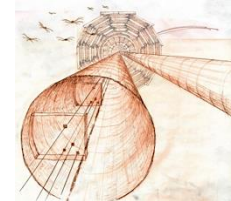




FAST 2025

**14th workshop on picosecond timing for
physics and medical applications**



The CMS Precision Proton Spectrometer and its upgrade for HL-LHC.

D. Druzhkin, KIT - Karlsruhe Institute of Technology (DE);
HUN-REN Wigner Research Centre for Physics (HU)

On behalf of the CMS collaboration

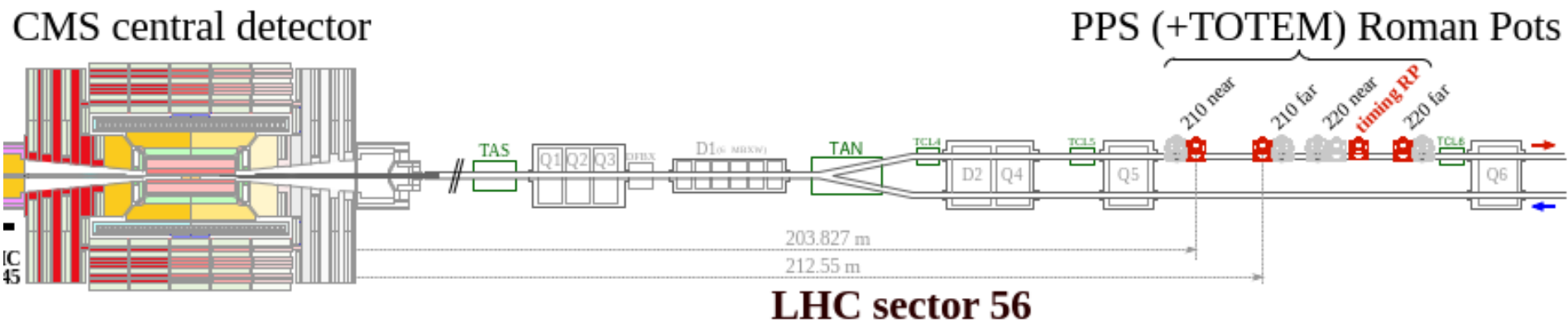
[FAST 2025 \(18-22 May 2025\): Overview · Indico](#)

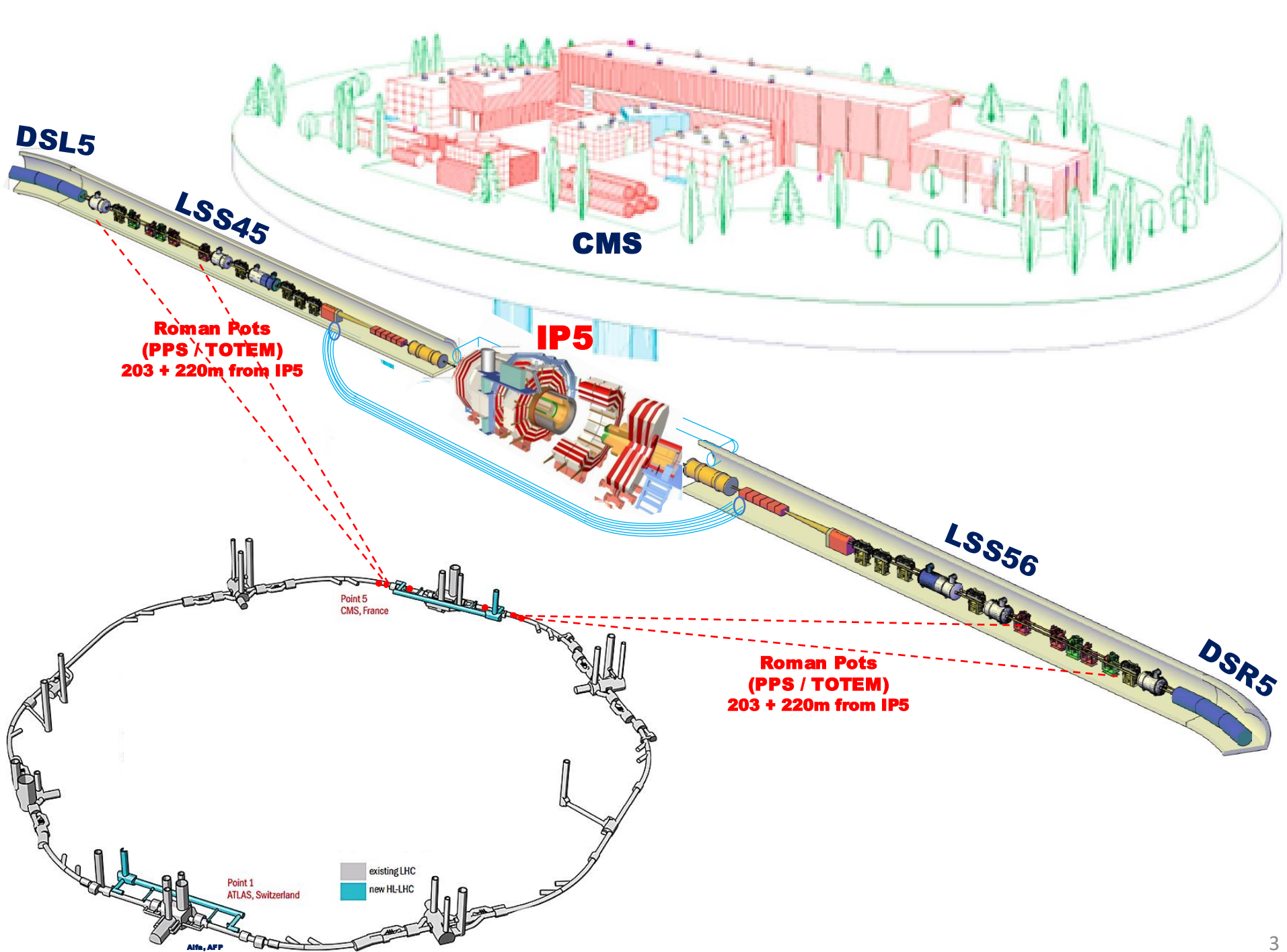
La Biodola, Elba, Italy

The Precision Proton Spectrometer (PPS) of CMS

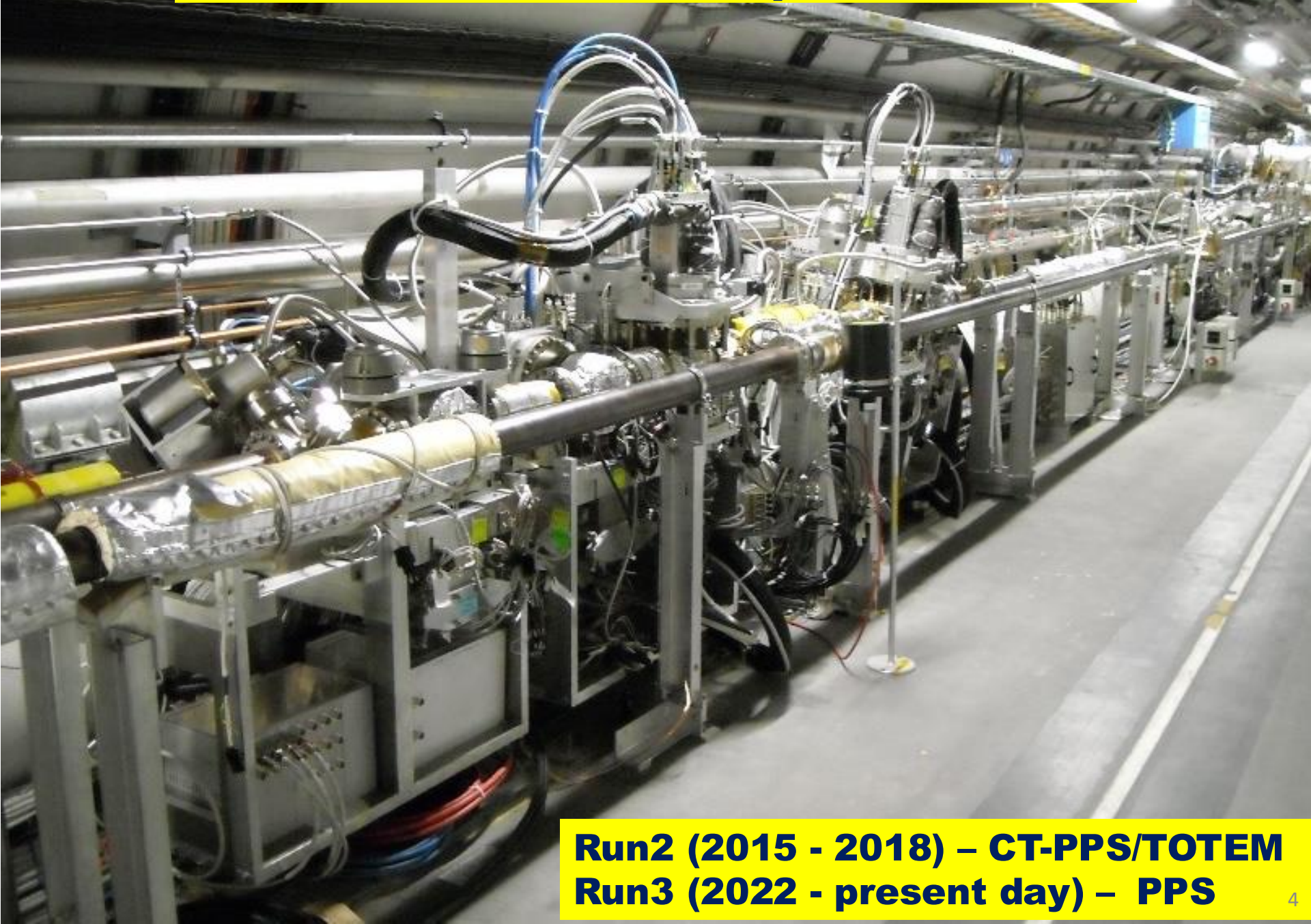
- PPS was proposed in 2012, initially as a joint CMS and TOTEM project (CT-PPS), and was installed in 2014.
- It has been successfully collecting data since 2016 (LHC Run 2 and Run 3).
- PPS measures the kinematics of protons scattered in the very forward region at about 220 m from CMS interaction point.
- Both tracking and timing information is available. Timing is important to reconstruct the longitudinal position of the interaction vertex, so as to suppress pile-up background.

EoI <https://cds.cern.ch/record/2750358?ln=en>; EDR [LHC-XRP-EC-0020.pdf](#)



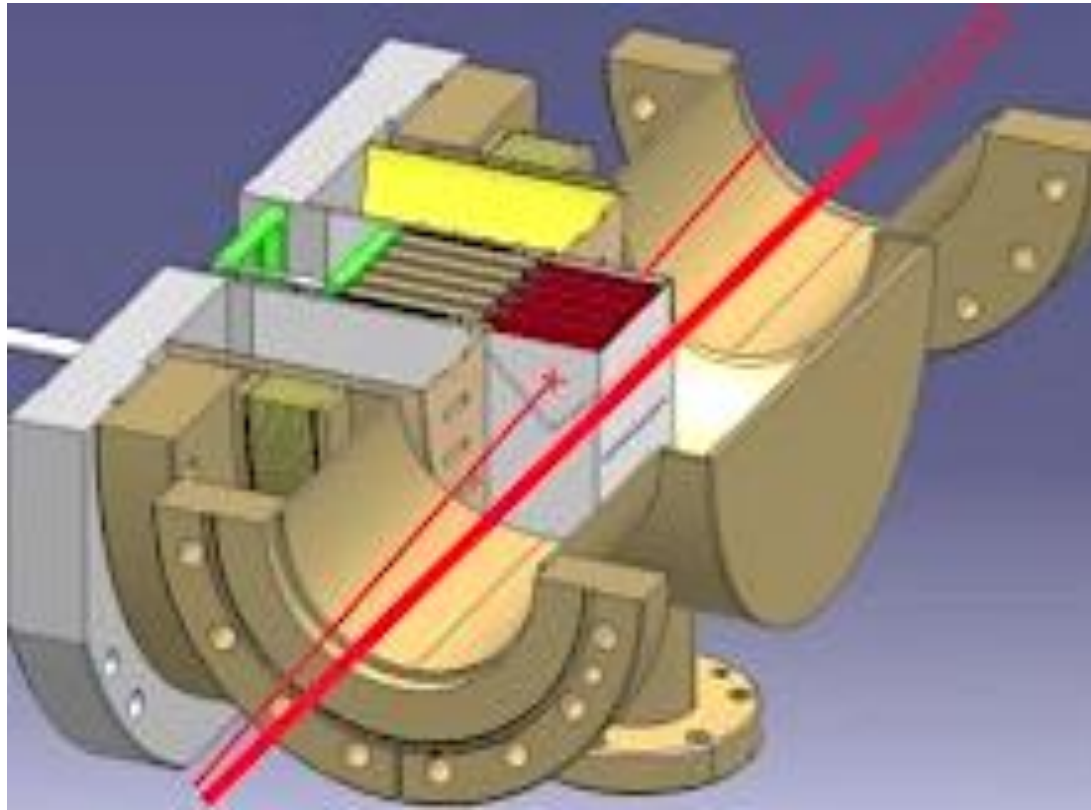


Present PPS/TOTEM setup in LHC tunnel



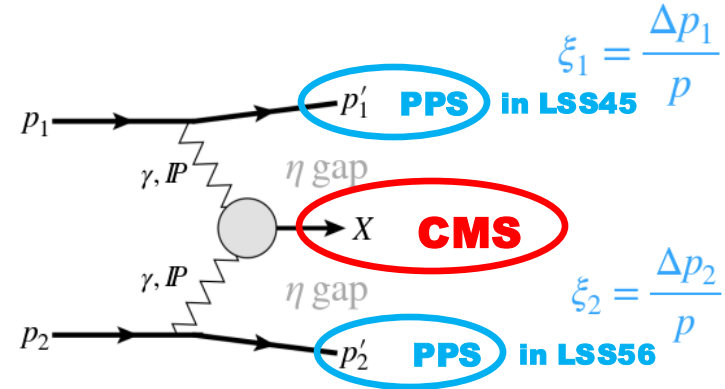
Run2 (2015 - 2018) – CT-PPS/TOTEM
Run3 (2022 - present day) – PPS

Central exclusive production



$$p + p \rightarrow p \oplus X \oplus p$$

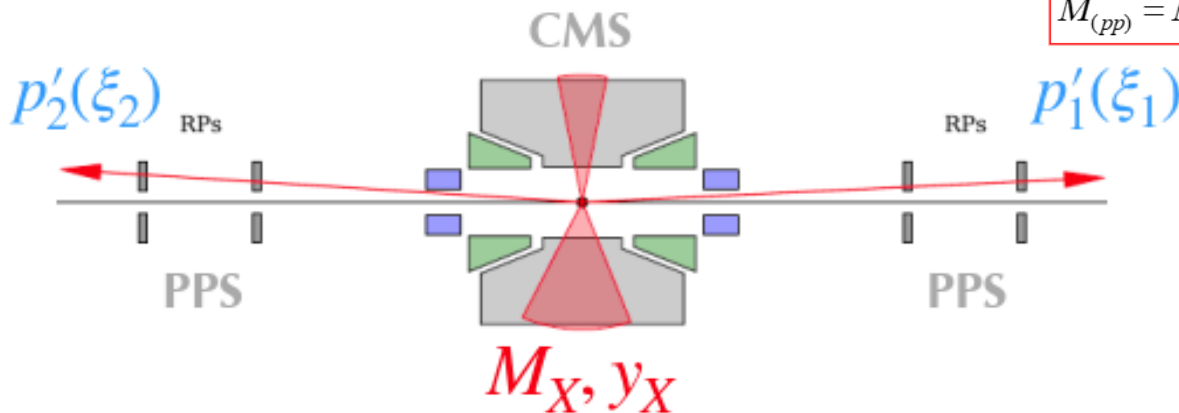
gap gap



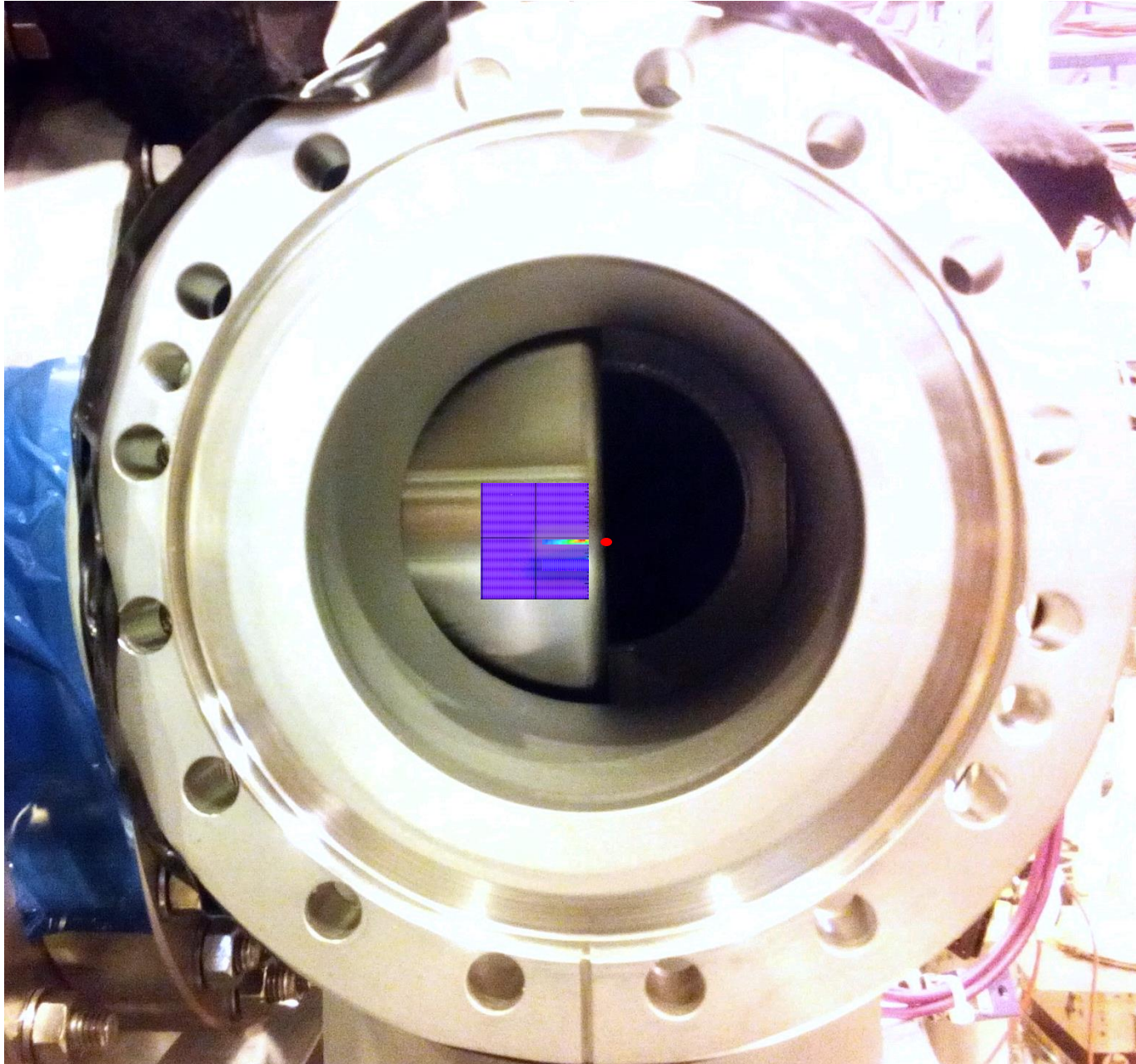
$$M_X = \sqrt{\xi_1 \xi_2 s} \quad y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$

$$\Delta \eta_{1,2} = -\ln \xi_{1,2}, \quad M^2 = \xi_1 \xi_2 s$$

$$M_{(pp)} = M_{(central)}; P_{T,Z(pp)} = P_{(central)}; \text{vertex}_{(pp)} = \text{vertex}_{(central)}$$

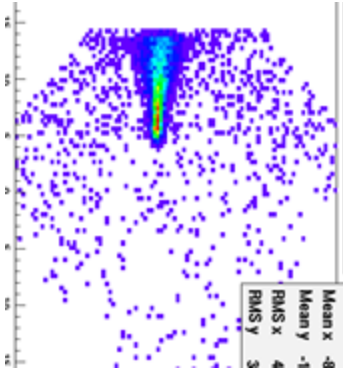


Location of sensors and scattered proton tracks relative to the LHC beam (LHC vacuum pipe)



Types of sensors used by PPS/TOTEM in LHC Runs 1, 2, 3

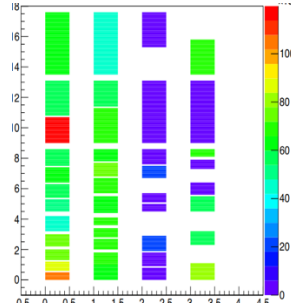
TOTEM



Si-strip
22mm



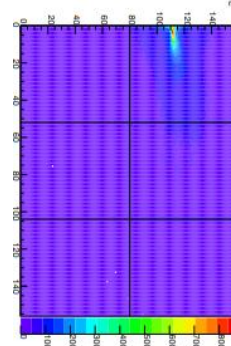
TOTEM



UFSD
6mm



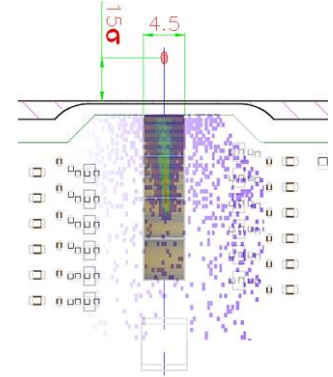
PPS



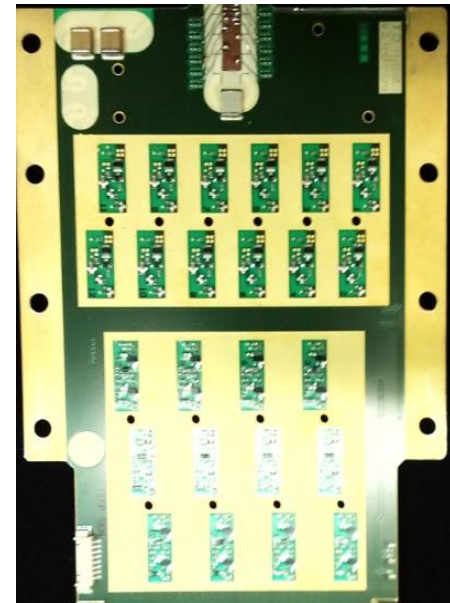
RPIX (3D-Si)
16 mm



PPS



Diamond
4.5mm



10 layers of silicon microstrip:

- “edgeless “ on the beam side; fully efficient at 50 μm from edge
- position precision of 10 μm ;
- space resolution - 10 μm , angle resolution - 1 μrad ;
- Rad/ hard $\sim 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2/100 \text{ fb}^{-1}$

4 layers CNM 50 μm

- Time resolution: $\sim 30\text{ps}$ / plane;
- pre-irradiate to $3 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$;
- on LHC in 2018

6 layers

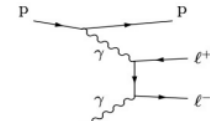
- CNM 3D pixel sensor 230 μm ; pixel size: 100 x 150 μm ;
- ROC (psi46dig), each module has 160 x 156 pixels;
- Spatial resolution 10 (30) μm along x (y) direction;

4 layers (installed on LHC in 2016) \rightarrow 8 layers double diamond (from 2018)

- time resolution $\sim 50\text{ps}$ per layer;
- high efficiency the edge (100mm)
- rad resistant up to $5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$;

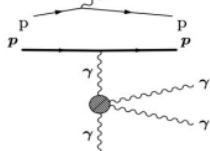
Physics results, Run 2 data

$$pp \rightarrow p \oplus \ell\ell \oplus p$$



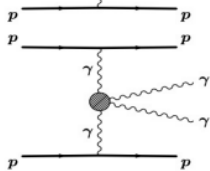
Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS-TOTEM precision proton spectrometer
JHEP 07 (2018) 153 ([doi](#))

$$pp \rightarrow p \oplus \gamma\gamma \oplus p$$



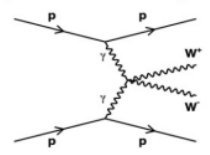
First search for exclusive diphoton production at high mass with tagged protons in proton-proton collisions at $\sqrt{s} = 13$ TeV
Phys. Rev. Lett. 129 (2022) 011801 ([doi](#))

$$pp \rightarrow p \oplus \gamma\gamma \oplus p$$



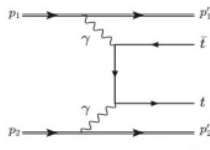
Search for high-mass exclusive diphoton production with tagged protons in proton-proton collisions at $\sqrt{s} = 13$ TeV
Phys. Rev. D 110 (2024) 012010 ([doi](#))

$$pp \rightarrow p \oplus VV \oplus p$$



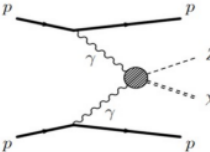
Search for high-mass exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV
JHEP 07 (2023) 229 ([doi](#))

$$pp \rightarrow p \oplus t\bar{t} \oplus p$$



Search for central exclusive production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with tagged protons
JHEP 06 (2024) 187 ([doi](#))

$$pp \rightarrow p \oplus ZX \oplus p$$

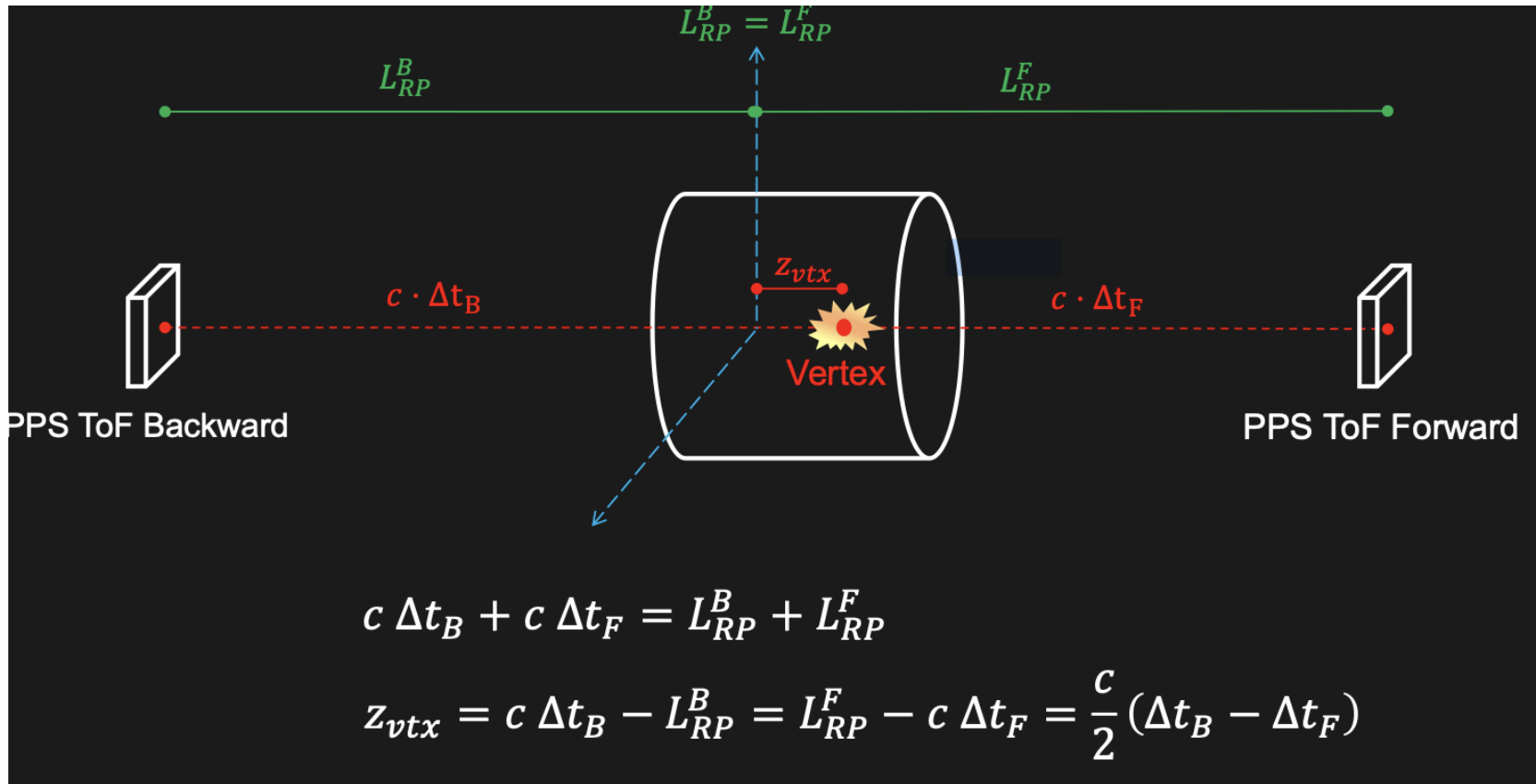


A search for new physics in central exclusive production using the missing mass technique with the CMS-TOTEM precision proton spectrometer
Eur. Phys. J. 83 (2023) 827 ([doi](#))

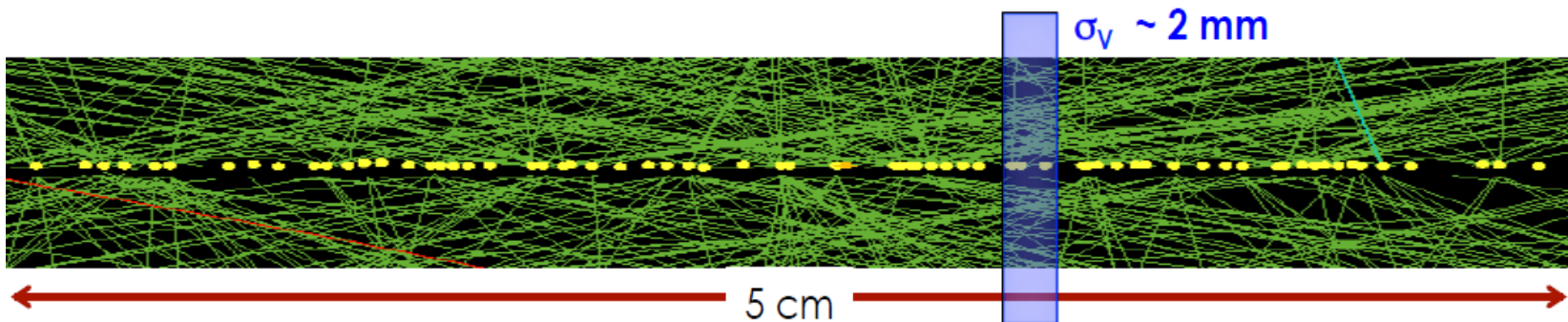
Timing detector performance publications

- **PPS Performance: first evaluation of the two-arm vertex resolution with timing detectors in 2023.**
CMS DP-2024/009
- **PPS Performance 2024: Efficiency and two-arm vertex resolution with timing detectors.**
CMS DP-2024/118
- **Improvement of the timing calibration in the CMS-PPS timing detectors,**
CMS-DP-2025-001 ; CERN-CMS-DP-2025-001
- **Time resolution of the diamond sensors used in the Precision Proton Spectrometer:**
CMS-DP-2019/034
- **Precision Proton Spectrometer timing detector efficiencies and two-arm timing resolution in 2018 data:**
CMS-DP-2020/036

Timing with RPs at Collider



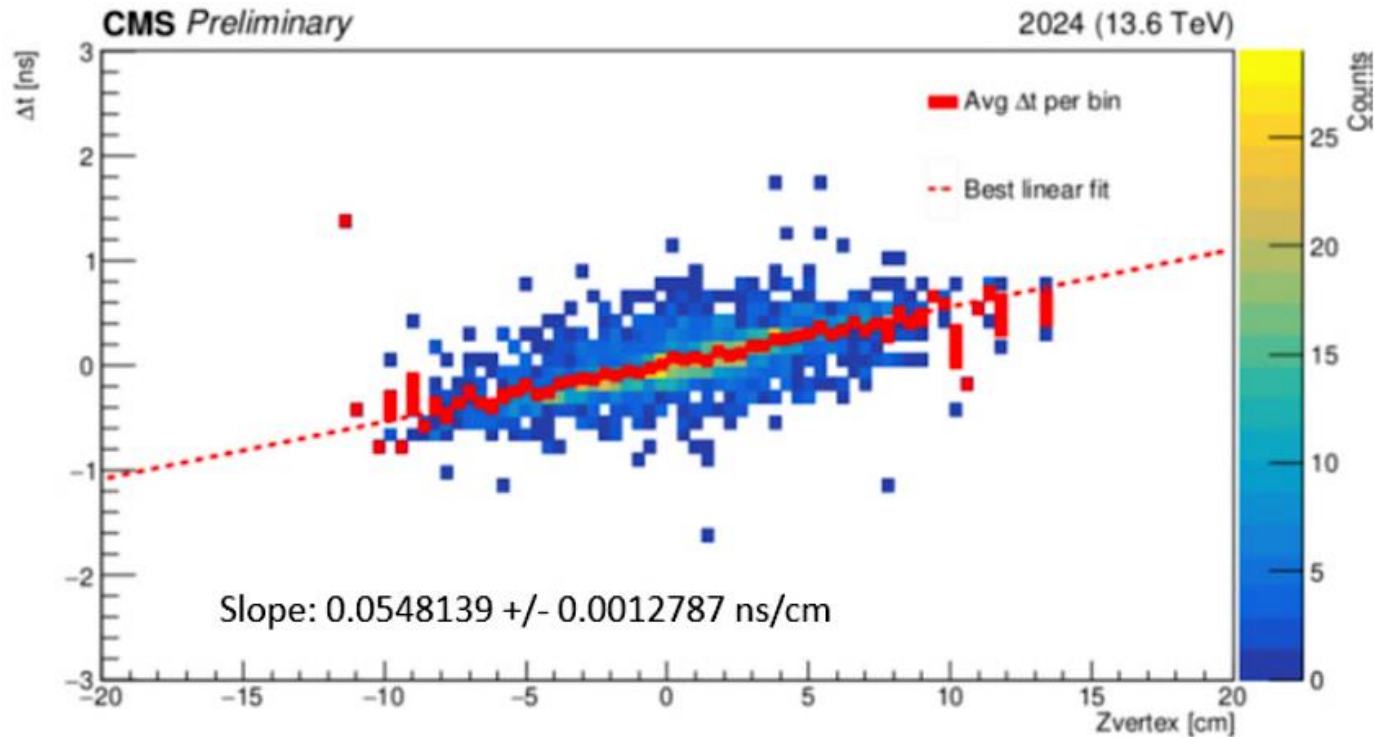
Joachim Baechler



Vertex Reconstruction with Proton ToF Difference

Correlation between proton ToF difference and vertex position from central tracker

- Vertex z position vs. Δt for the nominal sample for all events (signal + background)
- The red points show the profile of the mean Δt in bins of vertex z



Expected value:

- No correlation for purely random background
- $2/c$ (~ 0.066 ns/cm) for signal without background

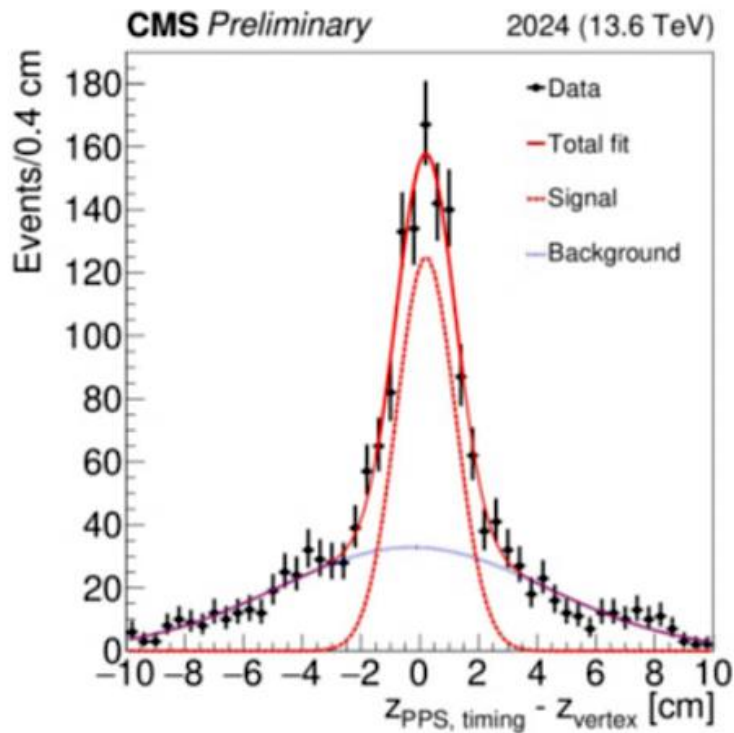
Vertex Reconstruction with Proton ToF Difference

Resolution of vertex position from proton ToF difference

Timing selection:

timing measurement in **ALL** stations on both arms -> at least 2 active planes in every timing RP.

The track time is reconstructed as the weighted average of all time measurements.



The double-gaussian fit gives a width of **1.0 cm (~47 ps per arm)** for the signal gaussian.

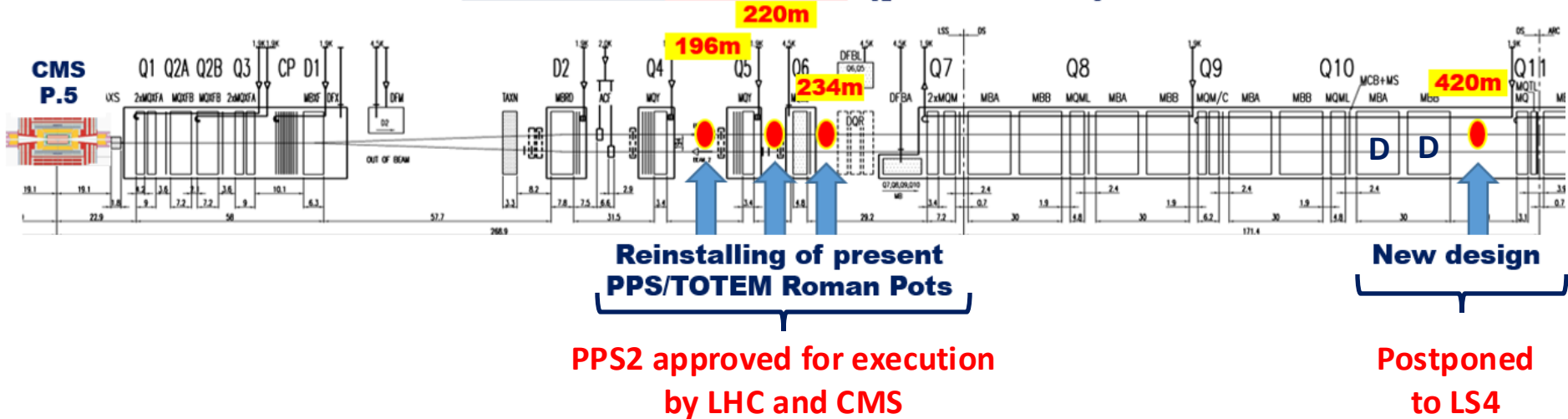
HL-LHC PPS2 Project

Approved by CMS and HL-LHC in 2023

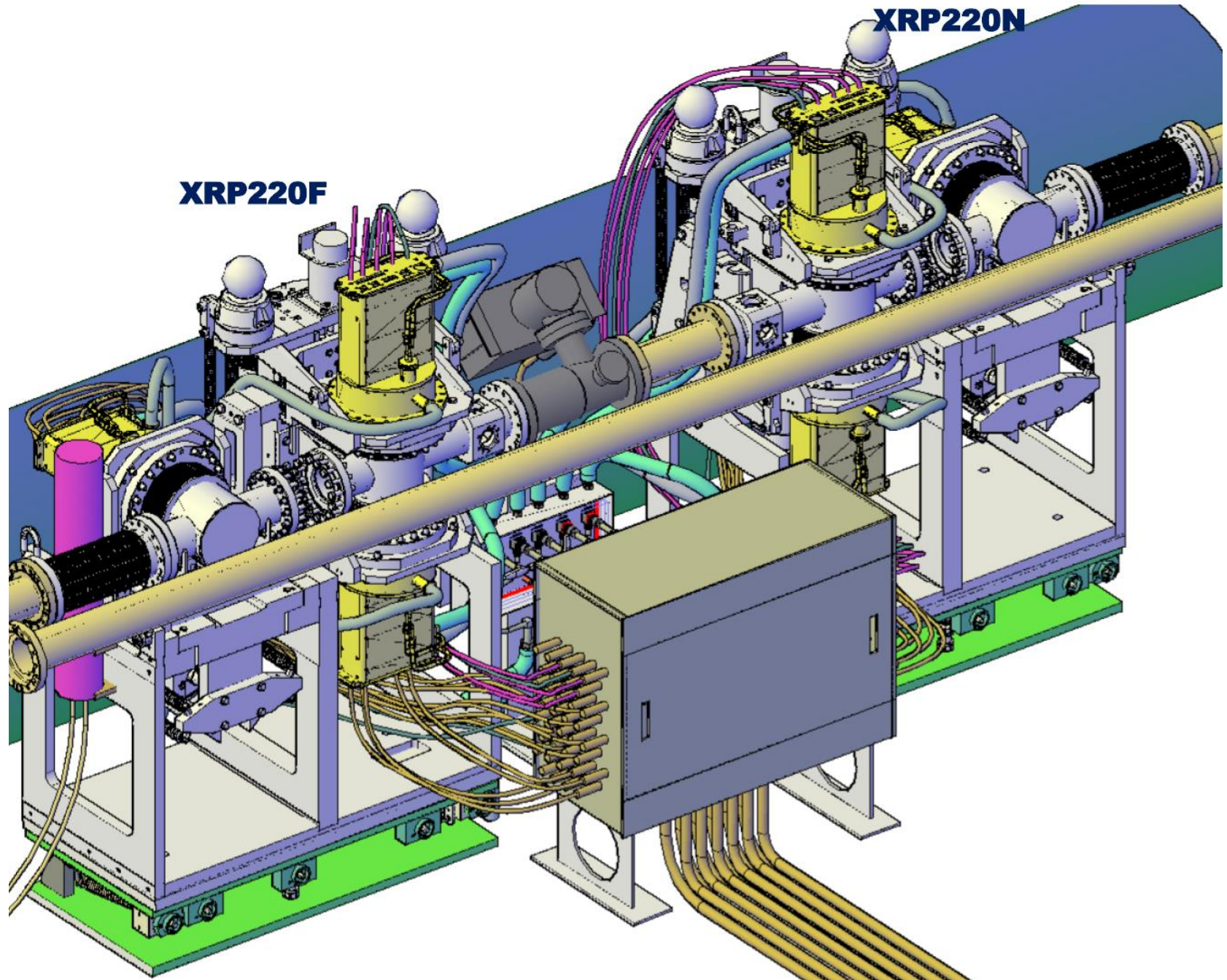
- CMS proposed to continue the PPS programme at the HL-LHC.
- In 2019, an updated design of the spectrometer (PPS2) was proposed to match the geometry and parameters of the HL-LHC (EoI).
- In 2024, the ECR has been signed and the PPS2 project moved to the implementation stage.

EoI <https://cds.cern.ch/record/2750358?ln=en>; ECR [LHC-XRP-EC-0020.pdf](#)

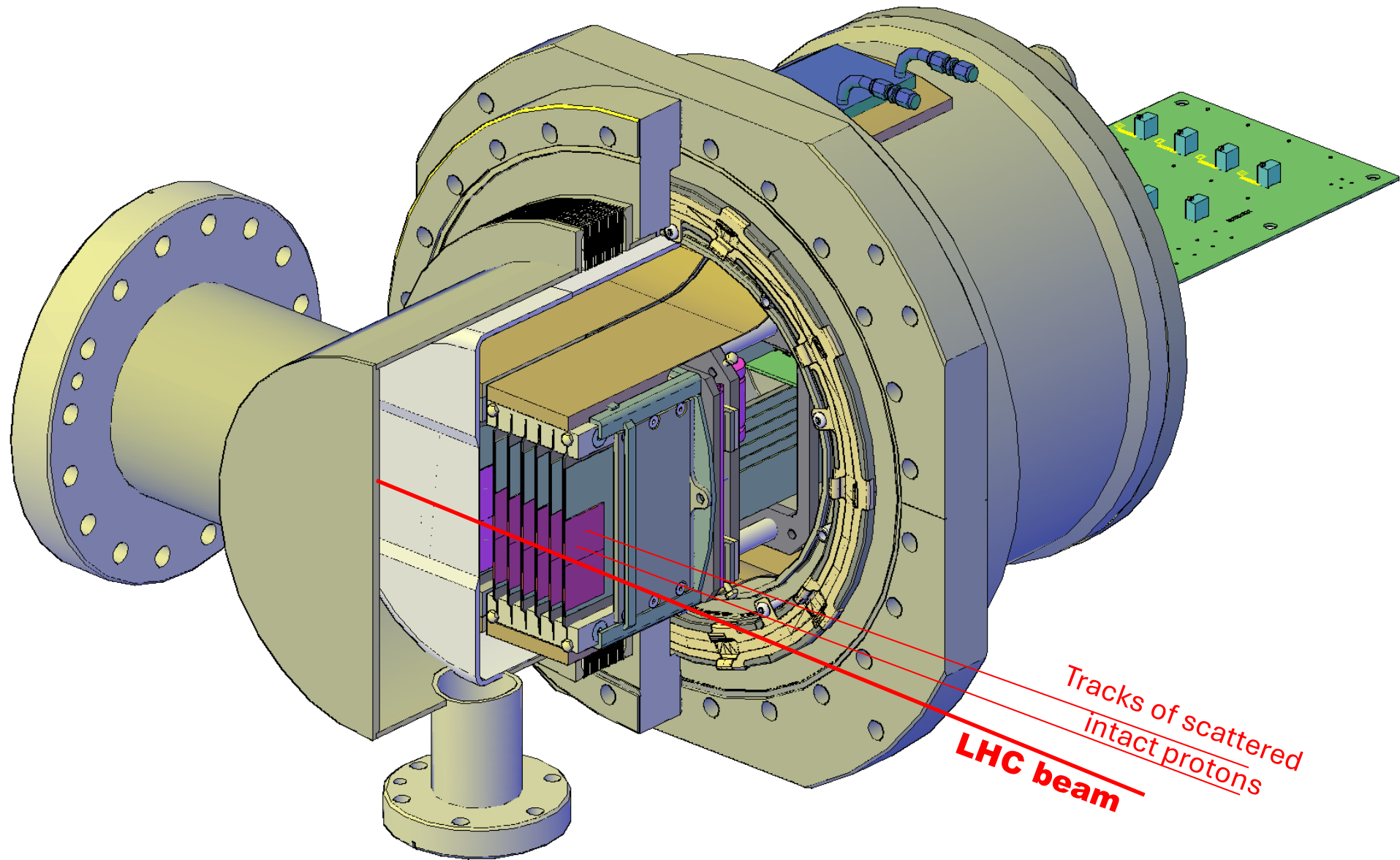
LSS5 at HL-LHC (post LS3)



An example of installing PPS2 detectors in HL-LHC tunnel.

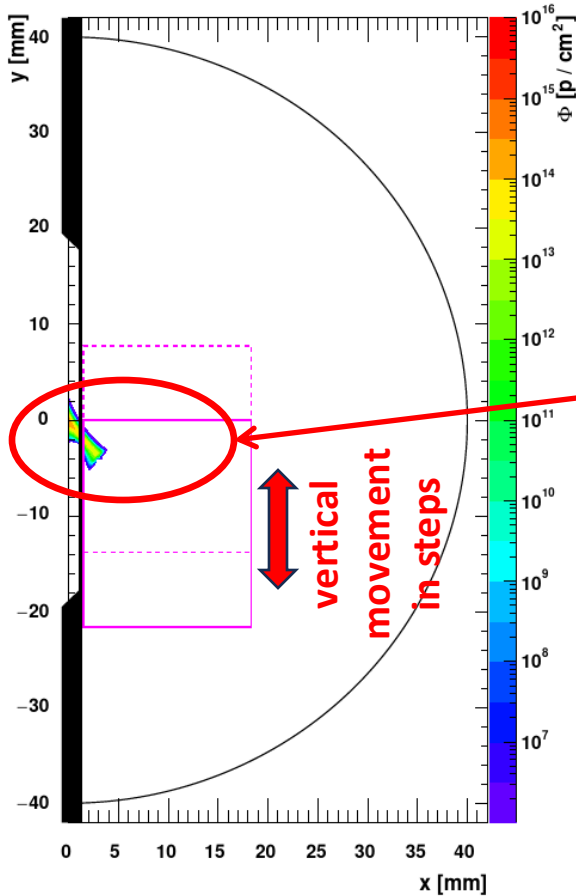


PPS2 detector at HL-LHC (design stage)



Due to limited space PPS2 detector must have both tracking and timing parts in one housing. The PPS2 detectors can be installed and removed without impact on the LHC vacuum.

Radiation levels in PPS2 detector volume (simulation)



Max proton fluence after 1 fb⁻¹

$$9.9 \times 10^{13}$$

(for XRP234)

Max proton fluence after 300 fb⁻¹

$$2.9 \times 10^{16}$$

Local area where radiation damage to the sensor and chip.

Sensors can be moved vertically as they become damaged, so as to mitigate the effect of radiation.

This mechanism allows using the detectors for one year of HL-LHC operation.

The mechanism has already been tested and is used at the present PPS.

Points of maximum proton fluence Φ (after 1 and 300 fb⁻¹)

Station	x_{peak} [mm]	y_{peak} [mm]	Φ [p/cm ²] (1 fb ⁻¹)	Φ [p/cm ²] (300 fb ⁻¹)
196 m	9.9	-11.6	0.18 (0.19) $\times 10^{13}$	5.4 (5.7) $\times 10^{14}$
220 m	4.5	-5.7	0.98 (0.99) $\times 10^{13}$	2.9 (3.0) $\times 10^{15}$
234 m	2.3	-2.7	4.7 (4.4) $\times 10^{13}$	1.4 (1.3) $\times 10^{16}$
420 m	6.8	0.2	2.0 (2.0) $\times 10^{13}$	6.0 (6.0) $\times 10^{15}$

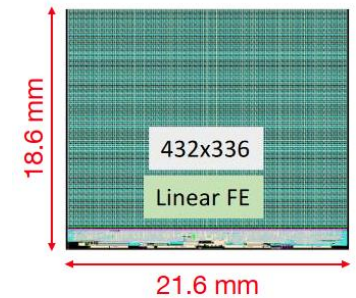
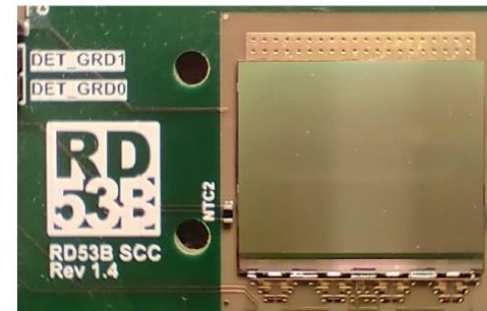
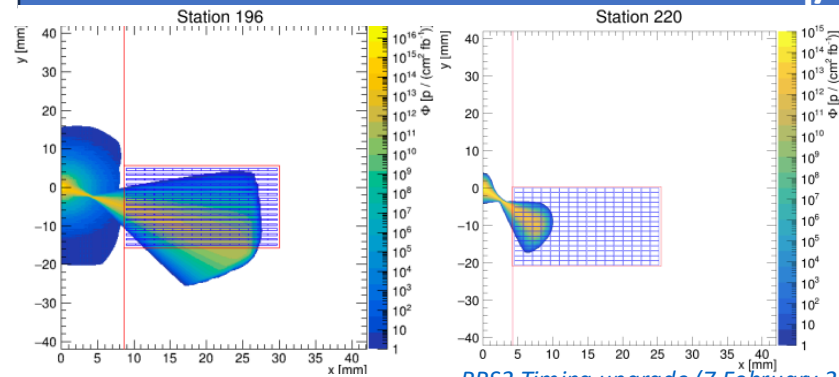
Timing and tracking sensors proposed for PPS2

LGAD Approach with ETROC, ETL Design:

- 16x16 square array of channels (both ETROC and LGAD)
- ETROC bump bonded to an LGAD sensor (16x16 array of pads, each pad $1.3 \times 1.3 \text{ mm}^2$)
- ETROC dimensions $21 \times 23 \text{ mm}^2$
- Current prototype is ETROC2, already a full size chip with all features implemented
- Design goal of $O(50\text{ps})$ resolution per hit
- LGAD radiation hardness $\sim 2 \times 10^{15} \text{ neq/cm}^2$

3D pixels read out by the CROC chip

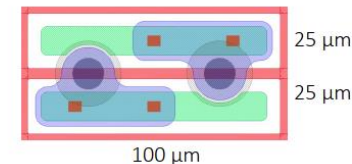
- 65-nm CMOS technology
- 432×336 pixel matrix; $21.6 \times 18.6 \text{ mm}$
- pixel size: $50 \times 50 \mu\text{m}^2$ (can also be coupled to $25 \times 100 \mu\text{m}^2$ pixel matrices)



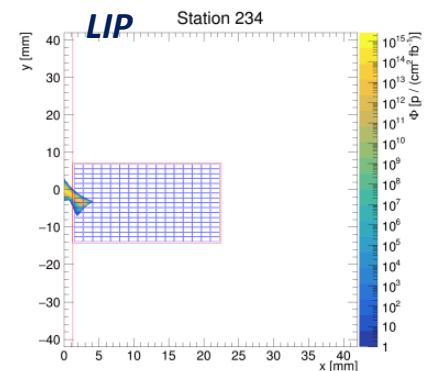
Cristóvão B. da Cruz e Silva,

PPS2 Timing upgrade (7 February 2025) - Indico

CROC - orders are made at TMSC in batches of 25 wafers each



Enrico Robutti, INFN PPS2 Tracker meeting (10 January 2025) - Indico

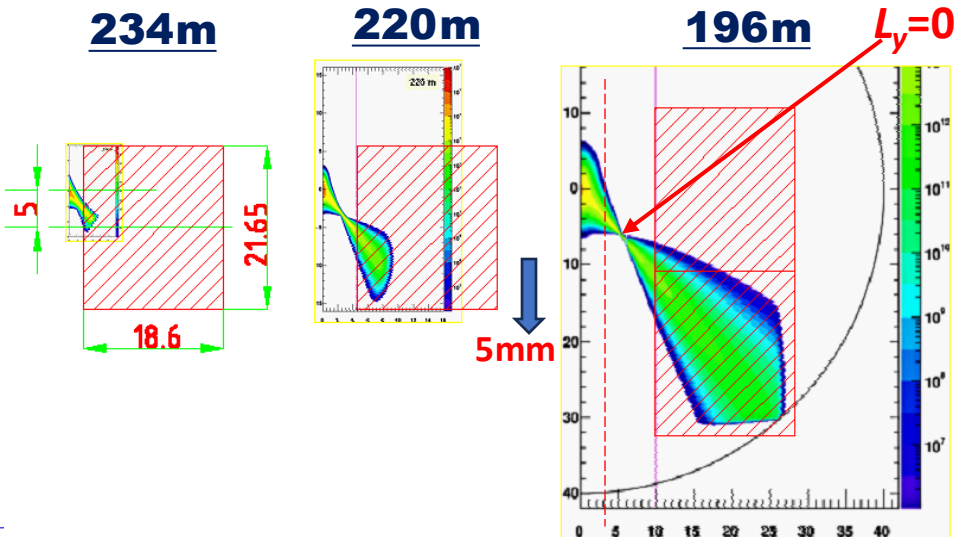


During one year of HL-LHC data taking, an integrated luminosity of 300 fb^{-1} is expected

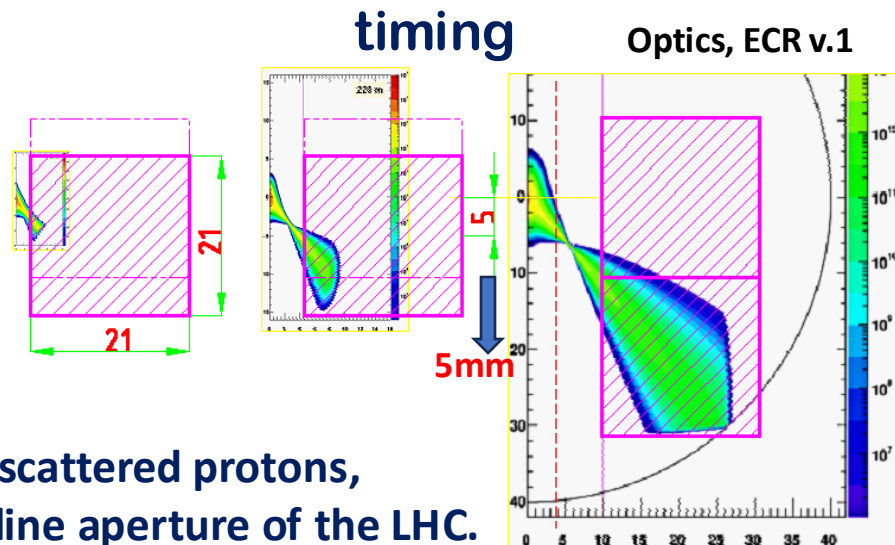
PPS2 hit map

For the PPS2 sensors the proposed technologies are silicon pixels (tracking) and Low Gain Avalanche Detectors (timing).

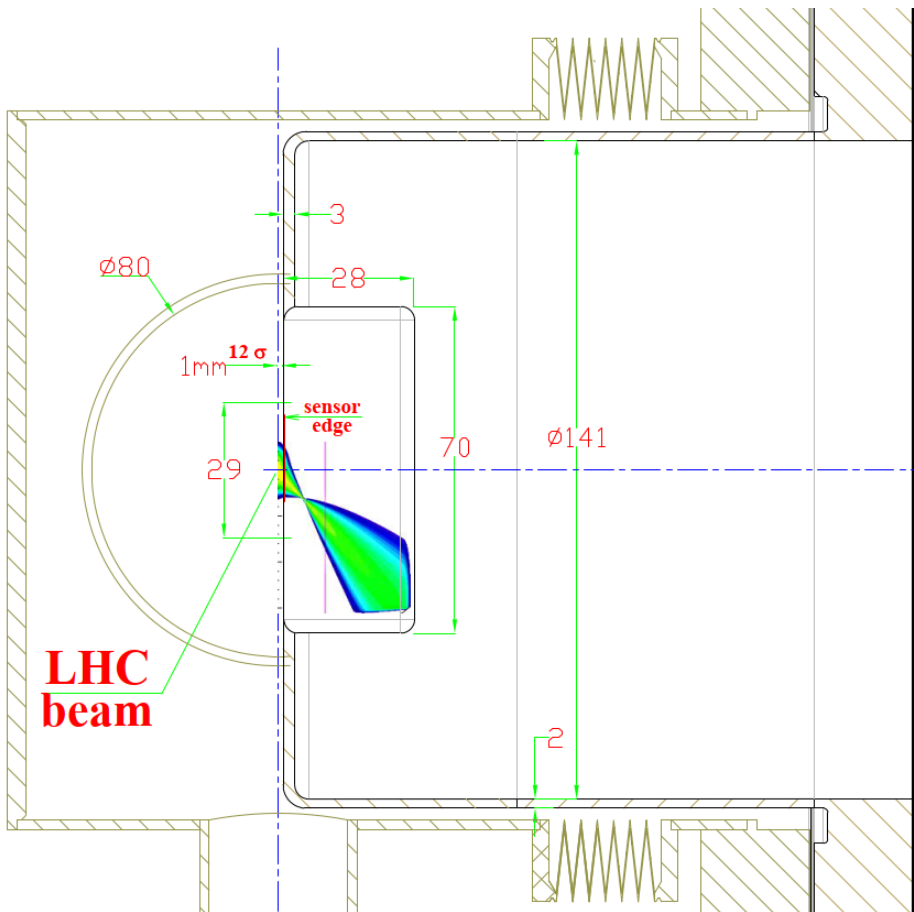
RPIX (SiPixel) with CROCv2 tracking



LGAD with ETROC2 timing



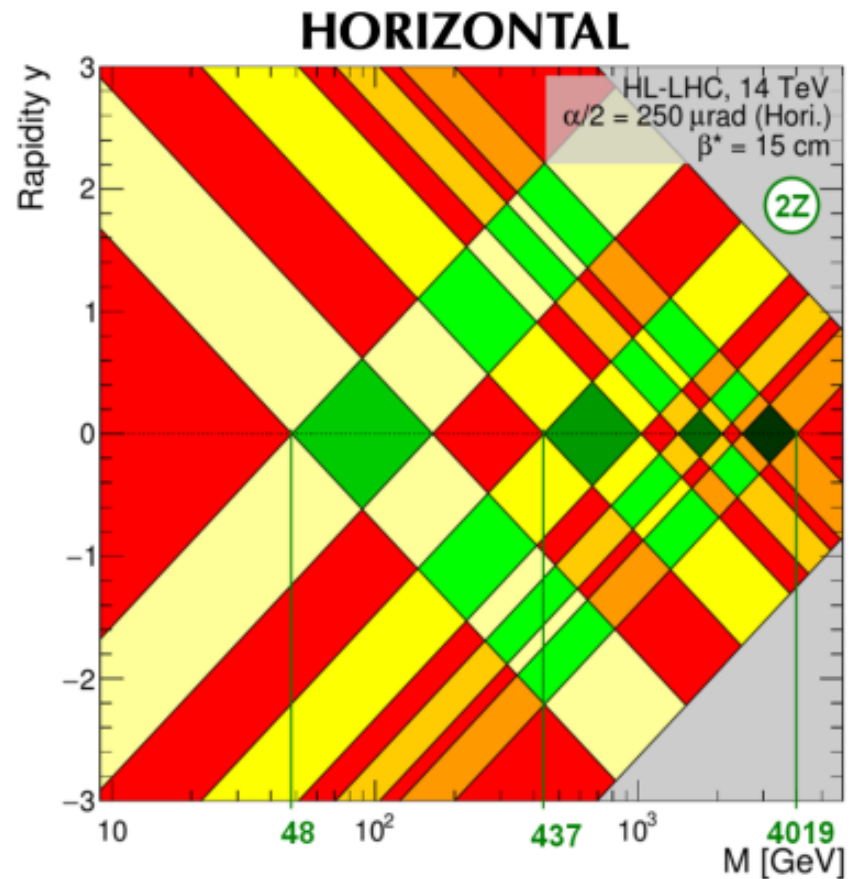
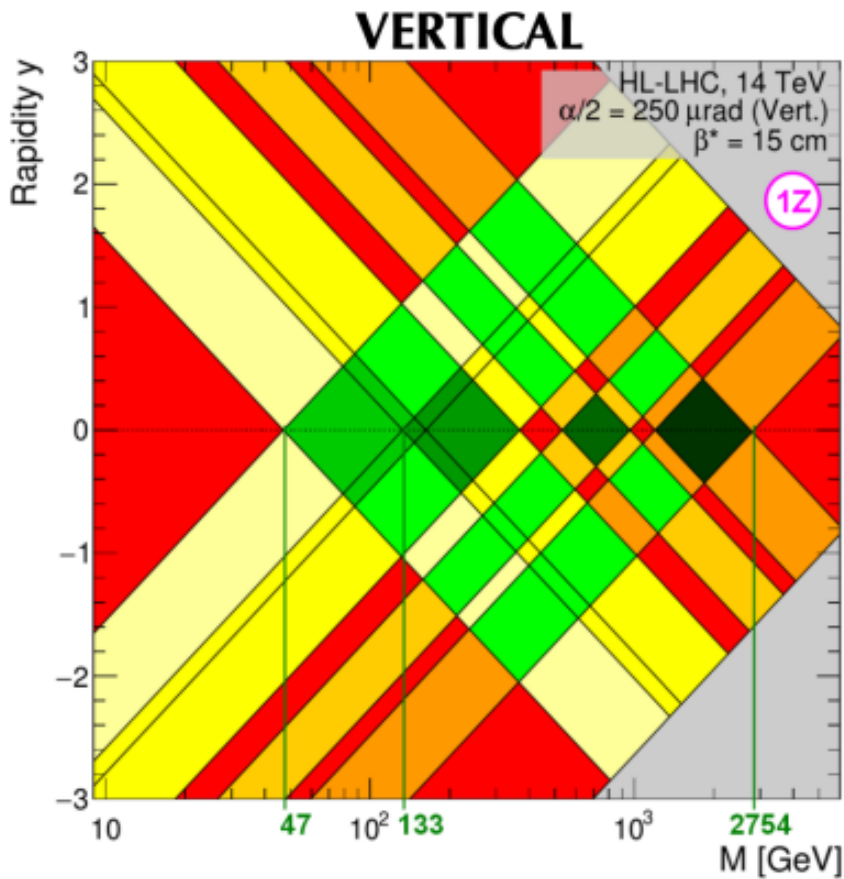
Optics, ECR v.1



LHC beam

The sensors cover the entire region accessible to scattered protons, which is limited by the collimators and the beamline aperture of the LHC.

Acceptance vs Mass and rapidity



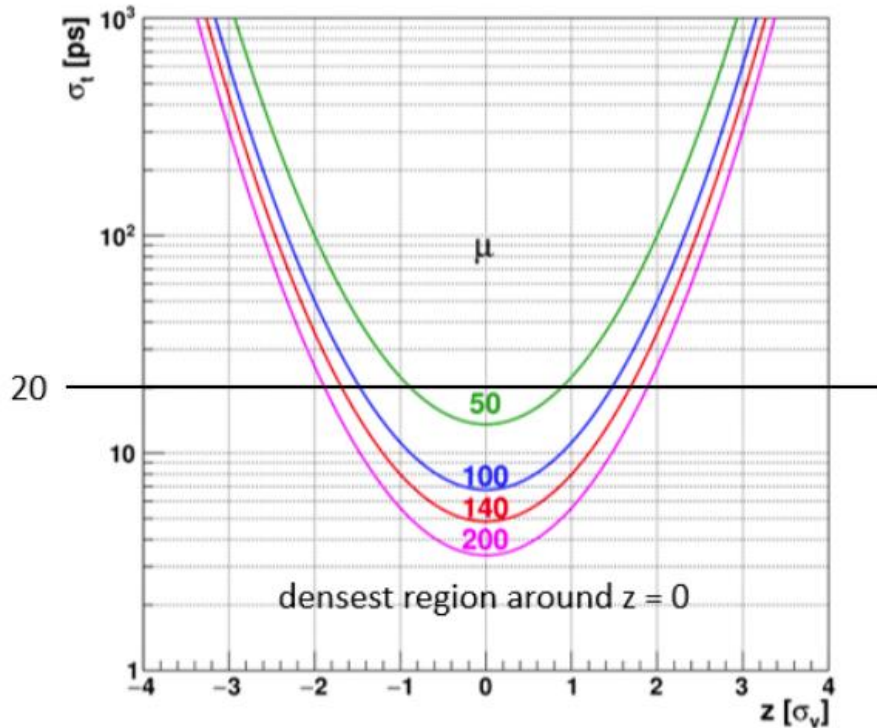
- No acceptance
- Single arm, 196 m
- Single arm, 220 m
- Single arm, 234 m
- Single arm, 420 m
- Double arm, 196 m
- Double arm, 220 m
- Double arm, 234 m
- Double arm, 420 m
- Double arm, mixed

ToF and Vertex Resolution

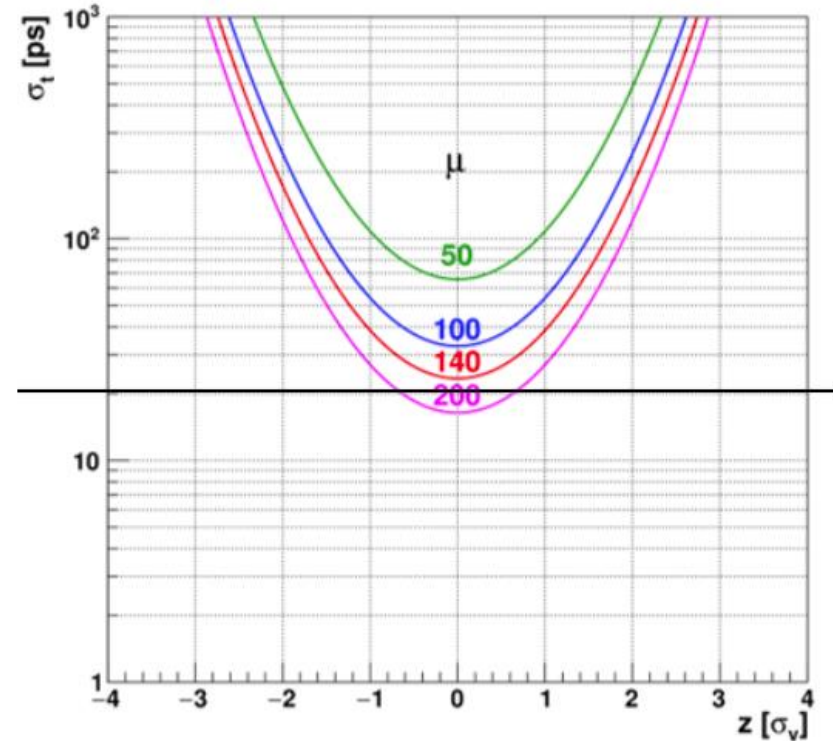
With present technology: expected time resolution $\sim 50 - 60$ ps / plane
→ with ~ 10 planes per spectrometer arm: 15 – 20 ps / arm

Required time resolution per arm to resolve mean vertex distance:

PPS alone



Combined with MTD timing



Plots for PP2 project

For $\mu = 140$ (200):
resolves vertices only outside 1.7 (1.9) σ

But: event topology selections reduce eligible vertices!

to be studied in detail

Summary:

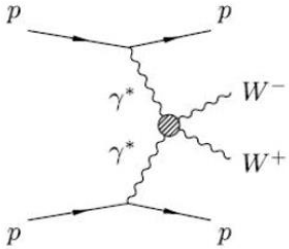
- 1. CMS has been successfully operating PPS since 2016, using both tracking and timing detectors.**
- 2. The PPS2 project is an upgrade of the present PPS, adapted to HL-LHC with new optics and highest pile-up.**

Thanks!

Back Up

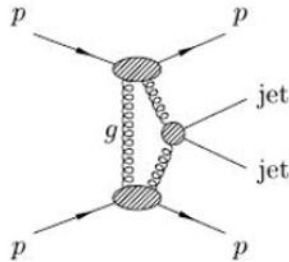
Physics motivation

1. EWK. LHC as photon-photon collider



- Anomalous quartic gauge couplings (aQGC)
- Measure $\gamma\gamma \rightarrow W^+W^-; e^+e^-; \mu^+\mu^-; \tau^+\tau^-;$
- Search for $ZZ\gamma\gamma; \gamma\gamma\gamma\gamma$ coupling;

2. QCD. LHC as gluon-gluon collider



- Exclusive two and more jet events;
- high- p_T jet production;
- Gluon jet samples with small quark jet component;
- Proton structure (GPDs) investigation;

3. BSM. Search for new resonances in CEP

Detector sensors parameters on the HL-LHC (for Run4).

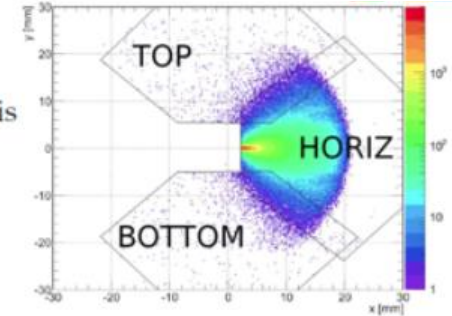
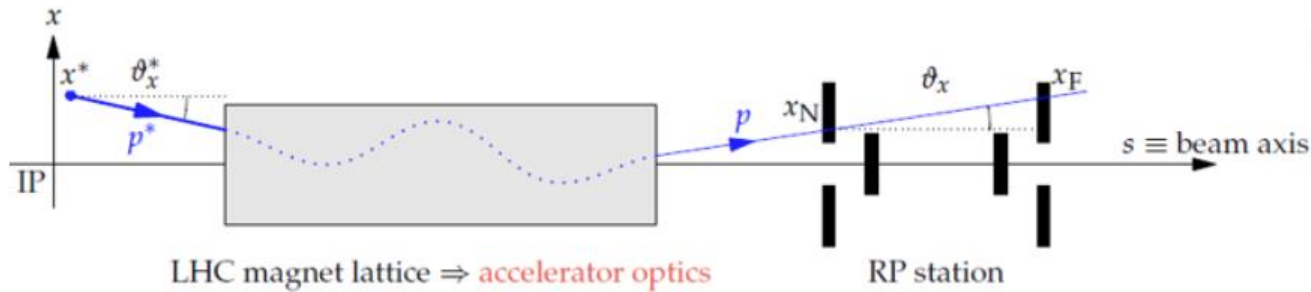
Diffractive Mass acceptance limits

Vertical Crossing-Angle				
Station	$ \xi_{\min} $	$ \xi_{\max} $	M_{\min} [GeV] @ $y = 0$	M_{\max} [GeV] @ $y = 0$
196 m	0.0786–0.0856	0.1967	1100.87–1197.80	2754.27
220 m	0.0371–0.0381	0.0688	519.89–533.18	962.70
234 m	0.0189–0.0095	0.0263	264.96–132.80	368.11
420 m	0.0031–0.0034	0.0116	43.38–47.04	162.66

Horizontal Crossing-Angle				
Station	$ \xi_{\min} $	$ \xi_{\max} $	M_{\min} [GeV] @ $y = 0$	M_{\max} [GeV] @ $y = 0$
196 m	0.1654–0.1779	0.2871	2316.15–2490.07	4018.94
220 m	0.0984–0.1014	0.1488	1377.48–1419.13	2083.04
234 m	0.0564–0.0312	0.0732	789.48–437.07	1024.60
420 m	0.0032–0.0034	0.0118	44.55–48.20	165.28

from Eol: <https://cds.cern.ch/record/2750358?ln=en>

Proton Measurements in Space and Time

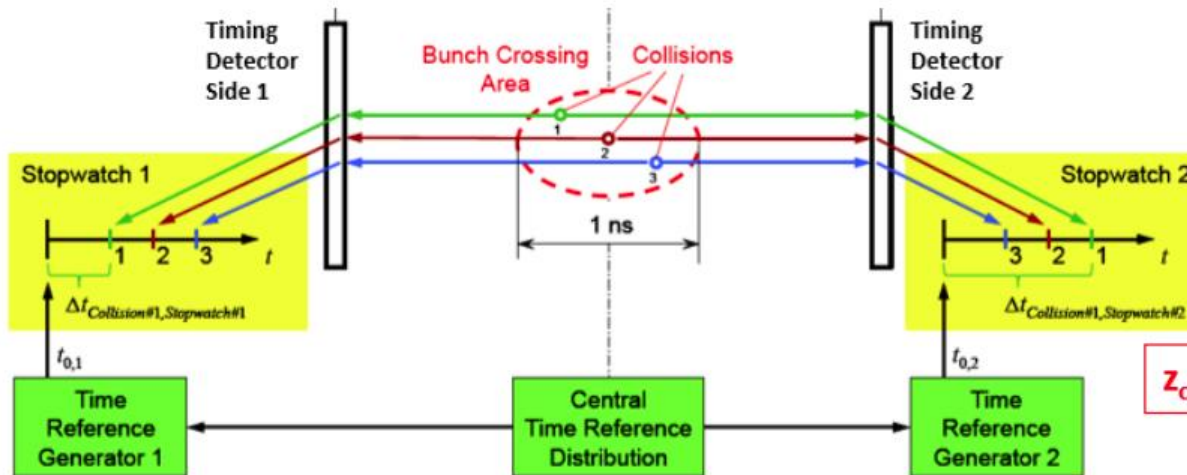


Proton kinematics in RP

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{\text{RP}} = \underbrace{\begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Product of all lattice element matrices}} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{\text{IP5}}$$

Values at IP5 to be reconstructed

Longitudinal Vertex Position Measurement via Time-of-Flight Difference



$$z_{\text{collision}} = \frac{1}{2} (t_{\text{stopwatch 2}} - t_{\text{stopwatch 1}})$$

Radiation level specification for HL-LHC



EDMS NO.	REV.	VALIDITY
2302154	1.0	VALID
REFERENCE: LHC-N-ES-0001		

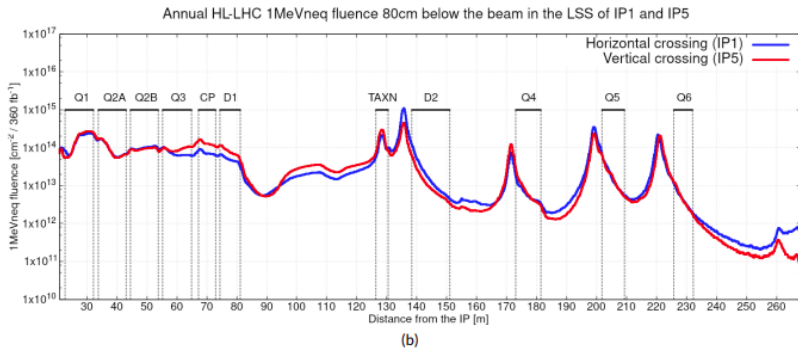
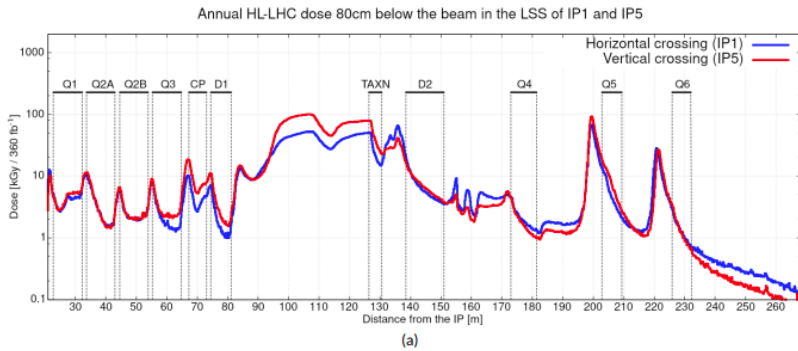


Fig. 2.3: Expected radiation levels below the cryostat in the LSS area of IR1 and IR5 for an annual integrated luminosity of 360 fb^{-1} during proton operation as a function of the distance from the IP. Figure 2.3a presents the TID levels, while Figure 2.3b shows the profile of the 1-MeV neutron equivalent fluence.

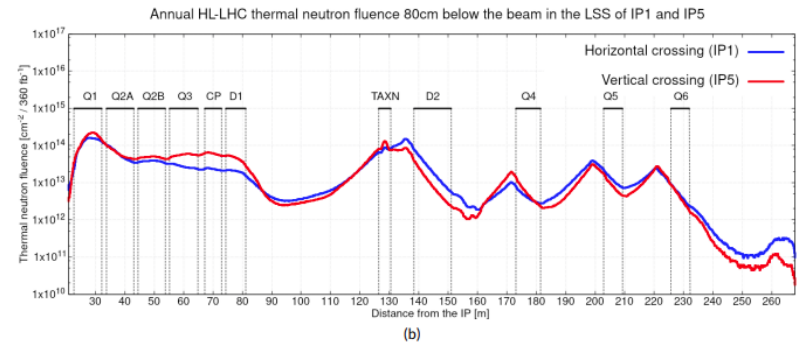
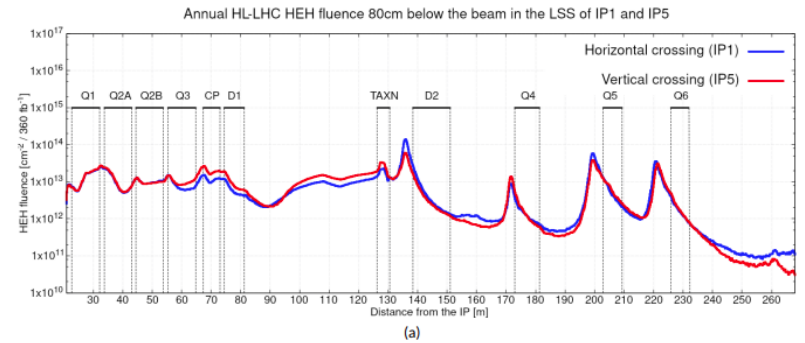
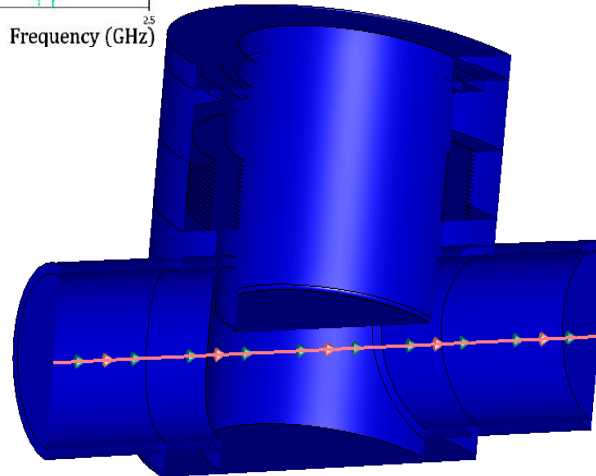
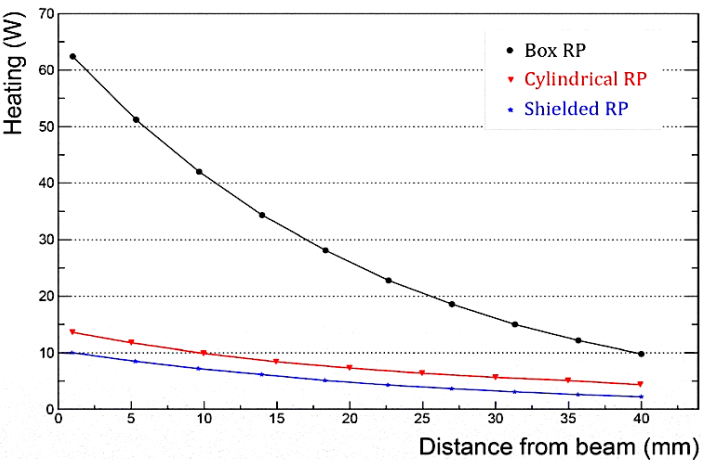
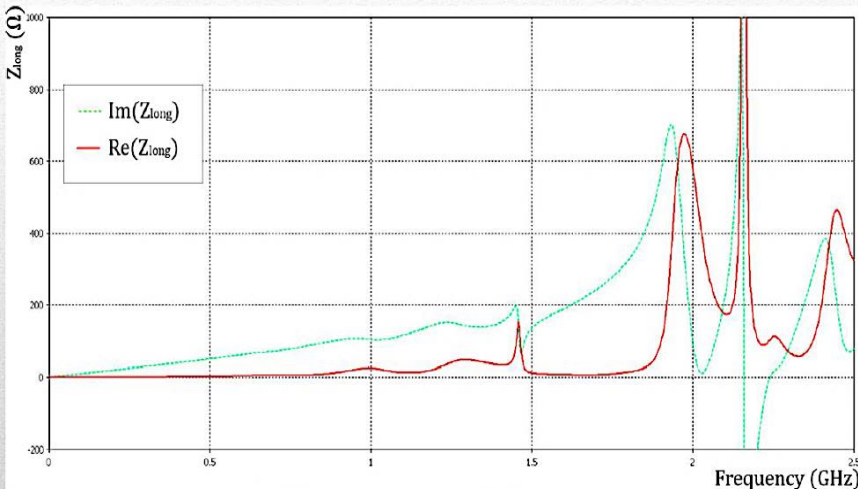


Fig. 2.4: Expected radiation levels below the cryostat in the LSS area of IR1 and IR5 for an annual integrated luminosity of 360 fb^{-1} during proton operation as a function of the distance from the IP. Figure 2.4a presents the HEH fluence, while Figure 2.4b shows the profile of the thermal neutron fluence.

PPS2 impedance impact to HL-LHC beam

The passage of the beam close to XRP produces electromagnetic fields that interact with the vacuum chambers (beam pipe, roman pots flanges) and can lead to:

- Beam energy loss
- Beam instabilities
- Excessive heating of the equipment



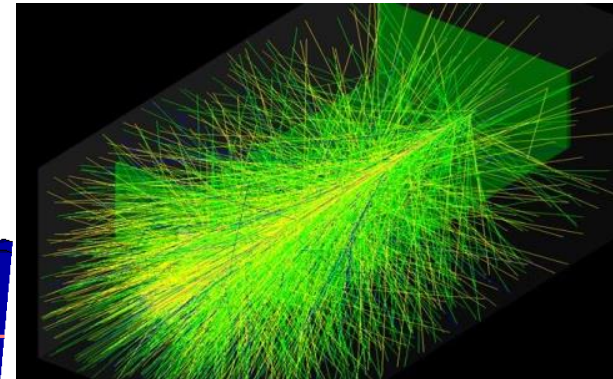
IMPEDANCES OF THE TOTEM RPs (2/3)

<i>Nicola Minafra</i>	Z_{\parallel}^{eff} / n (mΩ)	% to total LHC current impedance (90 mΩ)	\bar{Z}_{\perp}^{eff} (KΩ/m)	% to total LHC current impedance (25 MΩ/m)	Heating (W)
	Imaginary part		Imaginary part		
Present RP ¹⁾	1.7	1.9%	80	< 0.3%	62
Rotated RP ²⁾	2.6	2.9%	20	< 0.1 %	241
Cylindrical RP ³⁾	1.1	1.1%	50	< 0.2 %	13

35% better

~ × 5 better

Crossing the walls with a beam of protons. GEANT

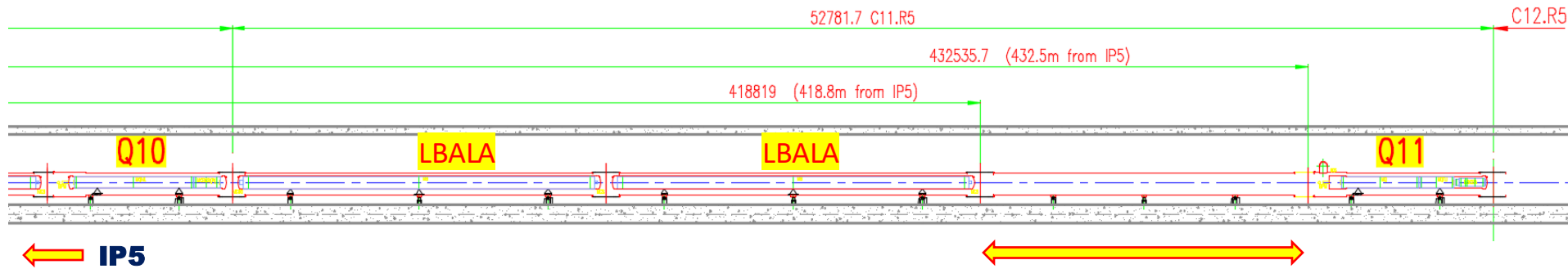


**420m Project
(Proposed as a post-LS4 project)**

**Not approved,
for discussion**

PPS XRP's on HL-LHC at 420m

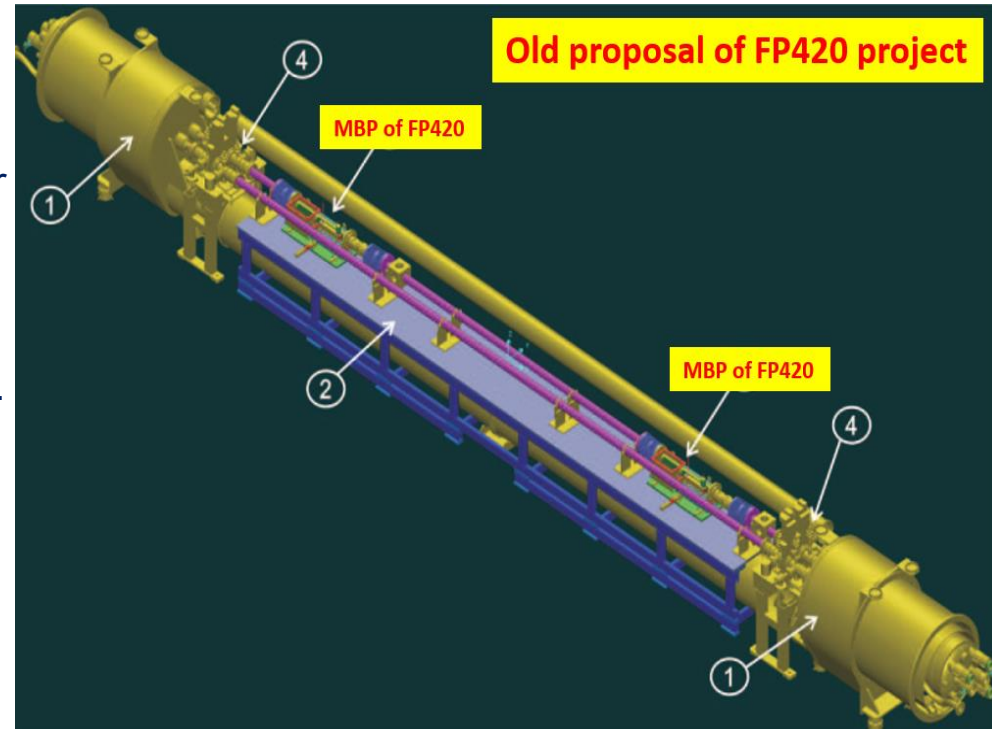
Sector C11.R/L5; 419 + 432 m (from IP5)



A station at 420m would give access to central exclusive production of small masses, including the Higgs boson.

The similar design was previously proposed for the “FP420” project (<https://arxiv.org/abs/0806.0302v2>).

Detectors can be a similar to the installed on LHC Roman Pots, but with reduced dimensions. The detector position relative to the beam can be measured both by employing beam position monitors and by using a high-rate physics process which produces protons of a known momentum loss.



All detector operations, control and monitor must take place remotely, at least between two YETs. The installation of detectors at the 420 m should not impact the operation or luminosity of the LHC.

Sensor sensitive area at 420m (from PPS2 Lol)

The Roman Pots detectors are just behind two LHC dipoles

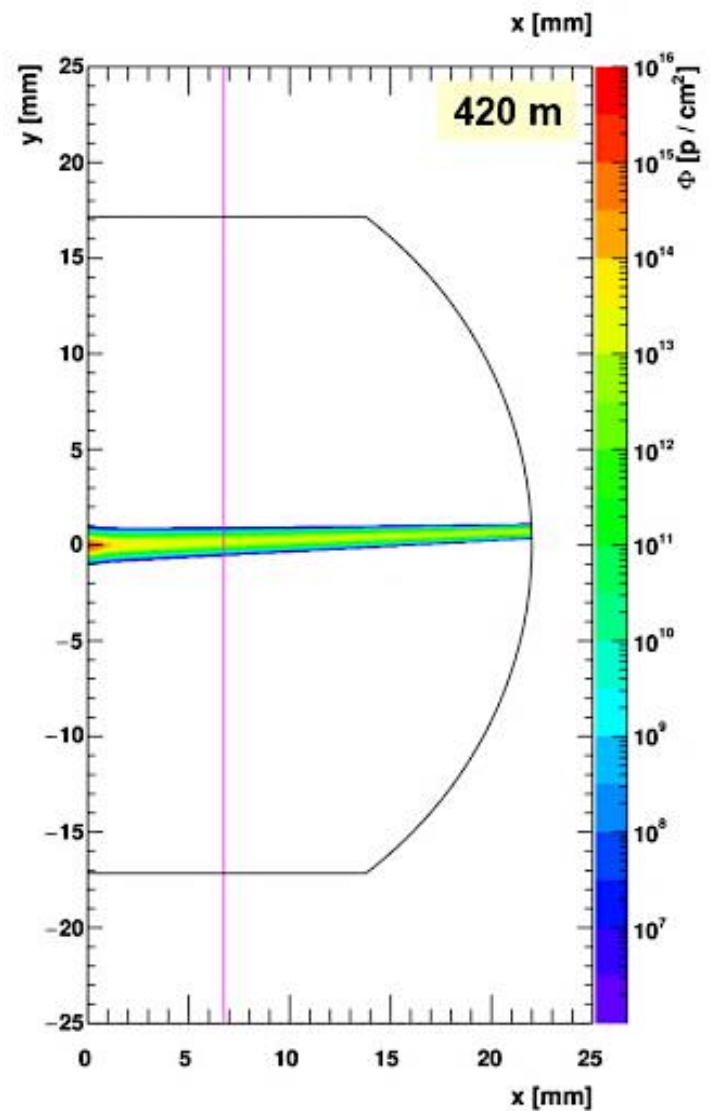
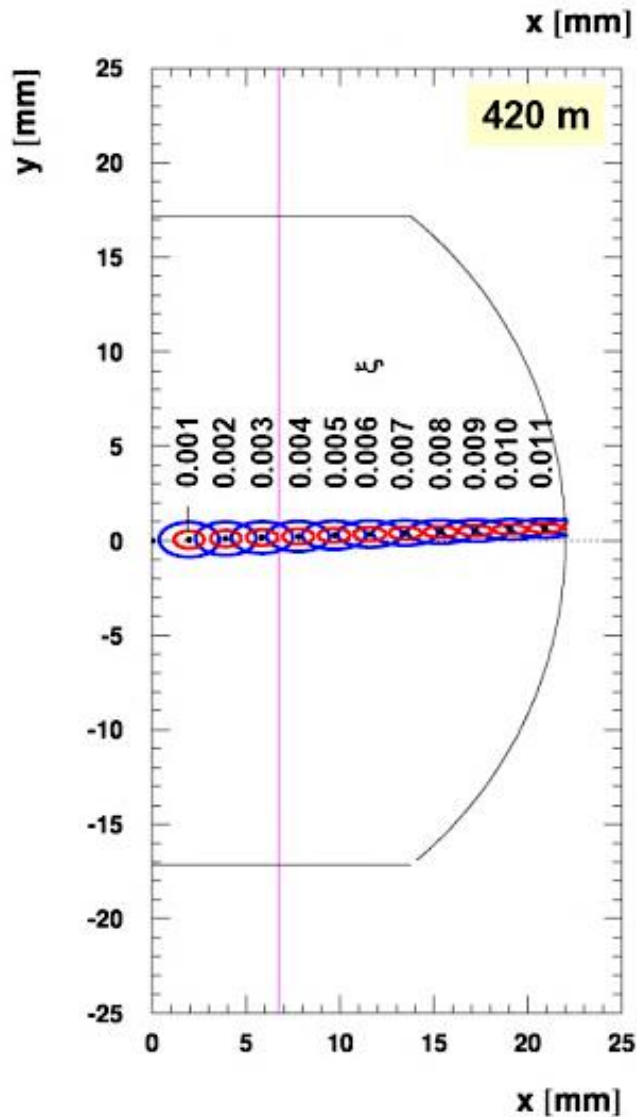
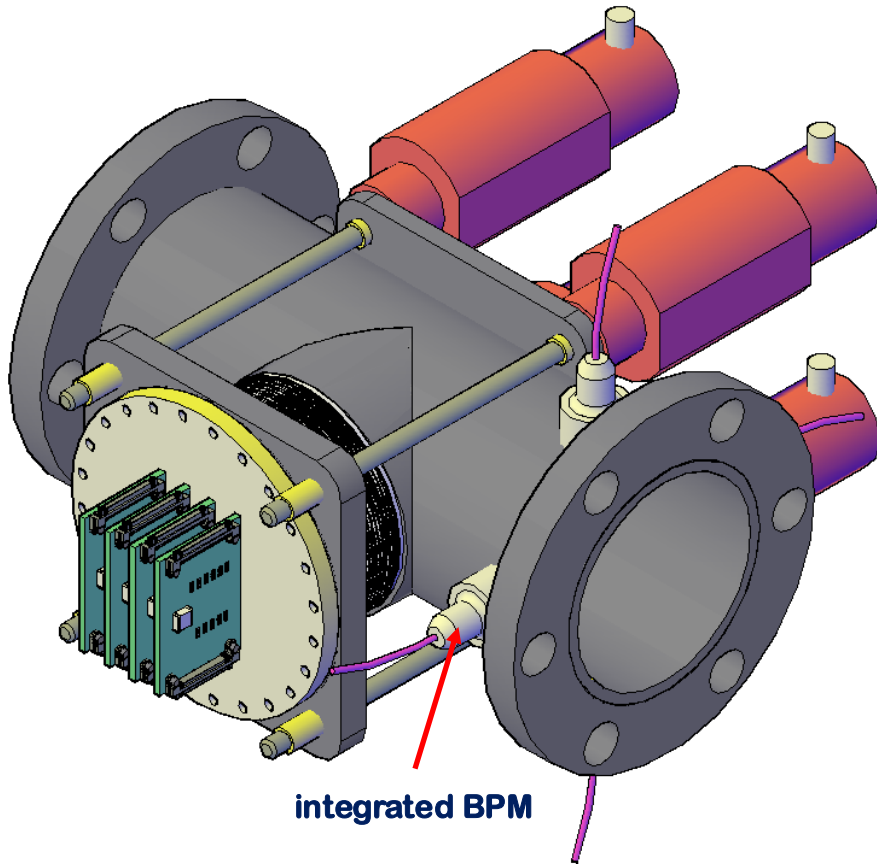


Figure 43: Mapping of the kinematic variables (ξ, θ^*) on the detector planes in the four locations for vertical crossing and $\alpha/2 = 250 \mu\text{rad}$. Several discrete values of ξ are shown. The black points are for $\theta = 0$. The red and blue ellipses are for $\theta^* = 100$ and $200 \mu\text{rad}$, respectively, with varying azimuth. Only points within aperture acceptance are shown. TCL and detector position settings

Figure 45: Hit maps for single diffractive events accumulated for an integrated luminosity of 1 fb^{-1} . The colour scale represents the fluence $\Phi [\text{p}/\text{cm}^2]$ calculated using the transformation integral (29). The violet vertical lines mark the positions of the detector edges near the beam in regular physics runs; the sensitive areas lie to their right. The black outer lines represent the shapes of the beamlines at the detector stations.

Possible Roman Pot concept for 420 m

**“Warm” module as present PPS XRPs,
compact element of LHC Beam Pipe.**



**...try to minimize the size of Roman
Pots as much as possible.**

This will make it possible to reduce:

- material budget > showers (in the 420m area there are no collimators);
- impedance > heating;
- electron clouds;

Precise positioning on the Beam;

Installation in the local limited space;

Simplify control and maintenance operations.

Integration inside TCLD, “cold” module

