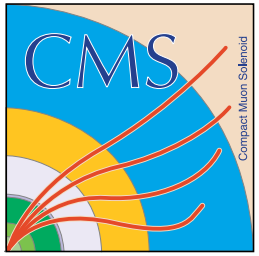


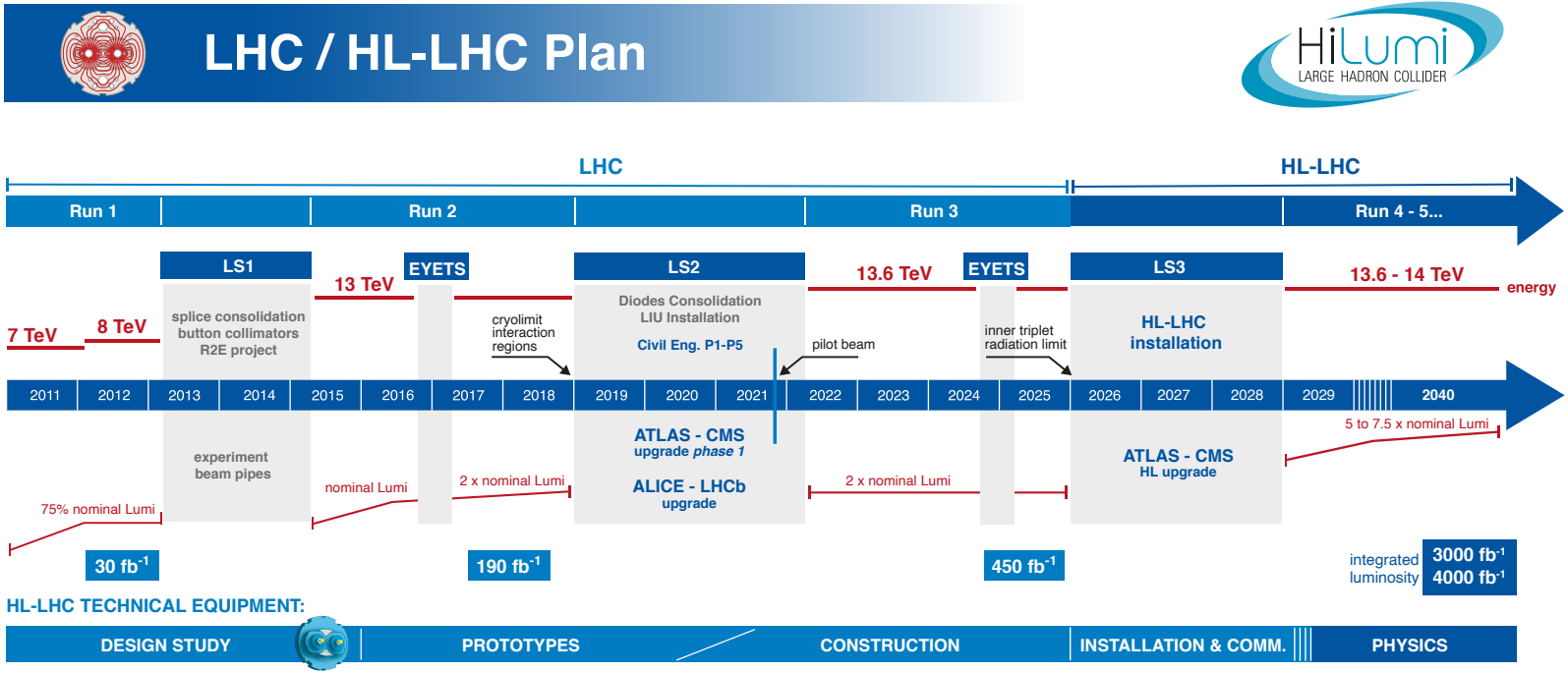
CMS Upgrades for the High-Luminosity LHC Era

THIAGO R. F. P. TOMEI

FOR THE CMS COLLABORATION

SPRACE-Unesp

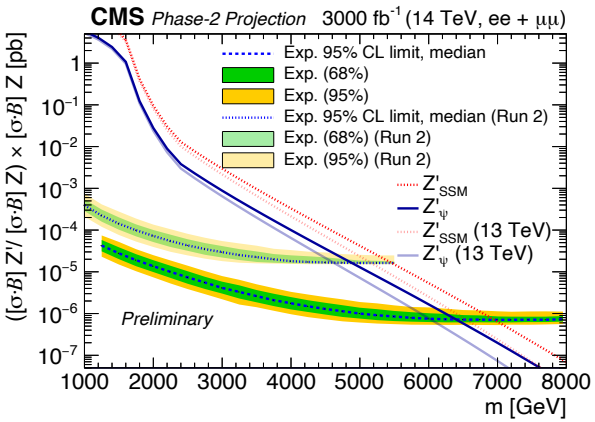
The High-Luminosity LHC

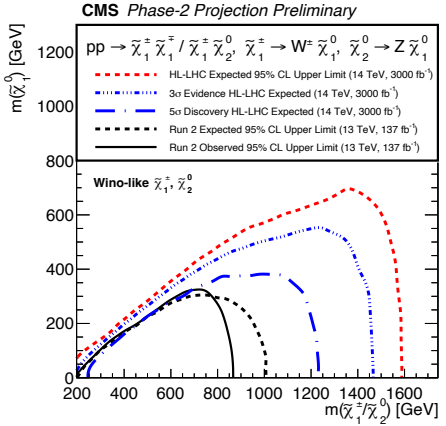


Expectations for the HL-LHC

Current limits on BSM
⟶ a rare process
even with 4000 fb^{-1}

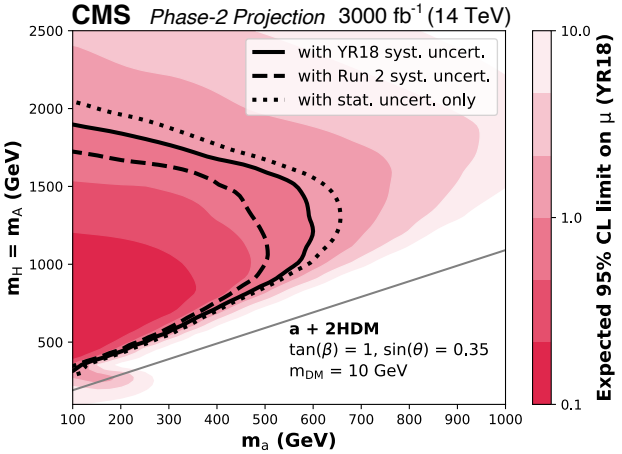
- Full luminosity needed for evidence of new physics





Important role for precision physics

- Precise measurements of SM parameters
- Searches for rare SM processes (*e.g.* H ⟶ μμ, HH)



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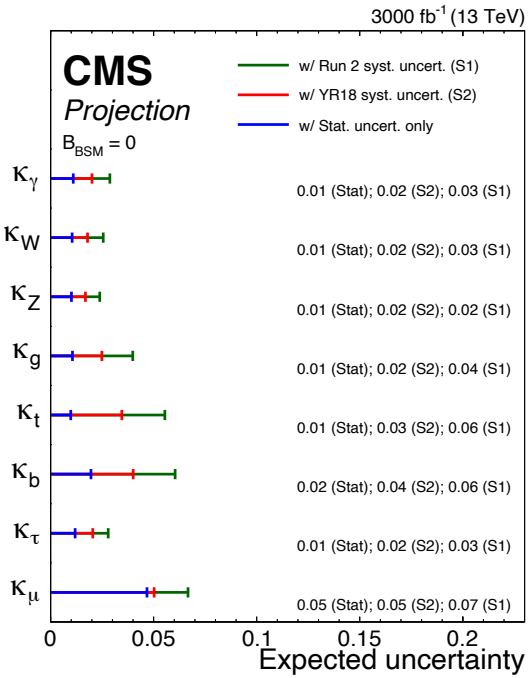
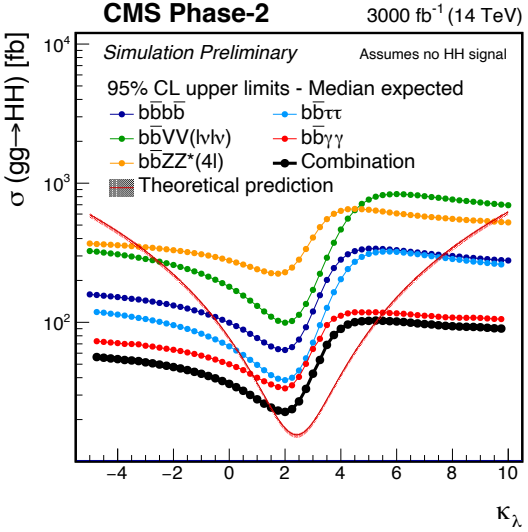




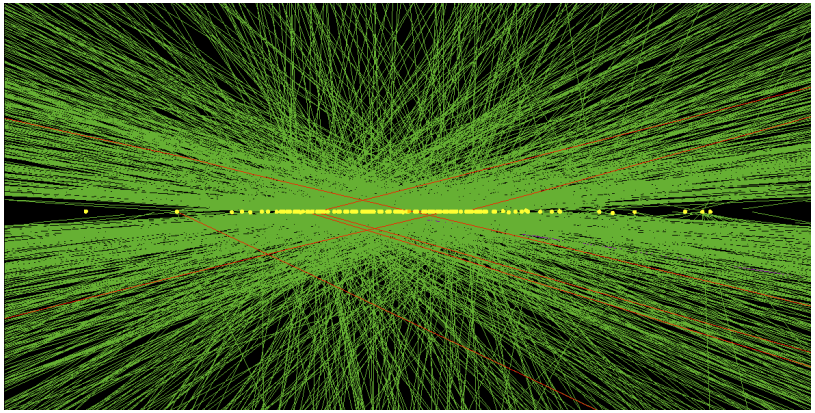
CMS in the High-Luminosity LHC Era

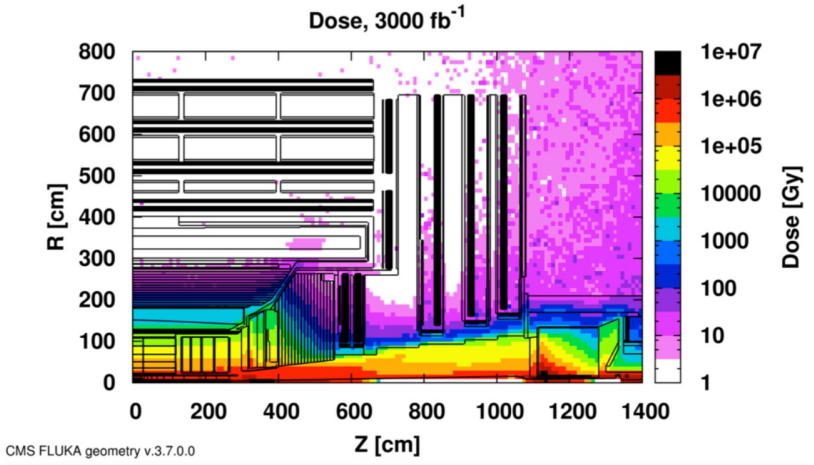
Goal

- Extend the physics programme to the 4000 fb^{-1} integrated luminosity target
- Keep the detector performance
  - Efficiency
  - Resolution
  - Background rejection

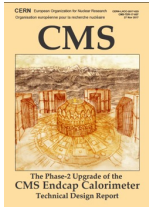
Obstacles

- High instantaneous luminosity (pileup)
  - Improved granularity and timing information
- High integrated luminosity (radiation)
  - Replacement of Tracker and Endcap Calorimeter
- Huge amount of data (computing and storage)
  - Overhauled Trigger and DAQ systems



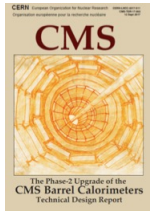


CMS Phase-2 Upgrade Overview



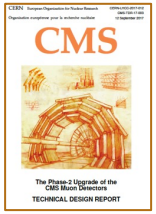
Endcap Calorimeter

- 3D showers + precise timing
- Si, Scint+SiPM in Pb/W-SS



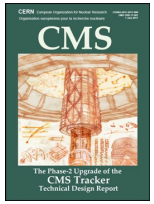
Barrel Calorimeters

- ECAL readout at 40 MHz w/ precise timing at 30 GeV
- ECAL/HCAL new back-end boards



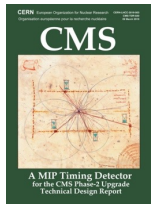
Muon Systems

- DT/CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended to $\eta \simeq 3$



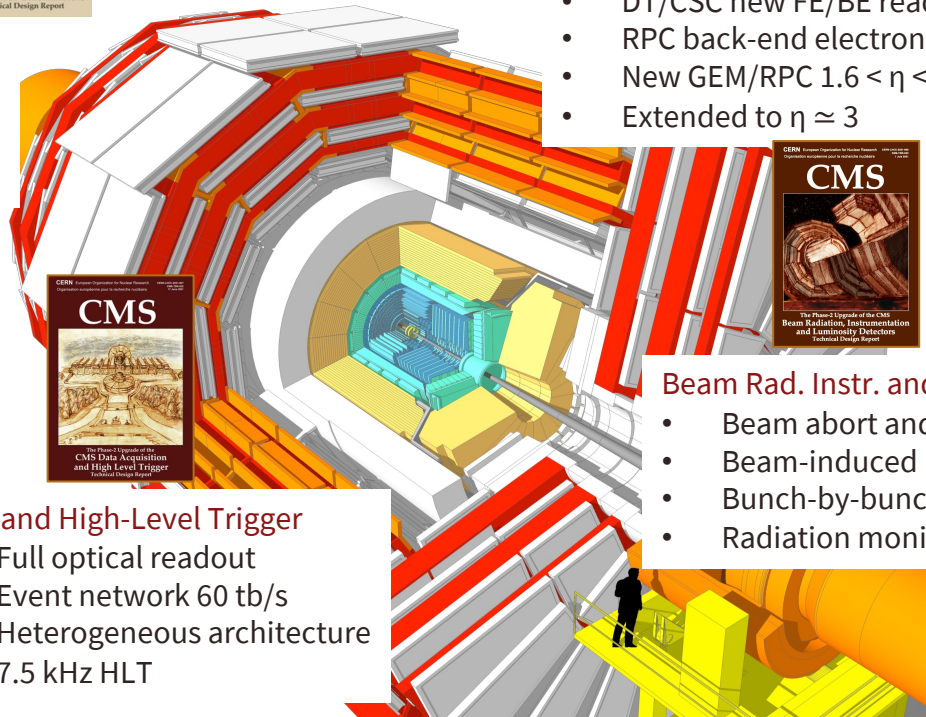
Tracker

- Si-Strip/Pixels increased granularity
- Tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



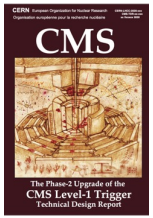
MIP Timing Detector

- Precision timing with:
- - Barrel layer: Crystals + SiPMs
- - Endcap layer: Low Gain Avalanche Diodes



Beam Rad. Instr. and Lumi

- Beam abort and timing
- Beam-induced backgrou
- Bunch-by-bunch lumino
- Radiation monitoring



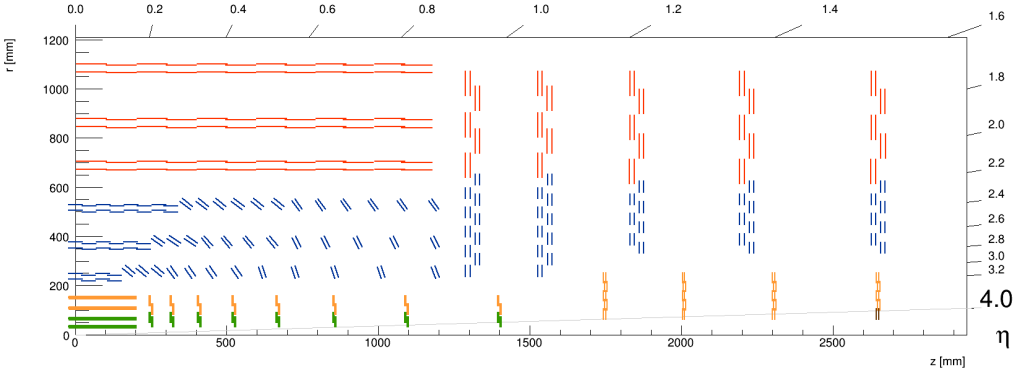
L1-Trigger

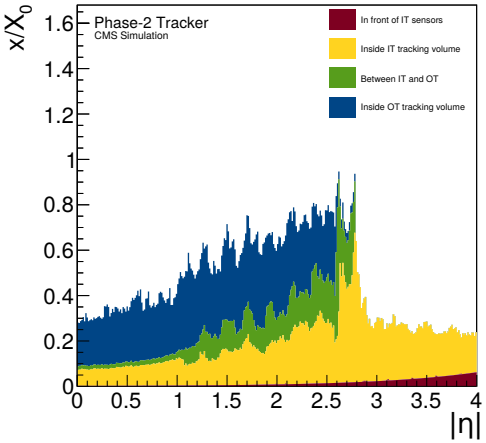
- Tracks in L1-Trigger at 40 MHz
- PFlow selection
- 750 kHz L1

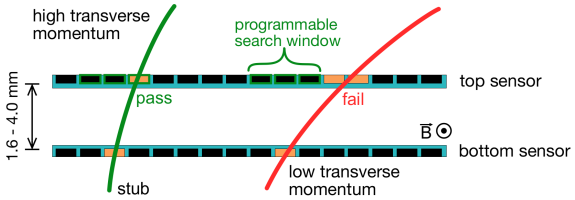
DAQ and High-Level Trigger

- Full optical readout
- Event network 60 tb/s
- Heterogeneous architecture
- 7.5 kHz HLT

The Phase-2 Upgrade of the CMS Tracker







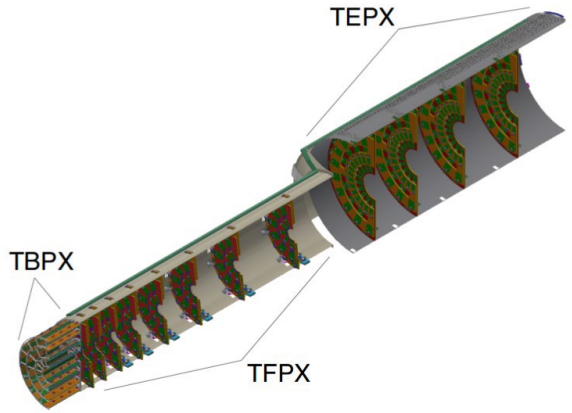
Requirements

- Radiation resistance
  - Max fluence up to O(10^{16}) n_{eq}/cm^2
- Increased granularity
  - $\sim$ 1200 tracks / unit of η
- Reduced material
  - Preserve calorimetric resolution
- Contribution to the L1 trigger
  - Outer Tracker: p_T modules $\longrightarrow$ stubs compatible with tracks $p_T > 2$ GeV
- Extended acceptance: $|\eta| < 4.0$

Phase-2 Tracker Geometry and Parameters

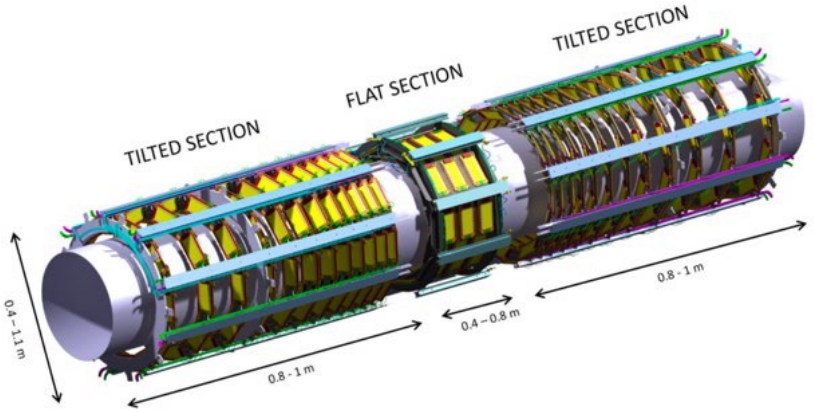
Inner Tracker

- 4 barrel layers,
- 8 small disks, 4 large discs per side
- Pixel size: 25 x 100 μm^2
- 2 x 10^9 channels



Outer Tracker

- 6 barrel layers
- 5 discs per side
- 44 million strips
- 174 million macropixels



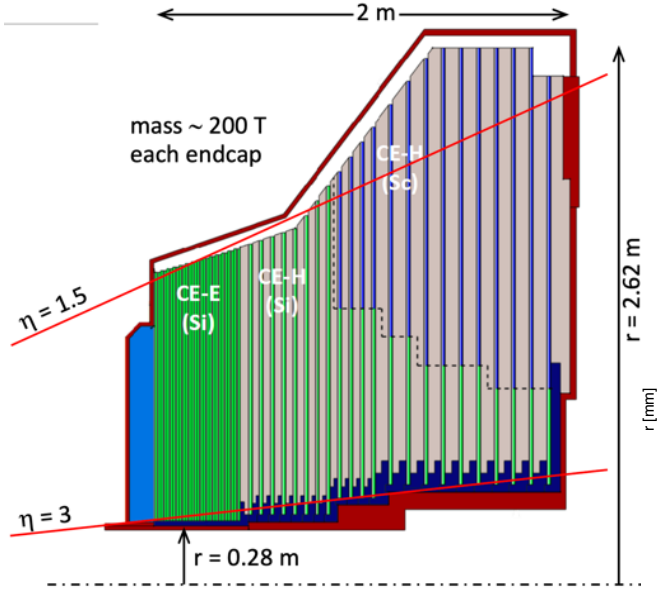
High-Granularity Calorimeter (HGCAL)

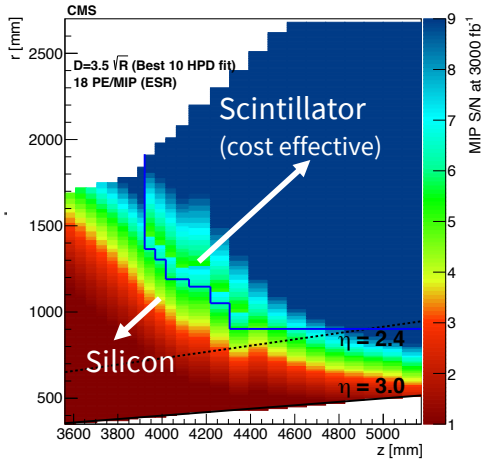
Requirements

- Radiation tolerance
- Dense calorimeter
  - Shower lateral compactness
- Fine lateral/longitudinal granularity
- Precision time measurement of the showers
  - Resolution: 20 ps /channel
- Contribution to the L1 trigger

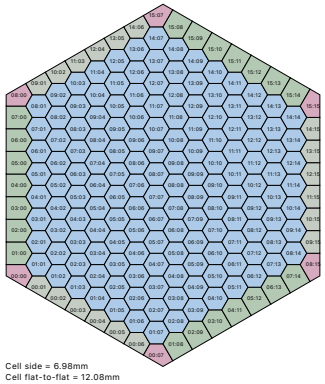
Sections

- Electromagnetic calorimeter (CE-E)
  - Si, Cu & CuW & Pb absorbers,
  - 26 layers, 27.7 χ_0 and ~1.5 λ
- Hadronic calorimeter (CE-H)
  - Si & Scintillator, stainless steel & Cu absorbers
  - 21 (7+14) layers, ~8.5 λ

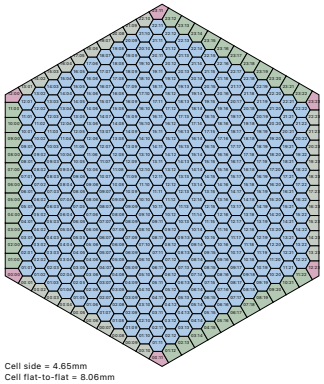




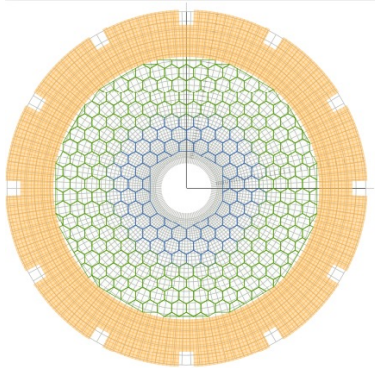
HGCAL Geometry and Parameters



(a) Low density Silicon sensors



(b) High density Silicon sensors



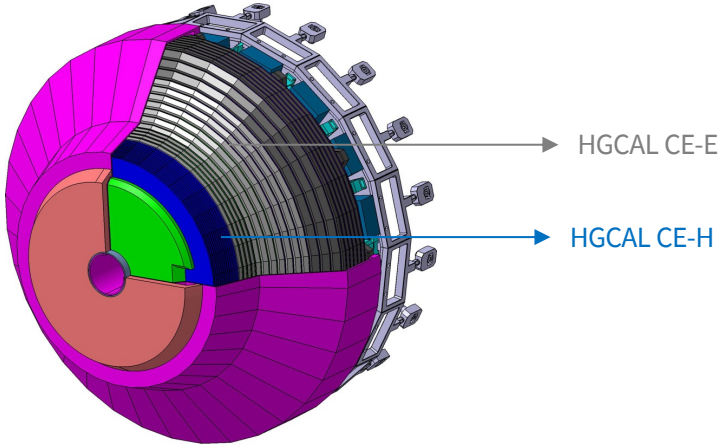
(c) Layout of a layer(38) with silicon and scintillator sensors

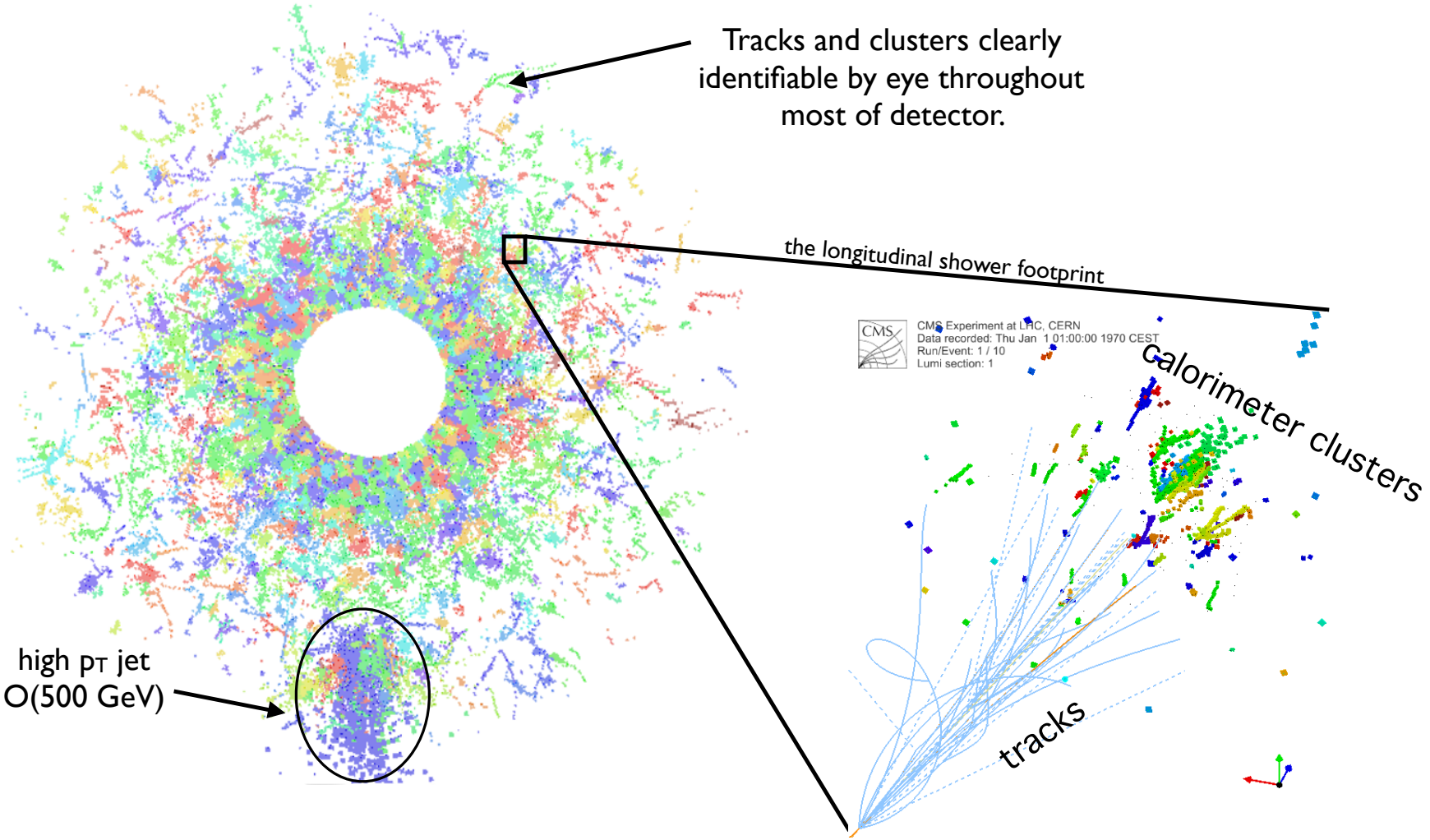
Sensors

- Silicon (120/200/300 µm)
  - Total 620 m^2
  - 0.5 – 1.0 cm^2 ⇒ 6M channels
- Plastic scintillators with SiPM readout
  - Total 370 m^2
  - 4 – 30 cm^2 ⇒ 280k channels

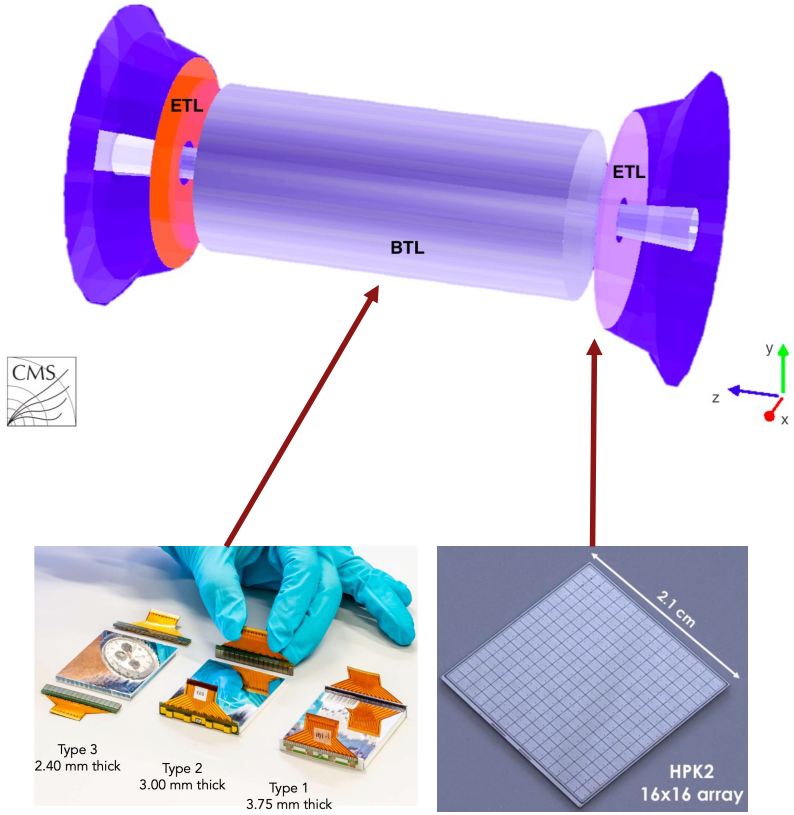
Intrinsic timing capabilities

- ~ 25 ps resolution for the HGCROC




Tracks and clusters clearly identifiable by eye throughout most of detector.
the longitudinal shower footprint
CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 10
Lumi section: 1
Calorimeter clusters
tracks
high pT jet
O(500 GeV)

MIP Timing Detector (MTD) for Phase-2 Upgrade



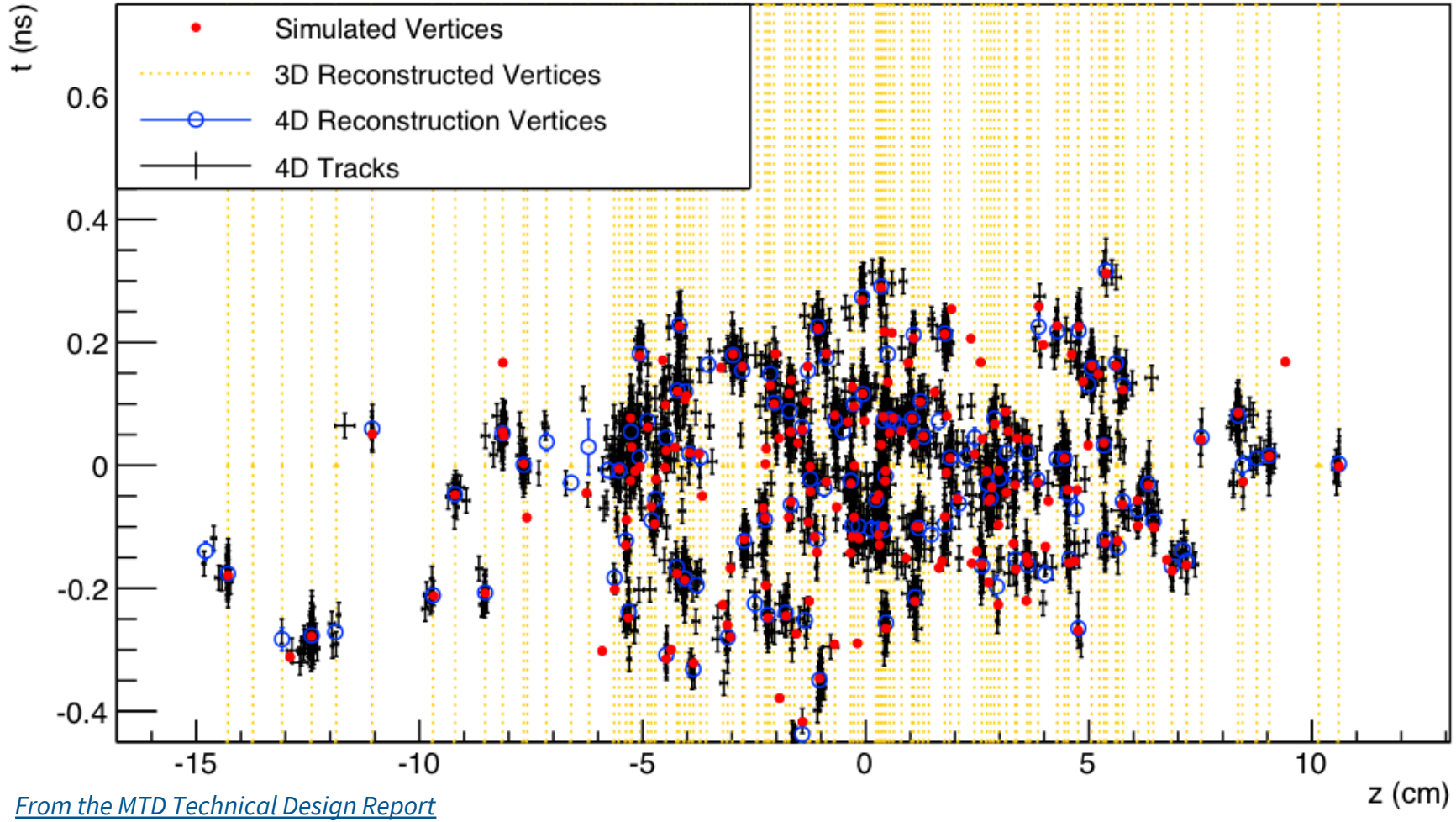
Measure the production time of minimum ionizing particles

- Longitudinal spread of bunches
- Interactions in a bunch crossing spread with rms ~ 200 ps

Motivations

- Pileup mitigation
- Searches for beyond the standard model
  - Delayed particles
  - Time-of-flight of heavy stable charged particles (HSCPs)
- Particle identification (PID) from time of flight

	Barrel Timing Layer (BTL)	Endcap Timing Layer (ETL)
Technology	LYSO crystal bars (with SiPM readout)	LGADs
Coverage in $\|\eta\|$	< 1.45	1.6-3.0
Surface area (m^2)	~38	~14
No. channels	332k	~8.5M
Fluence at 4 ab^{-1} (n_{eq}/cm^2)	2×10^{14}	2×10^{15} max



From the MTD Technical Design Report

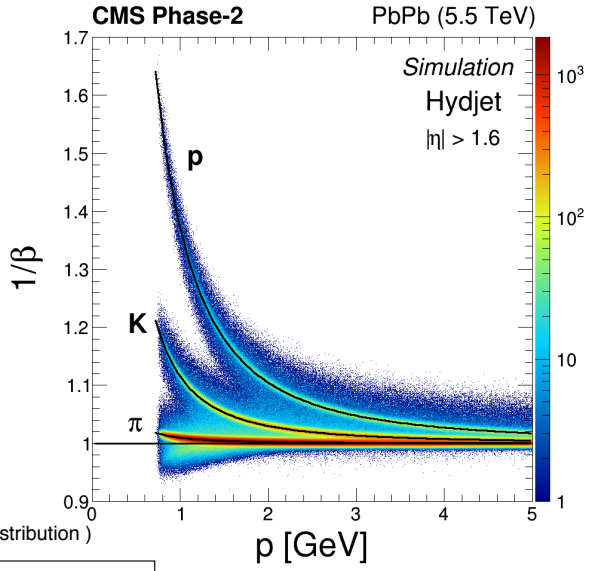
MTD Performance

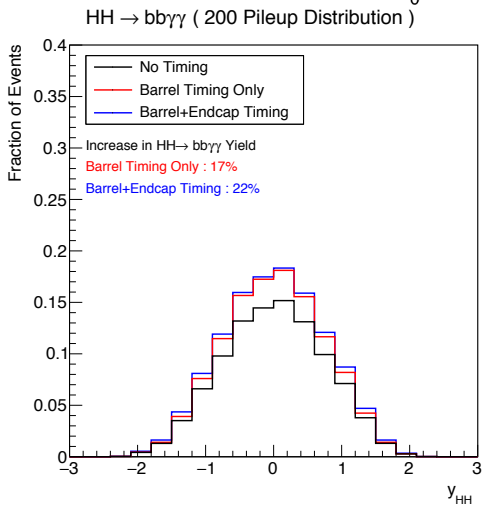
Timing resolution

- 30 – 60 ps in the barrel
- 35 ps per track in the endcap

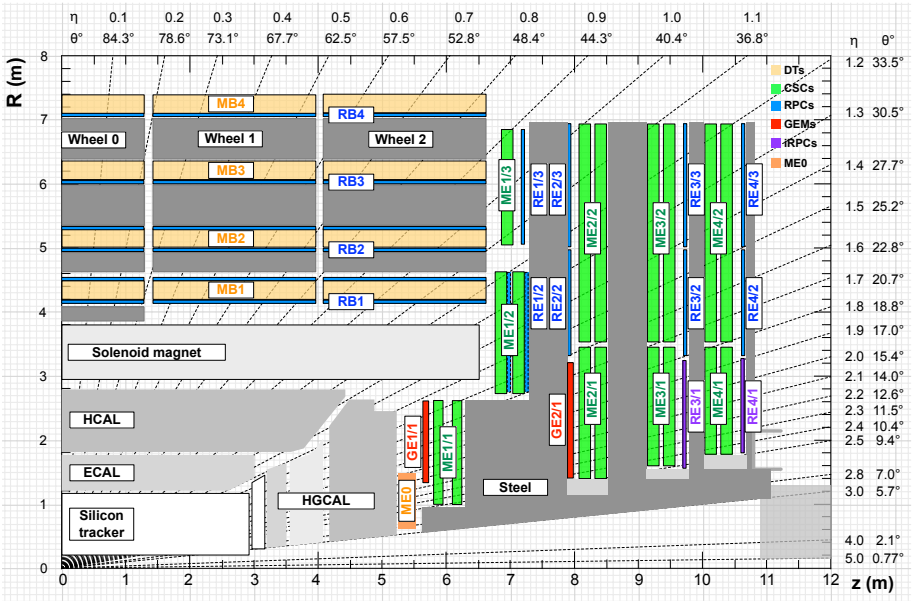
Impact on physics

- 10 – 12% improvement in p_T^{miss} resolution
  - H ⟶ ττ, BSM searches
- HH production: +20% signal yield
- PID for heavy ion physics





The Phase-2 Upgrade of the Muon Detector



Existing DT, CSC, and RPC detectors

- Upgraded electronics for HL-LHC conditions

Enhanced forward muons

- iRPC: RE3/1 and RE4/1
  - Short electrode recovery
  - Reduced total charge discharge
- GEM detectors: GE1/1 (already in) and GE2/1
  - Improved L1 μ trigger in endcap
- ME0 detector
  - Muon coverage to $|\eta|$ = 2.8:

The Phase-2 Upgrade of the Level-1 Trigger

Retain two-level trigger approach

- Level-1 + High-Level Trigger

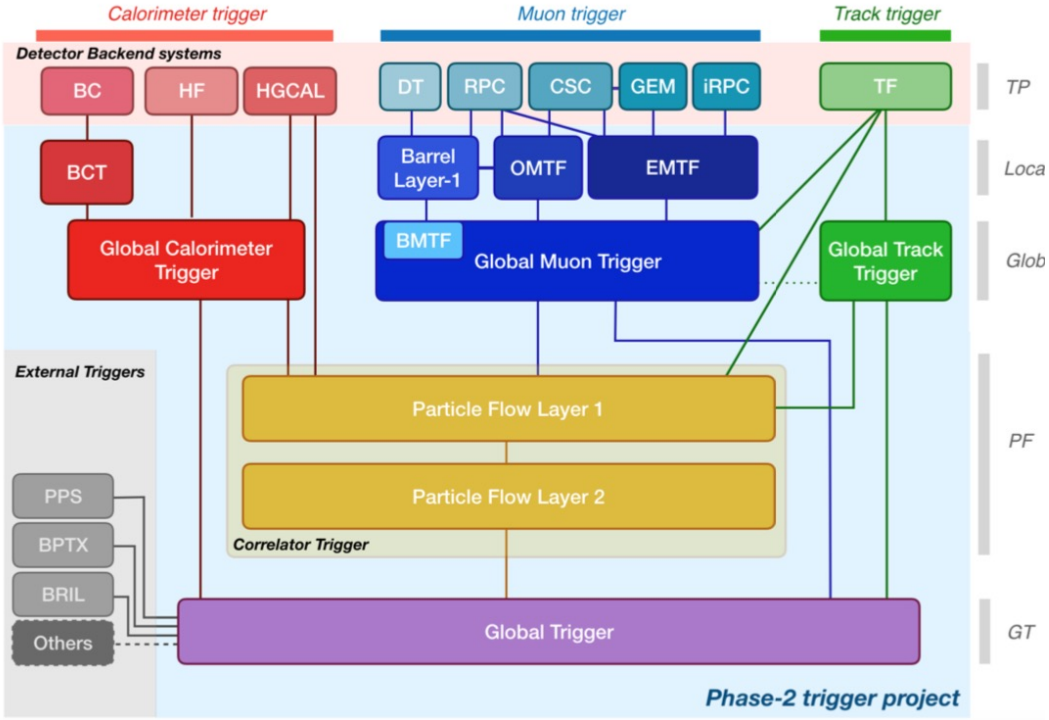
Key parameters

- Rate: 100 kHz ⟶ 750 kHz
- Latency: 3.8 µs ⟶ 12.5 µs

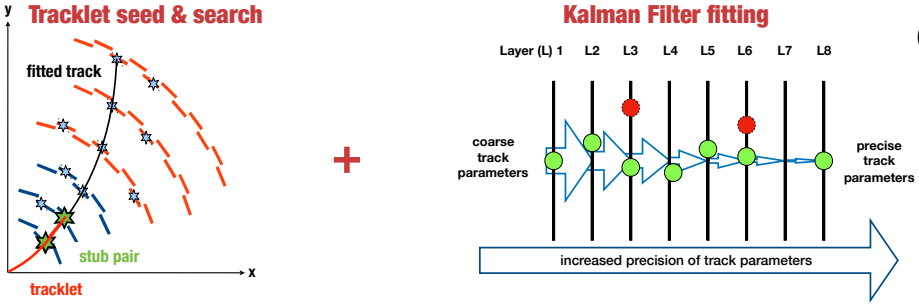
Inputs

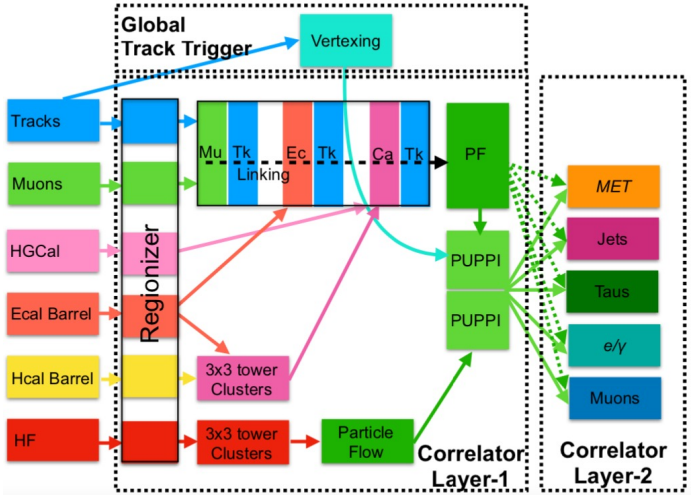
- Calorimeters
- Muon System
- Outer Tracker

Four independent
trigger processing paths



Level-1 Trigger Highlights





Charged particle track reconstruction

- Stubs from Outer Tracker
- Hybrid tracklet+KF track finder
- Extended L1 tracking for displaced trajectories

Correlator layer for sophisticated algorithms

- Particle-flow
- Machine learning

40 MHz Scouting

- Intermediate L1T data streams
- Diagnostics, monitoring and physics

The Phase-2 Upgrade of the DAQ/HLT

Data Acquisition (DAQ)

- Data pathway and time decoupling between detector readout and data reduction
- Local storage at experimental site
- Transfer to offline storage

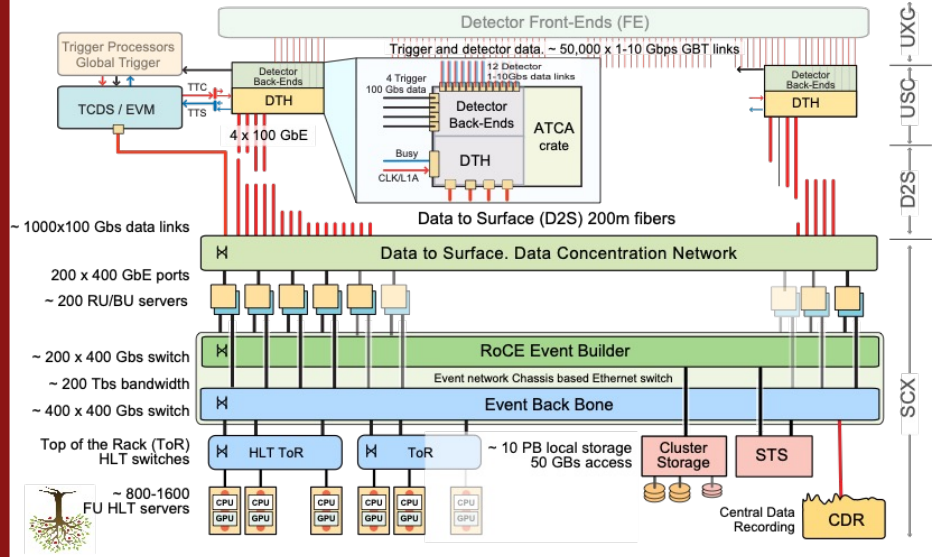
High-Level Trigger (HLT)

- Efficient selection of events of interest
- Data reduction 100:1 with respect to L1T
- Within computing resources envelope cost

Key Parameters

CMS detector	LHC Phase-1	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size at HLT input	2.0 MB	6.1 MB	8.4 MB
Event Network throughput	1.6 Tb/s	24 Tb/s	51 Tb/s
Event Network buffer (60 s)	12 TB	182 TB	379 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output	1.4 MB	4.3 MB	5.9 MB
Storage throughput	2 GB/s	24 GB/s	51 GB/s
Storage throughput (Heavy-Ion)	12 GB/s	51 GB/s	51 GB/s
Storage capacity needed (1 day)	0.2 PB	1.6 PB	3.3 PB

Phase-2 Data Acquisition System



Key parameters

- 50,000 high-speed front-end optical links
- Up to 60 Tb/s data rate
- Total event size 7—10 MB

Highlights

- Unified detector readout
  - ATCA form-factor for detector backend
- Dual-function board DTH-400
  - DAQ data aggregation
  - Timing and Trigger Control and Distribution
- Event Network
  - RDMA over Converged Ethernet
- Heterogeneous HLT nodes
  - GPU-equipped servers

Phase-2 Beam Radiation, Instr. and Lumi

Beam radiation monitoring

- Optimise protection and lifetime of subdetectors
- Both real-time and integrated fluence

Luminosity measurement

- Real time
  - Operational scenario optimisation
- Key parameter is precision:
  - 1% offline, 2% online
  - Both bunch-by-bunch lumi

	Available outside stable beams	Independent of TCDS	Independent of foreseeable central DAQ downtimes	Offline luminosity available at LS frequency (bunch-by-bunch)	Statistical uncertainty in physics per LS (bunch-by-bunch)	Online luminosity available at ~1s frequency (bunch-by-bunch)	Statistical uncertainty in vdM scans for σvis (bunch-by-bunch)	Stability and linearity tracked with emittance scans (bunch-by-bunch)
FBCM hits on pads	✓	✓	✓	✓	*0.037%*	✓	*0.18%*	✓
D4R1 clusters (+coincidences)	✓	✓	✓	✓	*0.021%*	✓	*0.07%*	✓
HFET [sum ET] (+HFOC [towers hit])	✓	*if configured*	*if configured*	✓	*0.017%*	✓	*0.23%*	✓
TEPX clusters (+coincidences)	*if qualified beam optics*	✗	*if configured*	✓	*0.020%*	✓	*0.03%*	✓
OT L6 track stubs	✗	✗	*if configured*	✓	*0.006%*	✓	*0.03%*	✓
MB trigger primitives via back end	✓	✗	✗	✓	*0.25%*	✓	1.2%	✓
40 MHz scouting BMTF muon	✓	✗	✗	✓	*0.96%*	✓	4.7%	✓
REMUS ambient dose equivalent rate	✓	✓	✓	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*

Highlights

- Luminosity measurement from IT Endcap Pixel
- Luminosity readout from OT stubs at 40 MHz
- New lumi detector: Fast Beam Conditions Monitor
- New system of neutron monitors

State of the CMS Upgrade – Highlights

Tracker

- Outer Tracker: about to start module production
- Inner Tracker: ASIC final and in production

HGCAL

- Considerable progress on mechanics
- SiPM, scintillator production started – 40% of the sensors received

MTD

- Barrel: about to start module production
- Endcap: sensor procurement review in July; ASIC functionality proven

Muon Detector

- RPC and GEM chambers production ongoing

Conclusions

The high-luminosity configuration paves the way for the full exploitation of the LHC.

- Complete the cycle LEP ⟶ LHC ⟶ HL-LHC

Full luminosity needed for the most extensive searches and most precise measurements.

- Elucidation of the EWSB and of the Higgs boson characteristics

The HL-LHC conditions will be the harshest to date.

- Event rate, pileup, radiation

The CMS Phase-2 Upgrade will allow us to profit from the HL-LHC era.

- Keep (and improve) the high performance delivered in Phase-1

Thanks!

References

- High Luminosity LHC Technical Design Report: https://cds.cern.ch/record/2284929
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