CMS Upgrades

Juliette Alimena (DESY) on behalf of the CMS Collaboration

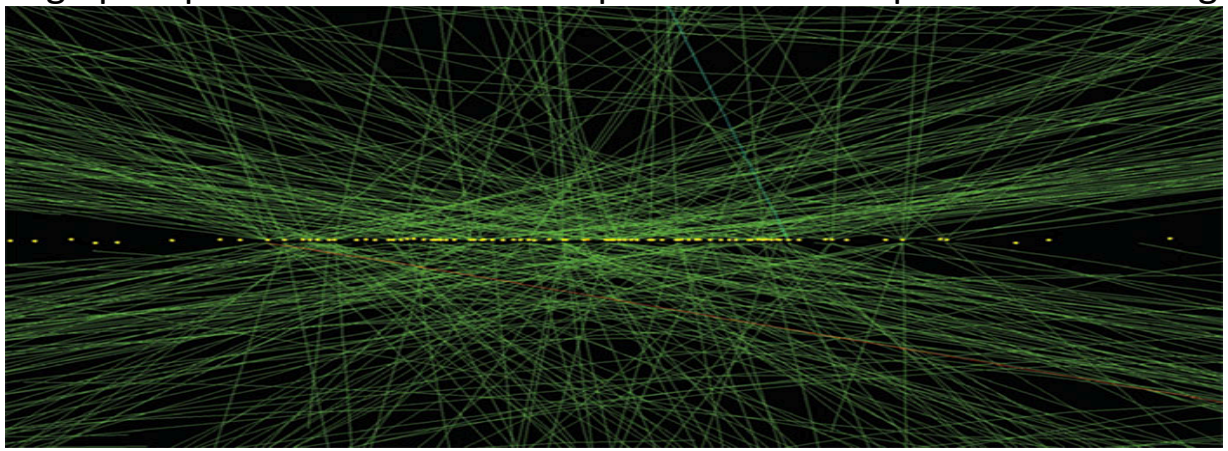
LHCP 2023 in Belgrade, Serbia

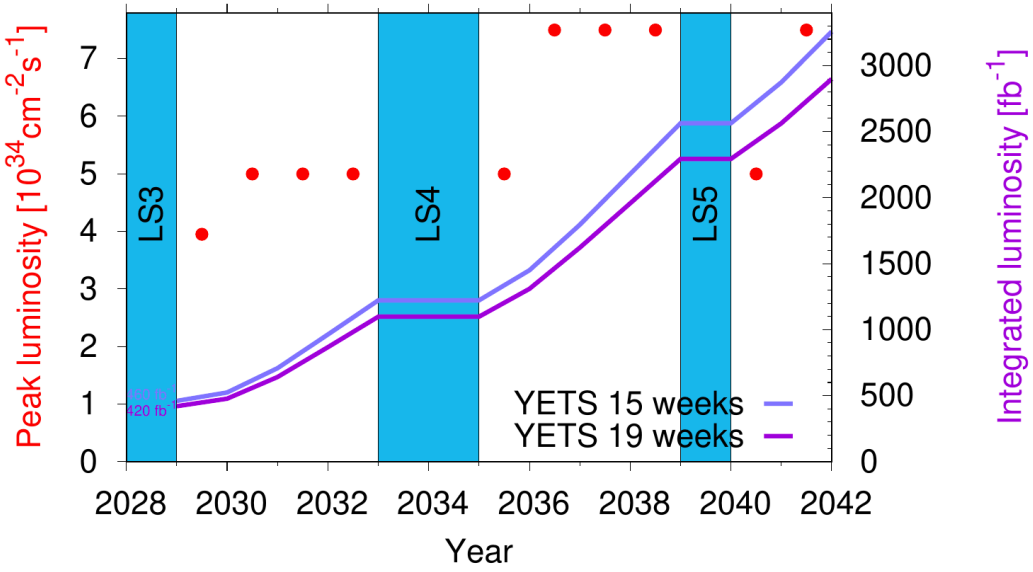
May 25, 2023

High-Luminosity LHC (HL-LHC)

- HL-LHC foreseen to operate from **2029-2041**
- Expect to collect **> 3 ab^{-1} in 10 years**
  - **> 10 times more data** by the end
- **Up to 7.5 times** the nominal **instantaneous luminosity**
- Expect **up to 200 interactions** per pp collision
- **Unprecedented amount of radiation!**

High pileup: about 200 additional proton collisions per bunch crossing



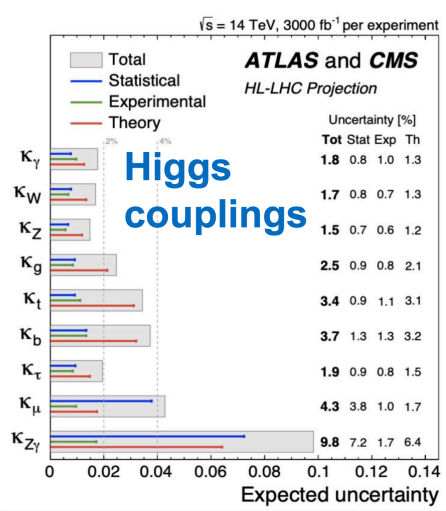


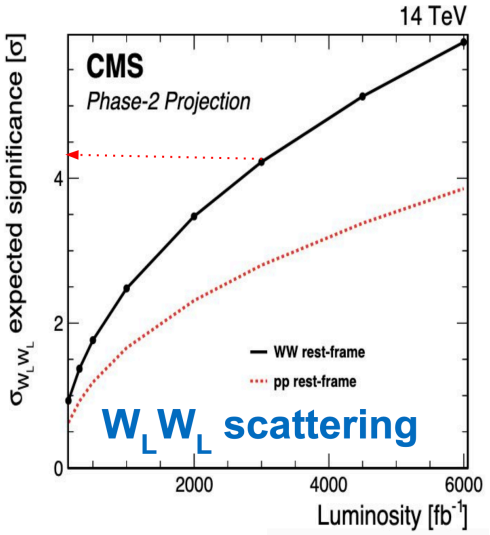
Physics at the HL-LHC

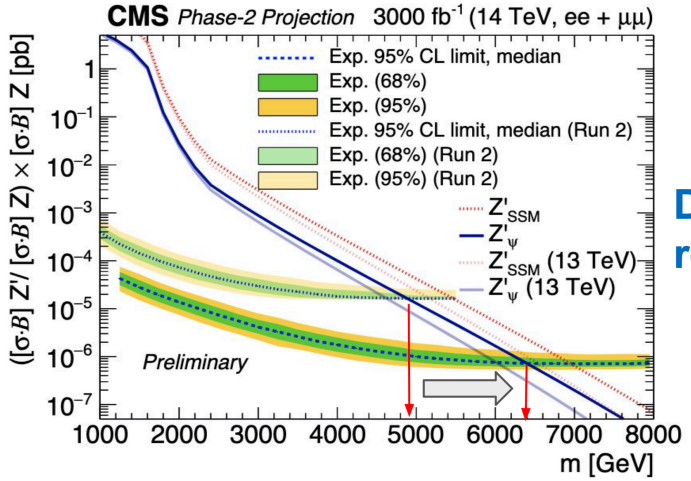
See Davide Zuolo's talk on Highlights from HL-LHC Physics Prospects (ALICE, ATLAS, CMS, LHCb) for more!

Precisely test the standard model, including the **Higgs boson**

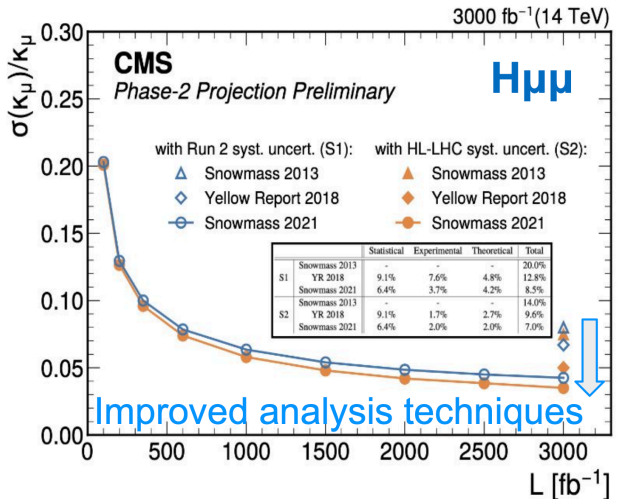
Hunt for **rare exotic processes**, including **dark matter**

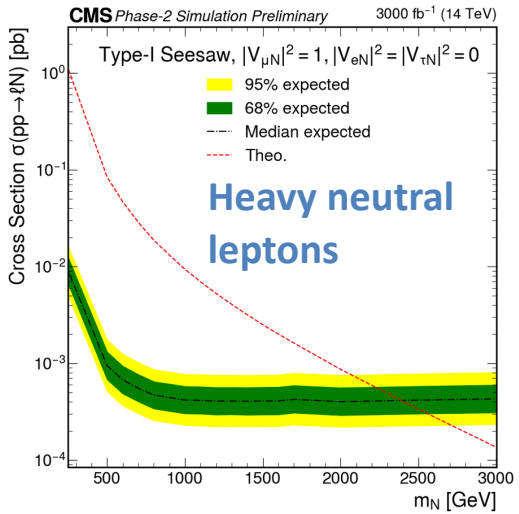


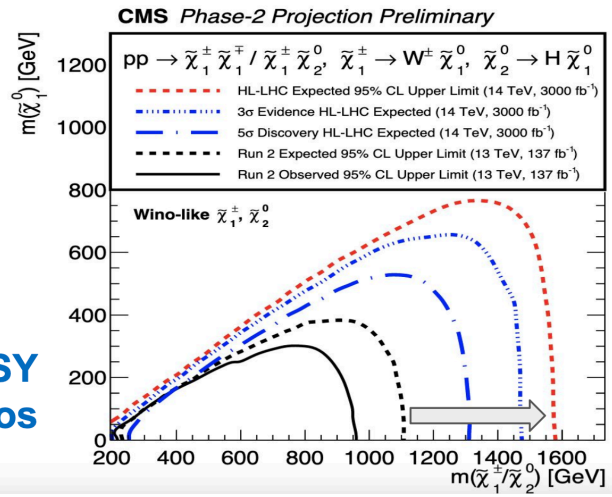




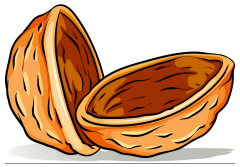
Dilepton resonances







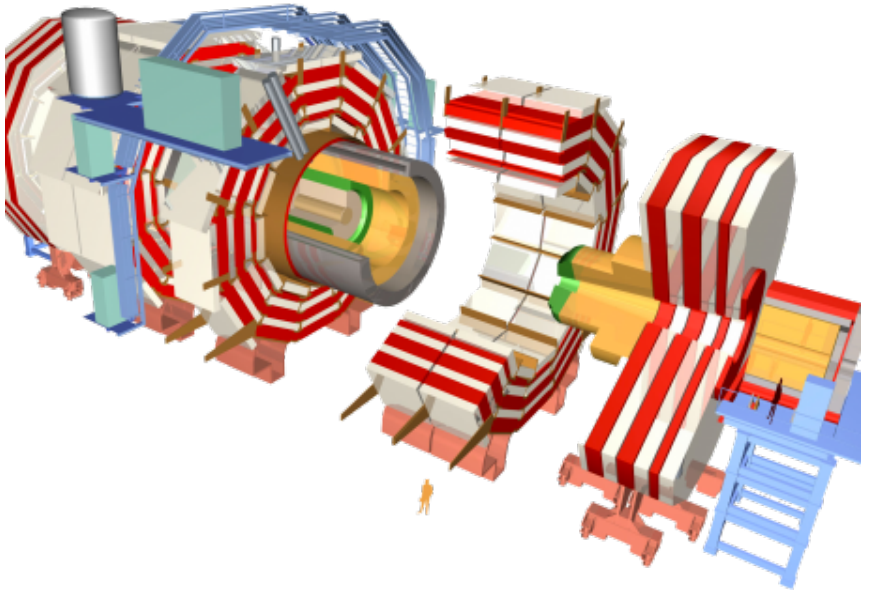
SUSY gauginos

CMS Phase 2 Upgrade in a 

Overarching goals:

- **Exploit** the **physics potential** of the HL-LHC
- **Cope** with the **demanding operational conditions** of the HL-LHC

- Higher **geometrical coverage**
  - E.g. extend Tracker to $|\eta| \sim 4$
- High **resolution** and **granularity**
  - E.g. new High-Granularity Endcap Calorimeter (HGCAL)
- **Precision timing** information
  - E.g. new MIP Timing Detector (MTD)
- High **radiation**
  - E.g. replace Tracker
- High **data rate**
  - E.g. upgrade Trigger and Data Acquisition (DAQ)



Phase 2 Upgrade Under a 

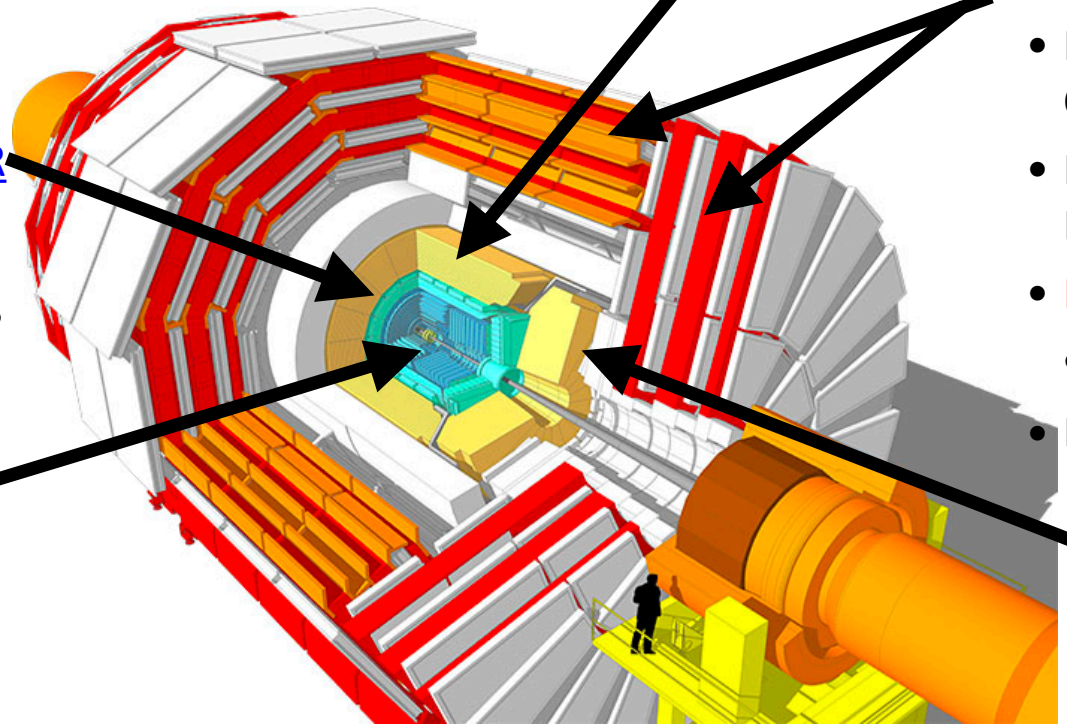
Level 1 Trigger TDR
- New track trigger at 40 MHz
- Particle flow selection
- 750 kHz L1 output
- 40 MHz data scouting (real time analysis)
- L1T latency: 12.5 μs

DAQ & High Level Trigger (HLT) TDR
- Full optical readout
- Heterogeneous architecture
- 60 TB/s event throughput
- 7.5 kHz HLT output

Barrel Calorimeter TDR
- ECAL crystal granularity readout at 40 MHz with precise timing for e/gamma at 30 GeV
- New ECAL and HCAL back-end boards

Muon System TDR
- New Drift Tubes (DTs) & Cathode Strip Chambers (CSCs) FE/BE readout
- New Resistive Plate Chambers (RPCs) BE electronics
- New Gas Electron Multipliers (GEMs) & new iRPCs $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| \sim 3$

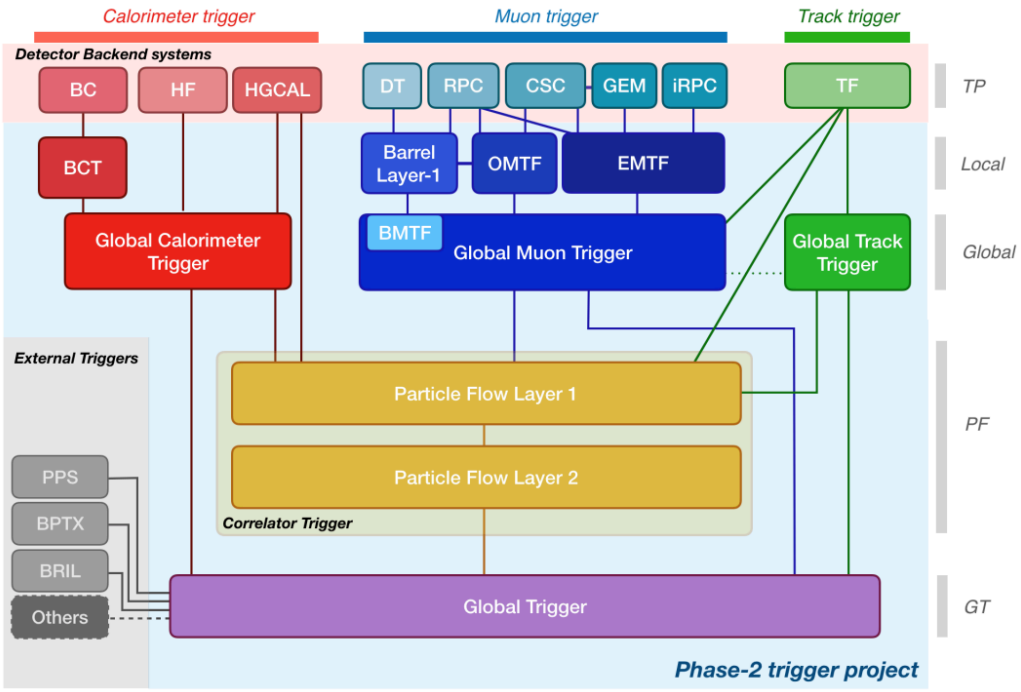
New MIP timing detector (MTD) TDR
- Barrel: LYSO crystals + SiPMs
- Endcap: Low-gain avalanche diodes
- 30 ps timing resolution
- Full coverage to $|\eta| \sim 3$



Replaced Tracker TDR
- Increased granularity
- Extended coverage to $|\eta| \sim 4$
- Designed for tracking in L1T

New High-Granularity Endcap Calorimeter (HGCAL) TDR
- Imaging calorimeter
- Si, Scint+SiPM in Pb/Cu-W/SS
- 3D showers and precise timing

Beam Radiation Instrumentation and Luminosity (BRIL) TDR
- Target 1% offline (2% online) luminosity uncertainty



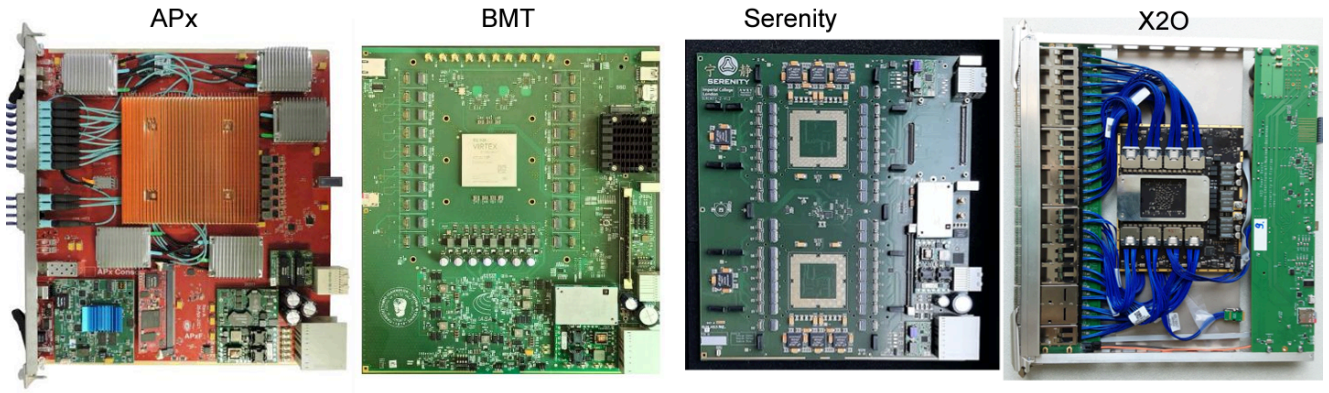
L1 Trigger

See Jose Enrique Palencia Cortezon's talk on the CMS Level-1 Trigger Upgrade for more!

- Hardware and firmware, with extensive use of state-of-the-art FPGAs
- Increased rate: 100 kHz (Run 3) ⇒ 750 kHz (Run 4)
- Tracking information (p_T > 2 GeV)
- Higher granularity for calorimeters & muon system
- Particle flow in correlator layer
- 40 MHz scouting system

Status:

- Hardware: **pre-production completed**
  - Pilot designs and pilot-production ongoing towards final production-ready designs
- Firmware implementation proceeding in all fronts
- **Algorithms prototyped in FPGAs** and demonstrated
- **Physics performance maintained and improved over Run 3**



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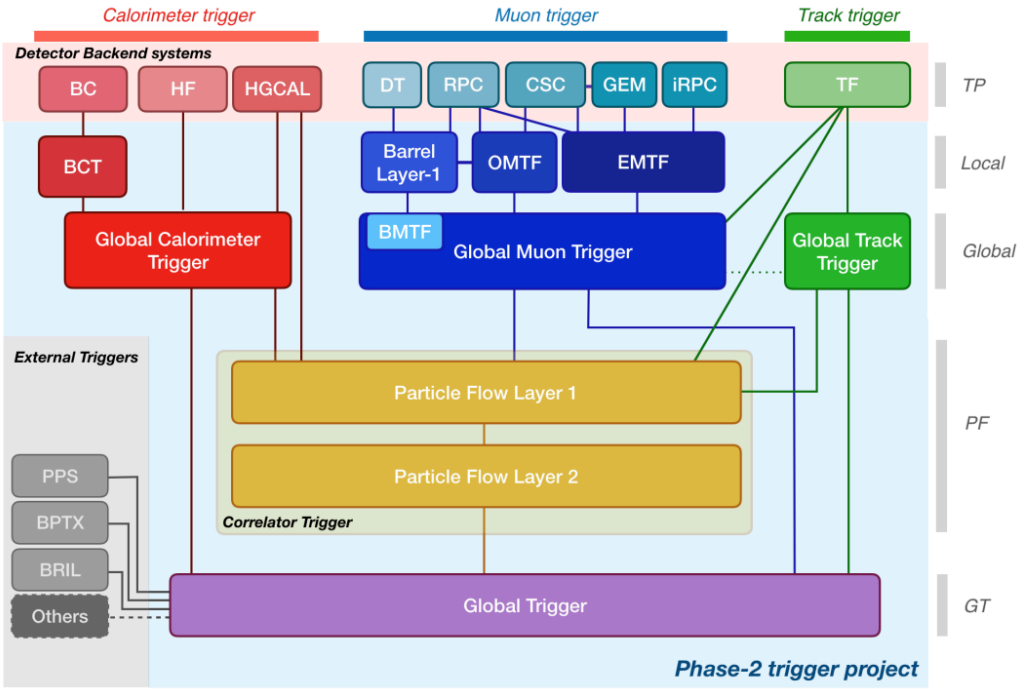

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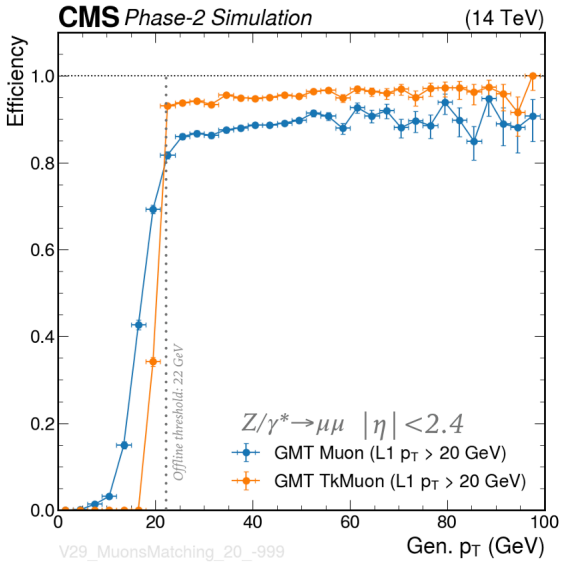
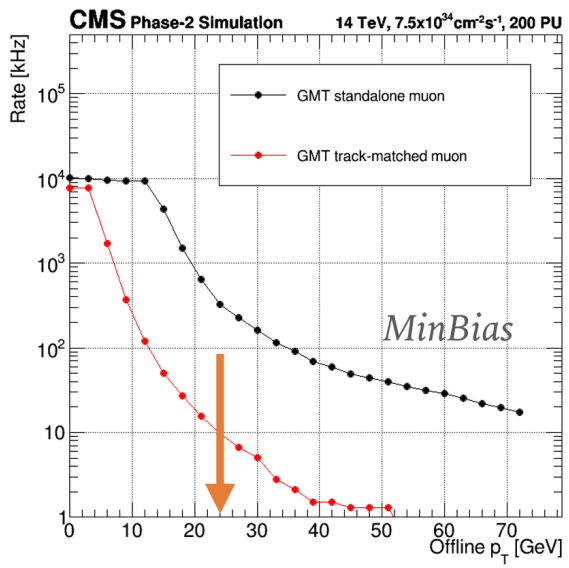
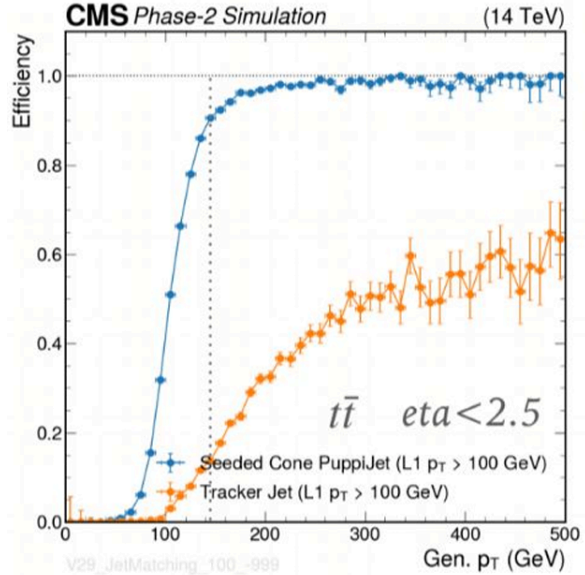
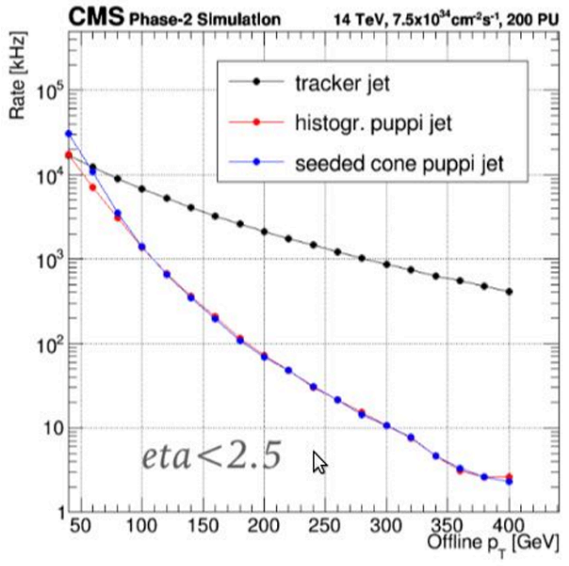
Muons





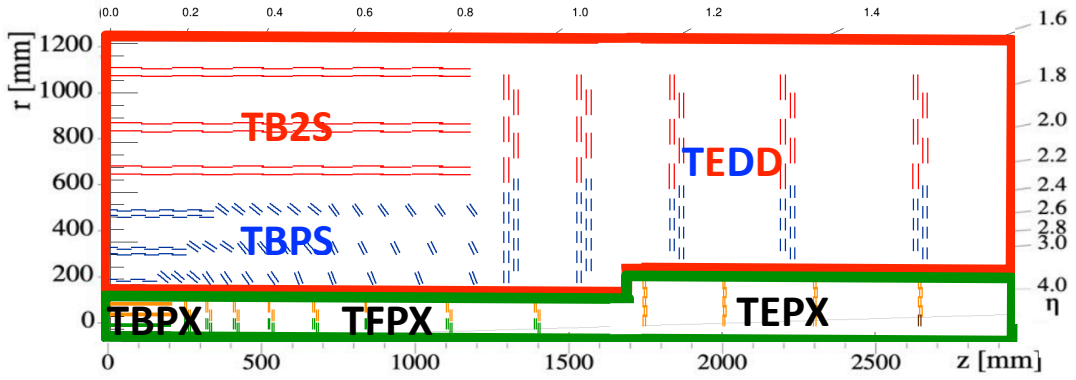
Jets





Tracker

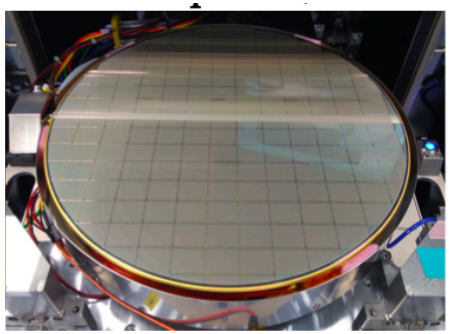
See Fabio Luongo's poster on "The CMS tracker upgrade for HL-LHC" for more!



Inner Tracker

- Almost **2 billion silicon pixels** read out by **13,500 chips** on **4,350 modules**: Active silicon area of **4.9 m²**
- 3D sensors in TBPX L1, planar sensors everywhere else
- New **CMS Read Out Chip (CROC)** from RD53 collaboration (ATLAS+CMS)

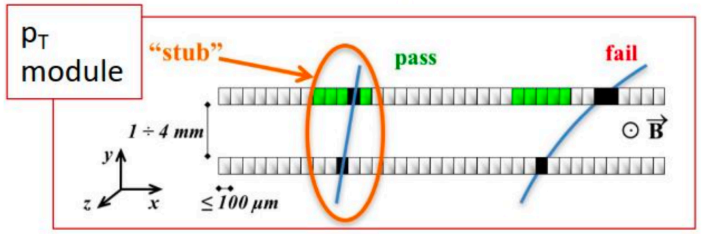
CROCv1



Status:

- **Sensor contracts** ready
- **Assembled and tested first CROC** quad (proto-)modules with sensors for all sub-systems
- Getting ready for **production-level module tests**

Outer Tracker

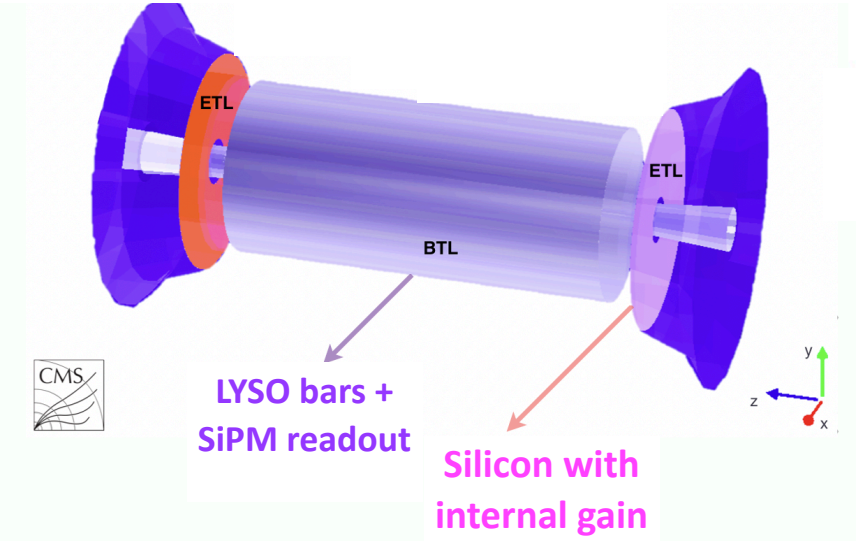


- **pT modules**: using two closely spaced sensors (with strong magnetic field), provide pT discrimination at frontend
- **Stubs**: correlated pairs of clusters consistent with pt > 2 GeV. Input for track finder, used at L1

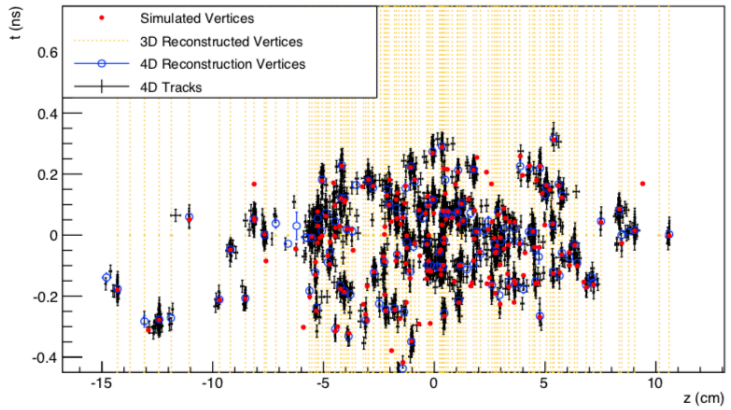
Status:

- **Sensors and ASICs in production**
  - ~60% of sensors delivered
- Kick-off batch for the FE hybrids of the modules is expected soon
- Pre-production for **mechanical structures and integration** ramping up

MTD



- Dedicated **MIP timing layers** with **30 ps precision***
- Located just outside tracker
- Hermetic coverage up to **$|\eta|$=3**
- Improved tracking and vertexing for pileup reduction, unique potential for Long-Lived Particles

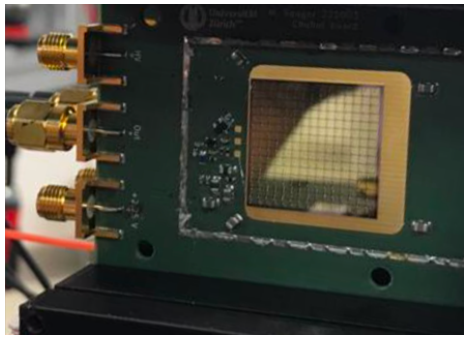


Status:

- **Barrel:**
  - Pre-production for LYSO crystal arrays in progress
  - Final SiPM prototypes being validated in test beams before production
  - Readout electronics: final versions are being validated
- **Endcap:**
  - Full-size (16x16) sensors tested - everything as expected
    - Testbeam at Fermilab and CERN to finalize specifications
  - Full-size and functionality readout chip under validation

LYSO and SiPM array

Full-size LGAD sensor

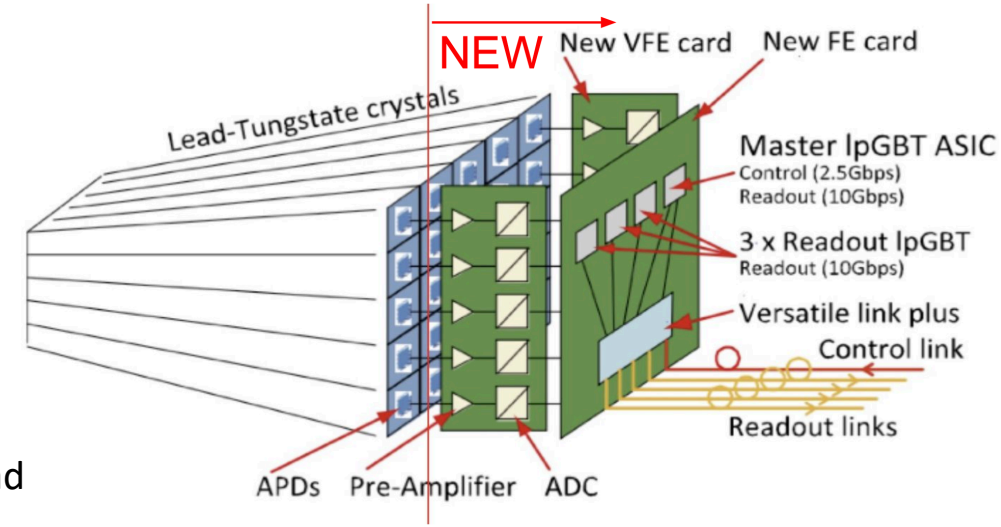


*Barrel will degrade to 60 ps by end of life due to radiation damage

Barrel Calorimeter

ECAL

- **Lead tungstate crystals** and Avalanche Photodiodes (APDs) will be kept
- **FE and BE electronics to be replaced**
  - **30 ps time resolution** for 30 GeV e/γ. Achieved through faster analog FE and higher sampling frequency (160 MHz)
  - **Single crystal at L1 trigger** (instead of 5x5). **Signal readout at 160 MHz** (instead of 40 MHz)



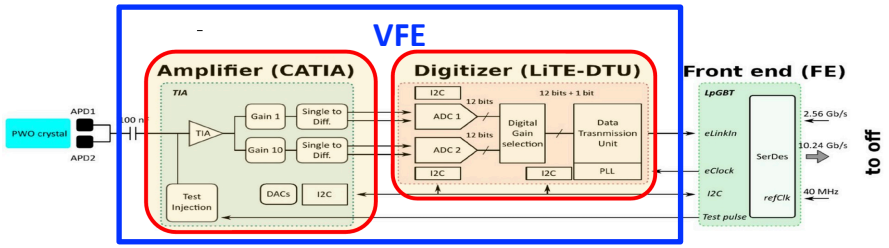
HCAL

- Plastic scintillator tiles and wavelength-shifting fibers will be kept
- FE electronics with SiPMs installed in LS2 will be kept

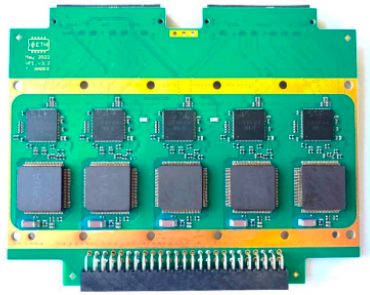
Status:

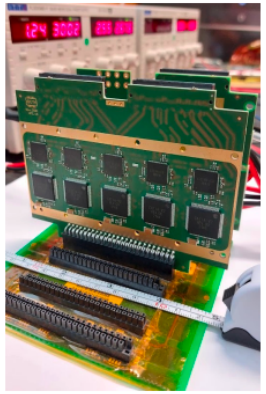
- Two custom **ASICs approved for production**
- **Prototype phase for VFE and FE cards is completed**
  - Large scale card production to begin ~end of 2023
- **Barrel Calorimeter Processor (BCPv2)** off-detector readout**: design mature**, testing circuitry designs, expected in late 2023

Custom ASICs: CATIA amplifier and LiTE-DTU digitizer



VFE with CATIAs and LiTE-DTUs





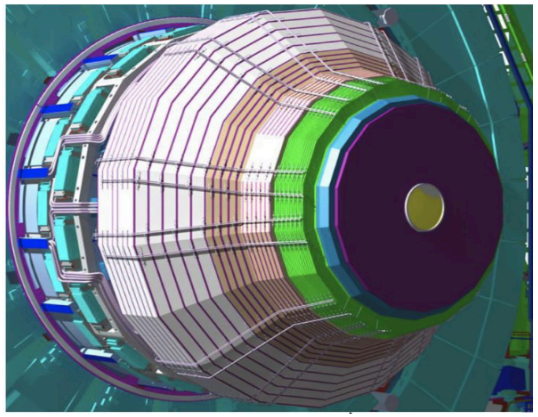
HGCAL

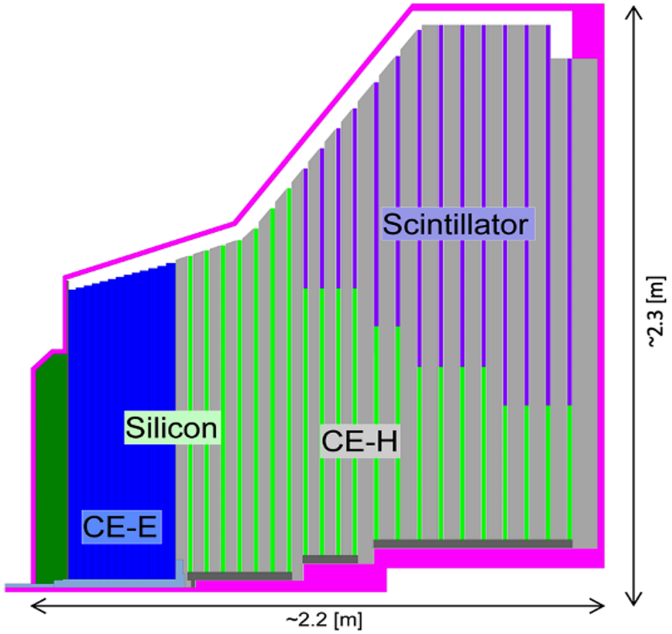
See Milos Vojinovic's poster on "Vertical Integration System Testing of the CMS HGCAL Electronics" for more!

- **Highly granular imaging calorimeter** in endcaps
- **3D showers** and **precise timing**
- **ECAL (CE-E):**
  - **Silicon sensors**
  - Cu, CuW, and Pb absorbers
  - 26 layers, X_0=25 and λ=1.3
- **HCAL (CE-H):**
  - **Silicon sensors** and **scintillating tiles** with **SiPM readout**
  - Stainless steel absorbers
  - 21 layers, λ=8.5

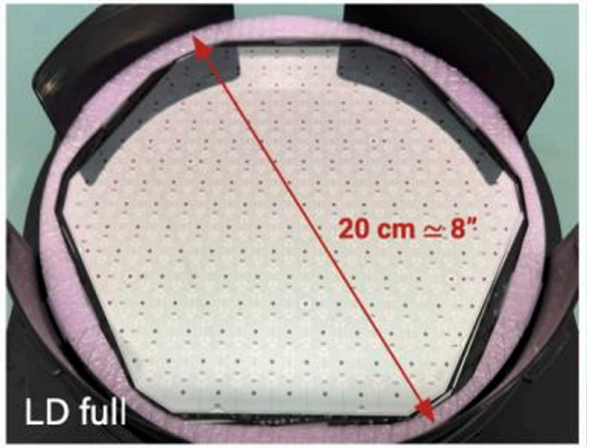
<u>Status:</u> Progressing well towards production

- Pre-production full-size silicon sensors arriving
- Latest prototype silicon and SiPM-on-Tile modules perform well
- Front-end ASICs going into engineering runs in 2023
- Pre-production stainless steel CE-H absorber plates presently being machined in Pakistan





8 inch hexagonal sensor



G. Millella at DESY test beam

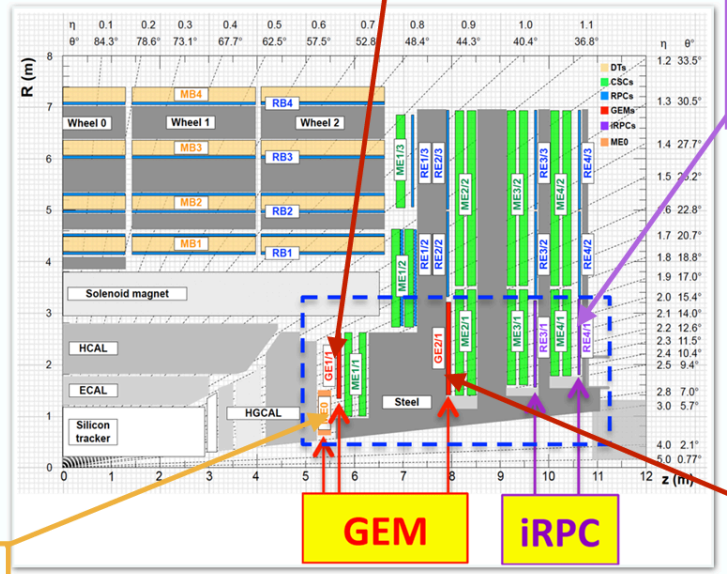
Muon System

See Arun Madhu's poster on "Longevity studies and search for eco-friendly gas mixture for CMS Cathode Strip Chambers" for more!

- Current Drift Tubes (DTs), Cathode Strip Chambers (CSCs), and Resistive Plate Chambers (RPCs) will stay
  - **DTs:** Replace FE/BE electronics
  - **CSCs:** Replace some FE boards and all BE boards
  - **RPCs:**
    - Add a new layer in the form of iRPC, along with backend
    - Replace off-chamber readout/control system
- **New detector: GEMs**
  - **ME0 extends the acceptance to $|\eta|$ =2.8**
- Extensive longevity and eco-gas studies

- GE1/1: 1.6<|η| < 2.2
- 72 triple-GEM chambers
- Installation done LS2

- iRPC: Extends RPC acceptance |η| from 1.9 to 2.4
- RE3/1 and RE4/1



- ME0: extend the acceptance |η|= 2.8
- 6 layers of Triple-GEM

- GE2/1:1.62< |η| < 2.43
- 4 triple GEM modules per chamber

Status:

- DTs: extension of a slice test with final on board electronics
- Many GEM detectors already installed during LS2 and many more before LS3
- iRPC and GEMs: chamber production ongoing and on track

Summary

- CMS upgrades are largely moving to the (pre)-production phase
- Ready to exploit physics at the HL-LHC!
  - Sub-percent precision on many SM processes
  - Direct and indirect probes of BSM
- Lots of exciting opportunities for CMS in Phase 2! Hopefully I've whetted your appetite

Backup

More CMS Upgrades at LHCP

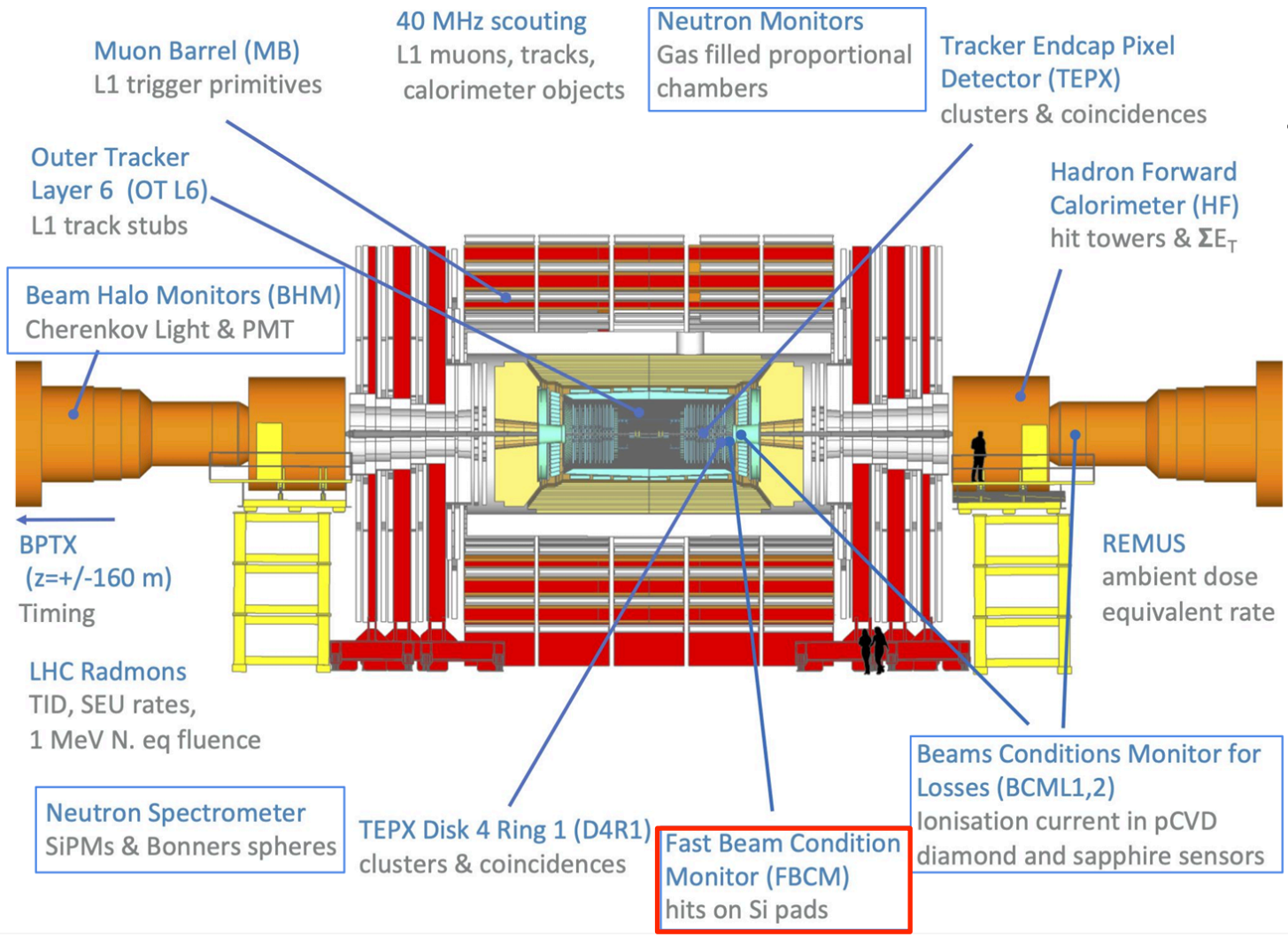
Parallel session talks:

- CMS Level-1 Trigger Upgrade, Jose Enrique Palencia Cortezon
- Highlights from HL-LHC Physics Prospects (ALICE, ATLAS, CMS, LHCb), Davide Zuolo

Posters:

- The CMS tracker upgrade for HL-LHC, Fabio Luongo
- Vertical Integration System Testing of the CMS HGCAL Electronics, Milos Vojinovic
- Longevity studies and search for eco-friendly gas mixture for CMS Cathode Strip Chambers, Arun Madhu

Beam Radiation Instrumentation and Luminosity



- **14 technical systems** for luminosity measurements and beam monitoring
- **Target 1%** offline (2% online) **luminosity precision**
  - Dominant experimental uncertainty for the most precise Higgs measurements

Status of FBCM (dedicated bunch-by-bunch luminometer):

- Good progress on the **FBCM design and test system**
- **ASIC submission** is planned for this month
- **FE electronics** test system design: flexible and modular
- **Thermal prototype production** with close to final material is ongoing