Input to PPTAP: CMS ECAL UK experience and lessons learned

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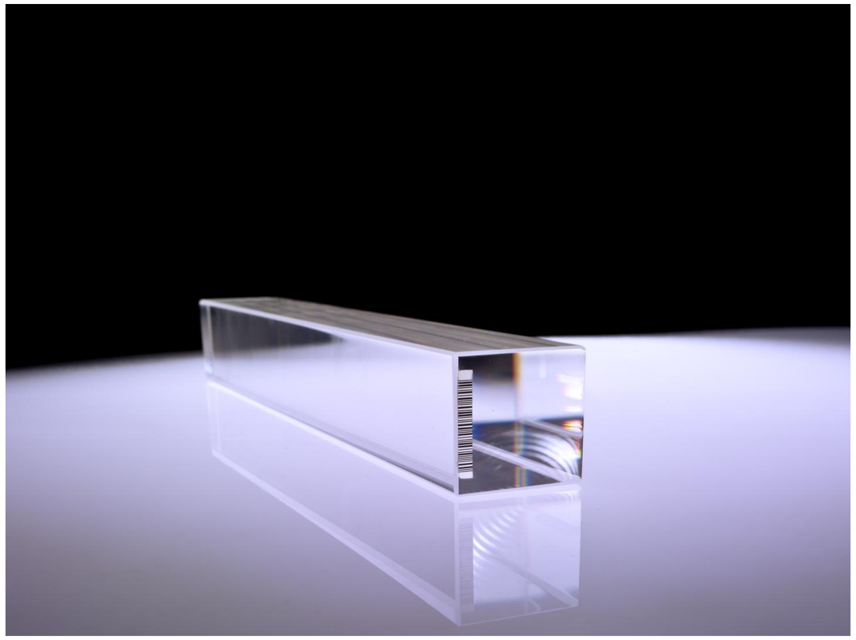
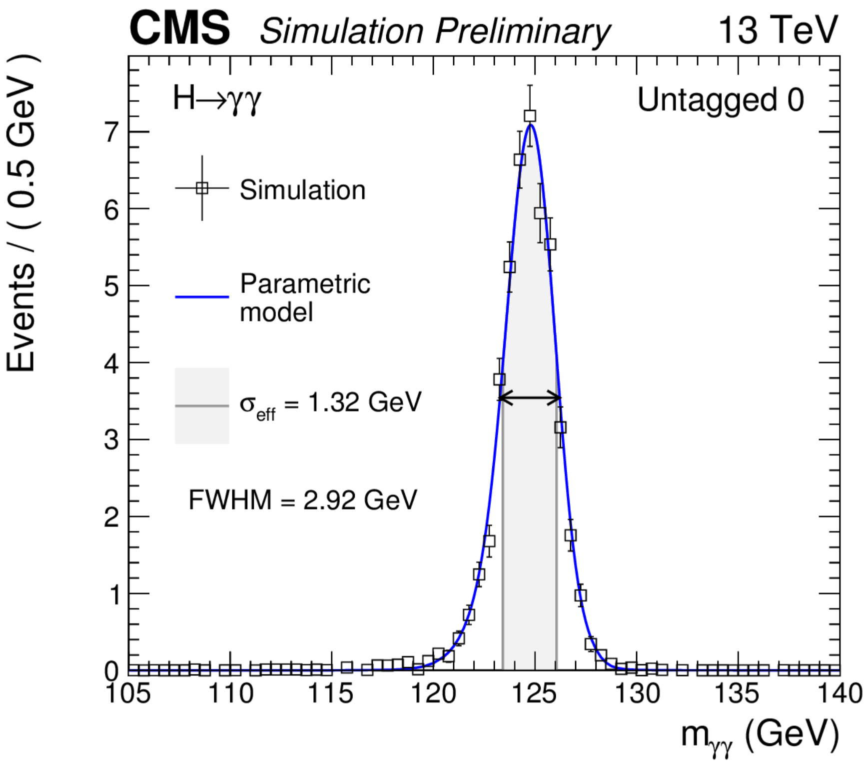
CMS ECAL

- **The CMS ECAL was designed with challenging goals:**
  - **Extreme energy resolution** in the harsh LHC radiation environment
    - **achieve 1% mass resolution** for low-mass Higgs in the γγ decay channel
  - **Hermetic and compact detector** with coverage up to |η| = 3.0
- **Lead tungstate ($PbWO_4$) crystal calorimeter**
    - compact, fast, radiation tolerant
  - Radiation and magnetic field tolerant **APD and VPT photodetectors**
  - Provide crystal energy sums at 40 MHz to **trigger on electrons and photons**



Lead Tungstate ($PbWO_4$) crystal



H→γγ Mass resolution ~1%

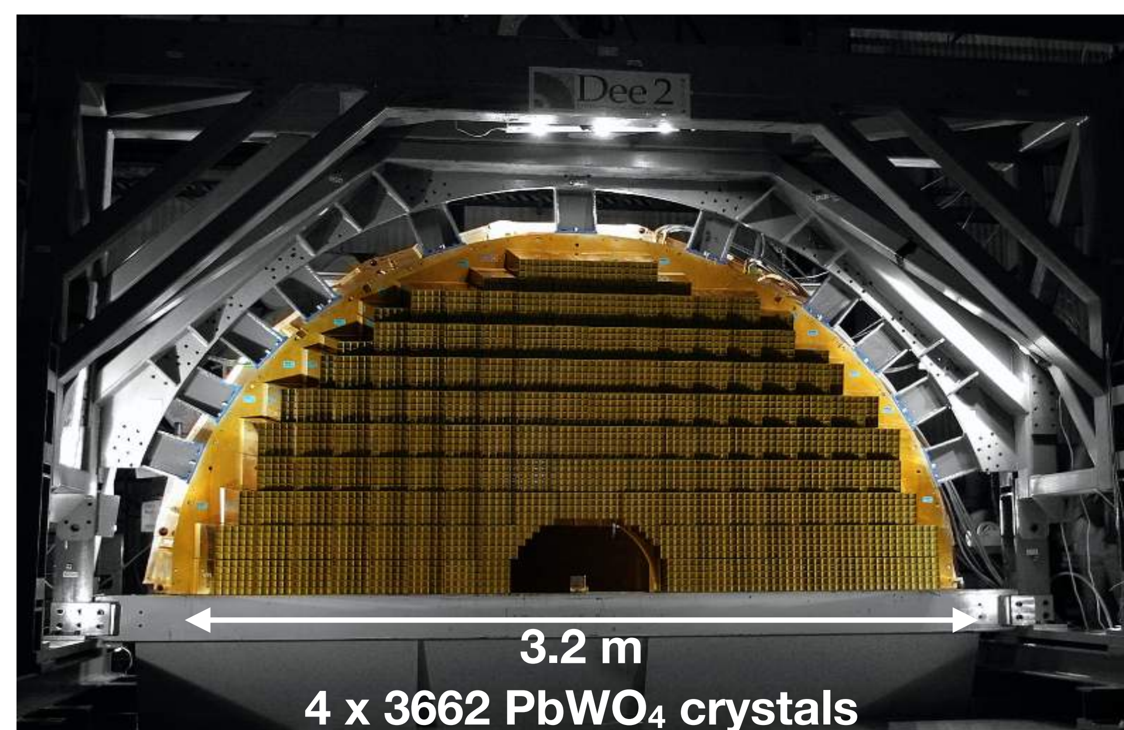
UK contributions to CMS ECAL

UK institutes: Bristol, Brunel, Imperial College, RAL

- **UK has played a leading role in ECAL design, construction and operation**
  - **UK led the design, construction & installation of ECAL endcaps (EE), in partnership with RAL TD**
  - RAL led development and testing of VPT photodetectors for EE (with Research Institute Electron, St Petersburg) and designed/operates the VPT High Voltage system
  - UK involved in Lead tungstate crystal R&D, performance characterisation and calibration
  - UK designed & manufactured radiation-hard, low noise front-end pre-amp ASIC for whole ECAL
  - Crystal and photodetector expertise directly followed on from previous experience on LEP
  - **Almost 30 years of UK involvement in CMS and ECAL (from initial Letter of Intent)**

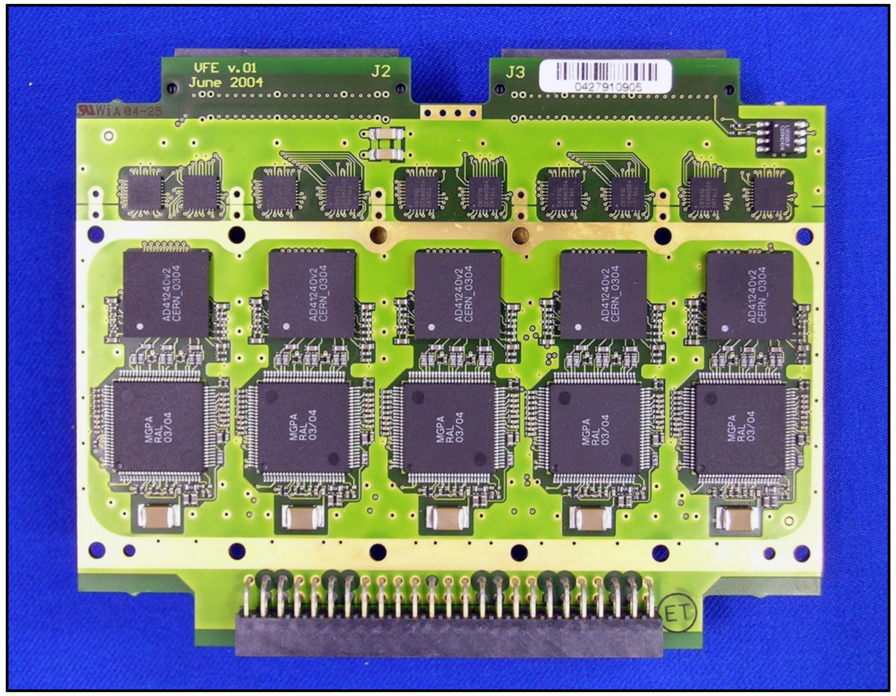
From concept…

…to reality

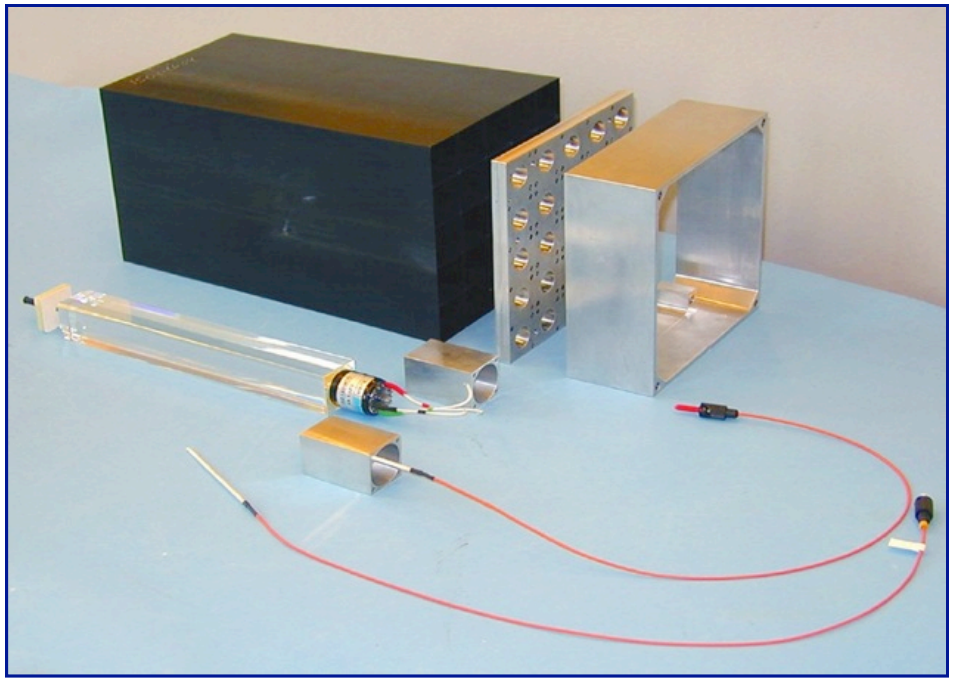


Selected UK contributions in photos

one of 14648 EE Vacuum Phototriodes (VPTs)



Very-front-end card with UK-designed MGPA pre-amplifier ASICs



Elements of a EE supercrystal (5x5 channels)

Endcap mechanics and construction

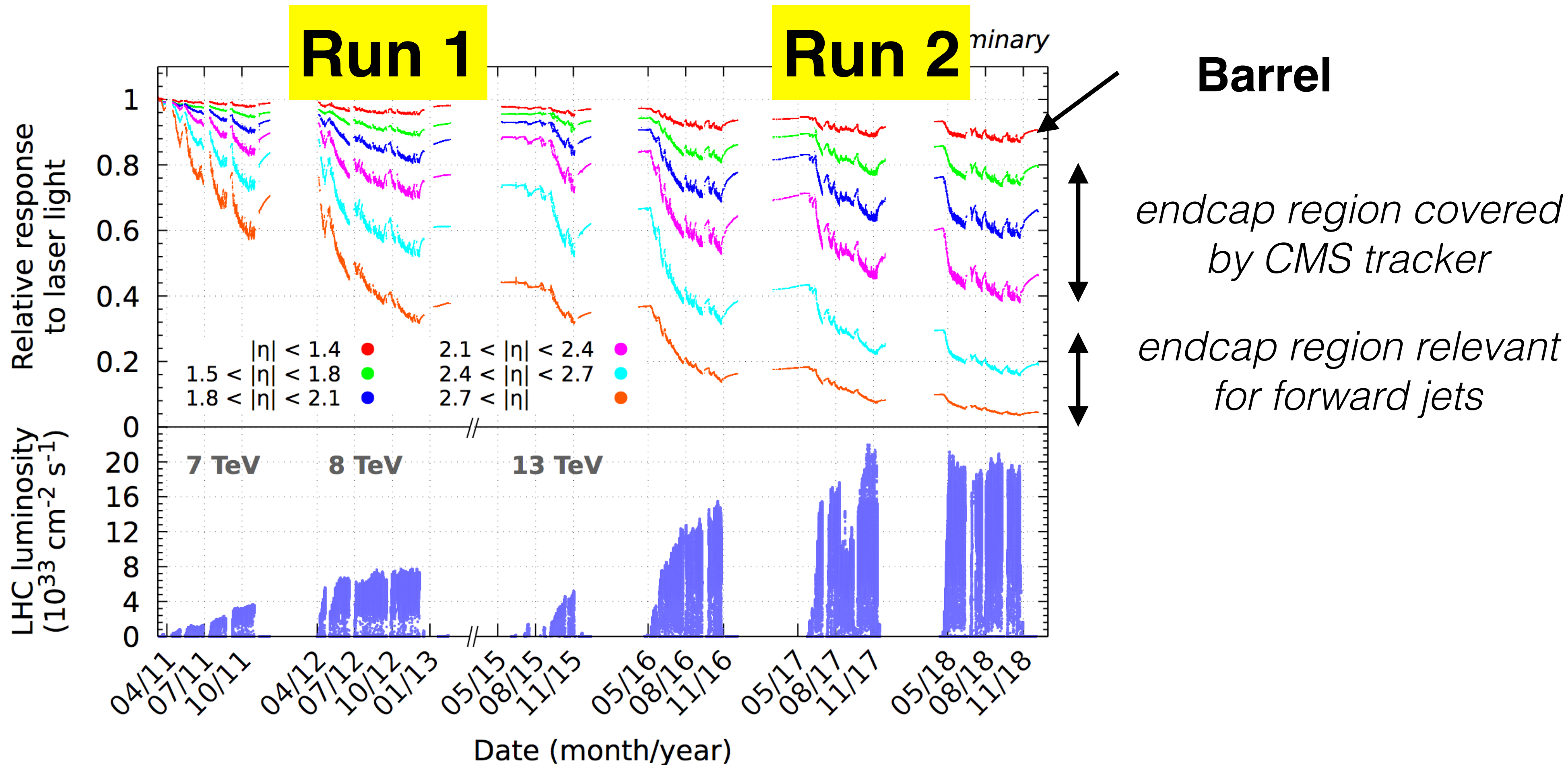
UK contributions to ECAL operations

- **UK has held a large variety of ECAL management/operations roles**
  - ECAL Project Manager (x2) - during initial construction and during Run 2 operations
  - EE Project Manager and EE Project Engineer
  - ECAL Field Technical Coordinator and ECAL Run Coordinator
  - ECAL Detector Performance Convenor (x2) - during startup and during period of Higgs discovery in Run 1
  - ECAL Software Coordinator, ECAL Trigger Coordinator, CMS Egamma Convenor (x2)
- **UK has contributed significantly to detector understanding, optimisation and performance**
  - Crystal and photodetector expertise - deep understanding of crystal radiation damage and photodetector response losses, particularly in EE
  - Electron/photon reconstruction expertise, both for HLT and offline - built on deep detector knowledge
  - Detector calibration and performance optimisation, based on the above
  - Optimisation of ECAL Trigger - hardware rejection of anomalous signals (“spikes”)
  - Leading roles in flagship physics signatures that depend on excellent ECAL performance ($H \rightarrow \gamma\gamma$, $Z' \rightarrow ee$)

Lessons learned from 10+ years of CMS ECAL operation

ECAL Calibration challenges

- **Significant response changes (crystal + photodetector) due to LHC irradiation**
  - on both short (few h) and longer timescales (EM and hadron damage to ECAL crystals)
- **Need for both short term and long term corrections - both online and offline**
  - via dedicated laser monitoring system (corrections within 48h)
  - and physics-based calibration using π^0/η, minimum bias, W, Z events
  - **special attention must be devoted to high eta region (with largest losses) to prevent biases in jets and MET**

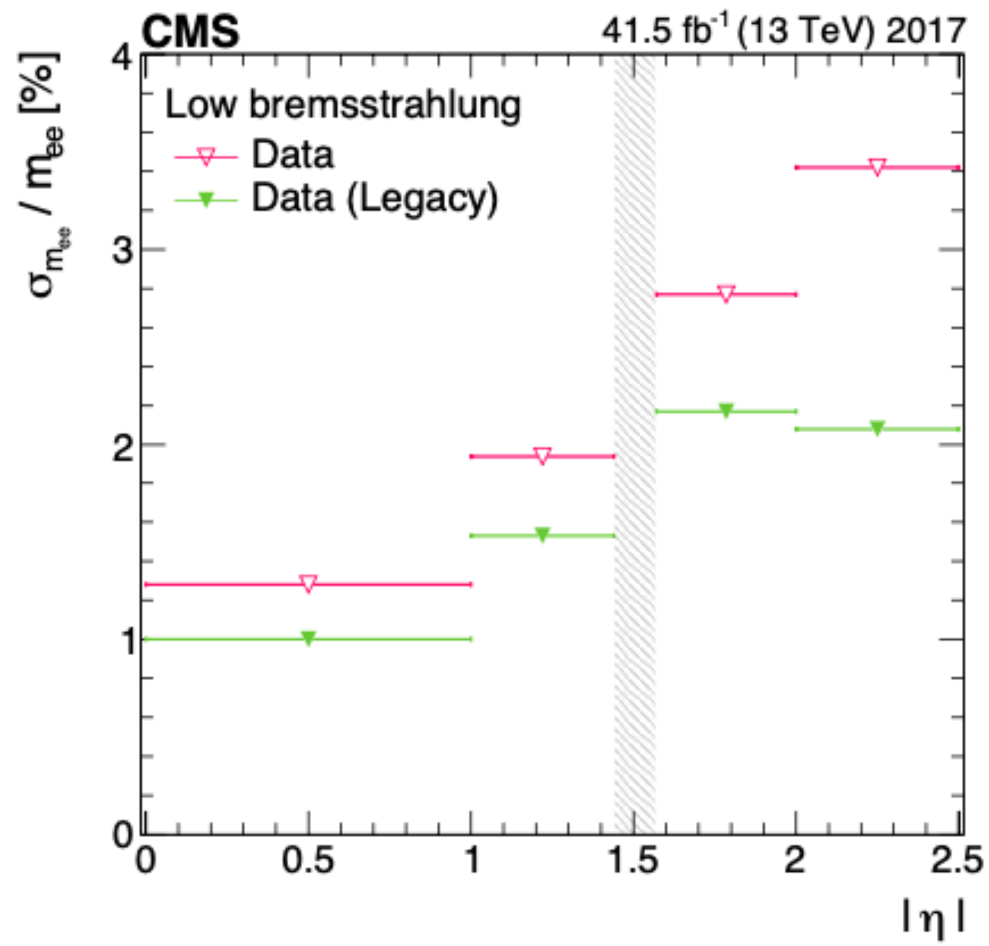


These corrections are crucial to maintain stable ECAL energy scale and resolution over time. Requires a dedicated team during LHC operations

Lesson learned - do not underestimate this challenge!

Importance of recalibration

- **Refined physics-based calibrations using full dataset are derived at the end of each running year**
  - **these are required to obtain optimal energy resolution in all regions of the detector**
    - **they correct for time-dependent drifts in calibrations**



Di-electron Z mass resolution before and after end-year recalibration

Lessons learned:

Do not assume that calibrations remain constant!

many relevant observables (pedestals, signal pulse shapes, channel response) can be affected by irradiation and require frequent calibration updates to maintain optimal pulse reconstruction, energy and timing resolution

Note that resolution vs eta largely follows distribution of upstream tracker material: need to minimise this in future detector designs to preserve intrinsic ECAL resolution

ECAL Calibration methods

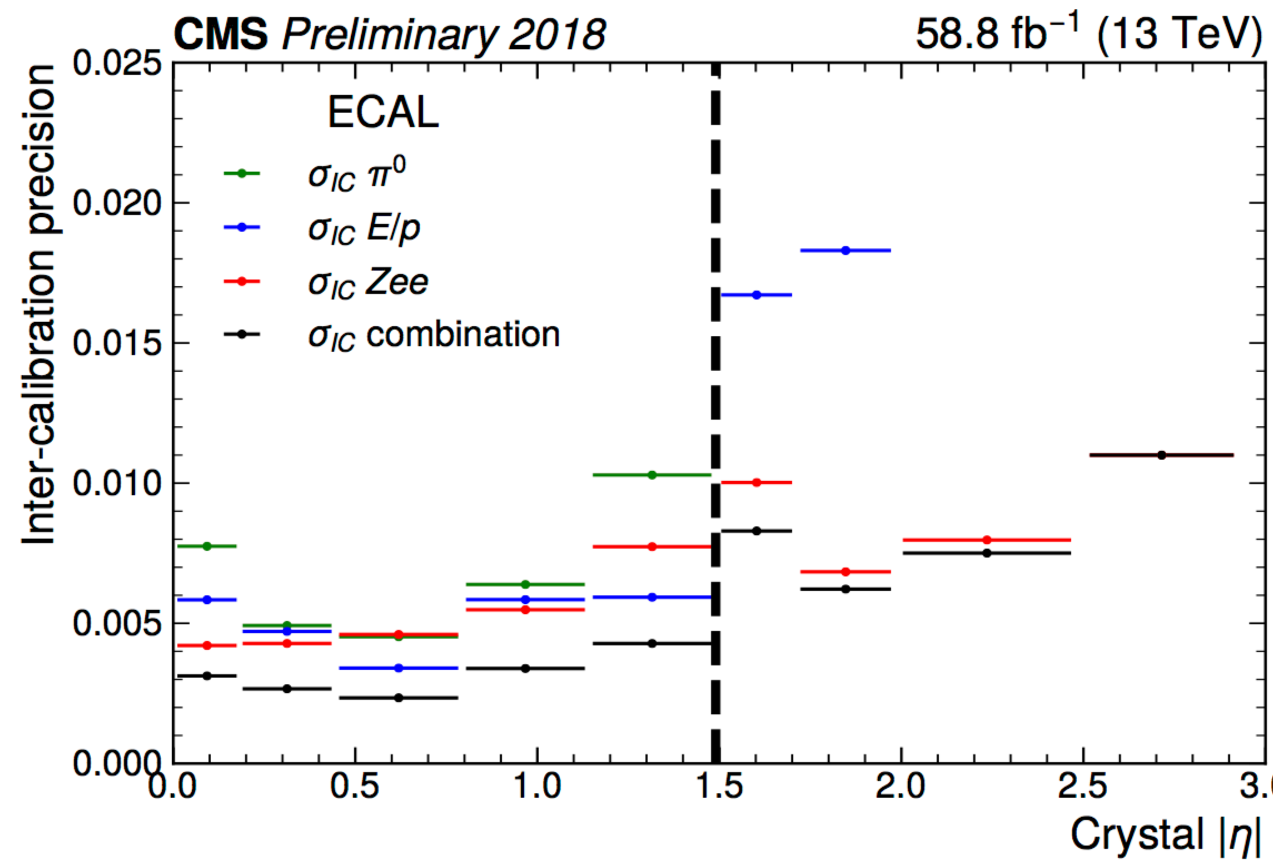
ECAL intercalibration sources

physics data are used to equalise the response of each channel in EB and EE

method	time needed
ϕ-symmetry	few days
$\pi^0/\eta \rightarrow \gamma\gamma$	1 month
electron E/p	20 fb^{-1}
Z→ee mass	20 fb^{-1}

Dedicated calibration streams (with limited event content) are used to collect enough stats.

ECAL intercalibration precision



Can achieve precision of better than 0.5% in EB and 1% in EE with a combination of calibration methods

Lessons learned:

Maintain multiple calibration methods

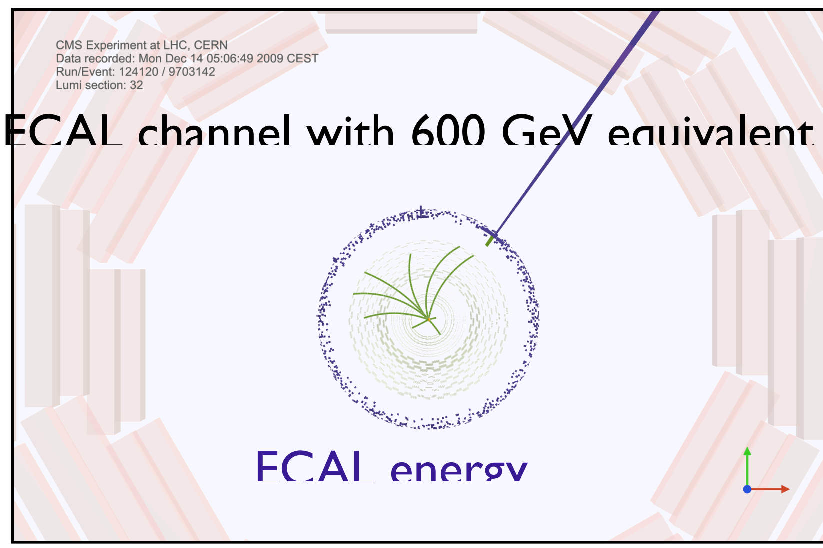
CMS ECAL experience:

1) calibration methods involving low energy signals (π^0/η, phi-symmetry) are affected by noise and pileup (these methods were not usable for |eta|>2.0 in 2018)
2) some methods (phi-symmetry, E/p from W→ev) suffer from systematics due to uncertainties in tracker material distribution in phi
3) Z→ee proved to be the most effective all-purpose calibration method in Run 2

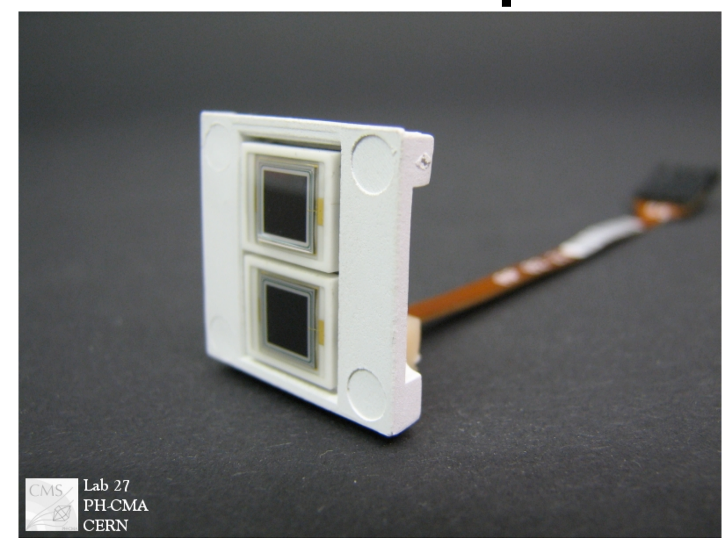
ECAL spikes

- **Anomalous signals ("spikes") unexpectedly observed in ECAL Barrel: large apparent energy deposits with non-physical topological and timing signatures**
- **Caused by direct ionisation of APD active volume by collisions products (chiefly hadrons/pions)**

ECAL APD "spike"



ECAL APD capsule



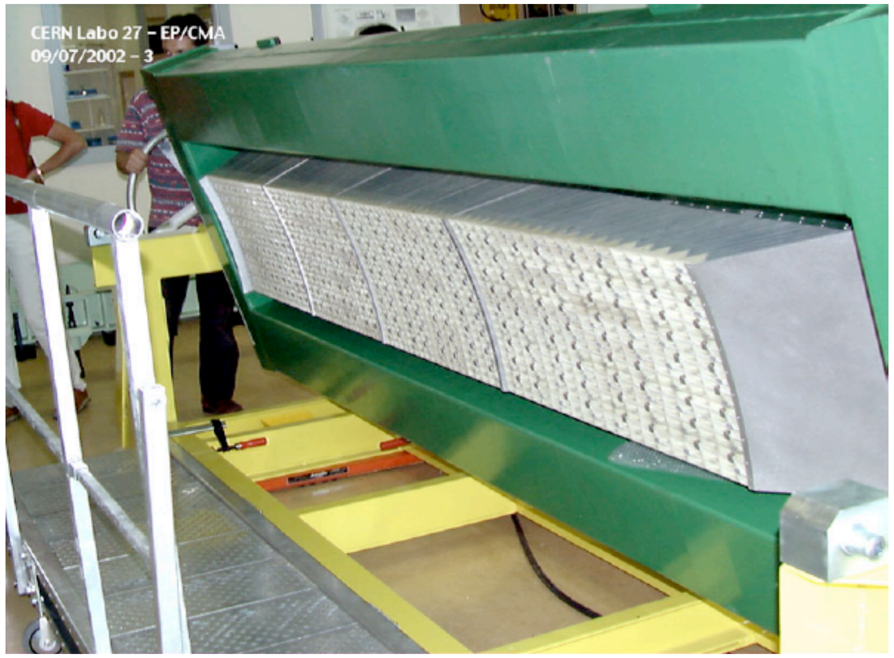
- **Mitigation was challenging, especially for L1 trigger:**
  - no possibility to cure at source - APDs inaccessible
  - spikes will typically hit one of 2 APDs serving one ECAL crystal. However, decision was made to sum these signals rather than read them out individually to reduce cost
  - eventually found a way to remove spikes using **extra unused feature of ECAL front-end ASIC**

Lessons learned: Must rigorously check system in test beam campaigns. Self-triggering would have revealed this problem. Build sufficient flexibility in on-detector and off-detector electronics to deal with unexpected signals. Add redundancy to readout signals?

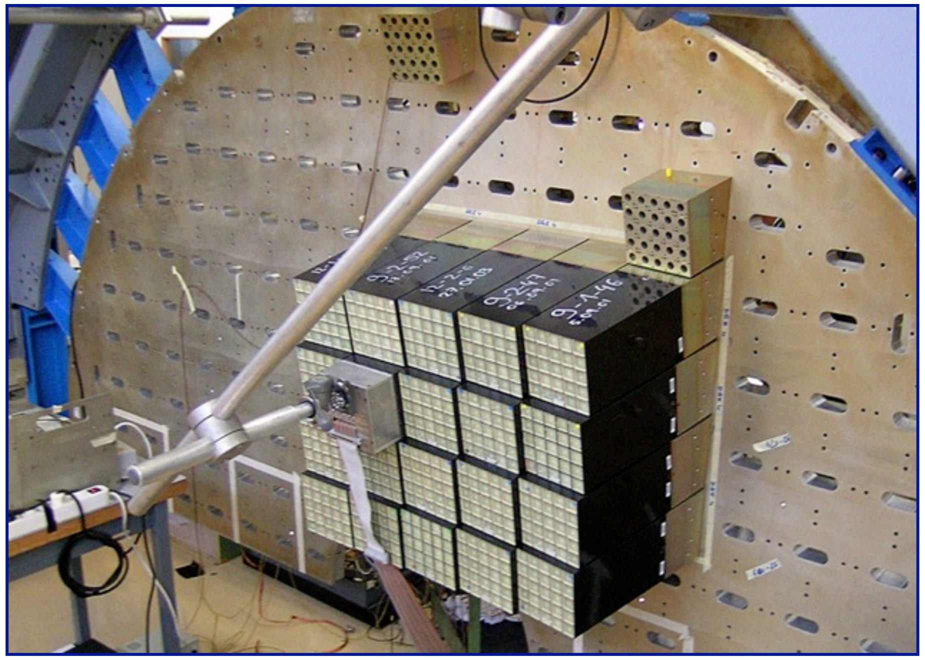
ECAL mechanics

- **Significant differences in mechanical design of ECAL Barrel and Endcaps**
  - barrel design incorporated 17 different module types and 17 different crystal shapes
  - endcap design involves a single module type and one crystal shape

Barrel mechanics: 17 crystal types



Endcap mechanics: 1 crystal type

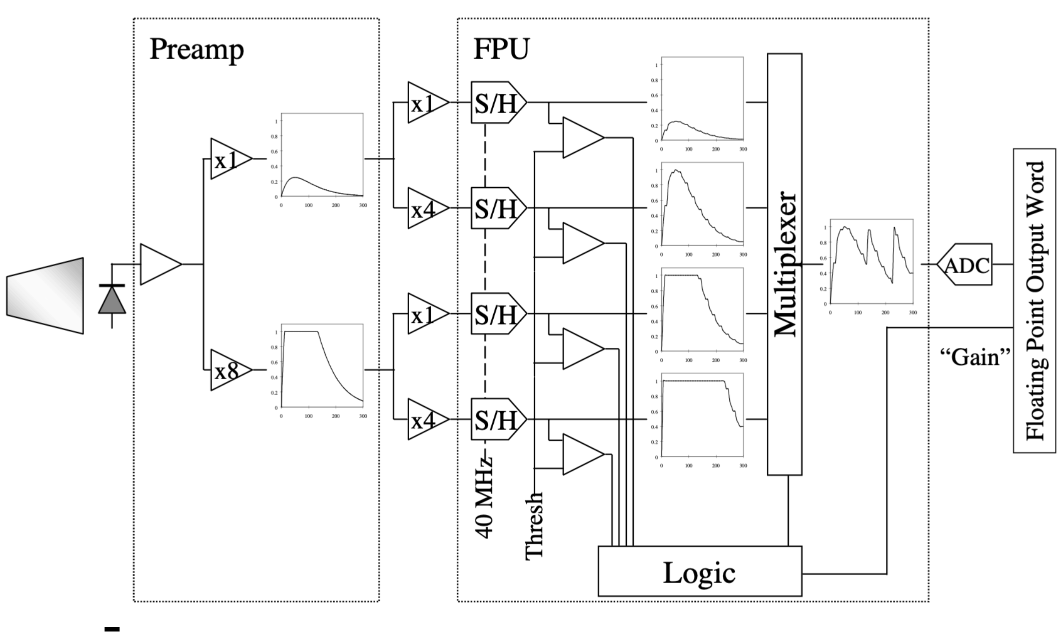


- **This has implications for crystal production and detector construction**
  - much simpler if you only have to deal with a single module/crystal type
- **Should also consider possibility for partial dismounting/replacement of modules**
  - ECAL was not designed with this possibility in mind - partial dismounting difficult/impossible
  - might be a desirable feature for future detectors if certain regions need to be removed/replaced due to large radiation-induced response losses or other performance issues

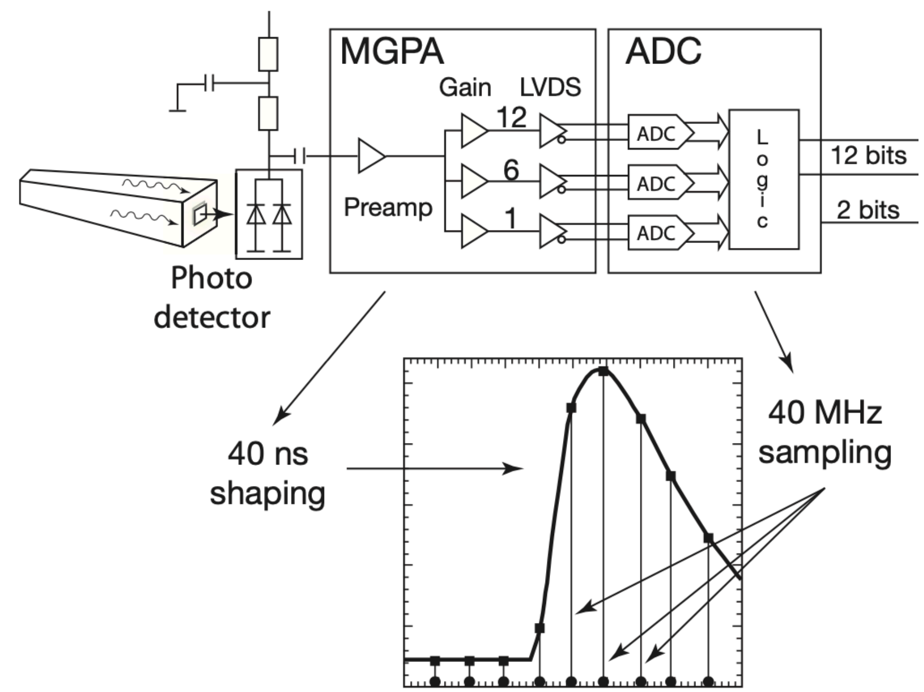
ECAL ASICs

- **UK involvement in ECAL very-front-end ASICs came about due to noise/ performance problems with the original TDR designs**
- **Original preamp and ADC designs had to be dropped and new ASICs developed from scratch**

TDR very-front-end design



Final very-front-end design

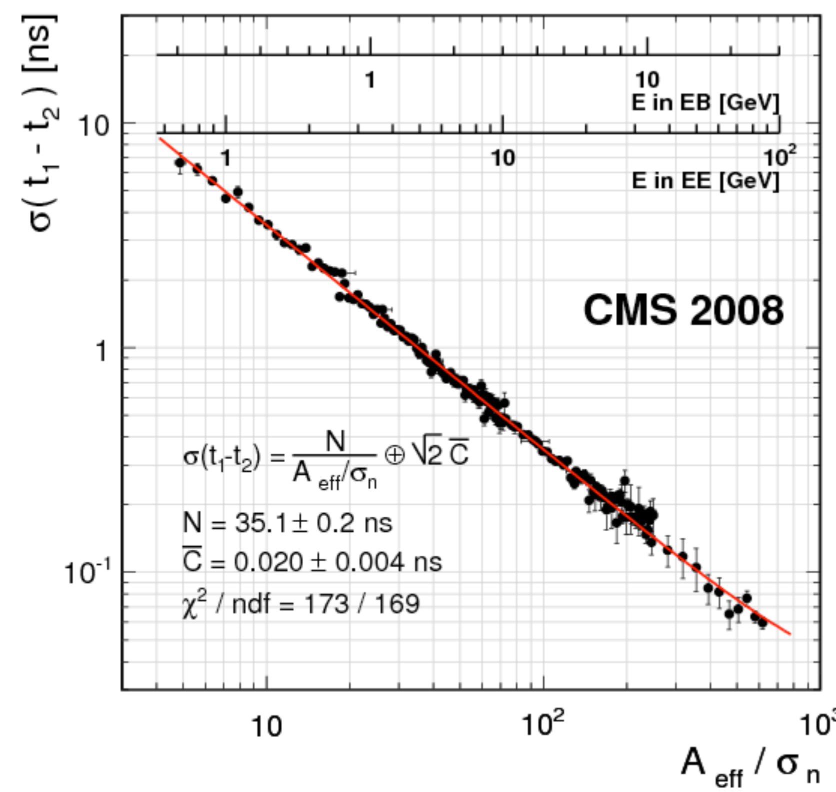


Lessons learned:

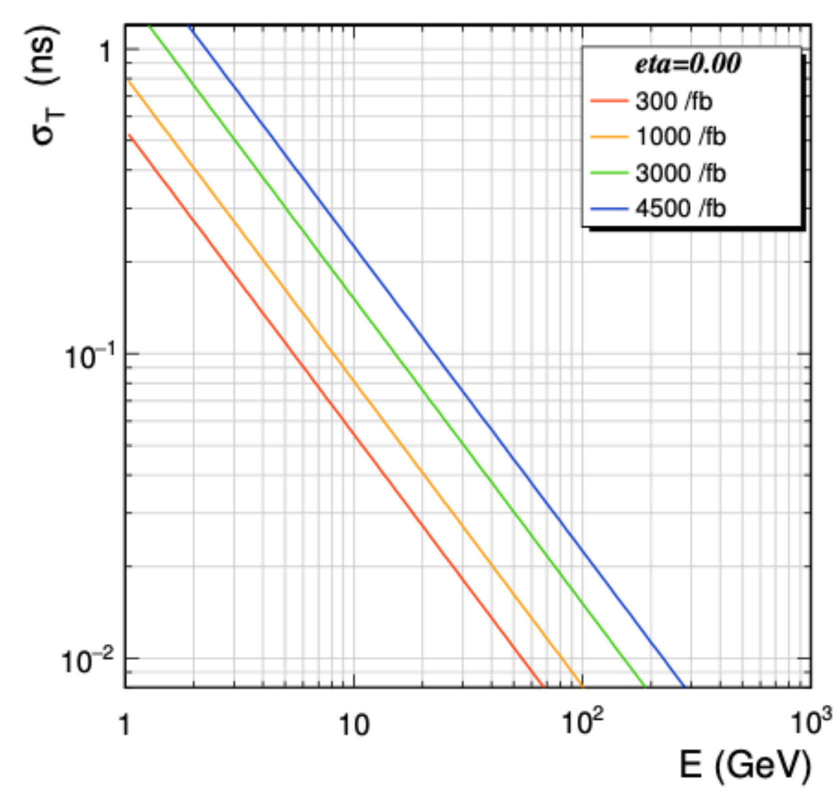
Issues with ASICs are not uncommon in HEP - but problems can be minimised by careful and conservative design methodologies. Early full-system tests with detector prototypes are a **must** to check system performance and identify any noise issues in a realistic data-taking environment

ECAL crystals are capable of precise timing

- **CMS ECAL crystals and APDs are capable of providing precise timing information**
  - **intrinsic timing resolution: ~20 ps**
- **ECAL timing distribution system was not designed for sub-ns timing measurements**
  - **achieved timing resolution is ~150ps, limited by timing distribution to front-end boards**
- **Phase-2 upgrade prioritises precise timing resolution**
  - **Crystals and APDs will remain in Barrel**
  - **ECAL will use a redesigned front-end preamp and ADC to minimise pulse shaping and over-sample signal pulse**
  - **dedicated timing distribution system to achieve 30ps resolution**
  - **ageing (APD noise increase) gradually degrades performance**



ECAL time resolution measured from test beam



Phase-2 ECAL time resolution vs luminosity

Future activities and prospects

Plans for HL-LHC - crystal ECAL

- **RAL/Bristol will continue to support the crystal ECAL Barrel (which will remain in place for HL-LHC with upgraded on-detector and off-detector electronics)**
  - Our main deliverable is to develop new and more advanced ECAL energy clustering and noise rejection algorithms for the calorimeter trigger in firmware and software
  - Another deliverable is the specification of an optical fibre router system for connecting between the ECAL off detector electronics boards to allow clustering and geometry-based noise rejection algorithms to be developed across boundaries.
  - We will also develop ECAL reconstruction code that makes the largest possible use of accelerators (GPUs/FPGAs etc)
- **CMS is developing silicon sampling calorimeter for Phase 2 endcap with significant UK involvement (see HGCAL talk)**
  - Specific UK interest in trigger algorithms and online/offline reconstruction

Future calorimetry plans:
RAL perspective

- **RAL CMS group: currently no calorimeter hardware project planned beyond HL-LHC**
  - **RAL detector expertise is in crystal calorimetry (albeit with a much smaller group than we had during CMS construction).**
    - Could contribute ideas and 20+ years of CMS experience, if there is significant interest in a crystal based calorimeter for ILC/FCC-ee within the UK community
    - We have strong links to CERN calorimeter groups who would likely be a significant driving force behind any crystal or fibre-based calorimeter for any future project based at CERN.
      - See M. Lucchini talk at ECFA TF6 symposium for a survey of R&D activities
  - **We have significant trigger expertise that can be leveraged for future projects**
    - Hardware/firmware/algorithm expertise, in both calorimeter, tracker and trigger systems
    - Potential interest in algorithms that combine tracker and calo signatures in future L1 trigger systems