp} = \sqrt{s \cdot \xi_1 \xi_2}$$
$$y_{VV} - y_{pp}, \text{ where : } y_{pp} = 1/2 \log\left(\xi_1/\xi_2\right)$$

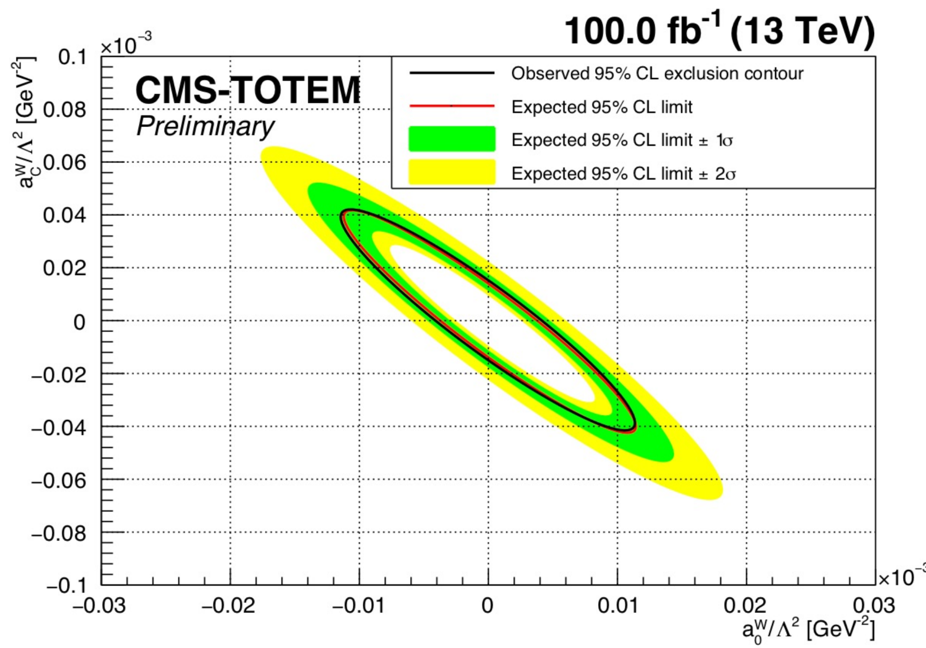




Exclusive VV (cont.)

CMS-SMP-21-014

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



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

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

Exclusive top quark pairs

CMS-TOP-21-007

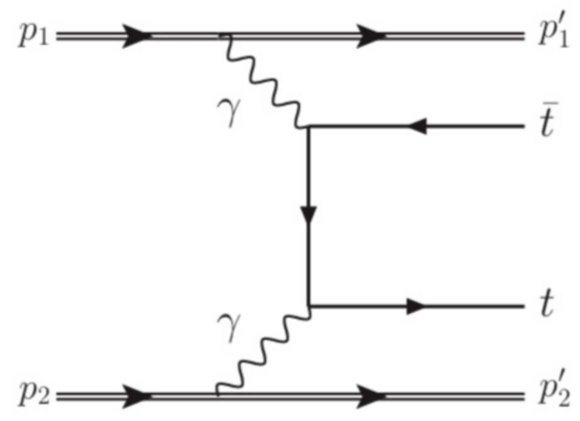
Top quark pair production in $\gamma\gamma$ interaction

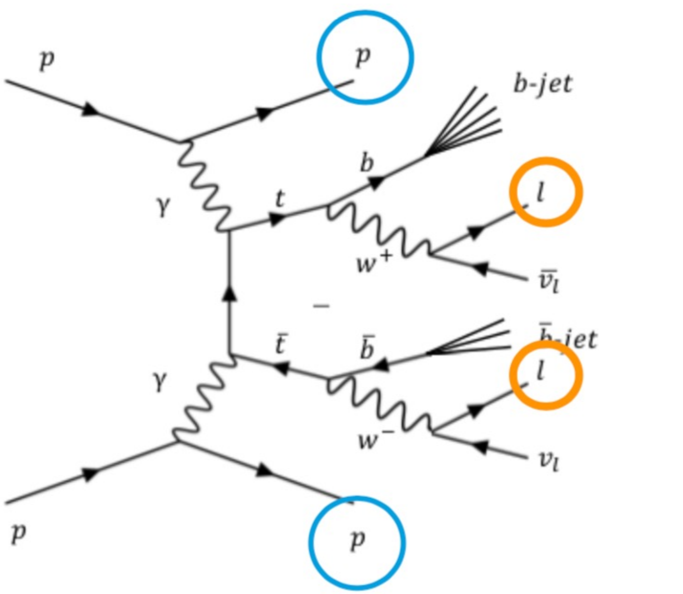
- Small x-section O(1fb)
- Sensitive to top-photon coupling
- First search of this process

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

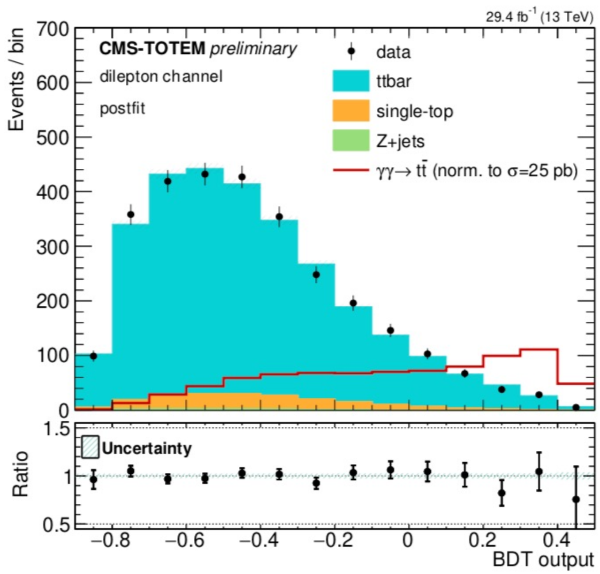
$$\xi_i = \frac{|\vec{p_f}| - |\vec{p_i}|}{|\vec{p_i}|} \qquad M_X = \sqrt{s\xi_1\xi_2}$$

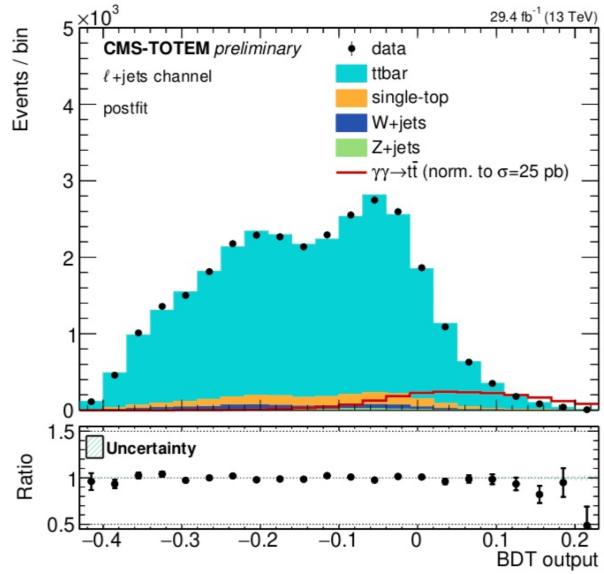




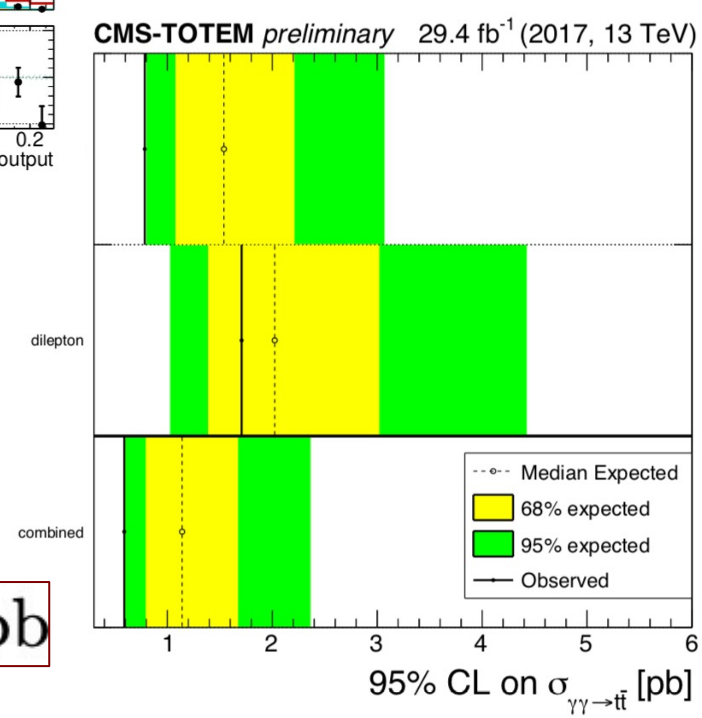
Exclusive top quark pairs (cont.)

CMS-TOP-21-007





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



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

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

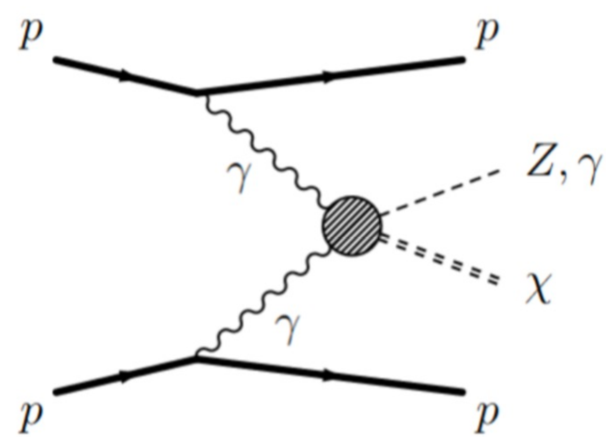
Exclusive Z/γ+X

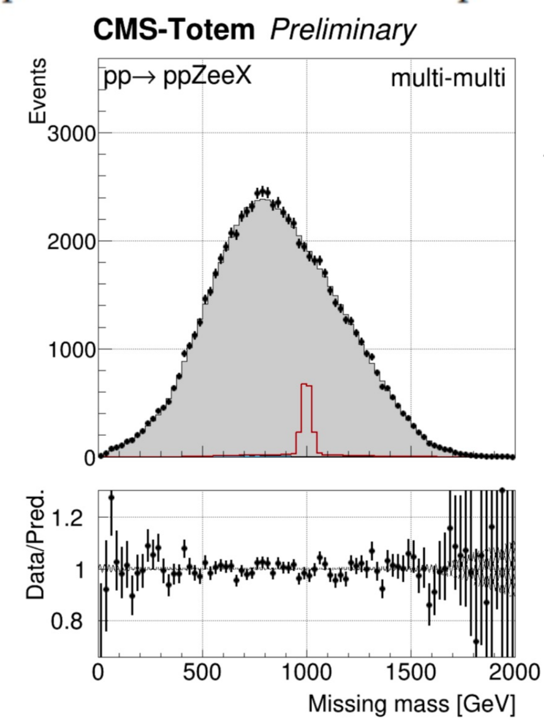
CMS-EXO-19-009

- 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

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

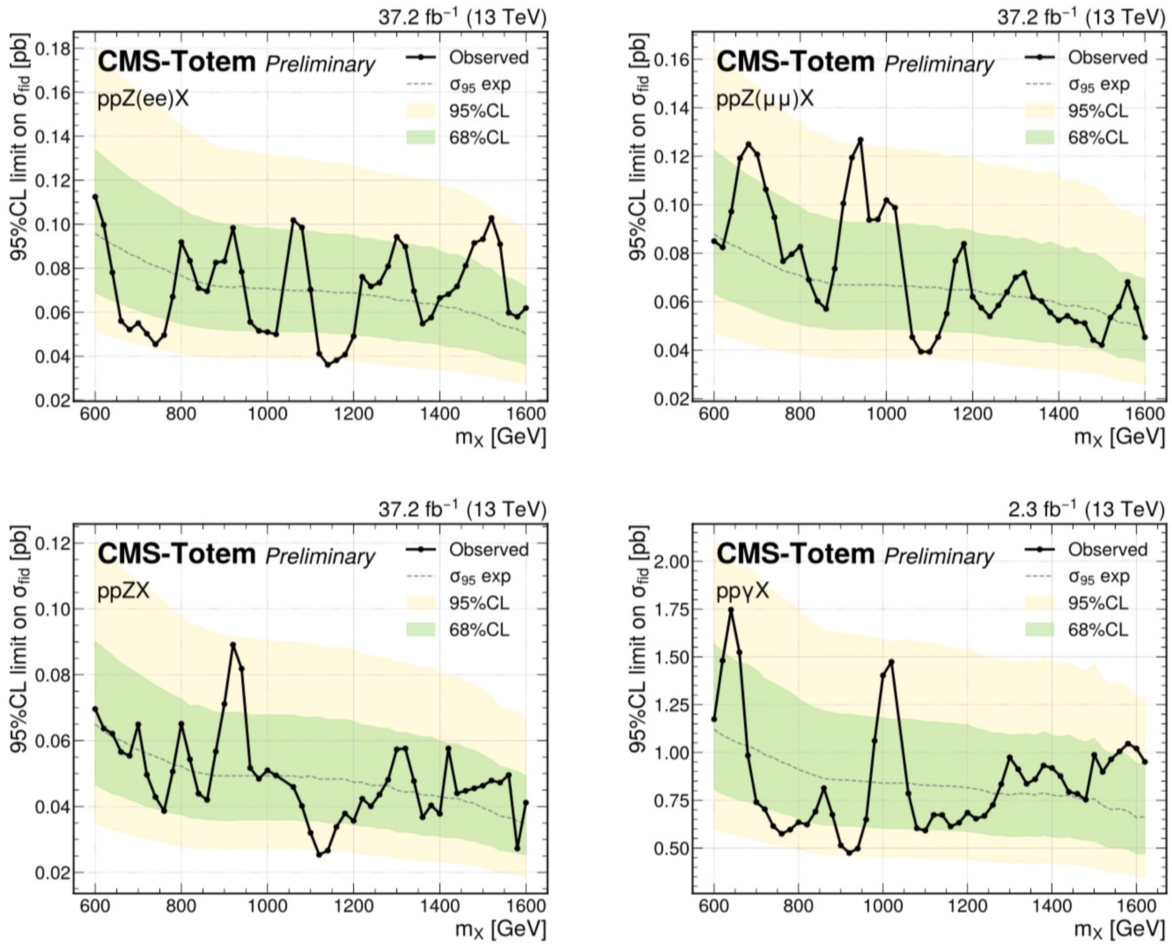
  - Look for weakly-interacting BSM particle
  - Relatively unknown region (600-1600GeV)
- Use Z leptonic decay or photon
  - Background mostly from random coincidence with PU protons
  - Use different proton categories (multi-multi, multi-single, single-multi and single-single methods)





Exclusive Z/γ+X (cont.)

CMS-EXO-19-009

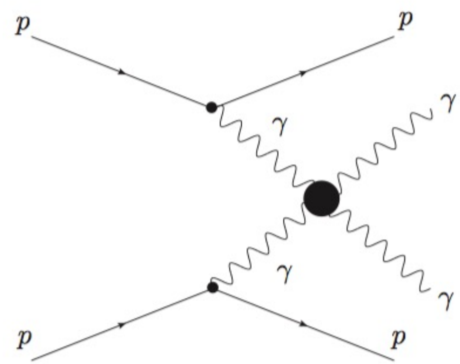


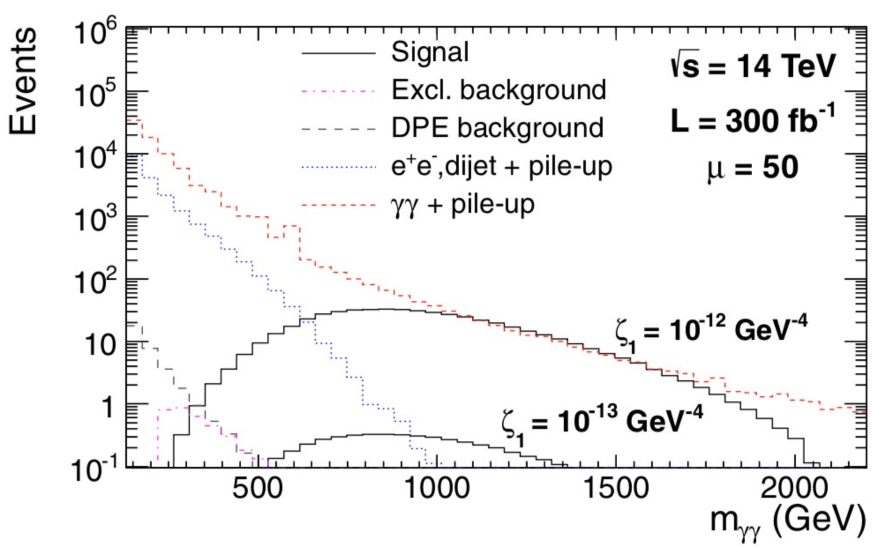
- No significant local excess/deficit of events observed

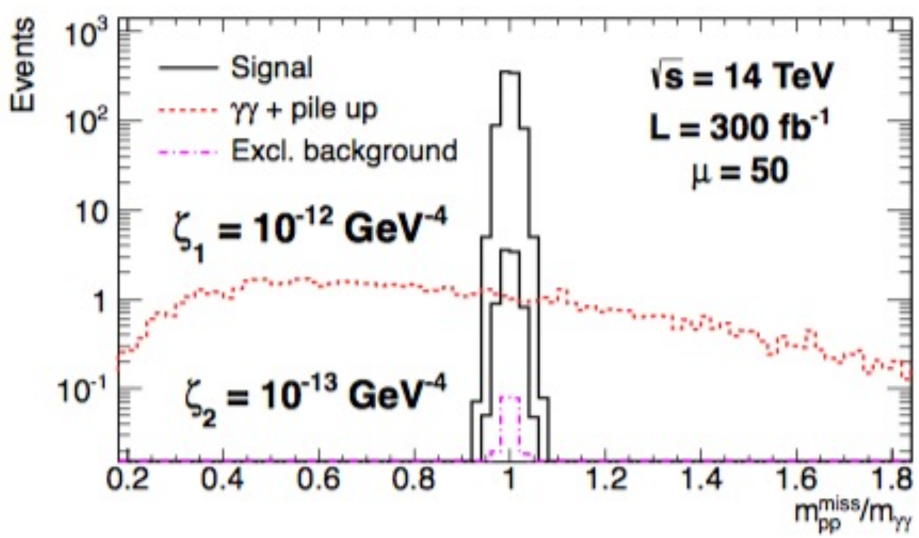
$\gamma\gamma \to \gamma\gamma$: Anomalous couplings, etc.

PRD 89(2014)114004

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





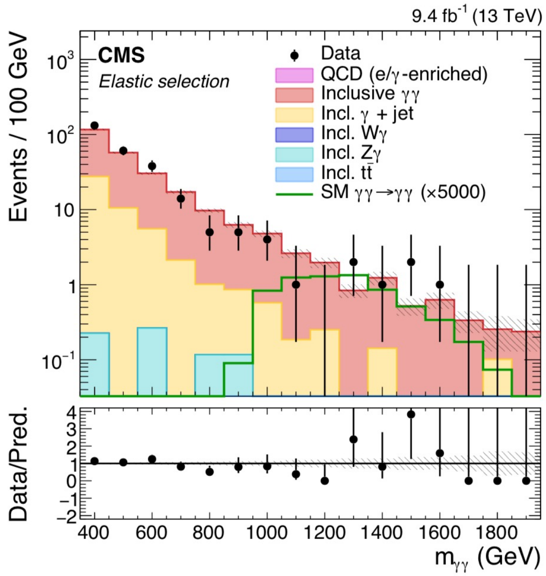


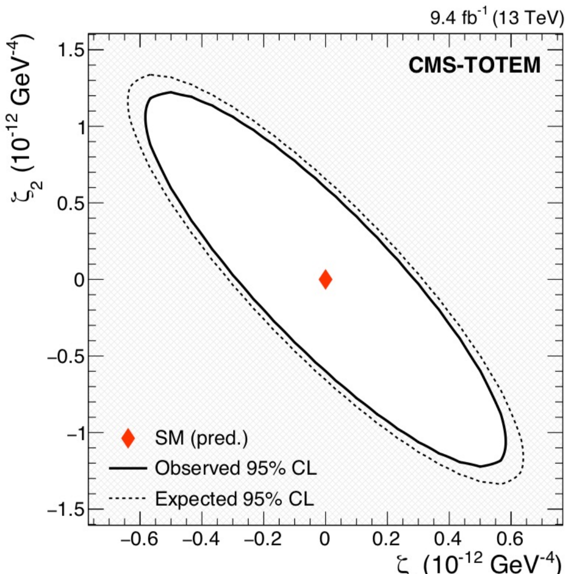
Exclusive $\gamma\gamma$ production

arXiv:2110.05916

- Light-by-light scattering
  - Study $m_{\gamma\gamma}$ > 350 GeV
  - Matching mass & rapidity: pp vs $\gamma\gamma$
  - No events observed
  - Expected bkg: 0.2(0.4) @2(3)σ
- Set limits on $\gamma\gamma$ scattering
  - First direct limits on anomalous couplings (four photon interation):

$$|\zeta_1| < 2.88 \times 10^{-13}\,\mathrm{GeV}^{-4} (\zeta_2 = 0)$$
$$|\zeta_2| < 6.02 \times 10^{-13}\,\mathrm{GeV}^{-4} (\zeta_1 = 0)$$

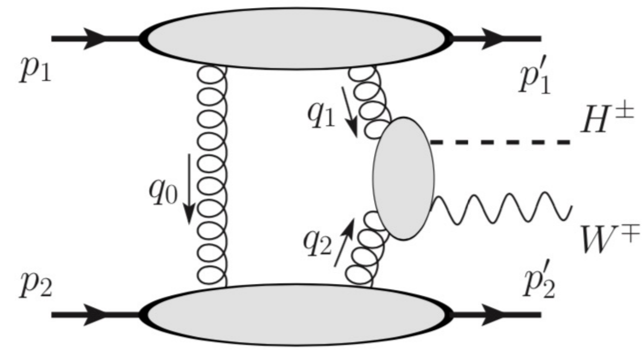


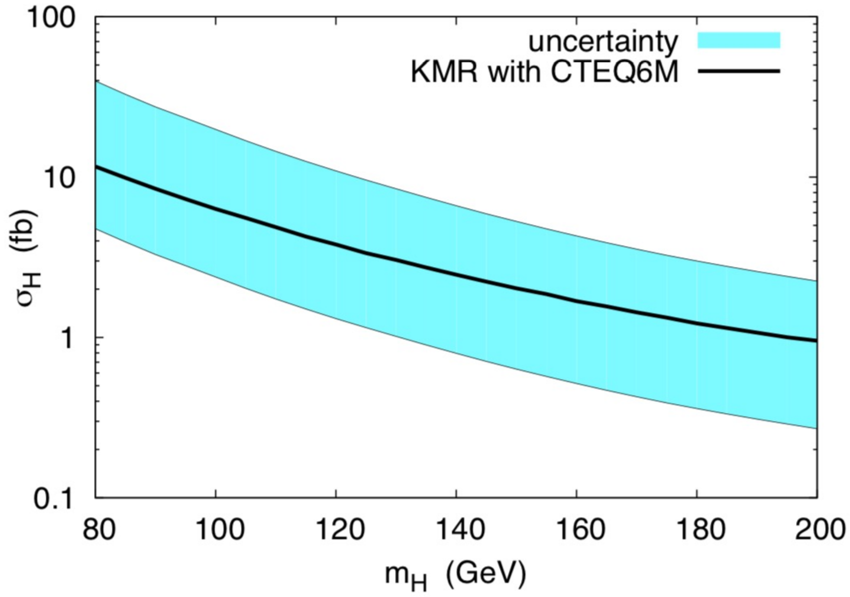


Associated $W^{\mp} H^{\pm}$

arXiv:1104.0889

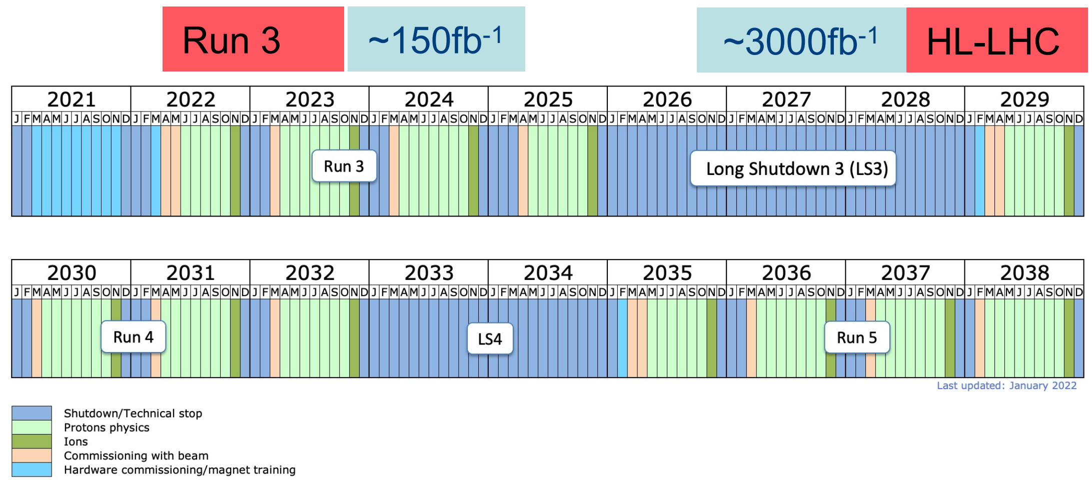
- Central exclusive production of a charged Higgs boson in association with a W boson as a possible signature of certain types of extended Higgs sectors
- $W^{\mp}$ and $H^{\pm}$ expected to be back-to-back

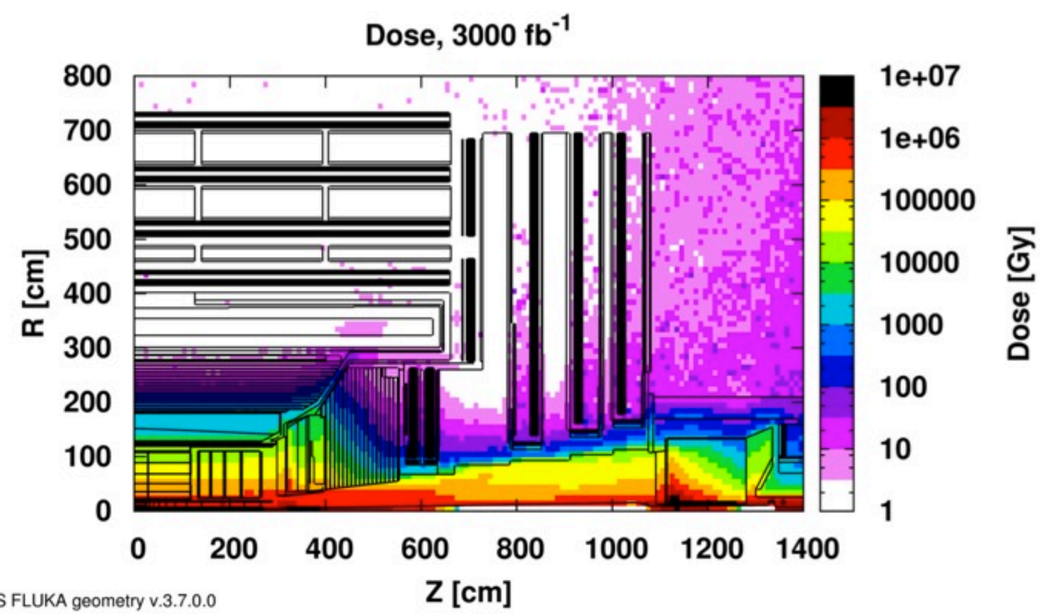




Prospects for Run3 and beyond

- 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 $2x10^{35}cm^{-2}s^{-1}$
  - pileup will be ~150 or higher (Phase2)
  - large radiation doses



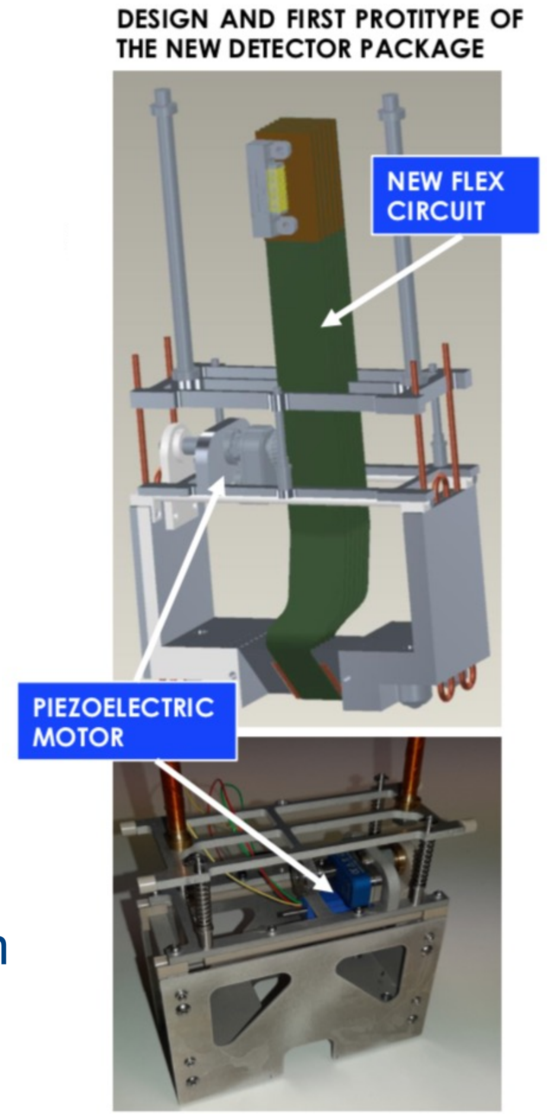


Prospects for Run3: Tracking

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: PROC600 (same as layer 1 of CMS pixel detector)
- New flex circuit design (different “look” but similar design)
- 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

- Optimize timing measurement in Run3
  - Aim at 50ps/plane (8 planes/arm)
  - Install and instrument a 2nd timing RP
  - Use 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

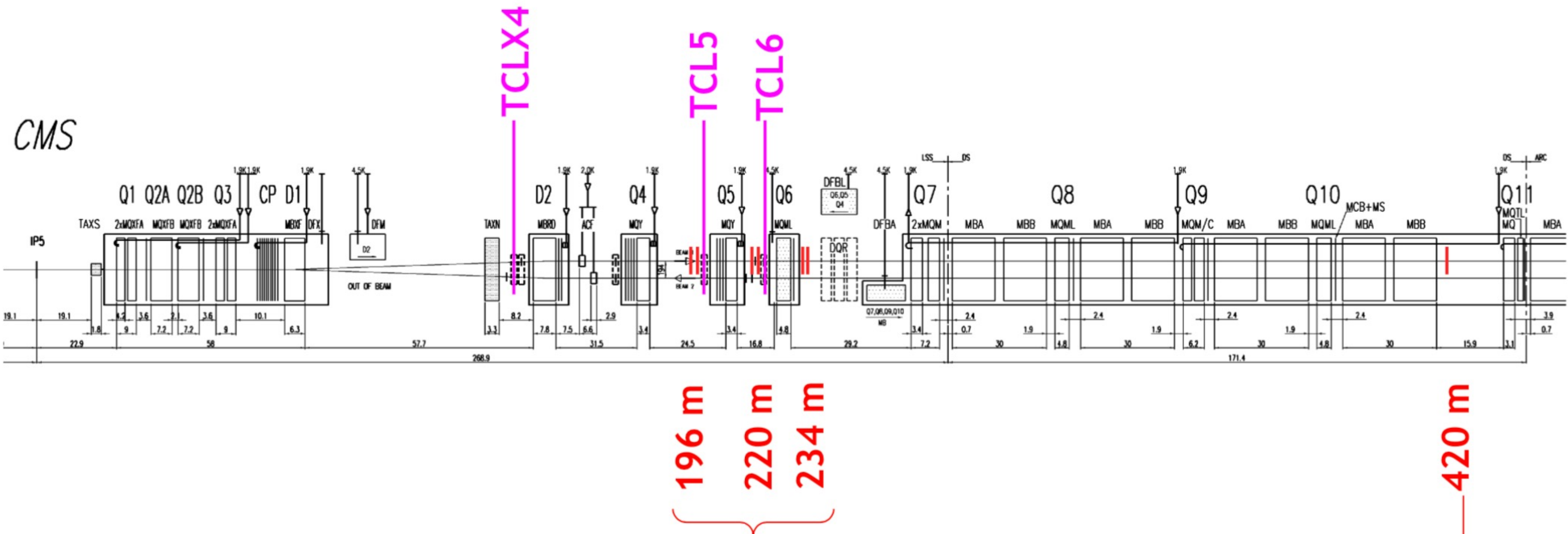
The CMS Collaboration intends to pursue the study of central exclusive production (CEP) events, pp → pXp, at the High-Luminosity LHC (HL-LHC) by means of a new near-beam proton spectrometer. In CEP events, the state X is produced at central rapidities, and the scattered protons do not leave the beam 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.

PPS@HL-LHC: Run4 and beyond

- After Run3 all RPs must be removed to allow for reconfiguration of HL-LHC
- Layout of proposed RP stations

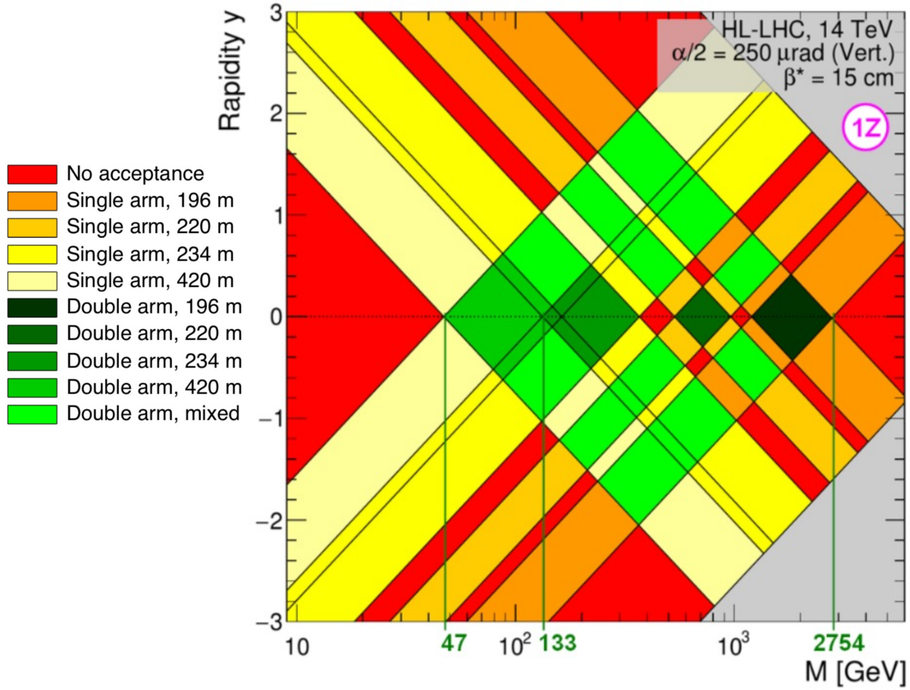


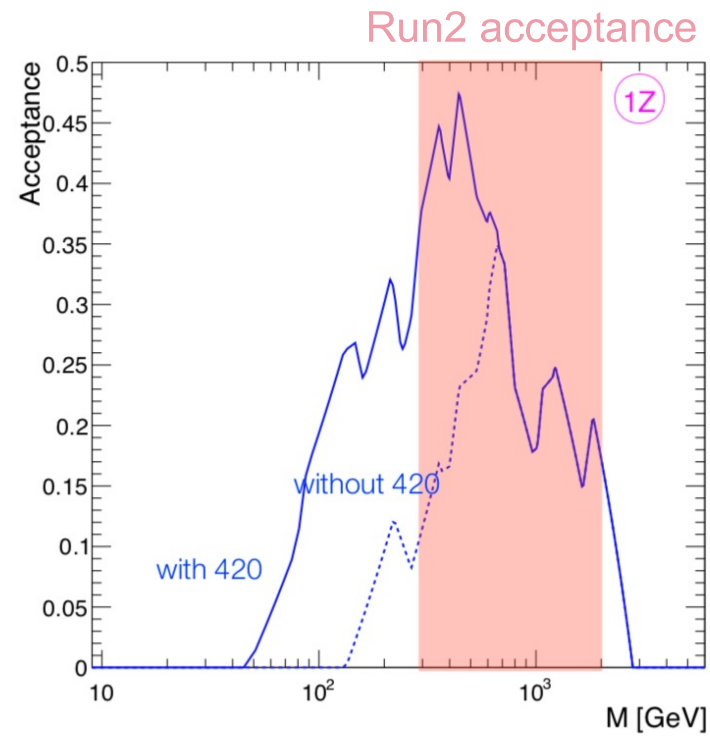
suitable for standard Roman Pot technology
in each location 2 units
with a few metres lever arm
(→track angles)

- needs cryogenic bypass
- signal protons between beam pipes
  →limited space

→new developments needed

Acceptance: HL-LHC vs Run2/3



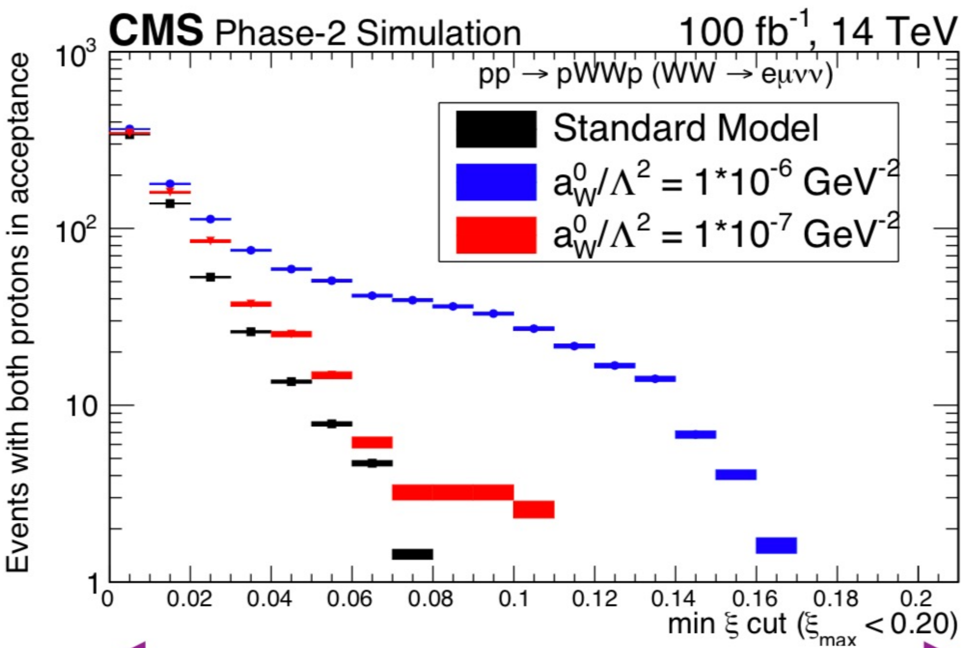


- Green diamonds: both protons in detector acceptance
- Improved acceptance over Run2/3:
  - almost continuos coverage in range 50-2700GeV

Impact on physics

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

Luminosity: increase statistics for rare processes

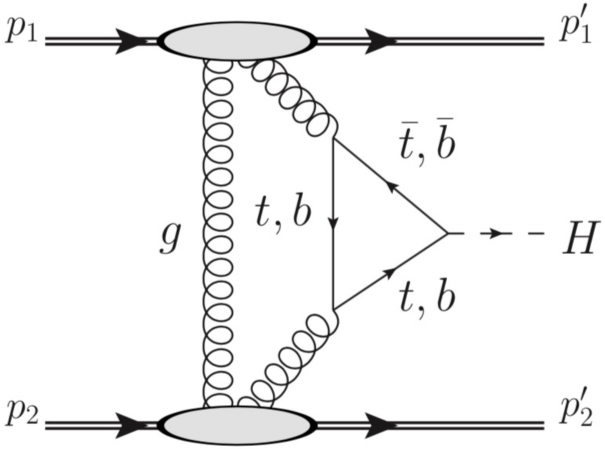


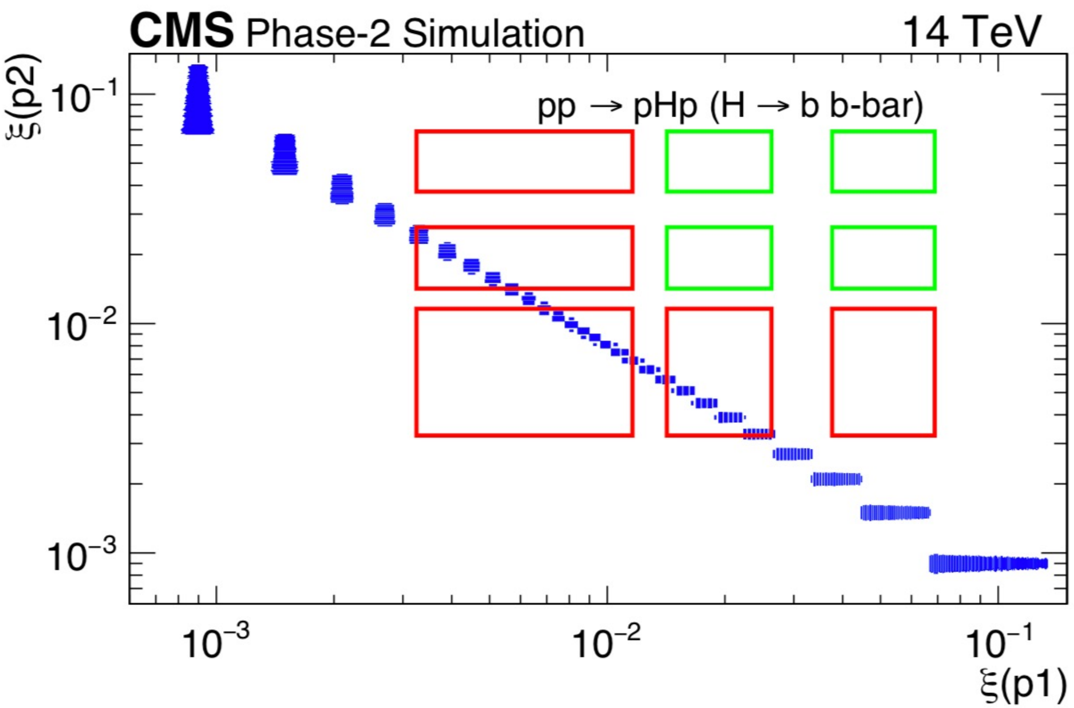
Low ξ/low mass coverage: increase acceptance for SM processes

High ξ/high mass coverage: increase acceptance for BSM searches

Acceptance: low mass with 420m

With 420m RP, acceptance extends from 130 GeV to 50 GeV

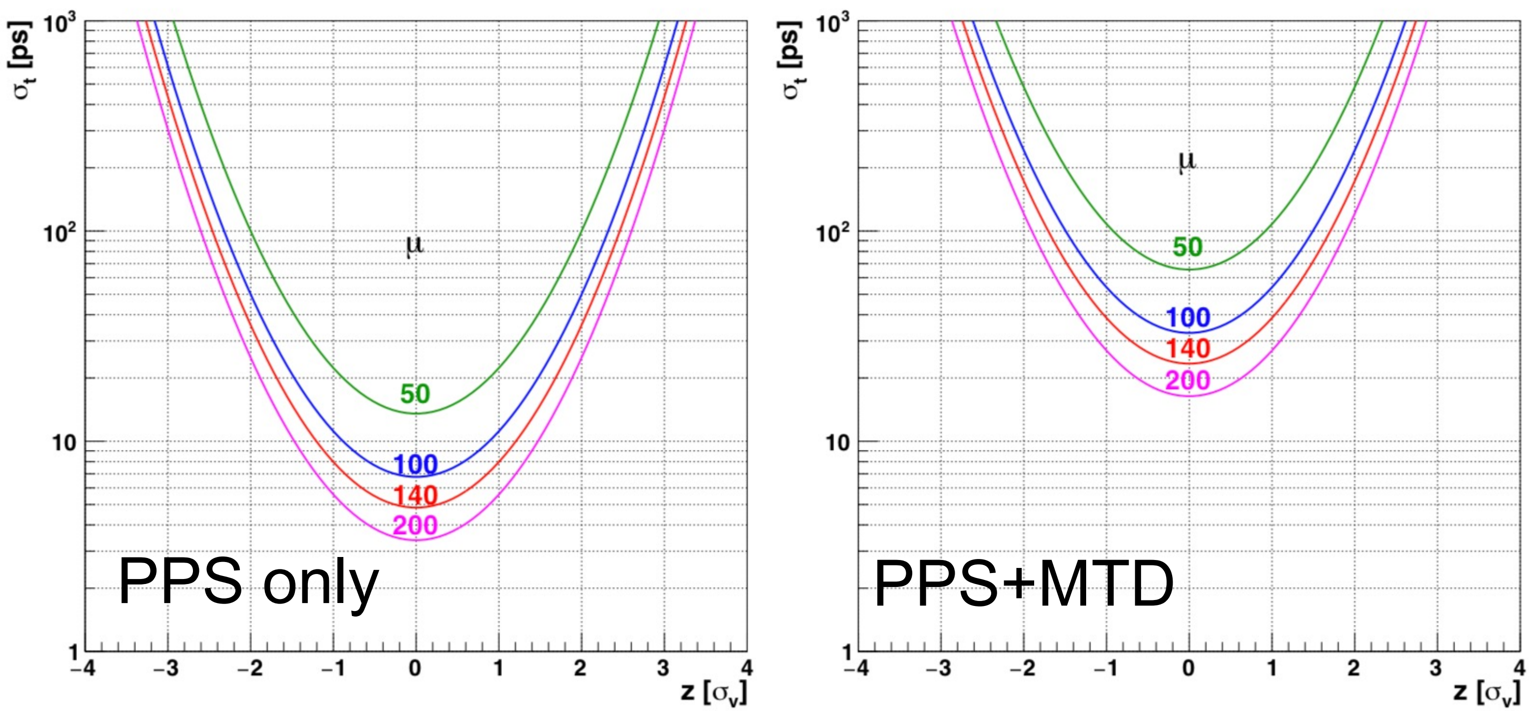




⇒ Unique feature: allows detecting exclusive production of 125 GeV SM Higgs (pp→pHp)

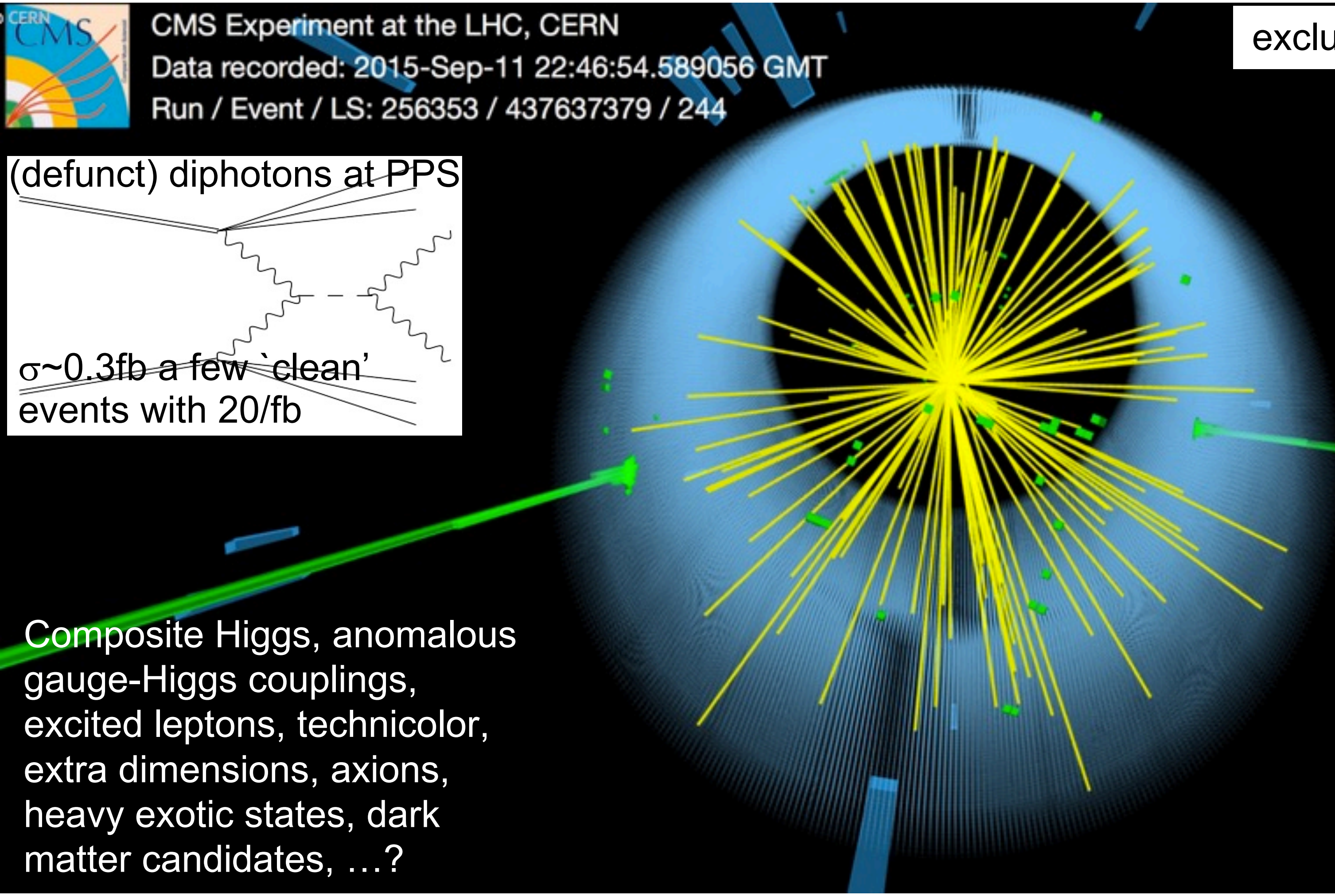
Detectors

- 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

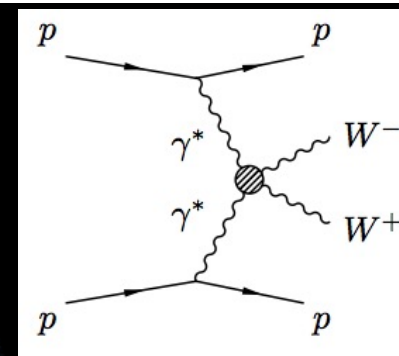
BSM searches: resonances, etc.

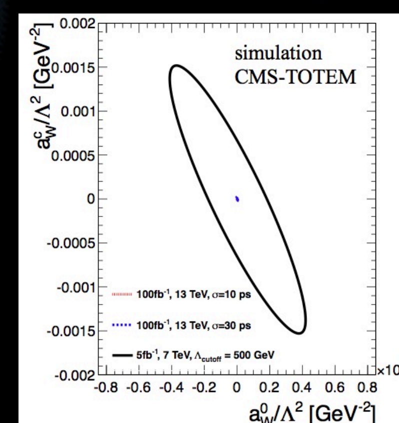


(defunct) diphotons at PPS

σ~0.3fb a few `clean' events with 20/fb

exclusive WW production





Composite Higgs, anomalous gauge-Higgs couplings, excited leptons, technicolor, extra dimensions, axions, heavy exotic states, dark matter candidates, …?

Prospects

Many BSM scenarios can be explored in $\gamma\gamma$ interactions

Composite Higgs, Anomalous gauge-Higgs couplings
JHEP 1407 (2014) 149
Phys.Rev. D90 (2014) no.1, 015035
JHEP 1403 (2014) 102
Nucl.Phys.Proc.Suppl. 179-180 (2008) 104-108

Extra Dimensions
Phys.Rev. D85 (2012) 014006
JHEP 1009 (2010) 042
Phys.Rev. D80 (2009) 075009
Phys.Rev. D84 (2011) 095002
JHEP 1403 (2014) 102

Magnetic monopoles
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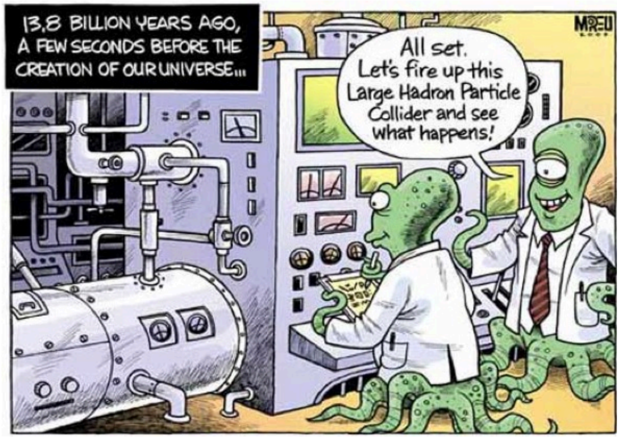
Summary

- Overall excellent LHC and detector performance
- PPS extends coverage to very forward regions
  - Additional sensitivity to New Physics searches
  - Collected ~115/fb
- Exclusive dilepton production
  - Exclusive process at the EWK scale
  - First physics results published
  - More data to be analyzed



- Regularly taking data in high-luminosity fills
- Preparing with improved detectors and extending sensitivity for Run3 and EoI for high-luminosity phase