Introduction to the calorimeter session

European context and UK outposts

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Introduction

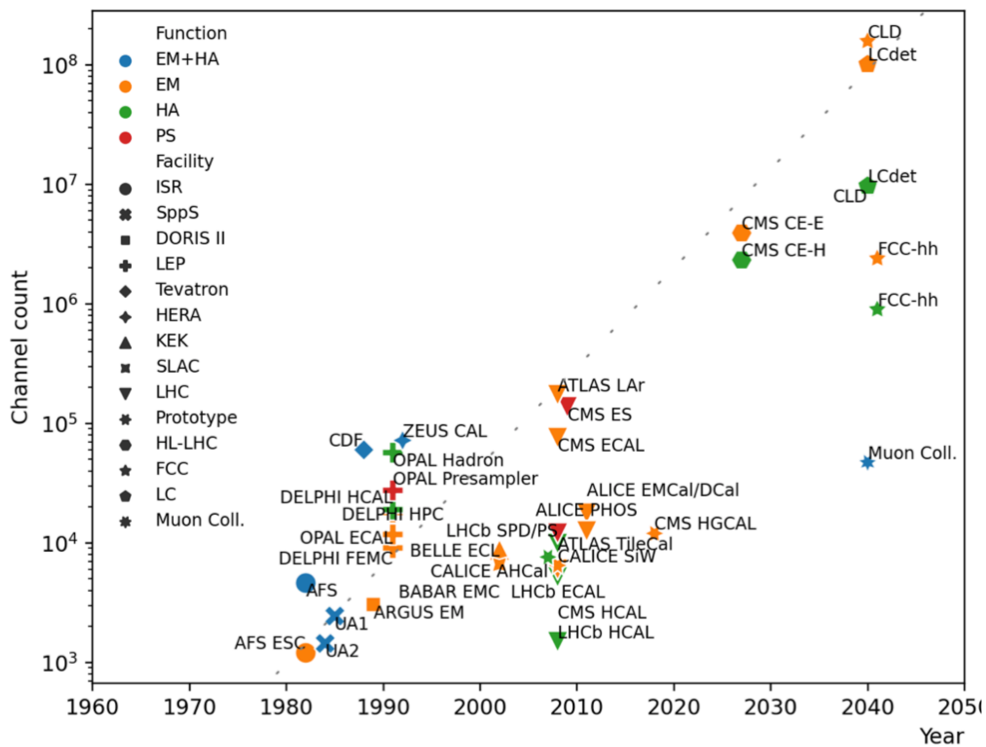
- Plan for this talk:
  - Touching upon material discussed in **ECFA TF6 symposium**
  - Connections with **existing UK activities**
  - Introduction to next talks
- ECFA TF6 - Calorimetry. Some details:
  - Coordinators: R. Ferrari, R. Pöschl. Symposium held on the 7th of May 2021 - 115 max concurrent users, 201 unique user connections
  - Full recording of the session here.
  - Questions from TF6 available here. UK response available here.
  - TF6 conveners' input to plenary drafting session here

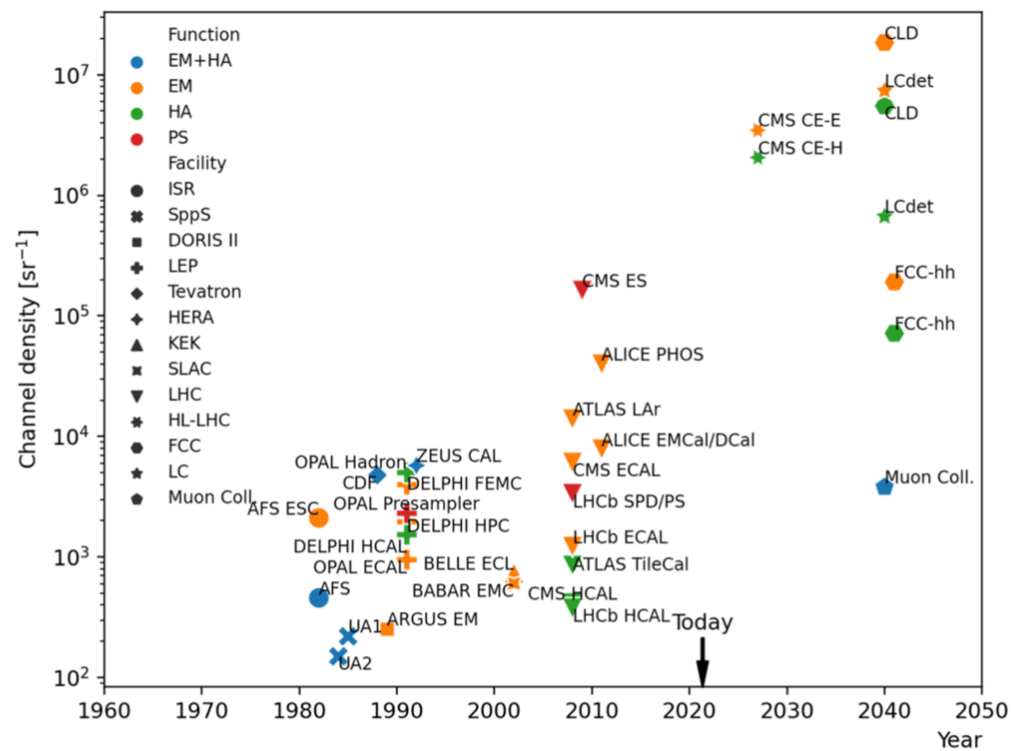
Calorimeter concepts

- **Calorimeter community** in UK **small** compared to, e.g., ID tracking community.
- However, **considerable efforts** in recent past and present makes it **relevant in international context.**
- Areas of UK involvement:
  - High-granularity calorimeters:
    - Si-based (Sci-based, Gas-based).
  - Optical readout calorimeters:
    - Crystal and fibre calorimeters
  - Noble liquid calorimeters

High-granularity calorimeters

Global challenges





…while improving on, e.g., time resolution

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Key Challenges for Main Calorimeters

European Strategy Update

- *Design*:
  - Embedded electronics: low noise (small cells, large dynamics: ½ –3000 mips)
  - Connectivity to PCBs for compact detectors, edge effects in particular in endcaps
  - System aspects crucial: Integrated approach needed for mechanics, electronics, cooling & services
  - Figure of merit for detector optimisation needs to be re-thought - Complex system performance question, not just energy resolution
- *Construction*:
  - Scalable designs crucial - increased industrialisation required in future, likely going beyond individual components and extending to larger units
  - Automatisation in assembly, book-keeping / documentation of data / parameters
- *Operation*:
  - Calibration of highly granular calorimeters with ~10^8 (or more) channels - handling, and possibly compressing of large calibration databases
  - Redundancy in detector design, complex monitoring

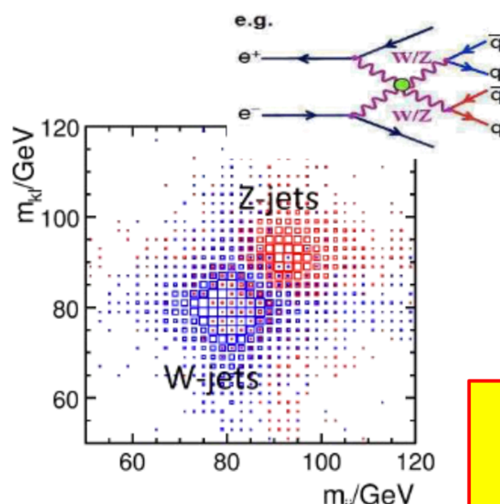
High-granularity calorimeters

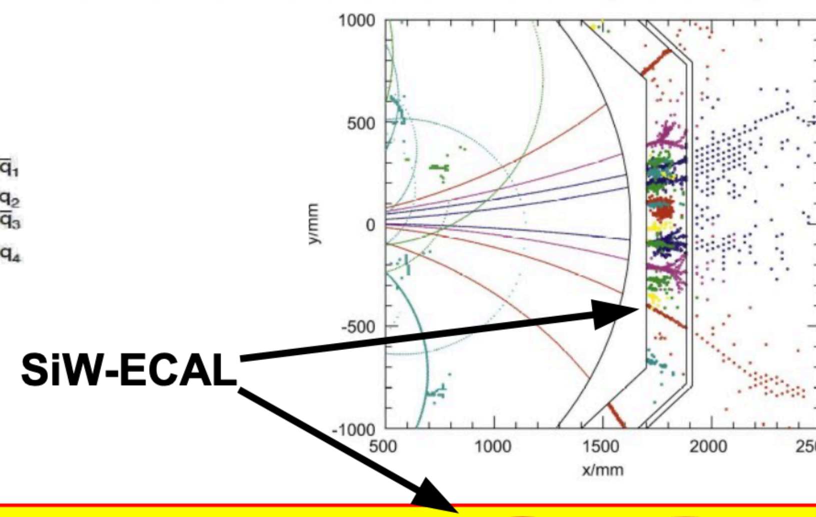
- Designed to ideally **resolve individual clusters** for, e.g., particle flow.
- Actual implementation using **different technologies** (Si, scintillators, gas)
- **Silicon:** flexibility and radiation hardness makes **a good candidate in various conditions.**
  - Initial linear collider design (CALICE)
  - Evolutions in hadron collider (CMS HGCal) and as beam monitor-forward calorimeters (FOCAL)

Current prototypes:
- 8 modules with embedded electronics
- Total of about 30k channels

Next step:
pilot production prototype (1M channel fully integrated)

Main challenge: production of many components and interaction with industry



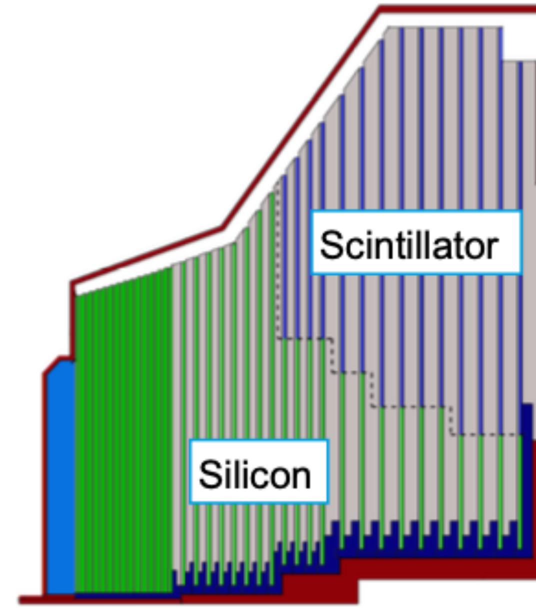


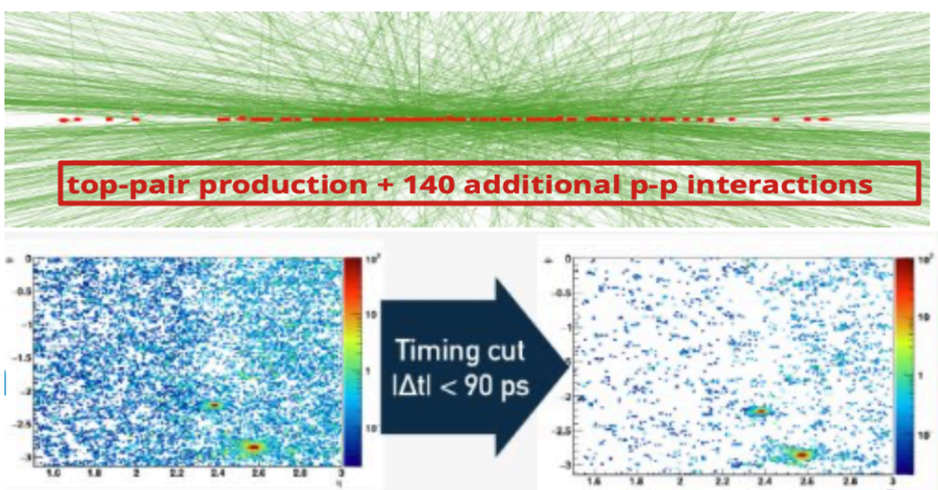
Particle Flow Algorithms :
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 CALO's
- TPC $\delta p/p \sim 5 \cdot 10^{-5}$; VTX $\sigma_{x,y,z} \sim 10$ μm **+ timing ?**

H. Videau and J. C. Brient, "Calorimetry optimised for jets," (CALOR 2002)

CMS-HGCal

- A practical implementation of Si-based high-granularity calorimeter
  - Challenges: very high doses (10^{16} n_{eq}/cm^2), high occupancies and rates. High number of channels ⇒ power consumption ⇒ active cooling.
  - Timing as integral part of the readout
    - See talk from P. Dauncey, A-M. Magnan
  - UK involvement: Bristol, Imperial



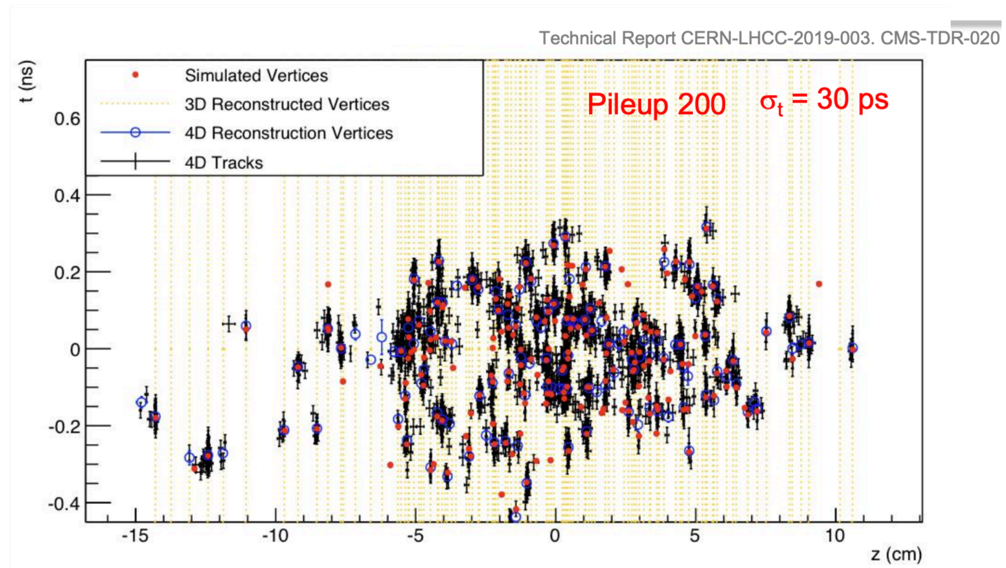


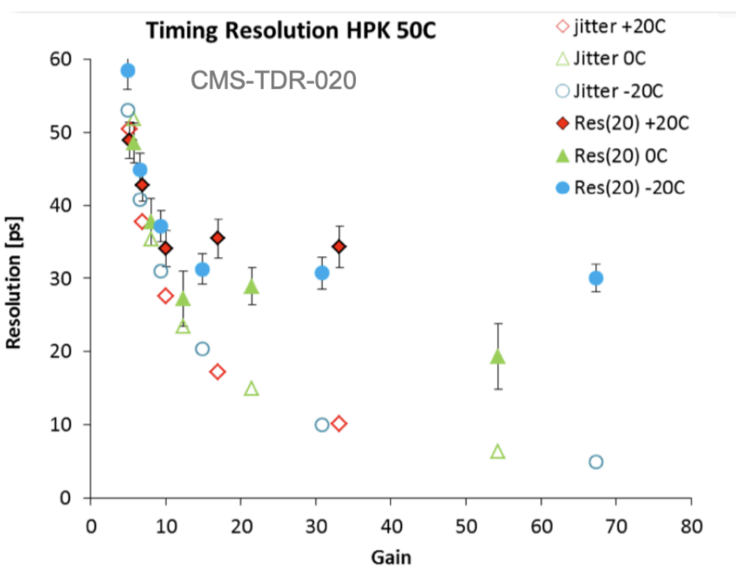
Simulated HGCAL event with and without timing selection

Endcap coverage: $1.5 < |\eta| < 3.0$		
Total	Silicon sensors	Scintillator
Area	620 m²	410 m²
Number of modules	29 900	3800
Cell size	0.5 — 1.2 cm²	5 — 30 cm²
N of channels	6 260 000	240 000
Power	Total at end of HL-LHC: 2x125 kW @ -30°C	

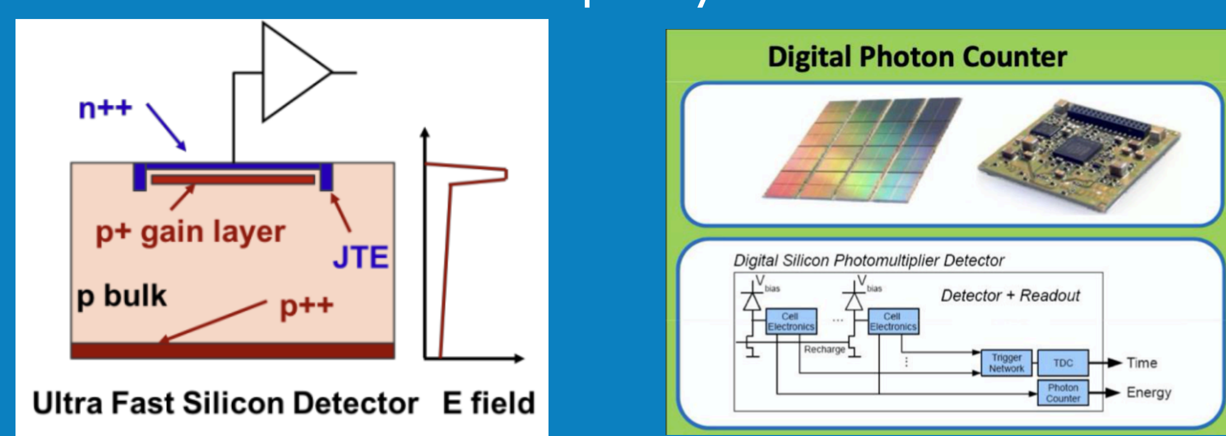
Timing

- 5D view essential in **high-pileup environments** (e.g. vertex identification)
- HG calorimeters have **cell size/c ~tens of ps**
  - **Extreme time precision** requires faster **electronics** ⇒ **power**.

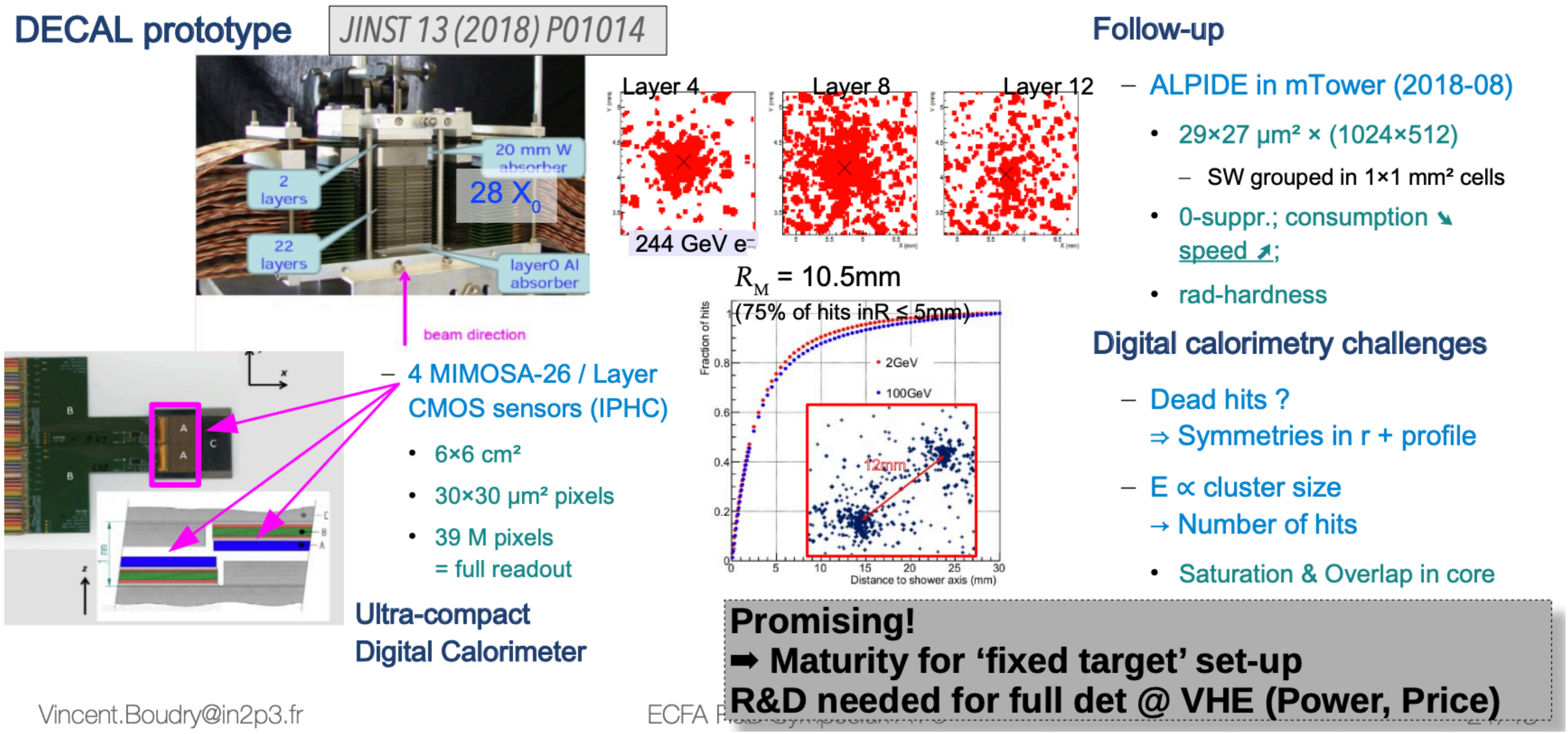




Present and future players



High Granularity Forward Calorimeters



- FOCAL - Forward calorimeter for ALICE upgrade
- See talk from N. Watson
- UK involvement: Birmingham, RAL, UCL

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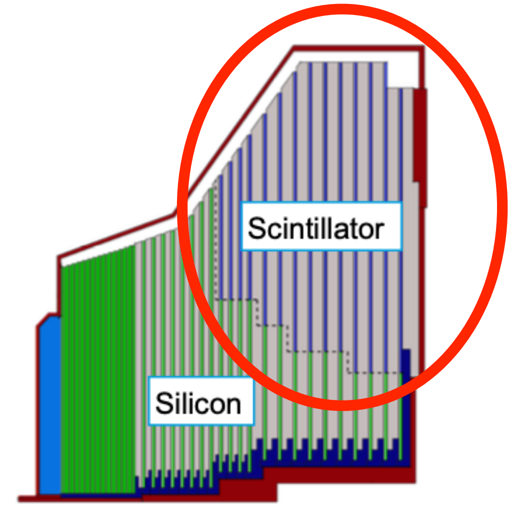
Si based Calorimeters – Key R&D Challenges

European Strategy Update

- *Reducing dead spaces*: Larger sensors to reduce impact of inter-wafer gaps - adoption of larger wafers can have unexpected pitfalls, close collaboration with producer(s) mandatory
- *Reducing dead spaces*: Guard rings as a complex issue - increases with sensor thickness, electrical properties require careful study to avoid noise issues
- *Increasing signal*: Thicker sensors provide improved em-resolution (higher sampling fraction), physical gain (LGADs et al.) boost S/N and thus timing
- *New technology:* Using CMOS MAPS for large area digital ECALs - with possible significant cost benefits
- *Improved intelligence*: Additional capabilities in CMOS sensors - power a key challenge. Fully digital approaches inspired by digital SiPMs - “SMAD” - Single MIP Avalanche Diode?
- *Reduced channel count*: Position-sensitive Si pad sensors for low-occupancy applications: lower power?
- *New materials*: GaAs and beyond - higher density, “right” band gap, processing, price, …
- *Radiation hardness*: For future hadron colliders no magic expected - need to develop suitable system designs that allow replacement of elements in most exposed regions without excessive mechanical complications

Not only silicon

- High granularity integrated tile calorimeters part of HGCAL

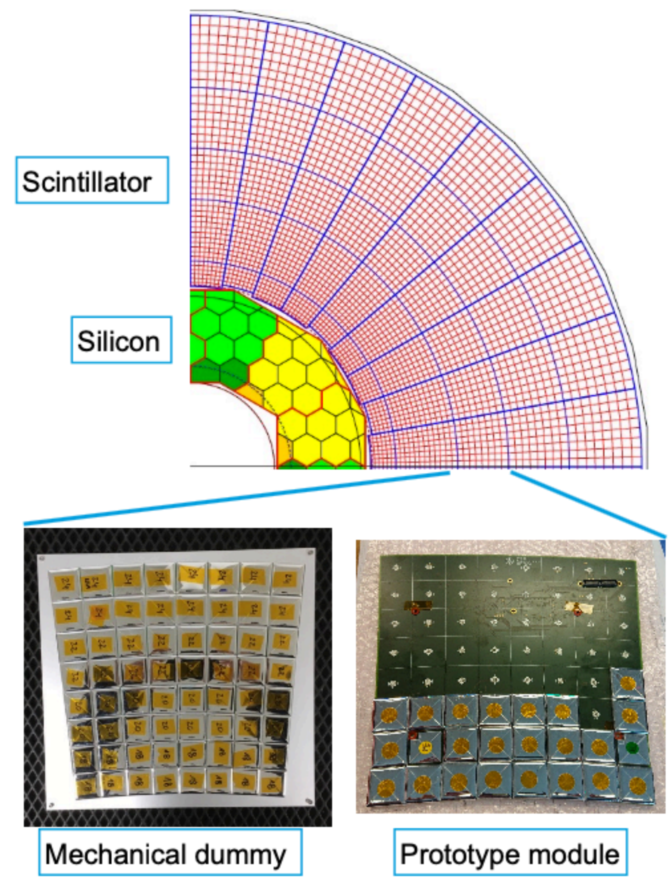


High granularity for HL-LHC

CMS HGCAL: scintillator part (for silicon see Vincent's talk)

- CMS calorimeter endcap up
- Scintillator tiles where radiation levels allow, otherwise silicon
- Design inspired by CALICE AHCAL
- Material composition: steel : scintillator = 3.5 (6.6) : 0.3 cm
- Thickness: 10.7 λ_I (total HCGAL)
- Maximum radiation
  - up to ~2 kGy
  - **~5 * 10^13 neq/cm²**
- **Granularity: 2.5 * 2.5 to 5.5 * 5.5 cm²**
- # of channels: ~240,000
- Scintillator and silicon share the same (cold) volume
  - Operation at -30° C beneficial for SiPM noise
  - Limited possibility to warm up for annealing

The first high granularity calorimeter in a collider experiment!



Optical readout calorimeters

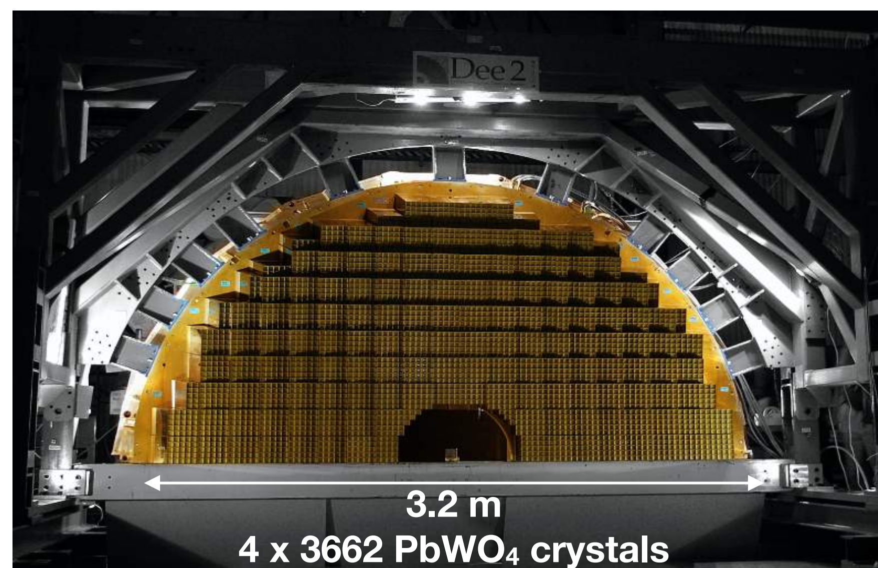
UK contributions to CMS ECAL

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)**

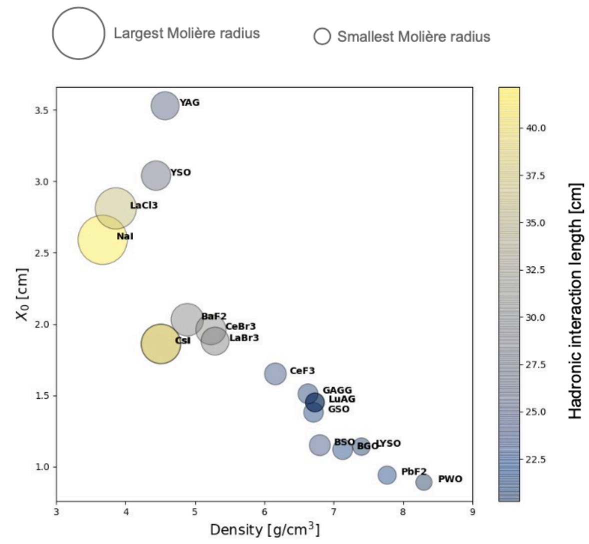
From concept…

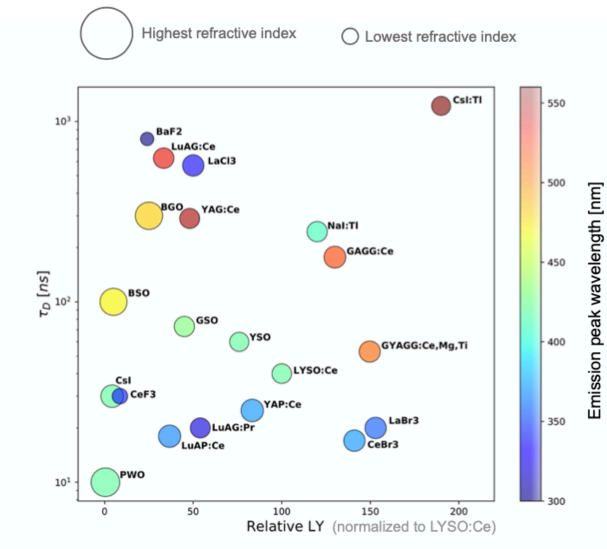
…to reality



Crystals

- UK involvement (RAL, Bristol, Imperial, Brunel) with current CMS ECAL
  - See talk from N. Watson
  - See slides from D. Petyt attached to the agenda

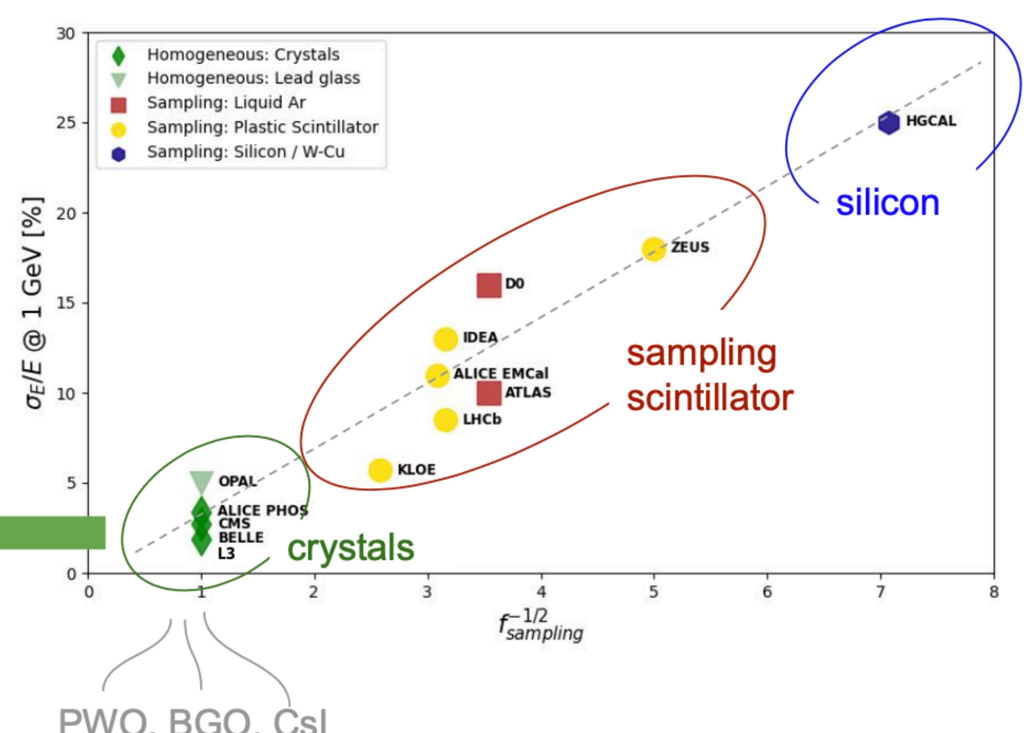




- Homogenous crystal calorimeters have a long **history** of **pushing the frontier of high EM resolution**
  - The entire EM shower is sampled
  - Large light signals are produced

$$\frac{\sigma_E}{E} \sim \frac{3\%}{\sqrt{E}}$$

A sample of existing and future calorimeters



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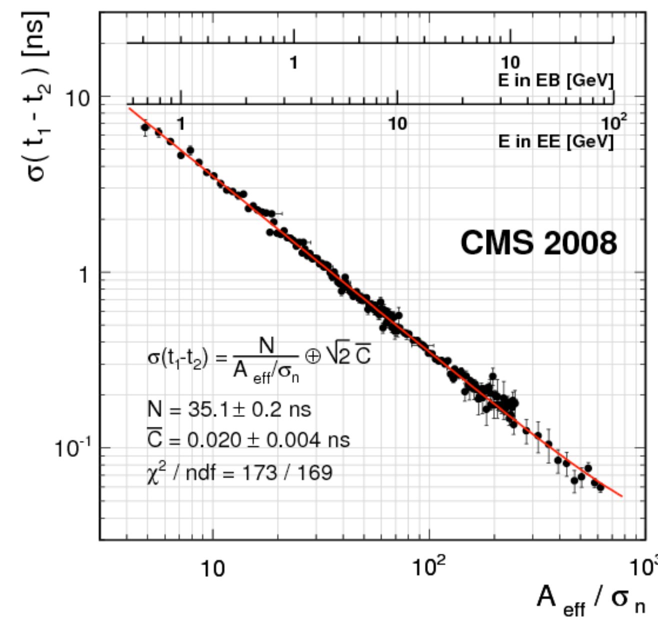
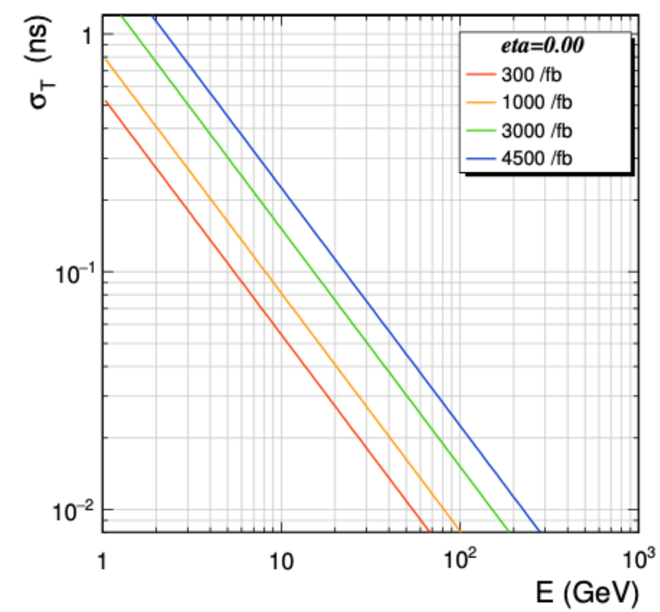
ECAL crystals are capable of precise timing

- **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**



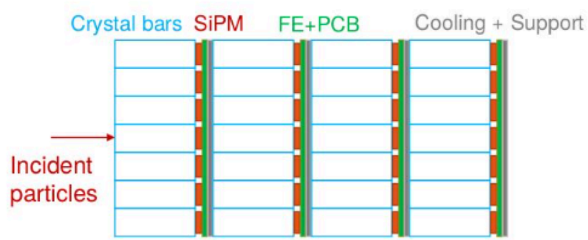
ECAL time resolution measured from test beam



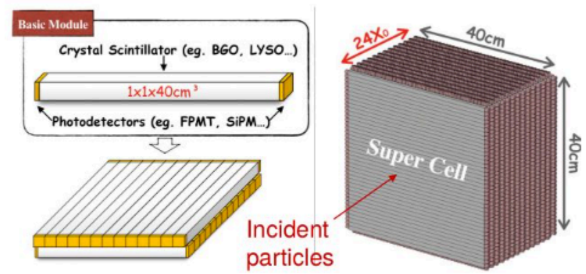
Phase-2 ECAL time resolution vs luminosity

Example of opportunities with crystals

Design 1

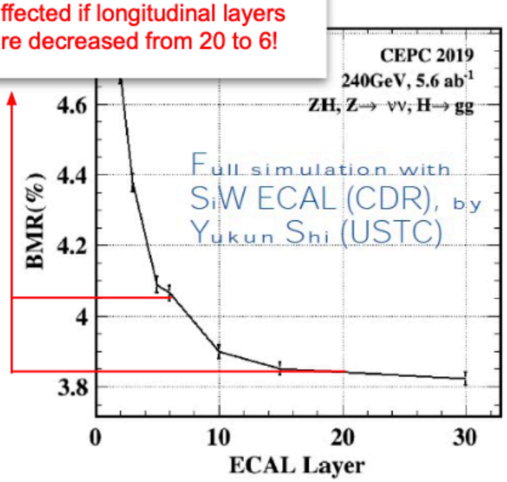


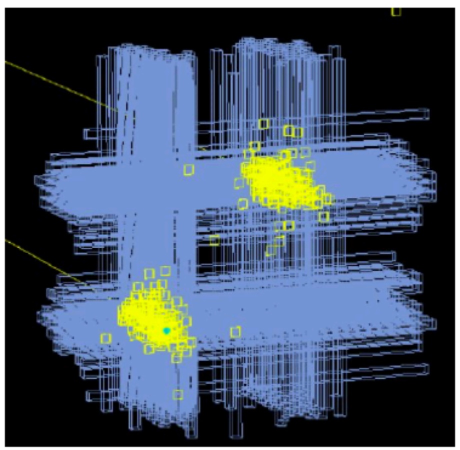
Design 2

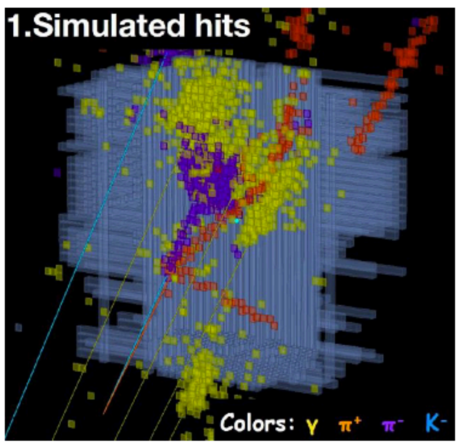


Evaluating optimal crystal configuration for granular 3D imaging

PFA performance not too affected if longitudinal layers are decreased from 20 to 6!







Developing precision particle flow optimized for crystal calorimetry

Merging high granularity and high energy resolution for precision physics at e^+e^- colliders

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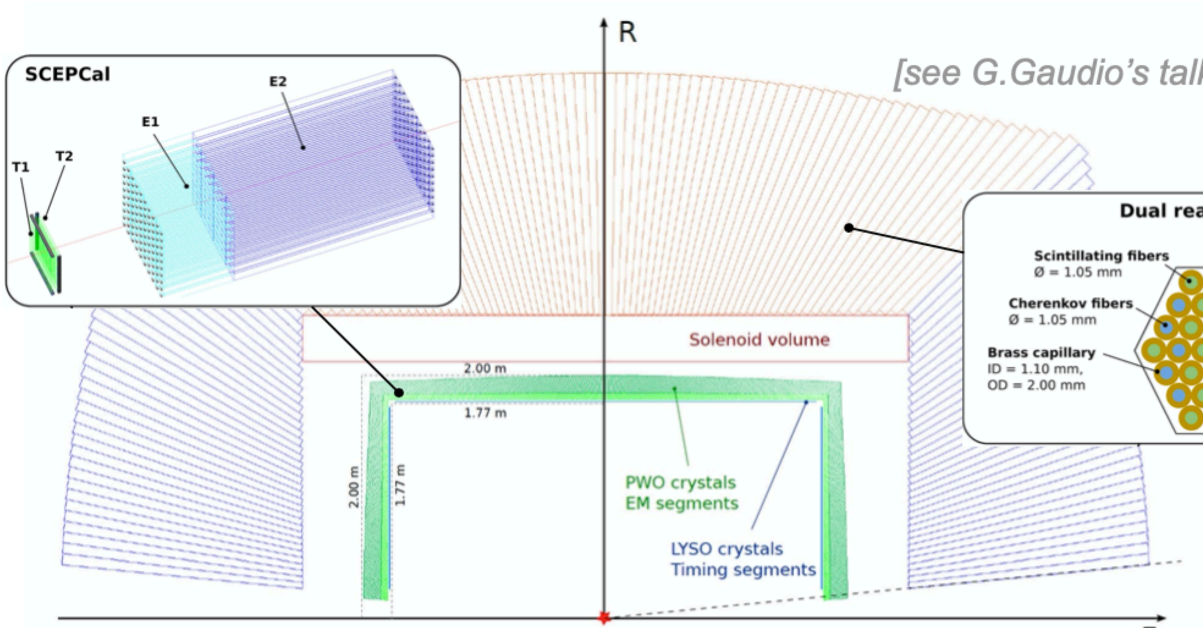
Example: opportunity with crystals

Integration of homogeneous crystals in a **hybrid dual-readout calorimeter**

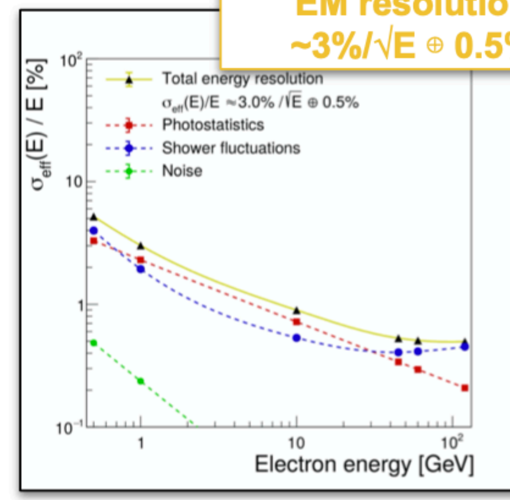
- Achieving **excellent energy resolution** for EM and HAD showers **in a cost-effective way**
- **A EM crystal section with dual readout capabilities**

[see G.Gaudio's talk]

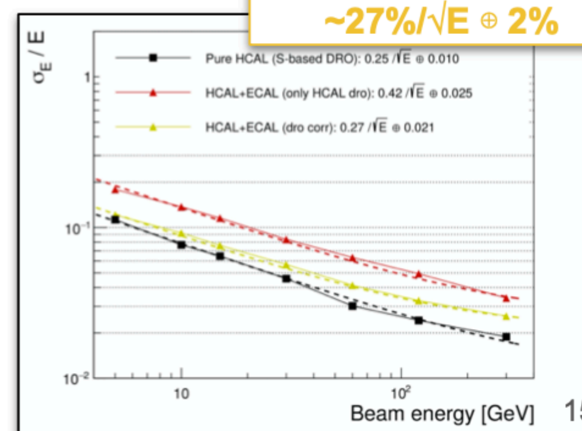


https://doi.org/10.1088/1748-0221/15/11/P11005

EM resolution ~3%/√E ⊕ 0.5%

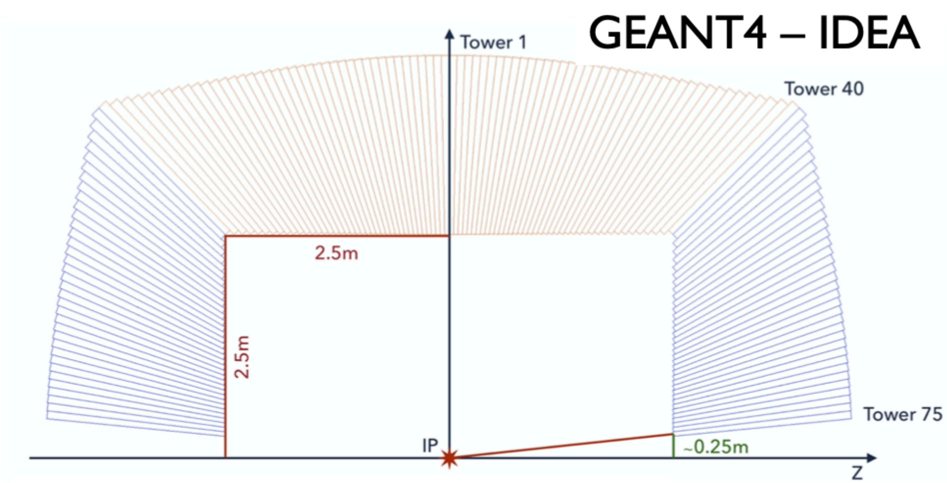


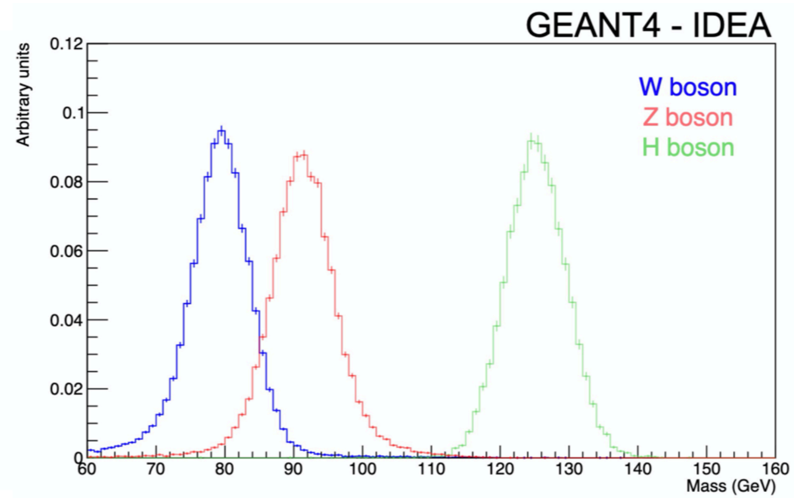
HAD resolution ~27%/√E ⊕ 2%

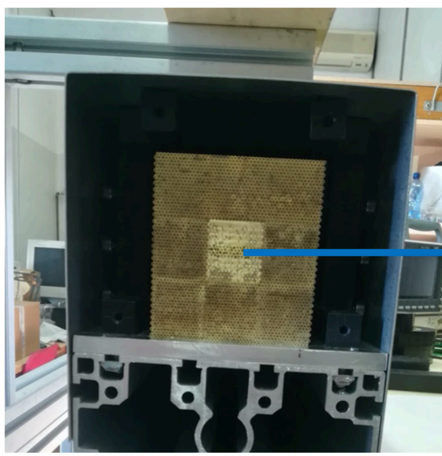


Dual readout fibre calorimeter

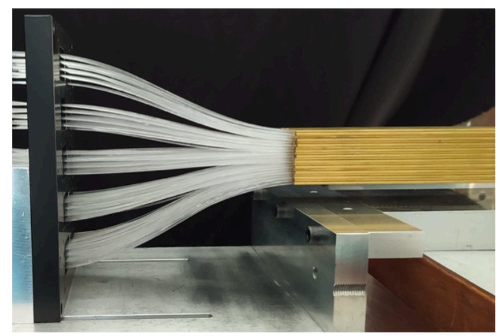
UK involvement:
University of Sussex



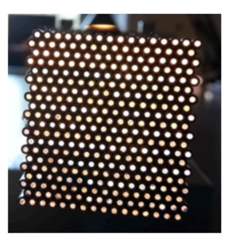




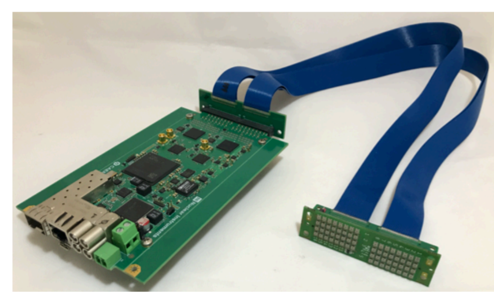
SiPM readout for central tower



2020 "EM-size" prototype
10x10 cm² divided in 9 towers
16x20 capillary each
160 C + 160 S fibres
Capillary: brass CuZn37
2 mm OD, 1.1 mm ID, L = 1 m



FEE – Boards
5 Boards
Each board:
64 SiPMs
(32 S +32 C)
Readout Boards:
5 FERS - A5202
CITIROC ASIC

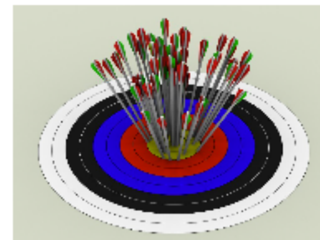


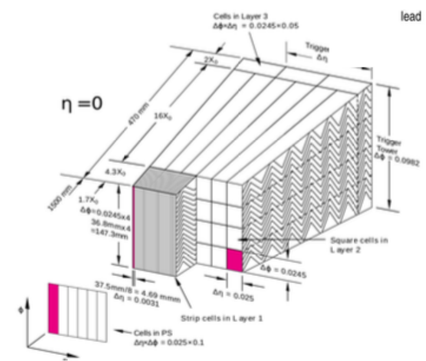
Optical readout: challenges

- Improved photodetectors: Spectral response matched to scintillation/Cherenkov emission (also for new media); field immunity (chiefly for vacuum devices); improved radiation tolerance (chiefly for FCC-hh); low power consumption (for integrated designs); digital SiPMs
- Integration: Thermal management (global or local cooling, options for in-situ annealing); complex integration (signal routing) for highly segmented calorimeters (chiefly crystals or tiles with longitudinal segmentation)
- 3D-printing: Explore 3D-printing of absorbers or even active materials
- Prototyping: Proof-of-principle with prototypes with full containment of hadron showers
- Crystals:
  - New materials fast, bright, and cost-effective (low-cost materials vs sampling calorimeters)
  - Combined EM calorimetry with dual-readout concepts without spoiling hadron resolution (e/h ratio, etc.)
  - Crystal radiation hardness (where needed)
  - Embedded timing
- Dual readout fiber-sampling calorimeter:
  - Further understanding the C/S calibration and energy components
  - Exploring novel methods for absorber production (3D-printing) and new materials (crystals) for fibers
  - Integration aspects (full size detector never built)
  - Potential for integration with other approaches (particle flow, front EM compartment, timing from fibers)

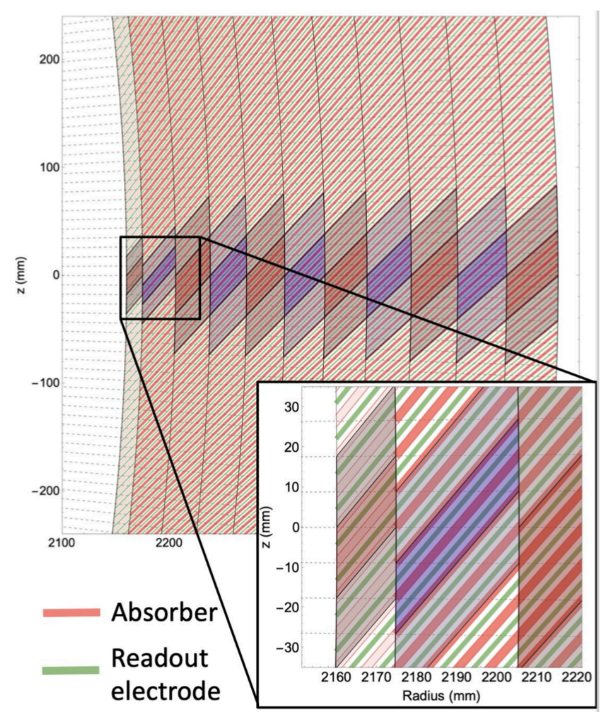
Noble liquid and gas calorimeters

- Key features
  - Radiation hardness, long term stability
  - Linear response, uniformity, high control over systematics
  - Good energy/timing resolution





- Challenges for future colliders:
  - increased granularity (high-density feed-throughs, high-granularity electrodes)
  - Warm or cold electronics?
  - Timing resolution: dedicated timing layer?
  - UK involvement: University of Edinburgh



Summary

- **UK calorimetry community** not very large, but with important activities on **recent past, present and future calorimeters.**
- In this session:
  - **High granularity calorimeters** at colliders:
    - Paul Dauncey, Anne-Marie Magnan - HGCal (focus on UK involvement)
  - **About future colliders**:
    - Nigel Watson: UK ongoing R&D and perspective

For discussion

- Are the areas discussed appropriate? Is the involvement too small/big?
- Potential for system construction? Milestones and demonstrators?
- Connection with electronics and integration.
- Framework of funding.