Precise energy and time measurement with a homogeneous calorimeter

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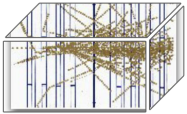

CALOR 2024 Tsukuba

Building the CMS ECAL

- precise energy measurement was the primary goal for the design of the CMS ECAL detector

  "...the width of the reconstructed (Higgs) mass distribution, and hence the signal/background ratio, will be limited by instrumental mass resolution, in particular by the **energy resolution of the electromagnetic calorimeter**.*" [ECFA 1990 Aachen workshop]*

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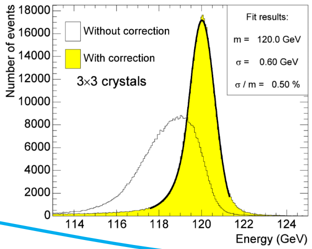
- extensive R&D phase and **validation with electron beam test in ideal conditions** (1993 - 2008)
  - no CMS: upfront tracker, magnetic field, ...
  - no LHC: radiation damage, pile-up, ...

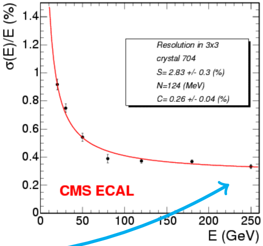
$$\frac{\sigma(E)}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

N = noise term = 120 MeV

S = stochastic term = 2.8%

C = constant term = 0.3%





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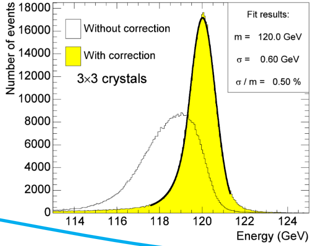
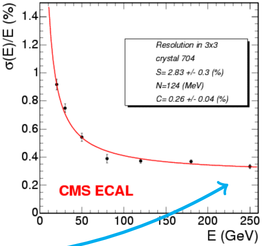
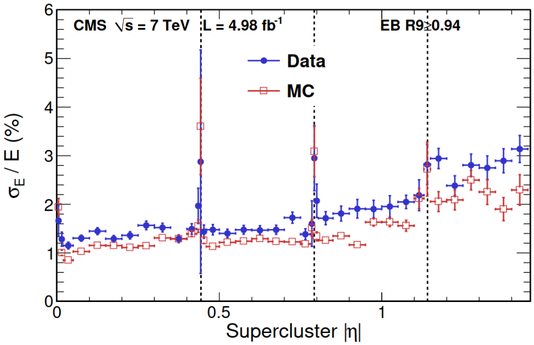


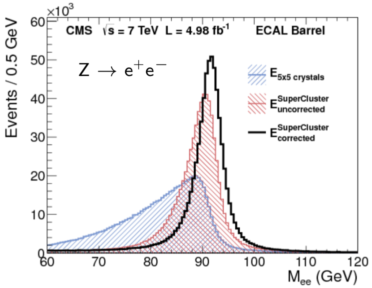


- **timing resolution was not a driving factor**
  - **requirement of timing stability within $\mathcal{O}(1)$ ns** to not bias the energy reconstruction

CMS ECAL in action during Run1

- multiple challenges faced in Run1 (2010 - 2012)
  - maintain an optimal trigger efficiency
  - inter-calibrate crystals response
  - reconstruction corrections
  - . . .





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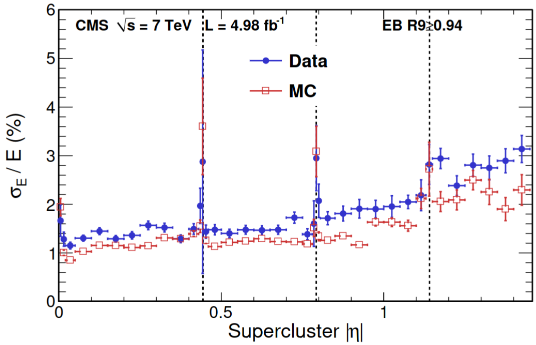
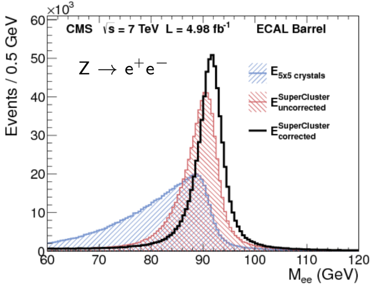
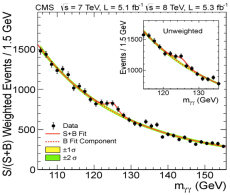
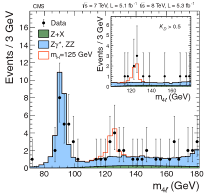




. . . **eventually a success!**



$H \to \gamma\gamma$



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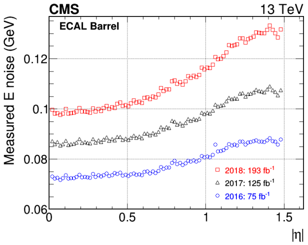
CMS ECAL meets the challenges of Run2

- Run2 (2015 - 2018) provided significantly more data but in an harsher environment

	Run1	Run2
center-of-mass energy [Tev]	8	13
peak-luminosity [$10^{34}cm^{-2}s^{-1}$]	0.8	2
recorded luminosity [fb^{-1}]	30	140
average pile-up events	20	35
minimum BX distance [ns]	50	25



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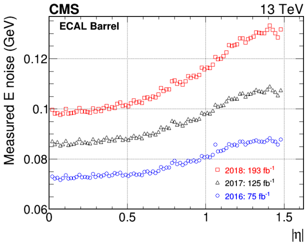
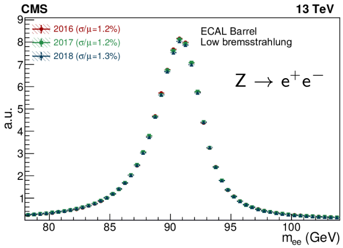
  - updates to trigger board firmware
  - more frequent response corrections at trigger level
  - new pulse-shape reconstruction algorithm
  - new complementary calibration techniques





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  - updates to trigger board firmware
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  - new pulse-shape reconstruction algorithm
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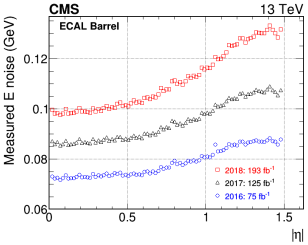
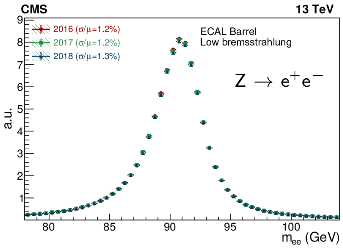
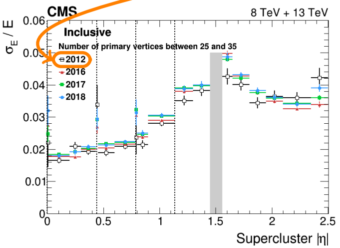
- **if the pile-up effects are factored out, Run1 performance is matched**

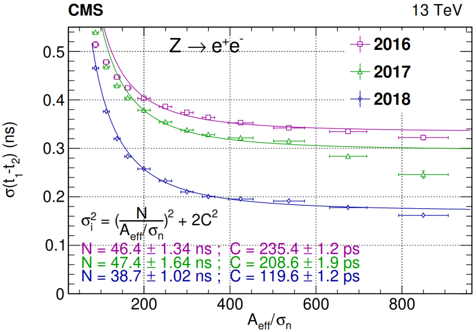






CMS ECAL timing resolution during Run2

- during Run1, estimated to be **190 (280) ps** in the Barrel (Endcaps) from **Z decay electrons**
- from electrons beam tests, cosmics rays and beam splashes events before LHC collisions, $PbWO_4$ has a scintillation timing resolution of $\sim$ 20 ps
- the **fast electronic** pulse-shaping (40 ns) and the **sampling rate** (40 MS/s) allow single-crystal **precise time measurement**, **limited by the clock distribution, impact point on the crystal, . . .**



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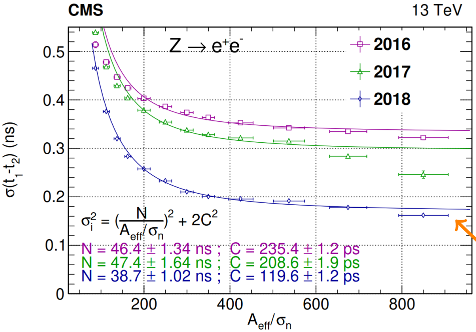
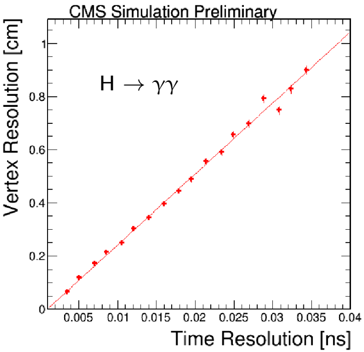
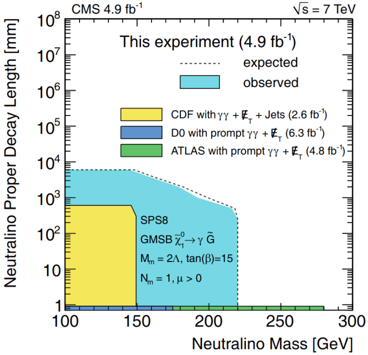


- **experience and reconstruction updates improve timing resolution to $\mathcal{O}$(150) ps**

CMS ECAL precise timing measurements

- **precise timing information used successfully in the CMS physics program**
  - jets/photon discrimination and primary vertex position reconstruction
  - BSM long-lived particles searches





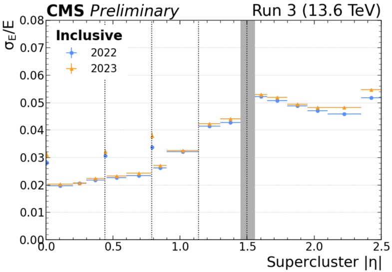
CMS ECAL performance during Run3

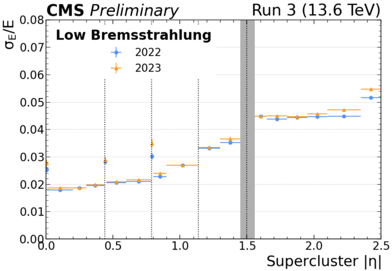
- Run3 (2022 - 2025) presents an even more challenging environment

	Run1	Run2	Run3
center-of-mass energy [Tev]	8	13	13.6
peak-luminosity [$10^{34}cm^{-2}s^{-1}$]	0.8	2	2.5
recorded luminosity [fb^{-1}]	30	140	200*
average pile-up events	20	35	50
minimum BX distance [ns]	50	25	25

* = expected (with some obvious uncertainties)

- **ECAL continues with its excellent performance** (more detail in J. Dervan and M. Tornago's talks)





CMS ECAL at High-Luminosity LHC

- the High-Luminosity (HL)-LHC (2029-2040) will generate an unprecedented amount of data

	Run1	Run2	Run3	HL
center-of-mass energy [Tev]	8	13	13.6	14*
peak-luminosity $[10^{34} cm^{-2} s^{-1}]$	0.8	2	2.5	5*
recorded luminosity $[fb^{-1}]$	30	140	200*	3000*
average pile-up events	20	35	50	140-200*
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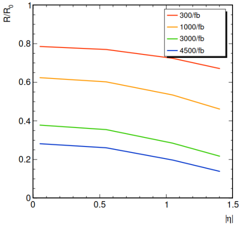
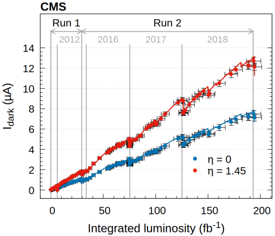
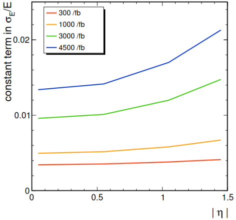
- **ECAL was not designed to operate in these conditions**
  - crystal transparency loss and APDs noise increase







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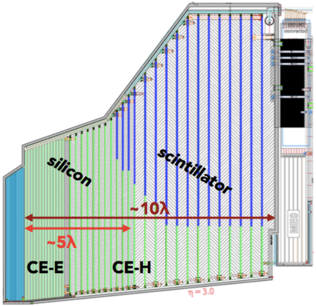
- the Endcaps of the calorimetry system will be replaced by the **High-Granularity Calorimeter** due to radiation damage (multiple talks and posters in the next days!)



CMS ECAL Barrel upgrade for HL-LHC

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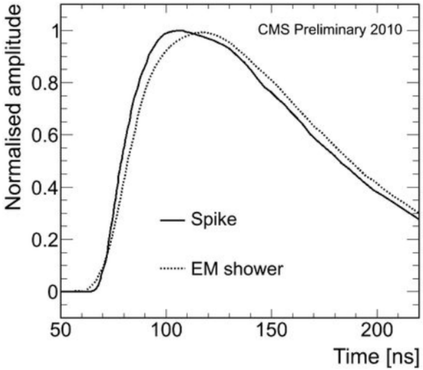
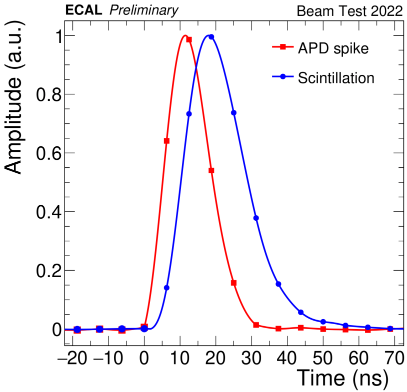
  - **faster electronics** to mitigate APDs noise and better reject spikes



legacy electronics



upgraded electronics

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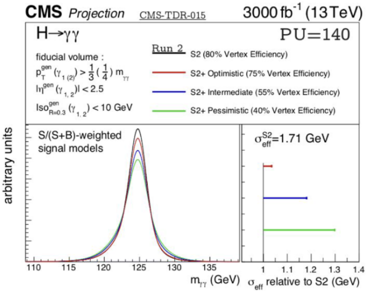

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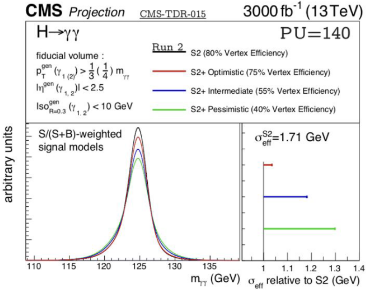

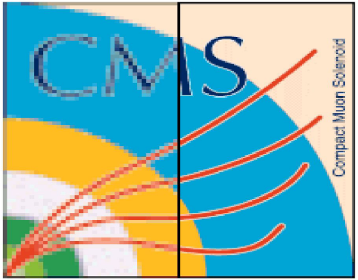

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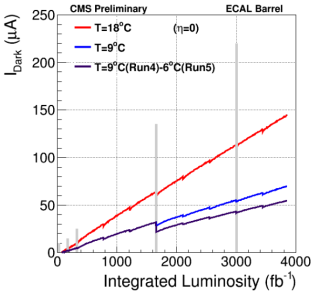
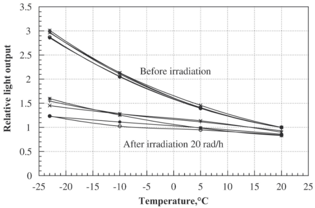
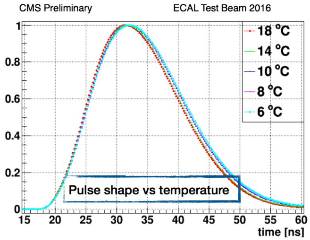
- the **crystals** and **APDs** will not be modified but the operational **temperature** will be reduced from 18 °C to **9 °C** to mitigate APDs noise (with an additional 10% gain in light yield)

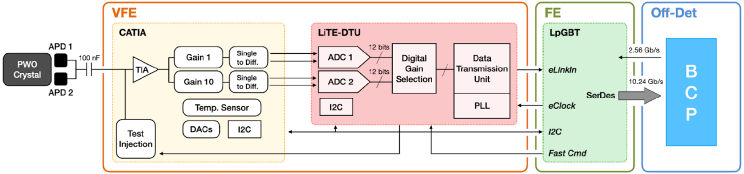






CMS ECAL Barrel upgrade for HL-LHC

- **redesigned front-end ASICs** on the new Very Front End (**VFE**) card
  - CAlorimeter Trans-Impedance Amplifier (**CATIA**) with x1 (LG) e x10 (HG) gains
  - Lisbon-Turin ECAL Data Transmission Unit (**LiTE-DTU**) with two 12 bits 160 MS/s ADCs



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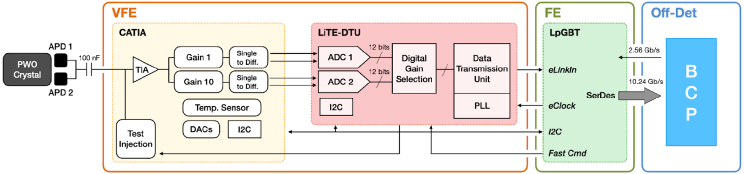
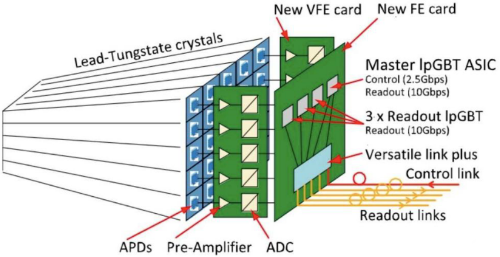


- new Front End (FE) card maintaining current geometry
  - LpGBT optical radiation tolerant transmission system
- new back-end Barrel Calorimeter Processor (BCP) board
  - powerful commercial FPGAs
  - clock and control signals distribution
  - trigger primitives generation
  - high-rate data transmission
- more detail in a dedicated poster!



CMS ECAL Beam Tests for HL-LHC

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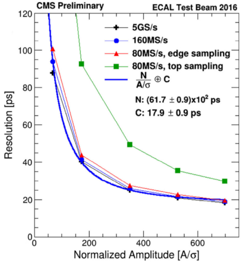
  - R&D to select and develop all the technologies and components
  - validation at beam tests

2016

- 5×5 crystals
- discrete TIA components
- commercial ADCs
- custom read-out boards



optimal sampling at 160 MS/s

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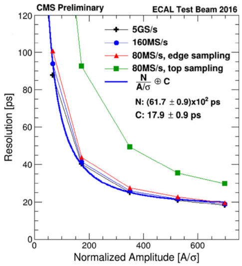

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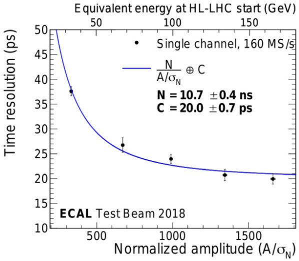
2018

- 5 × 5 crystals
- first CATIA prototype
- commercial ADCs
- custom read-out boards



30 ps target achievable

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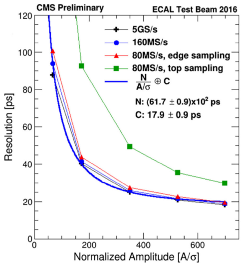

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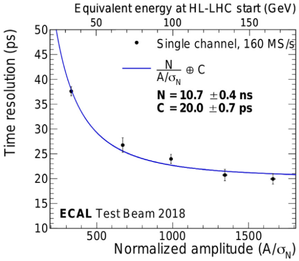
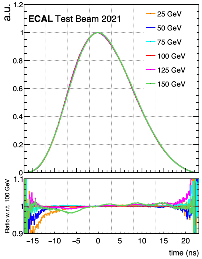


30 ps target achievable

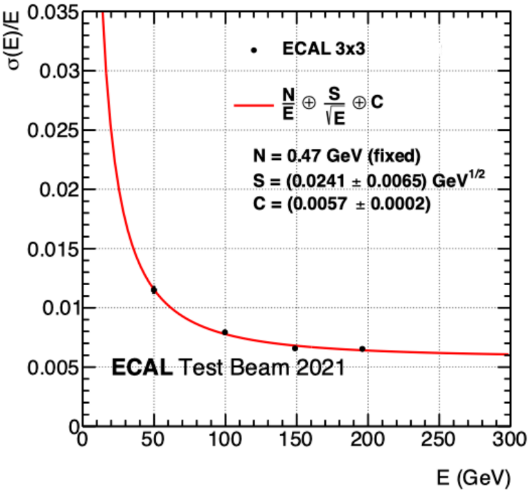
2021

- 5 × 5 crystals
- CATIA prototype
- first LiTE-DTU prototype
- custom read-out boards



timing analysis ongoing

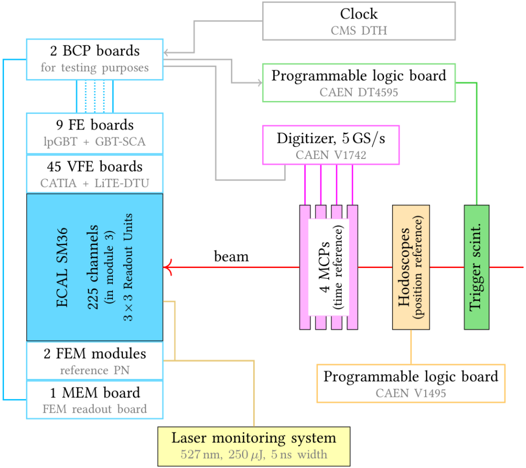
CMS ECAL 2021 Beam Test - energy resolution



- requiring only HG events
- N fixed from dedicated electronic noise studies (pedestals RMS)
- S compatible with the stochastic term measured during ECAL commissioning before Run1 (2.8%)
- C within the 1% requirement
  - caveat: not-irradiated crystals

CMS ECAL 2023 Beam Test - setup

- **H4 line** of **SPS** at CERN
  - $e^{+/-}$ continuous beam from 20 to 300 GeV in spill structures
- **3 × 3 RUs (225 channels) of the spare super-module** (36 in total) equipped with the new electronics
- 4 MCPs for timing reference
- 4 hodoscopes planes for position reference
- laser monitoring system (FEMs + MEM) for 6 RUs (more detail in M. Tornago's talk)
- **2 BCPs boards**
- **all the components in a near-to-final version**



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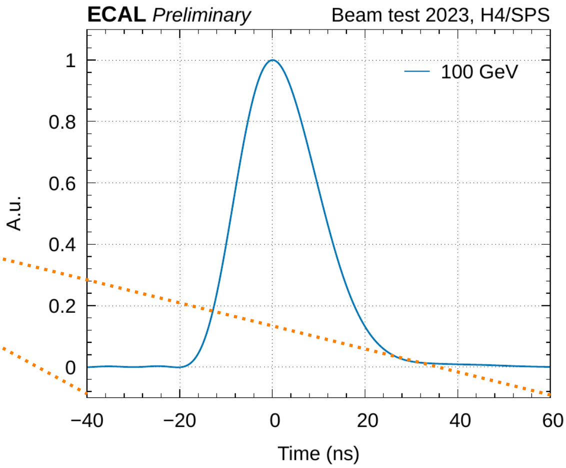
- **2 BCPs boards**
- **all the components in a near-to-final version**
- same movable mechanical structure used during ECAL commissioning before Run 1
  - **same pointing geometry of CMS**
  - additional elements in the beam telescope

CMS ECAL 2023 Beam Test - reconstruction

- the trigger is asynchronous (differently w.r.t CMS)
- electron signal **amplitude** $\boldsymbol{\mathcal{A}}$ and **time** $\boldsymbol{t_0}$ are reconstructed with a **template fit**

$$f(x) = \mathcal{A} \cdot \text{template}(t - t_0)$$

  - templates are obtained with **software over-sampling in the frequency domain**
  - the fit is performed over 16 samples (HL acquisition window)



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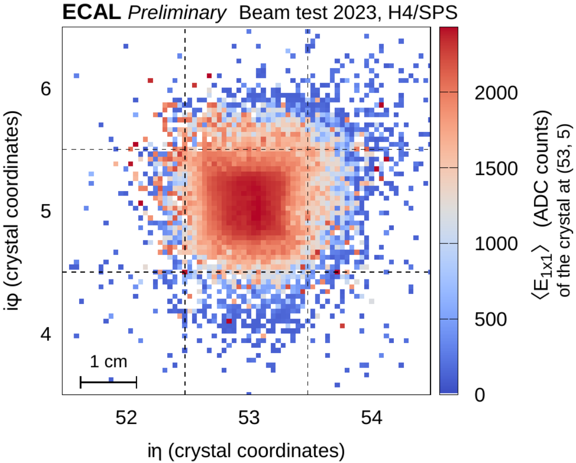
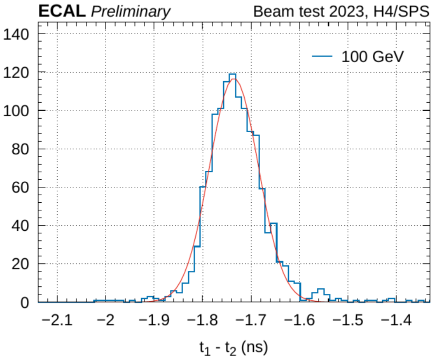
  - templates are obtained with **software over-sampling in the frequency domain**
  - the fit is performed over 16 samples (HL acquisition window)
- **analysis on hodoscopes and MCPs is ongoing**
- **electron impact position** reconstructed similarly to in CMS
  - weighted mean of energy deposits
  - for iη and iφ



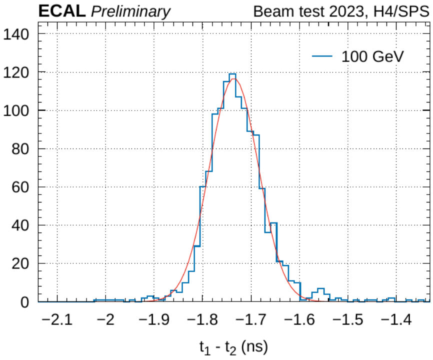
CMS ECAL 2023 Beam Test - timing resolution

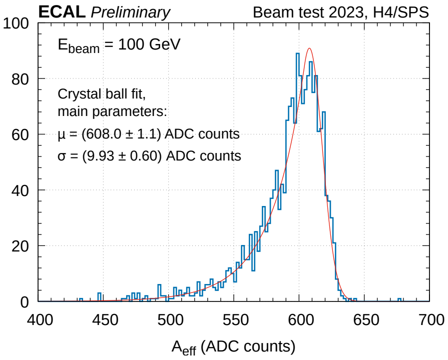
- **beam directed between two neighboring crystals**
- single-crystal **timing resolution**: width of the distribution of the **difference of the signal arrival times** $\boldsymbol{\Delta_t}/\sqrt{\mathbf{2}}$ (assuming identical resolutions)



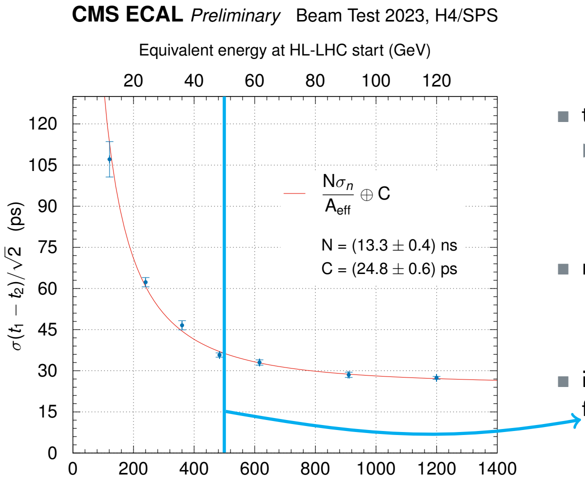
CMS ECAL 2023 Beam Test - timing resolution

- **beam directed between two neighboring crystals**
- single-crystal **timing resolution**: width of the distribution of the **difference of the signal arrival times** $\boldsymbol{\Delta_t}/\sqrt{2}$ (assuming identical resolutions)
- studied as a function of $\frac{A_{\text{eff}}}{\sigma_n} = \sqrt{\frac{2}{\left(\frac{\sigma_1}{A_1}\right)^2 + \left(\frac{\sigma_2}{A_2}\right)^2}}$





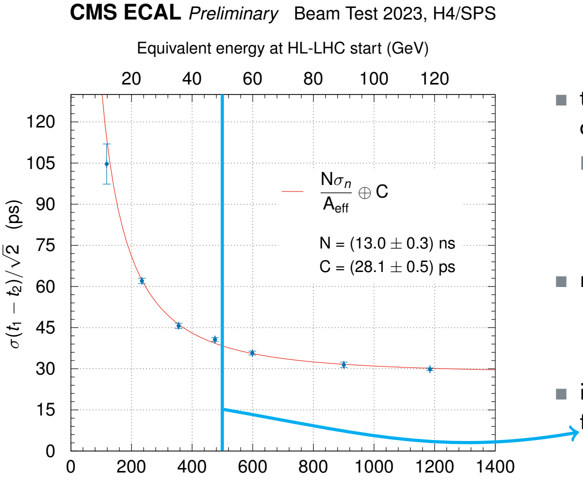
CMS ECAL 2023 Beam Test - timing resolution



$$\frac{A_{eff}}{\sigma_n} = \sqrt{\frac{2}{\left(\frac{\sigma_1}{A_1}\right)^2 + \left(\frac{\sigma_2}{A_2}\right)^2}}$$

- two channels on same VFE
  - **best possible case**
- requiring only HG events
- if we assume $\sigma_n = 100$ MeV at the HL-LHC start, for $A_{eff} = 50$ GeV: $\boldsymbol{\sigma_t = (36.3 \pm 0.7)}$ **ps**

CMS ECAL 2023 Beam Test - timing resolution



$$\frac{A_{eff}}{\sigma_n} = \sqrt{\frac{2}{\left(\frac{\sigma_1}{A_1}\right)^2 + \left(\frac{\sigma_2}{A_2}\right)^2}}$$

- two channels on different VFEs, different FEs, different BCPs
  - **worst possible case**
- requiring only HG events
- if we assume $\sigma_n = 100$ MeV at the HL-LHC start, for $A_{eff} = 50$ GeV: $\boldsymbol{\sigma_t = (38.3 \pm 0.5)}$ **ps**

Conclusion

- **the CMS homogeneous crystal electromagnetic calorimeter allows precise energy and time measurements in a harsh radiation environment**

- detector ageing and increasingly challenging experimental conditions can potentially degrade the performance

- expertise, innovative calibration techniques and a flexible DAQ/Trigger system are necessary to continuously meet the physics requirements

- beam tests with the **upgraded Phase-2 electronics** show promising preliminary results
  - energy resolution matches the current performance
  - **timing resolution meets the 30 ps target** for energies of photons from typical $H \to \gamma\gamma$

- **CMS ECAL will continue its successful journey at HL-LHC!**

Backup

References

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Figure references

- slide 3: [**2**]
- slide 5: [**3**]
- slide 6: [**4**]
- slide 12: left [**6**], right [**7**]
- slide 14: left and right [**8**]
- slide 15: A. Martelli on behalf of the CMS Collaboration, "The CMS HGCAL detector for HL-LHC upgrade", proceedings of the LHCP2017
- slide 17: [**8**]
- slide 19: [**9**]
- slide 22: [**9**]
- slide 23: [**10**]