Project Highly Granular Calorimeters

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Katja Krüger

Partners:

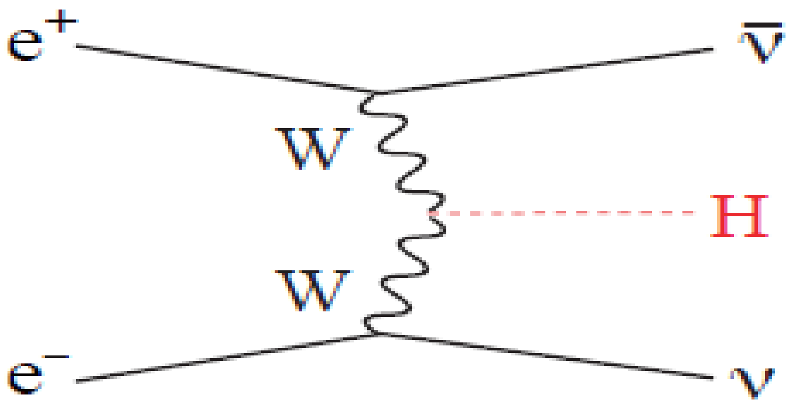
Kickoff Meeting December 2021

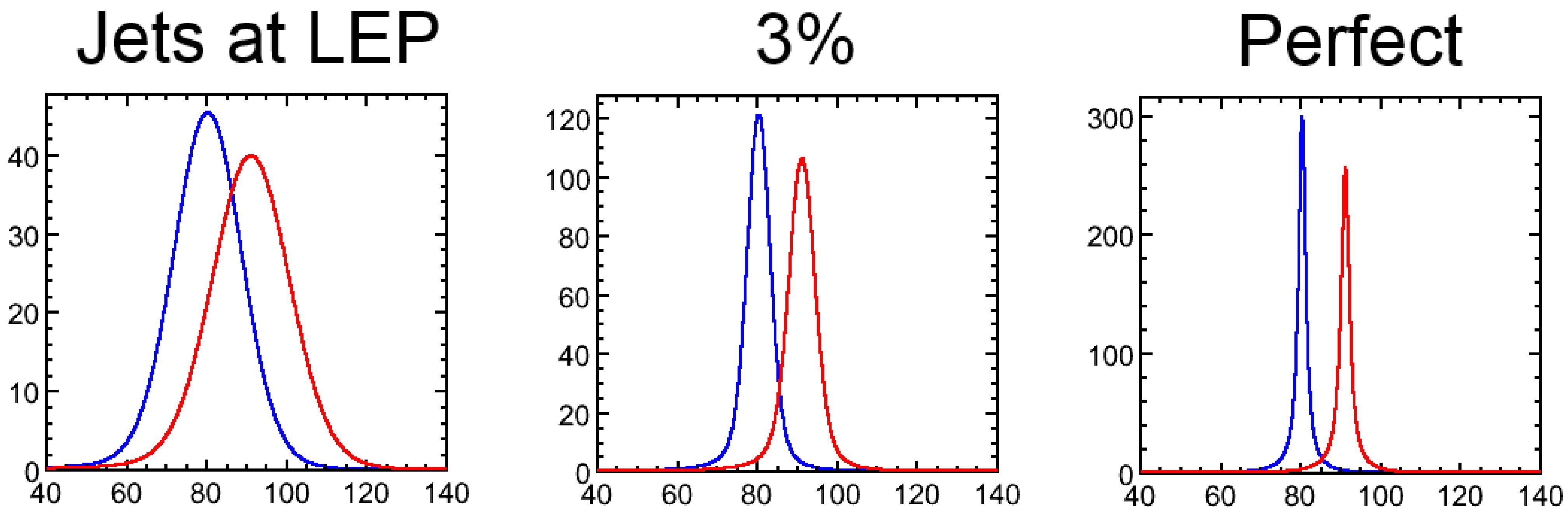
Detector requirements in high energy e+e- collision

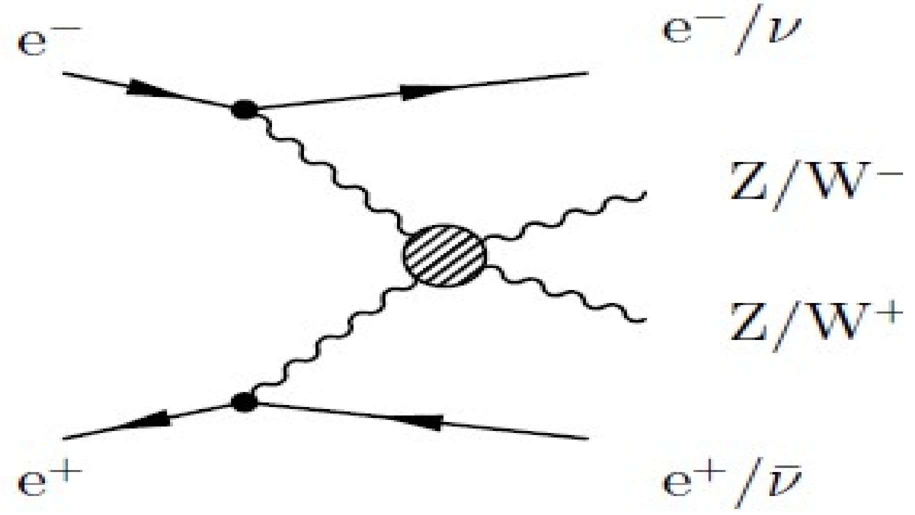
Examples:

- W Fusion with final state neutrinos requires reconstruction of H decays into jets

- Jet energy resolution of ~3% for a clean W/Z separation





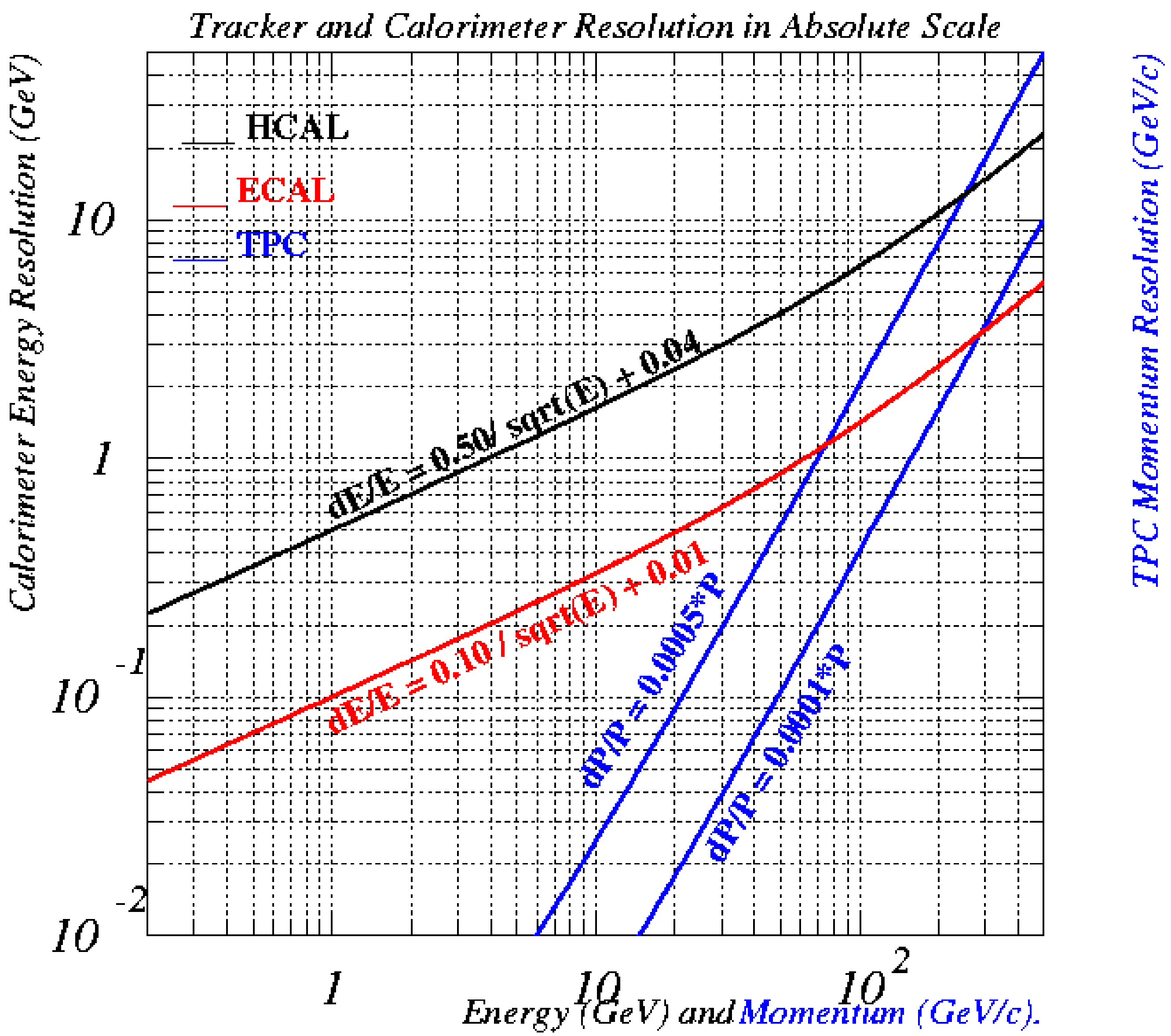


M. Thomson

Slide: F. Richard at International Linear Collider – A worldwide event

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

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

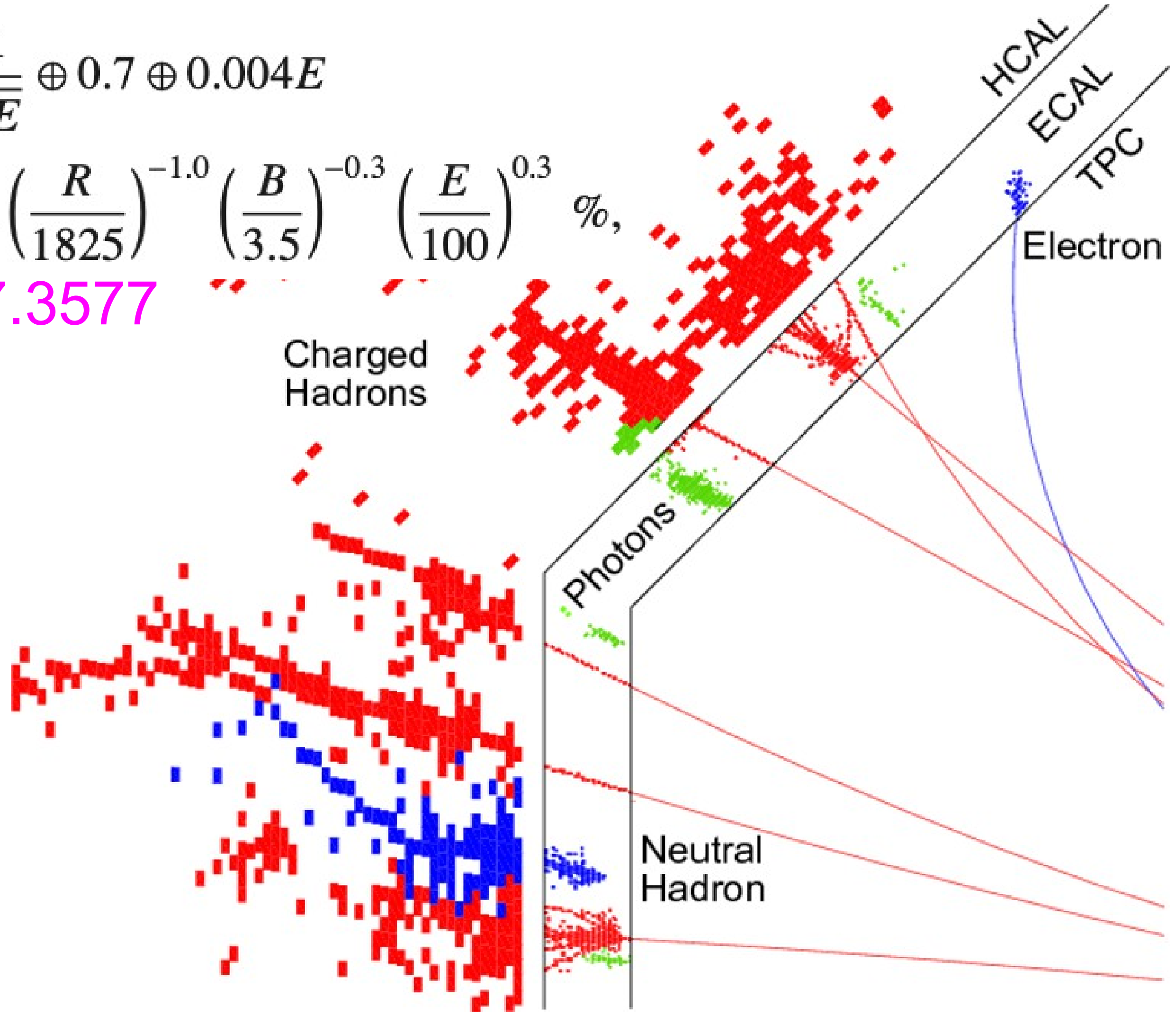
Confusion term

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

Ad hoc

$$\frac{\mathrm{rms}_{90}}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{R}{1825}\right)^{-1.0} \left(\frac{B}{3.5}\right)^{-0.3} \left(\frac{E}{100}\right)^{0.3} \%,$$

Arxiv:0907.3577



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

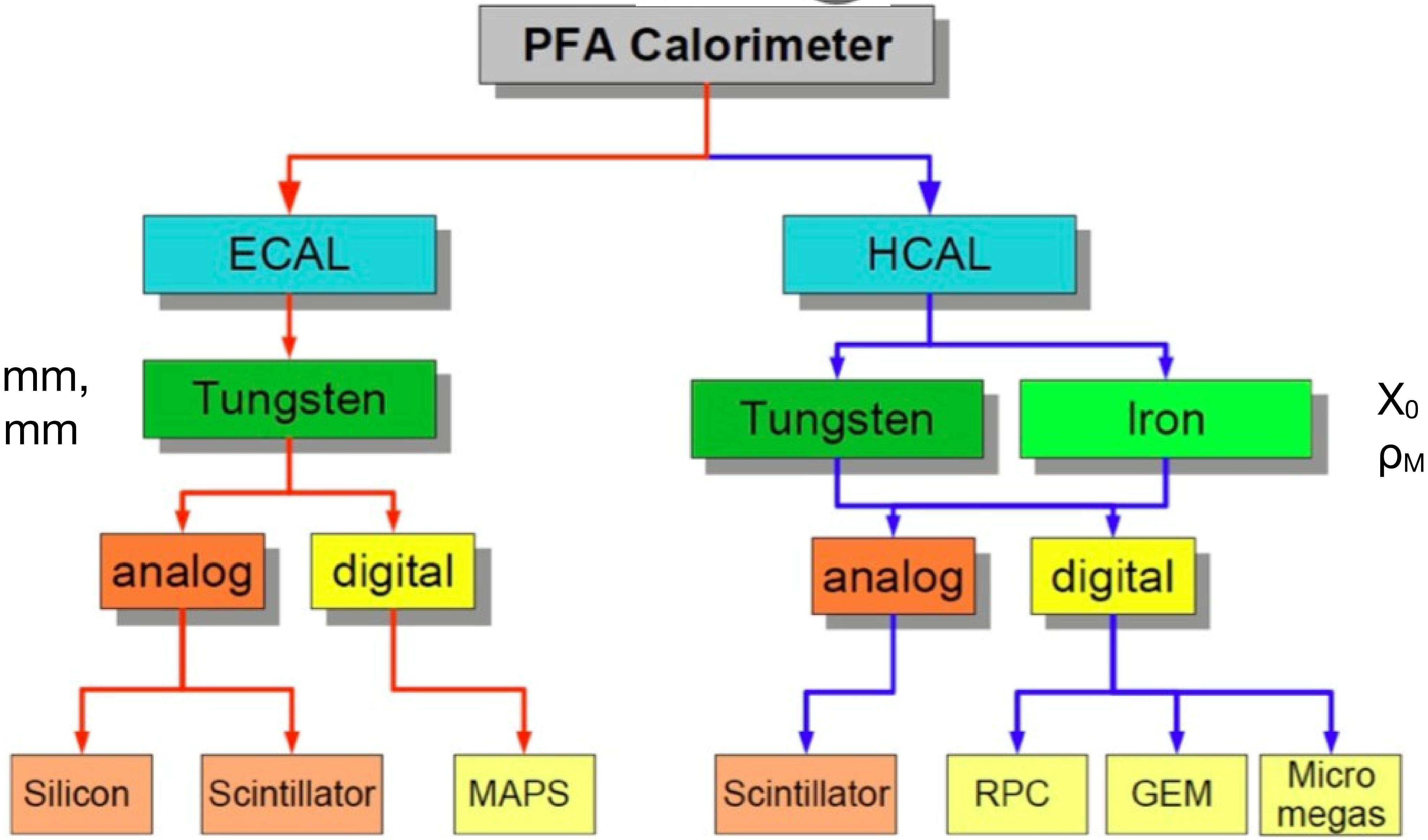
□ **Confusion Term**

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

=> Highly Granular Calorimeters

Calorimeters for PFA

Mainly organised within the CALICE Collaboration



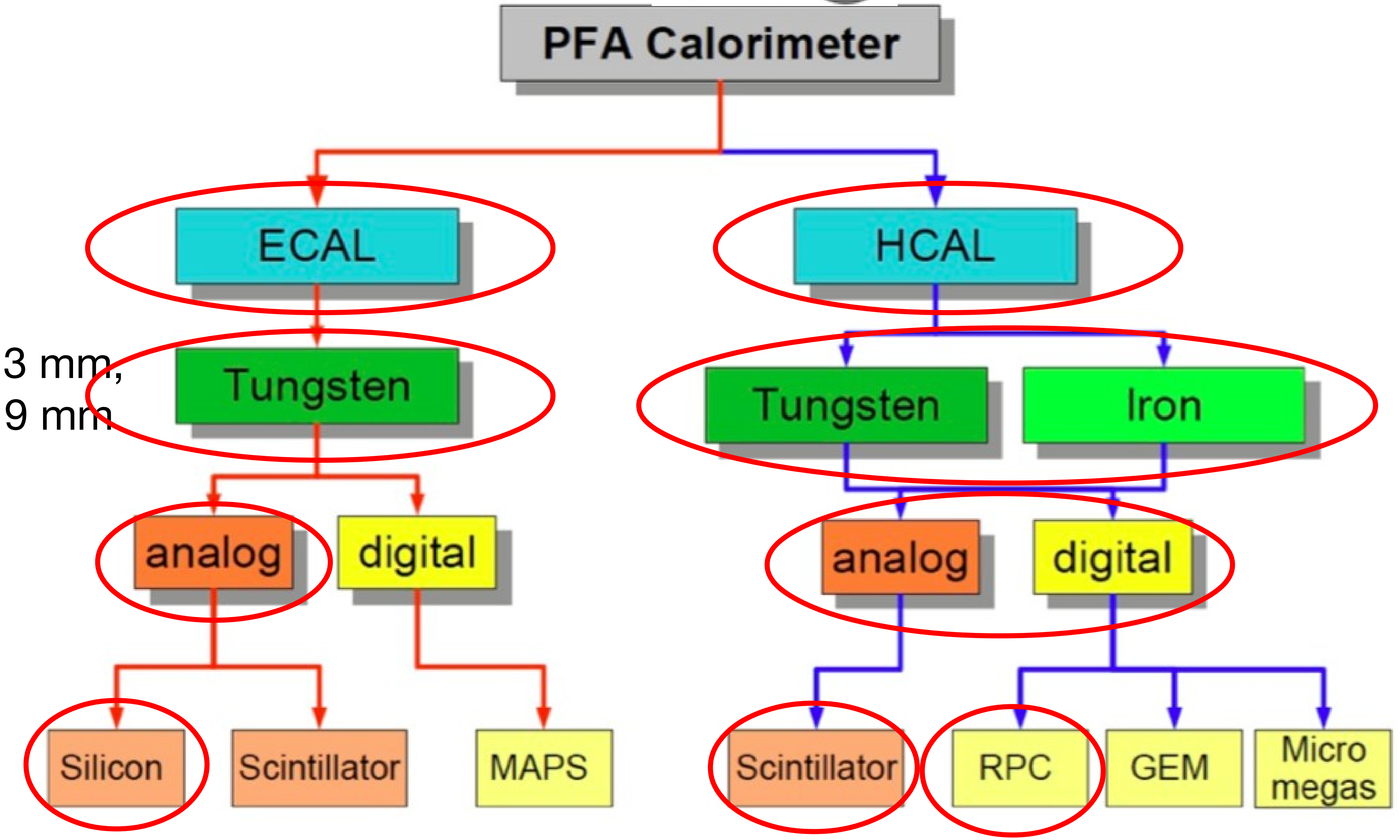
X_0 ~ 3 mm, ρ_M ~ 9 mm

X_0 ~ 20 mm, ρ_M ~ 30 mm

All projects of current future high energy colliders propose highly granular calorimeters

Calorimeters for PFA

Mainly organised within the CALICE Collaboration



$X_0 \sim 3$ mm, $\rho_M \sim 9$ mm

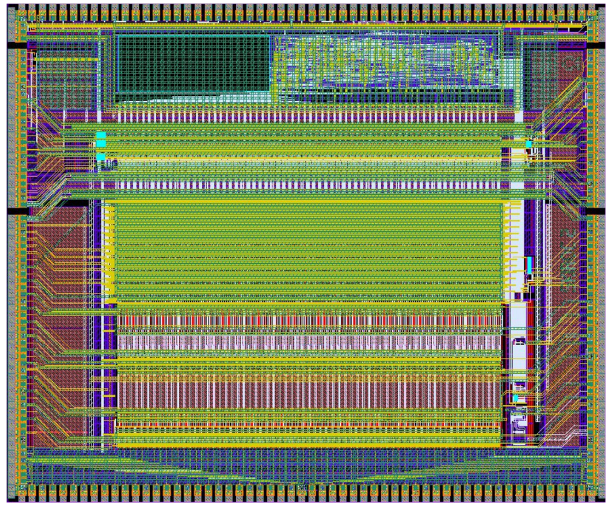
$X_0 \sim 20$ mm, $\rho_M \sim 30$ mm

Technologies covered within DMLAB

Calorimeters for PFA – Technological premises

Highly integrated front end electronics

e.g. SKIROC (for SiW Ecal)

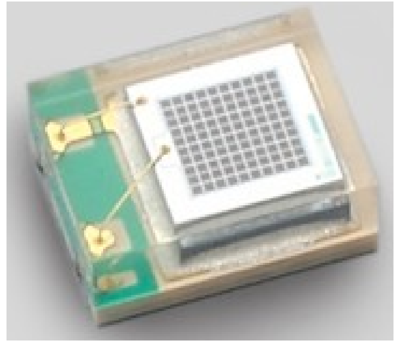


Size 7.5 mm x 8.7 mm, 64 channels

- Analogue measurement
- On-chip triggering
- Data buffering
- Digitisation

... all within one ASIC

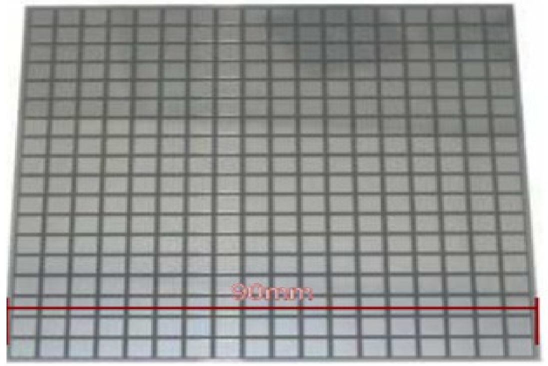
Miniaturisation of r/o devices



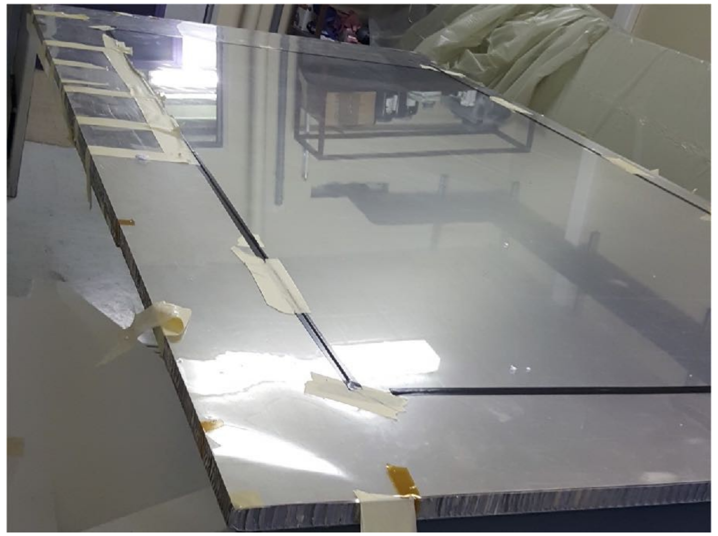
- Small scinitllating tiles
- (Low noise) SiPMs

Large surface detectors

Si Wafer



RPC layers

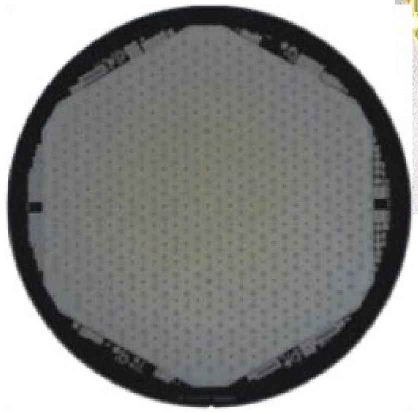


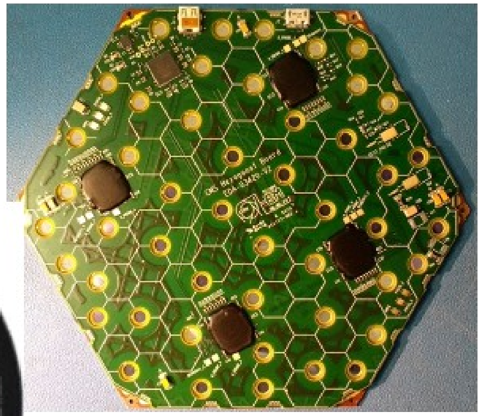
Many things that look familiar to you today were/are pioneered/driven by CALICE

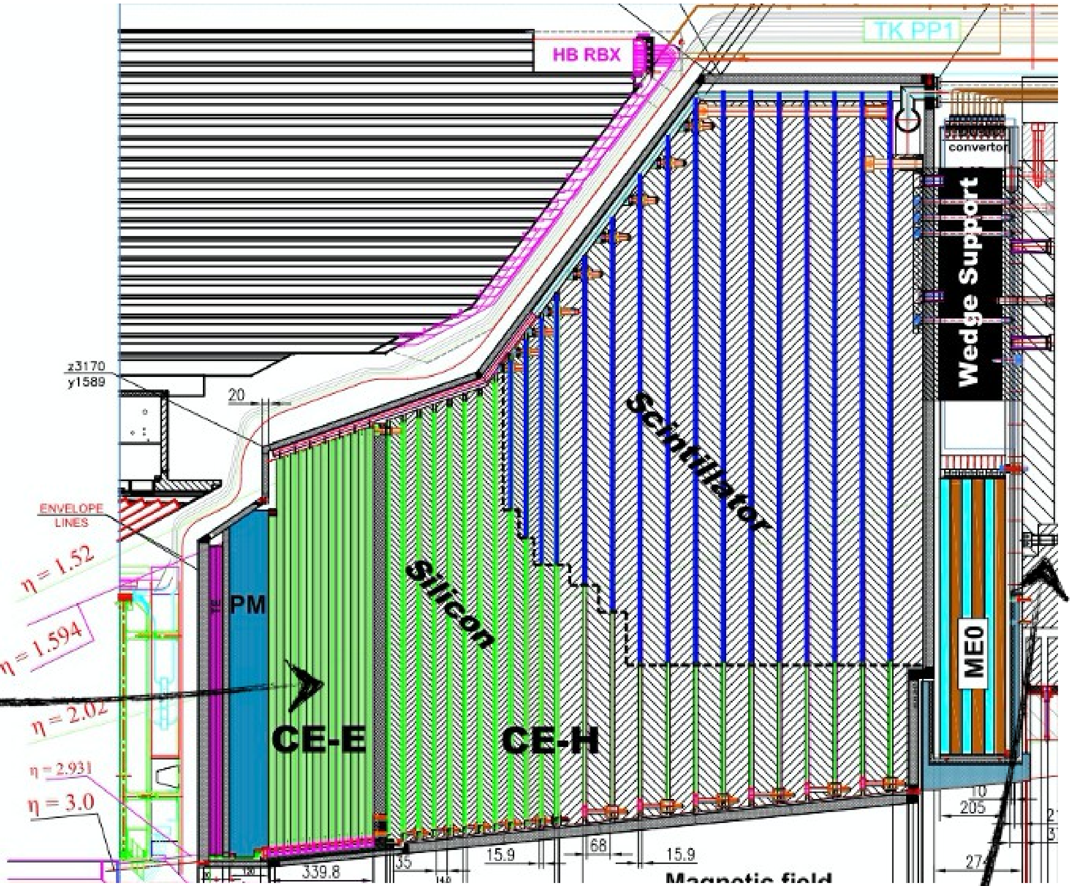
Applications of CALICE Technologies

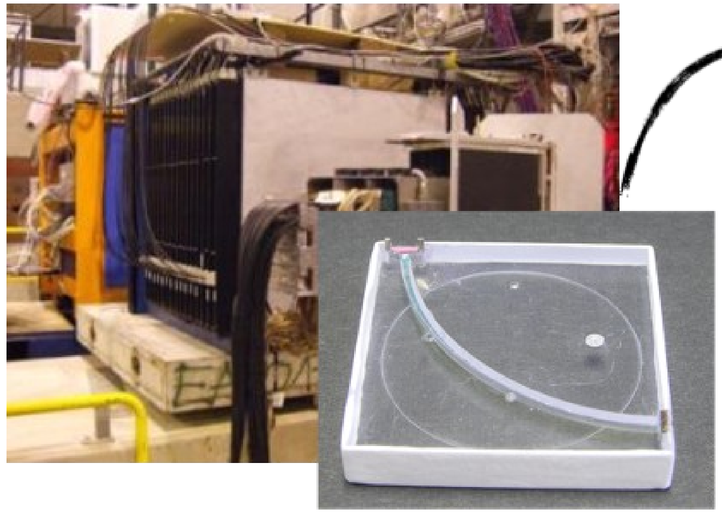
- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

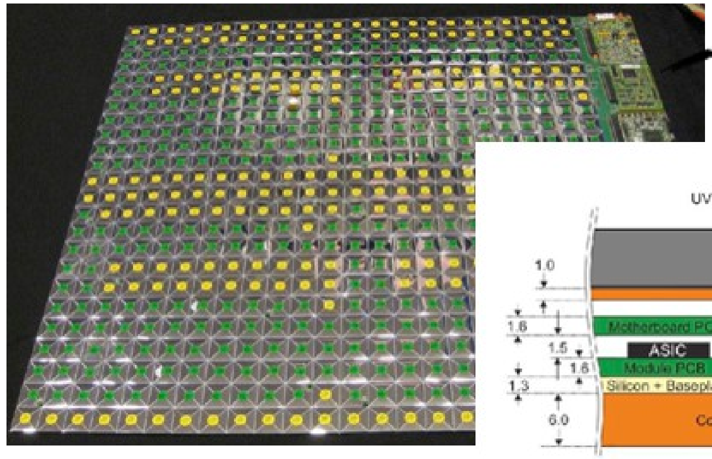
Most prominent: The CMS Endcap Calorimeter Upgrade HGCal

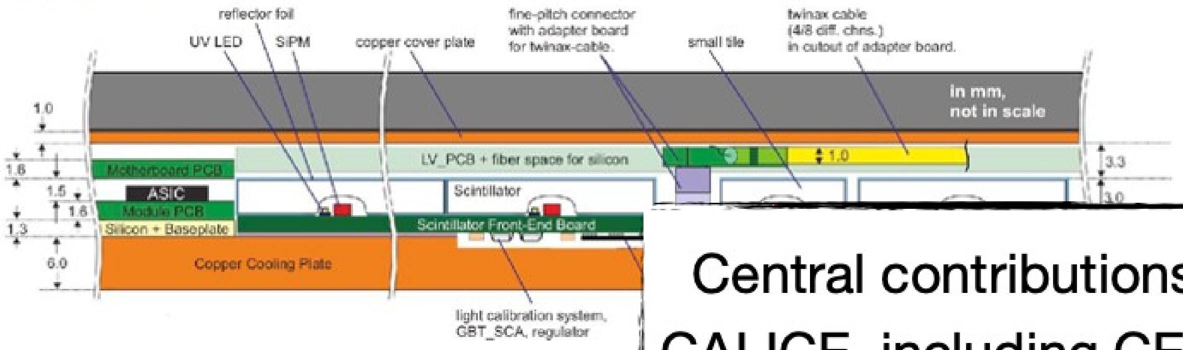






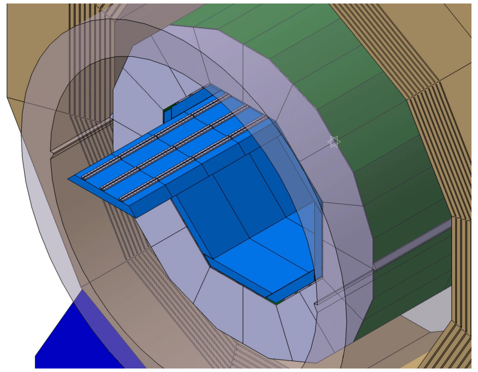




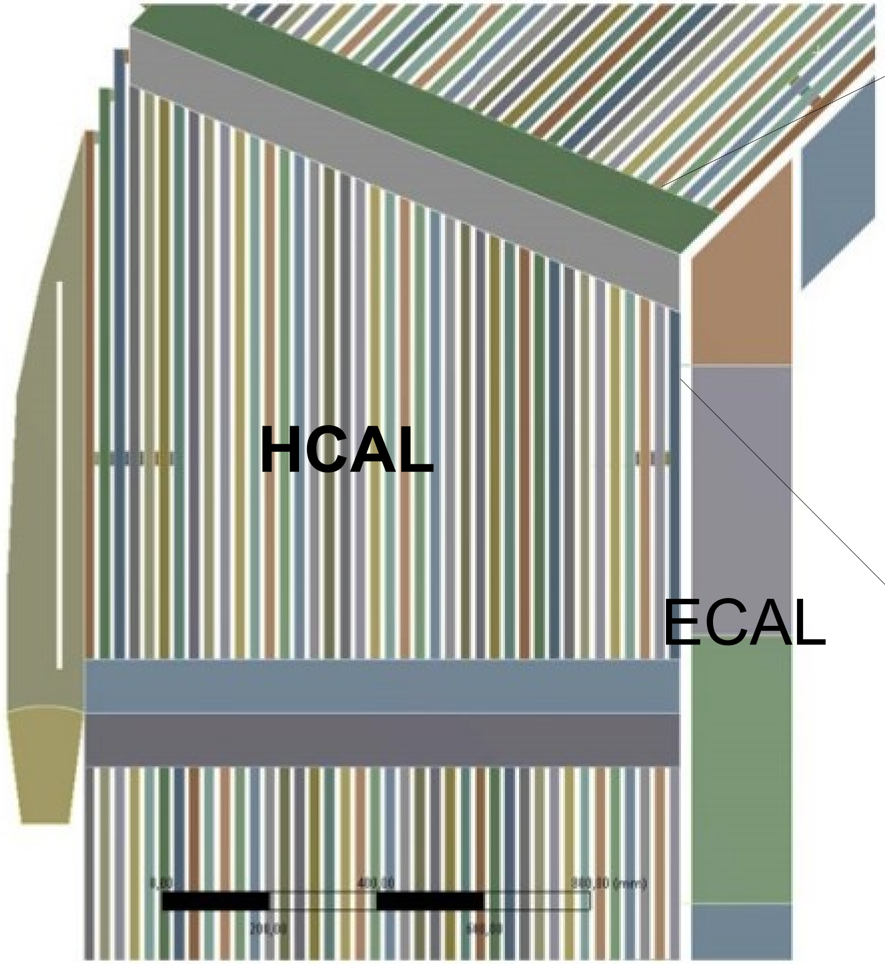


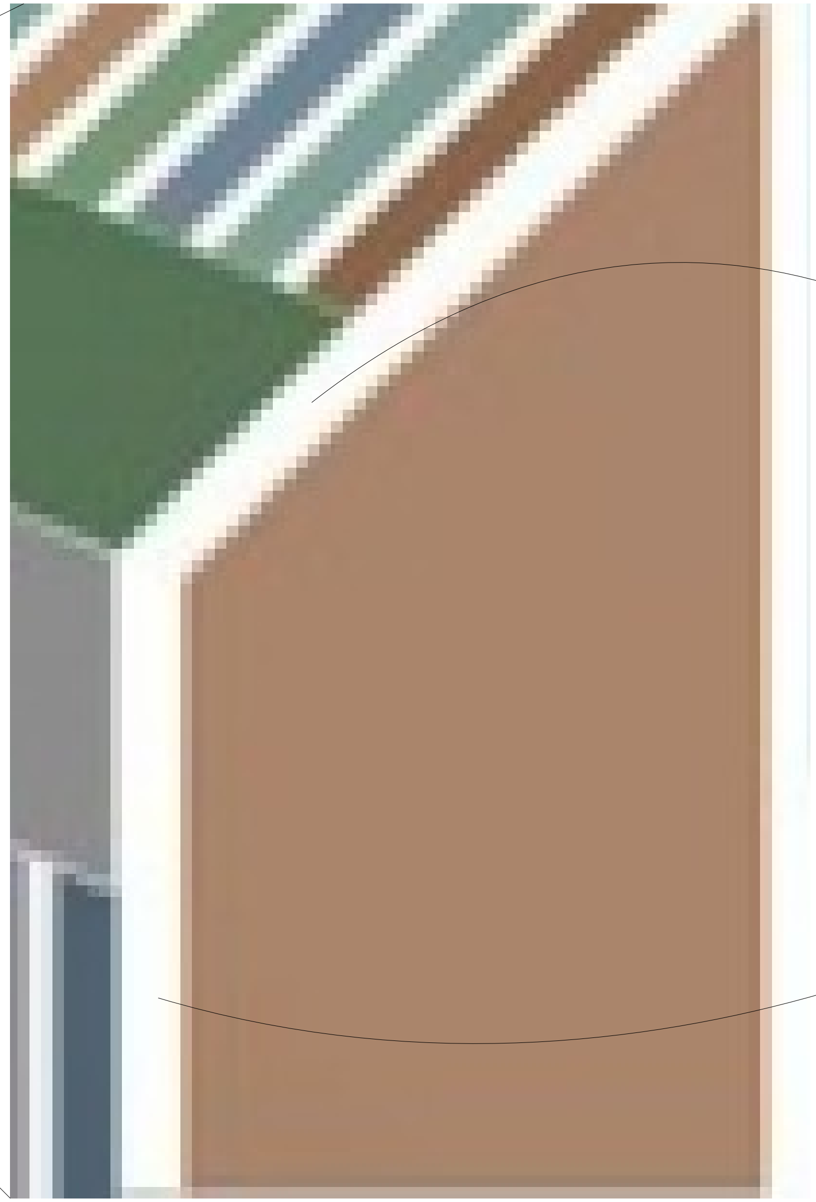
Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

Common Problem – No Space



- Successful application of PFA requires calorimeters to be inside the magnetic coil
  => Tight lateral and longitudinal space constraints

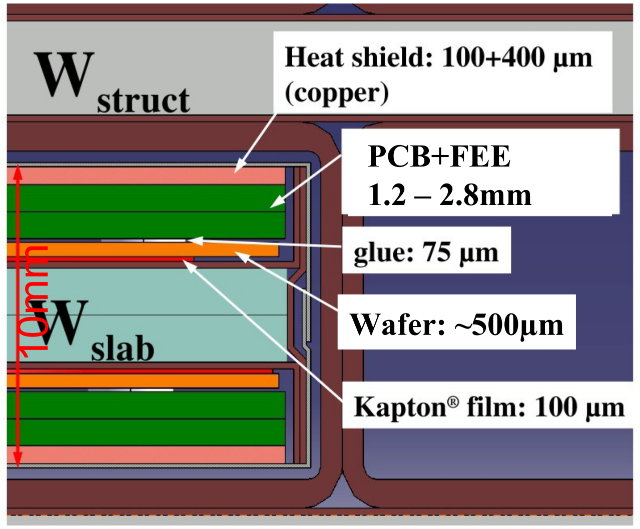




40-70mm for services as readout, cooling and power

Technological solutions for a final detector I

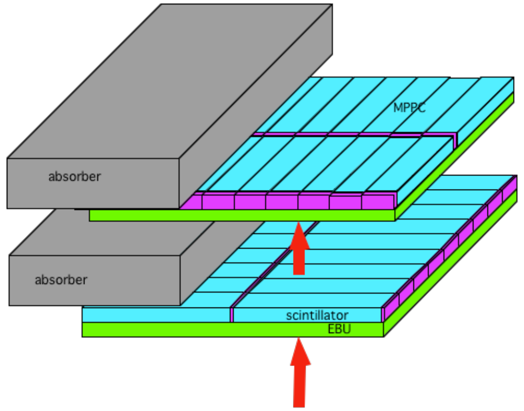
SiW Ecal

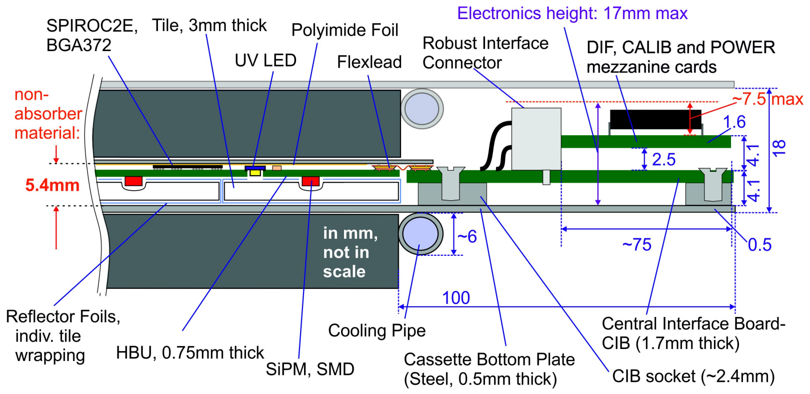


Semi-conductor readout

Typical sensor segmentation: $0.5x0.5cm^2$

Analogue Hcal and Scintillator Ecal



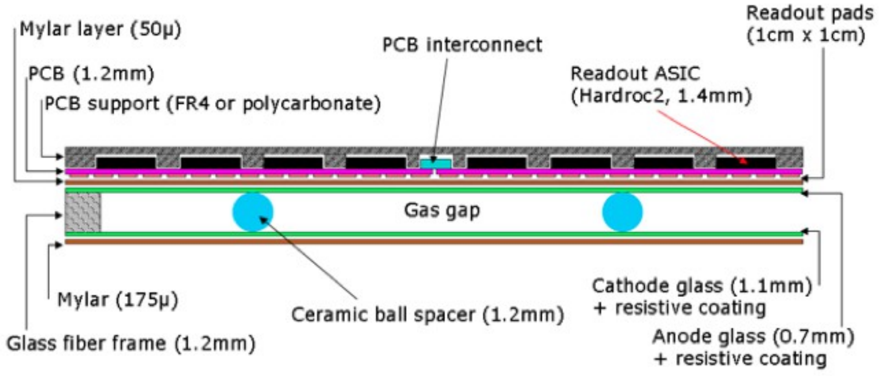


Optical readout

Typical sensor segmentation:

$0.5x5cm^2$ $3x3cm^2$

Semi-digital Hcal



Gaseous readout

Typical segmentation: $1x1cm^2$

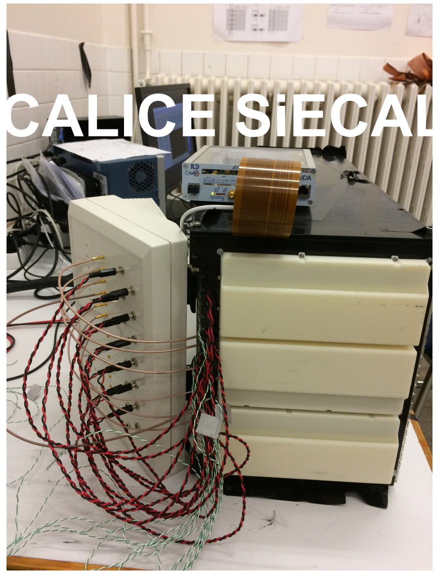
- Integrated front end electronic

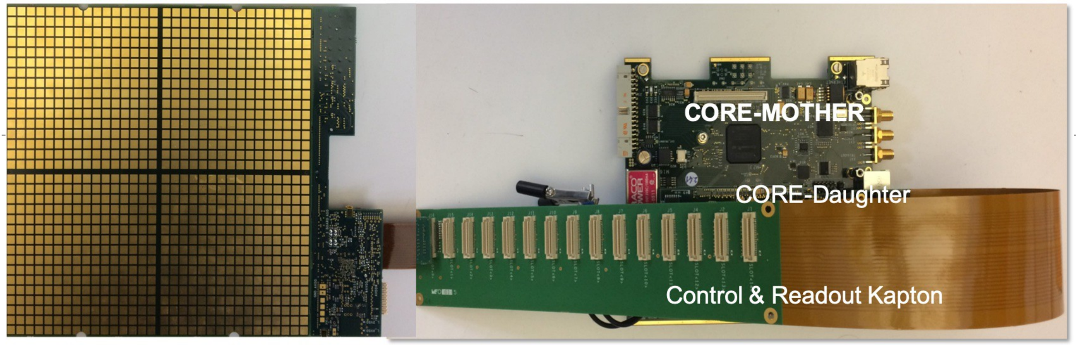
  No drawback for precision measurements *NIM A 654 (2011) 97*

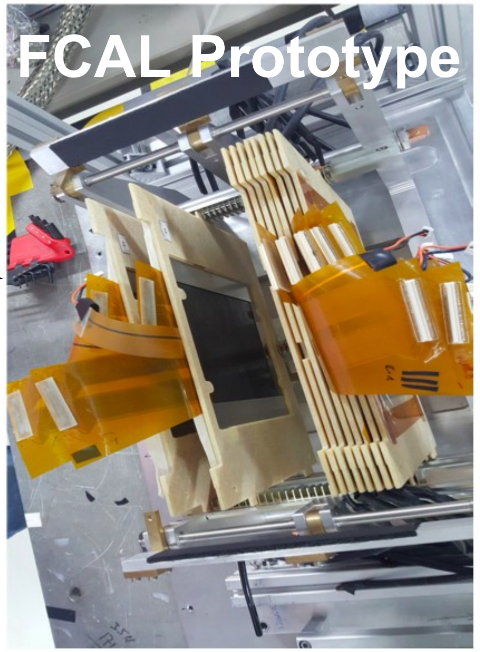
- Small power consumption
- Realistic dimensions
  - Structures of up to 3m

Common Projects – Hardware Development

Arxiv:1810.05133



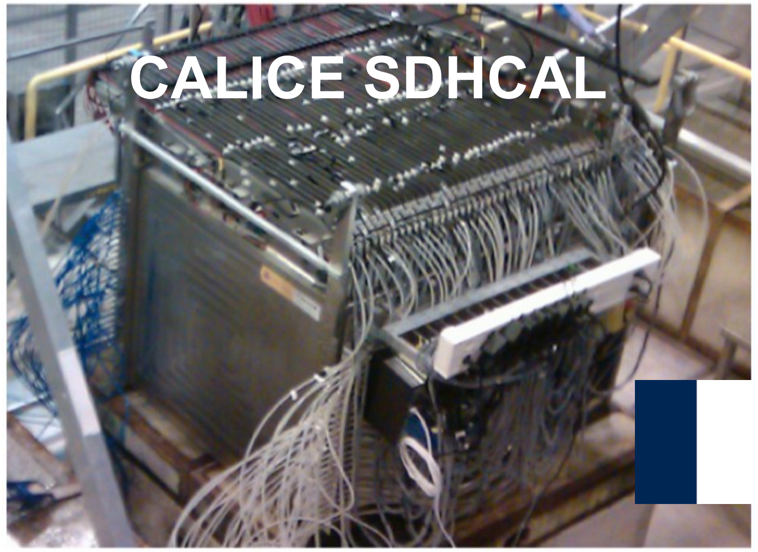


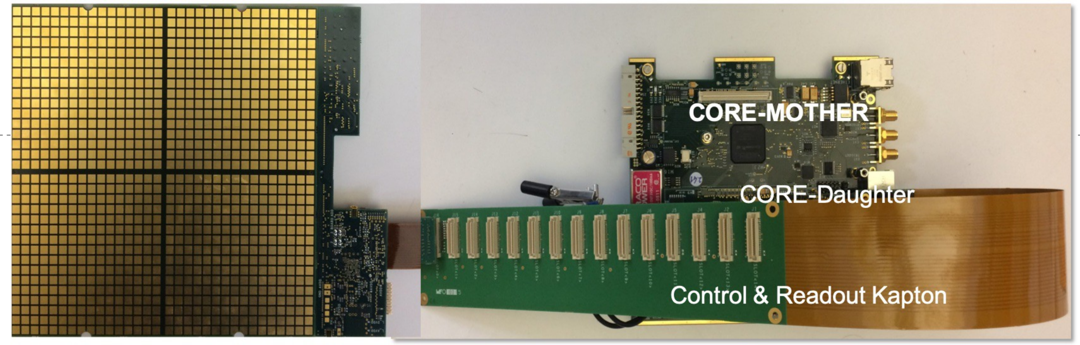


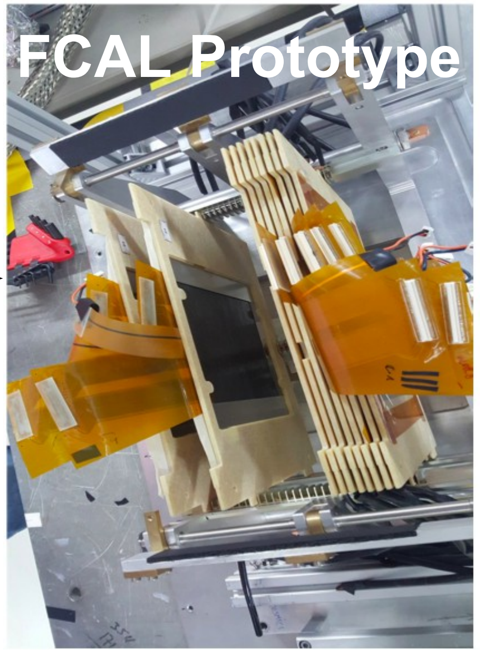
Adaptation of compact readout system developed for SiW ECALs to other prototypes of granular calorimeters

Common Projects – Hardware Development

Arxiv:1810.05133







Adaptation of compact readout system developed for SiW ECAL to other prototypes of granular calorimeters

AHCAL Beam test setup

CALICE SiW ECAL/SDHCAL (2018)

... to be repeated in next years

CALICE SiW ECAL/AHCAL (planned)

- Beamtests will benefit from commong approach on readout
  - Detectors readout will be integrated into EUDAQ system
  - Application of beam telescopes
  - High energy beams at CERN but DESY beam test is ideal place to test setup

DESY Beam test schedule – Spring 2022

DESY TEST BEAM.

DESY Test Beam Schedule 2022- Version 1 06/12/2021

Ralf Diener, Norbert Meyners, Marcel Stanitzki - DESY Test Beam Coordinators

	Week		TB21	DATURA	TB22	DURANTA	TB24/1 PCMAG	Telescope in PCMAG	TB24	AZALEA
3-Jan-22	1		Shutdown							
10-Jan-22	2		Shutdown							
17-Jan-22	3		Shutdown							
24-Jan-22	4		Shutdown							
31-Jan-22	5		Startup		Startup		Startup		Startup	
7-Feb-22	6		CMS-InnerTracker	X	HVMAPS	X			MONOPIX2	X
14-Feb-22	7		ARCADIA	X	HVMAPS	X			Mimosis	
21-Feb-22	8		ARCADIA	X	ATLAS-ITk-Pixels	X			Telescope-Dev	X
28-Feb-22	9		ATLAS-HGTD	X	ATLAS-ITk-Pixels	X				
7-Mar-22	10		ATLAS-HGTD	X	CALICE-SiW-ECAL	X				
14-Mar-22	11		CMS-InnerTracker	X	CALICE-SiW-ECAL	X			ALICE-ITS3	X
21-Mar-22	12		CMS Outer Tracker PS	X	DSiPM	X				
28-Mar-22	13				PSIMAPS	X				
4-Apr-22	14				PSIMAPS	X			APIX3	X
11-Apr-22	15									
18-Apr-22	16				Telescope-Dev	X				
25-Apr-22	17		CMS-InnerTracker	X	Mu3e	X			CALICE AHCAL	X
2-May-22	18		CMS-InnerTracker	X	Mu3e	X			TPEX	
9-May-22	19				MONOPIX2	X			TPEX	
16-May-22	20								LHCb-ECAL	X
23-May-22	21		CMS-InnerTracker	X	LHCb-MightyPix	X			LHCb-ECAL	X
30-May-22	22									
6-Jun-22	23		Telescope-Dev	X						
13-Jun-22	24		CMS Outer Tracker	X	ATLAS-ITk-Strips	X			ALICE-ITS3	X
20-Jun-22	25		CMS Outer Tracker	X	ATLAS-ITk-Strips	X				
27-Jun-22	26		TelePix	X	Belle-II CMOS	X				
4-Jul-22	27		TelePix	X	Belle-II CMOS	X				
11-Jul-22	28		CMS-InnerTracker	X						
18-Jul-22	29									

ANNOUNCED

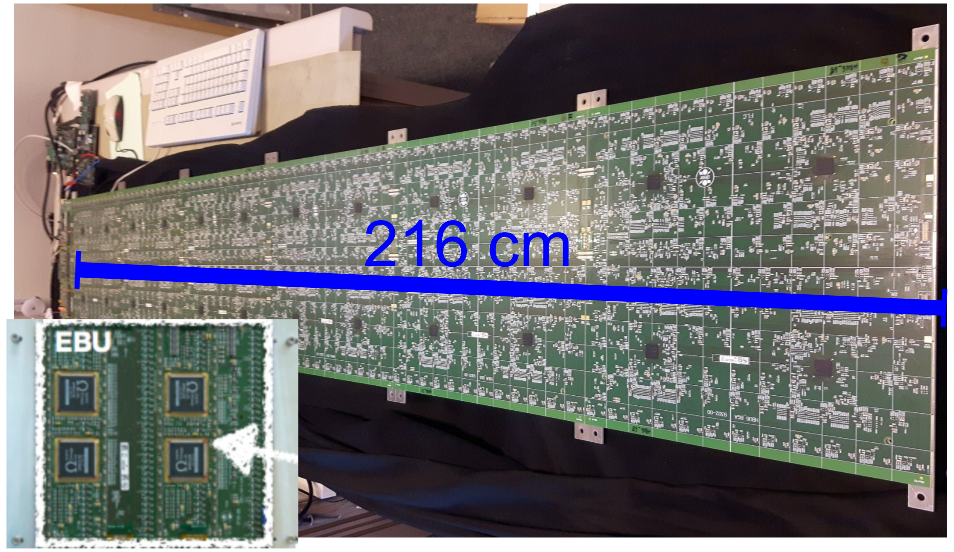
Testbeams at DESY in 2022 will be used to set up common running of SiW Ecal and AHCAL

New prototypes

SiW Ecal

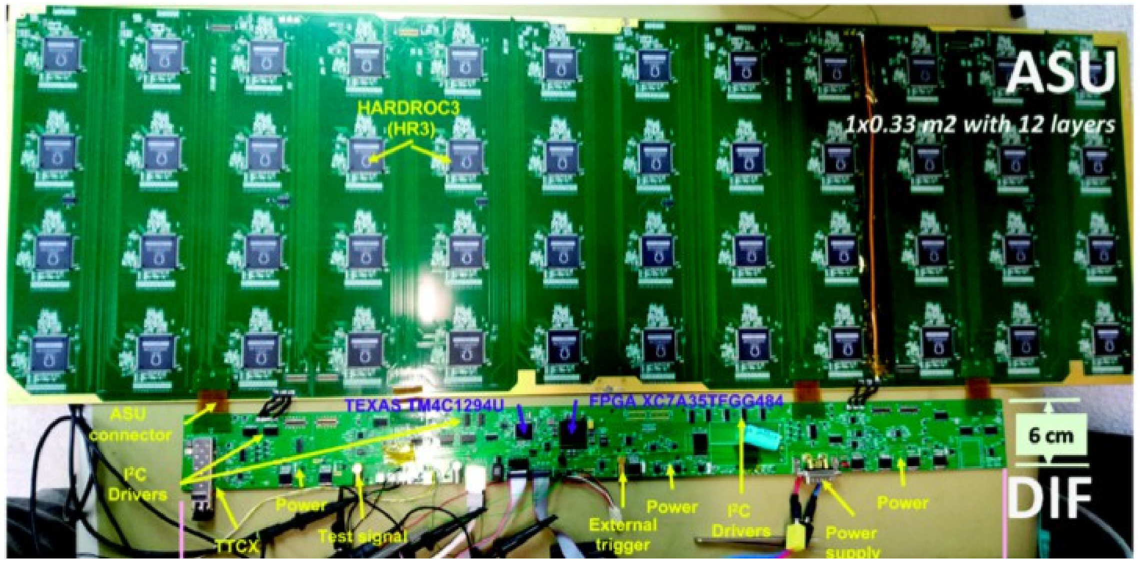
Semi-conductor readout

Analogue Hcal and
Scintillator Ecal



Optical readout

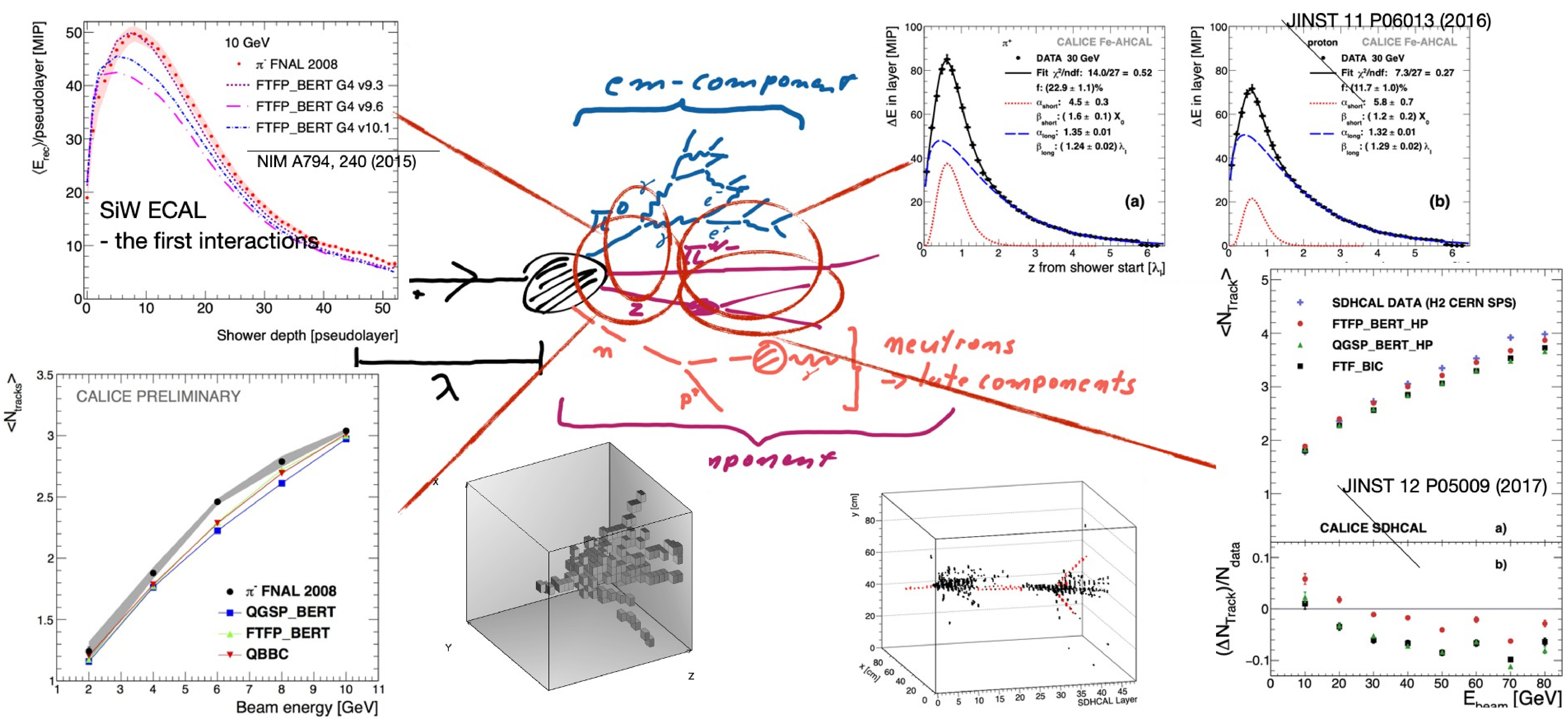
Semi-digital Hcal



Gaseous readout

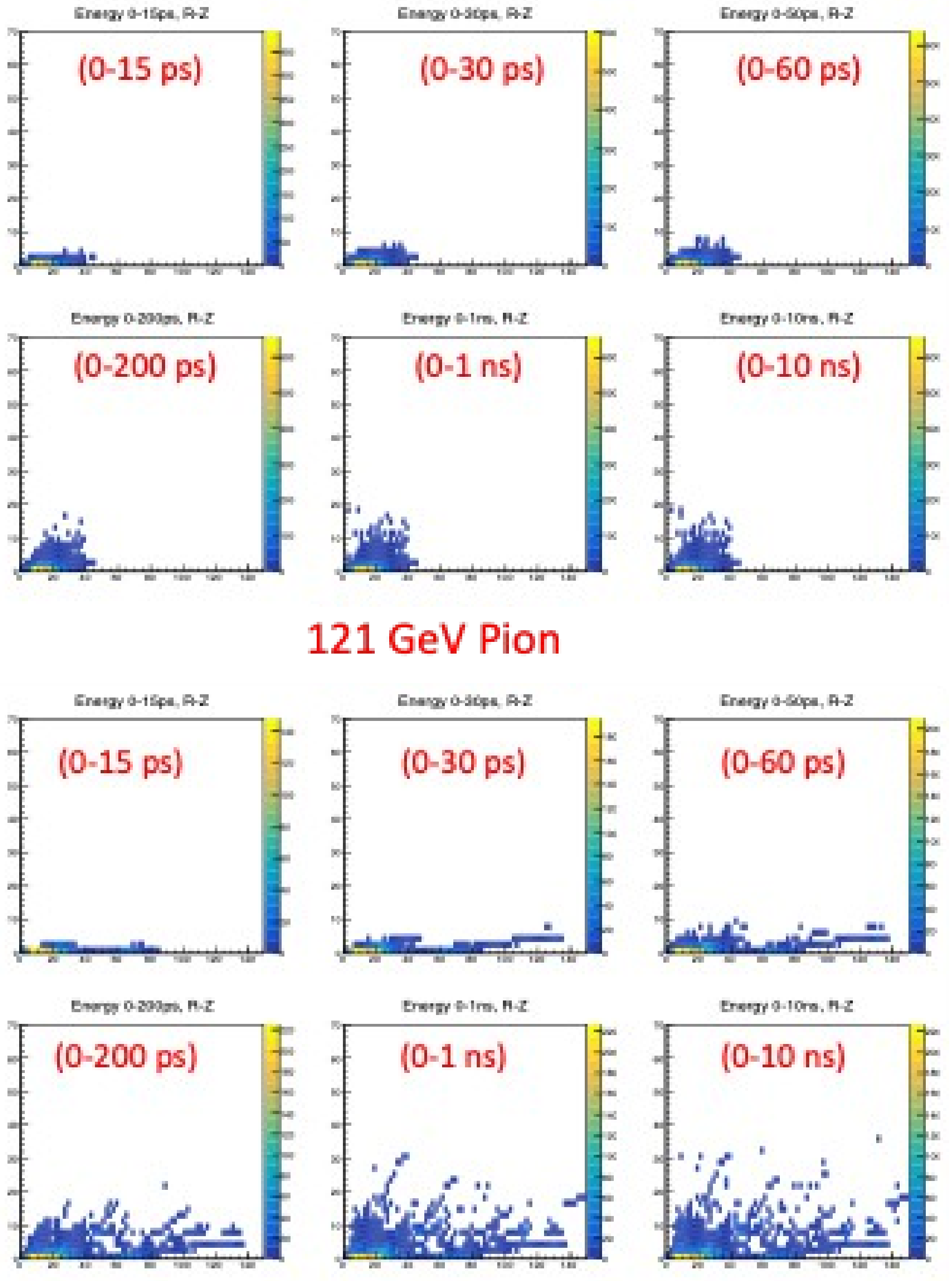
- Layers with realistic dimensions require further/new development of
  - Readout system and signal propagation over large distances
  - Assembly procedures and test stations
  - Large surface detectors

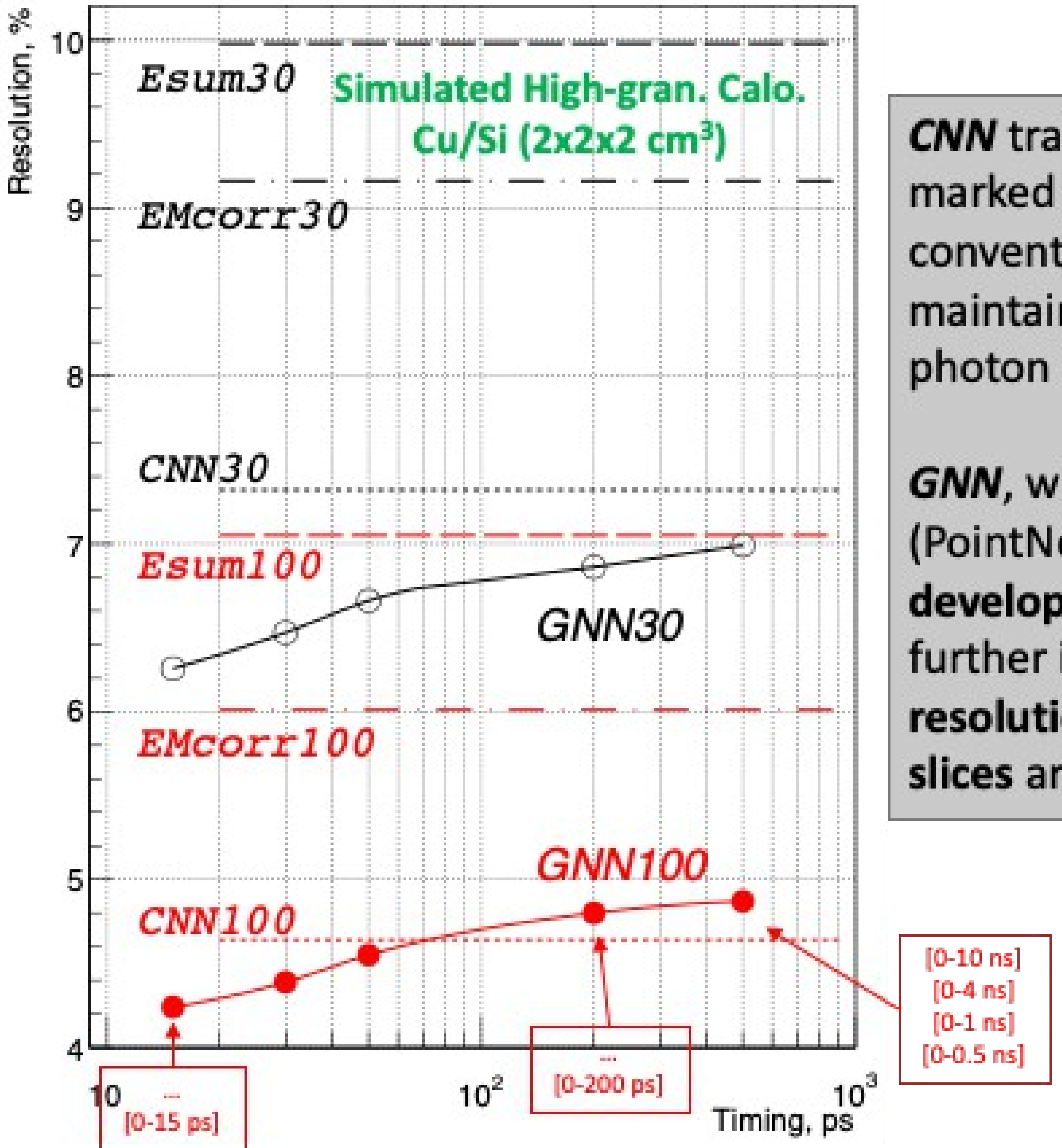
Exploiting the high granularity – Hadronic Cascades



Timing in calorimeters

Features that emerge in the time domain can help distinguish particle types and, with GNNs, enhance $\sigma(E)/E$



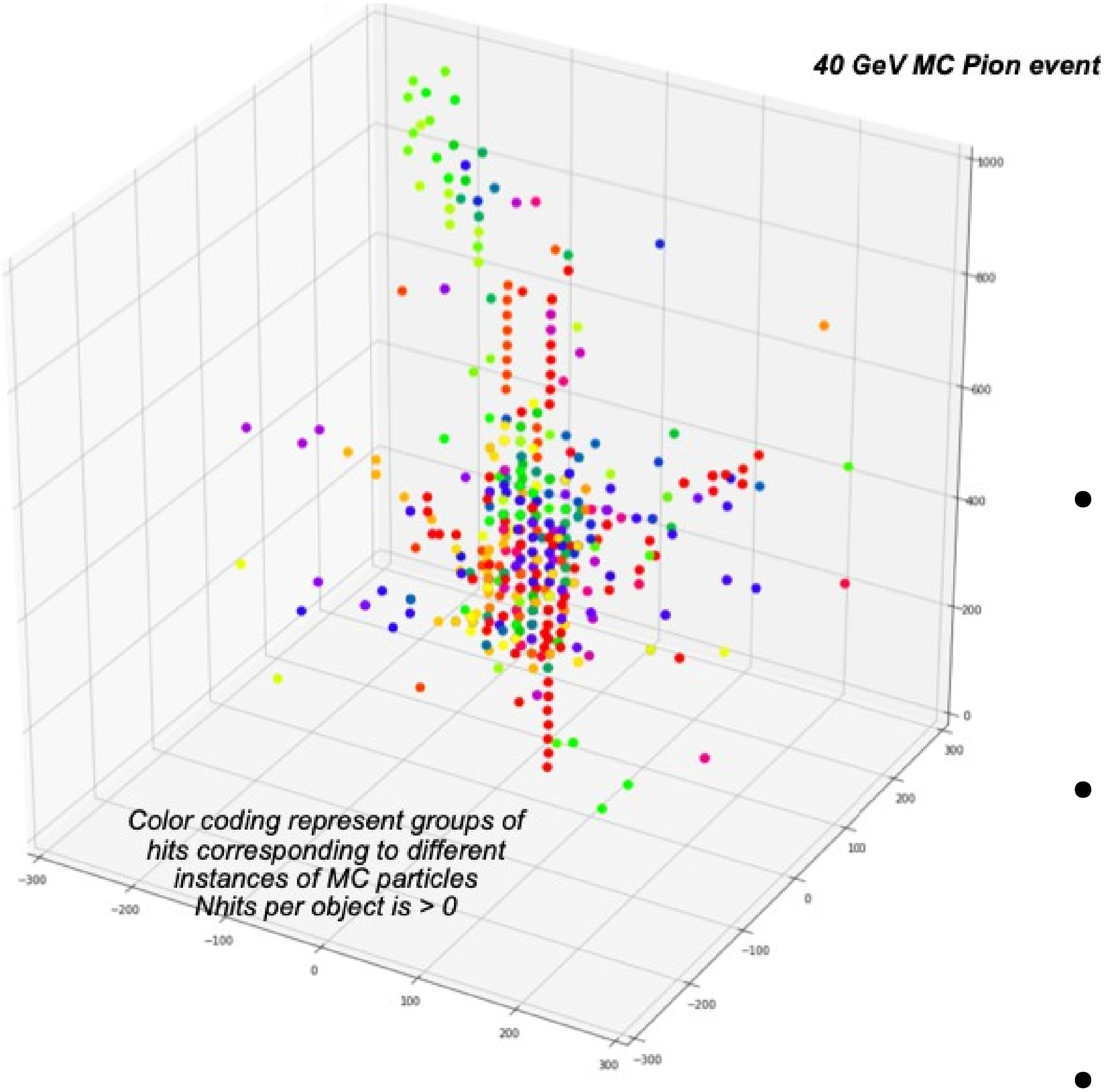


CNN trained on pions achieves marked improvement over the conventional approache while maintaining performance for photon reconstruction

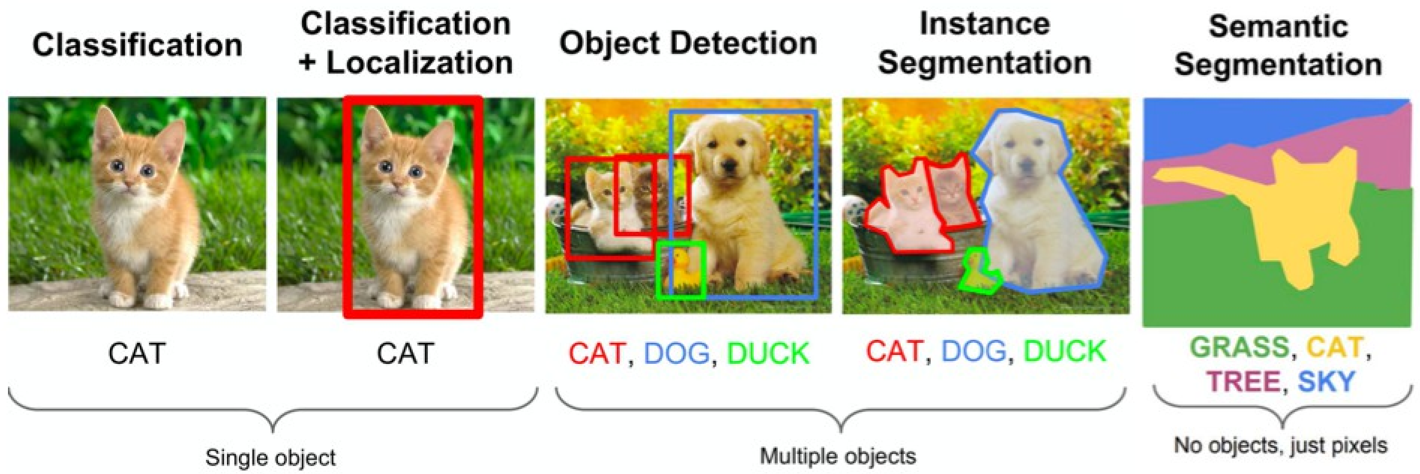
GNN, with edge convolution (PointNet), **with shower development timing information** further **improves energy resolution** when **shorter time slices** are included

arxiv:2108.10963

Analysing hadronic showers with ML

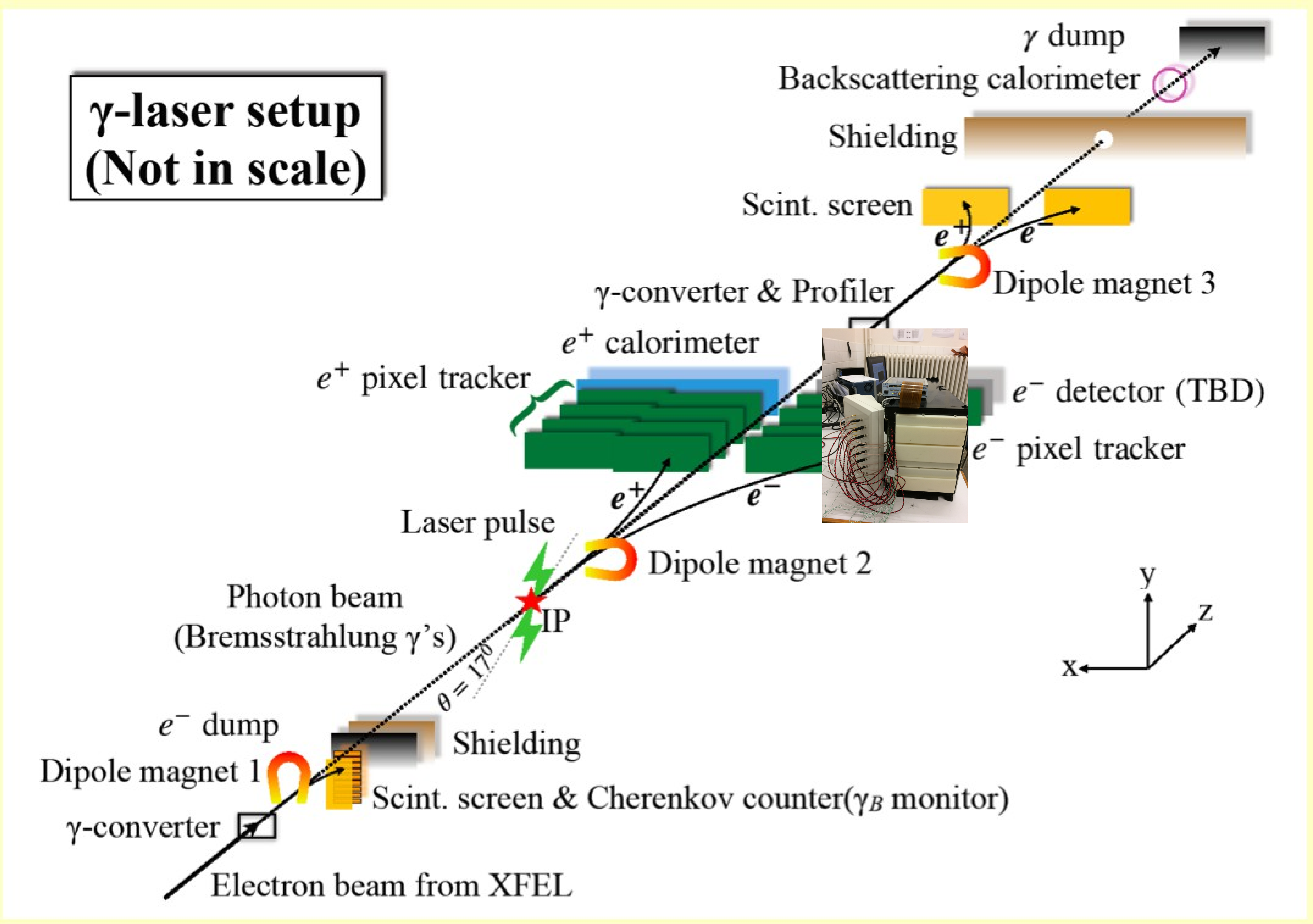


Images V. Bocharnikov



- CALICE data are excellent "playground" for application of machine learning and computer vision algorithms
  - Shower substructure
  - Particle identification and separation
- This is attractive in particular for young generation of physicists (and beyond)
  - Often (if not always) first steps are made with G4 simulated events
  - Can the algorithms be mislead by "wrong" models of hadronic showers?
- How to address a meaningful comparison with data?
  - Sophisticated combination of information

LUXE as application for granular Ecals



- LUXE test QED in extreme environment
- LUXE requires granular Ecals for e+ and e- detection
- CALICE SiW Ecal prototype Is operational and could be used (at least) for early start of LUXE
- LUXE may benefit from ongoing R&D work within CALICE and DMLAB frame
  - New detection elements
  - -> larger lateral extension

See also talk by B. Heinemann

Highly granular calorimeters and DMLAB

- Development of granular calorimeters is active field in France and in Germany
- Common development would benefit by “borderless” mutual access to facilities
  - Office space, workspace (e.g. For setting up testbenches), access to stores and (hardware) pools
  - DESY beam test is of course a unique asset for our field
  - A small French team on site at DESY would allow to make optimal use of this infrastructure
- A “sabbatical” at DESY may allow for example help to prepare a common infrastructure
  - For a seamless exchange a team at e.g. DESY is for sure helpful
- A running experiment as LUXE would clearly as well motivate longer stays at DESY
- Shorter stays (~weeks) in France or in Germany for data analysis and development of algorithms
  - Application of timing and/or ML is largely unchartered territory for granular calorimeters

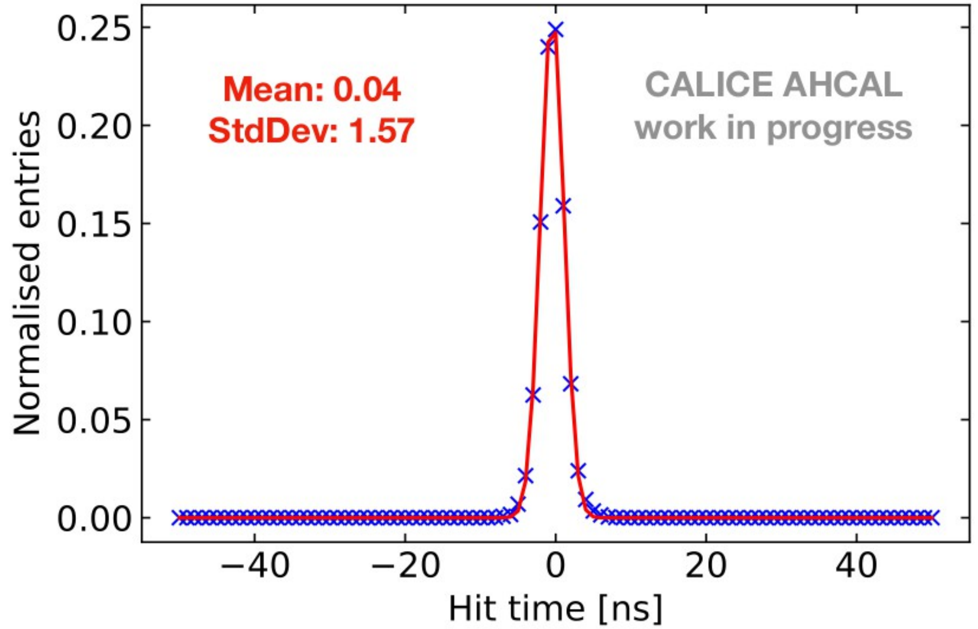
Backup

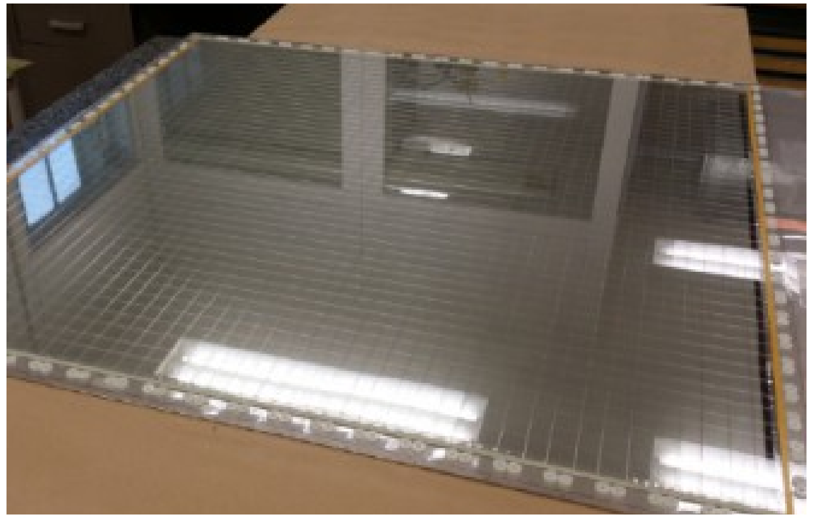
The next decade – ps timing in calorimeters

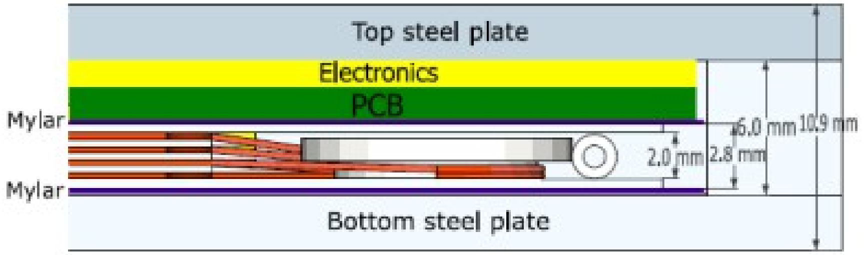
Pioneered by LHC Experiments, timing detectors are/will be also under scrutiny by CALICE Groups

Hit time resolution:
Results from 2018 beam test of AHCAL with muons

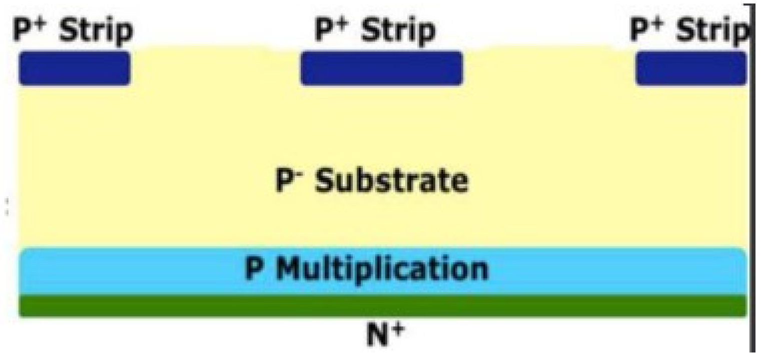
Clock frequency 5 MHz,
Powering pulsing







Inverse APD as LGAD?



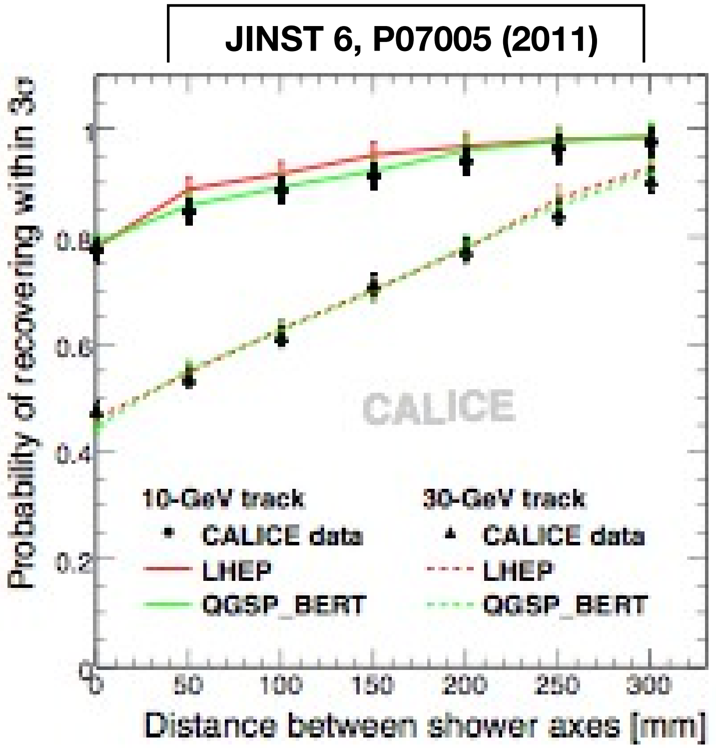
Inverse APD
by Hamamatsu

Gain ~ 50

CALICE – History and Steps of R&D

Physics Prototypes

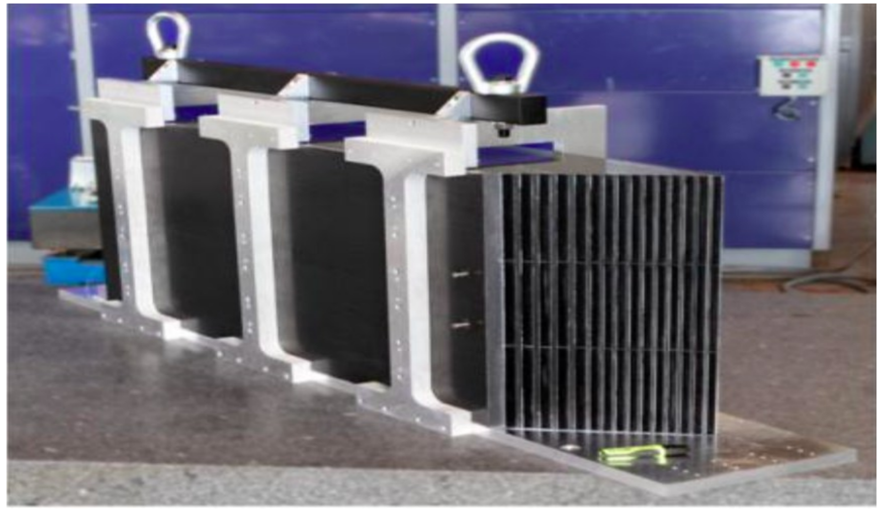
2003 - 2012



- Proof of principle of granular Calorimeters
- Large scale combined beam tests
- Validation of G4 Physics lists
- Main inspiration for CMS HGCAL Technology Choice

Technological Prototypes

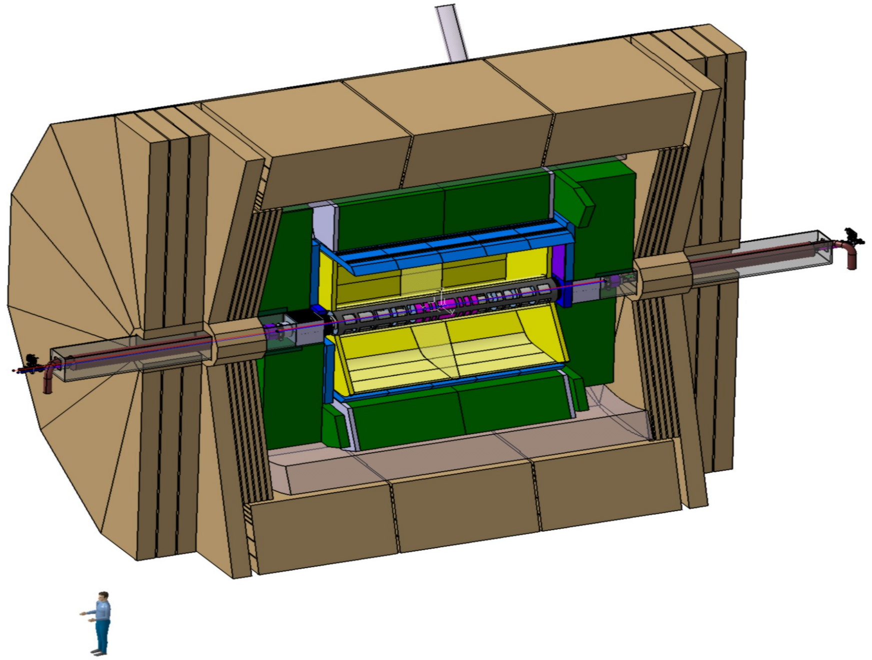
2010 - ...



Engineering challenges

This talk

LC detector

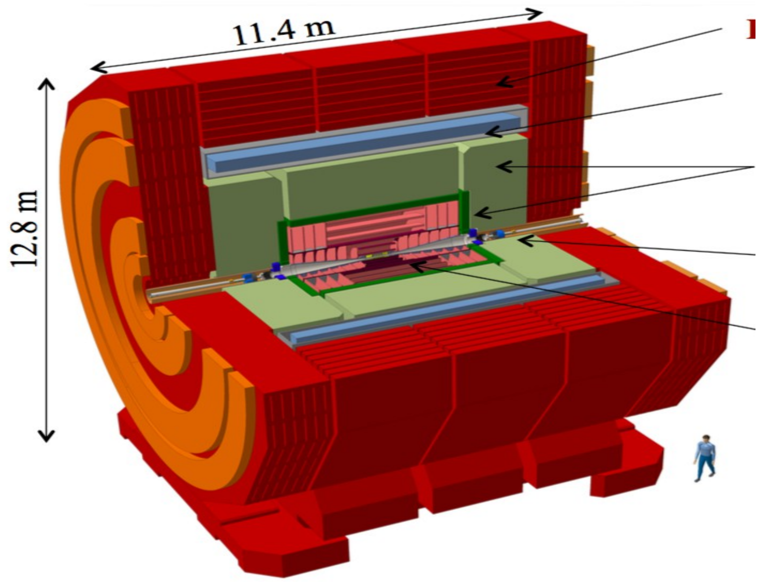


- The goal
  - Typically 10^8 calorimeter cells
- Compare:
  - ATLAS LAr ~10^5 cells
  - CMS HGCAL ~10^7 cells

Detector systems – e+e- colliders

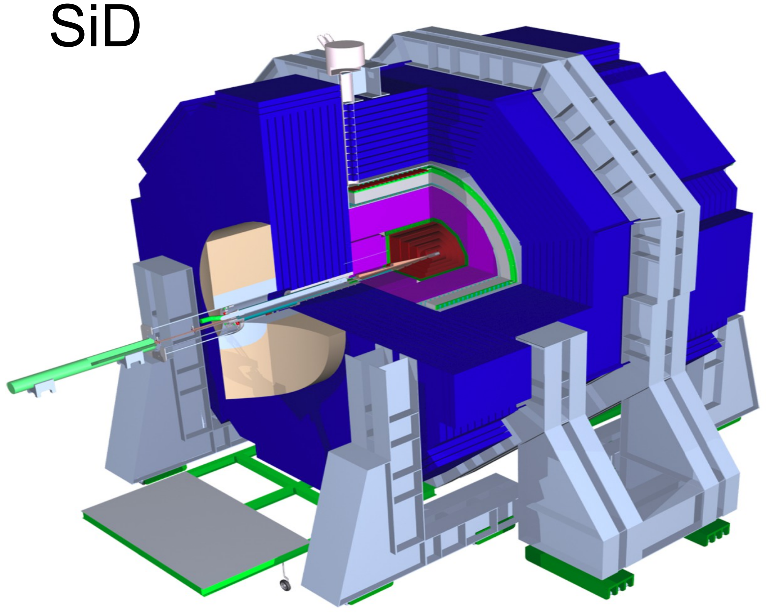
e+e- detector concepts for linear colliders
Preferred solution Particle Flow Detectors

CLIC Detector

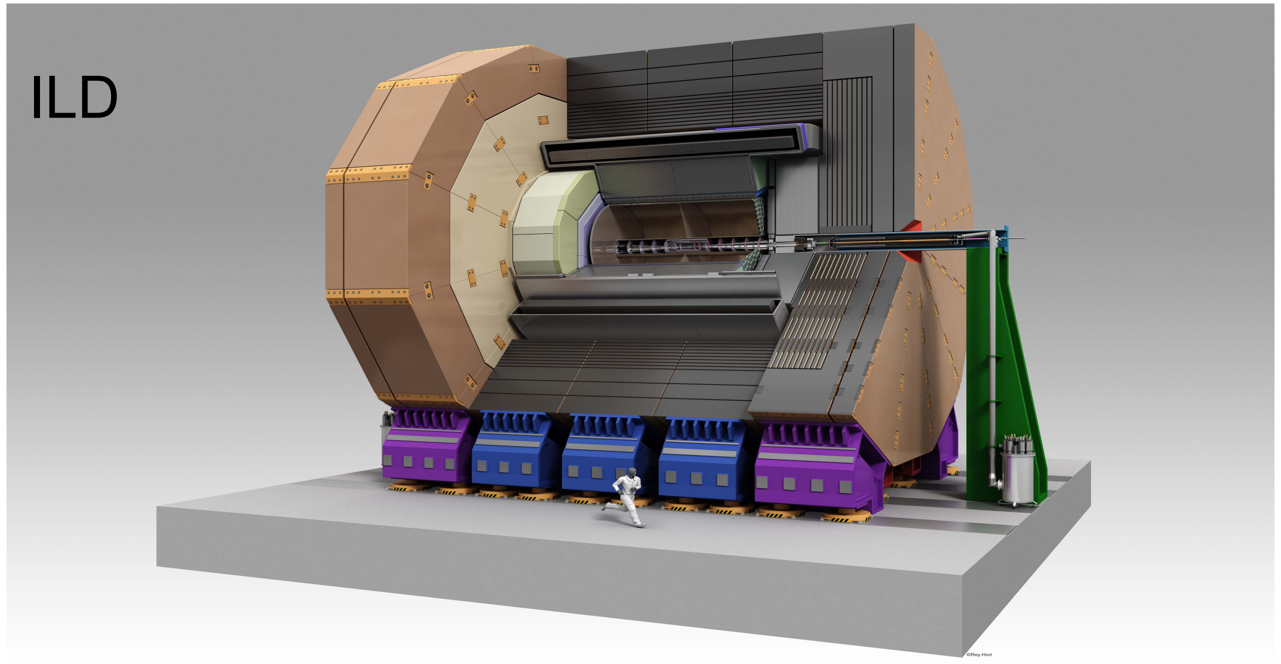


B= 4T

SiD



B= 5T



B= 3.5T

Highly granular calorimeters

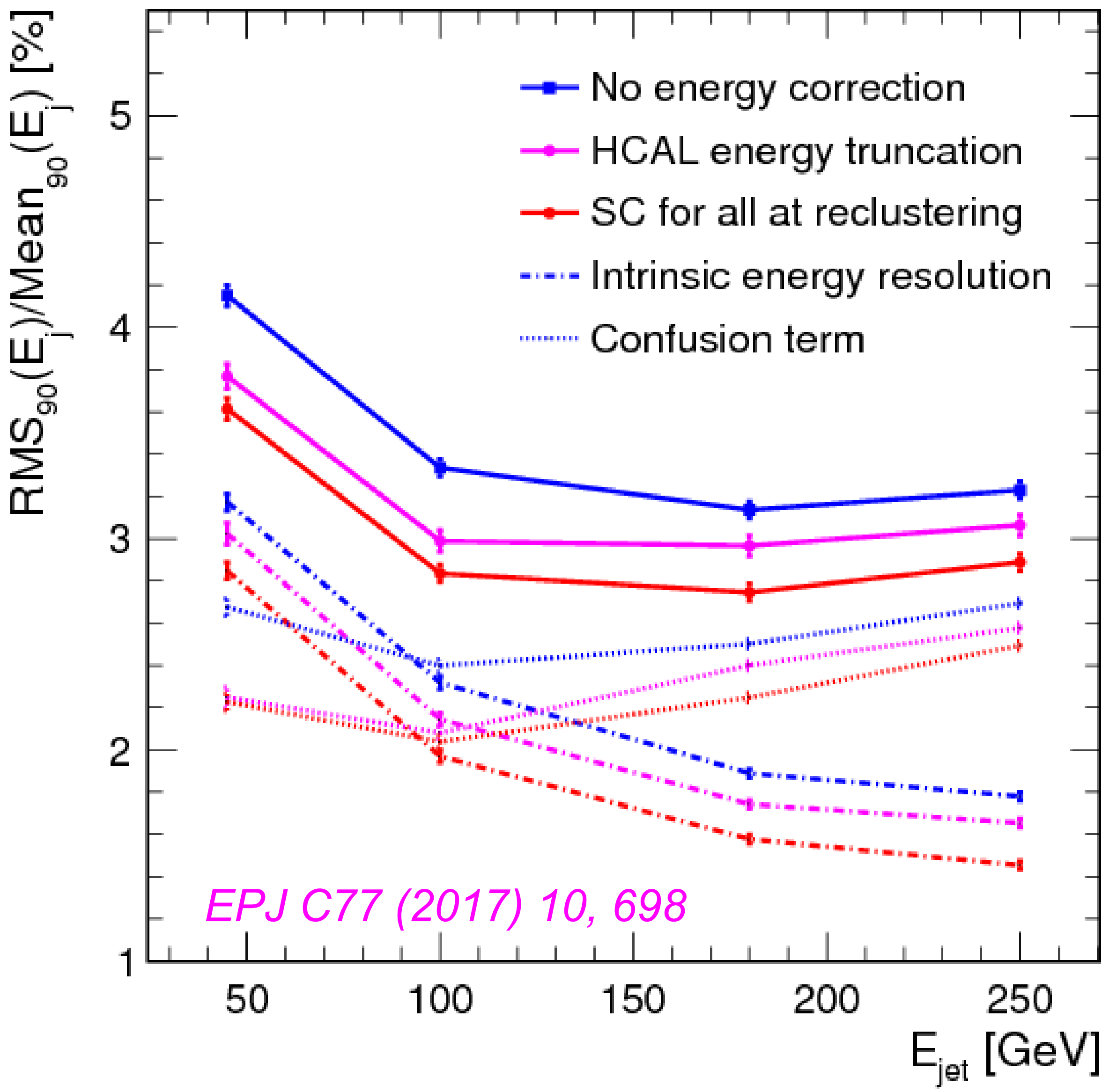
Central tracking
with silicon

Central tracking
with TPC

Inner tracking with silicon

Particle Flow Algorithms

Pandora PFA jet energy resolution



Study within ILD Concept

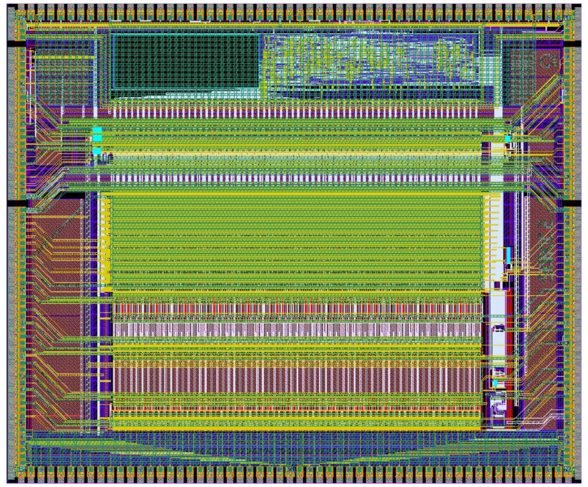
- Design goal: 30%/√E at 100 GeV
  - ~3-4% over entire jet energy range
- At lower energies < 100 GeV resolution is dominated by intrinsic calorimeter resolution
- At higher energies have more particles and higher boost
  - Smaller distance between particles
  - More overlap between calorimeter showers
  - Pattern recognition becomes more challenging

  =>Confusion
- Note particularly the gain by software compensation
  - i.e. exploiting the wealth of information available through high granularity

PFA ARBOR is algorithm of choice for CEPC Detector with similar performance

ASICs – The "ROC Family"

SKIROC
(for SiW Ecal)



SiGe 0.35µm AMS,

Size 7.5 mm x 8.7 mm, 64 channels

High integration level

(variable gain charge amp,

12-bit Wilkinson ADC, digital logic)

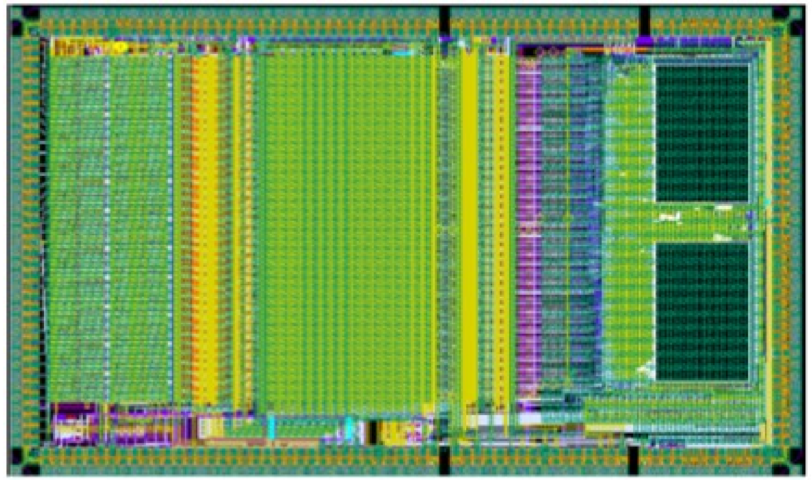
Large dynamic range (~2500 MIPS)

low noise (~1/10 of a MIP, 400 fC)

Auto-trigger at ½ MIP

Low Power: (25µW/ch) power pulsing

SPIROC
For optical readout, Tiles + SiPM



Variant of SKIROC

36 channels, 15 bit readout

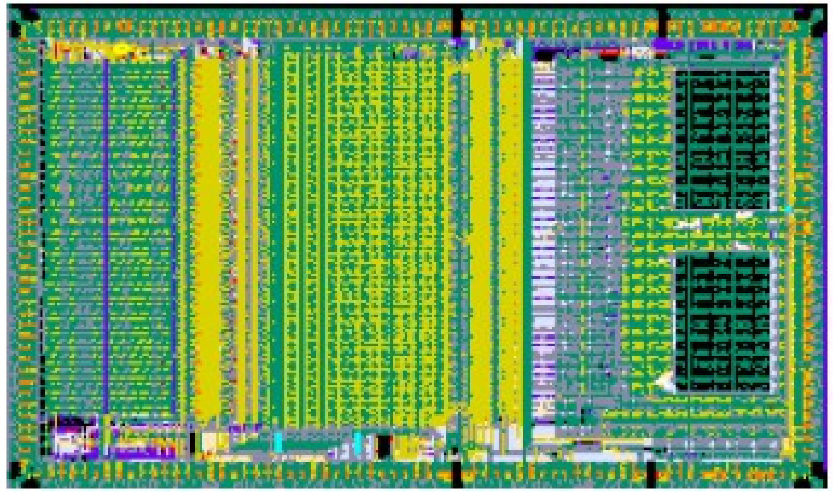
Auto-trigger down to ½ p.e,

80 fC for G=1x10^{6}

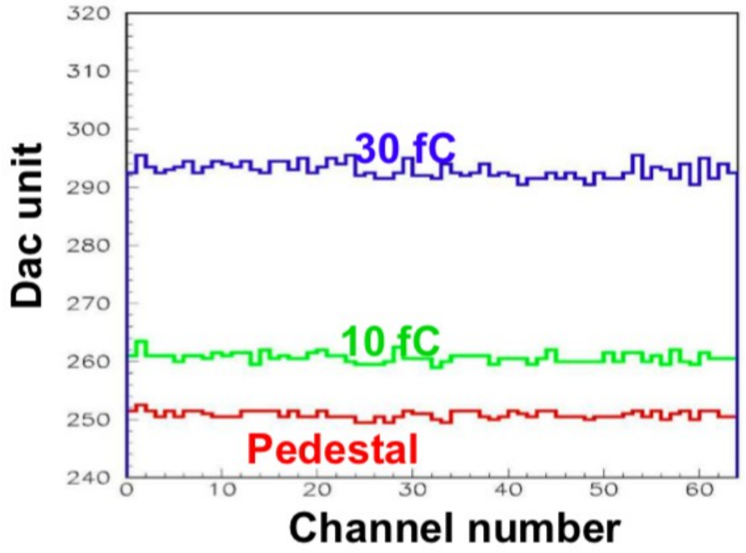
Timing to ~ 1ns

Low Power: (25µW/ch) power pulsing

HARDROC
For gaseous r/o - GRPC



64 Channels with three thresholds



Power pulsing

Variant for Micromegas: MICROROC

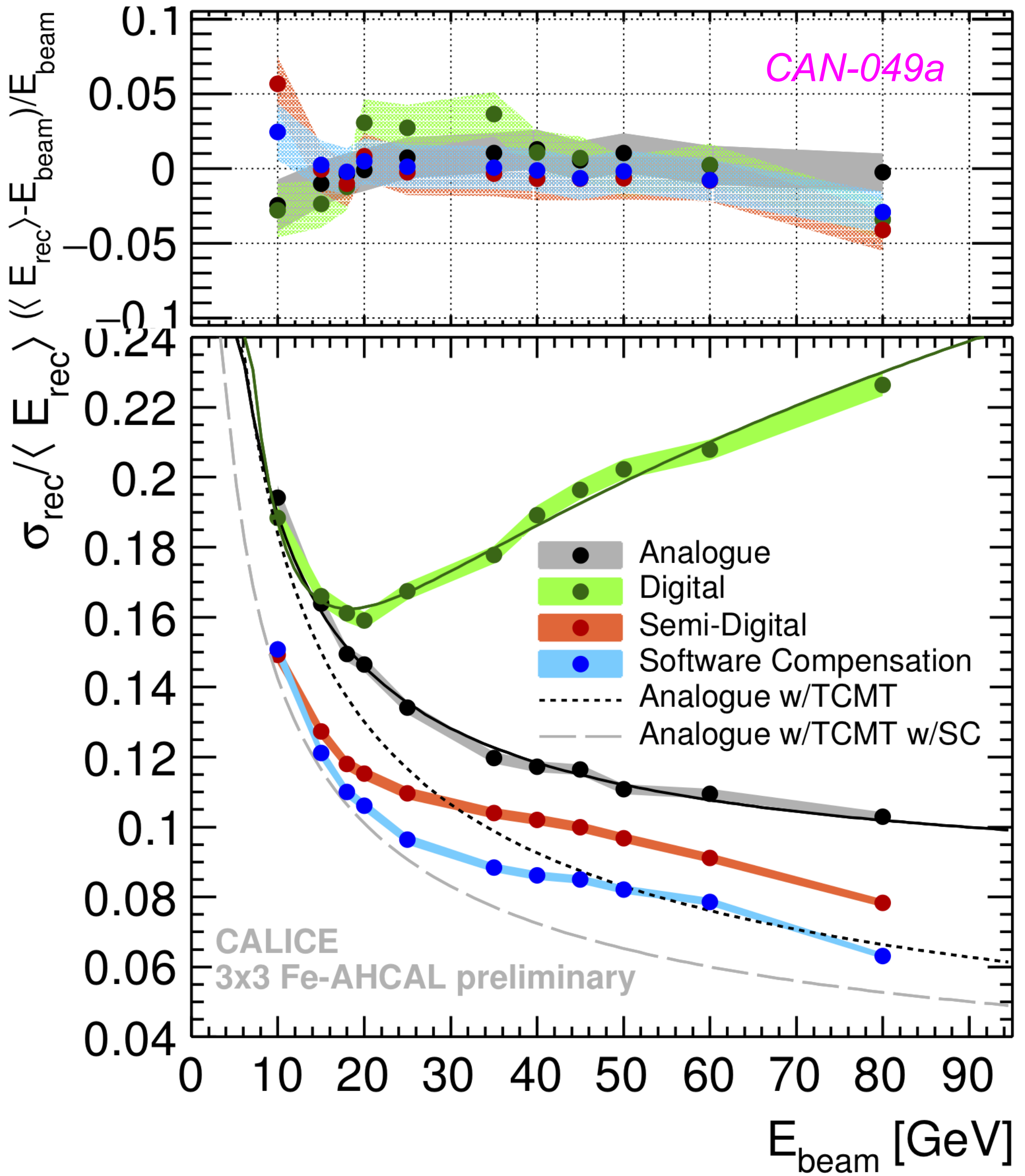
Different schemes of hadronic energy reconstruction II

Understanding the Performance of Highly Granular Calorimeters

- CALICE hadron calorimeters use different schemes for energy reconstruction - depending on readout technology:
  - *scintillator*: analog & software compensation
  - *gas*: digital (1 bit), semi-digital (2 bit)

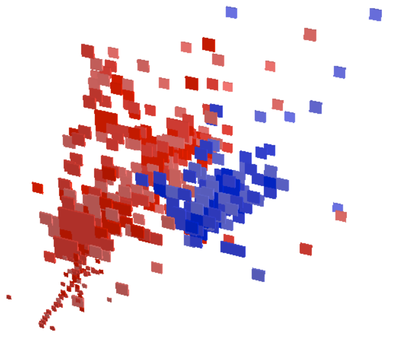
N.B.: Semi-digital reconstruction and software compensation are related: both use optimised hit or energy dependent weighting factors

Simulations used to study 1 x 1 cm2 granularity (scintillator)
Digital & fine granularity best at low energy:
Suppression of fluctuations SC & semi-digital comparable
NB: Sampling fraction matters: Semi-digital reconstruction in RPCs does not reach the same resolution



F. Simon, CALOR2018

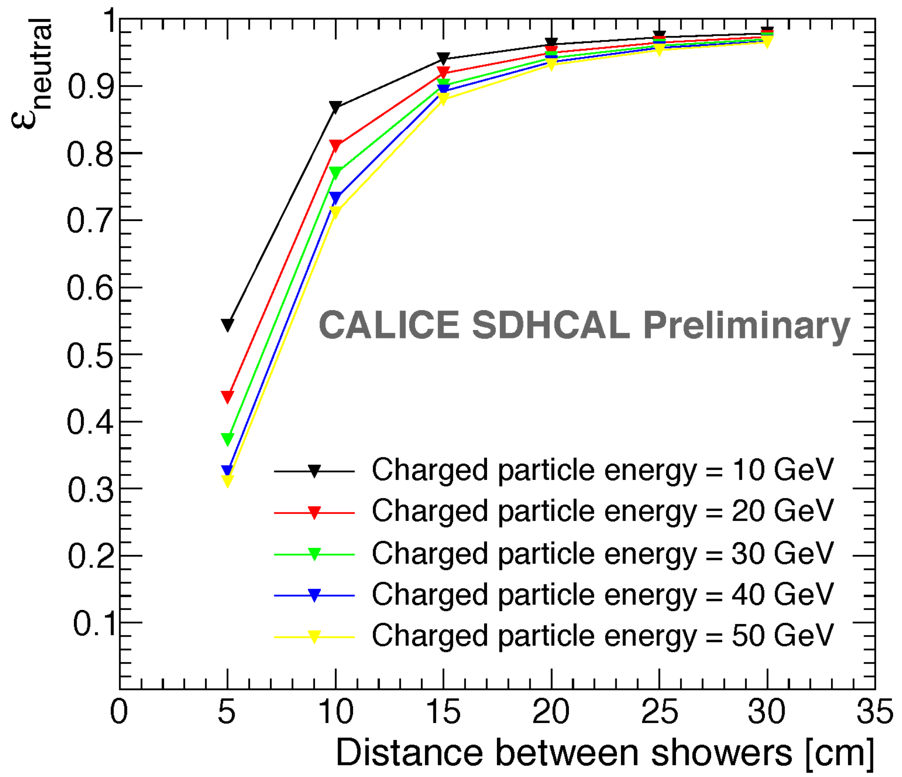
Particle Separation - SDHCAL

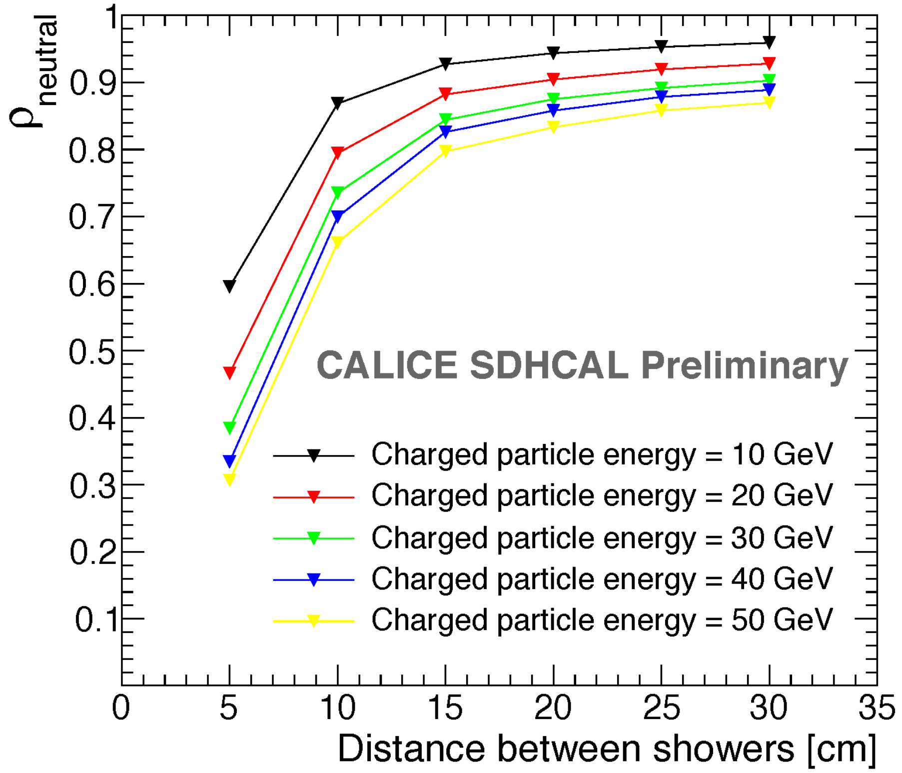


Particle Separation

- A key figure of merit for PFA performance
  - At the example of SDHCAL
  - see JINST 6, P07005 (2011) and CALICE-CAN-2017-001 for other CALICE prototypes

CALICE-CAN-2015-001



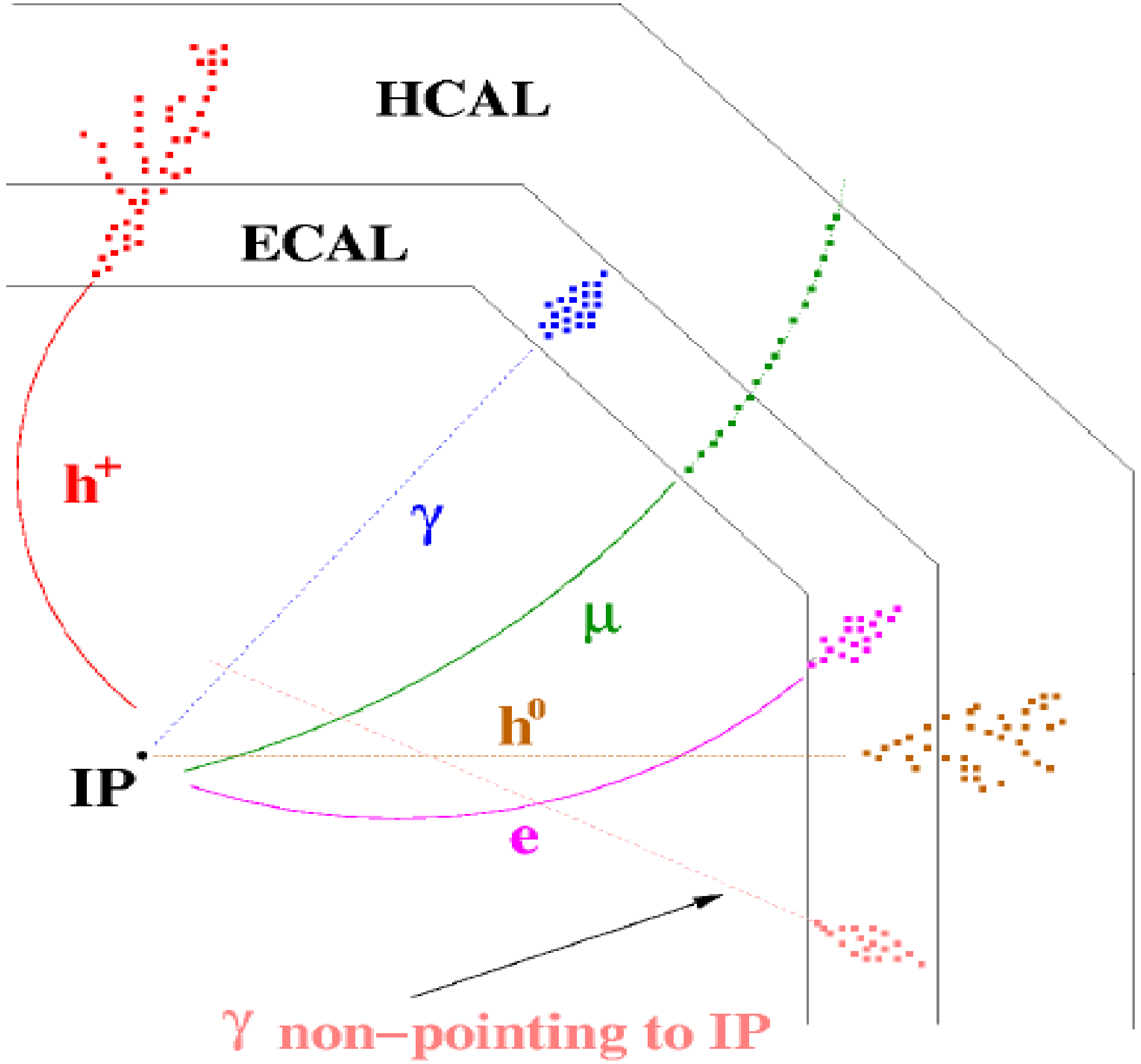


More than 90% efficiency and purity for distances ≥ 15 cm

Particle Flow Detector

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

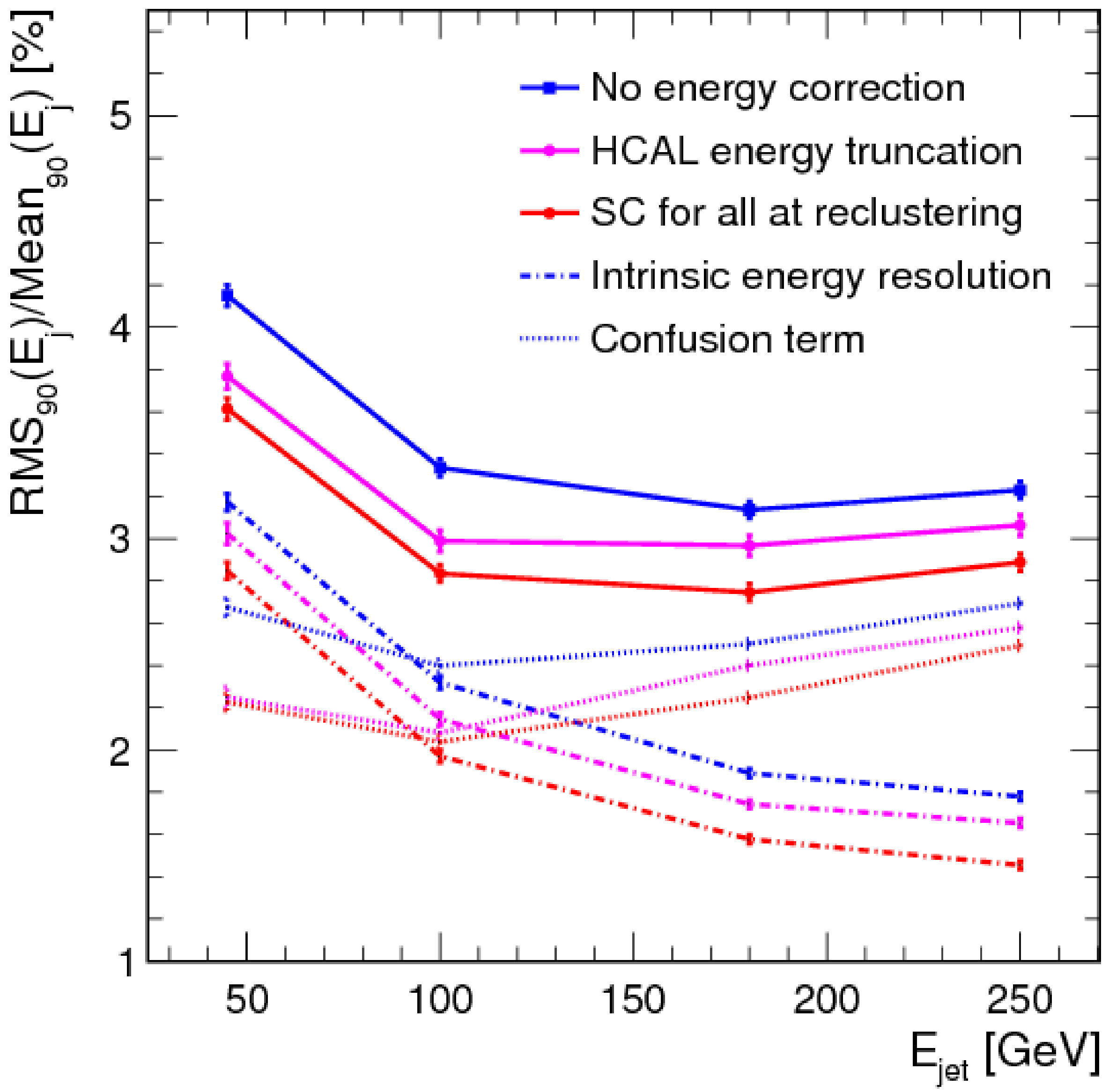
- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- “no” material in front of calorimeters
  - stay inside coil
- small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping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



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

Particle Flow Detector

Pandora PFA jet energy resolution



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