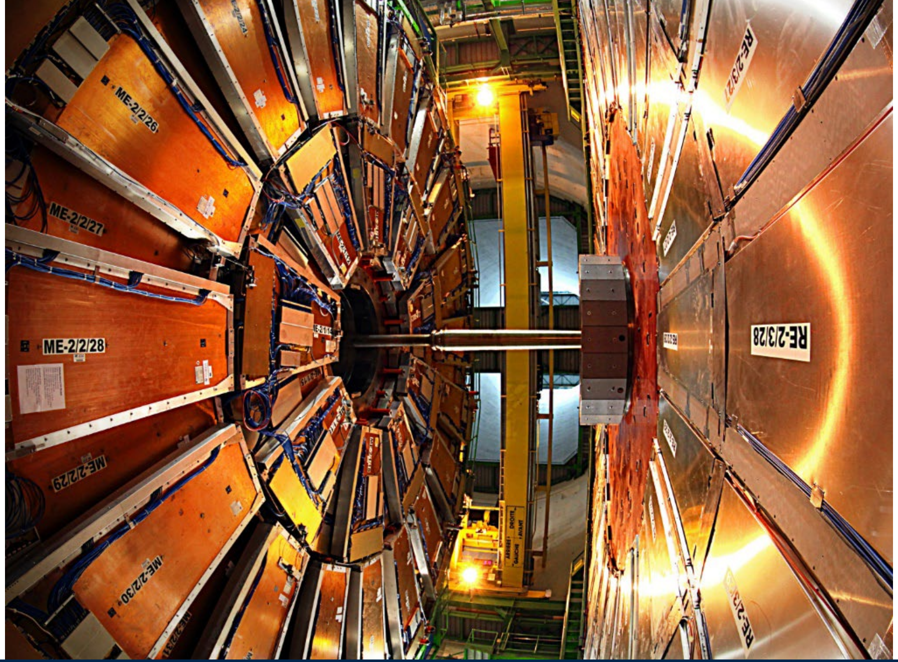

CMS and LHCb Calorimeters Run3 and Phase-II Upgrades status and plans

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25/10/2022

ICCUB

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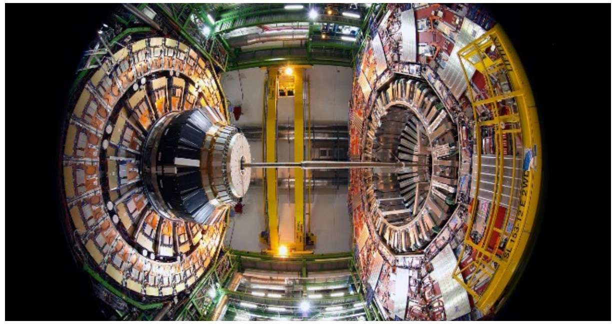
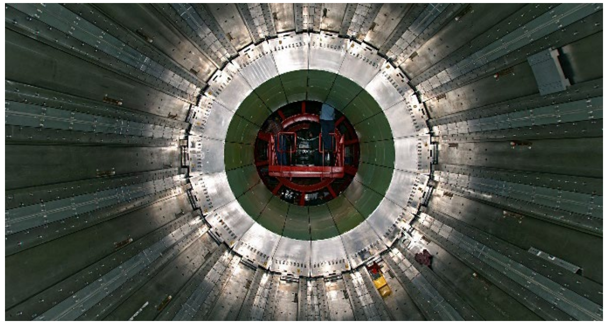
Introduction: CERN, the LHC, CMS and the LHCb

- Compact Muon Solenoid (or CMS):
  - General-purpose detector designed to observe any new physics phenomena
  - Barrel form designed to detect muons accurately with the most powerful solenoid magnet made
- LHCb:
  - LHC beauty experiment
  - Study of CP violation and rare decays in the b-sector.
  - Single-arm forward spectrometer

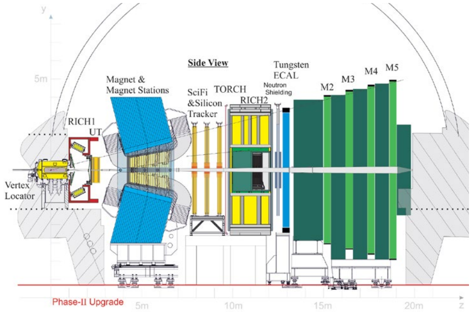
Contents



1) Status and Overview of the CMS HGCAL

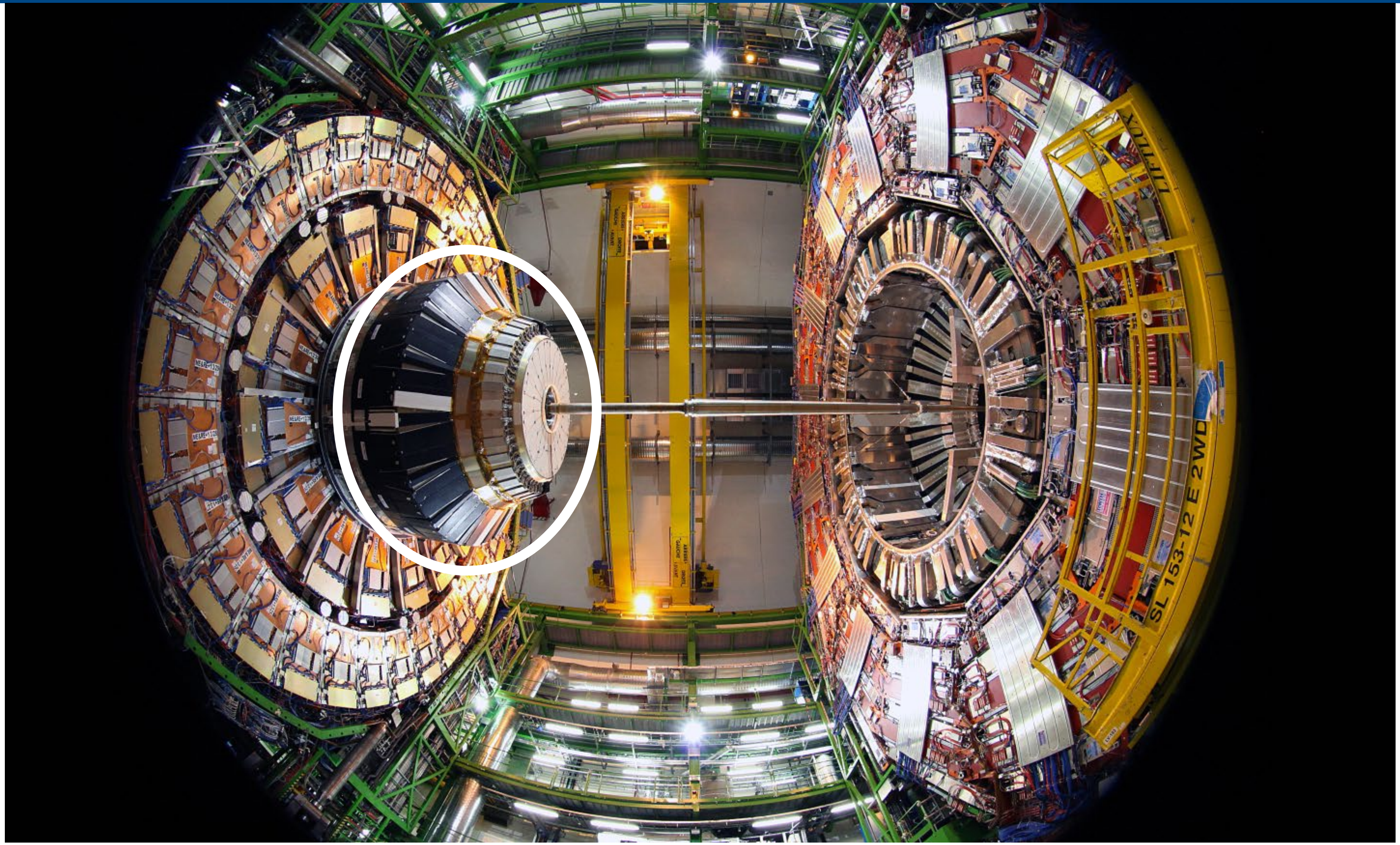


2) Upgrade of CMS Barrel Electromagnetic Calorimeter for LHC Phase-II



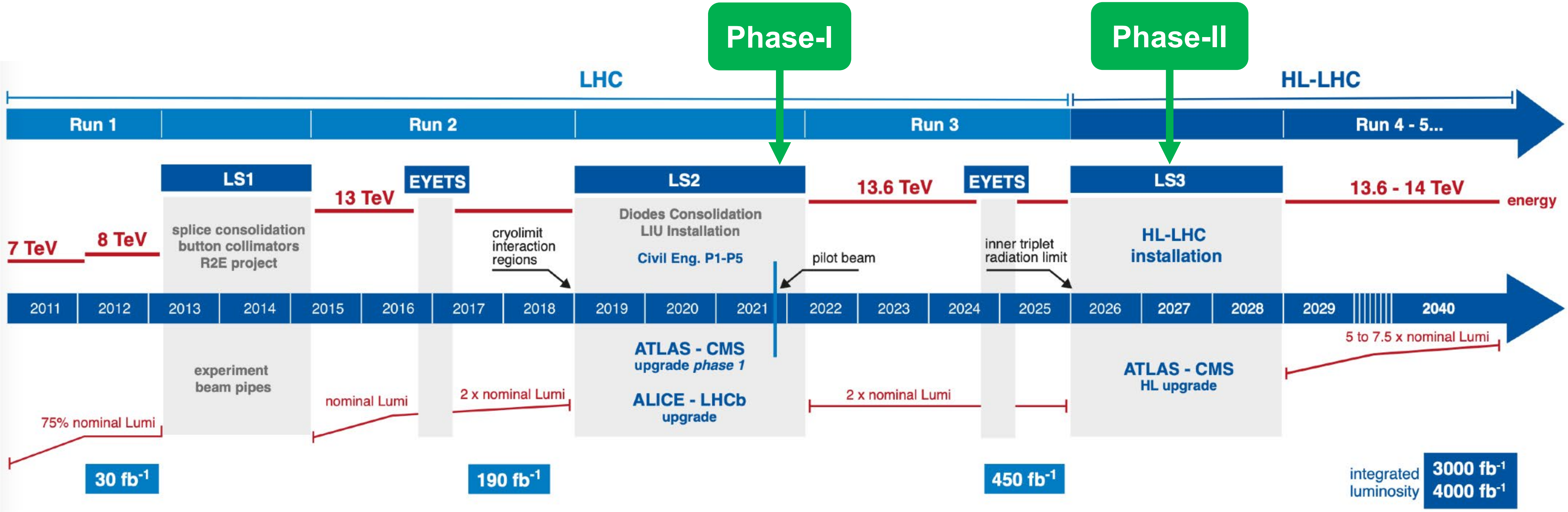
3) The LHCb Upgrades-I and II

Status and Overview of the CMS HGCAL



Check previous presentation by Huaqiao ZHANG

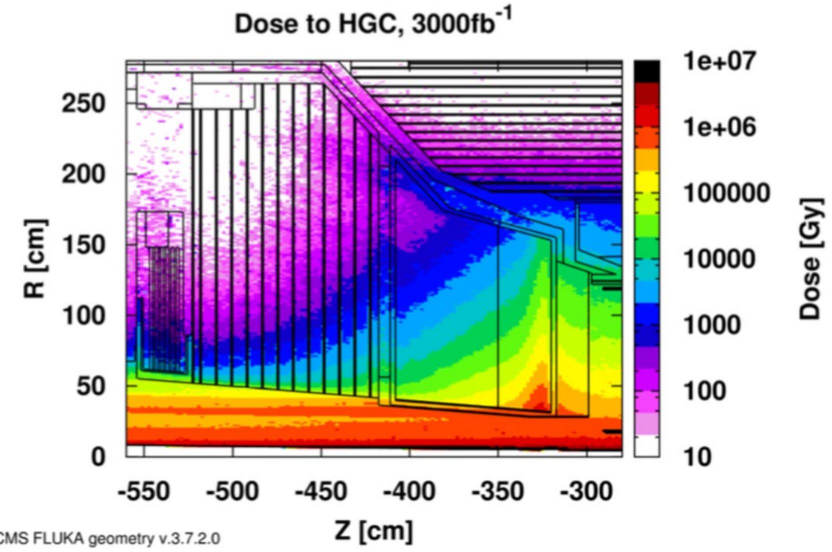
The High Luminosity LHC

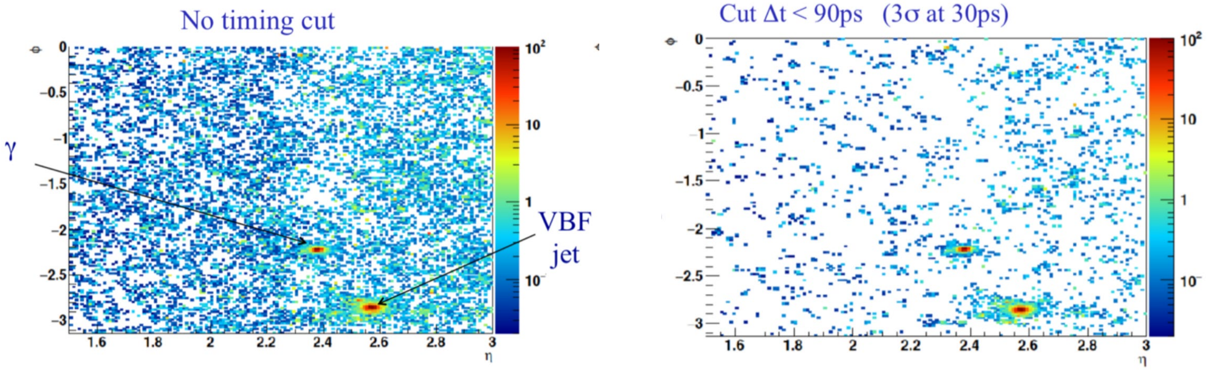


CMS HGCAL: Upgrade Challenges

- The HL-LHC will integrate ten times more luminosity than the LHC, posing significant challenges for radiation tolerance and event pileup on detectors
- Radiation hardness
  - Fluences of up to 10^{16} n_{eq}/cm^2 and doses of up to 2 MGy
  - Selection of silicon sensors to operate reliably (at -30ºC)
- Granularity is key for correct assignment of E deposits to tracks
  - 26 electromagnetic layers and 21 hadronic layers
  - Cell sizes
    - ECAL and most of HCAL: Si cell sizes of ~0.5-1 cm^2
    - Remainder HCAL: plastic scintillators os 4-30 cm^2
- Pileup suppression with timing
  - Concept: identify high-energy clusters, then make timing cut to retain hits of interest
  - Design HGCAL to obtain a ~30ps timing measurement for multi-MIP energy deposits

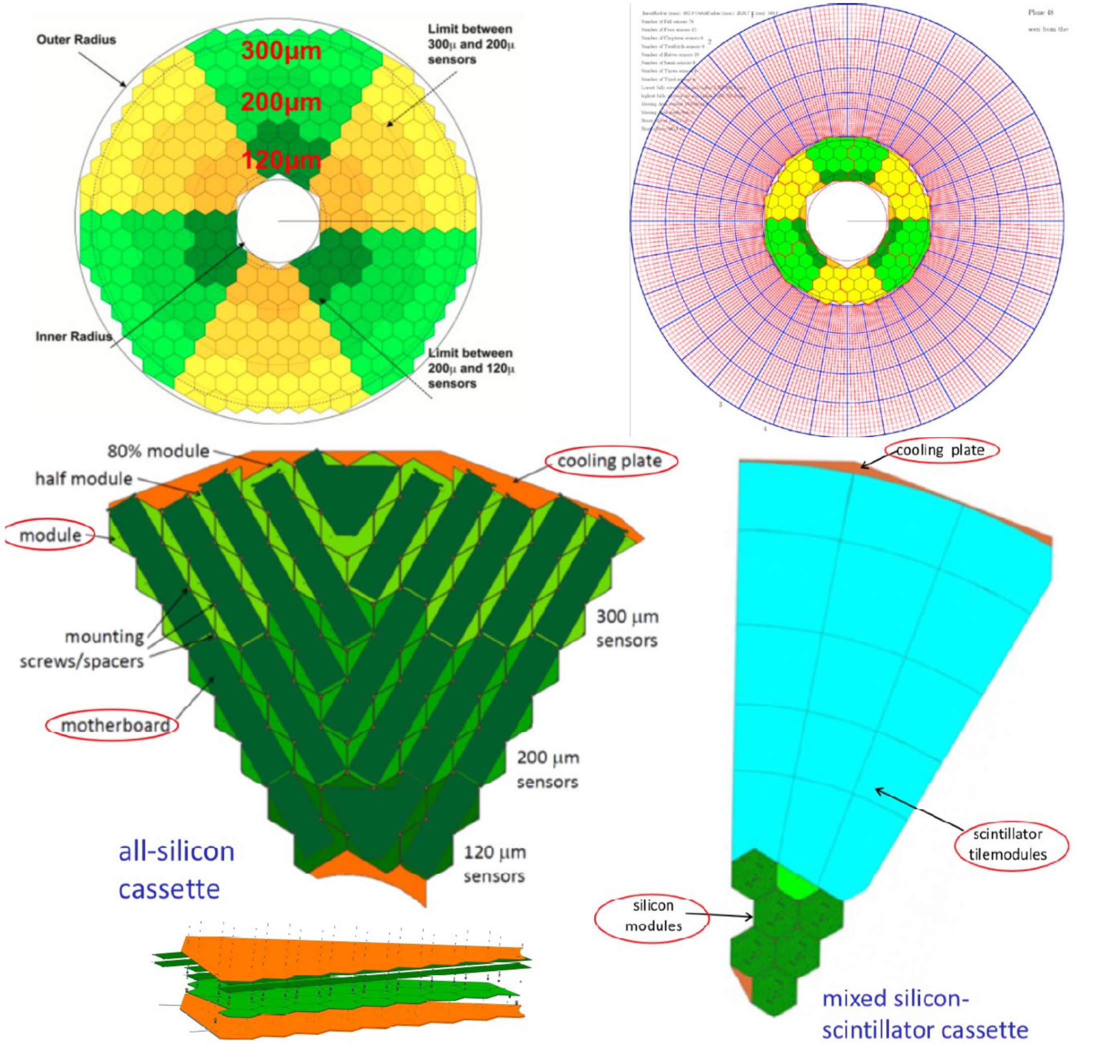
Expected total dose





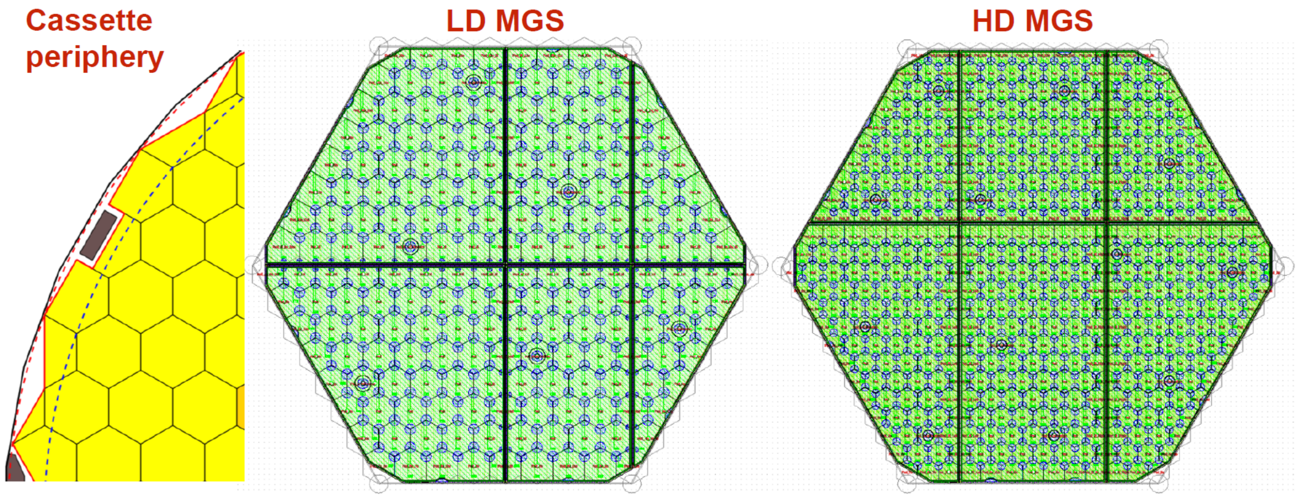
CMS HGCAL: Lateral Structure, Cassettes

- Silicon and scintillator modules assembled into cassettes
  - Glued stack of baseplate, sensor and readout hexaboard
  - Relative alignment within ~50um achieved with gantry based automated assembly
  - Electrical connections are done with wire-bonds
  - Scintillators are an economical solution for low radiation areas
    - 240k cast or molded tiles, 4-30cm^2
    - Read-out by SiPMs (2,4,9mm^2) assembled on PCBs
    - Successfully operated tileboards in beam tests
- Supported and cooled by copper cooling plate
  - Cooling with CO_2 to -35ºC
  - Cooling performance verified
- Data from modules collected by motherboards
- Cassettes house all services and DC2DC converters



CMS HGCAL: Silicon Sensors

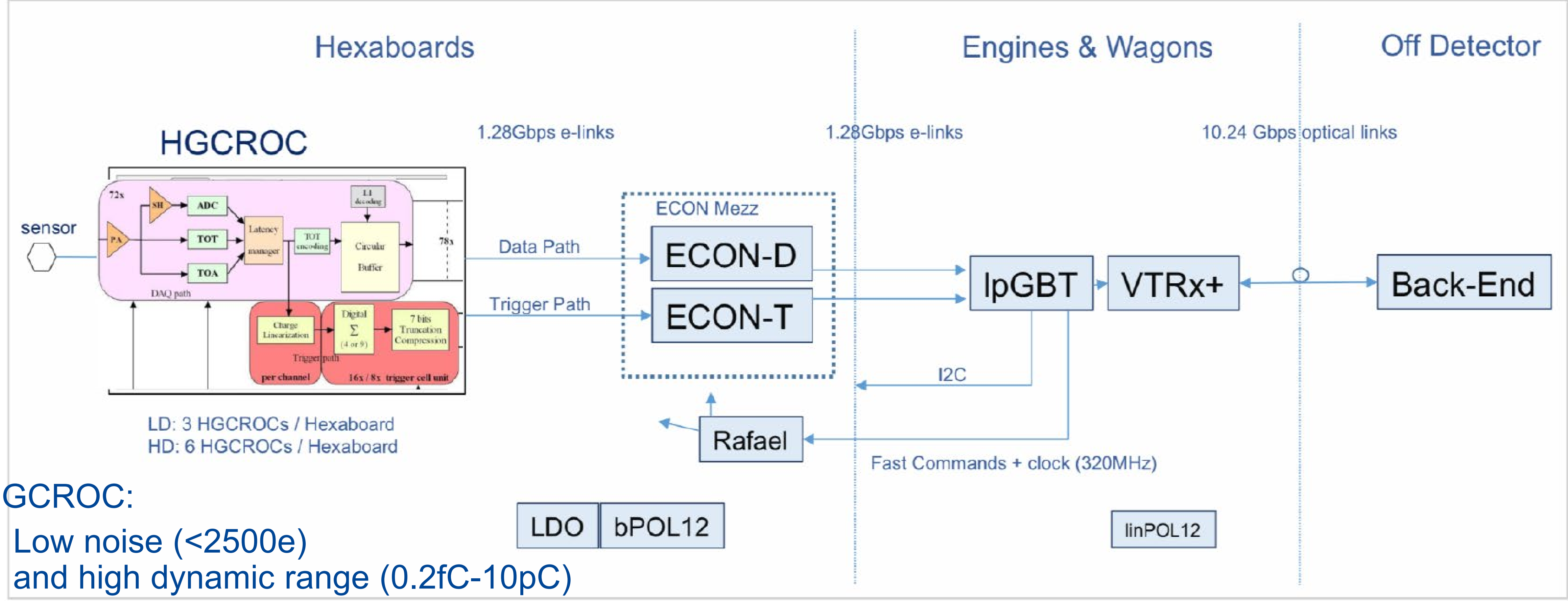
- Design
  - Design has been finalized in 2021
  - Hexagonal shape to maximize usage of circular wafers
  - 8” wafers to lower cost wrt 6” (new production line with Hamamatsu)
  - Planar, DC-coupled, p-type sensors (more radiation hard than n-type)
  - Thin sensors collect more charge at high fluence
- Radiation Hardness Qualification
  - In 2020/21 irradiated 40 sensors with neutrons up to 10^{16} n_{eq}/cm^2 at Rhode Island Nuclear Science Center, US
  - Most sensors met specs and identified the best production process (publication soon)
  - ~300 pre-series sensors mostly already delivered
- Multi-geometry sensor design
  - To save on the number of masks and all the associated tooling, we designed multi-geometry sensors (MGS)
  - All dicing lines have been collected on a single design and each of the resulting islands have been protected by an individual guard ring
  - Prototype testing on-going, ordering pre-series soon



LD: ~200 cells of 1.2cm2
300um & 200um thickness

HD: ~450 cells of 0.5cm2
120um active thickness

CMS HGCAL: Silicon Electronics



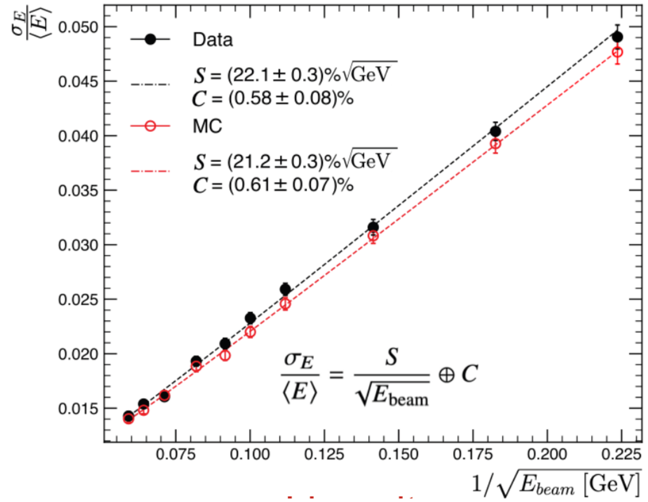
HGCROC:

- Low noise (<2500e) and high dynamic range (0.2fC-10pC)
  - 10bit ADC below ~50fC, 12bit ToT above
- Timing information (ToA) down to 25ps
- Radiation hard (TID <350 Mrad)

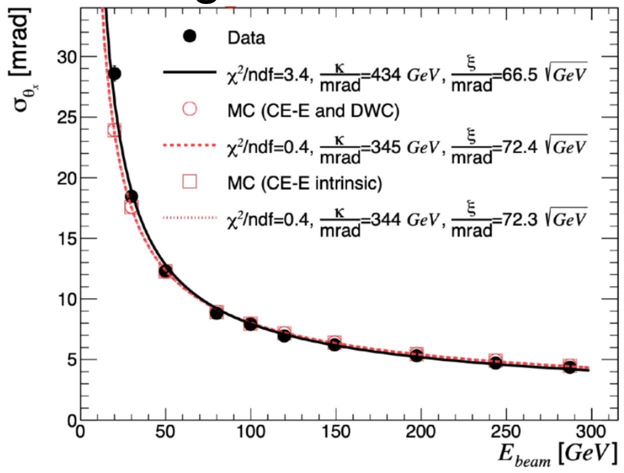
CMS HGCAL: Test Beam

- First large-scale test of more than 90 HGCAL modules data taking at CERN (Oct 2018) .
- Setup exposed to e⁺ and π beam of energies ranging from 20 to 300 GeV and 200 GeV μ beams.
- Results
  - Stochastic term is 22%
  - Constant term of 0.6%
  - Linearity within 3%
  - Good agreement between data and simulation, also for angular resolution

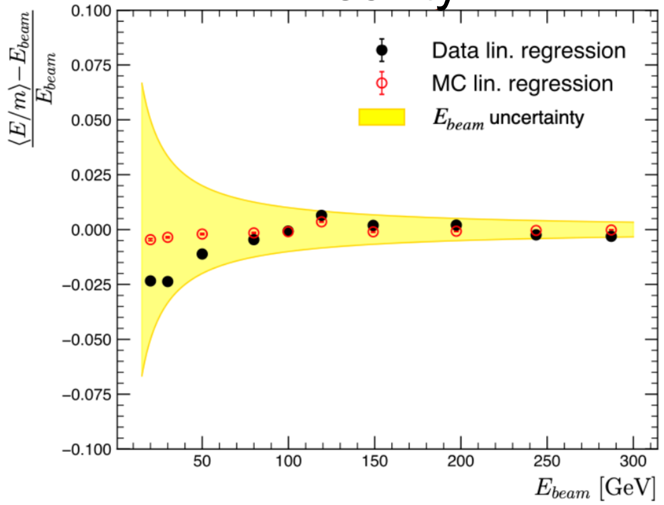
Energy resolution



Angular Resolution



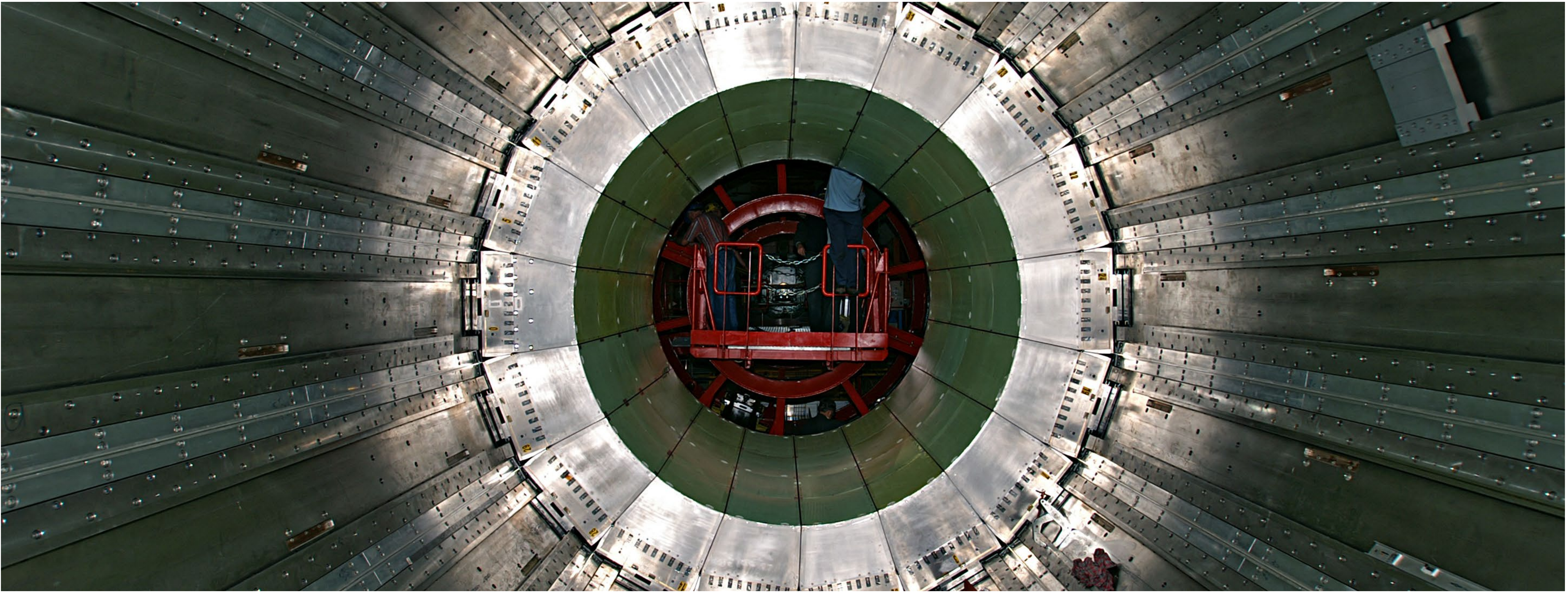
Linearity



CMS HGCAL: Conclusions and plans

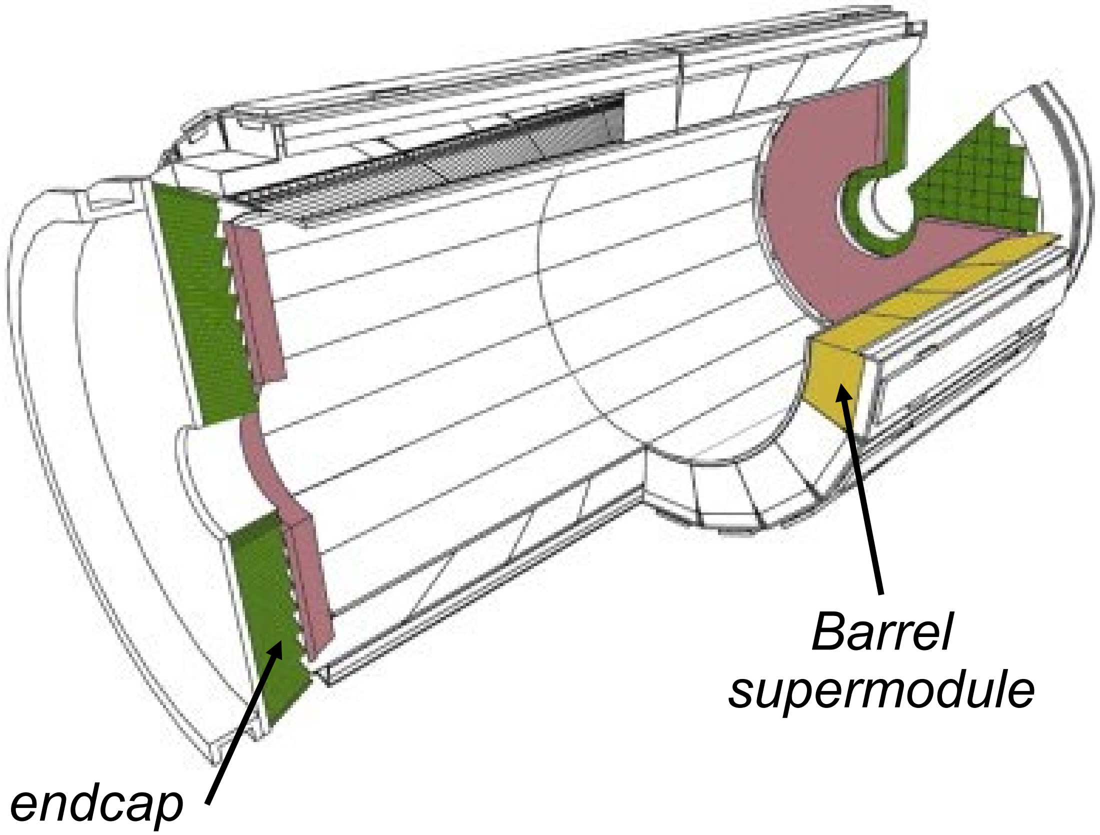
- HGCAL will be the first large scale calorimeter with Si and SiPM-on-tile technologies providing unprecedented granularity and time resolution
- Lots of progress since the Technical Proposal (2015) and the Technical Design Report (2018)
- Beam tests confirm expected performance
- Several key components approach end of prototyping phase
  - Sensors, SiPMs, HGCROC
- Timeline:
  - EDR in late 2022 or early 2023
  - mass-production to start in 2023 (sensors, scintillator tiles, electronics)
  - module assembly to start beginning of 2024
  - cassette assembly to start beginning of 2025
  - cassette assembly finished late summer 2026
  - first endcap ready for lowering March 2027
  - second endcap ready for lowering July 2027

Upgrade of CMS Barrel Electromagnetic Calorimeter for LHC Phase-II



CMS Barrel ECAL Overview

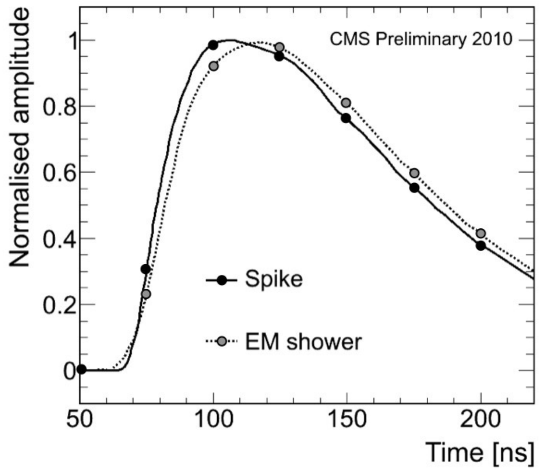
- Lead tungstate ($PbWO_4$) crystal calorimeter
- Provides excellent energy resolution in harsh radiation environment
  - Achieved 1% mass resolution for SM Higgs in γγ decay channel
- Hermetic and compact detector with coverage up to $|\eta| = 3.0$
- Barrel region:
  - Contains 61,200 crystals across 36 supermodules
  - Uses avalanche photodiodes (APDs) as photodetectors
- Endcap region:
  - Contains 14,648 in 4 half-disk “Dees”
  - Uses vacuum phototriodes



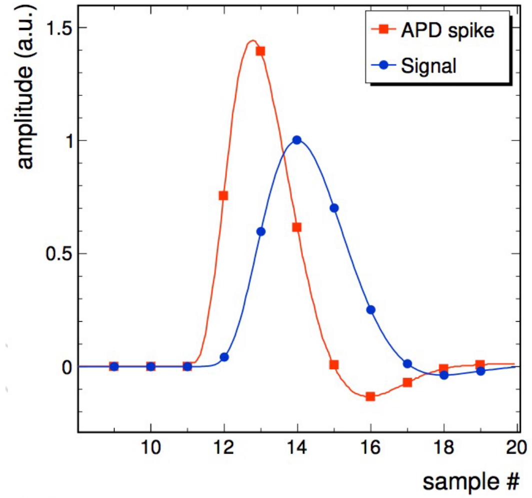
CMS Barrel ECAL Phase II Upgrade Overview

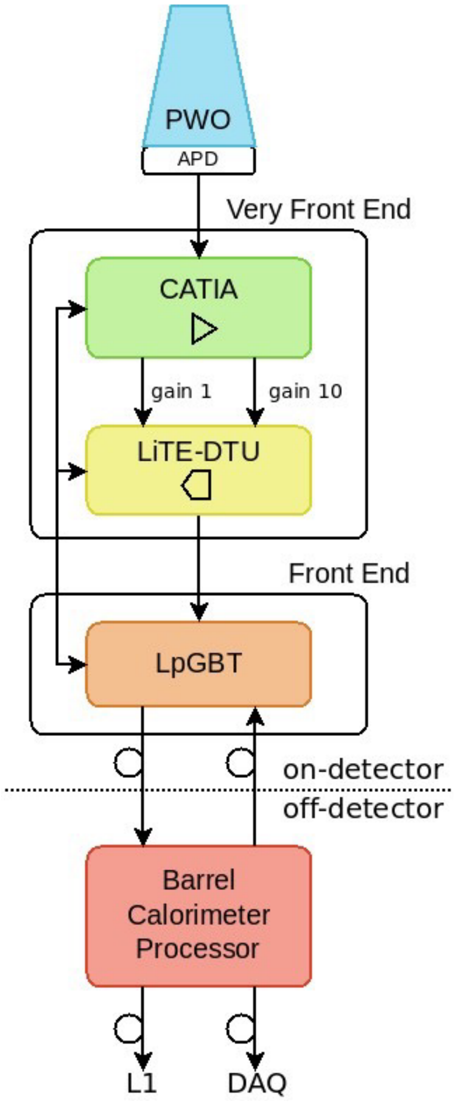
- Replace the endcaps with a high granularity calorimeter
- Refurbish ECAL barrel supermodules during Long Shutdown 3 (2026-2028)
- Keep the lead tungstate crystals and APDs in the barrel
  - Reduce temperature from 18ºC to 9ºC to keep noise below 250 MeV
- Replace the on and off detector electronics
  - Use new radiation hard ASICs with faster pulse shaping and factor of 4 increase in sampling rate:
    - Reduce impact of out of time pileup and limit increase in APD noise
    - Provide improved spike rejection via pulse shape discrimination
    - Provide 30 ps timing resolution for E > 50 GeV
  - Streaming Front-end board providing single crystal info to trigger via high speed radiation hard optical links (lpGBT)
    - More advanced algorithms in off-detector FPGAs

Current



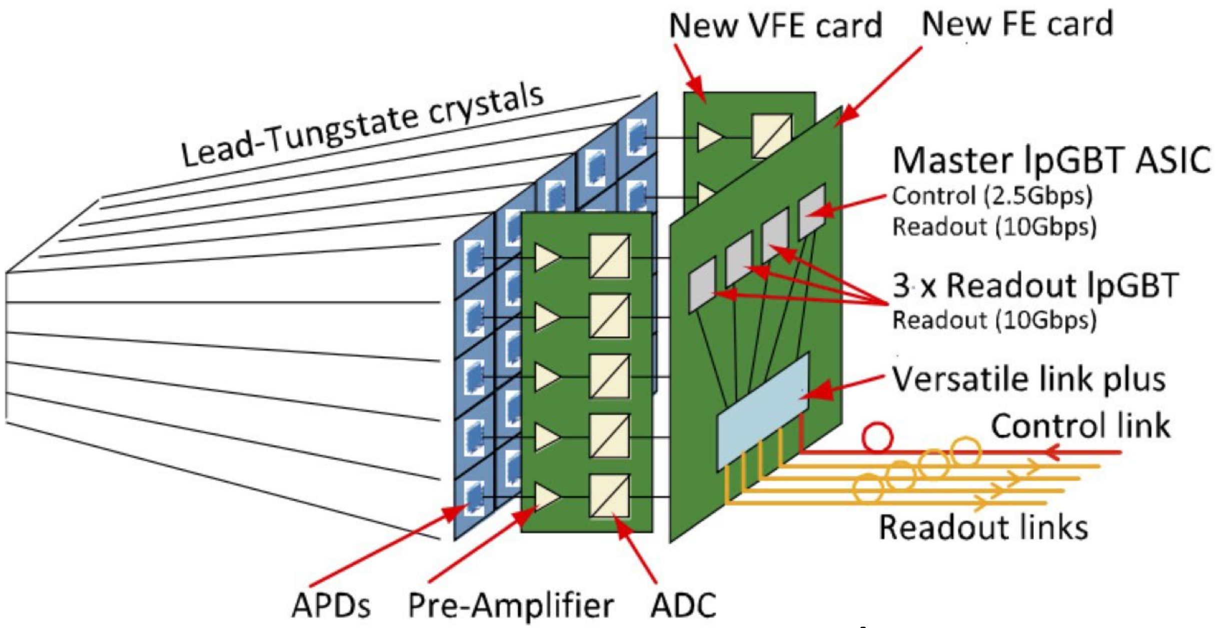
Upgrade





CMS Barrel ECAL Electronics Upgrade

ECAL Front End electronics implementation



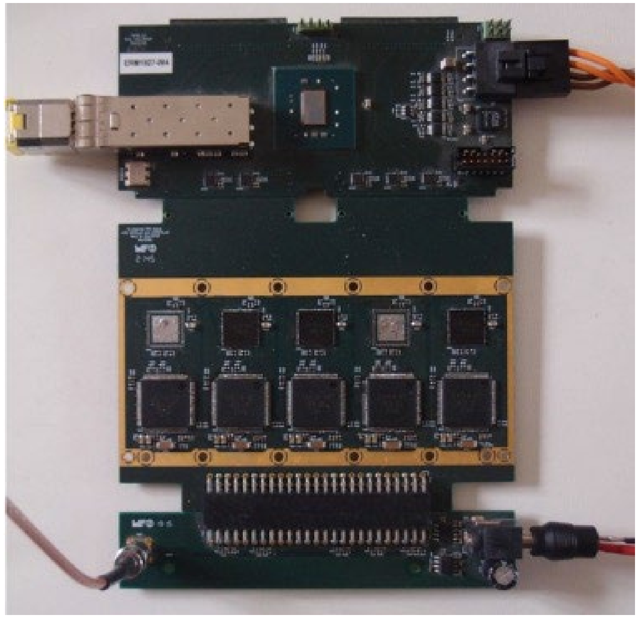
VFE = Very Front End

FE = Front End

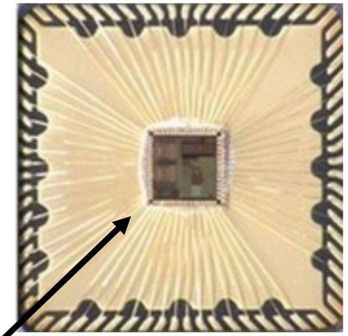
- Lead tungstate crystal longevity
  - Main concern: ageing due to radiation
  - Scintillation mechanism is not affected by radiation
  - Radiation creates crystal defects which reduce the crystal transparency and therefore light output
  - Effect is monitored and corrected using a dedicated light injection system
  - MC simulations have been used to predict the light output in Phase II
- Avalanche Photodiode (APD) Longevity
  - Radiation damage to APDs:
    - Gamma rays creating surface defects which increase surface current and reduces quantum efficiency
    - Hadrons creating bulk damage causing an increase in the bulk current
  - Main concern for HL-LHC is the increase of dark current
    - Electronic noise depends on square root of bulk current
    - Can be mitigated by reducing the operating temperature

CMS Barrel ECAL Electronics Upgrade

VFE multichannel



LiTE-DTU

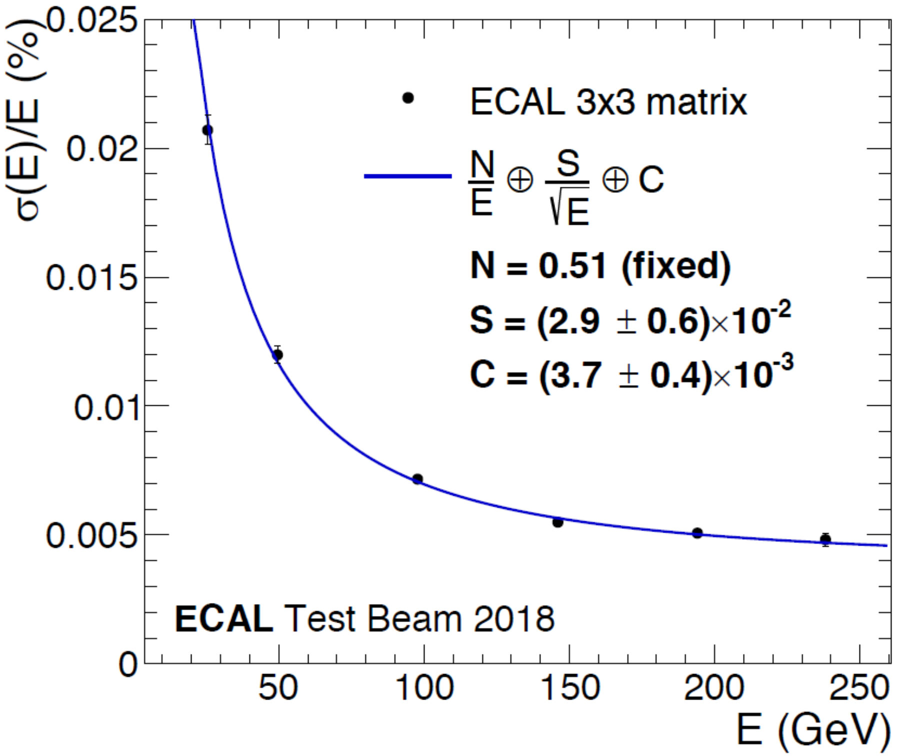


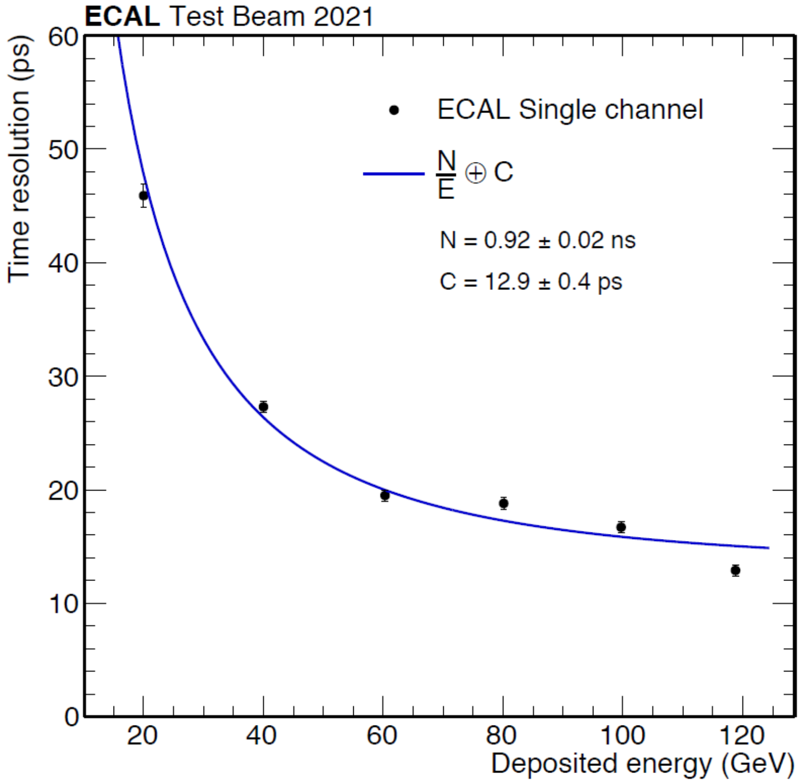
- Received ~600 packaged LiTE-DTU v2 in February
- All 600 tested with 98% passing
- SEU test performed at CRC Louvain
  - No I2C errors, No PLL loss of lock

- **CATIA:** pre-amp (TIA) with fast pulse shaping capabilities and 2 gain outs (1x and 10x)
- **LiTE-DTU:** Data conversion, compression and transmission ASIC
  - Two 12-bits ADCs, 160 MS/s data conversion
  - Lossless data compression
  - Look-ahead algorithm
- VFE:
  - Contains 5 x CATIA and LiTE DTU chips
- APD, CATIA and PCBs Pilot run of 8 VFE v3 have been tested
  - Initial noise and timing measurements are compatible with 30 ps timing for E > 50 GeV
- Larger production launched at May 2022

CMS Barrel ECAL Electronics Upgrade

- **Test Beam 2021**
- Single ECAL tower (5x5 crystal matrix) with Phase II CATIA v1.2 and LiTE DTU v1.2
- Electron beam with energies from 25 to 250 GeV
- Energy and timing resolution meet requirements

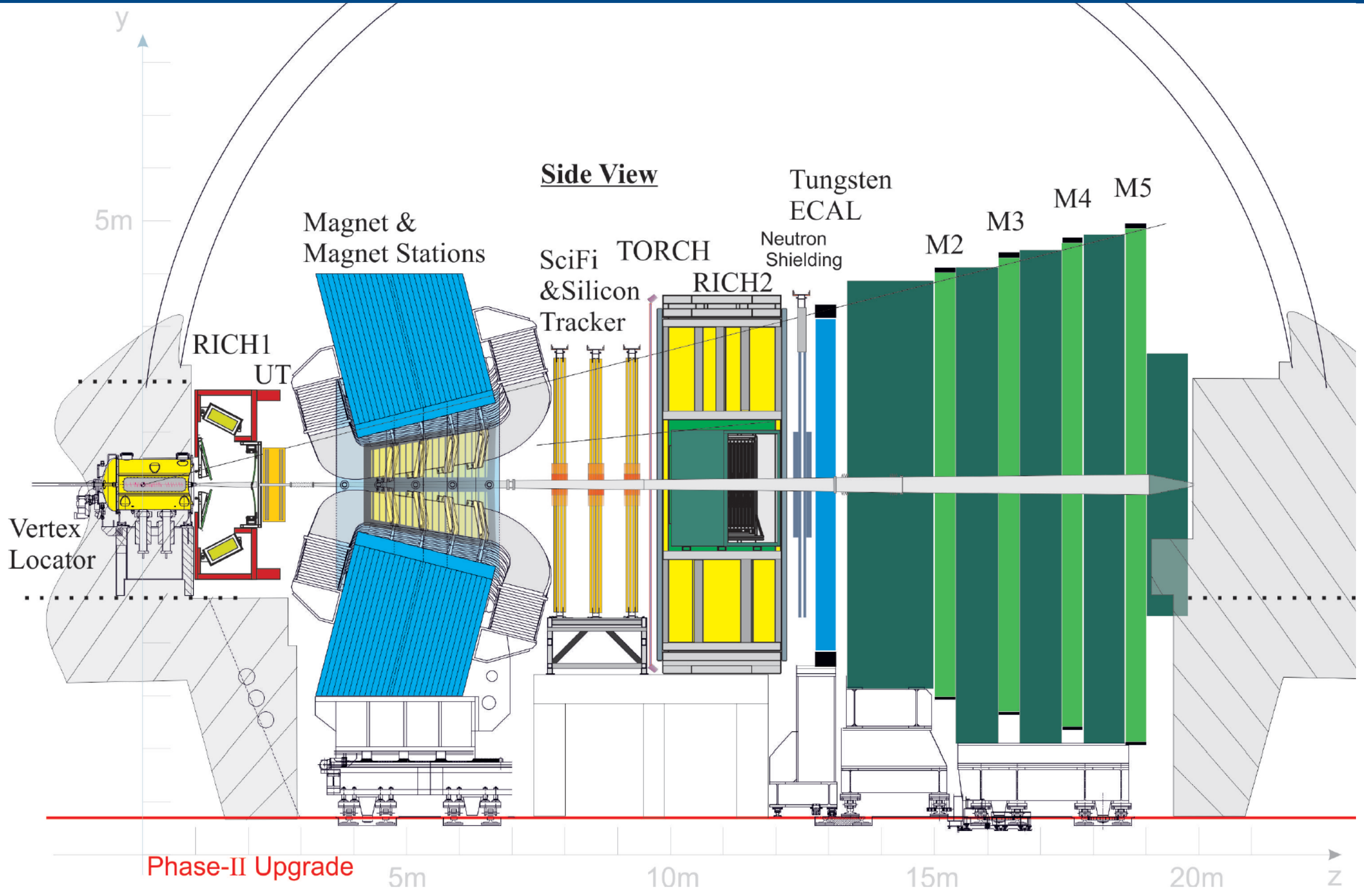




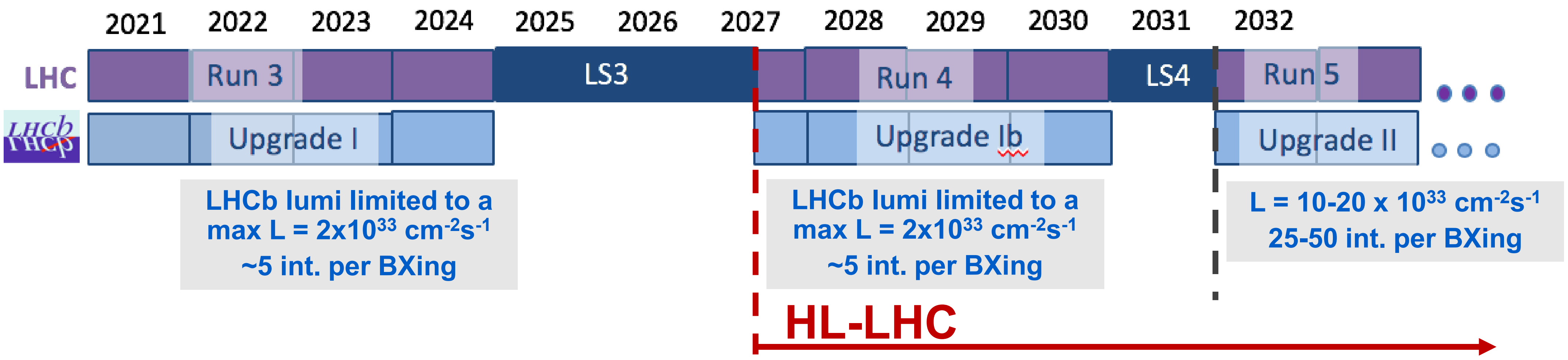
CMS Barrel ECAL Upgrade Phase-II: Conclusions and plans

- Both the on and off detector electronics will be replaced in the CMS ECAL for HL-LHC in order for the current performance to be maintained
- Full featured ASICs have been received
  - Initial test results are good
- Plans for this year:
  - System test (>400 channels) with spare supermodule
  - Supermodule test beam with electrons and pions
  - Engineering design review to provide green-light for the production of the front-end ASICs and electronics boards
  - Continue development of BCPv2 and associated firmware
- Will have production ready (and tested) versions of ASICs and on detector boards by the end of the year
- All barrel calorimeter components are on track for installation during LS3

The LHCb Upgrades-I and II



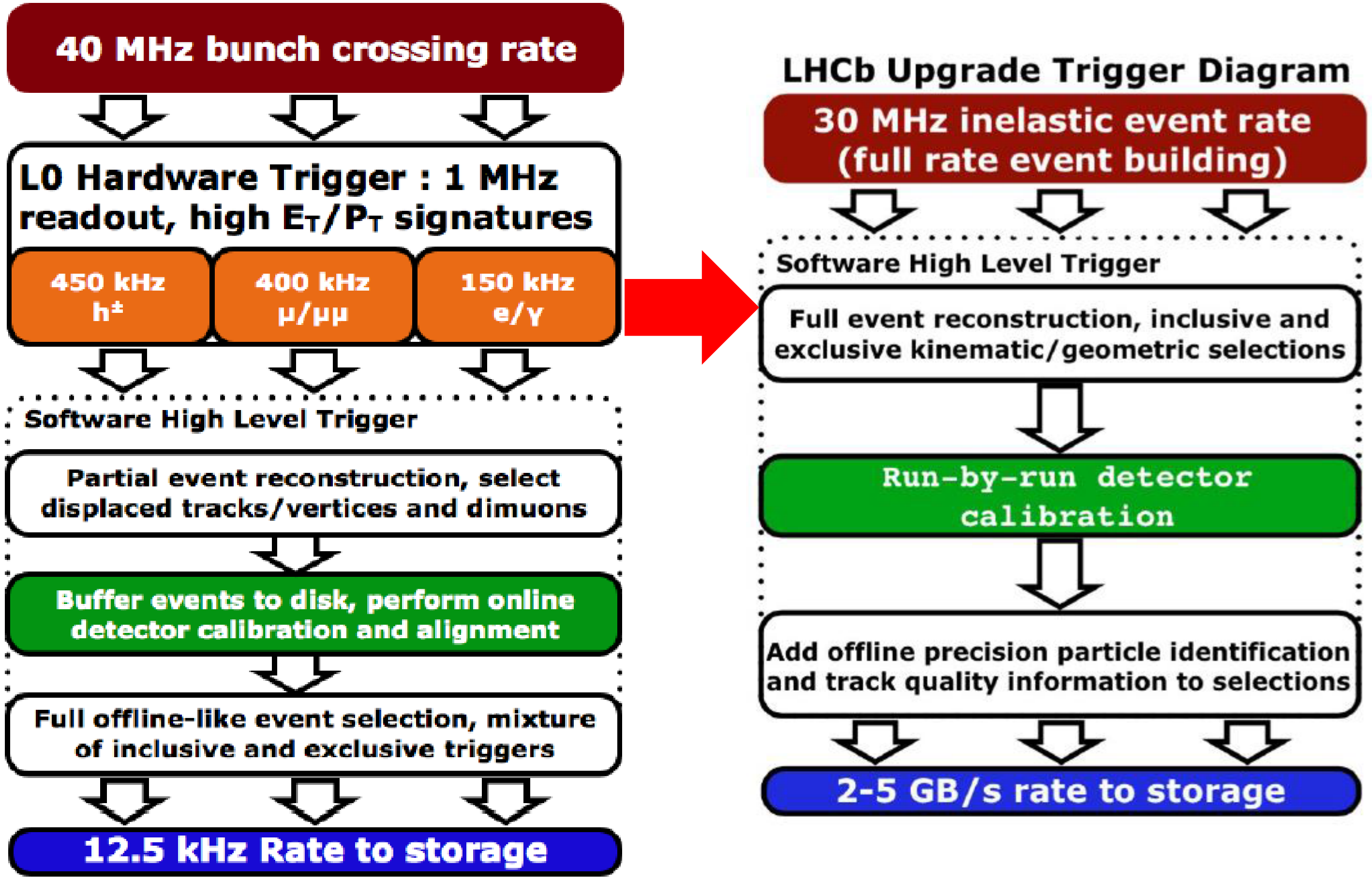
LHCb Upgrades timeline

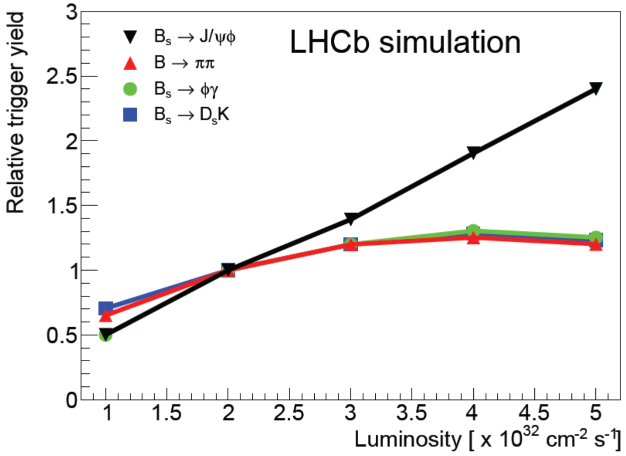


- Upgrade I – Run 3
  - Increase the luminosity from 4×10^{32} cm^{-2}s^{-1} to 2×10^{33} cm^{-2}s^{-1}
  - Detectors and electronics upgrades needed
  - Trigger and DAQ redefined
- Consolidation/enhancement phase in LS3
  - First stage of Upgrade II “Upgrade Ib”
  - No luminosity change (baseline)
- Main installation phase in LS4
  - Full Upgrade II (luminosity increase)

LHCb Phase-I upgrade strategy: trigger

- The 1 MHz L0 trigger saturates physics processes yield with increasing luminosity
- At high luminosity, need to increase p_T threshold to remain within 1 MHz

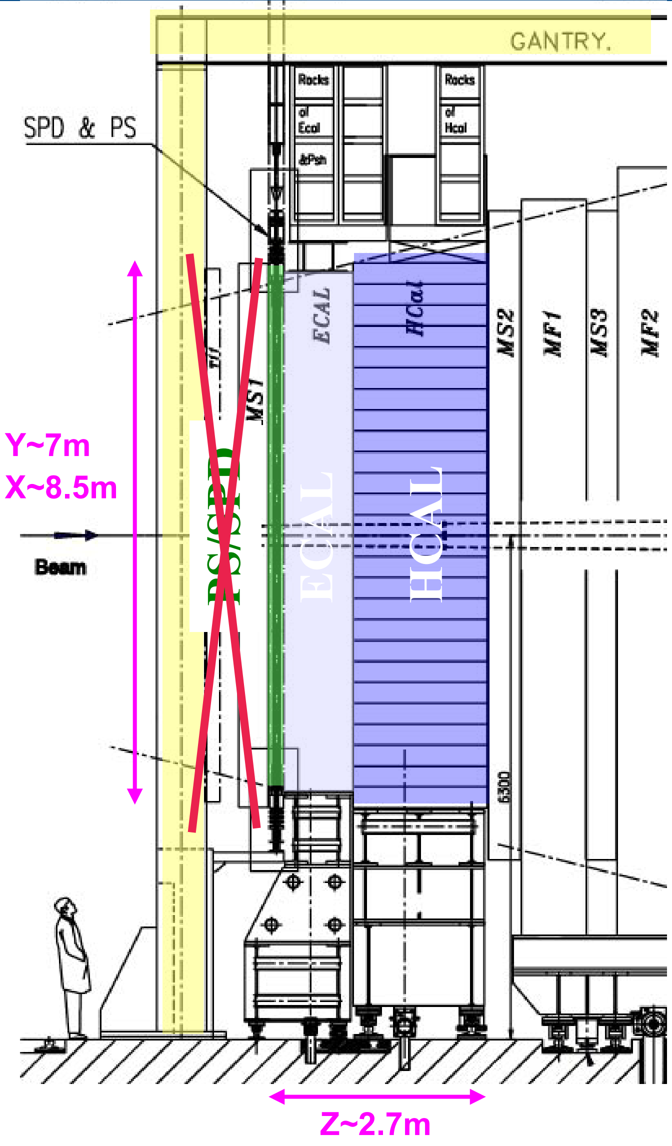




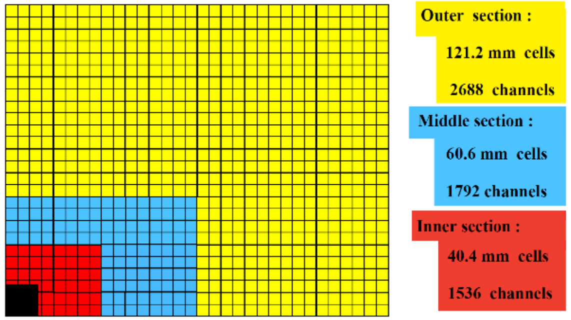
SOLUTION:

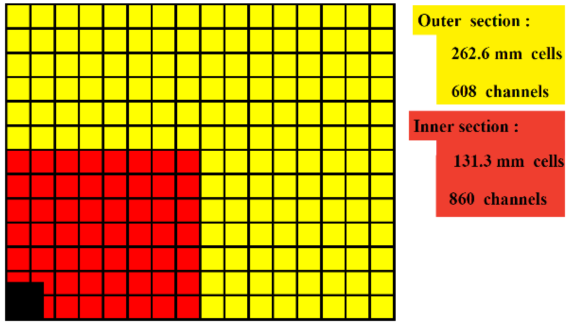
- Remove the first level hardware trigger
- Event selection will be based of full event reconstruction

LHCb Phase-I upgrade strategy: Calorimeter detector



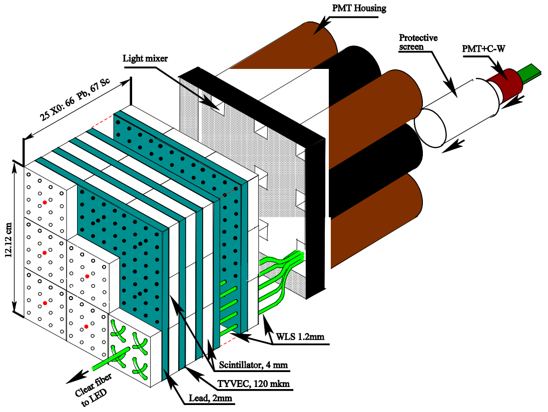
- 2 sub-detectors: ECAL, HCAL were kept
  - PS/SPD dismantled and not used in the Upgrade I
- Granularity
  - ECAL: 6016 cells
  - HCAL: 1488 cells



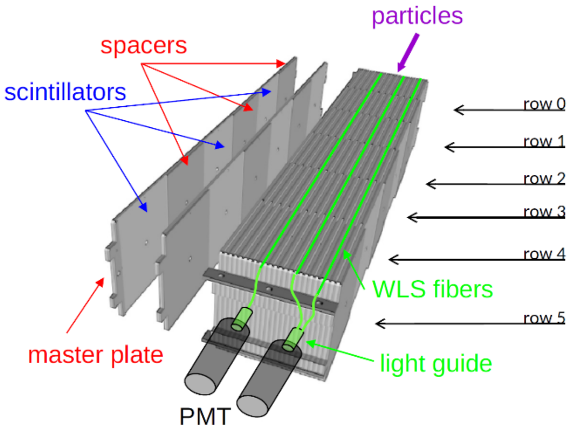


- Detection

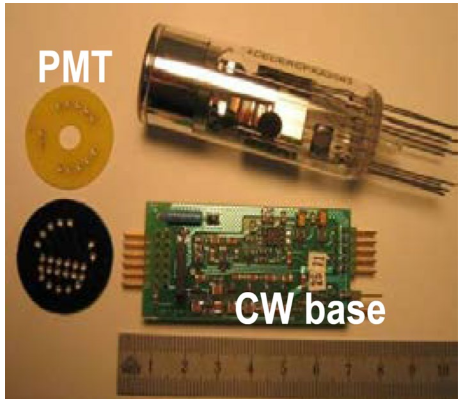
ECAL Shashlik: scintillator tiles and lead plates



HCAL: Tilecal technology iron+scintillator

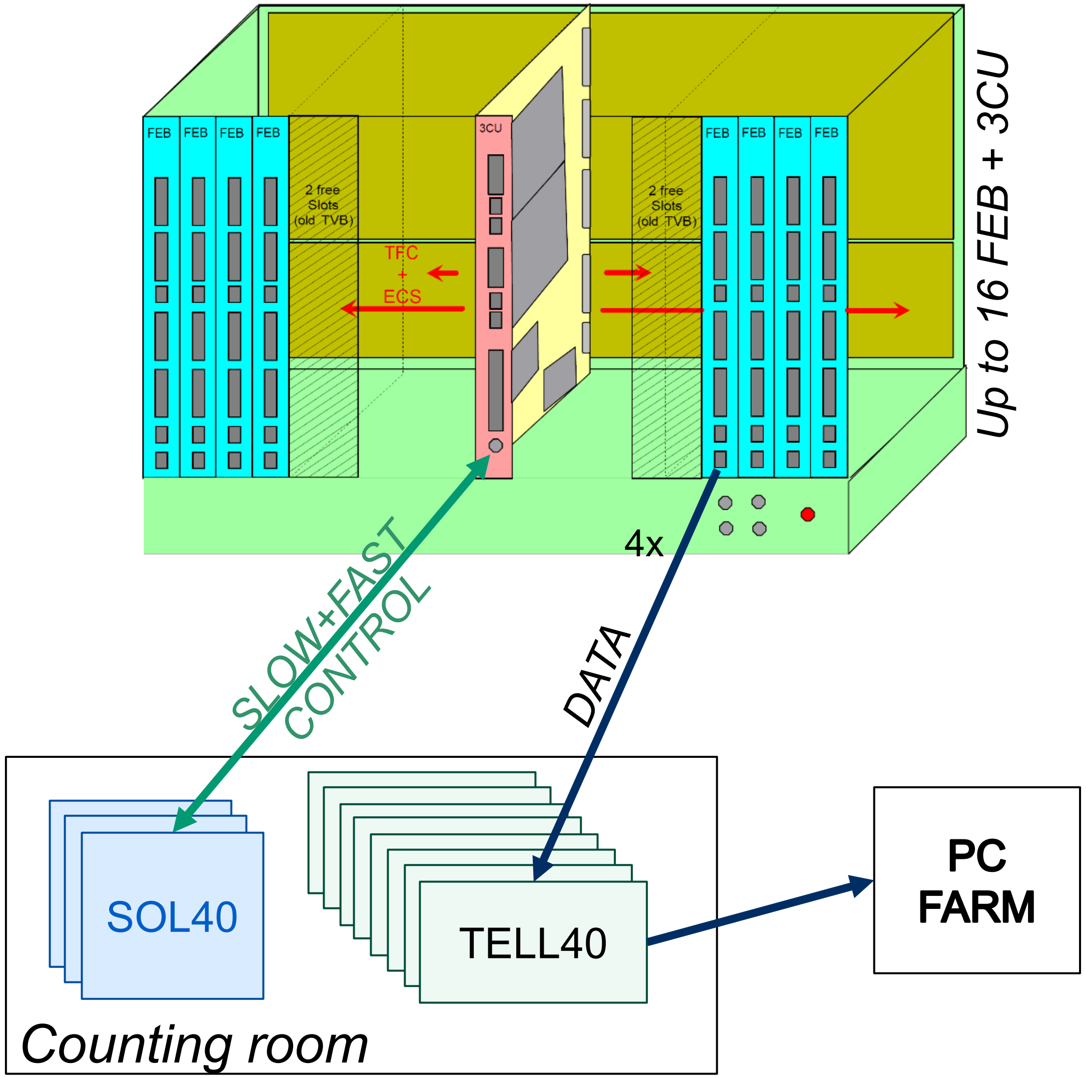


PMT R-7899-20, HAMAMATSU

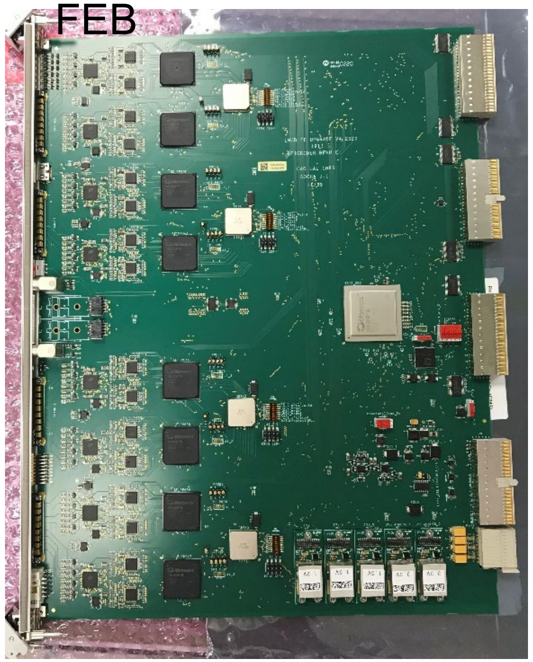


Phase-I upgrade strategy: Calorimeter electronics

18 crates on gantry above Calorimeter



FEB processing @ 40 MHz

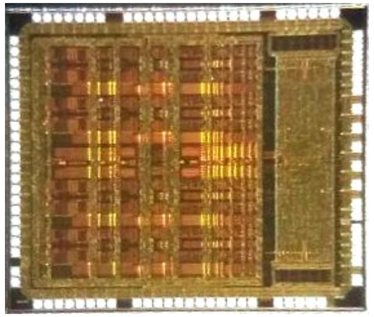


→ Each FEB receives clock, commands and configuration from 3CU (backplane) and provides data on 4 optical links (mono-dir) to TELL40

→ Data from 1 FEB is made of

- Signal from PMTs is integrated by the ICECAL chip
- ADC values of the 32 channels
- The Low Level Trigger (LLT), i.e. the result of a sum/comparison that can be used by the software trigger in the PC farm

ICECAL



- PMT gain ↓ 1/2.5 (reduce ageing)
- ICECAL ↑ x2.5 electronics gain
  - lower noise!
- 4 ch
- 2 alternated subchannels to avoid dead time

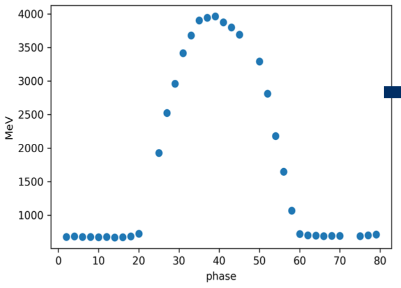
Phase-I upgrade: synchronization and calibration

Synchronization

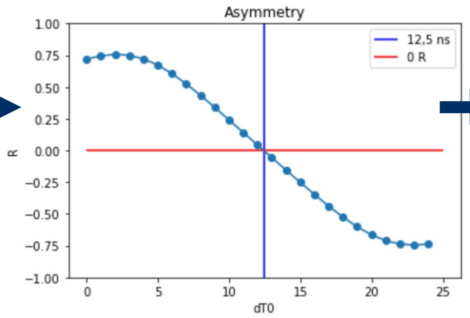
- Independent integration time per channel
- Depends on PMT bias voltage, particle arrival time, cable lengths, …
- Require stable beams and store window of consecutive bunches
- Synchronization is performed studying the spill over in previous and following BX

Calibration

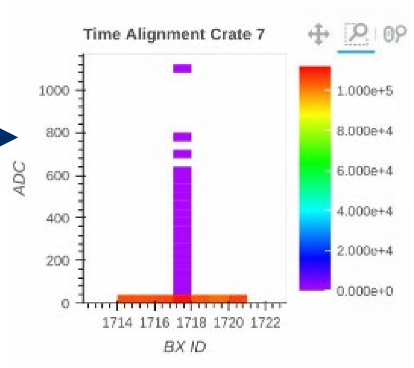
- LED system used for basic gain adjustment and for monitoring the ageing of PMTs
- Detailed gain calibrations performed with π^0 for ECAL and Cs dedicated runs for HCAL
- Initial PMT HV voltages were derived from Run 2 data
- Newer HV values already derived from detector data and applied



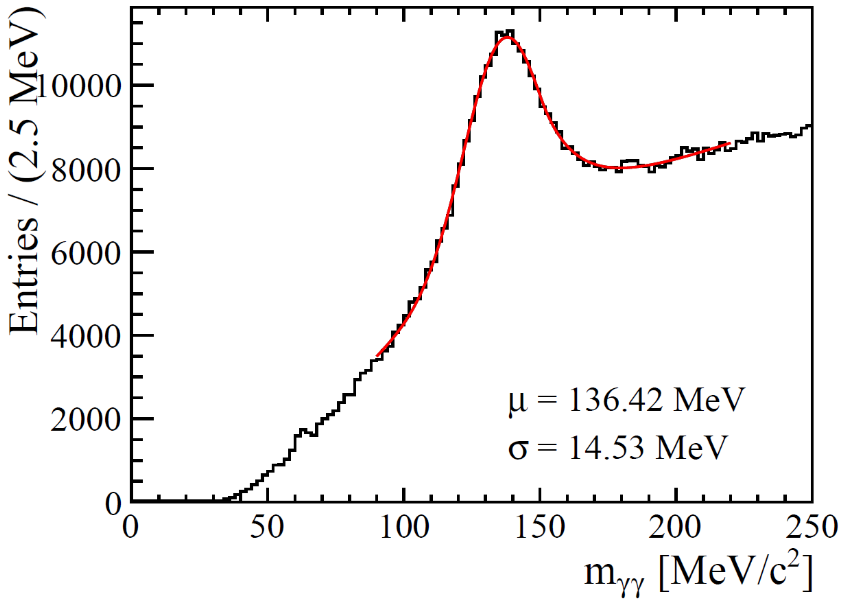
Signal shape from phase scans



Asymmetry curve



Histogram per crate showing energy in ADC counts per BX

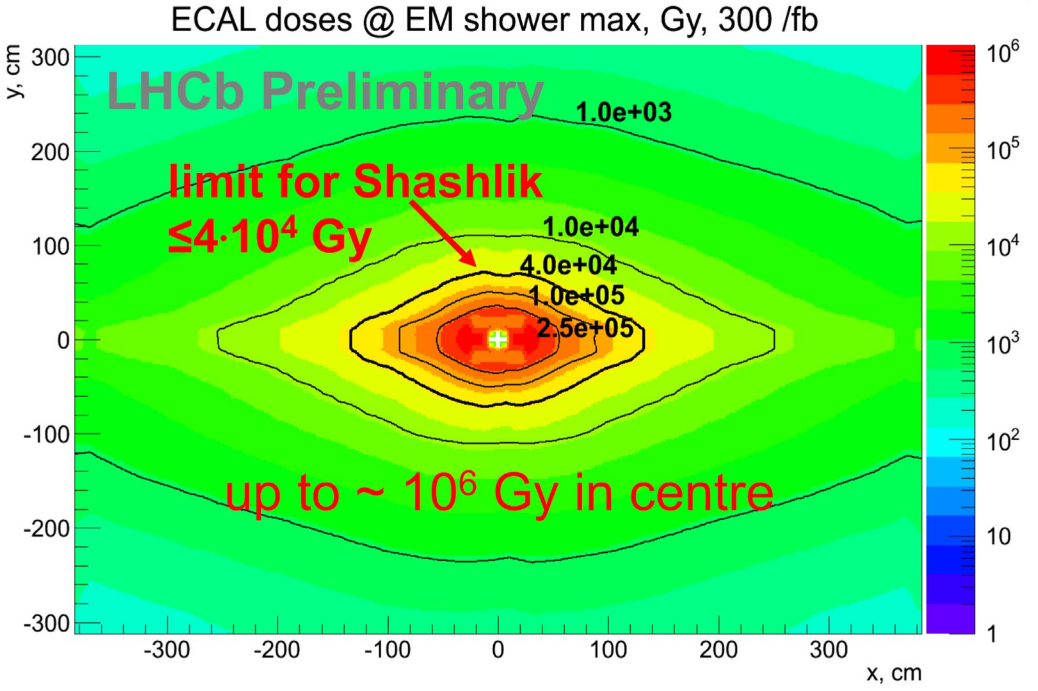


ICCUB

Motivation for the Upgrade II of the LHCb ECAL

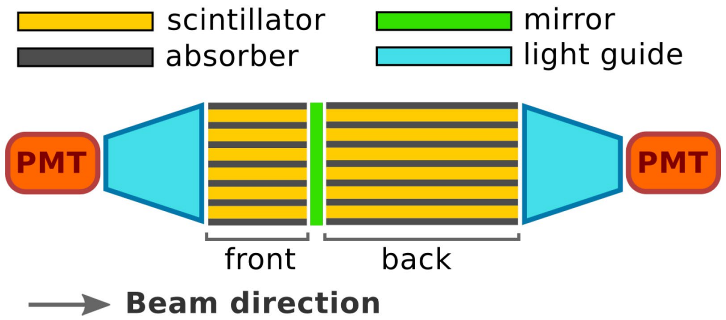
Requirements for the Upgrade II: operation at L = 1-2 x 10^{34} $cm^{-2}s^{-1}$

- Sustain radiation doses up to **1 MGy** and ≤ $6\cdot10^{15}cm^{-2}$ for 1MeV neq/cm^2 at 300 fb^{-1}
- Keep at least current energy resolution $\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 1\%$
- Pile-up mitigation crucial
  - Timing capabilities with O(15) ps precision, preferably directly in the calorimeter modules
  - Increased granularity to reduce occupancy
- Respect outer dimensions of the current modules: 12x12 cm^2
- Up to 30kch + 15kch with timing layer (2-tier longitudinal segmentation all around)
- Detector R&D looks into:
  - new topology (SpaCal/long. segment.)
  - high density absorber materials (W/Pb)
  - fast radhard scintillator (garnet:GFAG)
  - enhanced WLS (radiation tolerance)



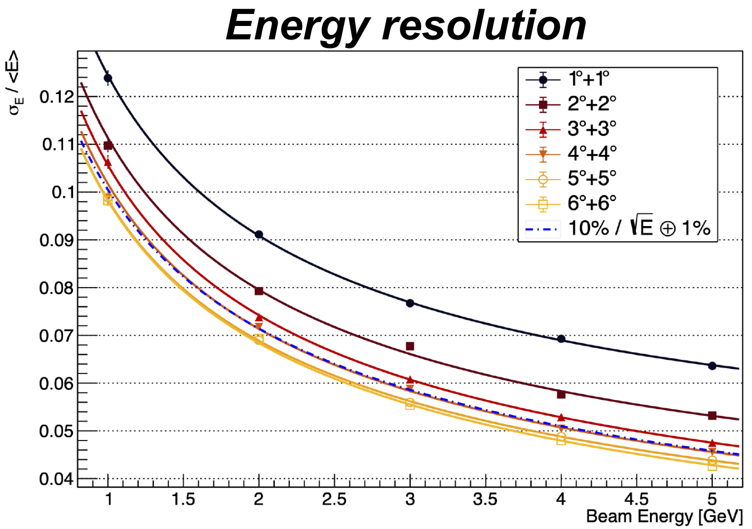
Cell Size	Rad. Dose	Module
15mm	1MGy	SpacalW
30mm	200kGy	SpacalPb
40-120mm	<40kGy	Shashlik

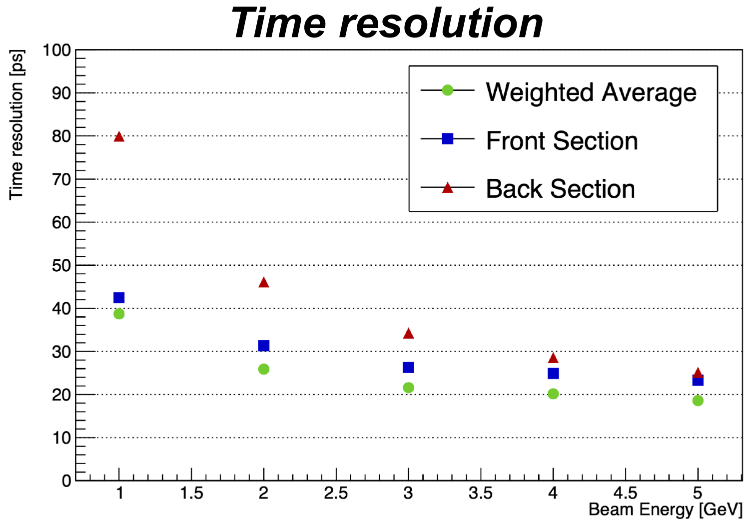
LHCb ECAL Upgrade II: SpaCal-W channel prototype



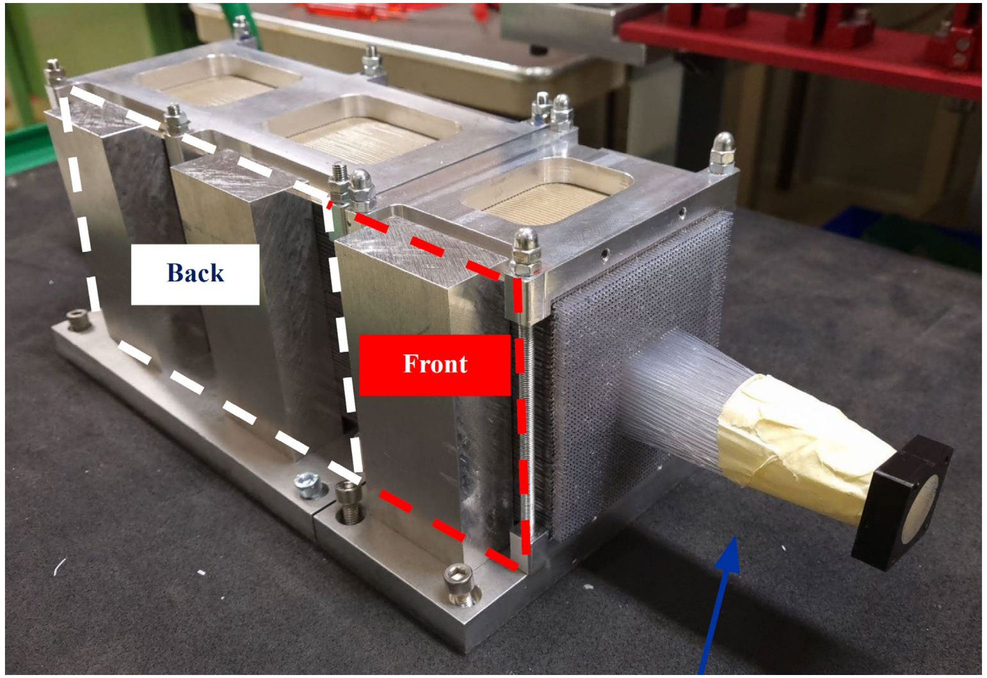
- SpaCal prototype module with W absorber and garnet crystal fibers:
  - Pure tungsten absorber with 19 g/cm^3
  - 9 cells of 1.5x1.5 cm^2 (RM ≈ 1.45 cm)
  - 4+10 cm long (7+18 X_0)
  - Reflective mirror between sections

DESY 2020 Test beam results



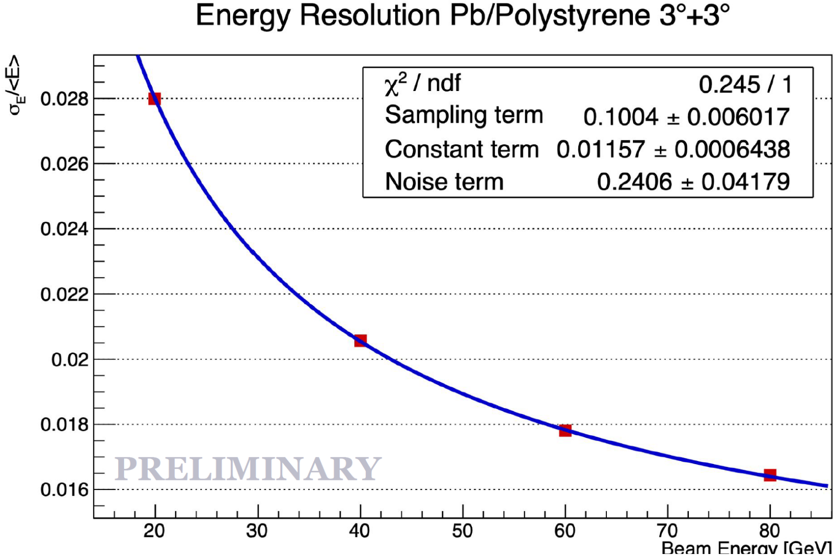


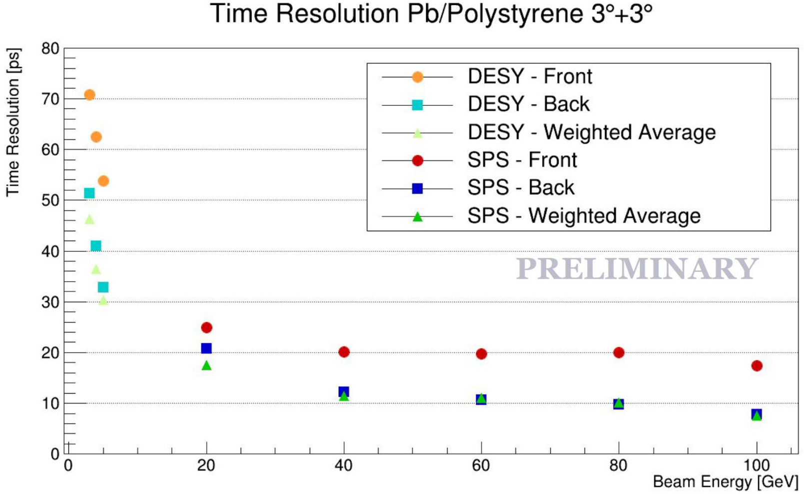
LHCb ECAL Upgrade II: SpaCal-Pb channel prototype



- SpaCal prototype module with Pb absorber and polystyrene fibers:
  - 9 cells of 3x3 cm2 (RM ~ 3 cm)
  - 8+21 cm long (7+18 X_0)
  - Reflective mirror between sections
  - Kuraray SCSF-78 round fibres Ø = 1.0 mm
  - Light guides 10 cm long

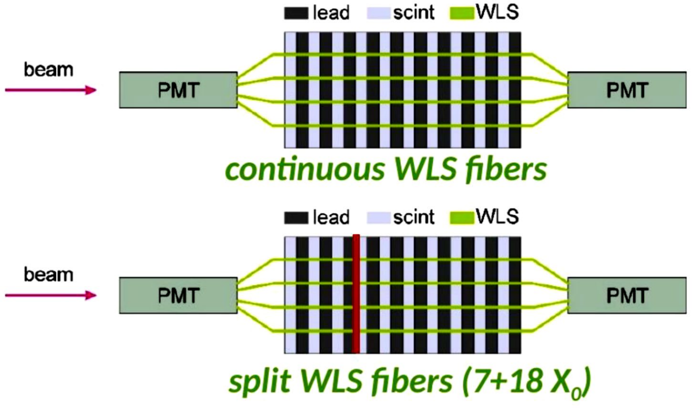
SPS 2022 Test beam results





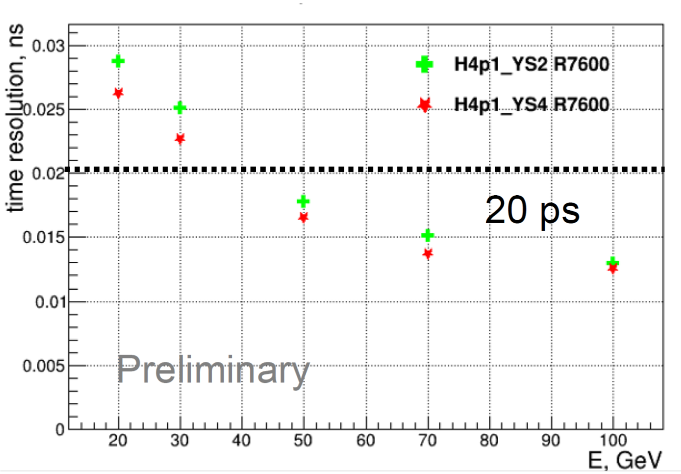
LHCb ECAL Upgrade II: Shashlik

- Shashlik technology can be used in Upgrade II in outer part of ECAL and provide timing information
- In order to reduce effect of shower longitudinal fluctuations, two versions of shashlik were prepared for 2019 beam test
  - Split WLS fibers (7+18 X_0, mirrored fiber ends)
  - Continuous WLS fibers

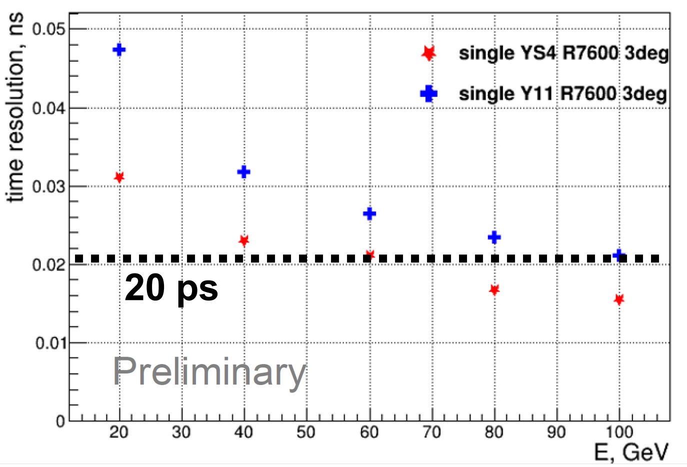


- Current Shashlik modules have good time properties, further improvement by replacing WLS fibres by faster ones (Kuraray WLS YS2 and YS4)

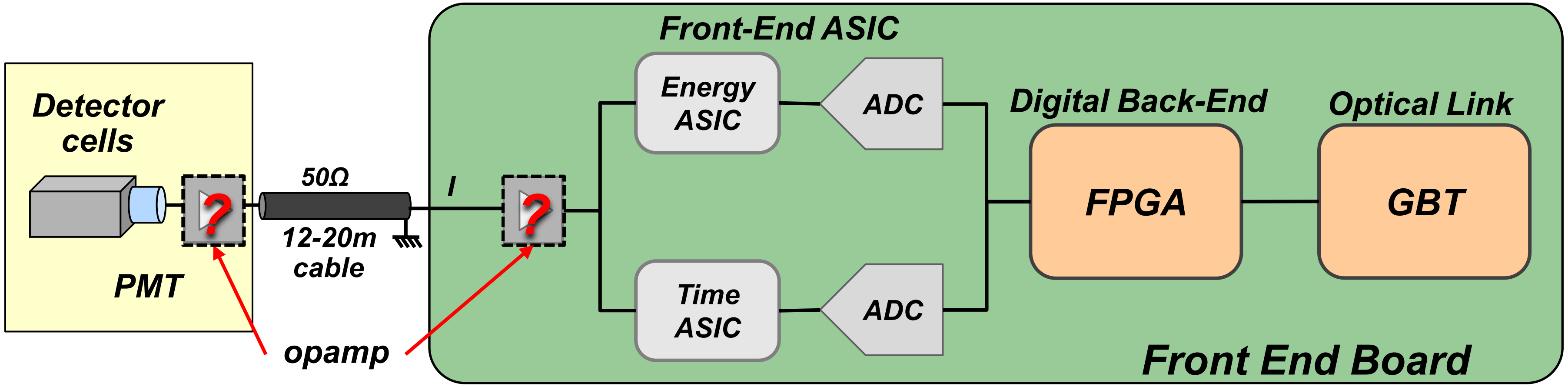
Double-sided readout (CERN SPS 2021



Single-sided readout (CERN SPS 2022)



LHCb Upgrade-II: photodetectors and readout



- Baseline solution follows the same scheme as in current ECAL:
  - Minimal light transport with PMT sensors near modules,
  - All electronics in crates on top of the detector (reduced radiation),
  - Connection via analog link (coaxial) ~12m long (up to 20m considered).
- ASIC/chipset in TSMC 65nm with separate processing paths:
  - Energy path following current ICECAL scheme (mostly analog processing),
  - Timing path based on waveform sampling with analog memory arrays.
- Amplifier + Shaper circuit included on the PMT base or FEB under consideration, to compensate cable attenuation, improve SNR, reduce spill-over effort and split the signal between the energy and time paths.

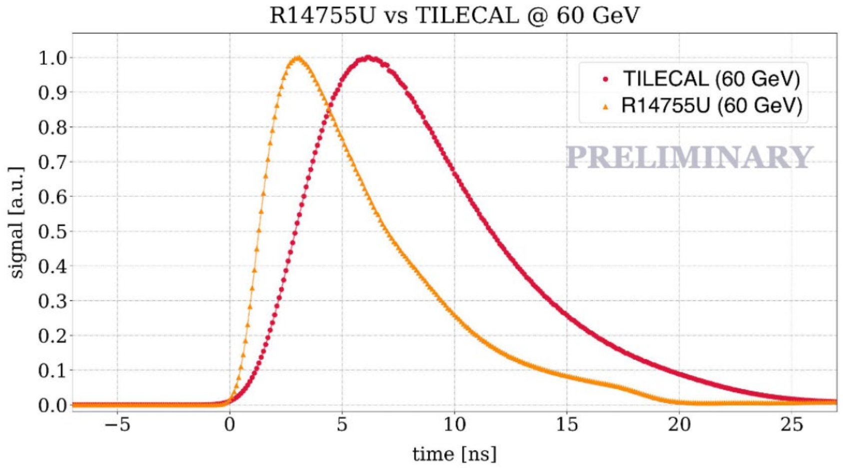
LHCb Upgrade-II: PMTs

- Different detector zones, different needs (gain, ageing, geometry)
- Stringent geometry in the innermost zone (15mm)
- Ageing is an important limit
- TTS order tens of ps homogeneous over cathode.
  - Metal channel dynode (MDC) devices comply.

Cell size case	Channel technology	High G (Imax lim.)	Low G (Imax lim.)
15 mm	SPACAL W	4k	1k
30 mm	SPACAL Pb	4k	500
40, 60, 120 mm	Shashlik	100k	11k

- Studying in detail the PMT response for the present channel prototypes

W-poly pulse shapes



Single Side Readout	Rise Time (10-90%) [ns]
TILECAL	3.6
R14755U-100	1.8

PMT: R11187

PMT: R14755U-100

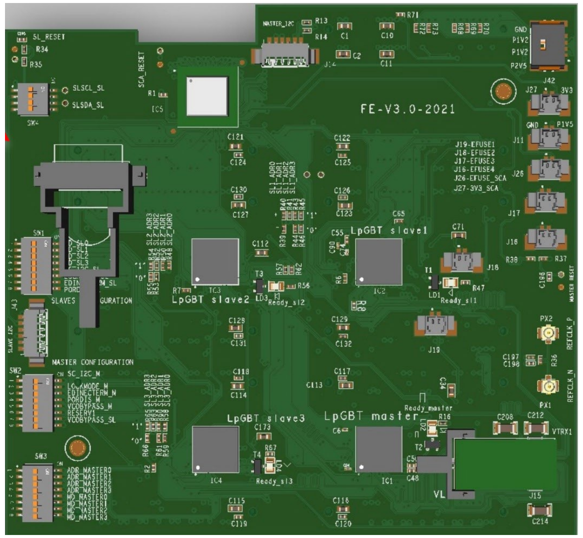
LHCb Upgrades I and II status summary

- Phase-I Upgrade. Increase of luminosity from $4x10^{32}$ $cm^{-2}s^{-1}$ to $2x10^{33}$ $cm^{-2}s^{-1}$
  - Remove the first level hardware trigger and the event selection will be based of full event reconstruction
  - The ECAL and HCAL are maintained but PS/SPD were removed
  - New ECAL electronics were developed to cope with the 40MHz data processing and the gain reduction for PMT live time increase
- Phase-Ib and –II
  - The ECAL will need an upgrade to sustain a much higher radiation dose, to mitigate pile-up, to reduce occupancy and keep good energy resolution
  - New technologies based in the Shashlik and Spaghetti modules have been proposed which offer radiation hard and fast response capabilities
  - Phase-Ib will be dedicated to the inner ECAL and Phase –II to the full detector
  - SPACAL and Shashlik prototypes have been developed and validated in Beam Tests with energy and time resolution within specifications
  - Different PMTs under study: R11187, R15755U-100
  - The readout electronic architecture is proposed, and the design is already started
    - Energy path ASIC similar to the one used in phase-I upgrade
    - Time path ASIC includes an analog memory based in a sampling capacitor array

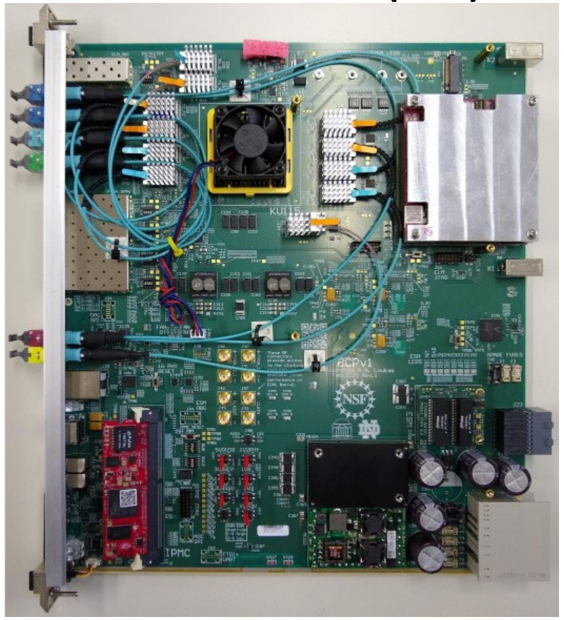
Thank you for your attention!

CMS Barrel ECAL Electronics Upgrade

Front End (FE)



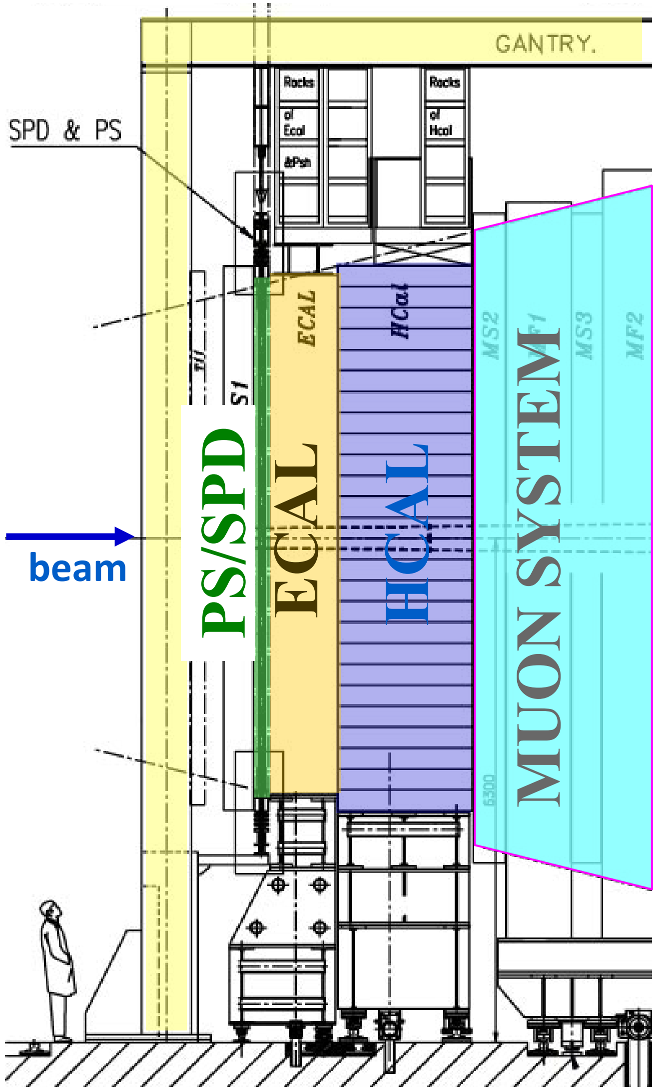
Back End (BE)



- Allows streaming of full granularity data off-detector at 40 MHz
  - Not possible in the current Phase I detector
- Sends clock to VFE directly from controller lpGBT
- I2C via controller-responder chain
- Monitors APD dark current
- FE v3 is close to the final version

- Barrel calorimeter processor (BCP)
  - Combines trigger and DAQ functionality and provides clock and control signals to the FE electronics
  - Each board handles signals from 600 crystals
  - Uses commercially available FPGAs
  - Algorithms being developed using high level synthesis to produce trigger primitives
- BCP v1 (KU115 FPGA) is being used for integration tests with VFE/FE boards and DAQ
- BCPv2 (one VU13P FPGA)
  - Increased signal processing capabilities (more memory, logic cells,…)
  - Schematics under development
- Testing results (including timing performance) are good

LHCb Run 1-2 LHCb calorimetry System

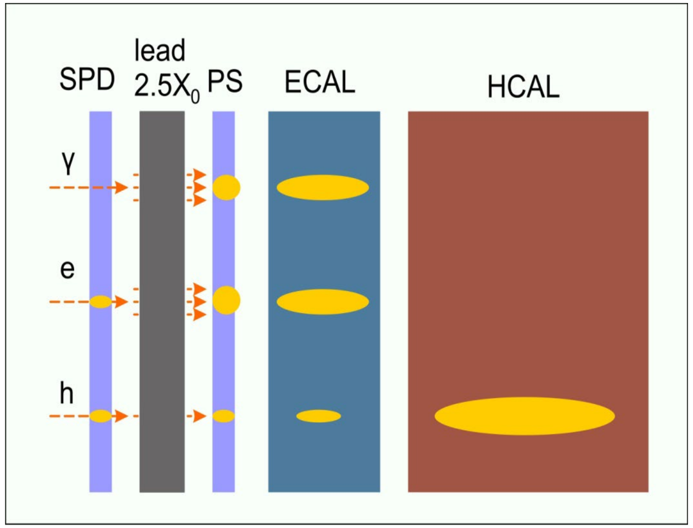


→ Solid angle coverage 300x250 mrad

→ Distance from interaction point ~12.5 m

→ Four sub-detectors: SPD, PS, ECAL, HCAL

→ Based on scintillator/WLS (with PMTs)



→ **L0 trigger** on high pT, e±, π0, γ, hadron

→ Precise **energy measurement** for e± and γ

→ **Particle identification**: e±/γ/hadron, and contributes to Muon ID (HCAL)