Overview of the Phase 2 upgrade of CMS detector

9th April `24

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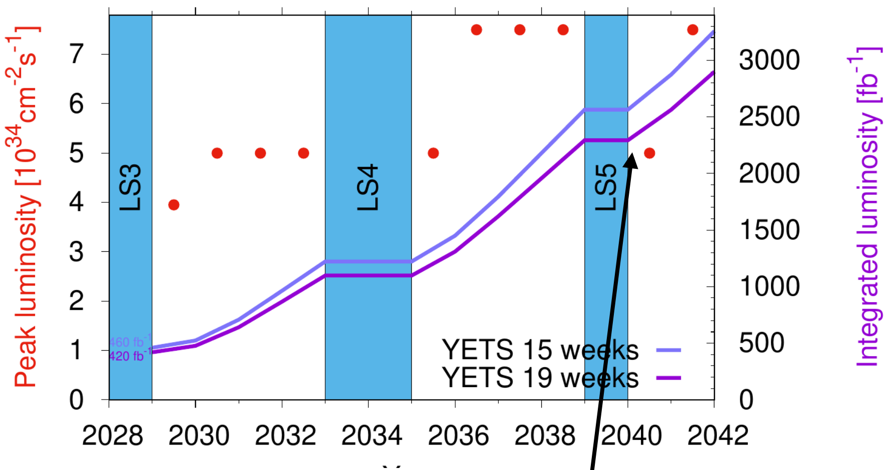
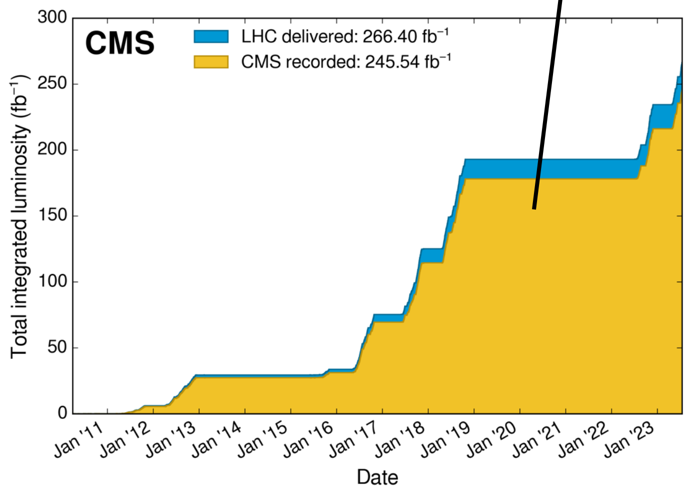
on behalf of **CMS** collaboration

We are living in the dark

- What causes particles to possess their specific masses?
- Is it possible that multiple types of Higgs bosons exist?
- What is the reason for the existence of three particle generations?
- Through what mechanism do neutrinos acquire mass?
- Is there a particular scale at which the four fundamental forces merge?
- Does gravity hold a unique status among the fundamental forces?
- Why is there CP violation?
- What has happened to all the antimatter that should exist in the universe?
- Does dark matter truly permeate the universe?
- Is dark energy a component of the cosmic landscape?

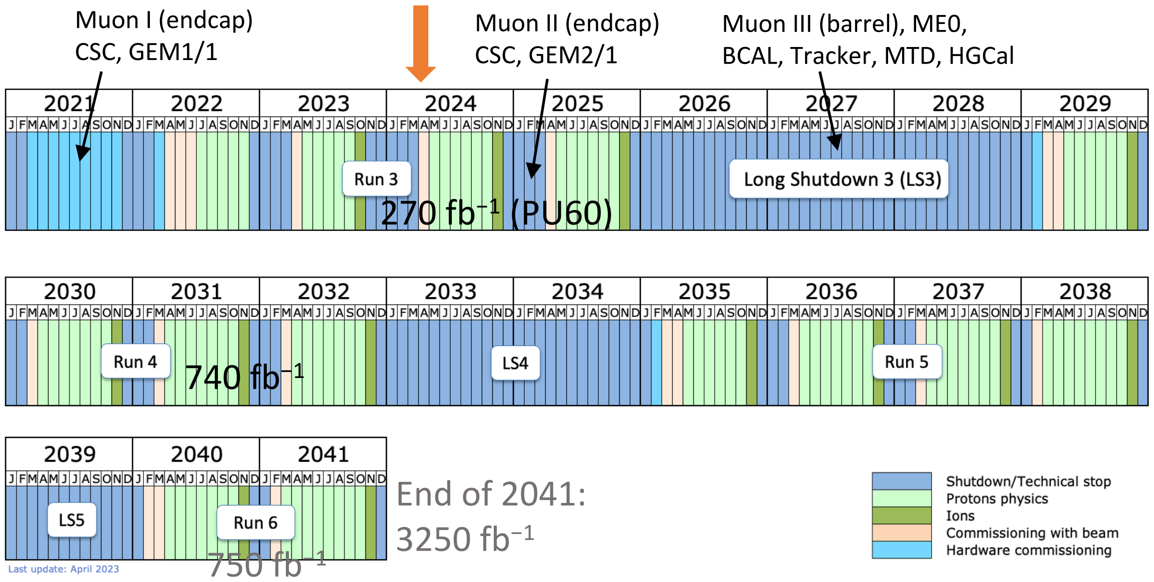
High Luminosity LHC (A Torch)





LHC and injectors will undergo significant upgrades to boost beam intensity.

- **Instantaneous luminosity ($\mathcal{L}_{inst}$) 5-7x10^{34} cm^{-2} s^{-1}**
- $\int \mathcal{L}\, dt$ = 3 ab^{-1} is the ultimate integrated luminosity goal.



HL-LHC to operate from 2029, for 10 years or more…

End of 2038: 2500 fb^{-1}

End of 2041: 3250 fb^{-1}

Opportunities at High Luminosity LHC (HL-LHC)

- **Standard Model:**
  - Precise measurements and Constraints within the Standard Model.
- **Higgs Physics:**
  - Detailed analysis of the properties of the Higgs boson.
  - Search for new phenomena in the Higgs sector.
- **BSM Searches:**
  - Supersymmetry
  - Long-lived particles
  - Dark Matter
  - Heavy Resonances
- **Flavor:**
  - CKM metrology and QCD spectroscopy
  - Rare decays → Flavor anomalies
- **Heavy Ions:**
  - Precision study of material properties of QCD media.
  - Study HI-like behavior in small systems (pp and pA).

3 Billion top/exp

Higgs Factory:
150 Million Higgs and 120k HH

Novel approaches, better detectors: stringent tests of BSM scenarios

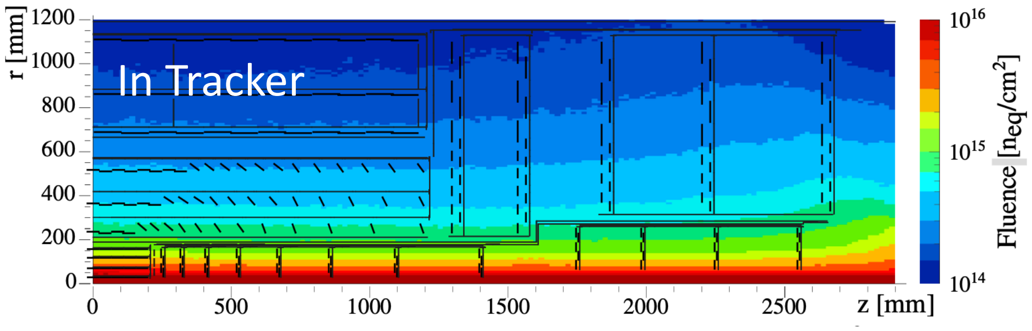
Low-P_T/high-P_T complementarity

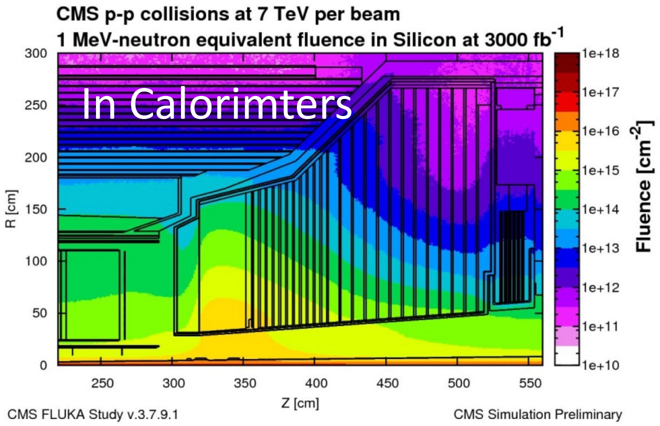
Precise differential measurements

Challenges at High Luminosity LHC

Expect unprecedented amount of radiation

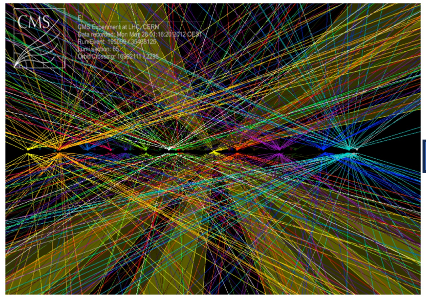
- doses of up to **1 Grad**
- fluences up to **2 × 10^{16} n$_{eq}$/cm^2**
- Rate up to **3 GHz/cm^2**

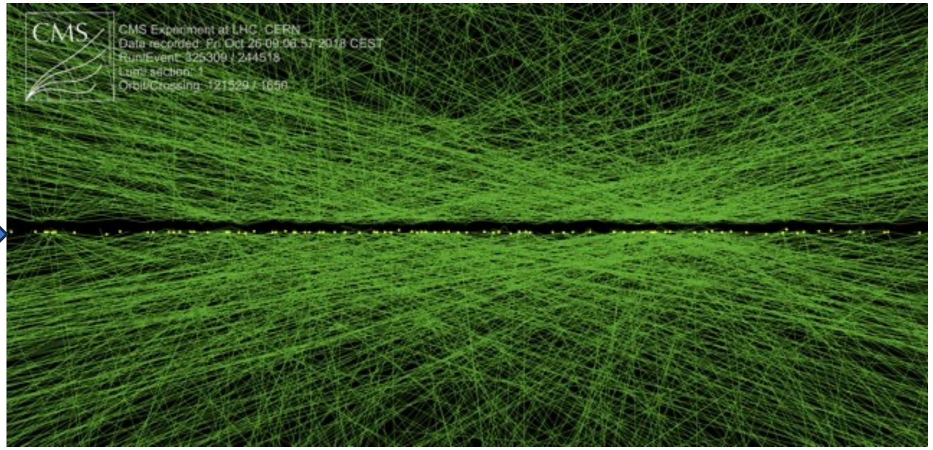




High Pile-up

- Luminosity levelling with **up to 200 pp interactions per bunch crossing** every 25 ns (40 MHz) **3-4 times current LHC Runs**.
- **Vertex and track** reconstruction algorithms **less discriminating**.
- Existing trigger and readout bandwidth constraints imply **tighter selection** requirements to increase purity at the cost of signal acceptance.

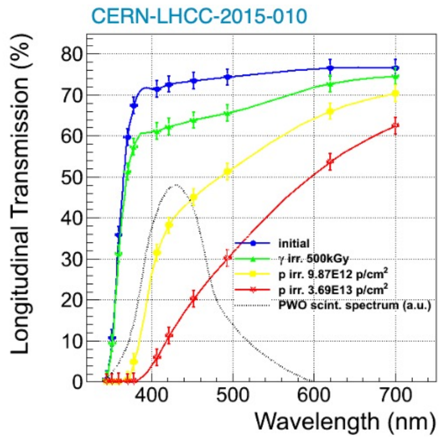


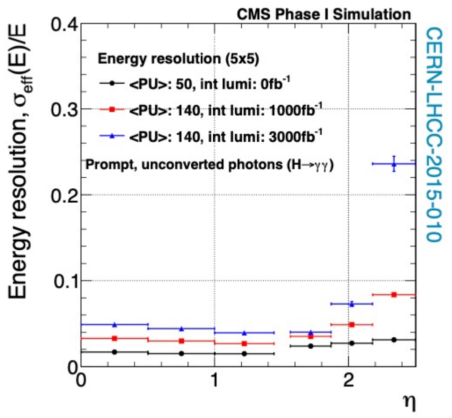


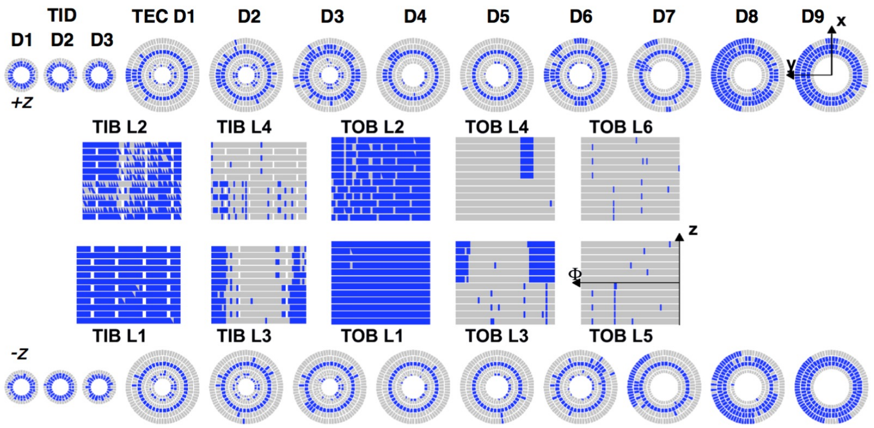
Challenges at High Luminosity LHC

Accelerated aging:

- Materials used in detectors must be capable of enduring **ten times higher levels of dose and fluence**.
- It is necessary to **preserve the optical transparency** of scintillators.
- There's a need to **control leakage current** and **charge trapping in silicon detectors**, as well as the **dark count rate in silicon photomultipliers**.
- Management of **single event upsets** in front-end ASICs is crucial.



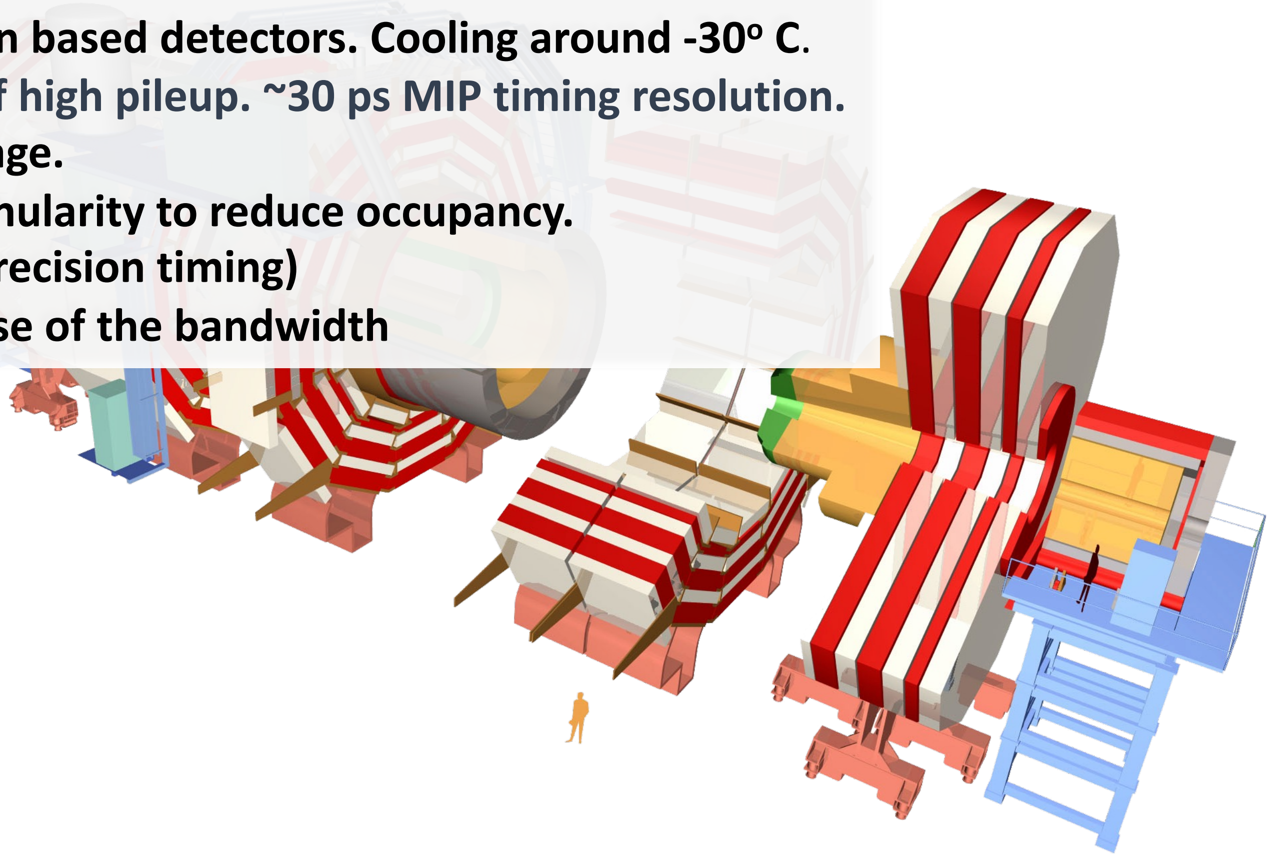




Detector design and technology requirements

HL-LHC conditions require significant upgrades of the detectors.

- **Radiation hardness. Silicon based detectors. Cooling around -30^{o} C.**
- **Mitigate physics impact of high pileup. ~30 ps MIP timing resolution.**
- **Higher geometrical coverage.**
- **Higher resolution and granularity to reduce occupancy.**
- **More information (*e.g.*, precision timing)**
- **Higher data rate, better use of the bandwidth**



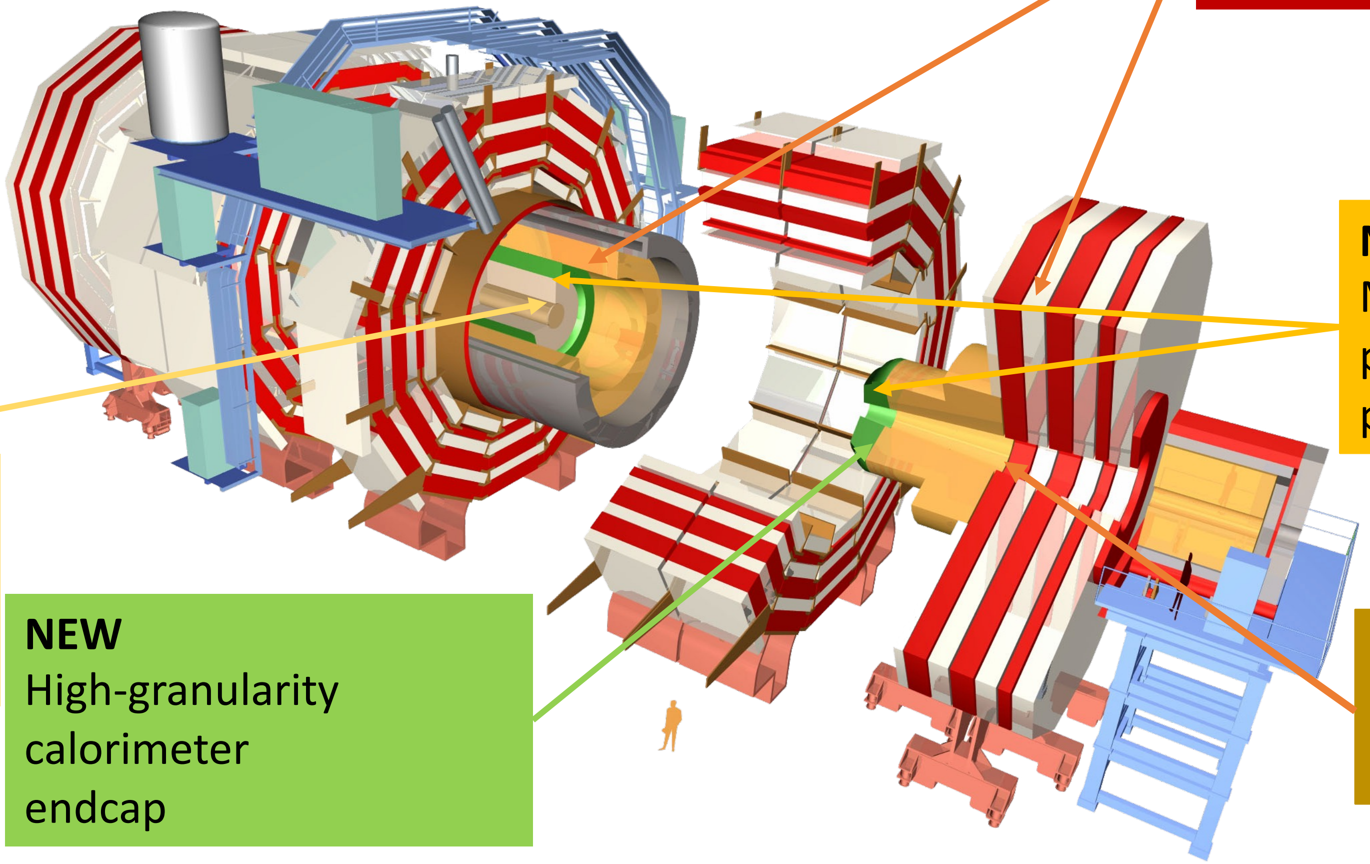
CMS detector upgrade in a nutshell

Upgraded Trigger and Data Acquisition system:

- Tracking in L1 at 40 MHz. Output rate 750 kHz.
- Latency 12.5 μs, longer pipelines.
- High Level Trigger output 7.5 kHz

Trigger requirements are driving most of the electronics upgrades

Electronics upgrade: Barrel Calorimeter and muon system



NEW
MIP Timing detector precision timing for pileup mitigation

NEW
Inner Tracker, coverage up to |η|= 3.8, reduced material

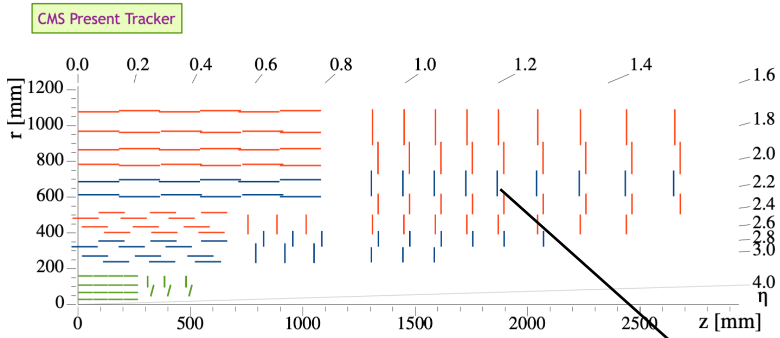
NEW
High-granularity calorimeter endcap

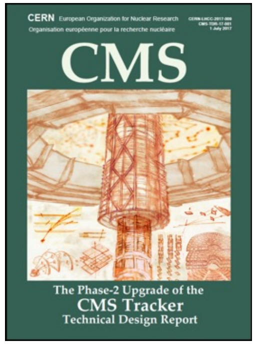
NEW
Muon detector
GEM/RPC 1.6<η<2.4

Challenge: **cold operation**
→ bi-phase CO_2 cooling at −35º C

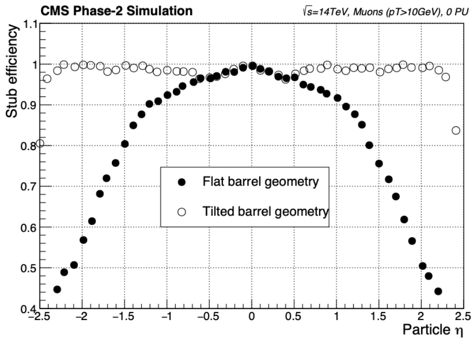
https://cds.cern.ch/record/2272264

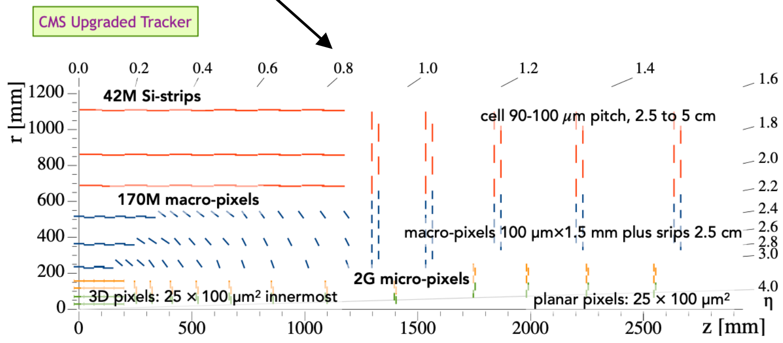
Tracker Upgrade I

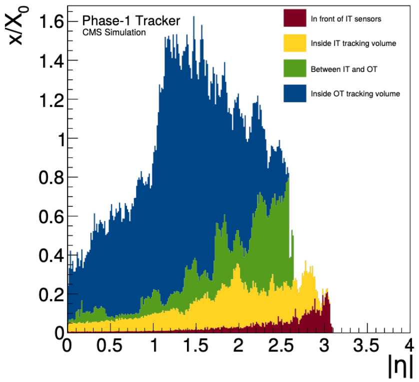


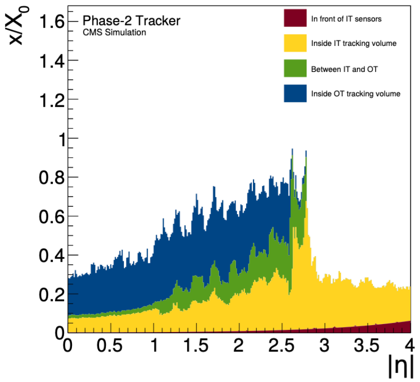


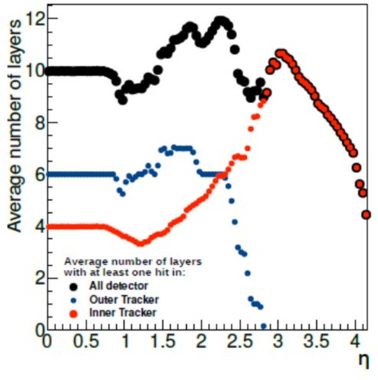
- The **entire silicon tracking system**, presently consisting of pixel and strip detectors, **will be replaced**.
- **The new tracker will feature**
  - increased forward acceptance **(|η|< 4)**
  - increased radiation hardness (fluences up to **2.3×10^{16} n_{eq}/cm^2 in pixel layer 1**)
  - higher granularity (**occupancy < 1%** in all tracker regions)
  - compatibility with **higher data rates and a longer trigger latency**.
- In addition, the **tracker will provide tracking information to the L1 trigger**, information presently only available at the HLT.











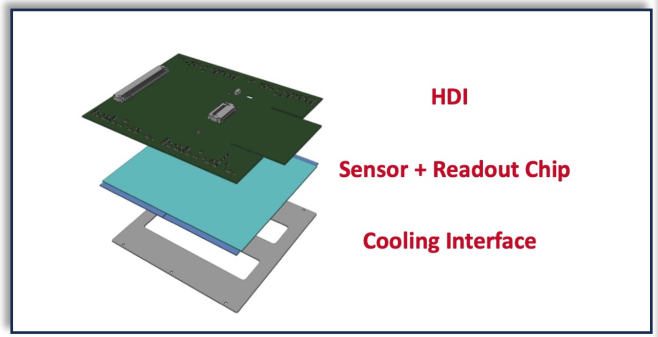
Tracker Upgrade II (Inner Tracker)

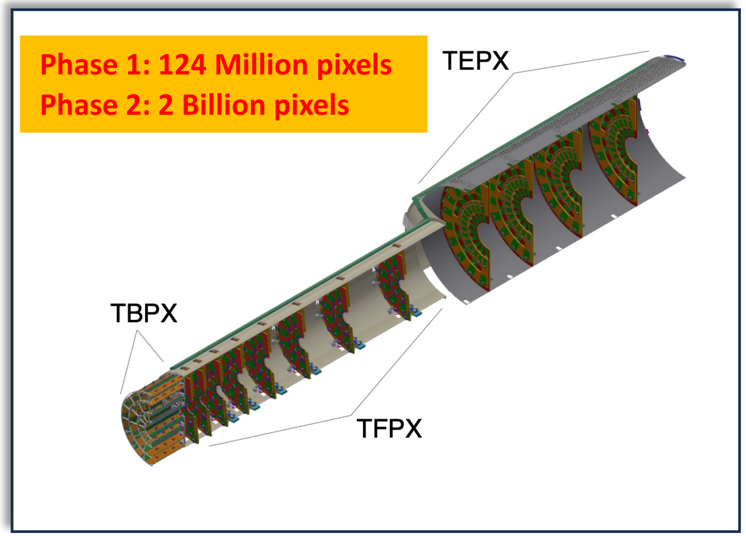
Increased granularity keeping occupancy at the per-mil level

Innermost layer: 3 GHz/cm^2

→ **new 65-nm technology** ASIC (RD53) enabling 25 × 100 μm^2 pixels

→ **3900 Modules, 4.9 m^2 pixel area**



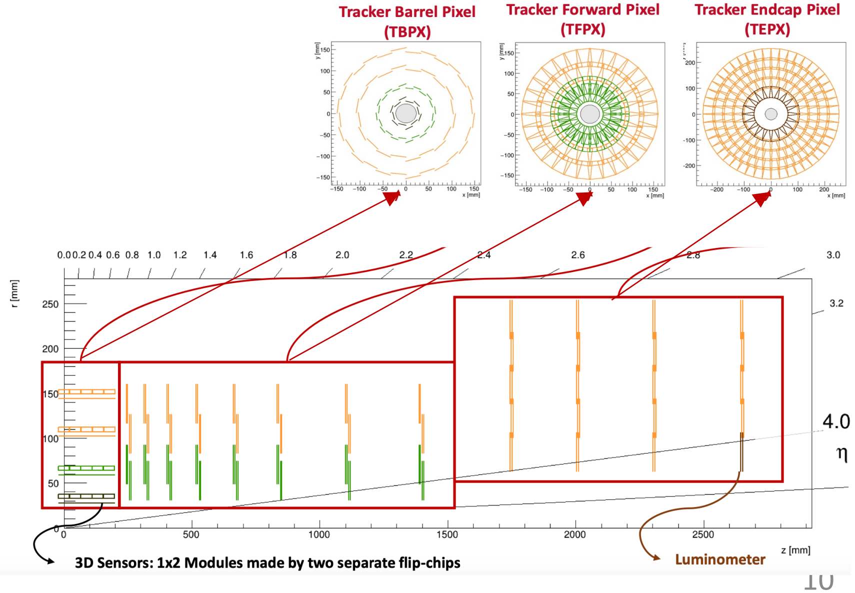


Sensors

- **3D** in TBPX L1, **planar** elsewhere
- **good radiation hardness, power consumption, cooling efficiency**
- **150 μm active thickness**

Mechanical structure designed for easy installation and **removal**

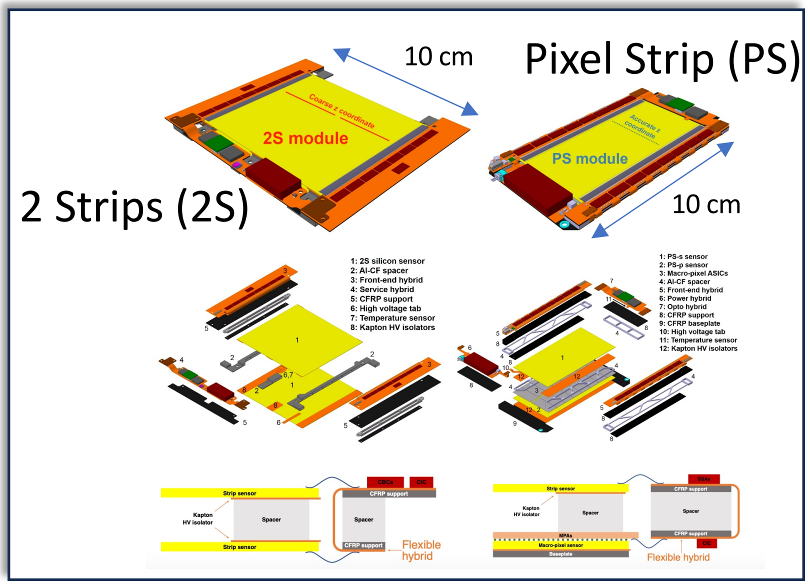
→ possibility to **replace damaged parts (New)**



TEPX Luminosity triggers (dedicated trigger stream, 75 kHz)

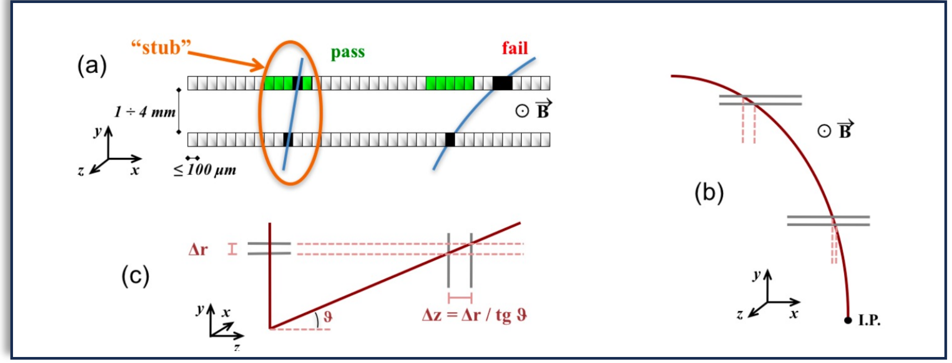
TEPX-D4-R1High-precision Luminosity triggers for real-time cluster counting (dedicated board with FPGA, 825 kHz)

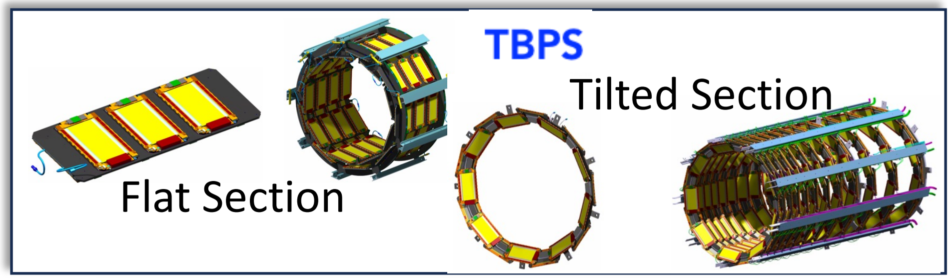
Tracker Upgrade III (Outer Tracker)



p_T module concept

- **Exploit** bending of charged particle tracks in CMS' **4T B-field.**
- **Correlate hits** from 2 closely spaced sensors to form **"stubs"** compatible with a track **p_T > 2 GeV**.
- **Tuneable offset and window** for homogeneous p_T threshold throughout the Outer Tracker.



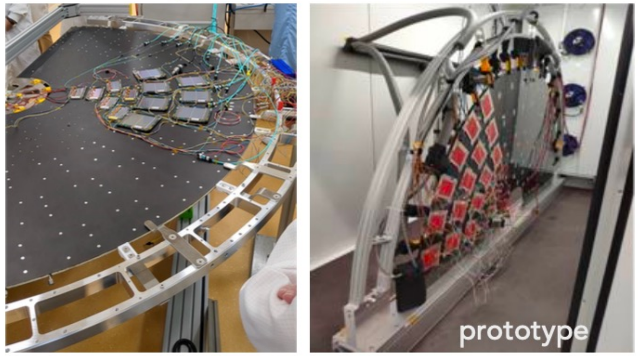


Tracker input to the L1 trigger

- **Stub information is sent** out at BX frequency of **40 MHz.**
- Full data read-out at **~750 kHz**

Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		**2872**	**4464**	**5960**	**13296**	

OT endcap dees



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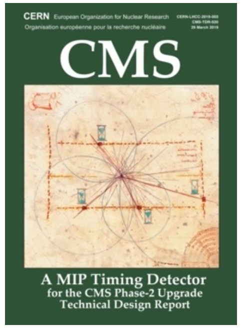
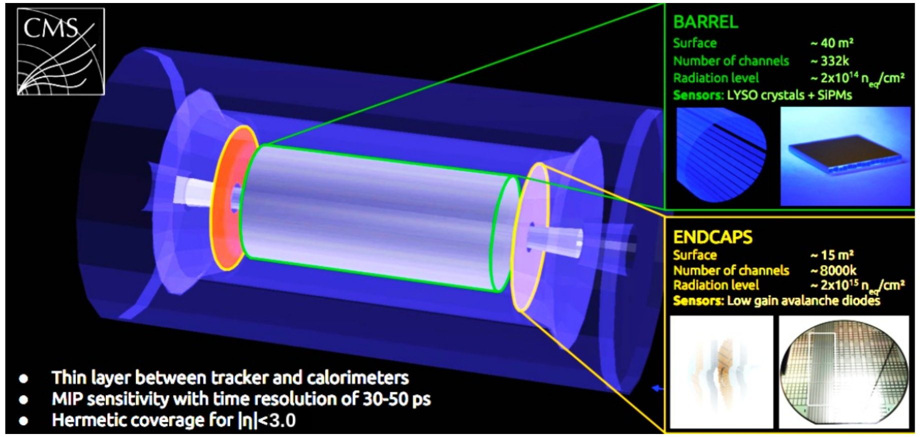


MIP Timing Detector (MTD) I

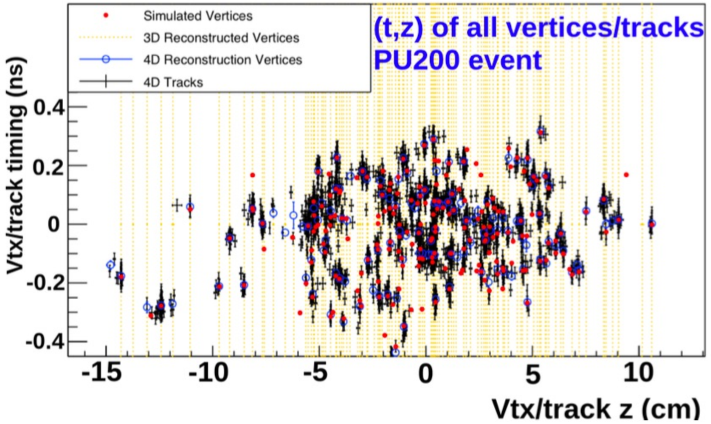
- **Thin layers between tracker and calorimeters**

- **MIP sensitivity with 30ps** time resolution at HL-LHC start (< 60ps at 3000 fb^{-1}) Hermetic coverage for $|\eta|<3.0$



Barrel - BTL

- Surface **~40m^2**
- Number of channels **~332k**
- Radiation levels ~**2*10^{14} n$_{eq}$/cm**^{2}
- Sensors: **LYSO crystals+SiPMs**



LYSO = Lutetium-Yttrium Oxyorthosilicate
SiPM = Silicon Photomultiplier
MIP = Minimum Ionising Particle
LGAD = Low Gain Avalanche Diode

4th Dimension for PU mitigation

Endcap - ETL

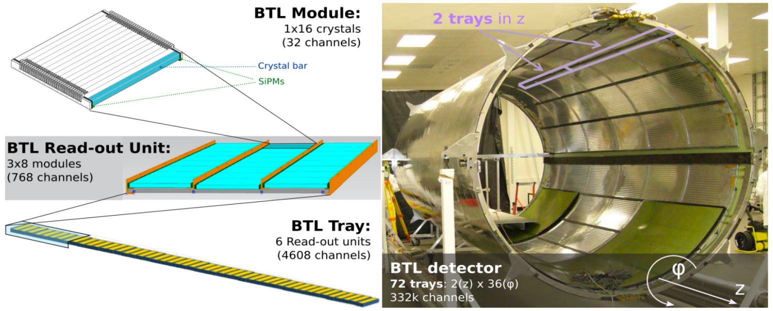
- Surface **~15m^2**
- Number of channels **~8.5 Million**
- Radiation levels ~**2*10^{15} n$_{eq}$/cm^2**
- Sensors: **LGAD (Low gain avalanche diodes)**

MIP Timing Detector (MTD) II

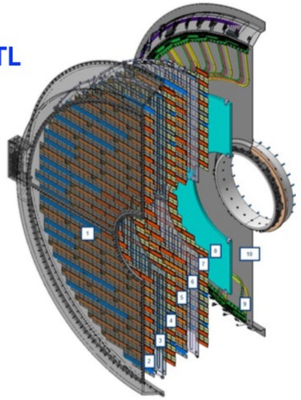
The MTD uses well-established technologies

- **Barrel:**
  - **LYSO crystals coupled to SiPM**.
  - Time resolution better than **70 ps till end of life**.
- **Endcap:**
  - **Planar silicon devices with internal gain**, Ultra Fast Silicon Detectors (UFSD).
  - **LGAD time resolution better than 50 ps** at end of life with 600V bias.

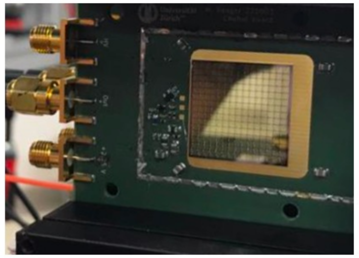
BTl

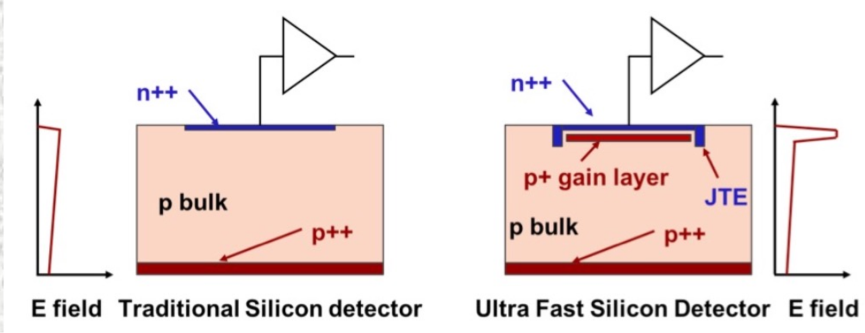


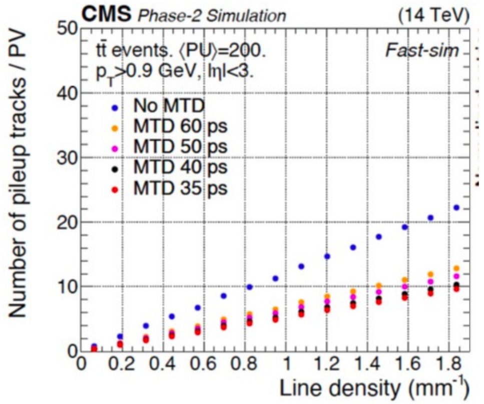
ETL

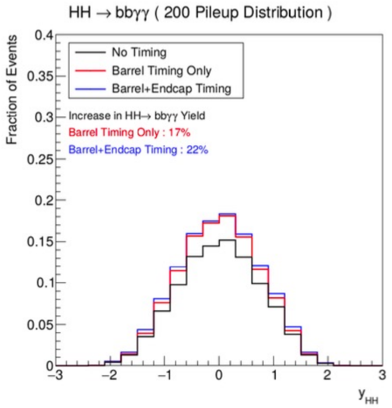


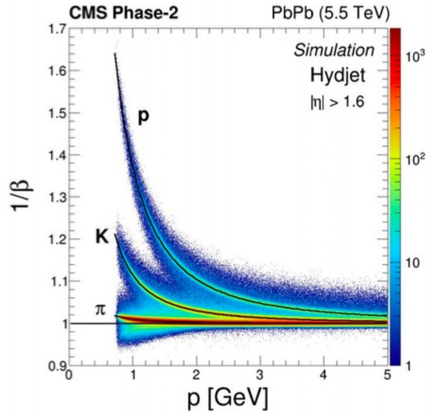
full-size LGAD sensor
(8.5 M channels)











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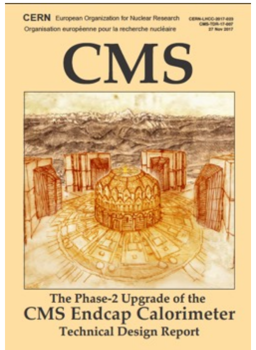


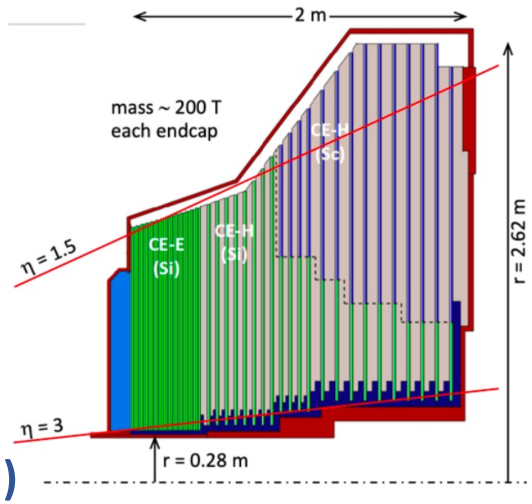
High Granularity Calorimeter (HGCal) I

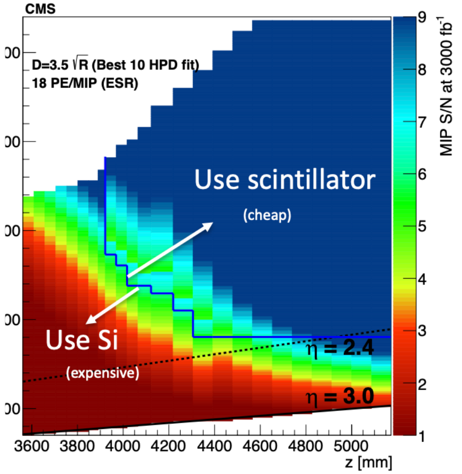
New endcap calorimeter of CMS, Adapts CALICE developments:

- Need to **replace ECAL crystals and HCAL scintillators** as they were designed for 500 fb^{-1}
- Need to **improve jet energy resolution**

- **Maximize granularity** to fully exploit CMS Particle Flow reconstruction
  - **fine lateral granularity**
    - two-shower separation + narrow jets observation
    - minimize pileup contribution to energy measurements
  - **fine longitudinal granularity**
    - **electromagnetic energy resolution** (e.g. for H →γγ)
    - **pattern recognition**
    - **discrimination against pileup**
  - **Fully utilise timing** (real novelty in calorimetry!)
  - **Use information at trigger level**

A 5D imaging calorimeter





Electromagnetic (CE-E)

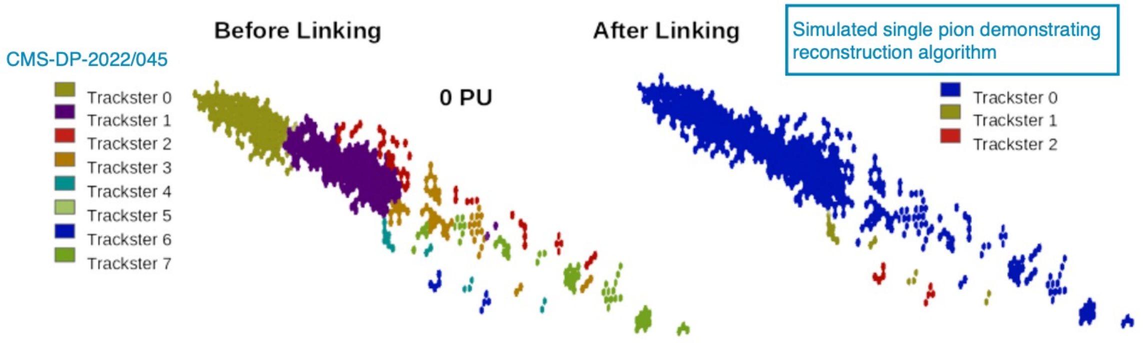
- Cu/CuW/Pb absorbers
- Si sensors, hexagonal modules
- 26 layers
- 25.5 Xo and 1.7 λ

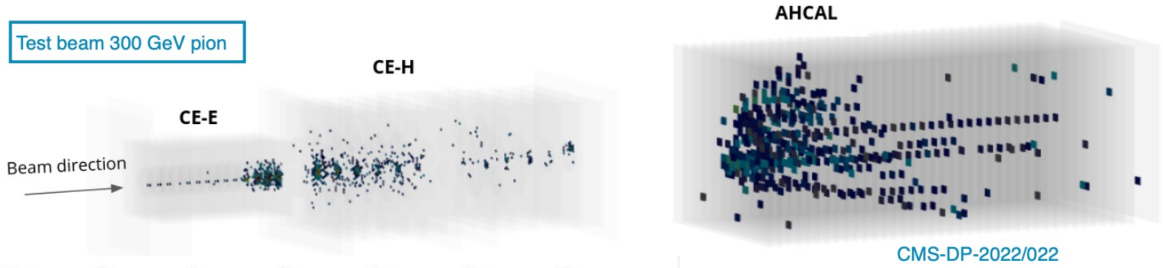
Hadronic (CE-H)

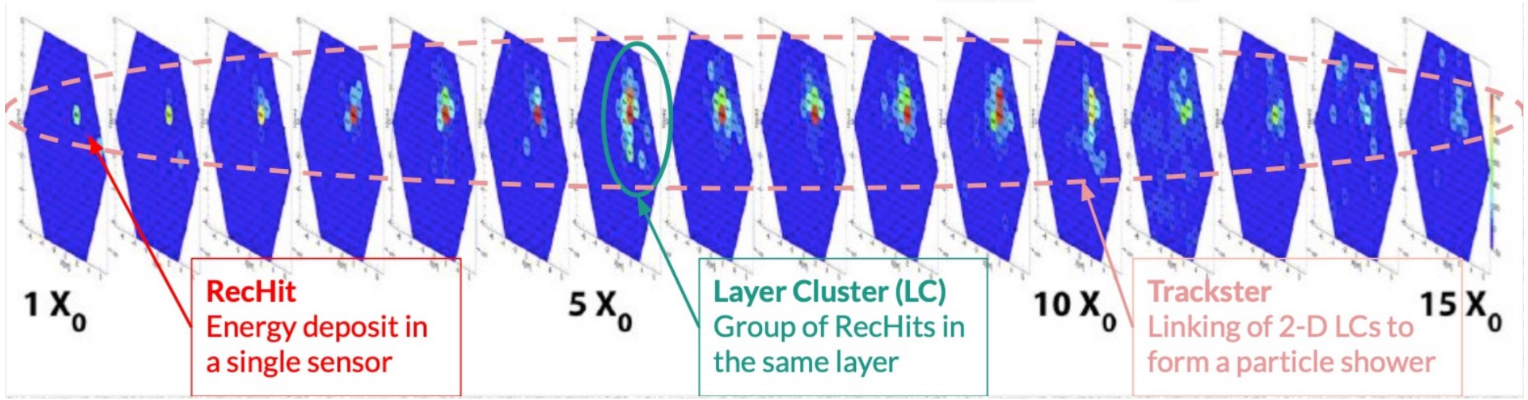
- steel absorbers
- High-radiation regions: Si sensors
- Low-radiation regions: scintillation tiles with SiPM readout
- 21 layers
- 9.5 λ (including CE-E)

High Granularity Calorimeter (HGCal) II

- **The Iterative Clustering (TICL)** is a modular framework integrated and under development in CMS software.
- Main purpose: processing calo **5-D rechits (x, y, z, t, E)** and returning particle properties and probabilities.
- **In a nutshell: grouping 2-D Layer Clusters into 3-D** clusters (Tracksters) iteratively to reconstruct different particle species using different seeding inputs







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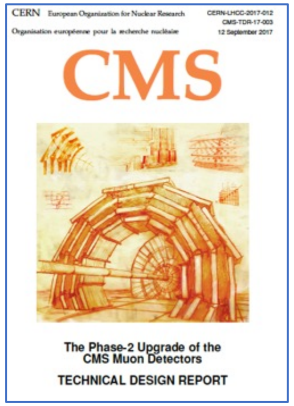
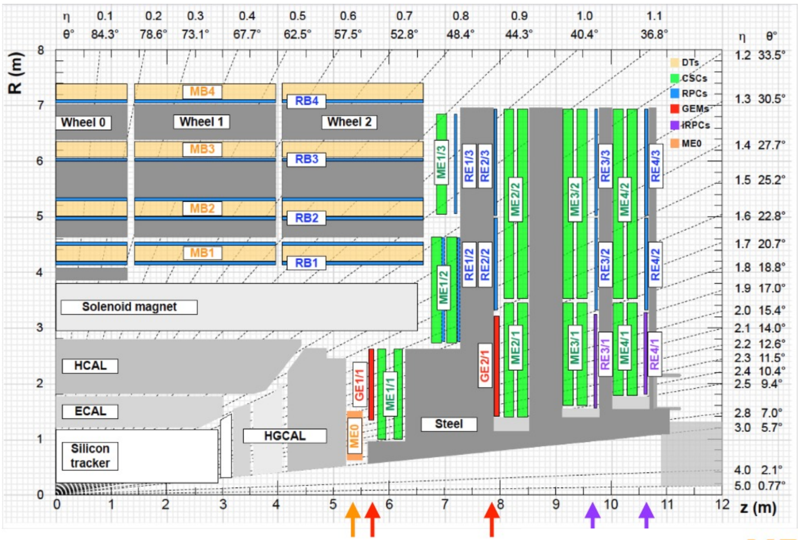
Muon System Upgrade I

- **Current muon detectors are expected to withstand HL-LHC radiation levels.**
- **Upgrading/replacing the electronics** of the existing DTs, CSCs and RPCs to ensure longevity and improve trigger performance.
- **Drift Tubes barrel chambers:** 40 MHz readout with improved z/t-precision
- **RPC Resistive Plate Chambers:** readout with improved t-precision
- **CSC Cathode Strip Chambers:** readout with higher bandwidth and latency in ME234/1 using current ME1 and replace ME1 with higher radiation tolerance components
- **New stations:**
  - – 2-layer **GEM stations: GE1/1, GE2/1**,
  - – iRPC: **RE3/1, RE4/1**, 1.6 ≤ η ≤ 2.4
  - – 6 Layer GEM station: **ME0 extended coverage** 1.15 ≤ η ≤ 2.8





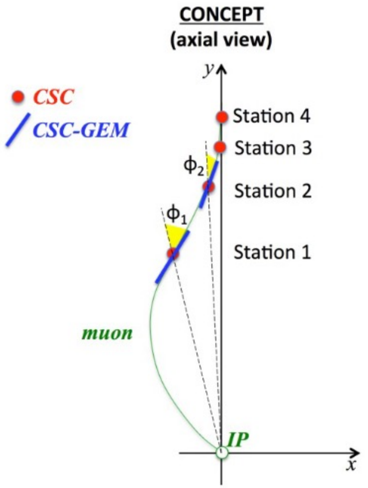
GE1/1 (LS2)

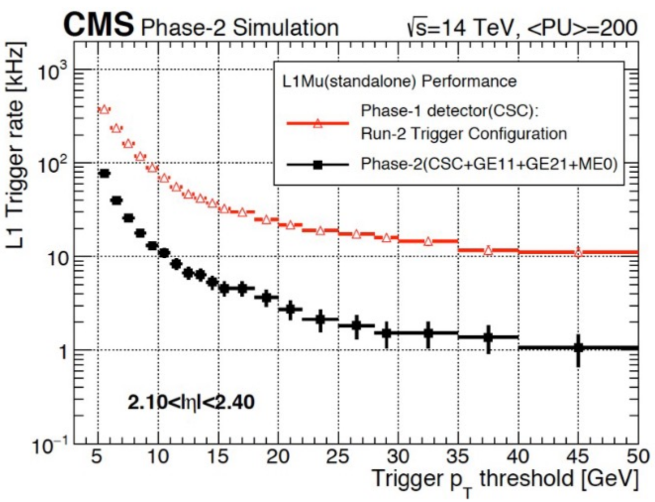
ME0

GE2/1

iRPC

Muon System Upgrade II

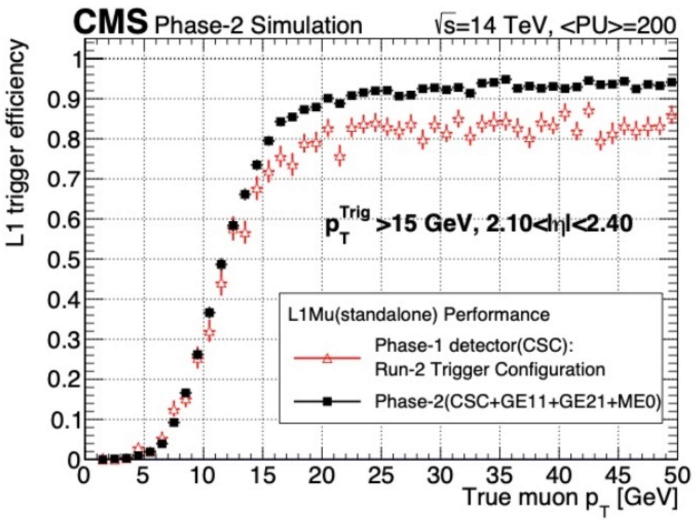


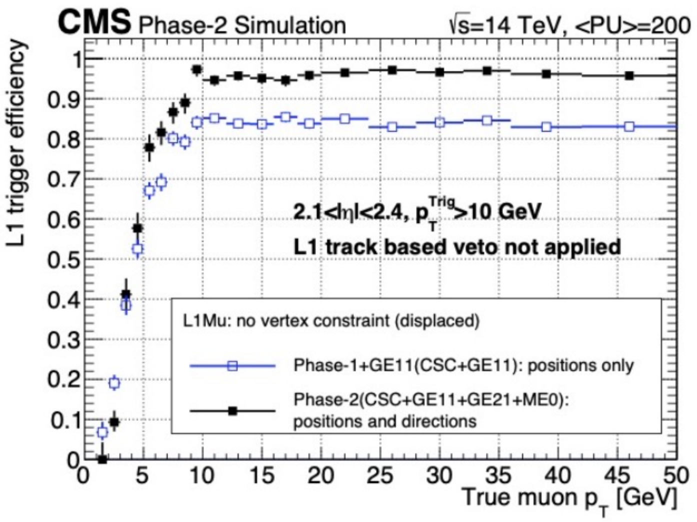


2 GEM/CSC "tandems"

- Measurement of **"local" μ direction** (sensitive to p_T)
- **Standalone L1-trigger** rate drops by factor up to 10
- Important for **off-pointing muon triggers** (search for LLPs)

L1 Muon trigger efficiency for the **prompt muon trigger (left)** and **displaced muon trigger algorithm (right)**, as a function of a true muon p_T in the region $2.1 < |\eta| < 2.4$. The L1 trigger p_T threshold is 15 GeV (left) and 10 GeV (right).





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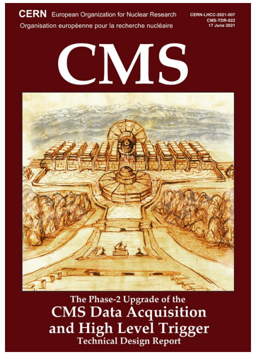
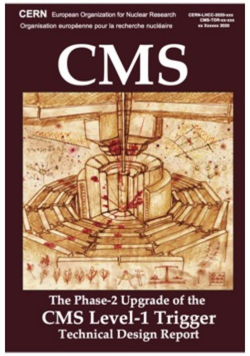
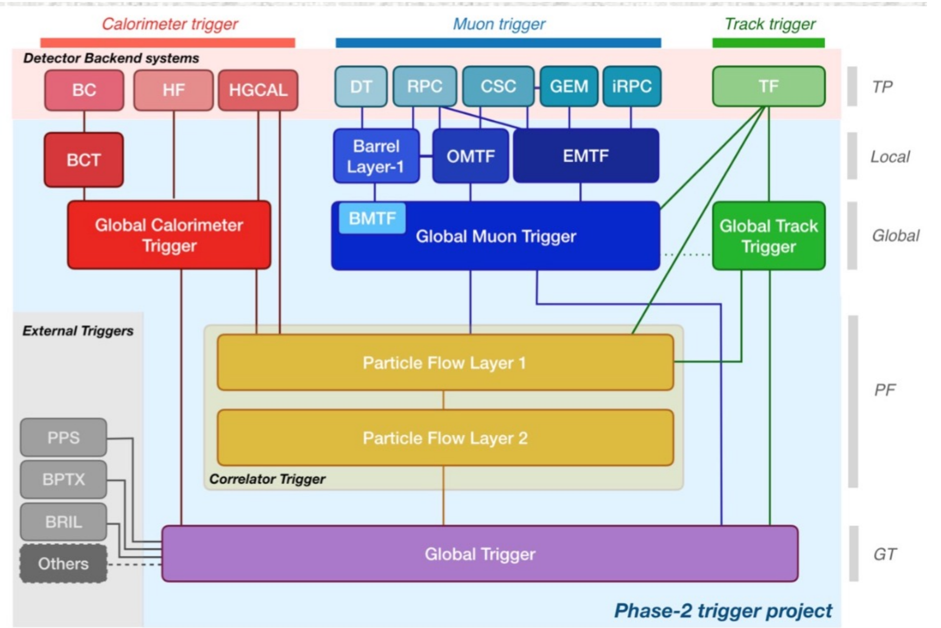
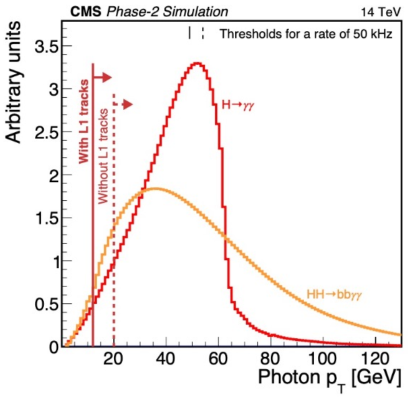


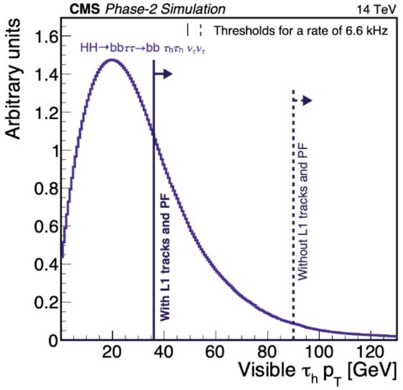


Trigger Upgrade

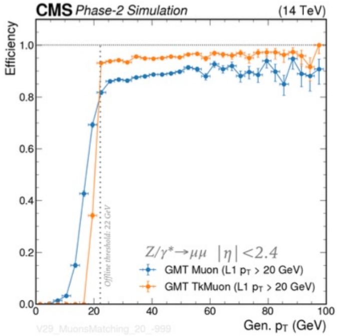
- **Increase trigger acceptance and physics sensitivity while maintaining Run 2 thresholds.**
- **Key features:**
  - **Increased bandwidth:** 100 kHz → 750 kHz
  - **Increased latency:** 3.8 µs → 12.5 µs
  - **Tracker information** (p_T > 2 GeV)
  - **Higher granularity in calorimeters and muon system**
  - **Particle flow layers:** FPGA-based algorithms using PF and ML
  - **40 MHz Scouting HL-LHC data:** storing only high-level information.

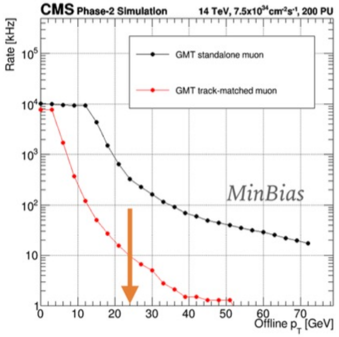




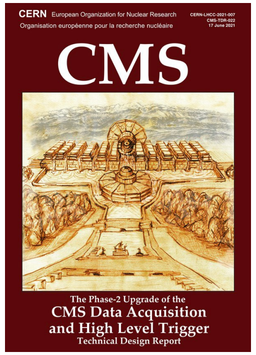


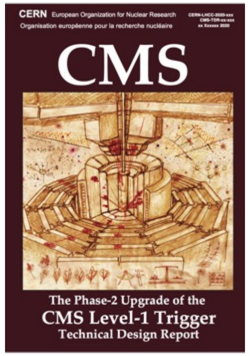
L1 Muons w/o track trigger info





https://cds.cern.ch/record/2759072 https://cds.cern.ch/record/2714892

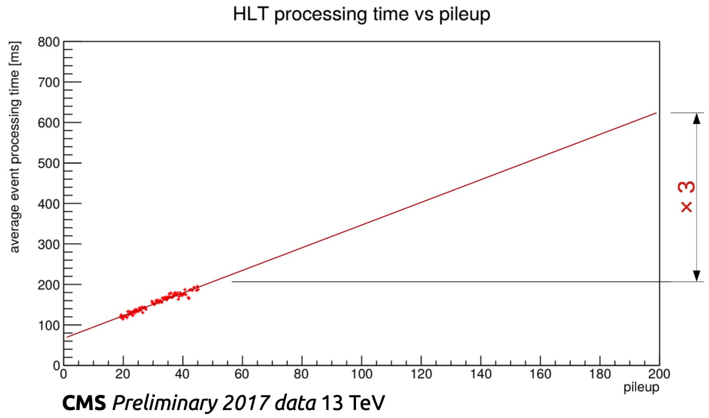


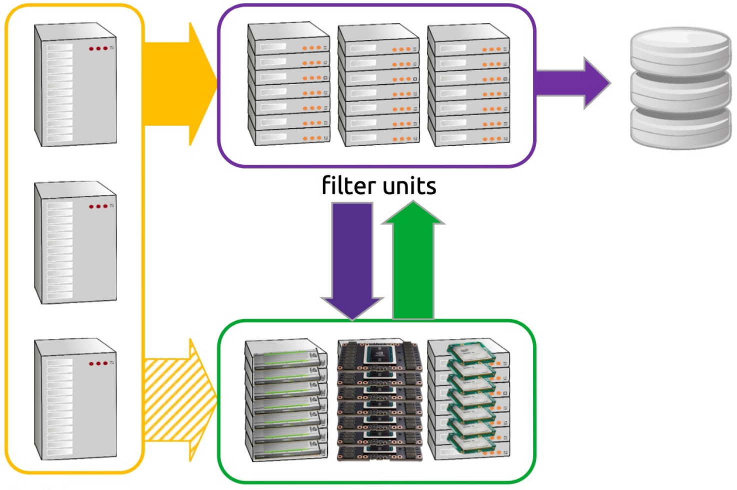


Trigger Upgrade

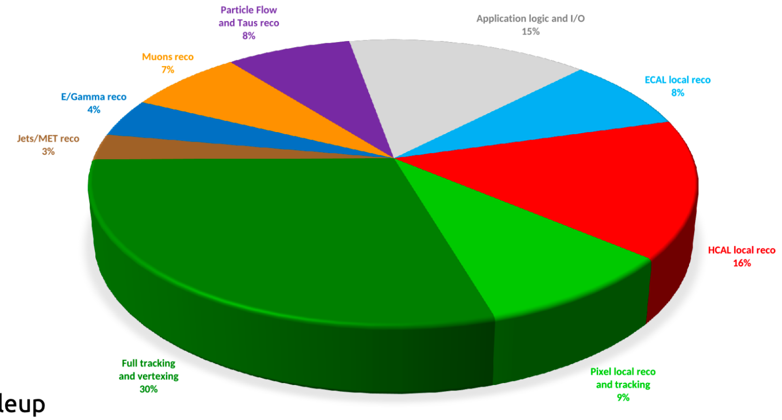
- **“Phase 2” HLT resource needs**
  - Optimistically … **× 30**

- **Key features:**
  - Reconstruct pixel-based tracks and vertices on the **GPU**
  - Leverage existing support for **threads and on-demand reconstruction**
  - **Minimise data transfer**





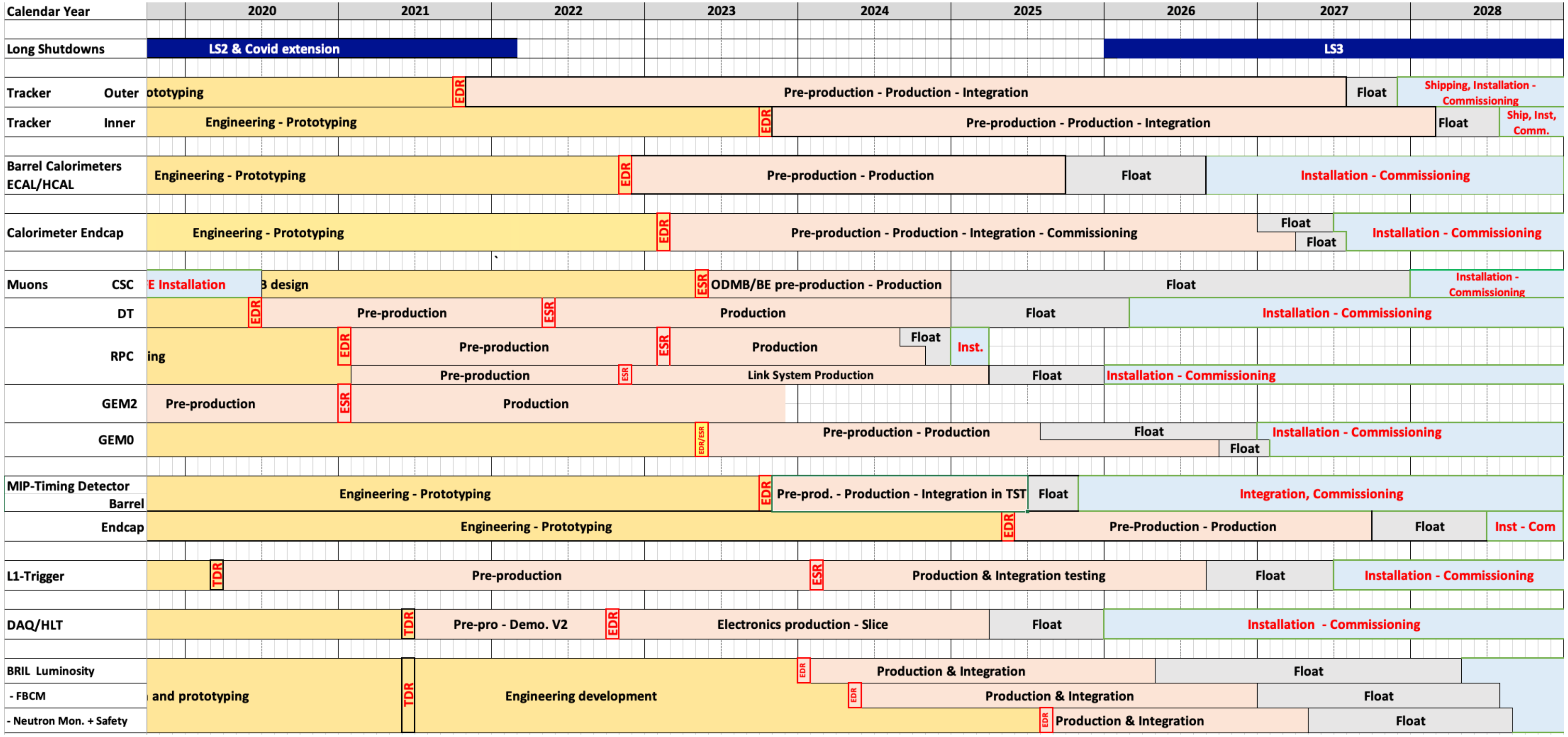
Heterogeneous HLT Farm



2018 data
- 50 average pileup
- 2018 L1T and HLT

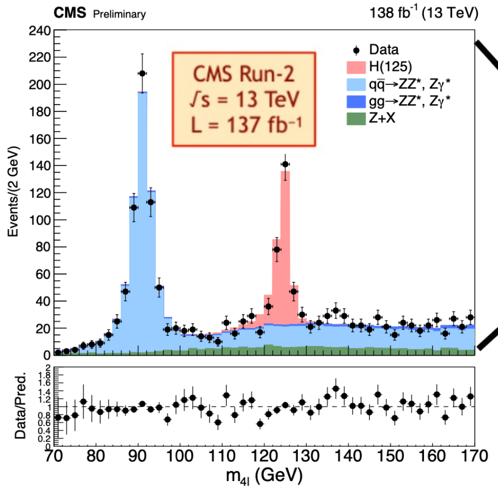
Status of the Upgrade

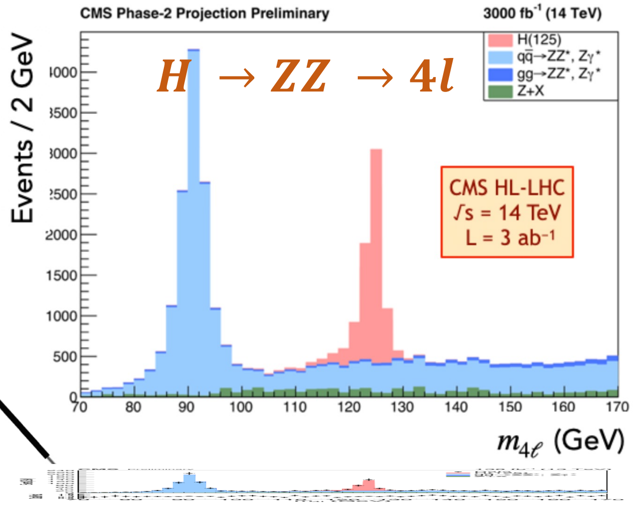
- All projects (except BRIL & ETL) will be in full production in 2024



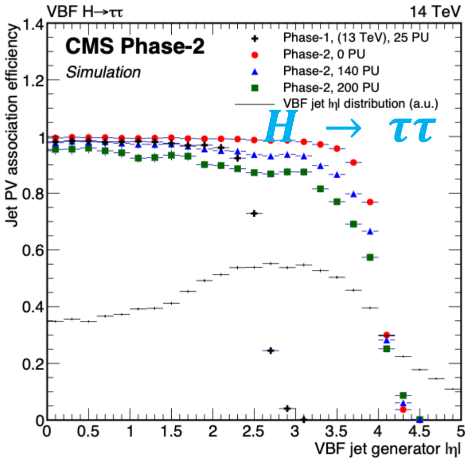
Higgs Physics at HL-LHC

20 times more data

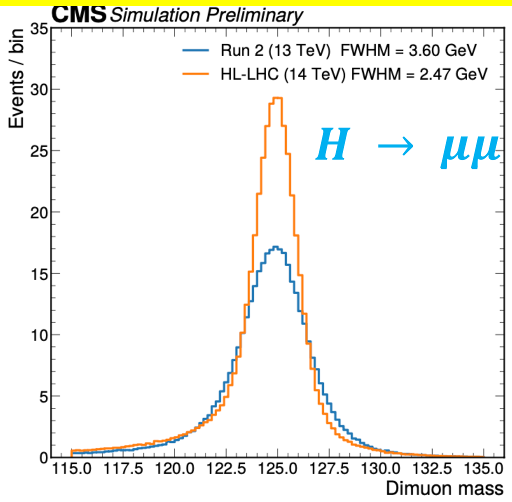


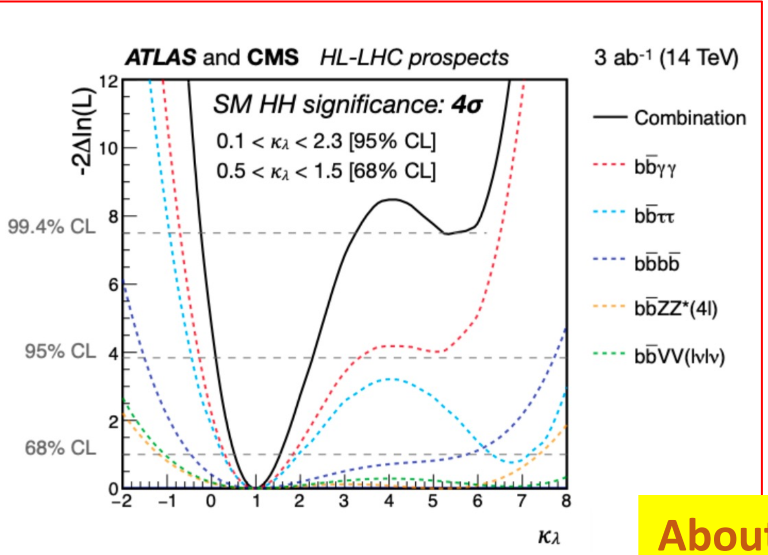


Increased acceptance

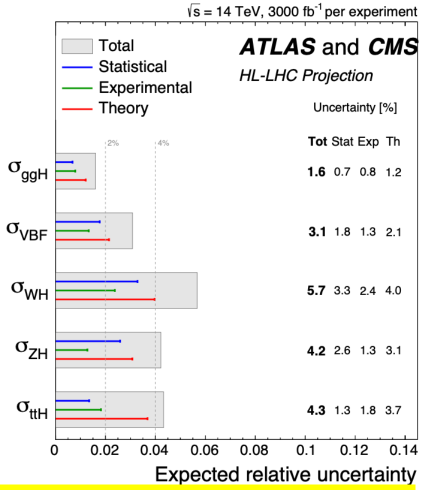


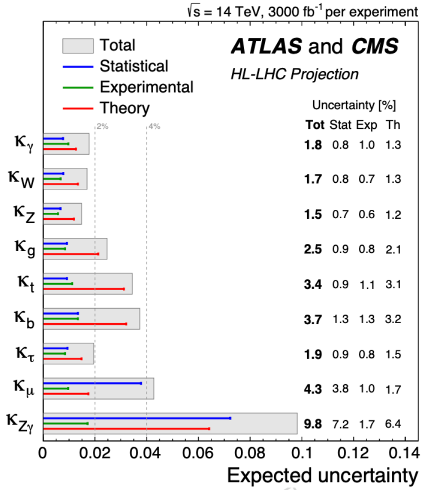
30% improvement in Mass resolution





Combined observation sensitivity of 4 σ for HH signal





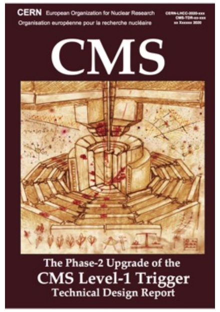
About 5 times more precise

Conclusions

- The HL-LHC will measure the Higgs couplings and details of electroweak symmetry breaking not currently accessible.
- In response to the **unprecedented challenges of HL-LHC experimental conditions** (level of radiation, pileup, data rate) **CMS is breaking new grounds in detector technology**
  - **tracking information** and **particle flow** algorithms **at L1 Trigger**
  - **high-granularity calorimeter** in the forward regions
  - **precision timing** for tracks, photons and jets
  - **extended acceptance** for muons
  - unprecedented data **bandwidth**

"… these [CMS upgrade] projects are unprecedented in scale in particle physics, shift various paradigms, and employ technologies that have never before been exercised by the field"
(a quote from external CMS upgrade review)

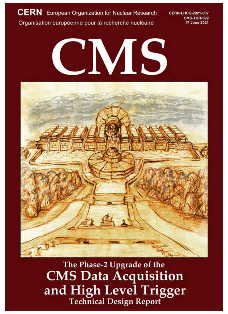
Backup



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

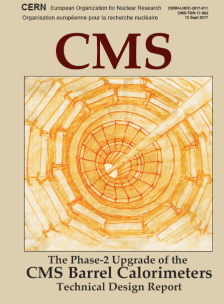
https://cds.cern.ch/record/2759072

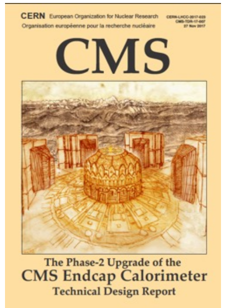
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

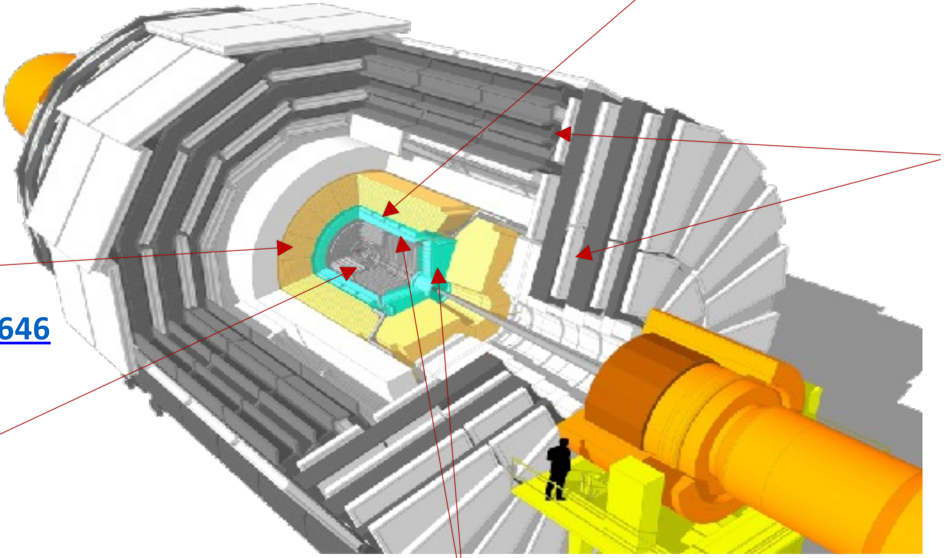




Calorimeter Endcap

https://cds.cern.ch/record/2293646

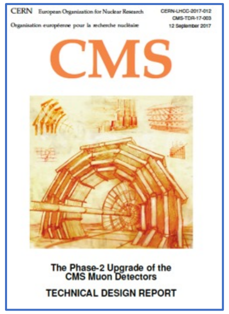
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

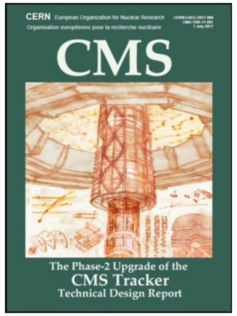


Muon systems

https://cds.cern.ch/record/2283189

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

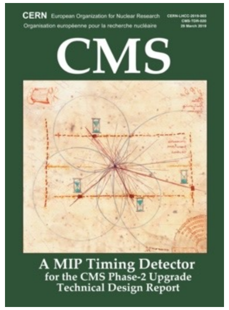




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector

https://cds.cern.ch/record/2667167

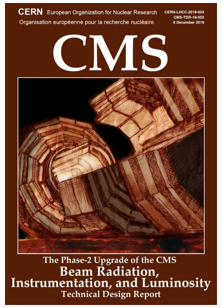
Precision timing with:

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

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

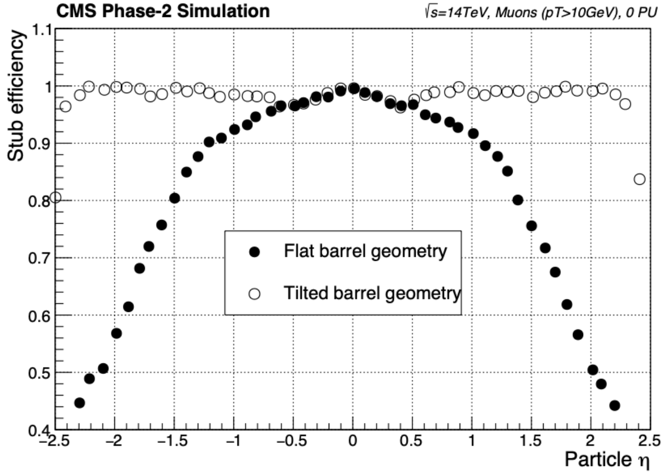
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

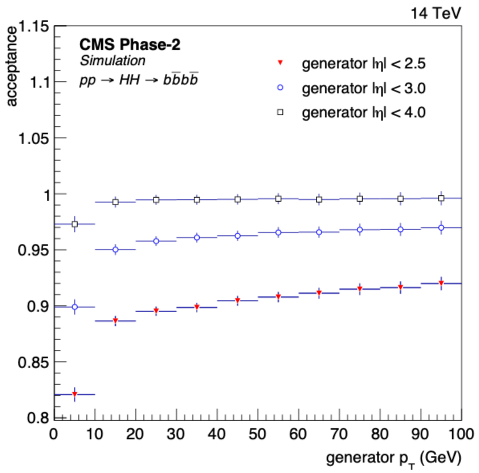


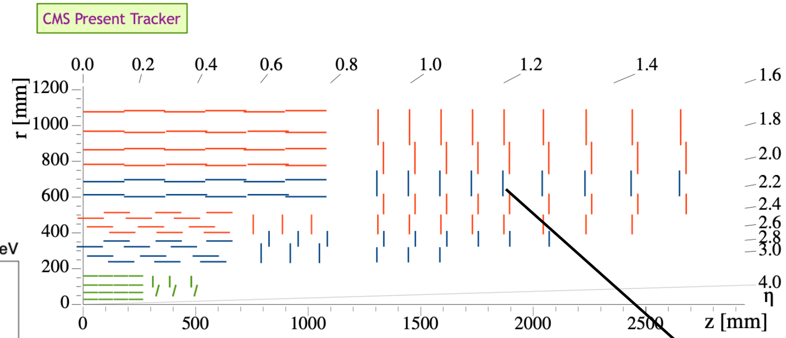
24

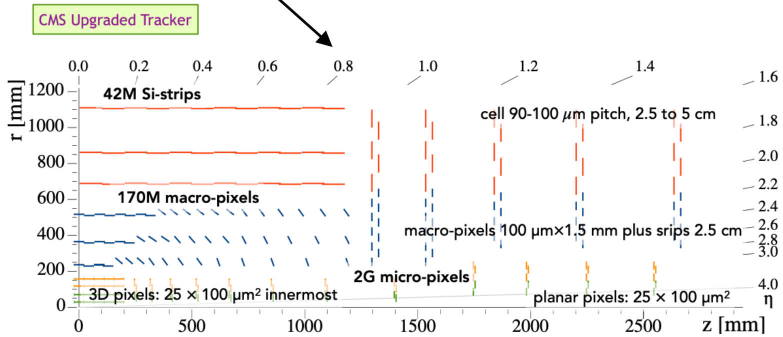
https://cds.cern.ch/record/2272264

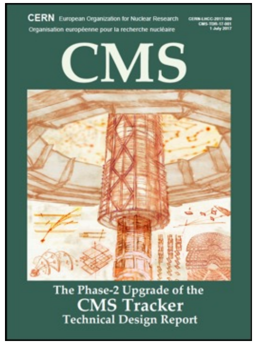
Tracker Upgrade I

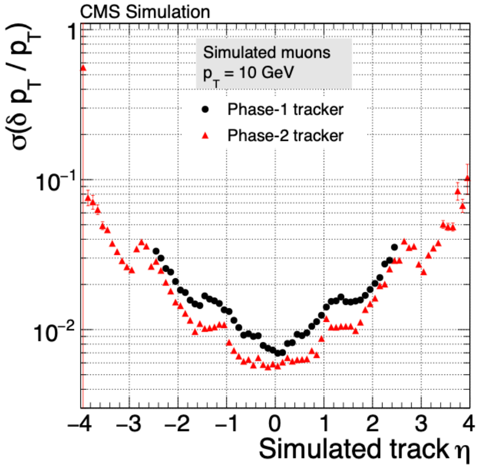


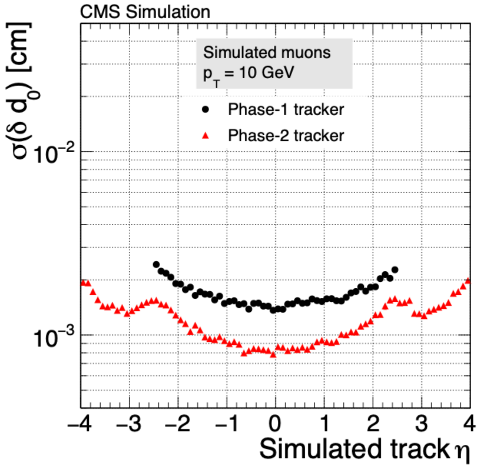


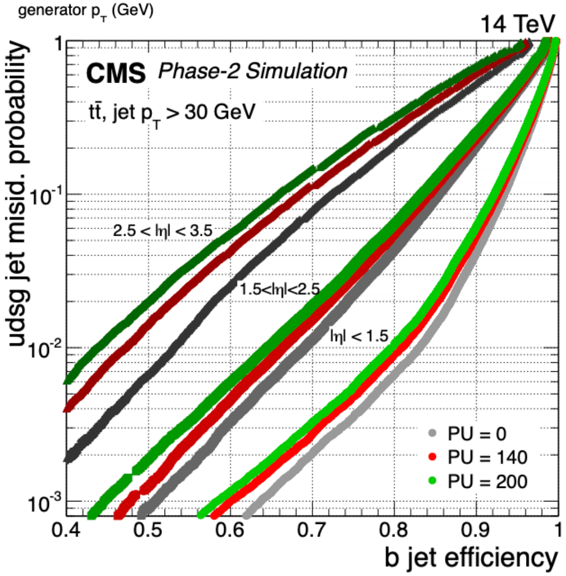


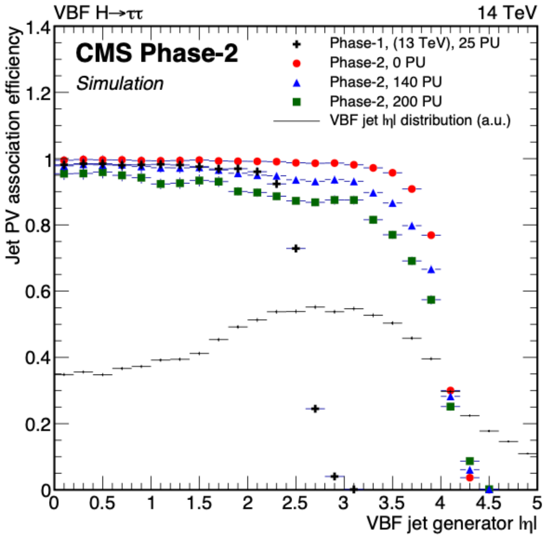


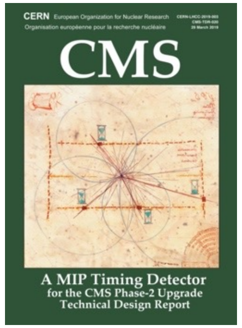




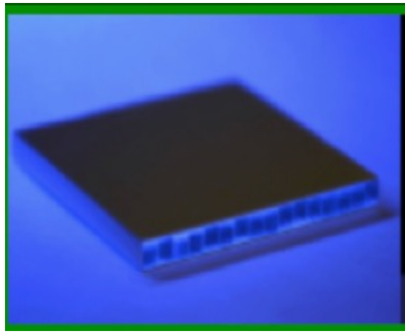




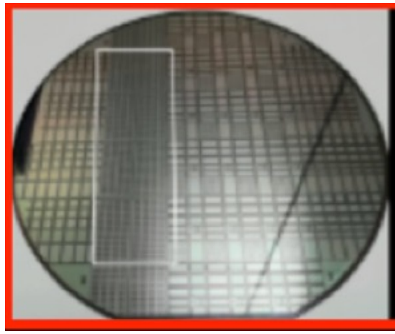




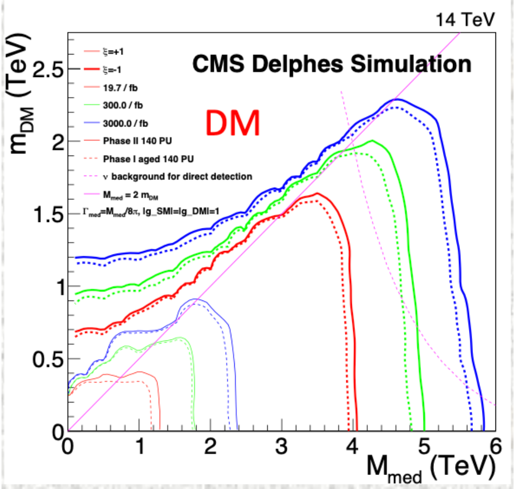
MIP Timing Detector (MTD) I

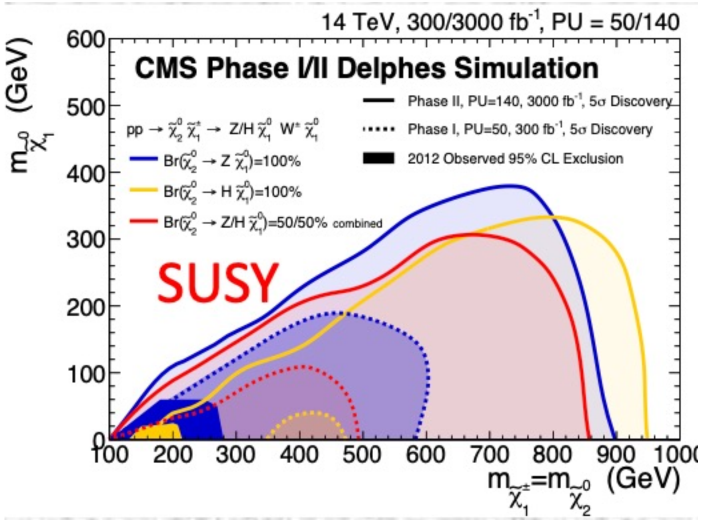


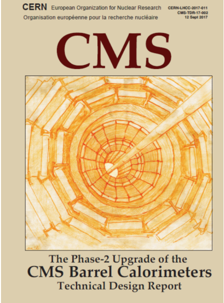
BTL: L(Y)SO bars + SiPM readout:
- TK/ ECAL interface ~ 45 mm thick
- $|\eta|<1.45$ and $p_T>0.7$ GeV
- Active area ~38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the HGC nose ~ 65 mm thick
- $1.6<|\eta|<3.0$
- Active area ~14 m^2; ~8.5M channels
- Fluence at 3 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2



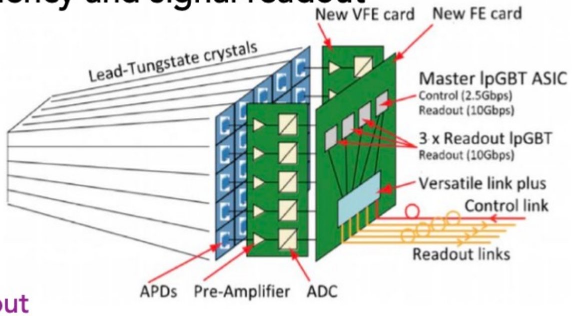




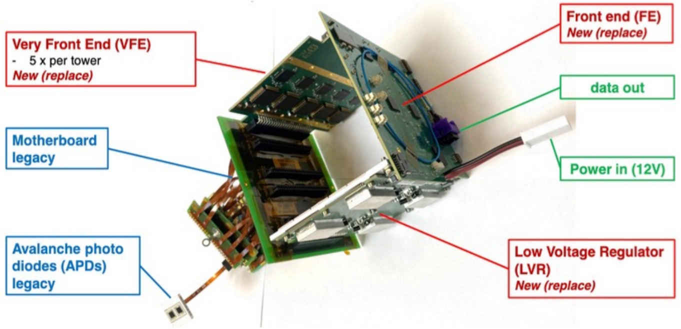
Barrel Calorimeter

Faster FE

→ 160 MHz sampling frequency and signal readout

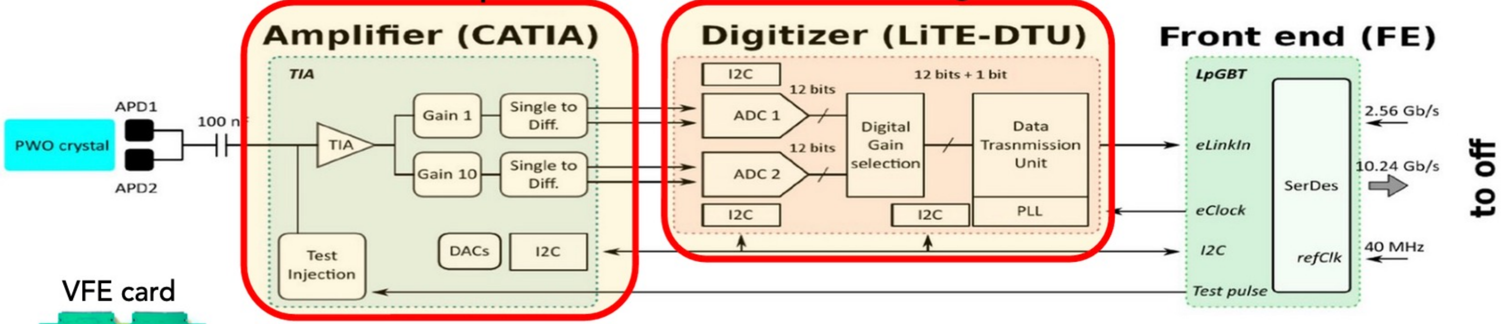


Tower (5×5 crystals) readout



CATIA amplifier

LITE-DTU digitizer



VFE card

transimpedance amplifier with higher bandwidth

digitisation, lossless compression, transmission

All samples sent **off-detector** thanks to lossless compression

- trigger primitive generation and trigger decision processed in FPGAs
- trigger information at single crystal level
- lifts 3.8 μs latency bottleneck