# The upgrades of the CMS detector for the HL-LHC

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**On behalf of the CMS Collaborations**

**University of Minnesota**

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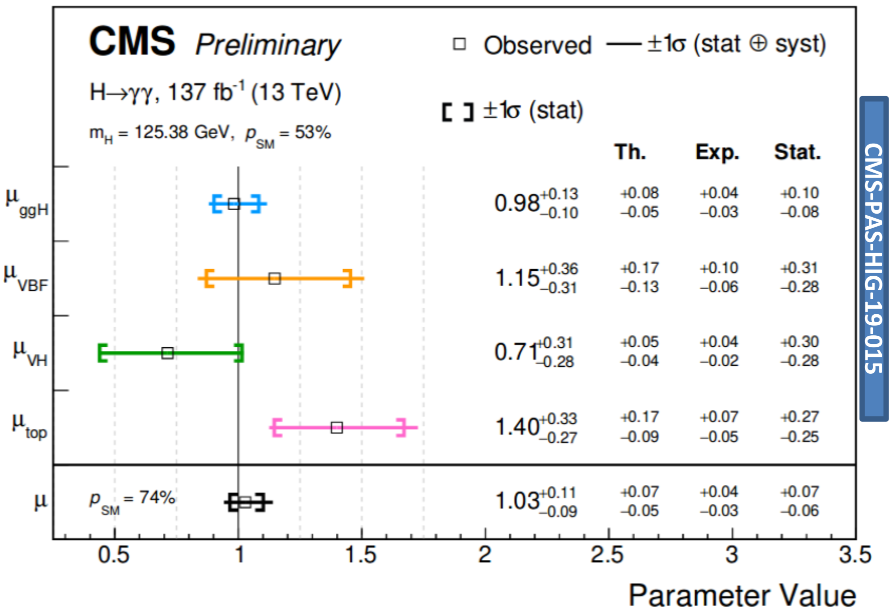
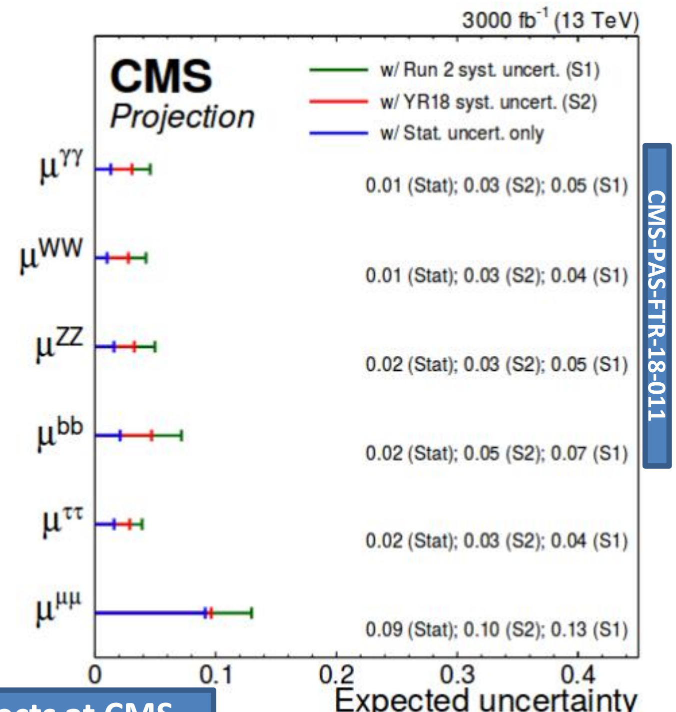
**A Zoom/Vidyo/Skype meeting can be setup on request

# The High Luminosity LHC: Physics motivation

- Runs 1 and 2 of the LHC have yielded a rich harvest of physics results (> 1000 papers) :
  - From the discovery of the Higgs boson to a comprehensive study of its properties with high precision.
  - Observation of rare decays like $B^0_s \rightarrow \mu^+\mu^-$ and rare processes like heavy triple boson production
  - An extensive set of searches for hints of physics beyond the standard model (BSM).
- However a decisive increase of the LHC luminosity in order to meaningfully improve on the current results in a reasonable timeframe:
  - O(1%) precision on SM Higgs couplings
  - Rare Higgs Decays (e.g H→μμ) and production ( e.g. HH )
  - Extending reach of BSM searches (e.g Dark Matter candidates)

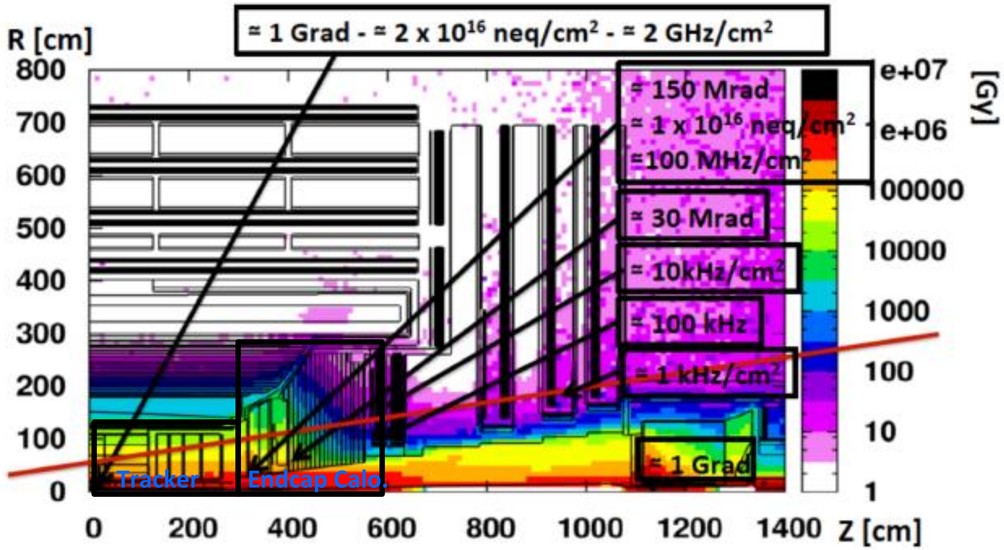


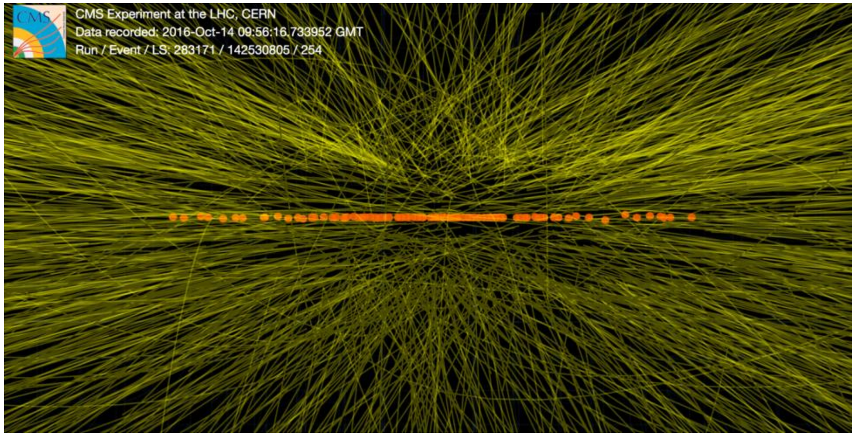

**See talk by A. Savin for the future physics prospects at CMS**

# The High Luminosity LHC: Challenges

The HL-LHC environment presents unprecedented challenges to the CMS physics program of searching for New Physics through Precision Measurements and Direct Searches for Rare Processes.




Simulation: Total of 3 $ab^{-1}$ with 300 $fb^{-1}$/year




A typical event from a 2016 High PU (<μ> = 100) run

HIGH RADIATION(due to high integrated lumi.)

- Radiation levels up to $2 \times 10^{16}$ $n_{eq}/cm^2$ or 1 Grad in the forward region or close to the collision point.

HIGH PILEUP(due to high instant. lumi.)

- Multiple collision per event: 140--200

# The plan to deal with the challenges

The basic goal of the upgrades to the CMS detector for operations at the HL-LHC is to maintain/improve the excellent performance of the detectors in terms of efficiency, resolution, and background rejection for all the physics objects used in the analysis of the data.

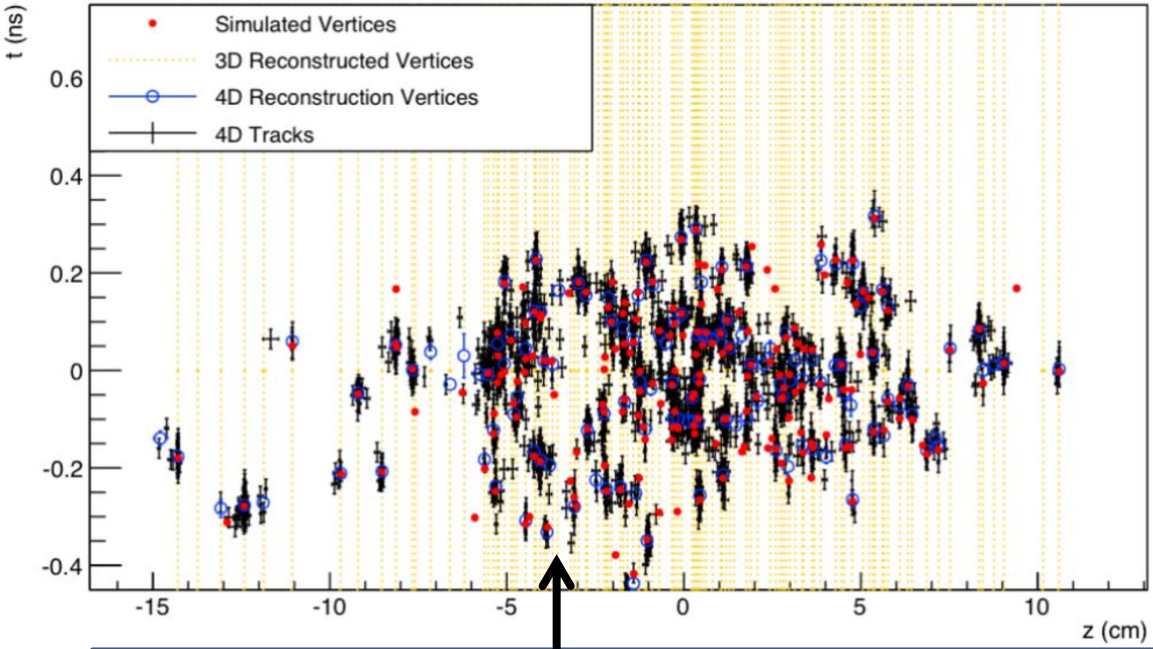
- **Radiation Environment**
  - The complete replacement of the Tracker and End-Cap Calorimeter systems with increased use of radiation tolerant Si
  - Colder operation of the Barrel ECAL (APD Noise Mitigation)
  - Major electronics overhaul and consolidation of the Barrel Calorimeters and Muon systems

- **High Pile Up**
  - Improved granularity
  - Precision time to separate collisions in time as well as space

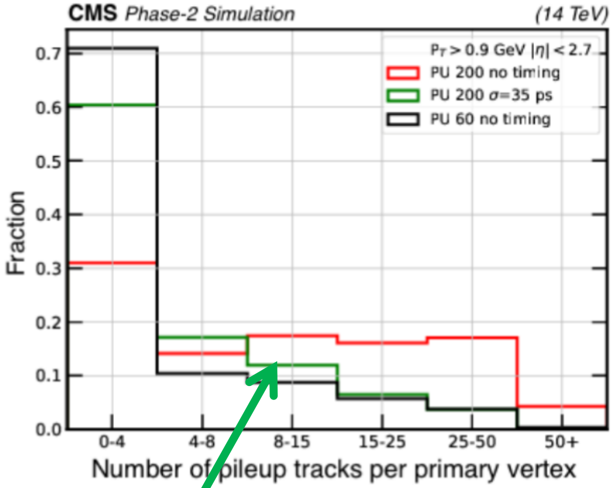
- **High Luminosity**
  - A complete overhaul of the Trigger and DAQ systems to enable faster processing of the data in real time

# Precision timing as a tool to mitigate pileup

**Collision vertices within a bunch crossing at 200 PU.**

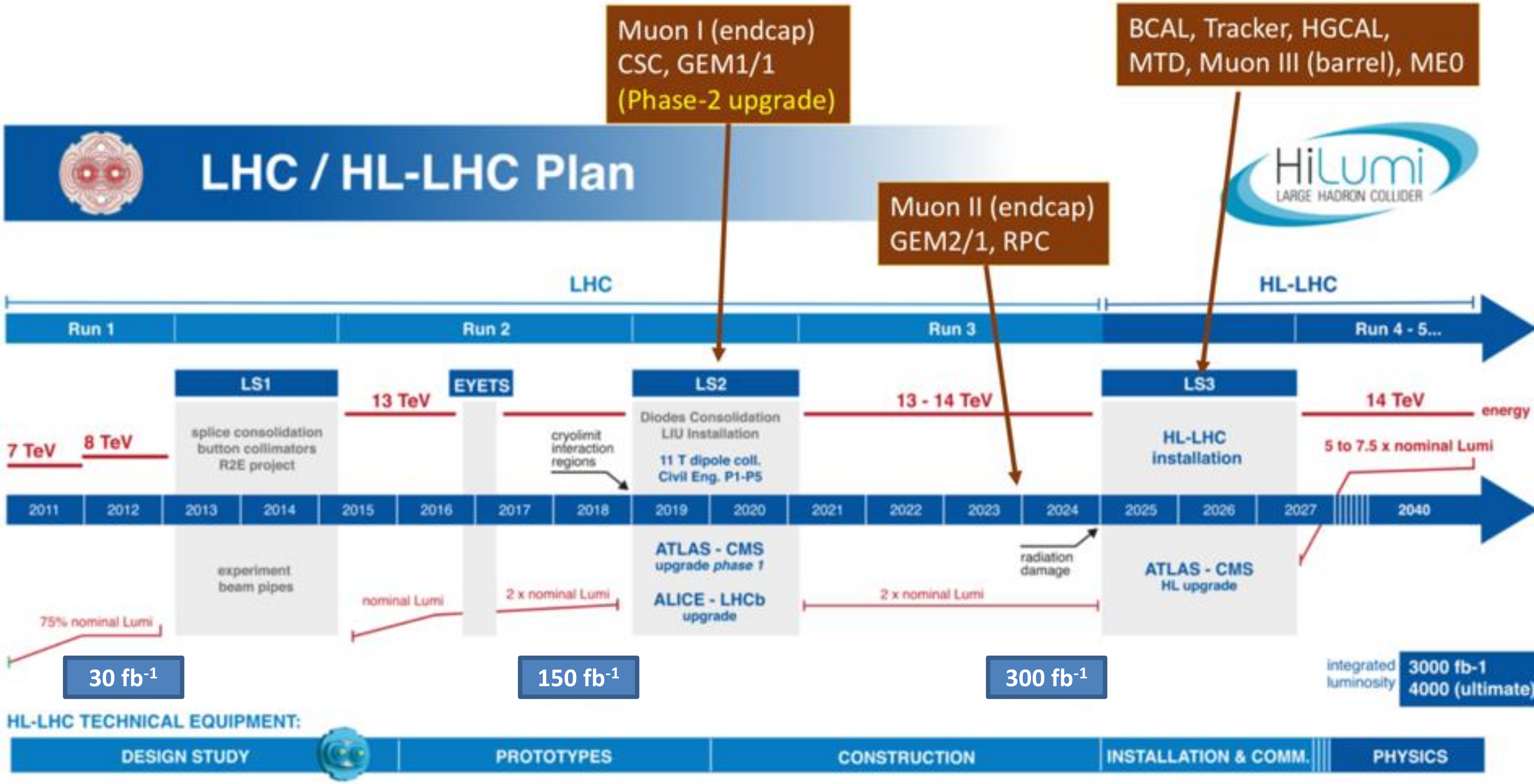



**Pileup tracks incorrectly associated to the interaction vertex**




- **Key idea:** Under HL-LHC conditions timing information can be used to "separate" pileup vertices that otherwise appear to be "merged" in 3D space.
  - → **This separation improves with the time resolution: ~30 ps resolution is already effective.**
- The upgraded Barrel ECAL will provide precision timing information for high energy photon showers.
- The new Endcap calorimeter will provide precision timing information for both high energy photons and hadrons.
- **The MIP Timing Detector (MTD) will be used at the HL-LHC for precision timing of tracks**

# CMS HL-LHC Upgrade: Timeline




**RUN 2:**
Design L = $10^{34}$ $cm^2s^{-1}$
<Pileup> ~ 34

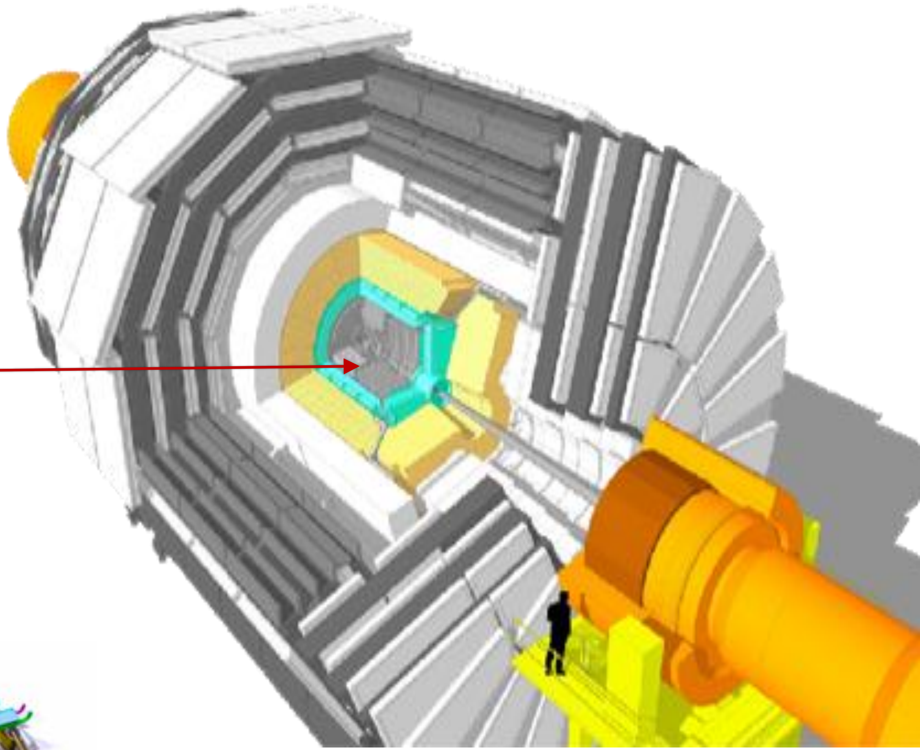
**RUN 3:**
Design L = $2\times10^{34}$ $cm^2s^{-1}$
Exp. <Pileup> ~ 60

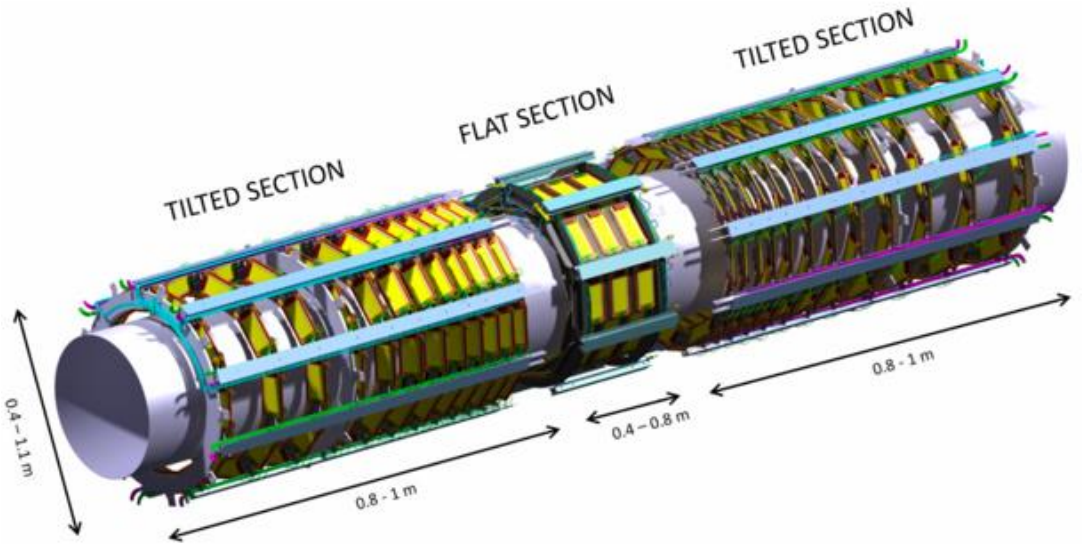
**HL-LHC:**
Design L = **5-7.5**$\times10^{34}$ $cm^2s^{-1}$
Exp. <Pileup> ~ **140-200**

# The CMS tracker for the HL-LHC

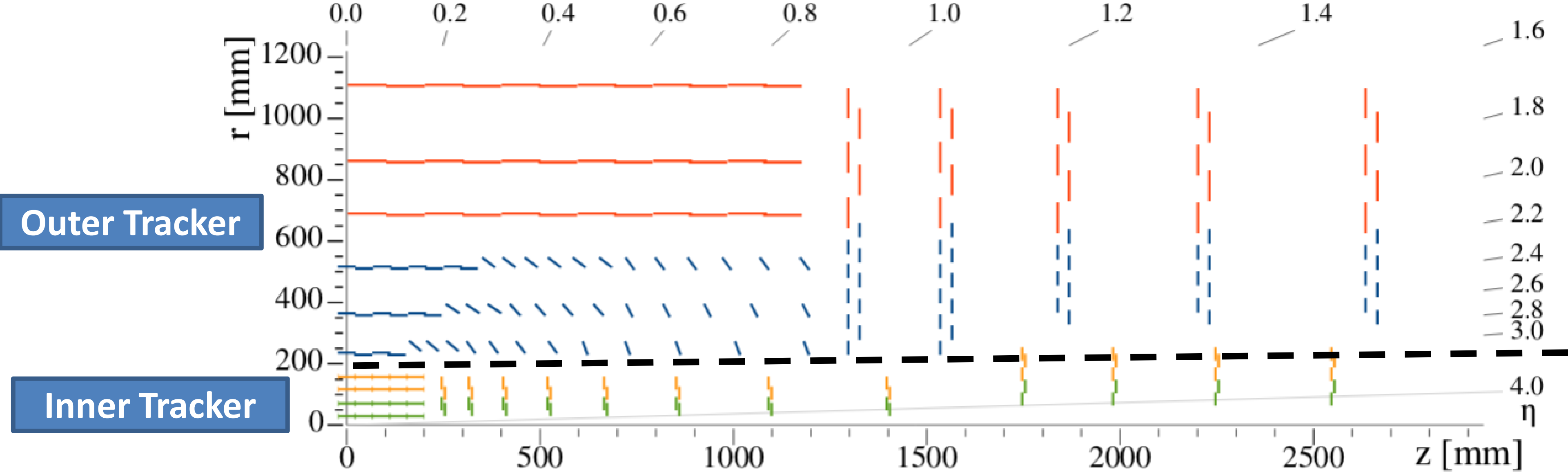
Key features:

- More granular
- Lower material budget
- Extended coverage to $\eta \approx 3.8$
- Tracking included in L1 Trigger for the first time

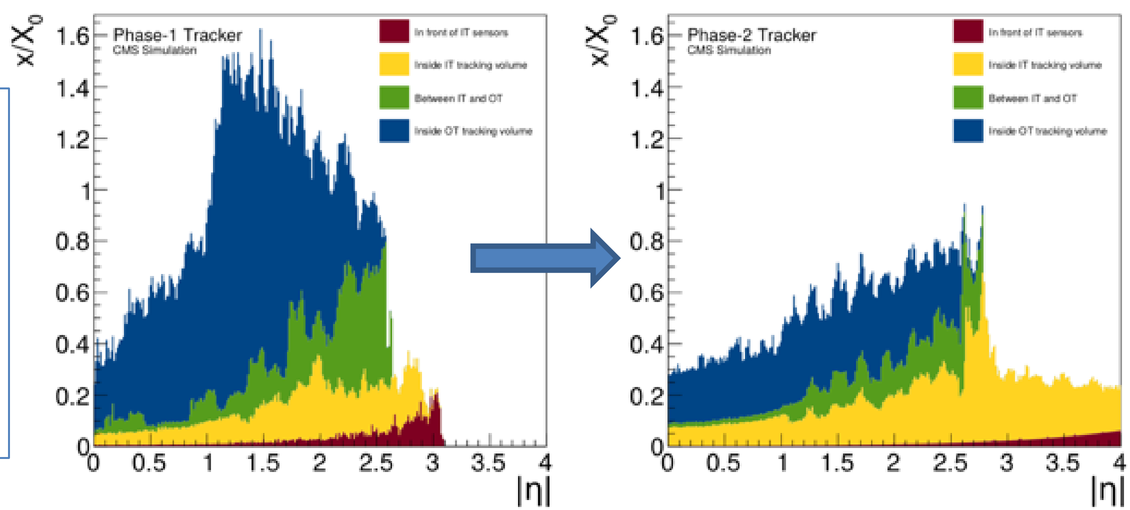




# CMS HL-LHC Tracker: Layout and Material Budget

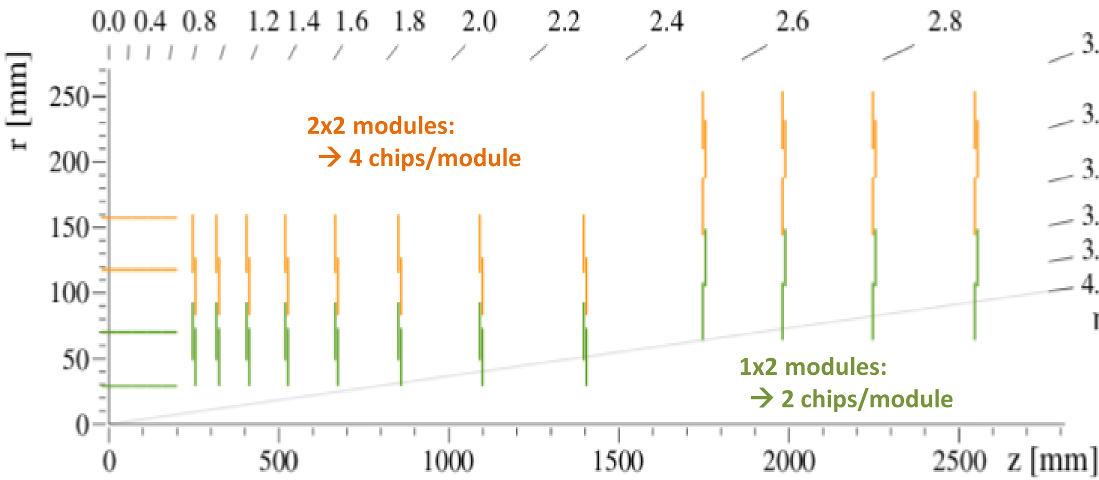


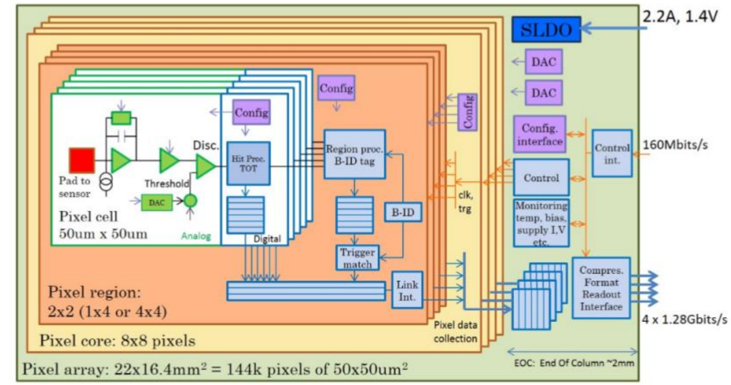

- Significant reduction in the material budget.
  - Improves both the tracker and calorimetric performance



# Inner Tracker : Overview

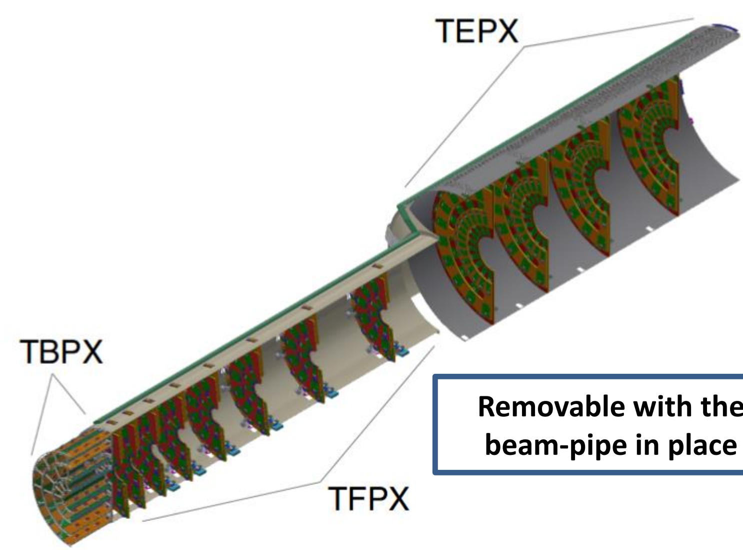
**The inner tracker must be tolerate a radiation dose of ~ 1 GRad , with a hit rate ≤ 3 GHz/cm²**
**→ Pixel size of 25 μm x 100 μm and 50 μm x 50 μm**



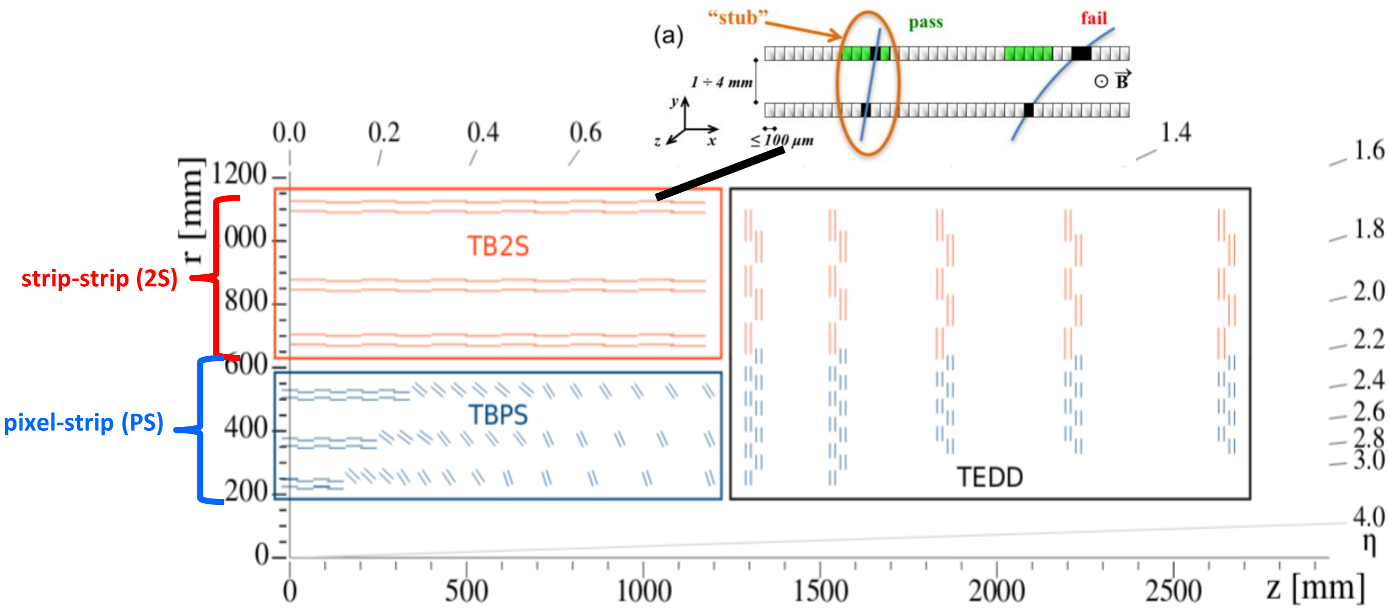

**Pixel readout chip in joint ATLAS + CMS development**
6x smaller pixels; ~5x more hit rate; ~10x more trig. rates

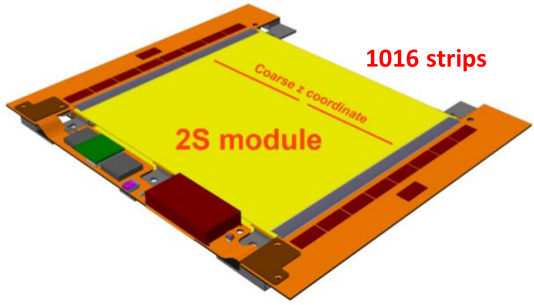
| | TBPX | TFPX | TEPX | Total |
|---|---|---|---|---|
| Active area [m²] | 0.99 | 1.89 | 1.99 | 4.87 |
| Pixels | 395 M | 757 M | 794 M | 1.95 G |
| FE power [kW] | 8 | 16 | 16 | 40 |

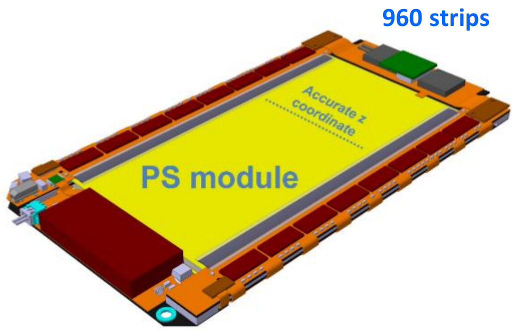



**Removable with the beam-pipe in place**

# Outer Tracker and the L1 track trigger : Overview



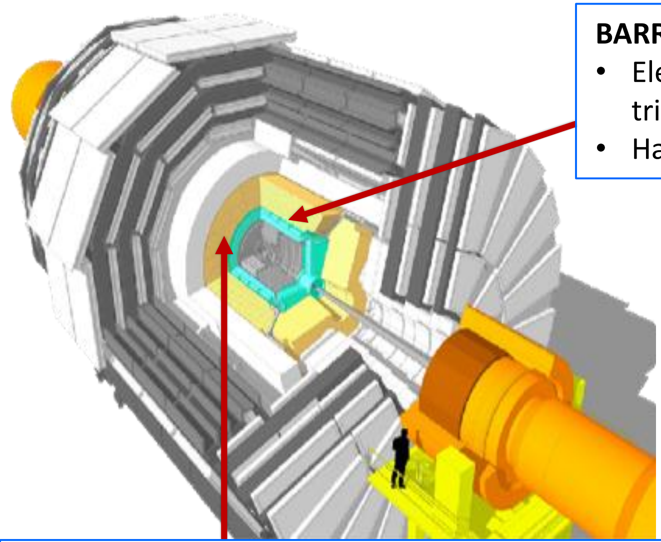




- Outer Tracker design has to provide tracks at 40 MHz to the L1-trigger ($p_T$ >2GeV)
  - **The $p_T$ modules select pair of hits (Stubs) compatible with track $p_T$ > 2GeV.**
  - **Two layer track stubs remove low $p_T$ tracks in trigger (< 2GeV) → Data rate reduction 10x.**
- Tilted modules in three OT layers to maintain geometric acceptance for the stubs.

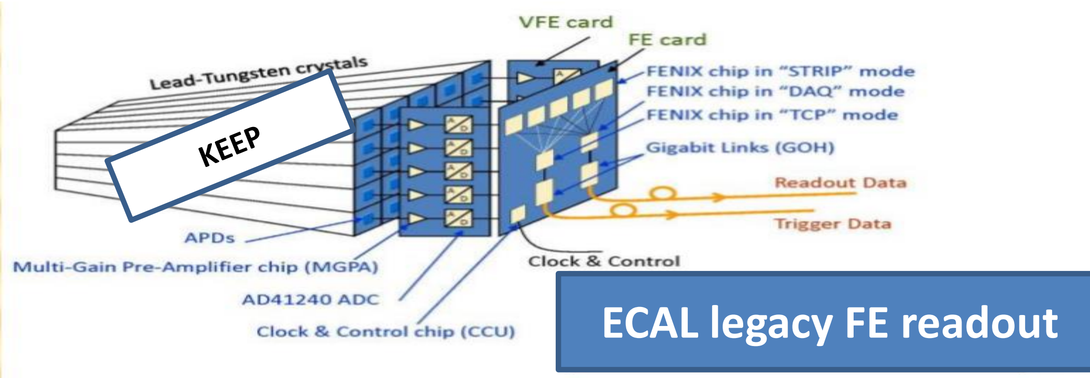
| | 2S module | PS module |
|---|---|---|
| Active area | **138 m²** | **50 m²** |
| Strip/pitch | **5 cm x 90 µm** | **2.4 cm x 100 µm (strips)<br>1.5 mm x 100 µm (macro-pixels)** |
| Channels | **31M** | **11M(strips) + 170M (m-pixels)** |
| FE power | **5 W** | **8 W** |
| Sensor power | **~ 1 W** | **1.4 W** |

# Upgrades to the CMS calorimeters: EM + Hadronic



**BARREL CALORIMETERS**

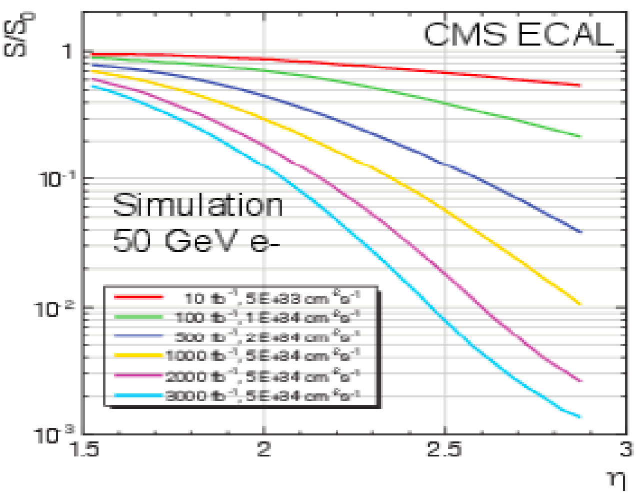
- Electromagnetic Calorimeter on-detector electronics replaced for precision timing and better trigger granularity
- Hadron Calorimeter electronics replaced for better signal strength and higher trigger rates

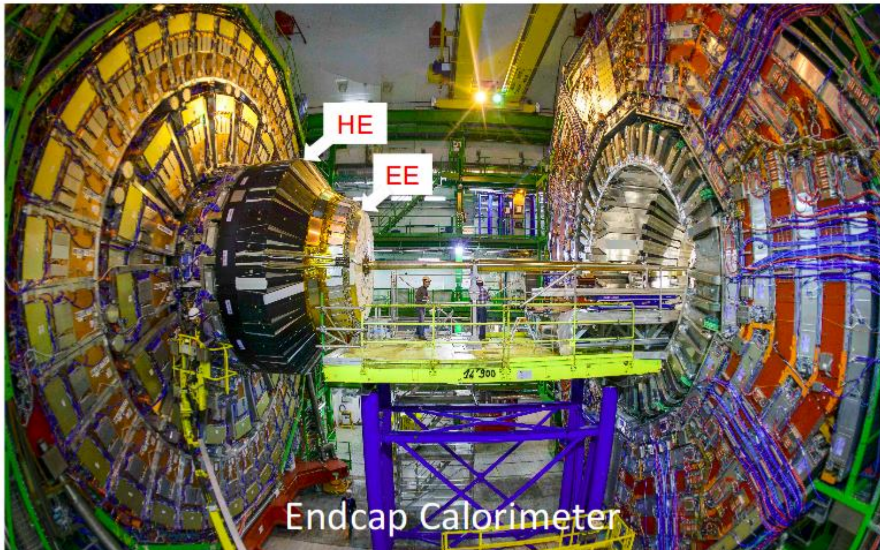



**ECAL legacy FE readout**

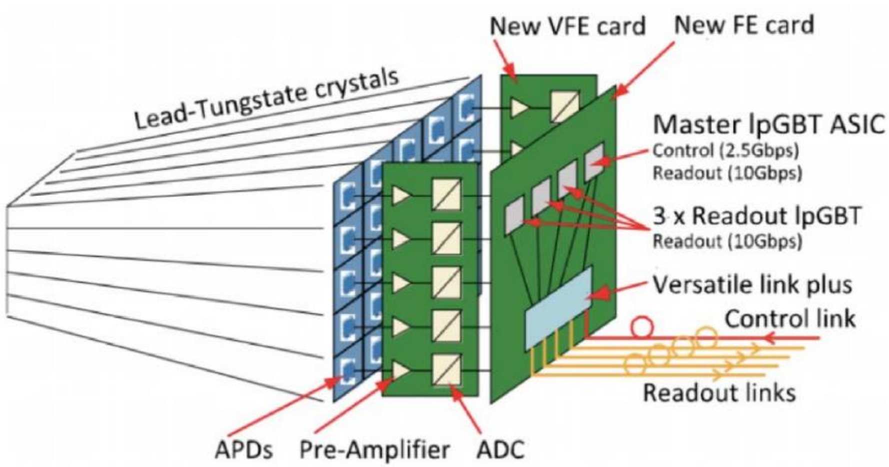
**ENDCAP CALORIMETERS**

- Radiation-induced darkening is reducing the signal from the current scintillator-based endcap calorimeters
  **→ The current endcaps will not survive with the radiation loads at the HL-LHC and need to be replaced**



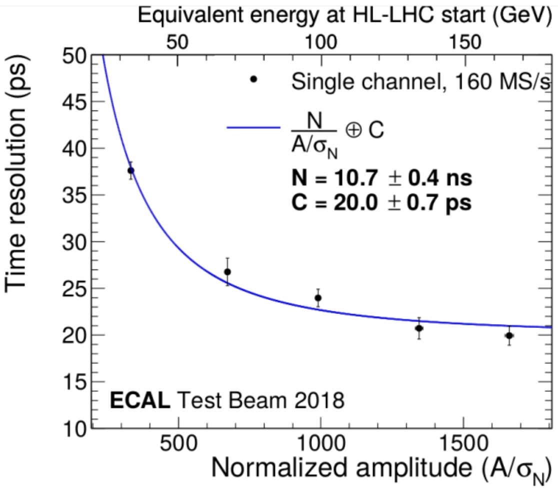



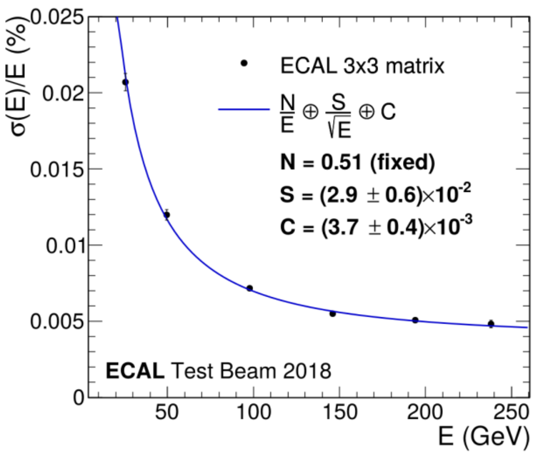
# Upgraded electronics for the Barrel calorimeters




- ECAL on detector electronics upgrades and operations updates
  - Digitization at 160 MHz to help discriminate against spikes (due to hadron interactions within the APD volume)
  - Faster response pre-amplifier to give 30ps timing for EM showers at ~50 GeV
  - Single crystal readout at trigger level.
  - Reduce the operating temperature from 18°C to 9°C to mitigate APD ageing effects.
- Replace all off-detector electronics components (HCAL+ECAL - ATCA)

## ECAL beam test results




- ECAL beam tests were performed to test the CATIA amplifier chip for the upgrades [using a commercially available ADC, FE and off-detector components ].
  - **Single channel time resolution of ~30 ps obtained for an equivalent energy of 50 GeV**

See talk by C. Biino for ECAL upgrade details

# The CMS HGCAL: design parameters

**Key Parameters:**

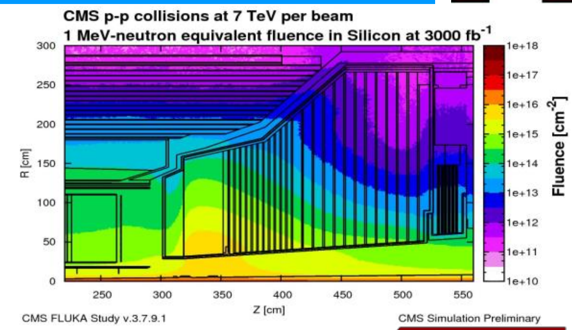
- The HGCAL covers $1.5 < |\eta| < 3.0$
- 215 ton/endcap, full system at -30C
- **620 $m^2$** of silicon sensors in 30k modules
  - 6M Si channels, 0.5 or 1 $cm^2$ cell size
- 400 $m^2$ of scintillator in 4k boards
  - 240k scintillator channels, 4-30 $cm^2$ cell size

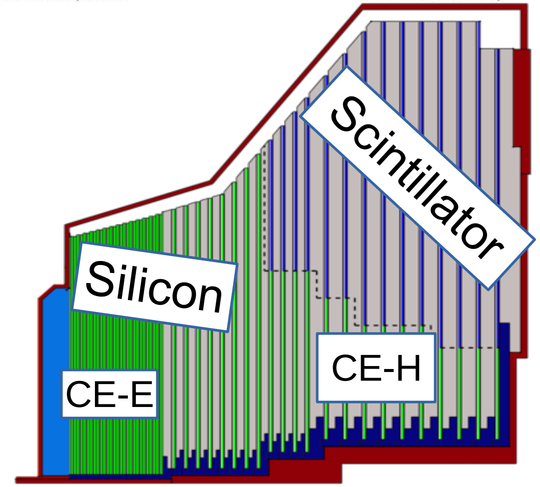
**Active Elements:**

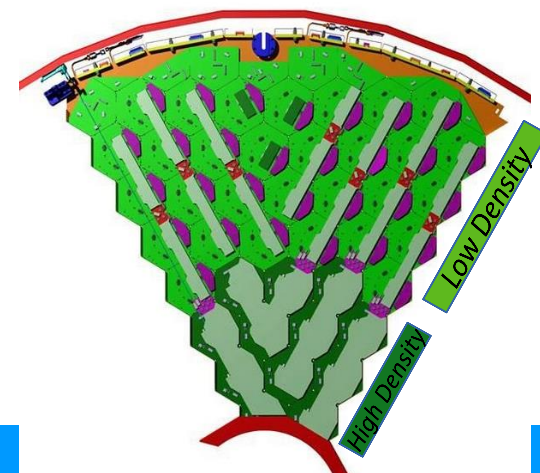
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers

**Detector Configuration:**

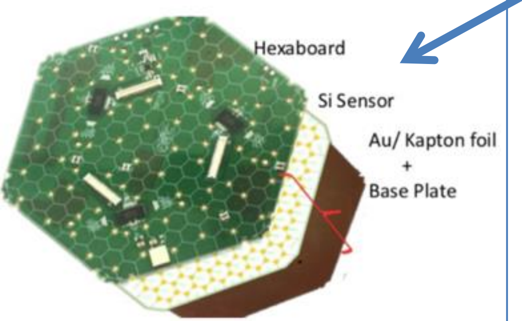
- Electromagnetic calorimeter (CE-E) : **Si,** Cu/CuW/Pb absorbers; 28 layers, 25.5 $X_o$ and 1.7 $\lambda$
- Hadronic calorimeter (CE-H) : **Si & scintillator,** steel absorbers; 22 layers and ~9.5 $\lambda$ (including CE-E)

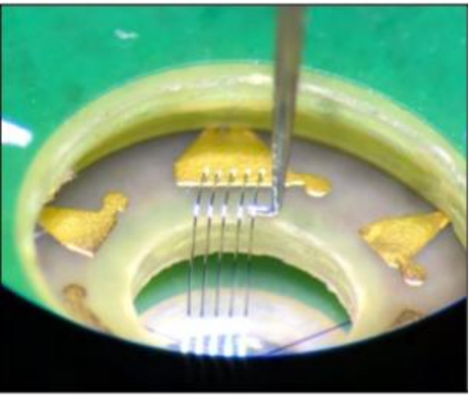


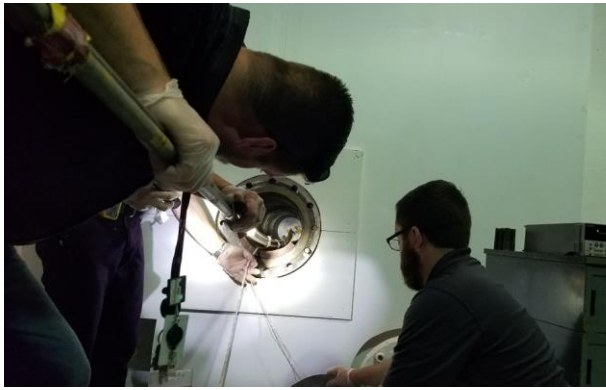



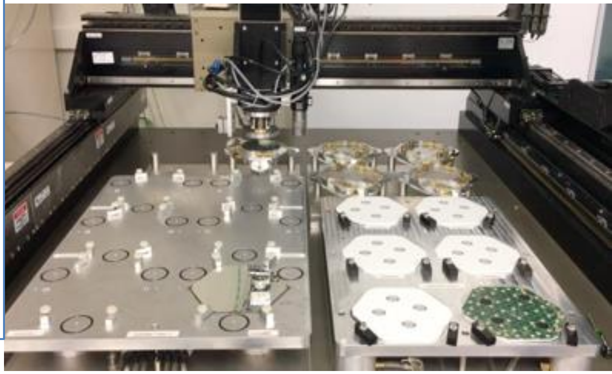
# The CMS HGCAL : Si sensor modules

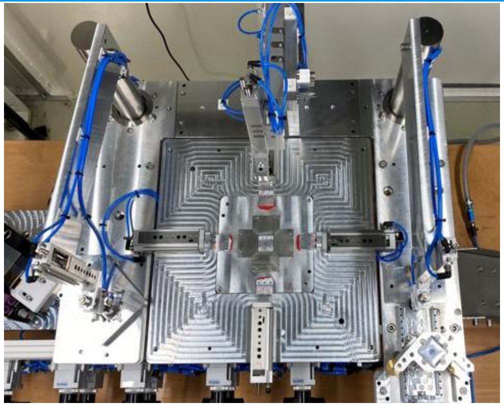



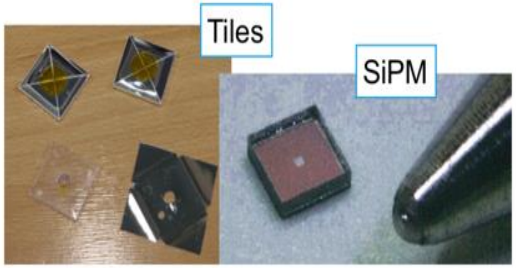
- The Silicon sensors are first use of 8" technology for large-scale HEP Sensors
  - **Hexagonal geometry to maximize use of wafer area**
- Robust module constructed from a baseplate, insulating layer, silicon sensor, and readout PCB
- Comprehensive test program including full-sensor tests with custom probe cards and reactor based neutron irradiations
- Automated assembly process using gantry and robotic wirebonder developed at UCSB
  - **Highly-repeatable, being replicated to five additional module assembly centers worldwide**

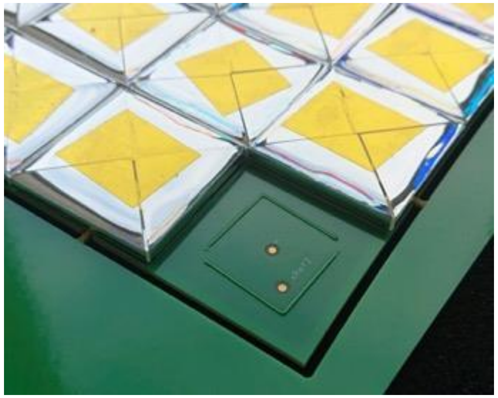




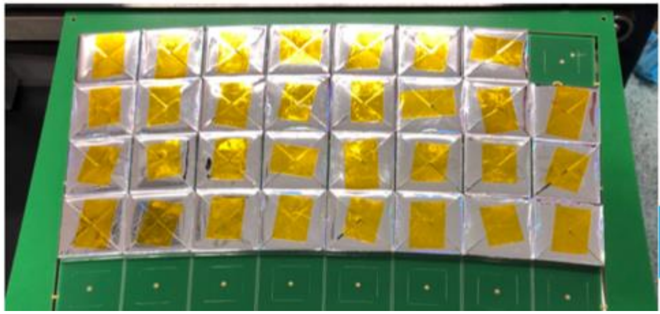
# The CMS HGCAL : SiPM-on-Tile modules

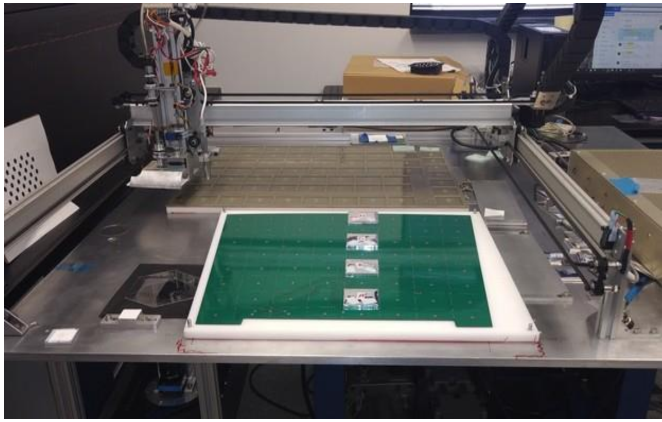




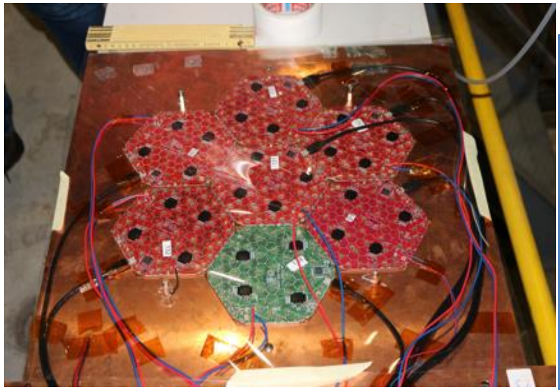



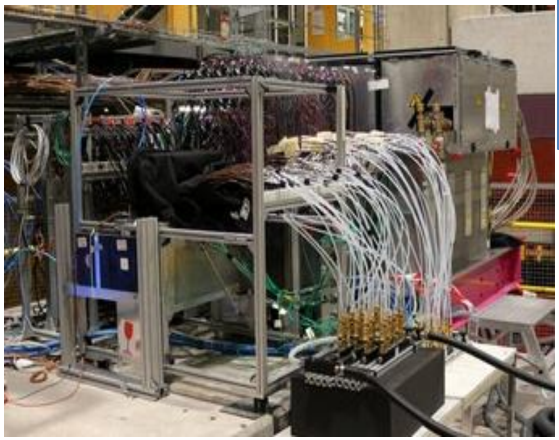
- Scintillator tiles will be produced using both injection molding and machining of cast scintillator
  - **Tiles will be wrapped with ESR foil in an automated wrapping machine.**
- SiPM photodetectors have been produced.
  - Sufficient signal-to-noise over the life of the experiment
- Automated construction of tile modules using pick-and-place of tiles onto tile PCB containing the SiPMs, readout chip, and other components



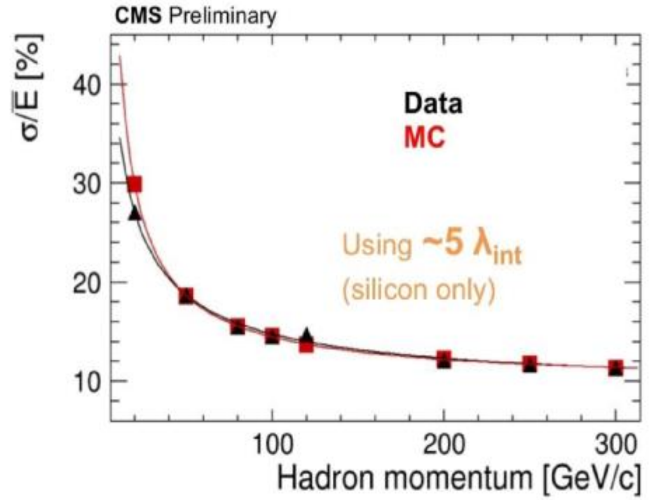


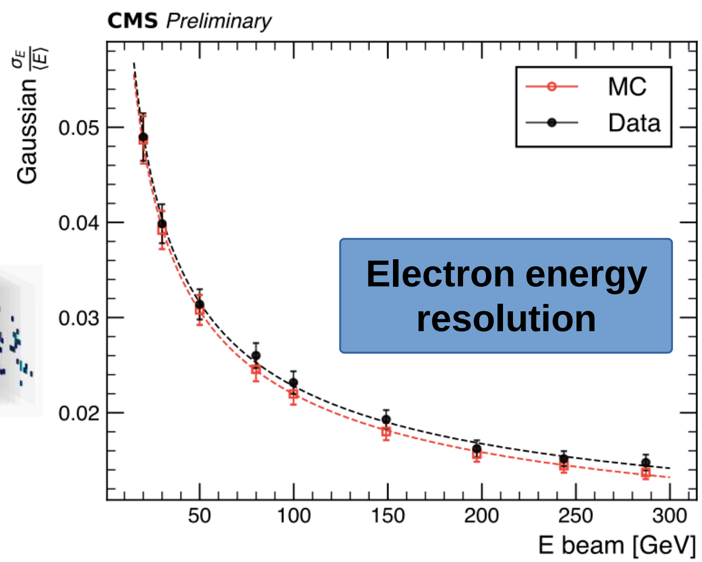
# The CMS HGCAL : Beam test results

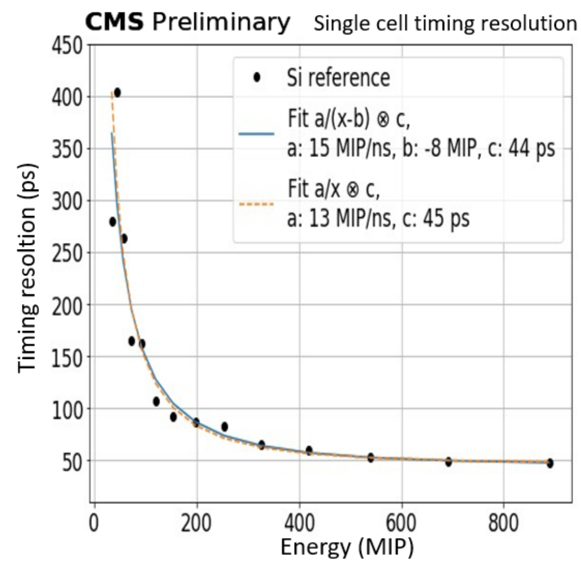




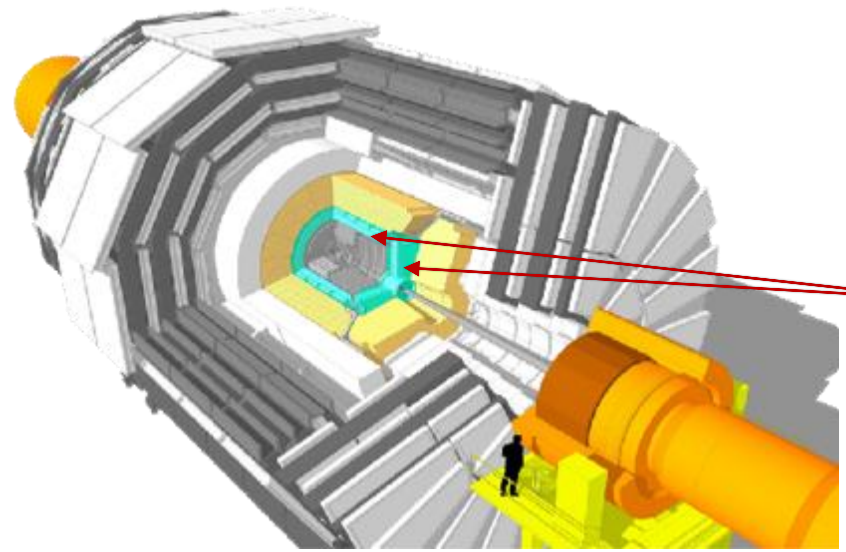

- 28 EM layers, 12 silicon HAD layers, 39 scintillator layers from CALICE AHCAL
- Measured electrons, pions, and muons with energies from 20 GeV to 300 GeV
- Papers under preparation/in final collaboration review

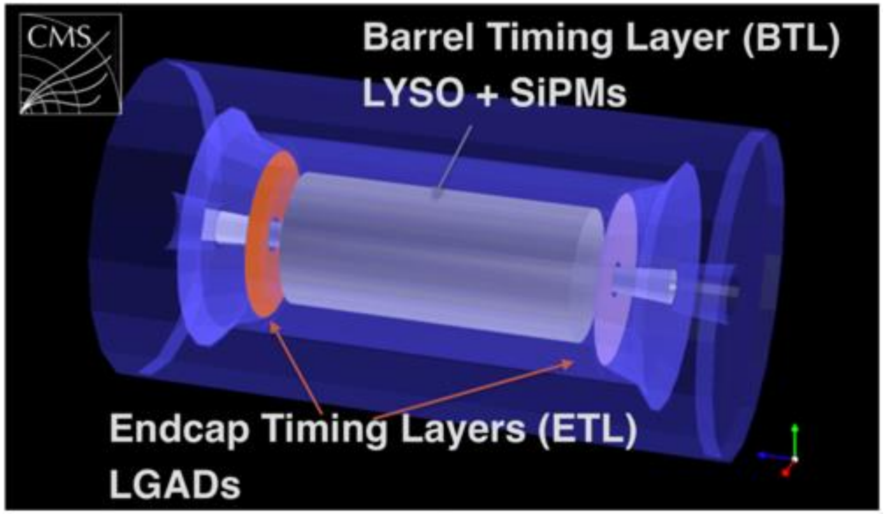


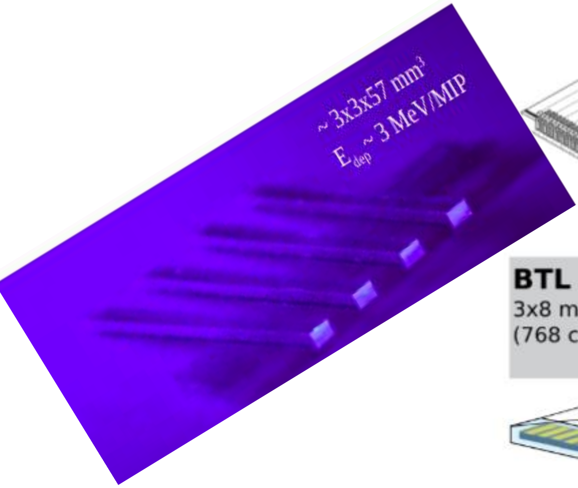
# The MIP Timing detector

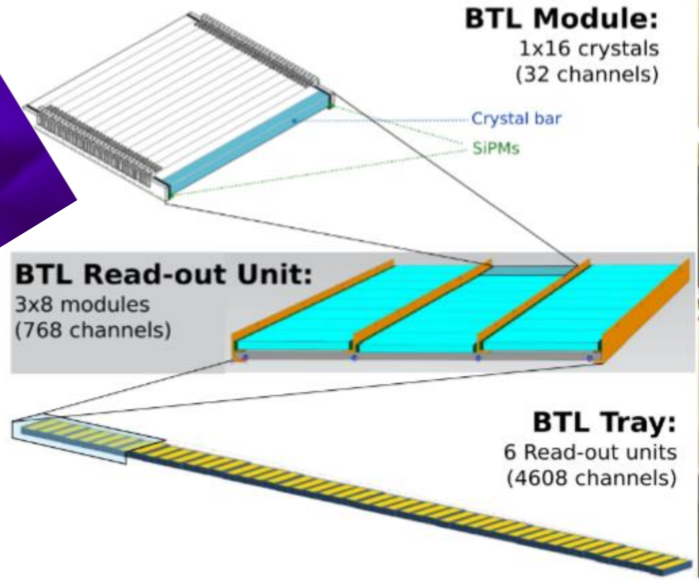


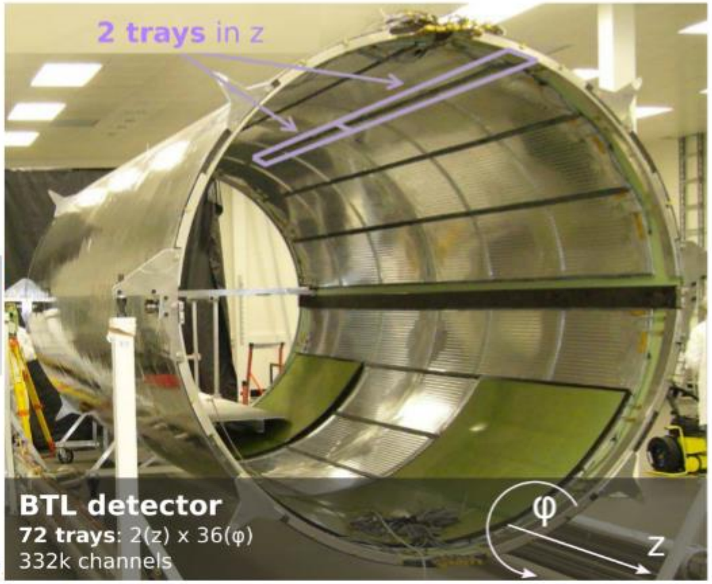



- Thin layers between the tracker and the calorimeters.
- Time resolution of 30 ps for MIPs at HL-LHC start and < 60 ps at 3000 $fb^{-1}$
- Hermetic coverage for $|\eta| < 3.0$

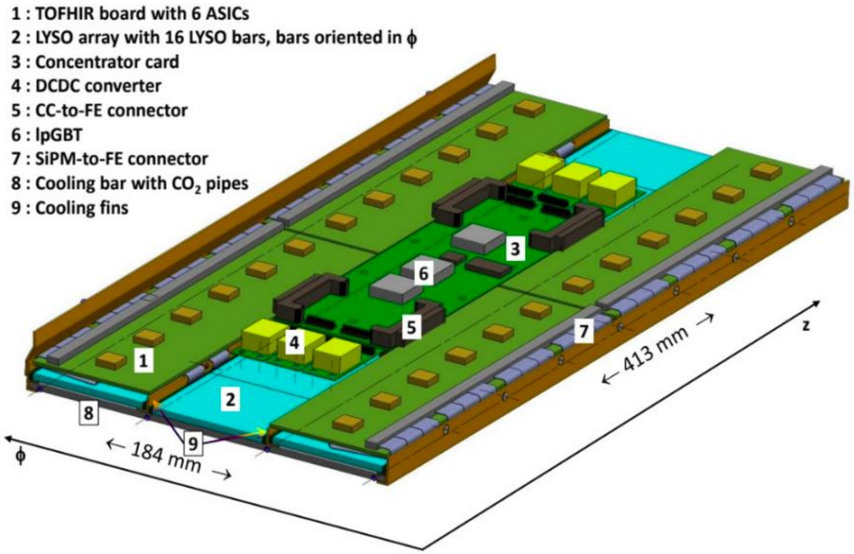
# The Barrel Timing Layer: Overview



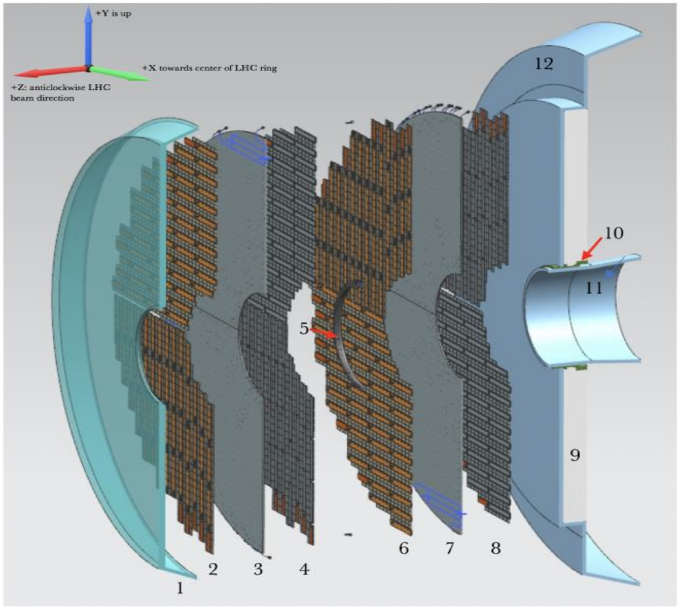



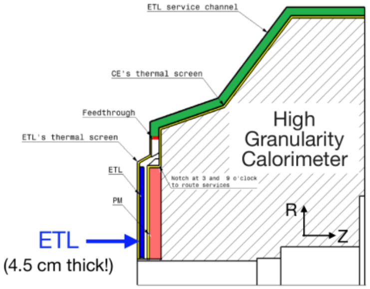




- LYSO crystals with dual end SiPM readout
- Basic unit : 1x16 array of crystals (~3x3x57 mm$^3$)
- Arranged in trays and segmented in readout units
- Coverage of $|\eta| < 1.45$, surface ~38 m$^2$, 332 k channels
- Nominal fluence : 2 x $10^{14}$ $n_{eq}/cm^2$
- Time resolution 35-60 ps [start – end of life]
- Readout using TOFHIR board with 6 ASICS each reading up to 16 crystals (32 channels)

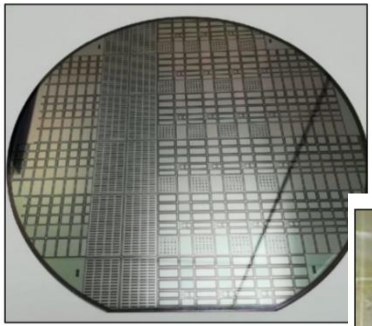


# The Endcap Timing Layer: Overview

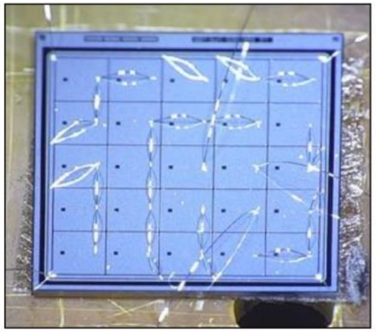



FBK UFSD3

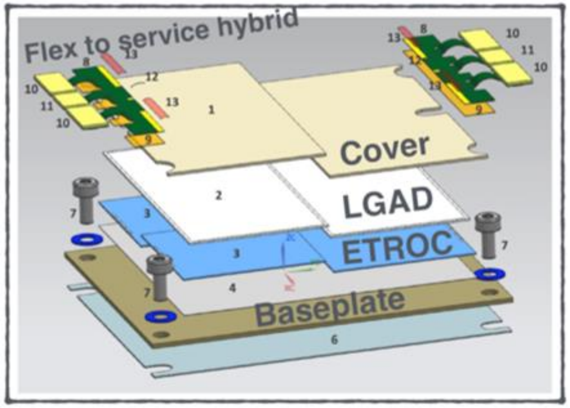


**LGAD prototype sensors**

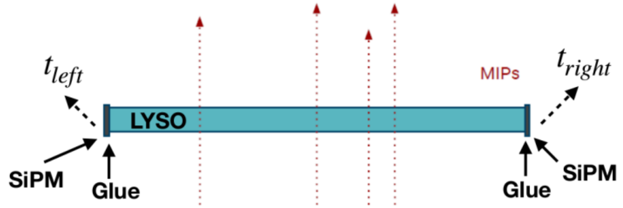


5x5 array from HPK

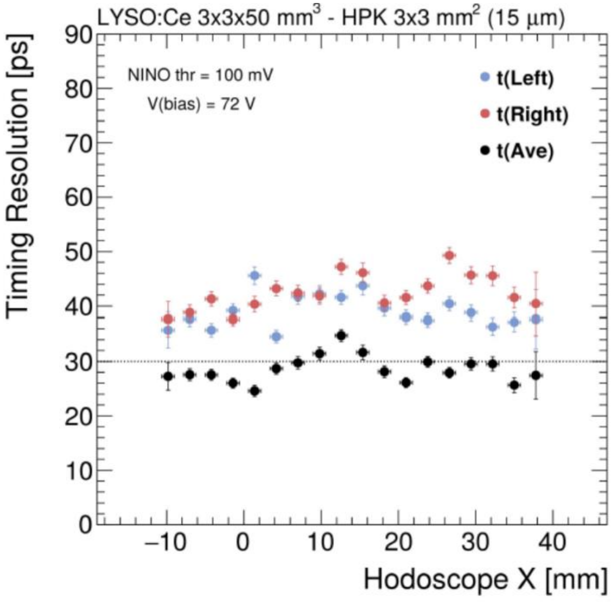
- Low Gain Avalanche Diodes (LGADs) with highly doped p+ region just below the n- implants.
- Two disks per endcap mounted on the HGCAL nose.
- Coverage of $1.6 < |\eta| < 3.0$, surface ~15.8 m$^2$, 8.5 M channels
  - **1.3*1.3 mm$^2$**
- Nominal fluence : $2 \times 10^{15}\ n_{eq}/cm^2$
- Time resolution 30 - 45 ps [start – end of life]
- Sensors are organized in arrays of 16x32 with a size of 21 x 42 mm$^2$
  - Two ETL ASICs (ETROC) needed to readout one module (each ETROC has 16x16 channels).
  - Each ETROC consists of pre-amplifier, discriminator and a TDC.



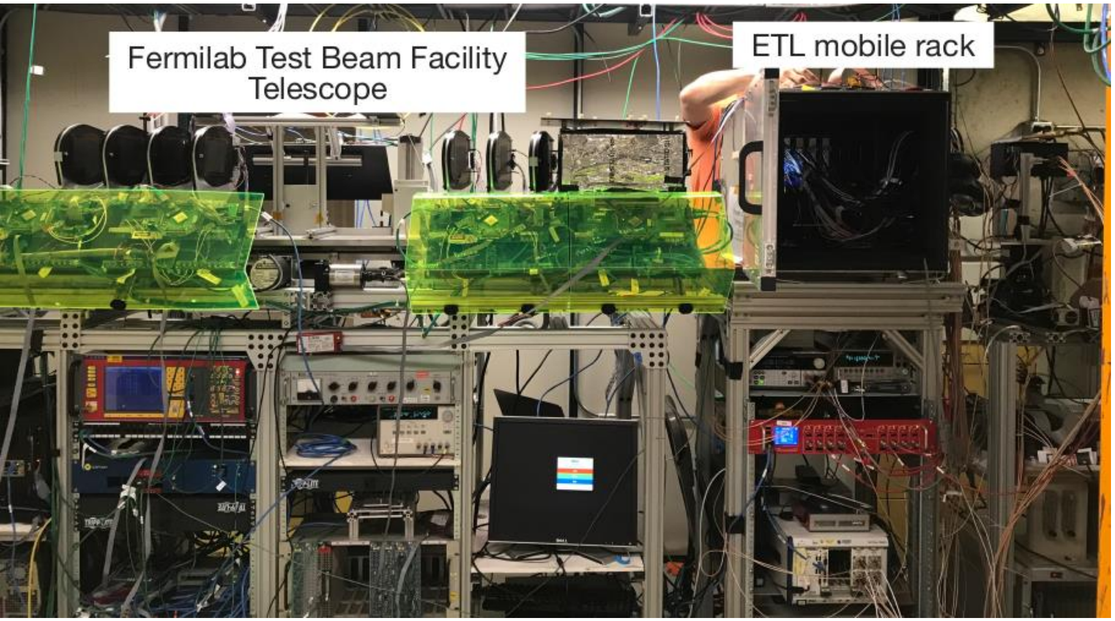
# Results from Beam Tests

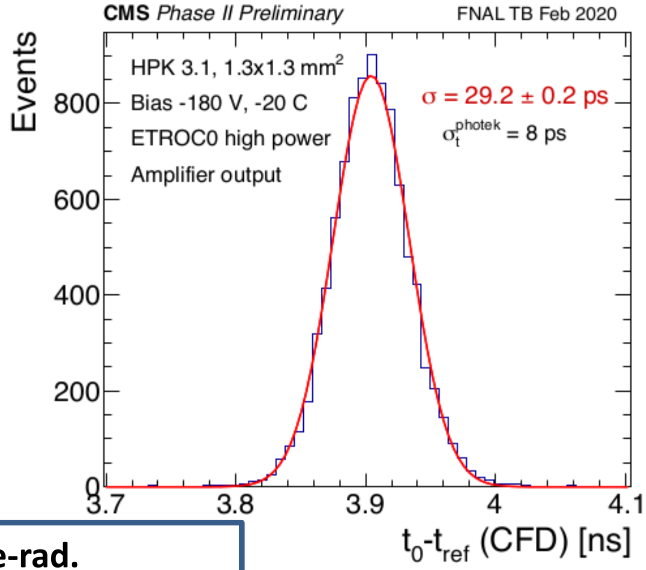







- **Achieved 30 ps time resolution per BTL sensor before irradiation**



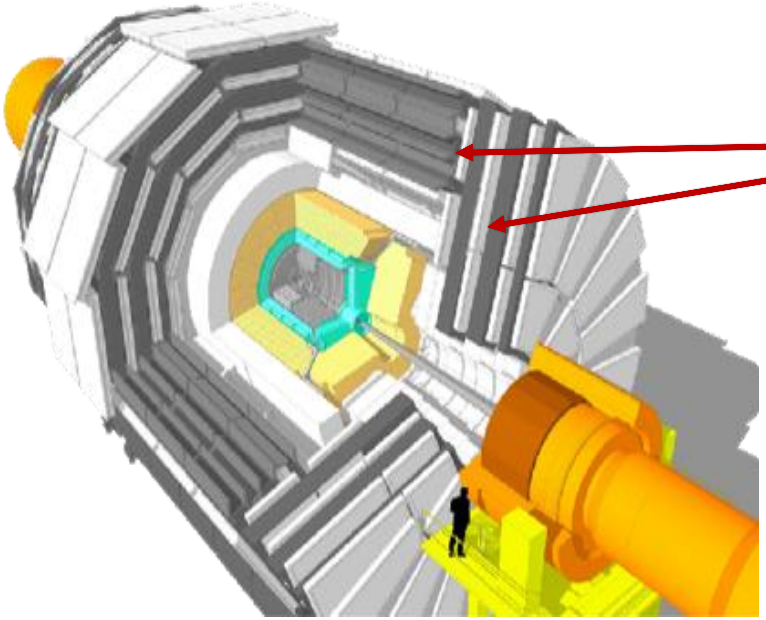




- **Achieved 30-35 ps time resolution for ETL sensors operating above 20 fC, pre-rad.**

# Muon detector upgrades

**Precision measurements crucially depend on how well we can reconstruct muons.**

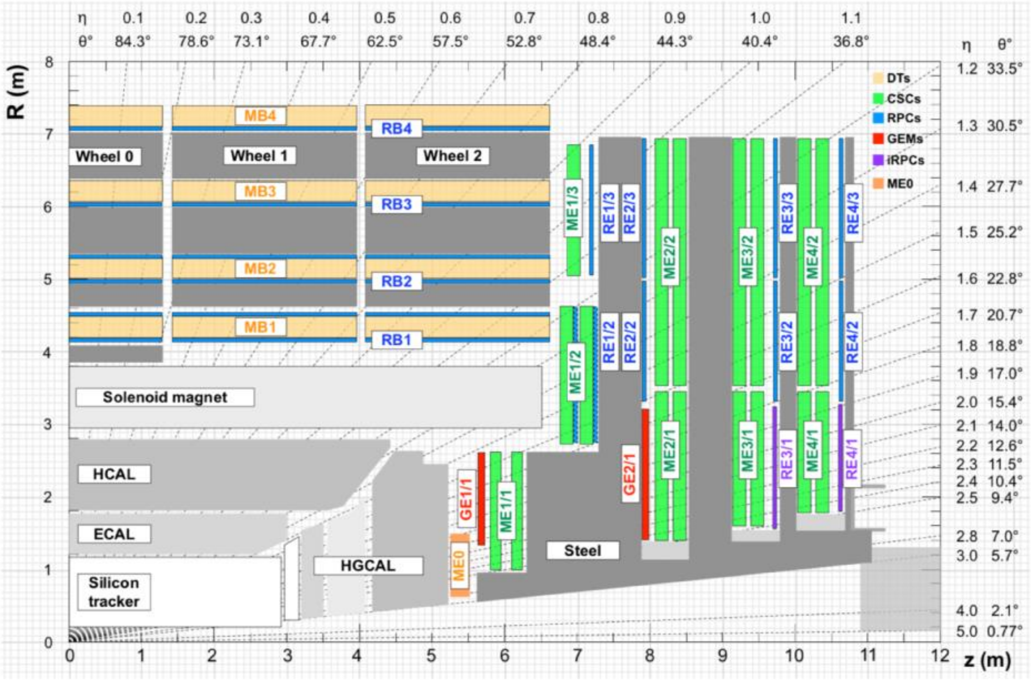
**→ The ultimate measurement of the Higgs boson mass is expected to be obtained from the H→ZZ→4μ channel at the HL-LHC**



**Muon system upgrades**

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

# Muon detector upgrades : Overview




**New stations:**

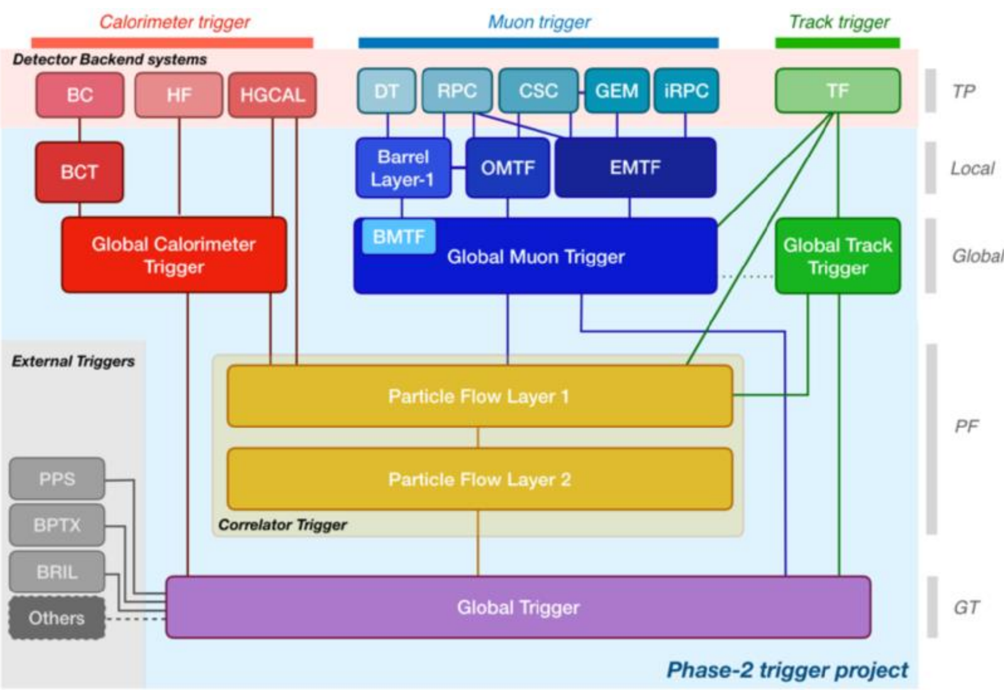
- GEM: **GE1/1**, GE2/1, iRPC: RE3/1, RE4/1: 1.6 ≤ η ≤ 2.4,
- **GEM: ME0 extended coverage 2.0 ≤ η ≤ 2.8**

**The current muon detectors are expected to withstand the HL-LHC radiation levels.** The upgrades focus on :

- Upgrading/replacing the electronics of the existing DTs, CSCs and RPCs to ensure longevity and to improve the trigger performance.
- Extending the coverage of the muon system to η ≃ 3 in order to benefit from the extension of the tracker and HGCAL as well as new features of the L1-trigger

See talk by C. Aruta for the Muon system upgrade details

# Upgrades to the Trigger and DAQ




**The Trigger parameters for HL-LHC**

-- Trigger primitives input rate ~ 63 Tb/s

-- L1 trigger rate of **~ 750 kHz @ 200PU** (now 100 kHz)

-- L1 latency of **12.5 μs** (now 3.4 μs)

-- High-Level Trigger (HLT) rate **~ 7.5 kHz** (now 1 kHz)

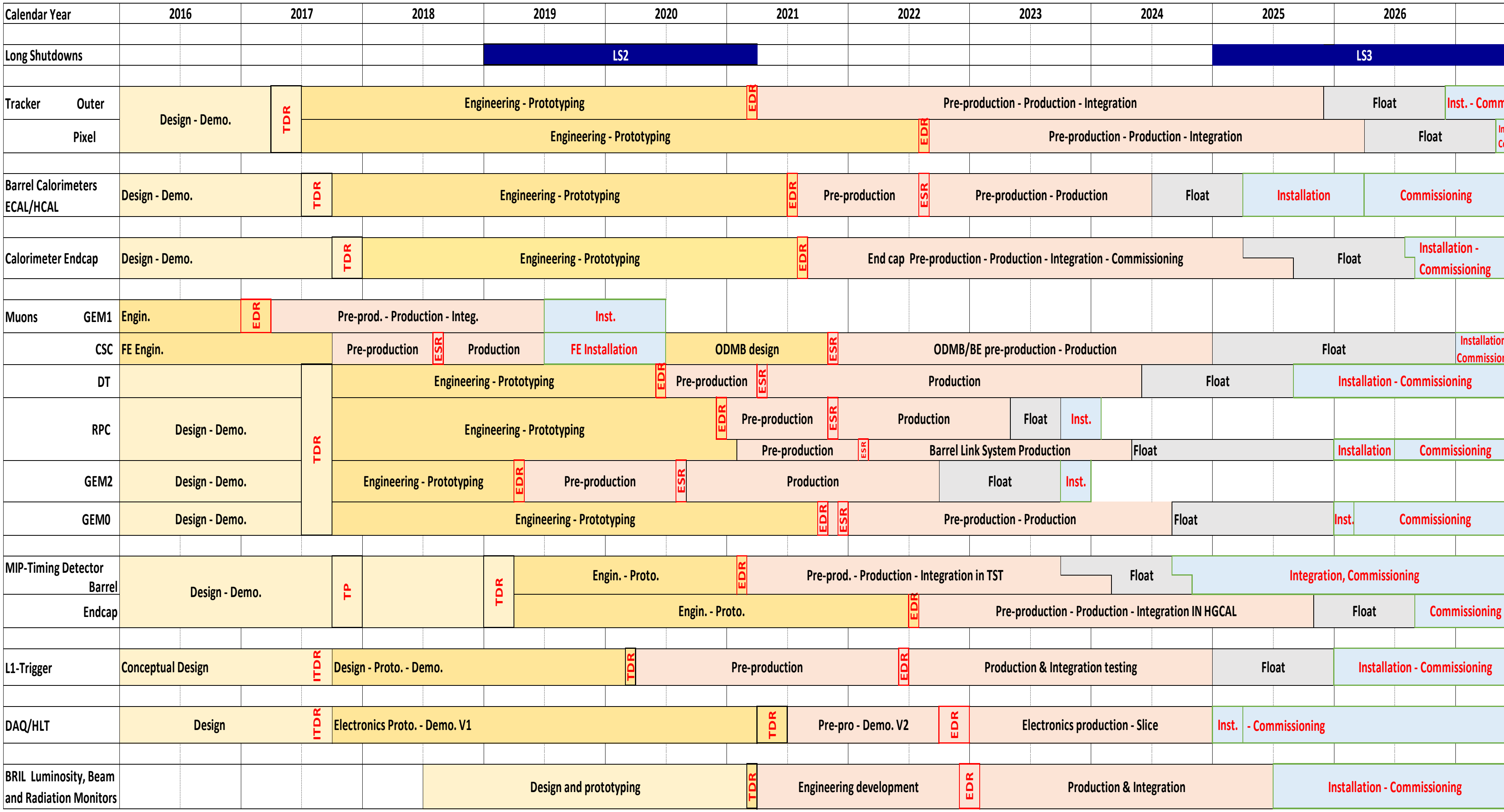
- **Take advantage of the new detector capabilities at L1**
  - Track trigger - better lepton $p_T$ resolution - @ 40 MHz
    - **More sophisticated algorithms for pattern recognition in general.**
  - More granular calorimeter information.
  - Additional muon chambers for η > 1.6
  - Sub-detector electronics upgrade to handle higher rate
    - **Made possible by high speed optical links (10 Gb/s) and GHz FPGA's**

# Summary

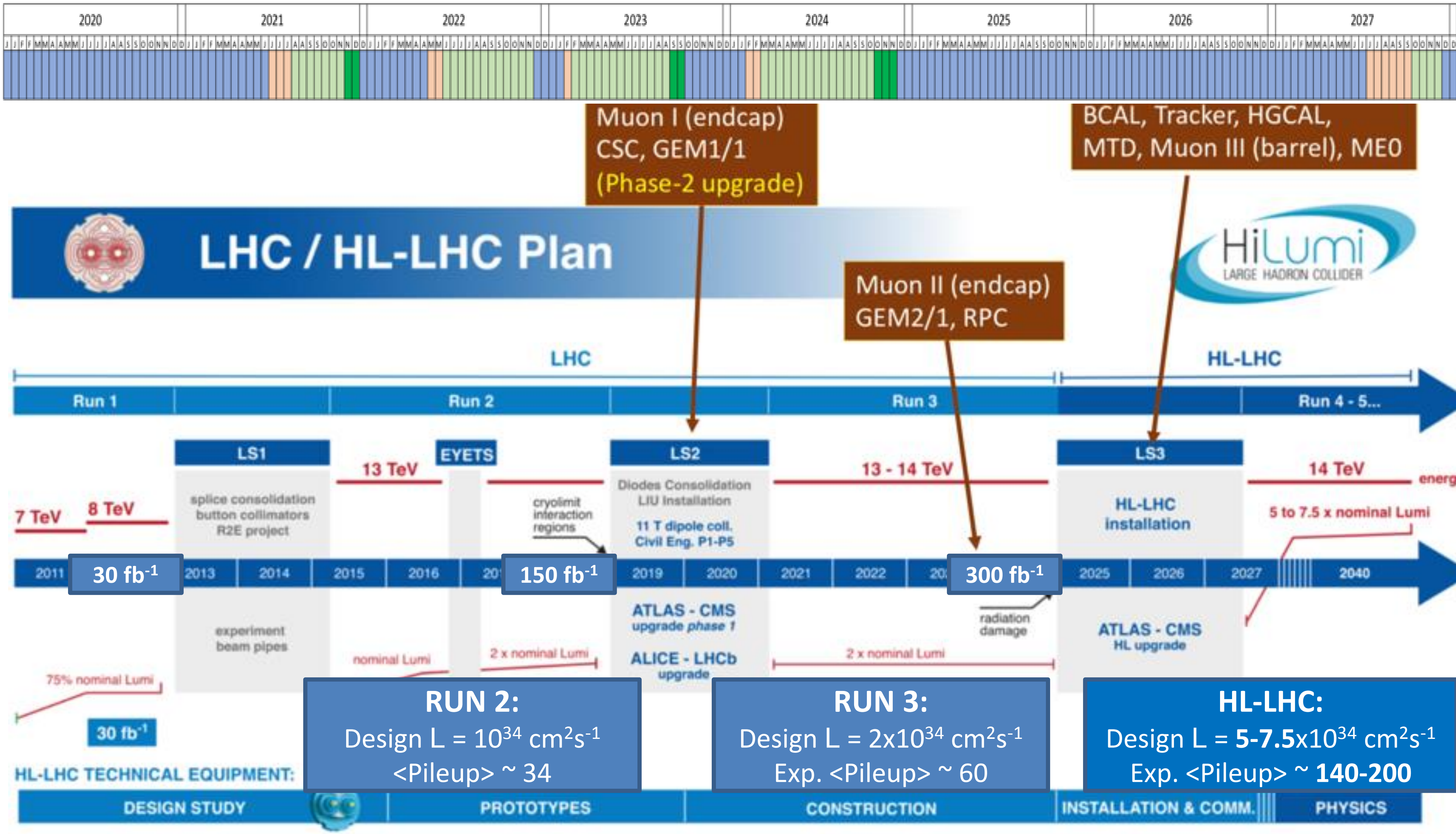
- The HL-LHC will enable measurements of Higgs boson properties with a very high precision as well as significantly extend the scope of new physics searches.
- The main challenges for the CMS detector are to cope with the high levels of radiation and to mitigate the impact of high pileup.
- The CMS collaboration is harnessing state-of-the art technologies to be able to fully exploit the HL-LHC luminosity.
- The Phase-2 upgrades program is well into the development phase and preparing for the production phase.
  - **The TDRs of the main detector and the Level 1 trigger are approved.**
  - **The small delay due to COVID-19, is possible to be absorbed in the planned contingency in the schedule.**

# BACKUP

# CMS HL-LHC Upgrade: Schedule



# CMS HL-LHC Upgrade: Timeline updated



# HL-LHC tracker : 2S module