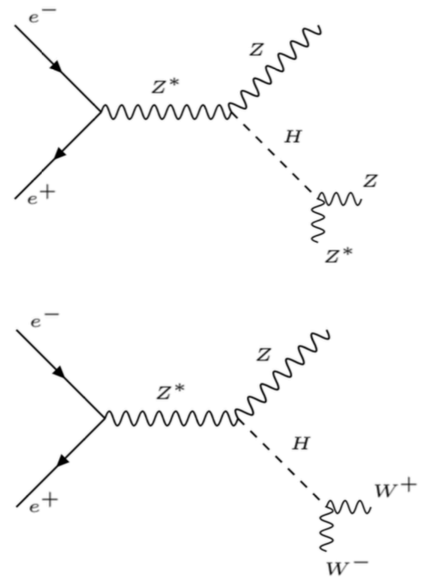
UNIVERSITY OF SUSSEX

Calorimeters for Future Colliders

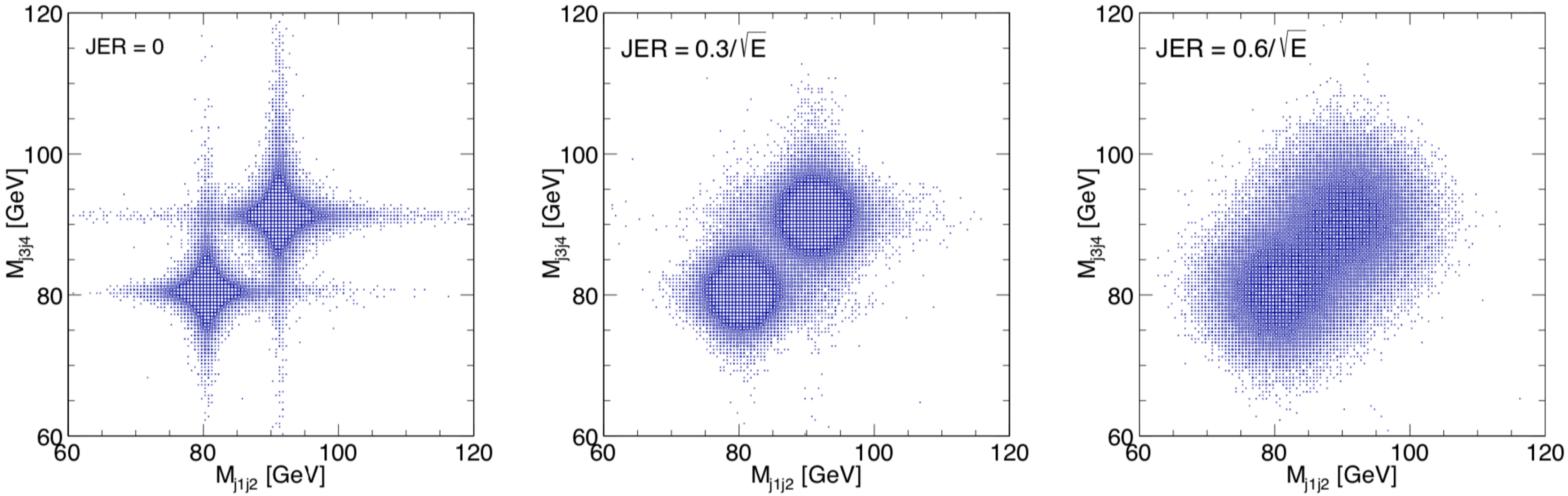
Fabrizio Salvatore (University of Sussex)
Nigel Watson (University of Birmingham)

Physics requirements for calorimetry

- **Precision physics** at e$^+$e$^-$ collider calls for **high-resolution calorimetry**



Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)



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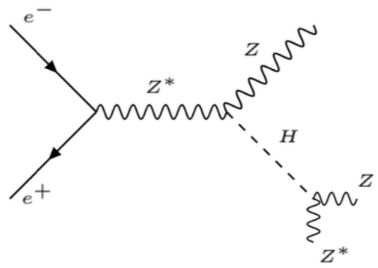
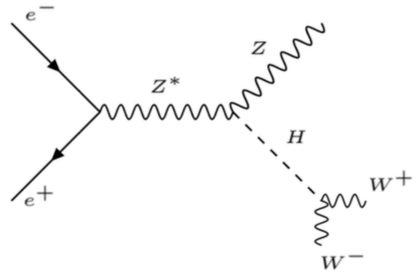




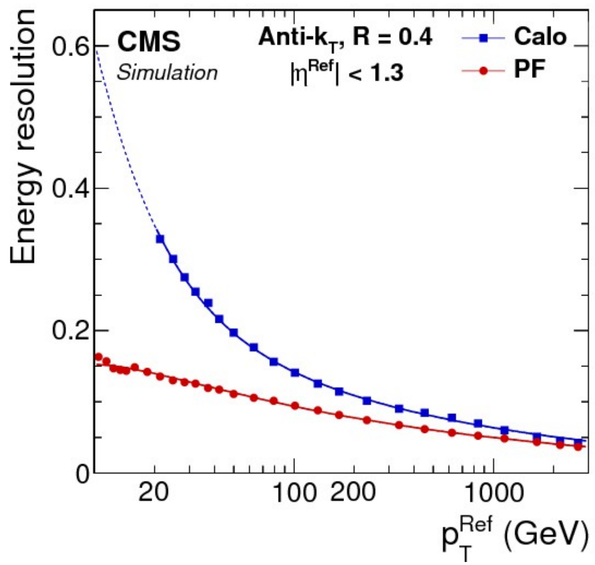
Two possible approaches:

- Particle Flow (PFA) Calorimeters
- Dual-Readout Calorimeters

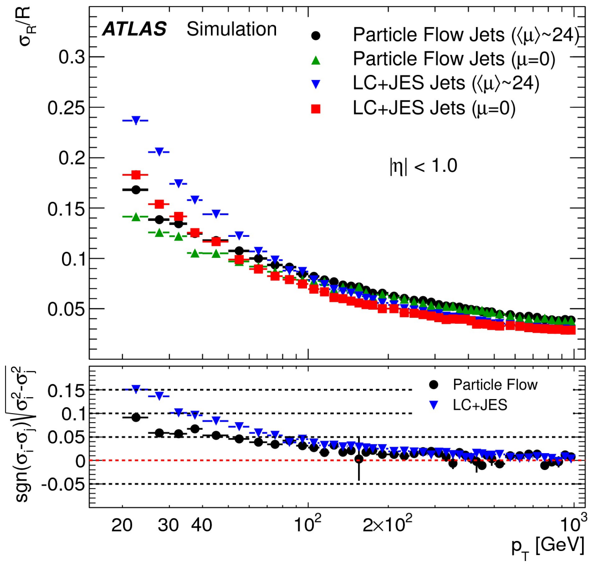
Particle flow approach

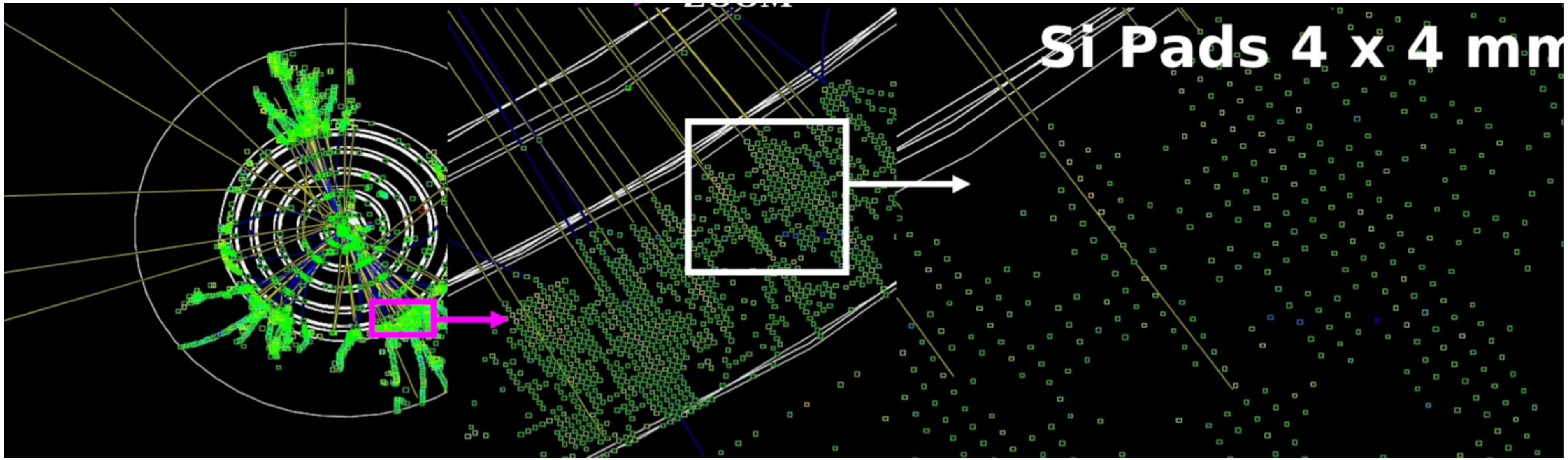
- Basic idea: tracking wins at low particle momenta
  - Use **tracks** to measure **charged particles** in the shower

From arXiv:1706.04965



From Eur. Phys. J C77 (2017) 466





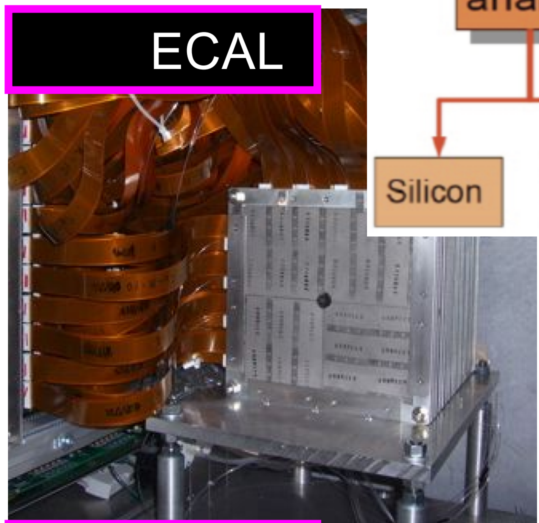
From https://warwick.ac.uk/fac/sci/physics/staff/academic/boyd/warwick_week/detector_physics/warwick_lecture_calorimetry.pdf

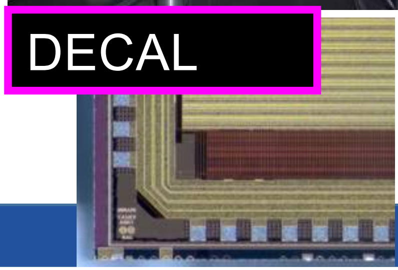
ECAL Design Principles

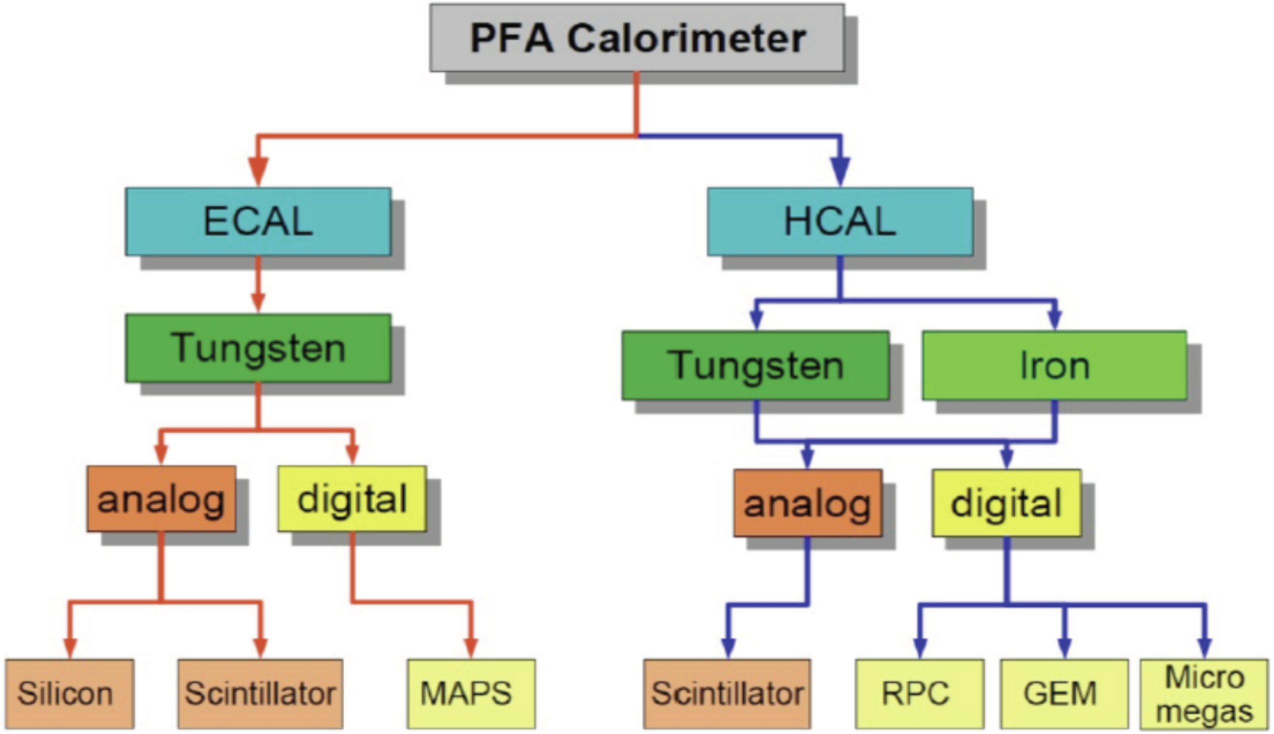
- Measure 100% EM energy
  - shower containment in ECAL, so X_0 large
- Resolve energy deposited by individual particles
  - small $R_{moliere}$ and X_0 – compact and narrow showers
- Separation of hadronic/EM showers
  - λ_{int}/X_0 large, so EM showers early, hadronic showers late
- Minimal material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

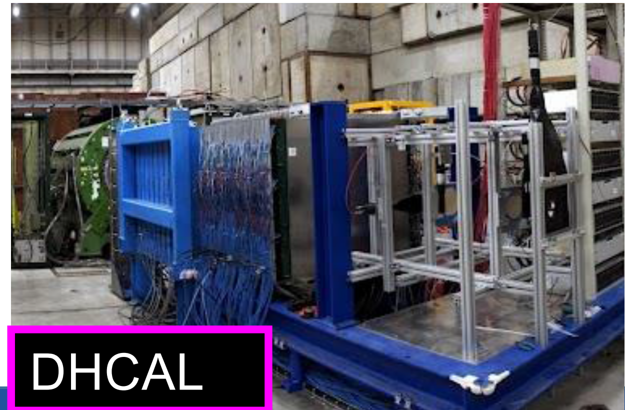
  } ECAL, HCAL inside coil (cost!)
- Active medium: Silicon (or scintillator)
  - Pixel readout, minimal interlayer gaps, stability

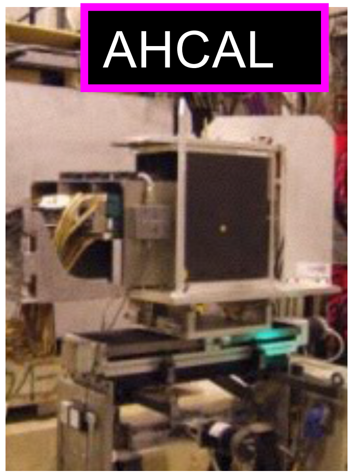
CALICE-like solution(s)

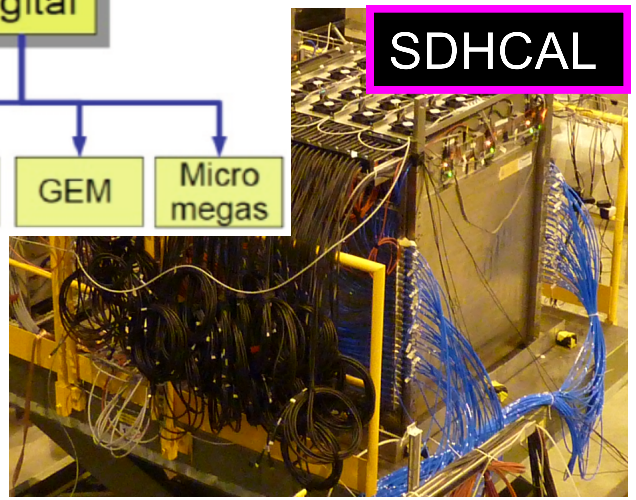


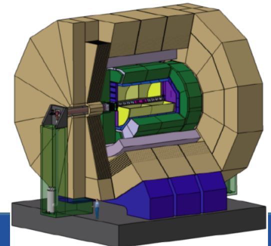












CALICE Collaboration

- 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 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)

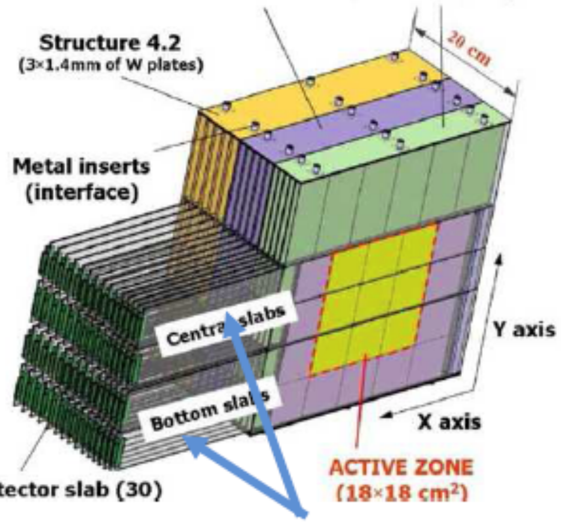
2.8 mm (0.8 X_0)

4.2 mm (1.2 X_0)

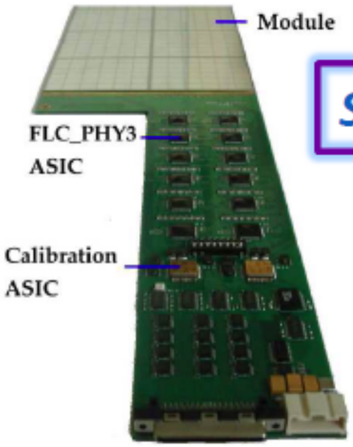
9720 channels

2005 - ECAL Physics prototype

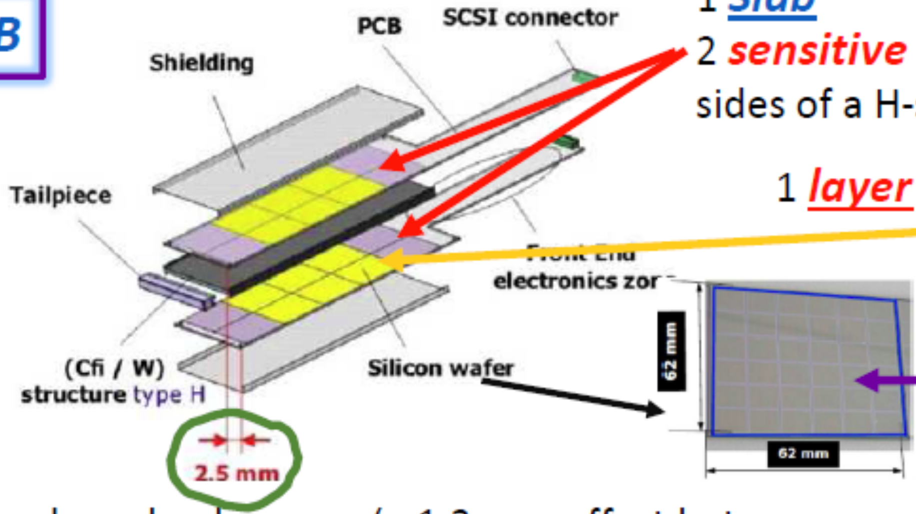
Lateral size: 18x18cm²



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)

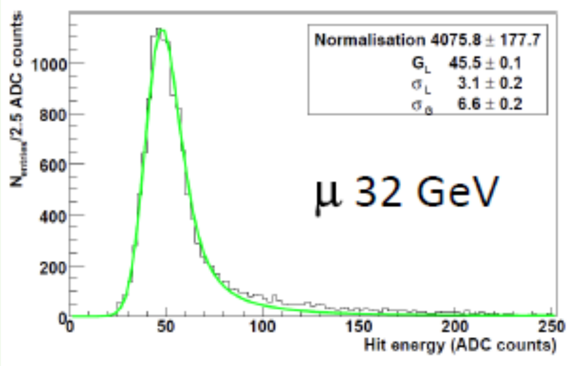
Si-W ECAL Calibration

original FNAL e^+ test beam

1.- Pedestal subtraction

2.- ADC-MIP calibration

Response of *single channels to μ*
Landau convoluted with a Gaussian
MIP signal=
most probable value of the Landau



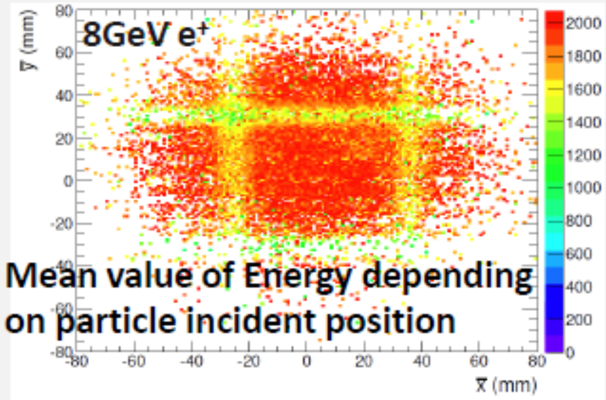
3.- Energy Reconstruction

$$E_{raw} = \sum_{i=0}^{9} E_i + 2\sum_{i=10}^{19} E_i + 3\sum_{i=20}^{29} E_i$$

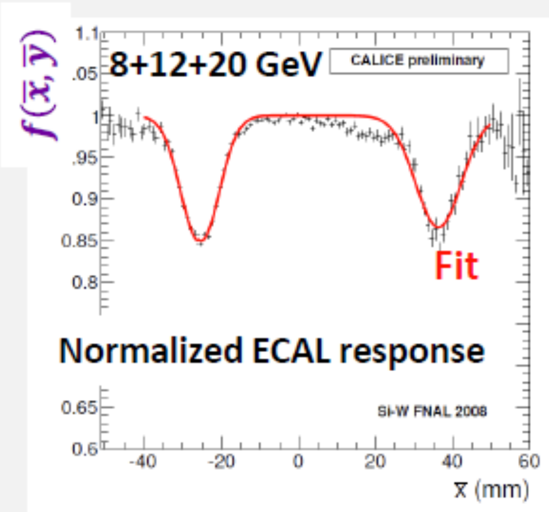
Stacks *weighted* according their thickness
E_i = Total energy plane *i*

4.- Gap correction

1+1 mm inactive area between wafers (guard ring)
➔ non-uniform energy response

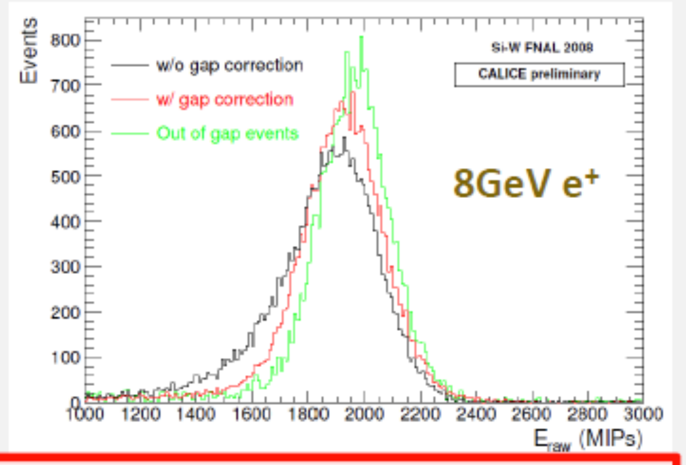


Mean value of Energy depending on particle incident position



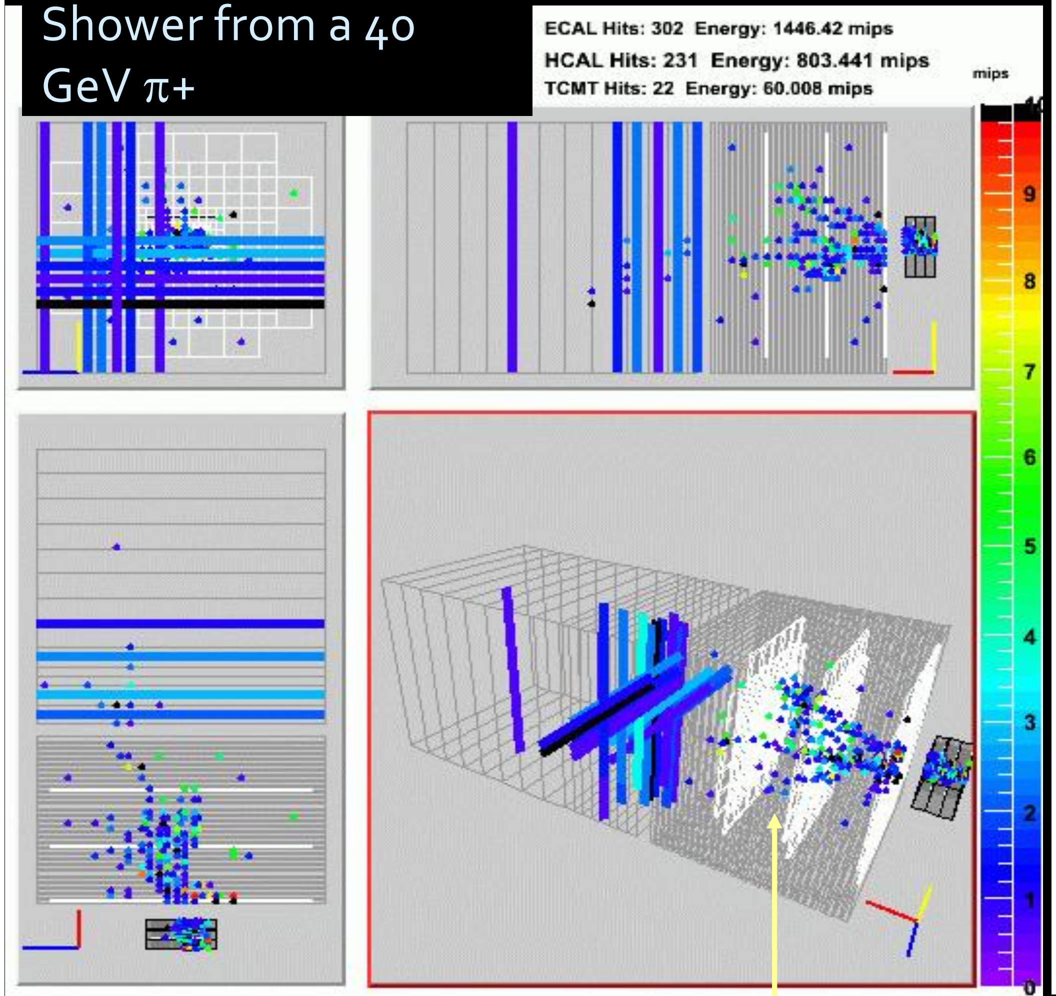
Normalized ECAL response

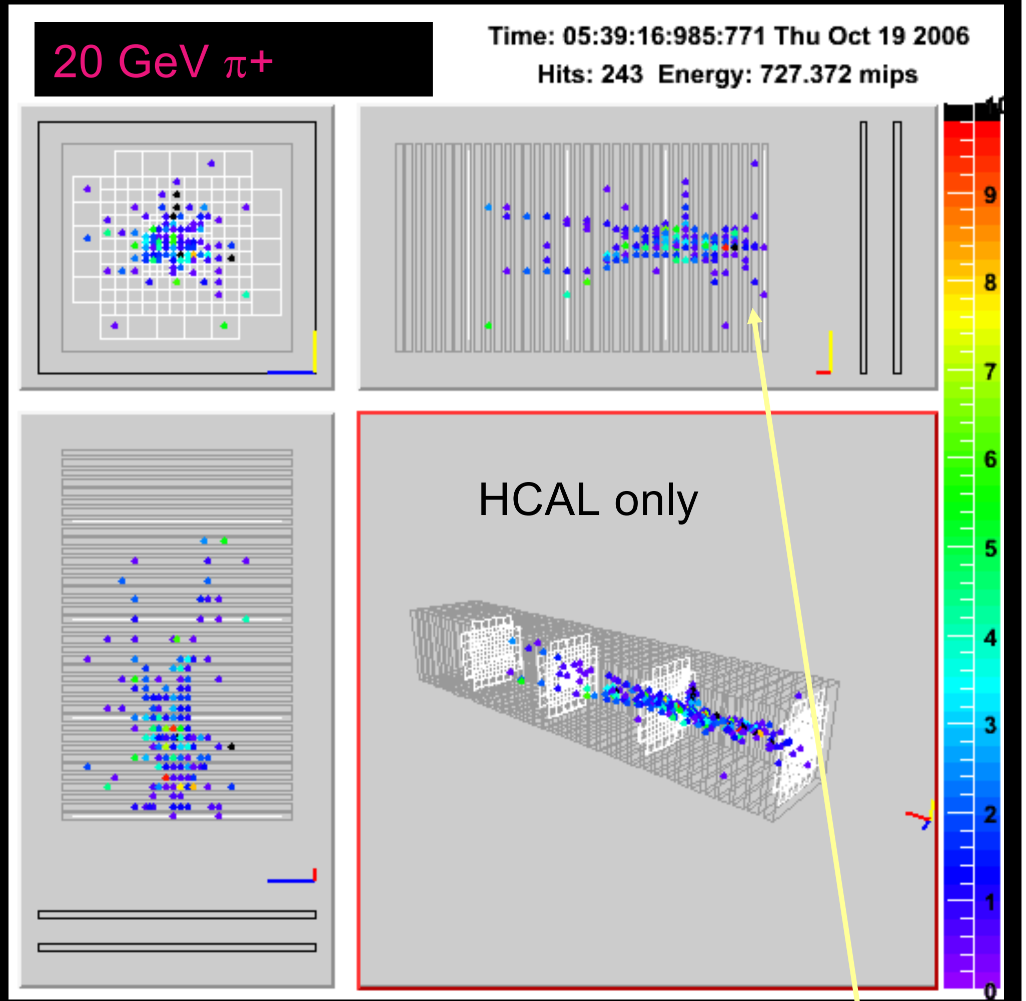
Energy can be corrected by $1/f(\bar{x},\bar{y})$



More Gaussian after gap correction

Event display





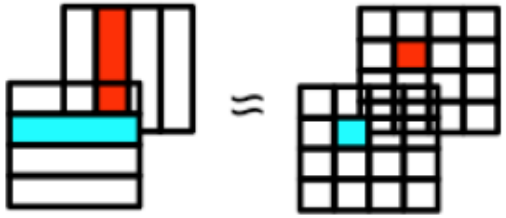
Clear structure visible in hadronic shower

Back-scattered particle

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

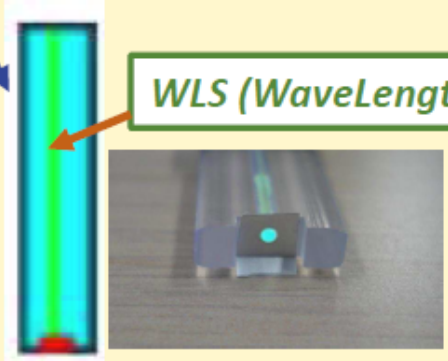
→ $1x1cm^2$ effective granularity

Less readout channels

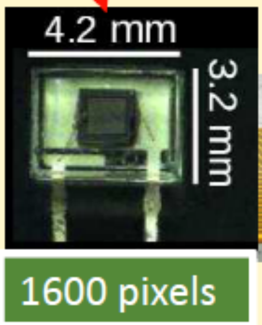
but shower reconstruction more complicated

Strip 4.5x1 cm^2 3mm thick

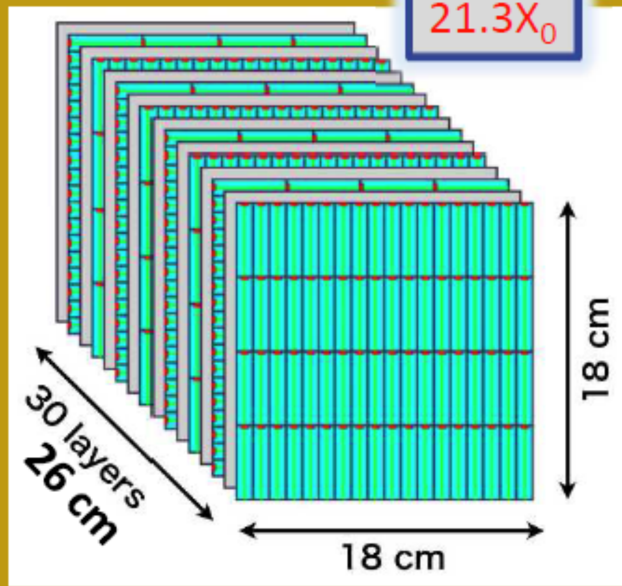
WLS (WaveLength Shifting) fiber



MPPC (MultiPixel Photon Counter)

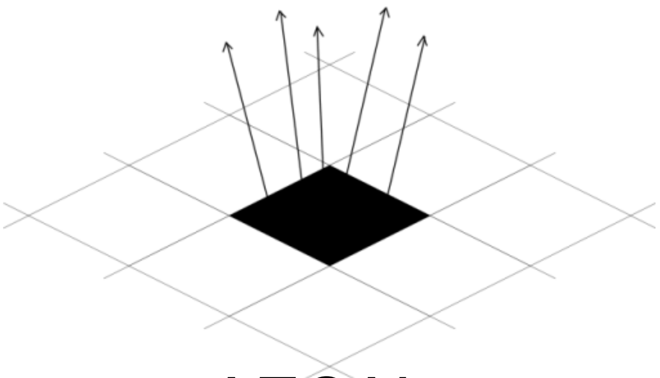


$21.3X_0$

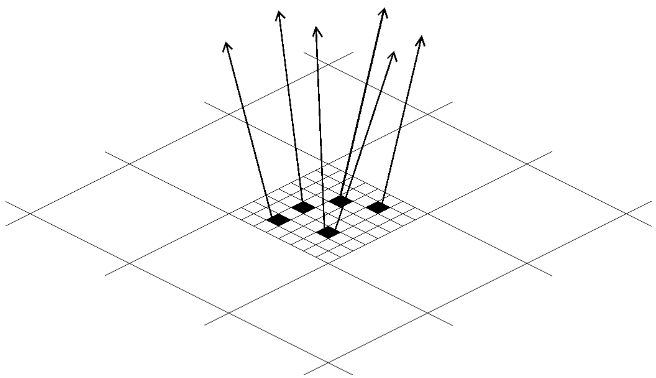


DECAL Concept – cost reduction for ECAL??

- Concept, swap ~0.5x0.5 cm^2 Si pads with small pixels ("Small" := at most one particle/pixel,1-bit ADC/pixel - digital)
- How small to avoid saturation/non-linearity?
  - EM shower core density at 500GeV is ~100/mm^2
  - Pixels must be<100x100μm^2
    - Used baseline 50x50μm^2
  - Gives ~10^{12} pixels for ECAL – "Tera-pixel APS"
  - Mandatory to integrate electronics on sensor

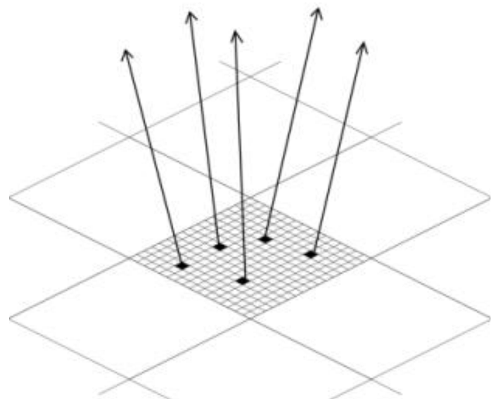


AECAL



DECAL

$N_{pixels}<N_{particles}$



DECAL

$N_{pixels}=N_{particles}$

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The Digital EM Calorimeter Concept

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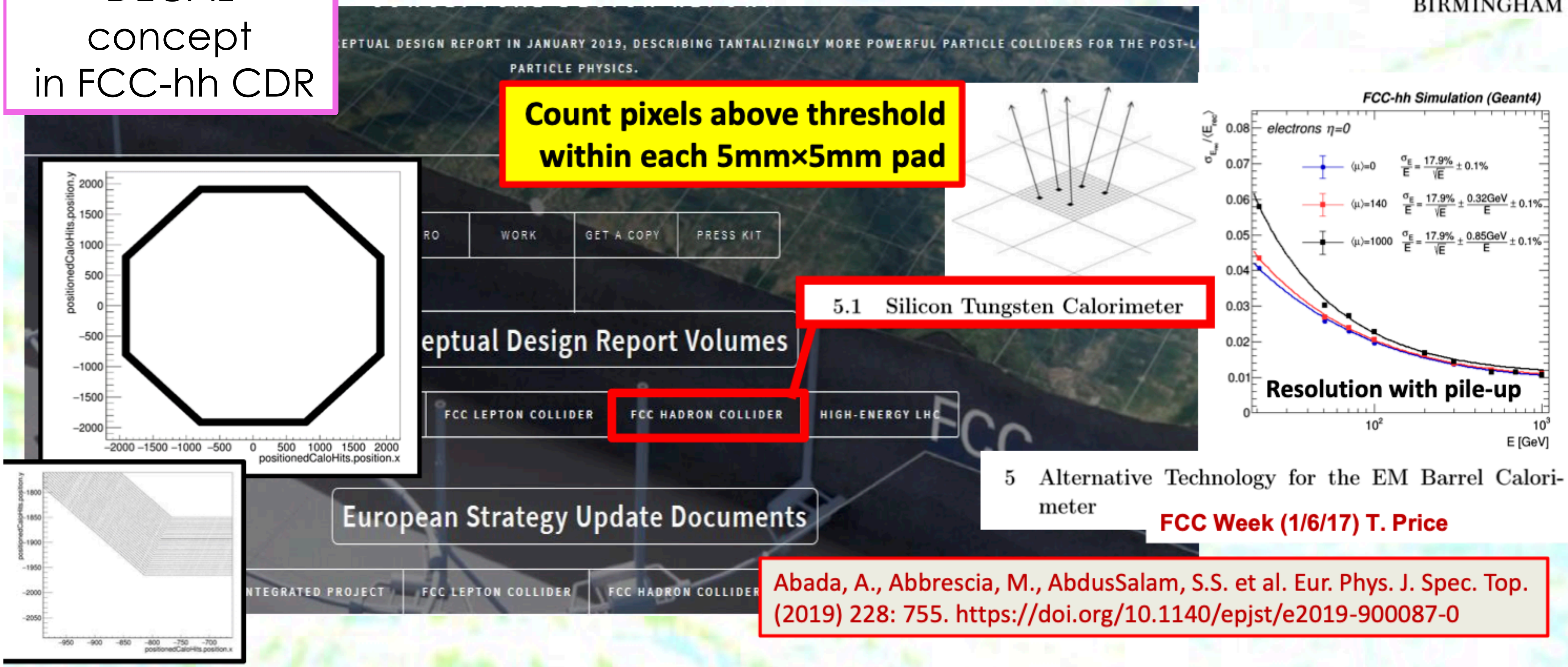
DECAL concept in FCC-hh CDR



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

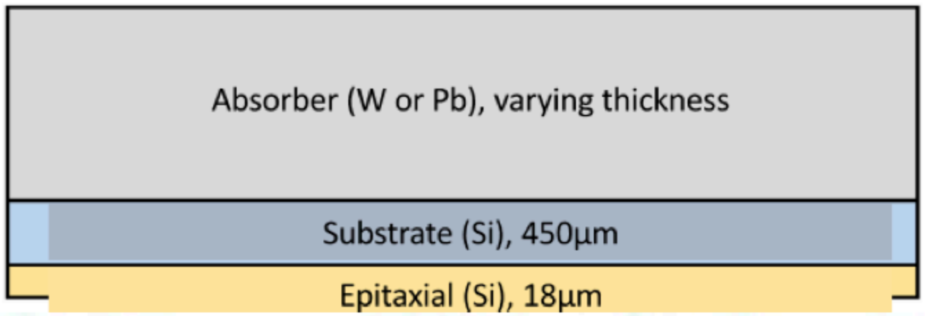
Simulated 4 different geometries:

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]

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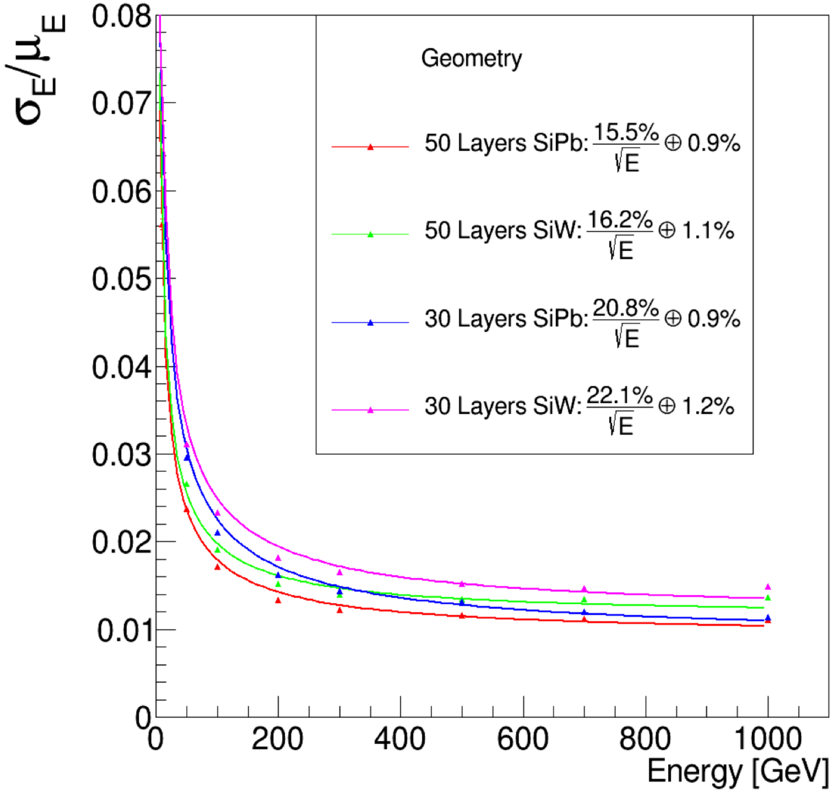
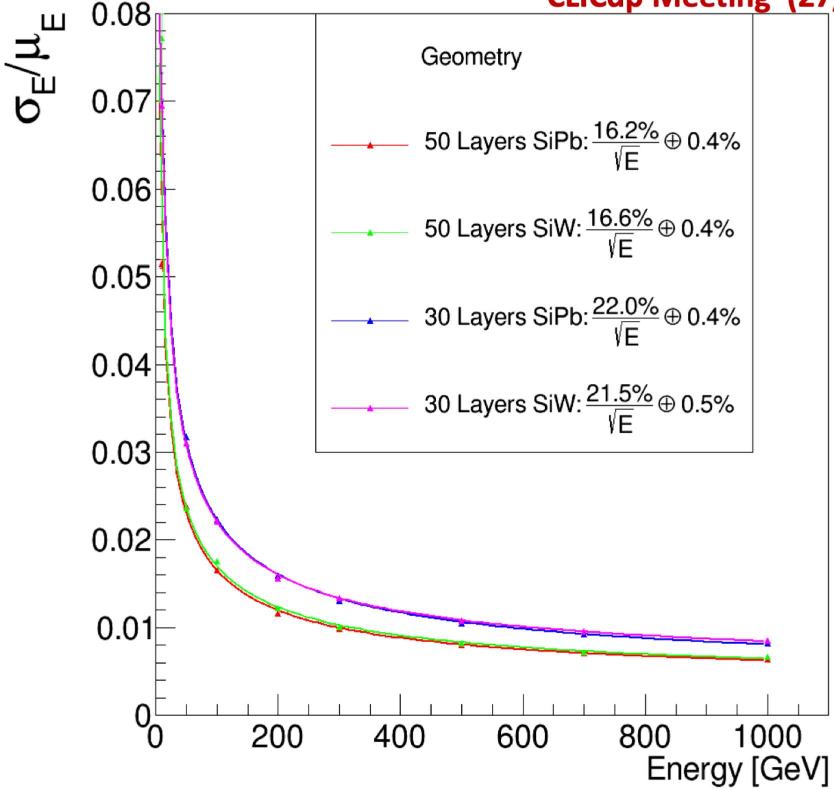
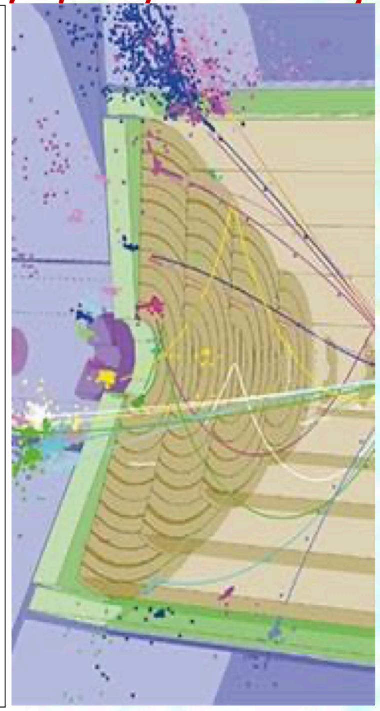
DECAL in full G4 CLIC
Comparable performance to analogue SiW





CLICdp Meeting (27/08/2019) Robert Bosley



- **For single electrons, similar performance of Digital ECAL (with realistic channel threshold per pixel of 480e*) 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 50μm × 50μm pixel) starts to impact performance of digital compared with analogue ECAL**

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

[c/o Phil Allport]

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ALICE Fo-Cal MAPS R&D

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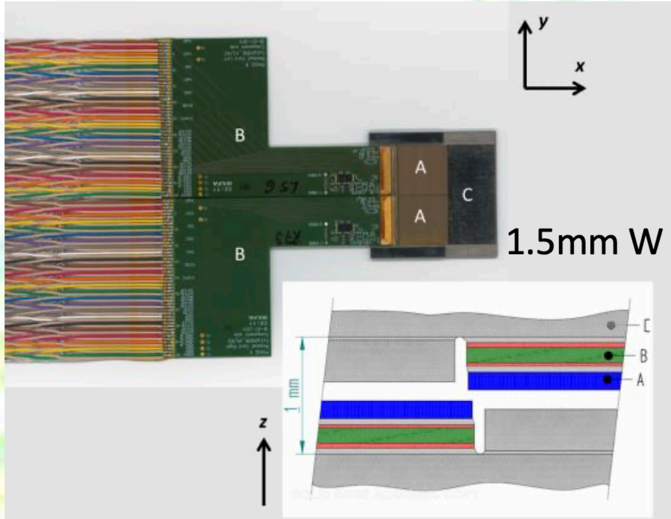
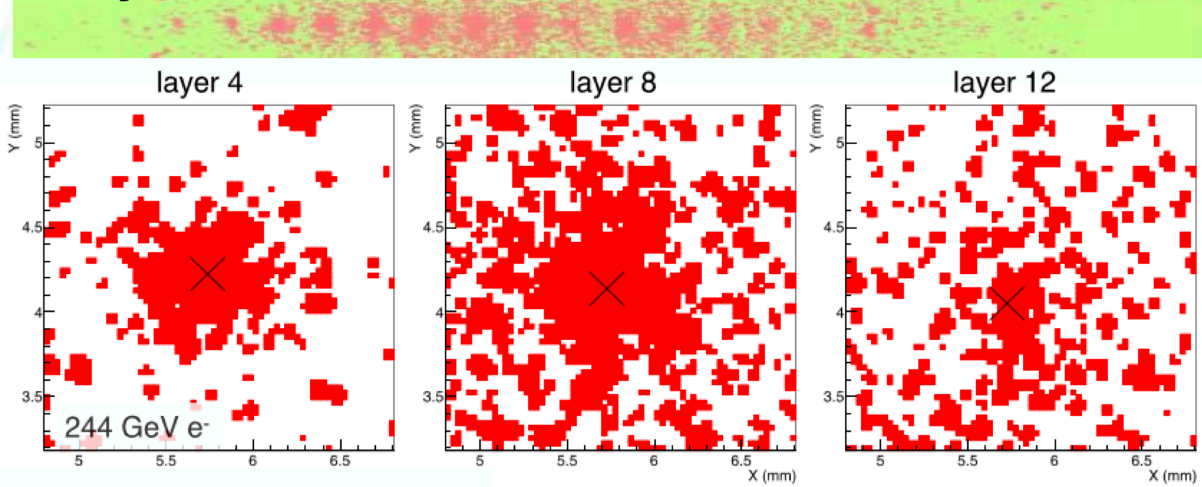
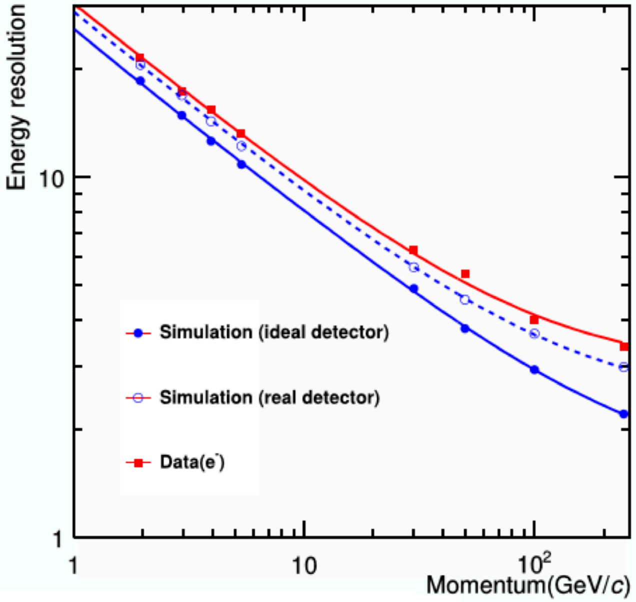
T. Peitzmann: International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE (Tsukuba, 08.03.2019)



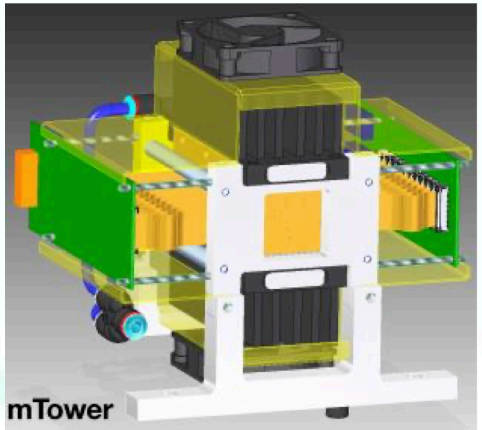
24 layer MIMOSA CMOS sensor calorimeter Si-W stack





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

$$a = (2.95 \pm 1.65)\%$$
$$b = (28.5 \pm 3.8)\%$$
$$c = 6.3\%$$



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

Looking forward to results from test-beams with this system

[c/o Phil Allport]

DECAL (4mm×4mm Array) Prototype Chip

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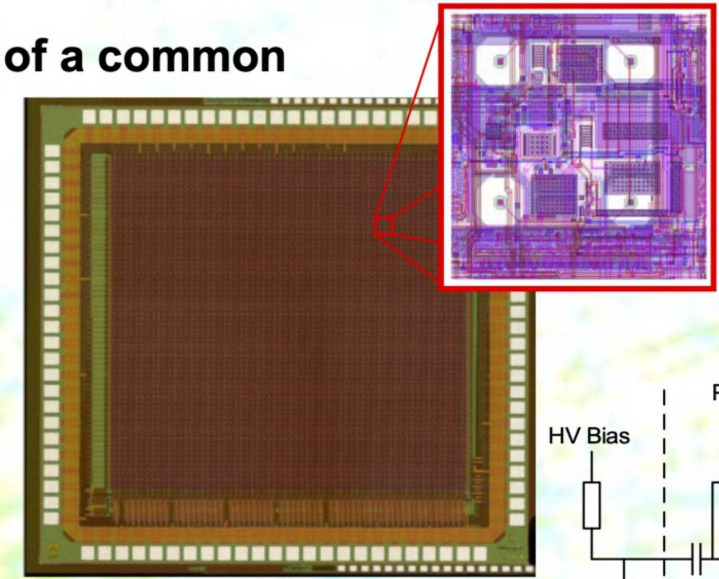
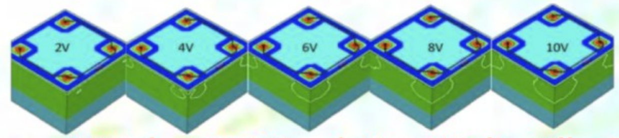
Concept in FCC-hh context of a common silicon development for:

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

Reconfigurable sensor as:

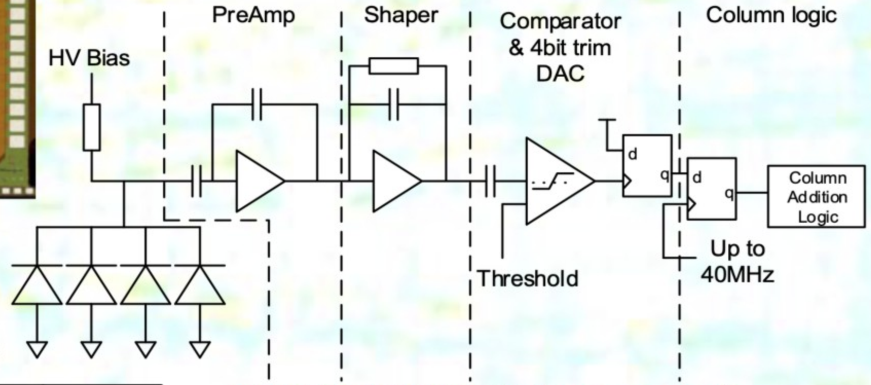
- **5mm×50μm strips**
- **5mm×5mm pad**





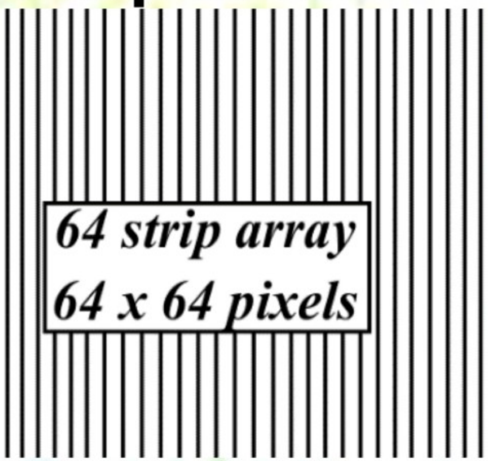
4 Diode TCAD Simulation: Giulio Villani

Prototype as proof of concept (180nm CMOS*)



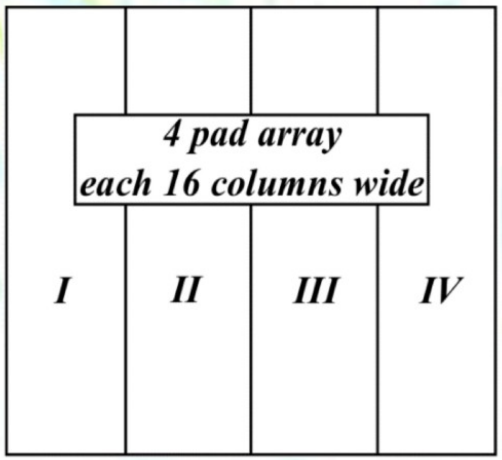
TWEPP (4/9/19) S.Benhammadi

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)**

[c/o Phil Allport]

Future Opportunities (CALICE/MAPS)

- **Si-W calorimetry should allow 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 Imaging Sensor 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
  - Currently, UK (Birmingham) working with ALICE FoCAL groups on mTower
  - Perfect time to take ownership/lead this novel concept for future projects

HCAL R&D: why is hadronic calorimetry challenging?

Typically* the calorimeter response to the electromagnetic (e) and hadronic (h) components is different

*This is actually true for non-compensating calorimeter (the vast majority of those in use nowadays)

The fraction of energy in EM and HAD components is energy dependent with large fluctuations

The calorimeter response to hadrons is energy dependent and has large fluctuations

Dual readout - the principle

- Suppose I read out **two calorimeter signals, S and C, with different h/e**. Then:

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

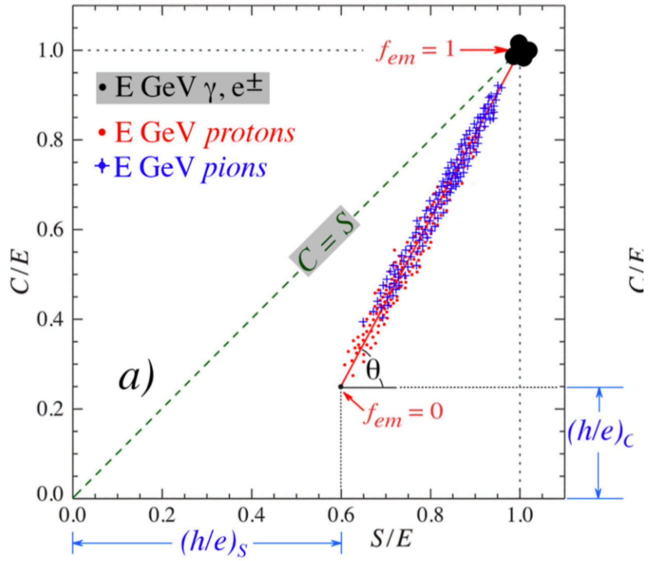
$$E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right)$$

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

$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

Depends **only on the detector**, it can be determined in test beam, for example.

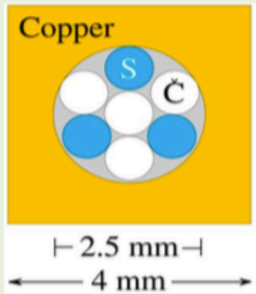


Dual readout calorimeters (PMT readouts)

UNIVERSITY OF SUSSEX

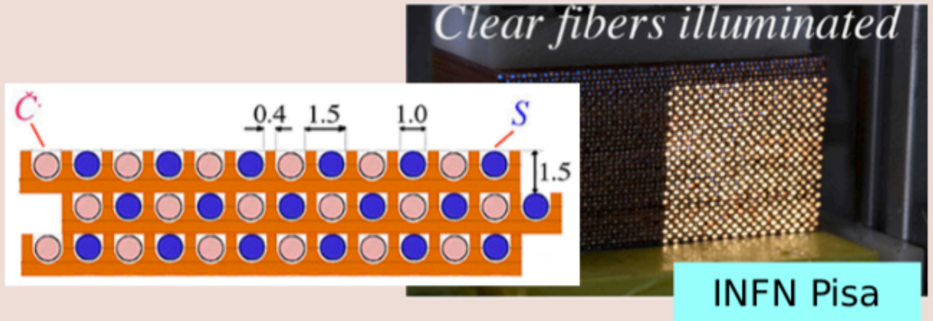
2003
DREAM

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



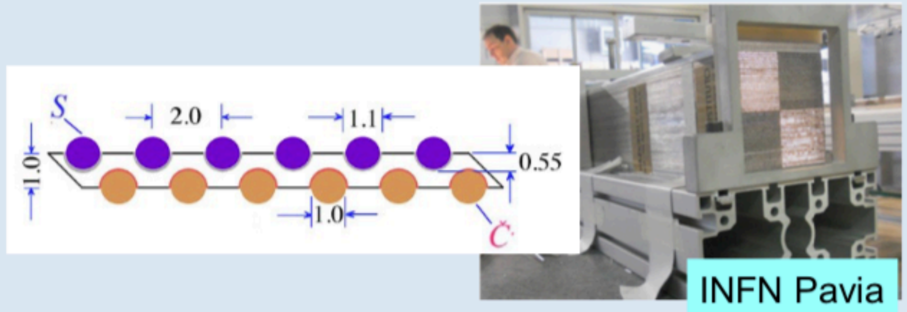
2012
RD52

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

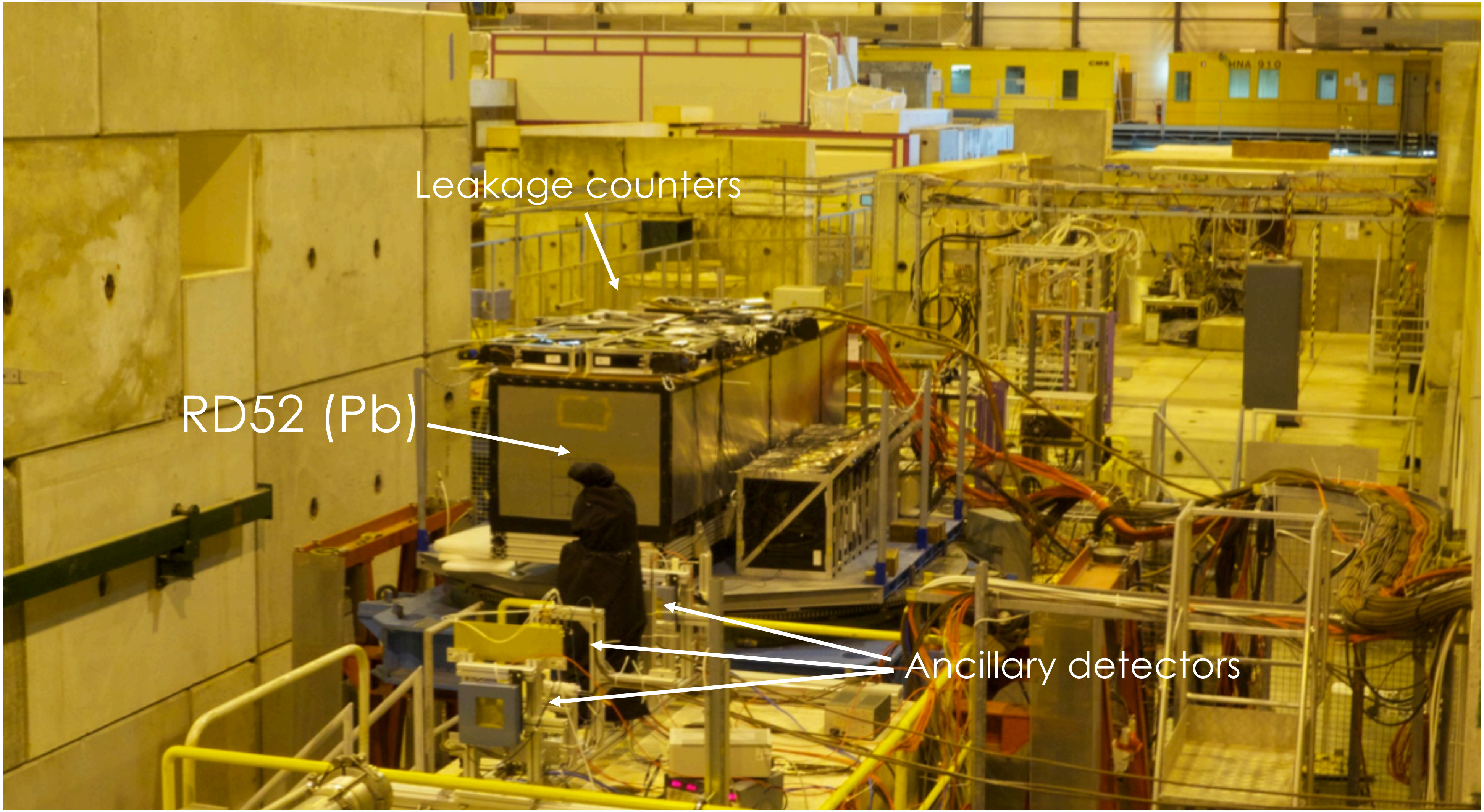


2012
RD52

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



Dual readout calorimeter at work



Significant UK participation in all ongoing activities

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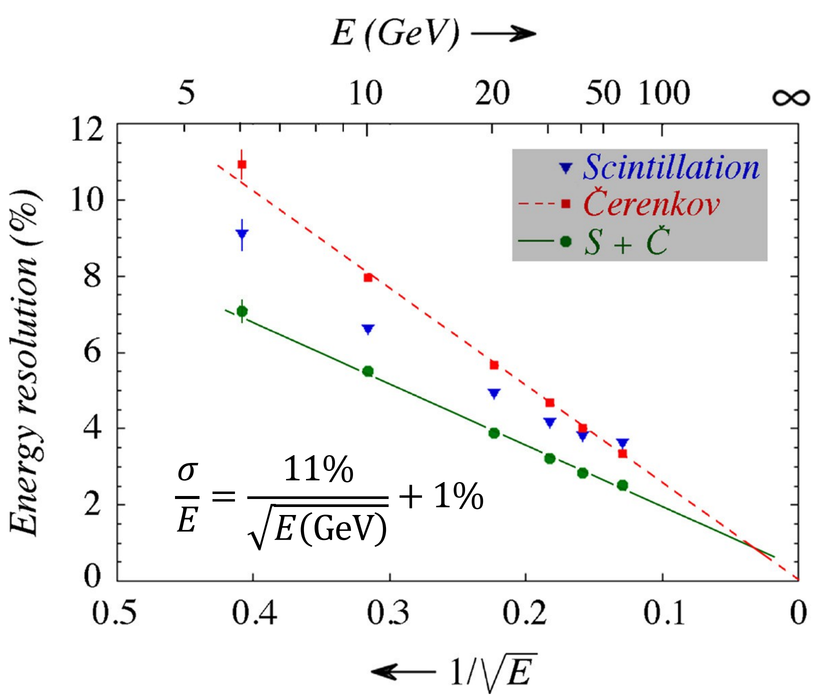
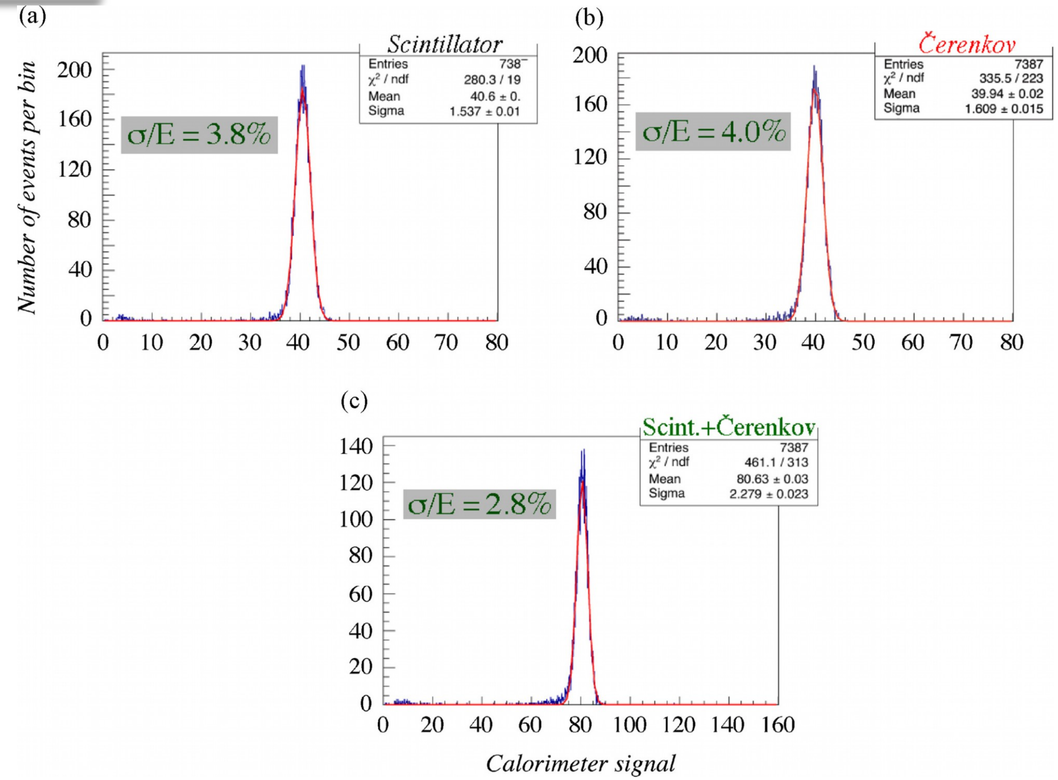
- **TB activities**:
  - Active Sussex participation in 2017 and 2018 test beams at CERN
    - Installation and data quality monitoring
    - Data analysis and related publications
  - Preparation for test of 10x10x100 cm^3 module @DESY (dates tbc)
    - Procuring and testing scintillating fibers for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

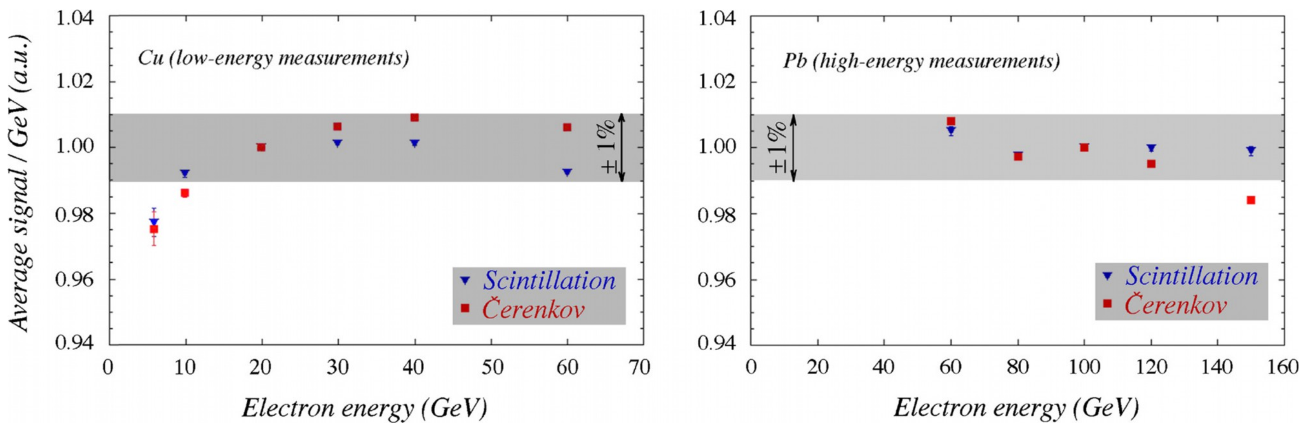
Electron response



40 GeV electrons

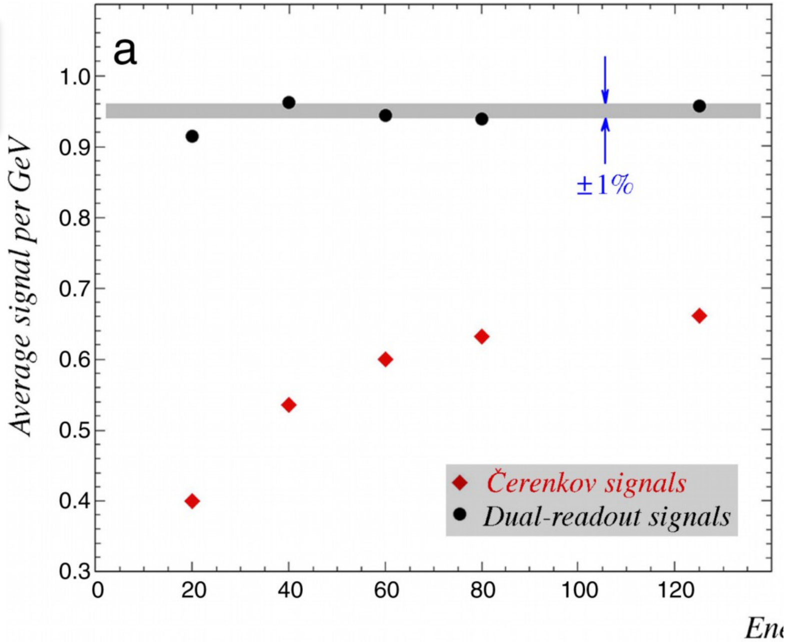


Test beam results



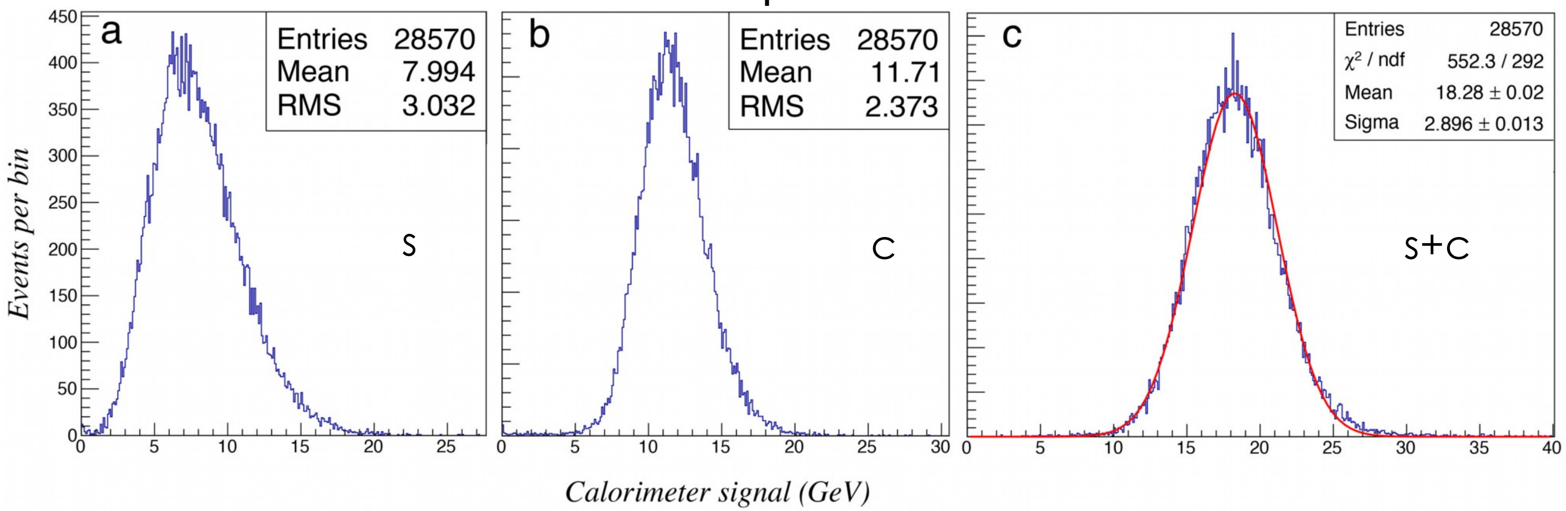
Single hadron response - linearity

NIM A 866 (2017) 76



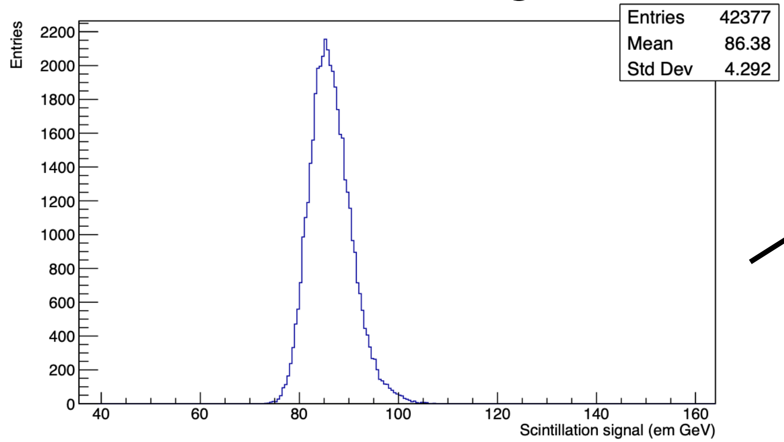
- Dual readout signal **largely recovers linearity** while vastly improving resolution.

20 GeV pions

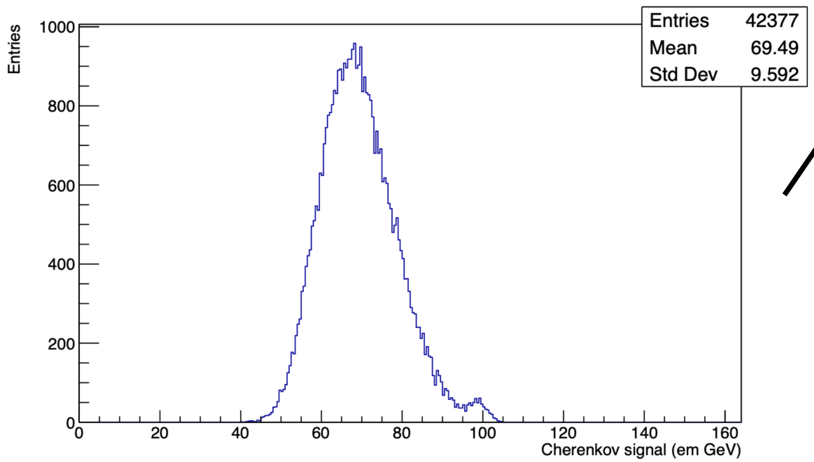


Single pion response

Scintillation signal

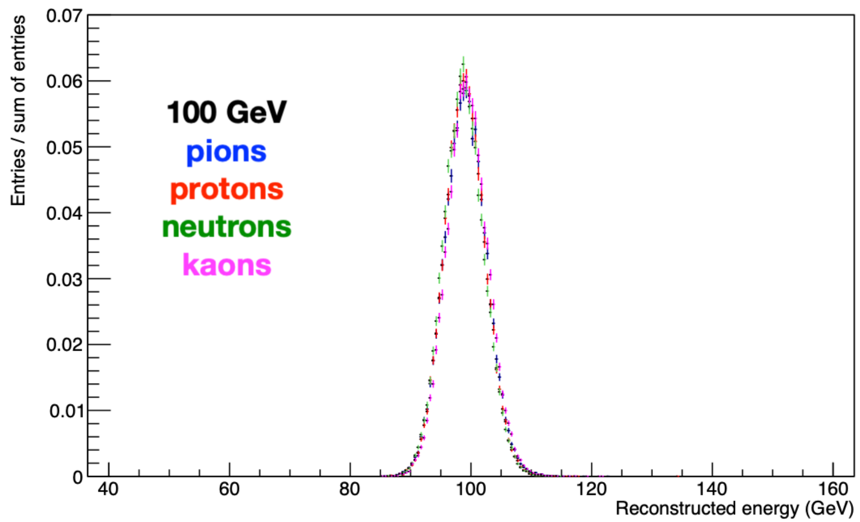


Cherenkov signal



$$E = \frac{E_S - \chi E_C}{1 - \chi}$$

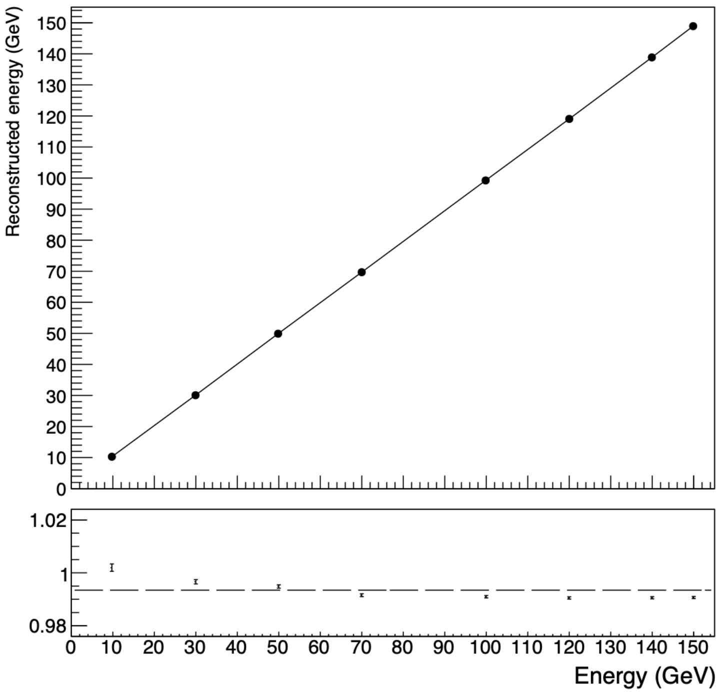
Uniform response from different hadrons with a single χ

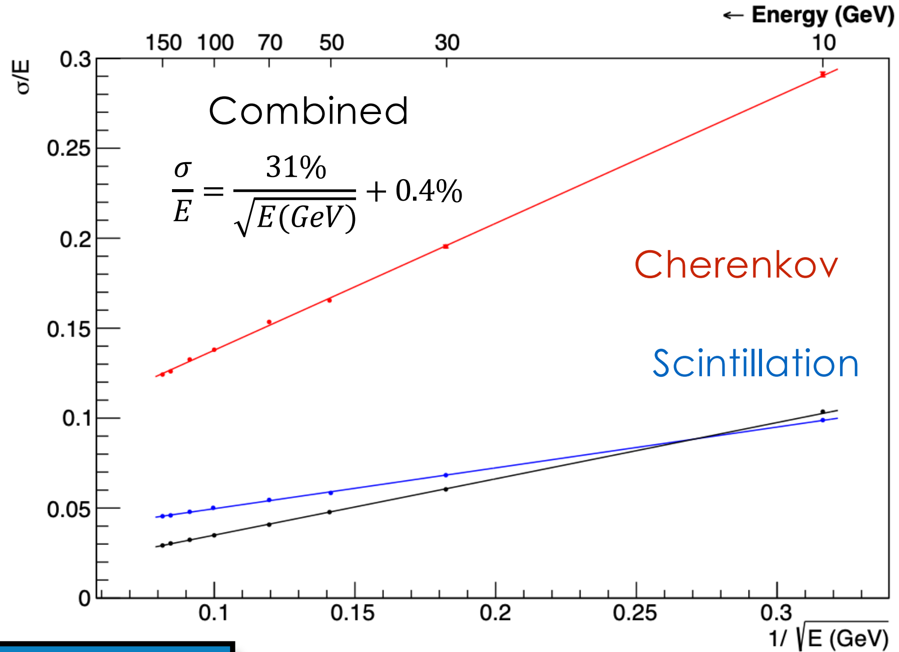


From simulation

Single pion response

- Linearity **within 1% “out of the box”**.
- Resolution **dominated by the S channel** and **clearly improved** by Dual readout



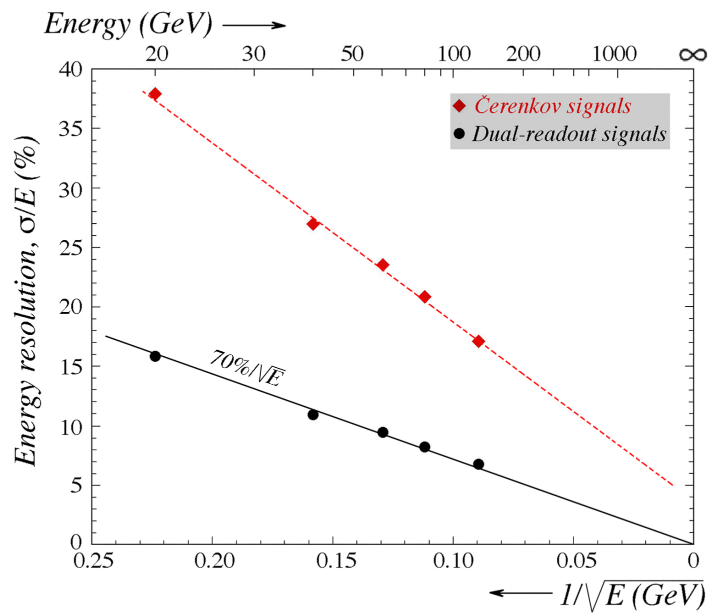


From simulation

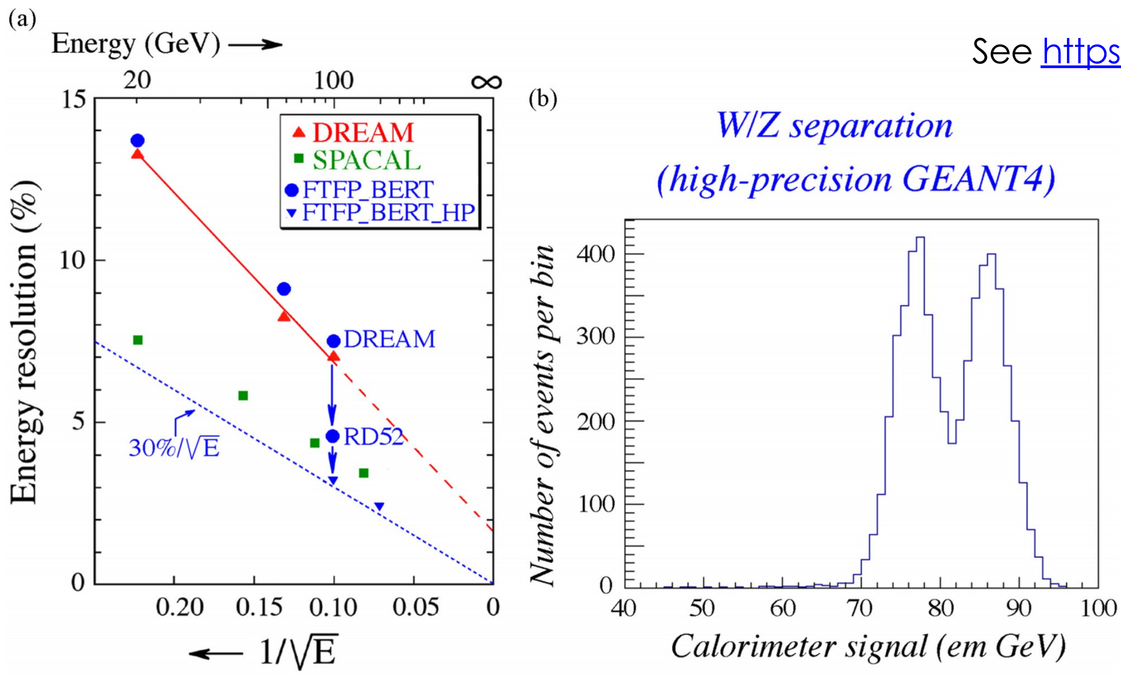
Performance of Dual Readout

- **Hadronic resolution** comparable to **compensating calorimeters**.
  - Resolution at TB (dominated by leakage). G4 estimate **with full containment**

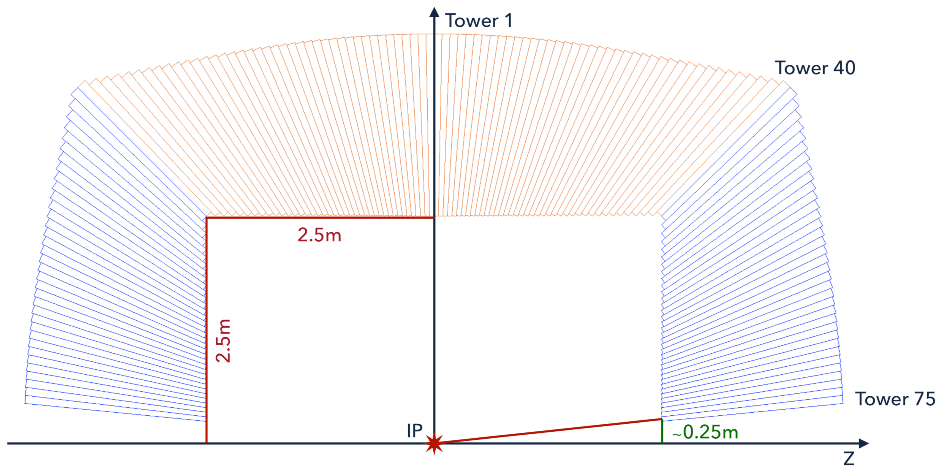
$$\frac{\sigma}{E} = \frac{34\%}{\sqrt{E}}$$



See https://doi.org/10.1016/j.ppnp.2018.07.003



Simulation



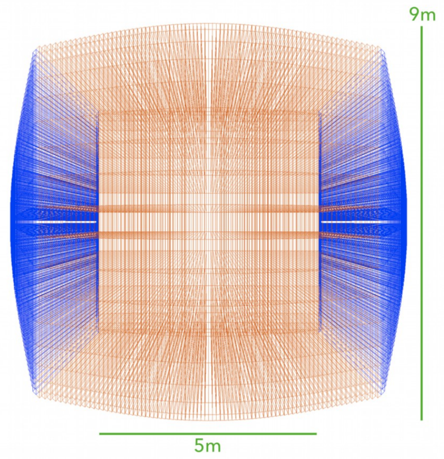
- Full G4 simulation of "final" geometry **is available**:
  - Cu absorber, 1 mm fibers, 1.5 mm pitch
- Also existing parametrised simulation for physics studies

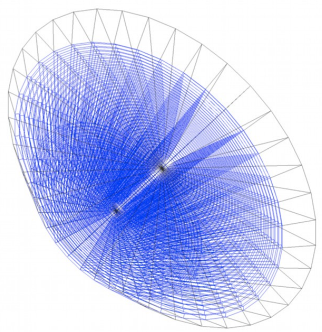
75 projective elements x 36 slices

$$\Delta\theta = 1.125°$$

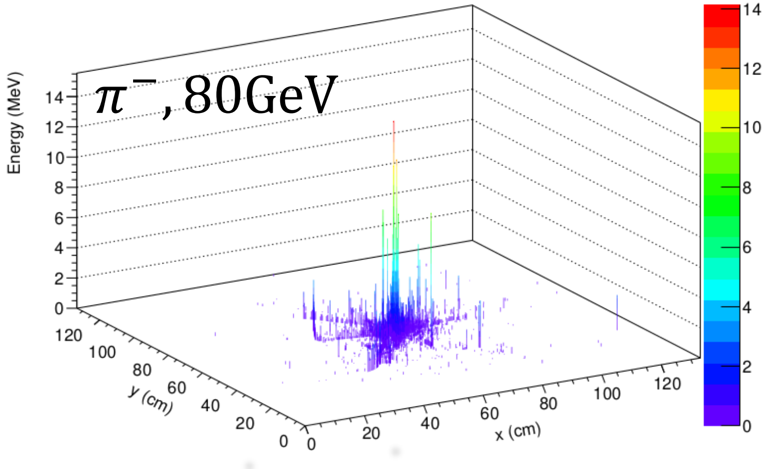
Tower size: $\Delta\phi = 10°$

Read out the single fibre: 130 M channels

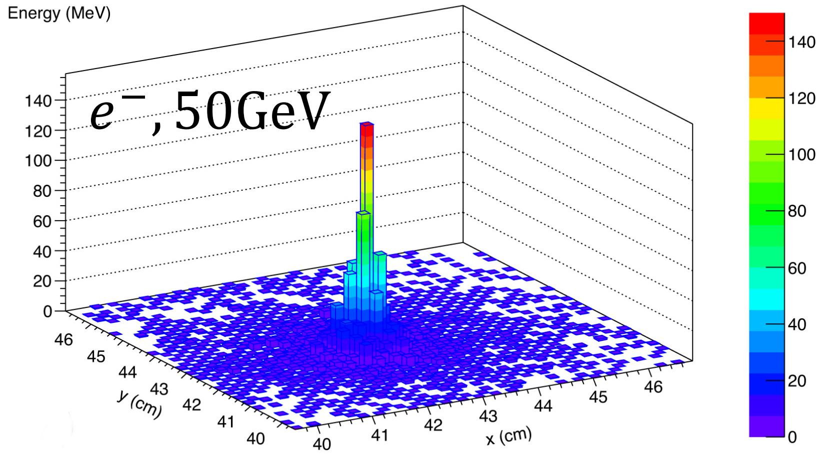


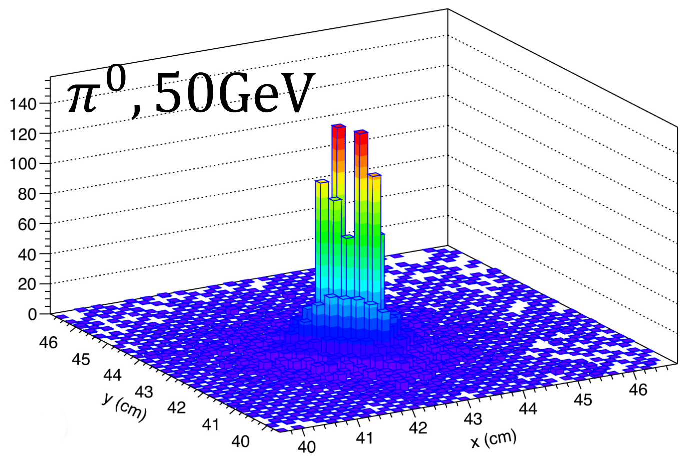


Shower shape



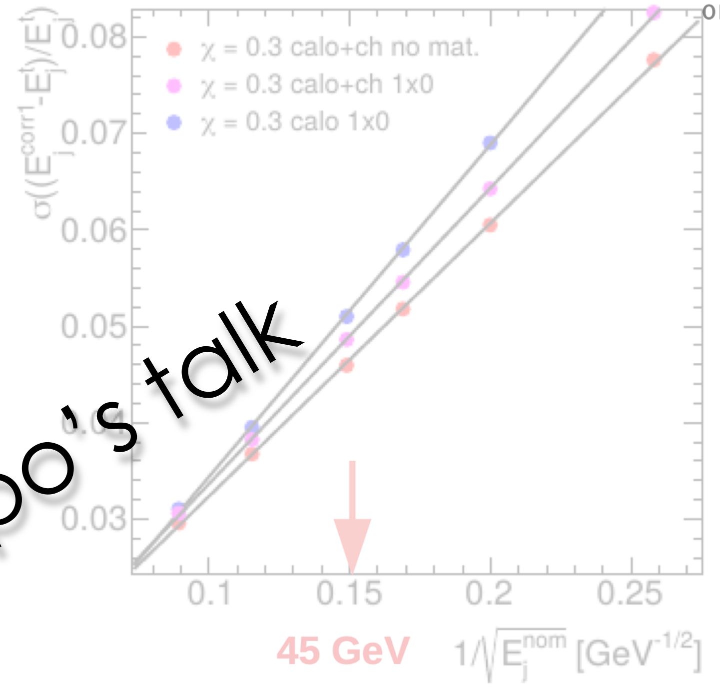
- Single particle shower shape
  - Using full implemented granularity





Jet response

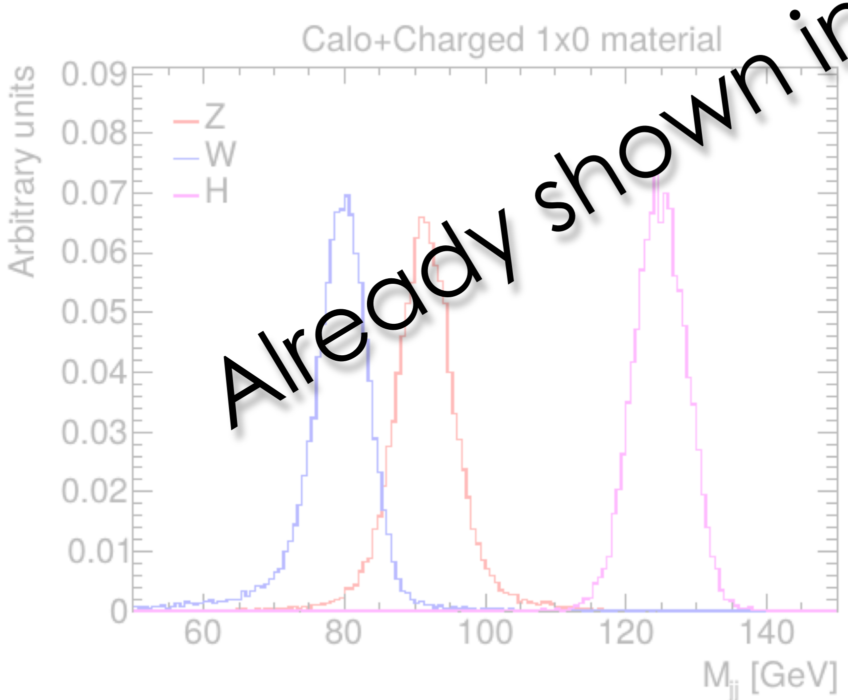
Dual readout achieves linearity with a resolution of **30%/√E with constant term ~ 0.5%**



Resonances studied with

$$e^+e^- \to ZH \to jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \to WW \to jj\mu\nu$$
$$e^+e^- \to ZH \to \nu\nu bb$$

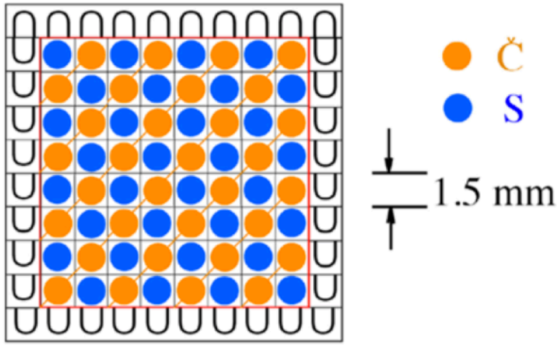
Already shown in Iacopo's talk

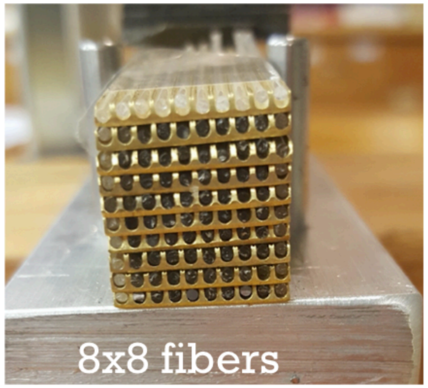


Configuration	W		Z		h	
	Δm	σ	Δm	σ	Δm	σ
Calo no material	-0.108	3.02	-0.009	3.14	-0.01	3.72
Calo+Ch no material	0.07	2.86	0.18	3.05	0.10	3.48
Calo 1X0	-0.08	3.14	-0.13	3.73	-0.18	3.95
Calo+Ch 1X0	0.08	3.01	0.21	3.26	-0.13	3.72

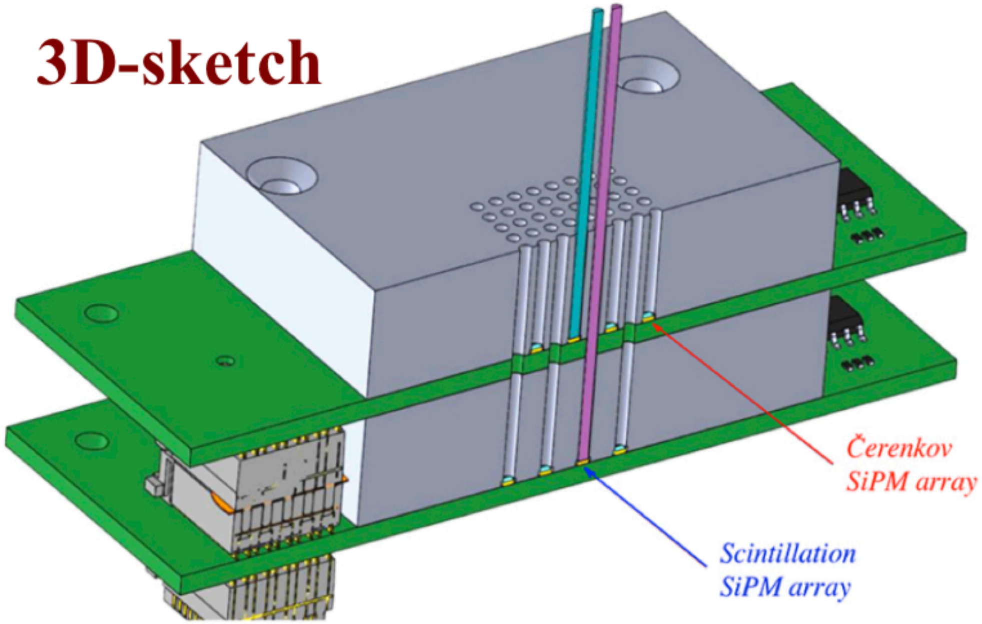
Recent developments

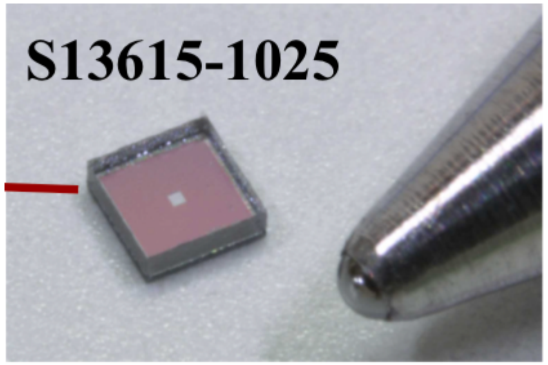
SiPM dual readout





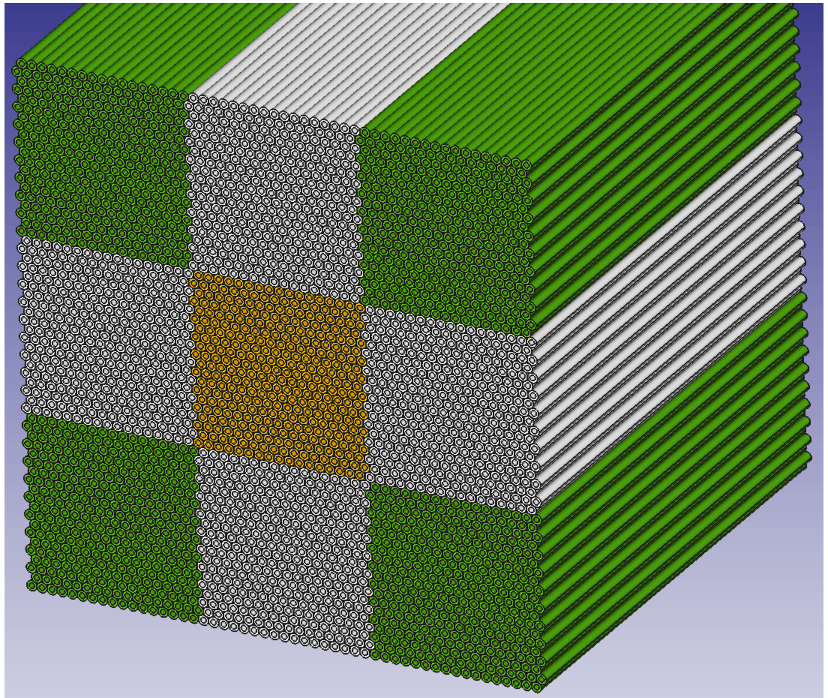
- Single fibre readout with **HAMAMATSU SiPM.**
- Readout for Cherenkov and Scintillation light **separated to minimise cross talk** (the latter expected to be ~ 50 times larger if not attenuated).

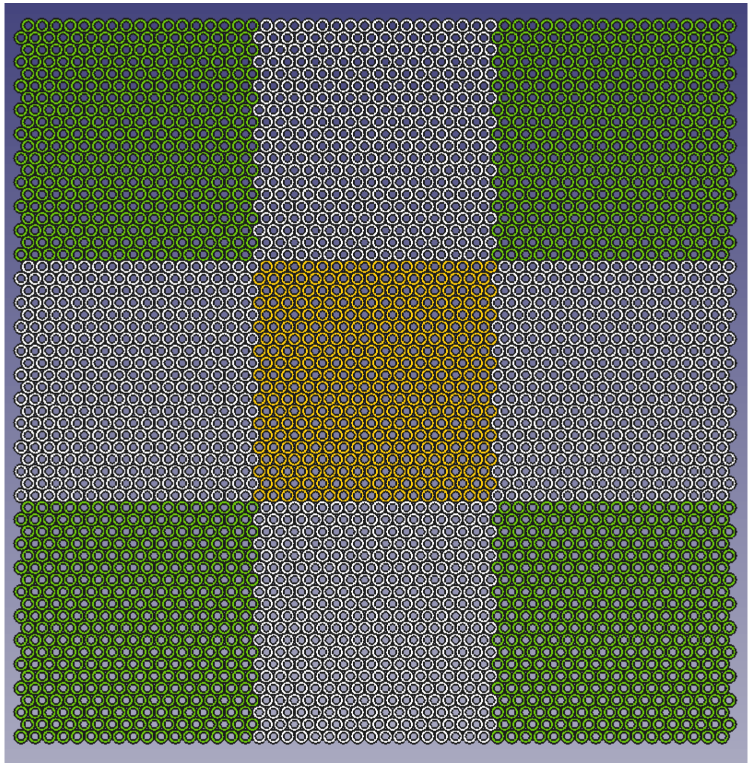




2020 target

- Build a 10 x 10 x 100 cm^3 prototype:
  - Use **2 mm diameter** tubelets (CuZn37, glued with araldite)
    - 60 horizontal layers of 51 tubes
    - 9 readout towers of 17x20 tubes each
    - **SiPM** readout for the **central tower**, PMs (with reduced granularity) otherwise





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

Conclusions

- 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

Backup

Single hadron response - resolution

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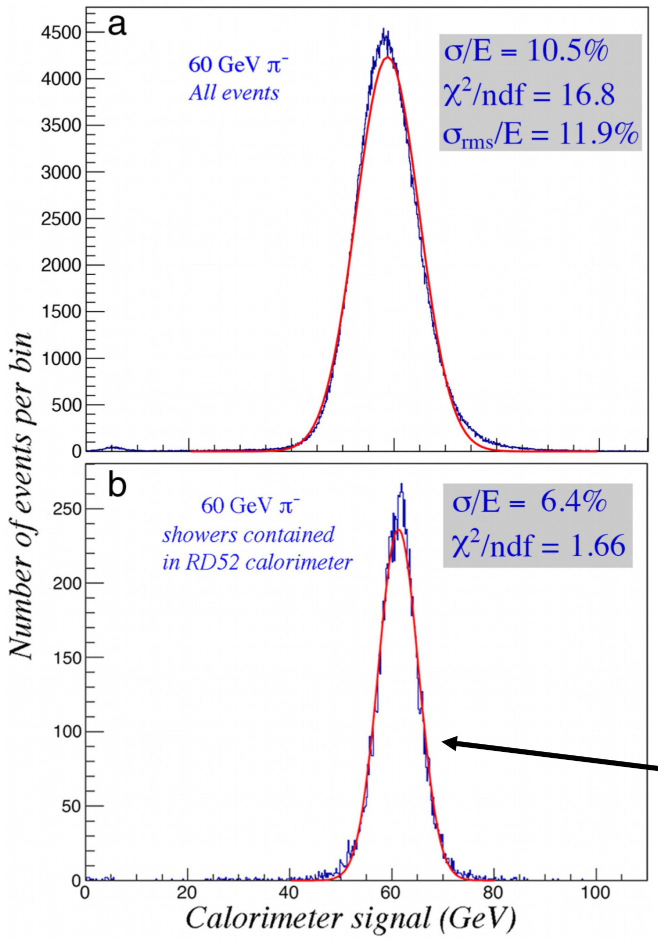
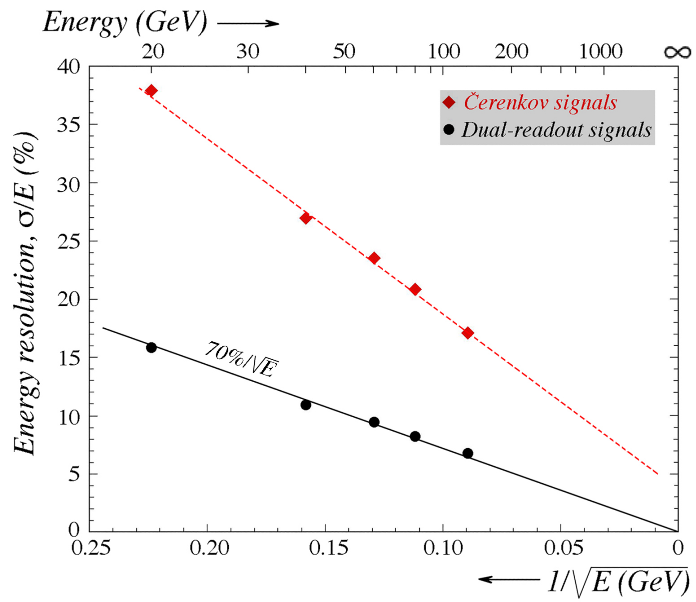
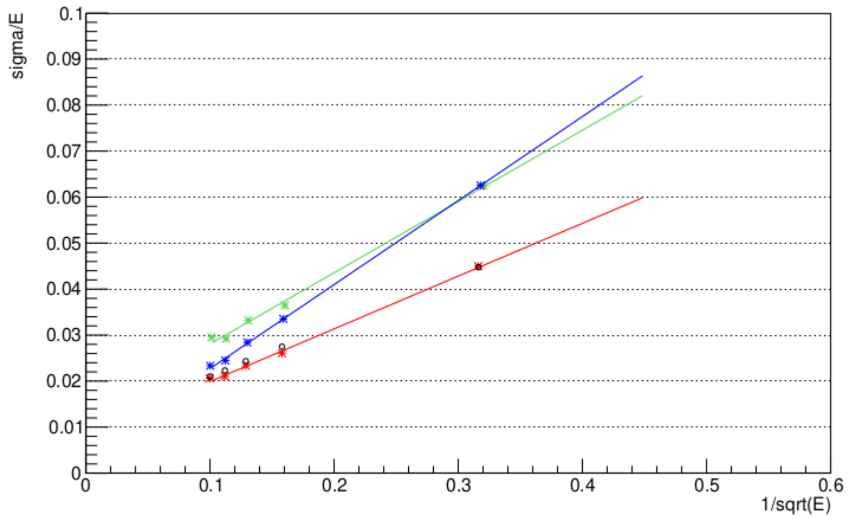




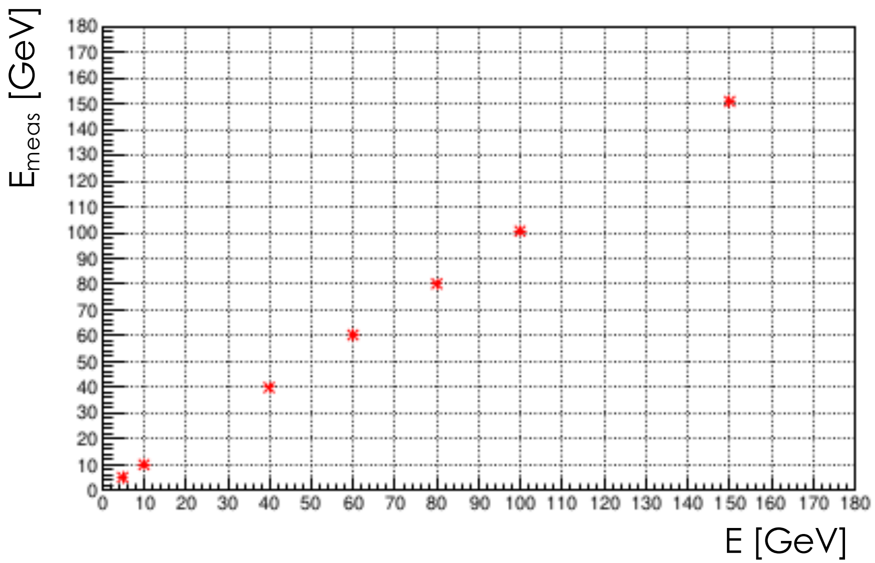
No signal in leakage counters

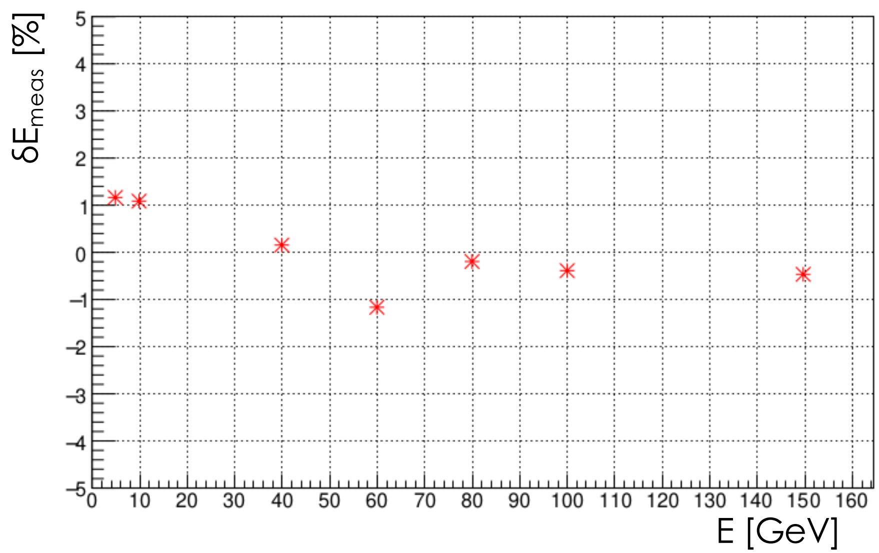
Electron response

Work in progress



- Scintillation (S): $\frac{\sigma}{E} = \frac{15.5\%}{\sqrt{E}} + 1.2\%$
- Cherenkov (C): $\frac{\sigma}{E} = \frac{18.3\%}{\sqrt{E}} + 0.5\%$
- Dual Readout: $\frac{\sigma}{E} = \frac{11.0\%}{\sqrt{E}} + 0.8\%$





Hadron response

Work in progress

100 GeV pions