The upgrade of the CMS electromagnetic calorimeter: future prospects for precision timing and energy measurements at the High Luminosity LHC

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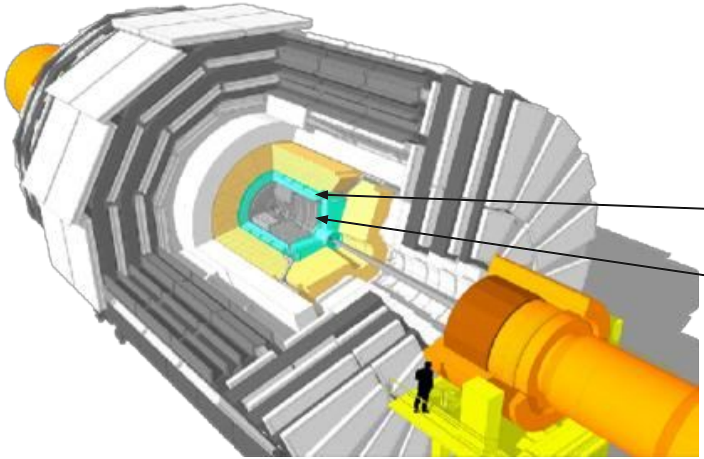
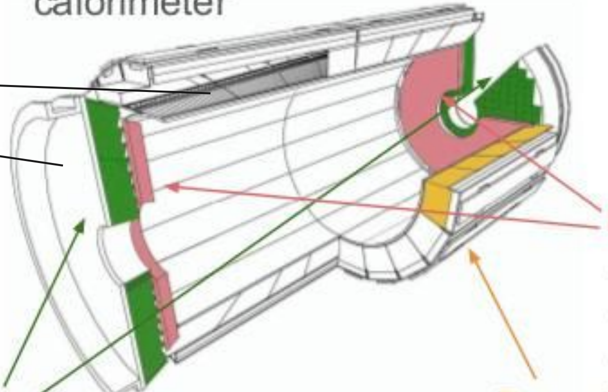
ECAL: overview



The CMS ECAL

- Hermetic homogeneous calorimeter
- Between tracker and hadronic calorimeter



Endcaps

- 7324 crystals / endcap
- Vacuum Photo Triode readout
- $1.48 < |\eta| < 3.00$

Barrel

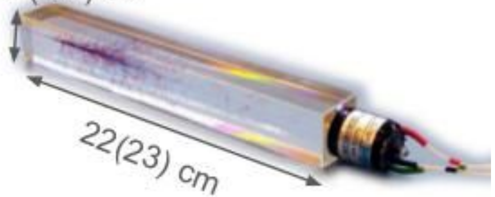
- 61200 crystals
- Avalanche photodiodes readout
- $|\eta| < 1.48$

Preshower

- Two Pb/Si planes
- $1.65 < |\eta| < 2.6$

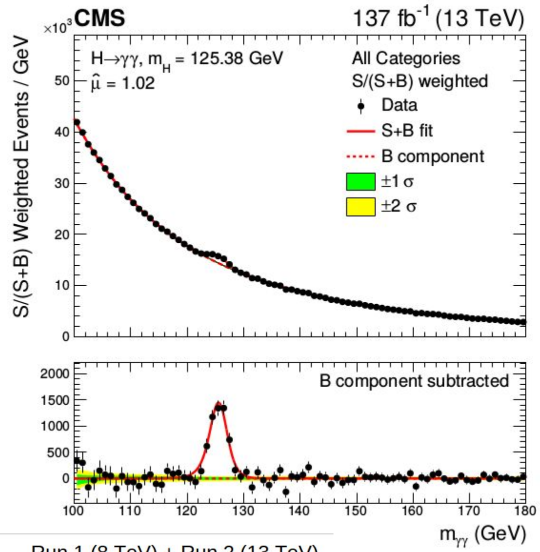
$PbWO_4$ scintillating crystal

- high density
- 80% light emission in 25 ns
- crystal dim. ~ em. shower



Role of ECAL in Run-2 Physics

- Conception of ECAL was driven by H—>γγ search
    - Excellent energy resolution, and position resolution, led to the discovery and the precise characterization of the Higgs Boson in H—>γγ and H—>ZZ channels
- Good timing resolution (~150 ps): key ingredient in searches for non conventional signatures like delayed jets.



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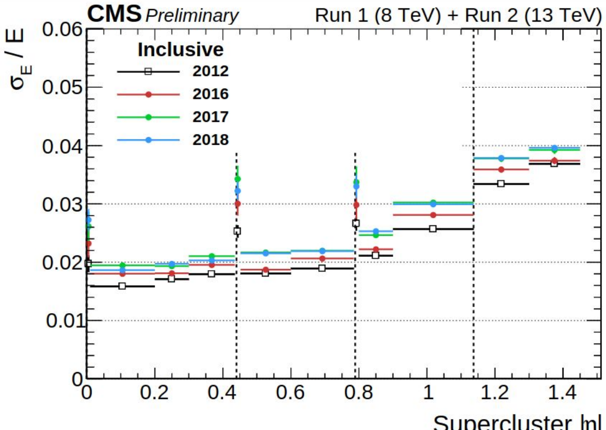
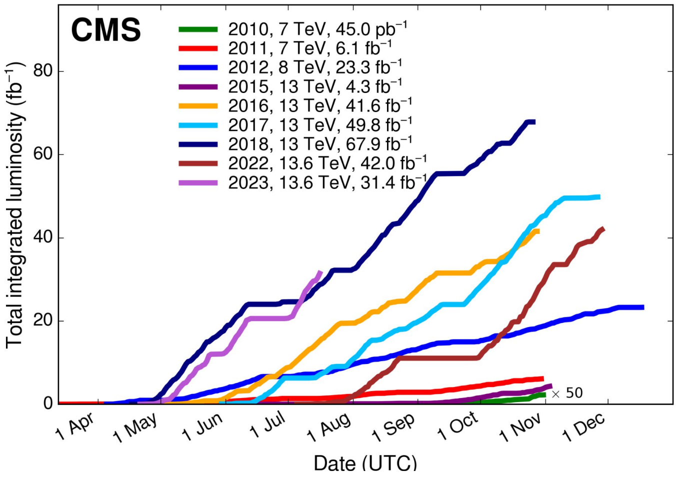
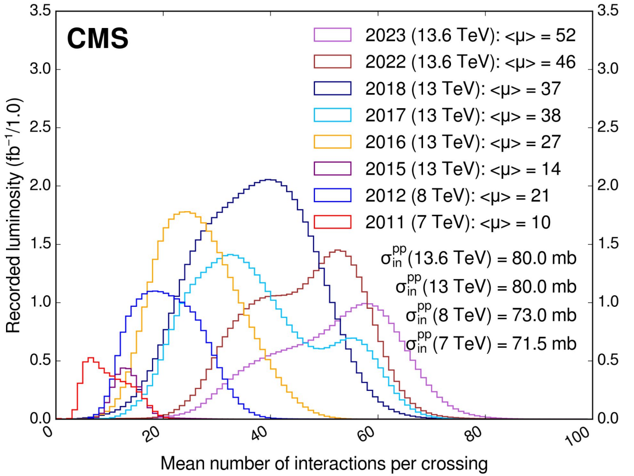


CERN-CMS-DPS-2021-021

Challenges faced so far..

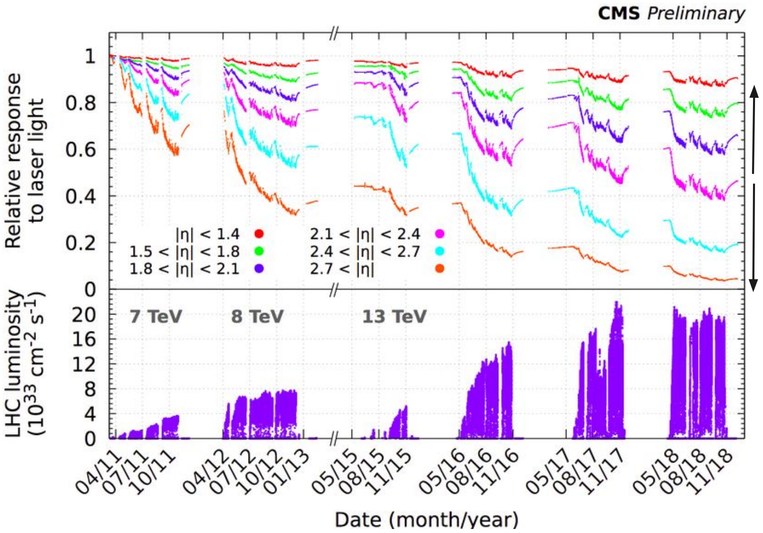
- Increase in the integrated luminosity over time results in:
    - Crystals facing larger radiation dose.
    - Reduction in the light output of the crystals and radiation induced ageing of the photodetectors and the ECAL readout systems.
- Increase in pileup resulting from:
    - Higher bunch intensities.
    - Larger out of time pile up → Impact on Pulse reconstruction.





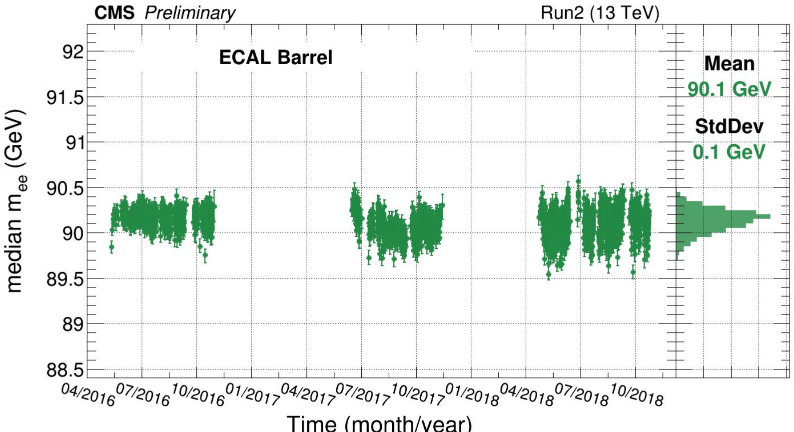
Strategies used in Run 2

- Each channel is monitored with a dedicated laser system every 40 minutes and transparency corrections are provided every 48 hours.
- A "multifit" algorithm was developed to reconstruct the pulse amplitude considering out-of-time pulse effects to mitigate the PU at the reconstruction level. [JINST 15 P10002]
- Good ECAL energy response stability over time is obtained with regular calibrations.



Endcap region covered by CMS tracker (62%)

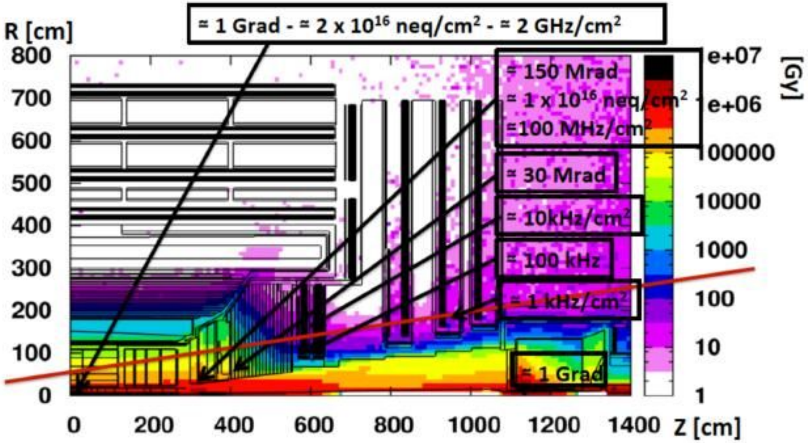
Endcap region relevant for forward jets. Low response (loss ~96%) due to ageing induces amplification of noise

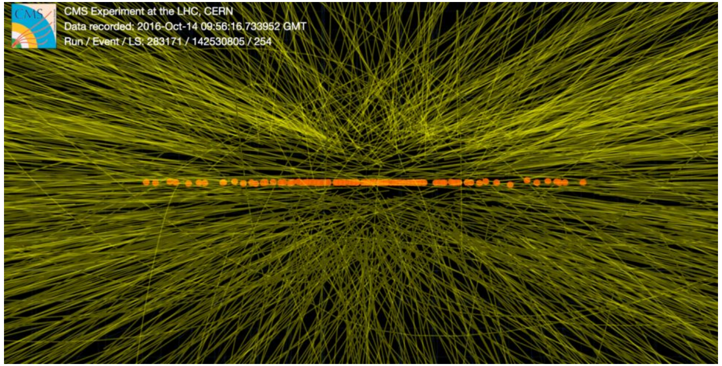


CMS-DPS-2020-021

HL-LHC

- Integrated luminosity expected to increase by a factor of 10 reaching ~3000fb^{-1}
- 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 Hμμ) and production (e.g. HH)
  - Extending reach of BSM searches.
- HIGH RADIATION (due to high integrated lumi.)
  - Radiation levels up to 2x10^{16} neq/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





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

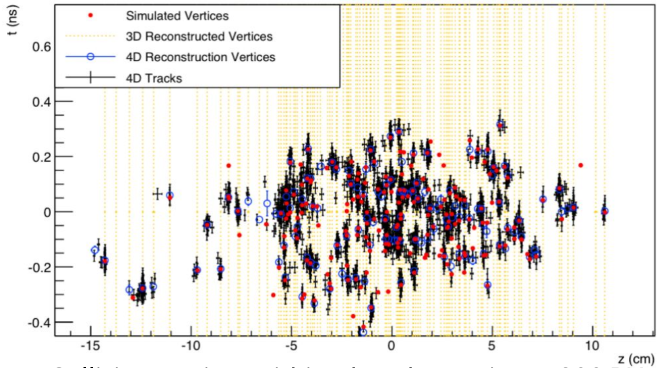
HL-LHC: upgrade requirements for optimal detector operations

- 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.
    - The ECAL must retain its performance during HL-LHC operations (Phase 2), when the pileup is 5-7 times larger

- Design requirements for ECAL operations in Phase 2:
    - Higher trigger rate (from 100 kHz to 750 kHz)
    - Higher data bandwidth
    - Higher radiation → More noise
    - Higher pileup results in more "spikes" [anomalous high energy (≥ 100 GeV) signals induced by hadrons interacting directly with the APD core]

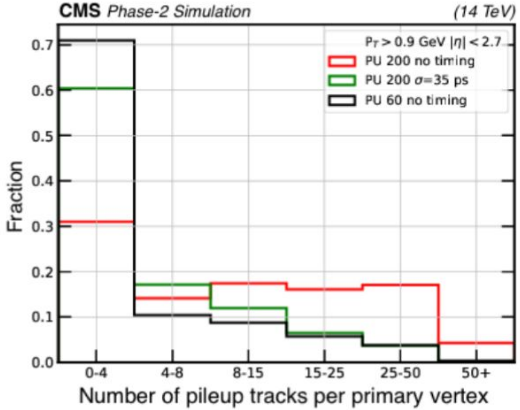
Precision timing as a tool to mitigate pileup

- 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 all charged particles.



Collision vertices within a bunch crossing at 200 PU.

Pileup tracks incorrectly associated to the interaction vertex



Upgrade for HL-LHC

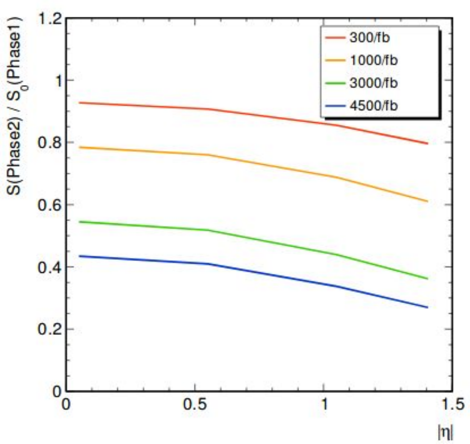
ECAL Barrel (|η|<1.48):

- will retain significant light output and will be retained for HL-LHC operation.
- Reduce the operating temperature from 18°C to 9°C to mitigate APD ageing effects.
    - Dark current reduced by 50% while the light yield is increased by 18%.
- On-detector electronics replaced for precision timing and better trigger granularity.

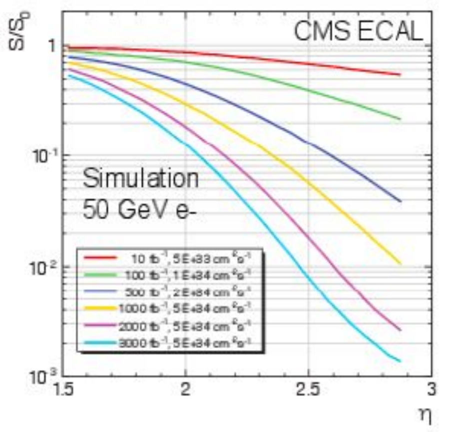
ECAL Endcap (|η|>1.48):

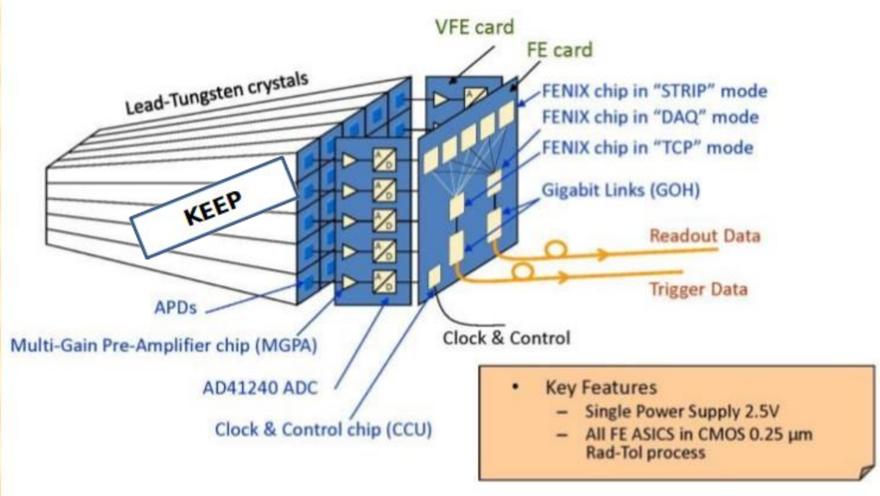
- will suffer significant radiation damage after ~500 fb^{-1}
    - Replaced by High Granularity Calorimeter - not covered in this talk

ECAL Barrel

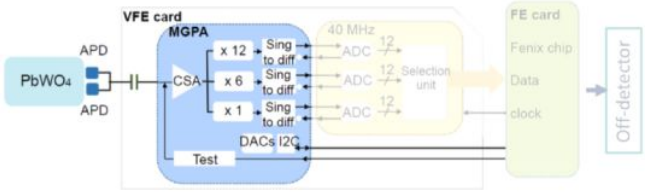


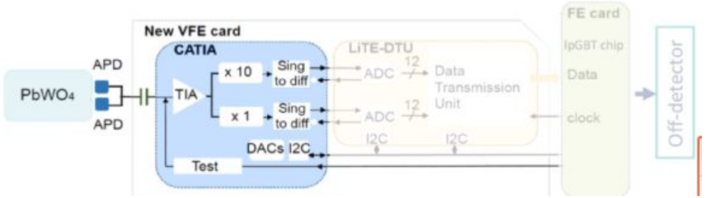
ECAL Endcaps





Legacy vs upgraded on-detector readout





Multi-gain pre-amplifier (MPGA):

- Charge sensitive amplifier
- 3 outputs, gain values: x1, x6 and x12

CATIA ASIC:

- Trans-impedance Amplifier (TIA) arch.
- 2 outputs, gain values: x1 and x10

Multi channel ADC:

- ADC resolution: 12 bit
- ADC sampling frequency: 40 MS/s

Lite-DTU ASIC:

- ADC resolution: 12 bit
- ADC sampling frequency: 160 MS/s

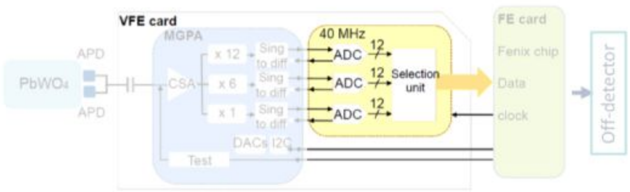
Front-End Card:

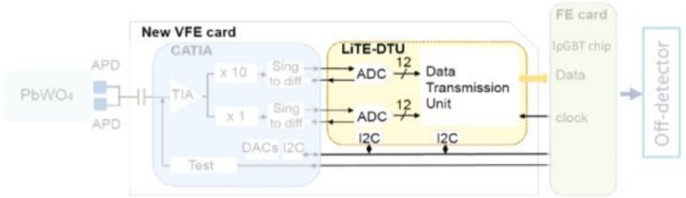
- Data pipeline
- Trigger primitives generation
- Trigger data granularity: 5x5 crystals

New Front-End Card:

- Fast rad-hard optical links to stream crystal data off-detector through CERN lpGBT/VL
- Trigger data granularity: crystal level

Legacy vs upgraded on-detector readout





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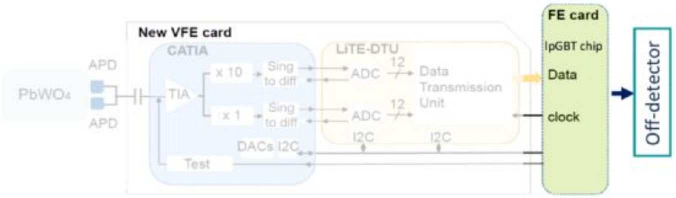

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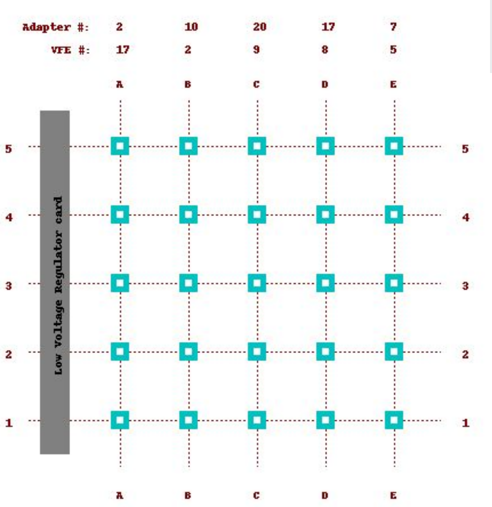
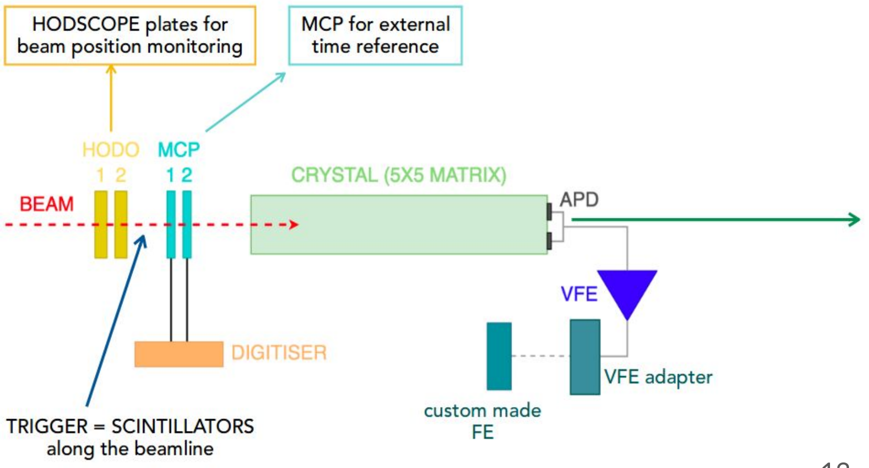
Test beams

- Beams tests are required for the testing and validation of each design parameter for the planned upgrade.
- It is a process carried out in systematic steps to ensure precision.
- 2018 and 2021 test beams were with 5x5 crystal matrix.
  - 2018: only with the CATIA-ASIC
  - 2021: with entire Very Front End (VFE) of upgrade design.
- 2022 and 2023 test beams were with 200 crystals and full representation.
  - 2022: full upgrade design of barrel was implemented.
  - 2023: physics runs with the finalised design taken.

- Test beam campaign carried out at the H4 beamline (Prevessin site)
- 5x5 crystal matrix equipped with Phase2 VFEs.





Some results from 2021 TB... (work in progress)

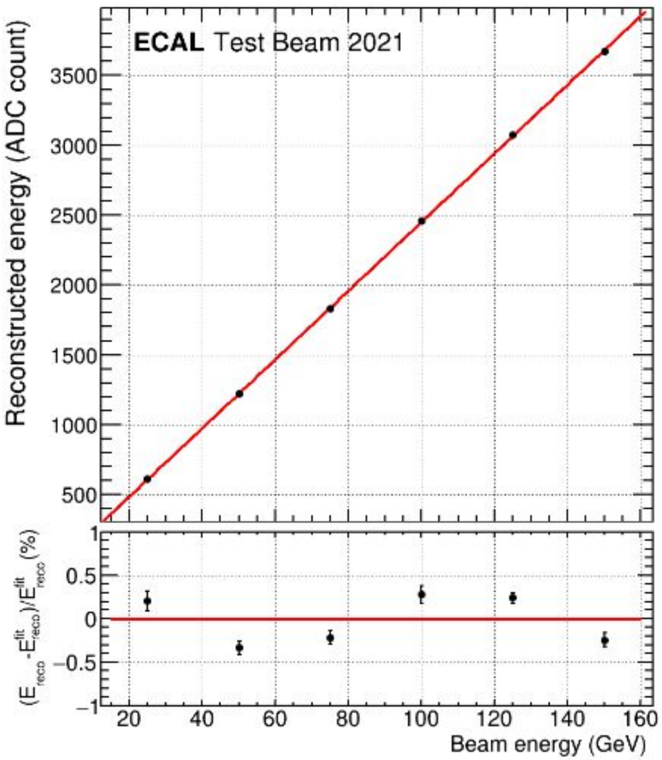
- Single crystal response in terms of average amplitude of the signal (in ADC counts) w.r.t. the energy of the incident electron-beam is shown.

- In the lower panel we report the deviation of the reconstructed energy (in ADC count) with respect to the linear fit, defined as

$$\frac{E_{reco} - E_{reco}^{fit}}{E_{reco}}$$

- With the upgraded readout, the ECAL crystal response is linear with respect to energy over a wide range.

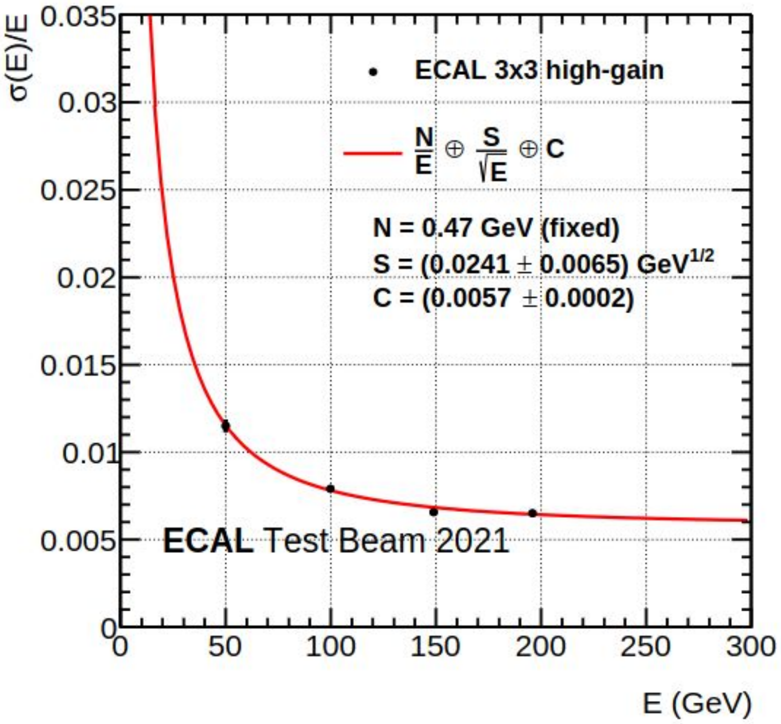
- Maximum deviation from linearity is < 0.3% and it will improve with the studies on the full 5x5 matrix.



Energy resolution Vs beam energy

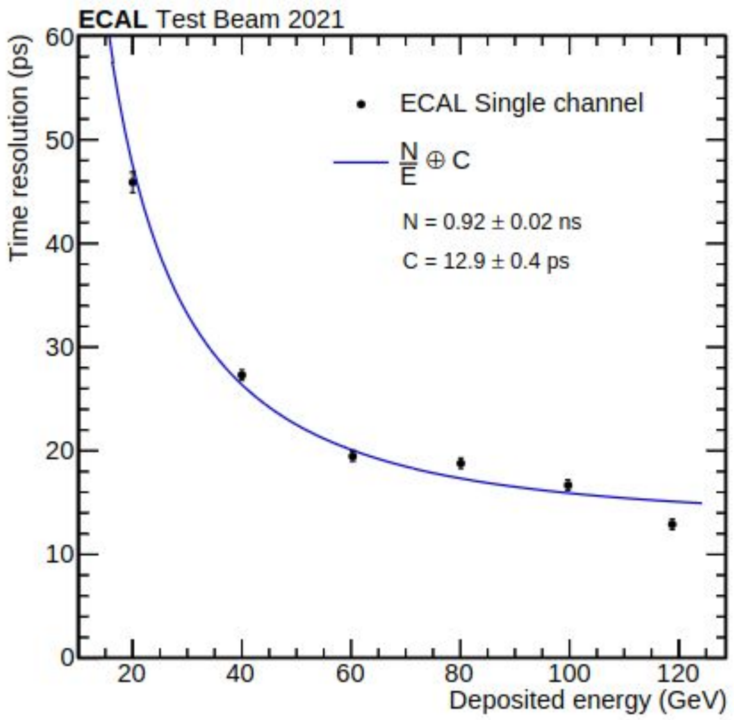
- Distribution of the total signal amplitudes in a 3x3 matrix around the central crystal.
  - crystal matrix intercalibration with dedicated runs at 100 GeV
- Fit function is a double side Crystal-Ball.
- Stochastic term S compatible with the expected value of 0.028 $GeV^{1/2}$.

  2007 JINST 2 P04004
- Constant term within the requirements



Time resolution Vs deposited energy

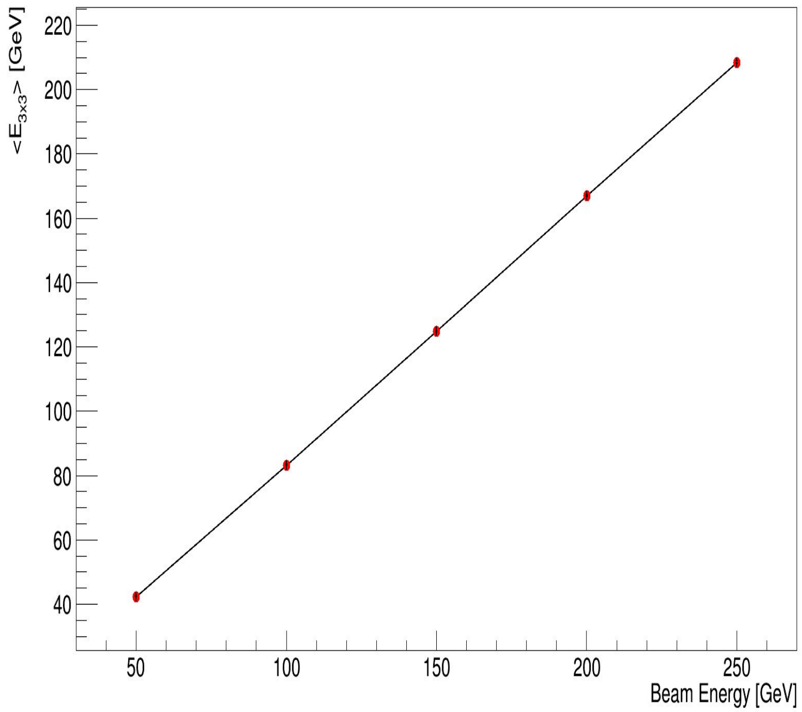
- The time resolution is performed by comparing the time measurement over a single channel to that of an external timing reference detector placed along the beamline.
- The solid blue line represents the fit with the resolution function N/E ⊕ C, where N denotes the noise, C the constant term, and E the deposited energy.
- The constant term of about 13 ps meets the requirements for the Phase 2 design.



Simulation studies (work in progress)

- Simulation studies are being carried out in the geant4 environment, in order to validate the results with data.
    - The energy deposited in the crystals is studied by shooting the target crystal with 4-5 different energies.
- More detailed study is ongoing.

Private Work (CMS ECAL Simulation)



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 Phase-2 ECAL upgrades program is at an advance stage.
- Preliminary results from beam tests have shown promising results with the upgraded electronics :
    - Time resolution for high energy electron showers is obtained to be ~13ps.
    - Energy response shows linear behaviour.
    - Energy resolution is within the requirements.
    - Exciting results for Moliere radius measurements.
- Simulations results are to be compared with the data.

Thanks...

Backup...

Energy reconstruction in ECAL

Energy is measured using all crystals in a shower

Intercalibration

Cluster Corrections

$$E_{e,\gamma} = \sum_{i \in shower} [S_i(t) \cdot C_i \cdot A_i] \cdot F_{e,\gamma} \cdot G(\eta)$$

Laser monitoring

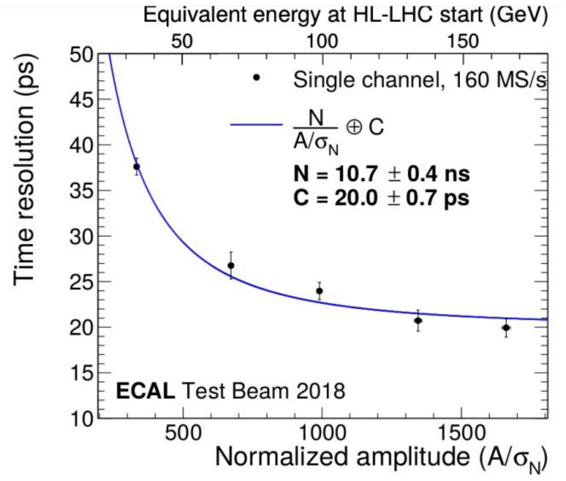
Pulse amplitude

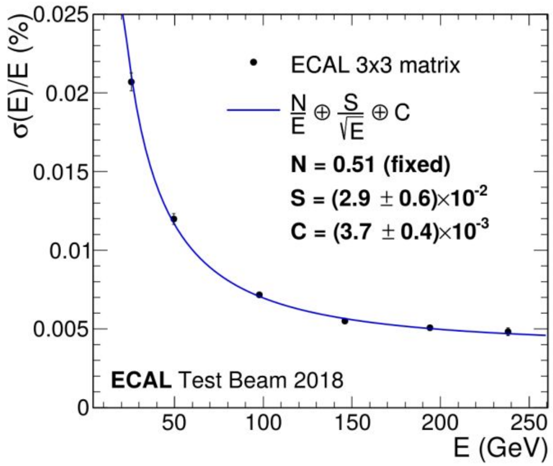
Global scale

CATIA ASIC performance in beam tests (2018)

ECAL beam tests were performed to test the CATIA amplifier chip for the upgrades :

- One ECAL tower (5*5 channels) equipped with a CATIA chip was connected with 160 MHz commercial ADC, FE and off-detector components.
- Electron beam, energy range: 25 - 250 GeV
- Single channel time resolution of ~30 ps obtained for an equivalent energy of 50 GeV.





- very pure $e^{\pm}$ beam ($\Delta p/p = 0.5\%$ with $20 < p < 250$ GeV)

2022 TB (12 days) 8 RUs of SM36 read out by 1 BCP
2023 TB (14 days) 9 RUs (+ MEM) of SM36 read out by 2 BCPs

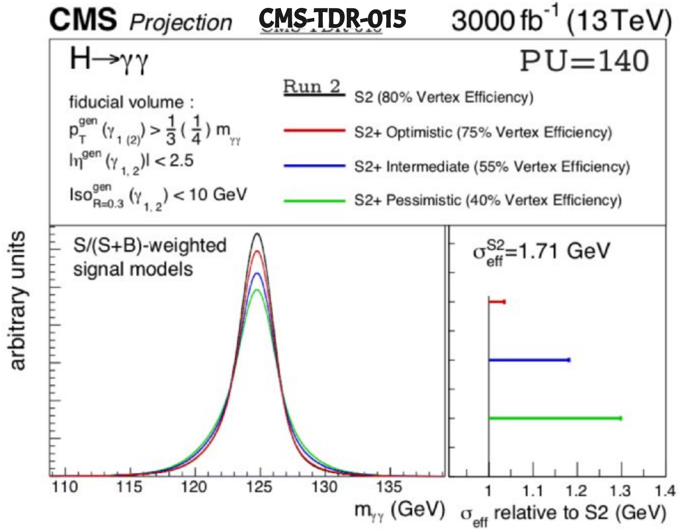
Scope of the 2023 TB campaign:

- Very Front End ASICs: test VFEs with CATIA 2.1 (1 RU + 3 spares VFEs)
- TB2022: VFEs with CATIA 2.0
- BCP firmware: decompressed mode and synchronization between 2 BCP boards
- TB2022: single-BCP read-out, compressed mode only
- Laser read-out: FEM and MEM, read out by BCP

Impact of precision timing on precision physics measurements

- If the chosen H→γγ vertex is within ~1 cm the mass resolution is dominated by the photon energy resolution.
- The H→γγ vertex localization efficiency is improved significantly with precision timing (~30 ps) information of EM showers.
- ~10% improvement in the fiducial cross-section sensitivity and H→γγ resolution compared to no precise timing case.
- The new readout chain is specified to deliver the desired time resolution of 30ps for energies > 50 GeV

$$m_{\gamma\gamma} = \sqrt{[2.E_{\gamma 1}.E_{\gamma 2}.(1 - \cos\theta_{12})]}$$



No precision timing
with precise timing (30ps) in calorimeter
Adding a dedicated timing layer to precisely tag MIPs