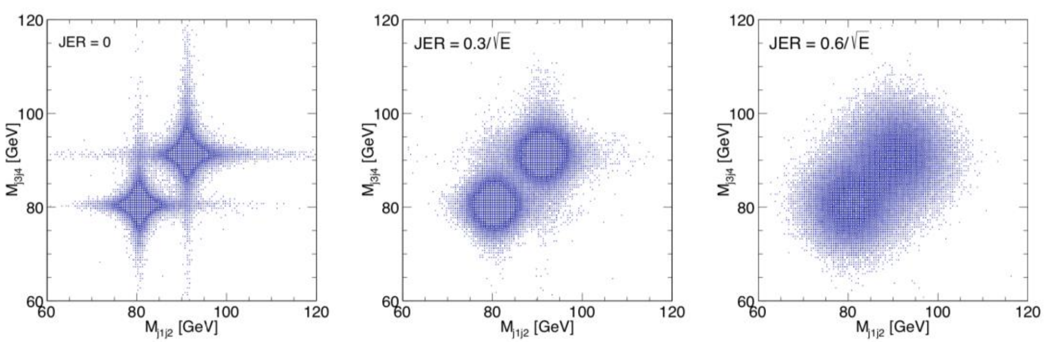
Calorimetry – UK opportunities

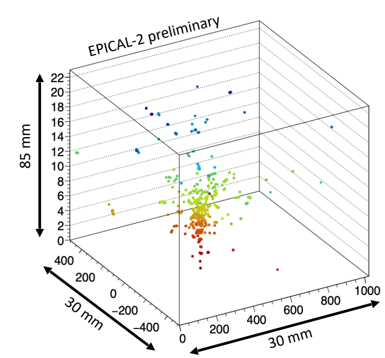
Nigel Watson (Birmingham)

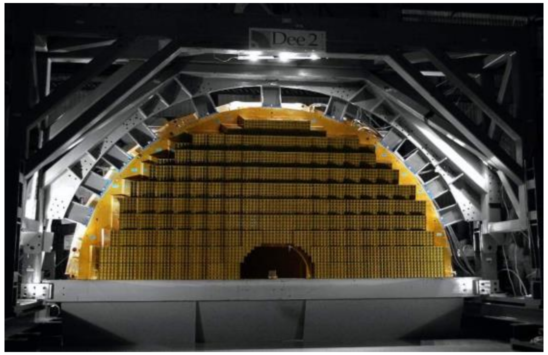
with thanks to Iacopo Vivarelli and Fabrizio Salvatore (Sussex) for material

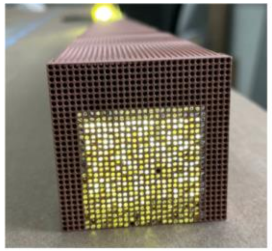
- Dual Readout
- High Granularity
- Opportunities

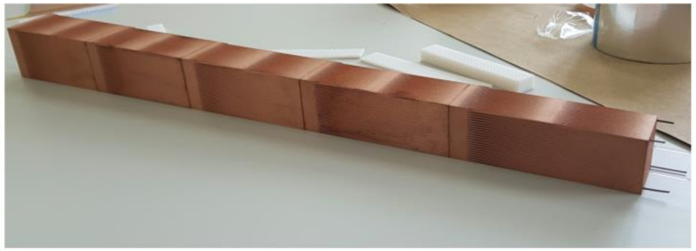
[[Thanks to Roman Poeschl, Tim Rogoschinki, Hiroi muryama, Yihui Lai]

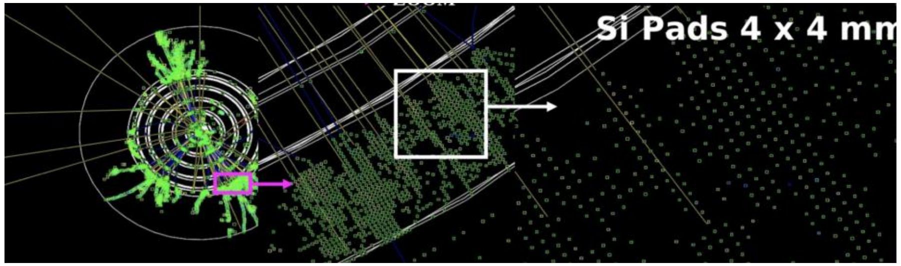












Physics Goals/Requirements

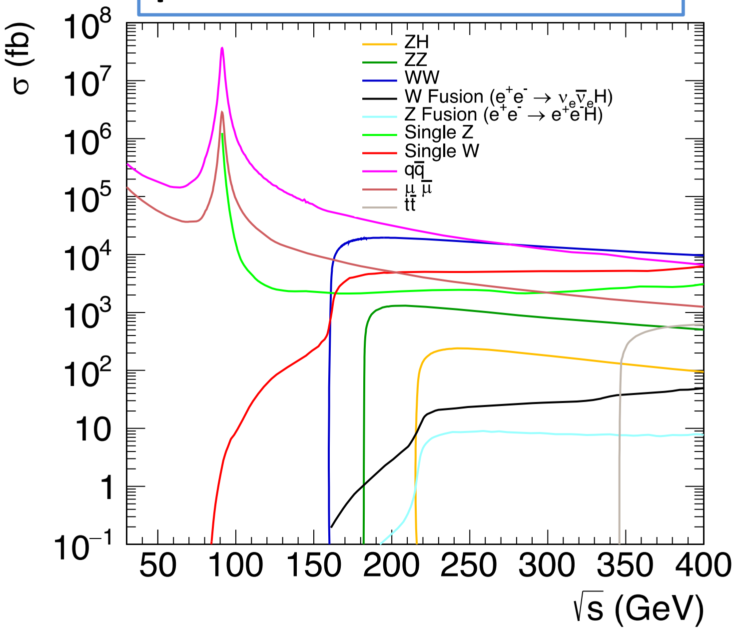
- Energy scale of all machines considered comparable
- Same measurable final states / physics
- Same energy resolution goals
- **Only** differences: bunch time structure and backgrounds
  - Use developments in fast timing, a la HL-LHC?
- Profit from huge overlap / re-use of ideas (slides)

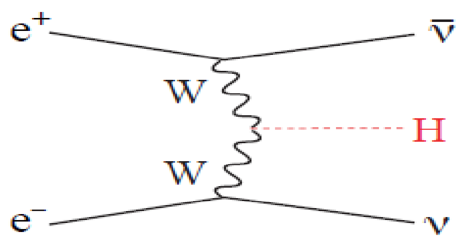
Physics Motivation – hadronic jets

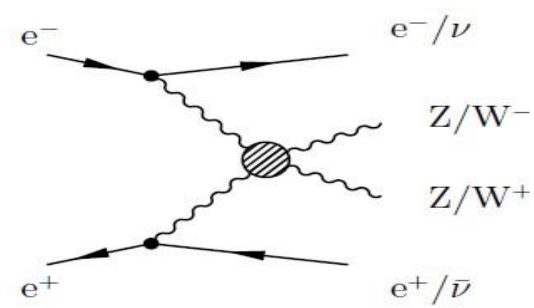
Motivation

- Jet energy resolution is a key benchmark of the e^+e^- detector performance because 97% of the SM Higgsstrahlung signal has jets in the final states
- A critical metric is how well the hadronically-decayed W/Z bosons can be separated
  - 3~4% jet energy resolution ~100GeV gives decent W/Z separation ~2.5 σ
- Very hard to achieve with a traditional approach to calorimetry

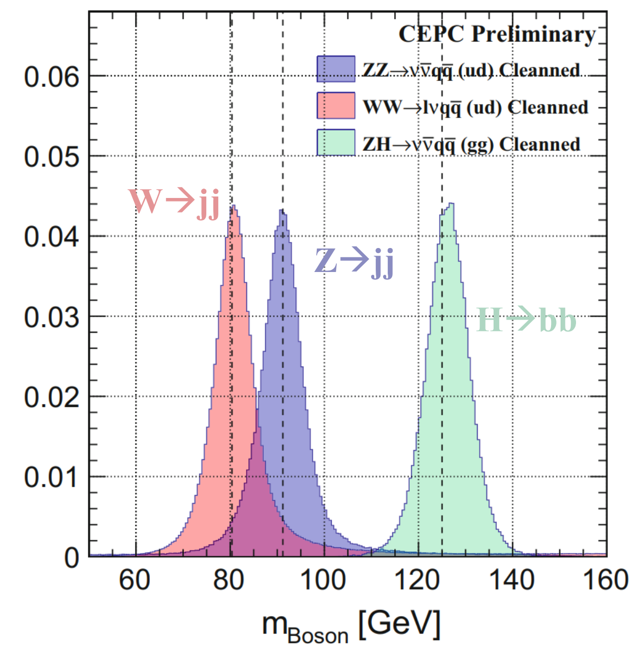
Cross sections for various processes in e^+e^- collisions







EPJC (2018) 78:426



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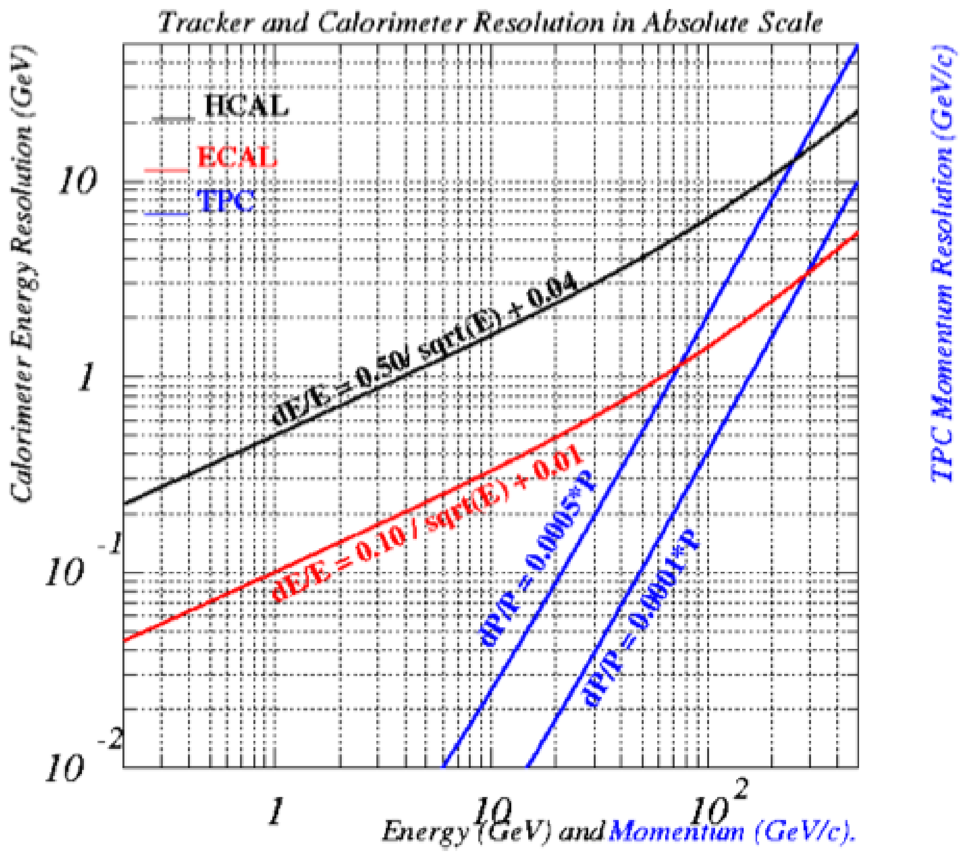
[Yihui Lai, Calor'22]

Jet Energy Resolution

Final state contains high energetic jets from e.g. Z,W decays
Need to reconstruct the jet energy to the utmost precision !
Goal is around dE_{jet}/E_{jet} - 3-4% (e.g. 2x better than ALEPH)



Jet energy carried by …

- Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$65% :((
  Most precise measurement by Tracker
  Up to 100 GeV
- Photons: 25%
  Measurement by Electromagnetic
  Calorimeter (ECAL)
- Neutral Hadrons: 10%
  Measurement by Hadronic
  Calorimeter (HCAL) and ECAL

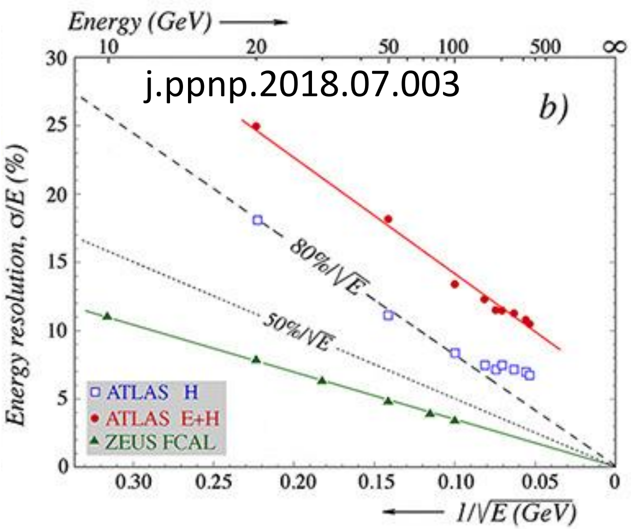
$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$

[Roman Poeschl, Calor'22]

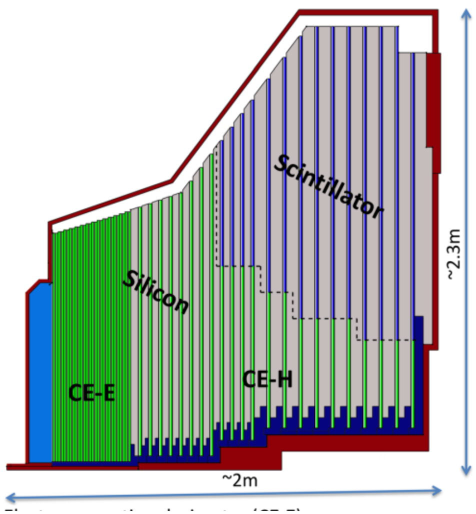
High-performance calorimetry: options

Motivation

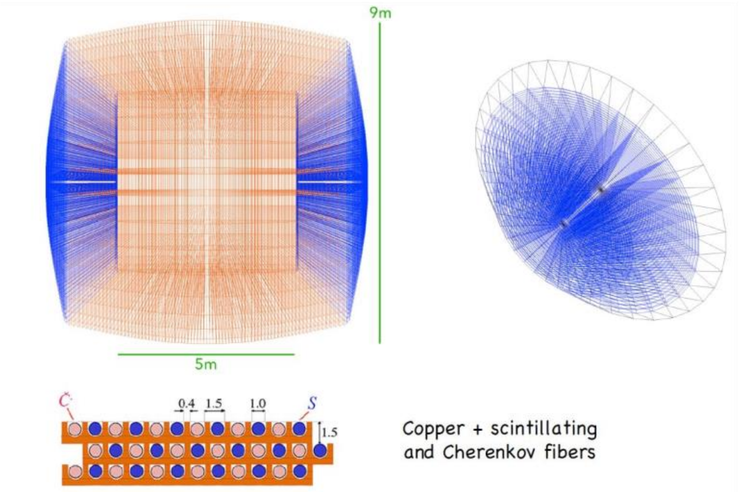
- A typical HCAL resolution of $\sigma_{HAD}/E > 50\%/\sqrt{E}$
- Two different but complementary approaches:
  - Particle Flow Algorithm (PFA) oriented, using High granularity calorimeter (HGC)
  - Dual Readout (DRO) calorimeter, improve the resolution by additional information from Cherenkov light and identify the EM fraction



ZEUS: 35%/√E



CMS High granularity calorimeter



Sketch of the IDEA calorimeter (left) and endcap geometry (right)

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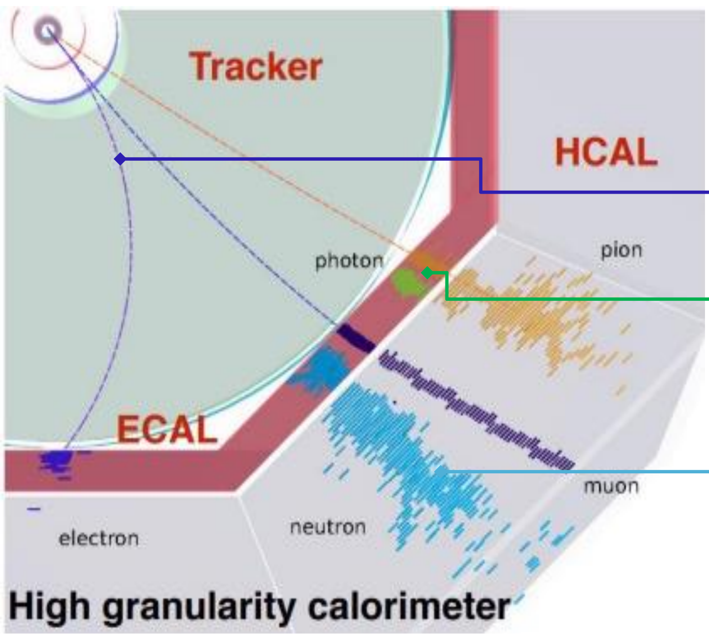
[Yihui Lai, Calor'22]

High Granularity Calorimetry

- HGCAL achieve excellent jet resolution by the tracker and shower pattern recognition
- Each individual particle in shower is reconstructed and identified with the subdetector providing the best energy resolution for that particle type
- Calorimeter resolution requirements not that stringent. EM ~ 15%/√E and HAD ~ 55%/√E

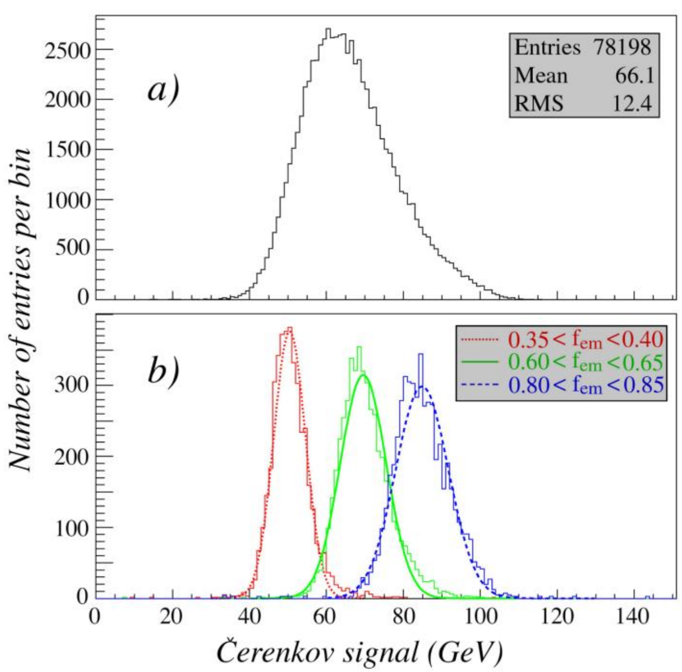


Particles	Energy fraction	Subdetector	Typical resolution
Charged particles	~65%	Tracker	$<5\times10^{-5}p_T$
Photons	~25%	ECAL	~15%/√E
Neutral hadrons	~10%	ECAL+HCAL	~55%/√E

[Yihui Lai, Calor'22]

Dual readout - the principle

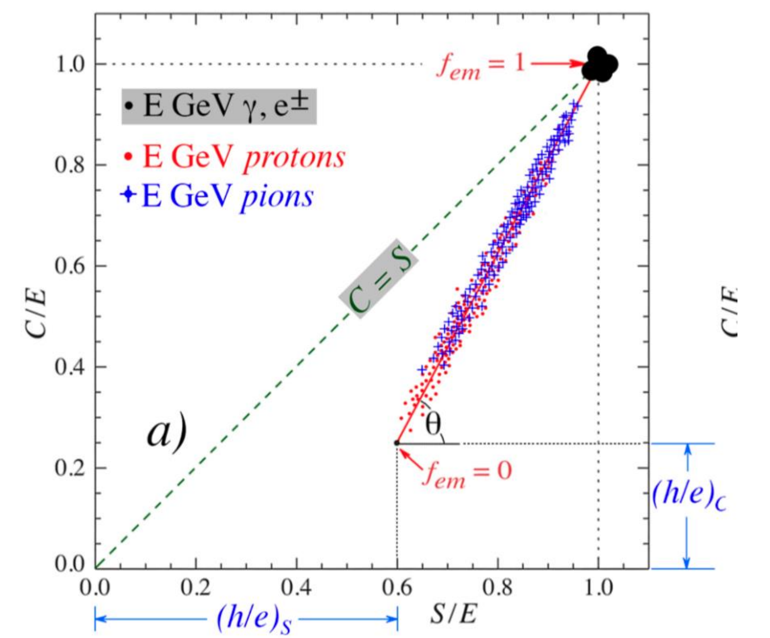
- Resolution of the **hadronic energy measurement** affected by fluctuations in the fraction of **energy carried by** $\pi^0 \to \gamma\gamma$ (f_{em}).
- **Two readouts with different e/h** allow the extraction of f_{em} and of the **incoming energy E**.
- For example: **spaghetti calorimeter** with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



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

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

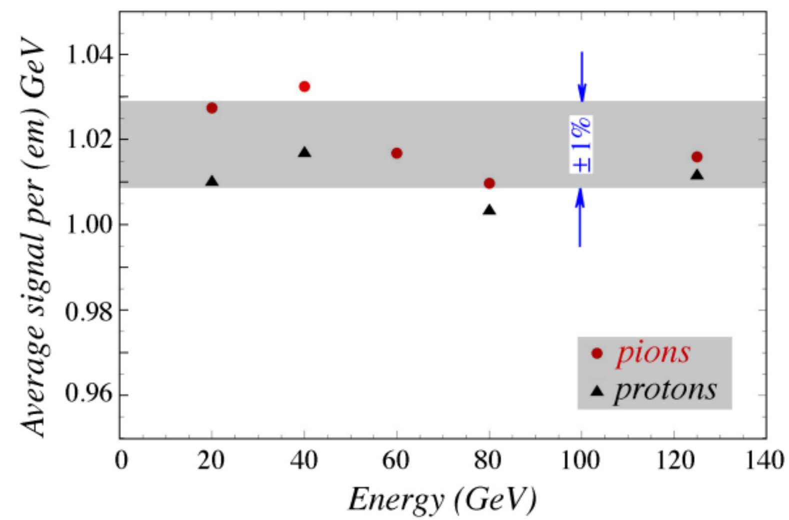
Solve for f_{em} and E



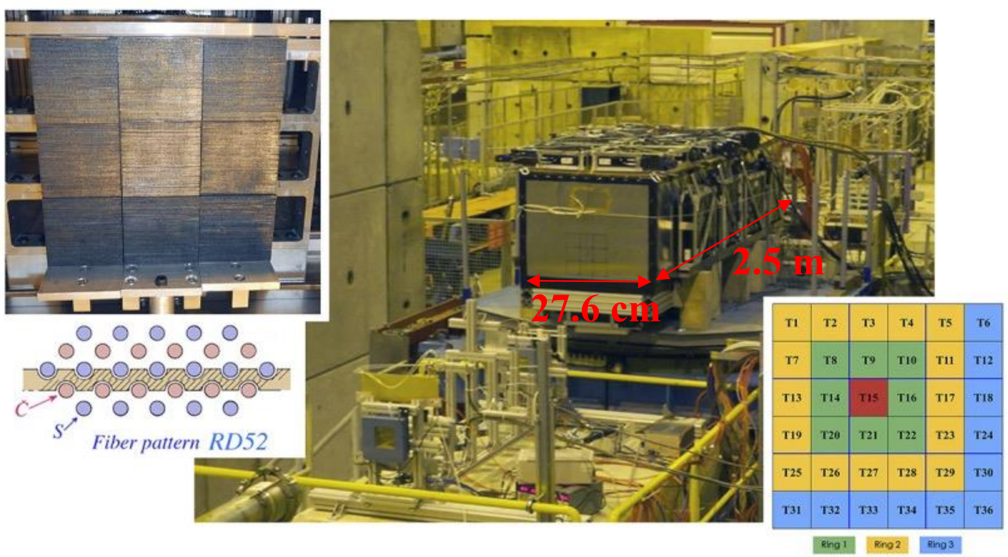
[Iacopo Vivarelli

Dual Readout Calorimetry

- Extensive R&D by the DREAM/RD52/IDEA collaborations (Rev. Mod. Phys. Vol 90, April 2018):
  - Sampling calorimeter with lead or copper absorber
  - Clear plastic fibers and scintillation fibers for C/S readout
- Linearity and HAD energy resolution are excellent. While the EM resolution is good enough to achieve the W/Z separation goal, could it be better ?



Lead absorber, 9 modules with ~36k fibers



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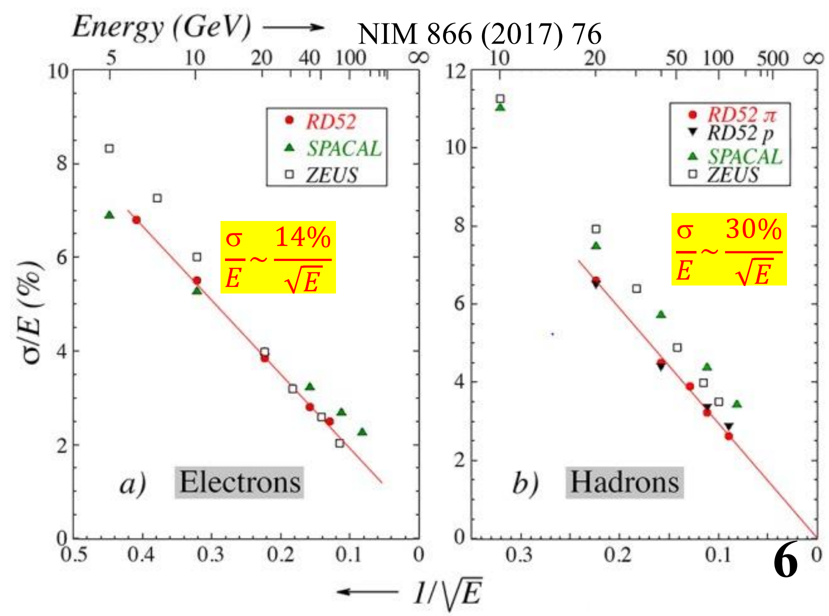


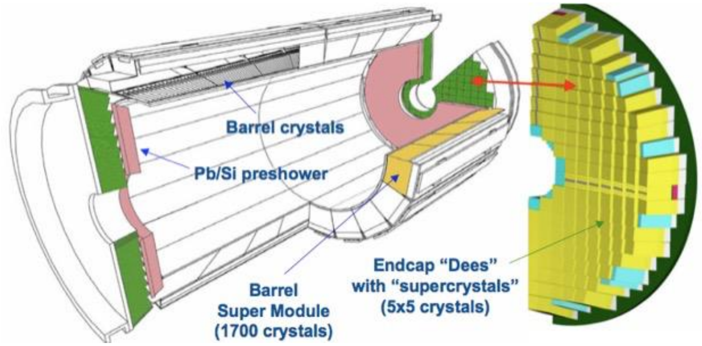
[Yihui Lai, Calor'22]

Can we get best of both?

Combine strengths from several calorimeter concepts

- Can we combine the strengths of a crystal ECAL with that of a DRO calorimeter?

Crystal Calorimeter



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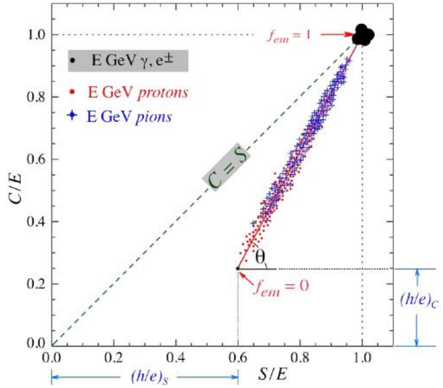
DRO Calorimeter



=> DRO crystal ECAL?

Excellent EM energy resolutions

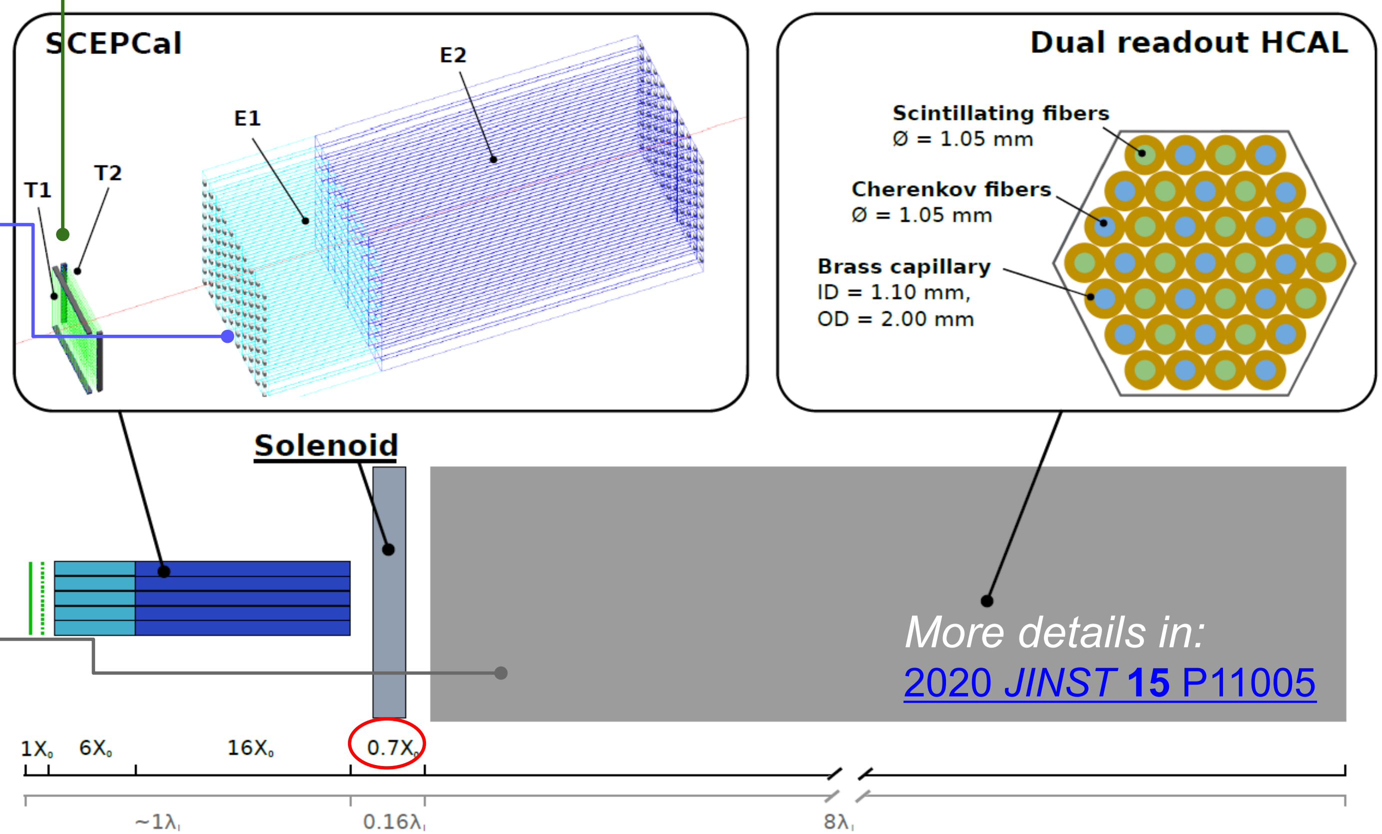
Excellent Linearity and HAD energy resolution

- Can a DRO crystal ECAL be combined with a DRO HCAL to have excellent energy resolution for both EM particles and hadrons?

[Yihui Lai, Calor'22]

A Segmented DRO Crystal ECAL with a DRO Fiber HCAL

- **Two Timing layers**
  - $\sigma_t \sim 20$ ps
  - LYSO:Ce scintillating crystals (~1 X_0)
  - $3\times3\times60$ mm^3 thin crystal bar
  - 3×3 mm^2 SiPM (15-20 μm cell size)
- **Two ECAL layers**
  - $\sigma_{EM}/E \sim 3\%/\sqrt{E}$
  - $PbWO_4$ crystals
  - Crystal cross-section: 10×10 mm^2
  - 5×5 mm^2 SiPM (10-15 μm cell size)
- **Ultra-thin IDEA solenoid**
  - $\sim 0.7X_0$
- **HCAL layer**
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers inserted inside brass capillaries



[Yihui Lai, Calor'22]

Summary

- With the advancement in SiPM technologies, the highly performant DRO hybrid calorimeter system is suitable for future Higgs factories
  - Excellent EM, HAD and jet resolution and high energy linearity by combining the DRO information from different calorimeter segments (homogeneous crystals + sampling fibers)
  - Enhanced particle identification capabilities by the moderate longitudinal segmentation
  - Further 3-4% improvement for E_{jet} > 50 GeV combining DRO with particle flow algorithm

	High granularity Si/W ECAL + scintillator-based HCAL	Fiber-based DRO calo	Hybrid DRO crystal and fiber
# longitudinal layers	>40	1	5
ECAL cell cross-section HCAL cell cross-section	25-100 mm^2 100-900 mm^2	2-144 mm^2	100 mm^2 400-2500 mm^2
EM energy resolution HAD energy resolution	15-25%/$\sqrt{E}$ 45-55%/$\sqrt{E}$	10-15%/$\sqrt{E}$ 25-30%/$\sqrt{E}$	~3%/$\sqrt{E}$ 25-30%/$\sqrt{E}$

[Yihui Lai, Calor'22]

Further reading from Calor'22

- Romualdo Santoro (DRO Testbeam and plans/SiPM)
  - https://indico.cern.ch/event/847884/contributions/4833179/attachments/2445325/4191419/santoro_Calor2022.pdf
- Yihui Lai (DRO/ crystals)
  - https://indico.cern.ch/event/847884/contributions/4833223/attachments/2446287/4193575/CALOR_Lai.pdf
- Roman Poeschl (SiW ECAL)
  - https://indico.cern.ch/event/847884/contributions/4833219/attachments/2446225/4191891/calor2022.pdf

Dual Readout

- International collaboration, currently two options:
  - Full fibre calorimeter (HAD + EM)
    - Discussed in many documents, incl. CEPC and FCC CDRs (baseline calorimeter option for the IDEA detector concept).
  - Fibre (HAD) + crystals (EM)
    - Appealing, superb EM performance, hardware longitudinal segmentation (improved PFA)
- Recent Snowmass White Paper summarises performance:
  - https://arxiv.org/abs/2203.04312

Dual Readout

- International collaboration
  - Researchers from: **INFN** (Italy), **CERN**, **USA institutions** (Caltech, Fermilab, Princeton, Purdue, Texas, Maryland, Michigan, Virginia), **Korea** (Kyungpook, Seoul, Yonsei), **UK** (**University of Sussex**)
  - Funding
    - INFN and University of Sussex: funded through AIDAInnova.
    - O(million currency units) grants obtained by:
      - INFN: HIDRA (construction of Had-size prototype)
      - Korea: construction of had-size prototype
      - USA: CalVision (dual readout with homogeneous crystal calorimeters)

Dual Readout

- Opportunities for collaboration
  - University of Sussex involved in
    - Simulation, performance, test beam analysis, monitoring, optical fibre characterisation, SiPM timing performance measurement.
  - Items where effort sub-optimal
    - Design of fibre+SiPM calibration system.
    - Front-end electronics optimisation (commercial CAEN FERS 5200 units used so far).
    - Dual Readout Crystal option.

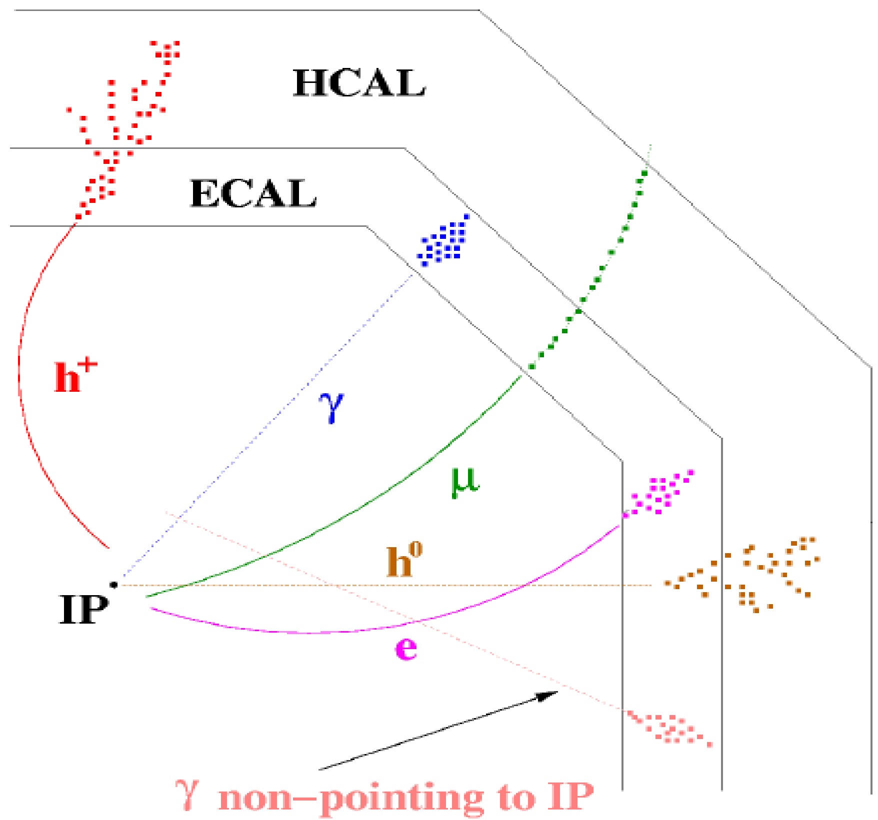
[David A. Petyt]

Future calorimetry plans:
RAL perspective (@2021)

- **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

Particle Flow Calorimetry

Jet energy measurement by measurement of **individual particles**
Maximal exploitation of precise tracking measurement



- large radius and length
  - → to separate the particles
- large magnetic field
  - → to sweep out charged tracks
- "no" material in front of calorimeters
  - → stay inside coil
- small Molière radius of calorimeters
  - → to minimize shower overlap
- **high granularity of calorimeters**
  - → to separate overlapping showers

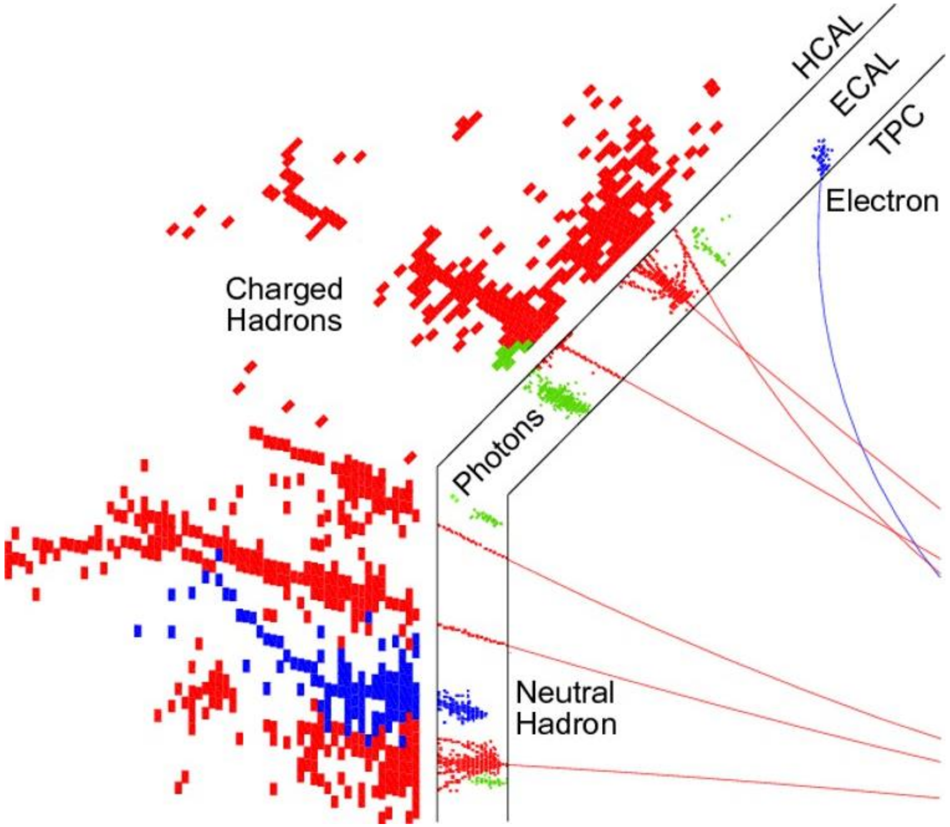
Also thin, reduce high-field solenoid cost

Particle flow as privileged solution for experimental challenges
=> Highly granular calorimeters!!!
Emphasis on tracking capabilities of calorimeters

[Roman Poeschl, Calor'22]

Silicon Tungsten electromagnetic calorimeter

- Base measurement as much as possible on measurement of charged particles in tracking devices
- Separate of signals by charged and neutral particles in calorimeter



- Complicated topology by (hadronic) showers
- Overlap between showers compromises correct assignment of calo hits

□ **Confusion Term**

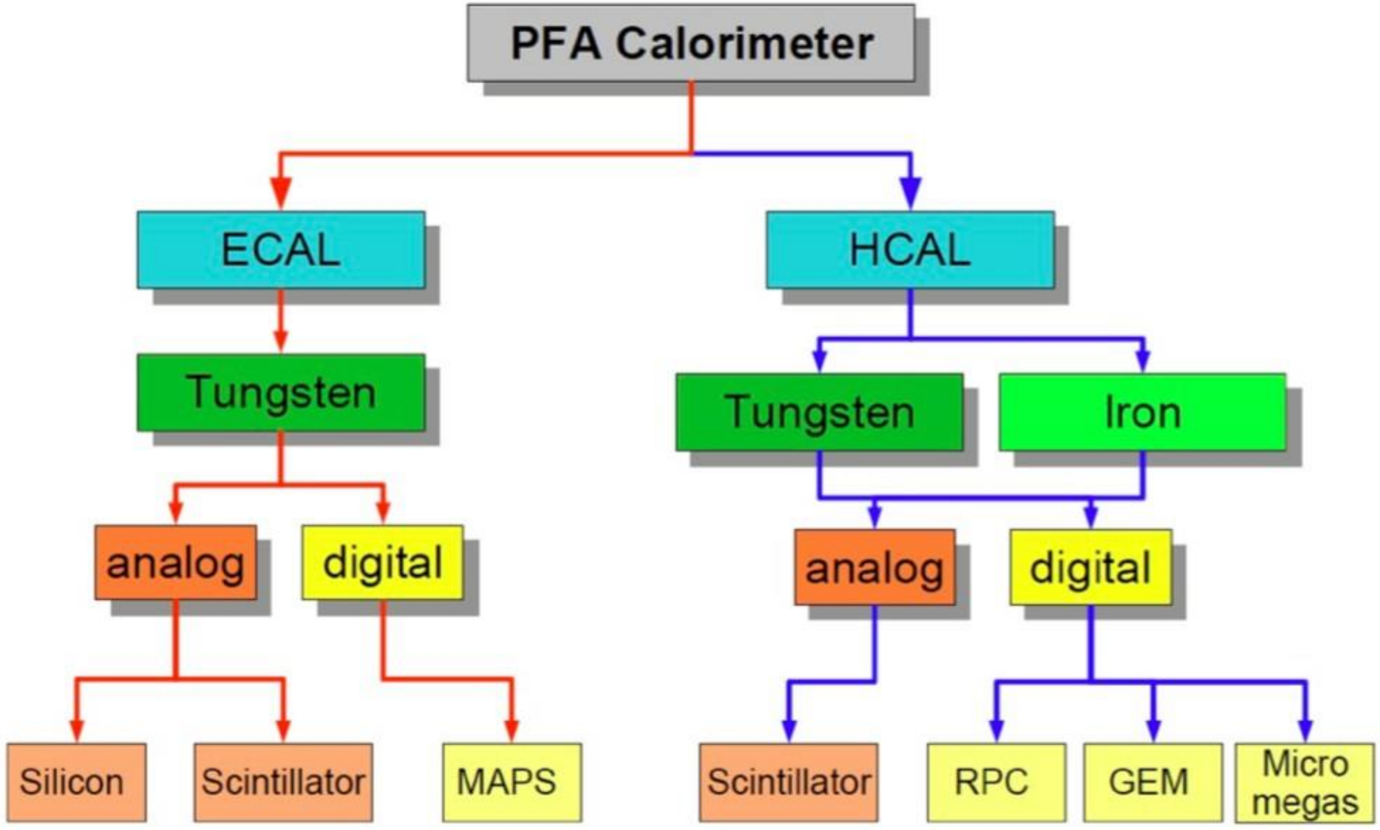
Need to minimize the confusion term as much as possible !!!

[Roman Poeschl, Calor'22]

e.g. cross-detector concept R&D

CALICE Collaboration

Mainly organised within the: CALICE Collaboration

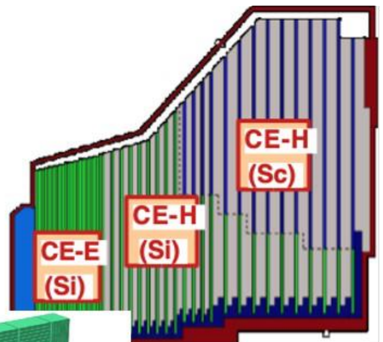


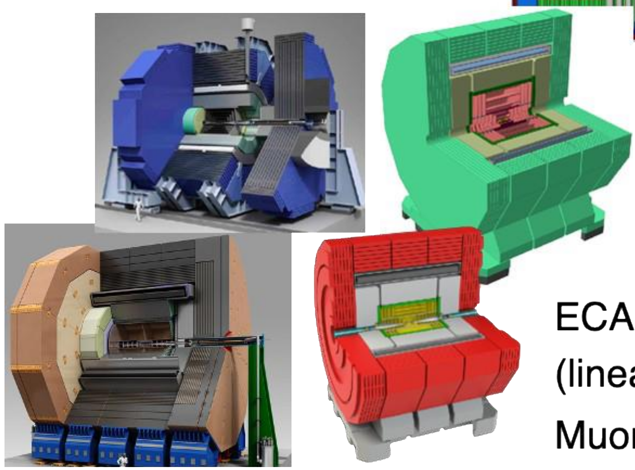
Si Based Calorimeters in Current and Future Experiments

- Grouped into two categories:

Main calorimeters of collider experiments
(barrel and / or endcap)

CMS HGCAL
(ECAL, part of HCAL)

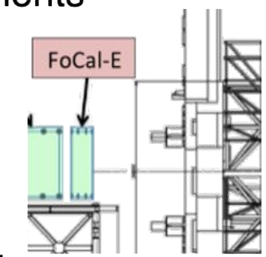


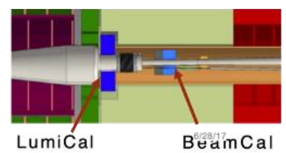


ECALs of Higgs Factory detectors
(linear and circular colliders);
Muon colliders

Smaller, specialized calorimeter systems
in collider and non-collider experiments

Very forward calorimeters: ALICE





Luminosity
measurement at e^+e^-

Non-collider experiments: LUXE, Satellites,
…

Main arguments for adopting silicon:
- Finely segmentable: High granularity
- Robust and stable performance
- Compact design, high density
  - typically combined with W absorbers for maximum compactness, small ρ_M

Main challenge: Cost

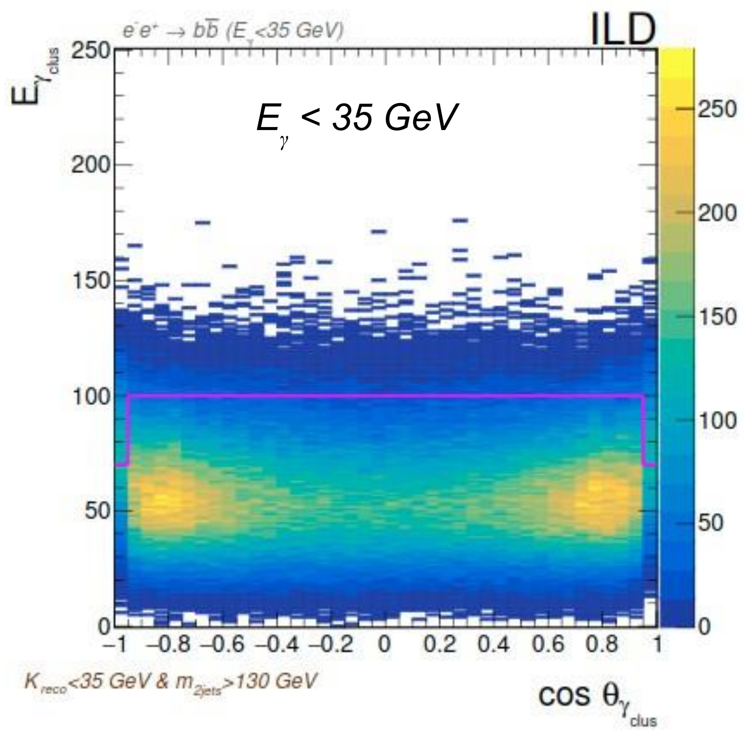
Symposium talk: V. Boudry

[Roman Poeschl, Calor'22]

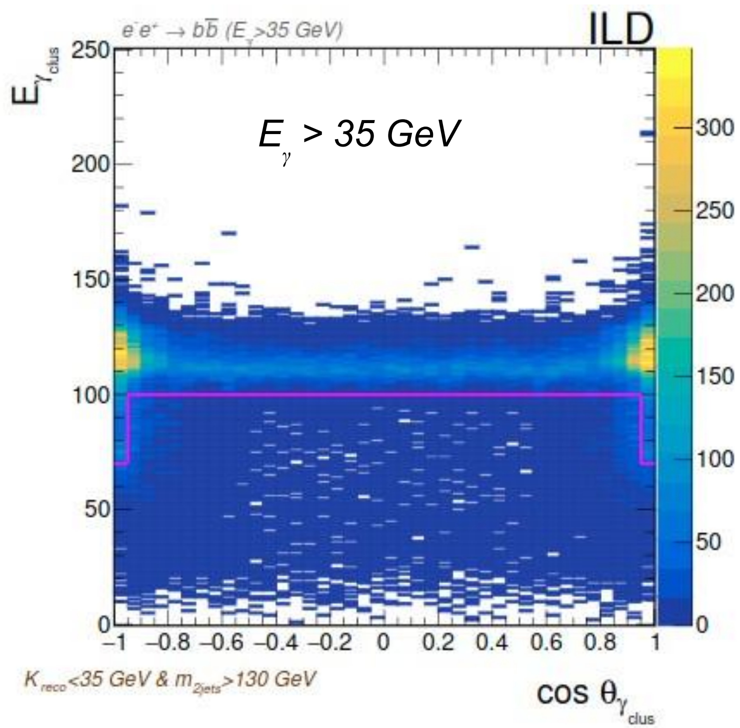
Granular calorimeters – Use case III

- Most ISR Photon are radiated collinearly but lead to a boost -> Check for acolinearity of dijet event
- Method doesn't work when photon is radiated into detector acceptance
  - ... and merged with a jet --> Busy environment

No or mild ISR



"Strong? ISR



- Excellent photon ID in granular calorimeter is key
- Identification of ISR photon within detector (jet) reduces ISR background by nearly a factor of six
- Would be interesting to carry out this analysis with less granular calorimeters

ILD: Irles, Richa

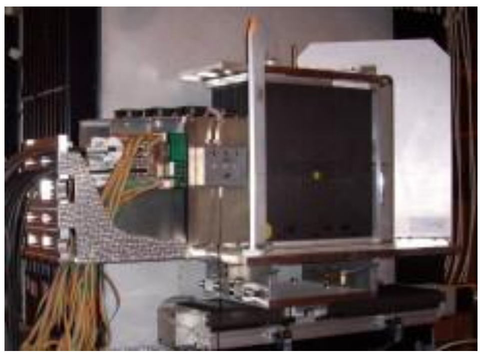
[Roman Poeschl, Calor'22]

Historical context

Steps of R&D

Physics Prototype

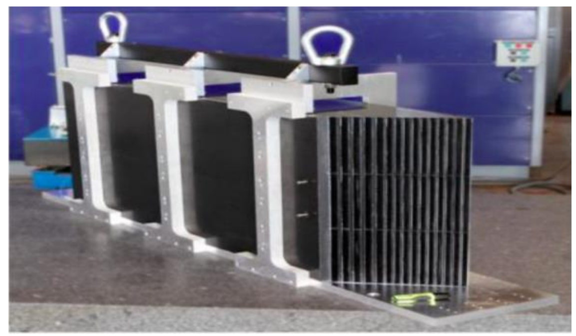
2003 - 2012



- Proof of principle of granular calorimeters
- Large scale combined beam tests

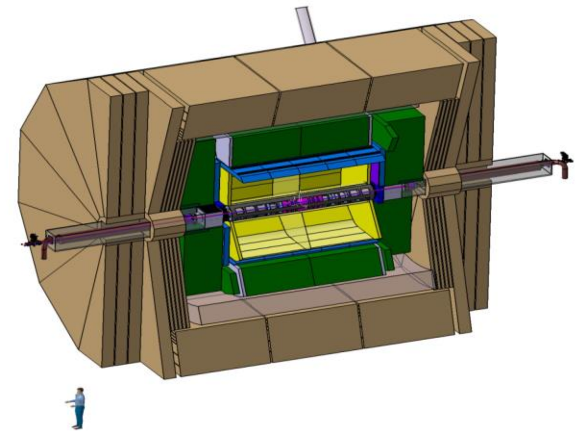
Technological Prototype

2010 - ...



- Engineering challenges
- Higher granularity
- Lower noise
  - **Today**

LC detector



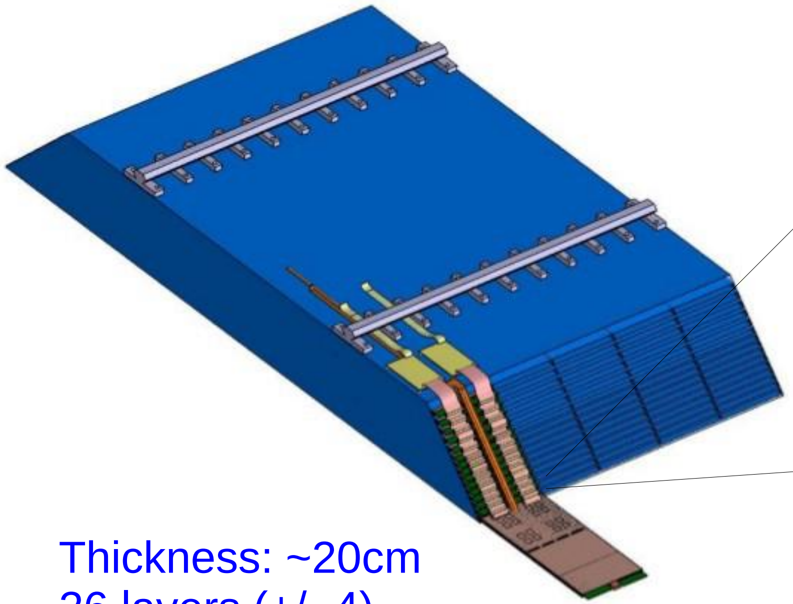
- The goal
  - Typically 10^8 calorimeter cells
- Compare:
  - ATLAS LAr ~10^5 cells
  - CMS HGCAL ~10^7 cells

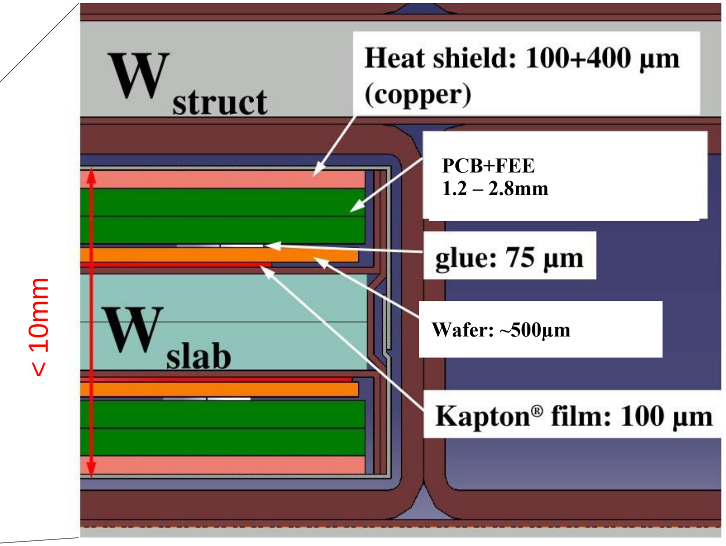
[Roman Poeschl, Calor'22]

Engineering/System R&D

Silicon Tungsten electromagnetic calorimeter – Example ILD

Ecal alveolar structure





Thickness: ~20cm
26 layers (+/- 4)
24 $X_0/1\lambda_I$
Expected elm. energy resolution 15-20%/√E

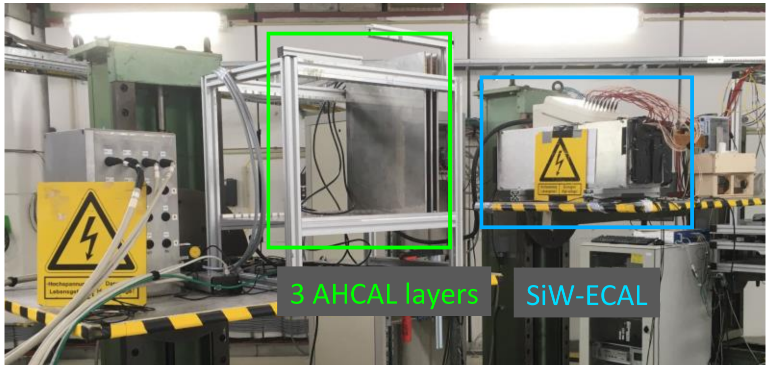
- Sandwich calorimeter
  - Si sensors as active material
  - W as absorber material
- Highly integrated design
  - ASICs in detector volume
  - Compact readout system

[Roman Poeschl, Calor'22]

(Well) beyond proof-of-principle

Common testbeams

Preparation for common SiW-ECAL AHCAL beam test



SiW-ECAL + AHCAL DAQ test @ DESY in March 2022

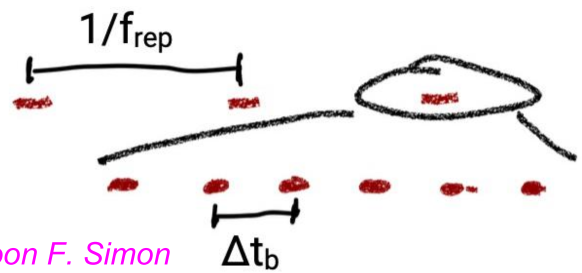
- Successful synchronisation of data recorded with SIW-ECAL and AHCAL
- Common running makes full use of EUDAQ tools (developed within European projects)

Gearing up for common beam test at CERN in June

Power not just a concern for machine

Reminder power pulsing

- Linear Colliders operate in bunch trains



Cartoon F. Simon

CLIC: Δt_b ~ 0.5ns, frep = 50Hz

ILC: Δt_b ~550ns, frep = 5 Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with 10^8 cells
- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Support compact detector design
- Have to avoid large peak currents
- Have to ensure stable operation in pulsed mode

- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in “continuous” mode opportunities

(Non exhaustive) "To do list" (for LC Detector)

	Today	LC Detector
#cells*	15360	10^8
Sensor surface/m^2	0.5	2000-2500
Sensor type	9x9cm^2 based on 6" wafers	Size ? Based on 8" wafers?
Real size slabs	1 "electrical" long layer	~10000 detector slabs (5000 double layers)
Front end ASICs	SKIROC2, ns timing	SKIROC3, ps timing? Need 1.2-1.5M
Digital electronics	SL-Boardv2 (already quite close)	New versions,need 9k
DAQ	Highly performant system for prototype	Scaling to full detector
PCB	FEV2.x (already quite close)	Integration of new FE electronics, need ~75k
Slow control	Integrated in SL Board	Solution for full detector?
Mechanical Structures	1 barrel alveaola structure (EUDET 2010)	40 barrel modules + e**ndcaps**
Carrier Boards	Simple carbon plates	"H Boards" with wrapped W (Studies date back to 2010-2016)
Cooling	Advanced studies (AIDA-2020)	Full detector integration Continous powering woulf be anew world
Engineering (electrical and mechanics)	Advanced studies (for ILD IDR)	Require full revision and consolidation
Software	**Few** skillful people	Needs consolidation and person power

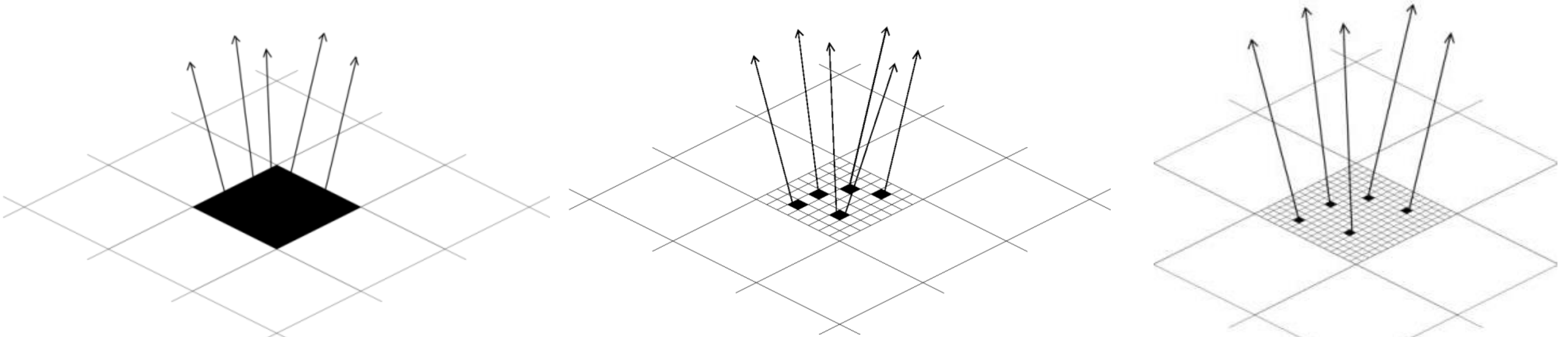
- A lot has been achieved
  - ... but the way is still long, as of today the team is too small and the funding is very (too) volatile
  - We are good in engineering but too few (young) physicists

Project timeline | | Career paths?

[Roman Poeschl, Calor'22]

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, …



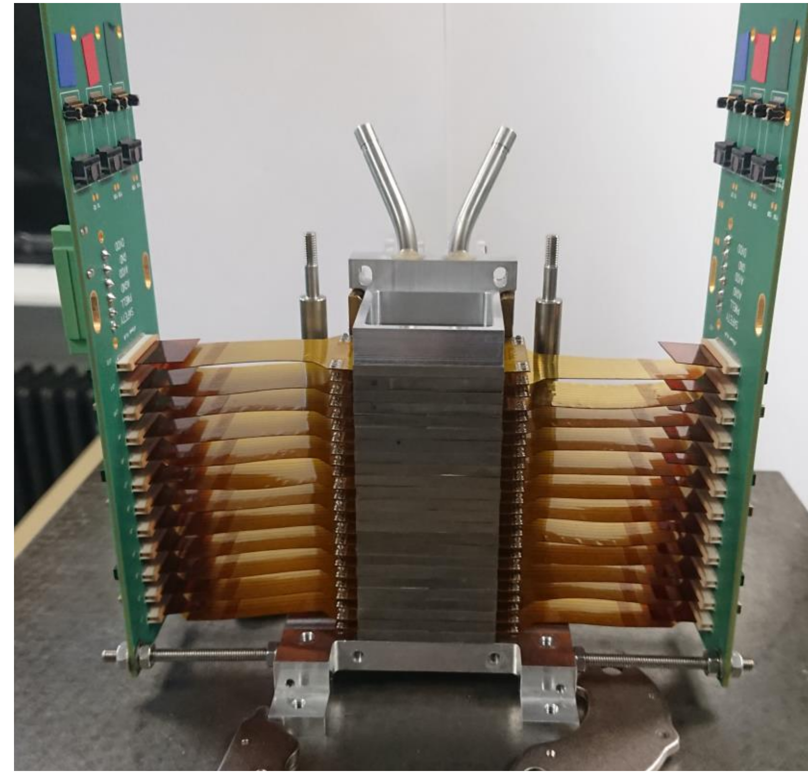
AECAL

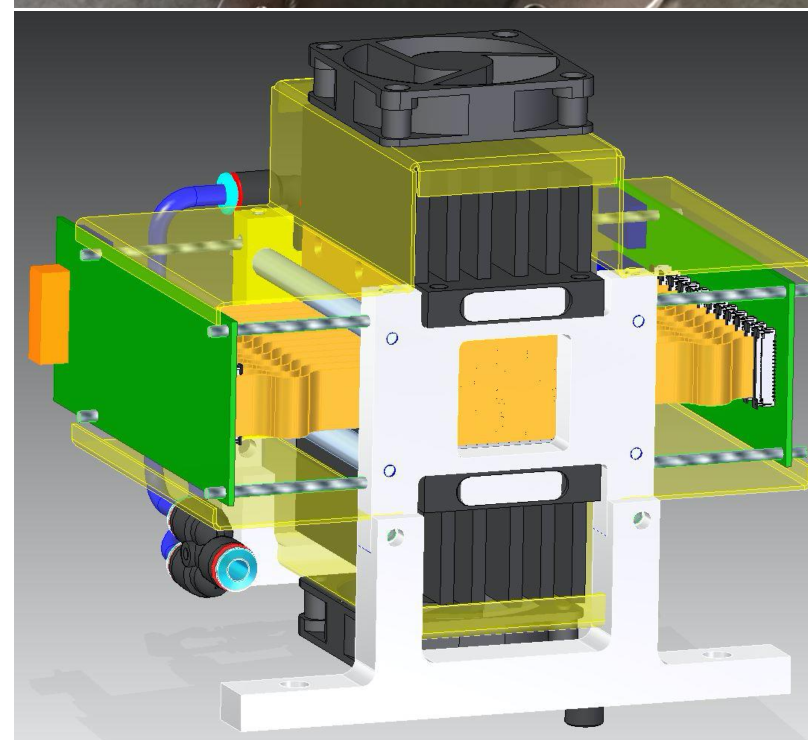
DECAL N_{pixels}<$N_{particles}$

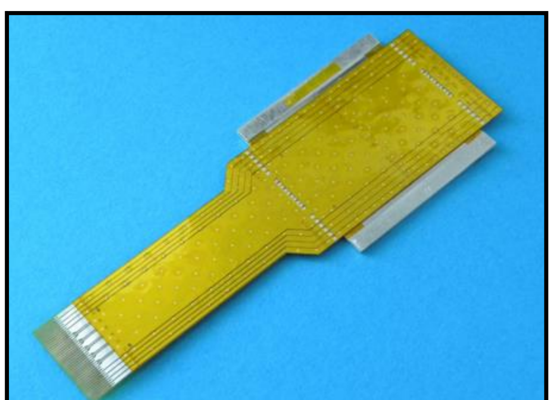
DECAL N_{pixels}=$N_{particles}$

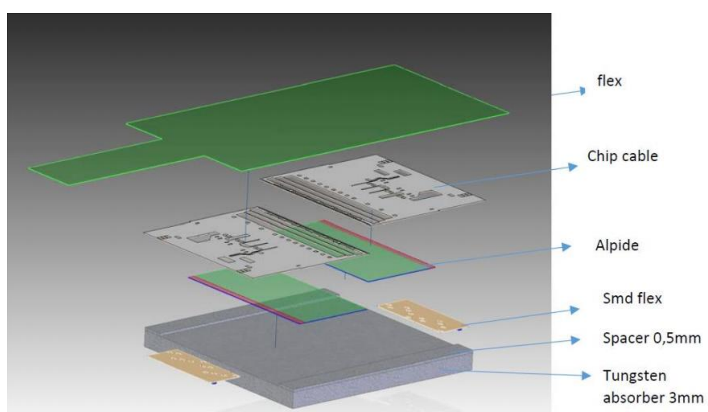
EPICAL-2
(Electromagnetic PIxel CALorimeter prototype-2)

- **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
- **Project goal:**
  - 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



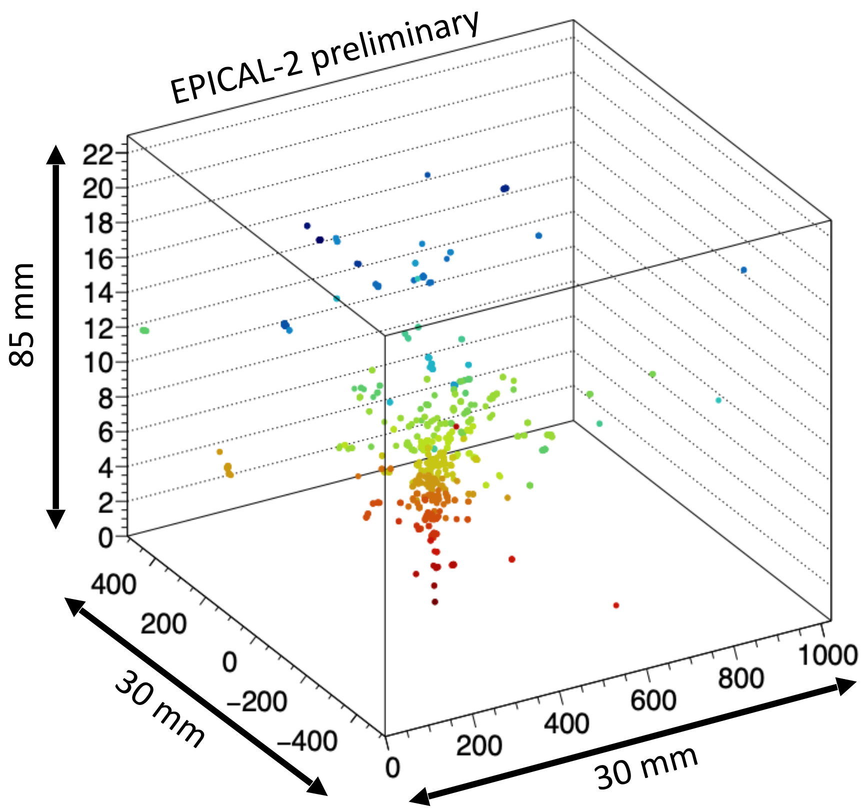




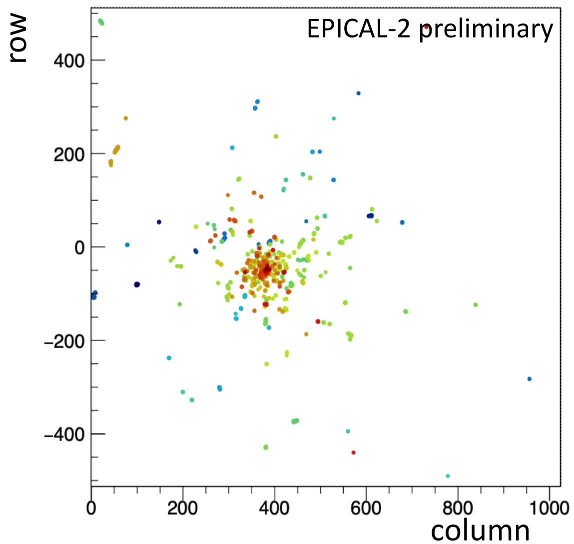


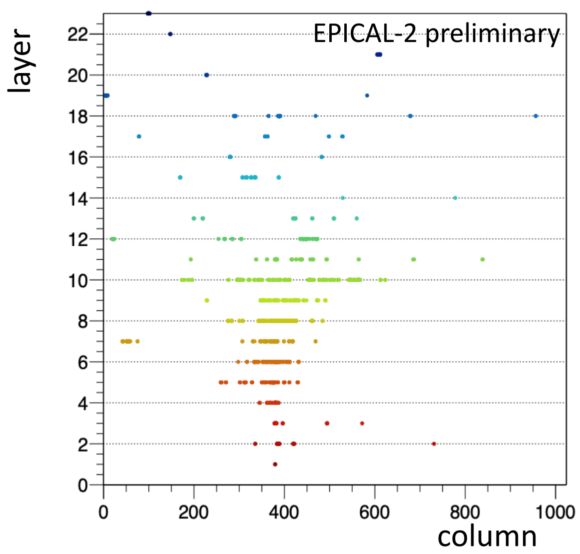
R&D for the ALICE-FoCal detector proposal
Current work performed in the context of the Bergen pCT collaboration

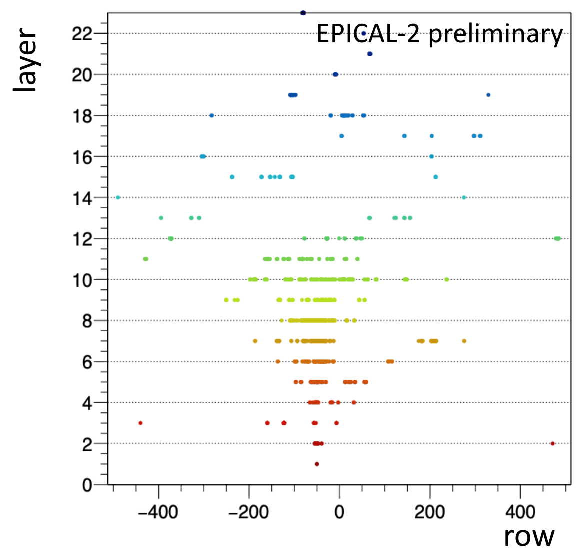
Event Display



one-electron event
5 GeV
raw data





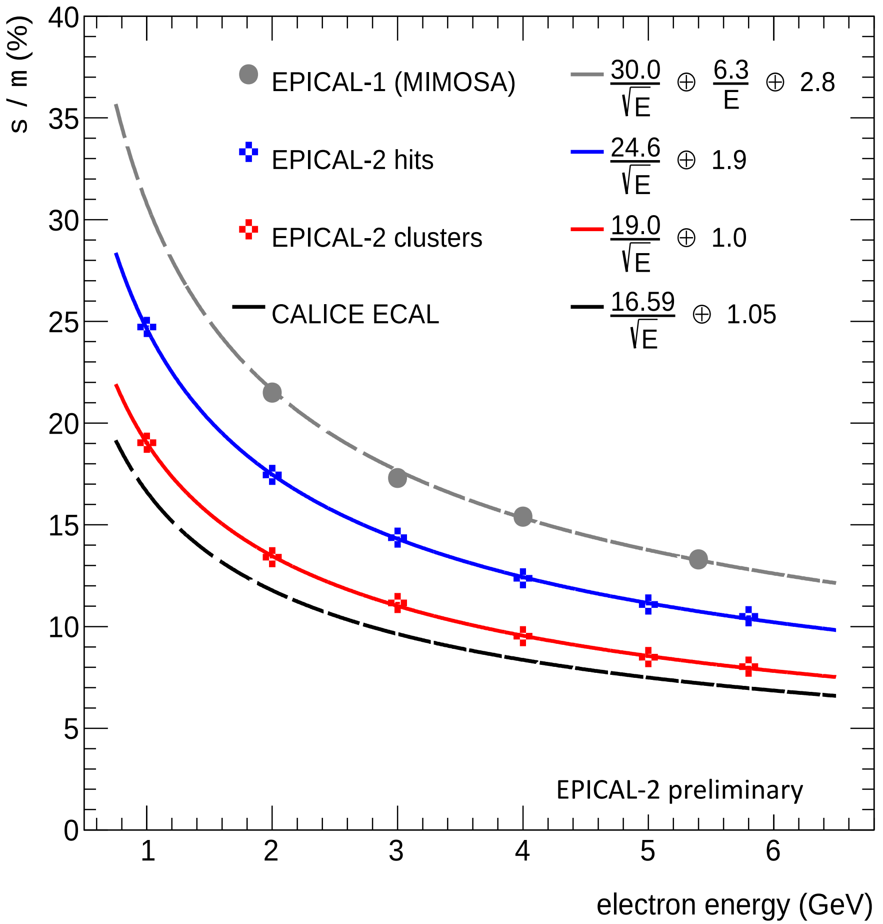


detailed evolution of shower

color coding: layers

Energy 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

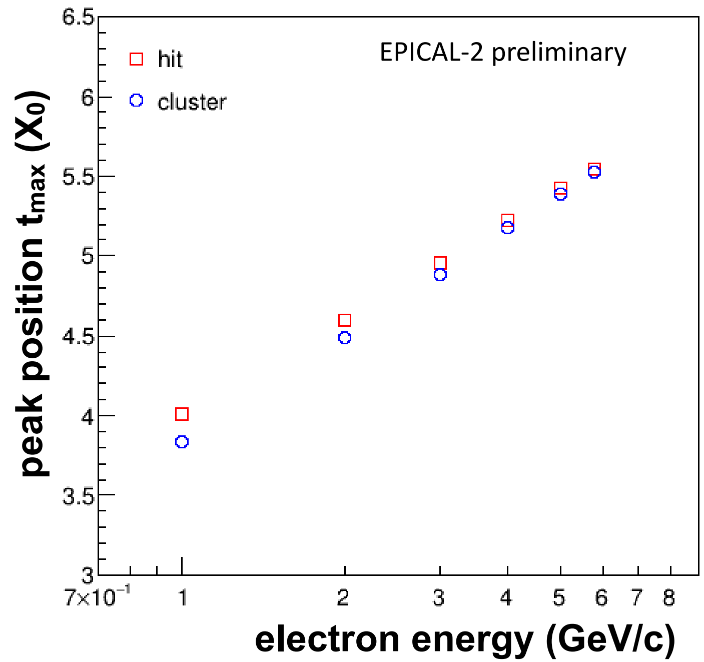


energy resolution superior compared to previous prototype

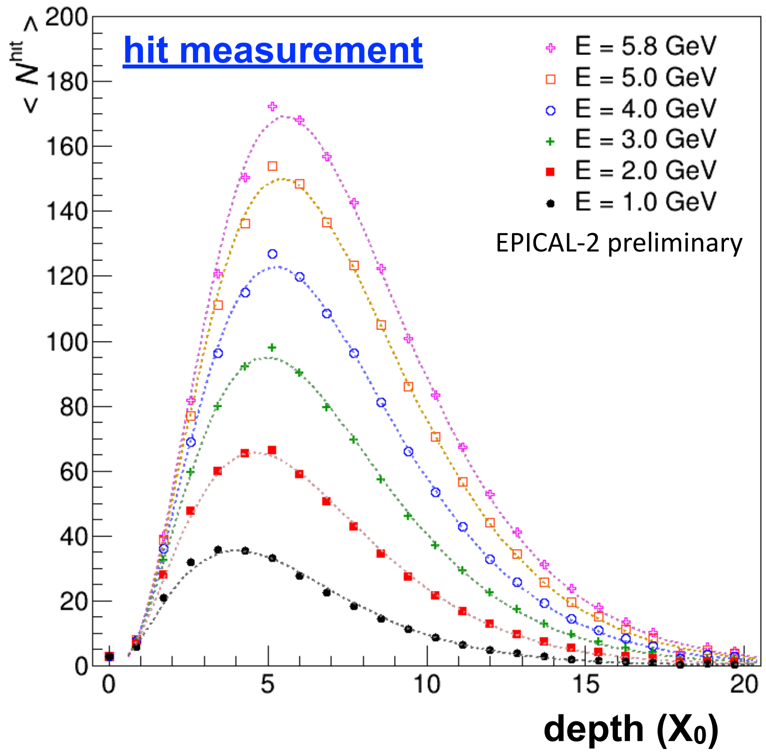
Longitudinal Energy Profile

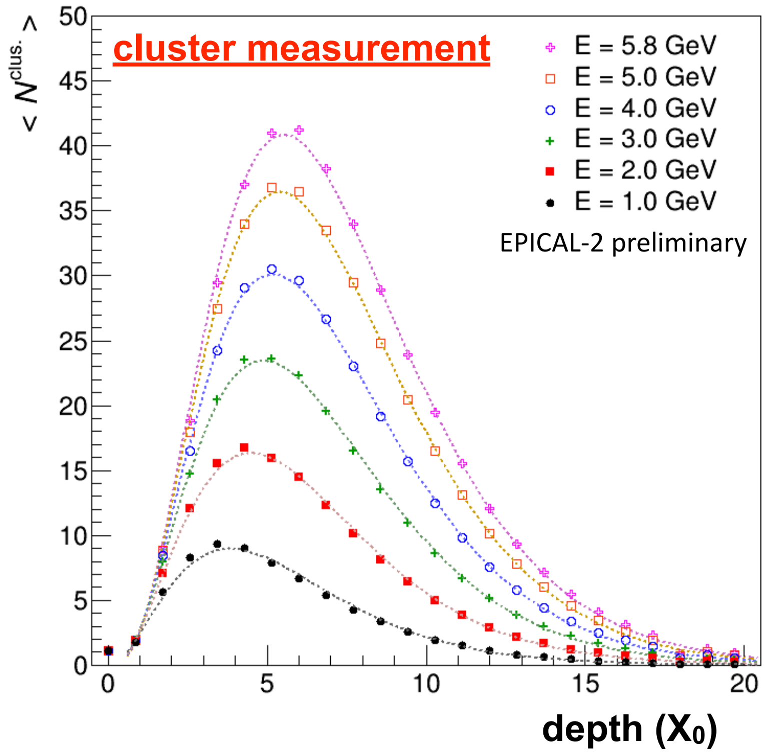
- ☑ **reasonable description by gamma distribution**
- ☑ peak position(t_{max}) proportional to log(E)
  - $t_{max}^{Hit} > t_{max}^{Cluster}$?
  - more accurate calibration for the conclusion

work in progress



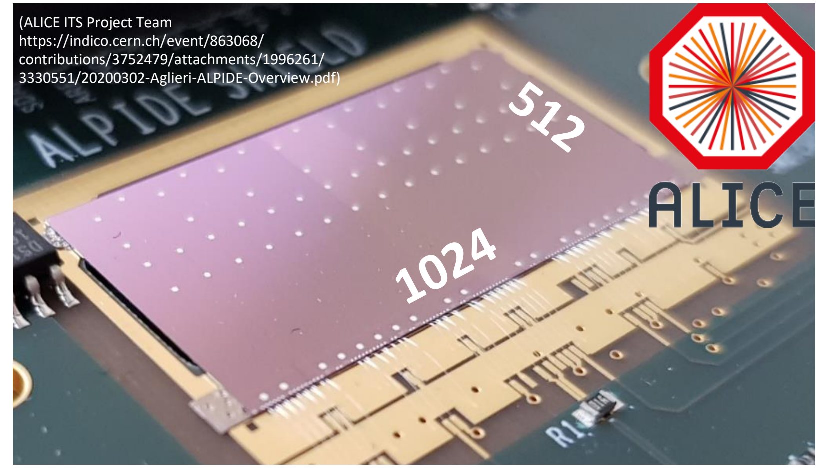
✐ **first step in detailed shower shape analyses**

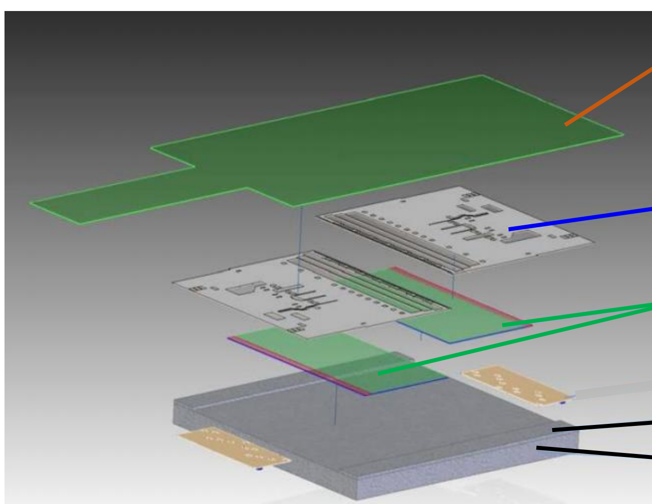


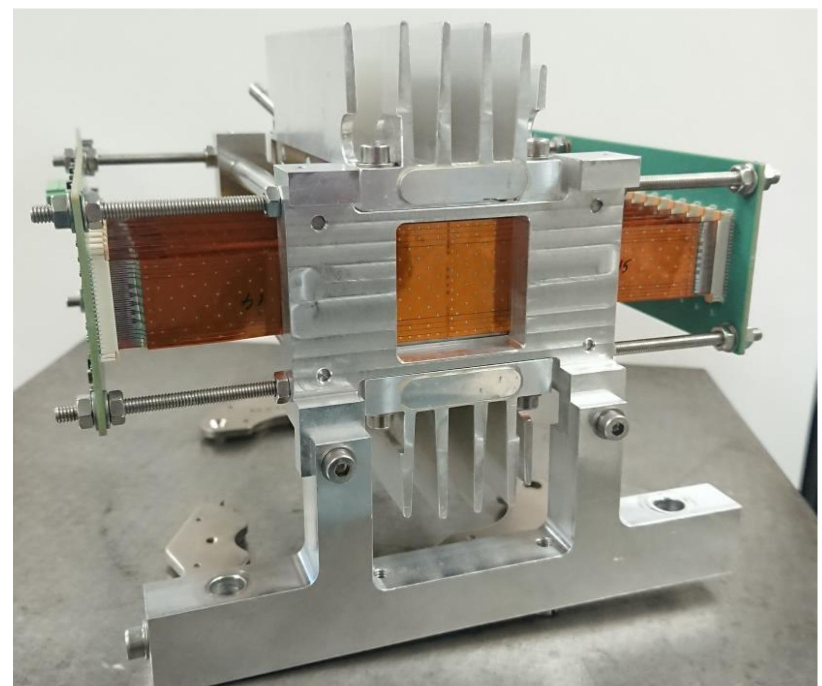


Electromagnetic **Pi**xel **Cal**orimeter 2 (**EPICAL**-2)

- **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







Electromagnetic Pixel Calorimeter 2 (EPICAL-2)

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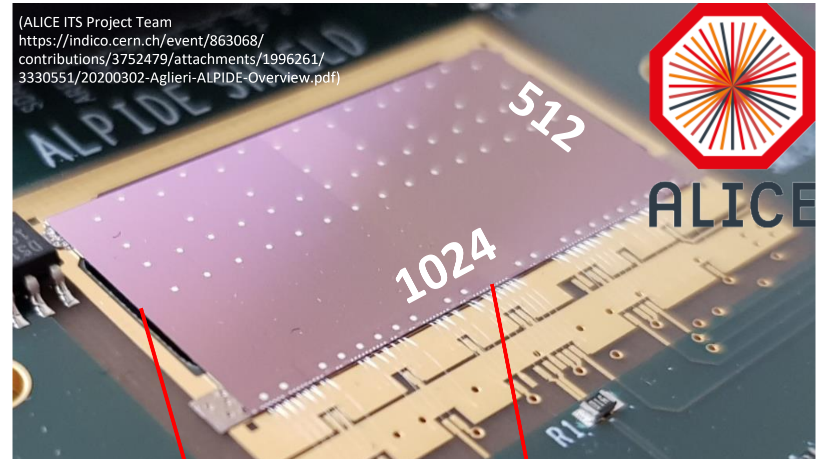
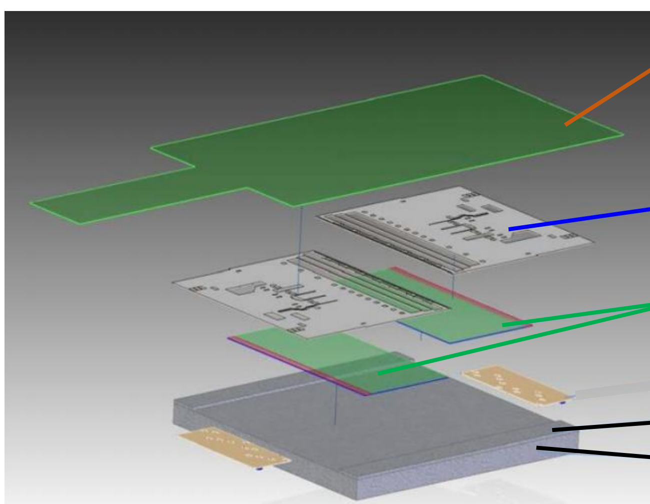
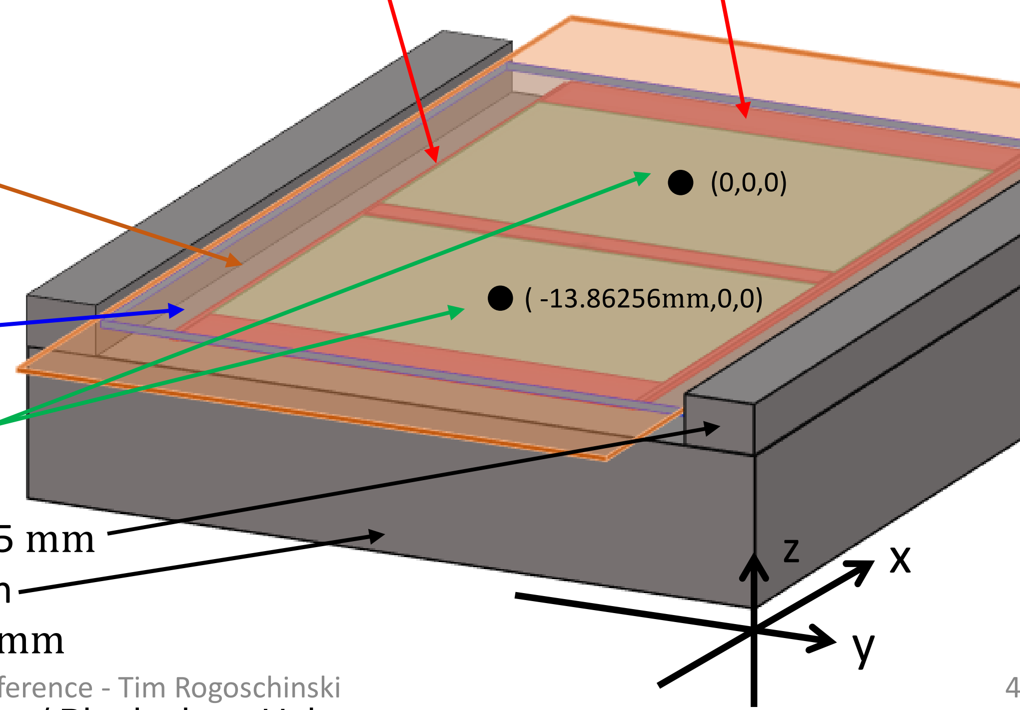
  → in context of R&D for planned LHC-ALICE FoCal upgrade in ~2026
  → **fully digital calorimeter** prototype
- **24 layers** with **two ALPIDE chips each**
  → chip size: 30 mm x 15 mm
- **512 x 1024 pixels per chip**
  → pixel size: 26.88 μm x 29.24 μm

- **simulation** utilizing **Allpix² framework**
  → **precise geometry implementation**







Electromagnetic Pixel Calorimeter 2 (EPICAL-2)

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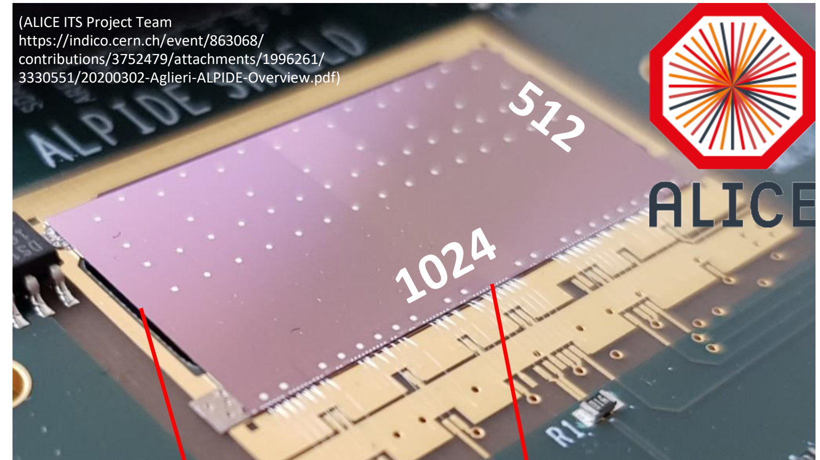
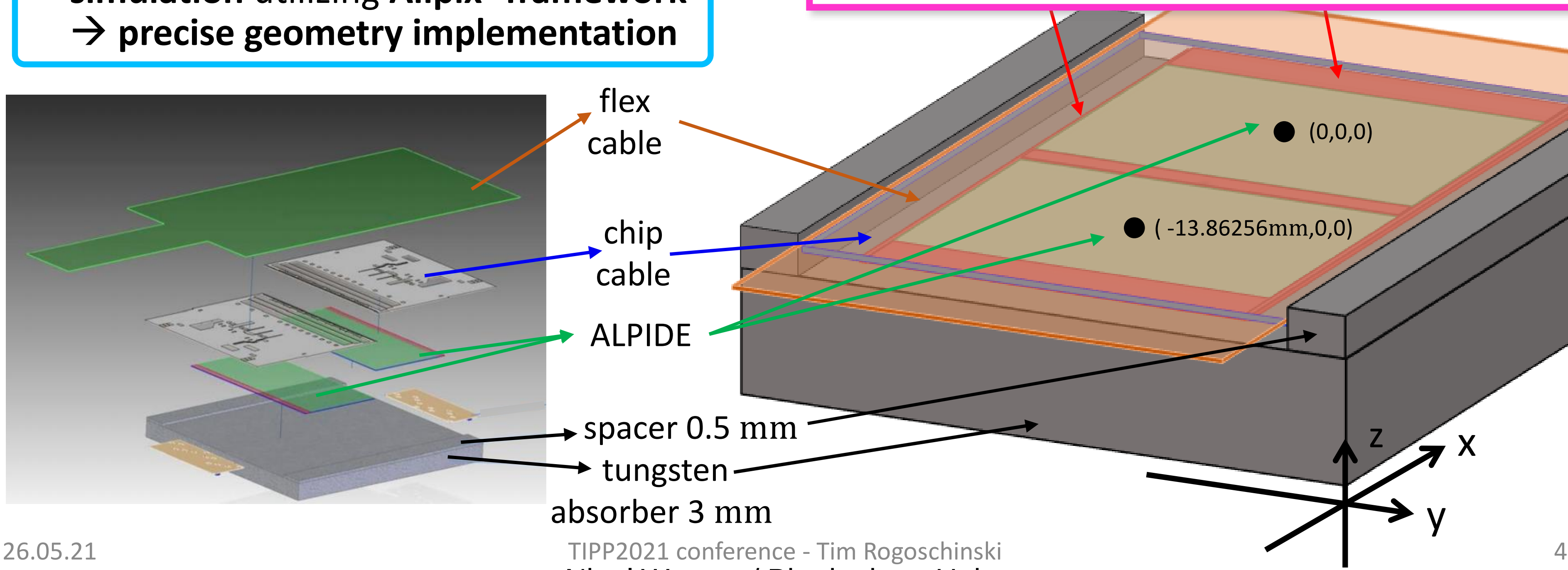
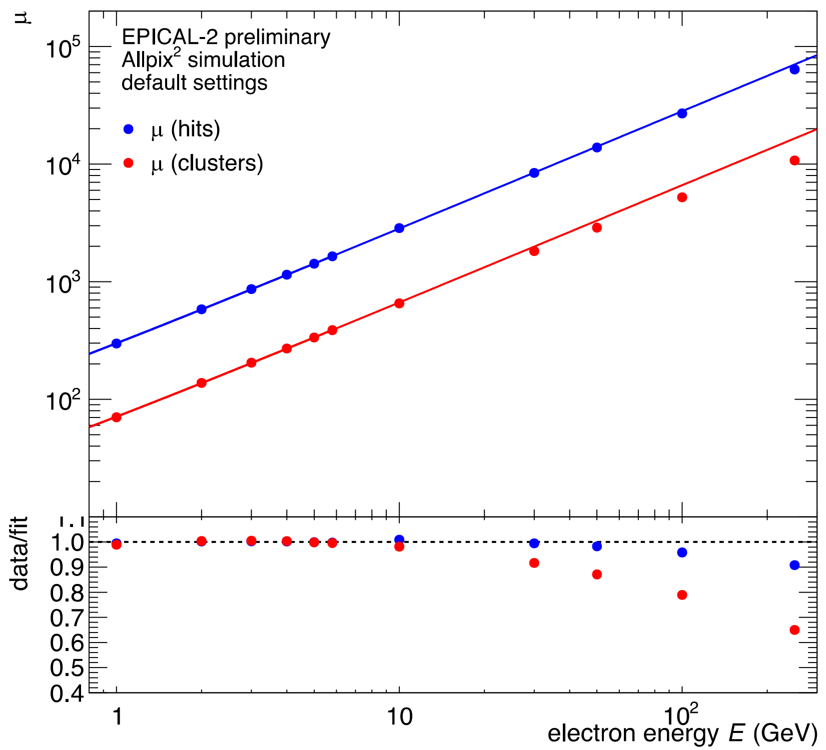
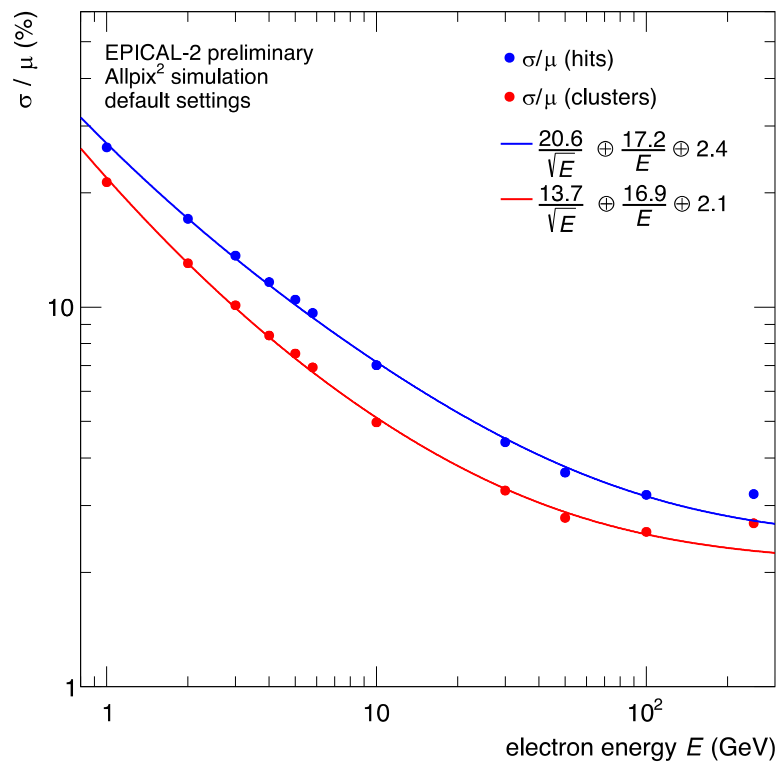


Derived from earlier UK student work

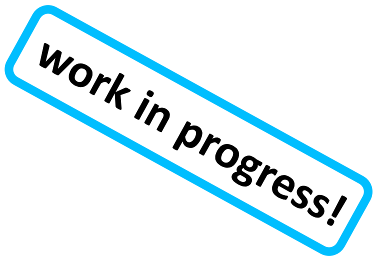


First look at higher energies
energy response and energy resolution





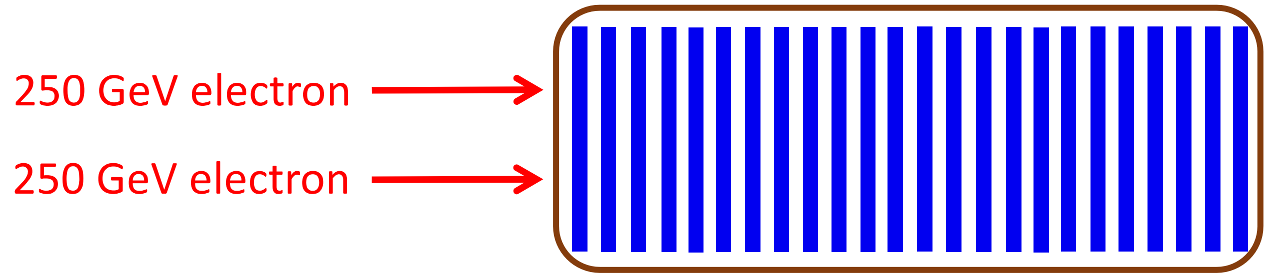
- **low energies: agreement** with **linearity** for hits and clusters,
  promising energy resolution
- **high energies: deviation** from **linearity** up to ~**10% for hits** and ~**35% for clusters,**
  worsening of apparent energy resolution
- resolution and linearity both affected by **leakage** 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

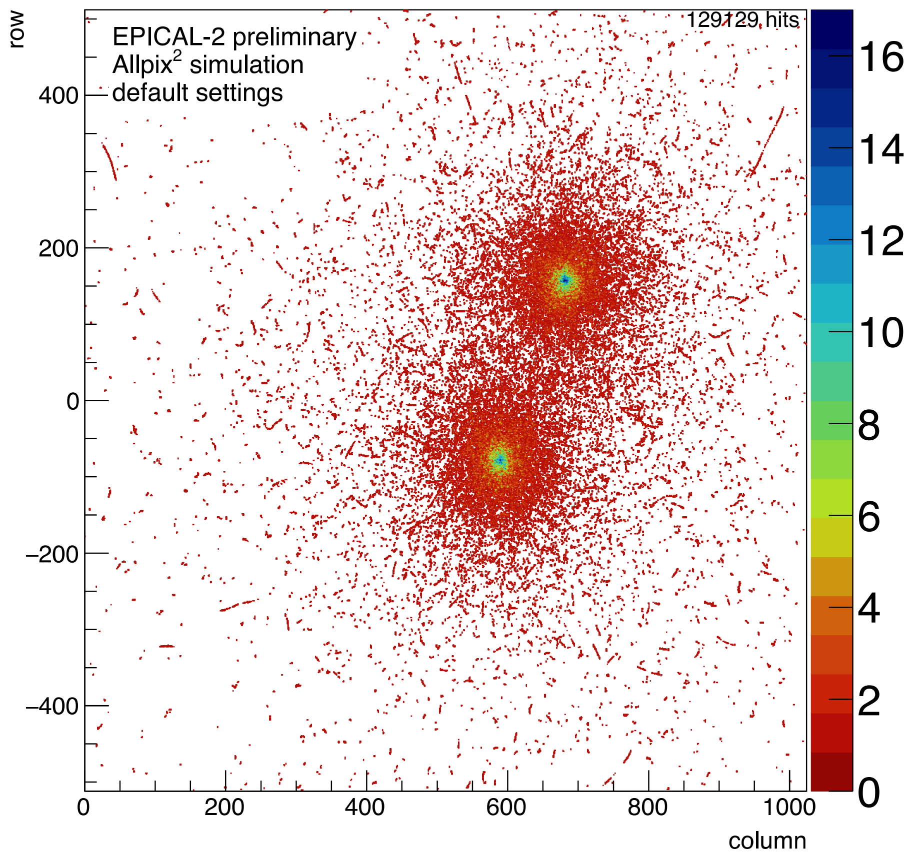


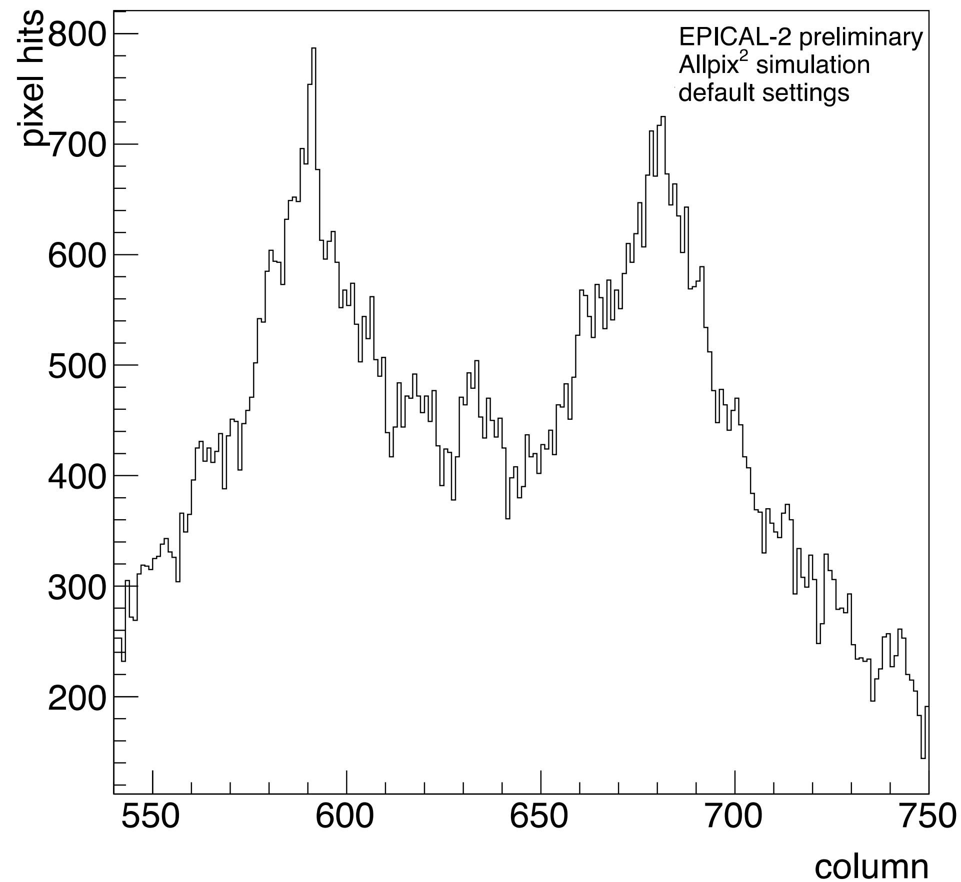
First look at higher energies

separation power

- same energy
- electrons separated by ~ 7.2 mm





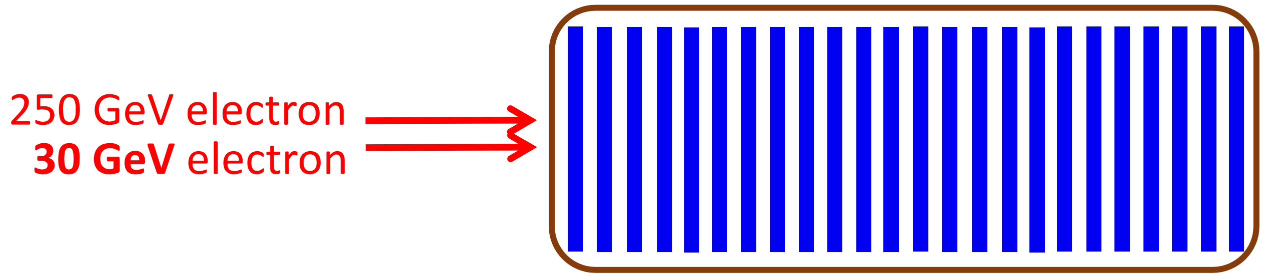


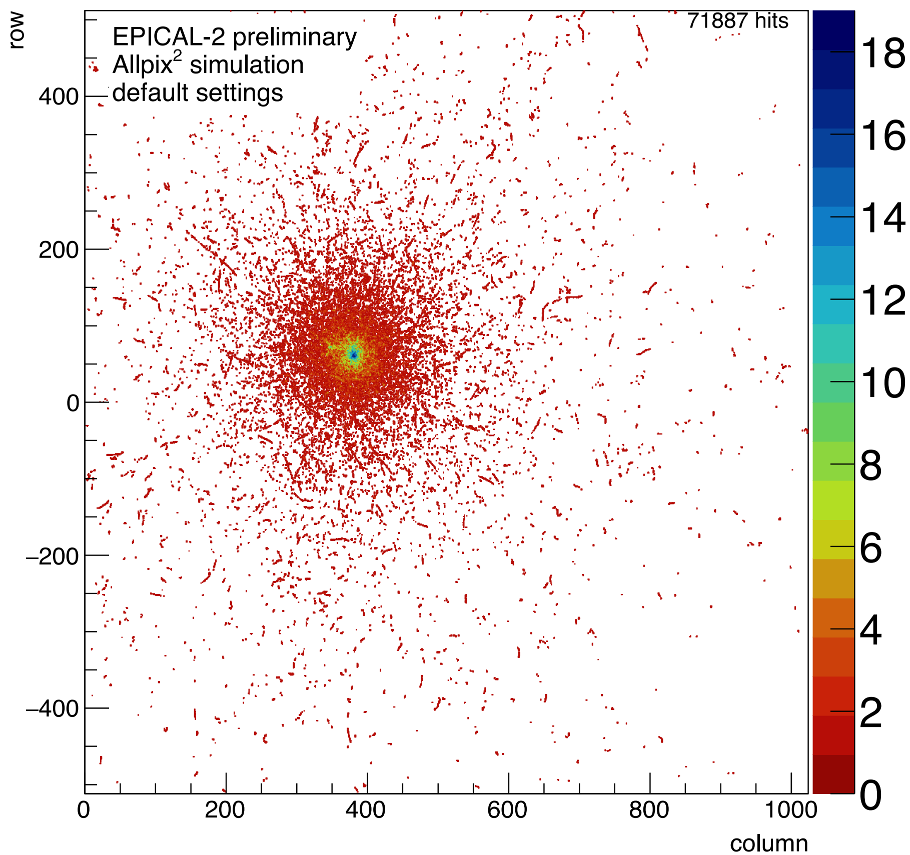
First look at higher energies

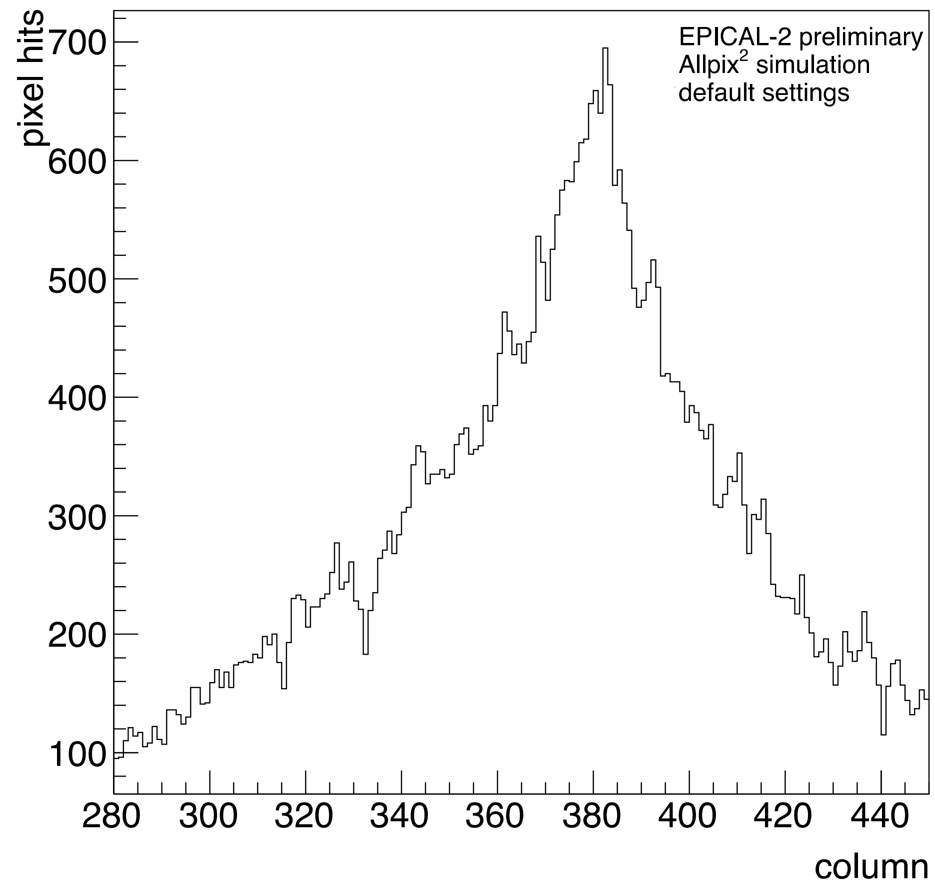
separation power

- large energy difference
- electrons close together

→ **challenging case**







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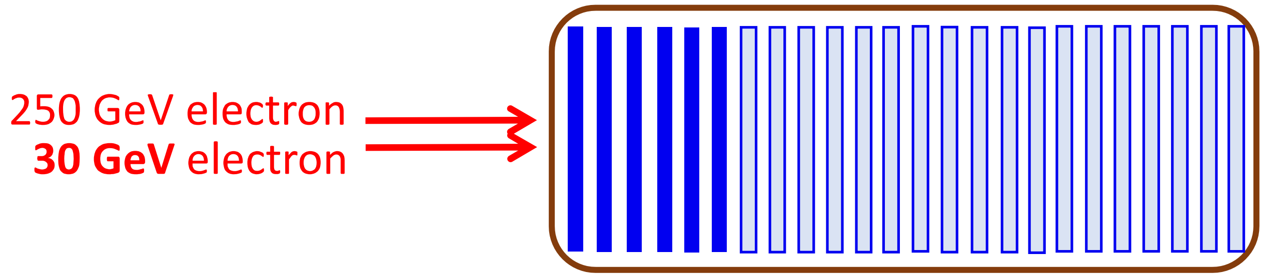
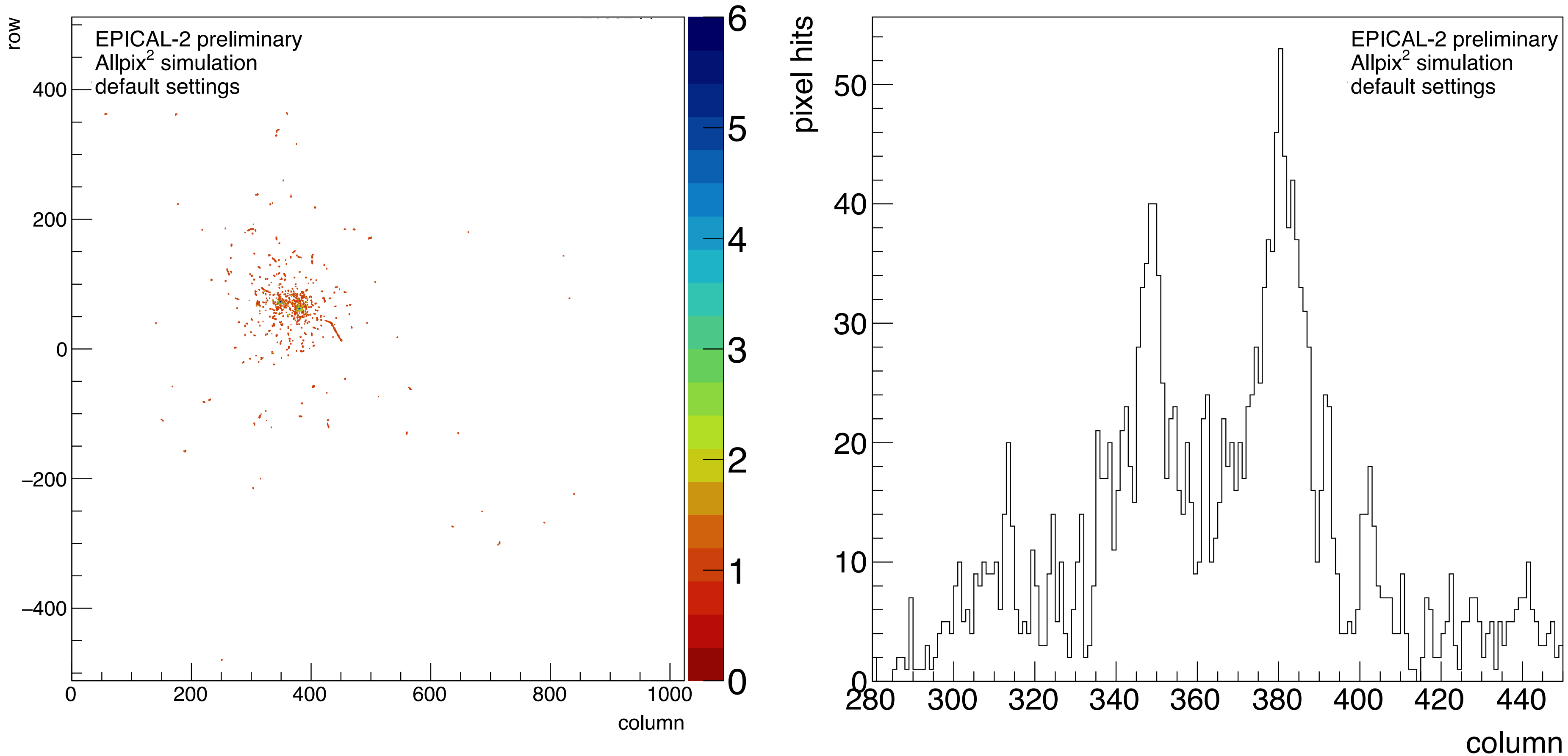
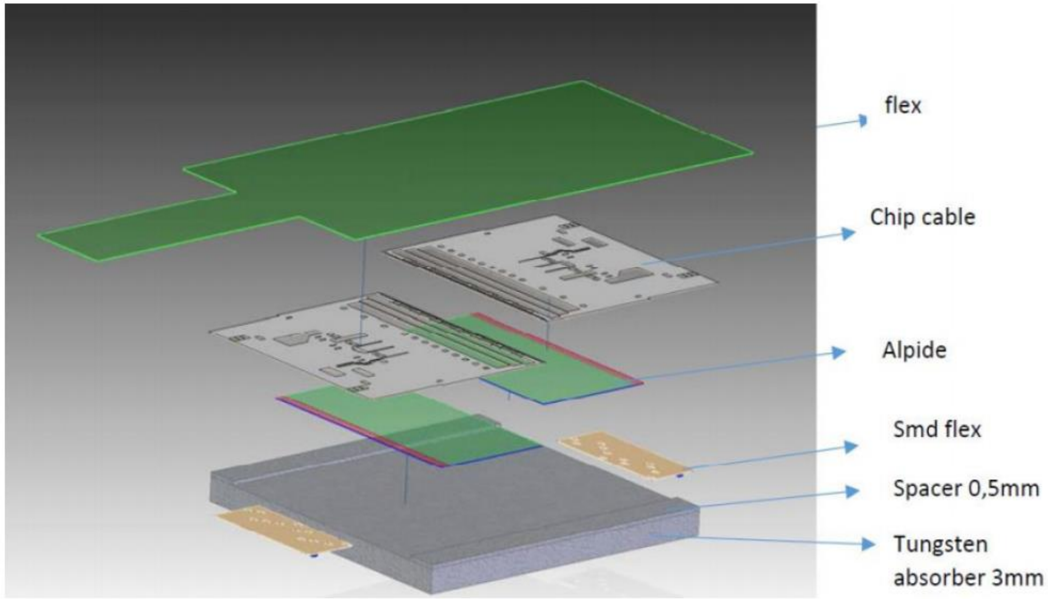


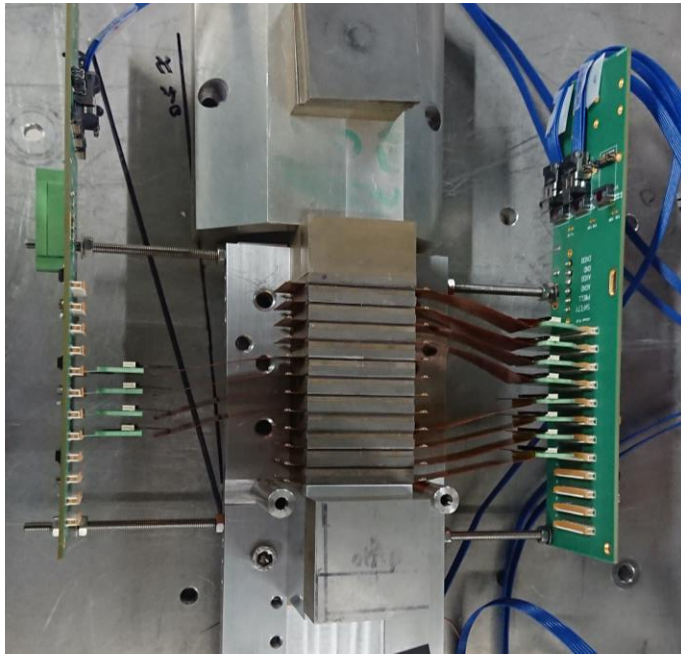


Further Reading Particle Flow Calorimetry

- Recent Snowmass paper (ILC) summarises state-of-the-art calorimetry and new technologies
- Machine, detector concepts x 2, subsystems
  - https://arxiv.org/abs/2203.07622
- DECAL/epical-2 – arxiv tomorrow (JINST few weeks)

Future Opportunities (DECAL)





- EpiCAL-2 prototype
- Demonstrates high level integration possible
- Using ‘off the shelf’ tracking sensor (ALPIDE) – **overlap/tracker**?
- Further optimise with new processes and sensor designed with calorimetry/reconfigurability
- See e.g. Snowmass submission

SNOWMASS21-IF6_IF0-067

UK could genuinely take a lead in this whole system

Demonstrated performance proposed in UK c. 2009

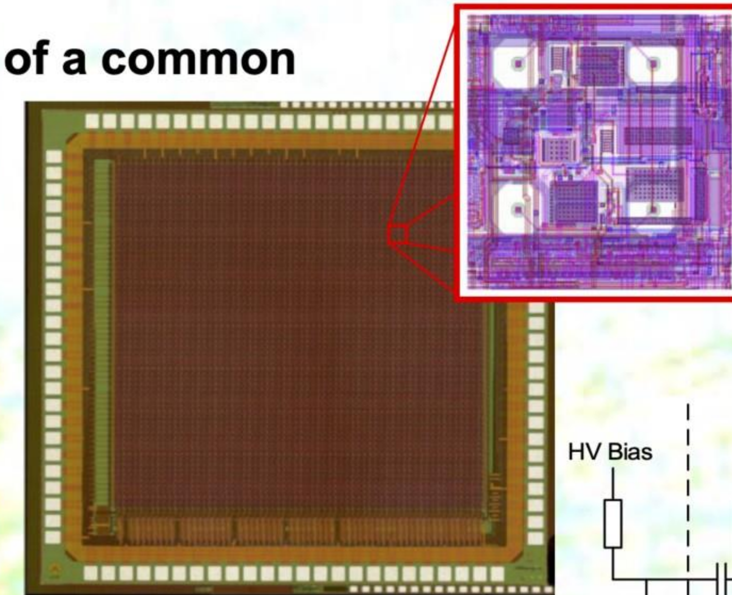
DECAL (4mm×4mm Array) Prototype Chip

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

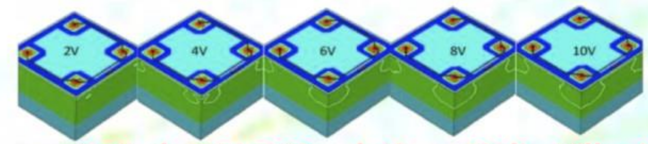
- **Outer tracking**
- **Pre-shower**
- **EM calorimeter**

Reconfigurable sensor as:

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

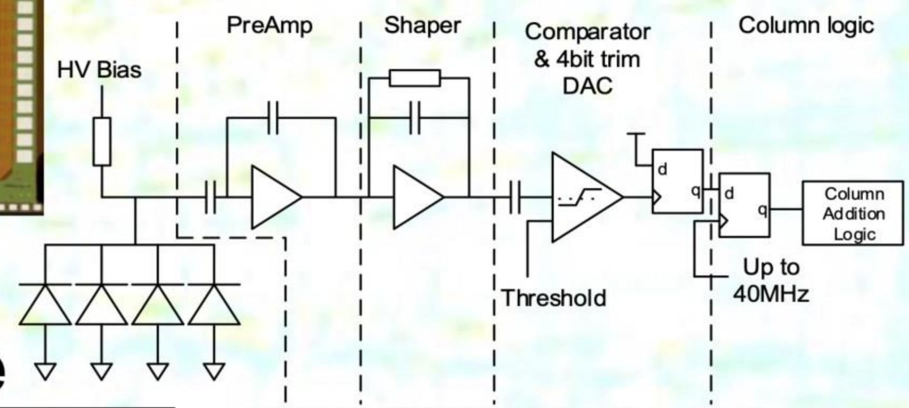


opportunities



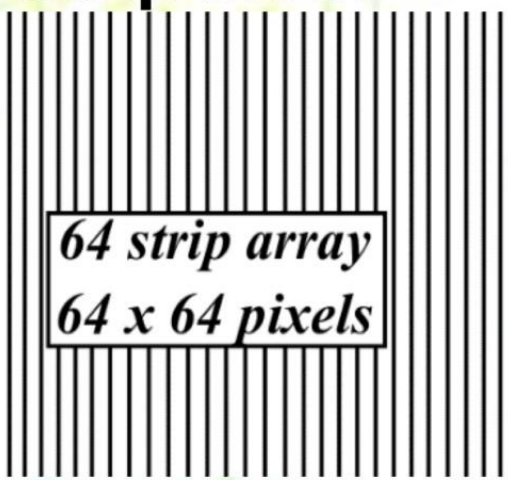
4 Diode TCAD Simulation: Giulio Villani

Prototype as proof of concept (180nm CMOS*)



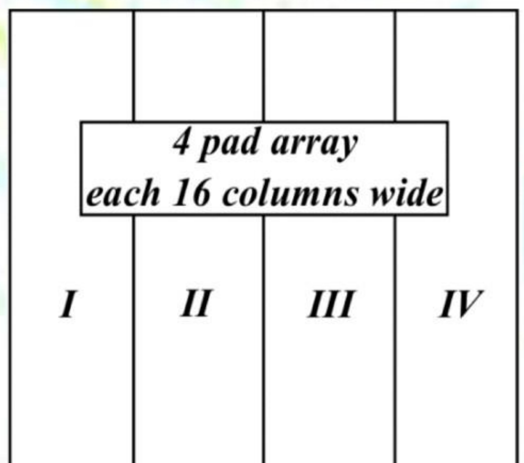
TWEPP (4/9/19) S.Benhammadi

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 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 > 10^7cm^2)
  - Potentially achievable with CMOS MAPS technologies, expanding 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

- Many opportunities in both Dual-Readout and High Granularity calorimetry for future experiments
- UK already contributing in major ways in both areas
  - Dual-calo R&D (IDEA)
  - DECAL (CALICE-like) with MAPS technology
  - We should continue to work across detector/machine concepts
- New UK collaborators welcome
  - Need to consider scale of projects befitting UK role in a future detector
  - Hardware development
  - Software/Simulation
  - Substantial expertise from past and ongoing projects