Calorimetry: Particle Flow Calorimeters

Eva Sicking (CERN)

EURIZON detector school
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Outline

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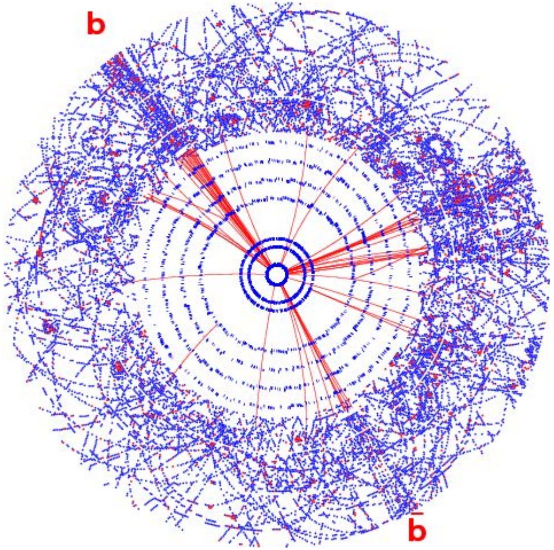
- Lecture 2
  - Modern HEP Calorimetry Systems
- Lecture 3
  - Particle-Flow Calorimeters
- Lecture 4
  - Dual Readout Calorimeters

- Introduction
  - Jet Energy Resolution
  - Particle Flow Approach
  - Performance improvement with PF in existing calorimeters
  - Future detector concepts
- Highly Granular Calorimeters for Linear Collider Experiments
  - CALICE concepts
  - Performance in Testbeam
  - Software Compensation
  - Pileup Rejection (timing)
- Highly Granular Calorimeters in upgrades for HL-LHC
  - CMS HGCAL
  - ALICE FoCal

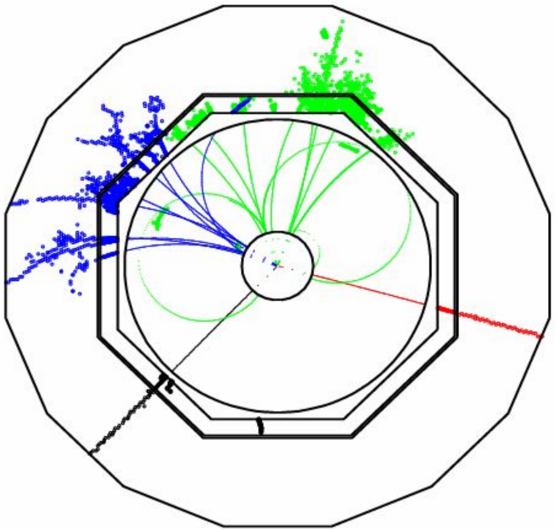
Introduction

e^+e^- colliders as next HEP project

$H \rightarrow b\bar{b}$ @ LHC



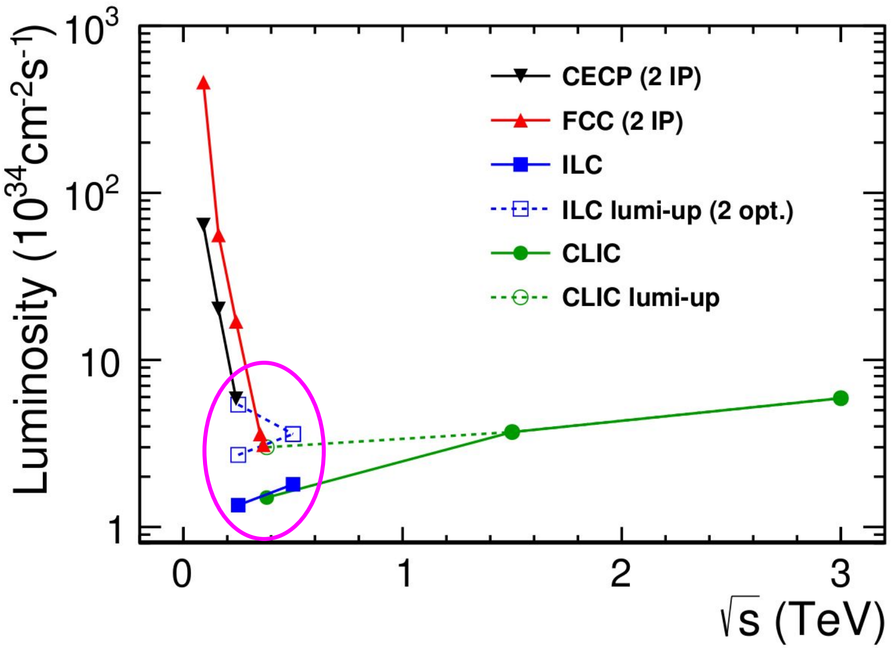
$ZH \rightarrow \mu^+\mu^- b\bar{b}$ @ e^+e^- colliders



- e^+e^- colliders provide **clean** environment for
  - Precision measurements of Standard Model particles **Higgs**, top, Z, W, …
  - Searches for signatures of Beyond the Standard Model (BSM) physics

Detector requirements at future e^+e^- colliders

- **Linear** e^+e^- colliders: ILC, CLIC
  - High centre of mass energies (ZH, $t\bar{t}$, $H\nu\bar{\nu}$, double Higgs, direct searches)
  - Beam polarisation → characterisation of new particles or processes in detail
- **Circular** e^+e^- colliders: FCC-ee, **CEPC**
  - Extremely high luminosities at low energies (Z, WW)
- **Linear and circular** e^+e^- colliders
  - Comparable luminosities in overlap region (ZH, $t\bar{t}$)



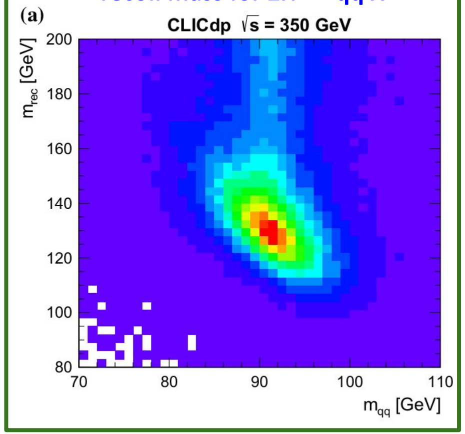
- Physics signal in overlap region and at high energies
  - High multiplicity final states (e.g. several jets plus backgrounds)
- Requirements
  - Detector optimised for precision physics in multi-jet environment

Precision physics at future lepton colliders: Examples

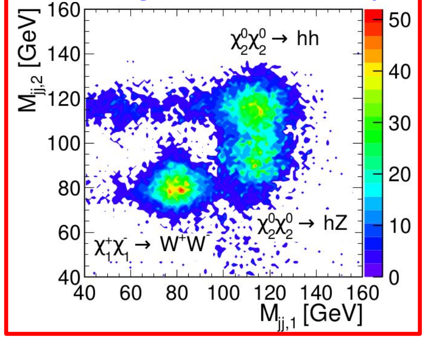
- Precision measurements with heavy bosons W, Z, and H in multijet final states and identified via their invariant mass
- Dijet invariant mass is given by $M^2 \approx 2E_1E_2\,(1-\cos\theta_{12})$
- Jet energy resolution of σ_E/E impacts mass resolution $\sigma_M/M \approx (1/\sqrt{2})\,\sigma_E/E$

- Example physics channels with **multi-jet final states** for which the reconstruction challenge is **dominated by the jet energy resolution**
  - $e^+e^- \rightarrow WW\nu_e\nu_e$ with $WW \rightarrow$ 4 jets
    - Probes WW scattering amplitude
    - Irreducible $ZZ\nu_e\nu_e$ background
  - $H \rightarrow WW \rightarrow$ 4 jets
    - Branching ratio measurement
    - Enters determination of the Higgs total width together with cross section for Higgs production in WW fusion channel
  - $e^+e^- \rightarrow ZH$, $Z \rightarrow$ 2 jets
    - Higgs reconstruction through recoil mass technique with hadronic Z decay
    - Sensitive to the calorimeter performance, even though kinematic constraints can be applied
  - $e^+e^- \rightarrow ZH$ final, with $Z \rightarrow \nu\nu$ (invisible) and $H \rightarrow$ 2 jets
    - Higgs decaying into a pair of jets is visible in clean conditions
    - Access to the Higgs coupling to charm quarks
  - $e^+e^- \rightarrow$ chargino pairs / neutralino pairs $\rightarrow$ 4 jets and missing energy

Di-jet invariant mass versus recoil mass for ZH → qq X



Di-jet invariant mass from H, Z, W from chargino/neutralino decays

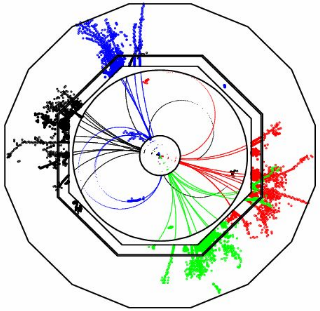


Detector requirements: Jet energy resolution

- Jet energy resolution (JER) requirements depend on physics goals of collider and detector
- Starting point for detector design
  - Ability to separate hadronic W and Z decays
- 3%–4% jet energy resolution needed at E_{jet}= 40-500 GeV to reach ~ 2.6−2.3σ W/Z separation

$ZW \rightarrow q\bar{q}\ q\bar{q}$

each q becoming a jet



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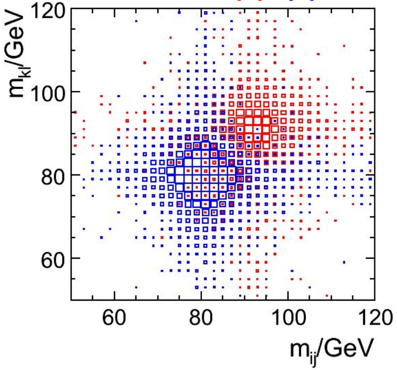
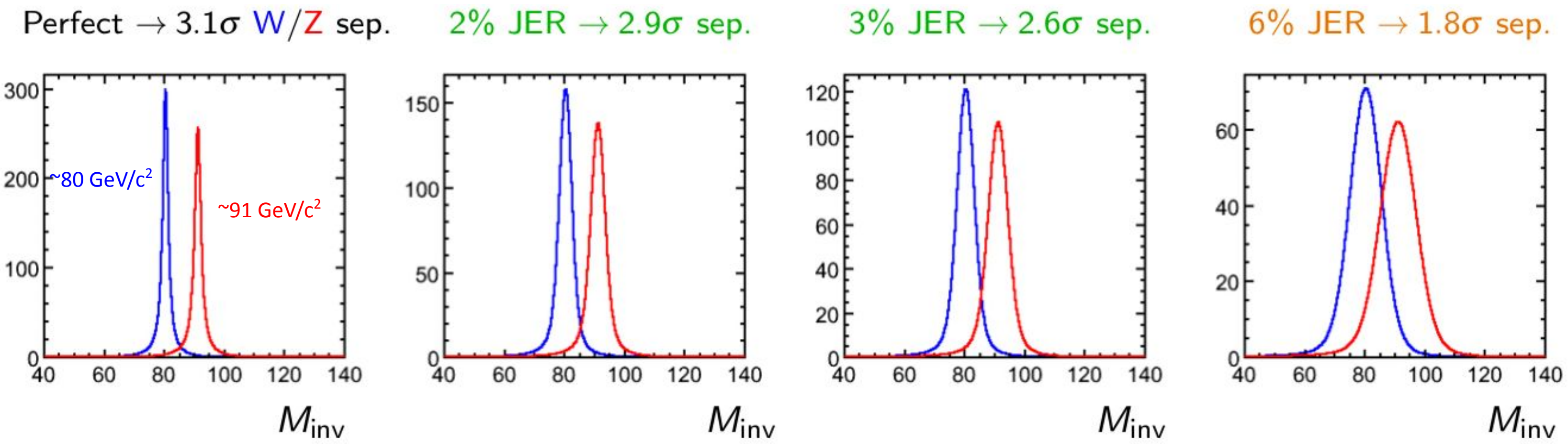
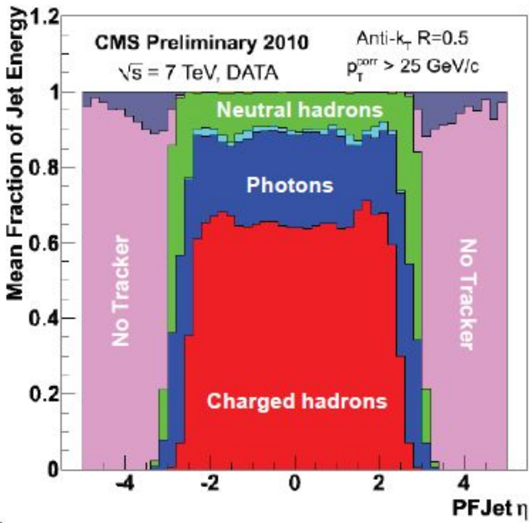
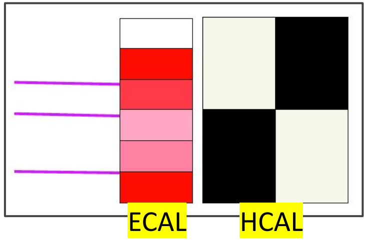




Traditional calorimetric jet energy resolution

- Classical way of measuring jet energies
  - Sum up the energy depositions of all charged and neutral particles of the jet in the calorimeter system $E_{jet} = E_{ECAL} + E_{HCAL}$
- Hadrons make on average ~70% of the jet
  - Jet energy resolution inherits poor performance of hadronic calorimeter





"Typical" calorimeter:

- $\sigma(E_{jet})/E_{jet} \approx 60\%/\sqrt{E(GeV)} \oplus 2\%$
- $\sigma(E_{jet})/E_{jet} \approx 10\%$ at E_{jet} = 50 GeV
- $\sigma(E_{jet})/E_{jet} \approx 4\%$ at E_{jet} = 500 GeV

Directions of research to improve situation

1. Compensating calorimeters
   - Design calorimeter system with e/h =1
2. Dual readout calorimeters
   - Reduce the effect of fluctuations in the electromagnetic fraction by measuring it event-by event
3. Particle Flow calorimeters

The Particle Flow Calorimetry Paradigm

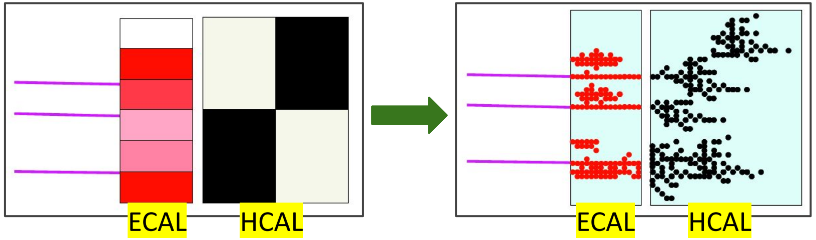
3%–4% jet energy resolution reachable with Particle Flow Analysis (PFA)

Idea:

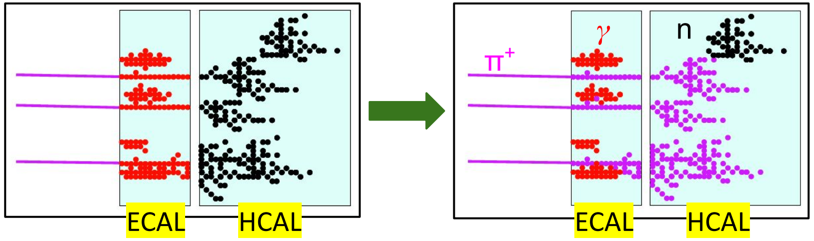
- For each individual particle, use the detector with the best energy resolution
- Average jet composition (fractions fluctuate from jet to jet)
  - 62% charged particles
  - 27% photons
  - 10% neutral hadrons
  - 1% neutrinos
- Always use the best information
  - 62% → tracker 🙂
  - 27% → ECAL 🙂
  - 10% → HCAL 🙁
  - ~~1%~~ 🙁

$$\sigma_{jet}^2 \approx 0.62\sigma_{tracks}^2 + 0.27\sigma_{EM\text{-}Calo}^2 + 0.10\sigma_{HAD\text{-}Calo}^2 + (\sigma_{loss})^2 + (\sigma_{confusion})^2$$

- Particle Flow Analysis: Hardware + Software
  - Hardware: Resolve energy deposits from different particles
    - High granularity calorimeters



  - Software: Identify energy deposits from each individual particle
    - Sophisticated reconstruction software



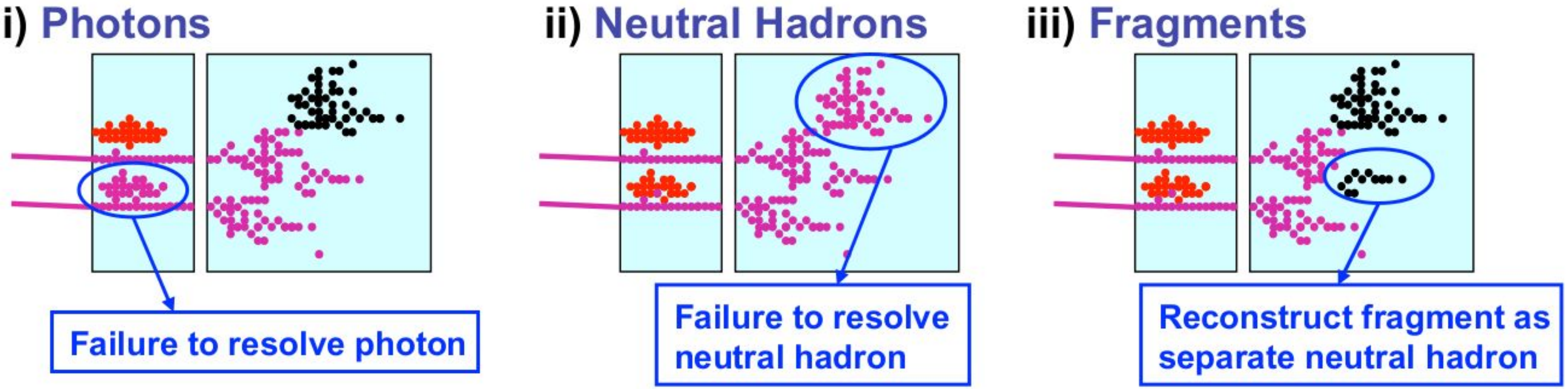
$$E_{jet} = E_{track} + E_{\gamma} + E_{n}$$

What is confusion?

- Incorrect assignment of energy depositions to particles

Colour code of Reconstructed particle type:

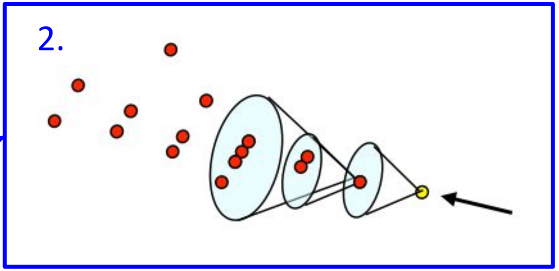
π^+ γ n



Particle Flow Algorithm **PandoraPFA**

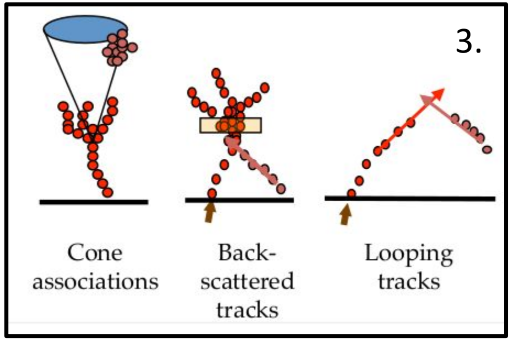
Reconstruction strategy

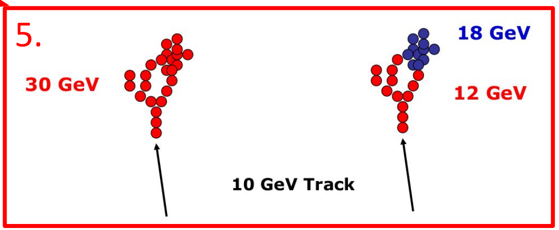
- Avoid double counting of energy from same particle
- Separate energy deposits from different particles



8 main reconstruction steps:

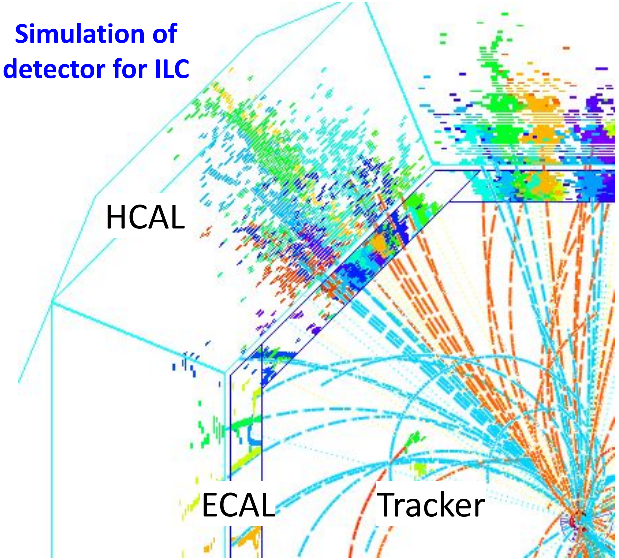
1. Track classification/extrapolation
2. **Loose clustering in ECAL and HCAL**
3. **Topological linking of clearly associated clusters**
4. Courser grouping of clusters
5. **Iterative re-clustering**
6. Photon Identification/Recovery
    a. optionally: Restart at step 2
7. Fragment removal
8. Formation of final Particle Flow Objects (= reconstructed particles)





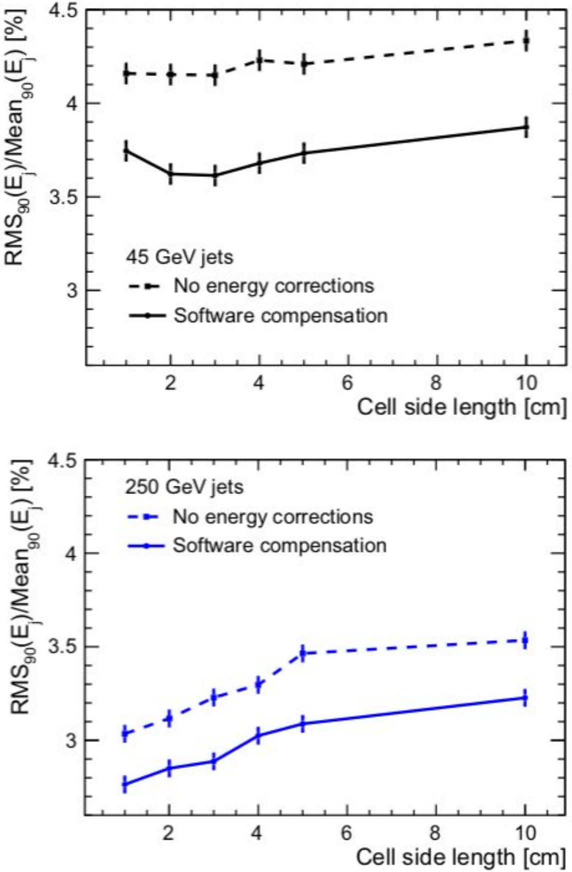
NIM A 611 (2009) 25-40
Eur.Phys.J.C 75 (2015)
Detector seminar

Reducing confusion term



$$\sigma_{jet}^2 \approx 0.62\sigma_{tracks}^2 + 0.27\sigma_{EM\text{-}Calo}^2 + 0.10\sigma_{HAD\text{-}Calo}^2 + (\sigma_{loss})^2 + (\sigma_{confusion})^2$$

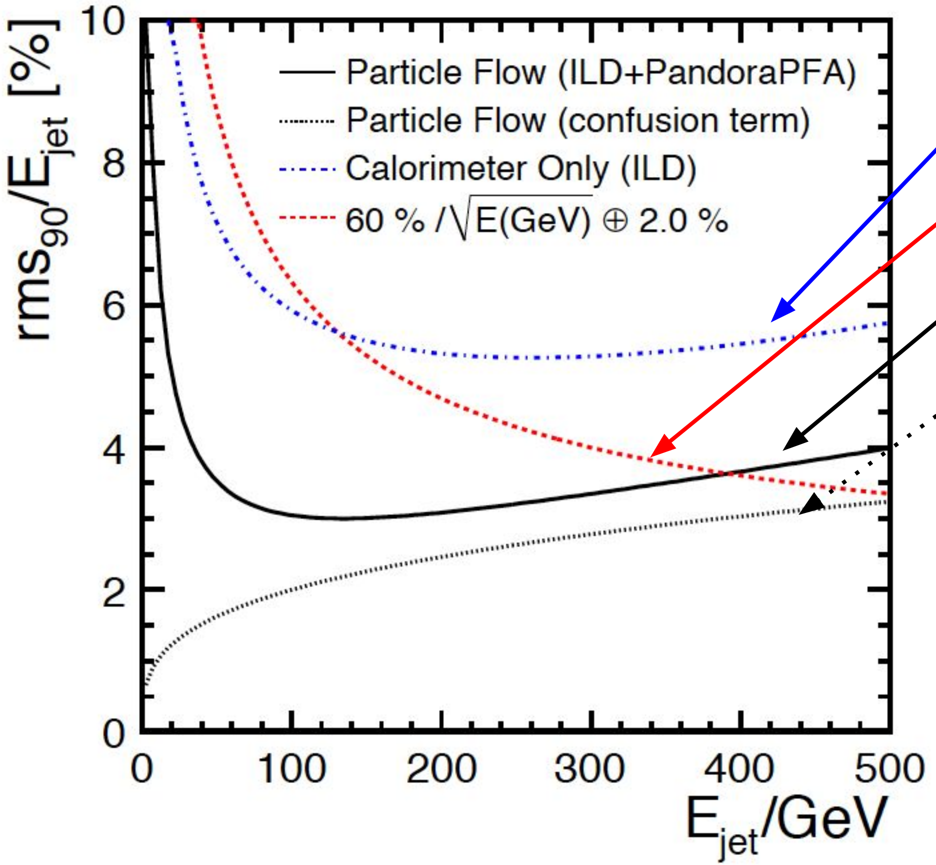
Example:
HCAL granularity optimisation



- High granularity of calorimeters
  - Separate overlapping showers to reduce confusion
- JER of 3%–4% reached when using
  - ECAL cell size: 1×1 cm^2
  - HCAL cell size: 3×3 cm^2

Eur. Phys. J. C 77, 698 (2017)

Jet Energy Resolution



Realistic calorimeter of a Linear Collider detector (calorimeter only)

“Ideal” traditional hadron calorimeter

Realistic LC calorimeter + Particle Flow Analysis

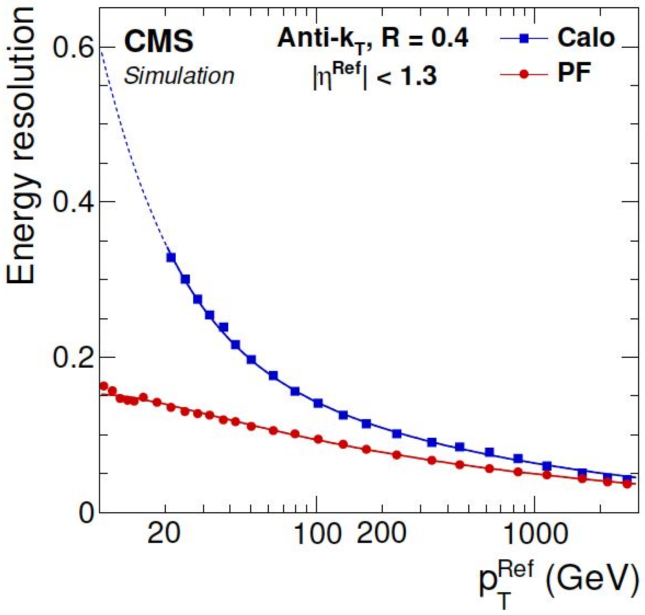
“Confusion”: wrong association between tracks and calorimeter clusters, dominates PFA resolution at large energies

- PFA jet energy resolution is better than calorimetric jet energy resolution
- Correct association between tracks and calorimeter clusters is very important
  - Requires high granularity

NIM A 611 (2009) 25-40

Impact of particle flow: CMS vs. ATLAS

- Particle Flow (or similar) algorithms have been used for jet reconstruction in the past by several experiments (ALEPH, CDF, H1, ZEUS, CMS, ATLAS)
- Improvement in resolution relative to pure calorimeter algorithms depends a lot on the detector itself
  - CMS: modest hadronic energy resolution, no material between tracker and calorimeter → large gain
  - ATLAS: good hadronic energy resolution, magnet between tracker and calorimeter → small gain



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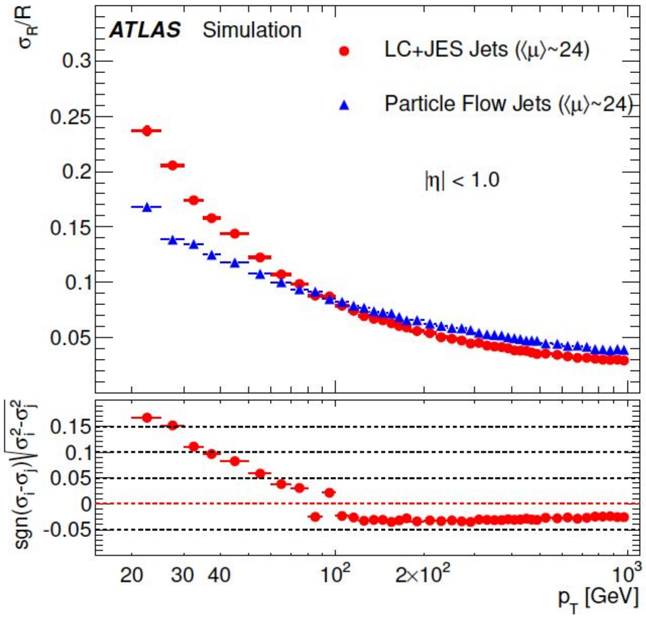

σ_R/R = relative jet transverse momentum resolution

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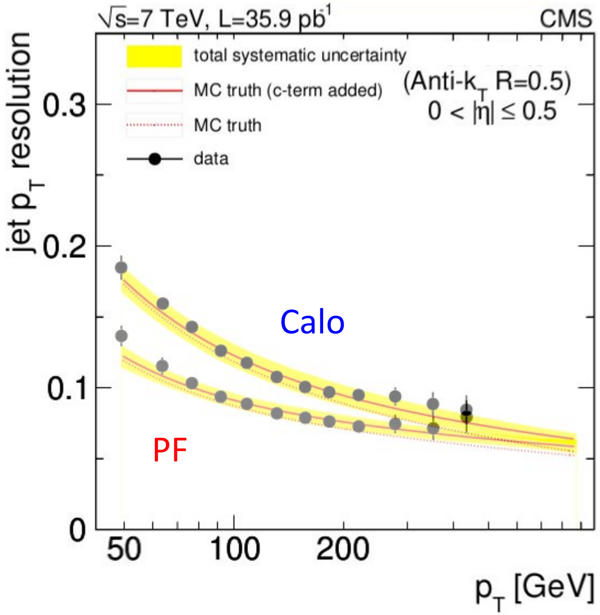
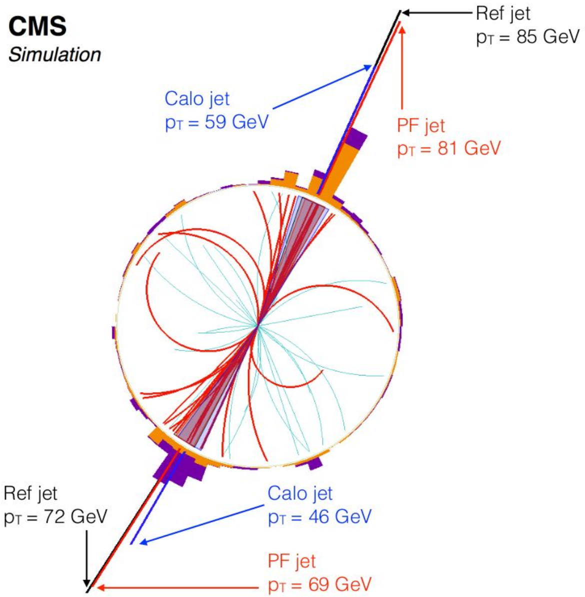
Overlay of Calo and PF figures





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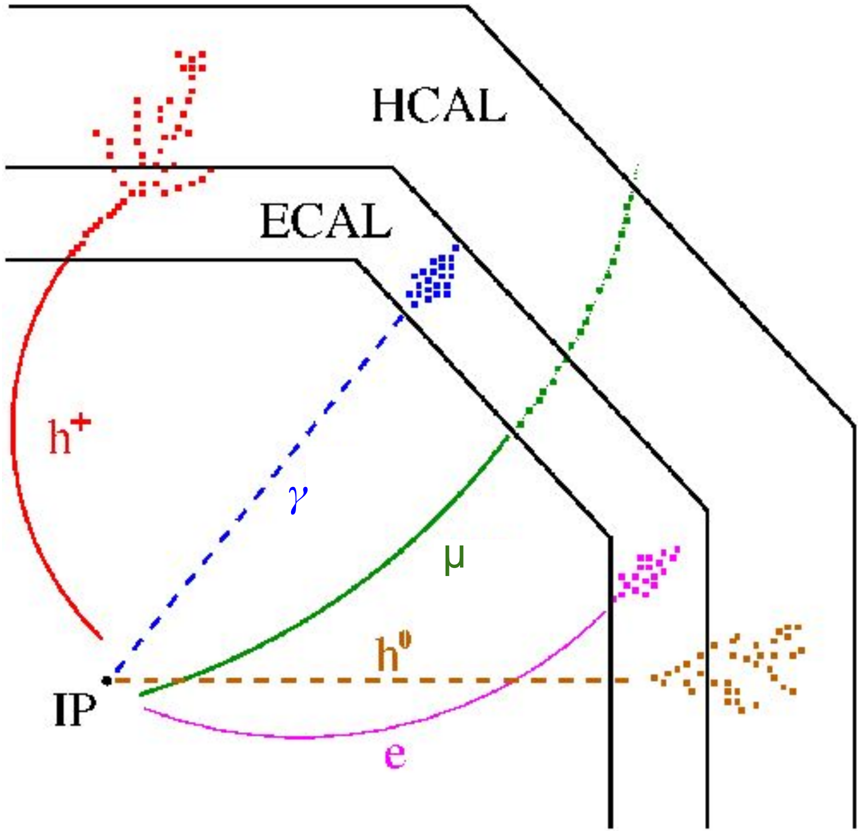
Future collider detectors optimised for PFA

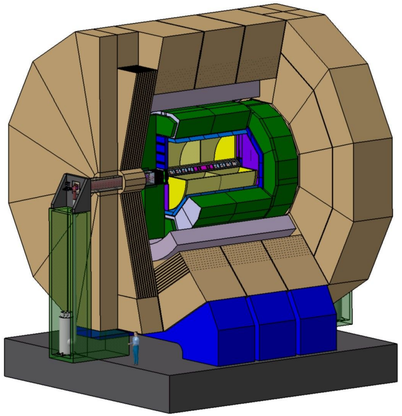
Detector optimised for Particle Flow

- Good separation of particles entering the calorimeter
  - Large detector radius and length
  - Large magnetic field to separate charged from neutral particles
- Compact showers to minimize overlap
  - Calorimeters with small Molière radius
- Minimal amount of dead material between tracker and calorimeter for track-cluster matching
  - Calorimeter inside magnet coil
- Detailed information about shower position and shape
  - Calorimeter with very high granularity

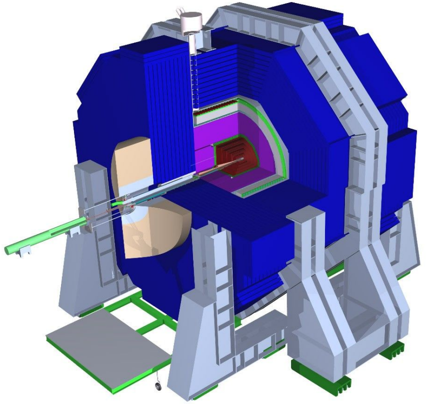


Future detector proposals optimised for PFA

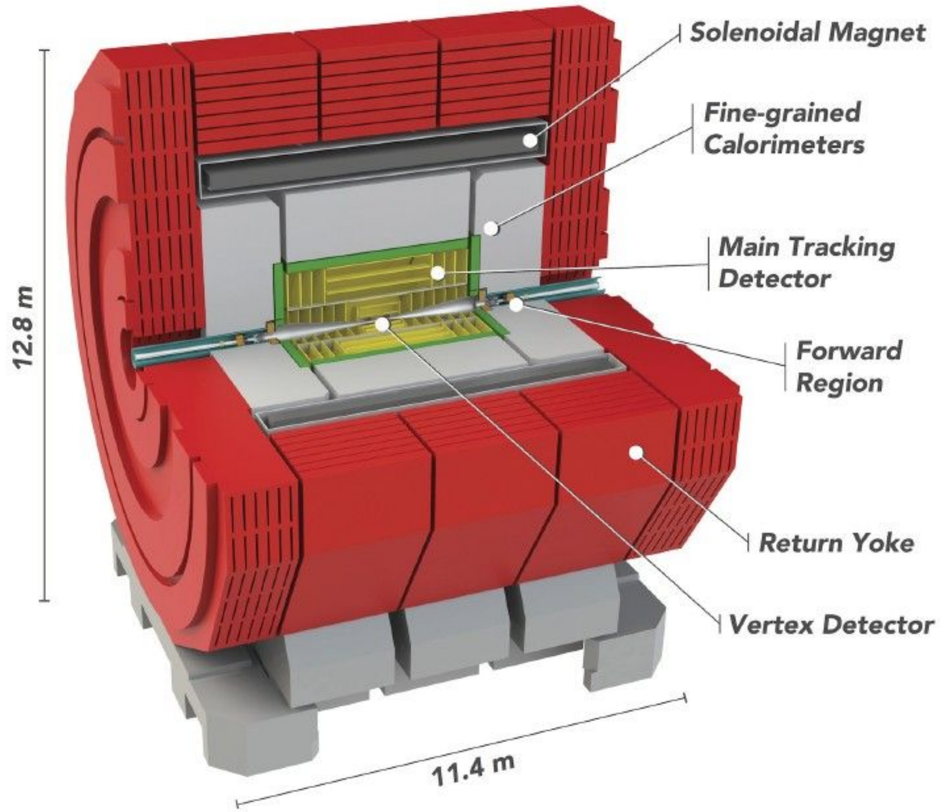
International Large Detector ILD for ILC



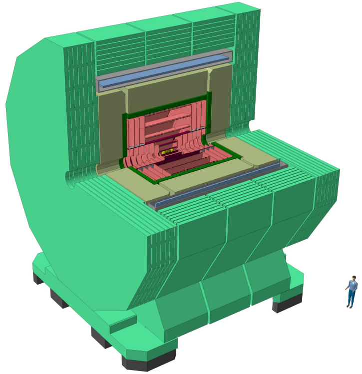
Silicon Detector SiD for ILC



CLIC detector CLICdet

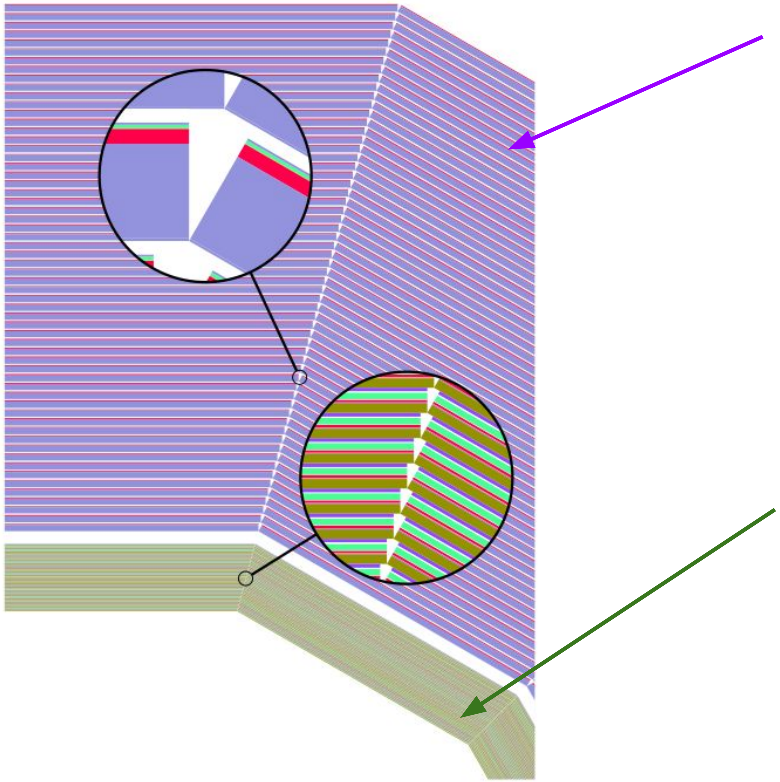


CLIC like detector CLD
for FCC-ee



All follow concept of
- Light tracker
- Highly granular calorimeters inside solenoidal magnet

Example: ECAL and HGCAL in CLIC detector



Scintillator-Steel HCAL

- 19 mm thick steel plates
- 3 mm thick plastic scintillator + SiPMs
- 60 layers: 7.5 λ
- 3 × 3 cm^2 scintillator cell size
  - ~ 9000 m^2 scintillator (24 x CMS HGCAL: 370 m^2)
  - ~ 10 million channels / SiPMs
- Compact design of all components
- Calibration of channels
- Time stamping < 1 ns

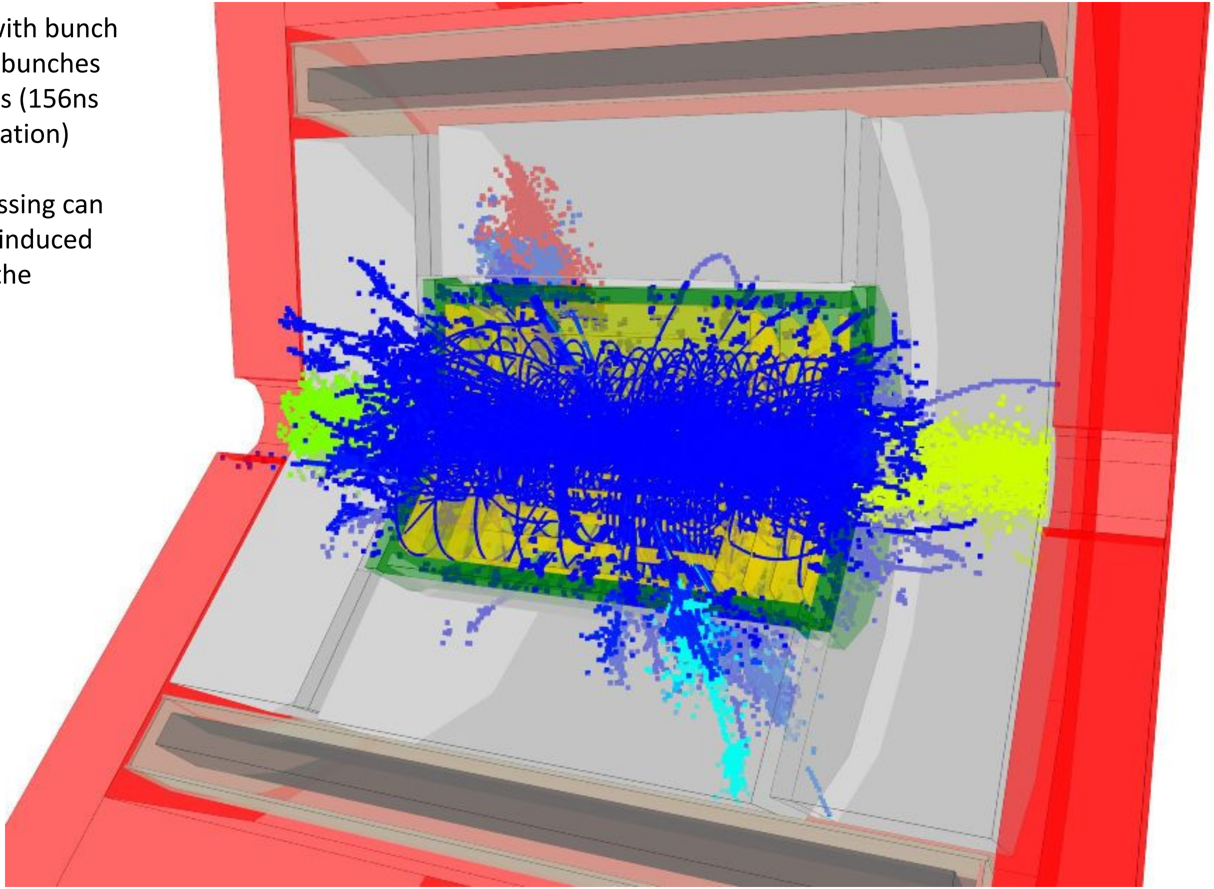
Silicon-Tungsten ECAL

- 2 mm thick tungsten plates interleaved with 500 µm thick silicon sensors
- 40 layers 22 X or 1 λ
- 5 × 5 mm^2 silicon cell size
  - ~ 2500 m^2 silicon (4 x. CMS HGCAL: 620 m^2)
  - ~ 100 million channels

Granularity and Timing for Background Rejection

CLIC operates with bunch trains with 312 bunches spaced by 0.5 ns (156ns bunch train duration)

Each bunch crossing can produce beam-induced background in the detector



$e^+e^- \rightarrow$ tt @ 3 TeV event with beam induced background from 60 bunch crossings overlayed

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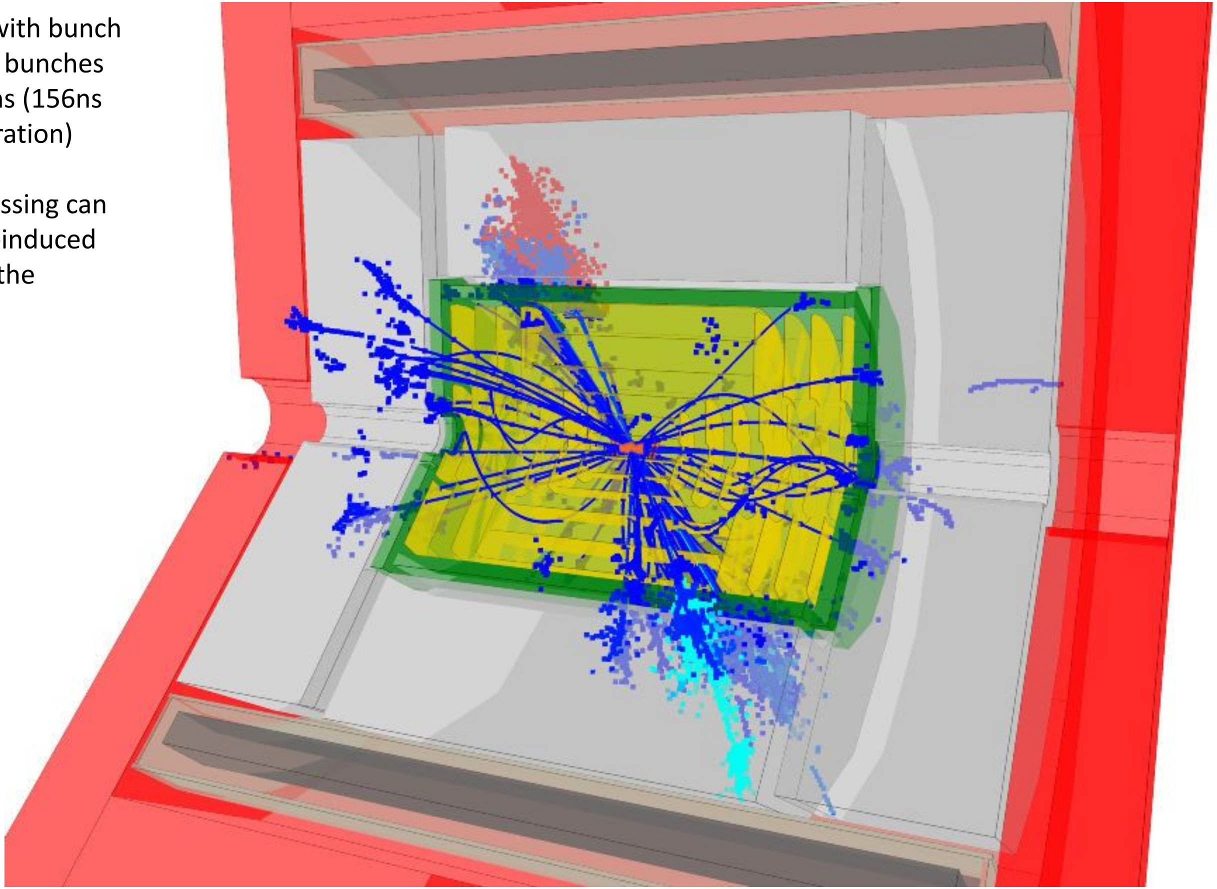


e^+e^- → tt @ 3 TeV event with beam induced background from 60 bunch crossings overlayed after nanosecond-level timing cuts, optimised for p_T and polar angle space

	Tight configuration	
Region	**p_T range [GeV]**	**Time [ns]**
	Photons	
Central	$1.0 \leq p_T < 4.0$	$t < 2.0$
$\lvert\cos(\theta)\rvert \leq 0.975$	$0.2 \leq p_T < 1.0$	$t < 1.0$
Forward	$1.0 \leq p_T < 4.0$	$t < 2.0$
$\lvert\cos(\theta)\rvert > 0.975$	$0.2 \leq p_T < 1.0$	$t < 1.0$
	Neutral hadrons	
Central	$1.0 \leq p_T < 8.0$	$t < 2.5$
$\lvert\cos(\theta)\rvert \leq 0.975$	$0.5 \leq p_T < 1.0$	$t < 1.5$
Forward	$1.0 \leq p_T < 8.0$	$t < 1.5$
$\lvert\cos(\theta)\rvert > 0.975$	$0.5 \leq p_T < 1.0$	$t < 1.0$
	Charge particles	
All	$1.0 \leq p_T < 4.0$	$t < 2.0$
	$0 \leq p_T < 1.0$	$t < 1.0$

➡ Together with ns time resolution, granularity enables efficient pileup rejection

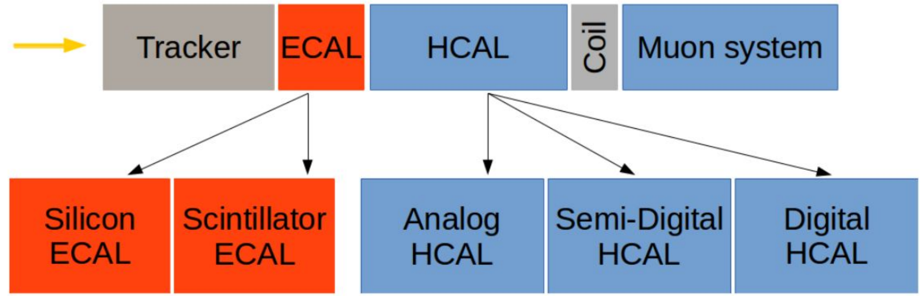
Highly Granular Calorimeter R&D

CALICE: Calorimetry for Linear Collider Experiments

Collaboration for development of highly granular calorimetry optimised for particle flow event reconstruction

- Large-scale prototype construction
  - ➡ Hands-on experience
- Beam tests with single particles and comparison to Geant4
  - ➡ Show that overall calorimeter system performance can be achieved
  - ➡ Show that Geant4 simulations can reproduce measurements (unprecedented shower sub-structure information)
  - ➡ Study realistic jet energy resolution in simulations

Existing large-scale CALICE prototypes



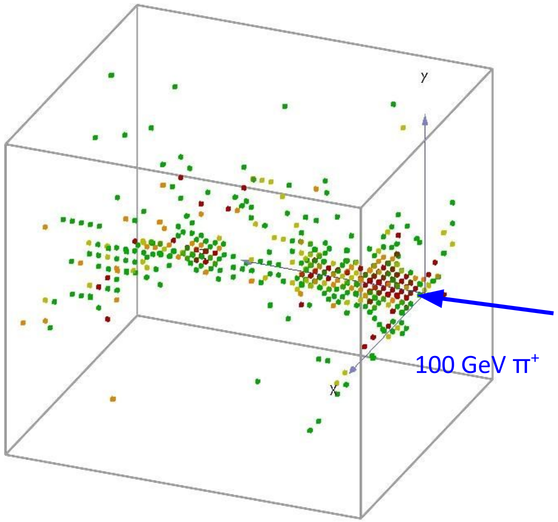
	Silicon ECAL	Scintillator ECAL	Analog HCAL	Semi-Digital HCAL	Digital HCAL
Active layer technology	Silicon PIN diodes	Scint. strips+ Silicon Photo Multipliers	Scint. tiles+ Silicon Photo Multipliers	RPCs (μMegas)	RPCs (GEMs)
Granularity (mm^3)	$10 \times 10 \times 0.5$	$45 \times 5 \times 3$	$30 \times 30 \times 5$	$10 \times 10 \times 1.2$	$10 \times 10 \times 1.15$
Absorber	W	W	Fe or W	Fe	Fe or W
Layer × thickness (mm)	$10\times1.4+$ $10\times2.8+$ 10×4.2	30×3.5	Fe: 38×21.4 W: 38×10	48×20	Fe: 38×20 W: 39×10
Name	Si-W-ECAL	Sc-W-ECAL	AHCAL	SDHCAL	DHCAL

➡ New: **Dual Readout** and **crystal calorimeter** options also under study within CALICE

Main readout concepts

Analogue Calorimeter:

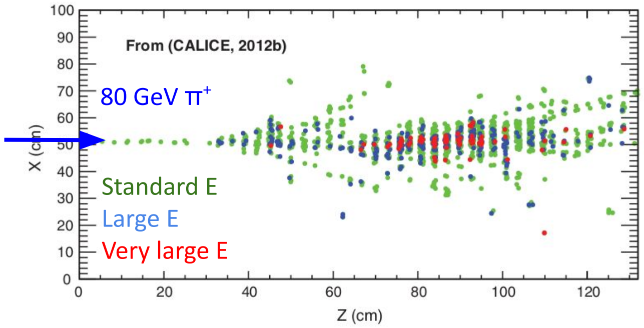
- **Scintillators + SiPM, Silicon**
- Sum up signals in (larger) cells
- = "Classical" calorimetric reconstruction



Scintillator tiles + SiPM (3×3 cm^2)

Semi-Digital Calorimeter:

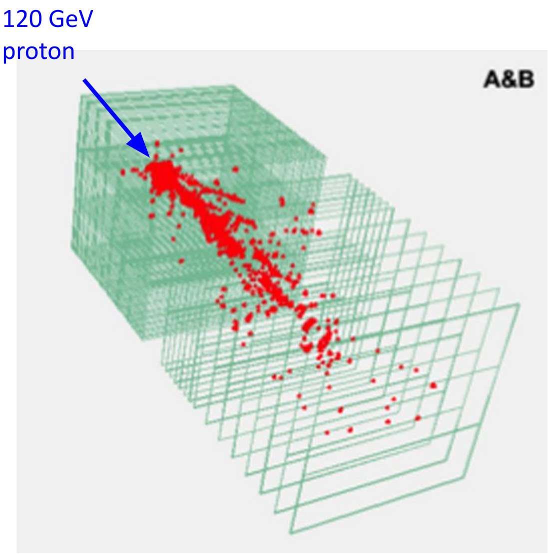
- **Resistive Plate Chambers**
- Additional information about number of particles within one readout cell by using 3 thresholds:
  off, standard, large, very large



RPC (1×1 cm^2)

Digital Calorimeter:

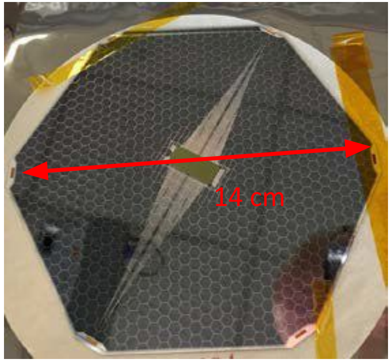
- **Resistive Plate Chambers**
- Count number of hit readout cells (off/on)



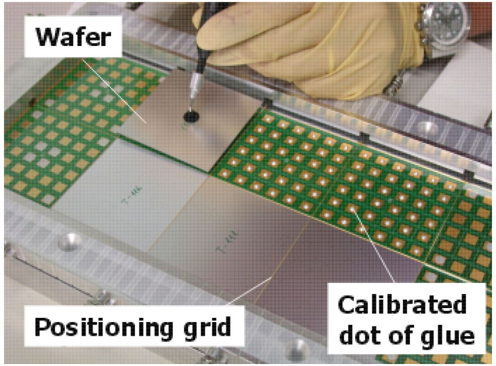
RPC (1×1 cm^2)

ECAL: active layer technologies

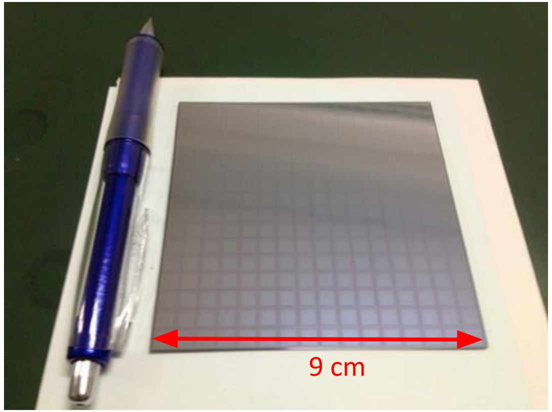
Silicon diodes (1024 cells of 13 mm^2)



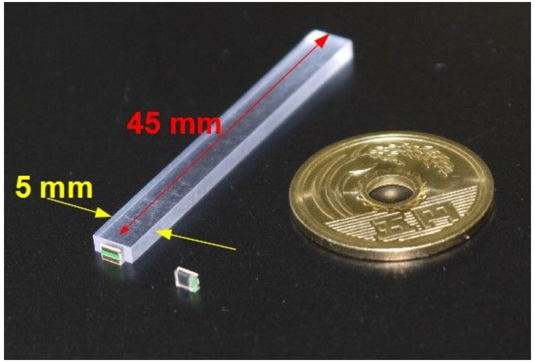
Silicon wafers (36 cells of 1 × 1 cm^2)

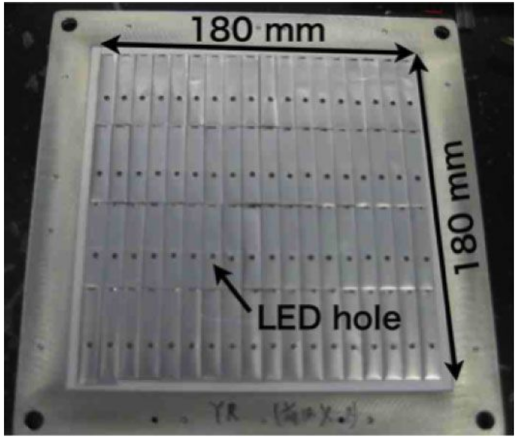


Silicon wafers (256 cells of 5.5 × 5.5 mm^2)



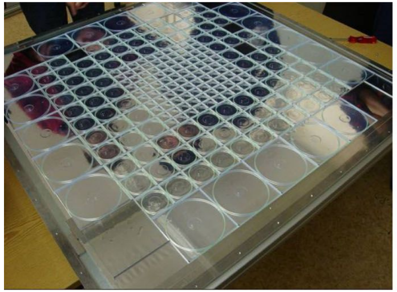
Scintillator strips with SiPMs

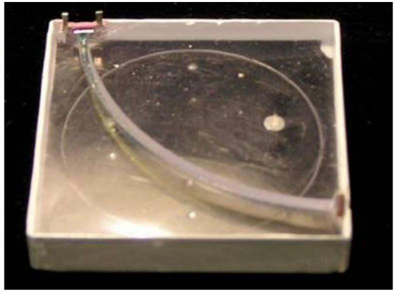




HCAL: active layer technologies

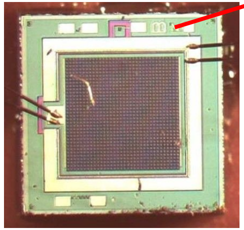
Scintillator tiles (3x3, 6x6, 12x12 cm^2) + WLSF + mirror + SiPMs (1st generation)

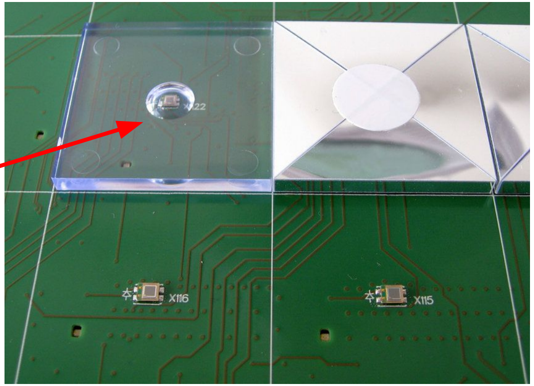




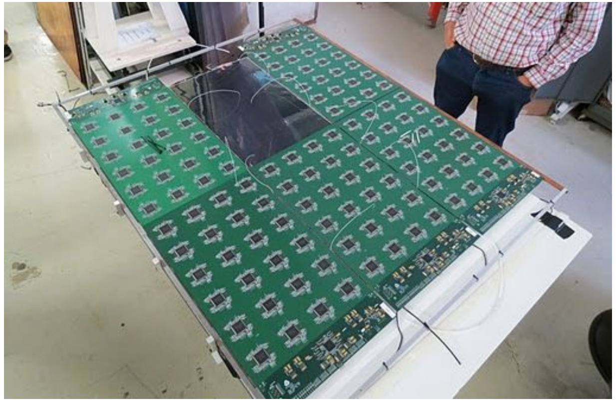
Scintillator tiles (3 × 3 cm^2) + SiPMs (2nd generation)

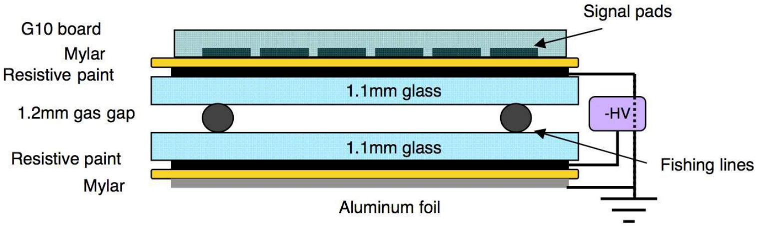
SiPM





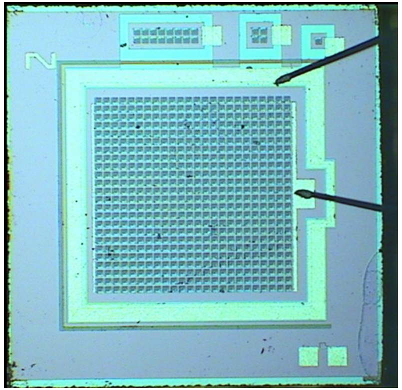
Resistive plate chambers (1 × 1 cm^2 signal pads)



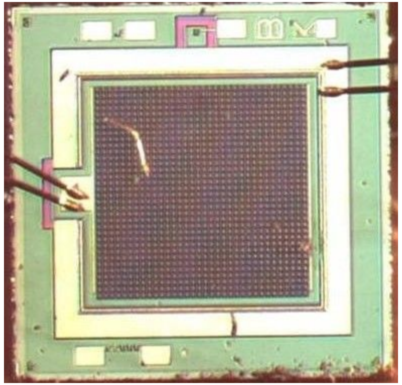


Silicon Photomultiplier (SiPM)

SiPM: ~500 pixels in ~1mm^2

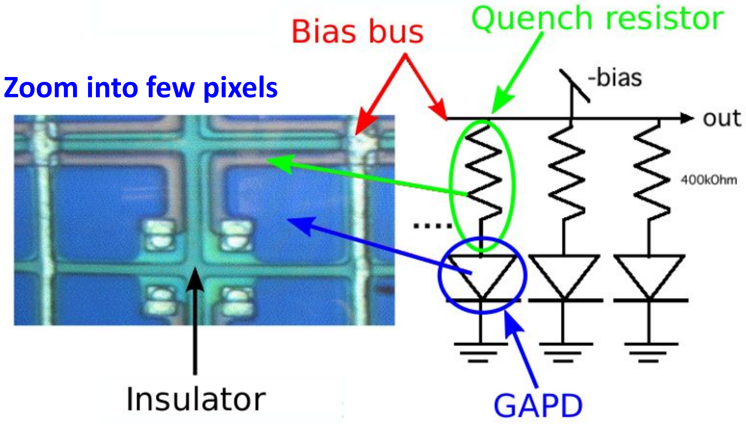


SiPM: ~1000 pixels in ~1mm^2

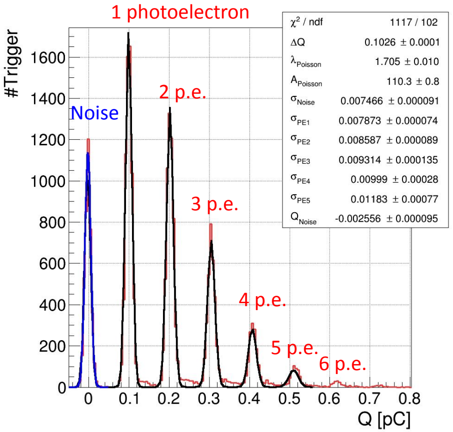


Zoom into few pixels

Schematics of components



Photoelectron spectrum

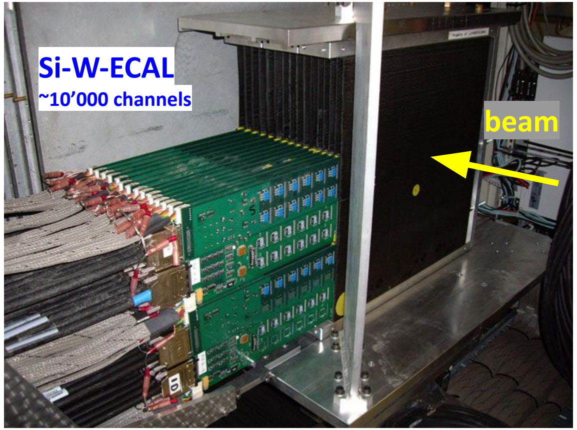


- Many Avalanche PhotoDiodes operated in Geiger mode (GAPD)
- Pixelated, read out in parallel
- Sensitive to single photons
- Gain of about 10^6
- Insensitive to magnetic fields
- Large progress over last decade to reduce noise and to increase active area (fill factor), increase radiation hardness

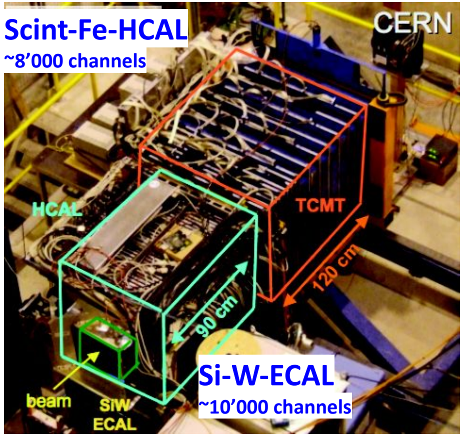
⇨ **Gamechanger for highly granular light-based calorimeters**

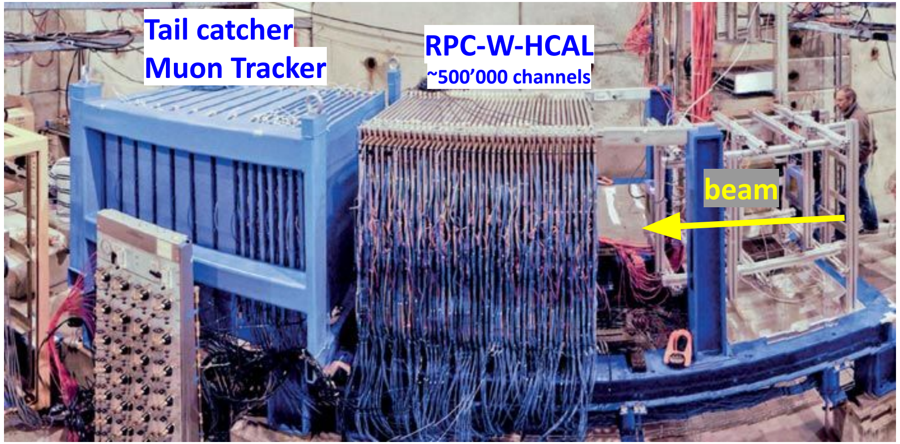
Lab exercise on SiPM characterisation:
Find out yourself on
- Quench resistor
- Noise
- Gain

CALICE prototype examples



- Large-scale prototypes tested in beam tests in 2006-today
- Very cost intensive endeavour
  - Example: Hadronic calorimeters > 1m^3



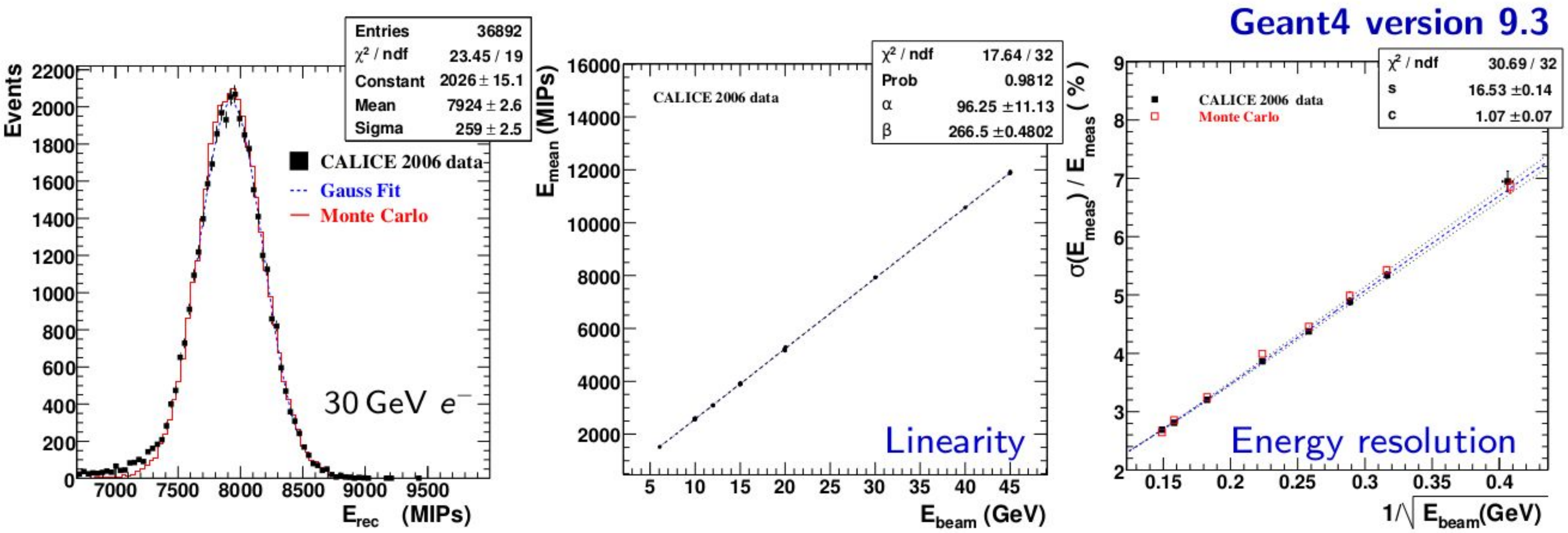


- Possibility to cover large phase space (active technology, absorber) by use of common of infrastructure:
  - Absorber stacks
  - DAQ system
  - Front end ASICs

Some examples of CALICE test beam results

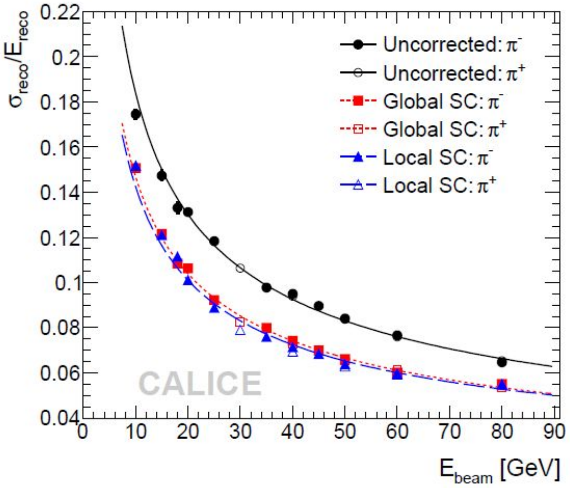
Si-W-ECAL: electron linearity and resolution

- Reconstructed energy of data and simulation agree within 1 %
- Linearity: E_{rec} versus E_{beam} , agreement with linear dependence within 1 %
- Energy resolution: $$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus b \rightarrow \frac{16.6\,\%}{\sqrt{E}} \oplus 1.1\,\%,\ \frac{17.0\,\%}{\sqrt{E}} \oplus 0.8\,\%$$



HCAL: Energy resolution: Readout option

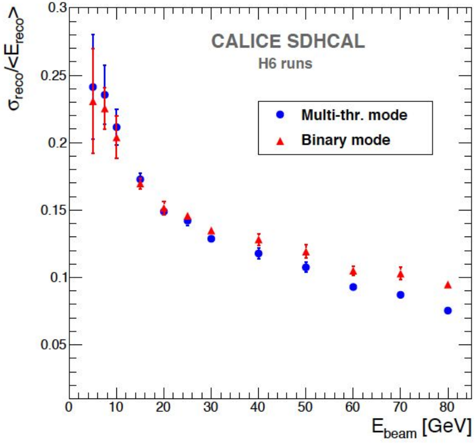
Analogue Scintillator HCAL



Energy sum of cells with analogue readout ("uncorrected):

$$\frac{\sigma(E)}{E} = \left(\frac{57.6}{\sqrt{E}} \oplus (1.6)\right)\%$$

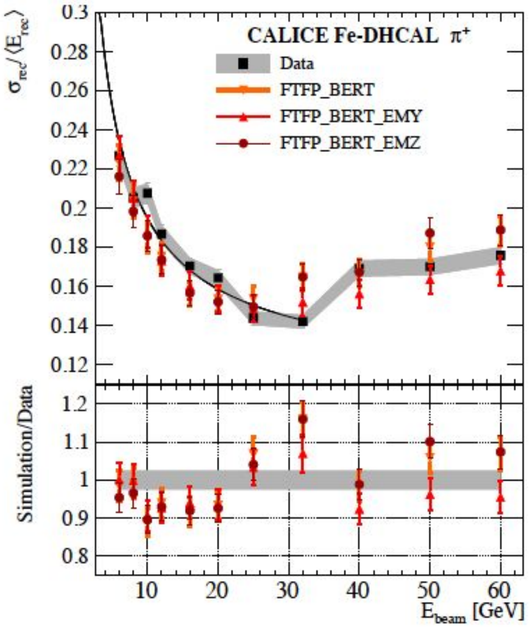
Semi-digital RPC HCAL



Measurement with 1 (digital) or 3 (semi-digital) energy thresholds

- Energy resolution at high beam energies improves with more thresholds

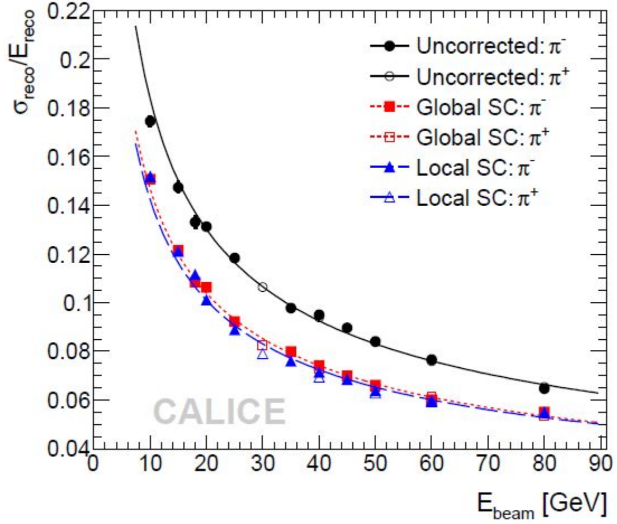
Digital RPC HCAL



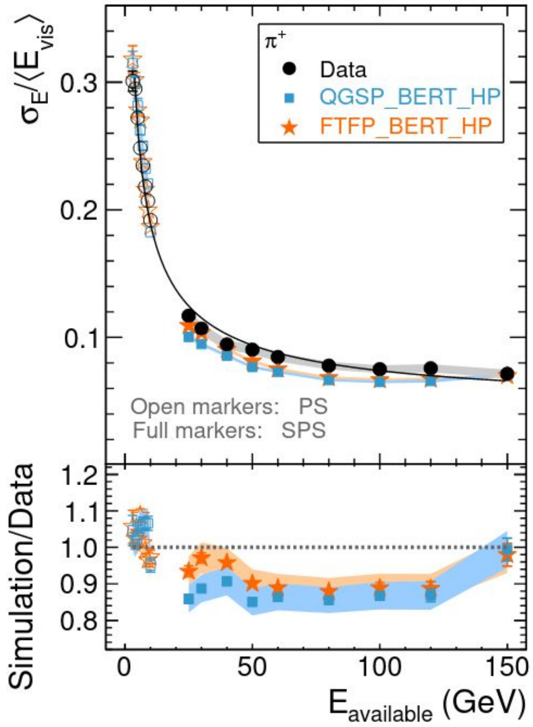
- Digital resolution degrades at high beam energies

Scintillator HCAL: Energy resolution: Absorbers

Steel absorber

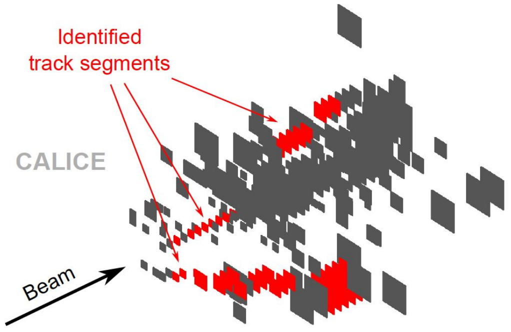


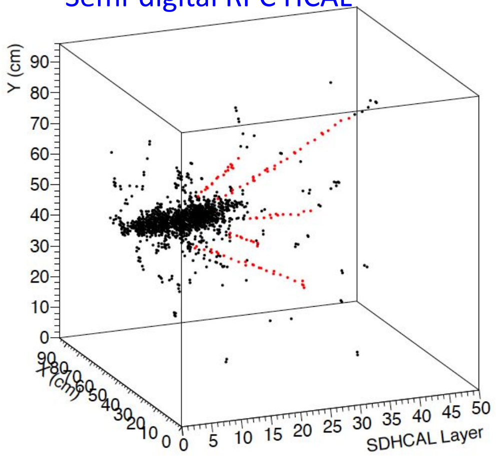
Tungsten absorber

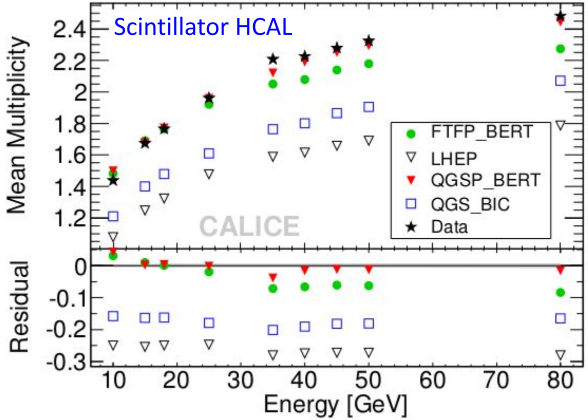


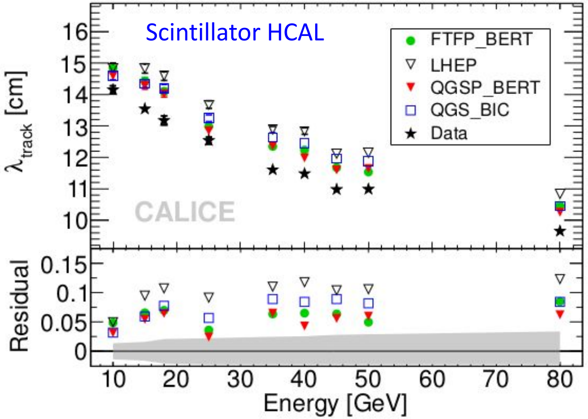
- Tungsten as absorber studied for high energy accelerator CLIC
- Steel absorber
  - a = 57.6 % √E
- Tungsten absorber
  - a = 57.9 % √E
- Hadronic energy resolution comparable

HCAL: Study shower sub-structure





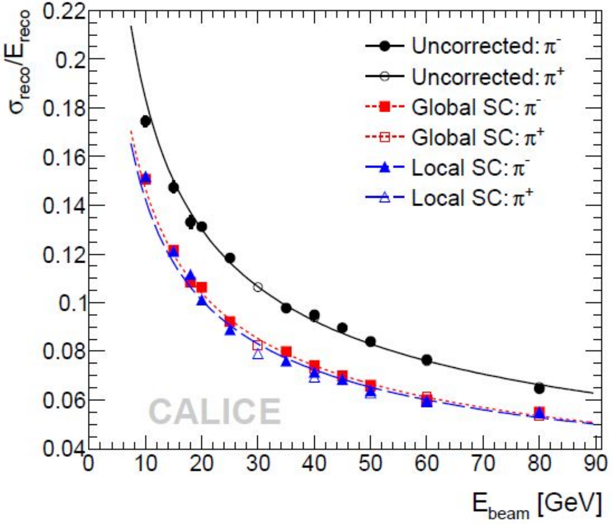




- Identify track segments of minimum-ionising particles within hadron showers
  - These MIPs can be used for calorimeter calibration

- Compare with Geant4 simulations
- Agreement crucial for simulation studies of Particle Flow Analysis

Analogue Fe-HCAL: Software compensation

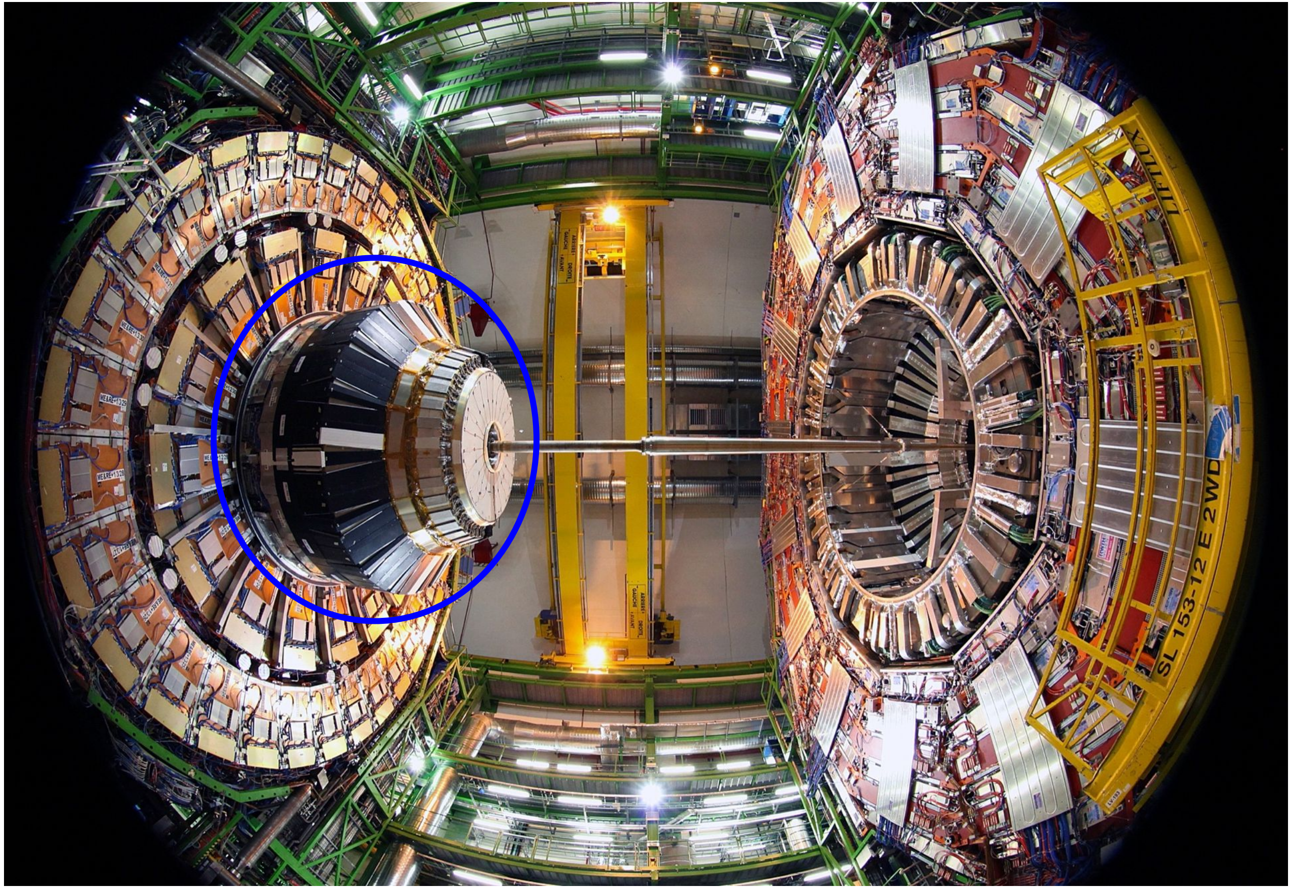


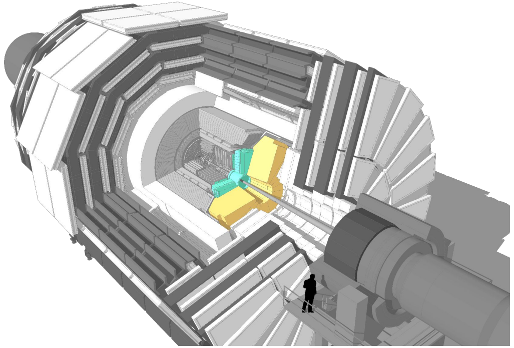
$$\frac{\sigma(E)}{E} = \frac{44.3 \pm 0.3\,\%}{\sqrt{E}} \oplus 1.8 \pm 0.3\,\% \oplus \frac{0.18\,\mathrm{GeV}}{E}$$

- Non-compensating calorimeters show different signals for electromagnetic and hadronic showers: e/h>1
- Identify the parts of the shower by their energy density
  - High energy-density: EM sub-shower
  - Low energy-density: hadronic shower component
- Weight:
  - Decrease weight for EM hits
  - Increase weight for hadronic hits
- Software compensation
  - Can improve single particle energy resolution significantly
  - Is only possible if information on shower substructure is available to distinguish the shower parts

Synergies with HL-LHC detector upgrades

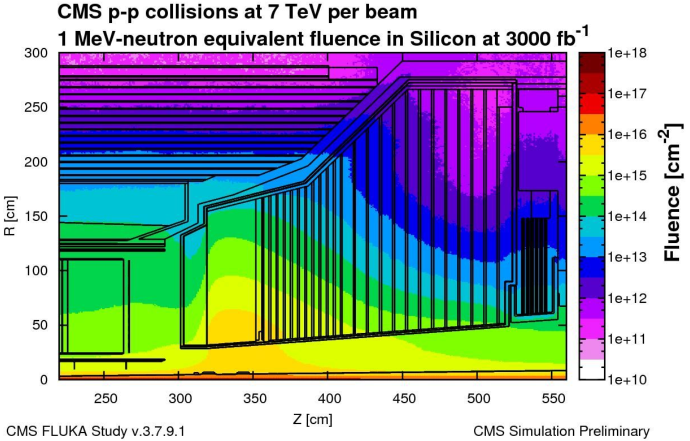
Current CMS Calorimeter Endcap (CE)

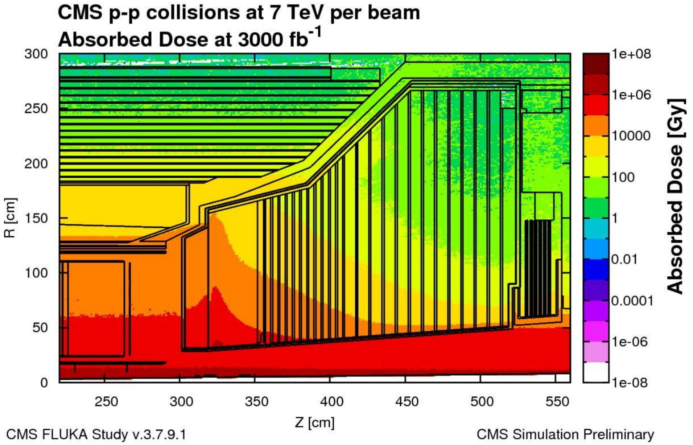




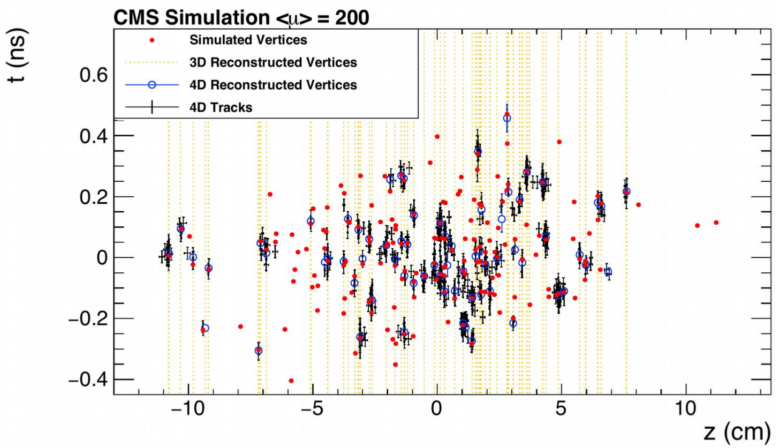
- Endcap calorimeters will have suffered severe radiation damage at the end of the LHC life time
- Require replacement for operation of HL-LHC
- Requirements
  - Needs to be able to cope with radiation environment and pileup

CMS CE: requirements at HL-LHC





- Radiation hardness
  - Fluence up to 10^{16} n_{eq}/cm^2
  - Dose up to 1 MGy
- Spatial and time resolution
  - Resolve energy deposits originating from pile-up vertices spread over O(10 cm) and O(100 ps)



- High granularity for pile-up rejection & particle flow
- Synergy with high granularity calorimeter concepts developed for e^+e^- colliders

CMS CE: HGCAL concept

High-granularity calorimeter (HGCAL)

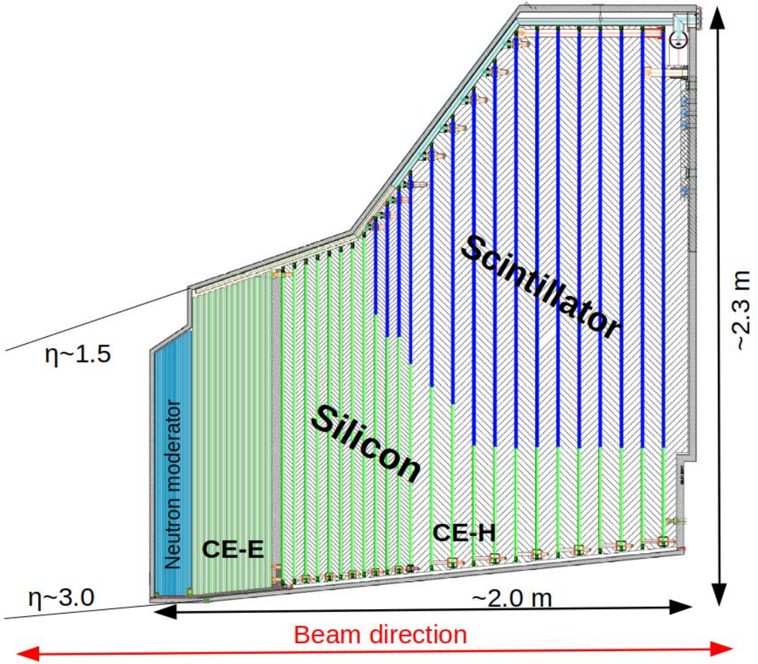
- 620 m^2 of silicon sensors,
  6M channels,
  cell size 0.5–1.1 cm^2
- 400 m^2 of scintillator,
  240k tiles + SiPMs,
  tile size 4–30 cm^2

New challenges compared to e^+e^- colliders

- Radiation levels
- Operation at -35°C → CO_2 cooling
- Data rates, continuous running

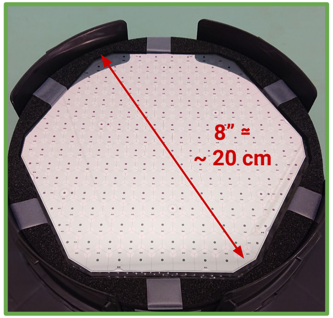
Needs to be ready for installation during 2026-2028 (LHC's Long Shutdown 3)

Valuable experience for the construction of a highly granular calorimeter as part of any future collider detector



Scintillator tileboard

Silicon sensor



Electromagnetic section CE-E:

- Silicon, Cu/CuW/Pb absorber, 28 layers, $25X_0$ &~ $1.3\lambda_I$

Hadronic section CE-H:

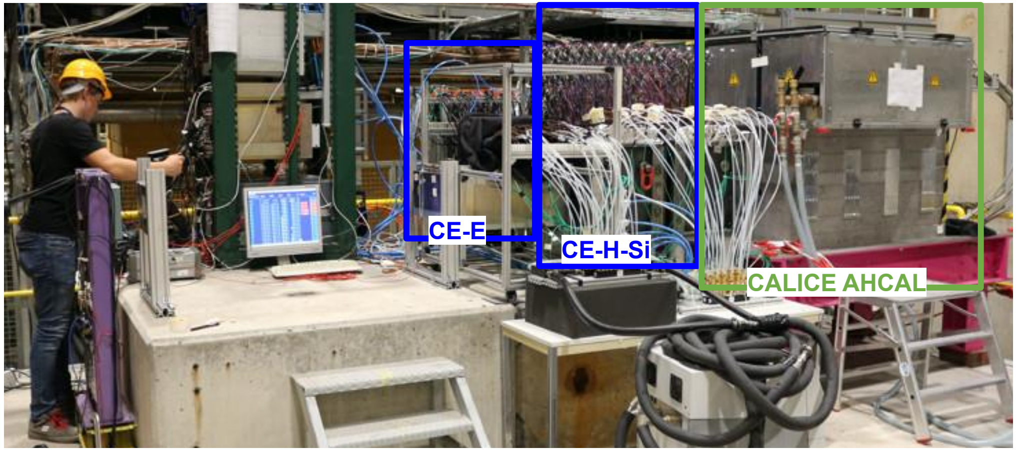
- Silicon+scintillator, steel absorber, 22 layers, ~ $8.5\lambda_I$

Video on HGCAL design

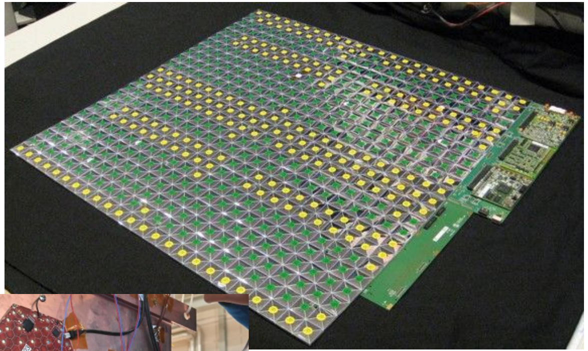
HGCAL prototype in beam tests

HGCAL 6” prototype:
~12’000 silicon channels

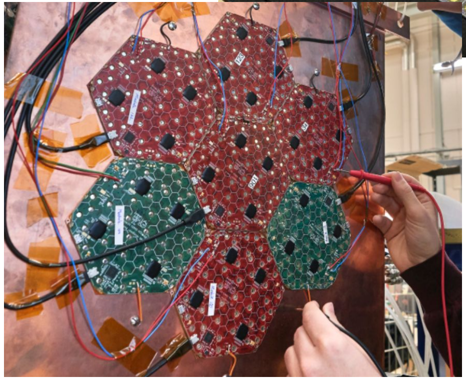
CALICE AHCAL
~22’000 channels



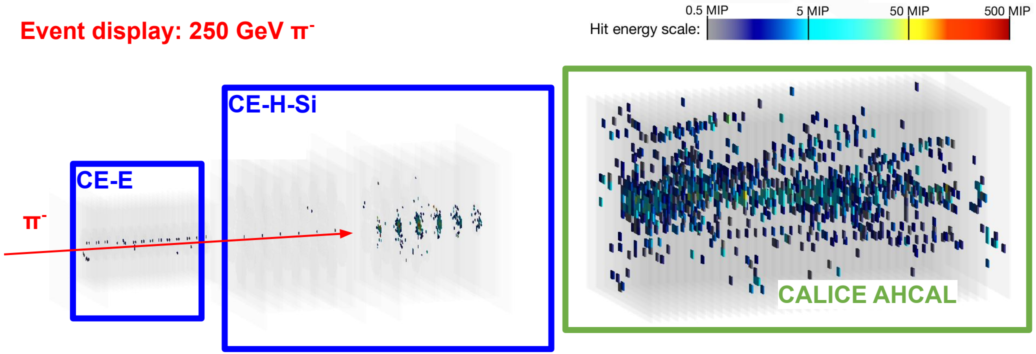
CALICE AHCAL layer:
576 scintillator tiles + SiPMs



CE-H-Si layer:
Seven 6” modules

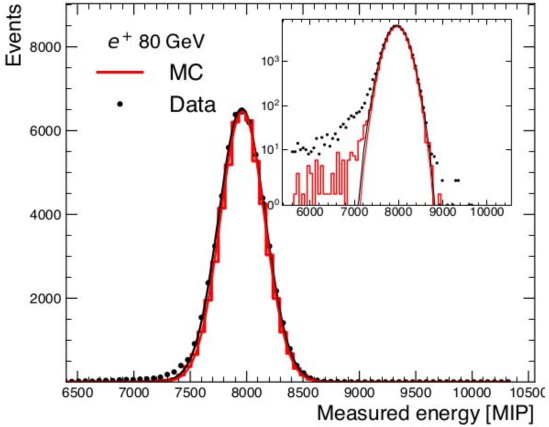


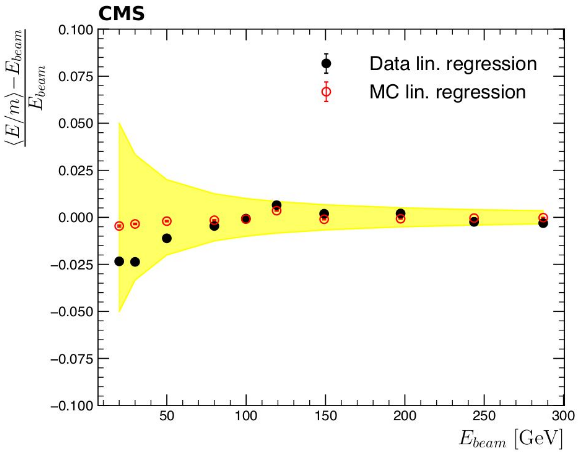
Event display: 250 GeV π^-

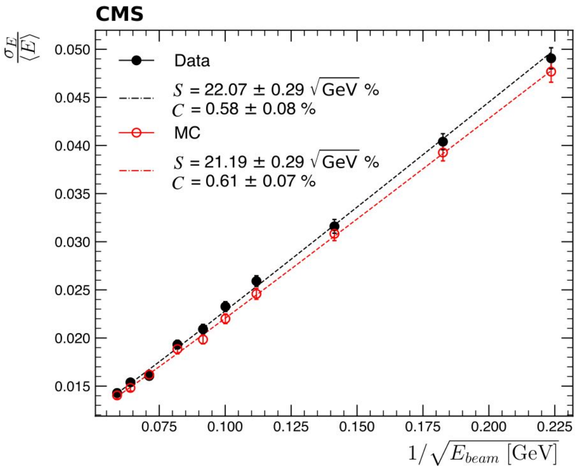


- Test beams with electrons and hadrons
- Close collaboration between CALICE and CMS

HGCAL: Linearity and energy resolution





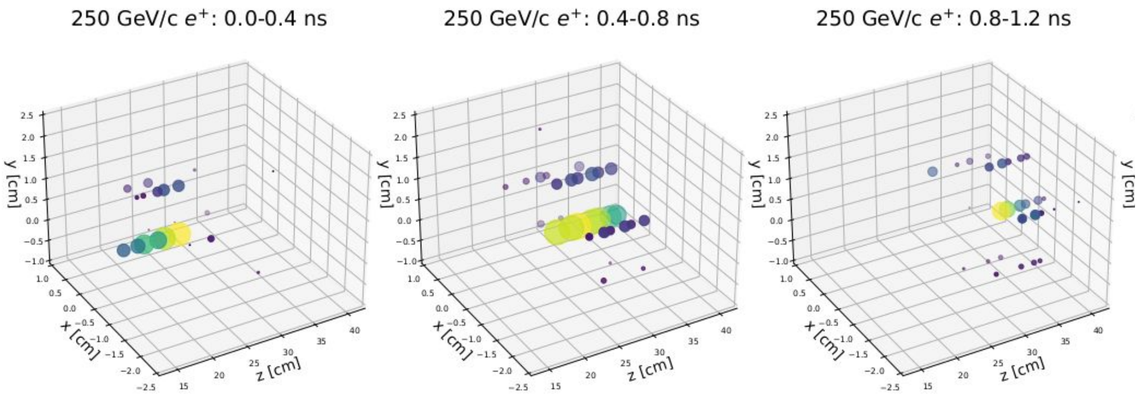


Silicon-section only

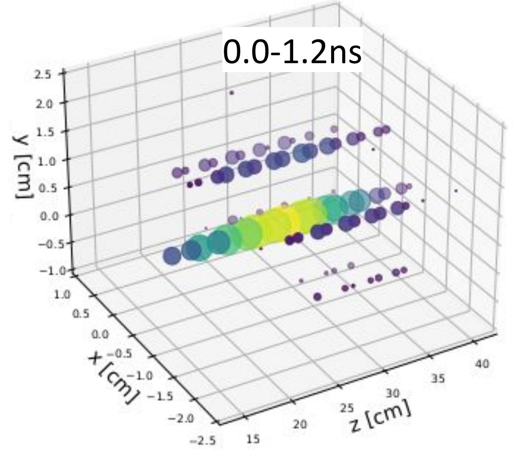
- Linearity better than 3% for data and 1.5% for simulation
- Energy resolution
  - Stochastic term of energy resolution of 21–22 √GeV%
  - Constant term of 0.6%

2022 JINST 17 P05022

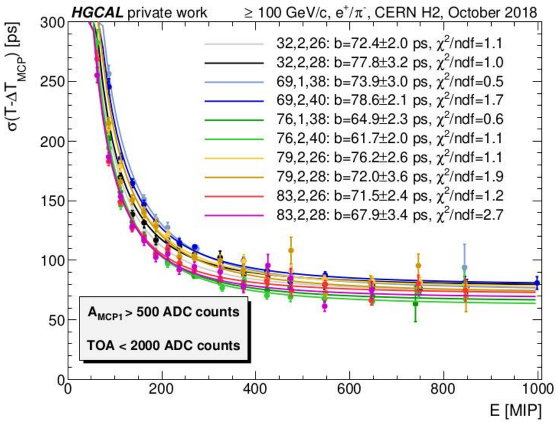
HGCAL: Time development of shower



(a) 0 ns ≤ T ≤ 0.4 ns. (b) 0.4 ns < T ≤ 0.8 ns. (c) 0.8 ns < T ≤ 1.2 ns.



Time resolution vs. hit energy



- Study time development of particle showers in HGCAL silicon prototype, through Time of Arrival (TOA) measurement
- Expect O(10 ps) of constant term of timing resolutions
- Analysis in progress

TIPP presentation
CERN-THESIS-2020-209

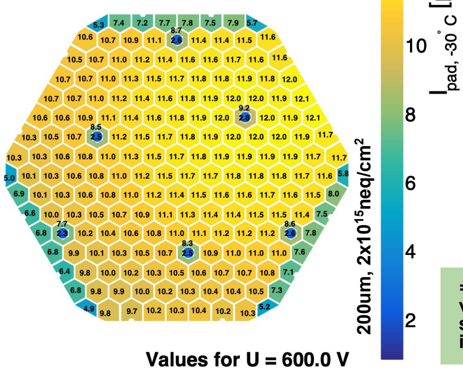
Silicon radiation hardness qualification

- HGCAL silicon sensors produced in new 8” process
- Requires validation of radiation hardness of bulk and oxide layer

- Neutron irradiation in new 8” neutron-irradiation facility: Rhode Island Nuclear Science Centre (RINSC)

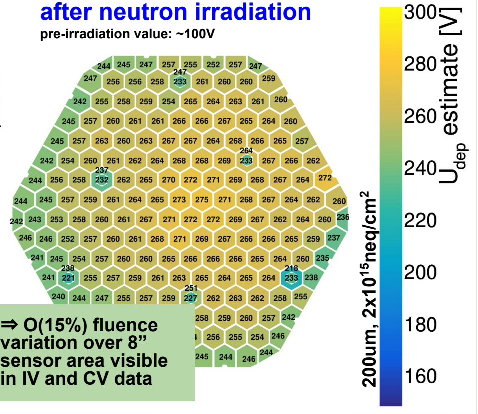
Per-cell leakage current after neutron irradiation

pre-irradiation value: O(1nA)



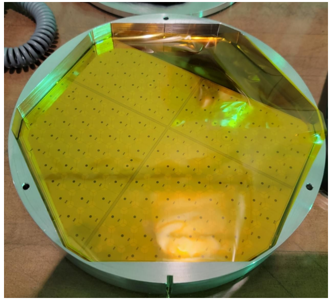
Per-cell depletion voltage after neutron irradiation

pre-irradiation value: ~100V

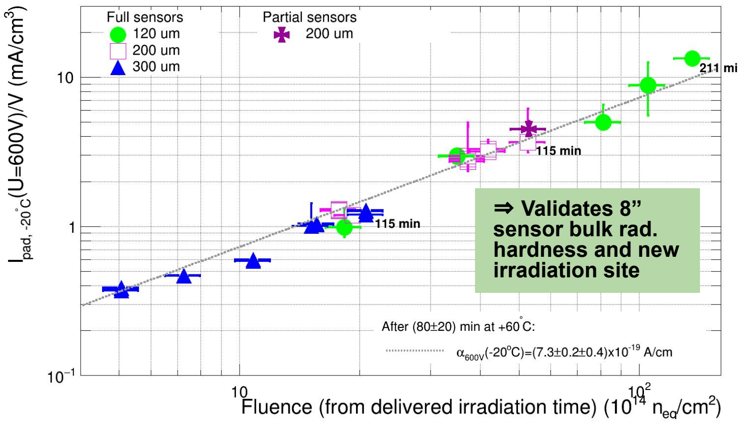


RINSC reactor beam port

Aluminum container hosting 8” partial sensors



Current density vs. fluence

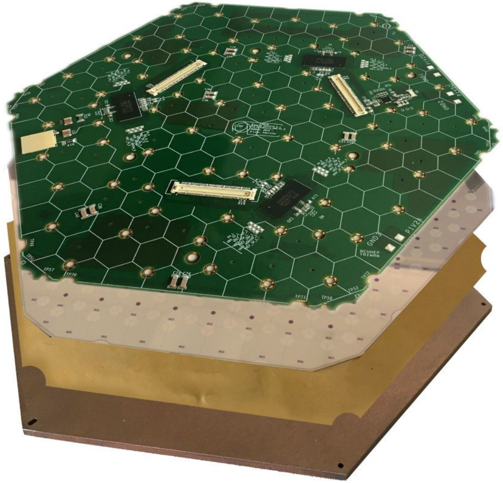


arXiv:2209.10159

620 m^2 of silicon modules

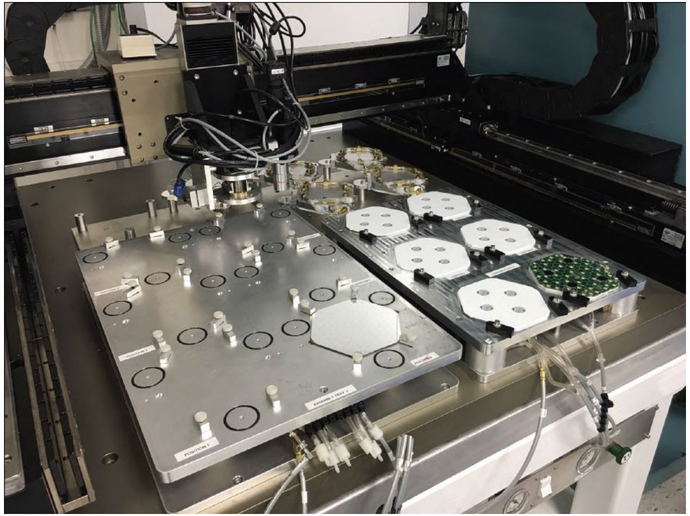
Handling of 8” sensors

8” module: Layer structure

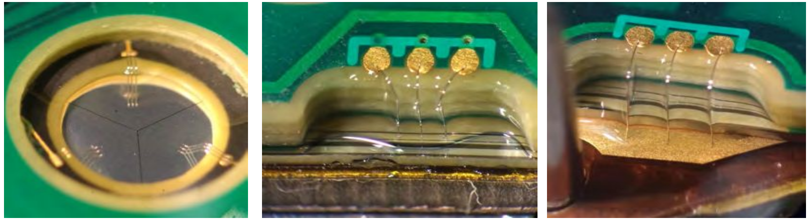


- Glued sandwich of PCB, Silicon sensor, biasing/insulation layer and baseplate (rigidity, cooling, absorber element)
- Wire-bonding from PCB to silicon
- Automated assembly on Gantries

Gantry for module assembly

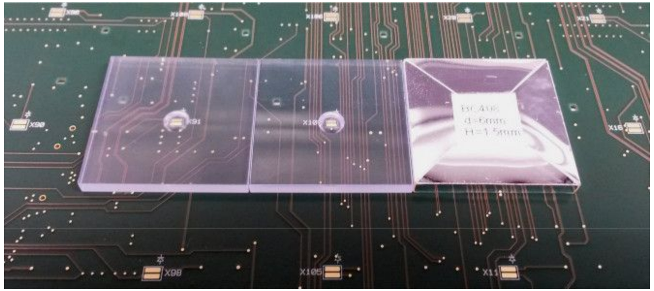


Wirebonds in module

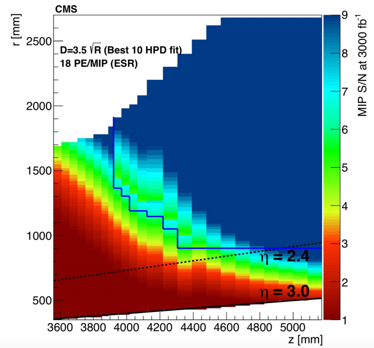


400 m² of scintillators + SiPMs

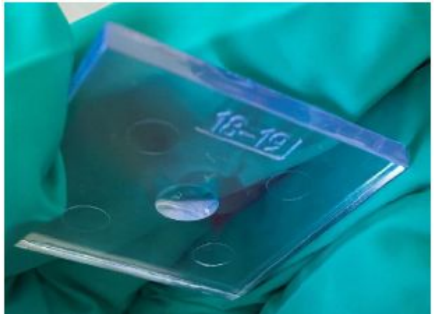
CALICE AHCAL SiPM-on-tile prototype



S/N>5 after 3 ab^{-1}



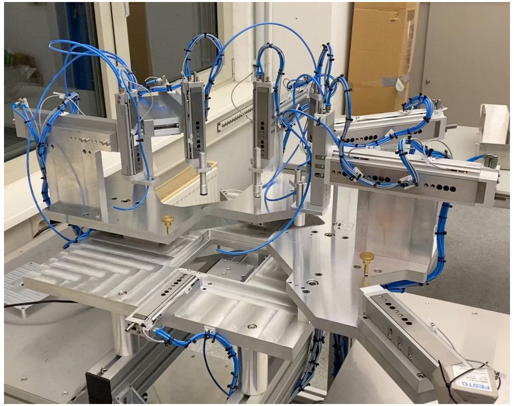
Injection molded tile



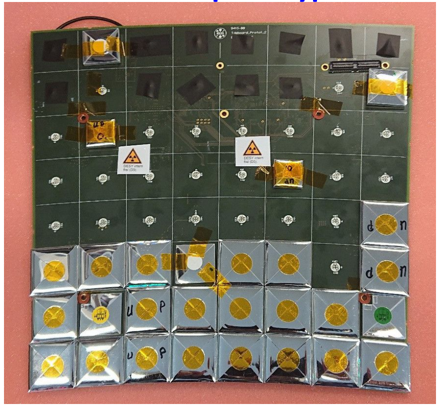
- Cheaper than silicon → use in low-radiation region with Signal/Noise > 5 up to full detector lifetime (3 ab^{-1})

- 240k SiPMs integrated into the PCB, cooled operation to mitigate increasing leakage current
- Prototypes of injection-molded tiles as well as cast and machined tiles
- Development of automated wrapping and automated assembly of tile-module
- Successfully operated tileboards in beam tests, including also irradiated SiPMs

Tile wrapping machine



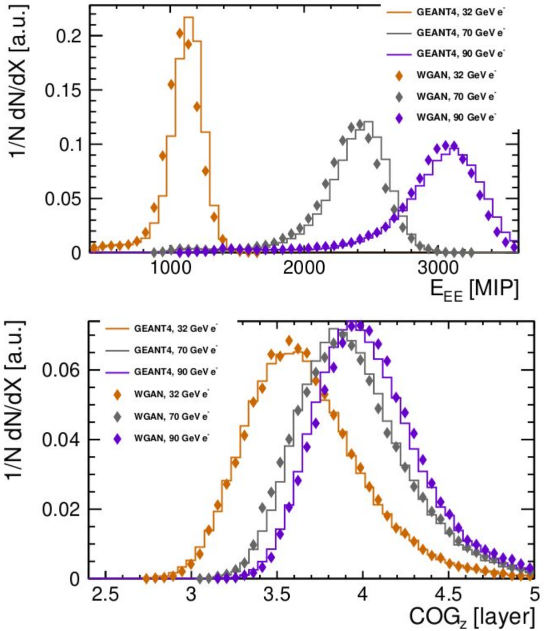
Tileboard prototype

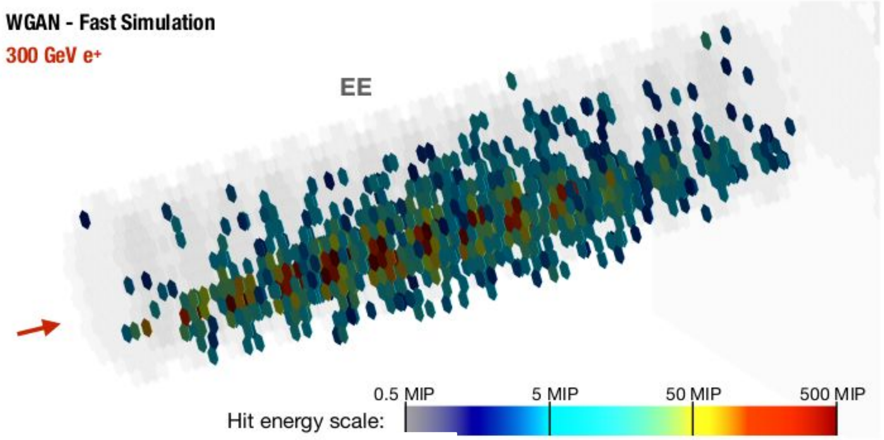


HGCAL: ML-based detector simulation

Examples of usage of machine-learning (ML) techniques within HGCAL:

- Full Geant4 detector simulations are very time intensive
- Investigate if ML tools can be used to simulate electromagnetic showers
- Used Wasserstein Generative Adversarial Neural Network (WGAN)
- Simulation speed-up by up to factor 20’000 while reproducing detailed shower properties





	GEANT4 std. (2017) CPU	WGAN Intel© Xeon© CPU E5-1620	WGAN NVIDIA© GTX™ 1080 GPU
20 GeV e^+	550 ms [x1]	10 ms **[x55]**	0.4 ms **[x1375]**
80 GeV e^+	2200 ms [x1]	10 ms **[x220]**	0.4 ms **[x5500]**
150 GeV e^+	4000 ms [x1]	10 ms **[x400]**	0.4 ms **[x10000]**
300 GeV e^+	8000 ms [x1]	10 ms **[x800]**	0.4 ms **[x20000]**

CERN-THESIS-2020-209

HGCAL: ML-based shower reconstruction

ML4Reco: End-to-end reconstruction approach to reconstruction software

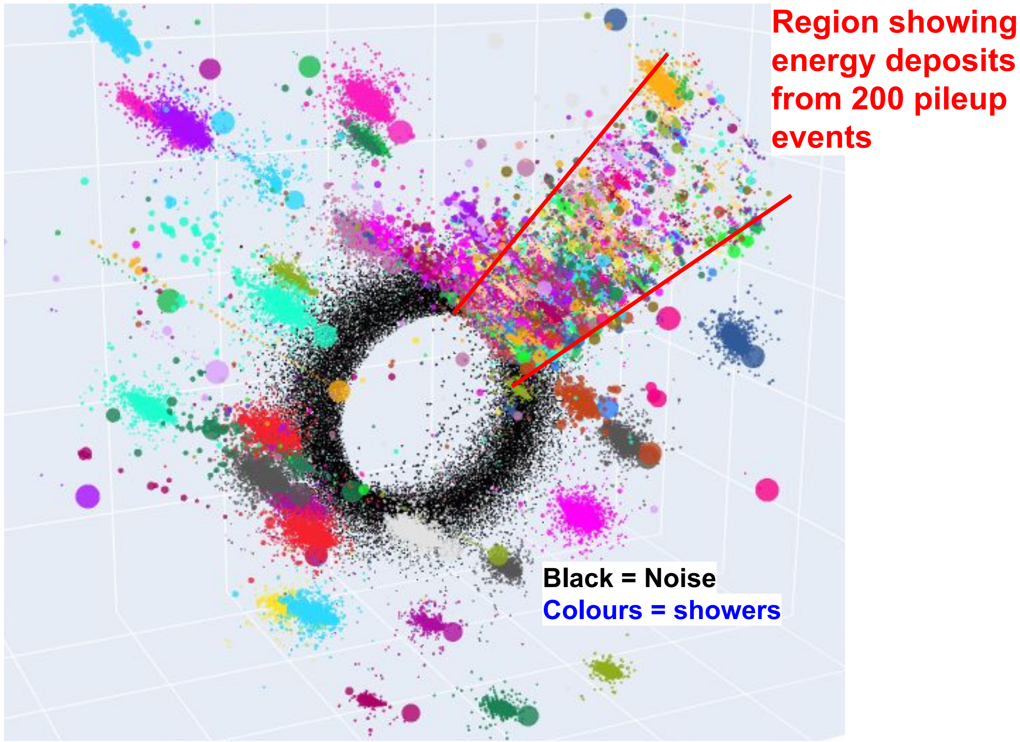
- Algorithm uses distance-weighted **Graph Neural Network**, trained with **Object Condensation**, a graph segmentation technique

- Promising reconstruction performance (efficiency, resolutions) of particles and jets in up to 200 pile-up (PU) events
- Energy resolution in many cases similar to resolution obtained through perfect clustering

- Less than 10s execution time for 200 PU events scaling linearly with number of detector hits (on NVIDIA 2080 Ti GPU)

- Adding tracks as additional network input to achieve end-to-end particle flow algorithm (work-in-progress)

Training event in HGCAL-like endcap calorimeter

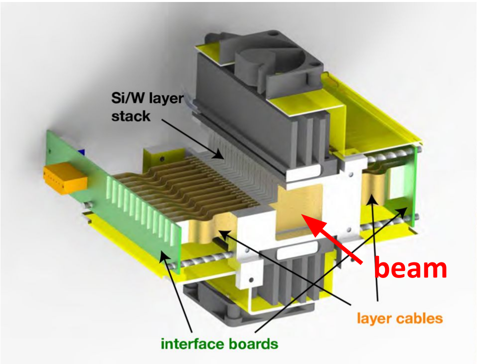


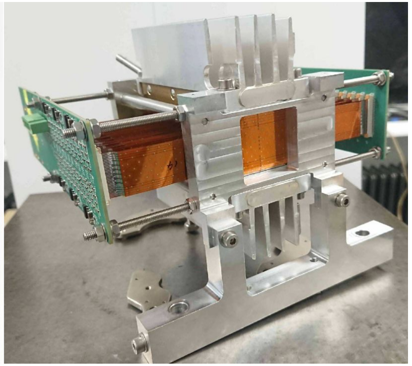
Circles = representation of tracks

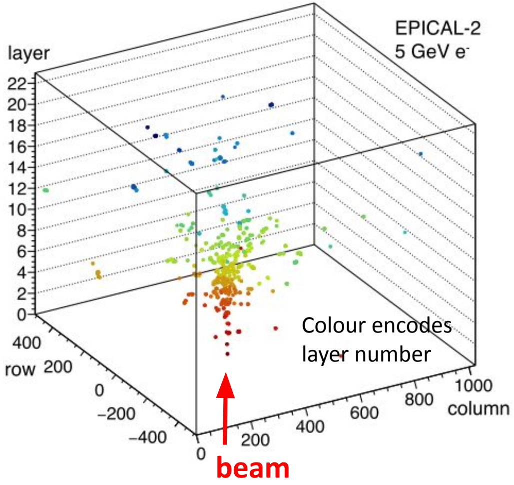
ML4Reco status

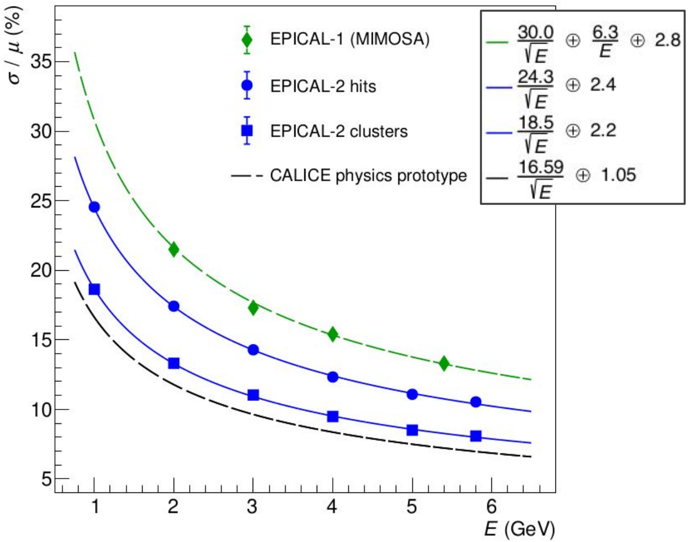
ALICE FoCal: Digital Pixel ECal R&D

- Digital ECAL R&D for ALICE FoCal upgrade
  - Goal: Separation of γ and π^0
- Epical-2 Si-W prototype tested
  - 24 layers of 3 × 3 cm^2 ALPIDE CMOS pixel silicon sensors with ~30µm pixel pitch
  - 3mm tungsten absorbers
  - 25M pixels 3 × 3 x 7 cm^3









- Low-energy calorimetric resolution close to CALICE analogue Si-W-ECAL
- Next steps: evaluate performance at high energy and for PFA

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Summary

Summary

- Calorimeters optimised for particle flow analysis
  - Have high granularity (imaging calorimeters)
  - Target excellent jet energy resolution
  - Allow for software compensation
  - Allow for event-by-event pile-up rejection
  - Come at a cost: single particle energy resolution

- Particle flow algorithms improve jet energy resolution
  - Shown for existing detectors, level of improvement depends on layout
  - Exploit full potential with optimised detector design, requiring highly granular calorimeters

- Highly granular calorimeters for
  - Precision measurements at future e^+e^- collider experiments, expecting multijet final states
  - HL-LHC calorimeter upgrades:
    - CMS HGCAL under construction
    - ALICE FoCal: in R&D phase

References

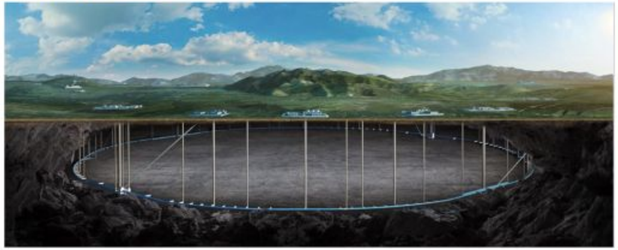
- Calorimetry III lecture at EDIT 2020 school by Katja Krüger Link
- Experimental tests of particle flow calorimetry, F. Sefkow et al., Rev. Mod. Phys. 88, 015003 Link
- Higgs physics at the CLIC e^+e^- linear collider, CLICdp collaboration, Eur. Phys. J. C 77, 475 (2017) Link
- Physics and Detectors at CLIC: CLIC Conceptual Design Report, L. Linssen et al. (eds.) 2012 Link
- The Phase-2 Upgrade of the CMS Endcap Calorimeter, CMS collaboration, technical design report, 2019, CMS-TDR-019 Link
- Response of a CMS HGCAL silicon-pad electromagnetic calorimeter prototype to 20–300 GeV positrons, CMS HGCAL collaboration, JINST 17 (2022) 05, P05022 Link
- Links listed within the presentation

Backup

e^+e^- collider options

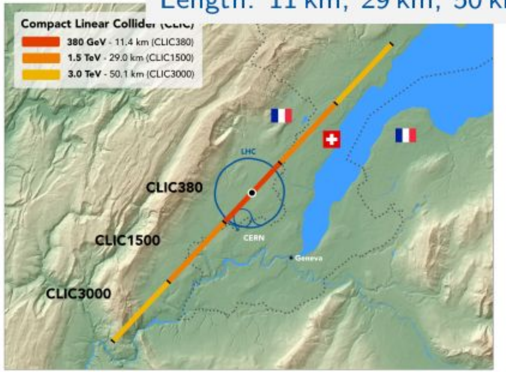
Circular Electron Positron Collider (CEPC)

$\sqrt{s}$ = 90–240 GeV;
Circumference: 100 km



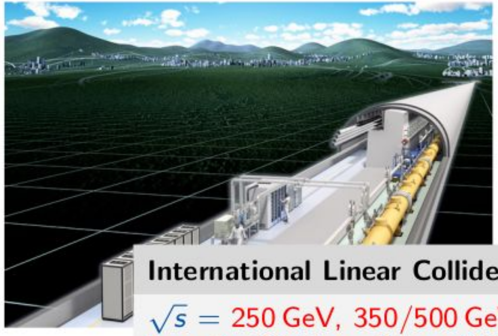
Compact Linear Collider (CLIC)

$\sqrt{s}$ = 350/380 GeV, 1.5 TeV, 3 TeV;
Length: 11 km, 29 km, 50 km



Future Circular Collider (FCC-ee)

$\sqrt{s}$ = 90–240 GeV, 350–365 GeV;
Circumference: 97.8 km



International Linear Collider (ILC)

$\sqrt{s}$ = 250 GeV, 350/500 GeV (1 TeV);
Length: 20.5 km, 31 km (40 km)

Classical vs. particle calorimetry

Classical calorimetry

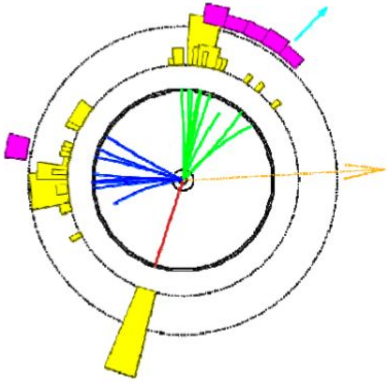
- Few large cells
  - Large dynamic range
  - Precise calibration of each cell needed
- Typically better single particle energy resolution
- Average pileup subtraction

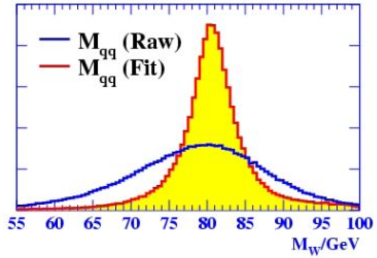
Particle Flow Calorimetry

- Many small cells
  - Smaller dynamic range
  - Precise calibration only of averages needed
- Typically worse single particle energy resolution
- Event-by-event pileup rejection
- Sophisticated shower reconstruction algorithms possible
- Targets best jet energy resolution

Beamstrahlung at LC and kinematic fit

- Large Electron Position Collider (LEP): 1989–2000
  - e^+e^- collider at CERN with $\sqrt{s} \leq 209\,\text{GeV}$
  - Signal dominated, $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$
  - Almost no background
  - Almost no beamstrahlung, $\sqrt{s}$ well known
- Possibility to do kinematic fit
  - Impose energy and momentum constraints on final state particles
    $\to \sum_i E_i = \sqrt{s}$ and $\sum_i \vec{p_i} = 0$
  - In case of particles-pair production, use additional constraint of equal masses
    $\to$ e.g. $m_{W_1} = m_{W_2}$
- Advantage
  - Kinematic fit can significantly improve invariant mass resolution

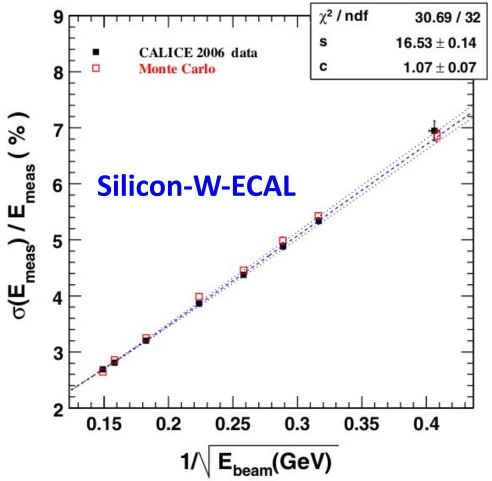


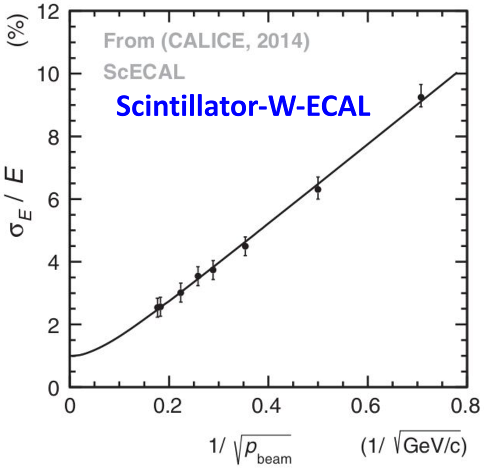


At CLIC

- Kinematic fit can in some studies also be used
- For complex events with beamstrahlung and missing energy, an excellent jet energy resolution can only be reached with very good calorimeters

Analogue ECAL energy resolution: Si vs. Scint.



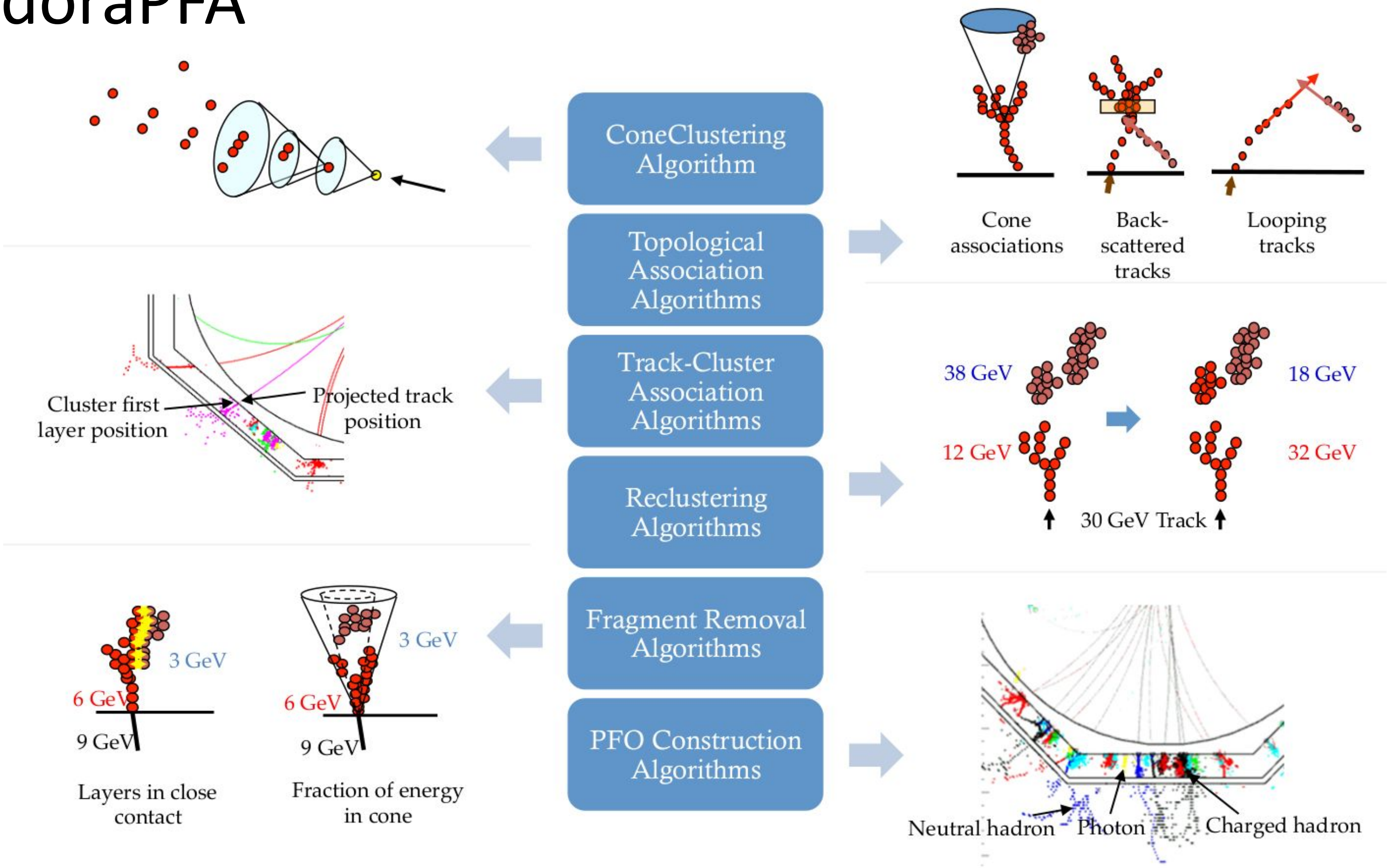


$$\frac{\sigma(E)}{E} = \left(\frac{16.6 \pm 0.1}{\sqrt{E}} \oplus (1.1 \pm 0.1)\right)\%$$

$$\frac{\sigma(E)}{E} = \left(\frac{12.5 \pm 0.4}{\sqrt{E}} \oplus (1.2 {}^{+0.6}_{-0.7})\right)\%$$

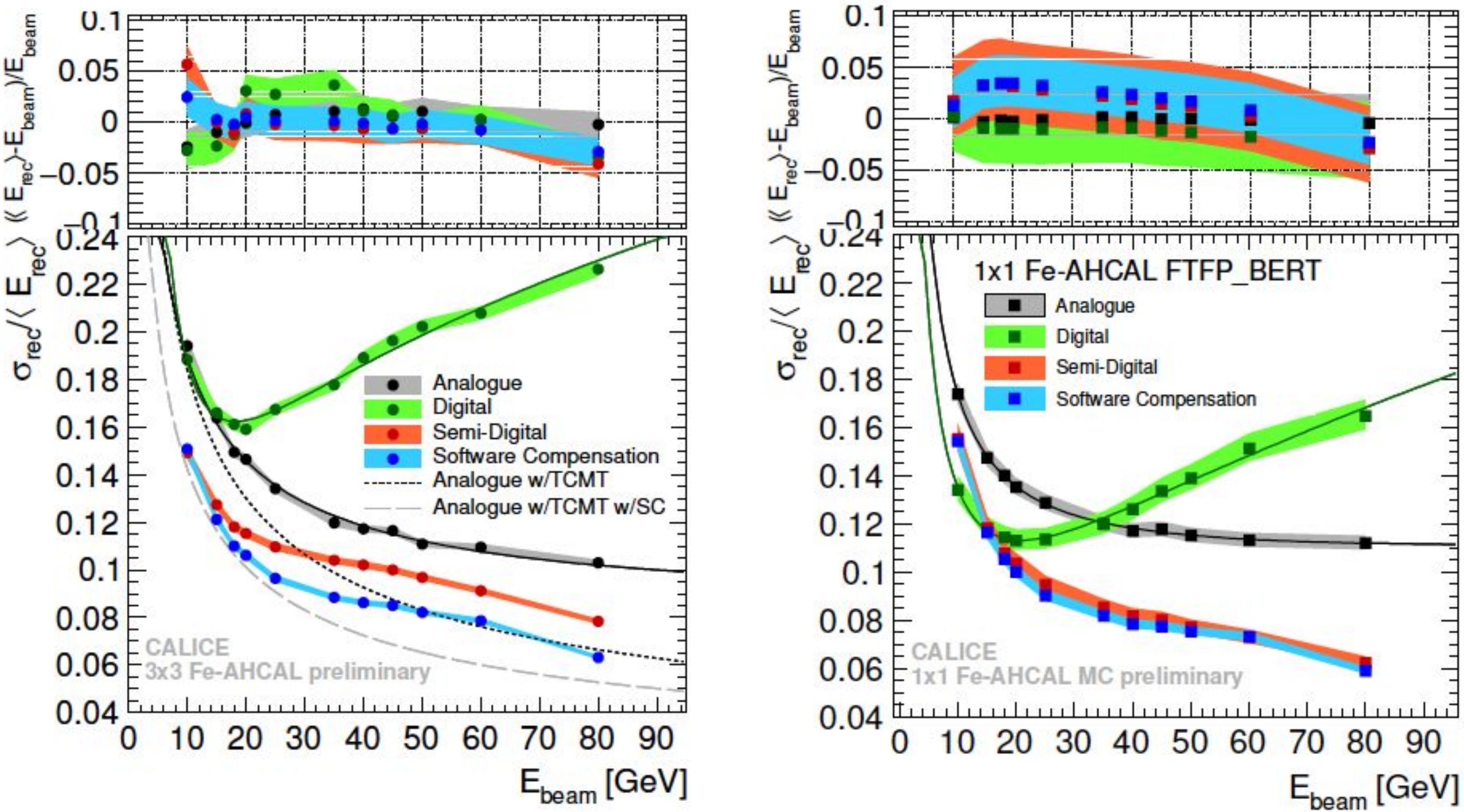
- Scintillator option has higher sampling fraction than Si option: Better energy resolution
- Reasonable energy resolution for electromagnetic showers w.r.t. LHC ECALs
  - CMS ECAL: 3%/√E ⊕ 0.2/E ⊕ 0.3%
  - ATLAS ECAL: 10 %/√E ⊕ 0.2/E ⊕ 0.2%
- ECALs are optimised for granularity, not single particle energy resolution

PandoraPFA



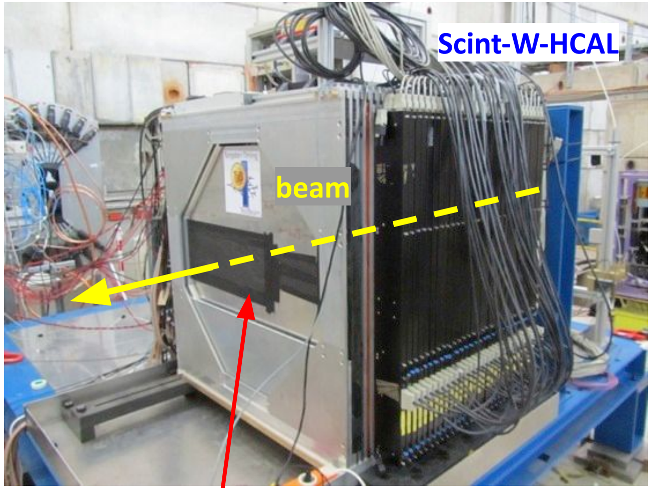
ConeClustering Algorithm
Topological Association Algorithms
Track-Cluster Association Algorithms
Reclustering Algorithms
Fragment Removal Algorithms
PFO Construction Algorithms
Cone associations
Back-scattered tracks
Looping tracks
Cluster first layer position
Projected track position
38 GeV
12 GeV
18 GeV
32 GeV
30 GeV Track
3 GeV
6 GeV
9 GeV
Layers in close contact
3 GeV
6 GeV
9 GeV
Fraction of energy in cone
Neutral hadron
Photon
Charged hadron

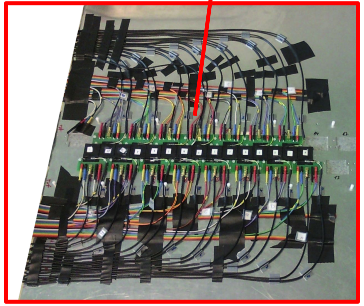
Energy resolution: Readout options and Granularity

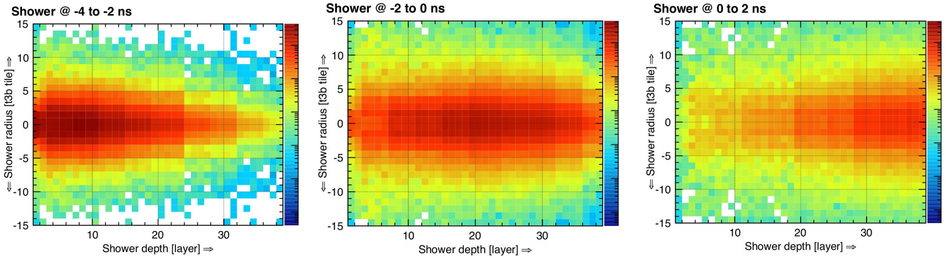


Coralie Neubüser 2017 *J. Phys.: Conf. Ser.* **928** 012038

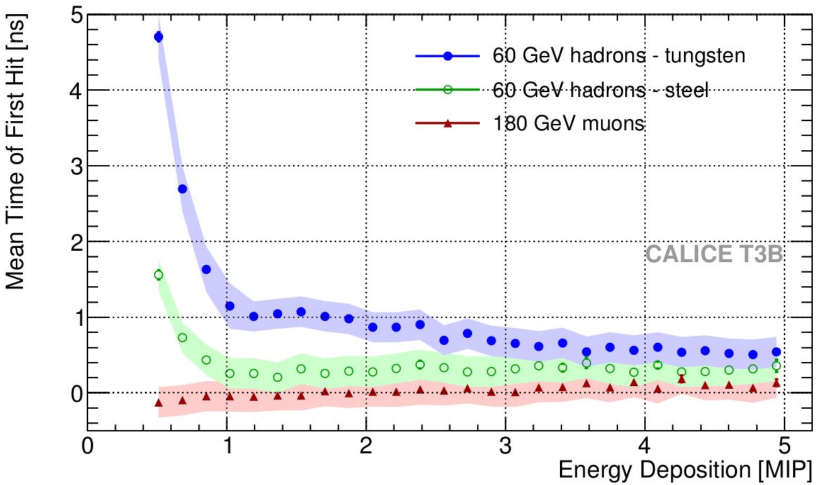
HCAL: Time structure



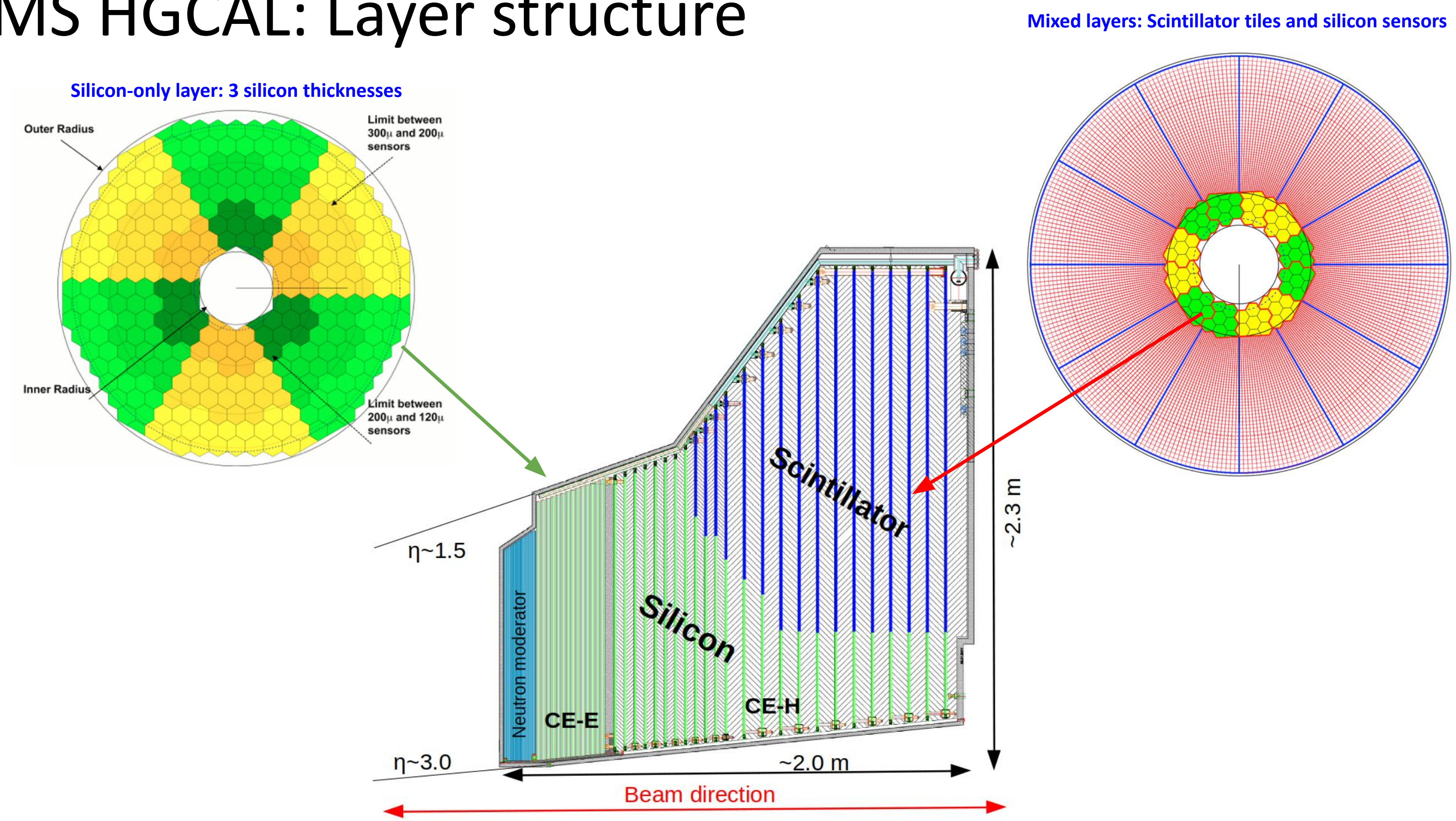




- t = 0: Activity peak in T3B (layer 39)
- Depth in calorimeter by identification of shower start layer

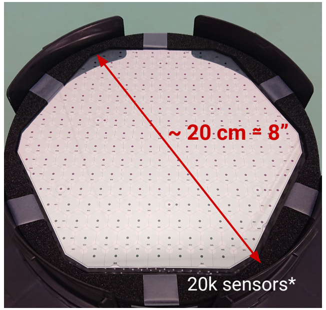


CMS HGCAL: Layer structure

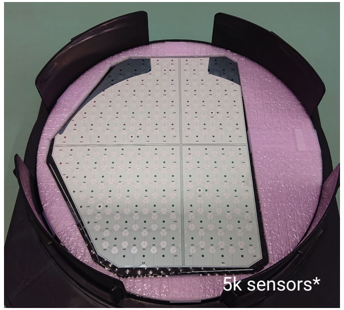


620 m^2 of 8-inch silicon sensors

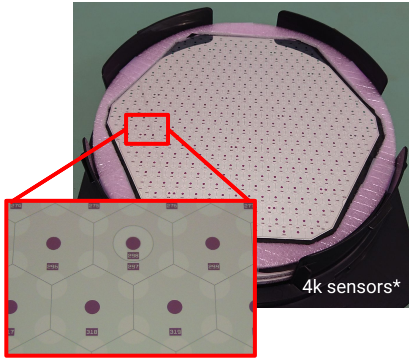
Low-Density sensor
~ 200 cells of 1.1 cm^2 size
300 μm & 200 μm active thickness



Low-Density “Partial sensor” example from “Multi-Geometry” sensor



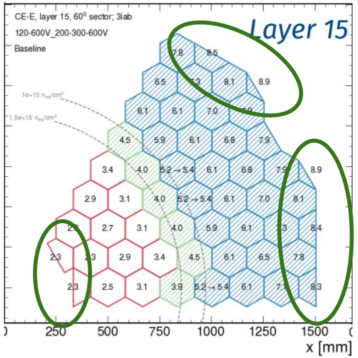
High-Density sensor
~ 450 cells of 0.5 cm^2 size
120 μm active thickness



High-Density “Partial sensor” example from “Multi-Geometry” sensor

* needed in the final detector

- Used for electromagnetic section and high-radiation regions in hadronic section of HGCAL
  - Thickness and granularity adapted to radiation field



- Hexagonal silicon sensor geometry
  - Largest regular tiling polygon
  - Maximise wafer usage
  - “Partial” sensors to tile border regions
- 8-inch wafers
  - Reduces number of modules w.r.t. 6-inch wafers
  - New production process and radiation-hardness qualification
- Planar, DC-coupled, p-type sensor cells
  - p-type more radiation tolerant than n-type sensors
- Sensor producer: Hamamatsu Photonics K. K. (HPK)

60

Silicon sensor characterisation

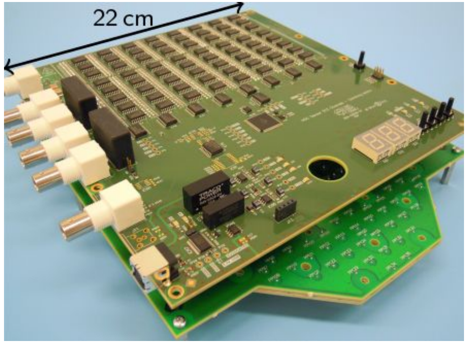
System for large-area multi-pad silicon sensor characterisation for

- Prototyping: Fast comparison of many sensor variants
- Production: Sensor Quality Control (SQC)

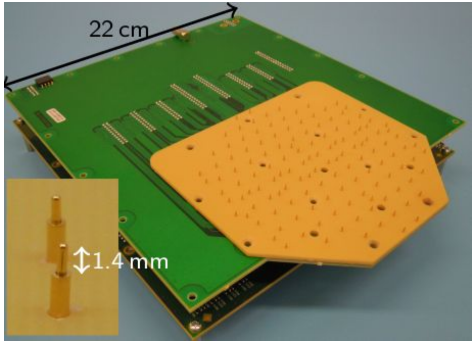
"ARRAY" system (hard-, software)

- Modular probe- and switch-card design, adaptable to different sensor layouts
- Essential tool for identification of problems in design, production process, sensor handling

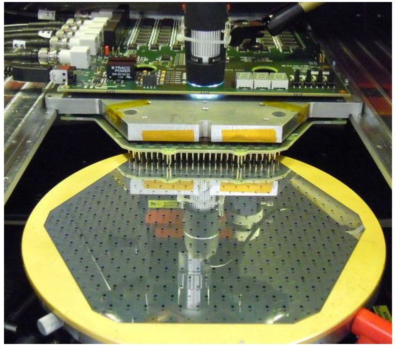
Switch card



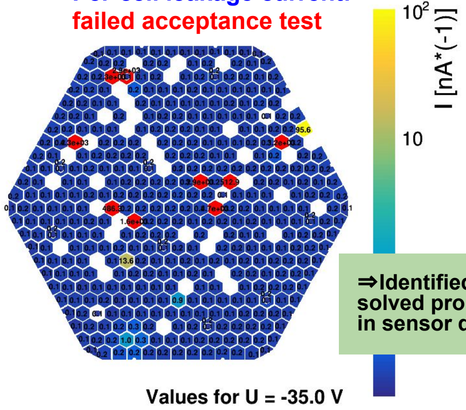
Probe card



ARRAY system in probe station



Per-cell leakage current: failed acceptance test



⇒Identified and solved problem in sensor design

Per-cell leakage current: passed acceptance test