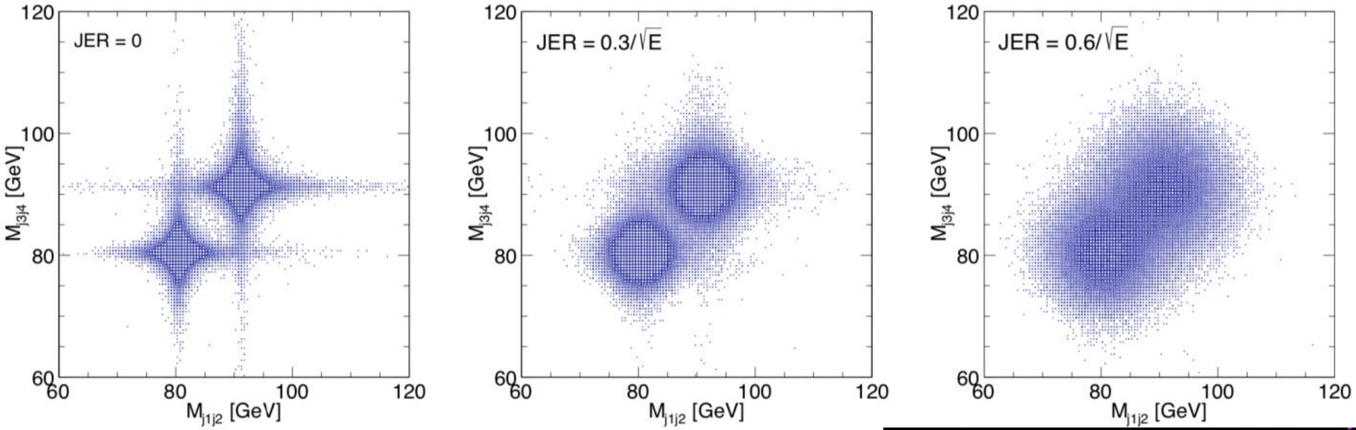
Calorimetry

Nigel Watson (University of Birmingham)
Fabrizio Salvatore (University of Sussex)



ECAL Design Principles

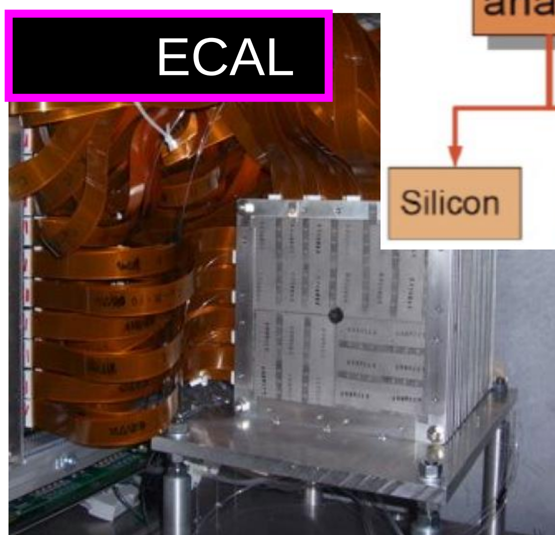
- Measure 100% EM energy
  - shower containment in ECAL, so X_0 large
- Resolve energy deposited by individual particles
  - small $R_{moliere}$ and X_0 – compact and narrow showers
- Separation of hadronic/EM showers
  - λ_{int}/X_0 large, so EM showers early, hadronic showers late
- Minimal material in front of calorimeters
- Strong magnetic field
  - lateral separation of neutral/charged particles
  - Keep beam-related background inside beampipe

  } ECAL, HCAL inside coil (cost)
- Active medium: Silicon (or scintillator)
  - Pixel readout, minimal interlayer gaps, stability

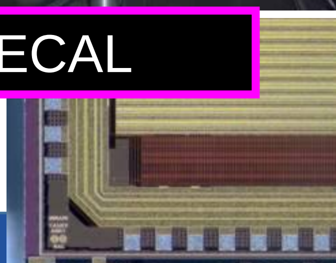
CALICE-like solution(s)

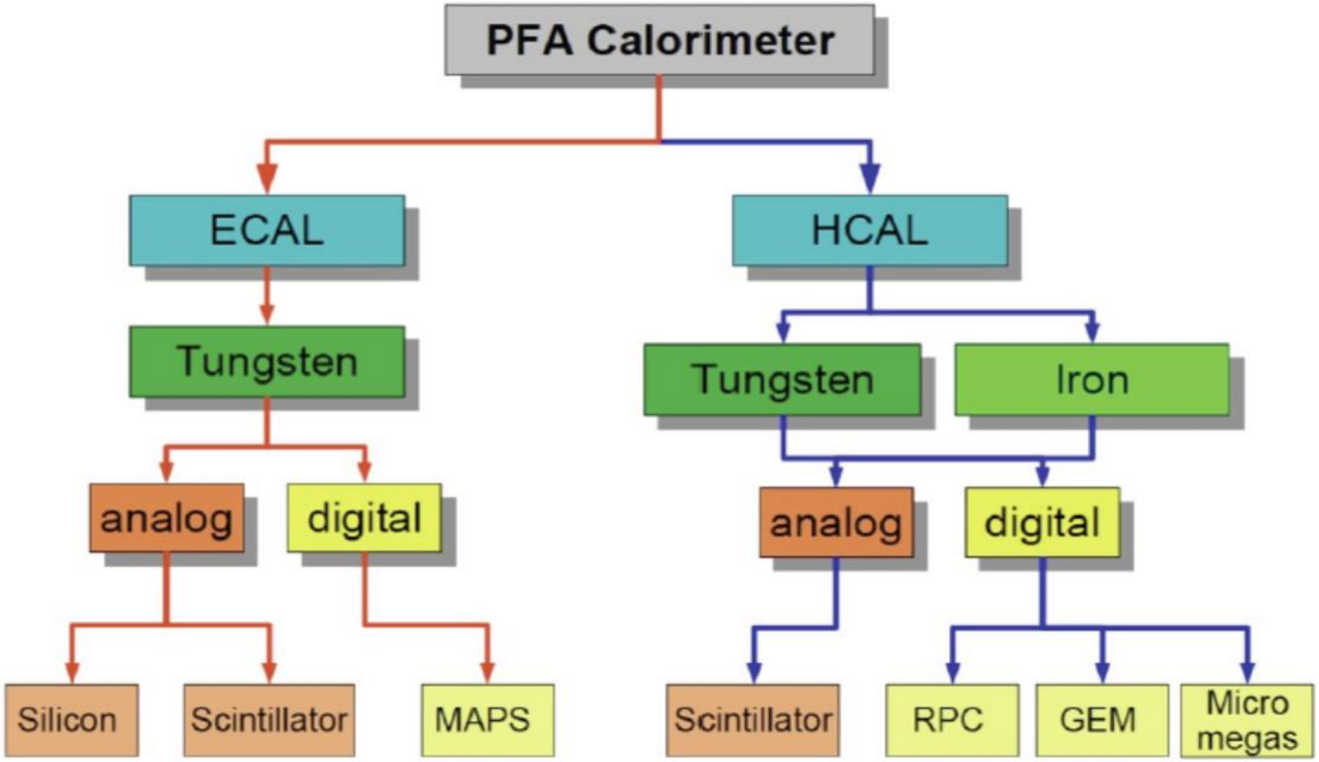
SiW ECAL

ECAL

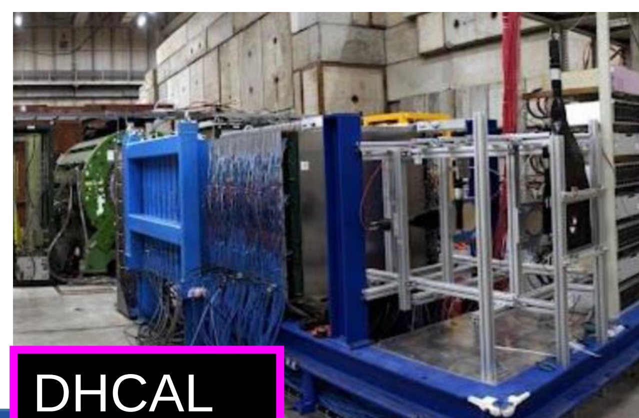


DECAL



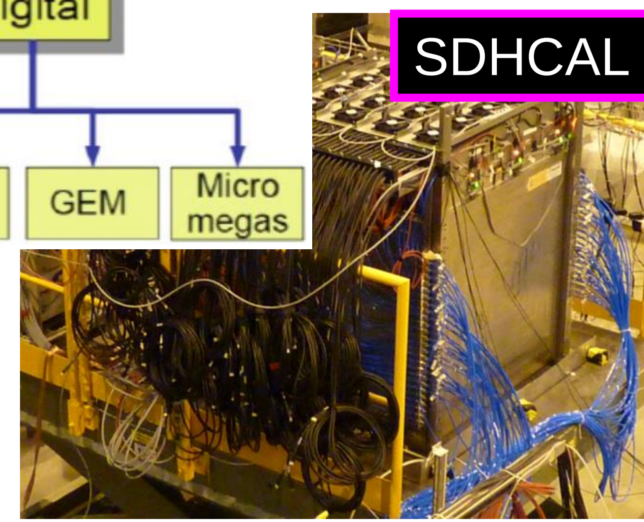


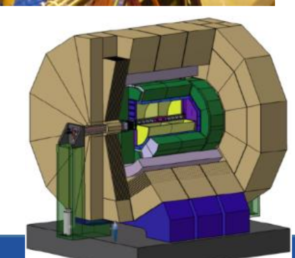
DHCAL



AHCAL

SDHCAL





CALICE Collaboration

Collaborating since 2001

The CALICE Collaboration

336 physicists/engineers from 57 institutes and 17 countries coming from the 4 regions (Africa, America, Asia and Europe)

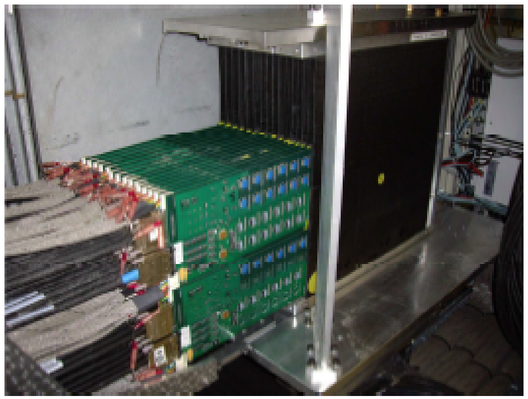
- All papers available from https://twiki.cern.ch/twiki/bin/view/CALICE/
  - (or google “calice cern” – top hit)
- Cost-effective approach of testing both h/w and s/w in common framework
- “Friendly competition” to ensure best technology chosen objectively
- UK activity - primarily ECAL (DAQ and MAPS)

Si-W Electromagnetic Calorimeter (Si-W ECAL)

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

Detector: **Silicon PIN diodes 1x1cm^2** (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 ($0.4\ X_0$)

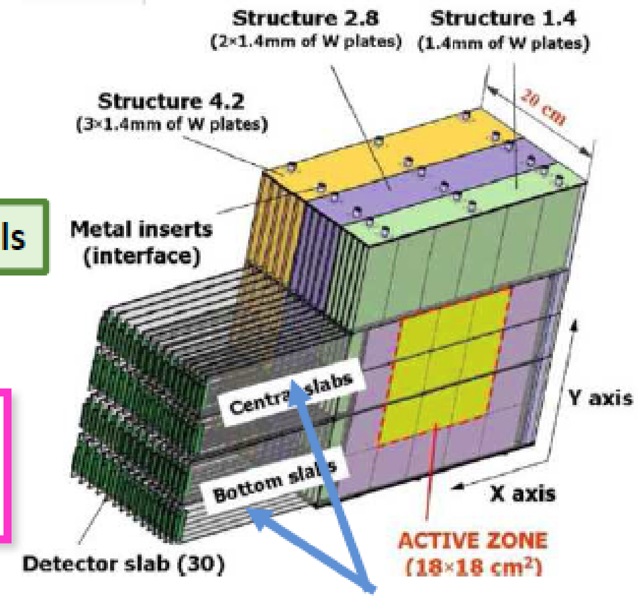
2.8 mm ($0.8\ X_0$)

4.2 mm ($1.2\ X_0$)

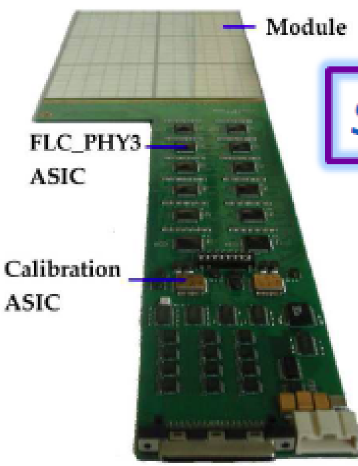
9720 channels

2005 - ECAL Physics prototype

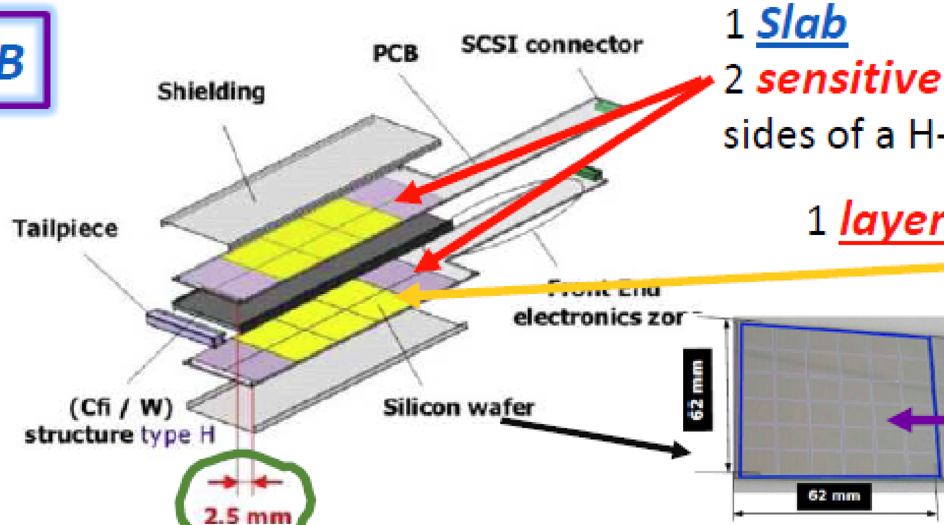
Lateral size: 18x18cm^2



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)

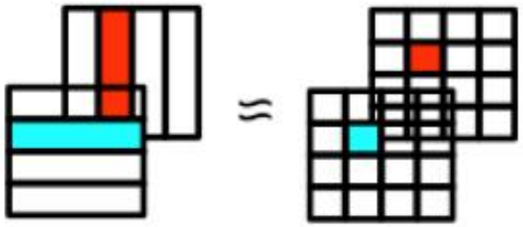
1 *wafer*= 6x6 ***pads*** 1x1cm^2

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

Scintillator – W Electromagnetic calorimeter (Sc-W ECAL)

Absorber: **Tungsten** (88%W 12%Co 0.5%C) 3.5mm thick

Detector: **Plastic scintillator**



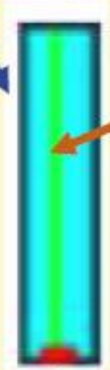
Odd layers orthogonal to even layers

→ 1x1cm^2 effective granularity

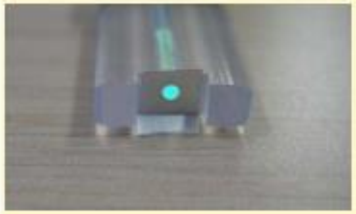
Less readout channels

but shower reconstruction more complicated

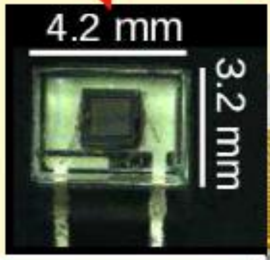
Strip 4.5x1 cm^2 3mm thick



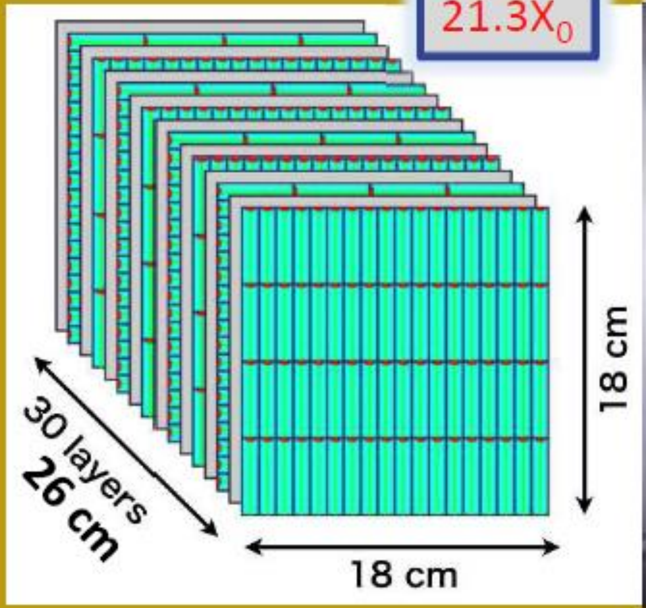
WLS (WaveLength Shifting) fiber



MPPC (MultiPixel Photon Counter)

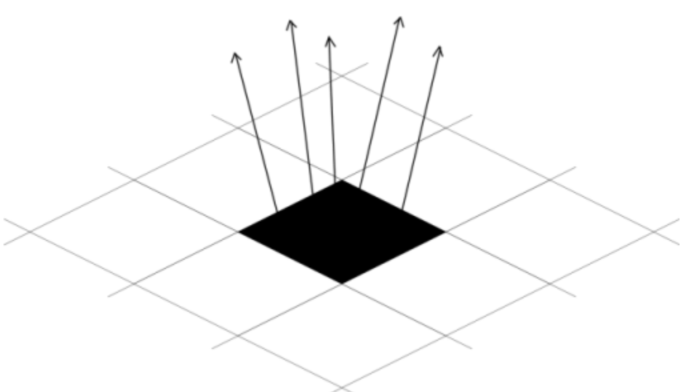


1600 pixels

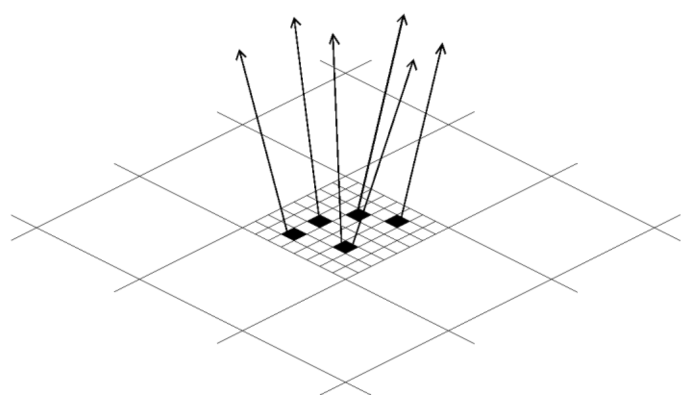


DECAL Concept – cost reduction for ECAL

- 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

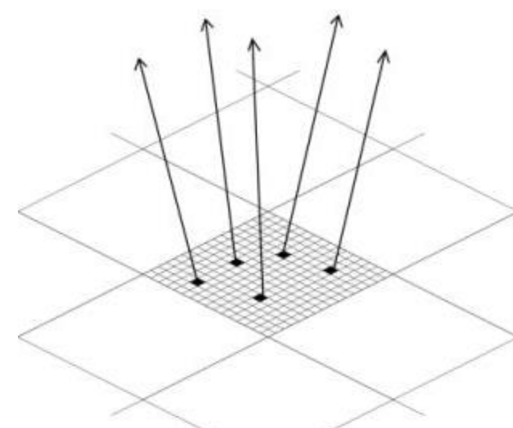


AECAL



DECAL

$N_{pixels}<N_{particles}$



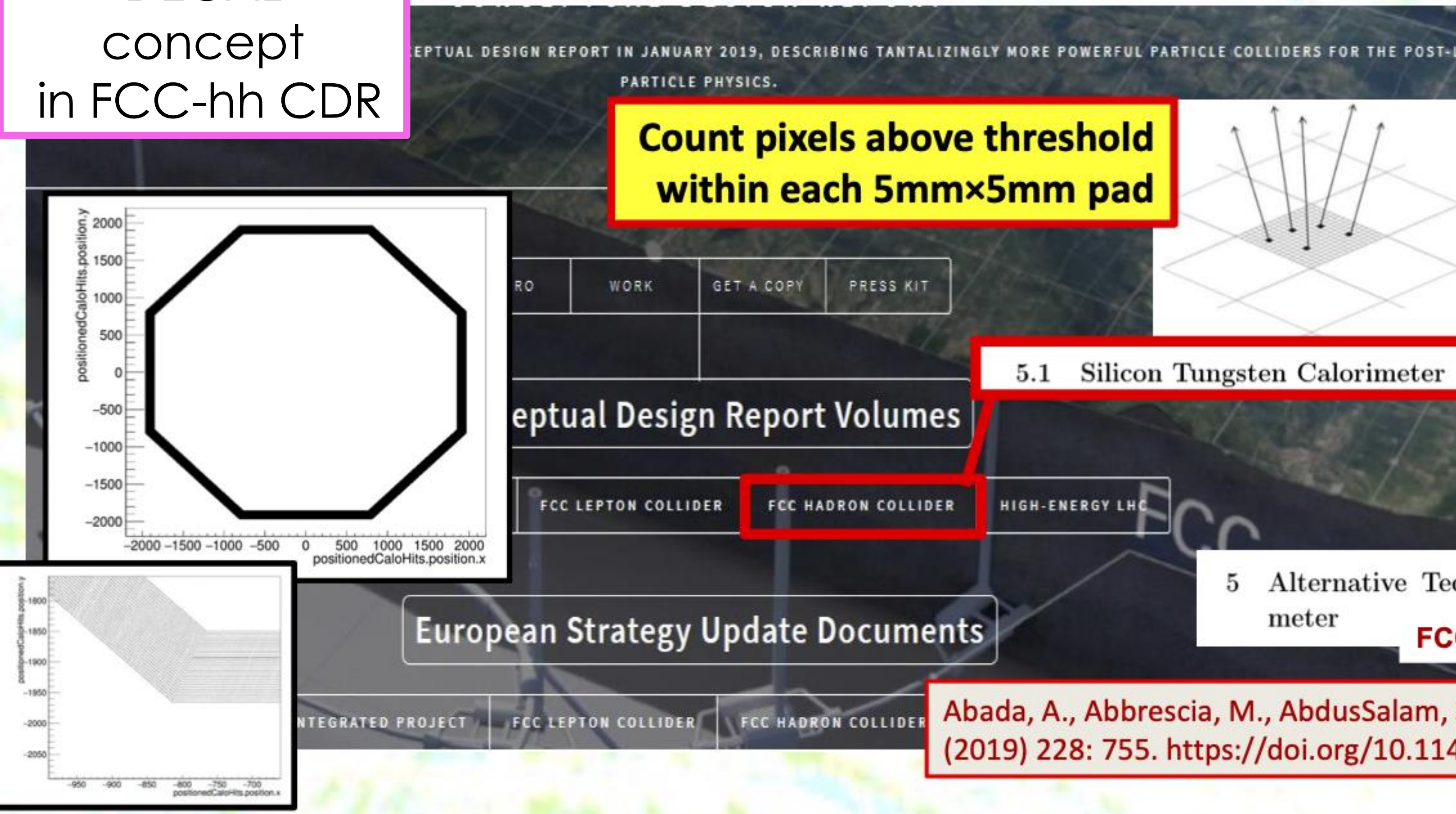
DECAL

$N_{pixels}=N_{particles}$

The Digital EM Calorimeter Concept

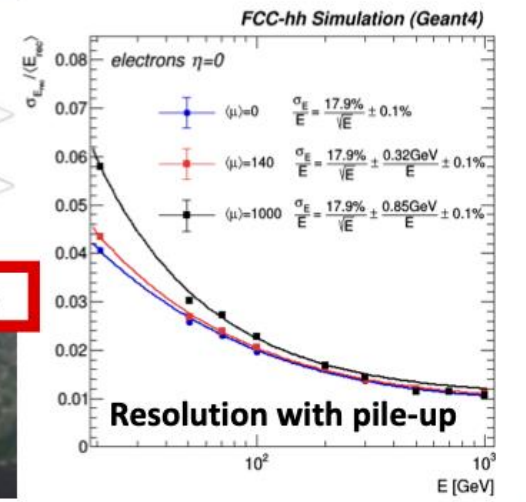
Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)
UNIVERSITY OF BIRMINGHAM

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

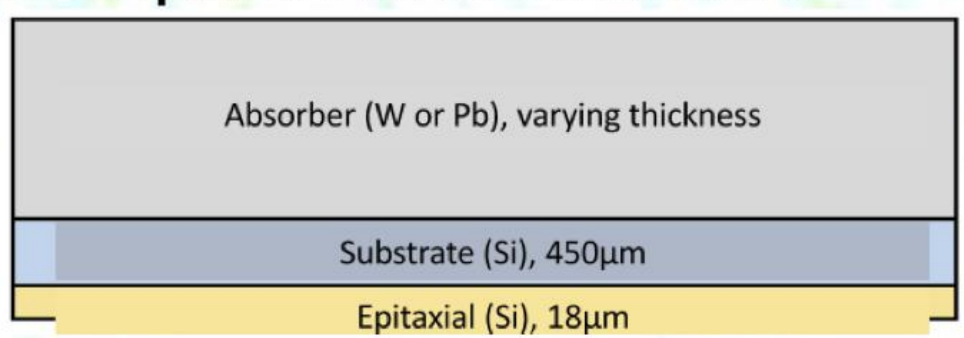
FCC Week (1/6/17) T. Price

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]

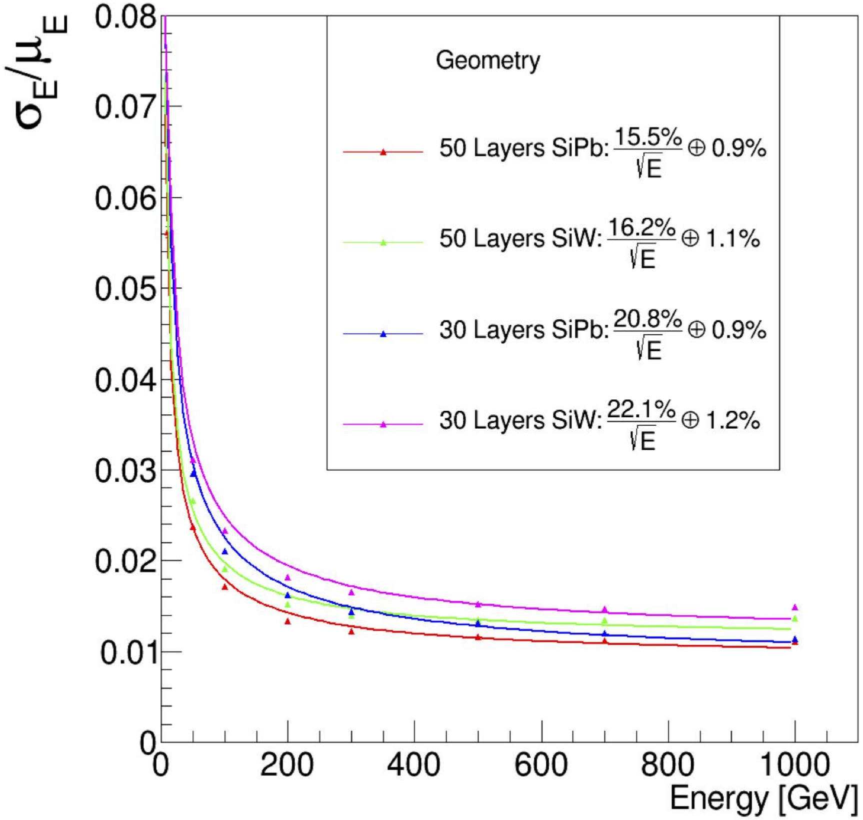
Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

UNIVERSITY OF BIRMINGHAM

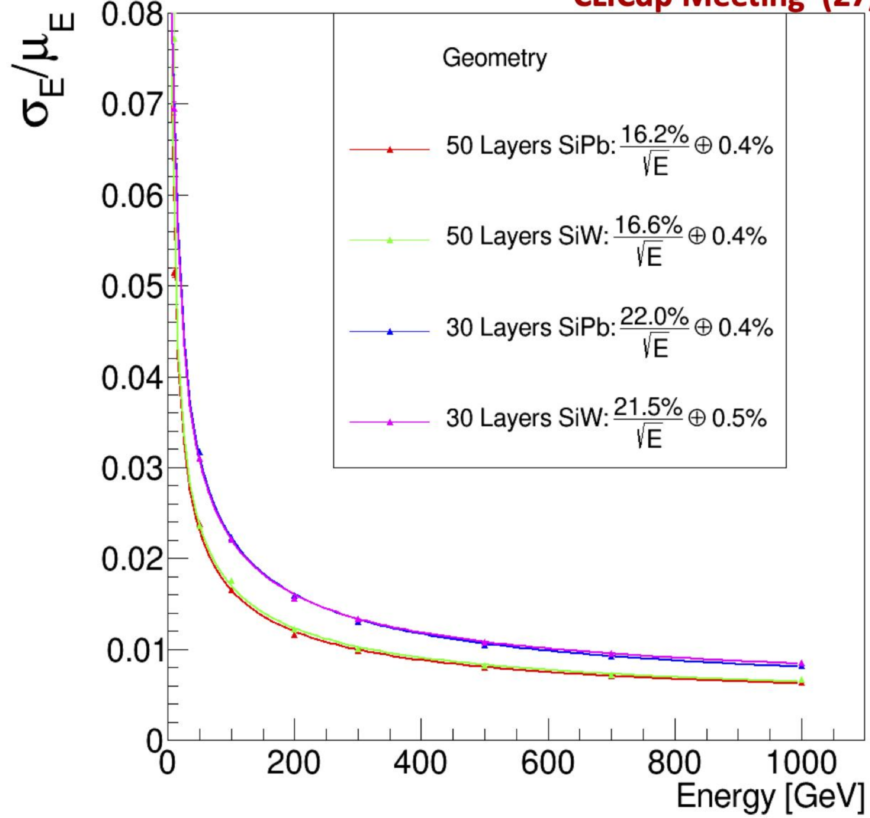
DECAL in full G4 CLIC
Comparable performance to analogue SiW

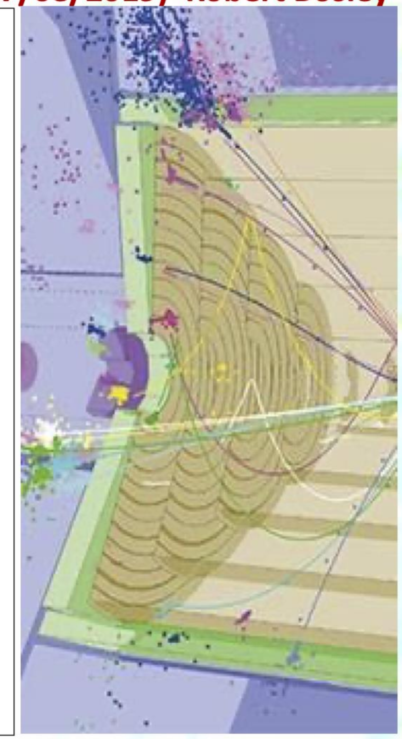
CLICdp Meeting (27/08/2019) Robert Bosley

DECAL



Analogue





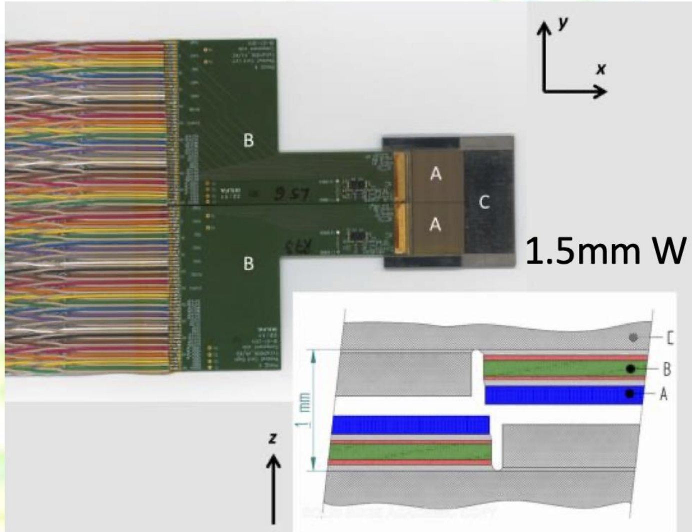
- **For single electrons, similar performance of Digital ECAL (with realistic channel threshold per pixel of 480*e**) and Analogue ECAL (with perfect performance and full substrate signal per pad) up to around 300GeV (4T field without pile-up)**
- **Above this energy, saturation (more than one hit per $50\mu m \times 50\mu m$ pixel) starts to impact performance of digital compared with analogue ECAL**

***$6 \times \sigma$ assuming noise of $\sigma = 80e$**

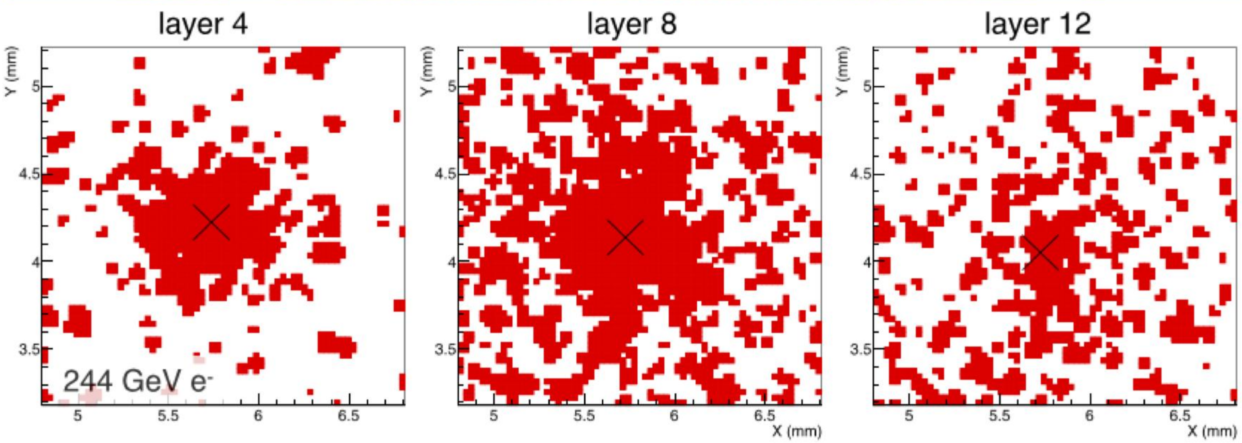
[c/o Phil Allport]

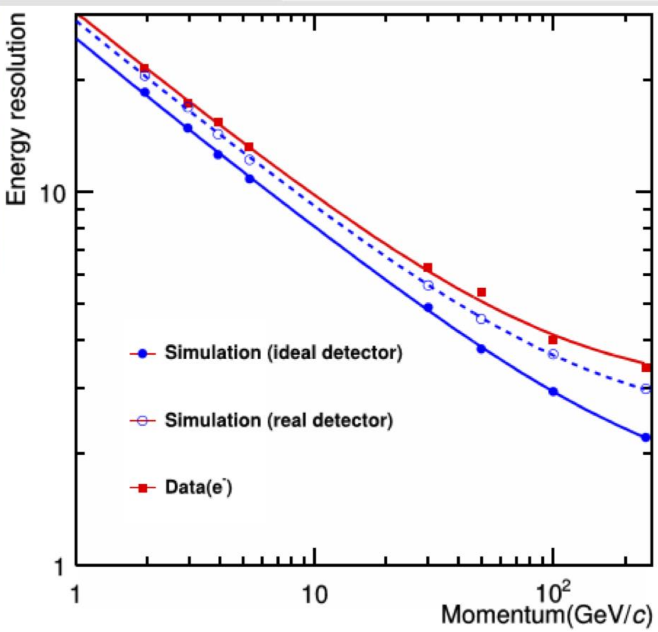
ALICE Fo-Cal MAPS R&D

T. Peitzmann: International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE (Tsukuba, 08.03.2019)



24 layer MIMOSA CMOS sensor calorimeter Si-W stack





$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{c}{E/\mathrm{GeV}}$$

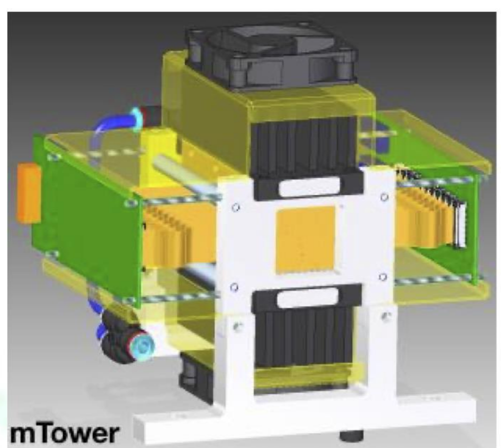
$a = (2.95 \pm 1.65)\%$

$b = (28.5 \pm 3.8)\%$

$c = 6.3\%$

244 GeV electron: very high single particle hit rate in shower core

Successor to original UK R&D on DECAL, now using 48 ALPIDE sensors. Birmingham group involved



New ALPIDE CMOS sensor based 3cm×3cm area 24 layer stack

Testbeam @DESY, Feb. 2020
Performance paper in preparation

[c/o Phil Allport]

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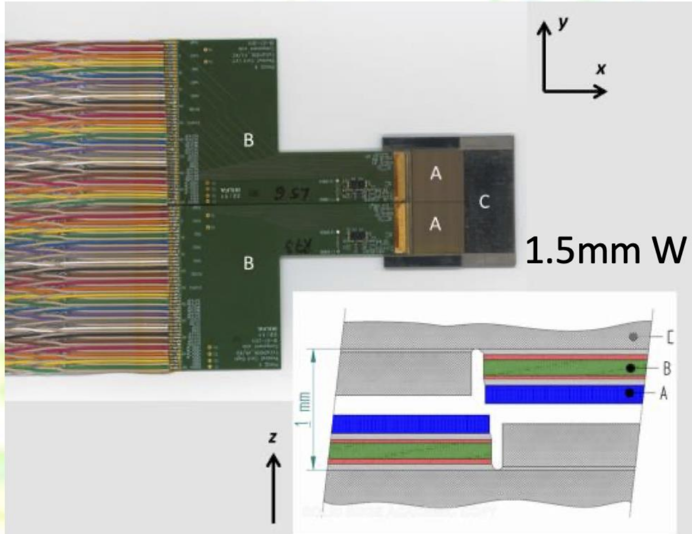

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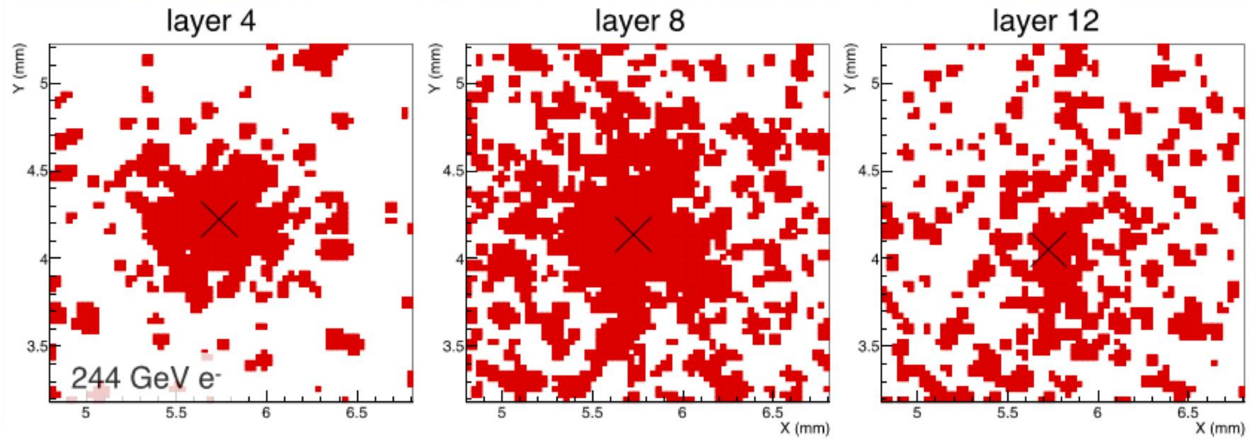

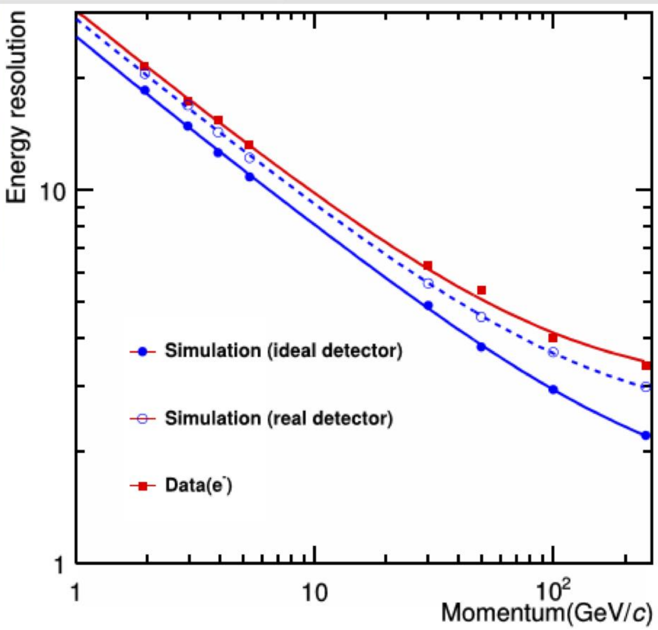

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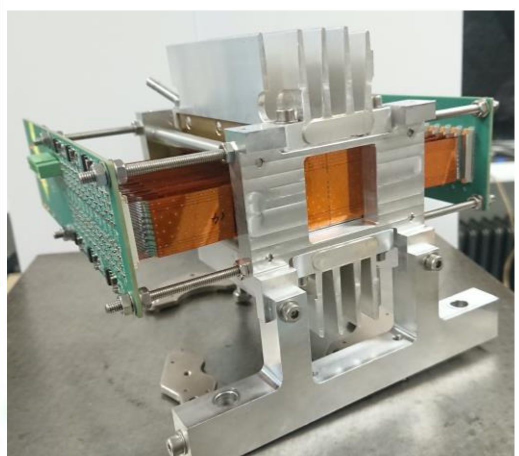

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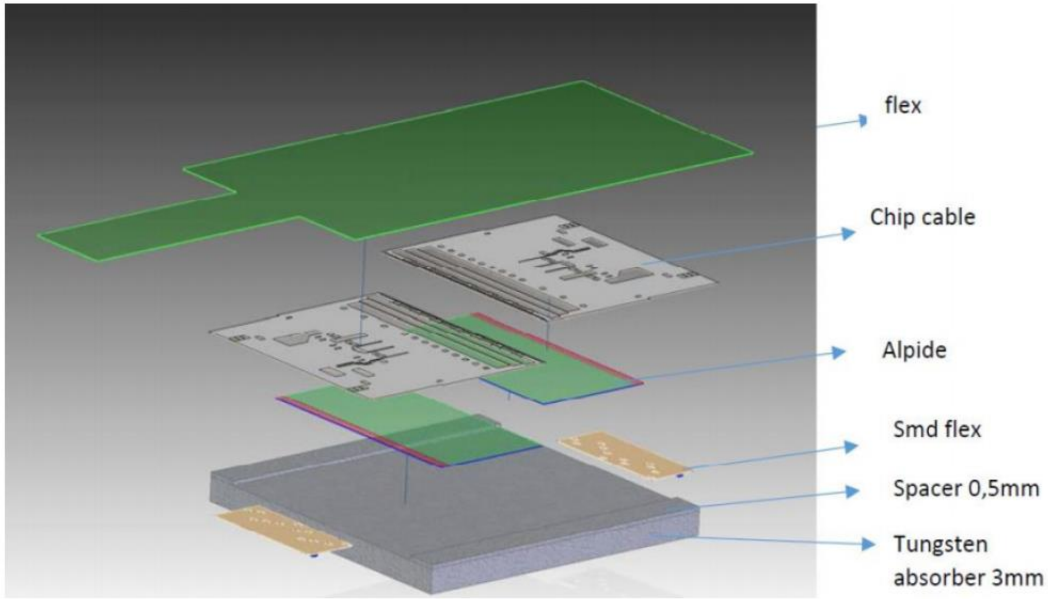
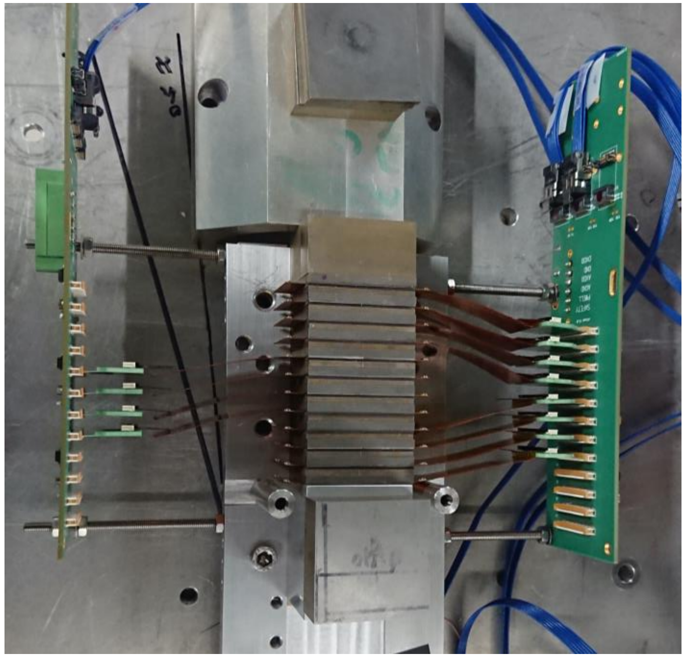
[c/o Phil Allport]

Future Opportunities (DECAL)





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

SNOWMASS21-IF6_IF0-067

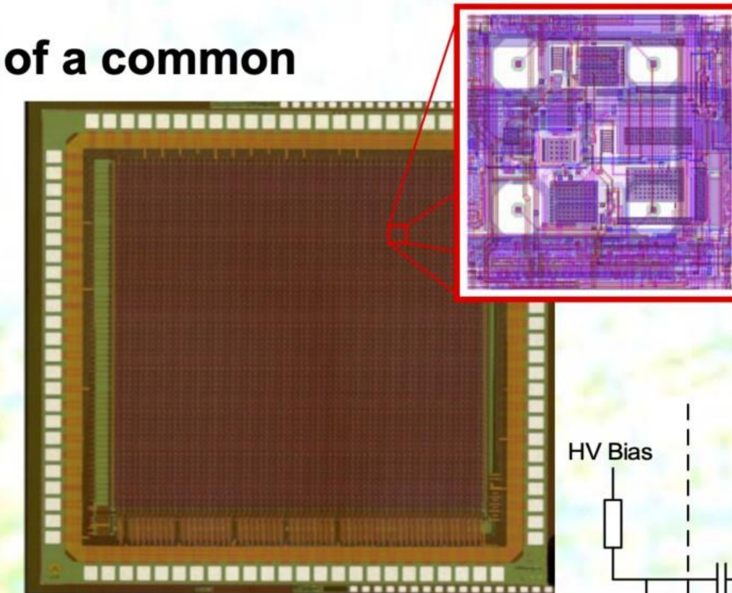
DECAL (4mm×4mm Array) Prototype Chip

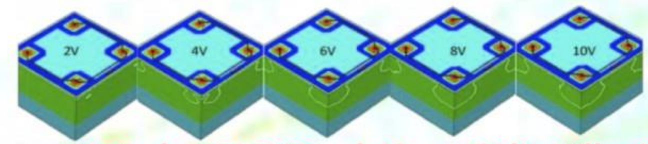
Concept in FCC-hh context of a common silicon development for:

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

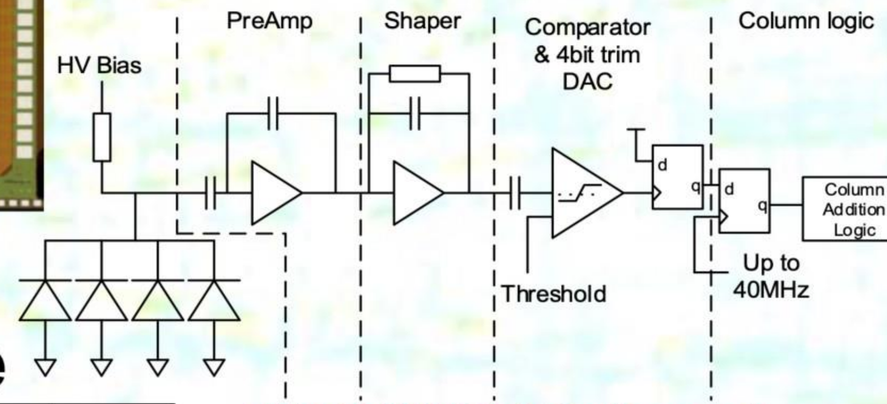
Reconfigurable sensor as:

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





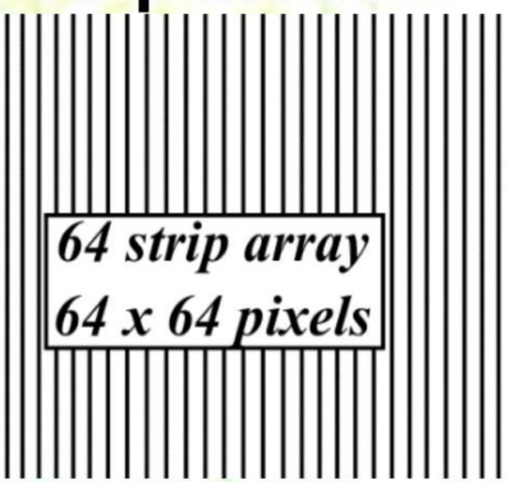
4 Diode TCAD Simulation: Giulio Villani



TWEPP (4/9/19) S.Benhammadi

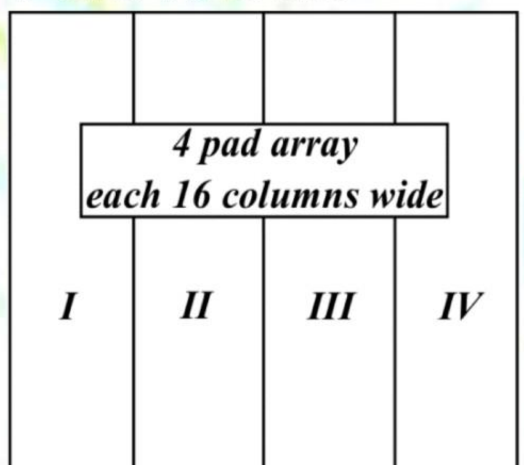
Prototype as proof of concept (180nm CMOS*)

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)**

[c/o Phil Allport]

Future Opportunities for UK

- There is always room for new ideas!

  e.g. Fabrizio Salvatore's summary for FCC, significant effort on Dual Readout

- **Si-W calorimetry can give excellent PFA performance**
  - Potential to use same technology for outer tracker/preshower/ECAL
- Affordable Si-W calorimeters, need sensor costs ~ CHF/cm^2 (active areas > $10^7 cm^2$)
  - Plausible with CMOS MAPS: large commercial market
- Power needs study, CMOS estimates range ~50-100mW/cm^2 (without pulsing)
- DECAL, in same CMOS line as CERN et al, 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 groups on mTower
  - Perfect time to take ownership/lead this novel concept for future projects

Backup

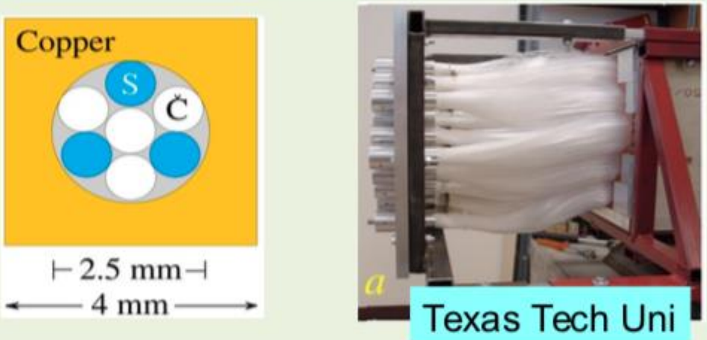
Future Opportunities (IDEA – Dual Calorimeter) – some examples

- **Hardware activities**:
  - Development of full-EM containment prototype (2021 - , tbeam at DESY in Jan/Feb 2021)
  - Development of a full-HAD containment prototype (2022 -)
  - R&D on readout architecture
    - Development of the readout for a 'full scale' detector using currently available SiPM technology
    - Development of a readout using D-SiPMs. (2022 -)
- **Detector Simulation**:
  - Simulation and digitisation of SiPM signals
    - Simulation of various beam configurations (also for general FCC-SW) – in collaboration with Uinsubria (Como) & UPavia
  - Optical photon transport in Geant4
    - Need to speed up the current optical transport for photons (very slow atm) - or study an alternative one - to allow full simulation of all readout channels
- **Software**:
  - Analysis of tbeam data: electron response, hadronic energy resolution, etc
  - Jet response in environment with 4/6 jets
  - Particle ID - in particular tau identification using ML/DL techniques
  - Calorimeter + tracking reconstruction for full simulation of detector prototype
  - Algorithms for energy/particle flow using the SiPMs' timing information

Dual readout calorimeters (PMT readouts)

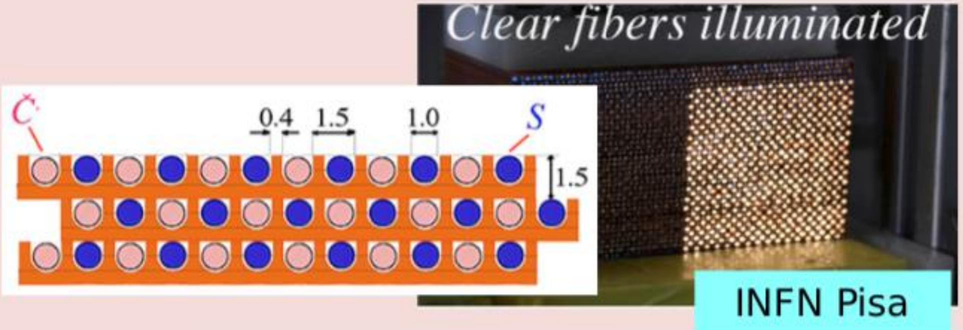
2003
DREAM

Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%



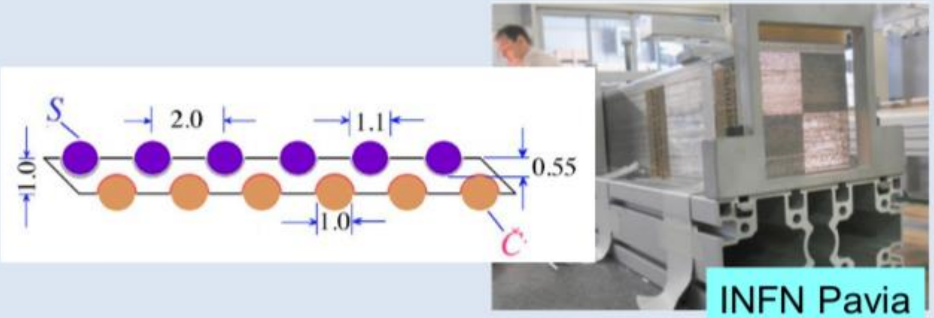
2012
RD52

Cu, 2 modules
Each module: $9.2 \times 9.2 \times 250\ \mathrm{cm}^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



2012
RD52

Pb, 9 modules
Each module: $9.2 \times 9.2 \times 250\ \mathrm{cm}^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



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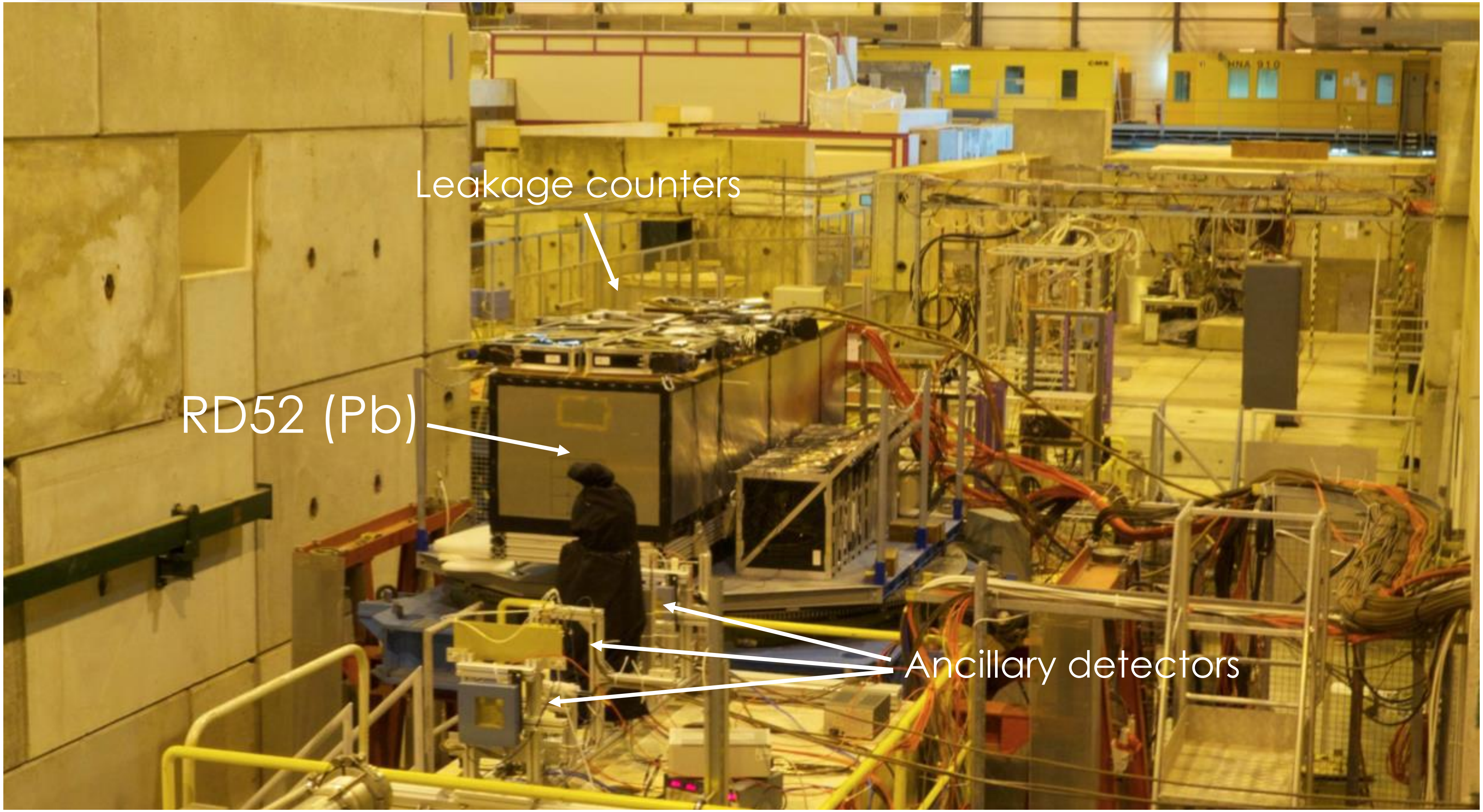
Dual readout calorimeter at work



Significant UK participation in all ongoing activities

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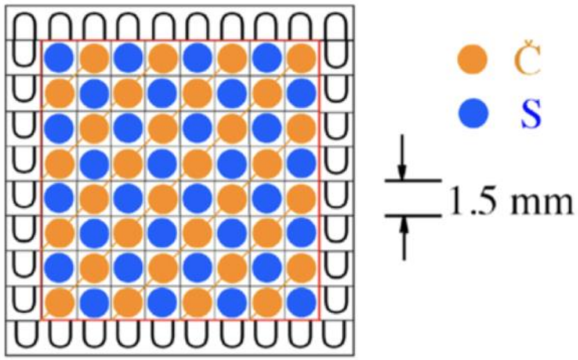
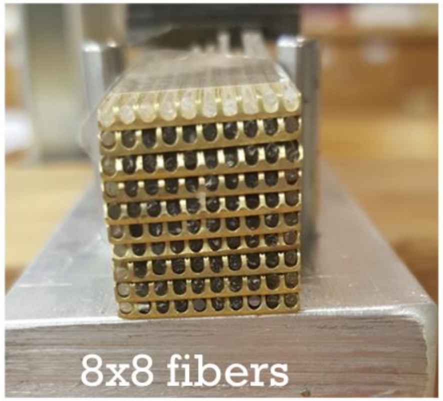
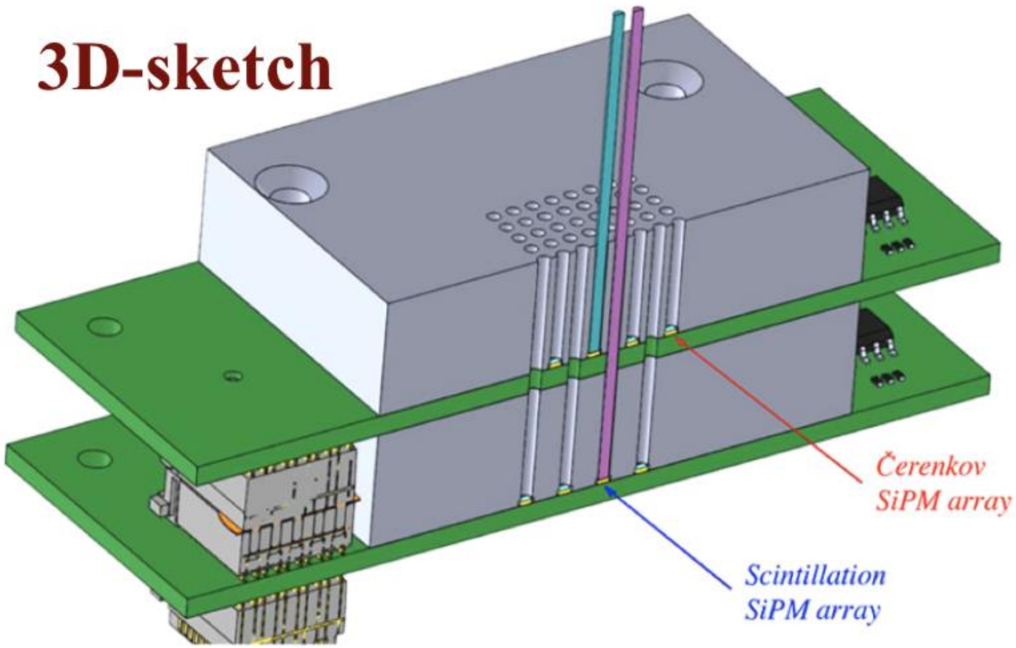
- **TB activities**:
  - Active Sussex participation in 2017 and 2018 test beams at CERN
    - Installation and data quality monitoring
    - Data analysis and related publications
  - Preparation for test of 10x10x100 cm^3 module @DESY (dates tbc)
    - Procuring and testing scintillating fibers for reading out SiPM signals
- **Software/Simulation**:
  - Simulation of the detector and integration in Geant4
  - Detector characterisation and physics studies
  - DAQ & Monitoring

SiPM dual readout







- Single fibre readout with **HAMAMATSU SiPM.**
- Readout for Cherenkov and Scintillation light **separated to minimise cross talk** (the latter expected to be ~ 50 times larger if not attenuated).