Extending the CMS physics program with the Precision Proton Spectrometer (PPS)

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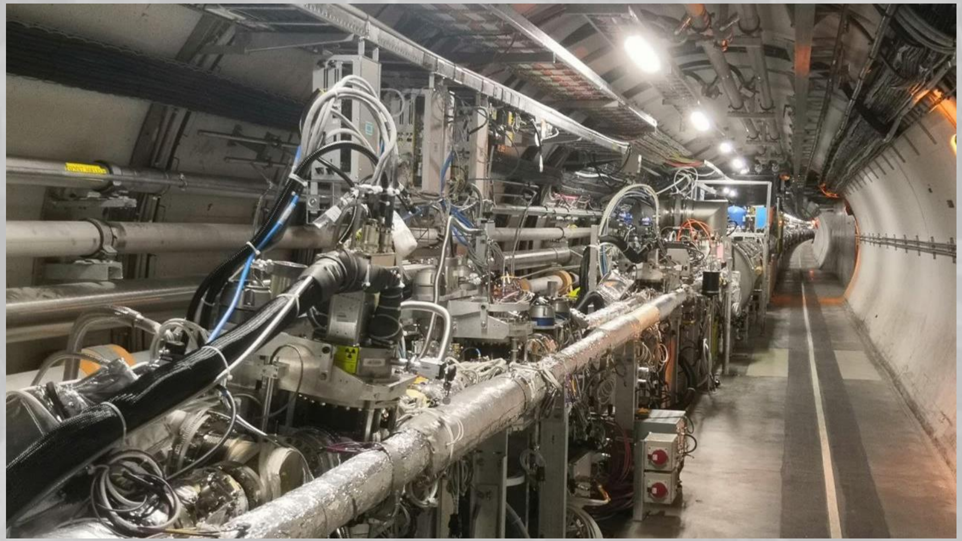


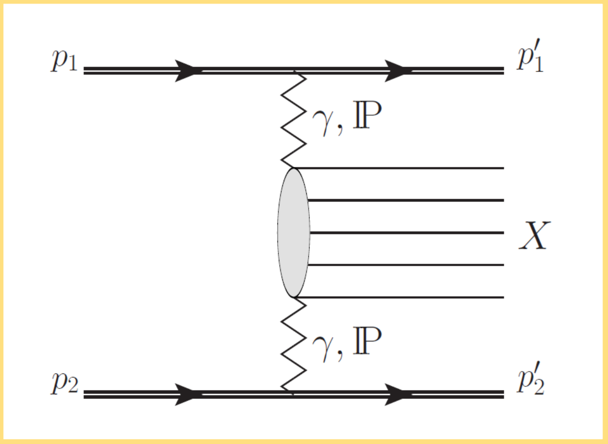
Structure of the presentation

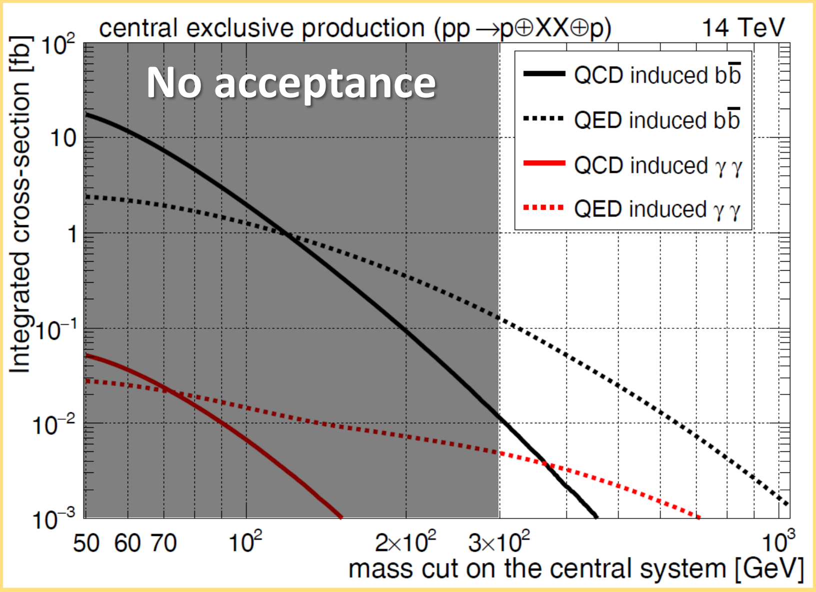
- Introduction to PPS
- Proton reconstruction
- Physics analyses with proton tagging
- PPS in LHC Run 3 and beyond

Introduction to PPS

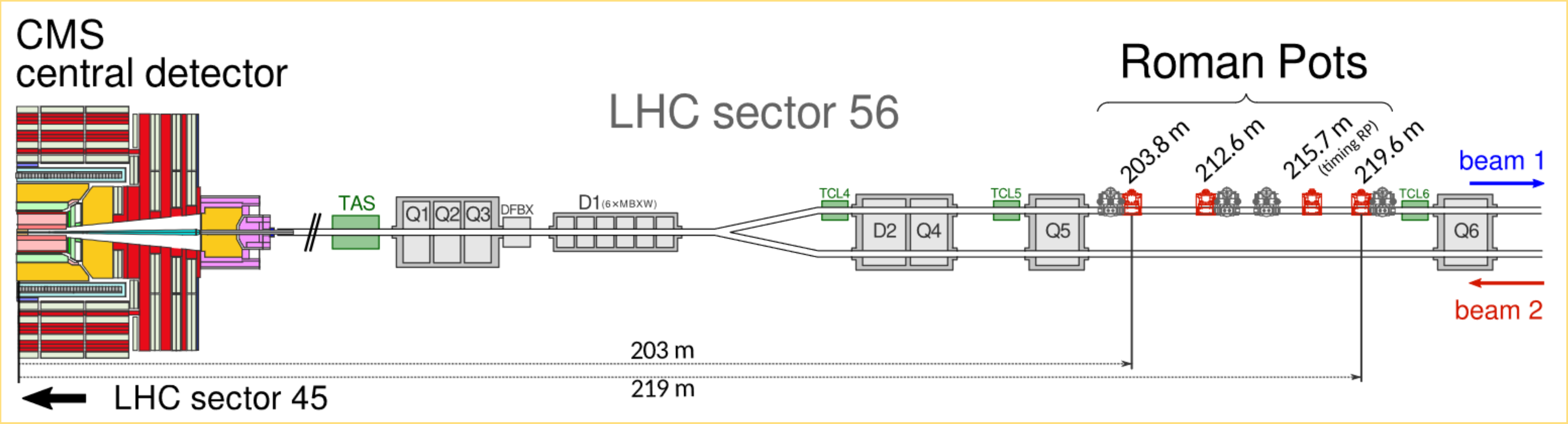
PPS physics case

- Study **central exclusive production** (CEP) at the LHC
  - **Protons remain intact**
- Proton tagging provides:
  - **Full reconstruction** of the final state
  - Strong **background rejection**
- Exploit LHC as a photon-photon collider:
  - **Test QED** processes (favoured at high mass)
  - **Search for BSM** physics:
    - Enhancements over high-mass tails
    - New resonances
    - High sensitivity to anomalous couplings



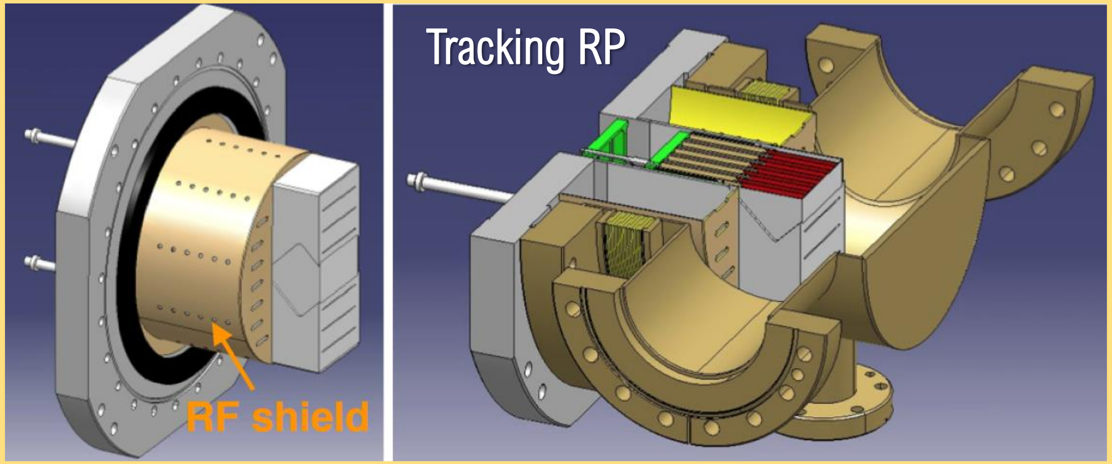


Precision Proton Spectrometer (PPS)



- LHC magnetic field bends **protons that survived the interaction in CMS**:
- **Tracking and timing** detectors installed in Roman Pots (RPs), to measure:
  - Track displacement from beam center → Fraction of momentum lost by the proton (ξ)
  - Time of arrival on both sides → Longitudinal coordinate of the vertex (z)

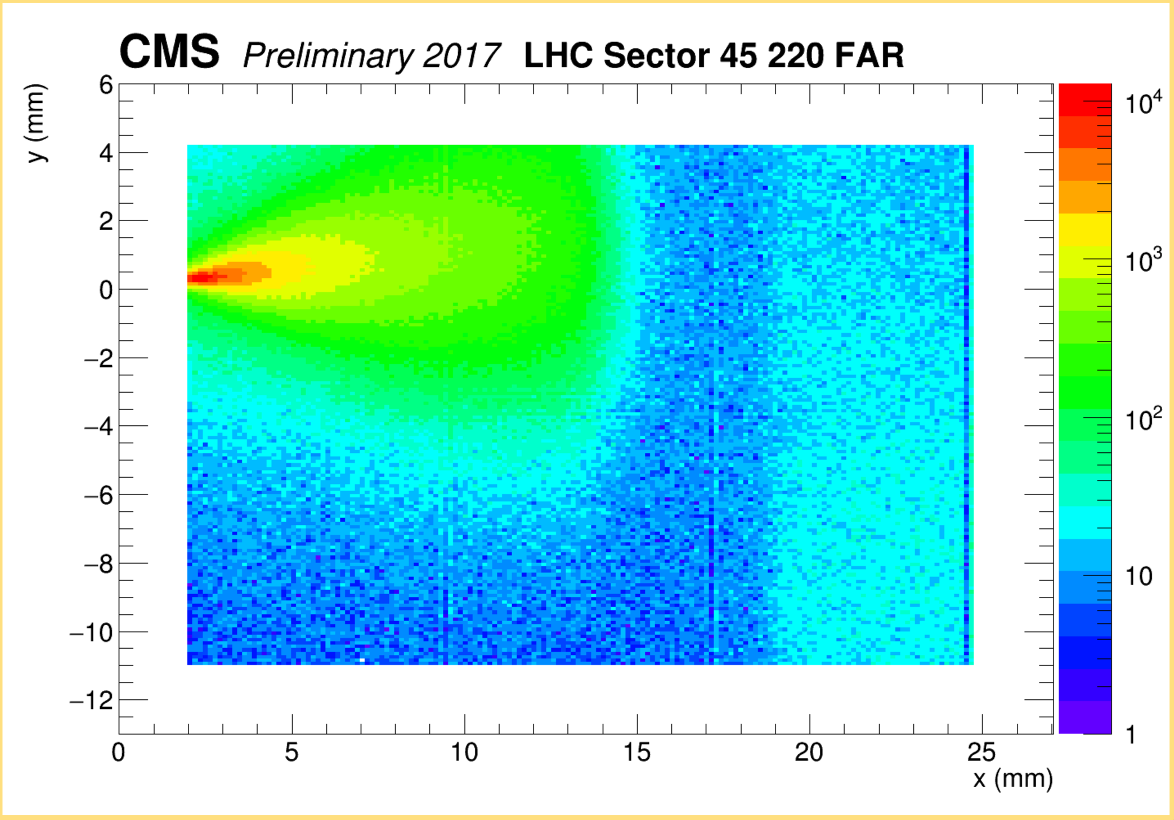
Precision Proton Spectrometer (PPS)



- …otons that survived the interaction in CMS:
- …s installed in Roman Pots (RPs), to measure:
  - …n center → Fraction of momentum lo…
  - → Longitudinal coordinate c…

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

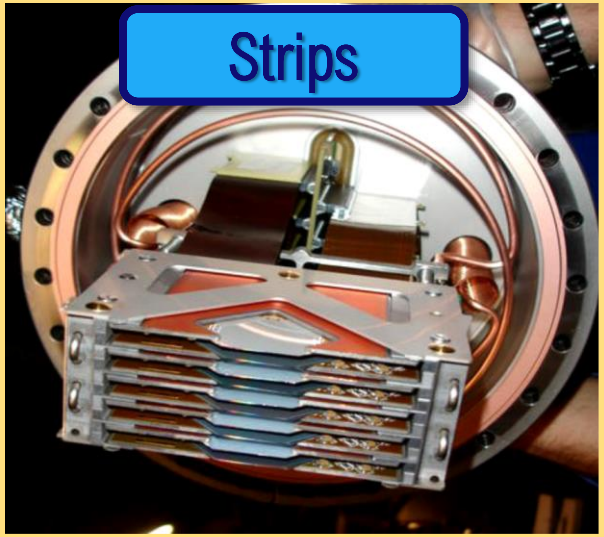
PPS radiation environment

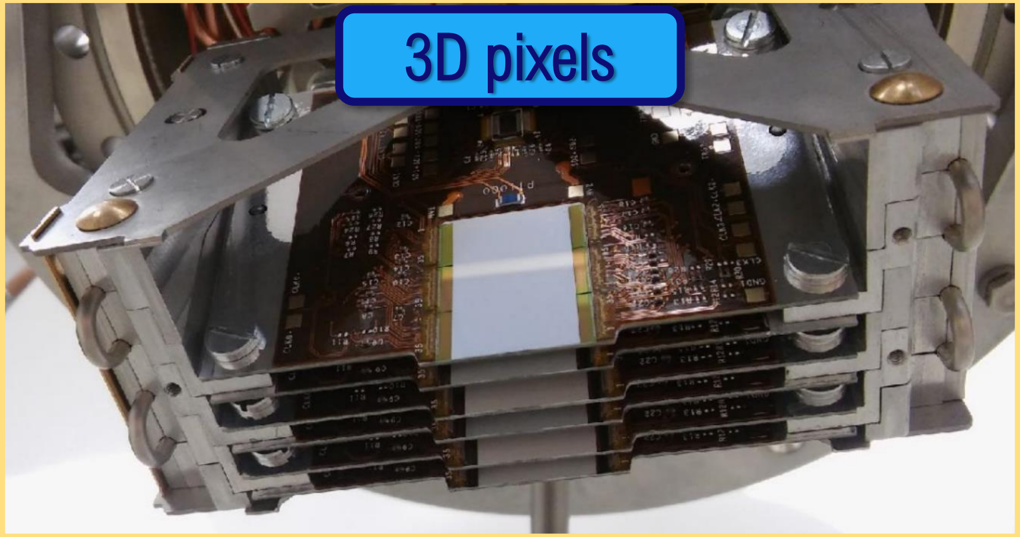


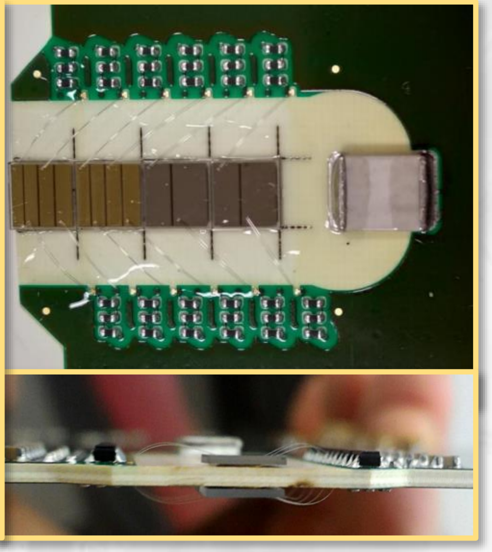
- PPS detectors approach the LHC beam down to ~2 mm
- High irradiation: $\sim 5 \cdot 10^{15}\ \mathrm{p/cm^2}$ for 100 $\mathrm{fb^{-1}}$
- Highly non-uniform irradiation
  - ~2 order of magnitudes difference over less than 1 mm

Very challenging environment for particle detectors

PPS throughout Run 2





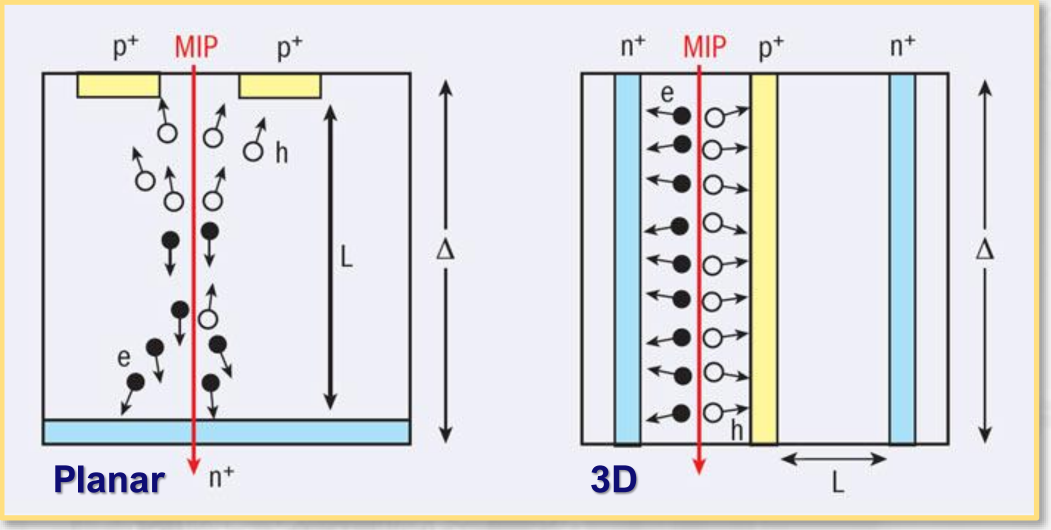


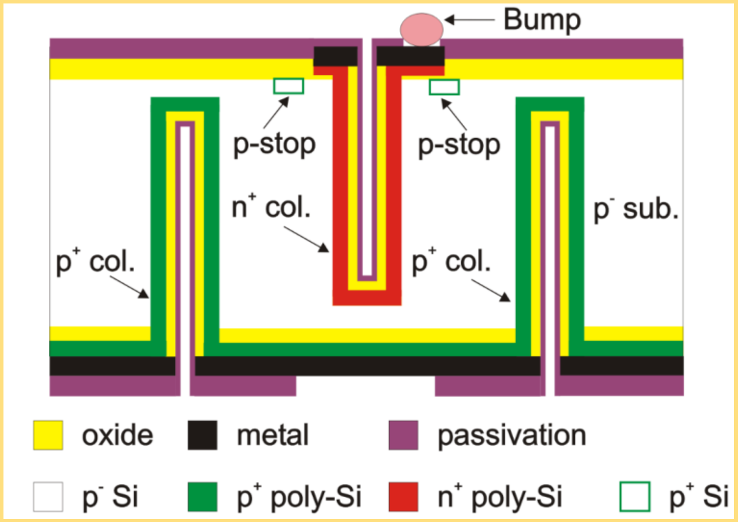
Diamonds

- 2016 → 210-far + 220-near stations:
  - Legacy TOTEM Si-strips (5+5 planes, 66 μm pitch, 300 μm thick)
- 2017 → 210-far + 220-far stations for tracking + 1 cylindrical RP for timing:
  - Tracking: Legacy TOTEM Si-strips + 3D Si-pixels
  - Timing: 3 planes of single-layer scCVD diamonds + 1 UFSD (LGAD) plane
- 2018 → same as 2017:
  - Tracking: only 3D Si-pixels
  - Timing: 2 planes of single-layer scCVD diamonds + 2 planes of double-layer

3D pixels for PPS Run 2

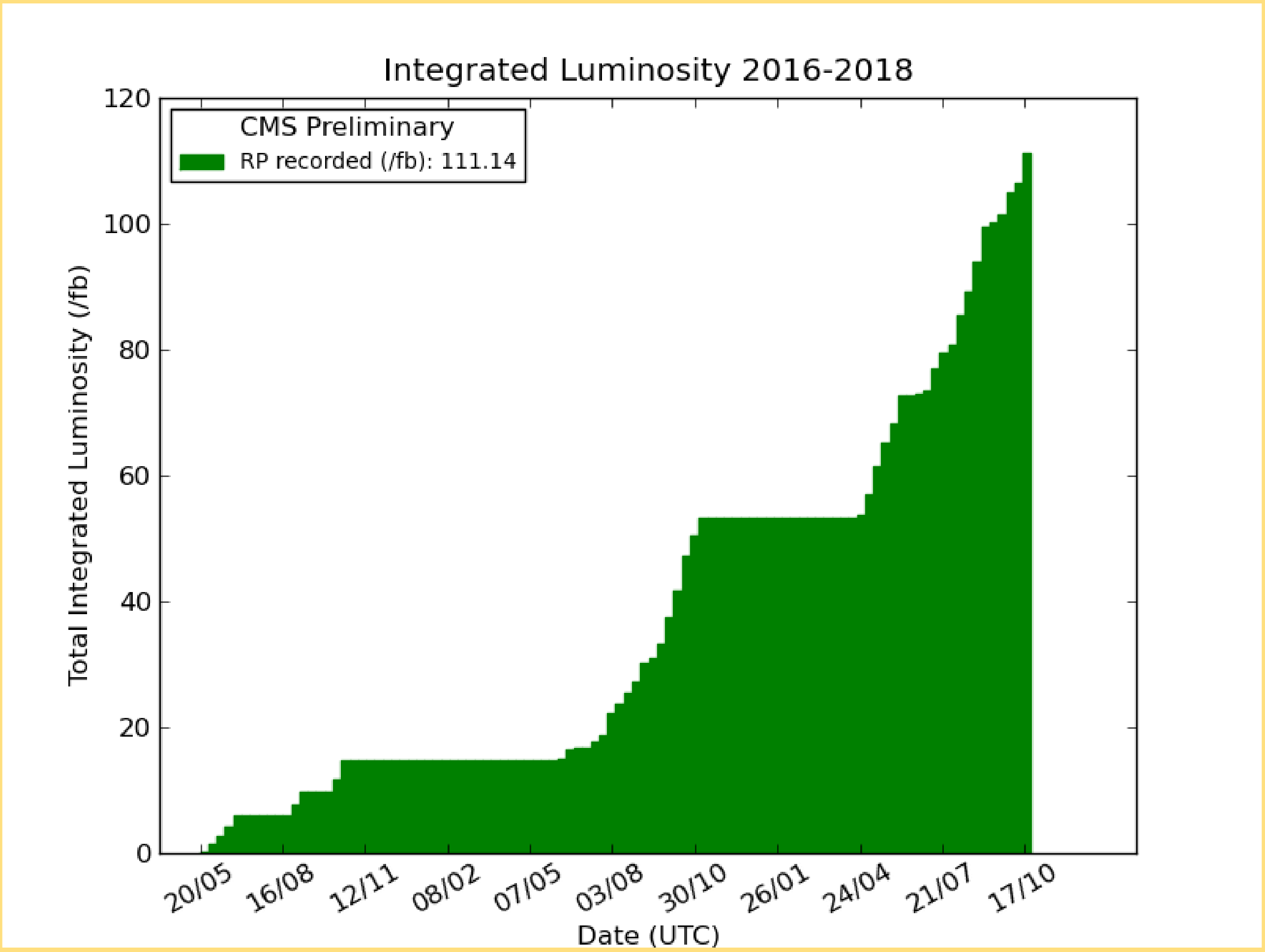
- Silicon 3D pixel sensors:
  - Optimal choice for high radiation hardness
  - Decouple thickness from drift path length
  - Low depletion voltage ($<$10 V)
  - Slim/active edge
- Sensors for PPS Run 2:
  - Produced at CNM with double-sided process
  - 230 μm-thick sensors
  - 200 μm-deep, 10 μm-diameter columns
  - 150×100 μm^2 pixel size
  - 2×2 or 3×2 matrix of 52×80 pixels





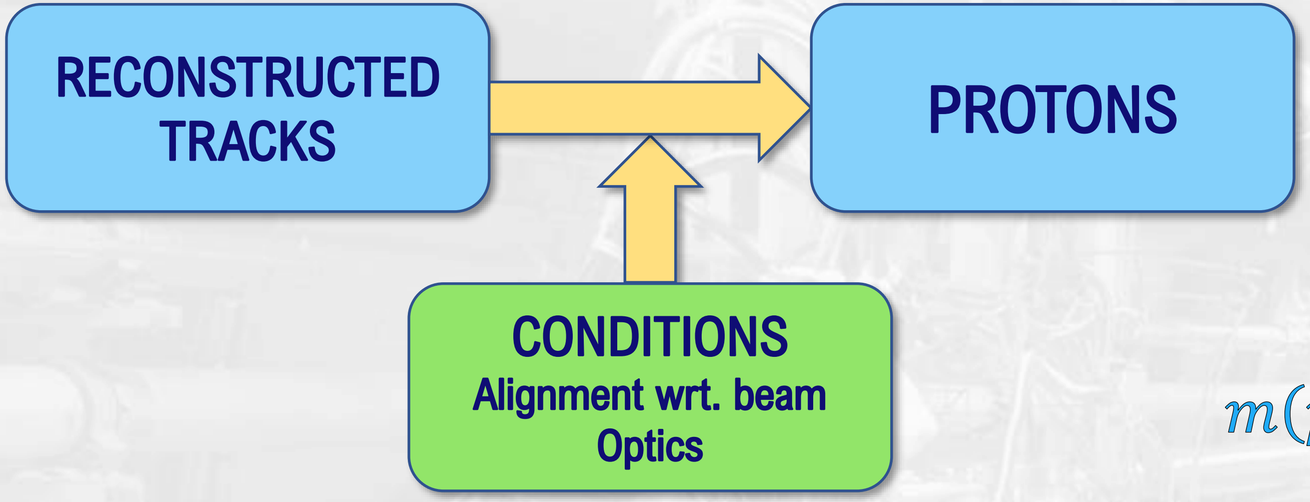
Run 2 data-taking

- PPS collected more than 110 fb^{-1} during Run 2:
  - Almost 100 fb^{-1} with pixels
  - ~84% of the CMS total luminosity
  - Very stable running in 2017-2018



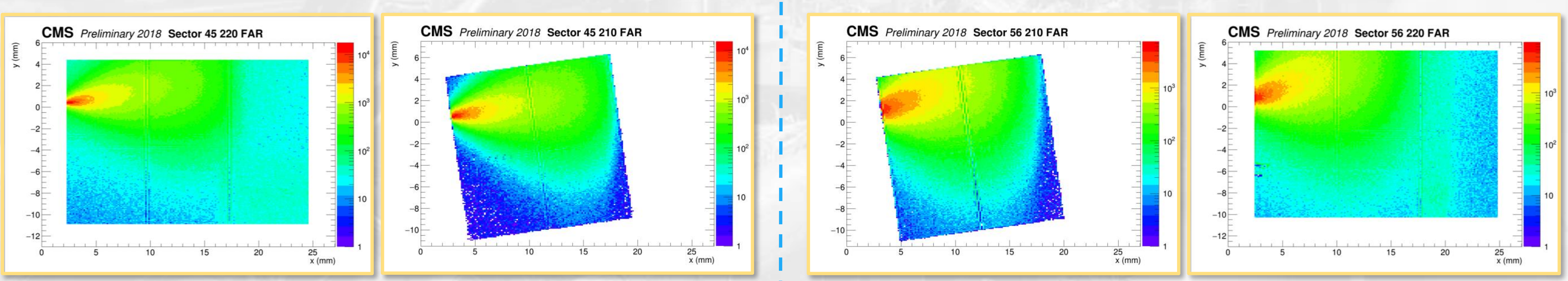
Proton reconstruction

Proton reconstruction



$$\xi = \frac{p_{nom} - p}{p_{nom}}$$

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



LHC Sector 45 ← **IP5** → **LHC Sector 56**

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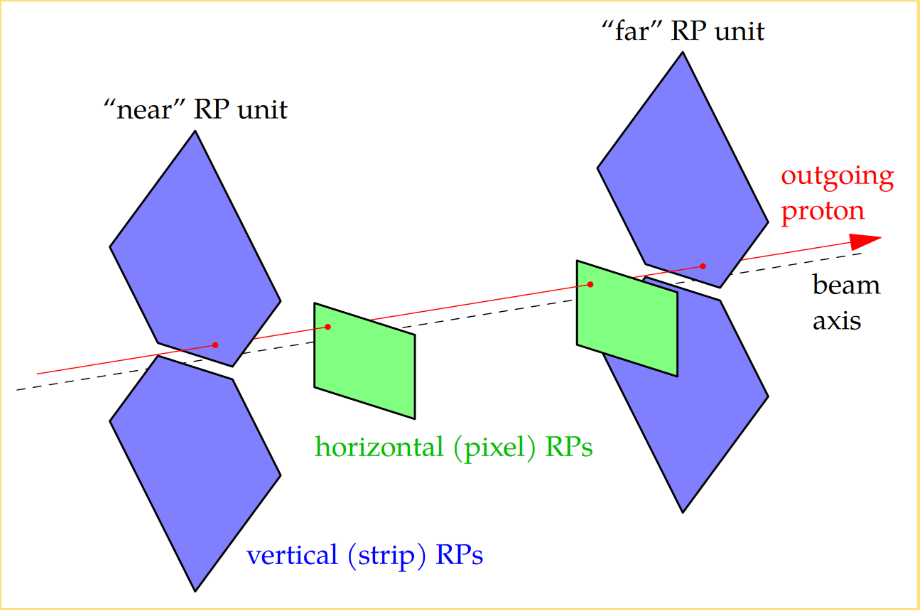
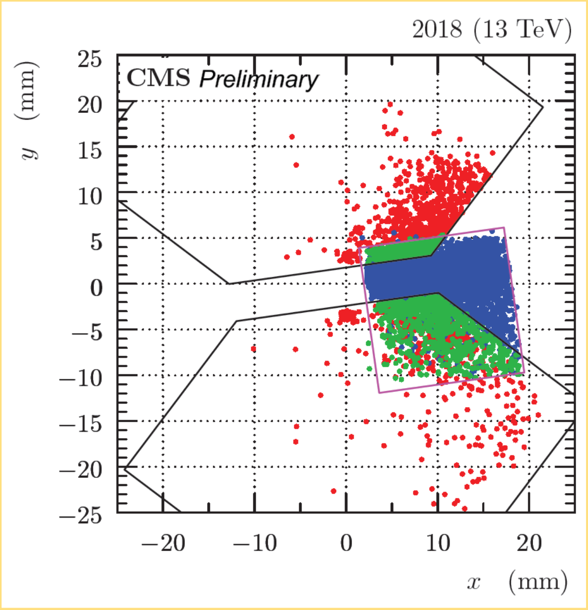
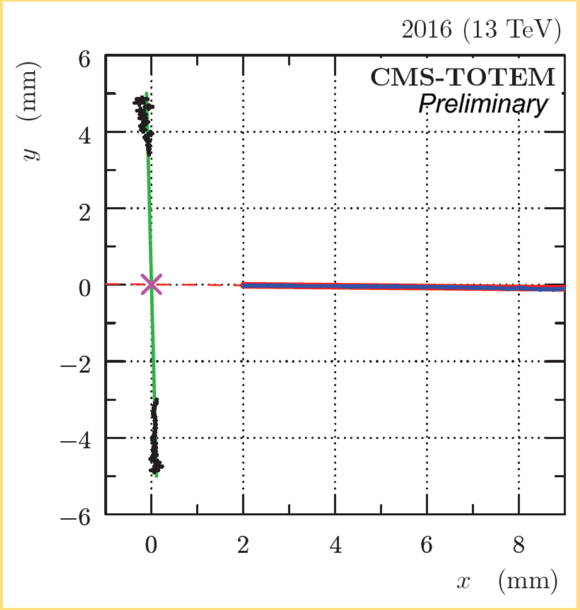
Detector alignment







Multi-step procedure: base measurement in dedicated fill, then corrected fill-by-fill

- Alignment fill: determine the beam position and the relative detector positions
  - Low intensity (2-3 bunches), detectors closer to the beam, vertical RPs inserted
  - Data collected for each LHC setting that will be used during future data-taking
  - Elastic scattering kinematic properties used to find the beam center
- Corrections: match dedicated observables to their alignment fill counterpart

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Proton transport

- Reconstruct the proton kinematics at the IP (d^*) from the measurements at the RP positions (d)
- Propagation modelled via the transport matrix T, containing the optical functions: $d = T \cdot d^*$

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \\ \xi \end{pmatrix} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & D_y \\ 0 & 0 & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \theta^*_x \\ y^* \\ \theta^*_y \\ \xi \end{pmatrix}$$

- Simplified version with leading terms:

$$x = v_x(\xi) \cdot x^* + L_x(\xi) \cdot \theta^*_x + \boldsymbol{D_x(\xi) \cdot \xi}$$
$$y = v_y(\xi) \cdot y^* + \boldsymbol{L_y(\xi) \cdot \theta^*_y} + D_y(\xi) \cdot \xi$$

Magnifications | **Effective lenths** | **Dispersions**

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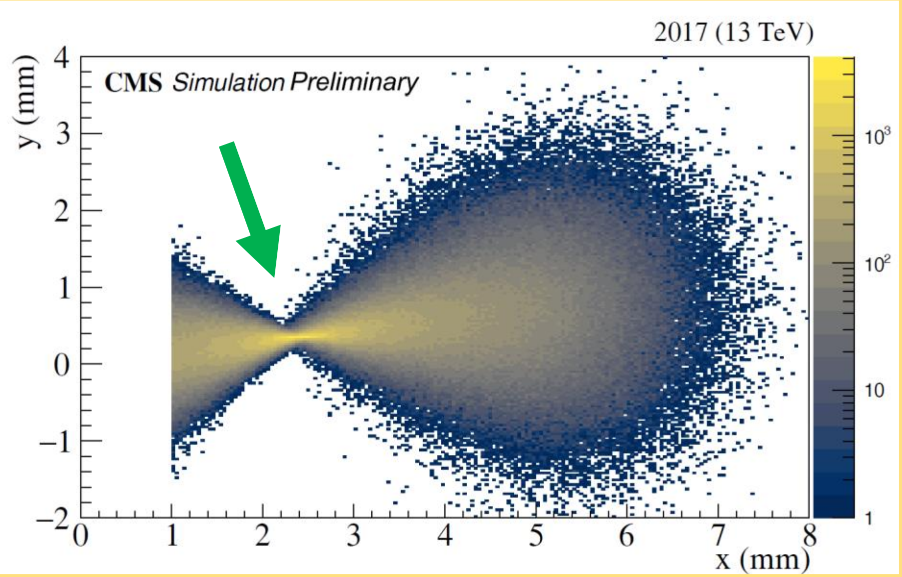
Optics calibration

- Precise knowledge of the LHC beam optics is needed for proper reconstruction
  - Nominal optics calculated with MAD-X (accelerator simulation based on LHC parameters)
- Further calibration with data:
  - L_y calibrated using elastic events in the alignment run
  - D_x derived with two methods:
    - Determination of the 'pinch' point ($L_y = 0$) in min-bias events
    - Validation with the $\mu\mu$ sample
- Optical functions vary with crossing angle
  - This means variable acceptance during data-taking!



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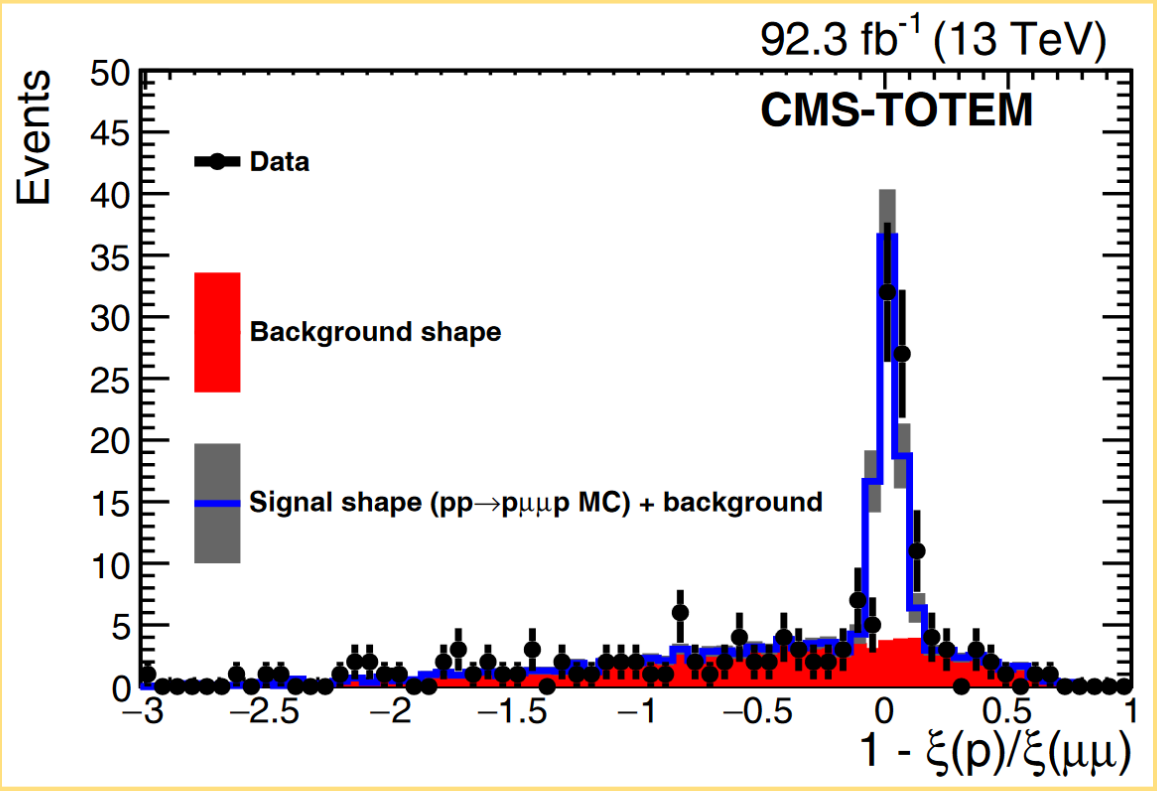
Validation with exclusive $\mu\mu$ events

- Select two oppositely charged μ:
  - $p_T > 50$ GeV
  - $m(\mu^+\mu^-) > 110$ GeV
  - Low acoplanarity
    - $1 - |\Delta\phi(\mu^+\mu^-)|/\pi < 0.009$
  - No close tracks to the $\mu\mu$ vertex
    - Closer than 0.5 mm
- Compute the ξ from $\mu\mu$ with:

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

- Compare with the proton ξ
  - Use results to further improve the proton ξ reconstruction



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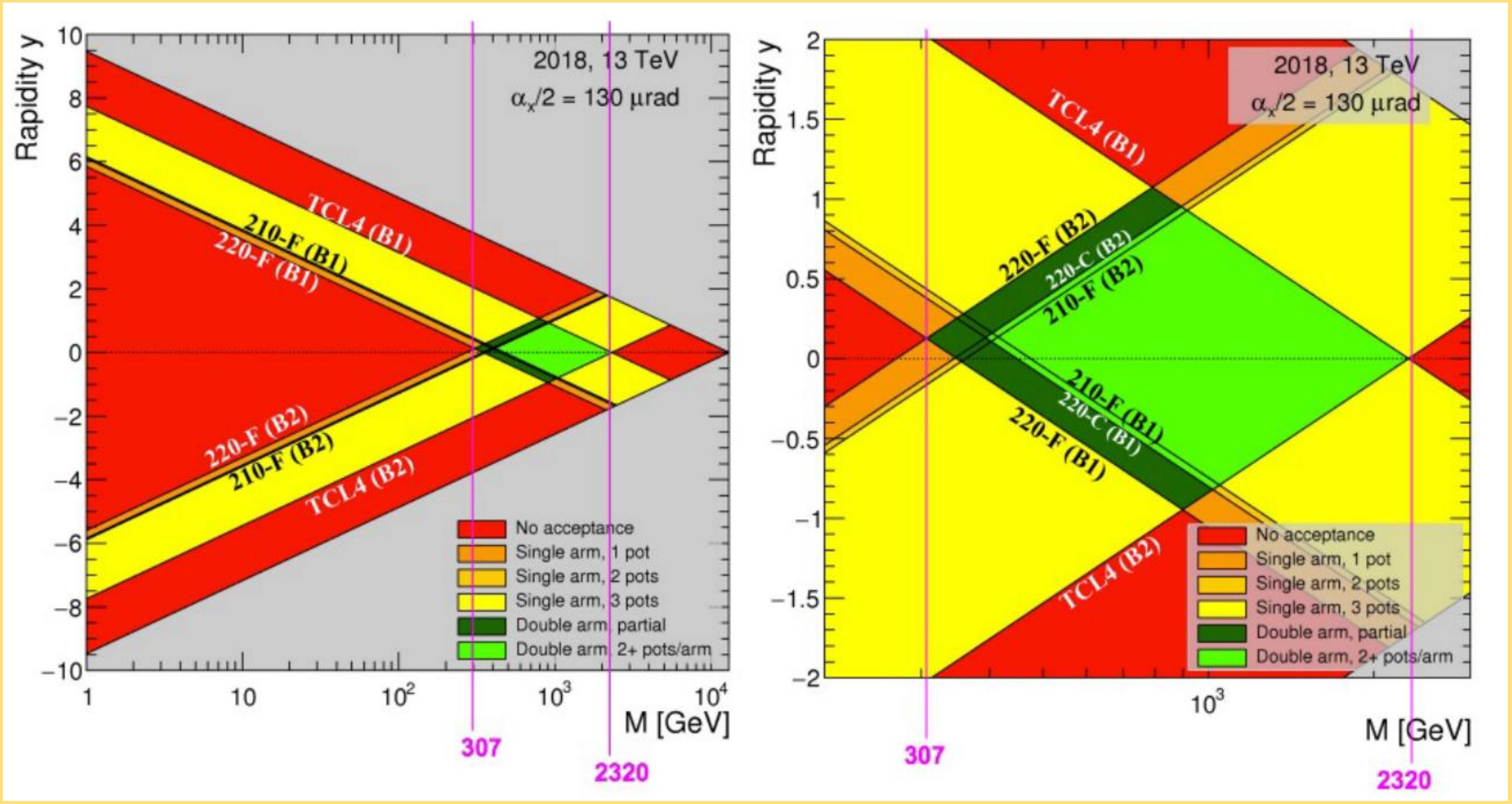
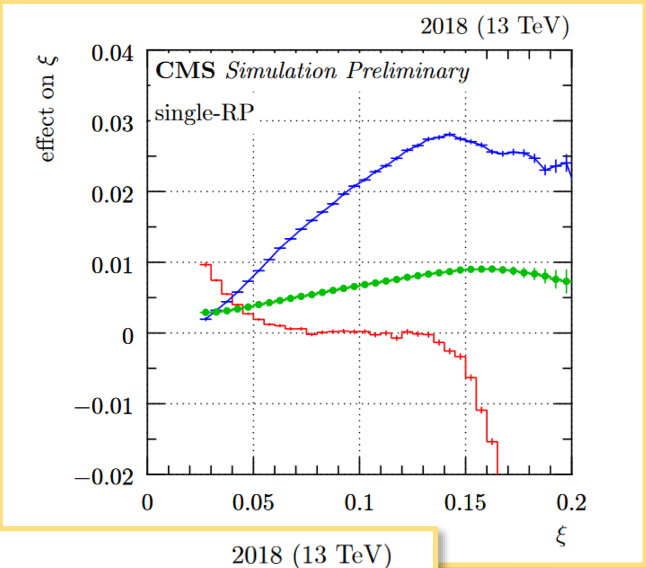
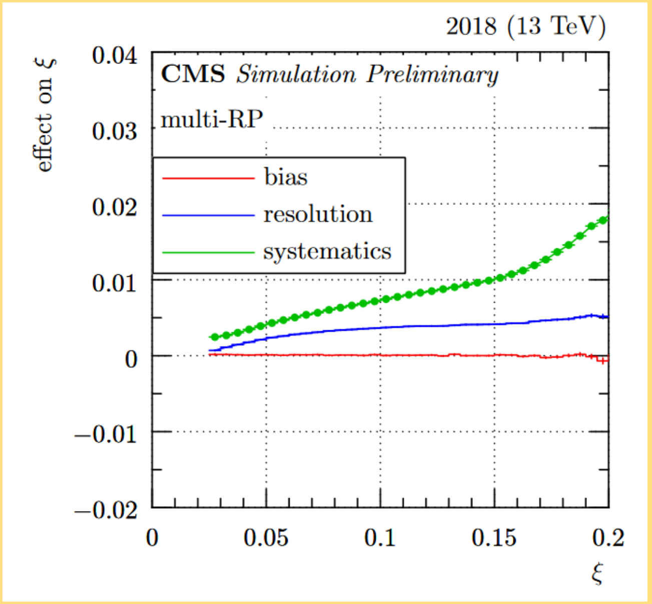
PPS mass/rapidity acceptance



Reconstruction strategies

- Single-RP protons:
  - Use data from only one RP → partial reconstruction
    $\xi = \frac{x}{D_x}$ and $\theta_y^* = \frac{y}{L_y(\xi)}$
  - Lower ξ resolution, less sensitive to systematics
- Multi-RP protons:
  - Combine measurements in 2 RPs (same sector)
  - Minimize $\chi^2 = \sum_{i:RPs} \sum_{q:\,x,y} \left[\frac{d_q^i - (T^i d^*)_q}{\sigma_q^i}\right]^2$
  - Better resolution, higher systematics (at high ξ)





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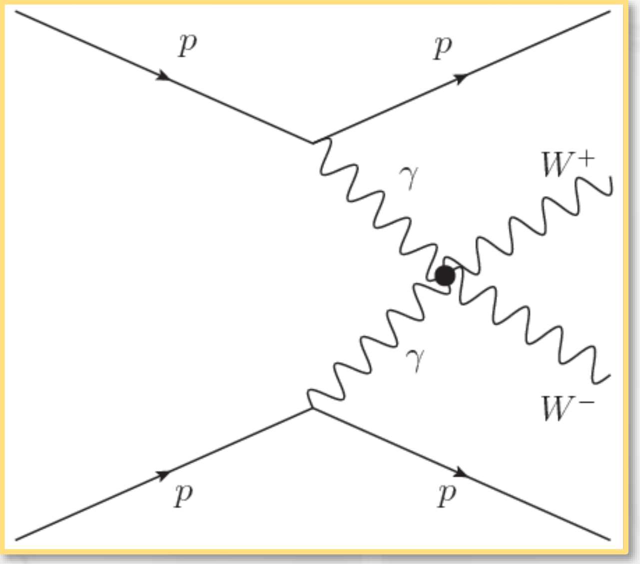
Physics analyses with proton tagging

Probing AQGC with exclusive $\gamma\gamma \to VV$

- Search for **anomalous WW/ZZ (VV) exclusive production** at high mass:
  - Exploring the **hadronic decay channel** (each V decaying into a boosted and merged jet)
  - Require **intact protons on both sides**
  - Look for **non-resonant enhancements** over high-mass tails (AQGC/EFT)
- Why not aiming for SM production?
  - **ZZ not allowed** at tree level
  - **WW exclusive production** concentrated in the low mass region:
    - Higher QCD background
    - **Out of reach** with the Run 2 trigger thresholds on jets
    - Dedicated trigger will be used in Run 3



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Selection on central variables

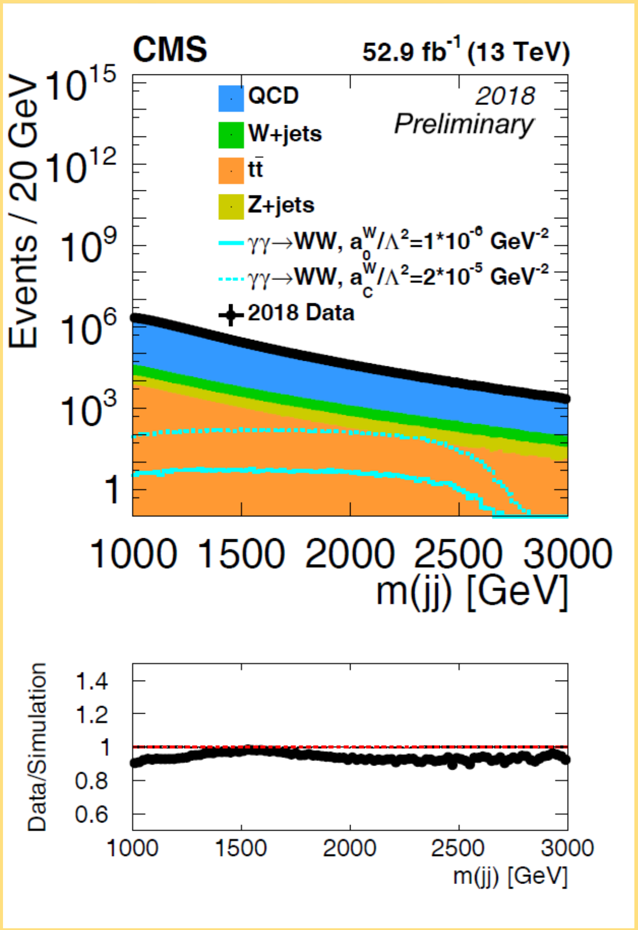
Trigger:

- Combination of triggers based on the highest jet p_T and sum of the p_T of all jets
- >99% efficiency for $m(j_1 j_2) > 1126$ GeV

Selection:

- ≥ 2 V-tagged ($\tau_{21}^{DDT} < 0.75$) AK8 (large radius) jets
- $|\eta(j_1, j_2)| < 2.5$
- $p_T(j_1, j_2) > 200$ GeV
- 60 GeV $< m_{pruned}(j_1, j_2) < 107$ GeV
- $|\eta(j_1) - \eta(j_2)| < 1.3$
- $p_T(j_1)/p_T(j_2) < 1.3$
- $a = |1 - \Delta\phi(j_1 j_2)/\pi| < 0.01$
- 1126 GeV $< m(j_1 j_2) < 2500$ GeV
- ≥ 1 proton per side of PPS (in acceptance)

- Backgrounds:
  - Main: QCD di-jet production (simulated with Pythia8) + pileup protons
  - Others: $t\bar{t}$, W/Z + jets (Madgraph/Powheg) + pileup protons



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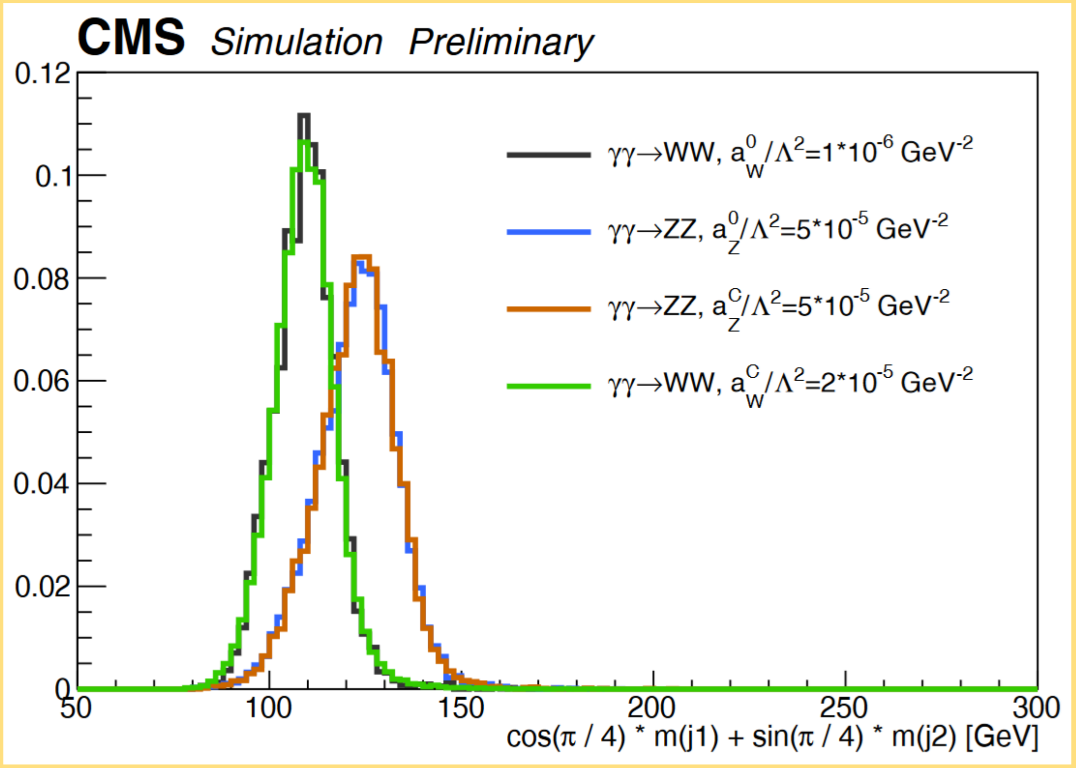
WW/ZZ separation



- WW/ZZ separation based on [sub]leading jet pruned mass $m(j_1)[m(j_2)]$
  - No dependence observed on anomalous coupling value

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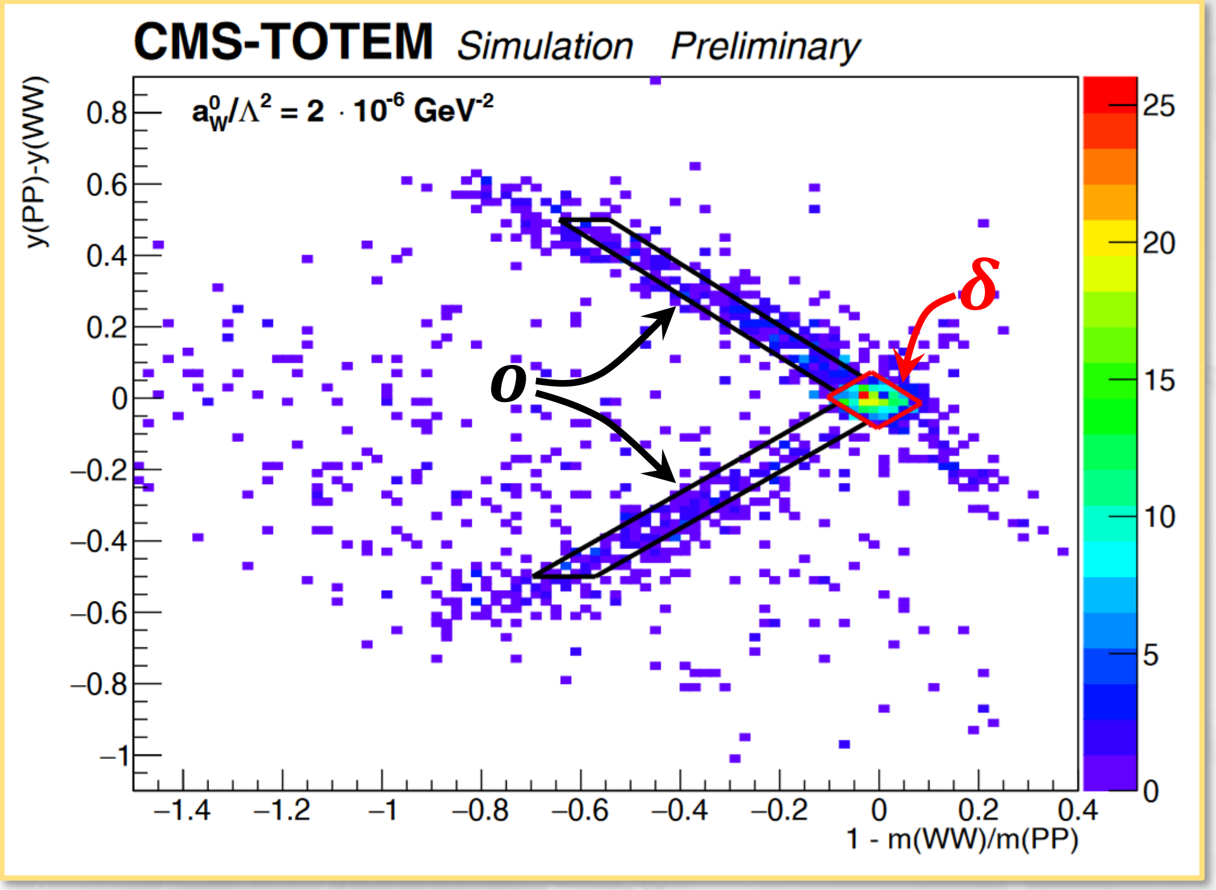
Proton matching: signal regions

- pp vs. VV matching with:
  - Mass match ratio:
    $$1 - m(VV)/m(pp),$$
    $$m(pp) = \sqrt{s\xi_1\xi_2}$$
  - Rapidity difference:
    $$y(pp) - y(VV),$$
    $$y(pp) = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)$$
- Two signal regions:
  - $\boldsymbol{\delta}$: both protons from the interaction
  - $\boldsymbol{o}$: one proton mistakenly chosen from pileup



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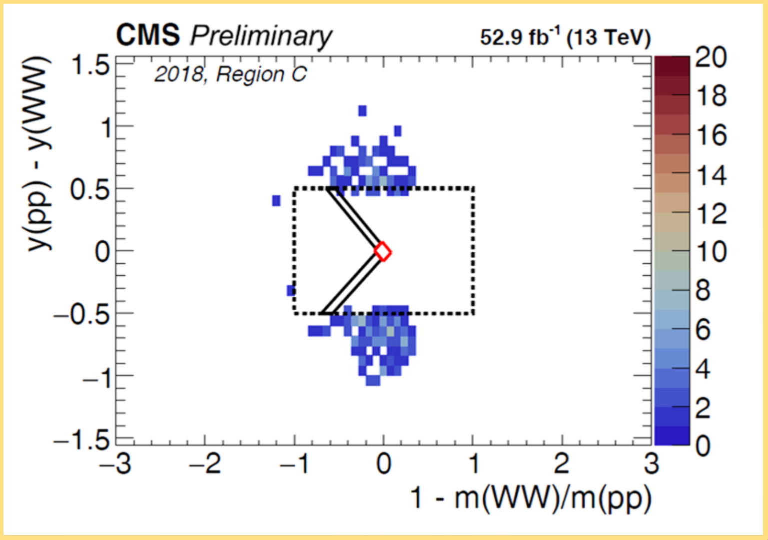
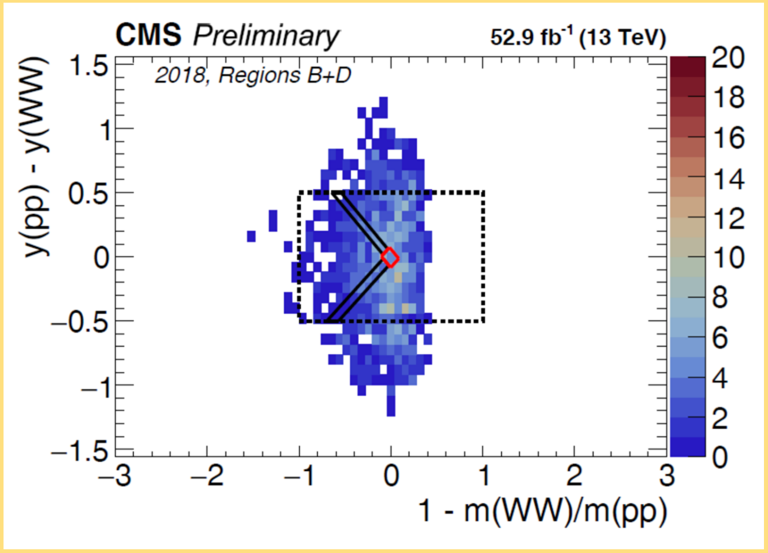
Background estimation

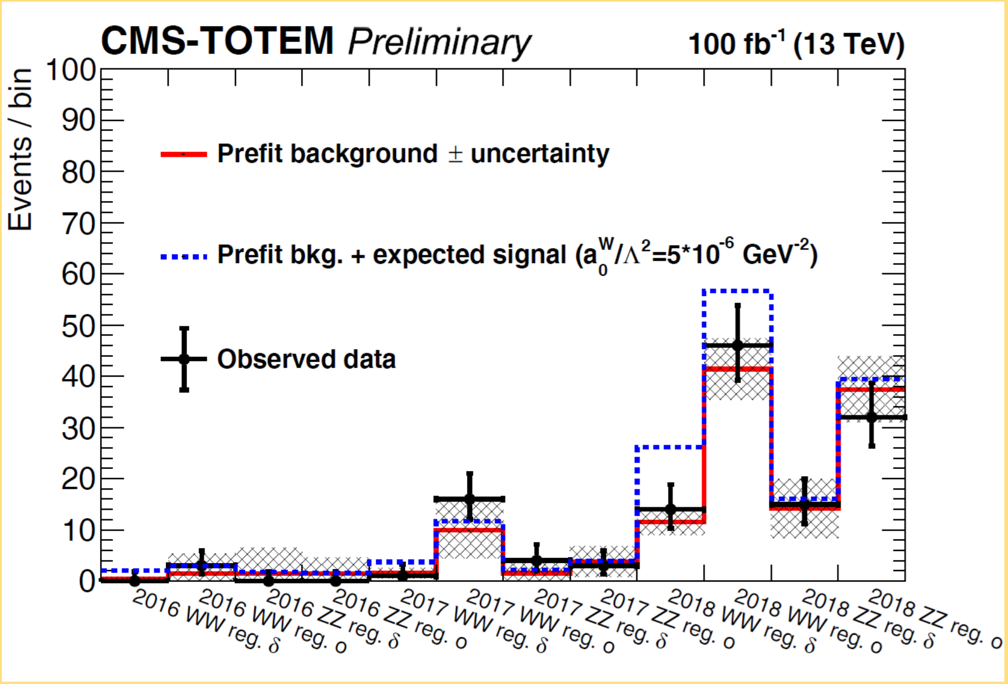


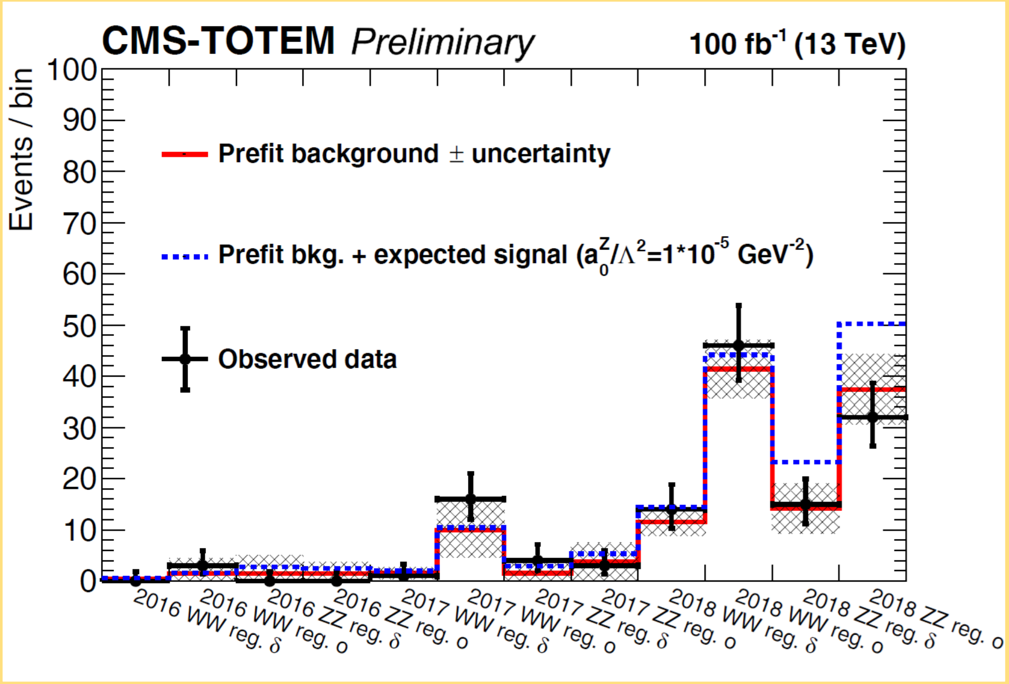


Region A $a < 0.01$ & Signal region	**Region B** $a > 0.01$ & Signal region
Region C $a < 0.01$ & $(\|1 - m(VV)/m(pp)\| > 1.0$ or $\|y(pp) - y(VV)\| > 0.5)$	**Region D** $a > 0.01$ & $(\|1 - m(VV)/m(pp)\| > 1.0$ or $\|y(pp) - y(VV)\| > 0.5)$

- Fully **data-driven background** estimation: sidebands method
  - $N_A = N_C \times N_B / N_D$
  - Other sidebands considered for systematics

Results





- Results show no excess over the BG-only expectation in both WW and ZZ
- Main systematic uncertainties:
  - Signal and BG: proton ξ and jet energy scale
  - BG-only: mainly affected by low statistics in the sidebands

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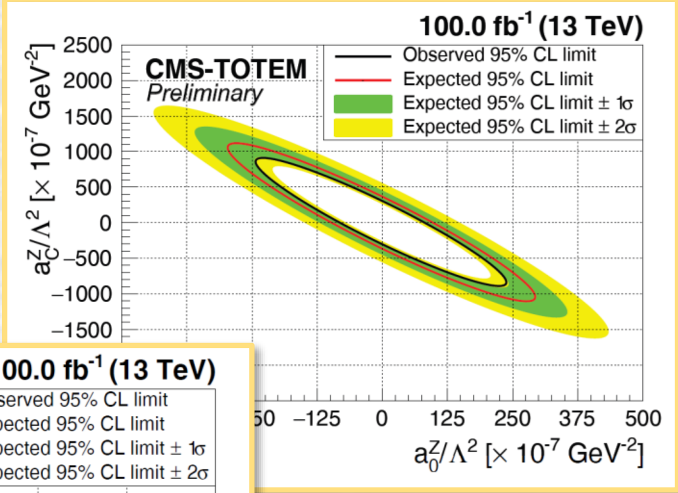
Results

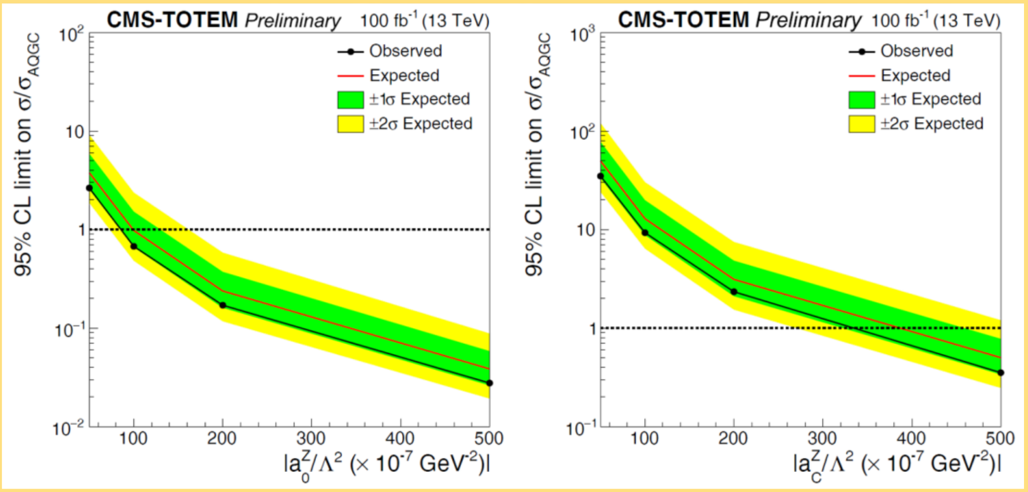
- Limits on fiducial anomalous production cross sections:

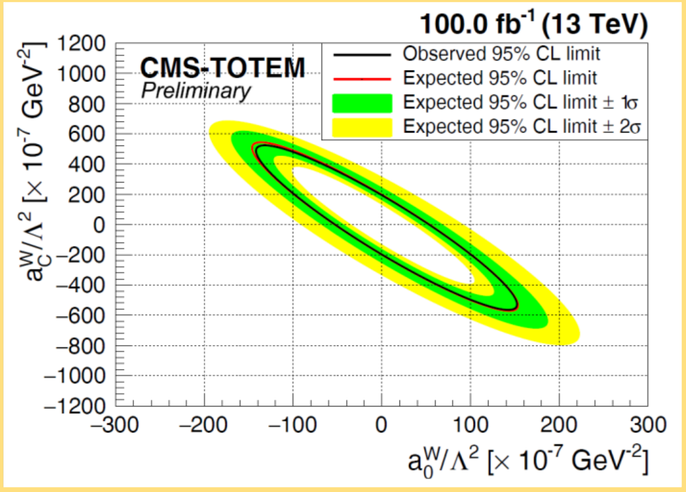
$$\sigma(pp \to pWWp)_{0.04<\xi<0.2, m(WW)>1\text{ TeV}} < 67(53^{+34}_{-19})\text{ fb}$$

$$\sigma(pp \to pZZp)_{0.04<\xi<0.2, m(WW)>1\text{ TeV}} < 43(62^{+33}_{-20})\text{ fb}$$

- Limits set on dim-6 AQGC parameters: with/without unitarization
  - Unitarization → EFT cross section diverges at high mass
  - Prevented by 'clipping' the distribution (cannot be done on ZZ channel)
  - Also converted to 2D limits







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Results

- Limits also converted to dim-8 AQGC parameters ($f_{M,0\ldots7}/\Lambda^4$)
  - Under the assumption all couplings are zero except one

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

- Comparison with other analyses → not very straightforward
  - Dim-6 limits: **15-20x tighter than CMS Run 1** exclusive WW analysis with unitarization
  - Dim-8 limits: limits on some parameters are close to CMS results in same-sign WW or WZ channels, after unitarization

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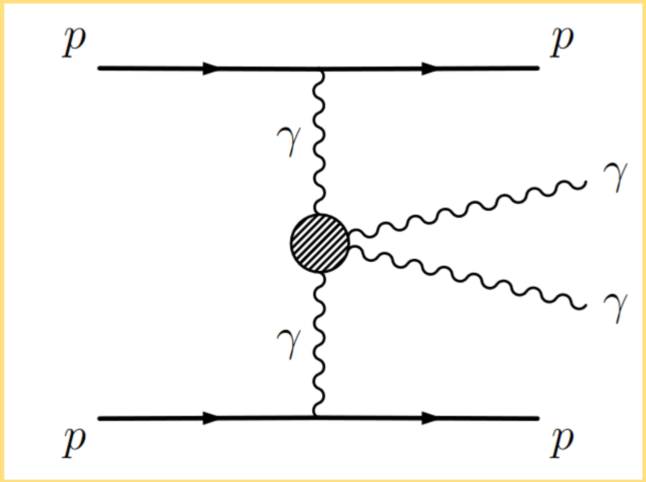
Exclusive $\gamma\gamma \to \gamma\gamma$

- Search for **LbyL scattering with proton tagging**
- Full Run 2 dataset, 102.7 fb^{-1}
  - Extending Phys. Rev. Lett. 129, 011801
- **Matching** requirement in the **mass and rapidity** between $\gamma\gamma$ and protons:

$$m_{\gamma\gamma} = \sqrt{s\xi_1\xi_2} \quad y_{\gamma\gamma} = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)$$

- **Main background: inclusive $\boldsymbol{\gamma\gamma}$ production + pileup**
- One candidate observed:
  - BG prediction of 1.1 events with 2σ matching



Event selection:

- ≥ 2 isolated γ $(H/E < 0.10)$
- $|\eta(\gamma_1, \gamma_2)| < 2.5$
- $p_T(\gamma_1, \gamma_2) > 75$ GeV
  - 100 GeV for 2017/8
- $m(\gamma_1\gamma_2) > 350$ GeV
- $1 - |\Delta\phi(\gamma_1\gamma_2)/\pi| < 0.0025$
- 1 proton per side of PPS within acceptance

CMS-PAS-EXO-21-007
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Exclusive $\gamma\gamma \to \gamma\gamma$

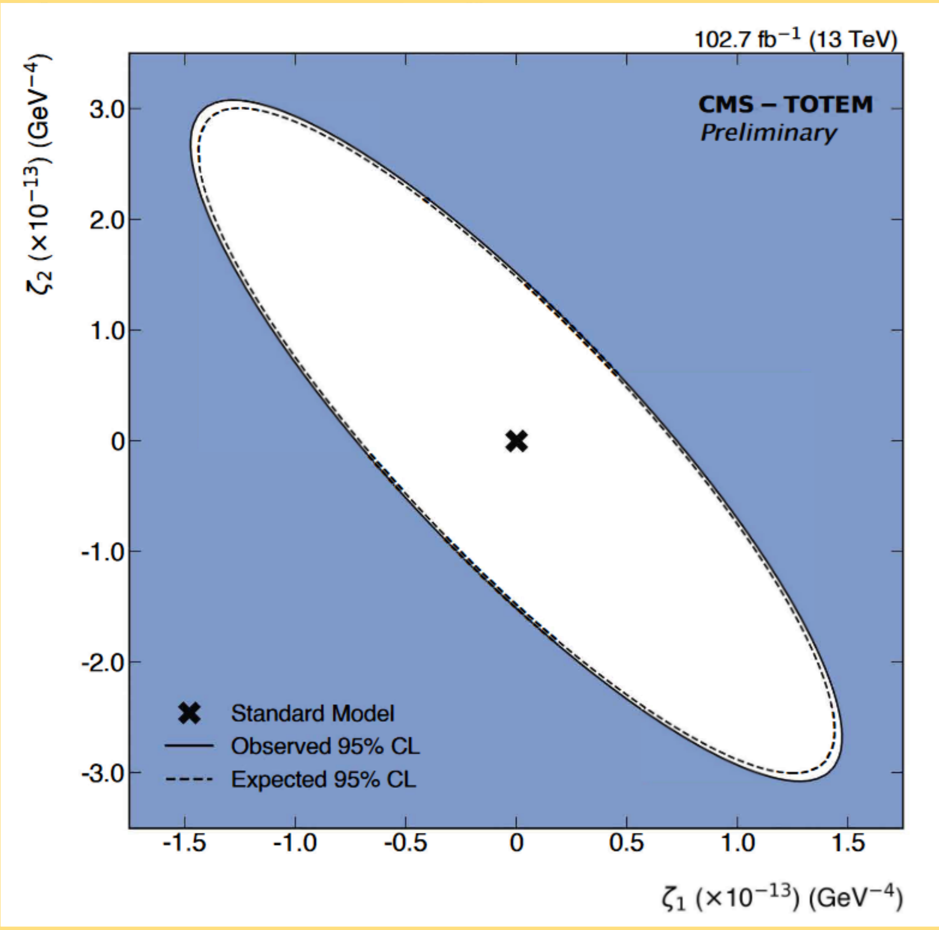
- Search for LbyL scattering with proton tag
- Full Run 2 dataset, 102.7 fb^{-1}
- Matching requirement in the mass and rap
  between $\gamma\gamma$ and protons:
- …oductio
- One candidate observed:
  - BG prediction of 1.1 events with 2σ matchin

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

~3-4x more stringent limits observed (expected) on 4γ coupling parameters:

$|\zeta_1| < 7.3\ (7.1) \times 10^{-14}$ GeV^{-4}

$|\zeta_2| < 1.5\ (1.5) \times 10^{-13}$ GeV^{-4}



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…0025

within acceptance

CMS-PAS-EXO-21-007
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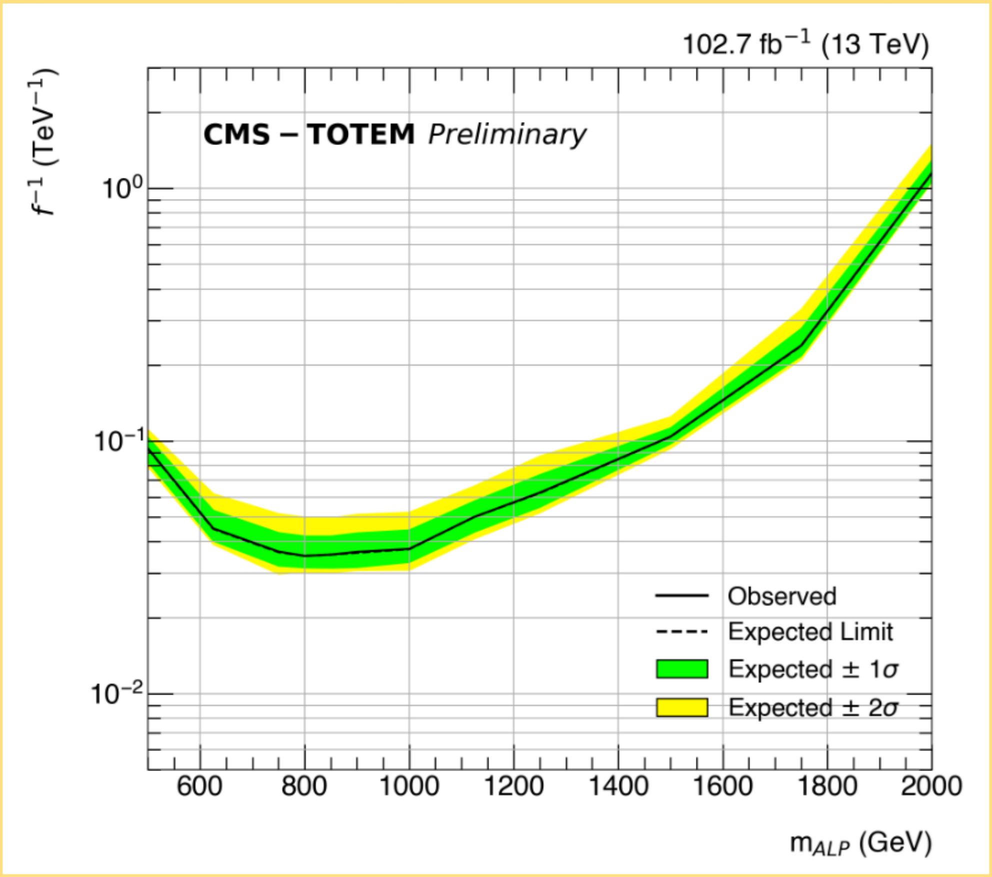
Exclusive $\gamma\gamma \rightarrow \gamma\gamma$

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

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



- 1 proton per side of PPS within acceptance

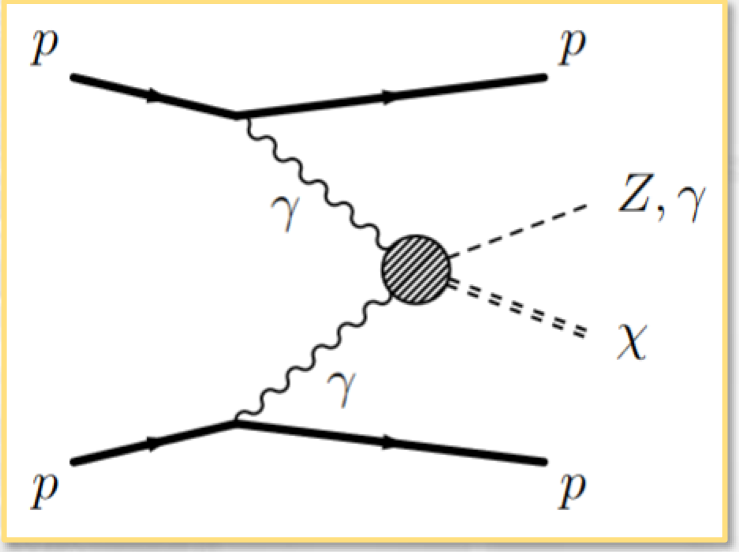
CMS-PAS-EXO-21-007
CERN-TOTEM-NOTE-2022-005

Searching for missing mass with Z/γ

- A **novel technique** to search for new particles at the LHC:
  - Use the so-called **missing mass**:

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

- Search for **missing mass produced in association** with a $\boldsymbol{Z}$ **boson or photon** in proton-tagged events
- Exploit the high-precision proton momentum measurement from PPS
- **Search for weakly interacting BSM massive particles**
  - QED interactions are favoured over QCD processes
  - Broad invariant mass spectrum explored (600-1600 GeV)



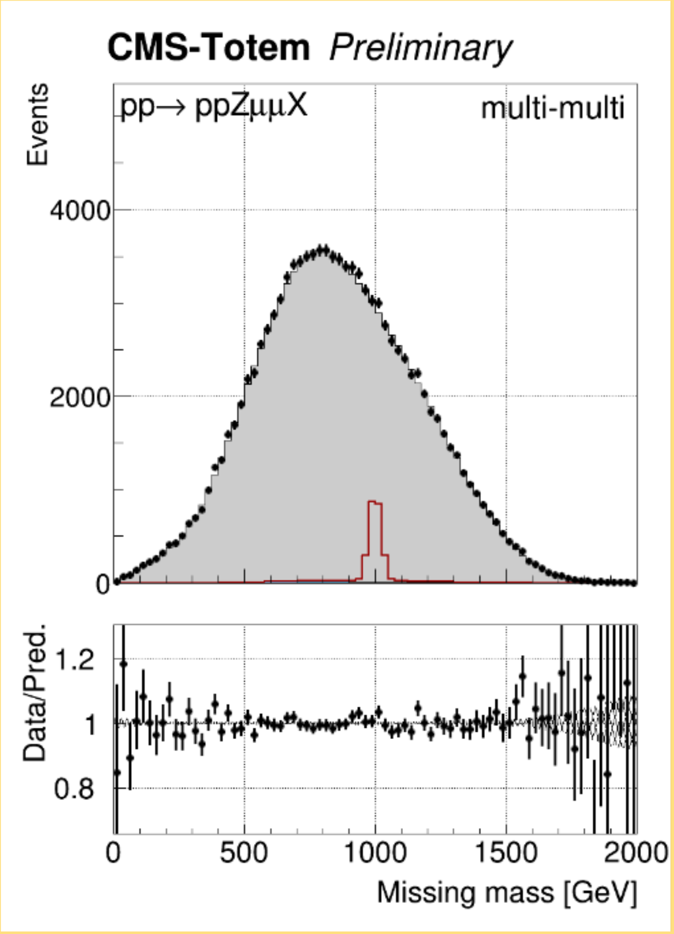
CMS-PAS-EXO-19-009
CERN-TOTEM-NOTE-2022-003

Searching for missing mass with Z/γ

Event selection

$Z \to e^+e^- / Z \to \mu^+\mu^-$	**Photon**
≥ 2 leptons (SF OS)	$= 1$ isolated photon
$p_T(\ell_1, \ell_2) > 30, 20$ GeV	$p_T(\gamma) > 95$ GeV
$\lvert\eta(\ell)\rvert < 2.4$	$\lvert\eta(\gamma)\rvert < 1.48$ (CMS barrel)
$\lvert m(\ell\ell) - m_Z\rvert < 10$ GeV	
$p_T(Z) > 40$ GeV	

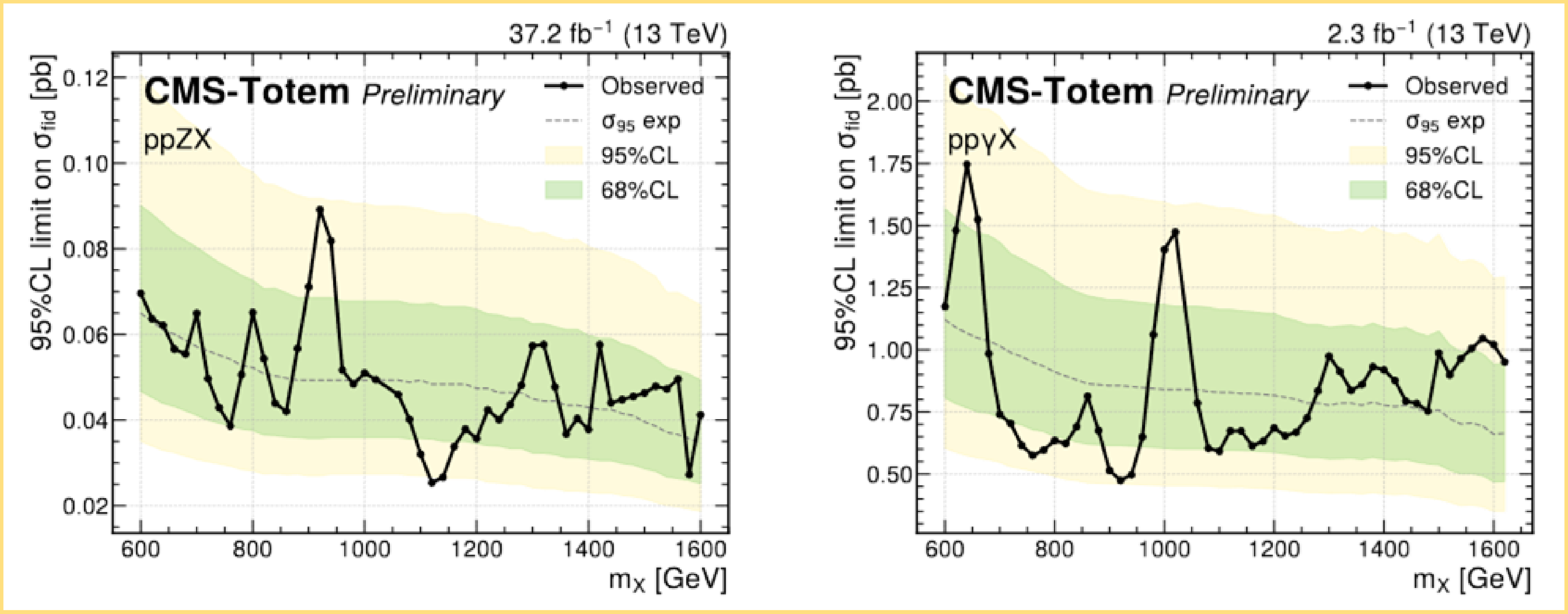
≥ 1 proton per side of PPS



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

CMS-PAS-EXO-19-009
CERN-TOTEM-NOTE-2022-003

Searching for missing mass with Z/γ

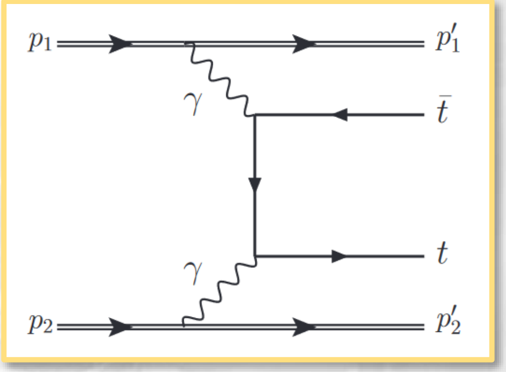


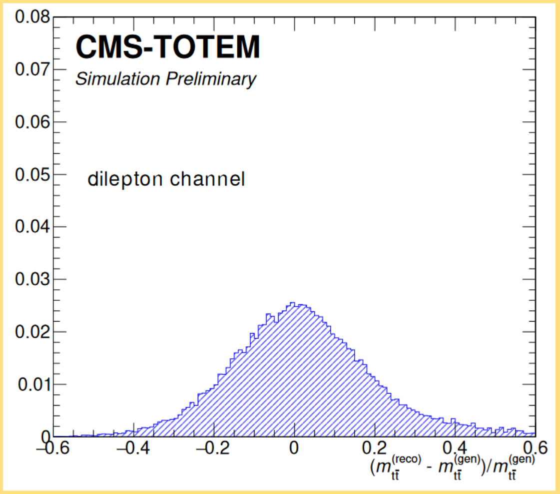
- Bump search over missing mass spectrum
  - **No major local excess/deficit observed**
  - Larger dataset will be analysed
- Setting **95% CL on fiducial cross section** as a function of m_X

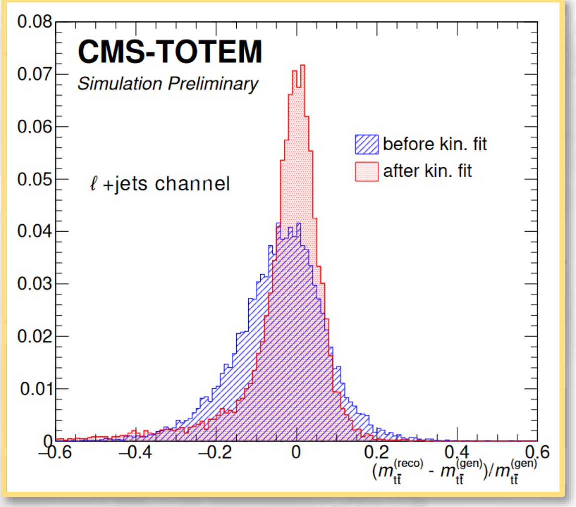
CMS-PAS-EXO-19-009
CERN-TOTEM-NOTE-2022-003

CEP of top quark pairs

- First search for **top quark-antiquark pair production with intact protons**
- **Low cross section** – $\mathcal{O}(0.3\text{ fb})$ in the PPS acceptance
  - Signal concentrated at low $t\bar{t}$ mass, where BG is dominant
- 2017 dataset: 29.4 fb^{-1}
- Two $t\bar{t}$ decay channels studied: $\ell\ell$ **and** ℓ**+jets**
- **Proton matching** criteria used as **BDT inputs** or kinematic **fitting constraints**



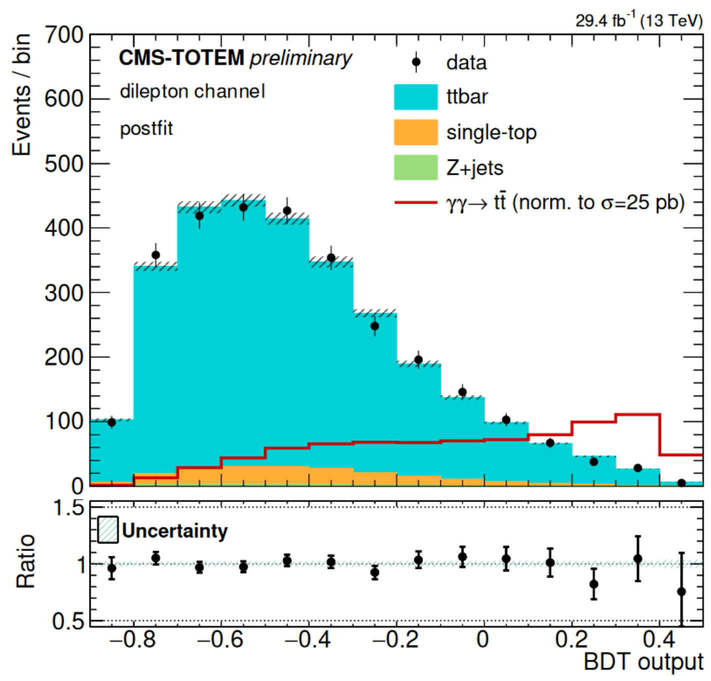


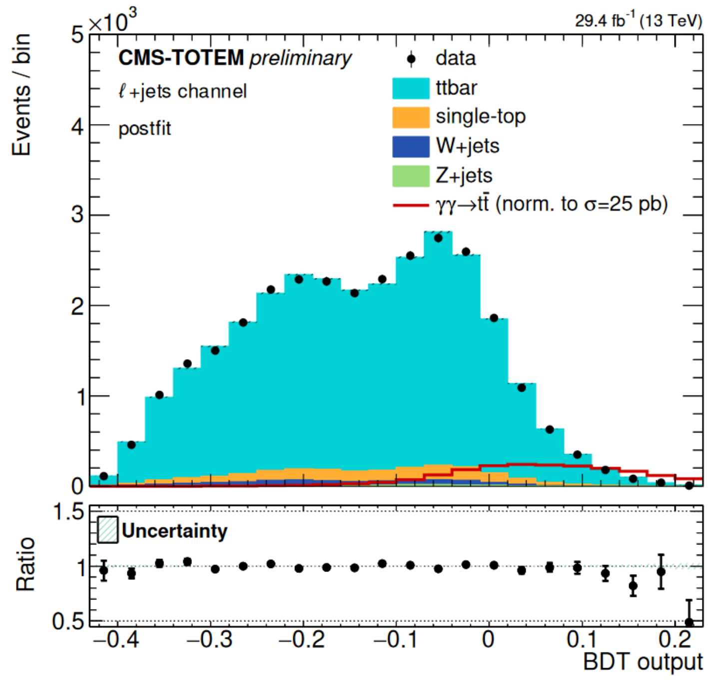


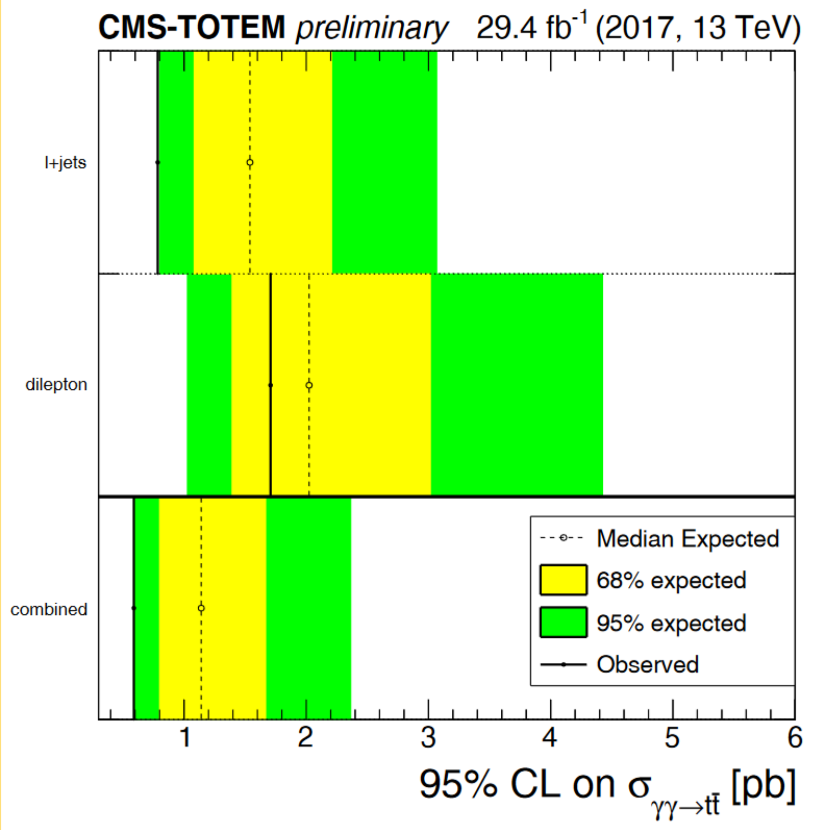
CMS-PAS-TOP-21-007
CERN-TOTEM-NOTE-2022-002

CEP of top quark pairs

- MVA approach used to tag exclusive $t\bar{t}$ events
- **Cross section upper limits** extracted from multivariate discriminant distributions:
  - Observed combined 95% CL limit: $\mathbf{0.59}$ pb ($\mathbf{1.14^{+1.2}_{-0.6}}$ expected)





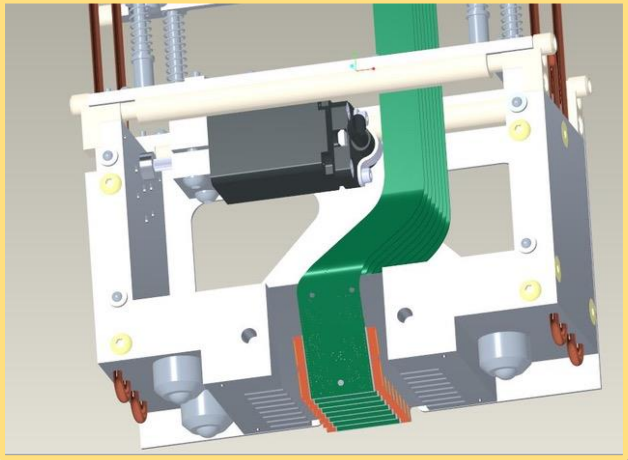


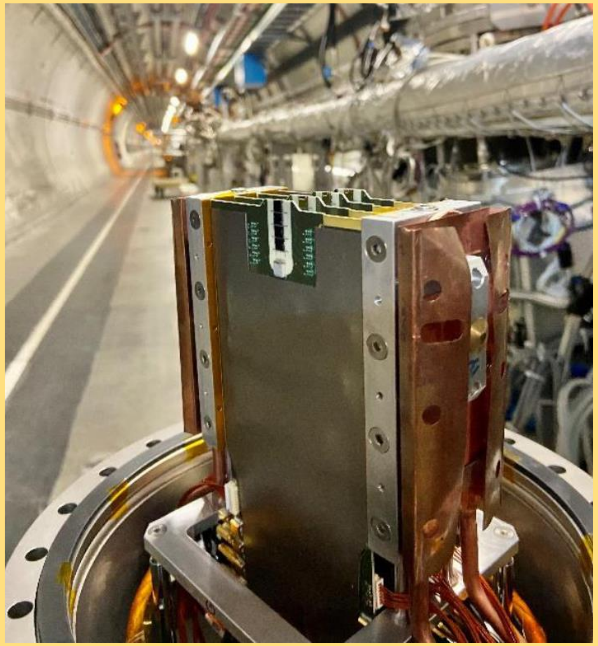
CMS-PAS-TOP-21-007
CERN-TOTEM-NOTE-2022-002

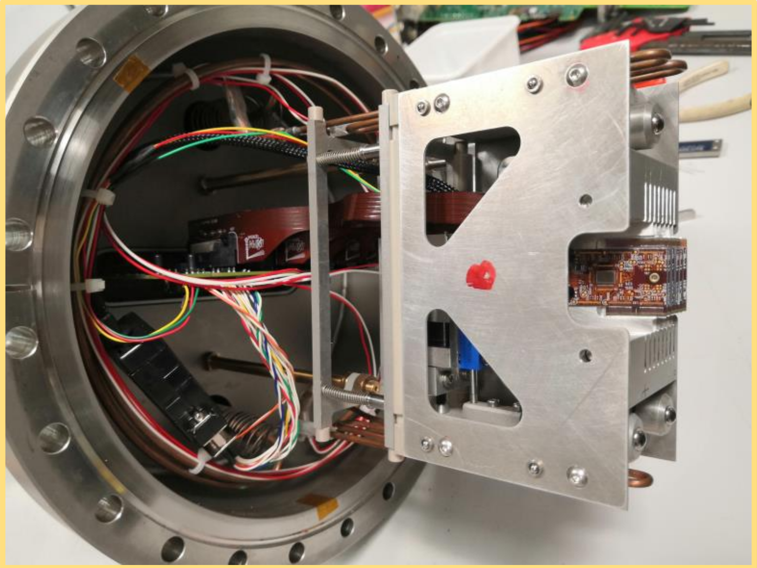
PPS in LHC Run 3 and beyond

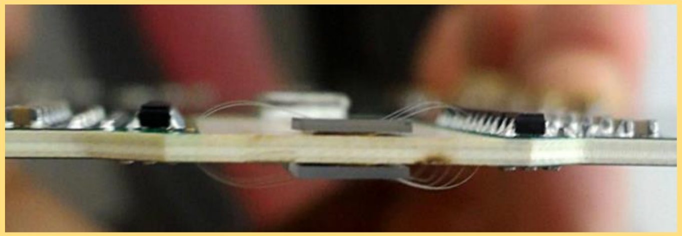
New detectors for PPS Run 3

- New tracker with 3D pixel silicon sensors:
  - Different technology wrt. Run 2
  - Internal movement system to improve radiation tolerance
- New timing detectors:
  - Only double-diamond detector planes
  - Improved electronics to optimize performance
  - Add two detector stations per side of CMS



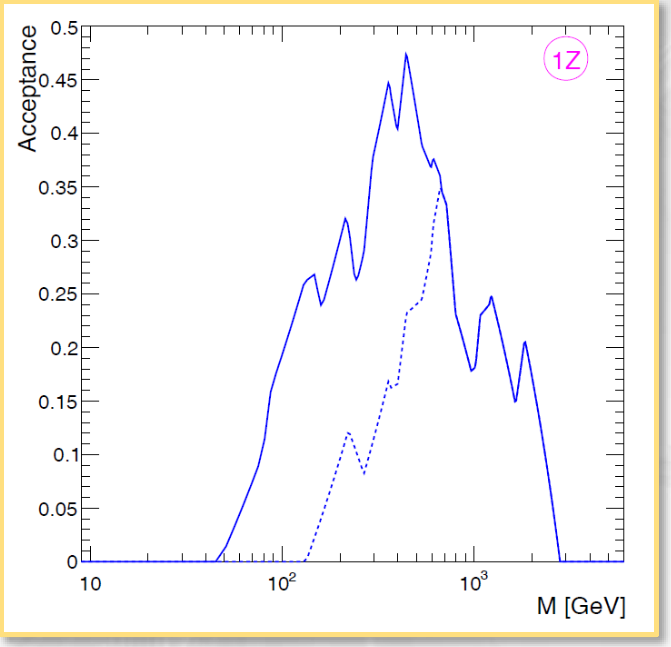


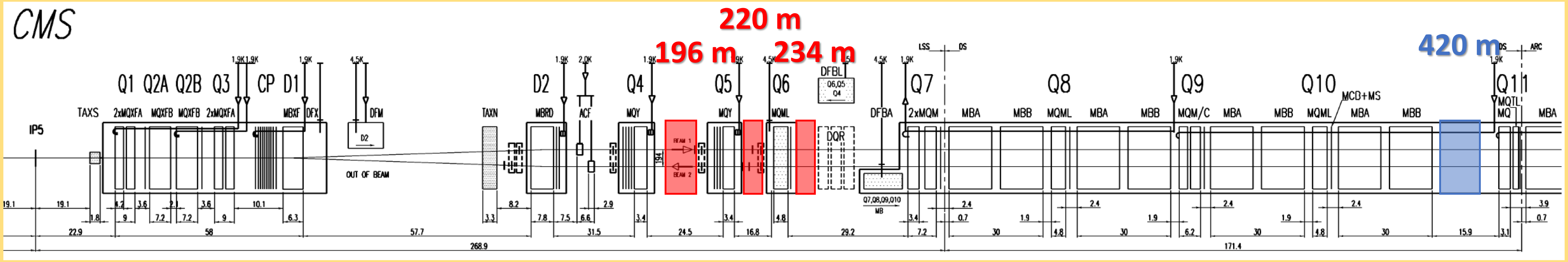




PPS in HL-LHC

- New proposal for HL-LHC:
  - Extending the mass acceptance range in two stages (350 GeV – 2 TeV in Run 2+3)
    1. 133 GeV – 2.7 TeV with the first 3 stations
    2. 43 GeV – 2.7 TeV adding the fourth
- Extend the current SM and BSM physics program
- Final decision on detector technologies to be taken





arXiv:2103.02752

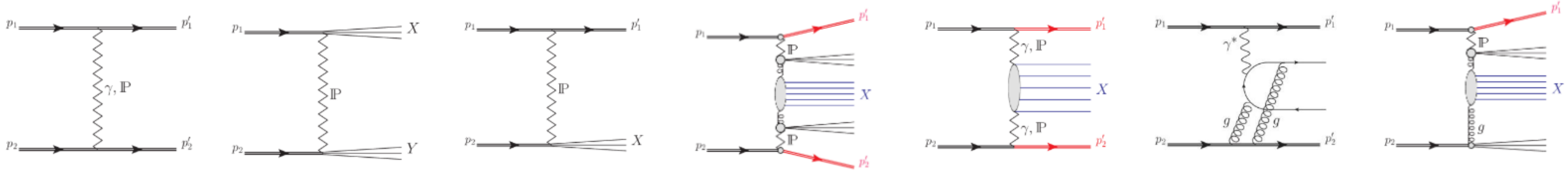
Summary

- The **CMS PPS tracker and proton reconstruction performance** in Run 2 was studied and specialized techniques were developed for proton reconstructions
- Protons are now being used for **SM and BSM physics analyses**, opening up **new strategies** for the CMS physics program:
  - Top quark pair production
  - Anomalous vector boson pair exclusive production
  - High-mass diphoton exclusive production
  - Missing mass in association with Z boson or photon
- PPS has prepared new detectors for **Run 3** and is willing to take part to **HL-LHC**

Thanks for your attention

BACKUP

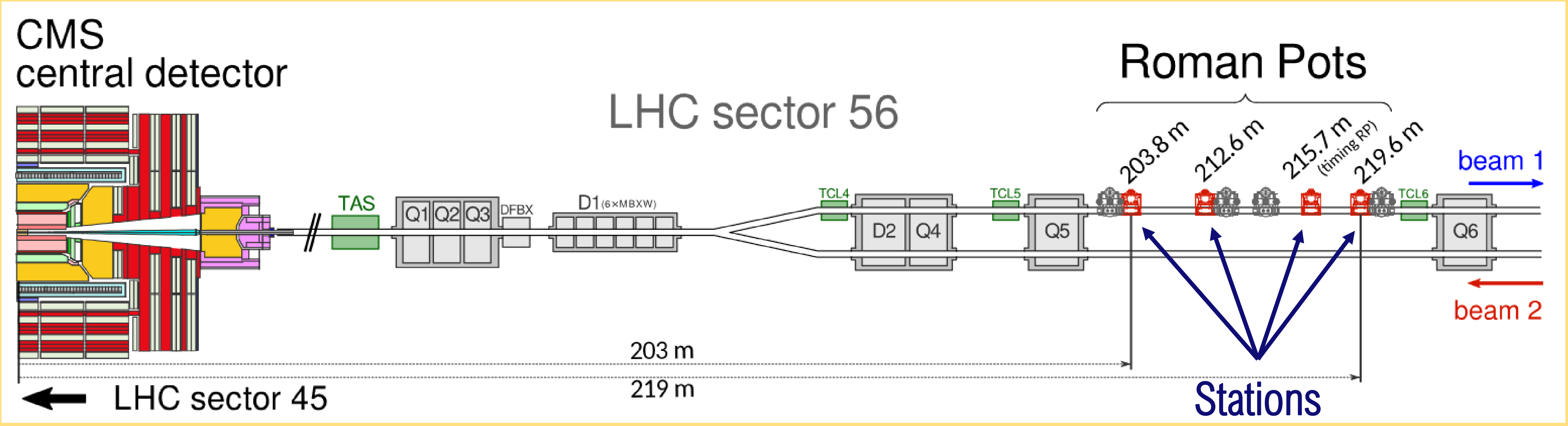
Diffractive *pp* interactions



Elastic scattering — Single/double diffractive dissociation — Double pomeron exchange — Central exclusive production — Exclusive photoproduction — Single-diffraction with central system

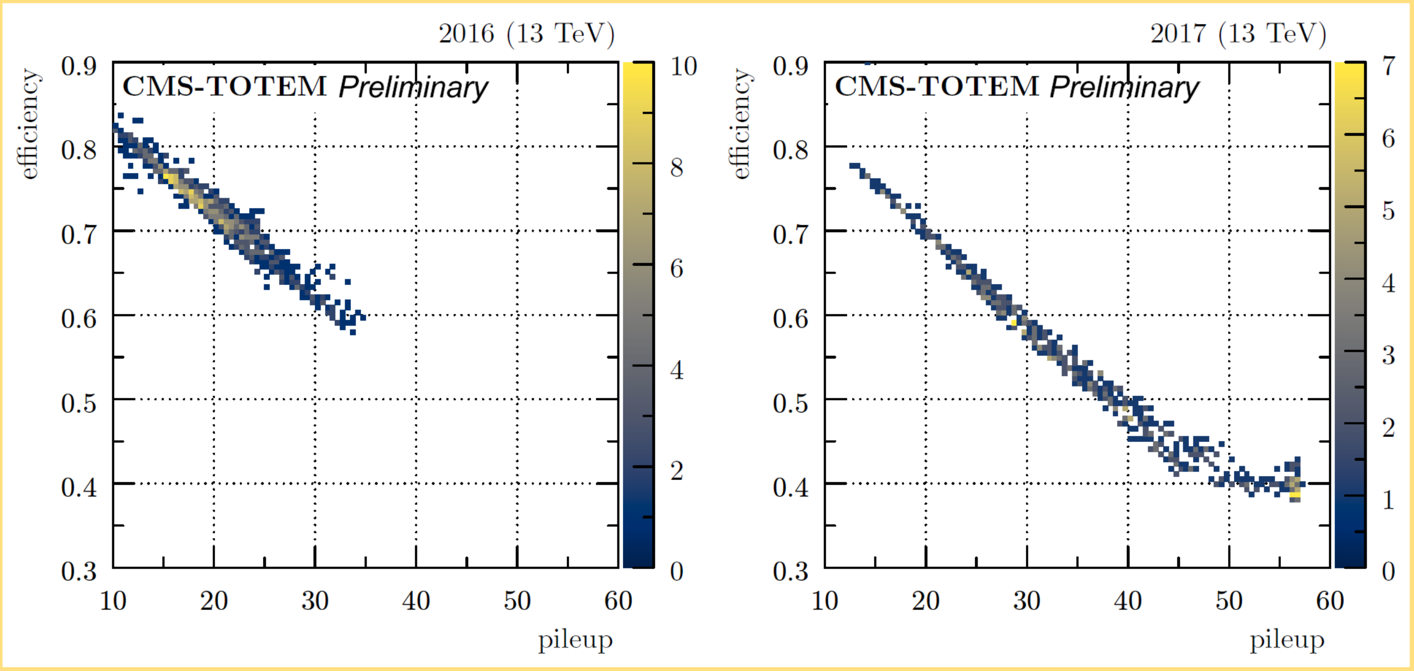
- t-channel processes, common denominator: colourless neutral particle exchange
  - It happens either via QED (γ) or QCD ($I\!P$) processes

PPS nomenclature



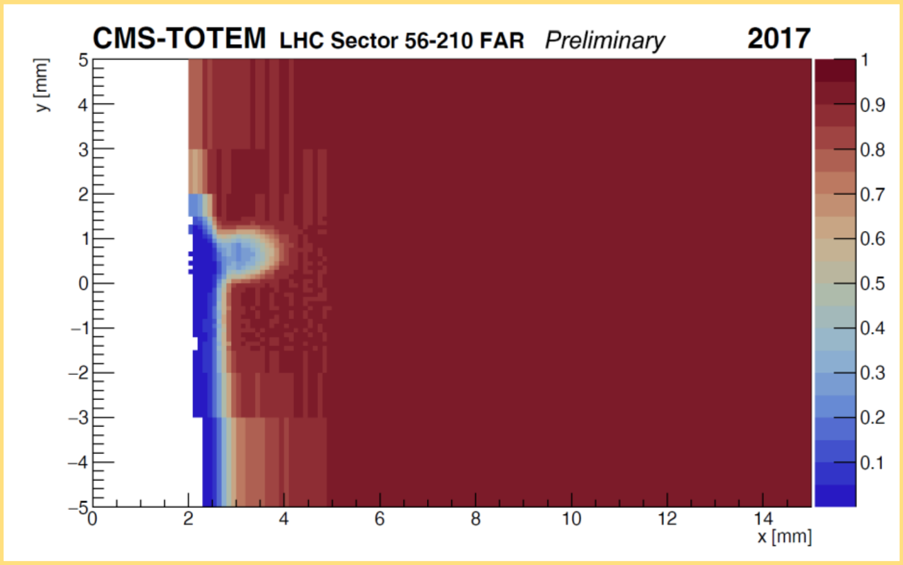
- 2 sectors (45 and 56)
- In each sector: 2 tracking stations + 1(2) timing stations in Run 2(3)
- In each tracking station: 2 vertical RPs (only for special runs) + 1 horizontal

Strips efficiency components

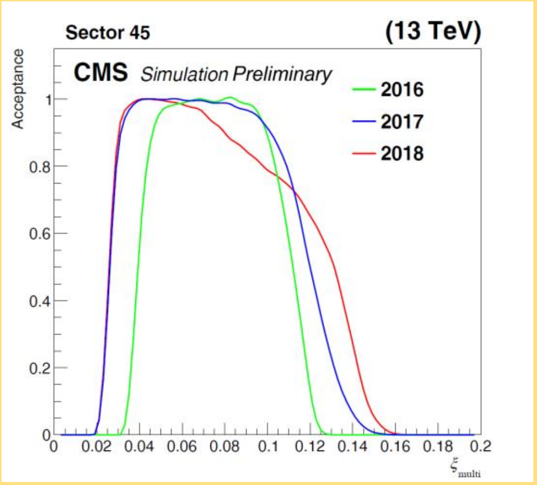


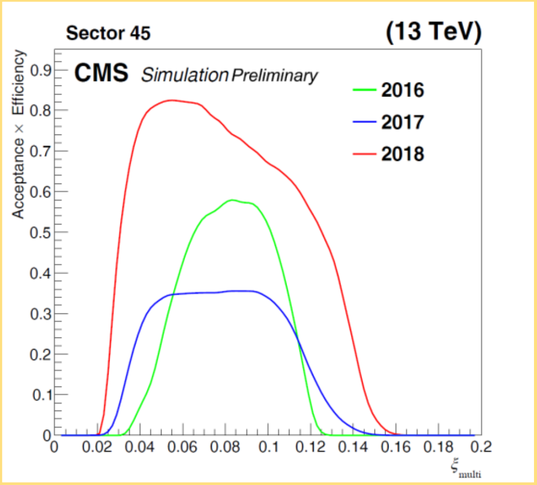
Multi-tracking efficiency

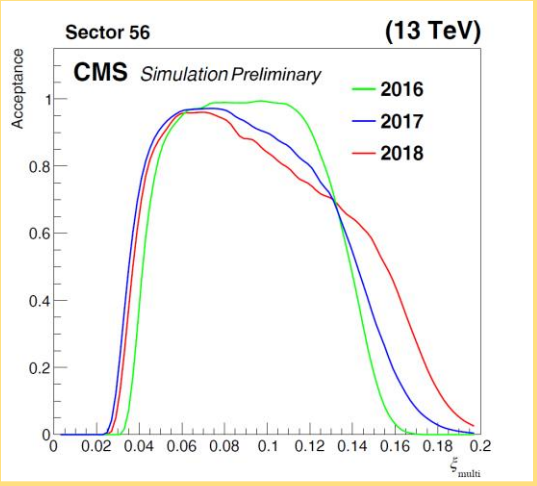
Strips detection efficiency

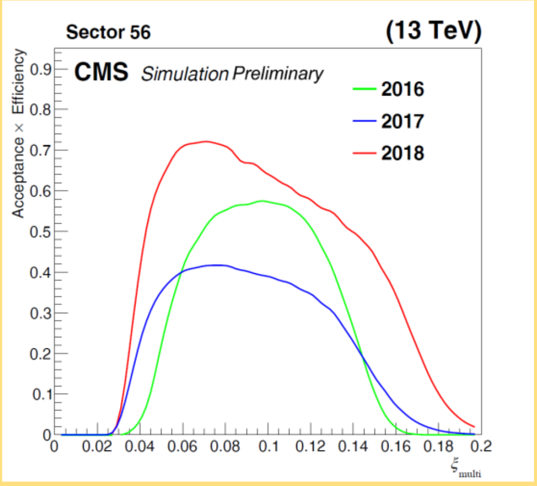


Multi-RP proton efficiency

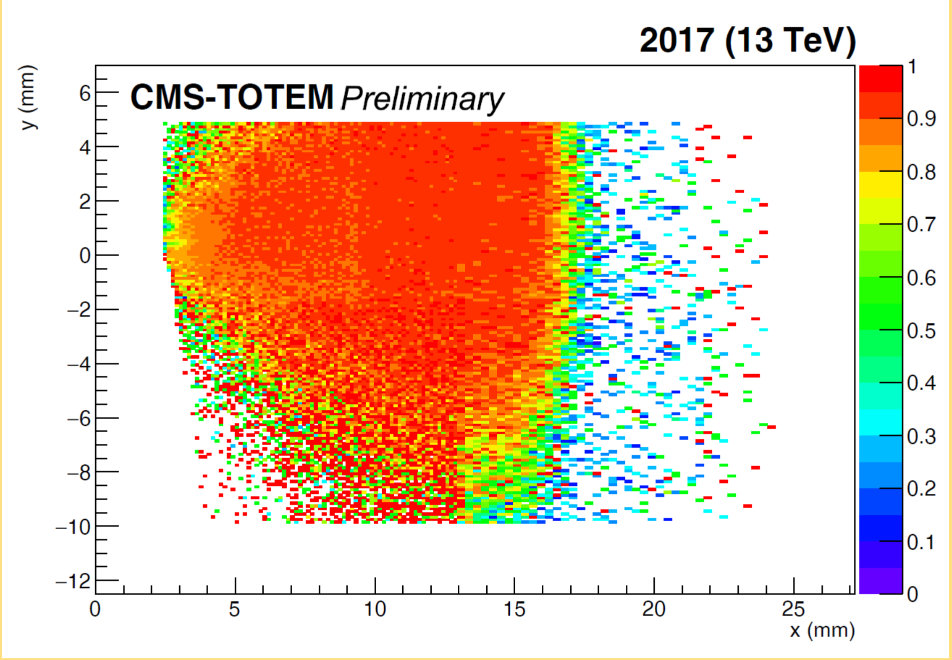




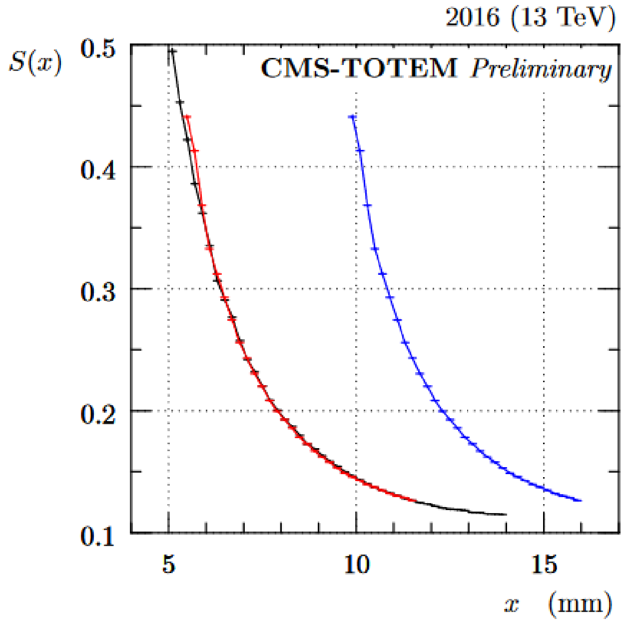


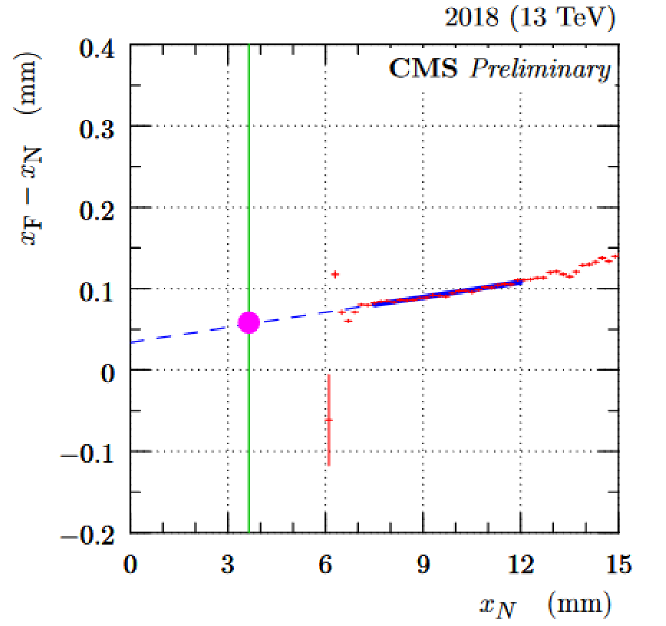


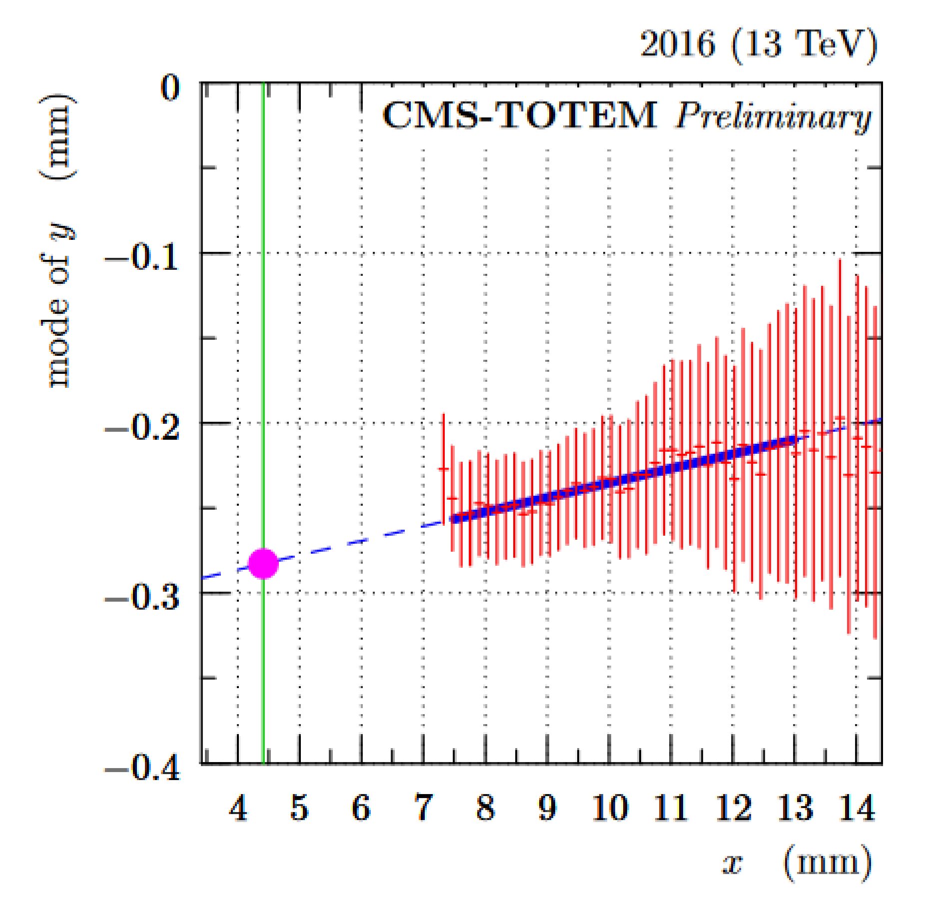
Multi-RP efficiency

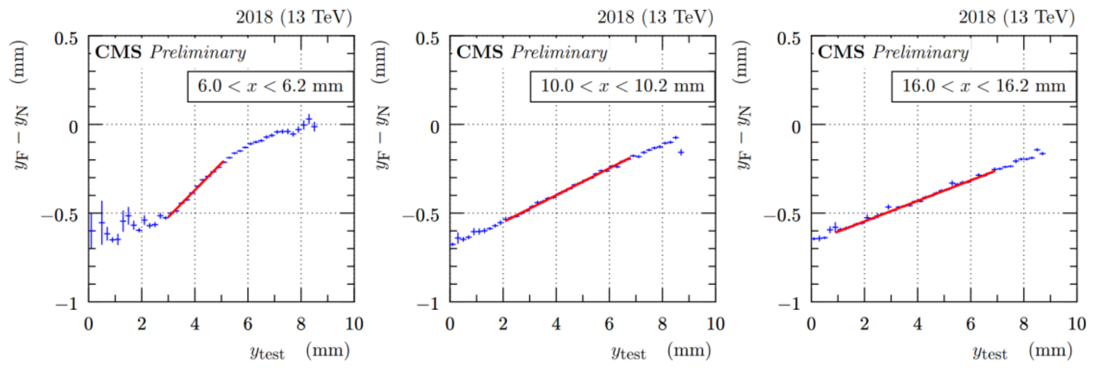


Fill-by-fill alignment

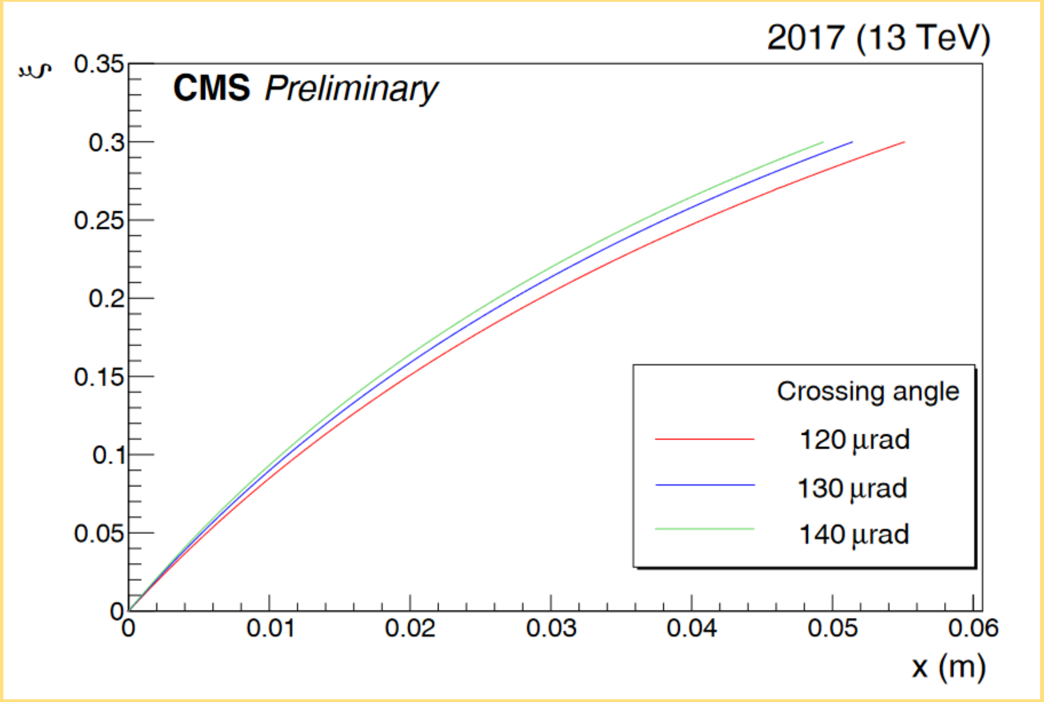


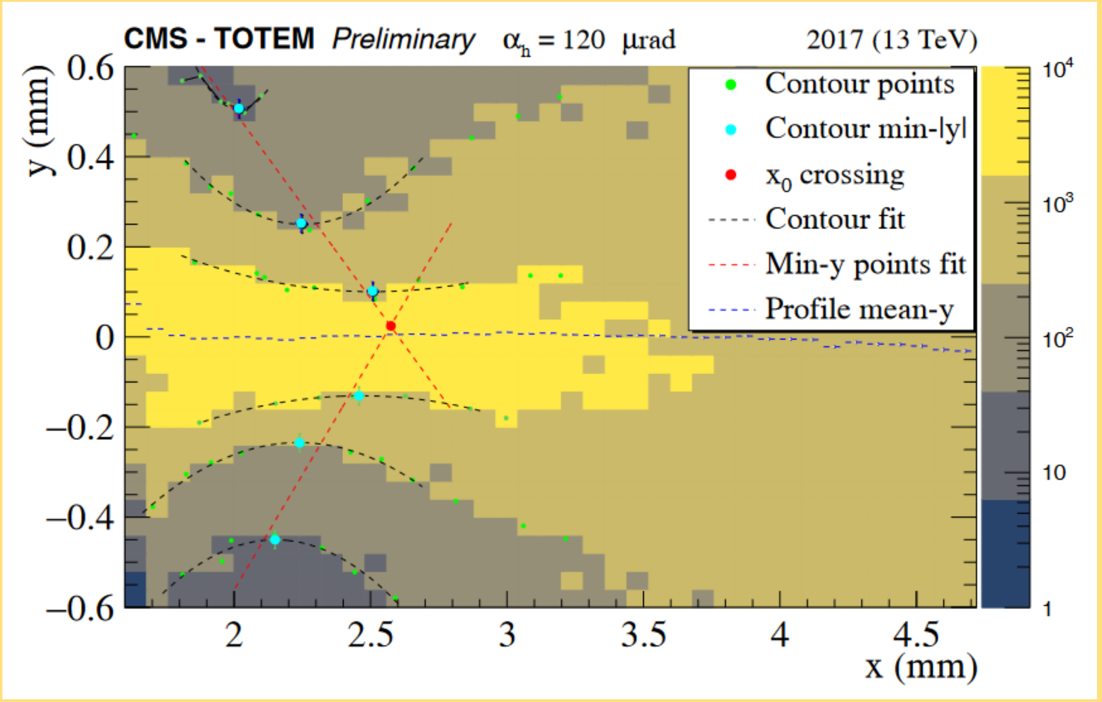






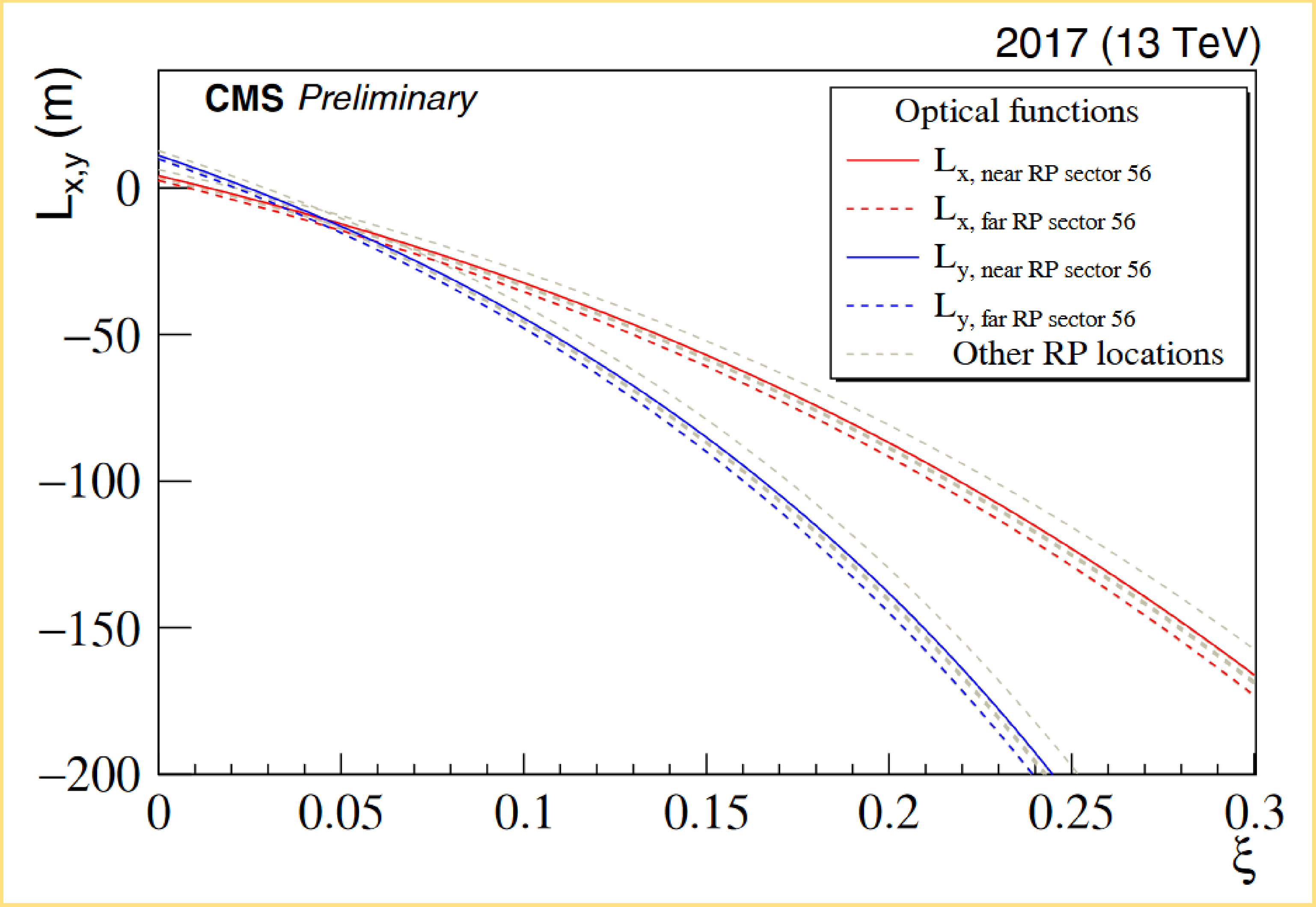
Optics calibration





- Horizontal dispersion calibrated for different crossing angles:
  - Interpolated for values in between

Vertical effective length

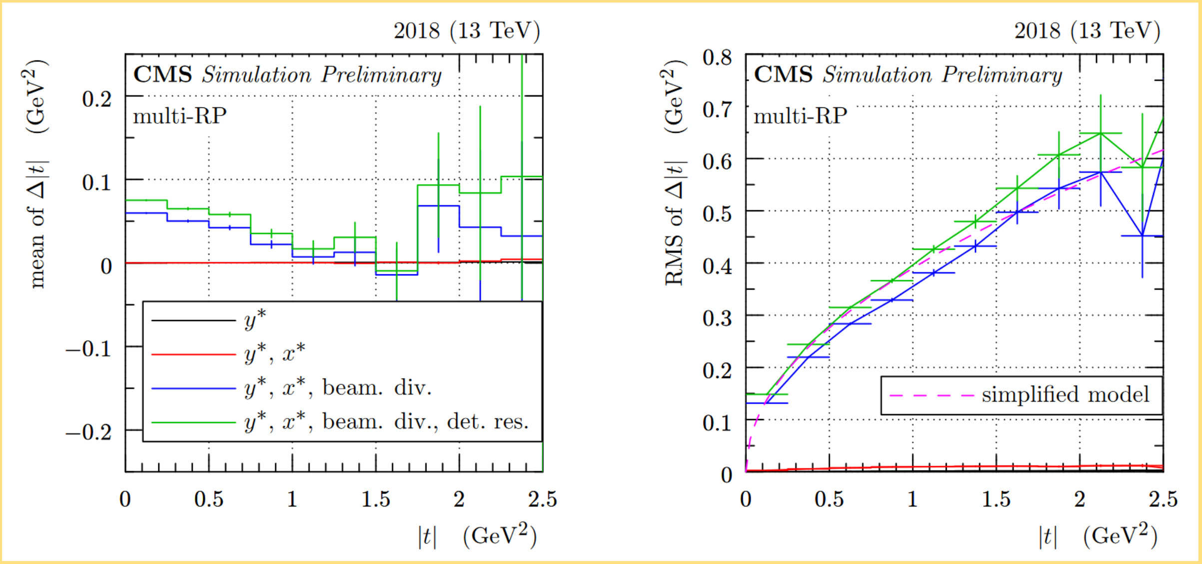


Proton t reconstruction

Four-momentum transfer squared $t = (p' - p)^2$:

$$t = t_0(\xi) - 4p_{nom}^2(1-\xi)\sin^2\left(\frac{\sqrt{\theta_x^{*2} + \theta_y^{*2}}}{2}\right),$$

$$t_0(\xi) = 2\left(m^2 + p_{nom}^2(1-\xi) - \sqrt{(m^2 + p_{nom}^2)(m^2 + p_{nom}^2(1-\xi)^2)}\right)$$



Data and Monte Carlo

- Data: full Run 2 dataset, with two inserted RPs per sector

Year	Integrated Luminosity [fb^{-1}]	Fraction of CMS total
2016	9.9	28%
2017	37.2	90%
2018	52.9	89%
Total	100.0	73%

- Signal MC:
  - Exclusive WW/ZZ produced via Forward Physics MC (FPMC), dim-6 AQGC model
  - Multiple coupling points to scan sensitivity
- Background MC:
  - Main: QCD di-jet production (simulated with Pythia8) + pileup protons
  - Others: $t\bar{t}$, $W/Z+$ jets (Madgraph/Powheg) + pileup protons

CMS-PAS-SMP-21-014
CERN-TOTEM-NOTE-2022-004

Conversion to dim-8 limits

- Conversion done following the approach of Eboli et al., Phys. Rev. D 93 (2016) 9, 093013

$$a_0^W = -\frac{M_W^2}{\pi\alpha_{em}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right]$$

$$a_C^W = -\frac{M_W^2}{\pi\alpha_{em}}\left[-s_w^2\frac{f_{M,1}}{\Lambda^2} - c_w^2\frac{f_{M,3}}{\Lambda^2} + 2s_w c_w\frac{f_{M,5}}{\Lambda^2} + \frac{s_w^2}{2}\frac{f_{M,7}}{\Lambda^2}\right]$$

$$a_0^Z = -\frac{M_W^2 c_w^2}{\pi\alpha_{em}}\left[\frac{s_w^2}{2c_w^2}\frac{f_{M,0}}{\Lambda^2} + \frac{f_{M,2}}{\Lambda^2} - \frac{s_w}{2c_w}\frac{f_{M,4}}{\Lambda^2}\right]$$

$$a_C^Z = -\frac{M_W^2 c_w^2}{\pi\alpha_{em}}\left[-\frac{s_w^2}{2c_w^2}\frac{f_{M,1}}{\Lambda^2} - \frac{1}{2}\frac{f_{M,3}}{\Lambda^2} - \frac{s_w}{c_w}\frac{f_{M,5}}{\Lambda^2} + \frac{s_w^2}{4c_w^2}\frac{f_{M,7}}{\Lambda^2}\right]$$

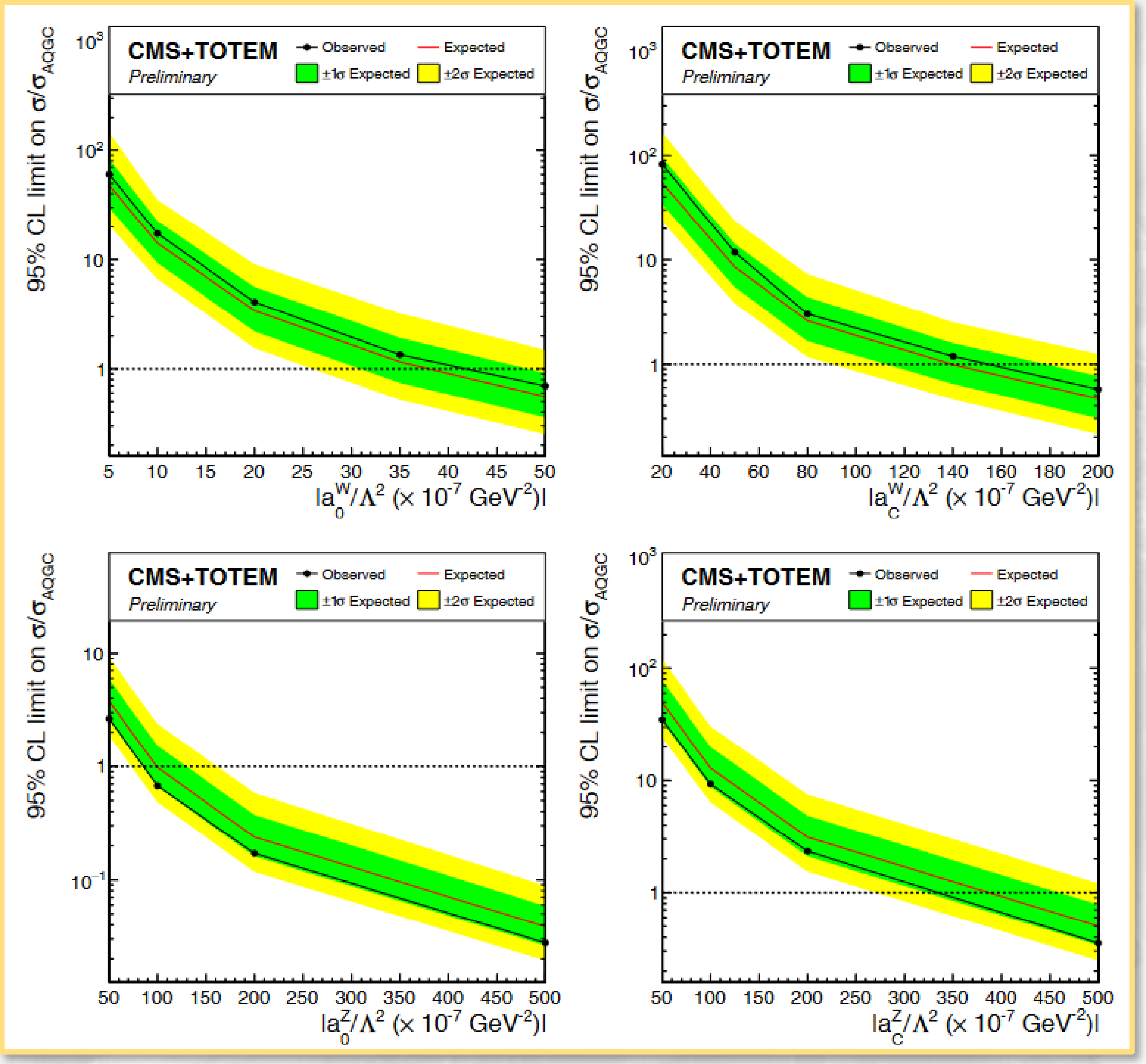
- Assume all couplings to be 0 but one

Conversion to dim-8 limits

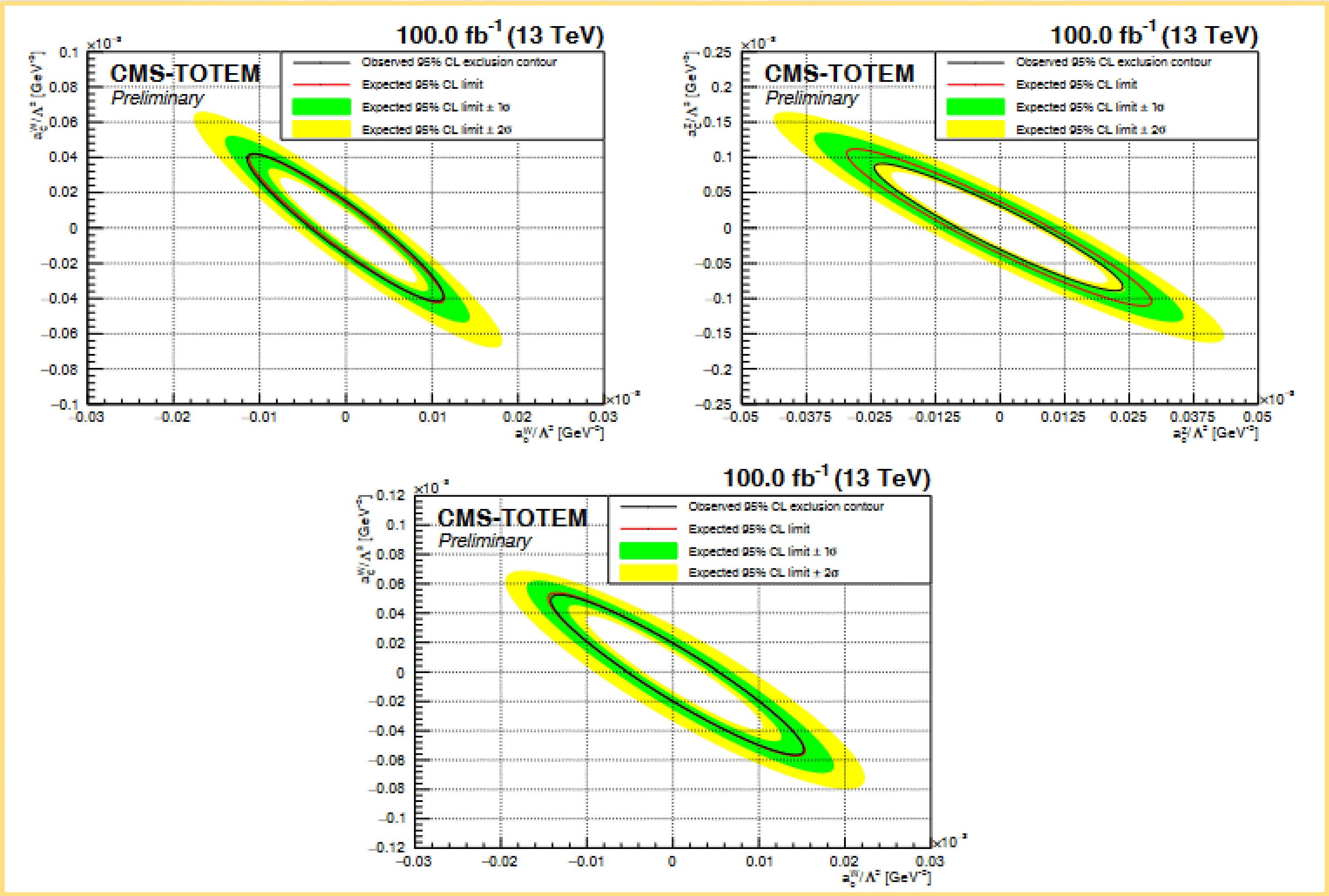
- Further imposing: $f_{M,0} = 2 \cdot f_{M,2} \rightarrow$ vanishing $WWZ\gamma$ coupling

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\|a_0^W/\Lambda^2\|$	$4.3\ (3.9) \times 10^{-6}\ \mathrm{GeV}^{-2}$	$5.2\ (5.1) \times 10^{-6}\ \mathrm{GeV}^{-2}$
$\|a_C^W/\Lambda^2\|$	$1.6\ (1.4) \times 10^{-5}\ \mathrm{GeV}^{-2}$	$2.0\ (2.0) \times 10^{-5}\ \mathrm{GeV}^{-2}$
$\|a_0^Z/\Lambda^2\|$	$0.9\ (1.0) \times 10^{-5}\ \mathrm{GeV}^{-2}$	-
$\|a_C^Z/\Lambda^2\|$	$4.0\ (4.5) \times 10^{-5}\ \mathrm{GeV}^{-2}$	-

Dim-6 limits: 1D

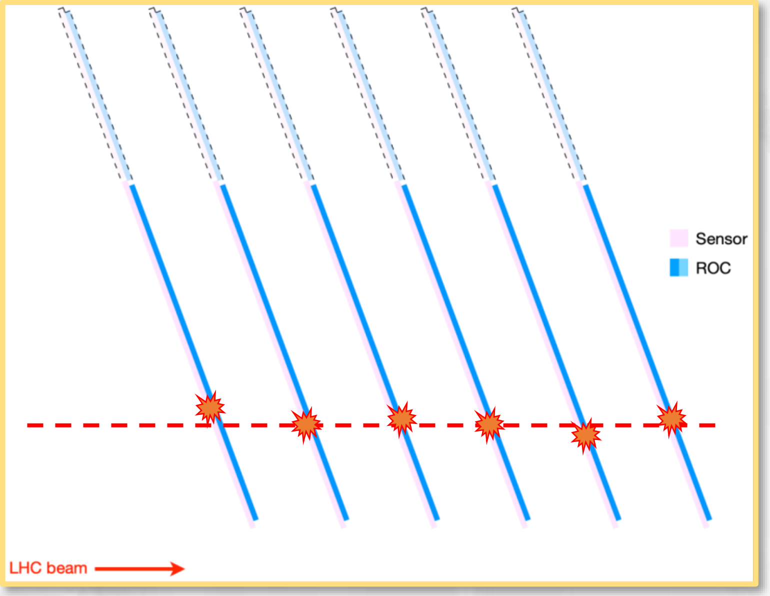


Dim-6 limits: 2D



Track reconstruction algorithm

- Only events with ≥3 planes with clusters are considered:
  - No reconstruction if ≥60 hits/station or ≥20 hits/plane
- Tracks are fitted with a straight line:
  - $\chi^2/NdF < 5$ is required
  - The combinatory procedure starts from 6-planes tracks and proceeds to fewer-plane ones
  - If number of tracks ≥ 10 the event is discarded

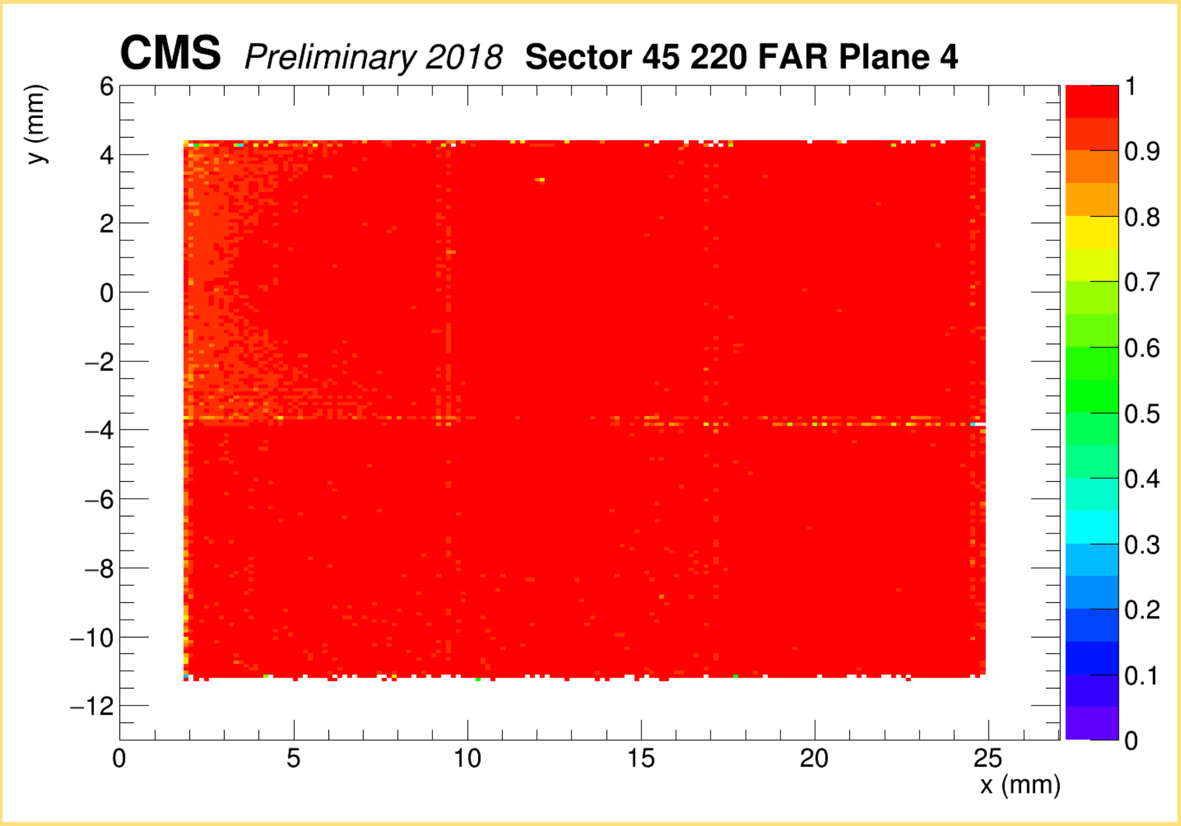


Plane efficiency measurements

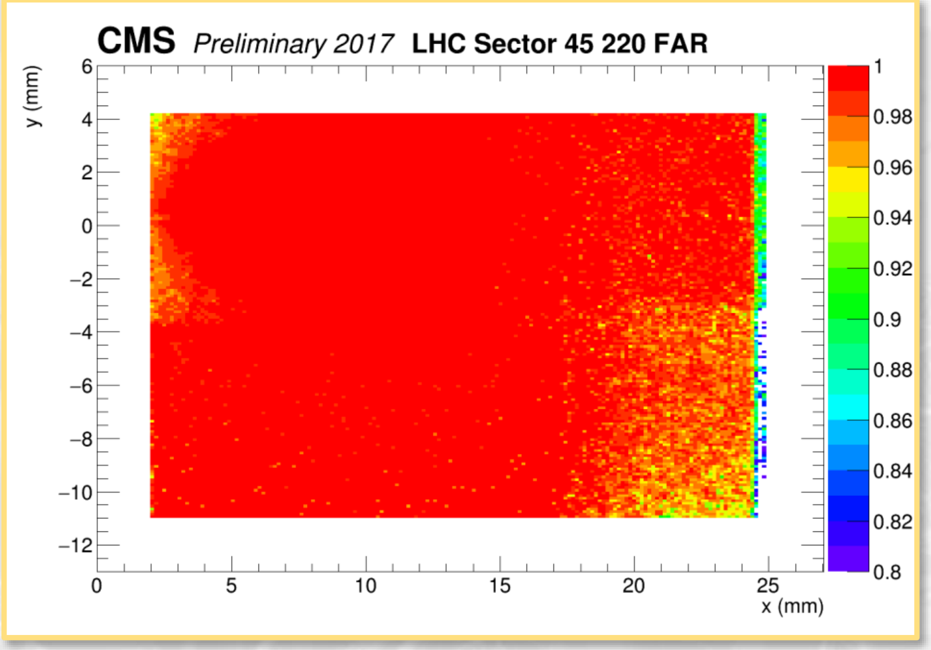
- Efficiency characterisation
  → mandatory task!
- Two-step procedure:

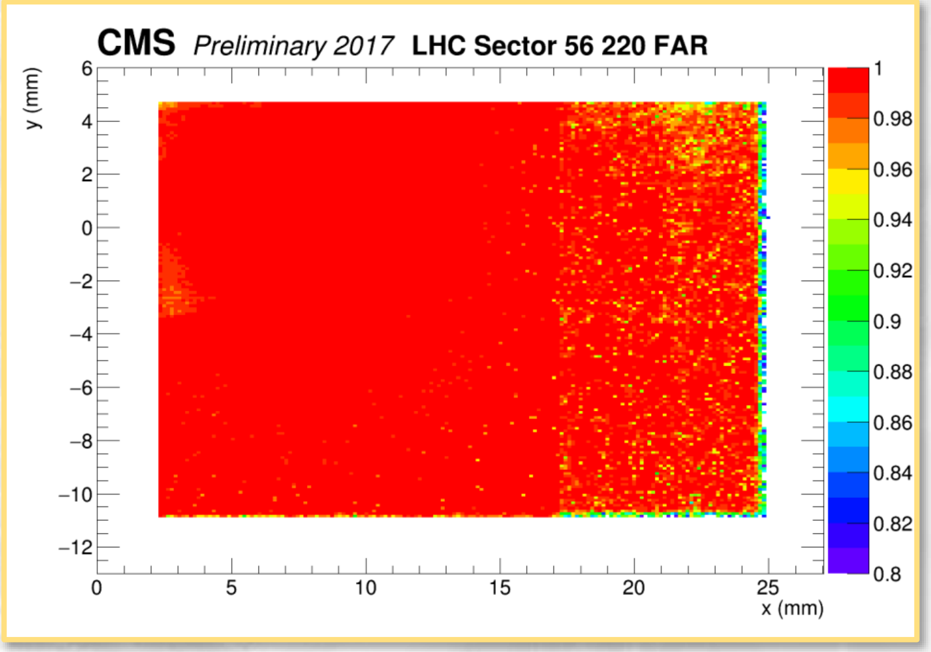
1. Evaluation of the efficiency map of each detector plane
   - Use data collected during physics run
   - Frequent measurement (every ~fb^{-1})
   - Efficiency evaluation as:

$$\varepsilon_k = \frac{N_{4,5,6}(k)}{N_3(\bar{k}) + N_{4,5,6}(k \vee \bar{k})}$$



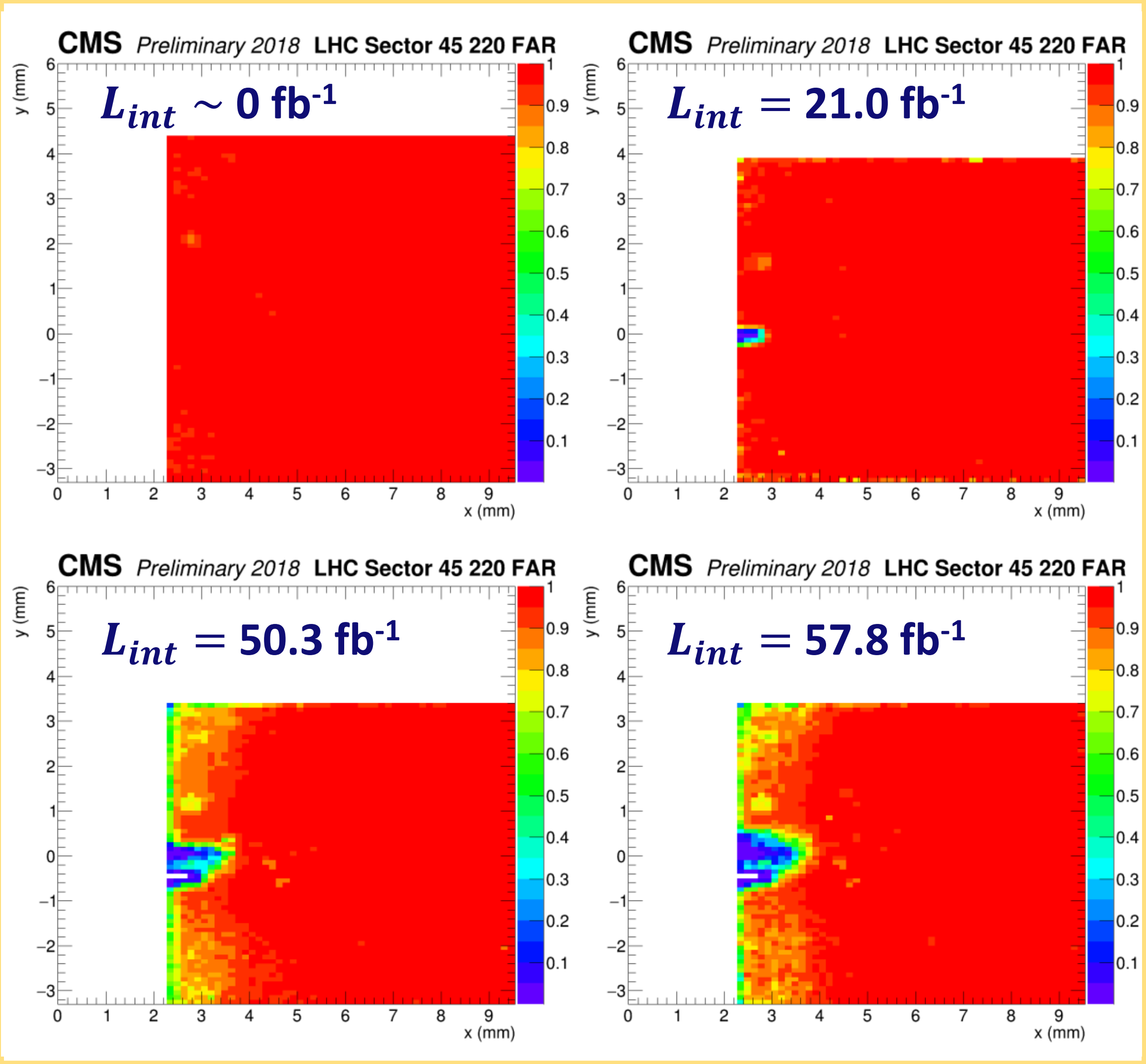
‘Radiation’ efficiency measurement

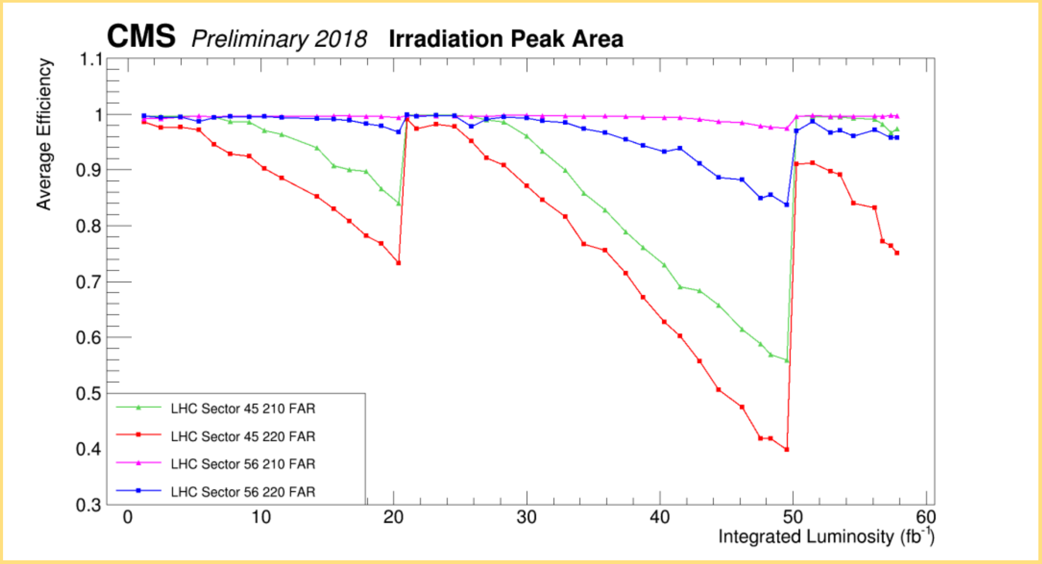




2. Evaluate the detection efficiency of the entire DP:
   - Reference sample taken at the beginning of data-taking used to model the track distribution
   - Compute the detection efficiency as the probability of having at least 3 efficient planes, assuming the plane efficiency computed in step 1
   - DP efficiency → average efficiency over all reference tracks binned in x, y

Efficiency during data-taking

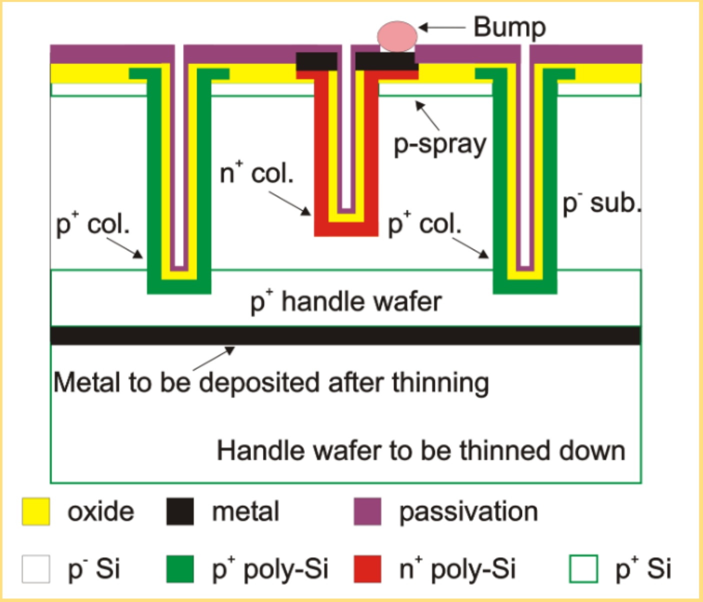


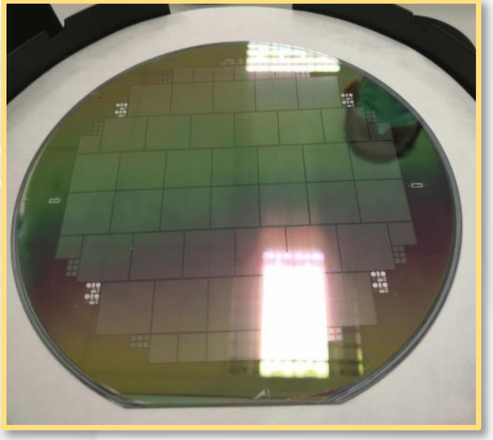


- Average efficiency in the irradiation peak
  → recovery due to movement of the RPs during Technical Stops

A new tracker for PPS: sensors

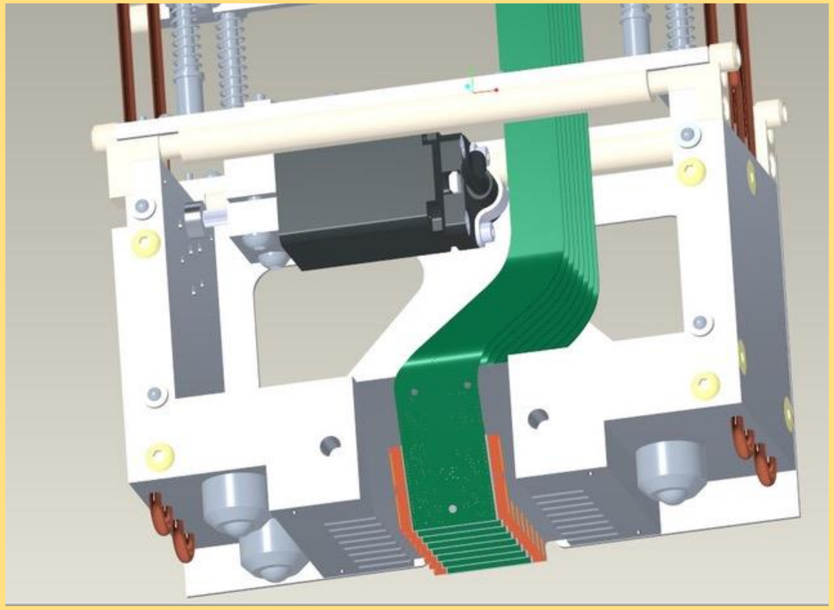
- Sensors for PPS Run 3:
  - Produced at FBK with single-sided process
  - 150 μm-thick active bulk
  - 80 μm handle wafer (after thinning)
  - 5 μm-diameter columns
  - $150 \times 100\ \mu m^2$ pixel size (same as Run 2)
  - 2×2 matrix of 52×80 pixels (same as Run 2)
- Requirements:
  - $V_{depl} < 10\ V$
  - $V_{bd} > 50\ V$
  - Wafer bow $< 200\ \mu m$
  - $I(25\ \text{V})/I(20\ \text{V}) < 2$
- Production statistics:
  - 468 sensors produced
  - 238 (50.9%) passed the requirements
  - All in Class A $[I(V_{depl} + 20\ \text{V}) < 16\ \mu\text{A}]$

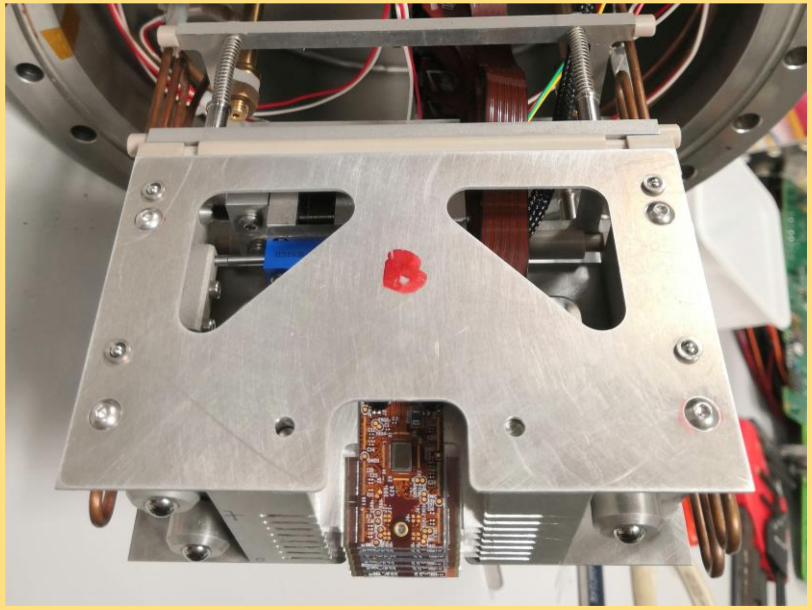




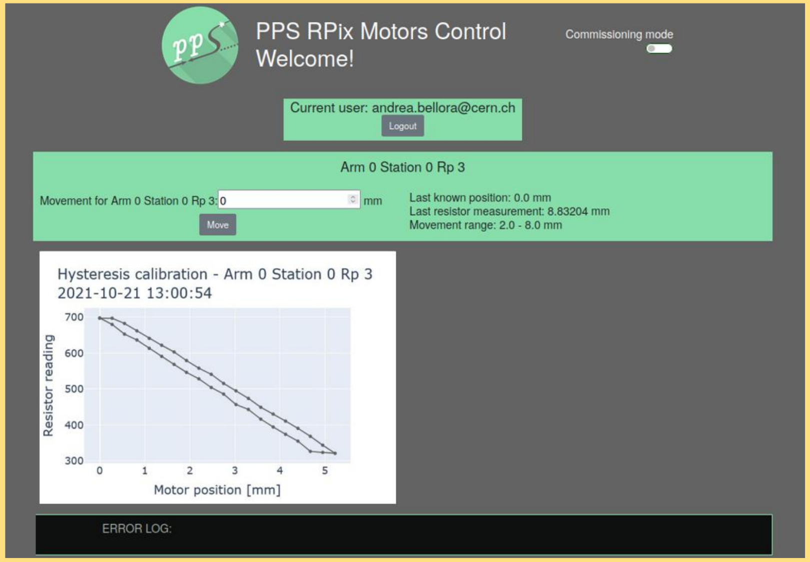
A new tracker for PPS: mechanics

- New detector package mechanics developed in Genova
  Key elements:
  - Slots for 2 additional planes (currently not in use)
  - Sliding rails to allow 'vertical' movement (~5.7 mm range)
  - Support for stepping motor + position sensor





The PPS pixel movement system



- Pixel movement system fully designed and installed in the LHC tunnel
  - Remote movements in ~500 μm steps over a ~5.7 mm range will distribute the irradiation and extend the detector lifetime
- Highlights:
  - Monitoring and control performed via Raspberry Pi micro-computers
  - Network connectivity provided via 4G network
  - Safe software implementation, with web GUI and DB logging