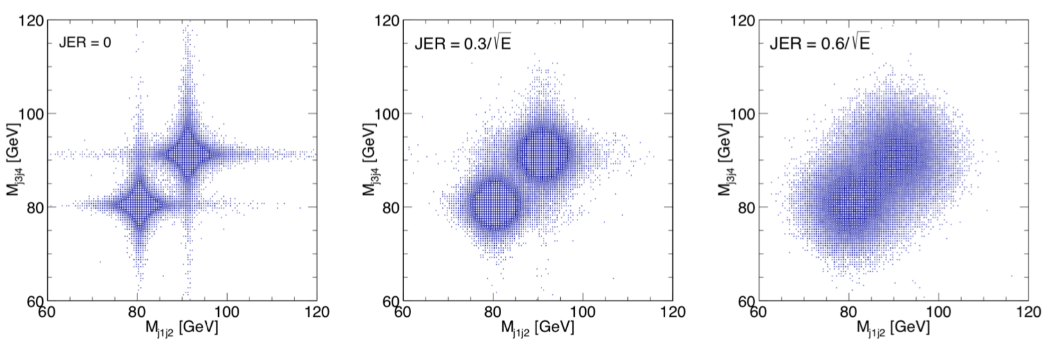
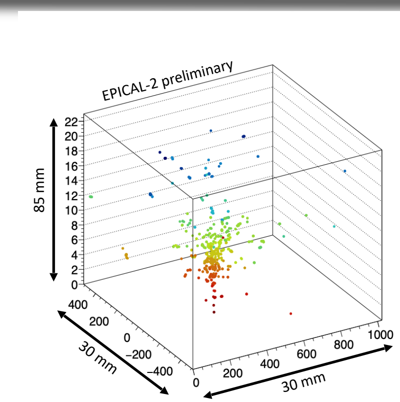
Calorimetry - UK ongoing R&D and perspective

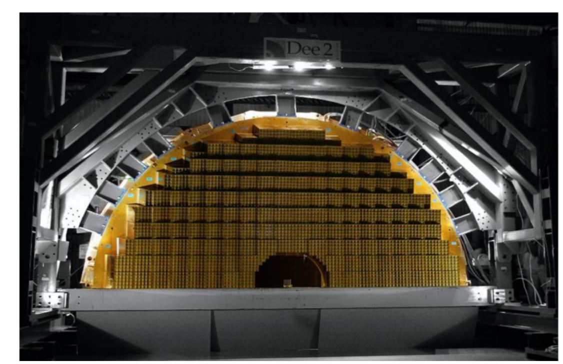
- Crystal
- Dual Readout
- Silicon

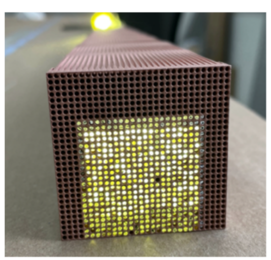
Nigel Watson (Birmingham)

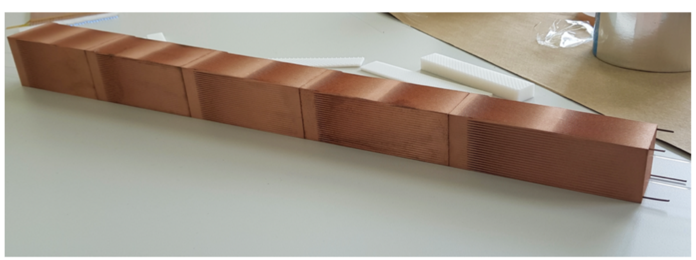
with thanks to Iacopo Vivarelli (Sussex), David Petyt (RAL), Hiroki Yokoyama (Utrecht), Tim Rogoschinki (Frankfurt)

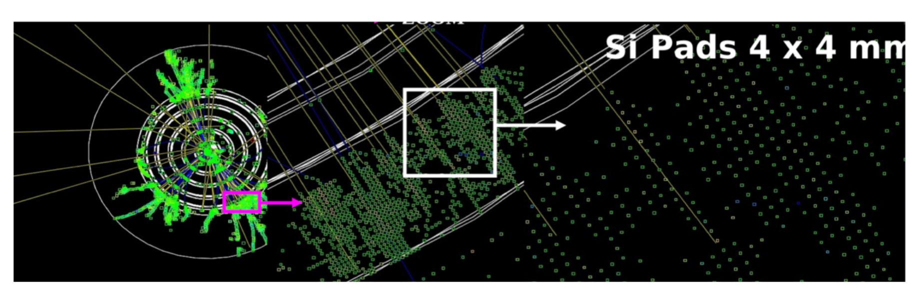








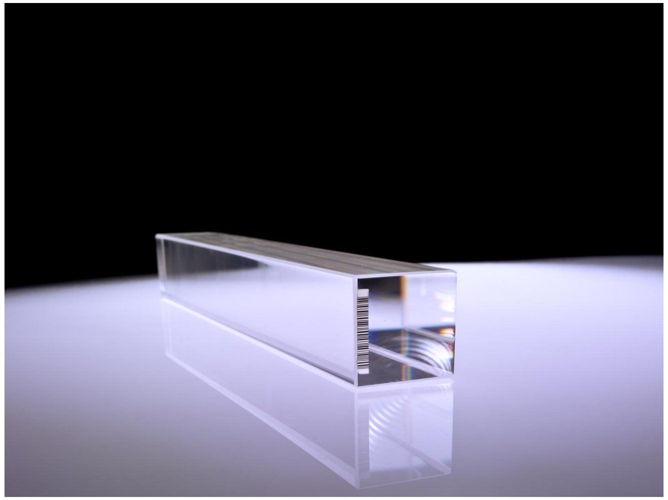




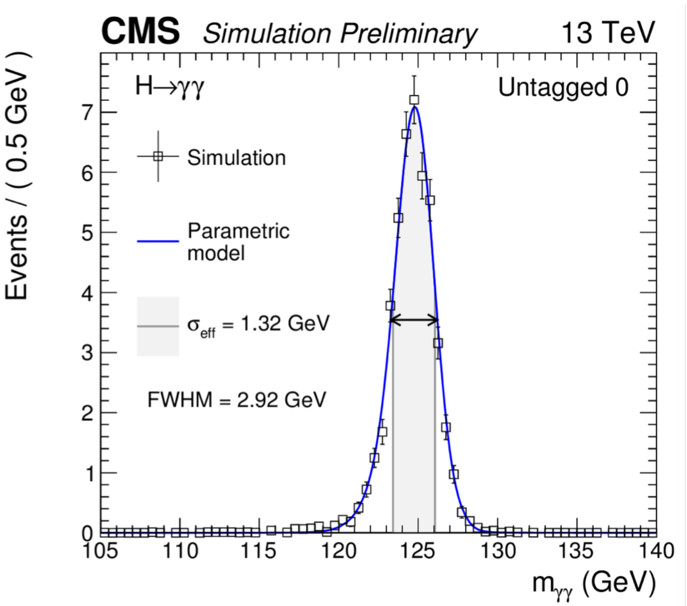
CMS Crystal ECAL

[David A. Petyt]

- **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

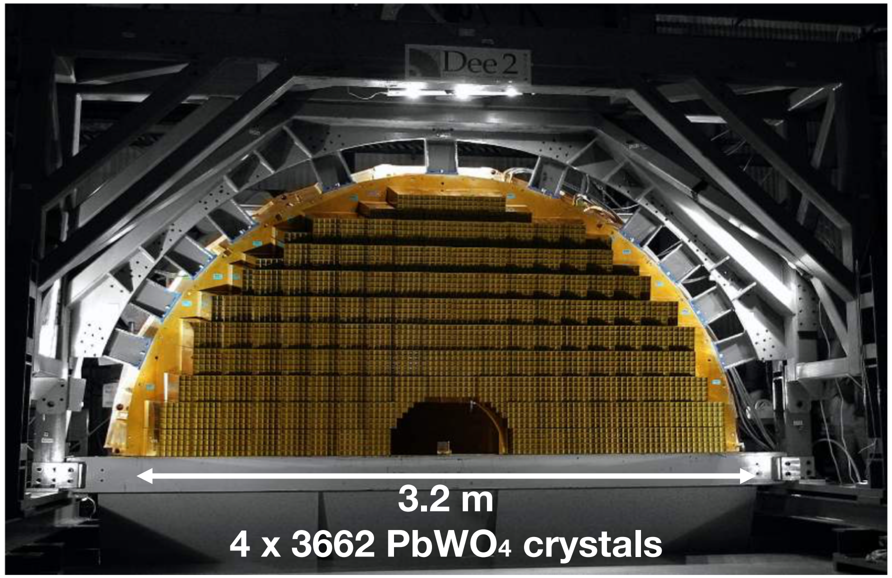
[David A. Petyt]

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)**

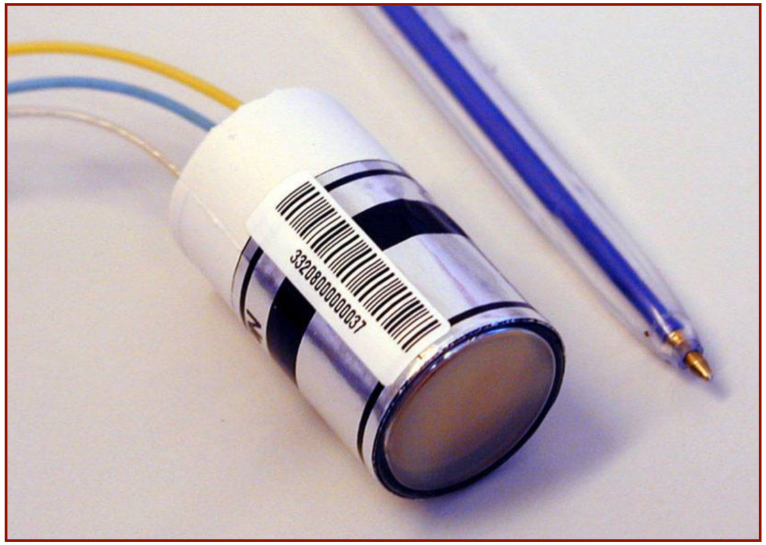
From concept…

…to reality

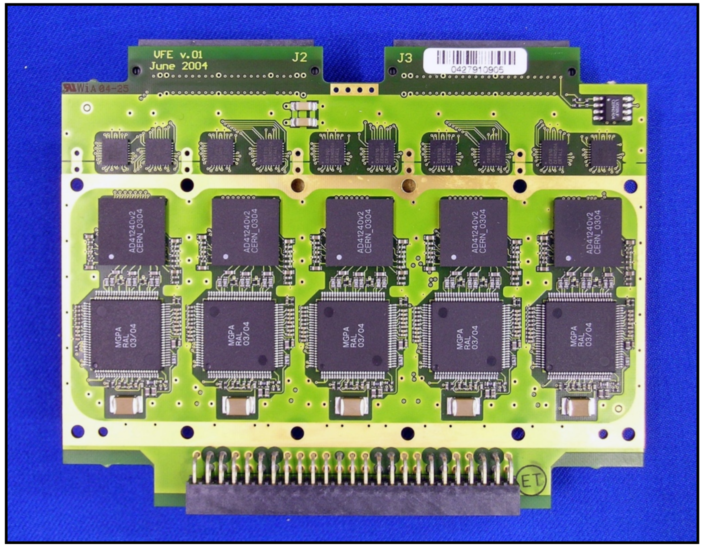


[David A. Petyt]

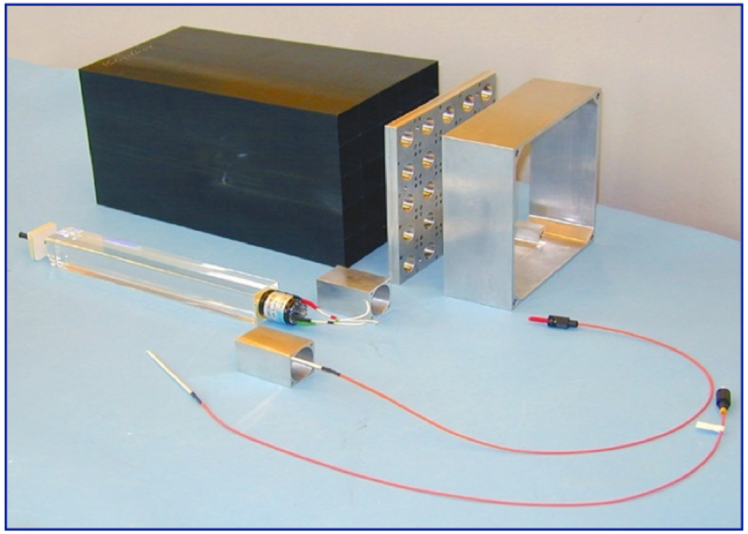
Selected UK contributions



one of 14648 EE Vacuum Phototriodes (VPTs)



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



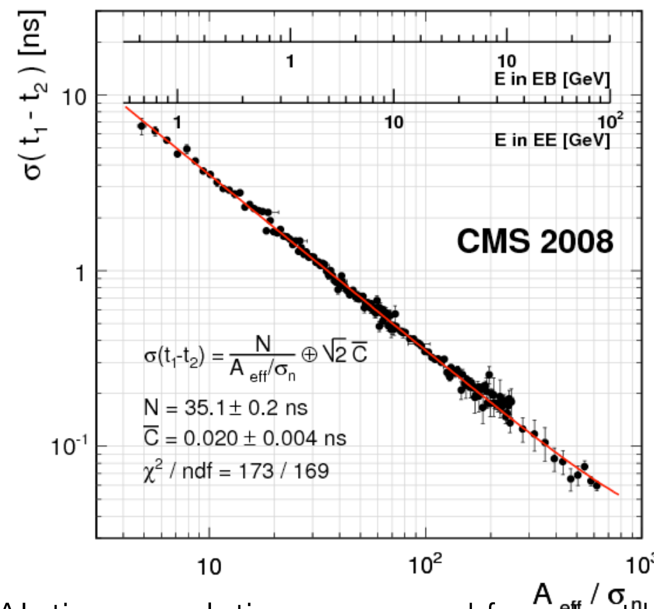
Elements of a EE supercrystal (5x5 channels)

Endcap mechanics and construction

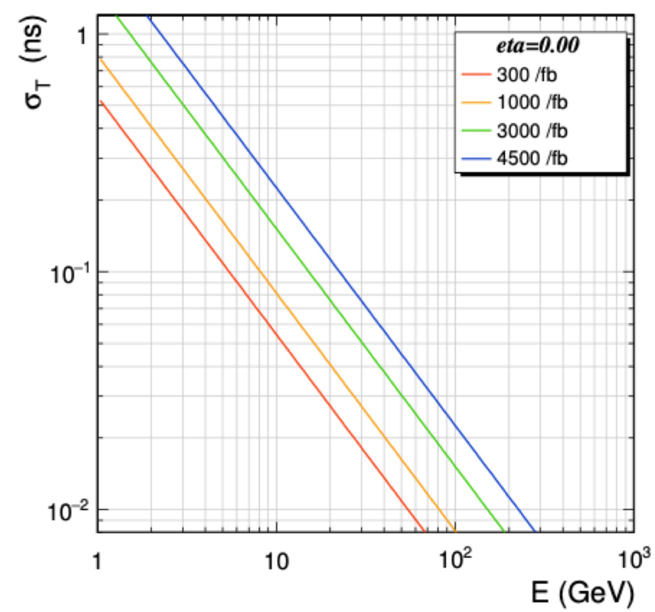
[David A. Petyt]

ECAL crystals are capable of precise timing

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



ECAL time resolution measured from test beam



Phase-2 ECAL time resolution vs luminosity

Plans for HL-LHC - crystal ECAL

[David A. Petyt]

- **RAL/Bristol continue support for crystal ECAL Barrel (through HL-LHC, with upgraded on-/off- detector electronics)**
  - Main deliverable: more advanced ECAL energy clustering and noise rejection algorithms for calorimeter trigger (firmware and software)
  - Specification of optical fibre router system, allowing clustering and geometry-based noise rejection algorithms across boundaries.
  - Develop ECAL reconstruction code for GPUs/FPGAs etc.

- **Significant UK effort for HGCAL – see AMM /PD talks**
  - Specific UK interest in trigger algorithms and online/offline reconstruction

[David A. Petyt]

Future calorimetry plans:
RAL perspective

- **RAL CMS group: no calorimeter hardware project planned beyond HL-LHC at present**
  - **RAL detector expertise is crystal calorimetry (much smaller group than during CMS construction).**
    - Could contribute ideas and 20+ years of CMS experience, if significant interest in a crystal based calorimeter for ILC/FCC-ee within the UK community
    - Strong links to CERN calorimeter groups, likely be a significant driving force in any crystal or fibre-based calorimeter for future projects based at CERN
      - See M. Lucchini talk at ECFA TF6 symposium for a survey of R&D activities
  - **Very significant trigger expertise, 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

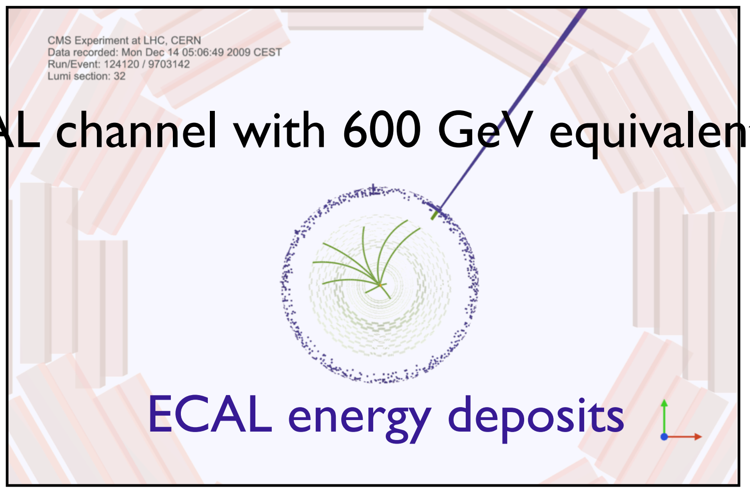
[David A. Petyt]

Expertise e.g. ECAL spikes

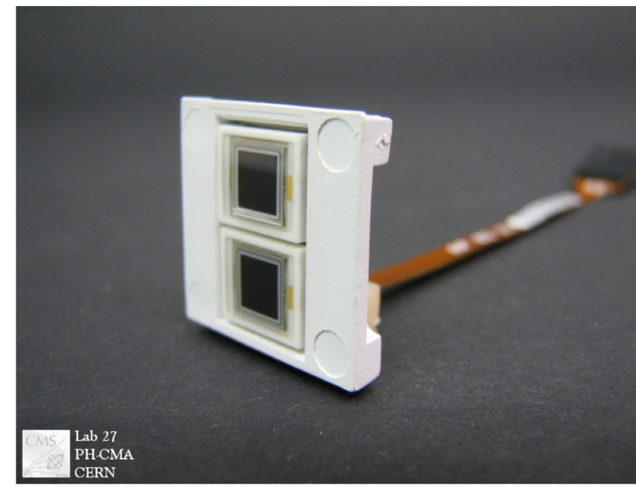
- **Anomalous “spikes” observed in ECAL Barrel**
  - **large apparent energy deposits, non-physical topological and timing signatures**
- **Caused by direct ionisation of APD active volume by collisions products (chiefly hadrons/pions)**

ECAL APD “spike”

single ECAL channel with 600 GeV equivalent energy



ECAL APD capsule



- **Mitigation was challenging, especially for L1 trigger:**
  - no possibility to cure at source - APDs inaccessible
  - spikes typically hit 1 of 2 APDs per single 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?

[Iacopo Vivarelli]

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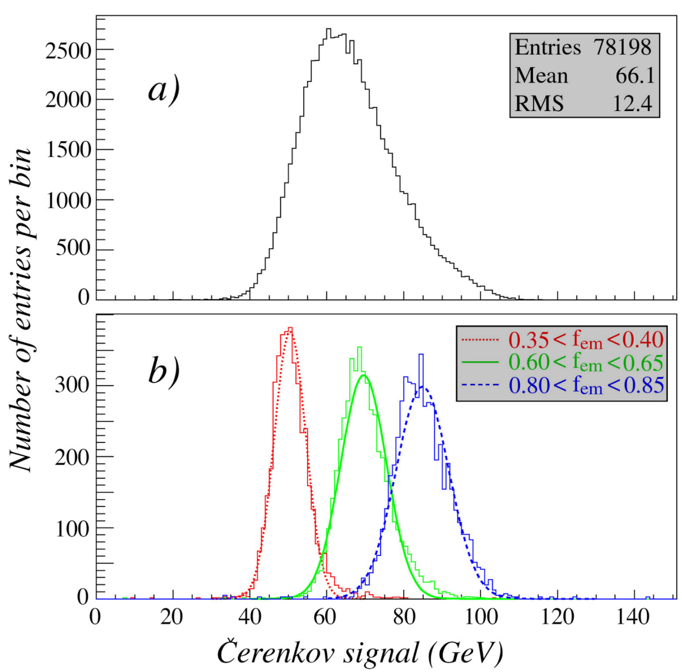
Dual readout - the principle

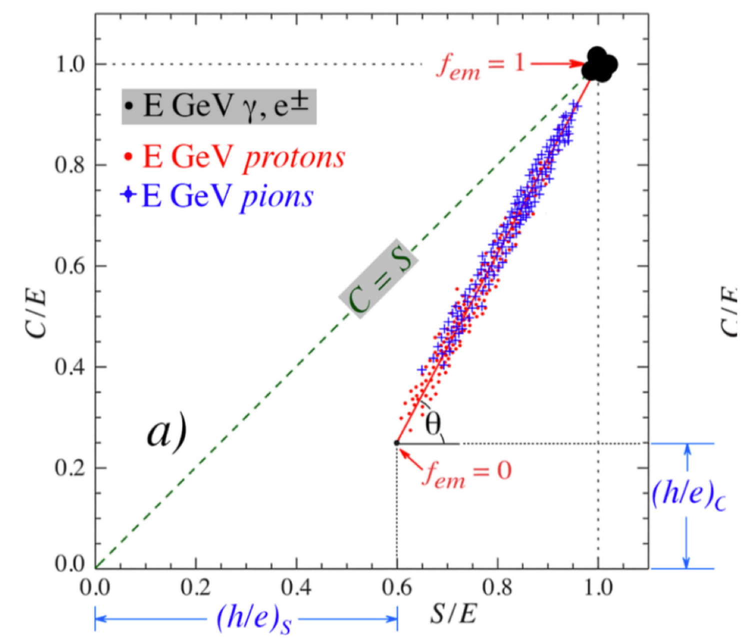
- Resolution of the **hadronic energy measurement** affected by fluctuations in the fraction of **energy carried by** $\pi^0 \rightarrow \gamma\gamma$ (f_{em}).
- **Two readouts with different e/h** allow the extraction of f_{em} and of the **incoming energy E**.
- For example: **spaghetti calorimeter** with alternating **doped (Scintillating) and clear (Cherenkov) fibres**.
- More details here.



$$E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right)$$

$$E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right)$$

Solve for f_{em} and E



[Iacopo Vivarelli]

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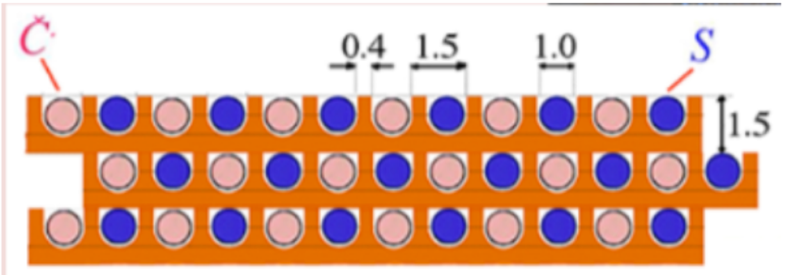
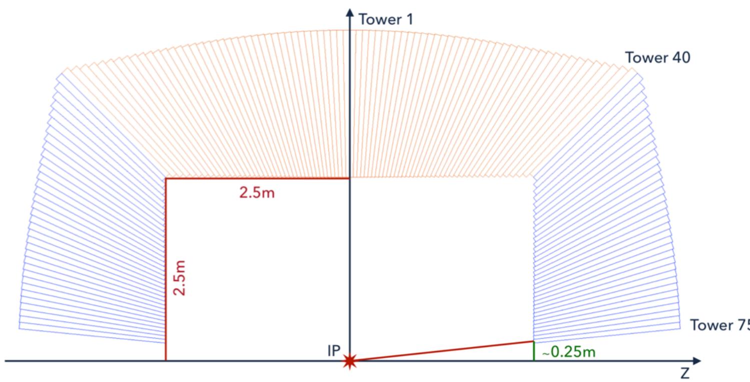
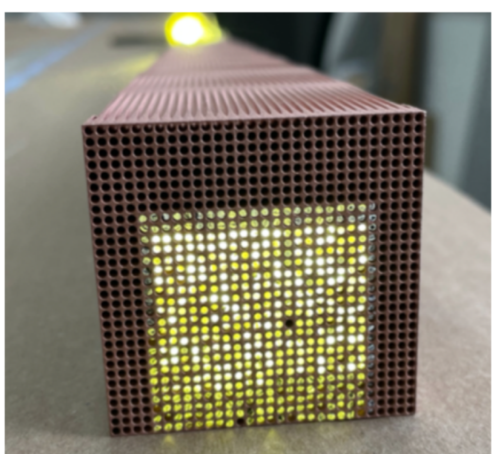
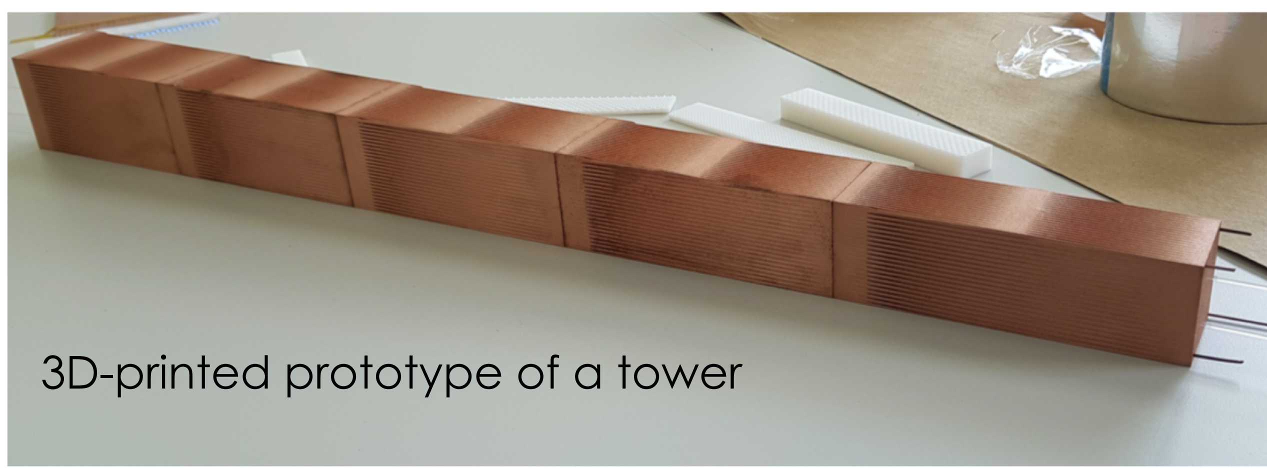
Dual Readout (fiber) calorimeter





- Embedded in **IDEA detector concept** (in FCC and CEPC CDRs)
  - Cu absorber, 1 mm fibers, 1.5 mm pitch, read by SiPM
  - Single device for EM and HAD calorimetry.
- Read out the single fibre: 130 M channels.
  - Ideal fibre grouping still to be determined.
  - Excellent angular resolution, lateral shower shape sensitivity.
  - However no longitudinal segmentation .





3D-printed prototype of a tower

[Iacopo Vivarelli]

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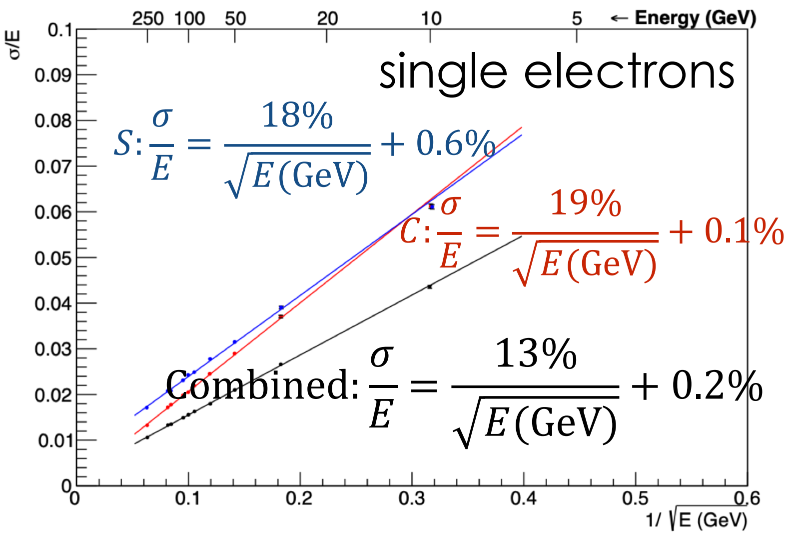
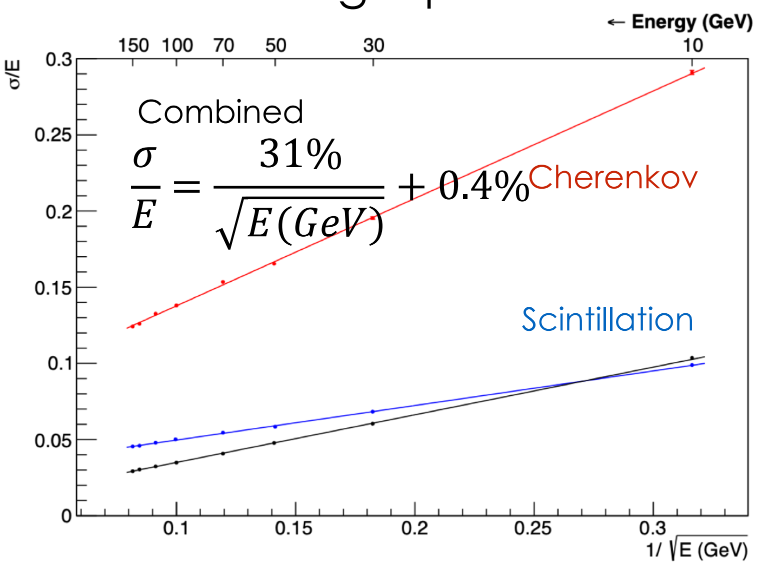
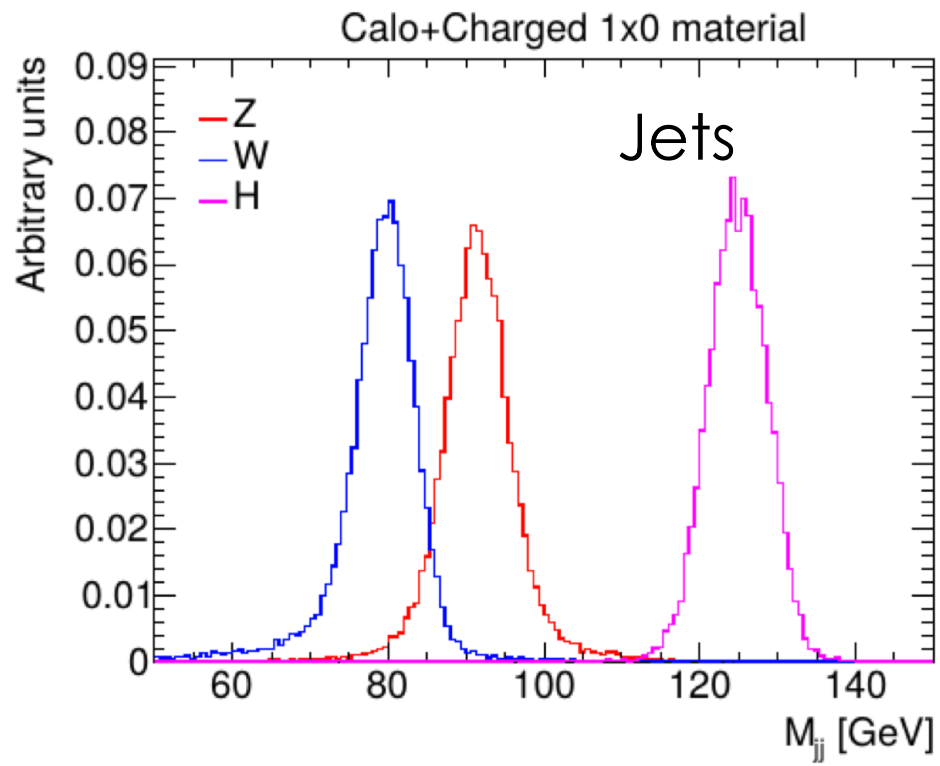
A glance at the performance



single pions

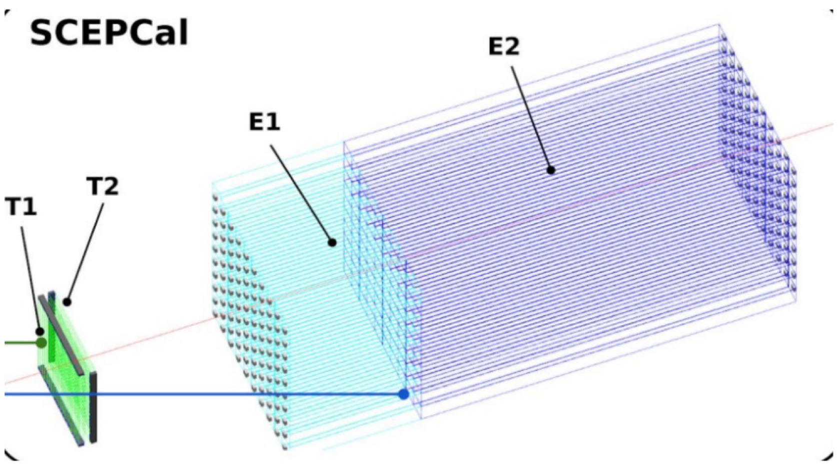


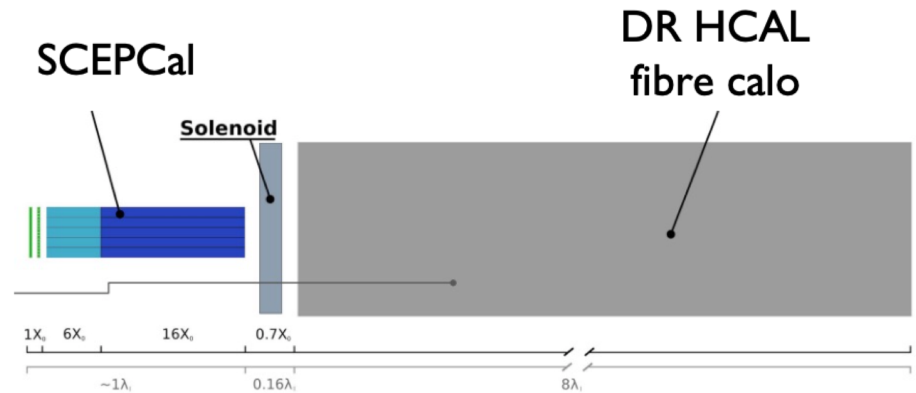


- Competitive energy resolution:
  - Universal response to hadrons
  - Very good pi/e separation and tau identification performance
- and also electronics all outside the calorimeter:
  - No need for cooling and services in the calorimeter volume

[Iacopo Vivarelli]

Under investigation: crystal-based EM layer





ECAL layers ← $\sigma^{EM}_{E}/E \sim 3\%/\sqrt{E}$

- PWO crystals
- Front segment (~6X_0)
- Rear segment (~16X_0)
- 10x10x200 mm³ crystal
- 5x5 mm² SiPMs (10-15 um)

other options are BGO/BSO

Majority of the energy deposit from hadron is in the rear ECAL section (E2) → apply DR here

Use two SiPMs to optimise independently C and S readout from each crystal

Sensitivity in both the UV and infrared regions with SiPM

[Iacopo Vivarelli]

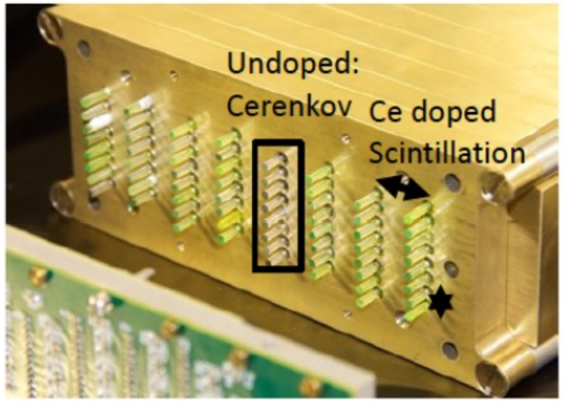
Items for R&D – Dual Readout

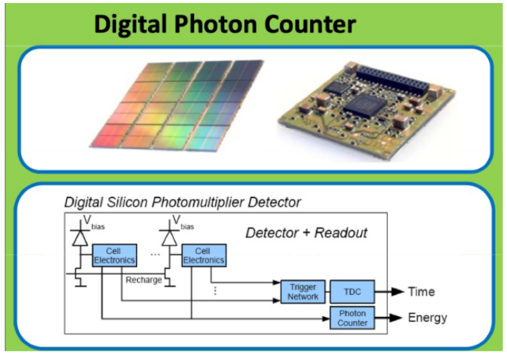
1. Cherenkov light is **never enough**:
   - crystal fibers (LuAG) can achieve 4x ph/GeV than PMMA currently in use.
   - Improved **SiPM response** in UV region for cheap desirable.
2. Integrated (digital) SiPM:
   - Simplified readout, improved trigger capabilities.
3. Scalable readout architecture

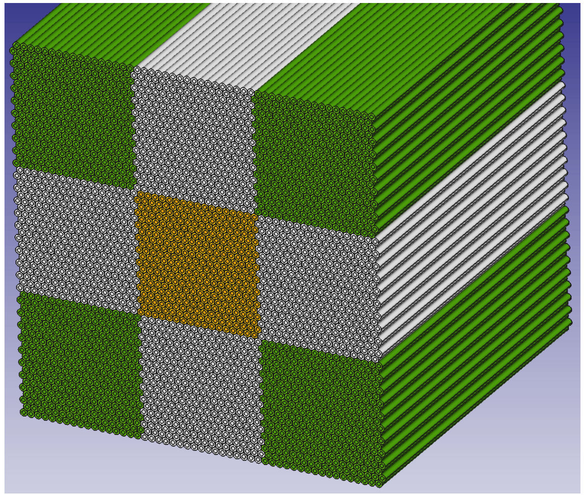
For more details see G. Gaudio's talk at TF6 ECFA

- Test beam(s) foreseen for **summer 2021** testing capillary tube, EM-size prototype.
- Active in the UK: Sussex with contributions on simulation and characterisation of the fibers + SiPM and TDAQ/Monitoring for TB.

- Funding:
  - Europe: AIDAinnova + (limited) national funds (mainly Italy, Croatia)
  - Korea: substantial grant aimed at delivering a hadronic scale prototype







Si-W Electromagnetic Calorimeter (Si-W ECAL)

Absorber: **Tungsten** sheets wrapped in carbon fiber

Detector: **Silicon PIN diodes 1x1cm²** (Comparable to R_M:0.9 cm)

Si allows high granularity & compactness

Length: 30 layers~ $24X_0$ ~ $1\lambda_I$

3 "stacks", 10 modules each

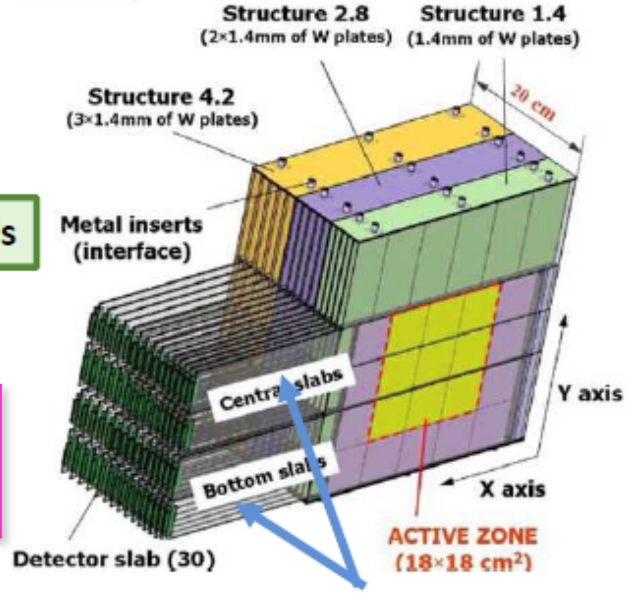
Different absorber thickness

- 1.4 mm (0.4 X_0)
- 2.8 mm (0.8 X_0)
- 4.2 mm (1.2 X_0)

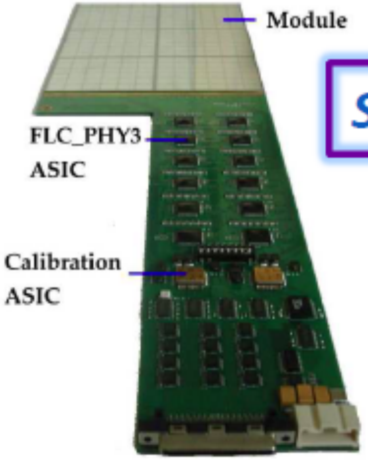
9720 channels

2005 - ECAL Physics prototype

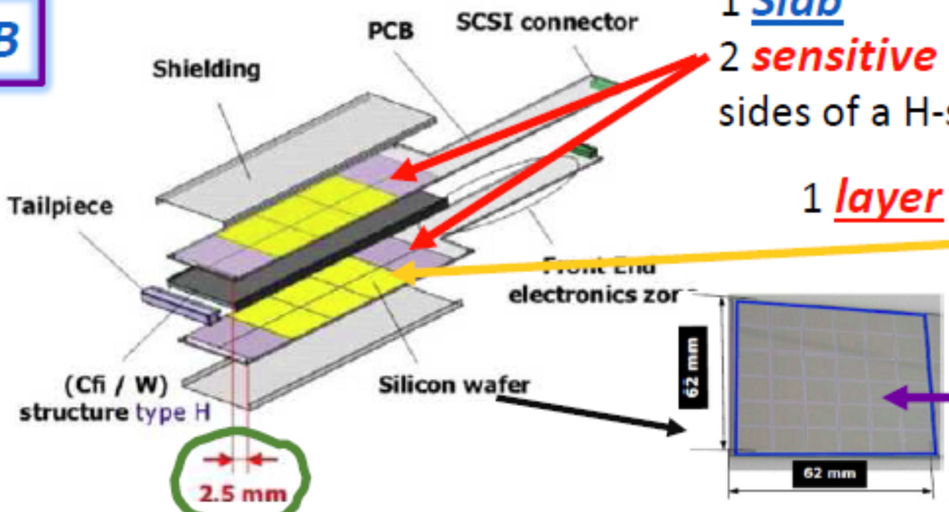
Lateral size: 18x18cm²



1 sensor plane= 2 detector *slabs*



SLAB



1 *Slab*

2 *sensitive layers* mounted on the two sides of a H-shaped W supporting structure

1 *layer* = 6 (3) *Si wafers* (525µm thick)

1 *wafer*= 6x6 *pads* 1x1cm²

Offset to reduce dead areas (+ 1.3 mm offset between successive slabs)

Si-W Electromagnetic Calorimeter (Si-W ECAL)

Calorimeter for ILC

Absorber: **Tungsten** sheets

Detector: **Silicon PIN diod**

Si allows high granularity

> ~15 years later → CMS HGCAL
> Message: need ongoing R&D funding - non-project specific

Length: 30 layers~ $24X_0$ ~ $1\lambda_I$

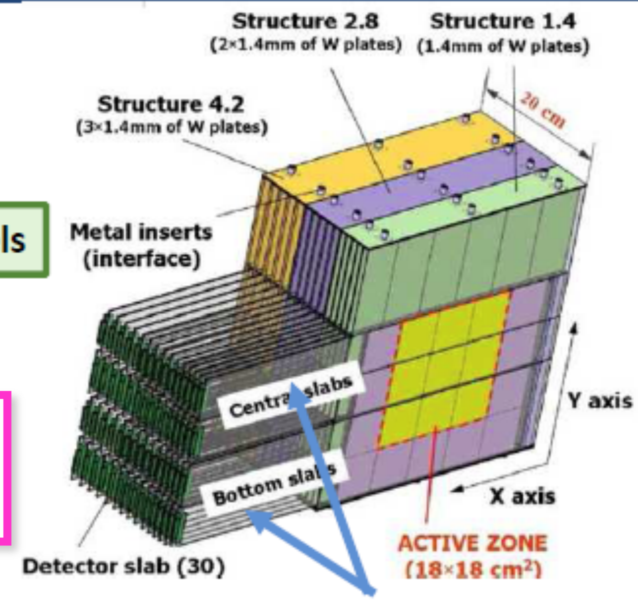
3 "stacks", 10 modules each

Different absorber thickness

- 1.4 mm ($0.4\ X_0$)
- 2.8 mm ($0.8\ X_0$)
- 4.2 mm ($1.2\ X_0$)

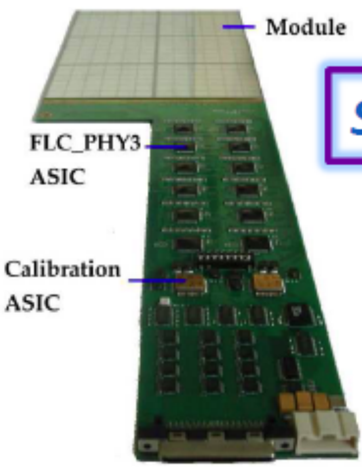
> 2005 - ECAL Physics prototype

9720 channels

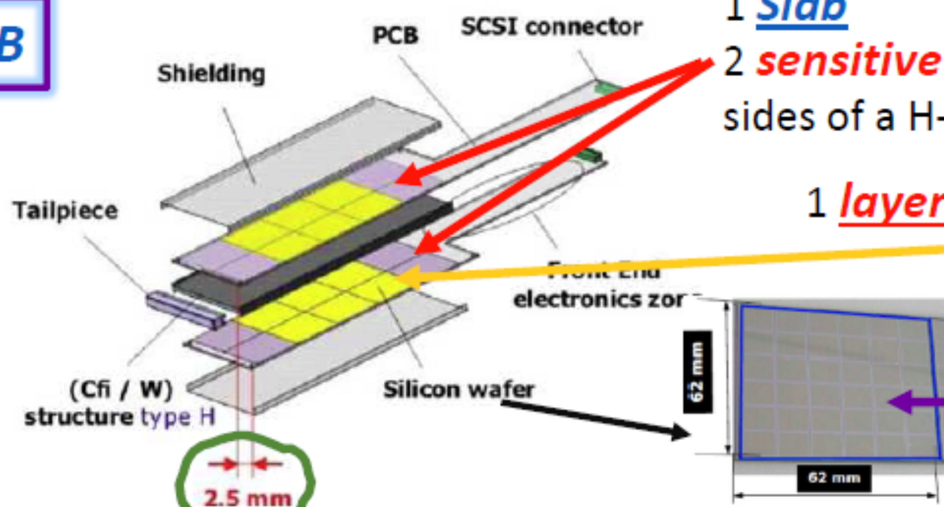


Lateral size: $18\text{x}18\text{cm}^2$

1 sensor plane= 2 detector ***slabs***



SLAB



1 ***Slab***

2 ***sensitive layers*** mounted on the two sides of a H-shaped W supporting structure

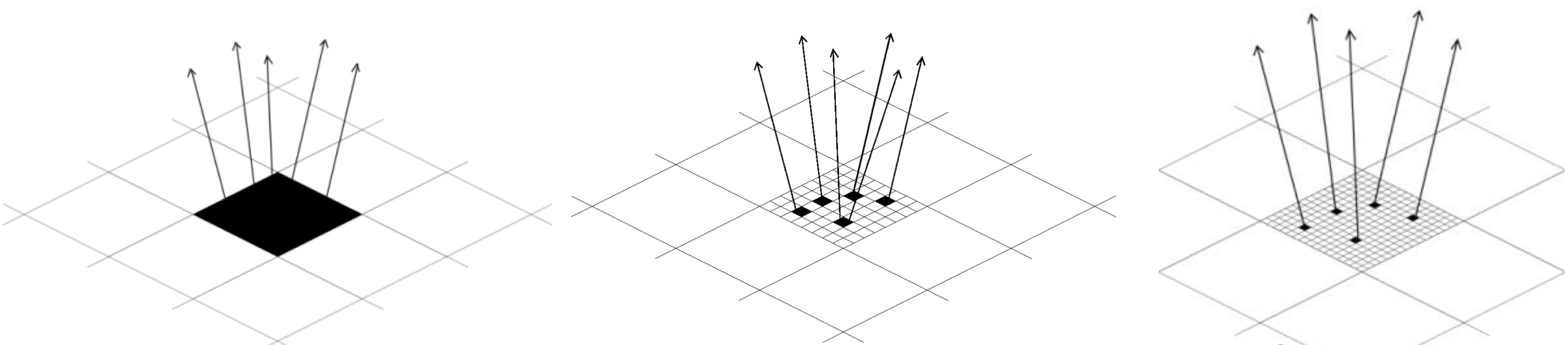
1 ***layer*** = 6 (3) ***Si wafers*** (525µm thick)

1 ***wafer***= 6x6 ***pads*** $1\text{x}1\text{cm}^2$

Offset to reduce dead areas (+ 1.3 mm offset between successive slabs)

DECAL Concept – cost /performance for SiW ECAL

- Swap ~0.5x0.5 cm^2 Si pads with small pixels
  - at most one particle/pixel,1-bit ADC/pixel - digital
- How small to avoid saturation/non-linearity?
  - EM shower core density at 500GeV ~100/mm^2
  - Pixels must be <100x100μm^2
    - Used baseline 50x50μm^2
    - Gives ~10^{12} pixels for ECAL
- Simpler construction (no bump bonding)
- DECAL prototypes to date 180 nm process → 65nm
- Performance gains? Tracking highly boosted decays, e.g. τ, …



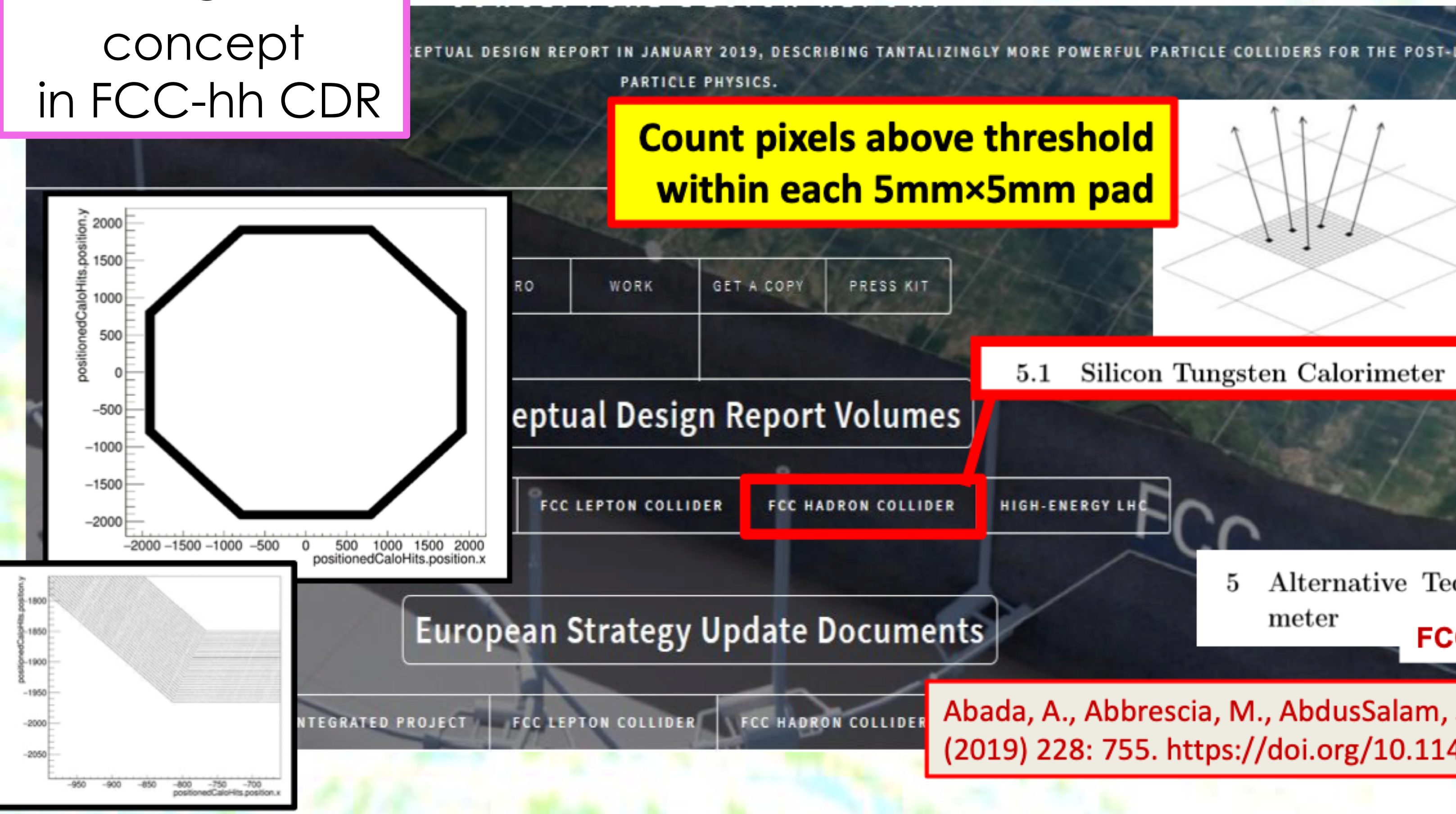
AECAL   DECAL $N_{pixels}<N_{particles}$ DECAL $N_{pixels}=N_{particles}$

The Digital EM Calorimeter Concept

Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

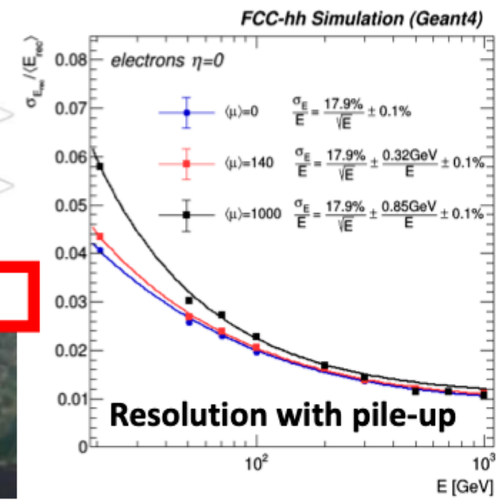
UNIVERSITY OF BIRMINGHAM

DECAL concept in FCC-hh CDR



Count pixels above threshold within each 5mm×5mm pad

5.1 Silicon Tungsten Calorimeter



5 Alternative Technology for the EM Barrel Calorimeter

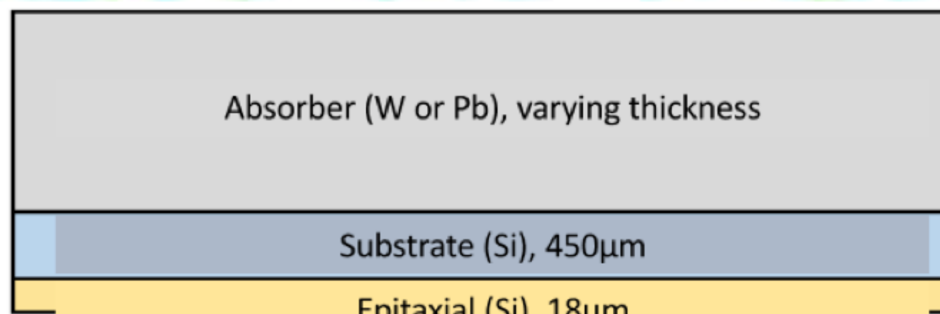
FCC Week (1/6/17) T. Price

Abada, A., Abbrescia, M., AbdusSalam, S.S. et al. Eur. Phys. J. Spec. Top. (2019) 228: 755. https://doi.org/10.1140/epjst/e2019-900087-0

Idea initially in context of CALICE but then adapted to FCC-hh environment.

Simulated 4 different geometries:

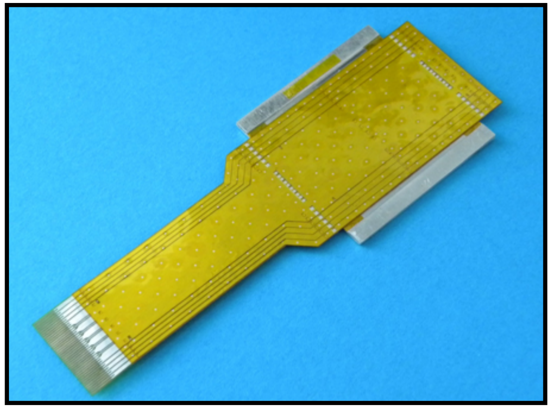
- **30 Layers, 3.5mm W (30 × 1.0 X_0)**
- **5.6mm Pb**
- **50 Layers, 2.1mm W (50 × 0.6 X_0)**
- **3.4mm Pb**

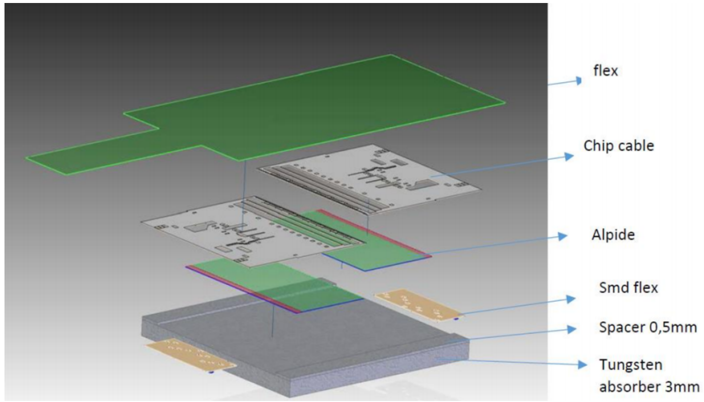


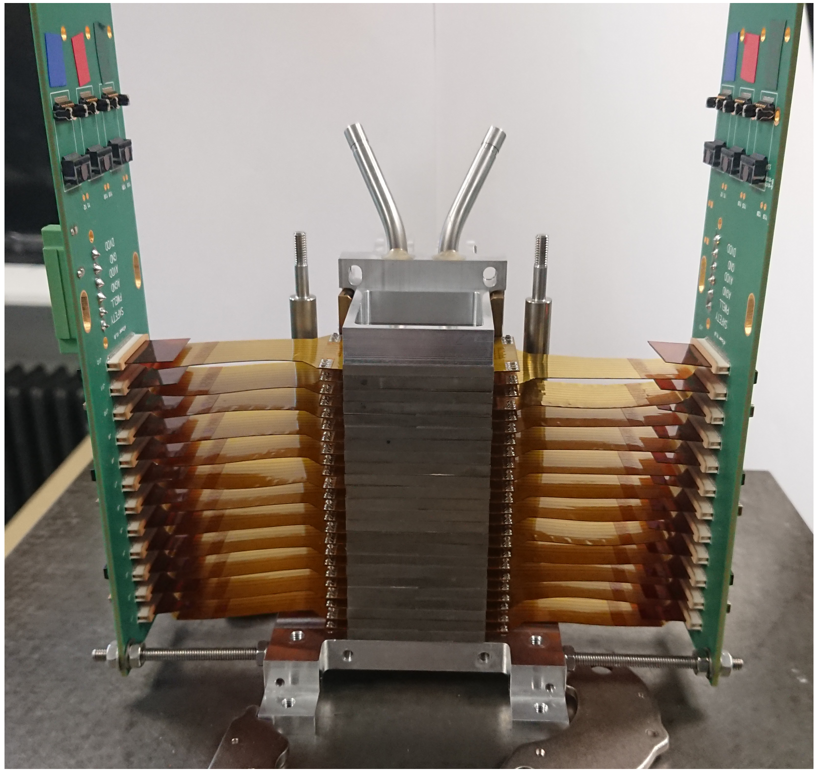
[c/o Phil Allport]

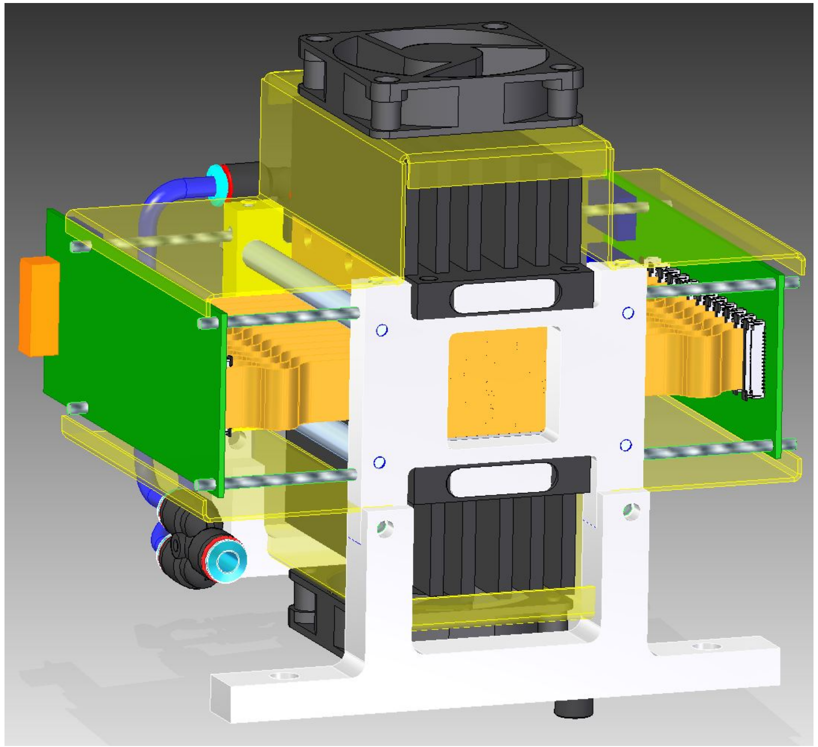
EPICAL-2
(Electromagnetic PIxel CALorimeter prototype-2)

- **New digital pixel calorimeter prototype**
  - small digital calorimeter (3x3 cm^2 cross section)
  - 24 layers with each
    - 2 ALPIDE CMOS MAPS
    - 3 mm W absorber
- **<u>Project goal:</u>**
  - prove that the ALPIDE is suitable for a calorimeter
  - demonstrate suitability of ALPIDE as solution for FoCal high-granularity layers
    - two-shower separation under high particle density environment



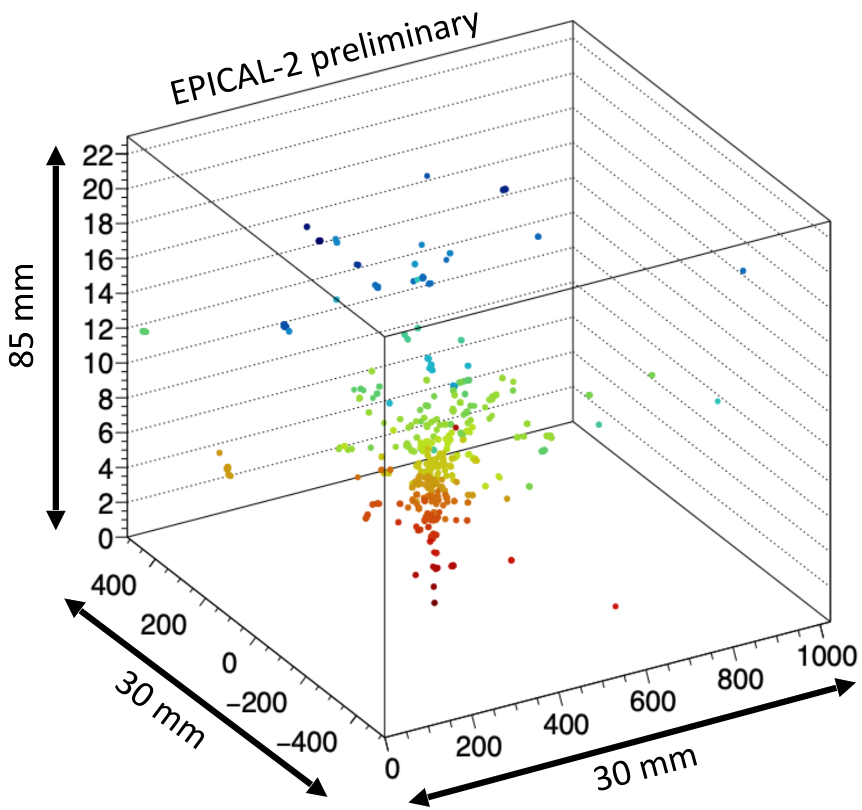




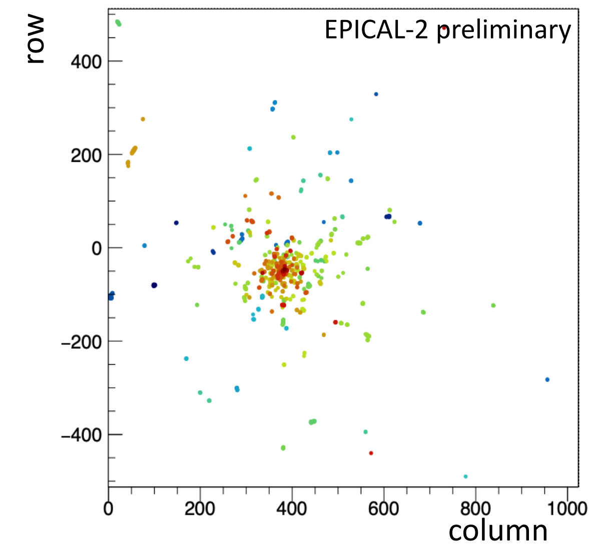


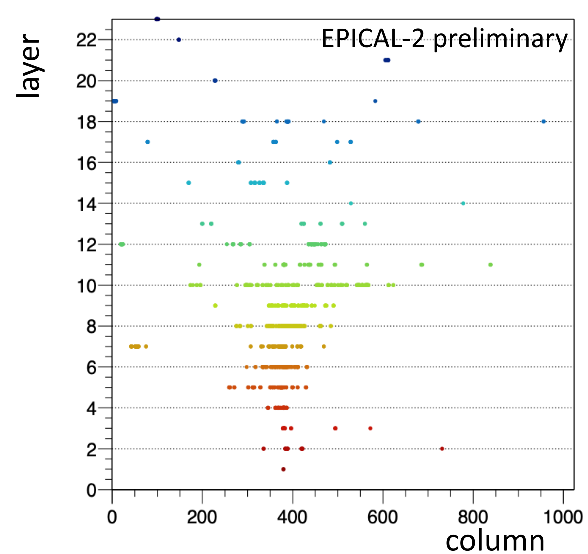
R&D for the ALICE-FoCal detector proposal
Current work performed in the context of the Bergen pCT collaboration

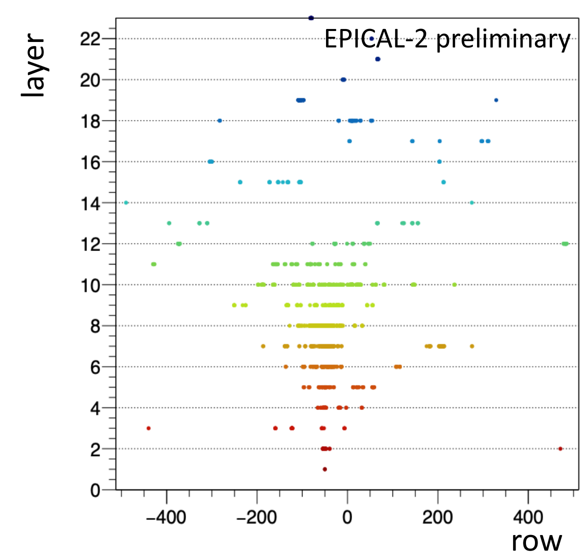
Event Display



one-electron event
5 GeV
raw data







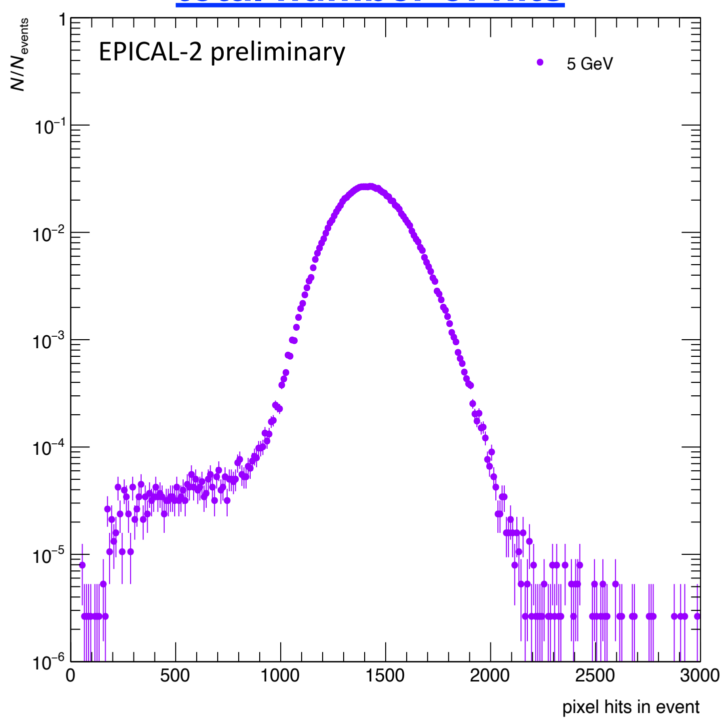
→ detailed evolution of shower

color coding: layers

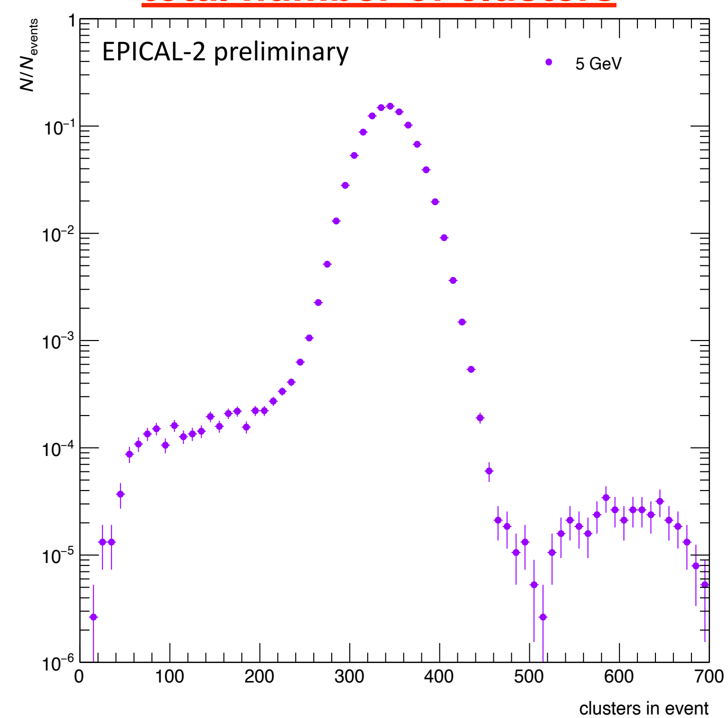
Energy Measurement

- ☑ **Total number of hits (clusters) per event**
  - Gaussian shape with small asymmetry
  - smaller width for clusters
  - residual pileup at higher energy side
  - low-energy contamination of beam
- ☑ current study uses numerical mean and standard deviation

total number of hits

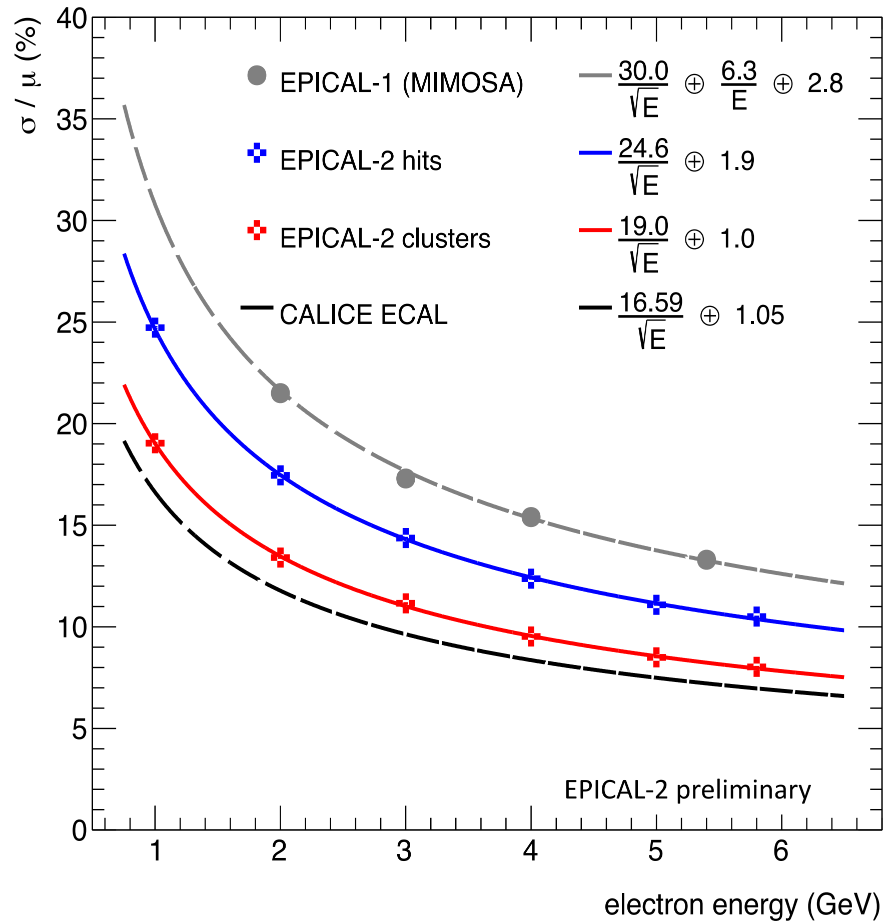


total number of clusters



Energy Resolution

- standard deviation (σ) / mean (μ)
  - better than EPICAL-1 (MIMOSA)
    JINST 13 (2018) P01014
  - close to analog SiW ECAL (CALICE) physics prototype
    NIM A608 (2009) 372
  - **better performance for clusters compared to hits**
    - large cluster-size fluctuation
    - vertically directed tracks creating large cluster
    - calibration can be improved



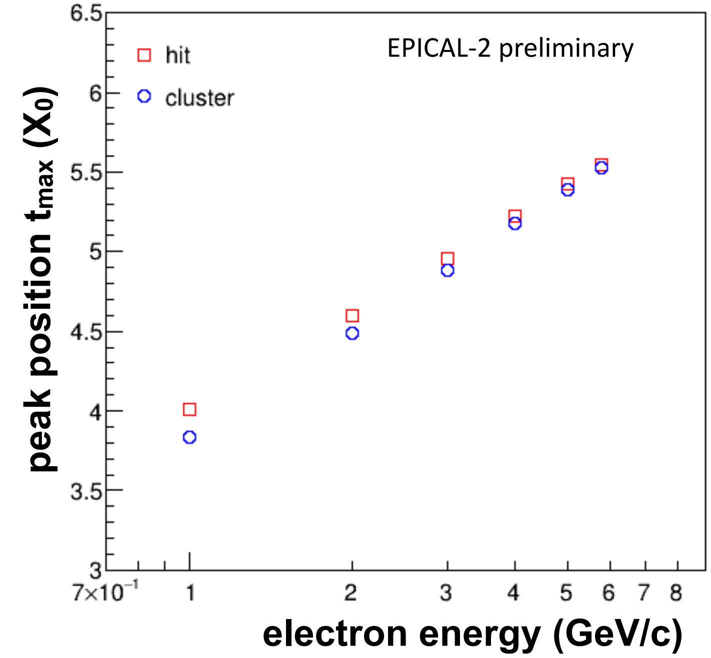
→ energy resolution superior compared to previous prototype

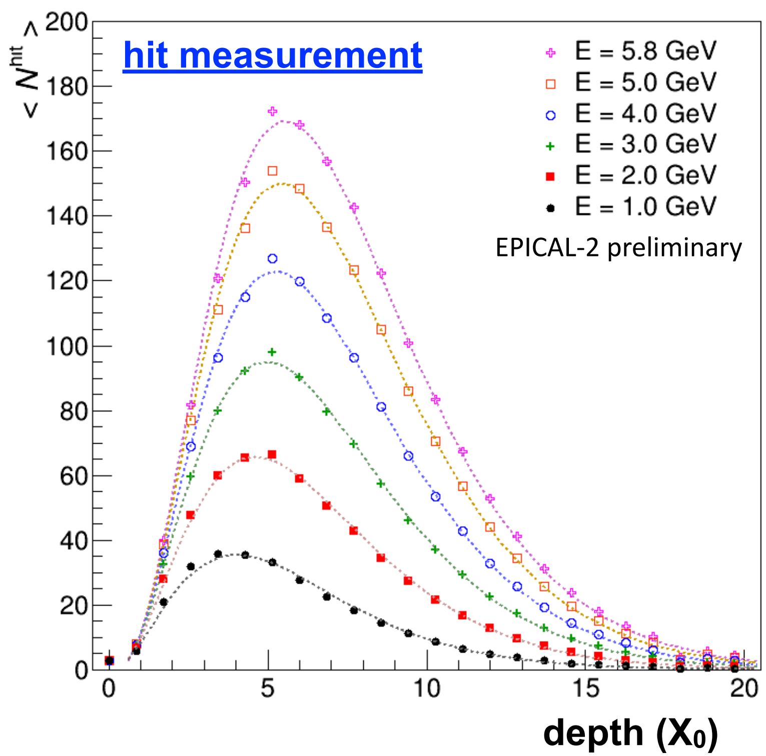
Longitudinal Energy Profile

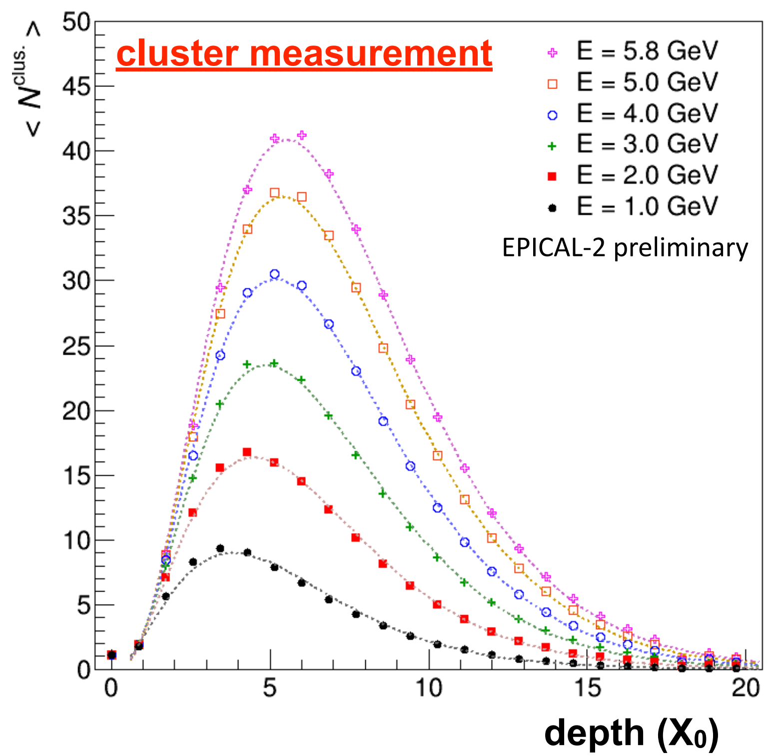
- ☑ <u>**reasonable description by gamma distribution**</u>
- ☑ peak position(t_{max}) proportional to log(E)
  - $t_{max}^{Hit} > t_{max}^{Cluster}$?
  - more accurate calibration for the conclusion

work in progress

→ **first step in detailed shower shape analyses**

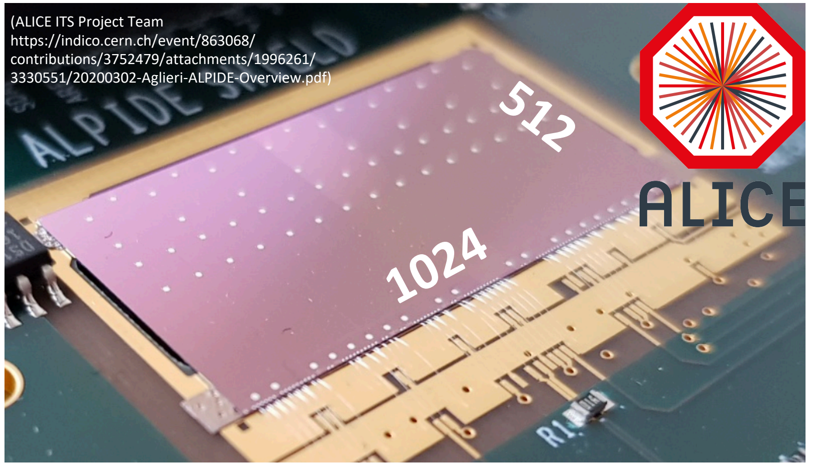


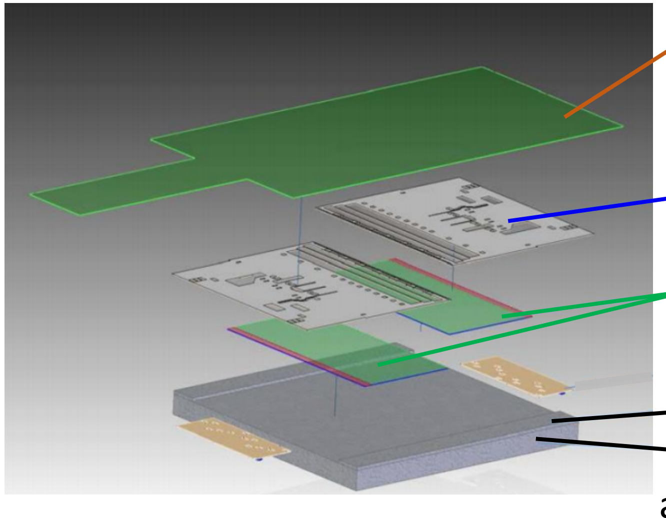


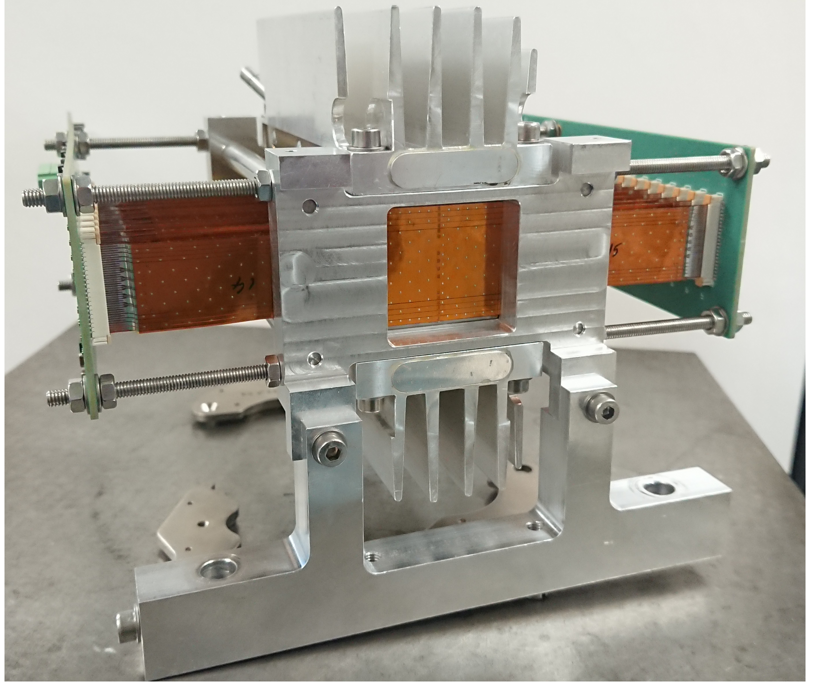


Electromagnetic Pixel Calorimeter 2 (EPICAL-2)

- **second prototype:**
  → related to Bergen pCT Collaboration
  → in context of R&D for planned LHC-ALICE FoCal upgrade in ~2026
  → **fully digital calorimeter** prototype
- **24 layers** with **two ALPIDE chips each**
  → chip size: 30 mm x 15 mm
- **512 x 1024 pixels per chip**
  → pixel size: 26.88 μm x 29.24 μm







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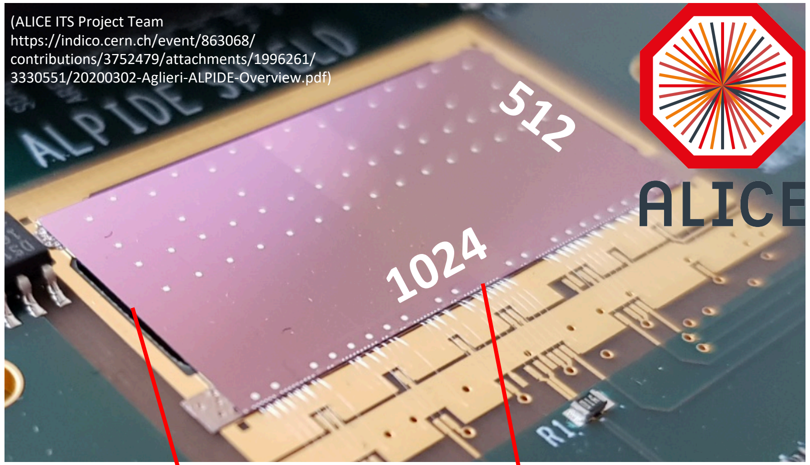
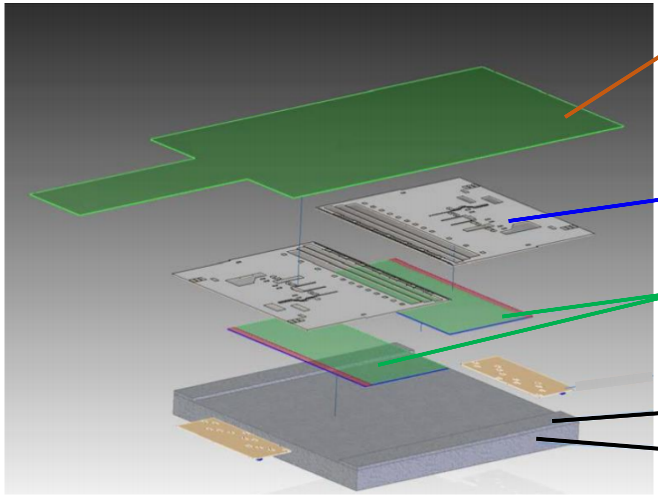
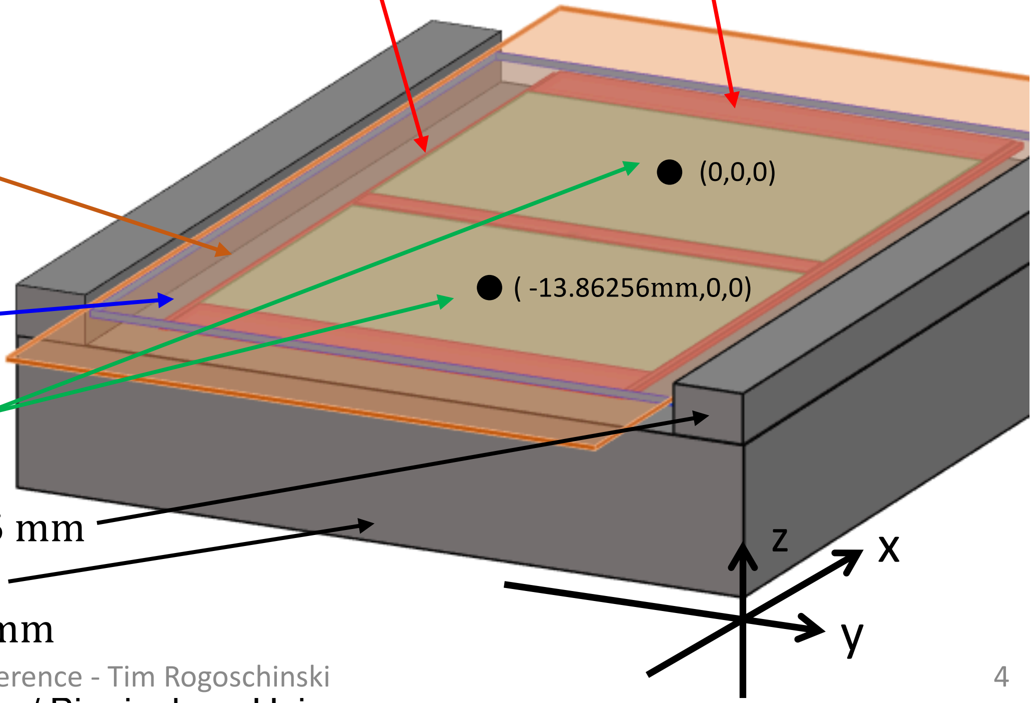
  → **precise geometry implementation**







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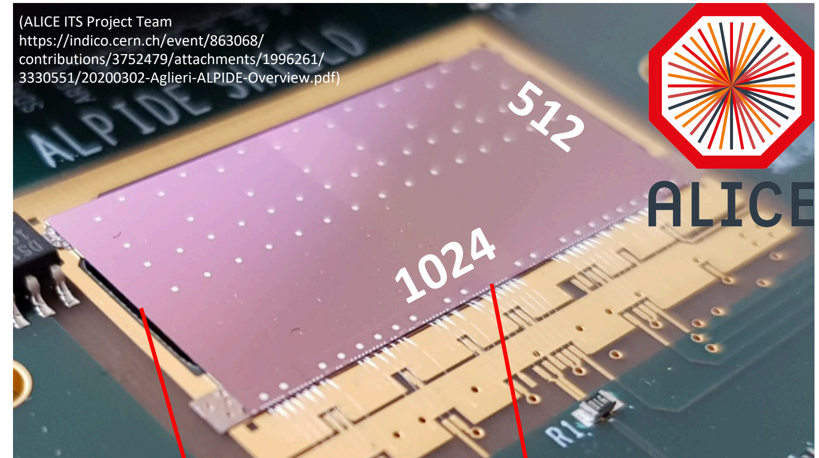
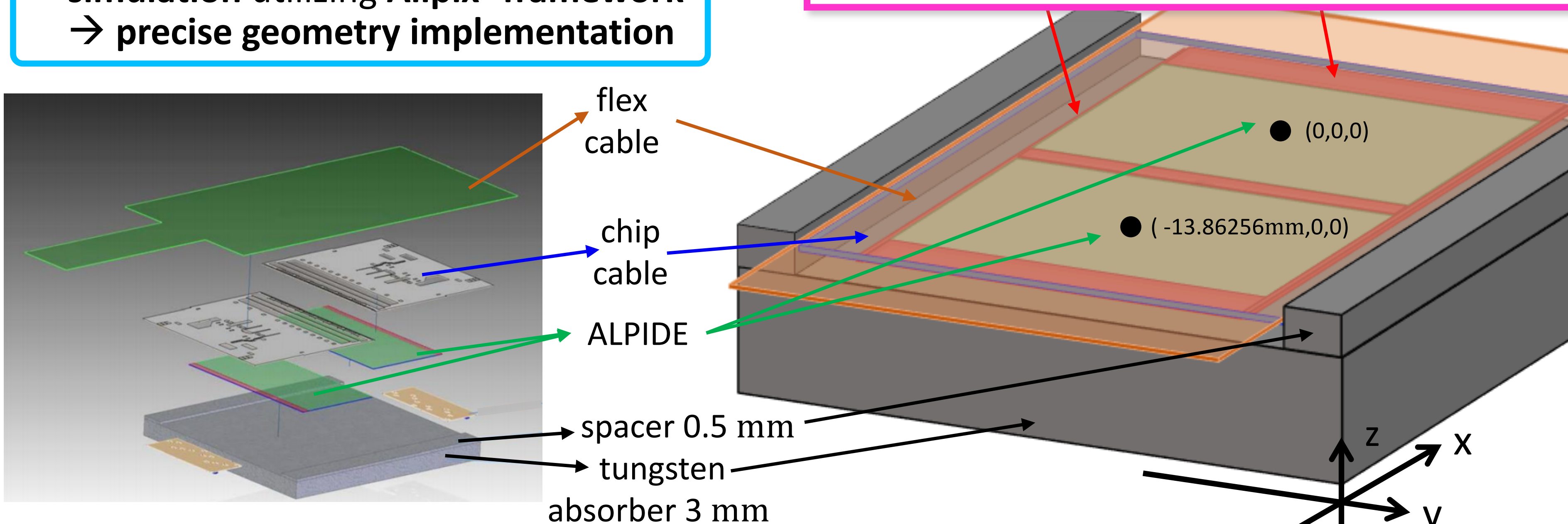
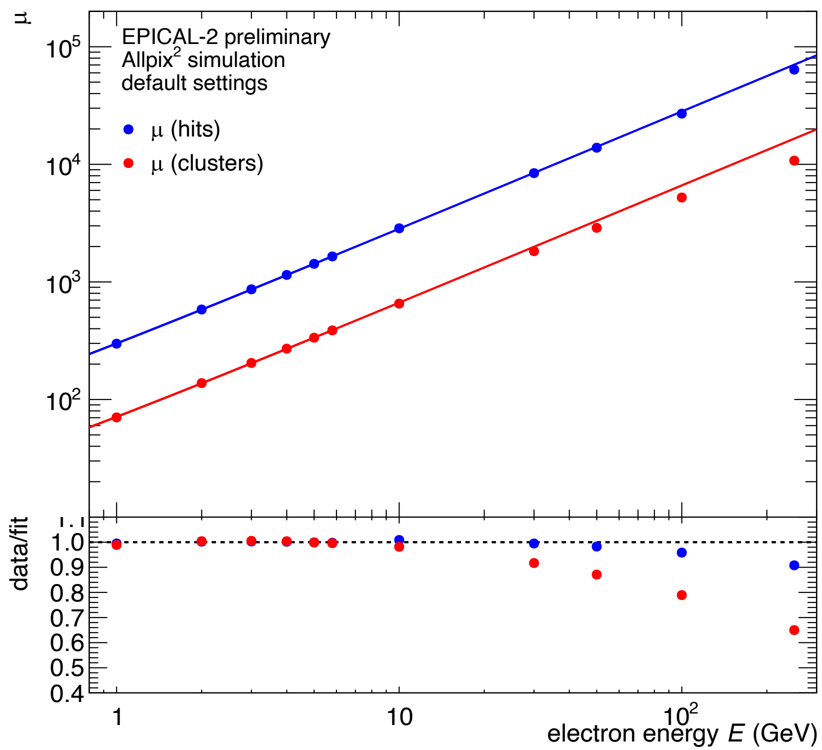


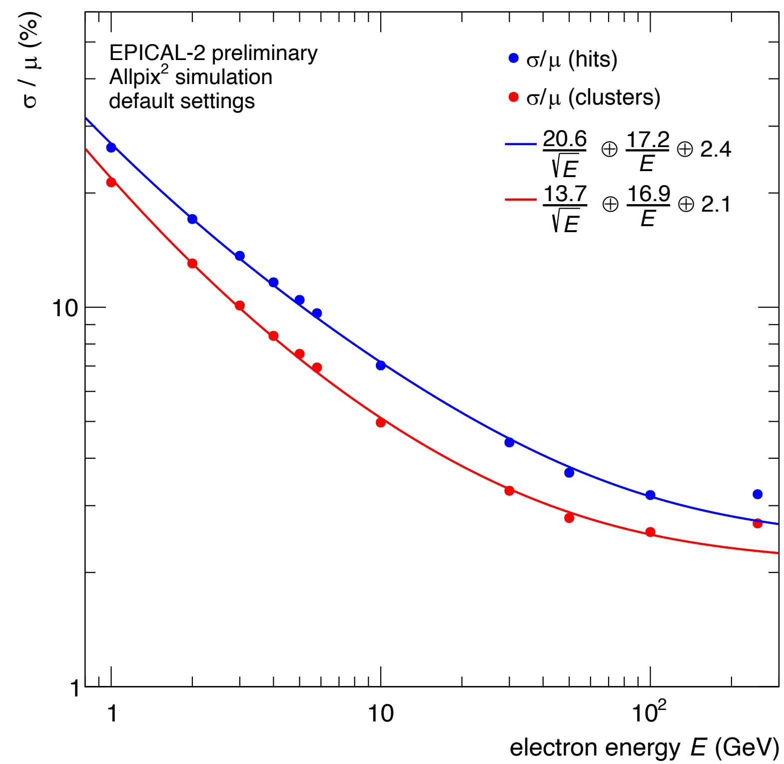
Derived from earlier UK student work



First look at higher energies

energy response and energy resolution





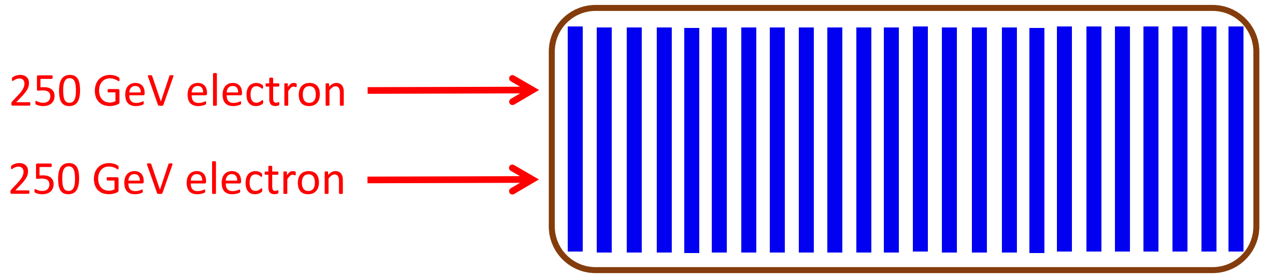
- **low energies: agreement** with **linearity** for hits and clusters,
  promising energy resolution
- **high energies: deviation** from **linearity** up to ~**10% for hits** and ~**35% for clusters,**
  worsening of apparent energy resolution
- resolution and linearity both affected by **leakage** for 20 X_0 detector, easy to overcome
- expect additional contribution from **cluster overlap**, possible corrections to be investigated
- note: ALPIDE sensor optimized for tracking
  → development of MAPS sensor with calorimeter-specific requirements could improve performance

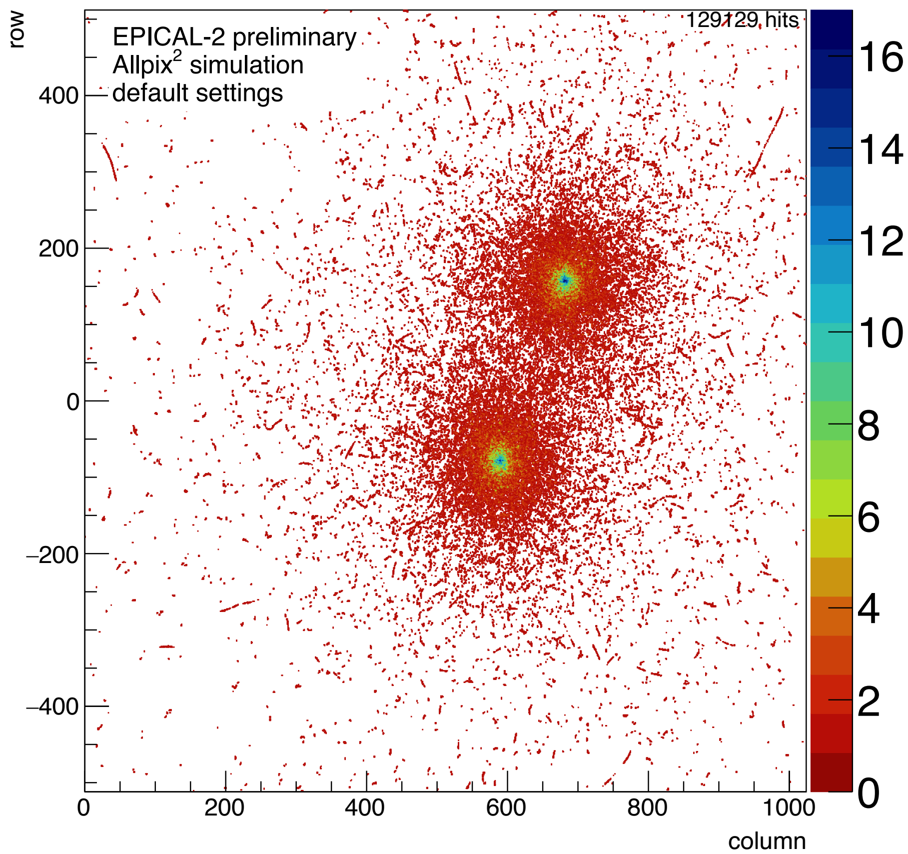
work in progress!

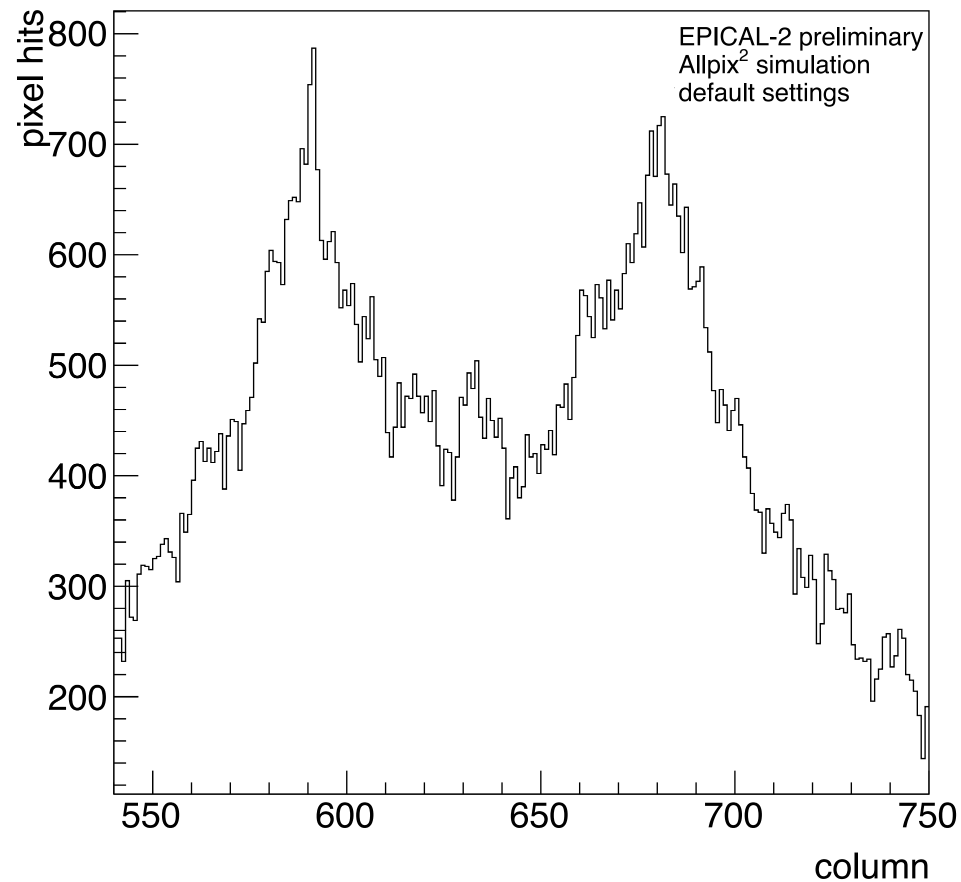
First look at higher energies

separation power

- same energy
- electrons separated by ~ 7.2 mm







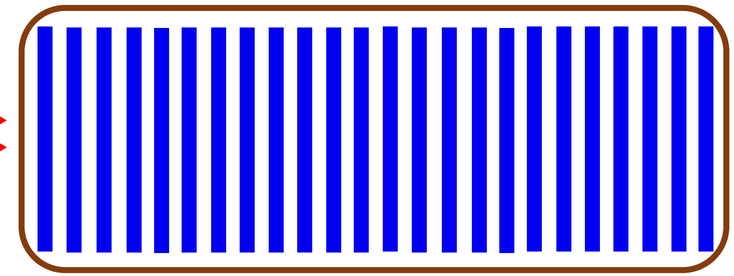
First look at higher energies

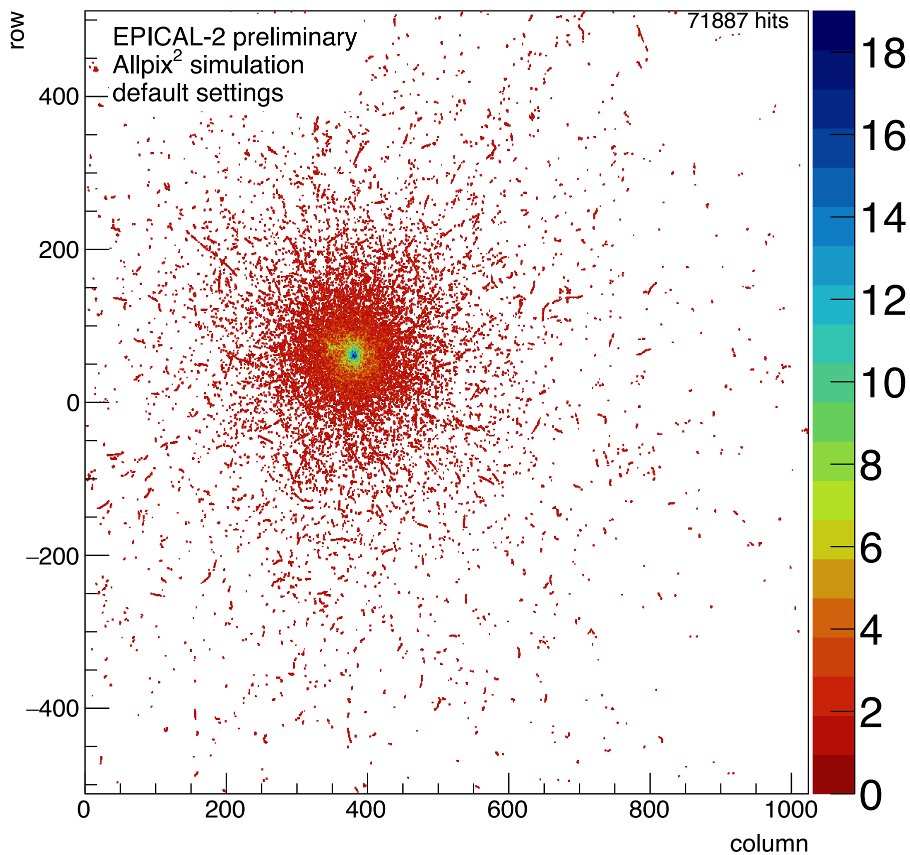
separation power

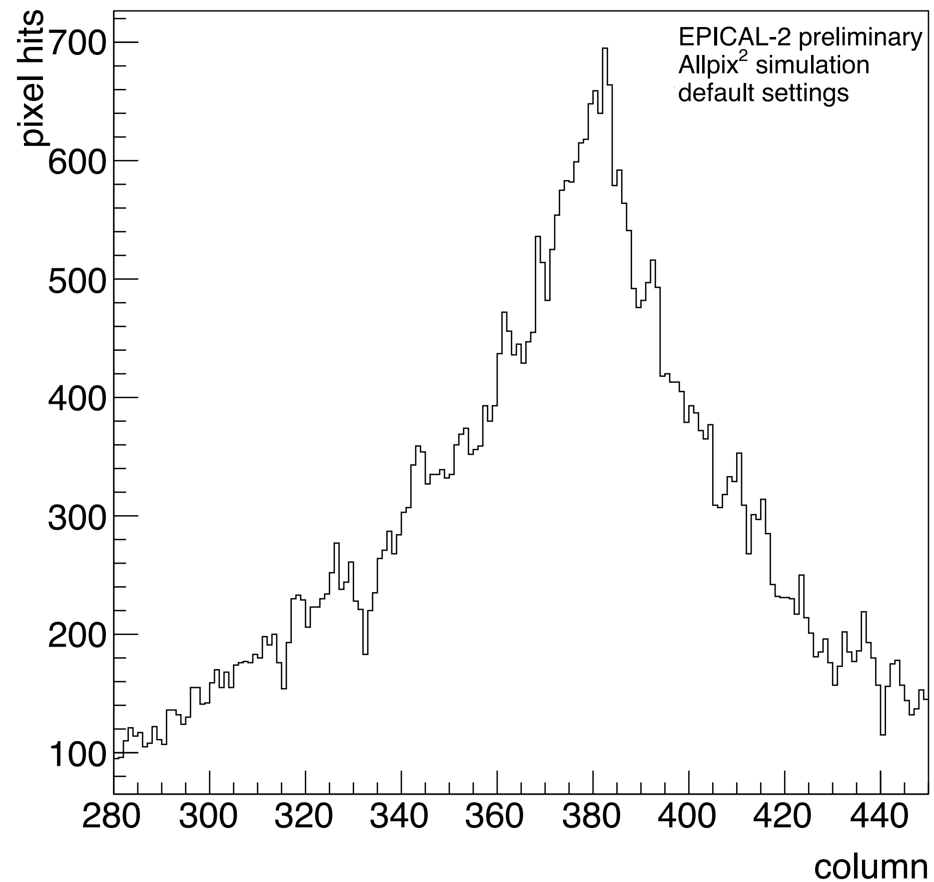
- large energy difference
- electrons close together

→ **challenging case**

250 GeV electron
30 GeV electron







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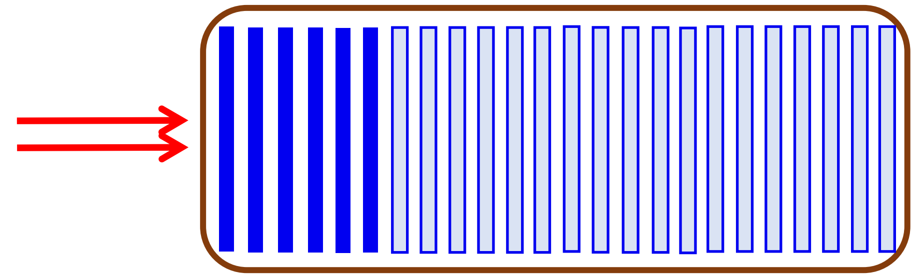
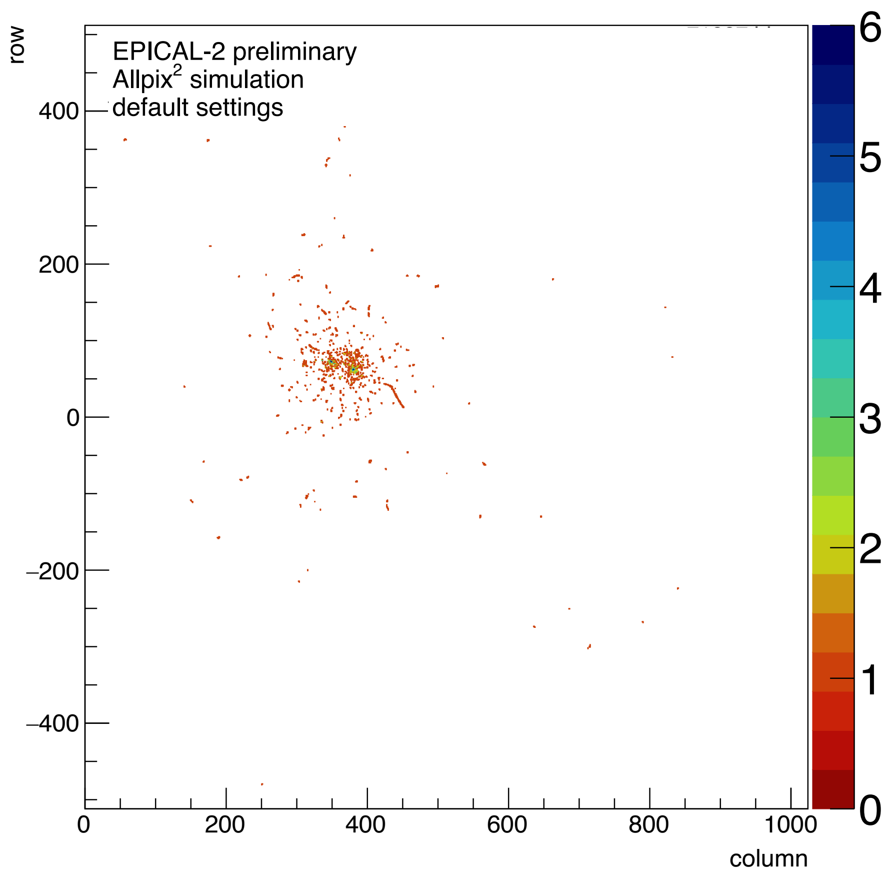
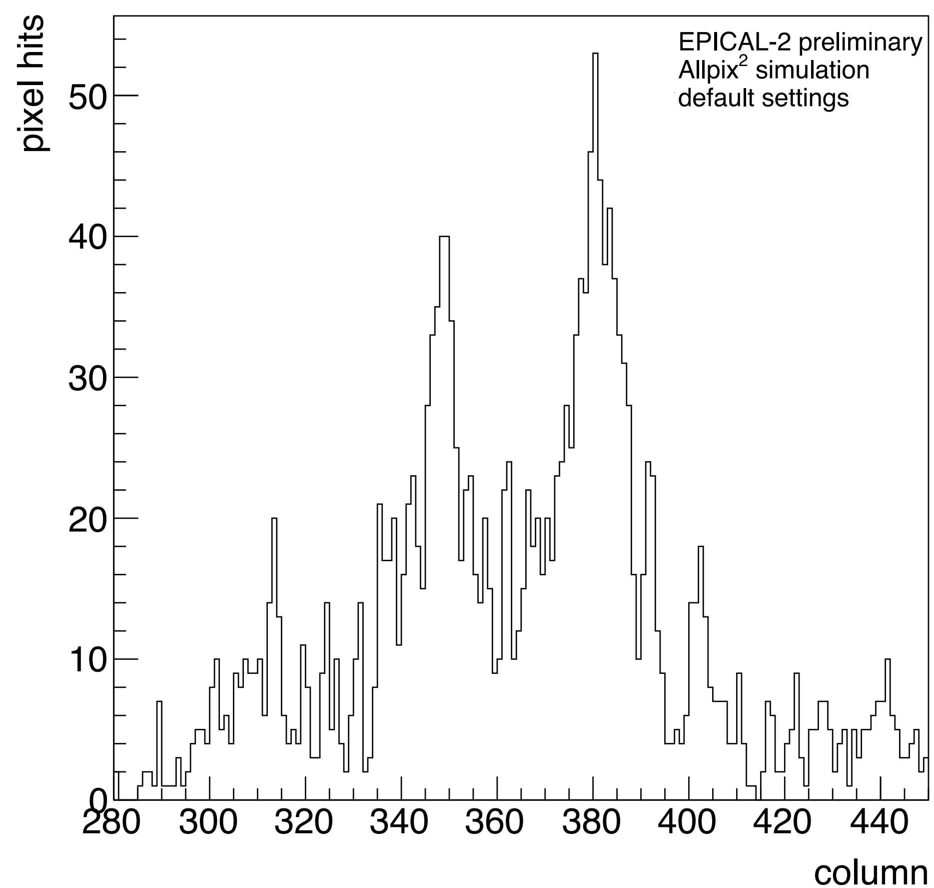
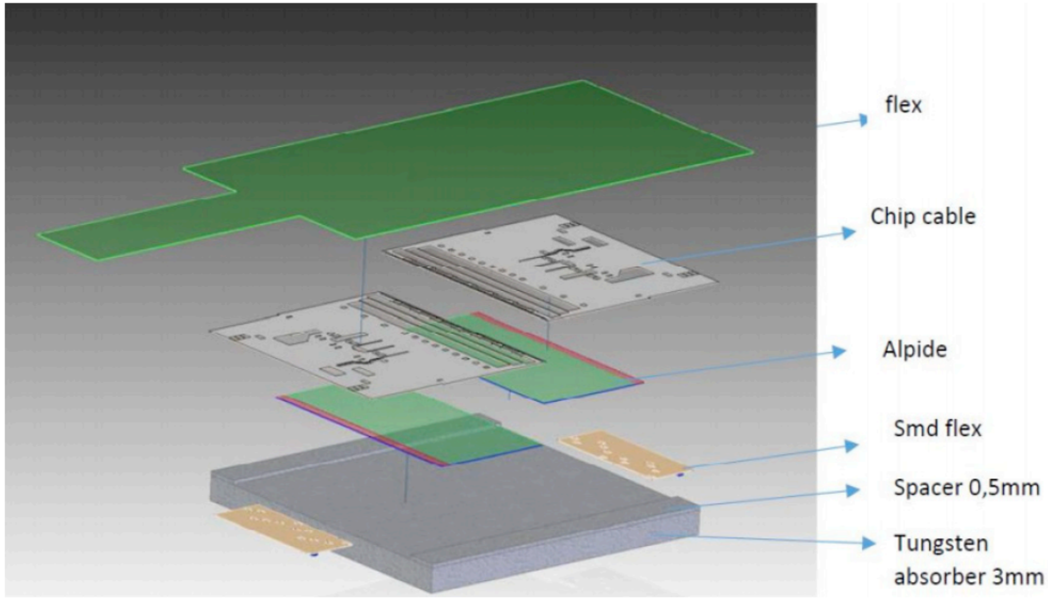
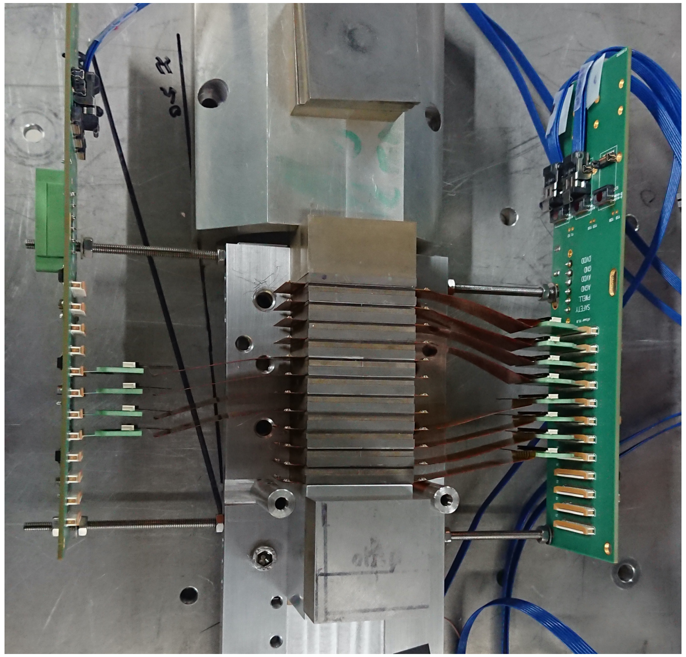






Future Opportunities (DECAL)





- EpiCAL-2 prototype
- Demonstrates high level integration possible
- Using 'off the shelf' tracking sensor
- Further optimise with new processes and sensor designed with calorimetry/reconfigurability
- See e.g. Snowmass submission

SNOWMASS21-IF6_IF0-067

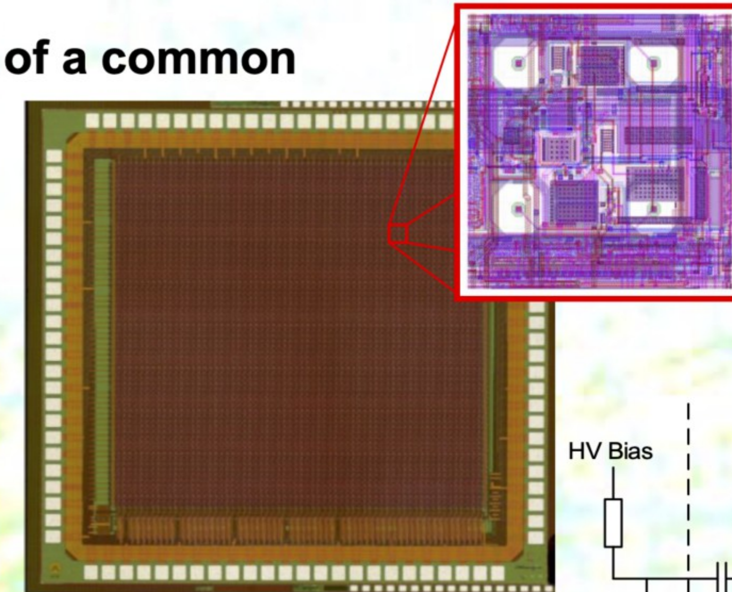
DECAL (4mm×4mm Array) Prototype Chip

Concept in FCC-hh context of a common silicon development for:

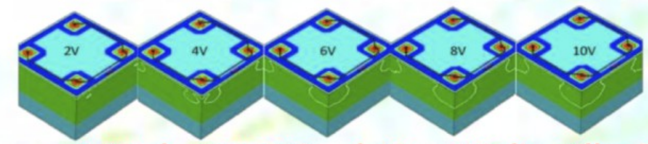
- **Outer tracking**
- **Pre-shower**
- **EM calorimeter**

Reconfigurable sensor as:

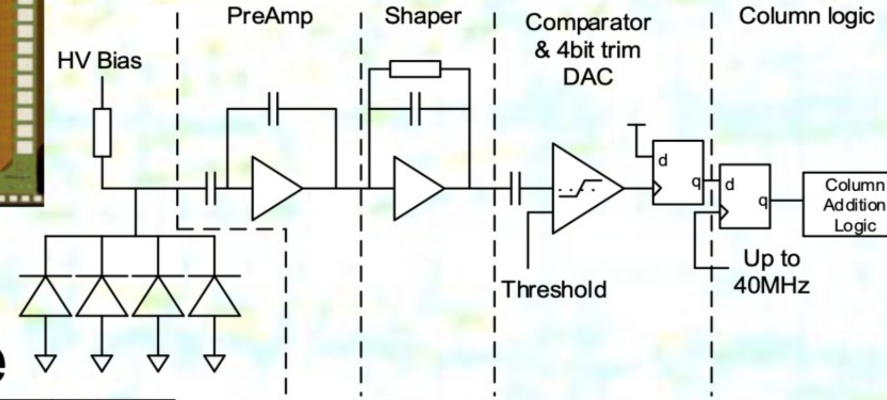
- **5mm×50µm strips**
- **5mm×5mm pad**



Prototype as proof of concept (180nm CMOS*)

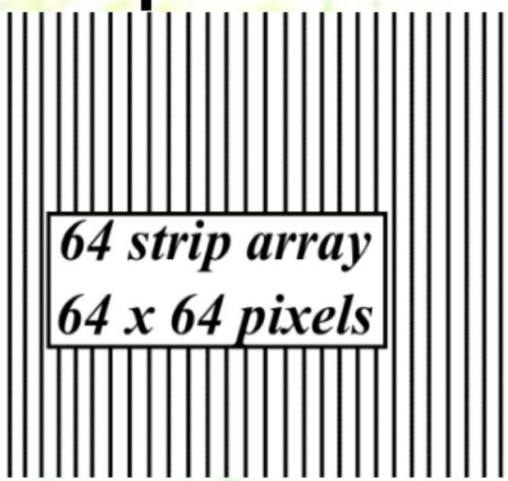


4 Diode TCAD Simulation: Giulio Villani



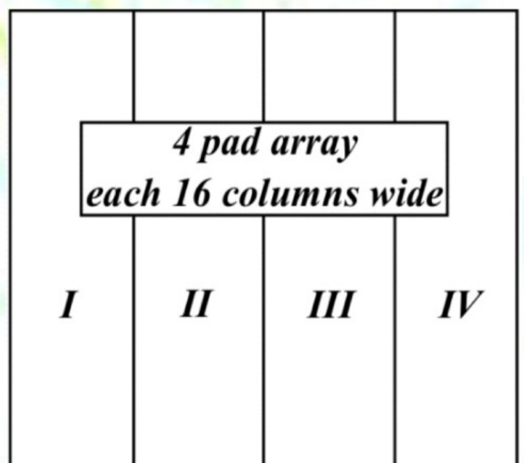
TWEPP (4/9/19) S.Benhammadi

Strip mode



Information on up to 3 hits per column gives data rate 5.12Gb/s

Pad mode



Information on up to 15 hits per column giving 240 hits per pad gives data rate of 2.56Gb/s

Specification	*Unit*	*Value*
Pixel Pitch	um	55
Resolution	pix	64 x 64
Frame Rate	MHz	40
Input Referred Noise	e- rms	80
Max hits/col (pad mode)	hits	15
Max hits/col (strip mode)	hits	3

***TowerJazz (Small collecting node)**

Future Opportunities for UK - SiW

- **Si-W calorimetry can give excellent PFA performance**
  - Potential to use same technology for outer tracker/preshower/ECAL
- Affordable Si-W (Si-Pb) calorimeters, need sensor costs ~ CHF/cm^2 (active areas > $10^7 cm^2$)
  - Potentially achievable with CMOS MAPS technologies - large, expanding commercial market
- Power needs study, CMOS estimates range ~50-100mW/cm^2 (no pulsing)
- Prototype demonstrating concept of digital ECAL, in same CMOS line as CERN et al, can deliver radiation hardness to > 10^{15}neq/cm^2
- **Digital EM calorimetry, high potential for future e^+e^- facilities**
  - Very fast charge collection, potential for triggering
  - Ultra-high granularity can benefit physics as well as cost (boosted decays)
  - Currently, UK (Birmingham) working with ALICE FoCAL/pCT groups on EpiCAL-2
  - Perfect time to lead this novel concept for future projects

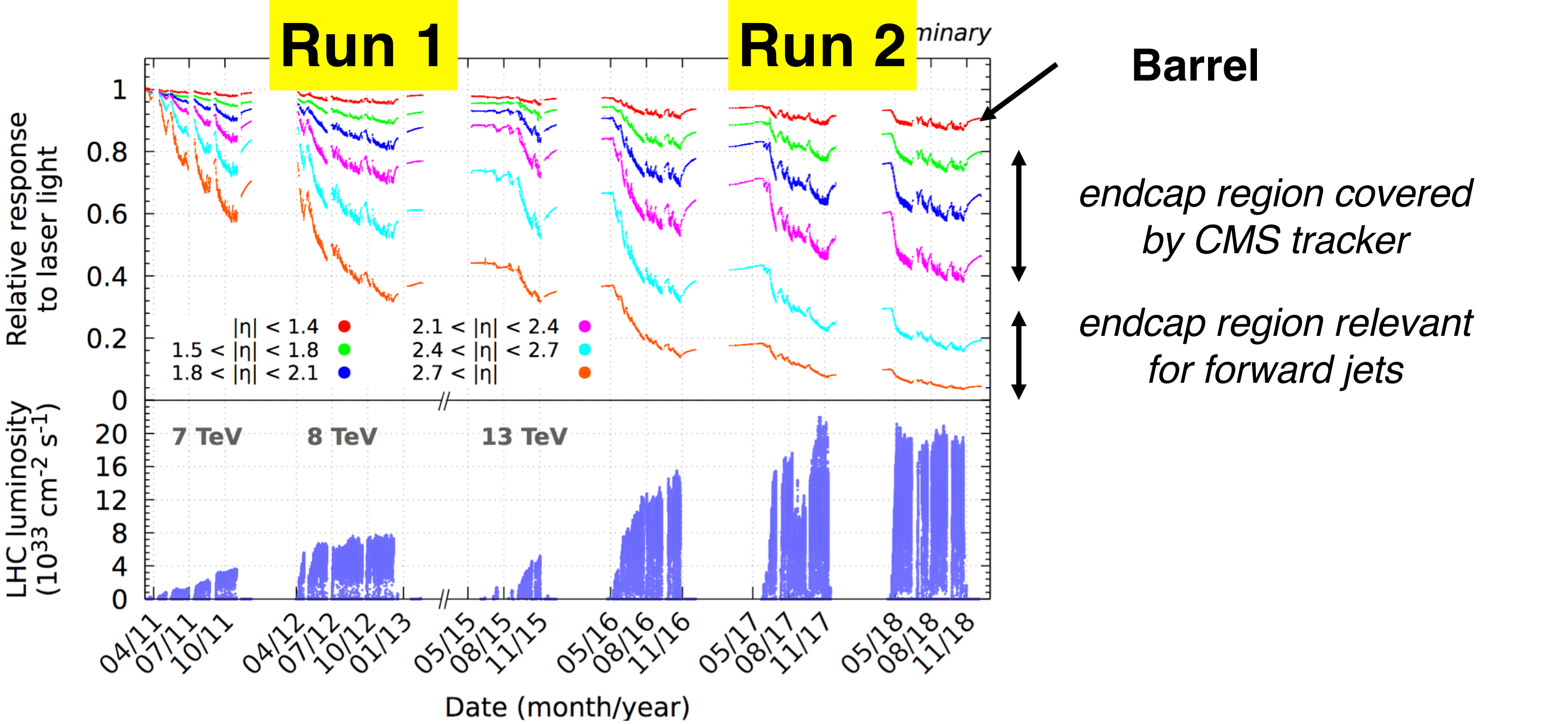
Outlook - calorimetry

- There are many opportunities in both PFA and Dual-Readout calorimetry for future collider experiments
- UK is already contributing in major ways in both areas
  - DECAL (CALICE-like) with MAPS technology
  - Dual-calo R&D (IDEA)
- There are many possibilities for new UK collaborators to make leading contributions
  - Hardware development
  - Software/Simulation
  - Substantial expertise from past and ongoing projects

Backup

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**

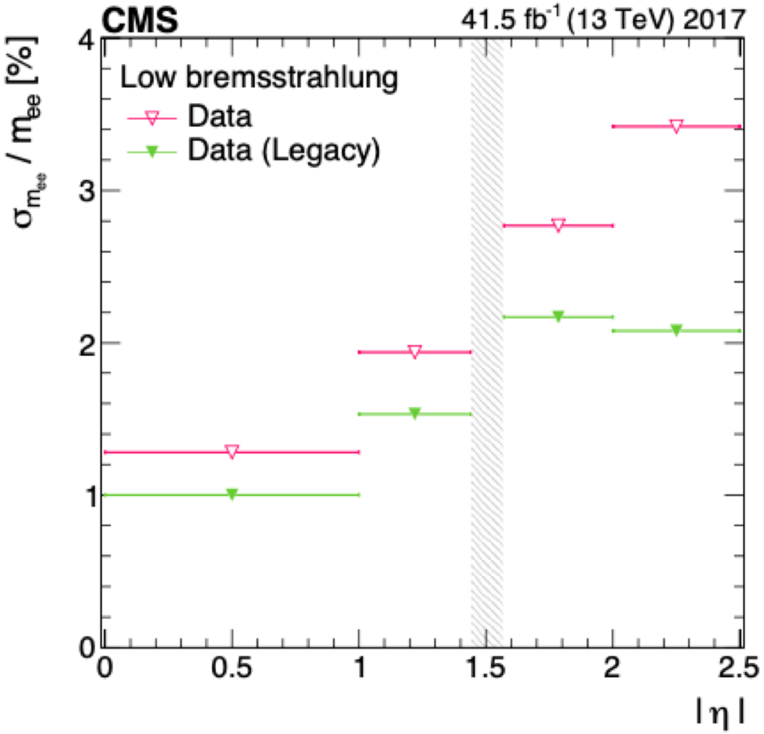


These corrections are crucial to maintain stable ECAL energy scale and resolution over time. Requires a dedicated team during LHC operations

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:

<u>Do not assume that calibrations remain constant!</u>

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 <u>intrinsic</u> ECAL resolution

ECAL Calibration methods

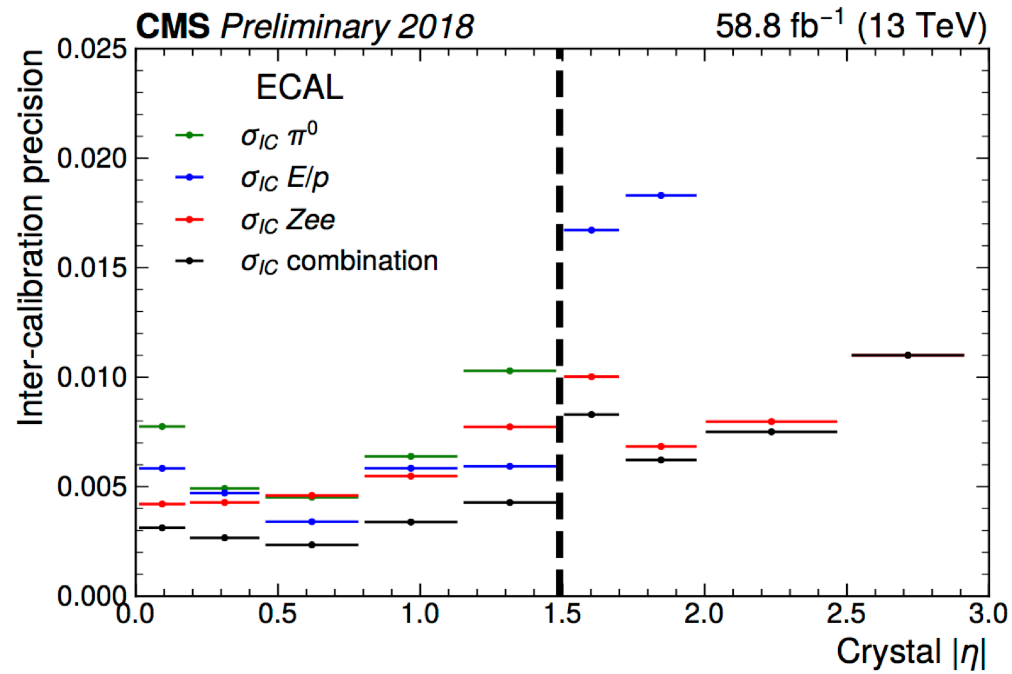
ECAL intercalibration sources

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)

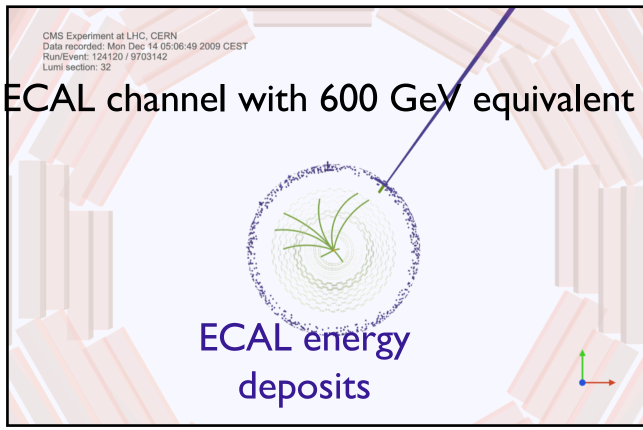
2) some methods (phi-symmetry, E/p from W→eν) suffer from systematics due to uncertainties in tracker material distribution in phi

3) Z→ee proved to be the most effective all-purpose calibration method in Run 2

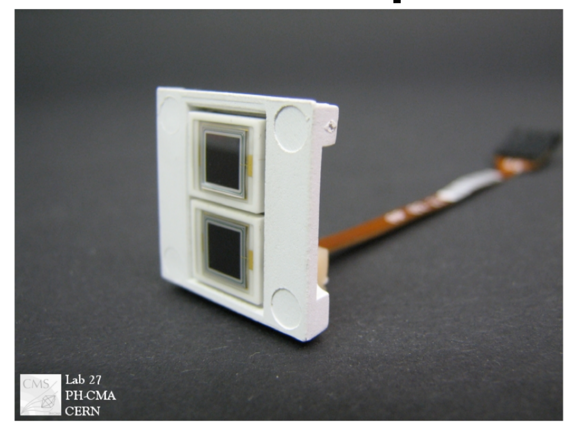
ECAL spikes

- **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



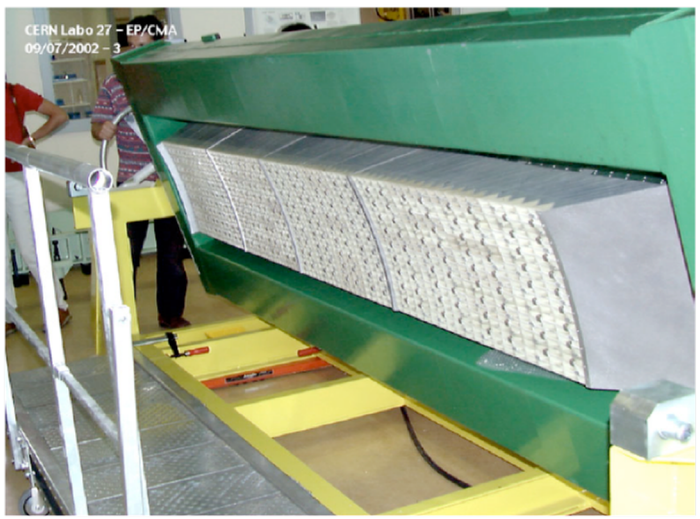
- **Mitigation was challenging, especially for L1 trigger:**
  - no possibility to cure at source - APDs inaccessible
  - spikes will typically hit one of 2 APDs serving one ECAL crystal. However, decision was made to sum these signals rather than read them out individually to reduce cost

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?

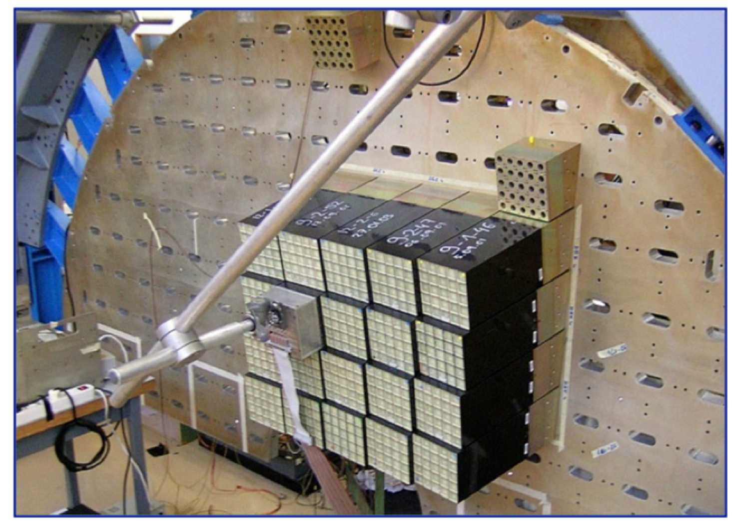
ECAL mechanics

- **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

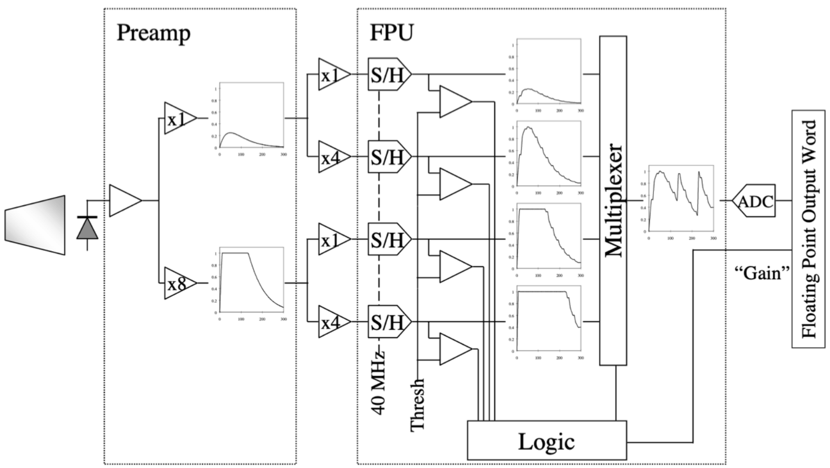


- **This has implications for crystal production and detector construction**
  - much simpler if you only have to deal with a single module/crystal type
- **Should also consider possibility for partial dismounting/replacement of modules**
  - ECAL was not designed with this possibility in mind - partial 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

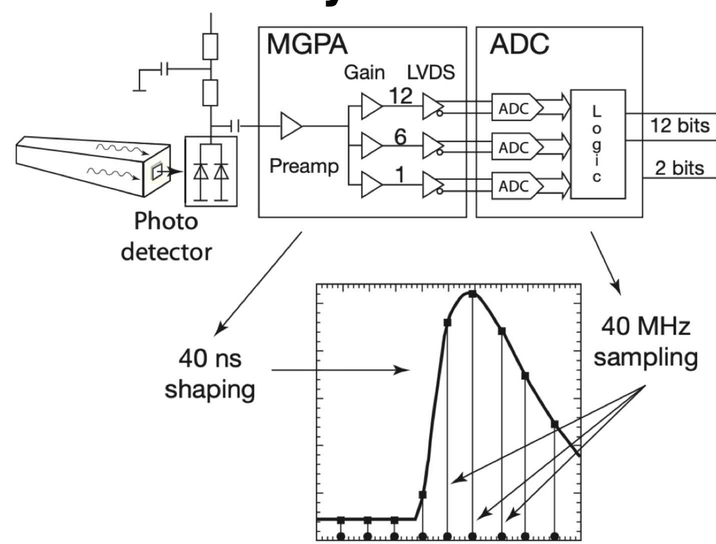
ECAL ASICs

- **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

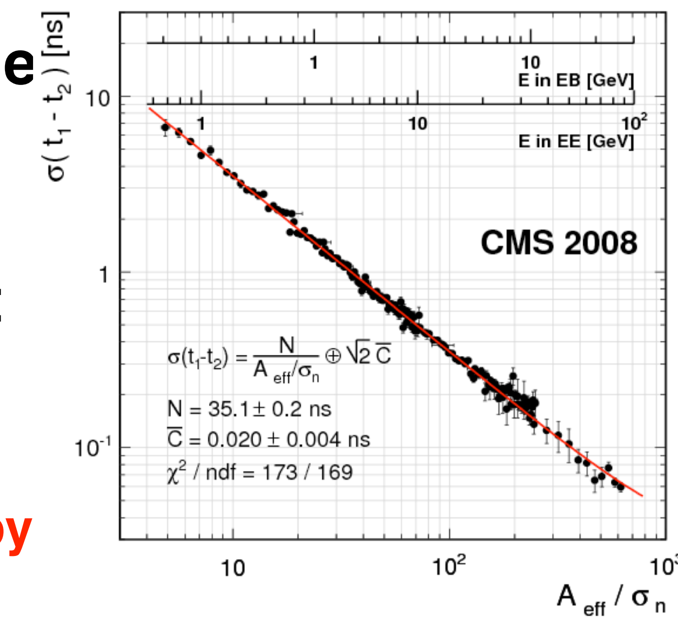


Lessons learned:

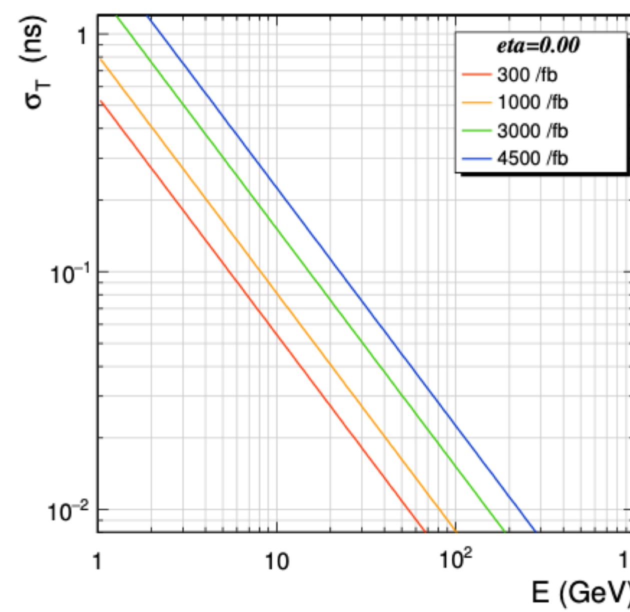
Issues with ASICs are not uncommon in HEP - but problems can be minimised by careful and conservative design methodologies. Early full-system tests with detector prototypes are a **must** to check system performance and identify any noise issues in a realistic data-taking environment

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



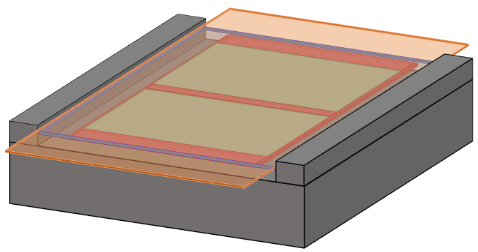
Phase-2 ECAL time resolution vs luminosity

EPICAL-2 simulation utilizing Allpix^2

A Monte Carlo simulation tool for silicon pixel detectors
From incoming particle(s) to readout

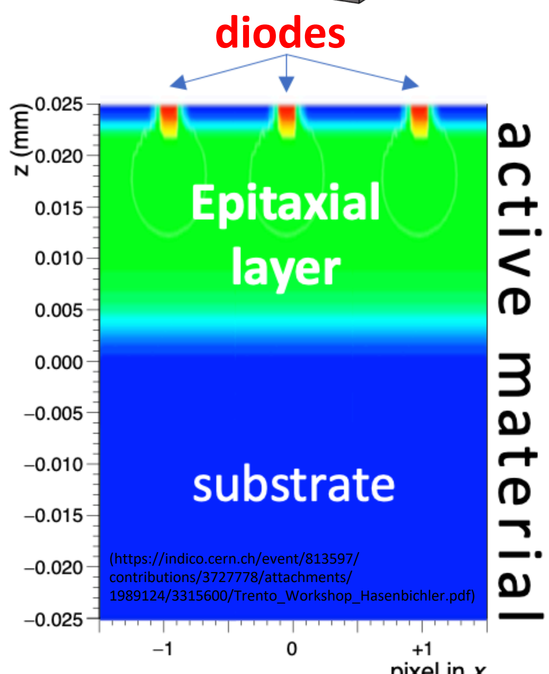
simulation chain:

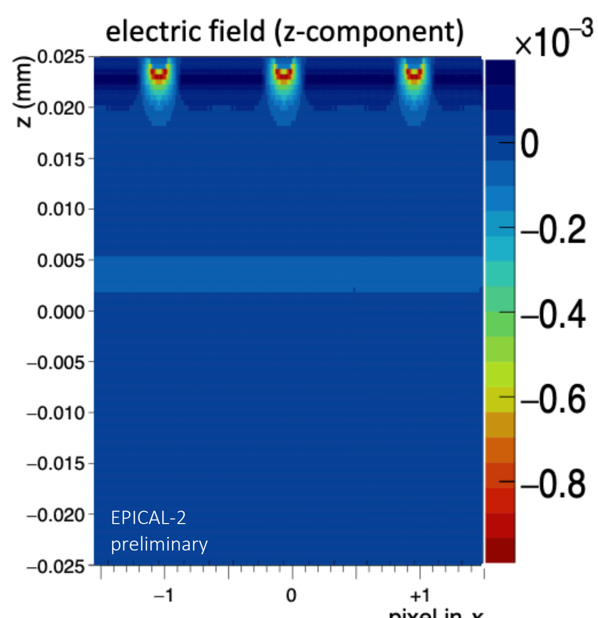
geometry builder → **electric field initialization** → **energy deposition** →

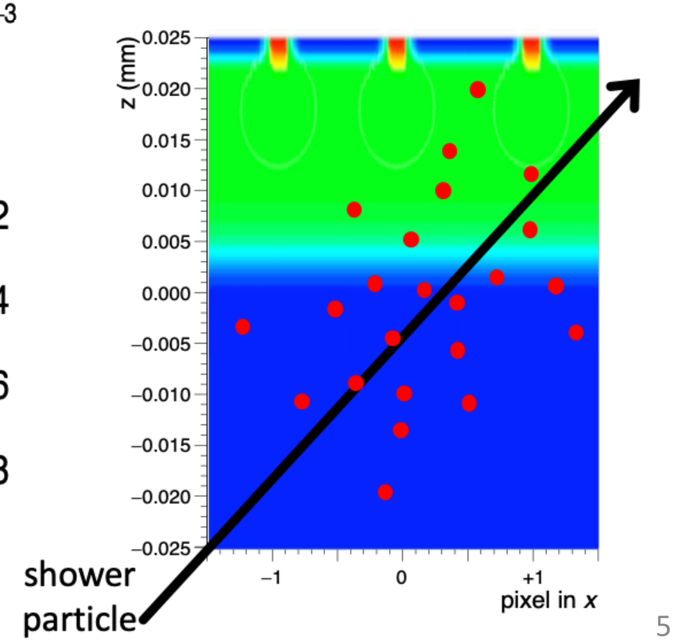


- electric field obtained from **TCAD** simulation by Jan Hasenbichler
- total reverse bias voltage of $V_{RB} = 1.4\ \mathrm{V}$

- particle transport and deposition of charges in active materials







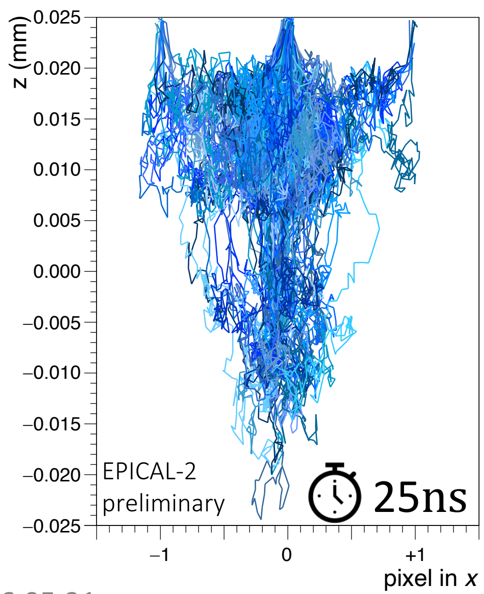
EPICAL-2 simulation utilizing Allpix^2 II

A Monte Carlo simulation tool for silicon pixel detectors
From incoming particle(s) to readout

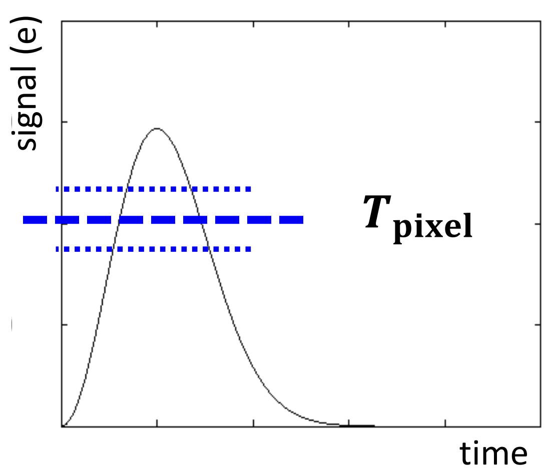
simulation chain:

propagation and transfer → **digitizer** → **output**

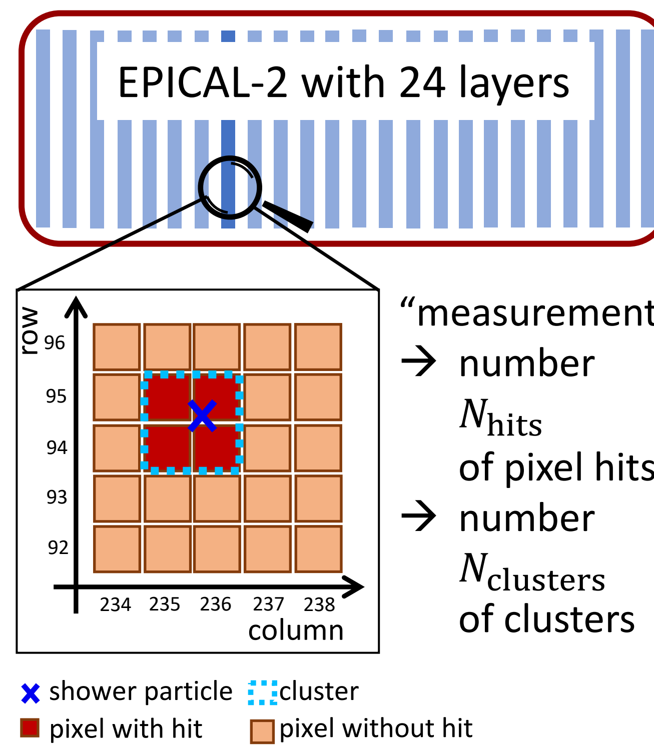
propagation and transfer
- propagation of charge carrier groups
  → set to **50 charges per group**
- diffusion and drift of groups within integration time t_{int}
  → set to $\boldsymbol{t_{\mathrm{int}} = 25.5\ \mathrm{ns}}$
- pixel assignment of charges



digitizer
- noise added by Gaussian (width σ_{noise}) to each pixel
  → set to $\boldsymbol{\sigma_{\mathrm{noise}} = 20\ \mathrm{e}}$
- accept as hit: pixel charges surpassing threshold value T_{pixel} (T_{pixel} is set per chip)
  mean: $\boldsymbol{< T_{\mathrm{pixel}} > = 82\ \mathrm{e} \pm 20\ \mathrm{e}}$



output
- 2D information of hits per layer
  → column and row



"measurement":
→ number N_{hits} of pixel hits
→ number N_{clusters} of clusters

Contributors

University of Bergen

University of Birmingham

CERN

Goethe University Frankfurt

University of Oslo

Research and Production Enterprise LTU Kharkiv Ukraine

Utrecht University/Nikhef

Yonsei University