1862
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Institute of Particle Physics and
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VPP-IZM-CERN-2022/1-0001

Status of the MIP Timing Detector (MTD) project for the CMS Phase-2 upgrade

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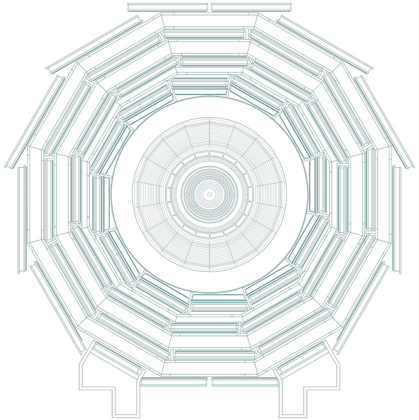
CERN Baltic Conference 23

Riga, Latvia
10.10.2023



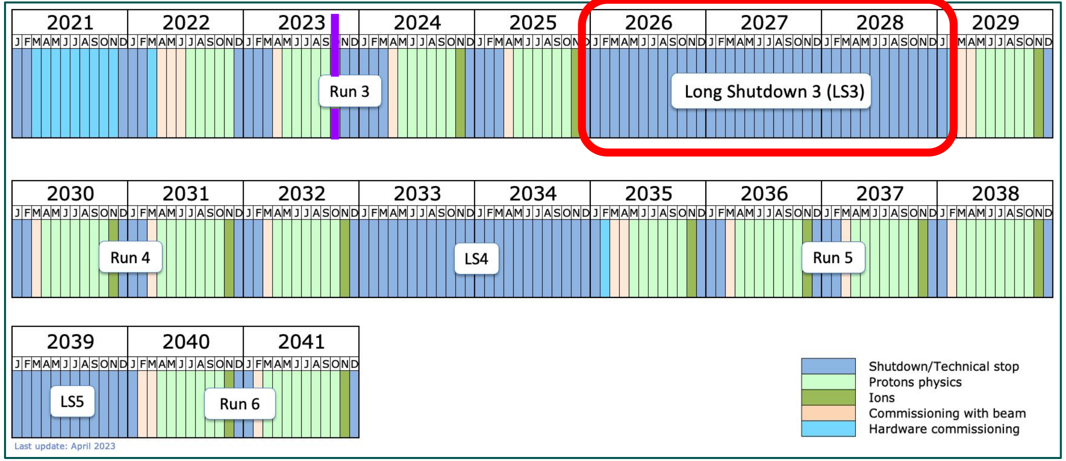
Outline

In today’s talk I plan to :

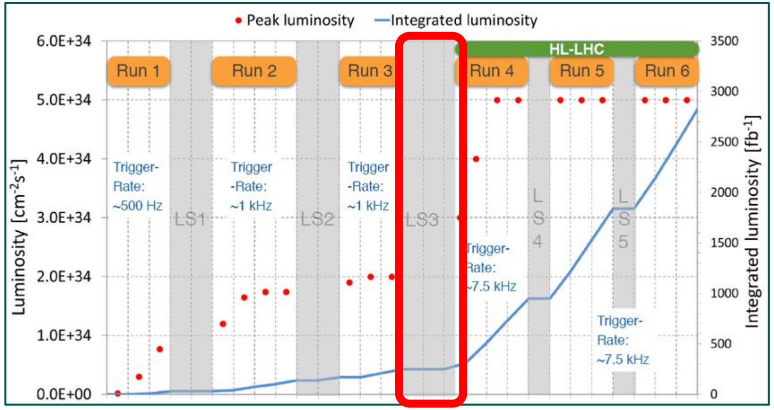
- Briefly introduce the Phase-2 upgrade and the necessity for a new sub-system at CMS;
- Introduce in detail the MIP Timing Detector (MTD);
  - End-cap Timing Layer;
  - Barrel Timing Layer;
- Discuss the current status of the project;
- Outline the next steps towards the integration & operation of MTD.

HL-LHC upgrade

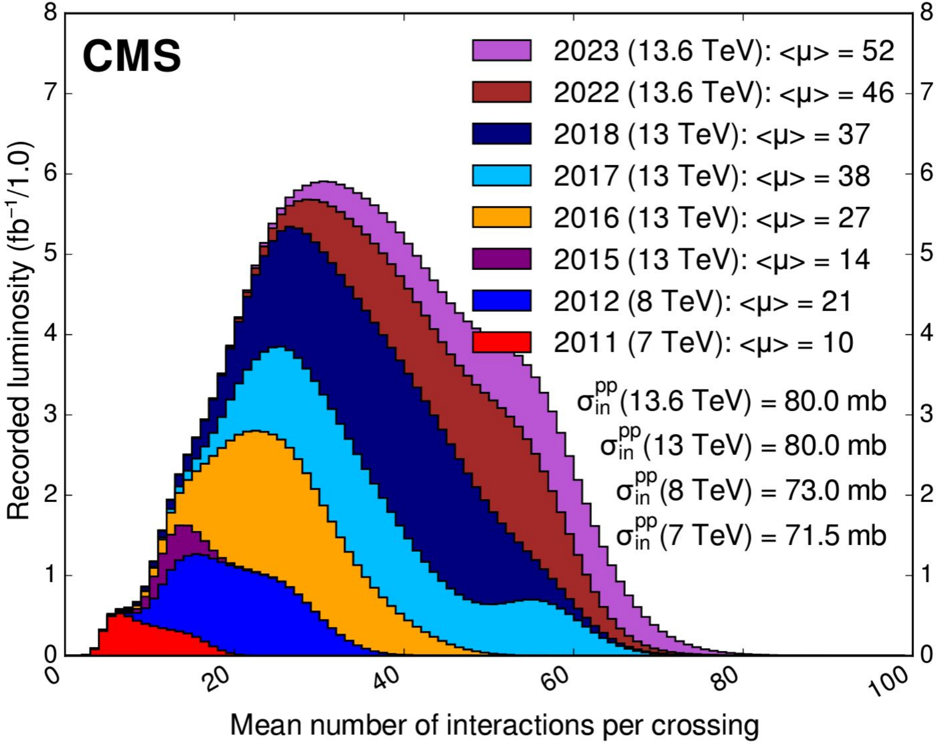
- The Large Hadron Collider (LHC) is **currently** two years into the Run 3 data taking period;
- Following this, during the **Long Shutdown 3 (LS3)**, scheduled for 2026-2028, the LHC will undergo a major upgrade known as the High-Luminosity (HL-LHC) upgrade;
- The aim of this upgrade is to increase the amount of physics data that LHC can deliver to its experiments;



- It is planned that the **HL-LHC** will be able to deliver **150-200 simultaneous proton-proton collisions (pile-up)** compared to the pile-up of ~60 during Run 3;
- In order to cope with the increased density of physics objects and maintain the current detector resolution, the ATLAS and CMS experiments will undergo and extensive upgrade programme known as the Phase-2 upgrade;



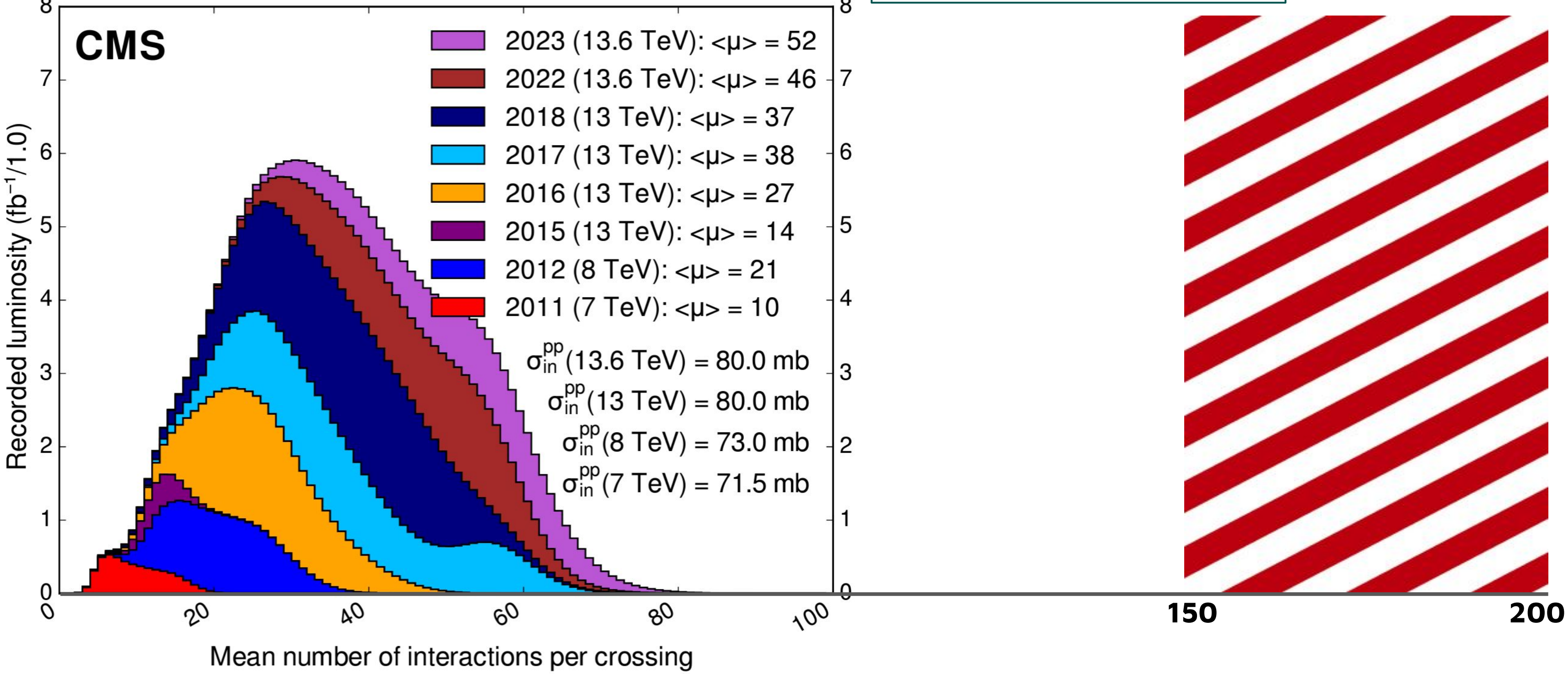
HL-LHC upgrade



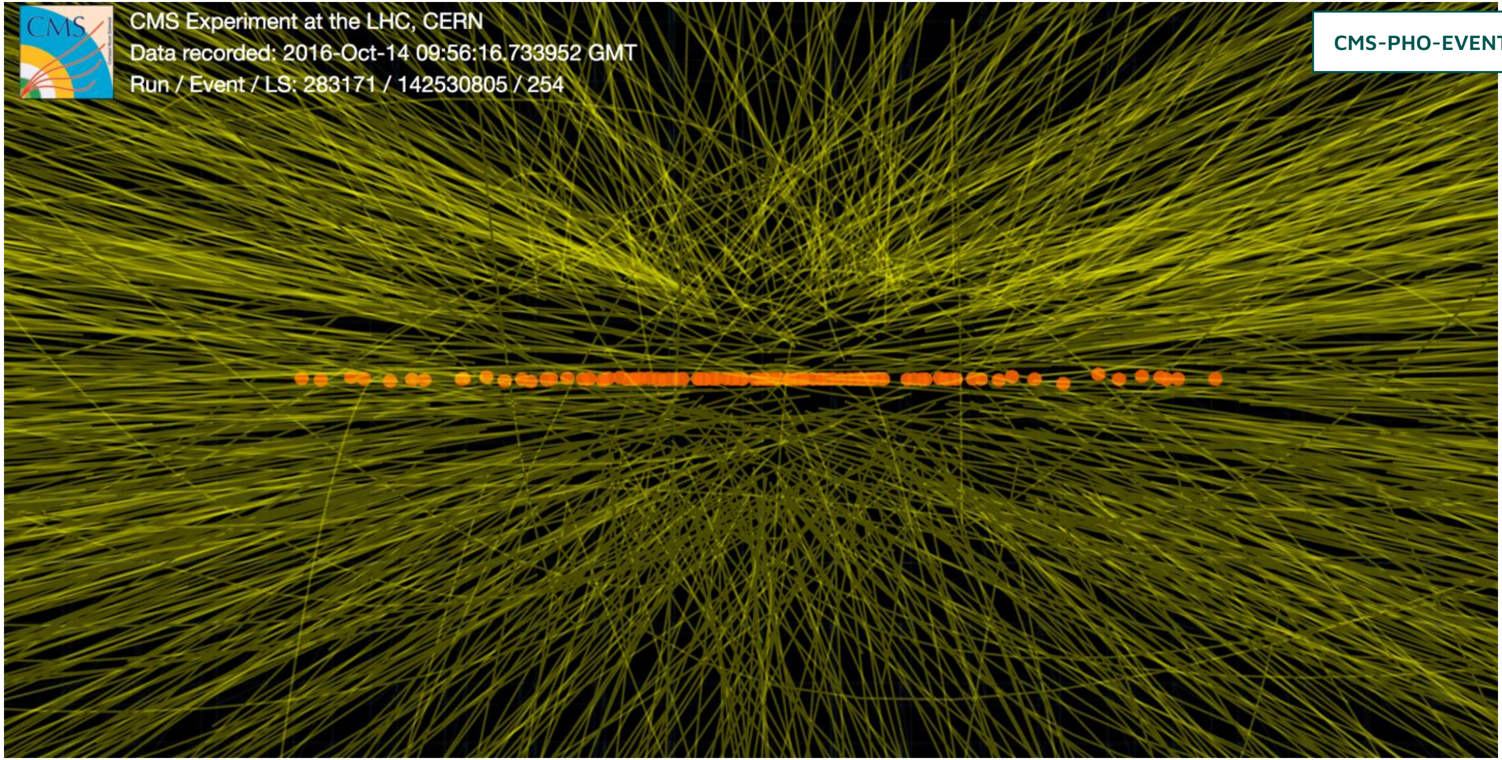
CMS Public Results

HL-LHC upgrade

CMS Public Results



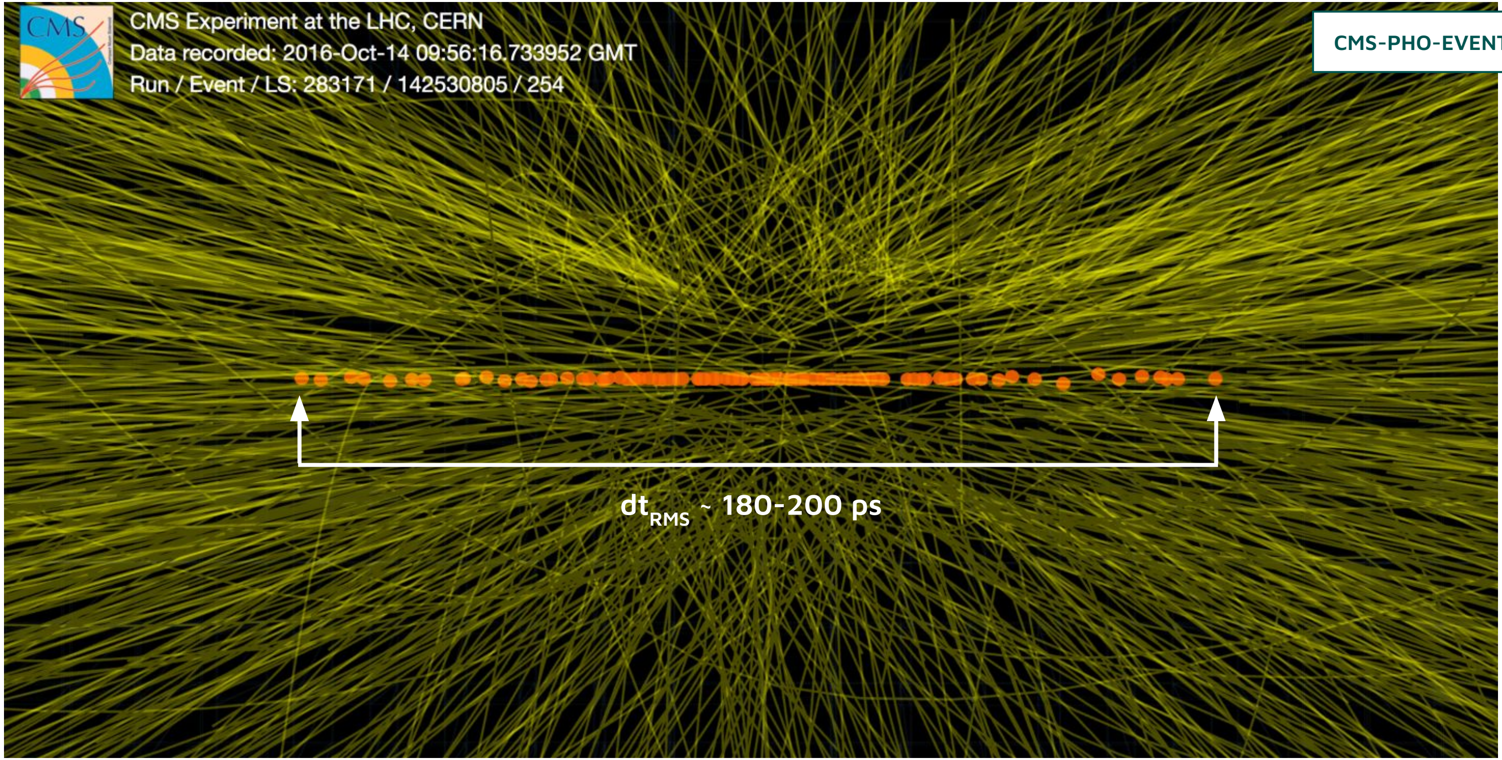
HL-LHC upgrade



CMS-PHO-EVENTS-2016-008

- Proton-proton collisions at CMS during a high pile-up run in 2016, containing around 100 primary vertices (PVs);
- HL-LHC will aim to have a pile-up ~2x greater;

HL-LHC upgrade



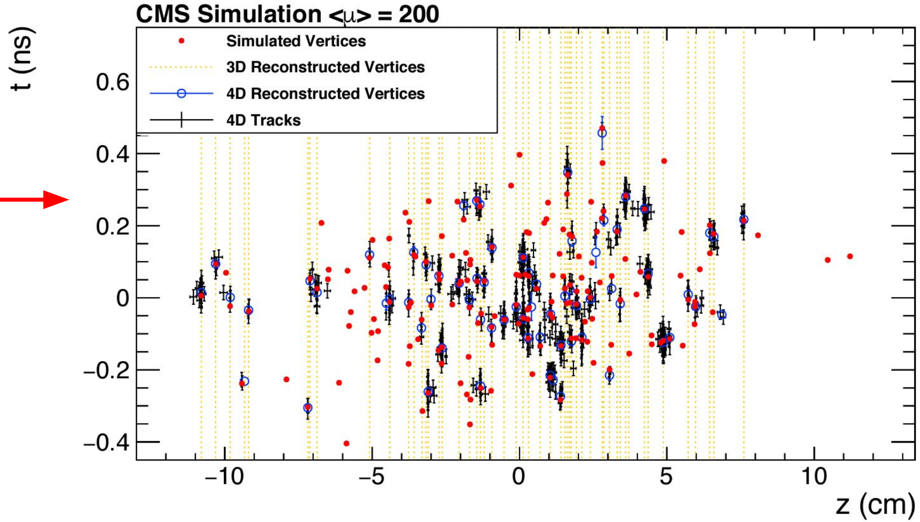
CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:56:16.733952 GMT
Run / Event / LS: 283171 / 142530805 / 254

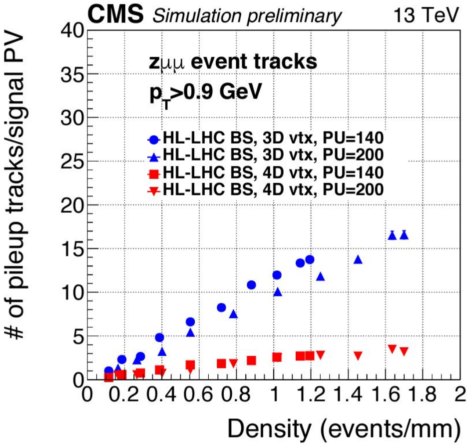
CMS-PHO-EVENTS-2016-008

- Proton-proton collisions at CMS during a high pile-up run in 2016, containing around 100 primary vertices (PVs);
- HL-LHC will aim to have a pile-up ~2x greater;
- **The PVs are distributed in time with the RMS of around 180-200 pico-seconds.**

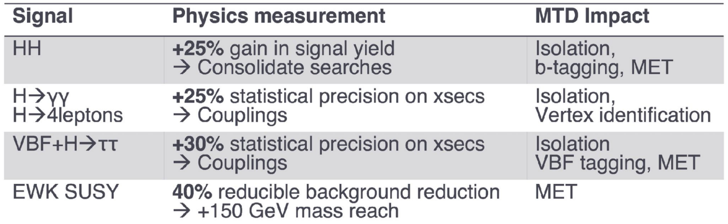
MIP Timing Detector - 4D vertexing

- Minimum Ionizing Particle (MIP) Timing Detector (MTD) will exploit this distribution in time (4D vertexting)!
- Vertices on the same dashed line unresolvable in 3D
- Significant improvement in track-vertex association & pile-up track rejection!





- Improvement expected in various physics analysis channels



Signal	Physics measurement	MTD Impact
HH	**+25%** gain in signal yield → Consolidate searches	Isolation, b-tagging, MET
H→γγ H→4leptons	**+25%** statistical precision on xsecs → Couplings	Isolation, Vertex identification
VBF+H→ττ	**+30%** statistical precision on xsecs → Couplings	Isolation VBF tagging, MET
EWK SUSY	**40%** reducible background reduction → +150 GeV mass reach	MET

- Real potential for implementation of Time-Of-Flight Particle IDentification (TOFPID) at CMS → potential positive impact for top quark and flavour physics!

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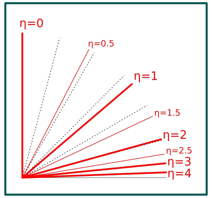
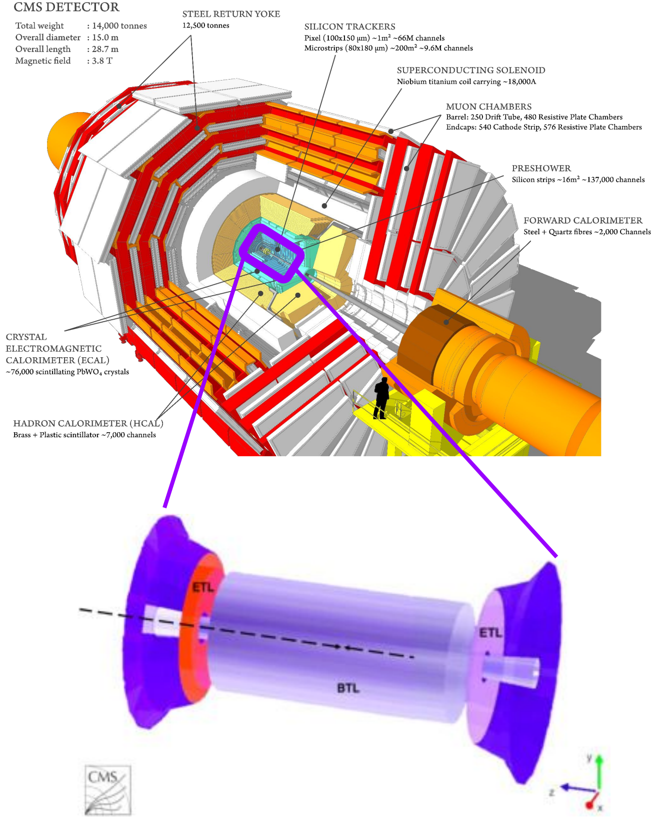
MIP Timing Detector - overview

- MTD aims to provide a track-time resolution of:
  - ~**35 ps** at the start of Run 4;
  - **<75 ps** by the end-of-life (end of Run 6).
- MTD consists of two main components:
  - End-cap Timing Layer (ETL):
    - covering pseudorapidity range: 1.6 < η < 3.0;
  - Barrel Timing Layer (BTL):
    - covering pseudorapidity range: |η| < 1.45;

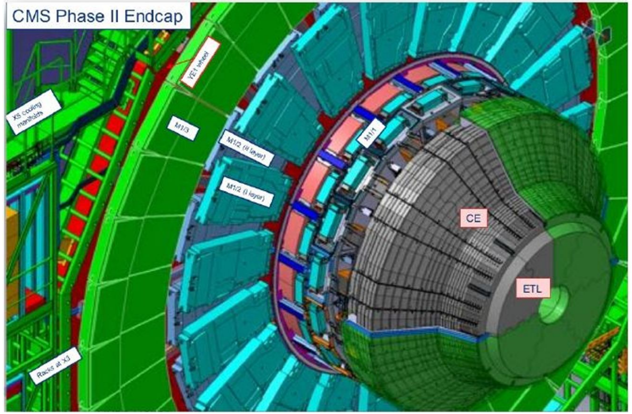


- MTD will be situated between the CMS silicon tracker and the first calorimeter layer in both the barrel and the endcaps;
- The two systems use different detector technologies due to vastly different radiation tolerance requirements;

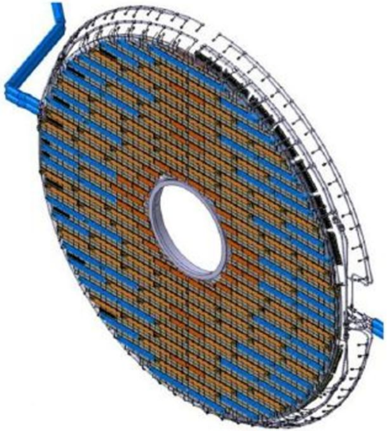


End-Cap Timing Layer: detector design

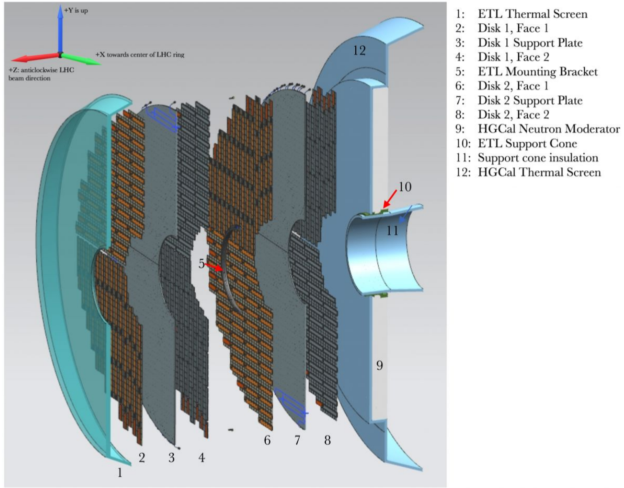
- ETL will cover the very *front* of both CMS endcaps;
- Placed in front of the ne High-Granularity Calorimeter (HGCal);
- ETL consists of two D-shaped halves, split in the vertical direction;
- Each ETL end is made of two 2-sided timing layers, providing full coverage for MIPs in $1.6 < \eta < 3.0$;
- Geometry chosen to ensure at least 2 hits per track;



Full ETL disk with services shown



ETL exploded view



End-Cap Timing Layer: detector design

- ETL will use Low-Gain Avalanche Detector/Diode (LGAD) technology:
  - Total active area ~14 m^2 (7 m^2 per endcap);
  - 16x16 LGAD arrays;
  - 1.3x1.3 mm^2 LGAD pad size;
  - 50μm thickness;
  - ~8.3 million channels;

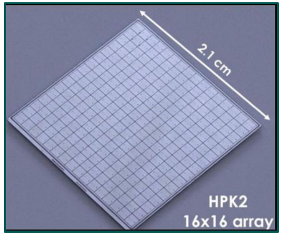
- LGADs are highly-radiation tolerant, ideal choice for forward detectors @ LHC;
  - Parts of ETL will experience a total fluence of **10^{15} n_{eq}/cm^2** by end-of-life (EOL);

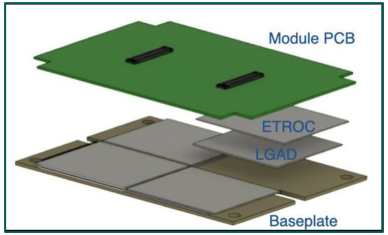
- LGADs bump-bonded to a custom readout ASIC (ETROC);

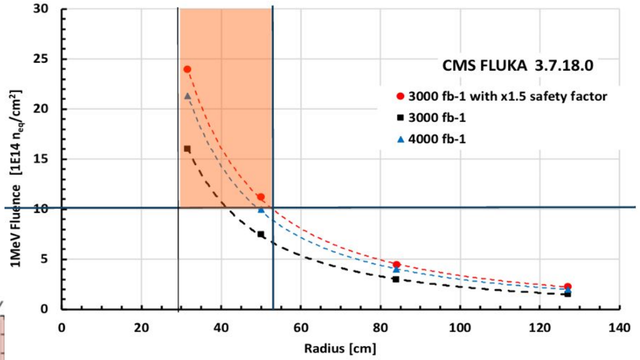
- Time-resolution:
  - Bare-sensor time resolution 30ps;
  - Target single-hit time resolution: 50 ps;
  - Target track-time resolution: 35 ps;

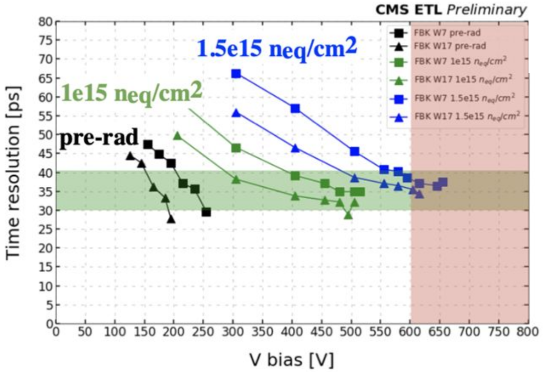
- Target performance recoverable until EOL within the safe operational bias window of ~11.5 V/μm;

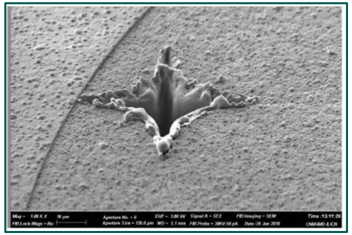
- Limit set by break-down single burn-out risk in high E-field;







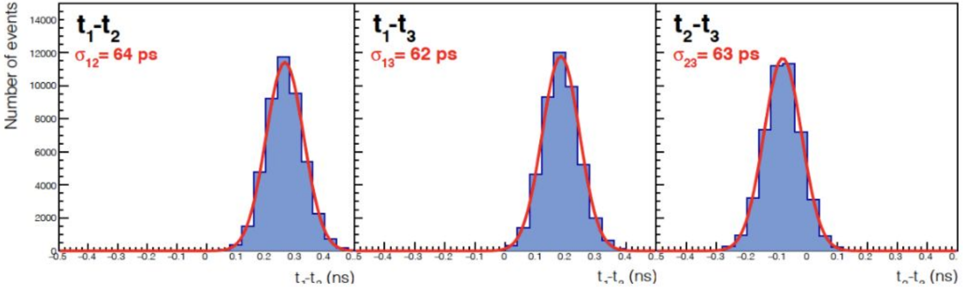




Single burn-out by (rare) highly ionising events in high E-field

End-Cap Timing Layer: status

- ETL prototyping phase is in full swing; detector must be ready for installation in 2027 (much later than BTL!);
- Successful test-beam campaigns used to demonstrate the target single-hit performance;
  full read-out chain operation demonstrated using the second iteration of the ASIC (ETROC1), with 4x4 LGAD pad;
- Full size (16x16) third iteration ASIC (ETROC2) September 2023 test-beam campaign data under study;
- Final chop design (ETROC3) to be submitted in 2024.



LGAD+ETROC1 resolution is 42-46 ps from TDC digital outputs

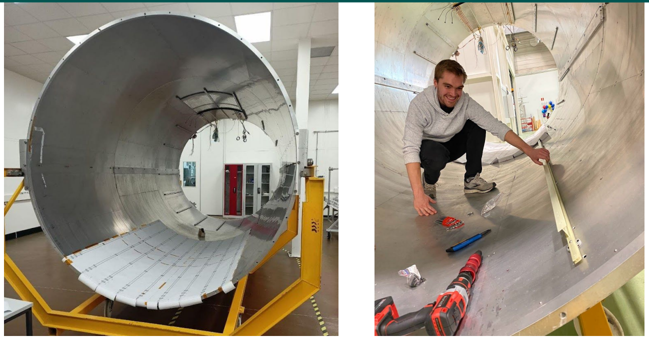
$$\sigma_i = \sqrt{0.5 \cdot \left(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2\right)}$$

From a talk by Paolo Meridiani (INFN Roma) @ TIPP 2023

Barrel Timing Layer: detector design

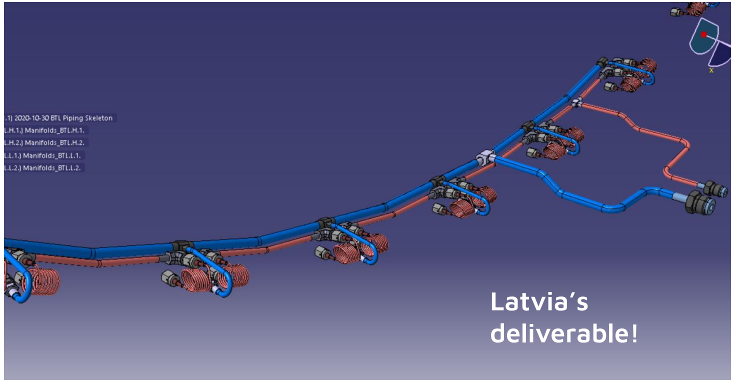
- BTL will cover the *central* acceptance of the detector, $|\eta| < 1.45$;

- The detector will be housed inside the BTL-Tracker Support Tube (BTST):
    - BTST to support the entire BTL and Tracker assembly;
    - Produced in USA; planned arrival @ CERN, Q1 of 2024;
    - Carbon-fibre / foam sandwich;
    - Excellent mechanical & thermal properties;

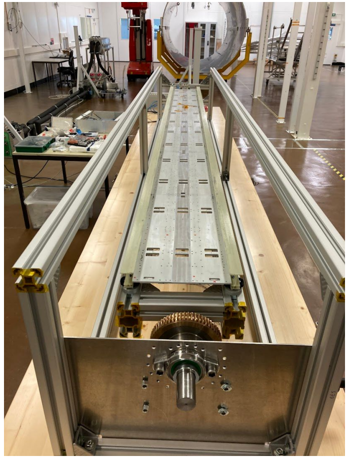


BTST mock-up at b.186

- BTL will consist of 72 trays, 36 x 2 in φ and z, respectively:
    - Mounted onto the BTST via glass-fibre rails and highly-adjustable feet (BTL envelope *float* in R only ~2mm!);
    - Trays consisting of 6 aluminium segments in Z, housing a steel evaporatour for dual-phase CO2 cooling (at -35 C);
    - 72 trays grouped in 12 super-trays, 6 on each end;
    - Super-trays sharing one CO2 manifold;
    - 2 capillaries per tray providing sufficient pressure-drop;

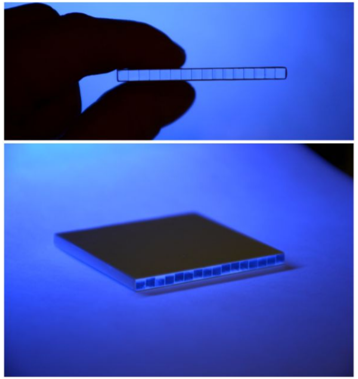


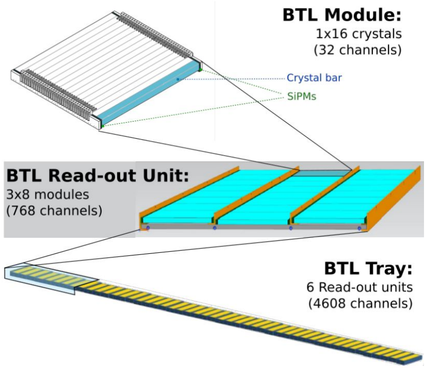
Latvia's deliverable!



Barrel Timing Layer: detector design

- Sensory material: Lutetium-Yttrium orthosilicate, Cerium doped (LYSO:Ce) crystals combined with silicon photomultipliers (SiPMs):
  - Final design crystal thickness of 3.75 mm (uniform in z);
  - Total area covered by BTL ~38 m2;
  - LYSO:Ce light-yield ~40k photons per MeV deposited;
  - Average energy absorption of 4.2 MeV per MIP;
  - SiPM photon detection efficiency ~30-50% @420nm;
  - SiPMs glued on both ends of the LYSO:Ce crystals;
  - Chosen SiPM pad-size : 25 µm;
  - 16 crystals (32 SiPMs) form a BTL array;
  - Total of ~332’000 SiPMs (~166’000 crystals);
  - Custom ASIC for BTL called TOFHIR (based on TOFPET [1]);

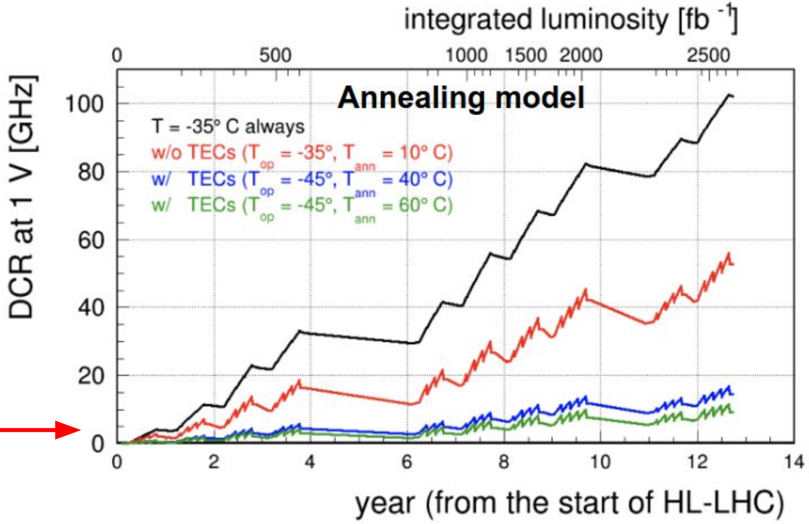




- 2 BTL arrays form a BTL module, held by a copper housing;
- Each BTL tray contains 6 read-out units (RUs), 1 per tray segment;
- Each RU consists of a concentrator card (CC) and 12 BTL modules;
- Radiation tolerance requirements lower in the barrel region;
- BTL is a single-detecting-layer device;
- Mechanical & cooling design validated at the Tracker Integration Facility (TIF), b.186 at CERN;

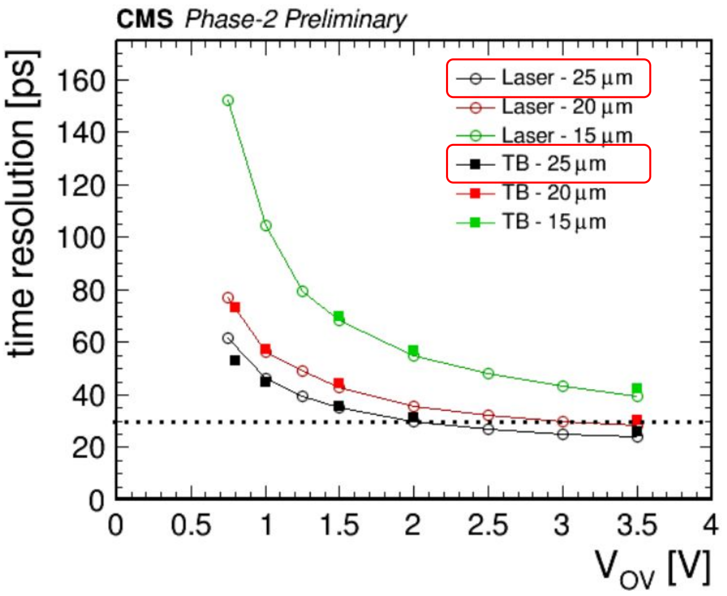
Barrel Timing Layer: performance & operation

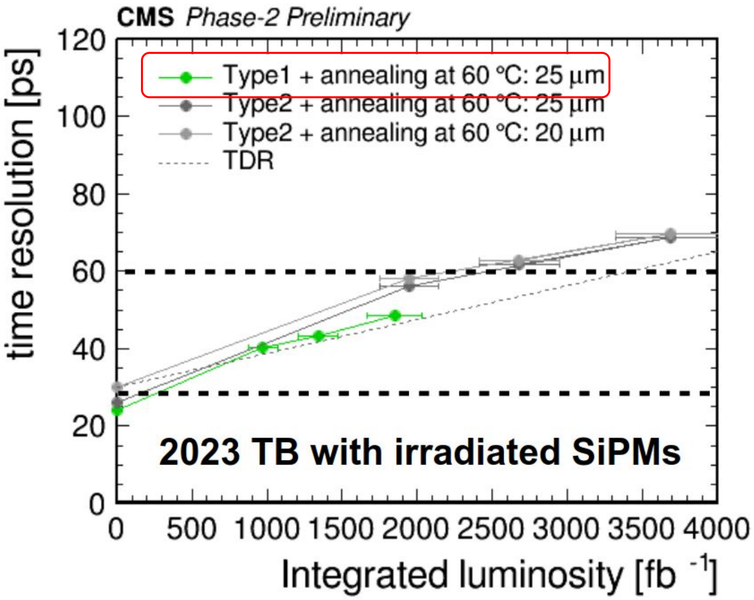
- One of the limiting factors on the time-resolution for the BTL the dark current rate (DCR);
- DCR increases with radiation damage, decreasing the Signal-to-Noise ratio;
- SiPM DCR strongly dependent on the SiPM operational temperature; (approximately doubling with each +10 C);
- Detail investigations recommended the inclusion of thermo-electric-coolers (TECs);
- TECs to add an additional ΔT of -10C for SiPMs (Demonstrated at TIF!); SiPM operational temperature approximately -45 C;
- Additional performance unlocked via *beneficial annealing*; (made more powerful by the ability to reverse bias the TECs [heating]);
- Short beneficial annealing at ambient (~+10C) aided by dedicated annealing periods during end-of-year-shutdowns;
- Use of TECs with reverse bias for heating demonstrated at TIF!



Barrel Timing Layer: performance & operation

- Extensive laser testing and particle test-beam programme at CERN and FNAL used for performance validation;
- Time resolution at the start-of-life of ~30 ps validated;
- EOL timing resolution of ~65 demonstrated (near TDR expectation!);

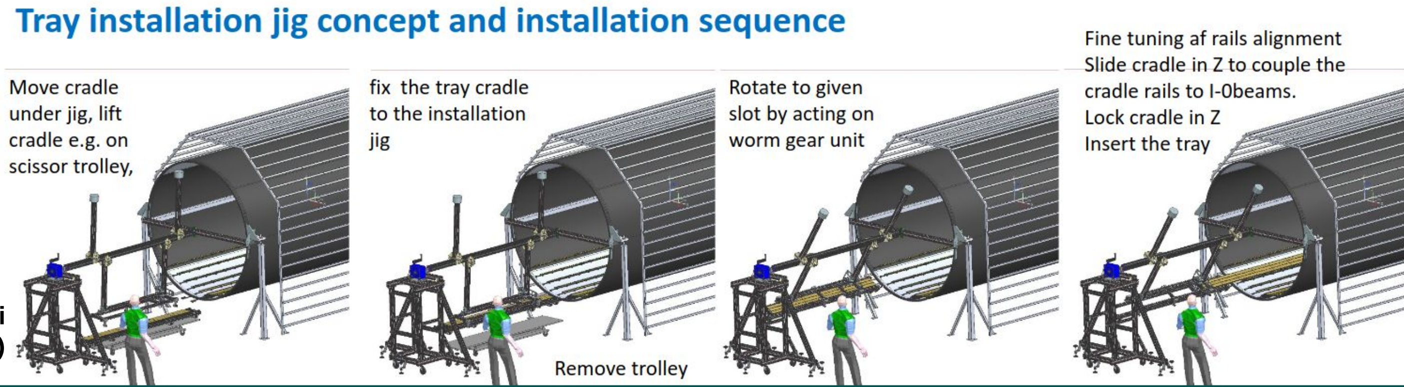




Barrel Timing Layer: status

- BTL is the first Phase-II upgrade detector required to be fully assembled & installed (Q2 of 2025);
- Recently *passed* the EDR/ESR (Engineering Design & Electronic Systems Reviews)
  → BTL officially in the construction phase!
- Cooling plates to be assembled at CERN; then sent to the BTL Assembly Centres (BACs):
  - Caltech;
  - University of Virginia;
  - University of Milano-Bicocca;
  - Peking University;
- Trays shipped to CERN fully populated for final tests & insertion;
- Insertion tooling prototype arrived at CERN in September;

- BTL feet & rail mounting, metrology, and tray insertion tests to be performed at CERN.



Tray installation jig concept and installation sequence

Move cradle under jig, lift cradle e.g. on scissor trolley,

fix the tray cradle to the installation jig

Remove trolley

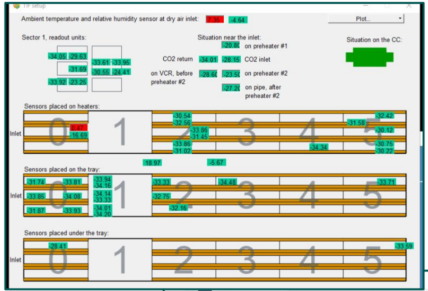
Rotate to given slot by acting on worm gear unit

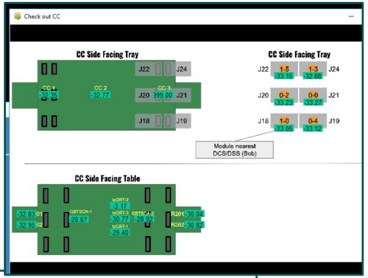
Fine tuning af rails alignment
Slide cradle in Z to couple the cradle rails to I-0beams.
Lock cradle in Z
Insert the tray

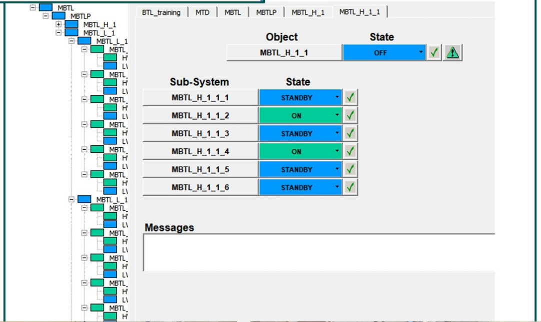
Courtesy of M. Benettoni (U. of Padova)

Detector Control & Safety Systems

- Detector Control and Safety Systems (DCS and DSS) are in development (see Antra's poster);
- DCS/DSS approach overhauled massively for Phase-II upgrade;
- Larger-than-before overlap with the Data Acquisition (DAQ) framework;
- For BTL, hardware interlock will rely on O(10) temperature/humidity sensors;
- DCS/DSS prototype systems for BTL created at TIF:
  - Extensive fine-tuning programme for the interlock to be undertaken;
  - Optimal sensor placement and safe temperature ranges to be studied;
  - User interface to be optimized;
  - Detector Warning/Alert procedures to be developed;
  - Final-State Machine *decision paths* to be developed for all operational modes!
- The lessons learned will be directly applied to the final DCS/DSS design for both BTL and ETL!

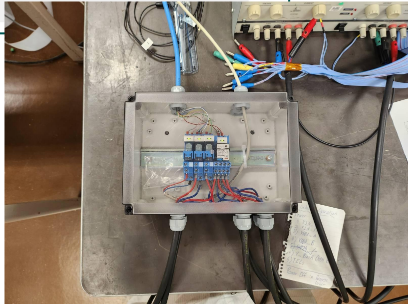






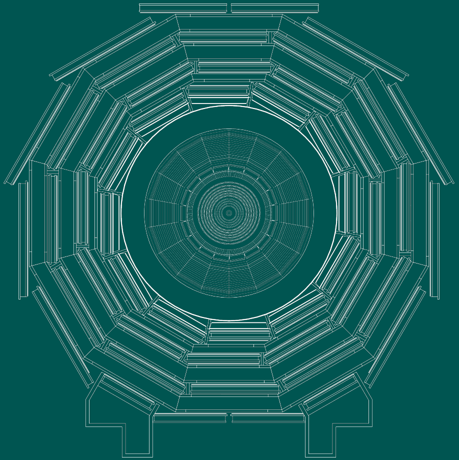
Object	State
MBTL_H_1_1	OFF

Sub-System	State
MBTL_H_1_1_1	STANDBY
MBTL_H_1_1_2	ON
MBTL_H_1_1_3	STANDBY
MBTL_H_1_1_4	ON
MBTL_H_1_1_5	STANDBY
MBTL_H_1_1_6	STANDBY



Summary

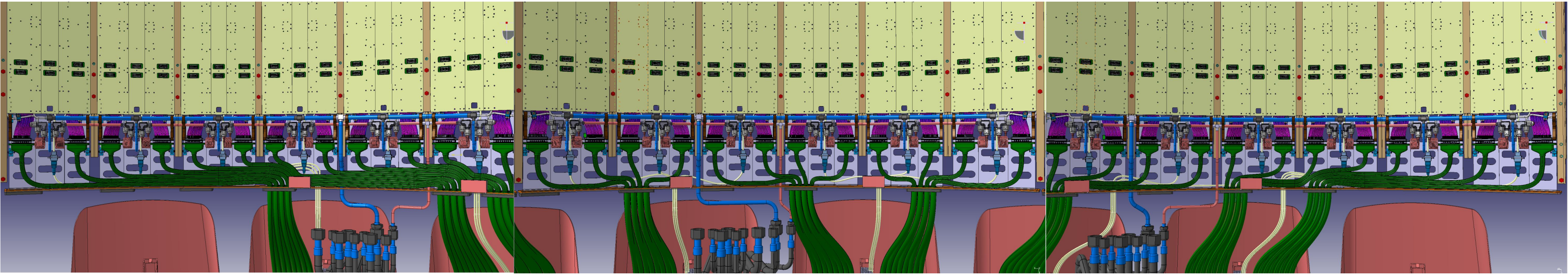
- MTD will enable CMS to use 4D vertexing to retain the current track-vertex association and pile-up track rejection efficiency during the HL-LHC era;
- MTD split into ETL and BTL, using different technologies:
  - ETL: LGAD;
  - BTL: LYSO:Ce + SiPMs;
- Both the systems have demonstrated TDR level time resolution performance:
  - BTL: ~35ps at the SOL and <75 ps at the EOL (with TECs and beneficial annealing);
  - ETL: ~45ps single-hit time resolution (leading to <35 ps track time resolution);
- ETL prototyping phase in full swing;
- BTL design mature → production phase underway;
- DCS and DSS system development underway as well;
- MTD is on track to become the first ps resolution timing detector at the LHC!



Thank you

BTL service routing in the service channel

- BTL service channel occupying the space between tray edge connections and the BTL super-seal;
- Cooling services split into 4 groups* of 3 super-trays: Z+ high, Z+ low, Z- high, Z- low;
- Electrical cabling channel space **reserved & guaranteed** for the current needs;
- Some challenges in cable routing within the service channel;

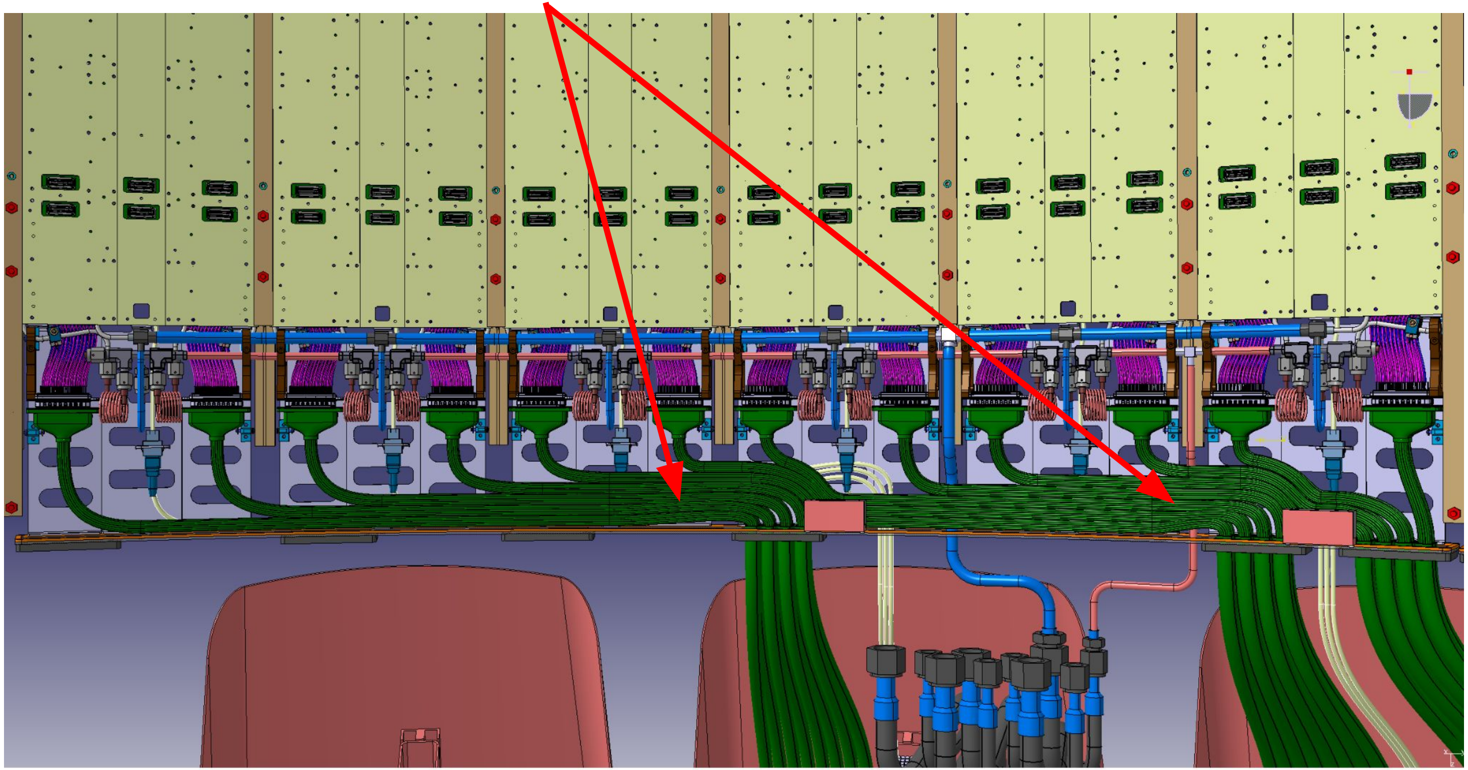


* Low/High refers to below/above the horizontal plane, respectively.

Courtesy of G. Pikurs (RTU)

BTL service routing in the service channel

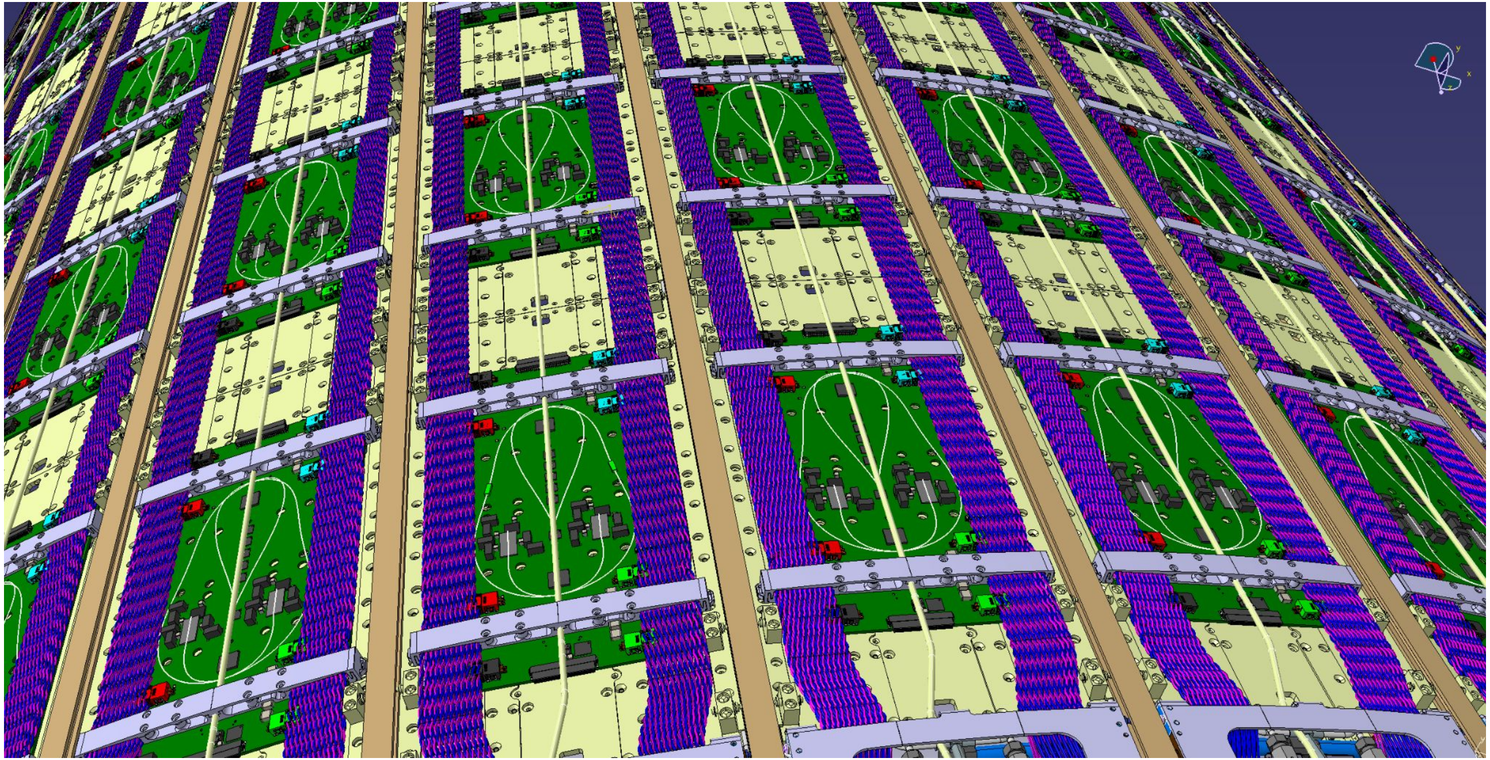
- Most challenging on the edge super-tray where the second channel contains the cooling transfer line connection;



Courtesy of G. Pikurs (RTU)

BTL electrical services & routing

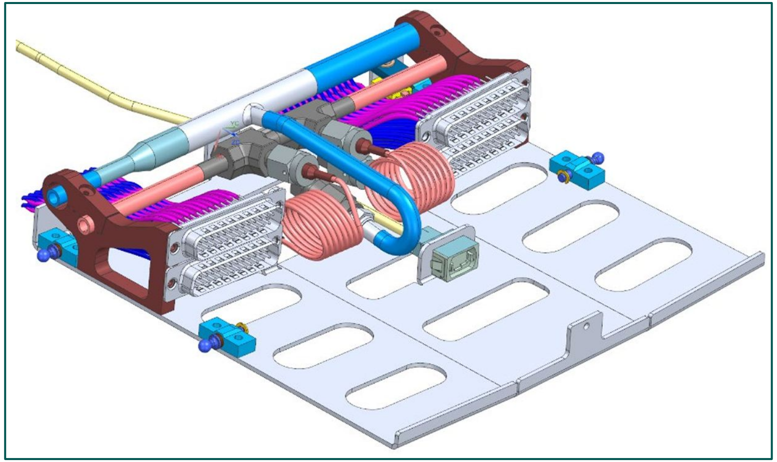
- BTL electrical services: on-detector cable routing; braided cabling (red & blue) visible.

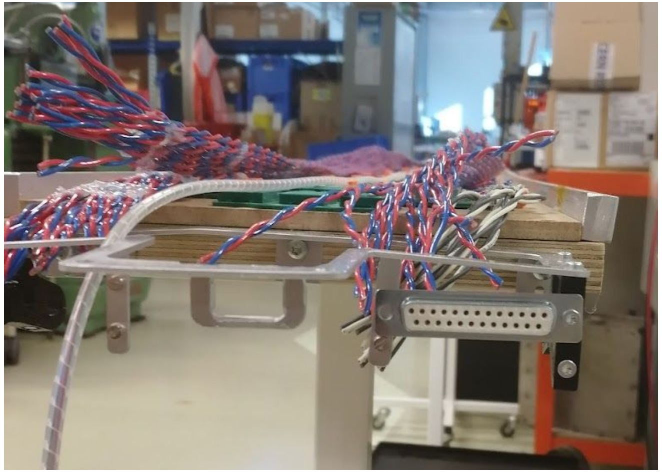


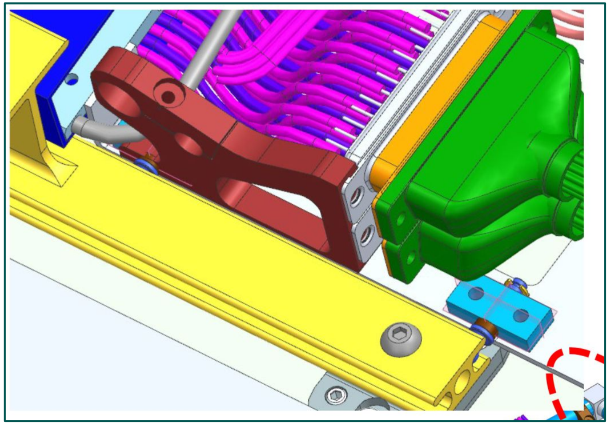
Courtesy of G. Pikurs (RTU)

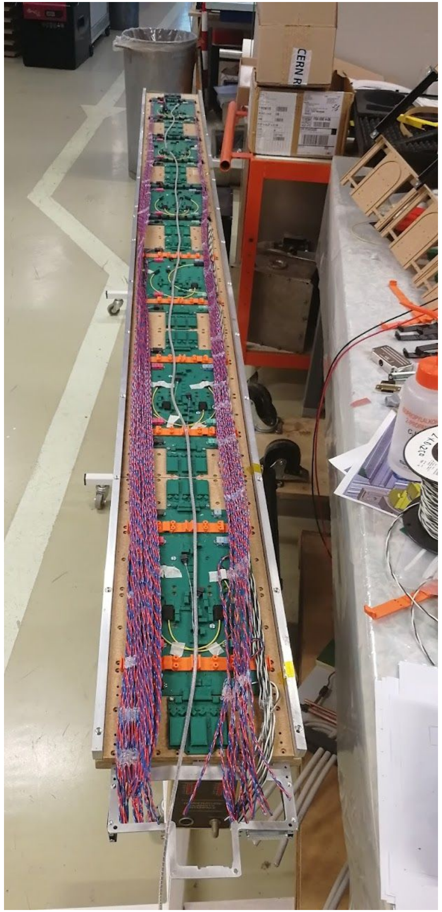
BTL service support, design & mock-up

- Tray service support design mature;
- Tray cabling and service channel mock-up used to validate the design for the cables and for the support structure;
- Cable arrangement is tight, but wholly doable;









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