CMS upgrade instrumentation activities

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Particle Physics Days 2024

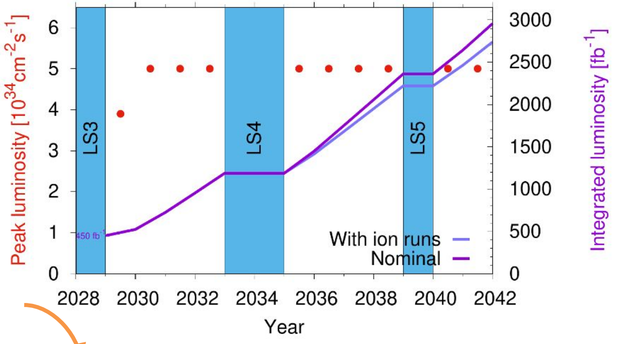
November 28, 2024

Motivation

Radiation damage

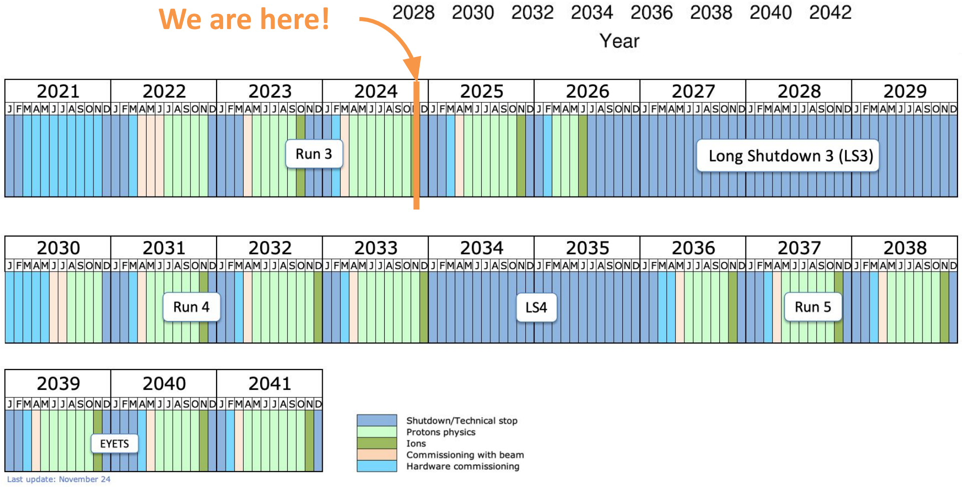
- High fluences take their toll on CMS detector parts.
- Efficiency of tracking gets worse over time.
- ⇒ Naturally, components need to be updated/upgraded over time.

High-Luminosity LHC



In the hope to answer the unknowns LHC will undergo a significant upgrade:

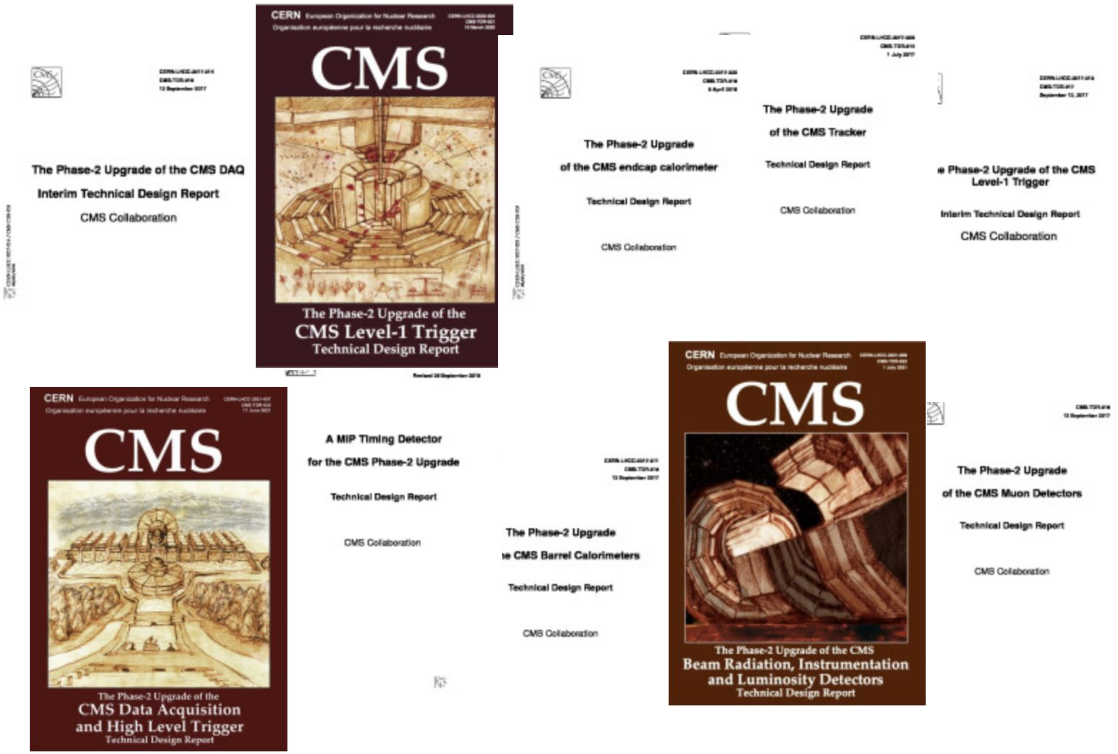
- Increase of beam intensity with instantaneous peak luminosity of up to $7 \times 10^{34} cm^{-2} s^{-1}$.
- Goal: 3000 fb^{-1} of integrated luminosity



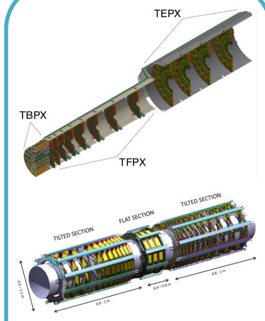
➩ Need detector with: radiation hardness, high resolution and granularity, excellent timing, better geometrical coverage, faster readout, etc.

Current CMS Phase-2 upgrades for HL-LHC

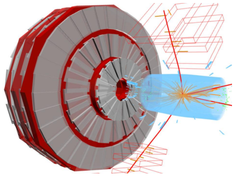
- Inner and outer tracking detector
- High-granularity calorimetry
- Muon detector
- MIP timing detector (MTD)
- Electronics upgrade for barrel calorimetry
- Level- 1 trigger system
- Data acquisition system and high level trigger
- Beam radiation, instrumentation and luminosity detectors (BRIL)
- Proton precision spectrometer



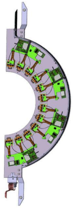
Overview of new detectors



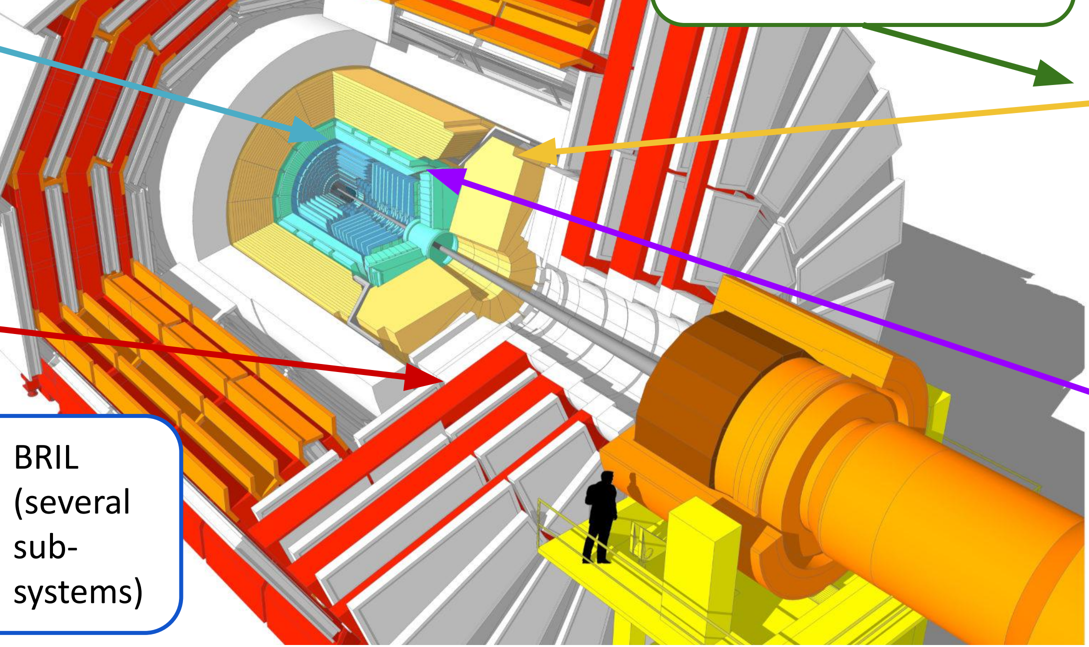
Inner and outer tracker

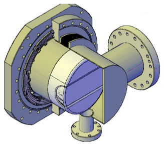


Muon detectors

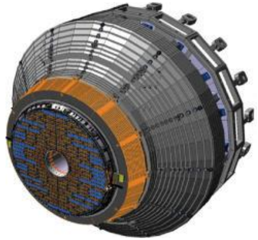


BRIL (several sub-systems)

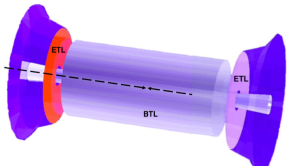




Proton precision spectrometer



High-granularity calorimetry



Minimum ionising particle timing detector

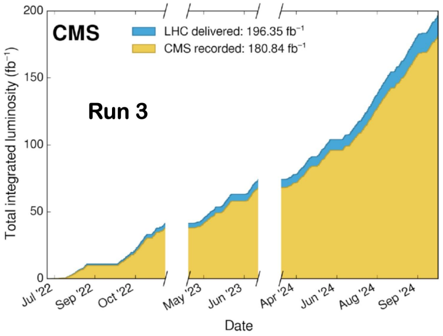
Finnish participation in upgrade activities

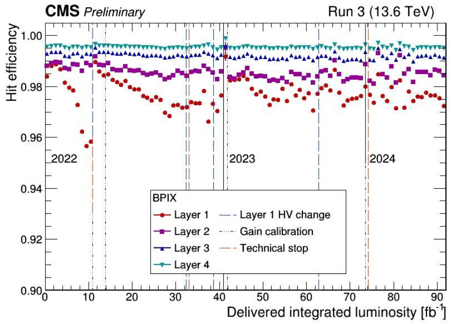
- Inner tracking detector construction and installation, i.e. TEPX module production and quality control (QC). (to be presented today)
- Outer tracker mechanics. (not presented today)
- Endcap timing layer (ETL) for the Minimum ionizing particle timing detector (MTD), i.e. LGAD sensor QC. (to be presented today)
- BRIL (Beam Radiation Instrumentation and Luminosity). (not presented today)
- Proton precision spectrometer (to be presented today)

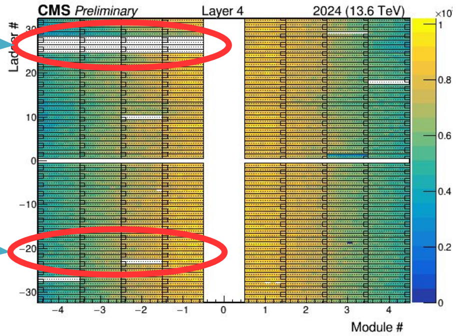
Current inner tracking detector status

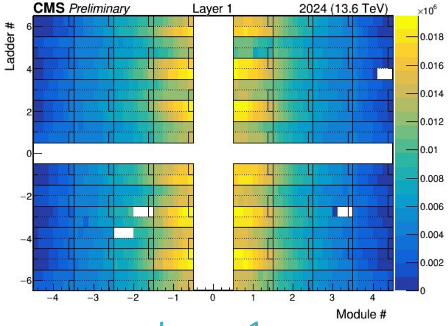
General remarks

- Successful year with **123 fb^{-1}** of pp collisions
- Pixel detector performs generally well in 2024
- Currently 3.2% ROCs masked
- Bottleneck in low voltage power supply system (relevant for run 3 extension until June’26).
- Some issues:
  - Since June’23 BPix Sec7 Lay3&4 lost.
  - Earlier this year: automasking failed on BPix Sec5 Lay4. Seems “flaky” sector.
- Fraction of active modules 96.1 %.
- Considering radiation damage only, detector will perform fine until end of Run 3.









Layer 1 mostly fine

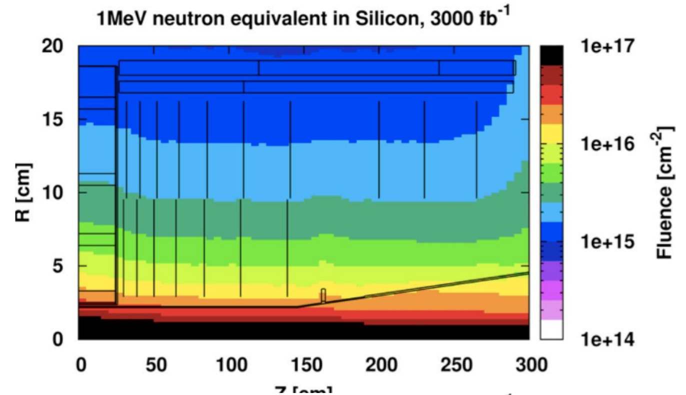
Tracking detector upgrade for HL-LHC

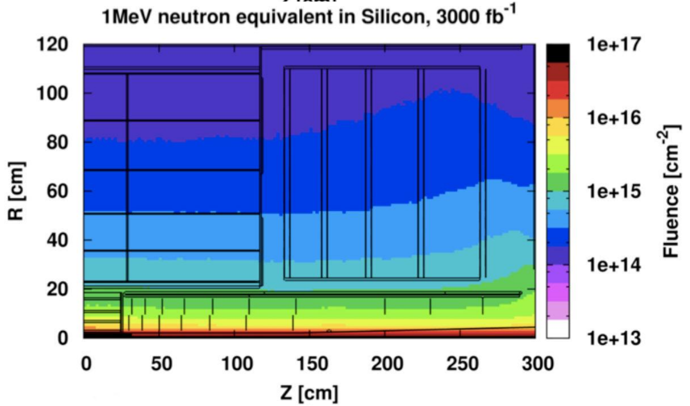
High luminosity LHC

- Pile-up increases substantially with around 200 collisions per bunch crossing at start of a store.
- Integrated luminosity approximately 3000 fb^{-1}
- High dose of about 10 MSv (1Grad), fluences of about $2x10^{16}neq/cm^2$ ⇨ leading to radiation damage.

Tracker requirements

- High granularity to reduce occupancy
- Reduction of material budget to improve tracking performance
- Radiation hardness

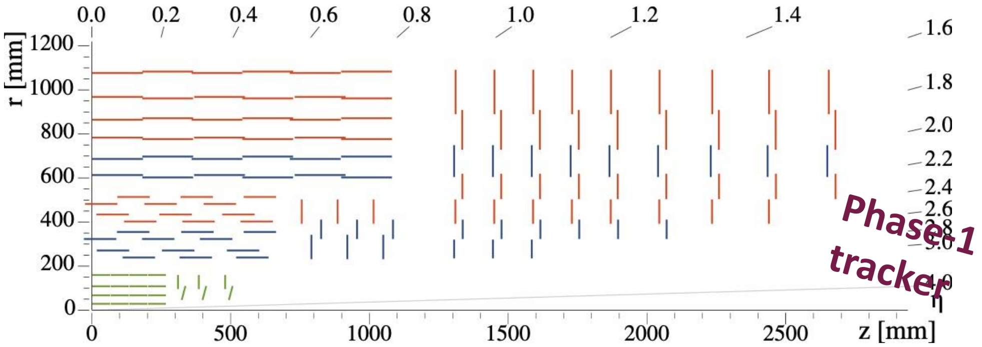


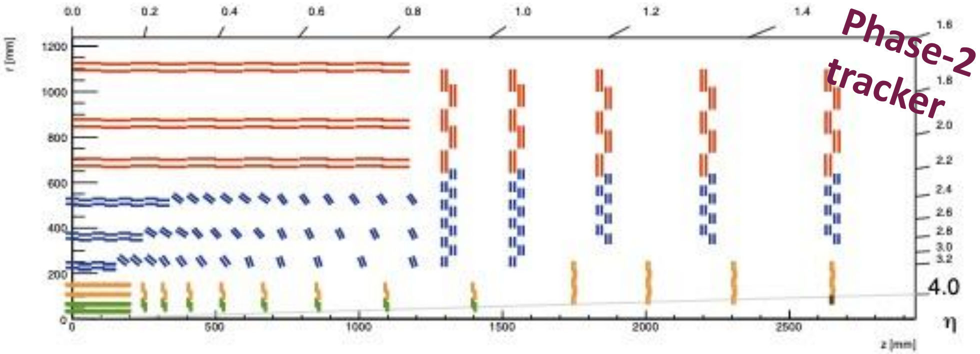


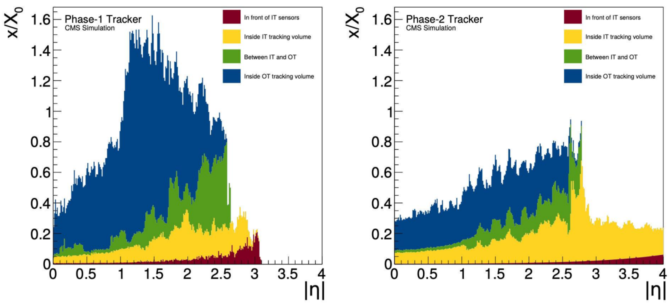
Tracking detector upgrade for HL-LHC

Evolution from Phase-1 to Phase-2 tracker

- Better coverage up to rapidity of 4.0.
- More and smaller pixels (higher granularity, reduce occupancy).
- Less material budget.
- Better radiation hardness.
- Inclined outer tracker modules / planes.





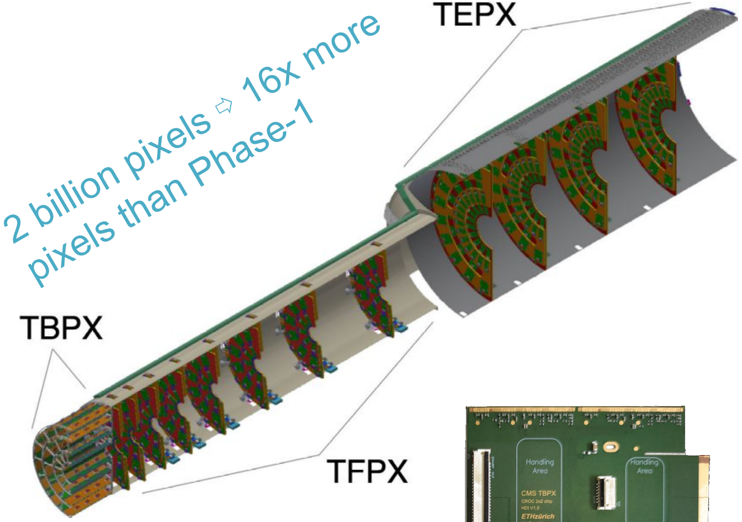


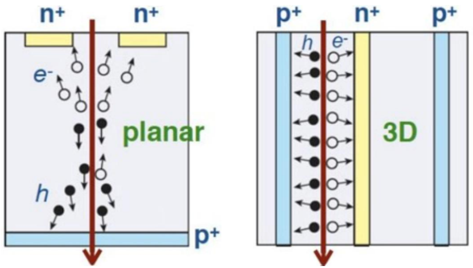
Inner tracking detector upgrade

Main design aspects

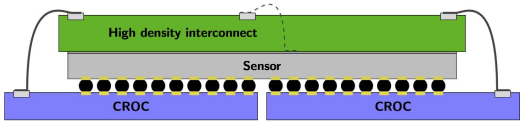
- Hybrid pixel detector modules using new CROC ASIC (derived from RD53 chip, 65nm technology, 50x50 μm^2).
- Smaller pixels for less occupancy (25x100 μm^2).
- Thin (150μm) planar n-in-p Si sensors baseline.
- Radiation hard 3D Si sensors for innermost layer.

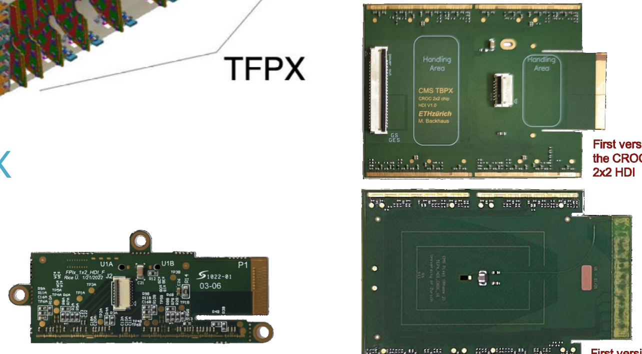
2 billion pixels ⇨ 16x more pixels than Phase-1





Cross section drawing of TEPX module




First version of the CROC TFPX 1x2 HDI

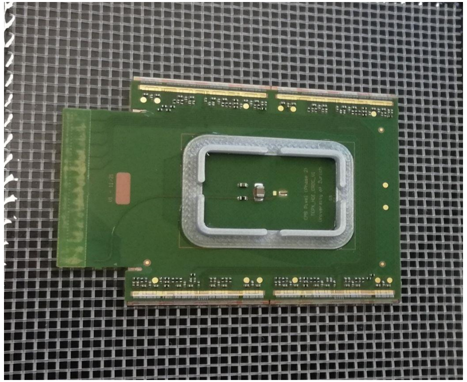
First version of the CROC TBPX 2x2 HDI

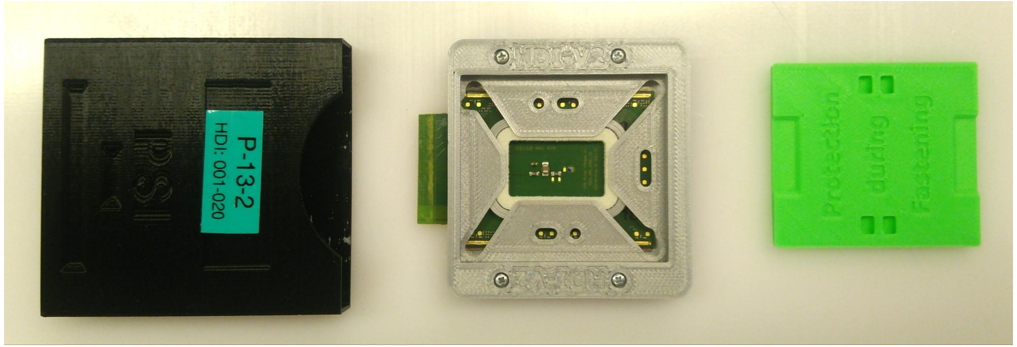
First version of the CROC TEPX HDI

Inner tracking detector upgrade

Finnish contributions

- Building, testing and calibrating at least 250 TEPX modules (collaboration with Rudjer Boskovic Institute (RBI), University of Zurich and Paul Scherrer Institute (PSI)).
- Build-up of quality control and module production centres in Helsinki (HIP) and at CERN.
- CERN center stays as auxiliary and backup center for module production in PSI and HIP (main users: RBI and University of Zurich).
- During this autumn: producing and testing first full pre-production modules.
- Contributions to the mechanical design of the Outer Tracker: MSc students at CERN testing and optimising pressure cycling rig for CO_2 cooling of outer tracker



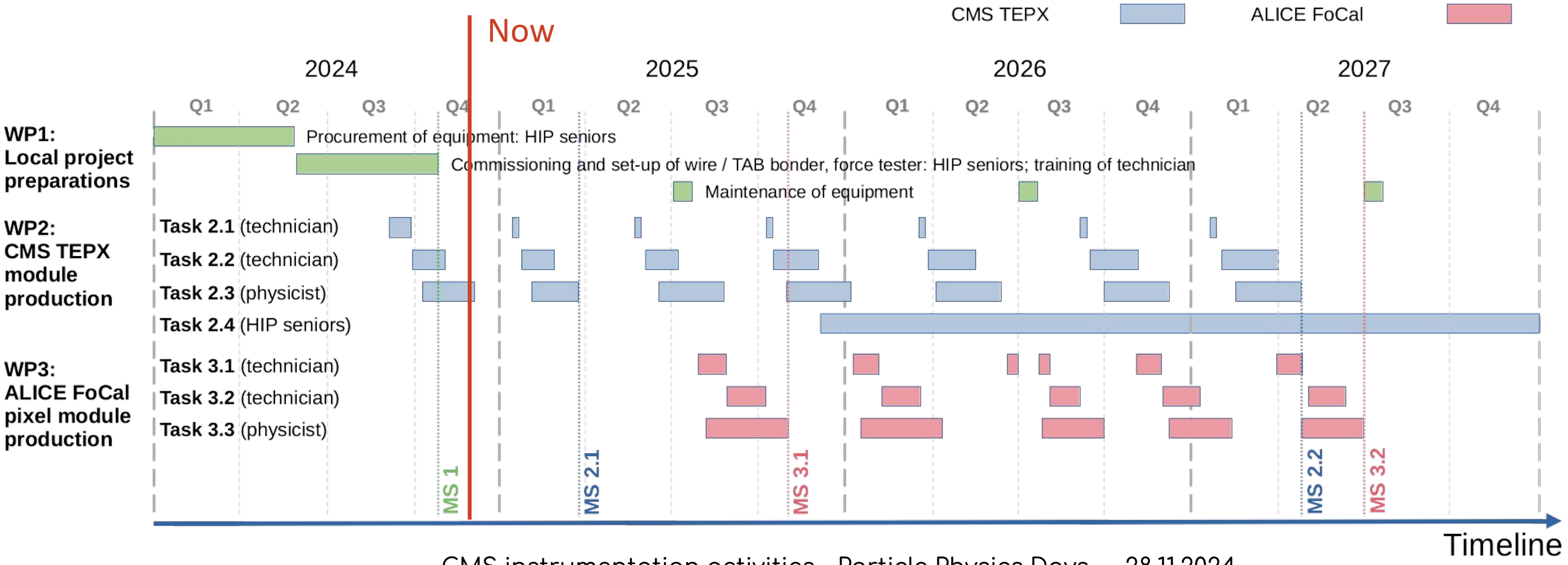


TEPX module production centre at HIP

Production in Helsinki

Improving the Finnish instrumentation infrastructure and providing opportunities for the PhD, MSc and BSc students to participate in or follow CMS and ALICE module production.

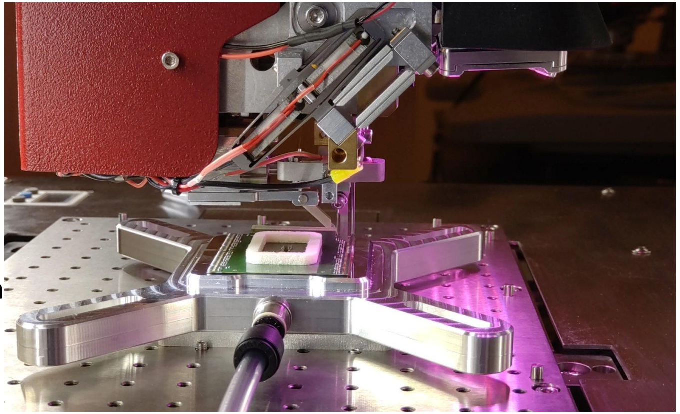
- Funded by Finnish Infrastructure funds from Research Council of Finland for 2024 to 2027.

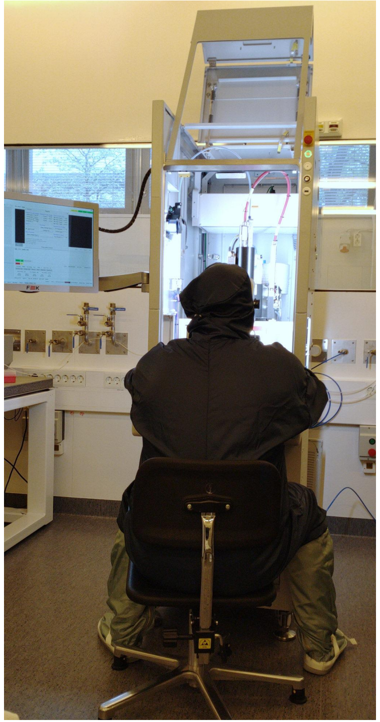


TEPX module production centre at HIP

Wirebonding

- Automatic wire bonder delivery, installed and commissioned last September.
- Bonding scheme challenging:
  - close to 800 wire bonds per module
  - 2^{16} different flavors of modules due to individual 4 bit IREF values of each CROC. Working on solution for dynamic programming to speed up wire bonding.
- Currently studying bond strength with destructive pull test (up to 24 test bonds per module).
  - Typical bond pull strength 8 - 12 g; min pull strength 5 g.
  - Depends on bonding parameters, pad material and quality as well as on bonding wire.

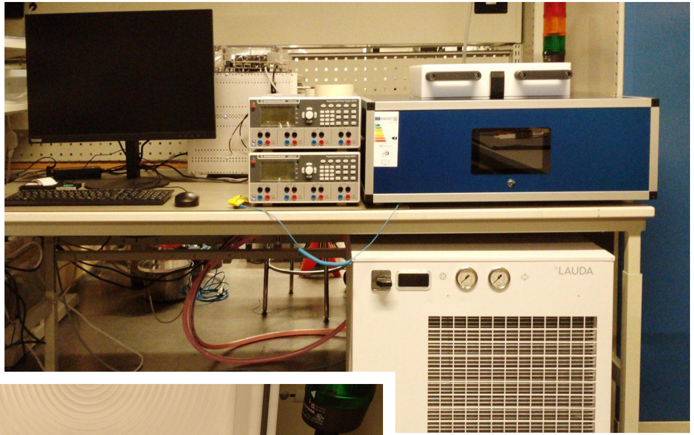


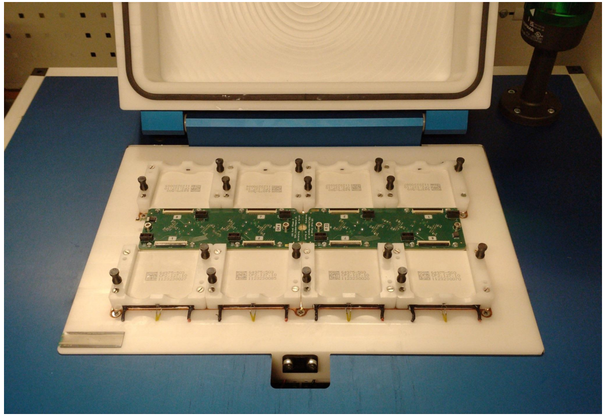


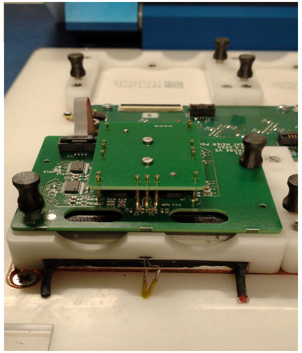
TEPX module production centre at HIP

Electrical testing

- So called Cold box for testing TEPX modules is fully assembled.
- Currently commissioning ongoing.
- Can test up to 8 TEPX modules in parallel
- QC tests:
  - Voltage-current characteristic,
  - pixel alive,
  - noise,
  - thermal cycling,
  - burn in from -40 to 40° C,
  - and many more.

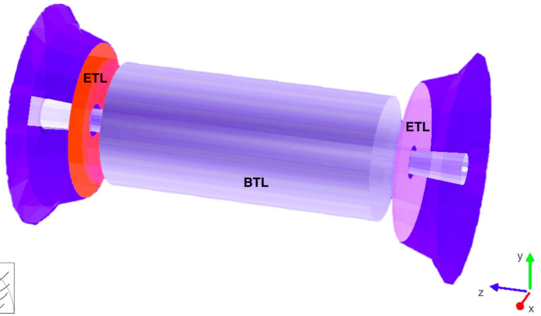






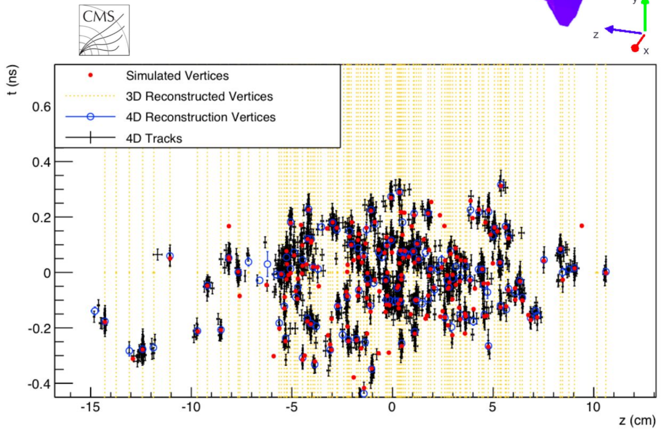
Minimum ionising particle Timing Detector

- In HL-LHC we aim for luminosities of 5 x 10^{34} $cm^{-2}s^{-1}$. We expect huge pile-up, up to 200 interactions per bunch crossing.
- For better tracking performance CMS follows 4D tracking idea by introducing a thin timing detector between tracker and calorimetry.
- Timing detector aims for 30ps resolution.
- Coverage up to $|\eta| < 3.0$.



Barrel Timing Layer (BTL)

- Lutetium-Yttrium Oxyorthosilicate (LYSO) scintillator on Silicon Photomultiplier (SiPM).
- About 37 m^2 surface area.



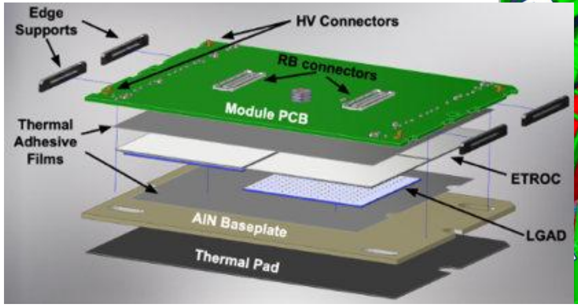
Endcap Timing Layer (ETL)

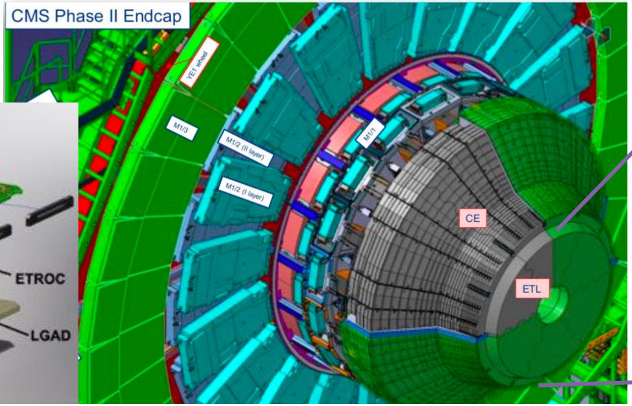
- Low Gain Avalanche Diodes (LGAD)
- About 12 m^2 surface area.

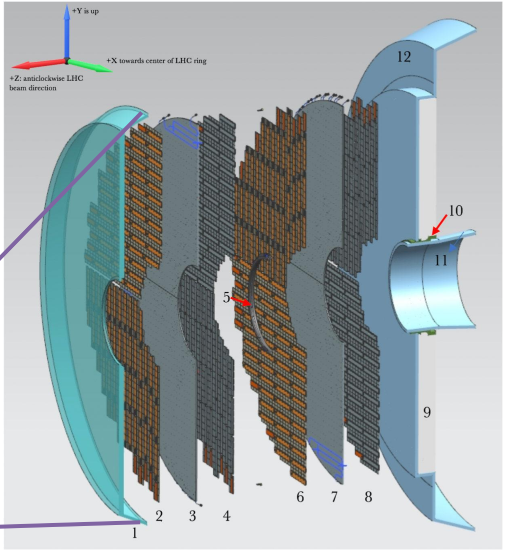
MTD Endcap Timing Layer

ETL

- Collaboration converged on using detector modules of Low Gain Avalanche Diode pads (LGAD).
- Technology can achieve about 30ps timing resolution (after fluence of 2×10^{15}neq/cm^2 better than 60ps).
- ETL consists of 2 double sided disks of LGAD modules.
- Directly mounted on CMS endcap nose.
- Readout via custom made ETROC ASIC







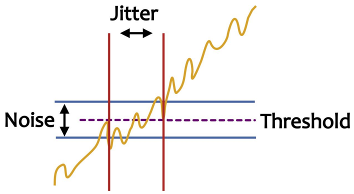
MTD Endcap Timing Layer

LGADs

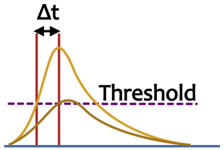
- Good timing resolution depends on several factors:

$$\sigma_t^2 \sim \sigma_{\rm jitter}^2 + \sigma_{\rm Landau}^2 + \sigma_{\rm distortion}^2$$

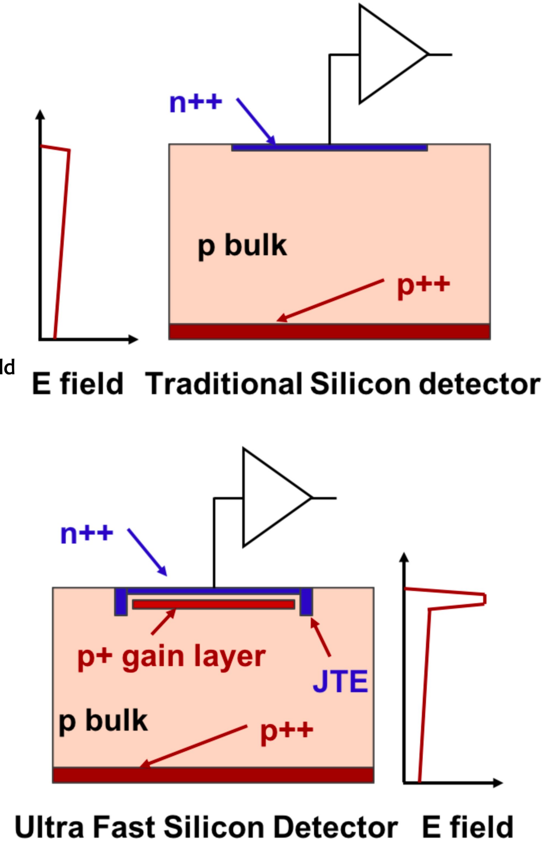
- Jitter due to electronic noise.
  - Trade-off between low bandwidth electronic and high slew rate of signal (large bandwidth).
  - Increasing S/N ratio:
    ➪ Good S/N ratio due to highly doped layer (p+) close to n++ implant (high fields (~300 kV/cm), charge multiplication).



- Landau due to non-uniform ionisations. Thin sensor helps:
  ➪ Thin planar silicon diode detectors (50µm).
  - Time walk can be avoided by Constant Fraction Discrimination

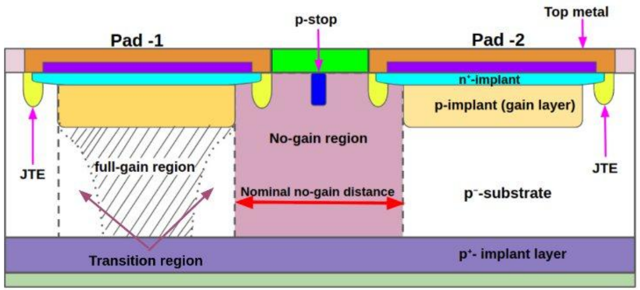


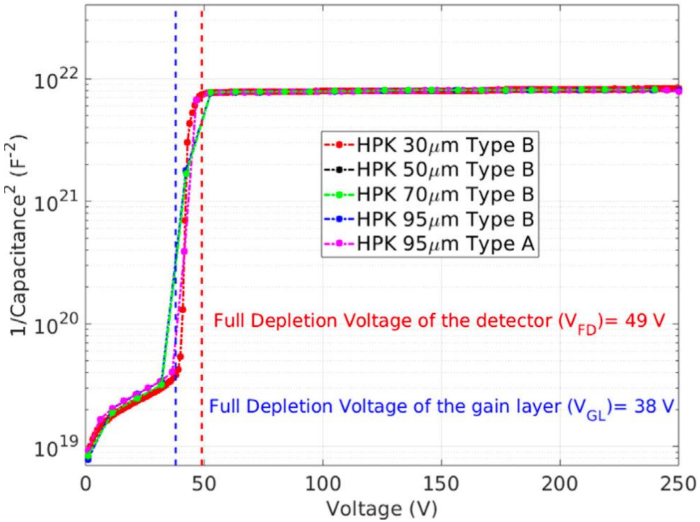
- ➪ LGADs with good S/N and thin and planar design allow for good timing resolution.



HIP contribution to MTD ETL

- Important contributions to characterisation of LGAD test structures in order to find final design for ETL.
- Studied in detail
  - General properties using standard probestation.
  - LGAD geometrical coverage (fill factor) using TCT (samples with varying interpad-gap values).
  - Radiation hardness (irradiated with 10 MeV protons at local facilities).
- Now QC center / ETL testing site for production:
  - Test structures: IV/CV, single pad gain bias curve, irradiation tests, etc.
  - Production LGADs: IV/CV on sample basis, all 256 pads of sensors.

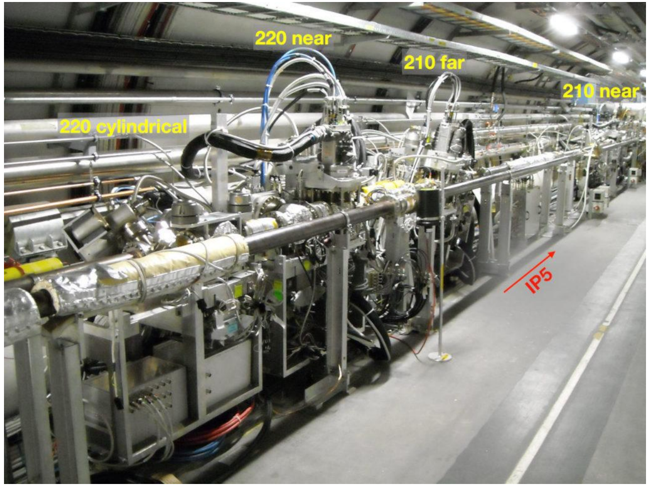


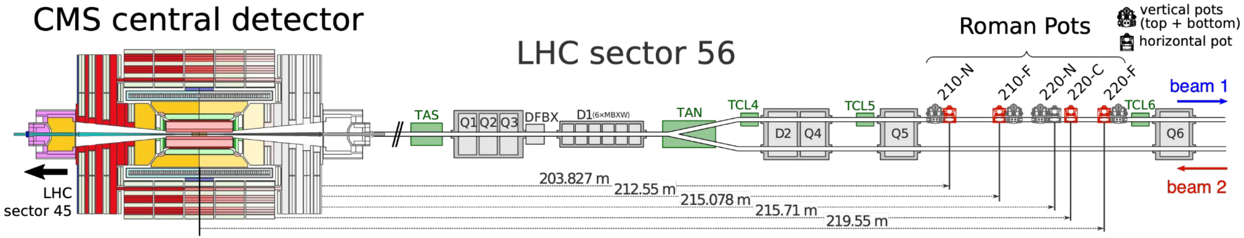


Precision Proton Spectrometer

The CMS Precision Proton Spectrometre (PPS), originally a joint CMS-TOTEM project, is designed to detect intact protons after interaction in LHC Run 2 and 3 under standard running conditions.

- Tracking and timing detectors located along the beam line at ±210-220 m from CMS interaction point.
- Detectors hosted in horizontal Roman pots, allowing sensor approach to the beam (in the LHC plane) down to a few mm.





Precision Proton Spectrometer for HL-LHC

Motivation

- Extension of PPS program for HL-LHC improves physics reach significantly.
- More integrated luminosity
  - Results from Run 2 and 3 limited by statistical uncertainties.
- Broader mass acceptance for central exclusive processes
  - Current acceptance in range of approximately 350 GeV to 2 TeV (detecting both protons).
  - In HL-LHC configuration, upper limit up to about 4 TeV (with horizontal beam crossing), lower limit down to about 200 GeV (with vertical beam crossing).
- Expression of interest submitted in 2021
  - Proposal rescoped to re-use existing Roman pot mechanics and to consider only “warm” locations (“cold” location at 420 m much more technically challenging)
- Proposal approved by CERN Research Board in September 2023.
  - PPS2 included in HL-LHC baseline; design of detector vessels and units started.
  - ECR for mechanical implementation under iteration with LHC machine groups.

PPS2 physics reach for low mass

- Several standard model processes can be probed, mainly in γγ, to measure couplings and check theory predictions

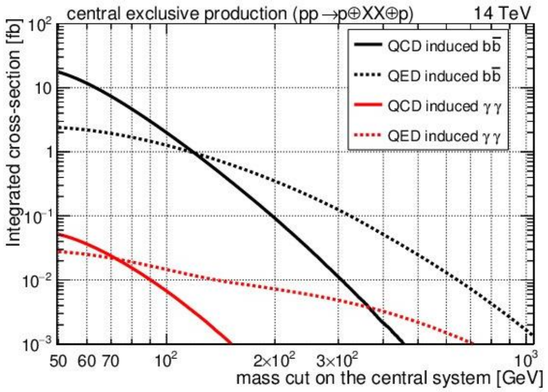
SM cross sections for CEP processes

Process	Fiducial cross section [fb] 2 tags	1 tag
jj	2	219
bb	0.04	6.3
W^+W^-	15	152
$\mu\mu$	1.3	172
tt	0.1	0.65
H	0	0.23
HW^+W^-	0.01	0.06
ZZ	0.03	0.23
$Z\gamma$	0.02	0.15
$\gamma\gamma$	0.003	0.19

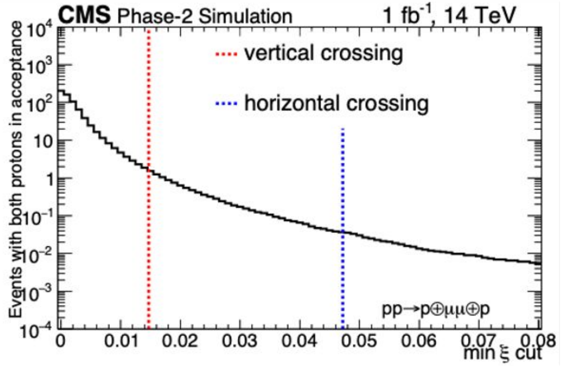
$pp \to p\, b\, \bar{b}\, p$

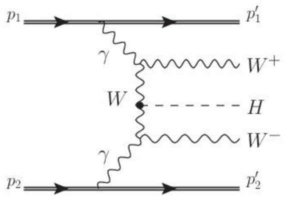
$pp \to p\, \gamma\gamma\, p$

QCD and QED contributions

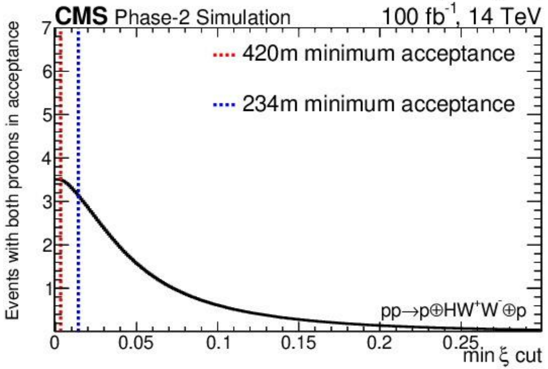


$pp \to p\, \mu^+\mu^- p$





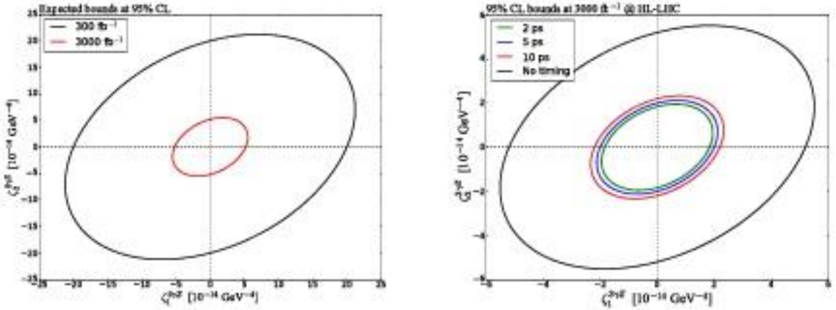
Decay-mode-inclusive using missing mass technique



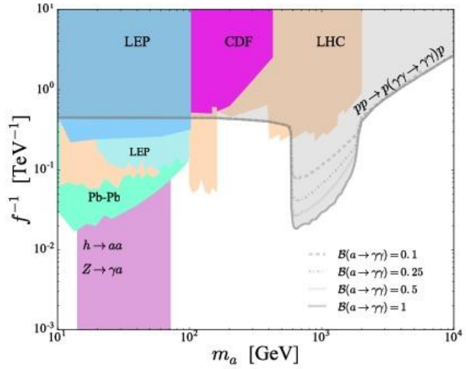
PPS2 physics reach for high mass

- Tagged protons may be a powerful tool in studying various BSM scenarios where new particles are produced in γγ interactions

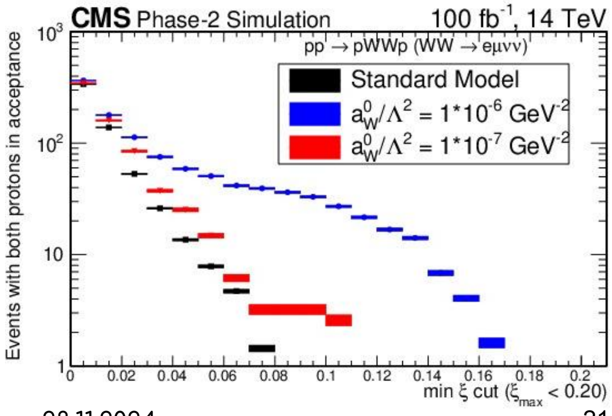
AQGC in
pp ⟶ p γ Z p

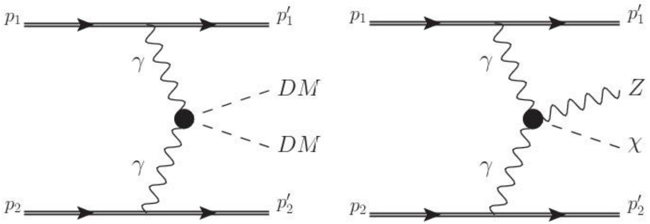


ALP search in
pp ⟶ p X p, X⟶γγ



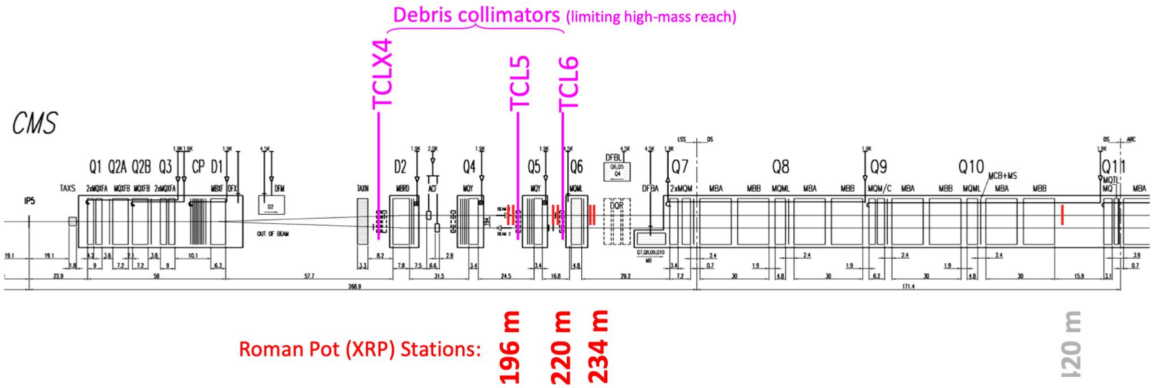
AQGC in
pp ⟶ p W⁺W⁻ p





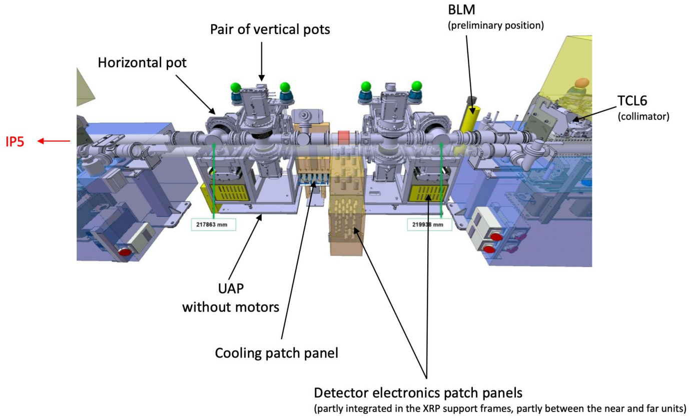
DM searches with missing mass technique

PPS2 detector locations

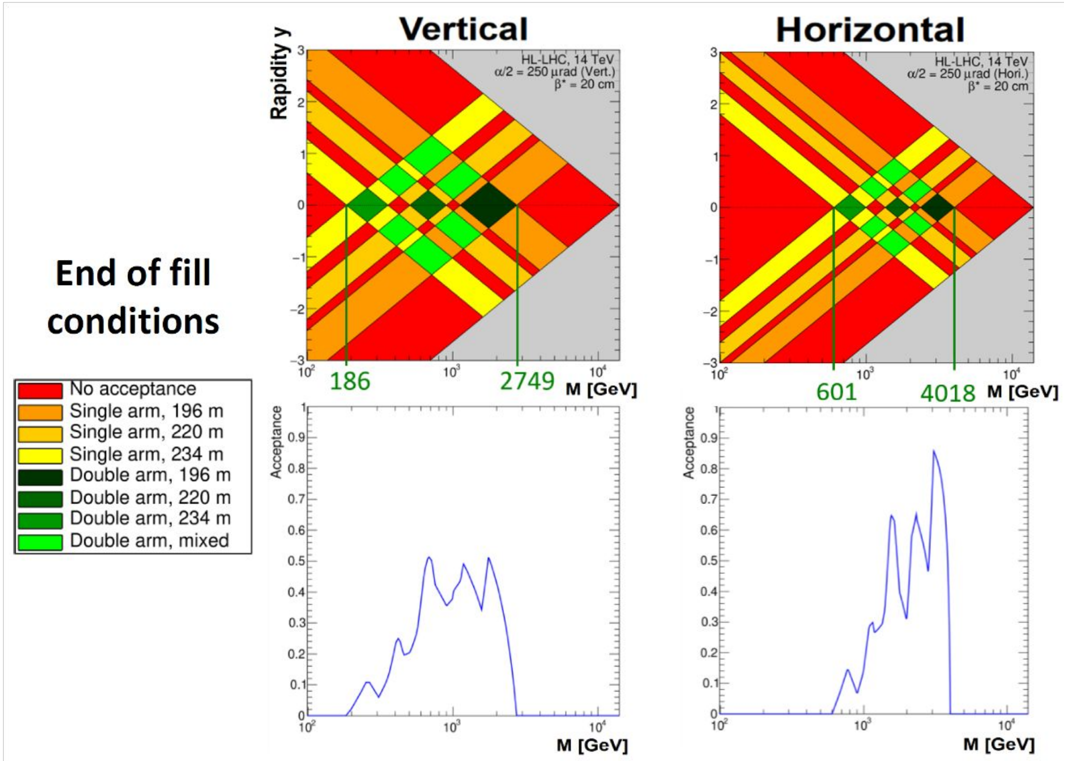


Three locations selected per side, with available space, in the LHC straight section:

- In each location, two horizontal Roman pots.
- At 220 m, two additional pairs (top-bottom) of vertical Roman pots, for detector alignment.

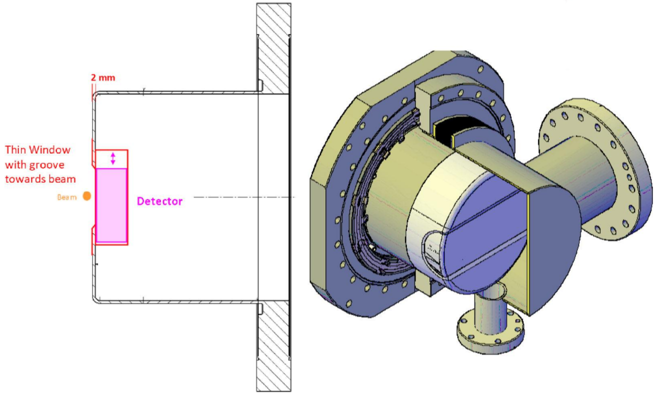


PPS2 detector acceptance

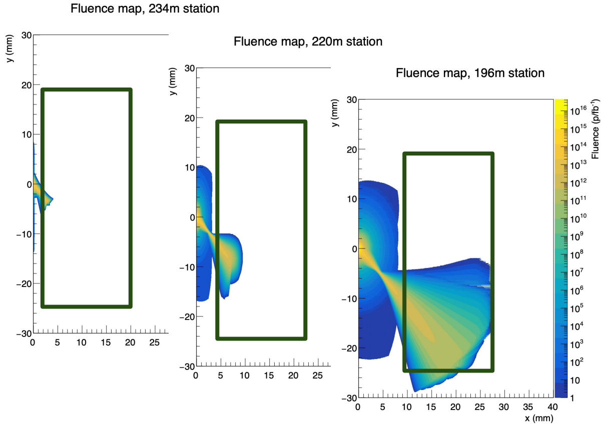


- Two different beam crossing schemes in the IP foreseen during LHC operations.
  ⇨ different proton acceptance in the two cases
- Double proton tag can use different stations on the two sides
- Larger combined acceptance for central mass compared to current setup

PPS2 detector packages



- Each Roman pot will host both tracking and timing detectors (or 4D detectors).
- New design for detecting vessels:
  - Cylindrical housing, maximizing available space.
  - Larger thin window.



- Most services in common between tracking and timing:
  - vacuum (~10 mb), cooling (~–30° C);
  - common readout "motherboard."
- Proton fluence highly non-uniform over detector area
  - ⇨ internal vertical shift system necessary to distribute radiation damage.

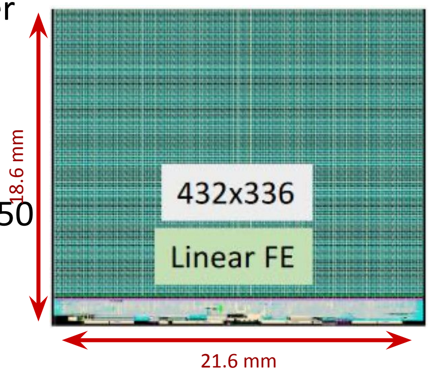
PPS2 detector technologies

Baseline design exploiting detectors being developed for CMS Phase 2

- Similar position and timing resolution required;
- Similar radiation doses expected, although much less uniformly distributed;
- Smaller occupancy w. r. t. hottest regions in CMS;
- Same readout chain and integration in DAQ.

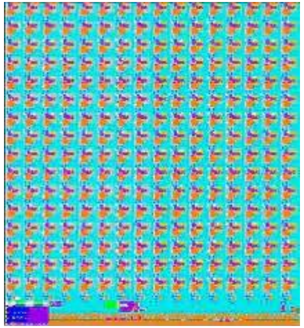
Tracking

- Based on Inner Tracker design
- 6 planes of 3D silicon pixels
- Front-end: CROC (50x50 μm^2 pixels)
- 2 or 3 chipoc/module



Timing

- Based on Endcap Timing Layer design
- 5 double-layer planes of LGADs
- Front-end: ETROC (1.3x1.3 mm^2 pads)
- 2 or 3 chipoc/module

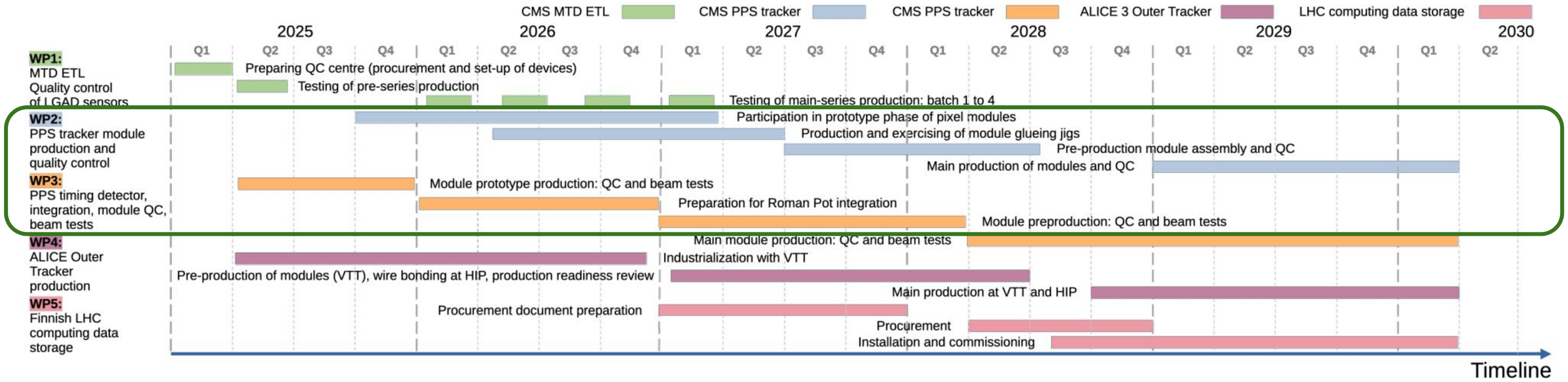


PPS2 activities in Helsinki

Readout and sensors are the same or similar as for the inner pixel tracker and the MTD ETL:

⟹ Large synergies with the work done for the inner tracker and the MTD in Helsinki.

- Funding request of HIP PPS2 part included in HL-LHC roadmap application to RCF.
- PPS2 pixel tracking detectors: model assembly and extensive QC:
  - Plan: assembly and QC test of about 110 modules at HIP (about 50% of required modules).
- PPS2 LGAD timing detectors: module QC tests in HIP laboratory and at test beams, module integration to Roman pots and installation of detector packages in LHC tunnel in spring 2030.



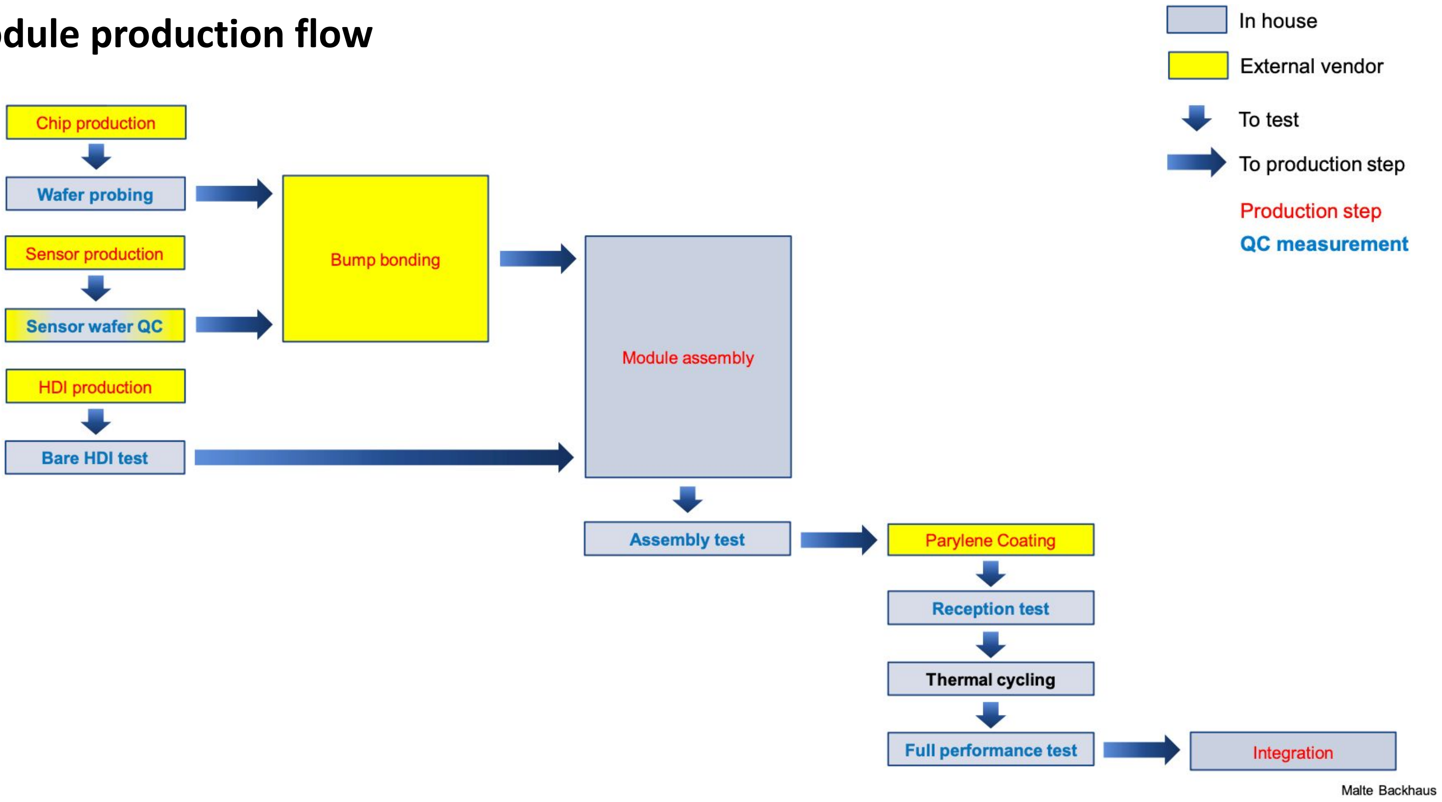
Summary

- Introduced CMS hardware activities for HL-LHC
    - Highlighting of Finnish contributions
    - ⇨ Plenty of hardware activities for CMS in HIP during the next years.
- Almost ready for ramping up TEPX production in January 2025.
- Hoping for successful FIRI roadmap application to build-up QC of LGADs for the start in spring 2025.
- Very likely to have seemingless transition to PPS2 module production starting with pre-production in 2027.

Backup

Inner tracking detector upgrade

TEPX Module production flow



Inner tracking detector upgrade

Quality Control of pixel module production