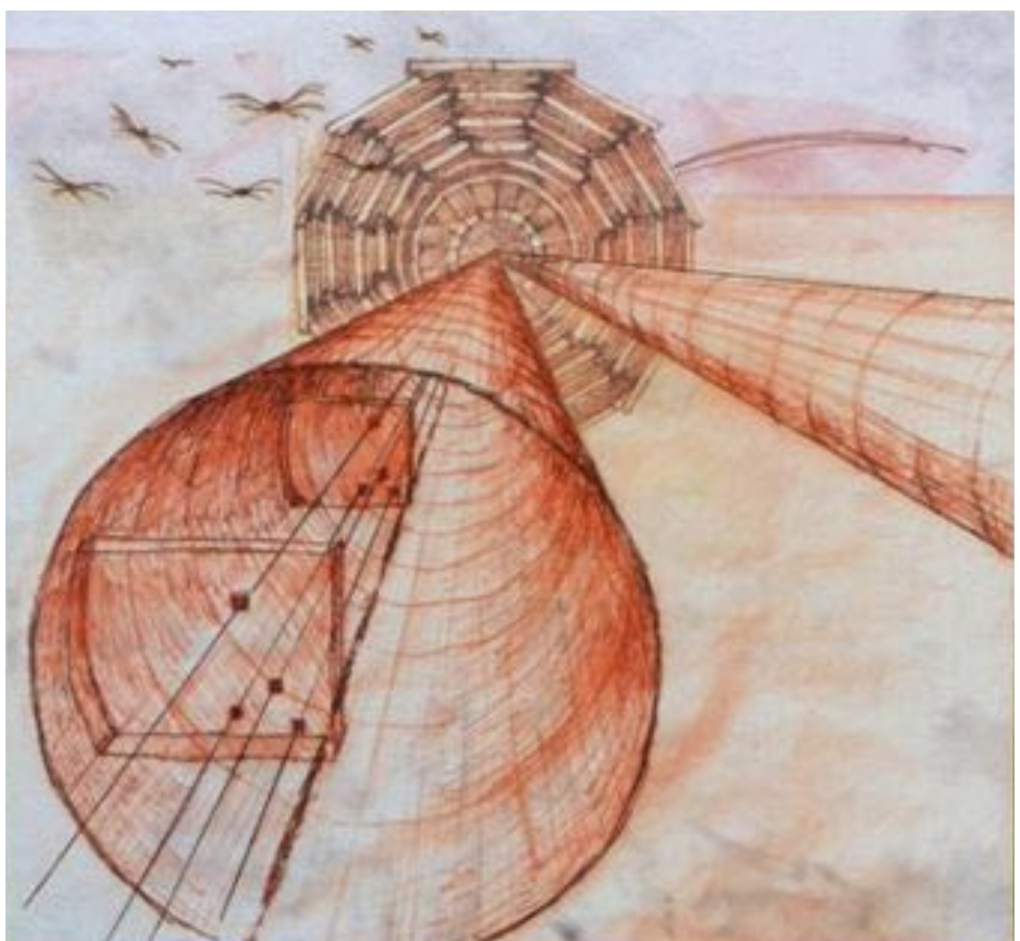
Results and prospects with the CMS-TOTEM Precision Proton Spectrometer



Finn Rebassoo, Lawrence Livermore National Lab
on behalf of CMS/TOTEM collaborations

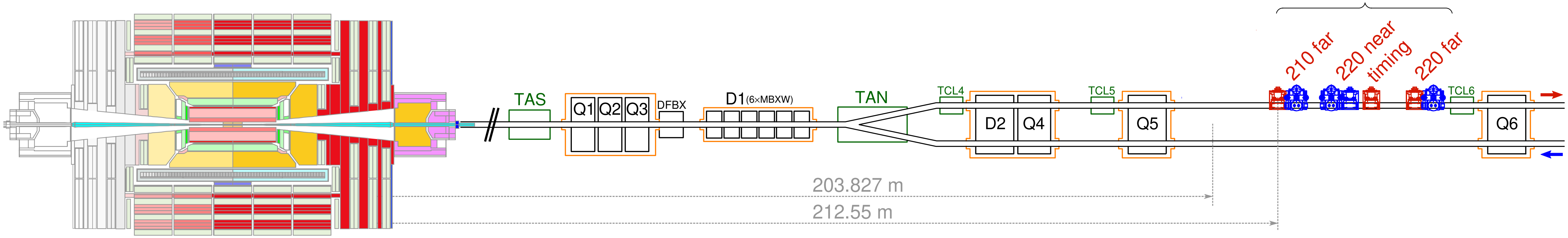
DPF, July 29th - Aug 2nd, 2019

Introduction to PPS

- **Near beam proton spectrometer at IP5 of the LHC**
  - Conceived as common project between CMS and TOTEM, TDR in 2014 [CERN-LHC-2014-021]
  - Tracking and timing detectors in Roman Pot stations few mm away from beam, ~210-220 m from IP
  - Designed to operate at full LHC luminosity

Detectors on either side of CMS ~210-220 m from IP (diagram just shows one side of CMS)
Each side called an arm

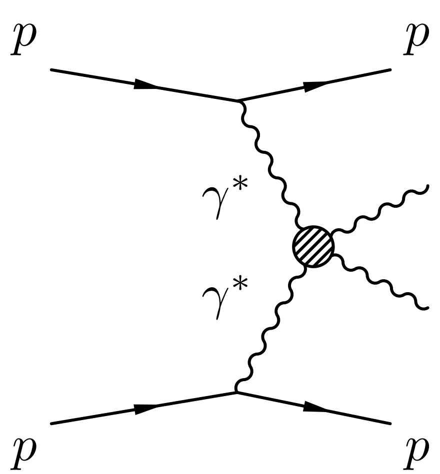
PPS Roman Pots containing Detectors

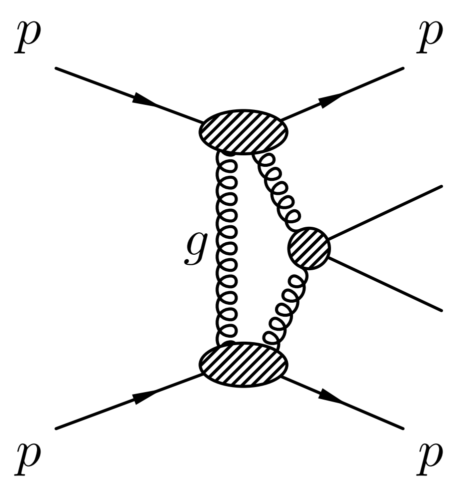


- **Initial data taking in 2016 using existing TOTEM silicon strips (~15 fb^{-1})**
  - Commissioning dataset to establish safe Roman Pot insertions, detector operations, alignment and optics corrections procedures
- **2017+2018 ~100 fb^{-1} collected with PPS using upgraded detectors**

Physics Program

- **High energy $\gamma\gamma$ or gg interactions, with intact protons**
  - Very clean signature, no underlying event





Electroweak physics: diboson and dilepton production, searches for anomalous couplings

QCD, top: dijet, trijet, tt production; can obtain gluon jet sample with small quark jet component

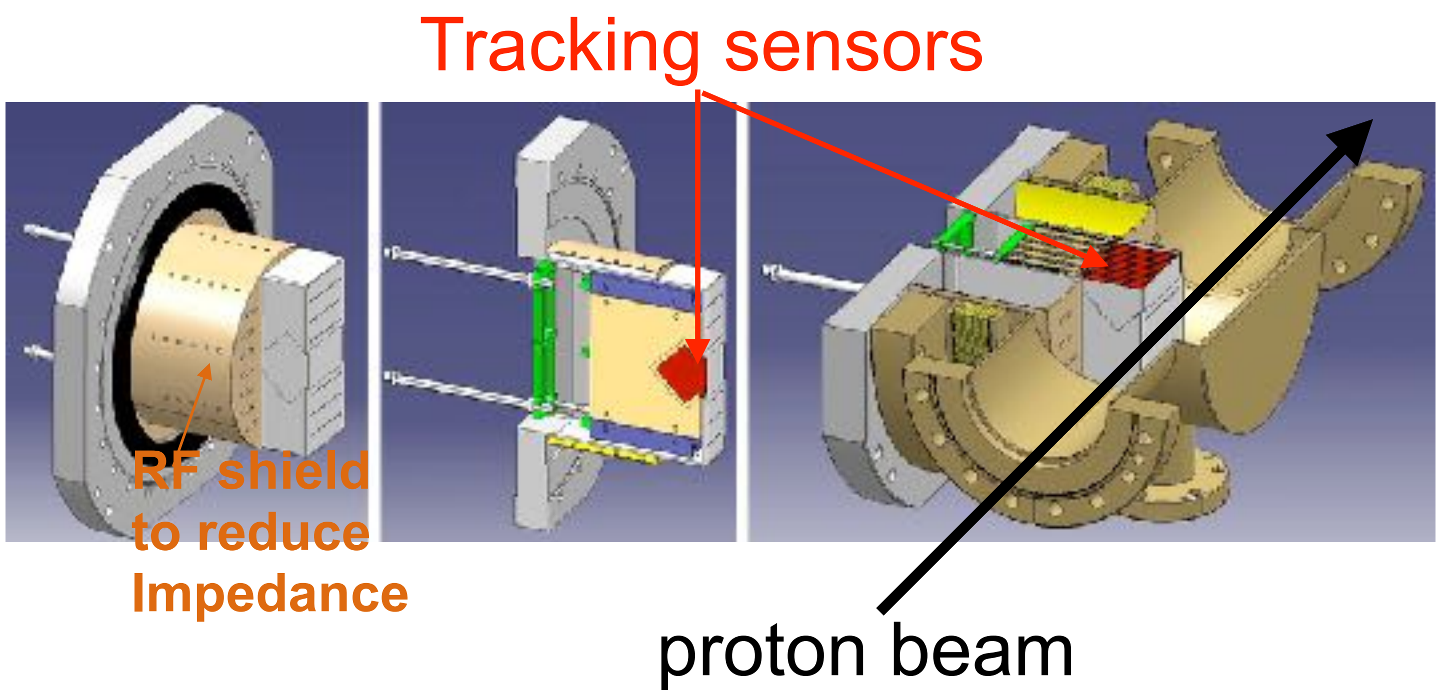
BSM direct searches: new resonances, missing mass…

- **Advantages of detecting forward protons and matching to central system**
  - Strong background suppression
  - Event-by-event constraints on the invariant mass of $\gamma\gamma$ or gg interaction, independent of final state
  - Reduced theory uncertainties related to dissociation of the protons

Experimental Challenges

- **Non-standard use of LHC: magnetic proton spectrometer, need to understand LHC optics**
- **Need to operate detectors few mm from beam to maximize mass acceptance**
  - Use Roman Pots to move detectors in and out of beam line, only inserted once beams stable
  - Limit impedance introduced by beam pocket with improved RF shielding of Roman Pots

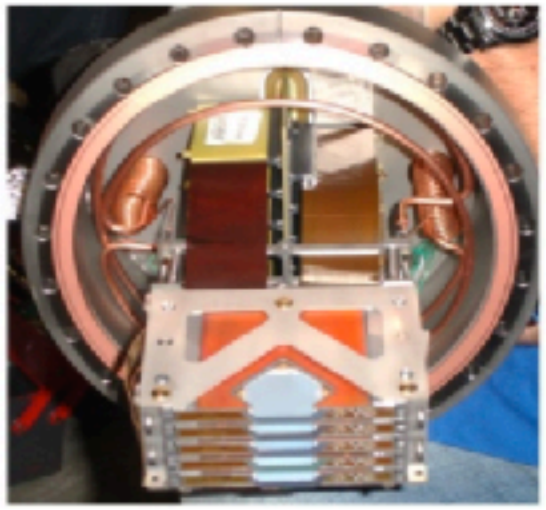
<u>Roman Pots for tracking stations:</u>



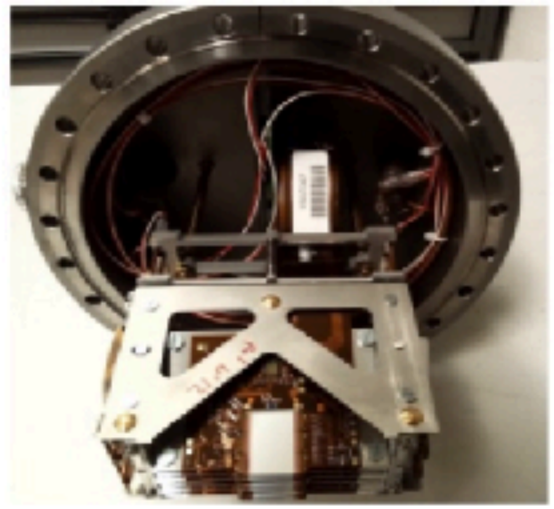
Detectors in secondary vacuum to separate from LHC vacuum

- **Need to withstand high radiation levels**
  - For 100 fb^{-1}, proton flux up to $5x10^{15}$ p/cm^2 in tracking detectors,
- **Must reject background in high pileup LHC running (<μ>~30 in 2018)**
  - To do this use proton momentum information determined from tracking detectors and proton time-of-flight determined from timing detectors

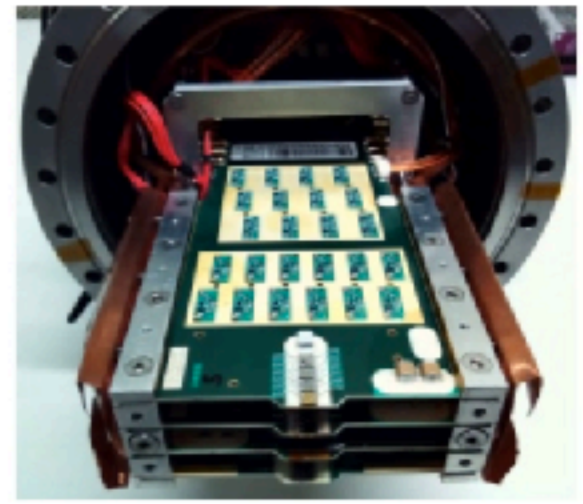
Detector Technologies for Run 2



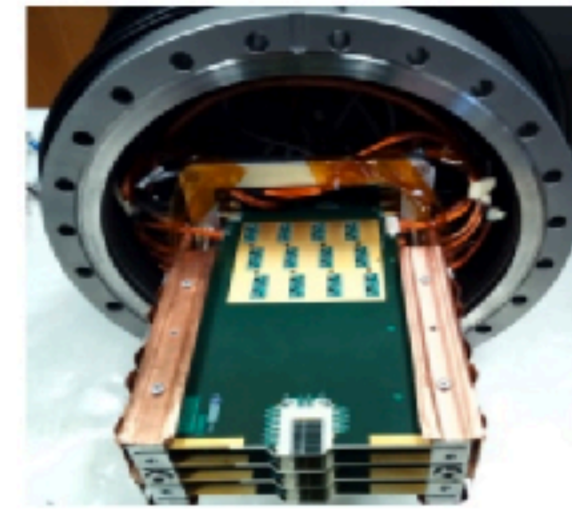
TOTEM strips



3D pixels



scCVD (diamond)



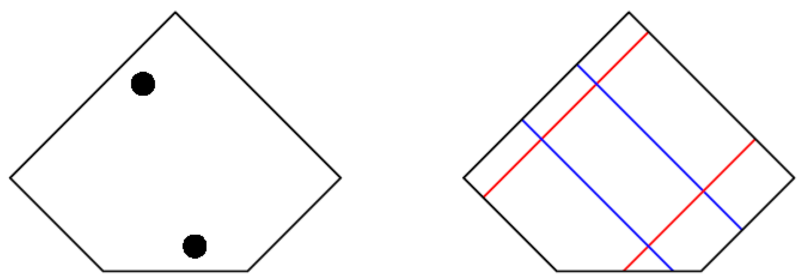
ultra-fast Si-detector

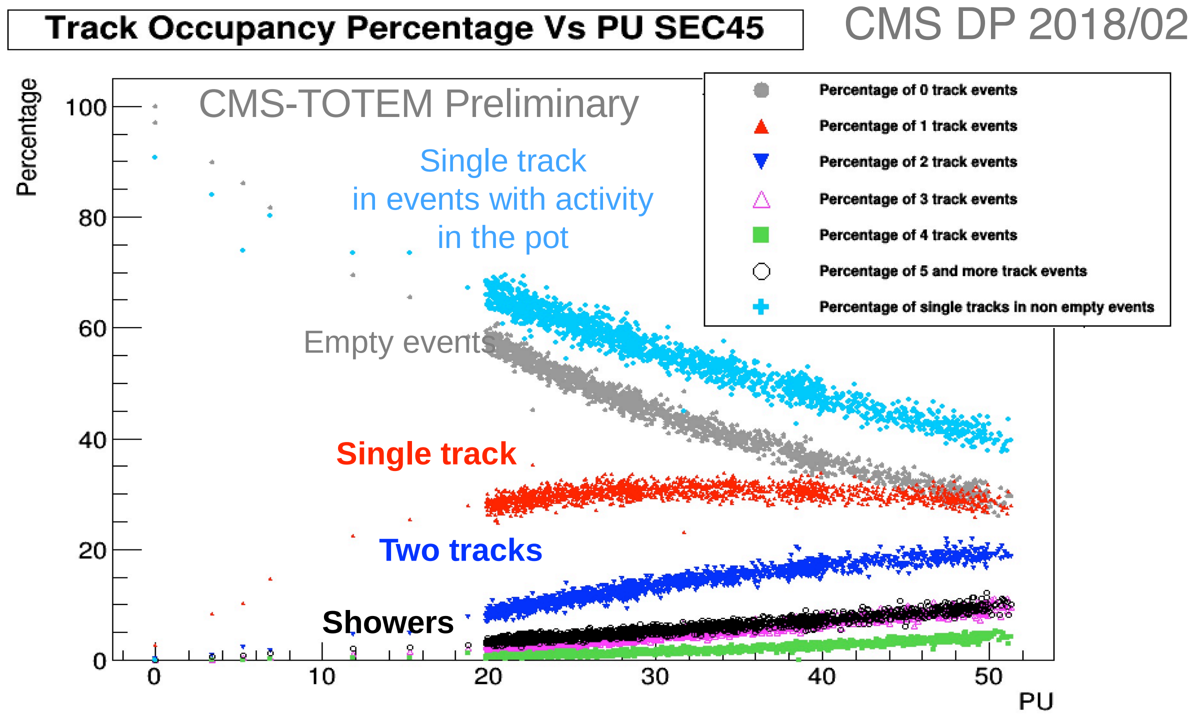
Description below for one side of CMS, same for other side

- **2016**
  - **Tracking**: 2 stations of TOTEM silicon strips (10 planes), σ ~ 12 um, designed by TOTEM for low-lumi running (no multi-tracking, radiation damage at 5 x 10^{14} p/cm^2)
  - **Timing**: diamond timing detectors with small amount of data (operational after 2016 TS2)
- **2017**
  - **Tracking**: 1 station of silicon strips, 1 station of 3D pixels (6 planes, same readout as CMS phase 1 central pixel), σ_x ~ 15 um, σ_y ~ 30 um, pixels have multi-track capability
  - **Timing:** 1 station with 3 planes of single-layer diamond with expected δt~80 ps/plane + 1 plane of UFSD with δt ~30/plane,
- **2018**
  - **Tracking:** Two stations of 3D pixels
  - **Timing:** 1 station of 4 diamond planes (2 single-sided planes, 2 double-sided planes)

Tracking efficiency studies

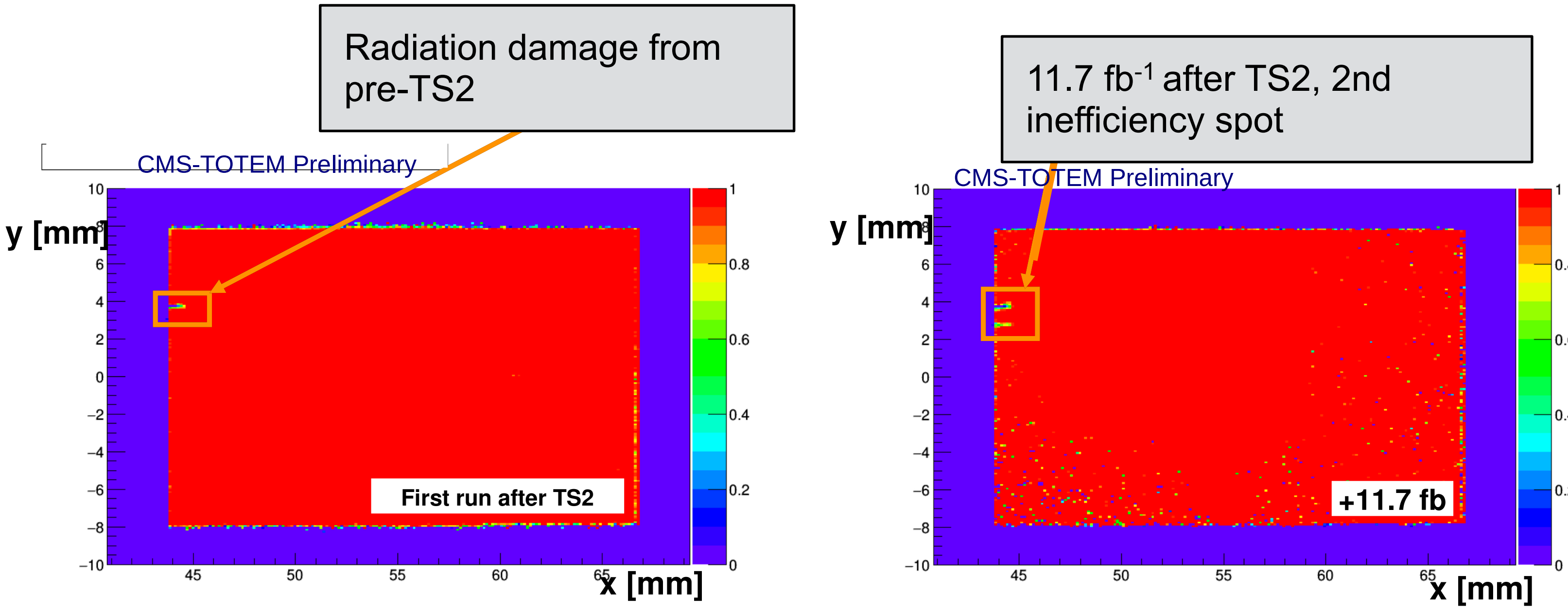
- **Inefficiency in strips due to no multi-tracking capability**





  - At pileup of 50, silicon strips reconstruct 30% of signal protons
  - Not an issue with pixels

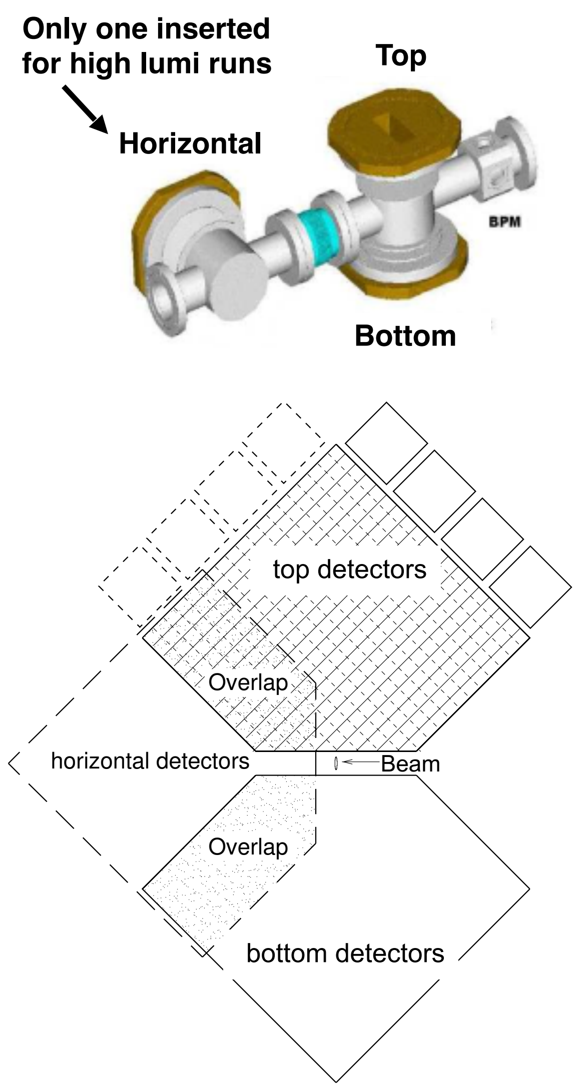
- **Impact from radiation damage reduced when switching to pixels**
  - However, the non-uniform radiation does effect readout chip for pixels
  - To mitigate the damage tracking stations lifted during technical stops



Outside of radiation damage region pixel efficiency very high

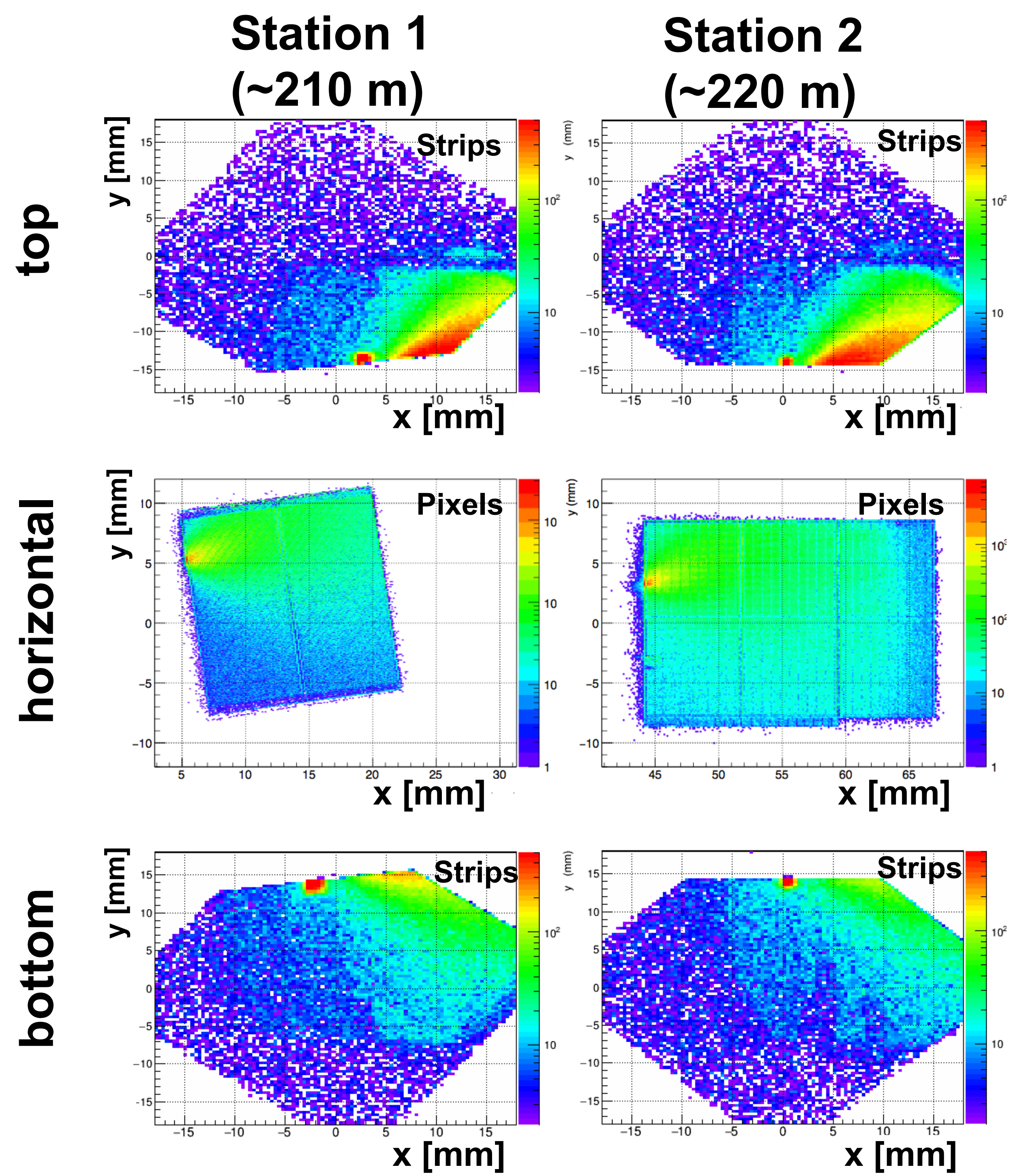
Reconstructed Tracks, 2018

Each station consists of 3 Roman Pots



For low-lumi alignment runs also use Totem strip detectors above and below beam

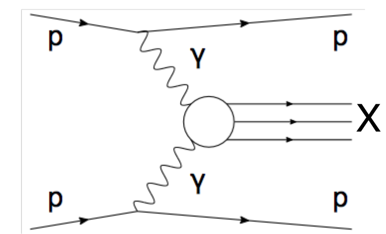
Right arm, Sector 56

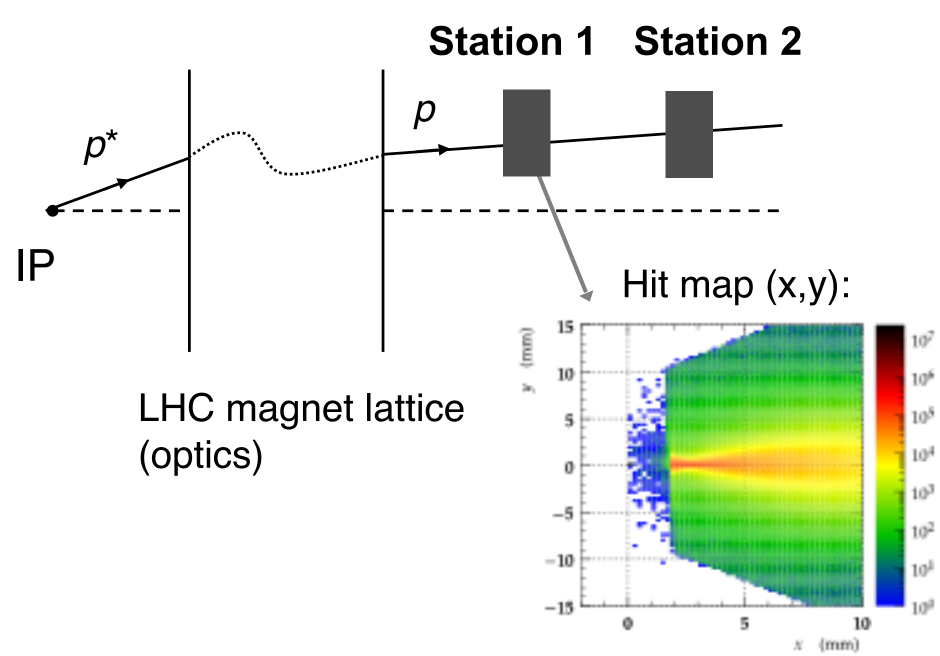


Similar distributions in left arm, Sector 45, see backup slides

Proton reconstruction:
Determining proton momentum from track position

- **Final physics variable of interest is proton fractional momentum loss** $\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|}$
  - From ξ can determine invariant mass and rapidity of proton collision $M_X = \sqrt{s\xi_1\xi_2}$ $\quad y_X = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$
- **Mass acceptance for 2 tagged protons ~400-2000 GeV**
  - Lower limit determined from how close to the beam we can get
  - Upper limit from collimators
- **2 crucial ingredients to determine ξ**
  - aligned track positions at RP
  - precise knowledge of LHC optics and dispersion

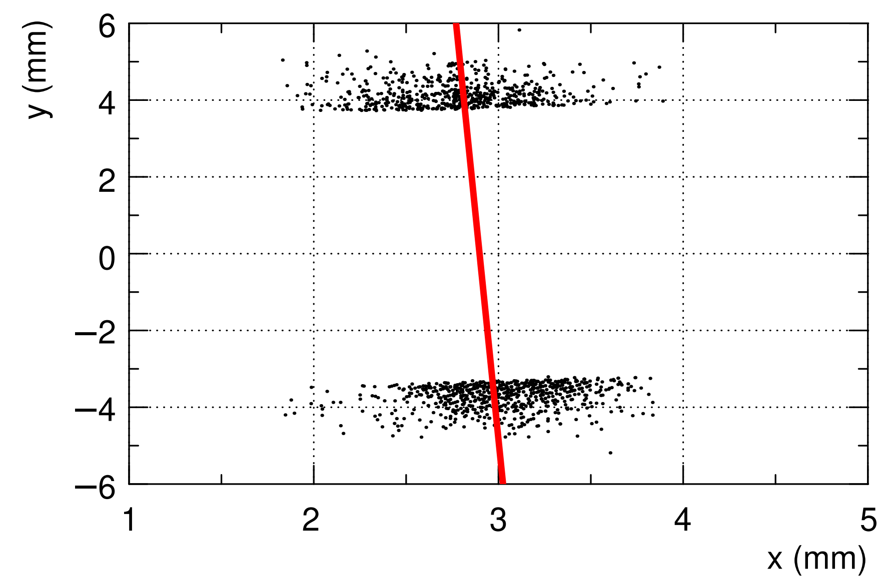




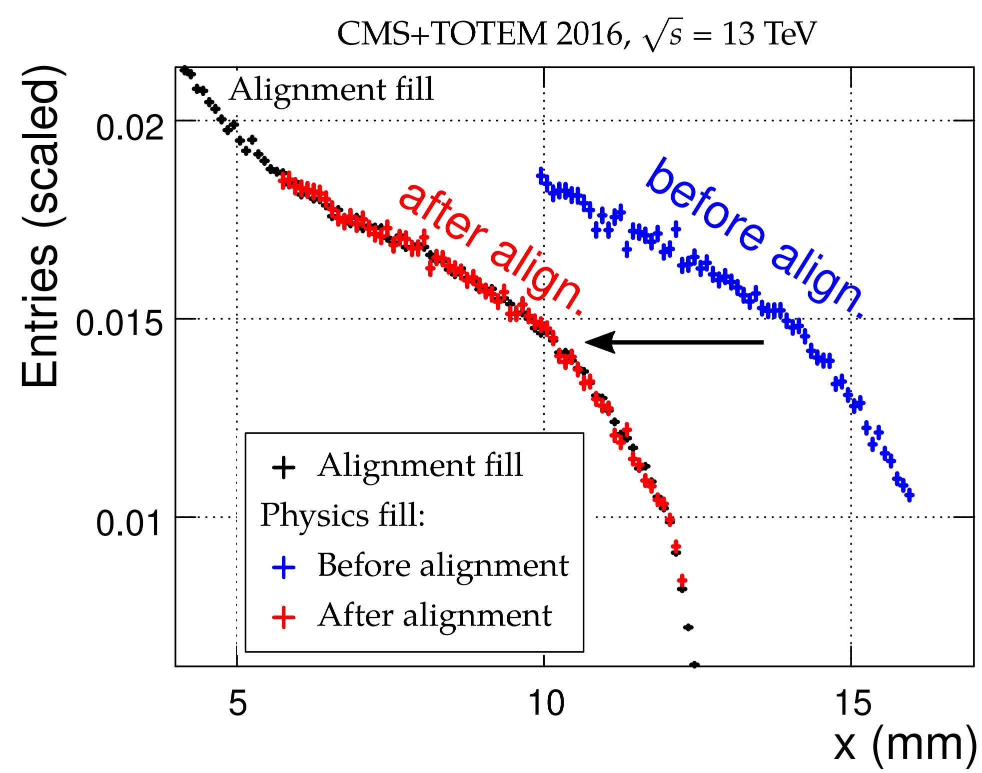
PPS detector alignment

Alignment procedure performed in 2 steps

1. **Absolute alignment using dedicated low-luminosity runs**
   - Beam-based alignment between LHC collimators and RPs (rate monitoring with BLMs of beam edge scraping pots)
   - Relative RP alignment: determine positions and rotations of each sensor using overlap between horizontal and vertical RPs. Use track-hit residuals within each station
   - Absolute alignment w.r.t beam using elastic-scattering events



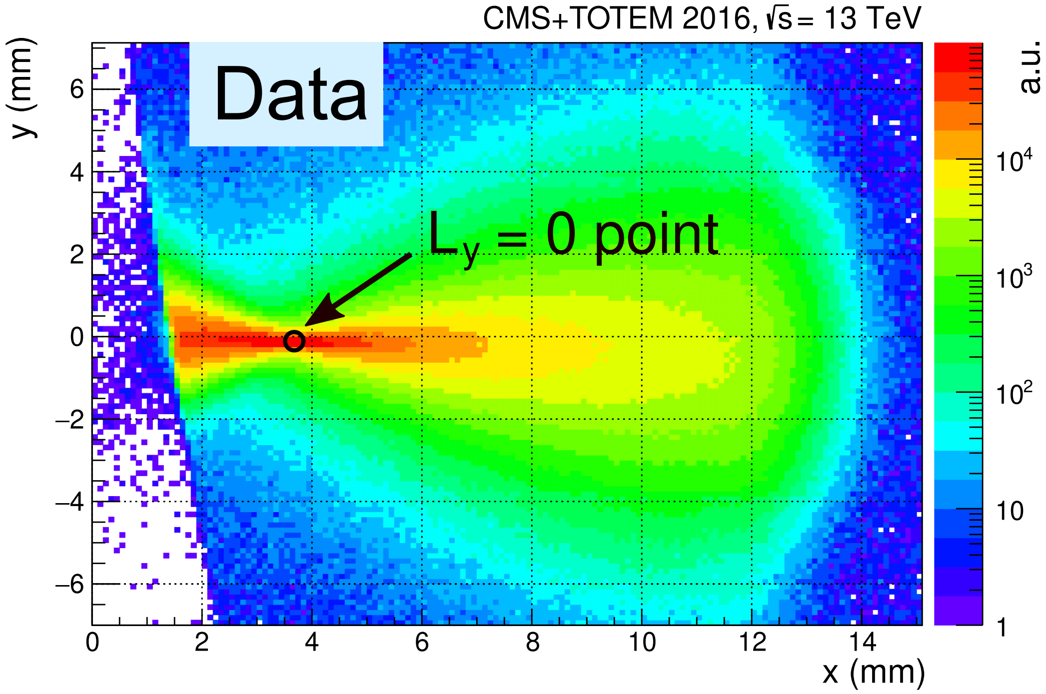
2. **Fill-by-fill alignment of standard high-luminosity runs**
   - RPs move and beam position can change so need to redetermine each fill
   - Match proton track positions of inclusive sample of proton triggered by central detectors to those from alignment runs

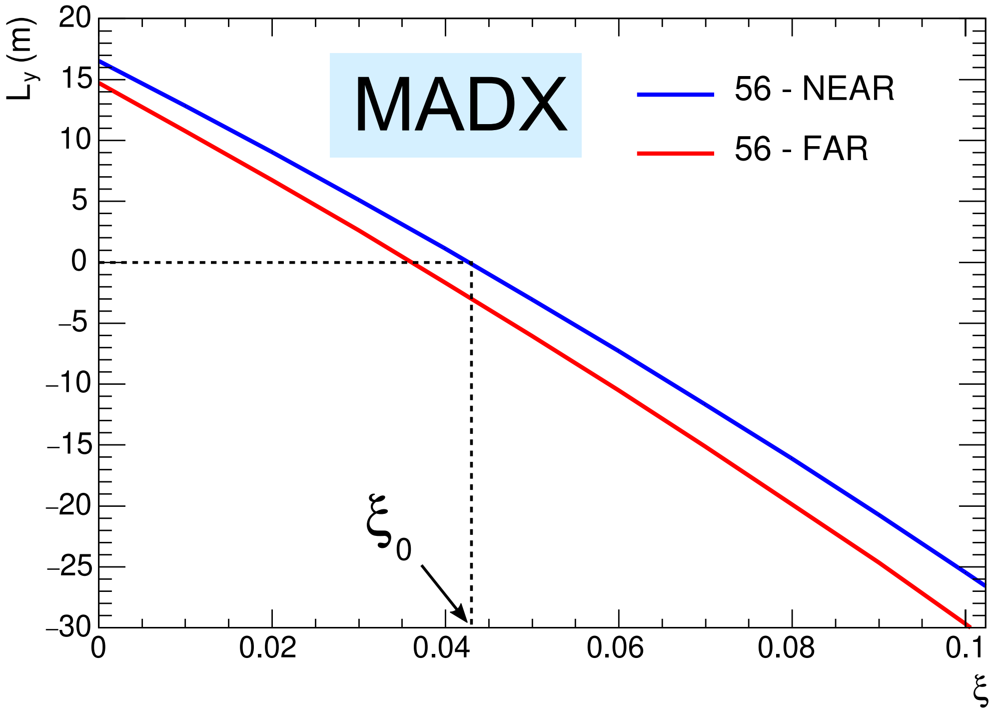


CERN-TOTEM-NOTE-2017-001

Correcting LHC optics and dispersion

- **Significant corrections to nominal optics needed**
- **Use MADX program to model optics of LHC**
  - Includes full beam line optical components (quarupole strengths, RPs/BPMs positions, …)
  - "matching" = tuning model parameters to observations in RPs and beam-position monitors.
- **Dispersion calibration uses the vertical effective length pinch point, i.e. $L_y(x) = 0$**
- **Final result is (non-linear) calibration of ξ vs. the measured track position, $\xi = D_x(\xi)/x$**





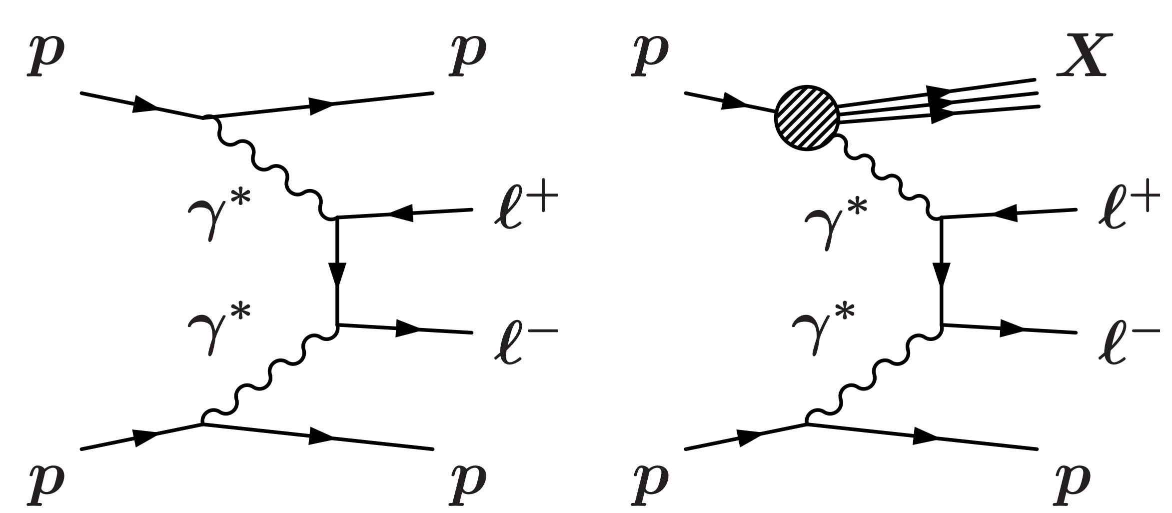
Full documentation: New J. Phys. 16 (2014) 103041, CERN-TOTEM-NOTE-2017-002

Validating full reconstruction/analysis using high mass semi(exclusive) $\gamma\gamma \rightarrow l^+l^-$

- **Standard Candle, known EWK physics**
- **9.4 fb^{-1} of pre-TS2 data from 2016 used**
- **Only 1 proton required to increase acceptance at lower masses**
- **Signal is mix of "elastic" (both protons stay intact) and single-dissociation (1 proton stays intact)**
  - Fractional momentum loss of proton related to p_T and η of leptons

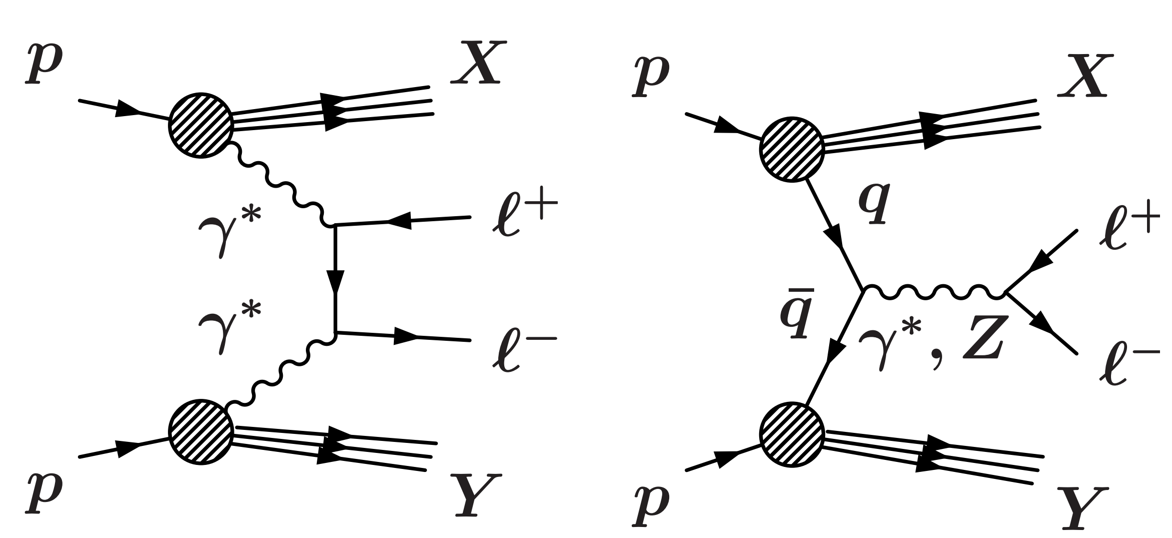
$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_{\mathrm{T}}(\ell^+)\mathrm{e}^{\pm\eta(\ell^+)} + p_{\mathrm{T}}(\ell^-)\mathrm{e}^{\pm\eta(\ell^-)}\right]$$

Signal



- **Backgrounds mainly from Drell-Yan and double proton dissociation**
  - Real dileptons in coincidence with random RP tracks from pileup protons or beam backgrounds
  - Momentum loss not related between PPS and CMS central detector

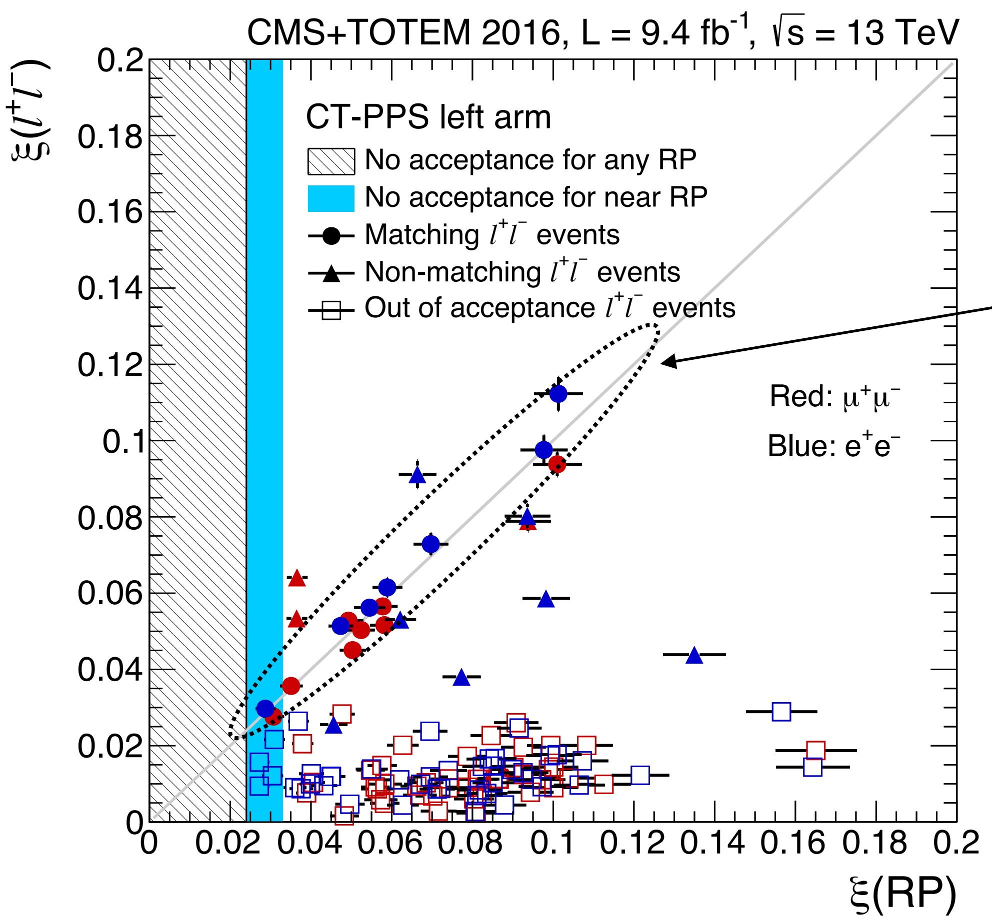
Backgrounds



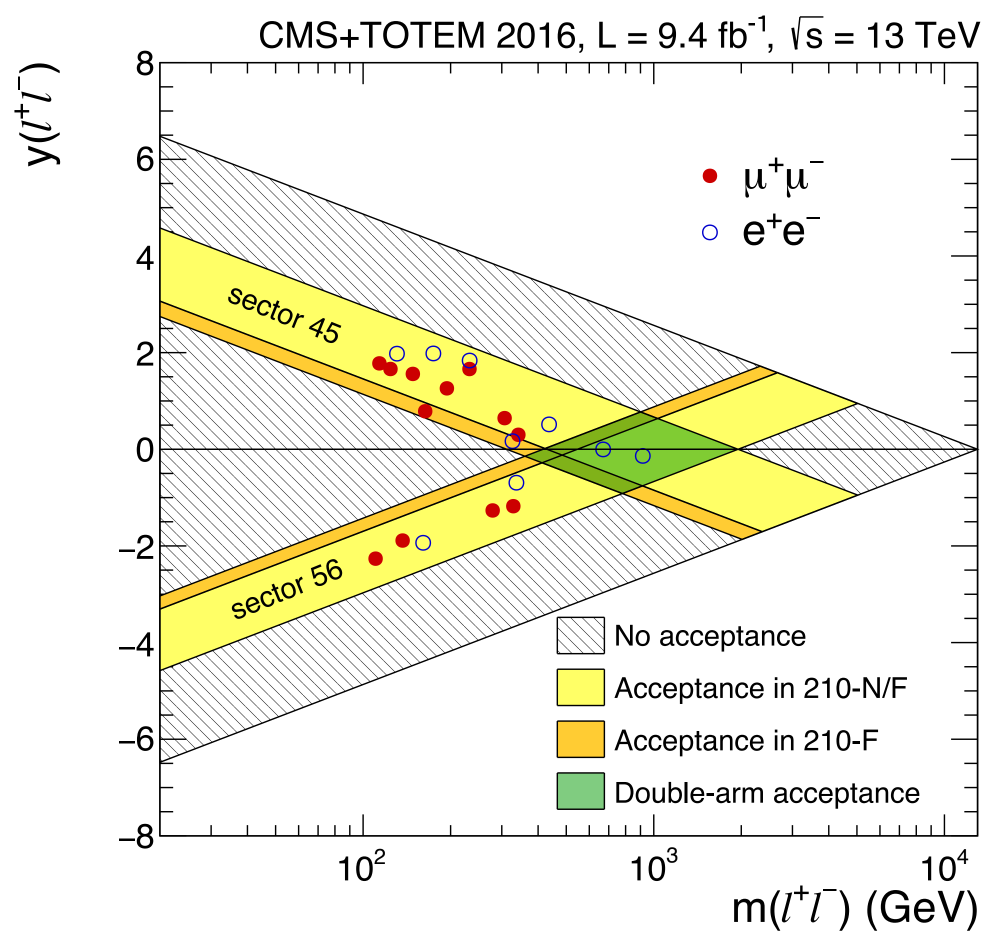
JHEP 07 (2018) 153 (arXiv:1803.04496 [hep-ex])

(Semi)Exclusive $\gamma\gamma \rightarrow l^+l^-$ results for 2016 data

- **To remove background require 2-σ matching between ξ from central CMS detector and PPS detectors**
- **First observation of semi(exclusive) (two-photon) production of dileptons with tagged protons**
  - 20 matched events (12 $\mu\mu$ + 5 ee), estimated background $\mu\mu$: 1.49 ± 0.07 (stat.) ± 0.53 (syst.), ee: 2.36 ± 0.09 (stat.) ± 0.47 (syst.)
  - Combined significance 5.1σ over background only hypothesis



Events matched between CMS and PPS in Left arm (Sector 45)

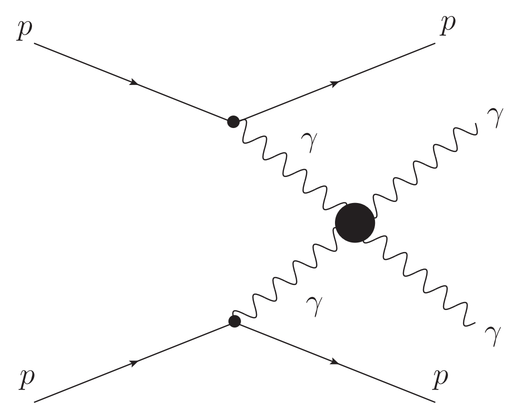


This measurement demonstrates that PPS performs according to design specifications

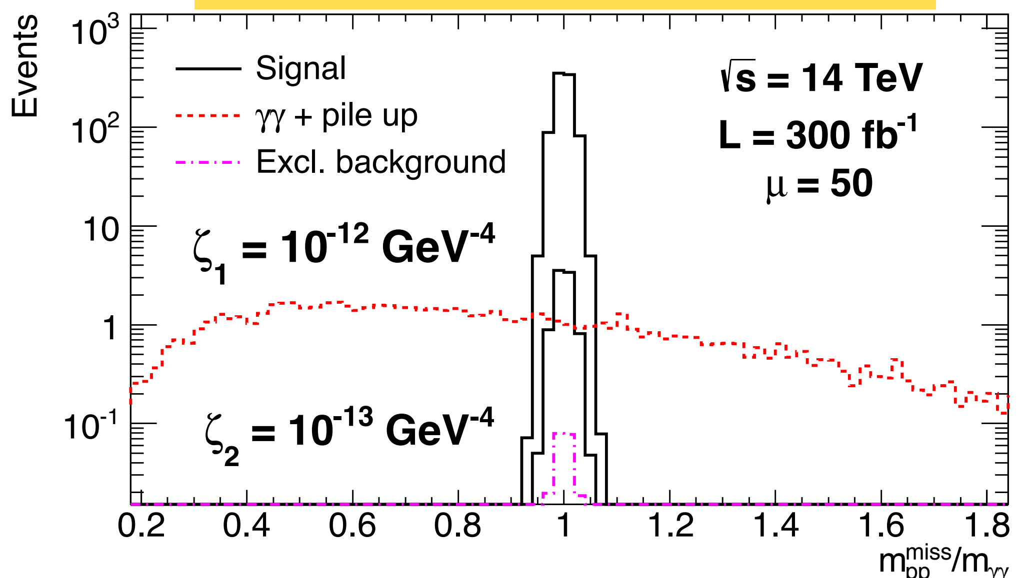
JHEP 07 (2018) 153 (arXiv:1803.04496 [hep-ex])

Prospects: Search for two-photon production of a gauge boson pair

- **Search for two-photon production of a photon pair (i.e. light-by-light scattering)**
  - Probe neutral quartic gauge couplings (forbidden in SM)
  - Best sensitivity at LHC
- **Sensitive to resonances: axion-like particles, new particle exchanges**
- **Can provide model-independent bounds on massive charged particles, only parameterized by spin, mass and "effective charge"**
- **Analysis robust against very high pileup, potential even for HL-LHC**



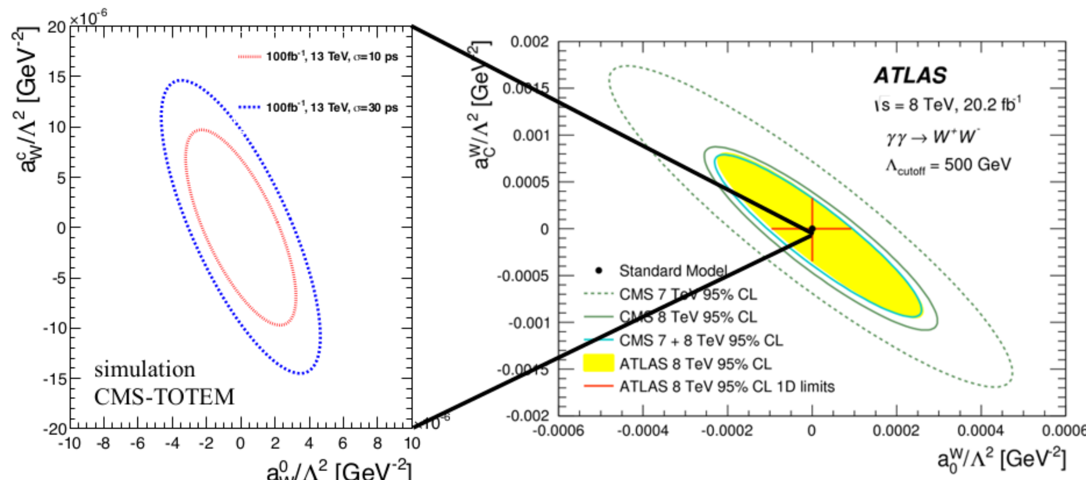
Matching mass from CMS and PPS to remove background



S. Fichet et al (2015)

Prospects: Search for anomalous $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to \gamma Z$, $\gamma\gamma \to ZZ$, …

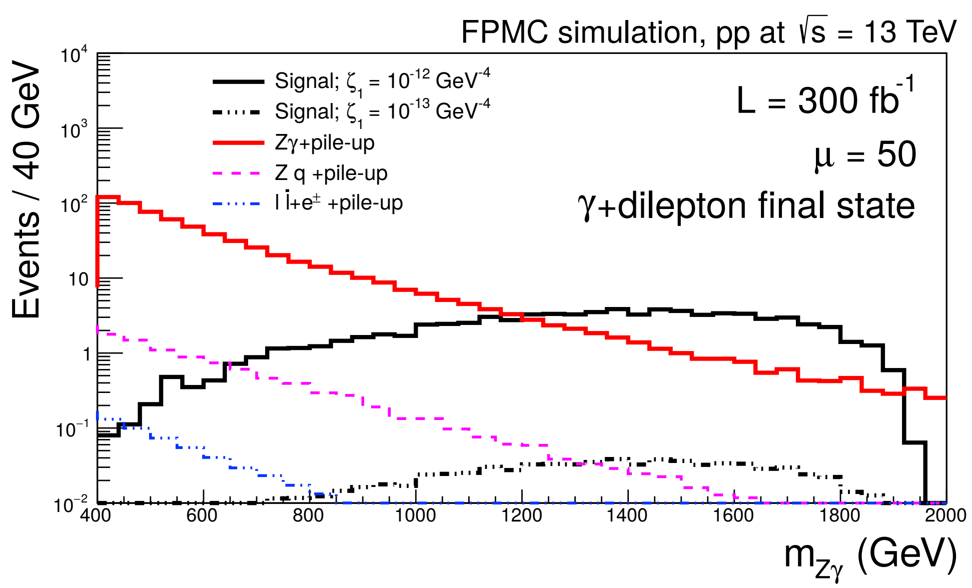
- **For $\gamma\gamma \to WW$: PPS TDR expectations (100 fb^{-1}) 2 order of magnitude wrt run 1 attempts (arXiv: 1604.04464, arXiv:1607.03745)**



CERN-LHCC-2014-021

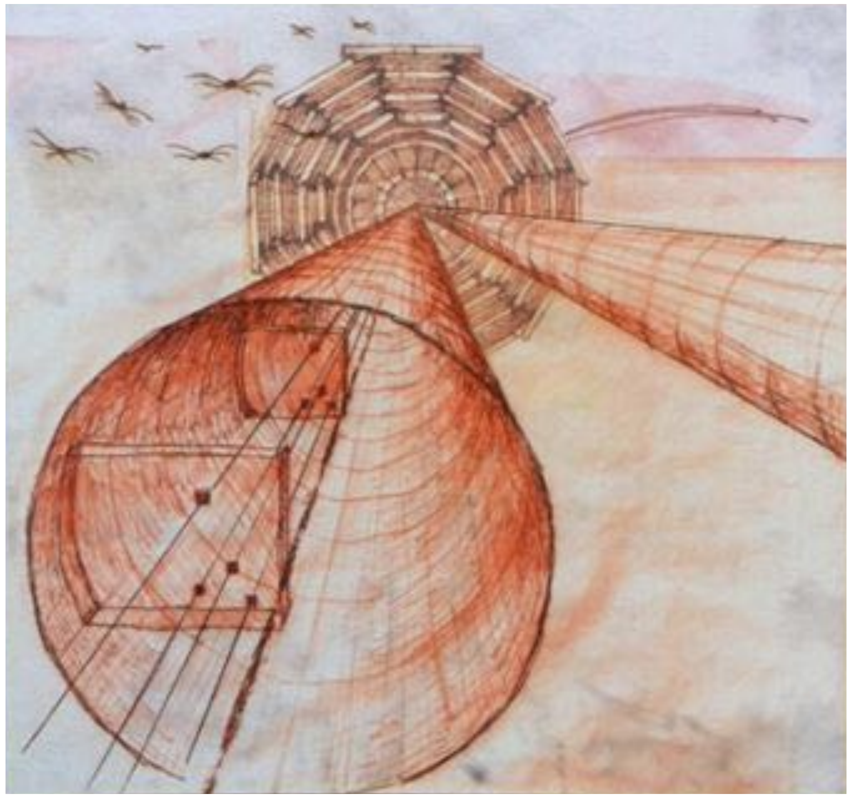
Phys.Rev. D94 (2016) no.3, 032011

- **For $\gamma\gamma \to \gamma Z$: Combined dilepton+dijet final states yield 3 order of magnitude lower than inclusive limits on $Z \to \gamma\gamma\gamma$ BR (for 300 fb^{-1}, arXiv:1703.10600)**



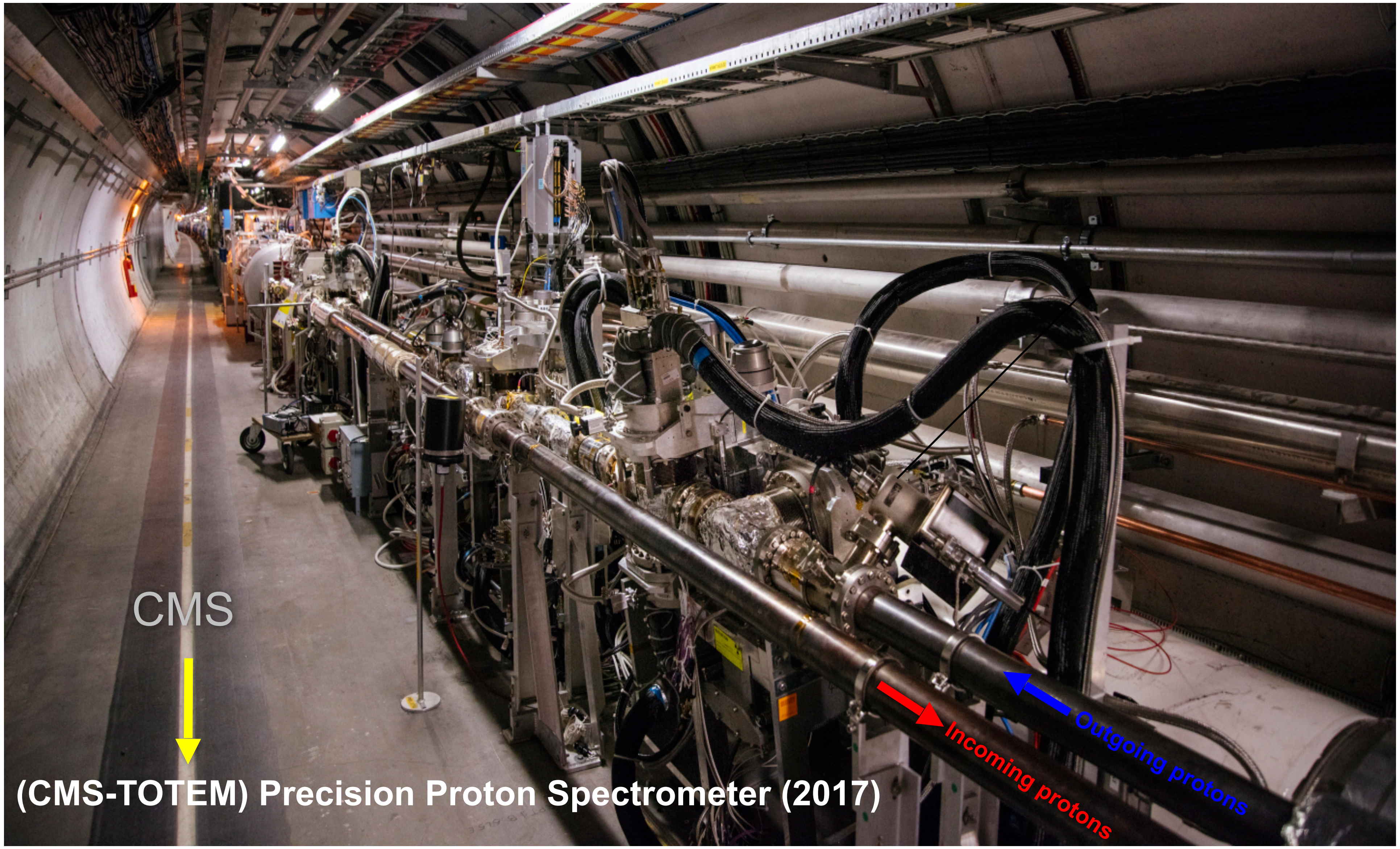
Conclusions

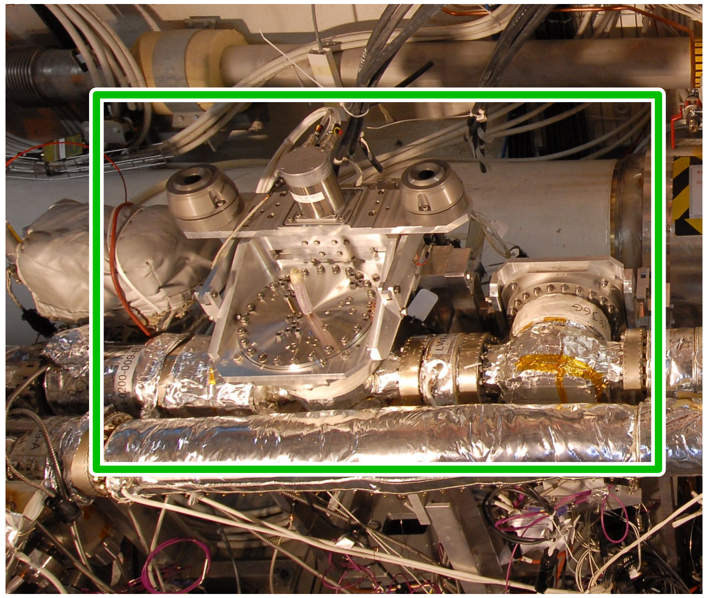
- **PPS operating with high efficiency**
- **Large data set collected during Run 2, over 100 fb^{-1}**
- **Current results highlight understanding of detectors, alignment, and LHC optics**
- **Rich amount of physics capability with PPS:**
  - Probe for anomalous quartic gauge boson couplings
  - Allows model-independent searches for BSM signatures
  - Study of Central Exclusive Production (CEP) with gluon-gluon initial processes (e.g. exclusive dijet production)
- **LHC run 3 preparation ongoing:**
  - Similar location of detectors and similar detector technologies with 1 additional timing station on each side of CMS



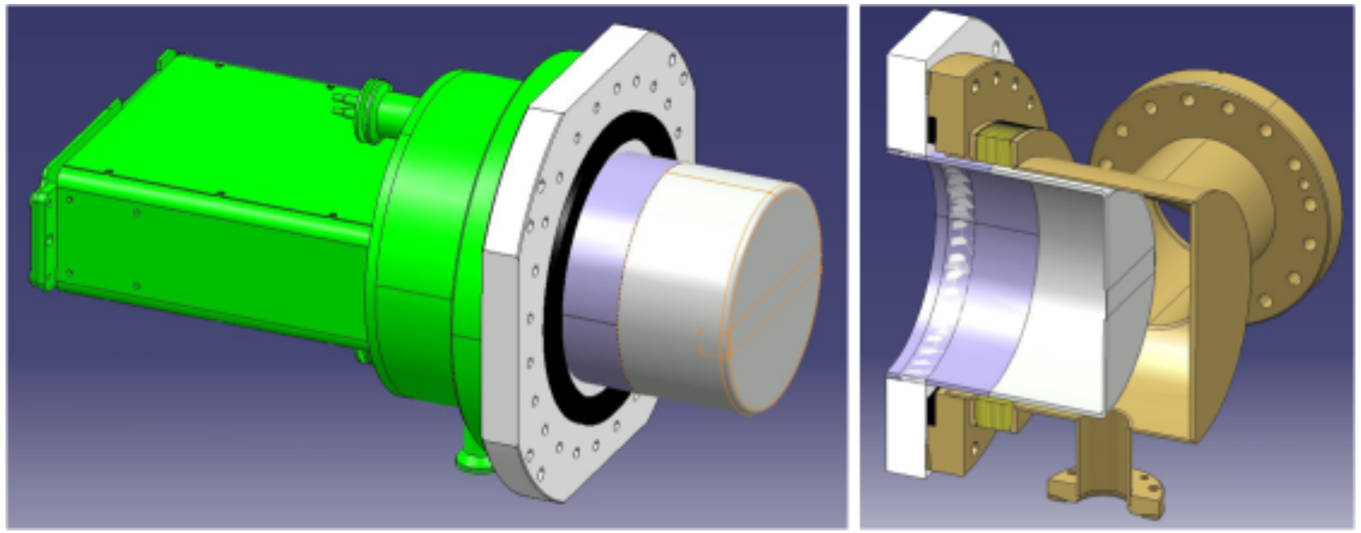
Backup Slides

Roman Pots in beam tunnel





RP for timing stations



New cylindrical design to host larger detectors and reduce the impedance and increase available space.

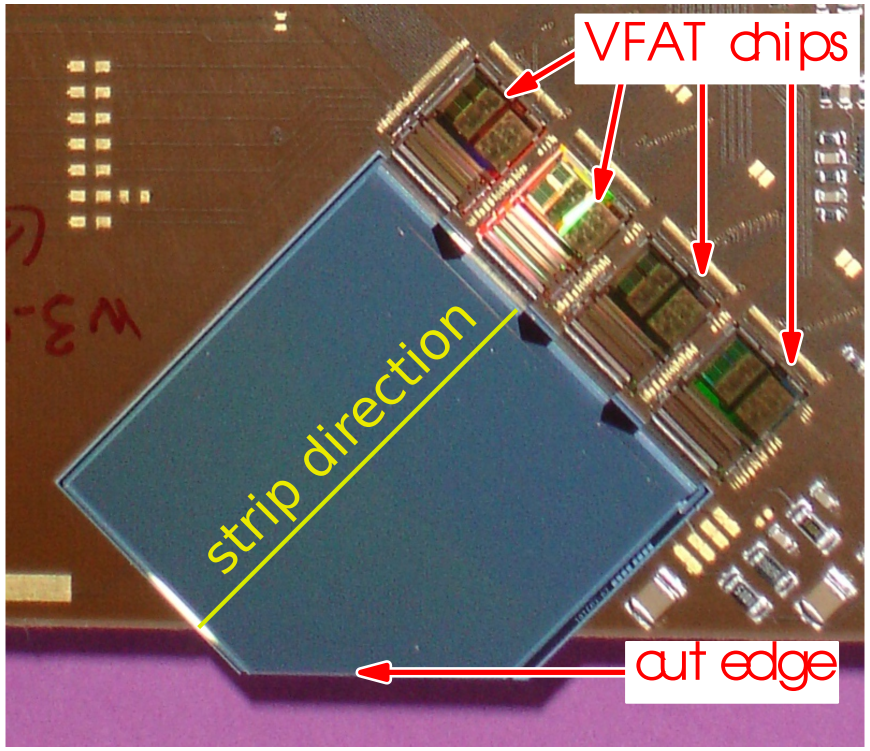
•The timing RPs are **equipped with a 300 μm thick window towards the beam.**

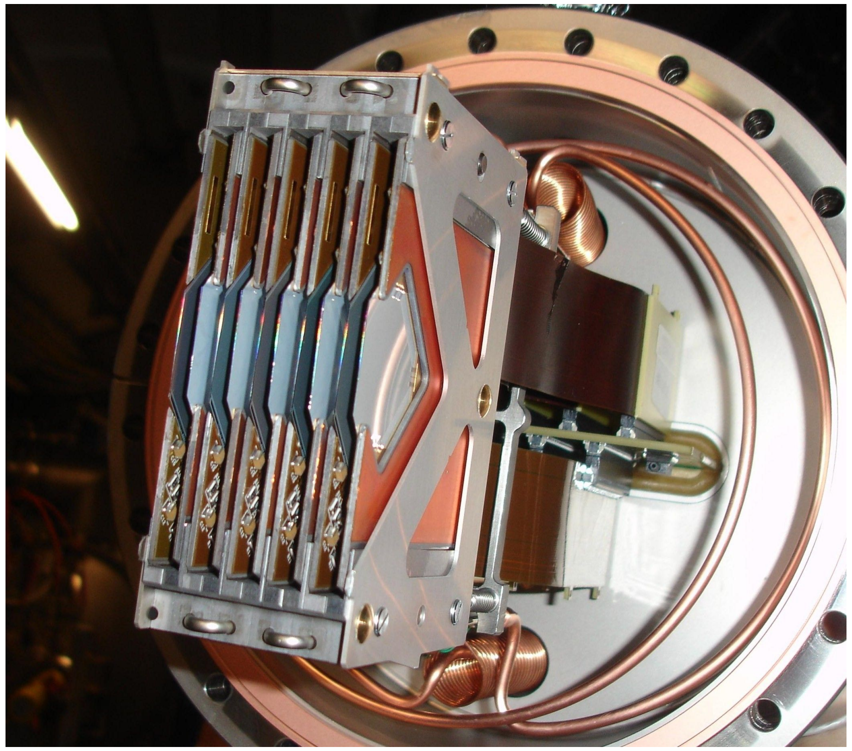
•The thickness is required to compensate the pressure gradient on the larger window.

•No vertical stations needed because the alignment is done by propagating tracks from the tracking stations.

Tracking: Si Strips

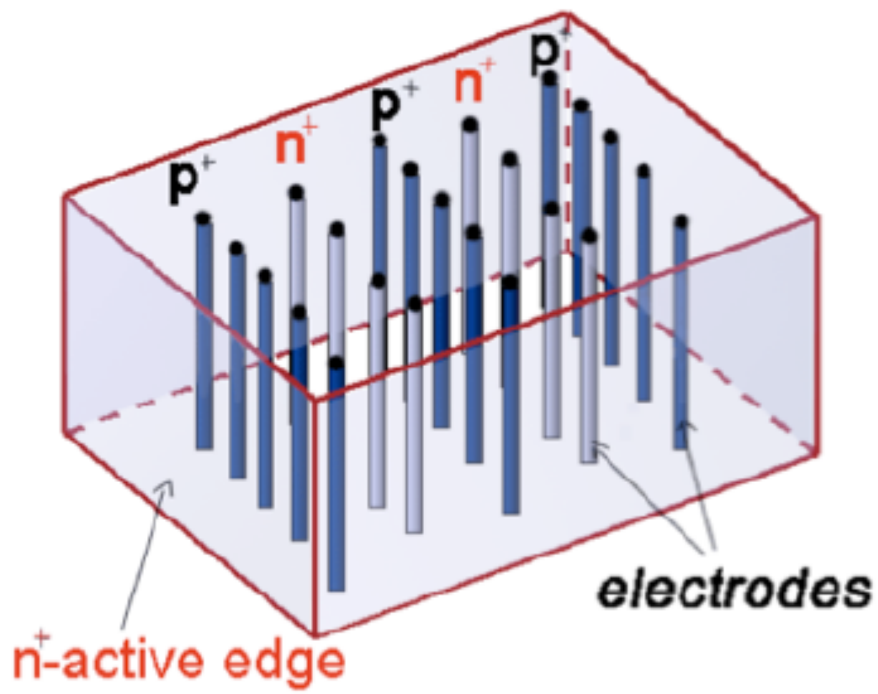
- **Pitch 66 μm**
- **Strips oriented at 45 degrees wrt. edge facing beam, 512 strips per plane**
- **Cut edge: insensitive margin only ~50 μm**
- **Operated at -20° C, bias voltage ~ 100 V**
- **5+5 planes per RP (2 strip orientations for 2D reconstruction)**

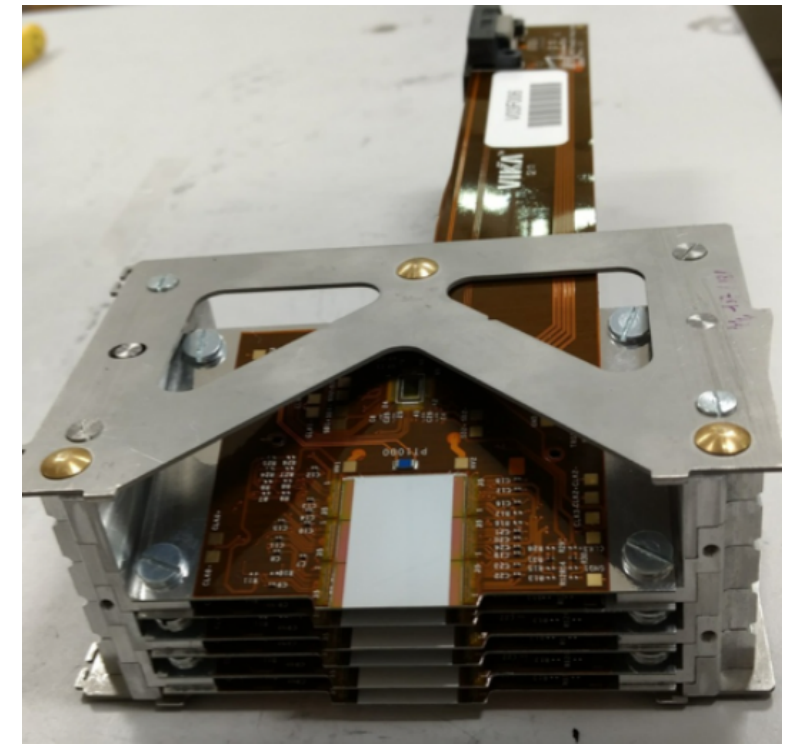




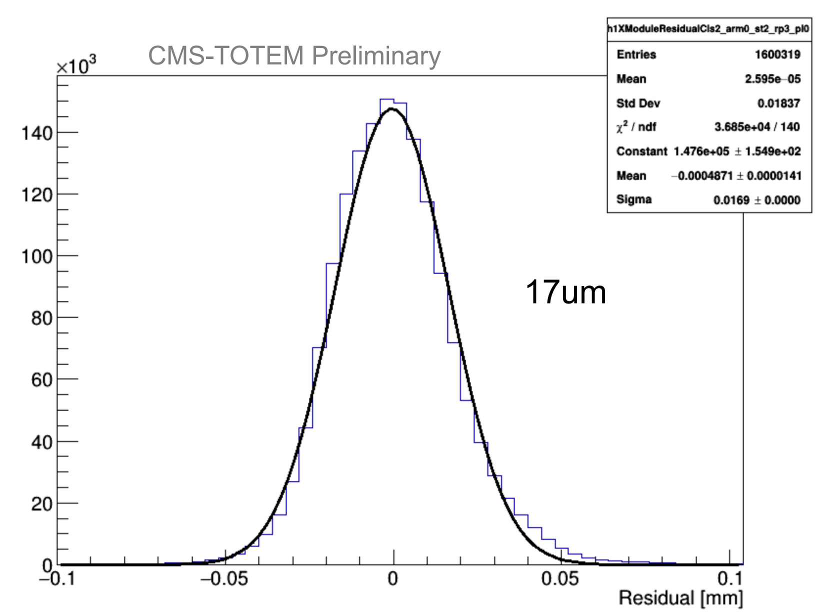
Tracking: Silicon pixels

- **3D technology chosen because of intrinsic radiation hardness and possibility for slim edges**
- **pixel size 100 x 150 μm**
- **Insensitive edge 200 μm**
- **6 planes per RP**
  - Planes tilted by 18 degrees for improved resolution
  - Pixel tracker works as expected
- **Run at -20° C and in vacuum (pressure < 20 mbar)**
- **Readout chip and front-end electronics as for CMS Phase 1 pixel upgrade**
- **Pixel tracker works as expected**
  - Residuals consistent with those obtained with beam test

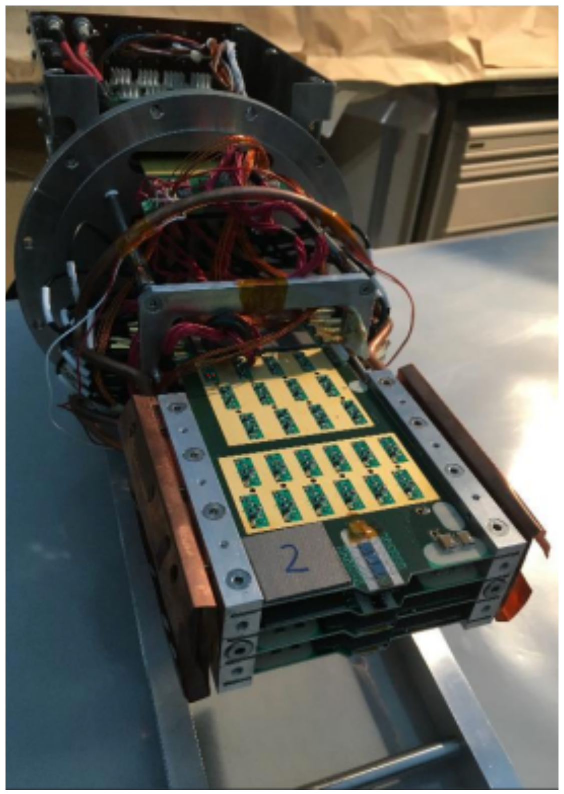




Pixel detector - Hit residual

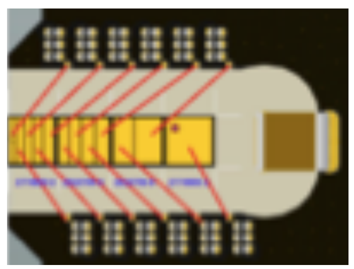


Timing detectors 2017

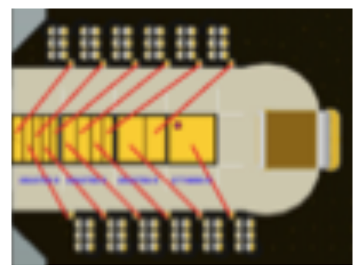


Each timing station hosts 3 scCVD diamond (σ_t ~ 80 ps) and one Ultra Fast Silicon Detector (σ_t ~ 30 ps) planes.
Digitization is done with NINO chip + HPTDC.

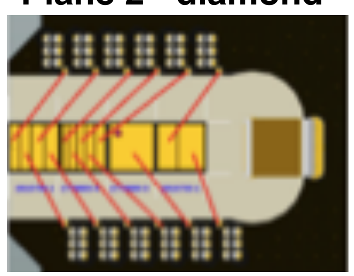
Plane 0 - diamond



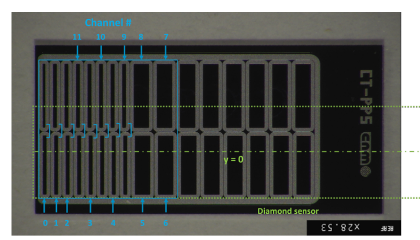
Plane 1 - diamond



Plane 2 - diamond



Plane 3 - UFSD



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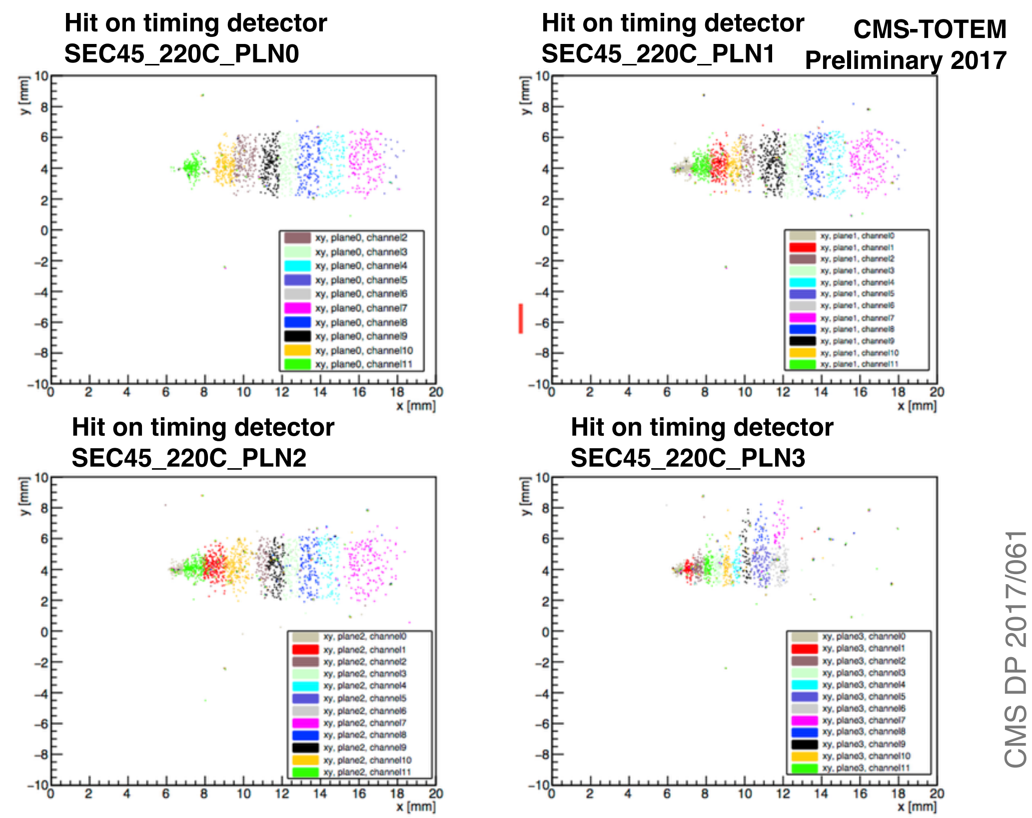
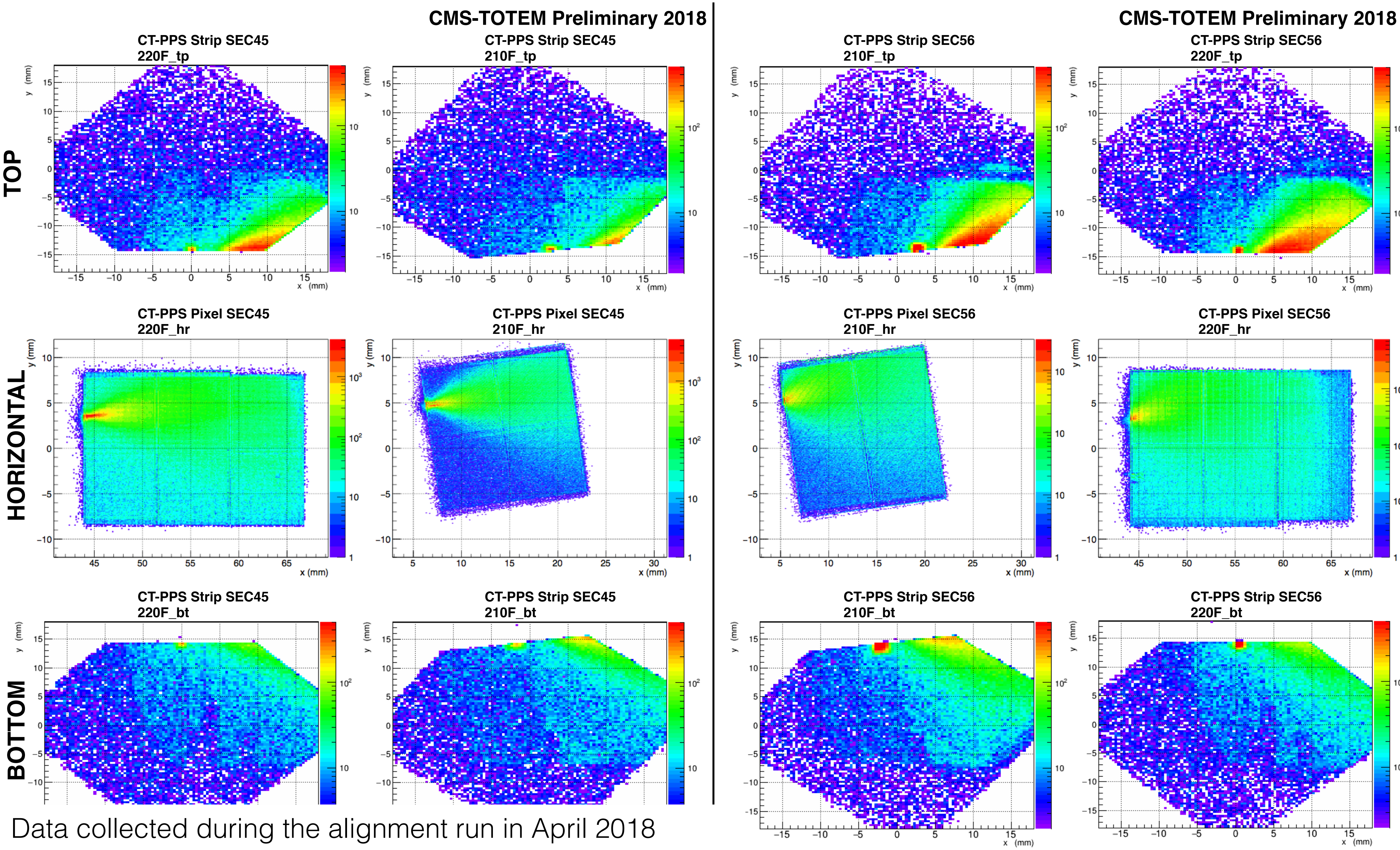
Hit map as measured in the strips requiring a coincidence with timing detectors.



PPS tracking detectors 2018

CMS DP 2018/021

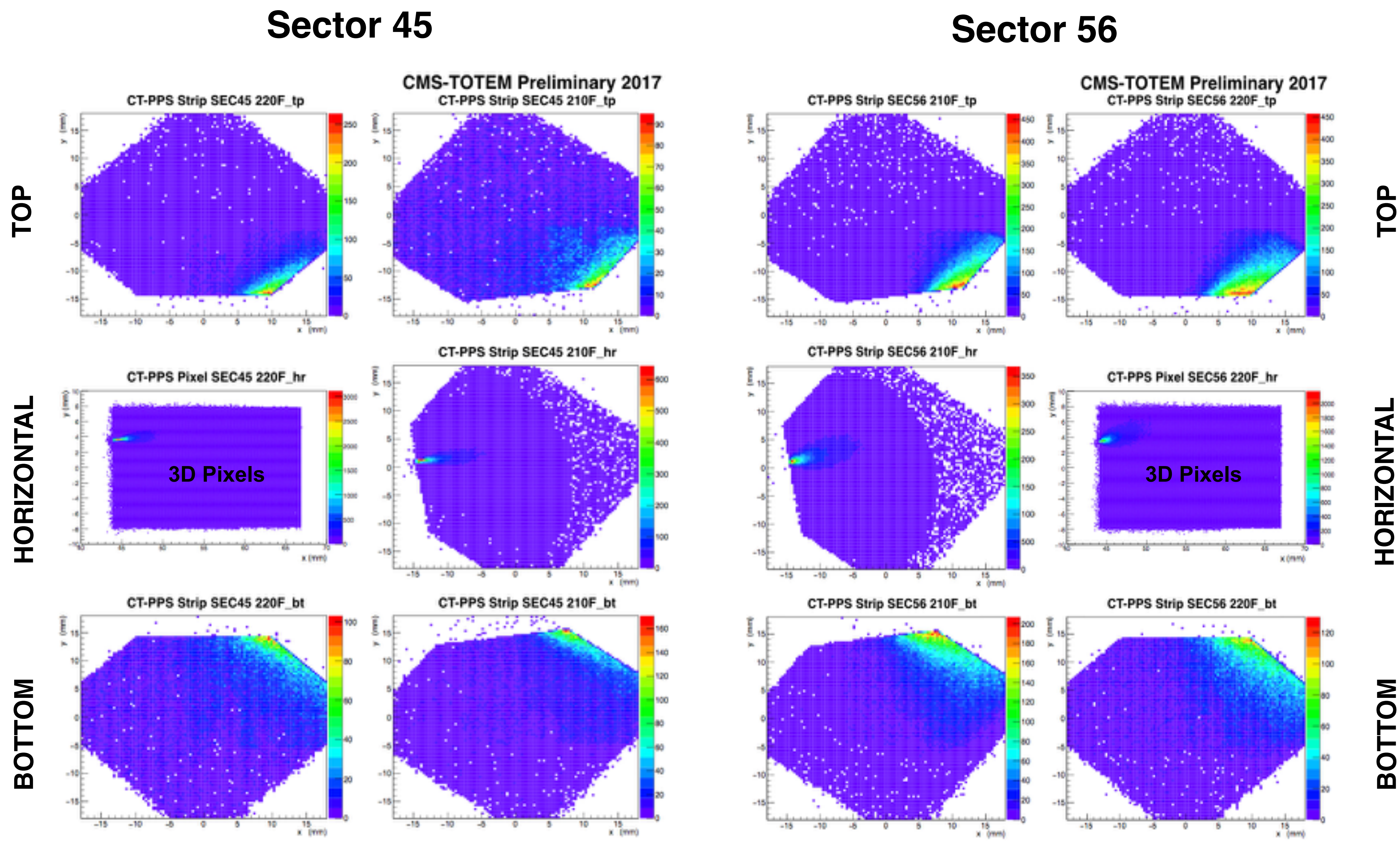
Sector 56



Data collected during the alignment run in April 2018
x-y coordinates relative to an arbitrary system of reference

8

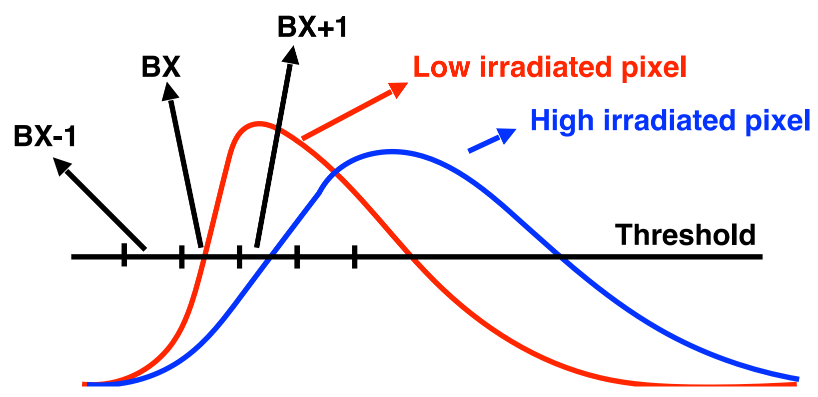
PPS tracking detectors 2017



CMS DP 2017/061

Readout chip radiation damage

- PPS ROC same as in layers 2-3-4 of CMS central pixel detector
- Chip not optimized for non-uniform irradiation
- After several irradiation test, understood that non-uniform irradiation causes a difference between the analog current supplied to the most and least irradiated pixed
- Net result is amplified signal is slowed and associated to following 25 ns clock window (BX)
- Effects appears after an irradiation compatible with collected integrated luminosity ~8 fb^{-1}. To mitigate the impact on data quality, tracking stations have been lifted during 2017 TS2 to shift occupancy maximum away from the damaged region.



CMS DP 2018/021

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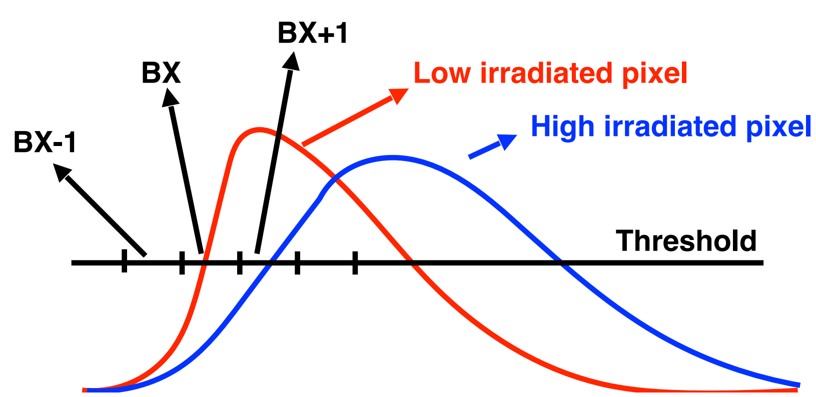
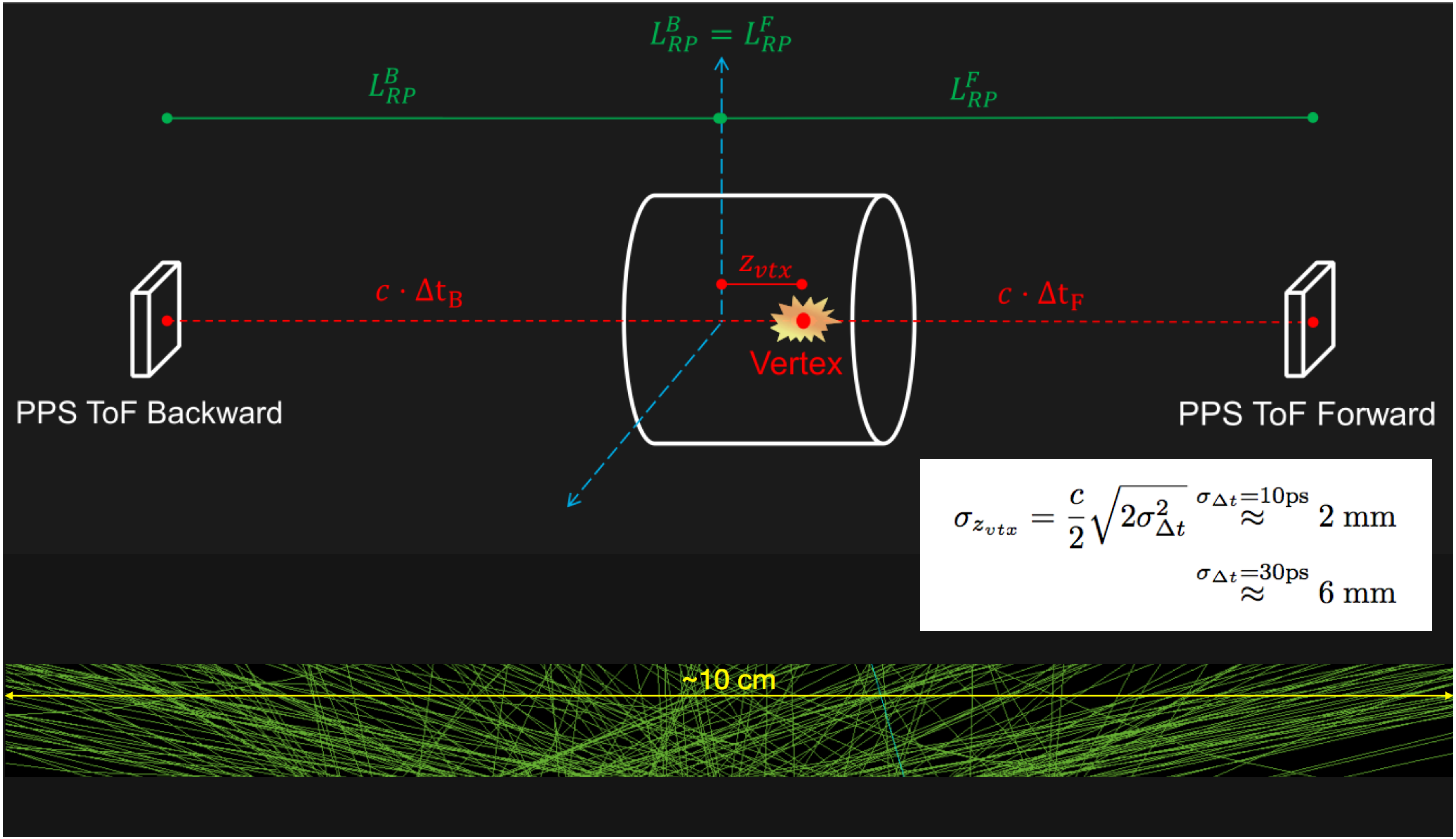
- Net result is amplified signal is slowed and associated to following 25 ns clock window (BX)
- Effects appears after an irradiation compatible with collected integrated luminosity ~8 fb^{-1}. To mitigate the impact on data quality, tracking stations have been lifted during 2017 TS2 to shift occupancy maximum away from the damaged region.



CMS DP 2018/021

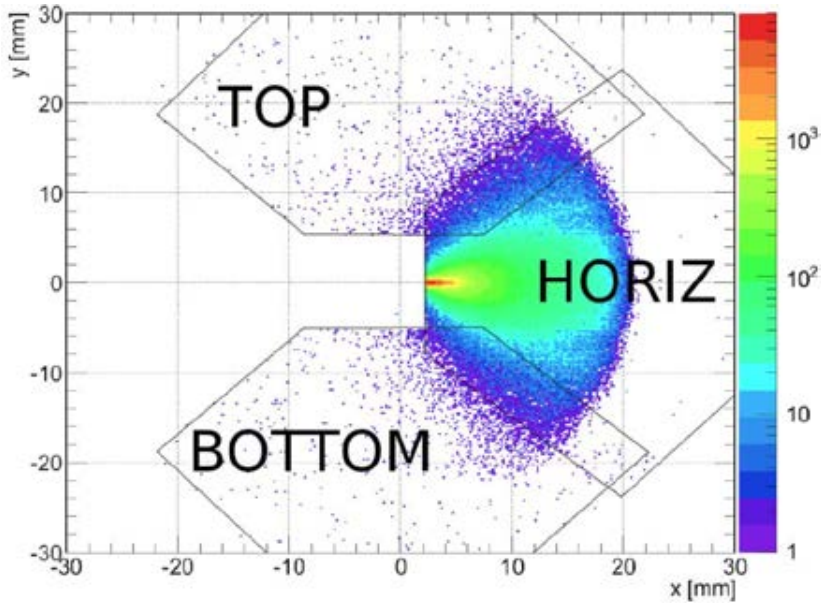
PPS timing measurement



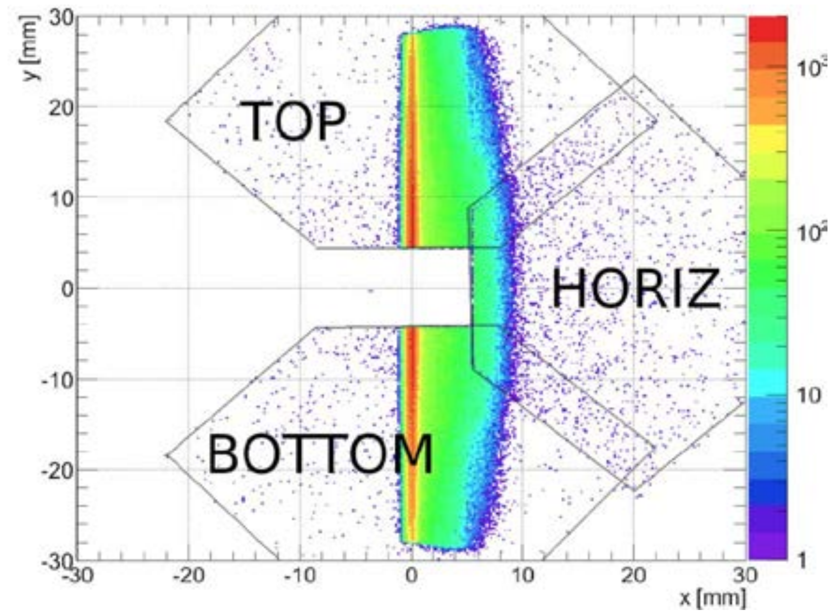
$$\sigma_{z_{vtx}} = \frac{c}{2}\sqrt{2\sigma^2_{\Delta t}} \overset{\sigma_{\Delta t}=10\text{ps}}{\approx} 2\text{ mm}$$
$$\overset{\sigma_{\Delta t}=30\text{ps}}{\approx} 6\text{ mm}$$

Detector acceptance vs. β*

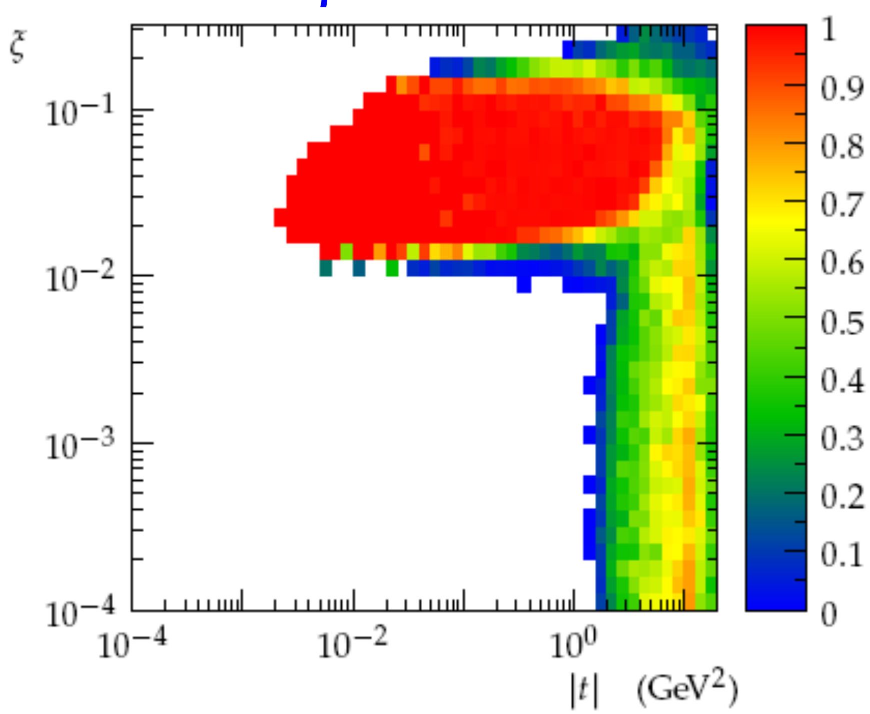
β* = 0.55 m (low β* = standard at LHC)



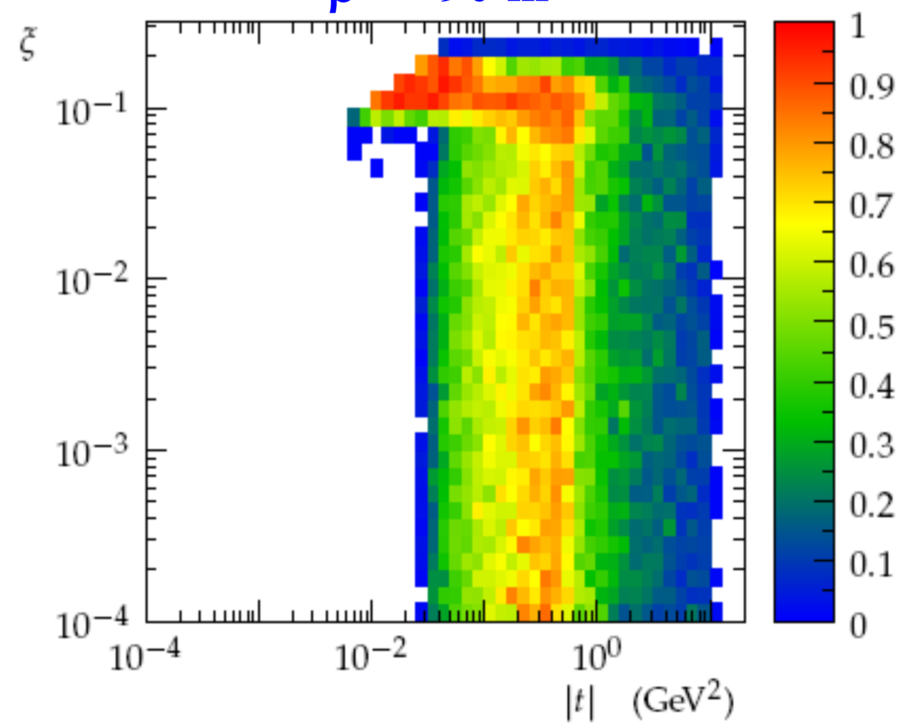
β* = 90 m (special development for RP runs)



β* = 0.55 m



β* = 90 m



M. Deile, 2015

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14