Highly Granular Hadronic Calorimeters at High-luminosity e^+e^- Colliders

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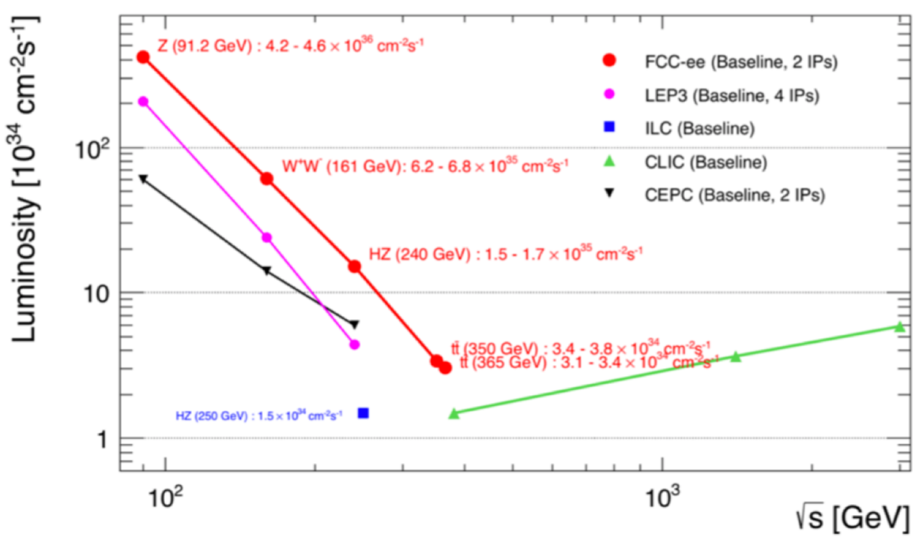
Outline

- Physics drivers
- PFA approach and high granularity
- Experimental environments
- Detector concepts of PFA hadronic calorimeters
- Technology options and development
- Challenges
- Latest optimization and R&D activities for CEPC
- Summary

Future e$^+$e$^-$ Colliders

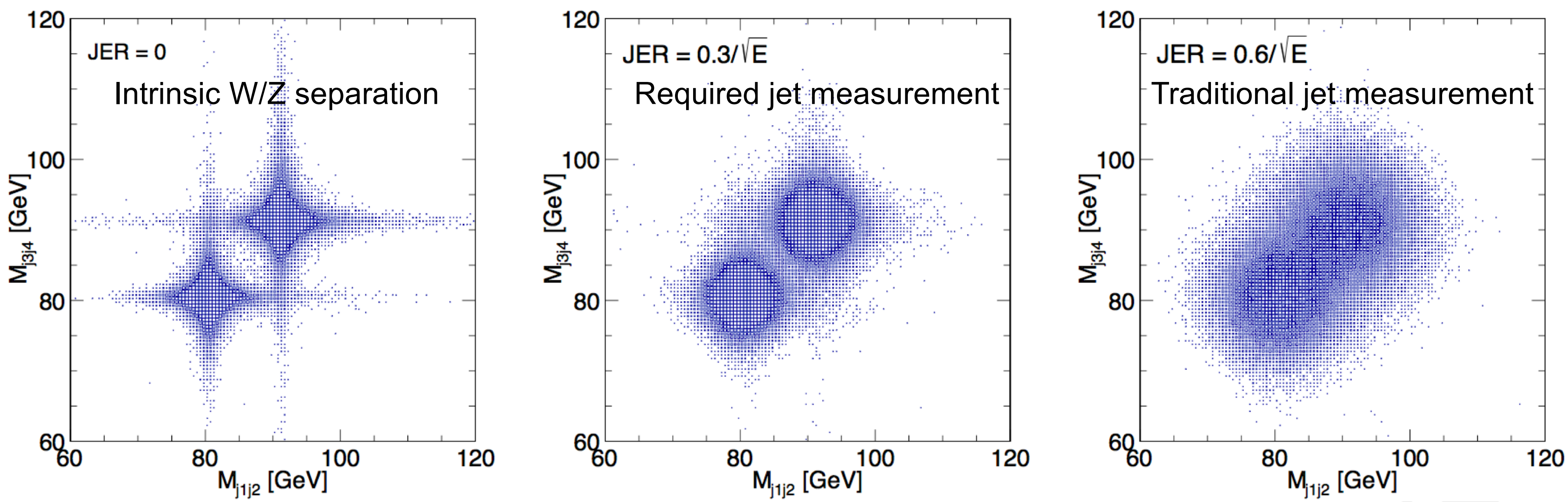
- Essentially, factories of bosons: W, Z, H
- Physics program heavily relies on precise measurements of/with the bosons
  - Eletroweak physics with W/Z, Higgs properties, new physics …
- Dominant decays of the bosons are hadronic: hadronic jets
- Precise measurement of hadronic jets is a primary driver in the experiment designs for next generation e+e- colliders.



from "FCC-ee machine design overview" by Manuela Boscolo at FCC Week 2018

Jet Measurement Precision

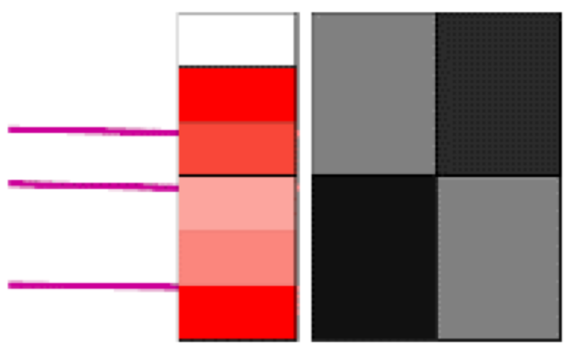
- Figure of merit: separating W and Z bosons in their hadronic decays .
- This translates into a jet energy resolution requirement of ~ 3-4% over a wide jet energy range (~ 30% /√E).
  - A factor of two improvement w.r.t. traditional jet measurement



WW→4j and ZZ→4j

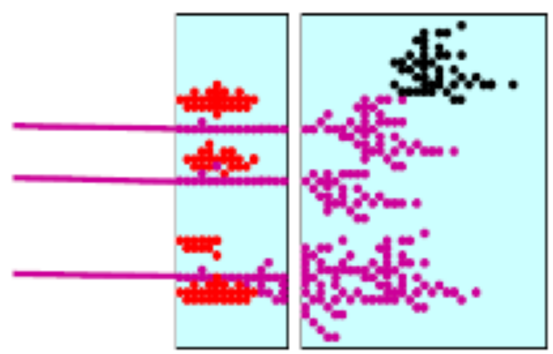
Particle Flow Algorithm

- Particle Flow Algorithm (PFA) is a very promising approach to achieving the unprecedented jet energy resolution of 3%-4%.
  - All particles are individually reconstructed.
  - Energy/momentum of each particle in a jet is determined by making use of the optimal sub-detector for the particle.
    - Charged particles by trackers (~65%)
    - Photons by ECAL (~25%)
    - Neutral hadrons by HCAL (~10%)
  - Impact of poor HCAL measurement is largely limited.



$E_{JET} = E_{ECAL} + E_{HCAL}$

Traditional jet measurement with calorimeters

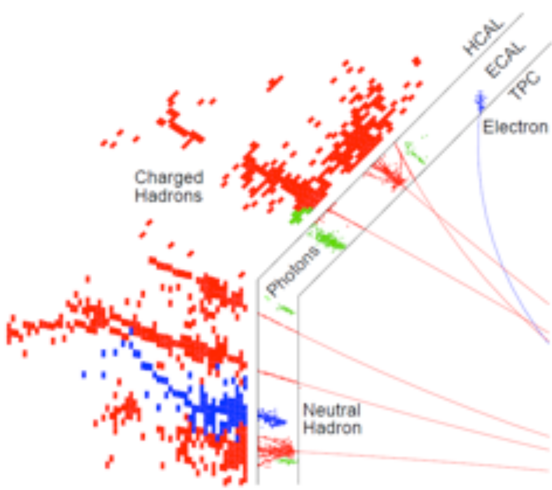


$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Jet measurement with PFA

Key to PFA: High Granularity

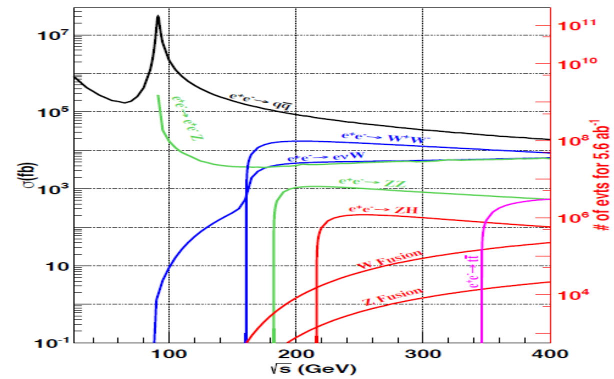
- Central requirement: separate showers in calorimeters produced by charged and neutral particles in a jet
  - To avoid double or under-counting of shower energy
- A highly segmented and full-contained calorimeter system is the core element in realizing PFA.
  - Combined with a transparent tracking system.
- High-granular calorimeters also provide essential information for particle identification: electrons, hadrons, muons



- High 3-d granularity of both ECAL and HCAL is the key to PFA
  - → Granularity should be significantly smaller than typical shower size.
- A highly-granular HCAL plays a central role in realizing PFA
  - → Hadron showers account for 75% of a jet

Experimental Environments

- Beam structure affecting readout and cooling
  - Very low duty cycle (linear colliders) vs. Continuous operation (circular colliders)
- Event rate
  - 32 kHz at Z pole at CEPC (CDR)
  - 20 kHz (?) at Z pole at FCC-ee*
  - ➢ A maximum of 100 kHz by safety margin.



- background and occupancy

FCC-ee*

Source	CLIC 3 TeV*		FCC 350 GeV	
	N / BX			
	total	P_T > 20MeV	total	P_T > 5MeV
IPC	$3x10^5$	60	2600	33
CPC	$6x10^8$	0	0	0
hadrons	102	54	0.05	~0.05
Syn. rad			~$5x10^6$ †	

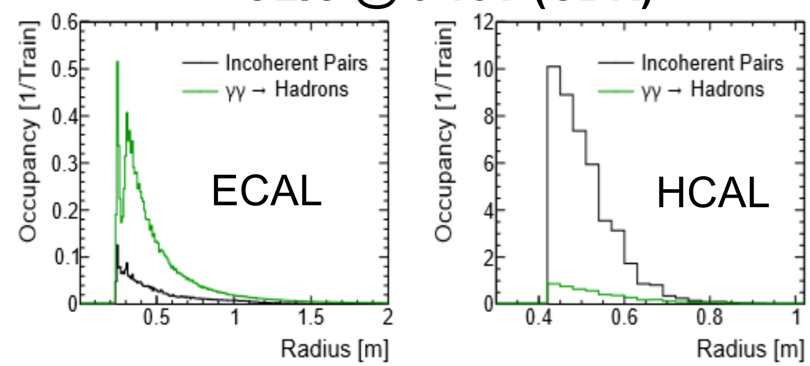
First investigations show inner detector occupancies due to beam background at the ~10^{-4} level

CEPC (CDR)

	Total # channels [M(10^6)]	Occupancy [%]
ECAL		
Barrel	17/7.7	0.17
Endcap	7.3/3.3	0.31
AHCAL		
Barrel	3.6	0.02
Endcap	3.1	0.12
DHCAL		
Barrel	32	0.004
Endcap	32	0.01

Occupancies of calorimers due to Z→qq and beam background ~ $10^{-3\sim-5}$

CLIC @ 3 TeV (CDR)



Occupancies of calorimers due to beam background reach 50% (ECAL) and even exceed 100% (HCAL) per bunch train.

Limited event rate and low detector occupancy when operating in a sub-TeV domain

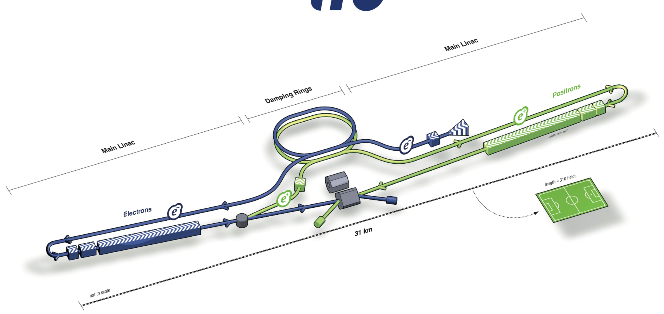
* “FCC-ee physics & experiments CDR plan and status” by Roberto Tenchini at FCC Week 2017

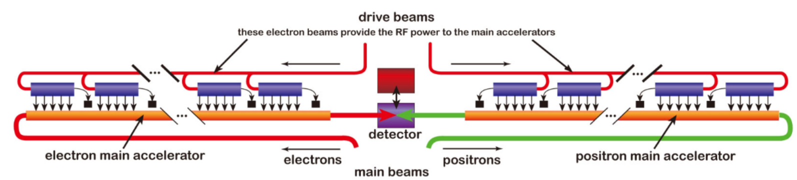
Detector Concepts of PFA HCAL

- Various PFA HCAL detector concepts have been proposed for experiments at future e+e- colliders.

Linear

- ILC
  - ILD
  - SiD
- CLIC
- FCC-ee
- CEPC





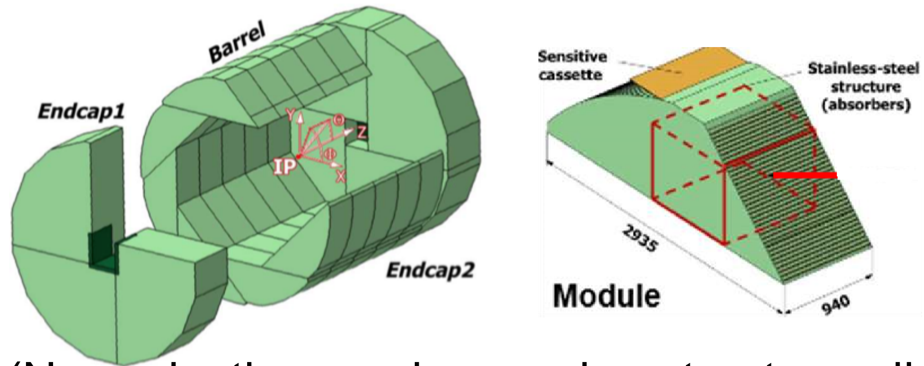
Circular

Ultimately, all the PFA HCAL detector concepts originated from those for ILC

ILC

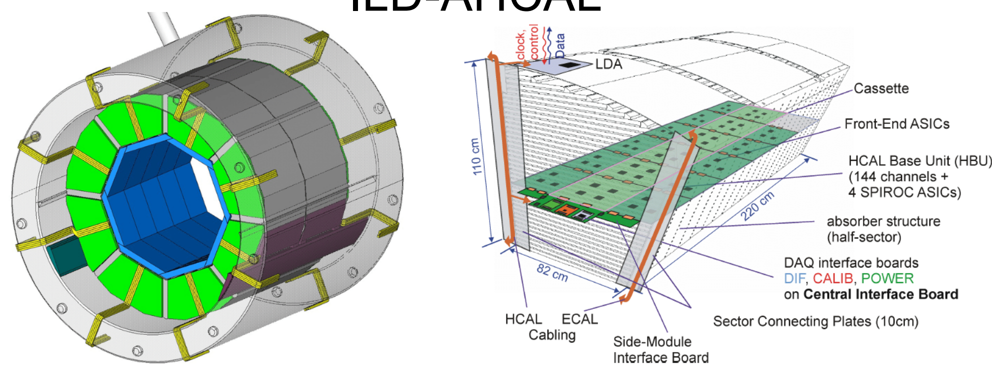
- ILD-HCAL (Fe, $6\lambda_I$)
  - 48 layers
    - 2cm steel + ~6mm active layer
  - AHCAL
    - Sci+SiPM, cell-size: 3cm×3cm
  - SDHCAL
    - glassRPC, cell-size: 1cm×1cm
- SiD-HCAL (Fe, $5\lambda_I$)
  - 40 layers
    - 2cm steel + ~6-8mm active layer
  - AHCAL(Sci+SiPM): baseline
  - DHCAL (glassRPC): alternative

ILD-SDHCAL

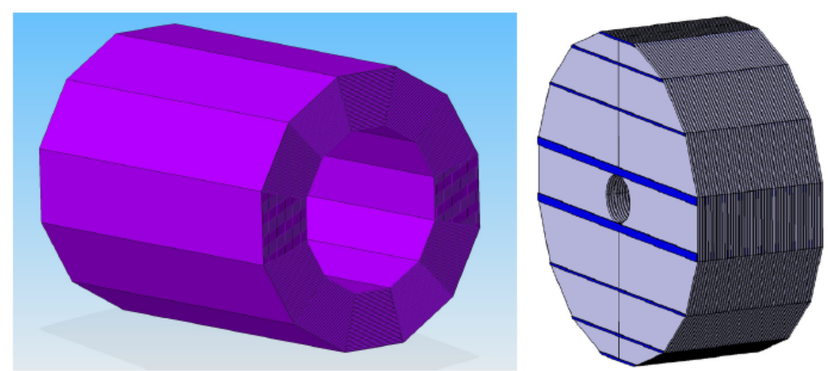


(No projective cracks, service at outer radius)

ILD-AHCAL



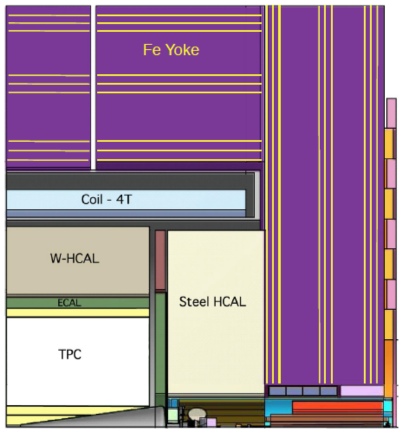
SiD-HCAL



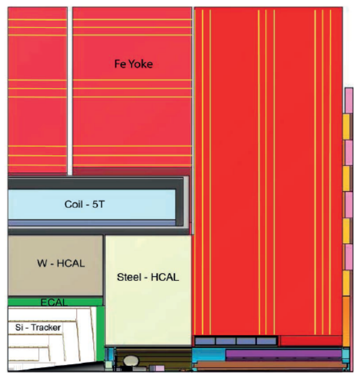
CLIC

Orignal in CDR

CLIC-ILD (adapted from ILD)



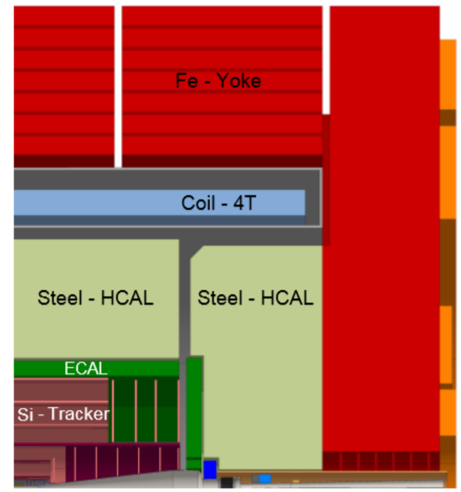
CLIC-SiD (adapted from SiD)



- Two readout concepts
  - DHCAL (glassRPC, 1cm×1cm)
  - AHCAL (Sci+SiPM, 3cm×3cm)
- Absorber: 7.5 λ_I
  - Barrel: W, 75 layers × 1cm
  - Endcaps: Fe, 60 layers × 2cm
  - to contain events at 3 TeV

Optimised now

CLICdet

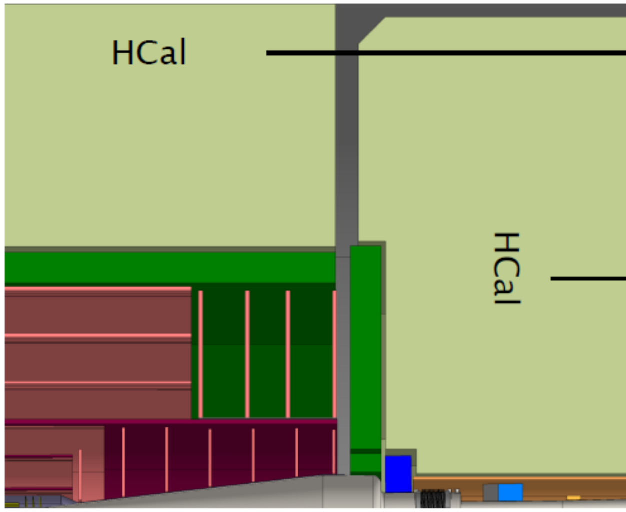


AHCAL

- Active layer : 6.5mm
  - Sci+SiPM, 3cm×3cm
- Absorber: 7.5 λ_I
  - Fe, 60 layers × 2cm

FCC-ee

CLD – a detector derived from CLICdet for FCC-ee



- HCal BARREL INNER RADIUS changed to 2.4m
  - due to larger tracker

- HCal ENDCAP
  - size adjusted
    - outer radius = 3.57 m
    - outer z = 3.71 m (CLIC: 4.13 m)

- STRUCTURE unchanged:
  - steel + scintillator sampling calorimeter

- Segmentation adjusted:
  - Number of layers: 44
  - Number of interaction lengths: 5.5 λ_0
    - CLIC: 7.5 λ_0
    - ILD: 5.5 λ_0 (optimized for 500GeV => similar energy scale as FCC)

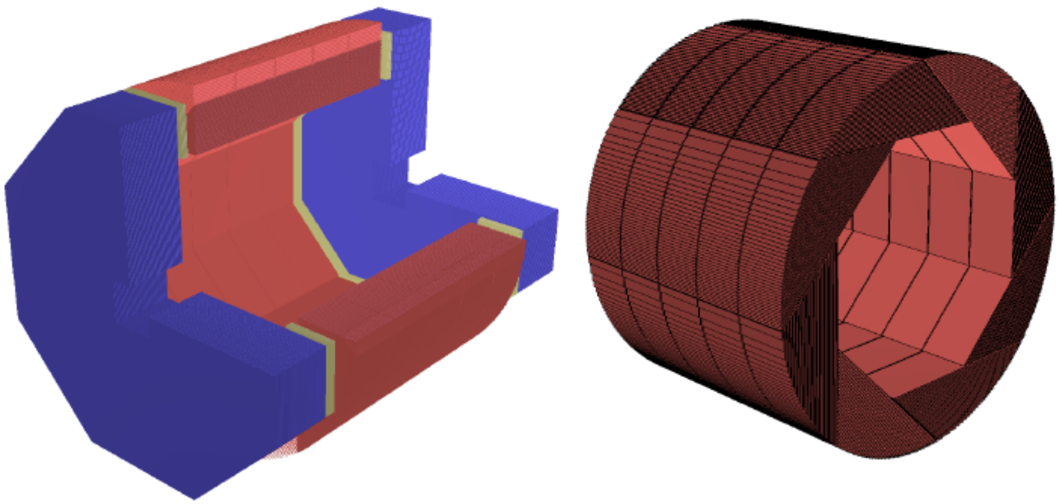
AHCAL

- Active layer : 6.5mm
  - Sci+SiPM, 3cm$\times$3cm
- Absorber: 5.5 λ_I
  - Fe, 44 layers $\times$ 2cm

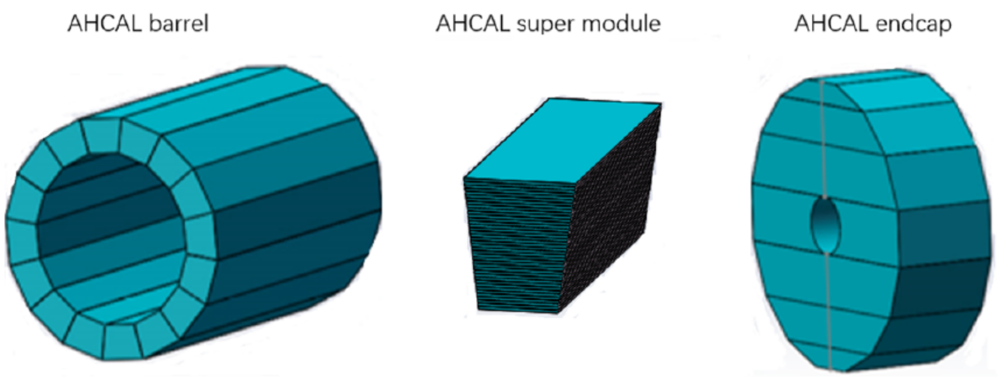
from "A CLIC-inspired detector for FCC-ee" by Emilia Leogrande

CEPC

SDHCAL



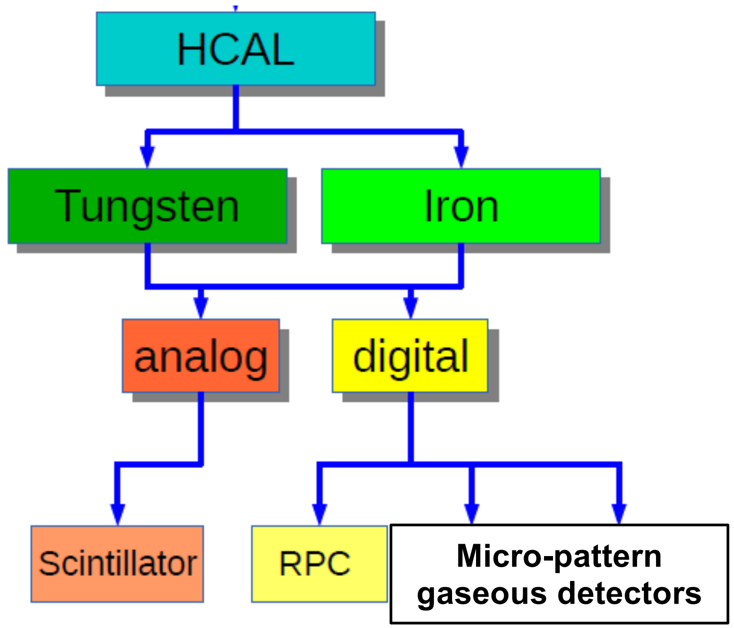
AHCAL



Both adapted from ILD

- Absorber
  - Fe, 40 layers × 2cm, $5\lambda_I$
- Active layer
  - SDHCAL
    - glassRPC, 6mm thick
    - cell-size: 1cm×1cm
  - AHCAL
    - Sci+SiPM, ~5mm thick
    - cell-size: 3cm×3cm

PFA HCAL Technology Options



- Absorber material
  - Tungsten
  - Iron

W vs. Fe

Material	λ_I [cm]	X_0 [cm]	λ_I/X_0
Fe	16.77	1.76	9.5
W	9.95	0.35	28.4

- Active medium
  - Dense: scintillator
    - Analog readout

    good linearity, large cell size allowed $\rightarrow$ less channels.
  - Thin: gaseous detectors
    - Digital readout

    simple readout, subjected to saturation $\rightarrow$ multi-threshold readout (semi-digital), finely segmented readout required $\rightarrow$ more channels.

W: dense$\rightarrow$ a compact detector, expensive, large λ_I/X_0 ratio$\rightarrow$EM under-sampled, poor mechanical properties.

Fe: cost-effective, rigid & self-supporting, moderate λ_I/X_0 ratio, large volume.

PFA HCAL Development

- R&D conducted in the framework of CALICE
- Proceeded in two steps
  - Physics prototypes
  - Technological prototypes

➔ Physics prototypes

- provide a proof-of-principle of the viability of a given technology in terms of construction, operation and performance.

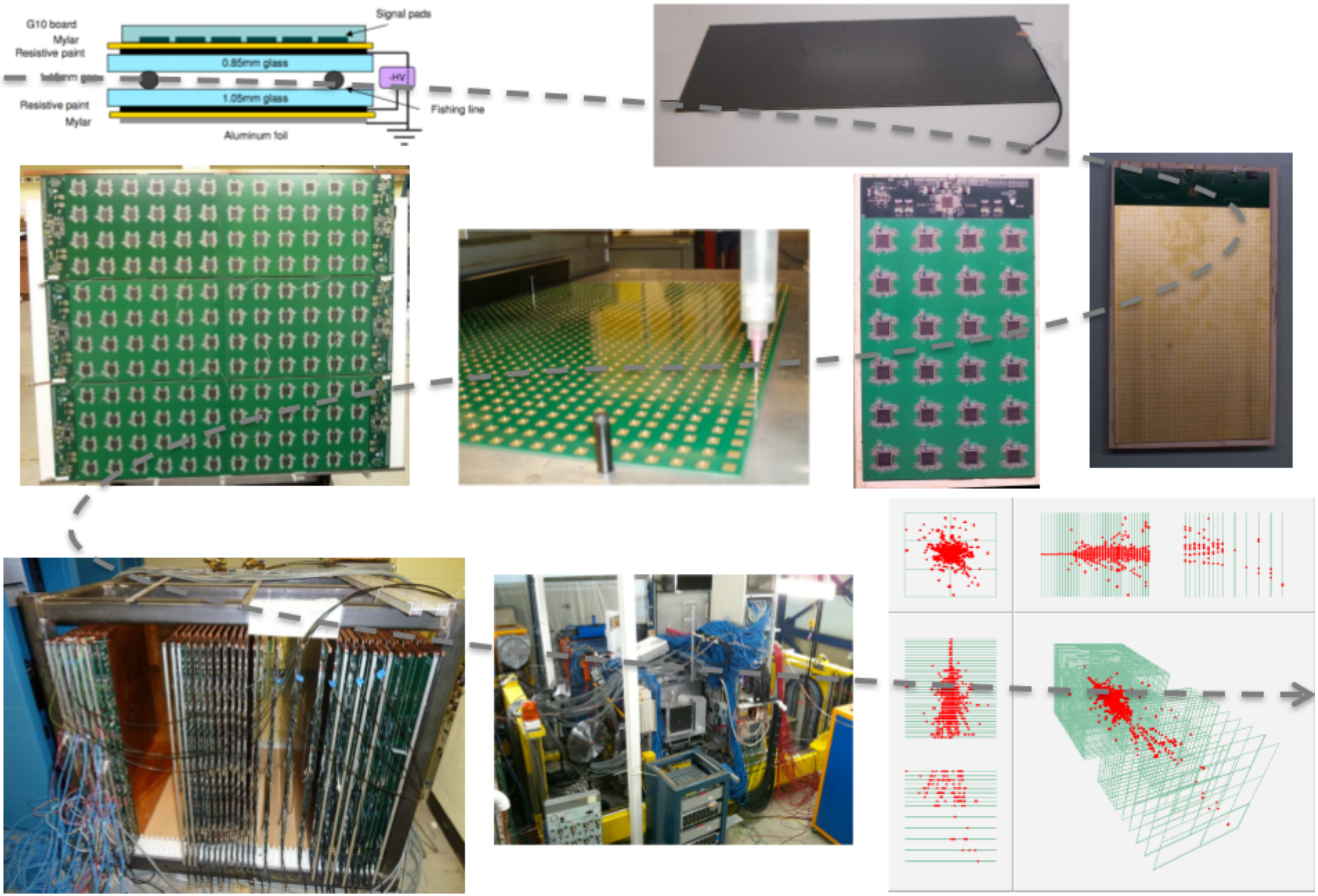
➔ Technological prototypes

- address issues of scaling, integration and cost optimization.

RPC-DHCAL

- A full-size prototype with embedded readout electronics was constructed
  - 3 glass-RPC chambers (32×96 cm^2 each) spliced to form a RPC layer: ~ 1×1 m^2
  - The RPC layer combined with readout boards to form a 8-9mm thick active layer
  - An active layer was sandwiched by a 2mm copper front-plate (to cool electronics) and a 2mm steel back-plate (to support each active layer).
  - 54 layers in total. The layers were inserted into a steel or tungsten absorber stack to form a DHCAL prototype.
  - 1×1cm^2 RPC readout pads, 0.54 M channels, 1-bit digital readout
- Both Steel-DHCAL and tungsten-DHCAL were tested with particle beams.

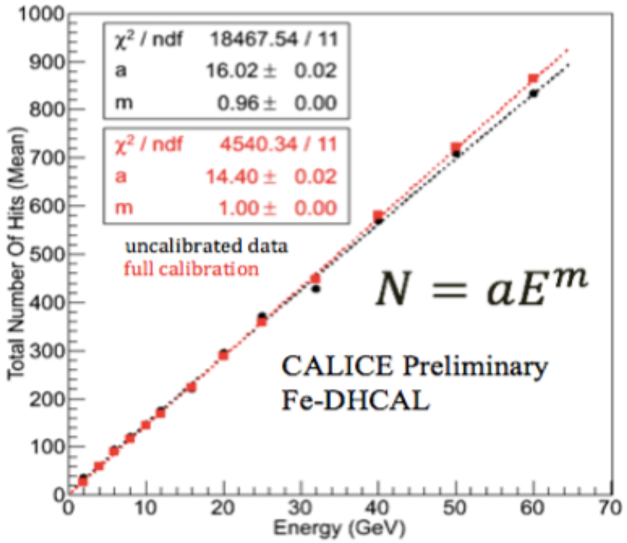
Prototype Construction

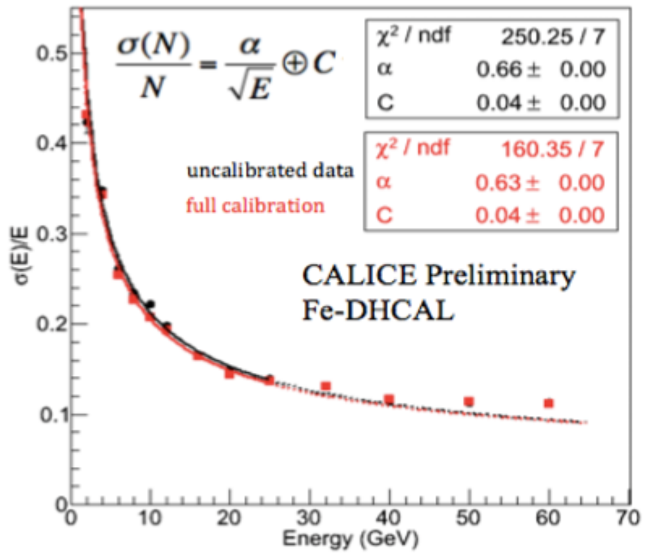


From “Digital Hadron Calorimetry” by Burak Bilki at CHEF2017

Results from beam tests

Fe-DHCAL, single π

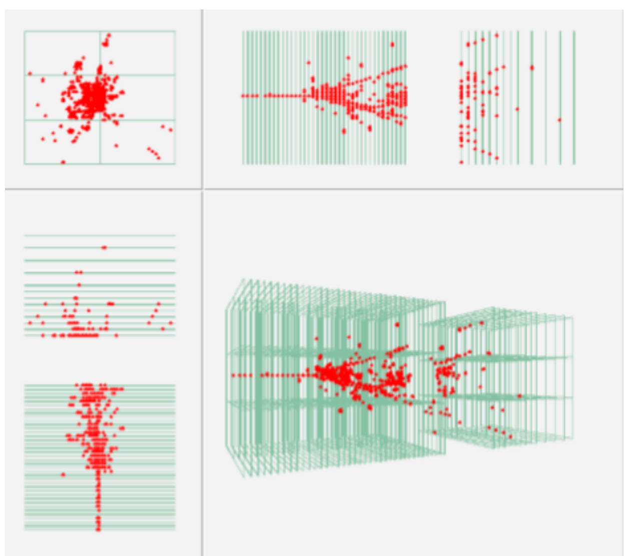




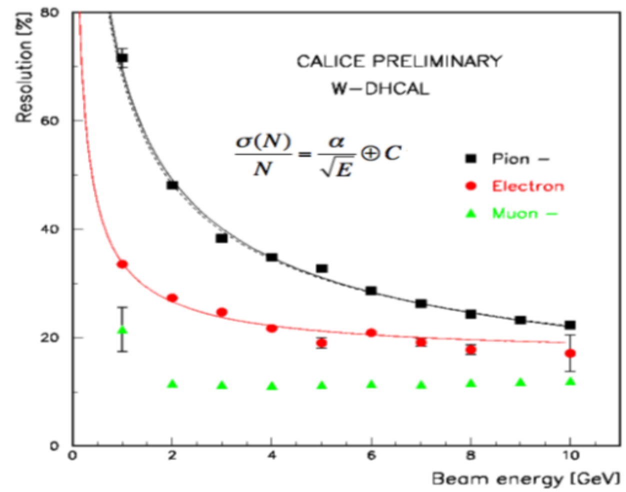
MIP: efficiency (ε) ~ 96%, pad multiplicity (μ) ~ 1.6

Calibration

$$H_{calibrated} = \sum_{i=RPC_0}^{RPC_n} \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$$



W-DHCAL



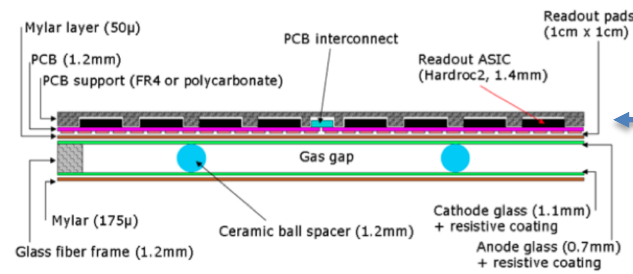
Particle	α	c
Pions	(68.0±0.4)%	(5.4±0.7)%
Electrons	(29.4±0.3)%	(16.6±0.3)%

- First large-scale PFA calorimeter prototype with embedded front-end electronics !
- The concept of DHCAL is validated.

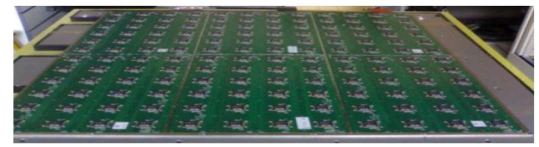
RPC-SDHCAL

- 48 layers with cross-section of $1m^2$, a total active volume of $1.3m^3$.
- Very compact active layers of RPC with embedded FEE: 6mm/layer $1{\times}1cm^2$ readout pad.
- Each active layer is sandwiched by two 2.5mm steel plates for mechanical supporting.
- 3-threshold readout (2 bit): semi-digital, ~0.5M channels.
- Active layers inserted into a steel absorber structure

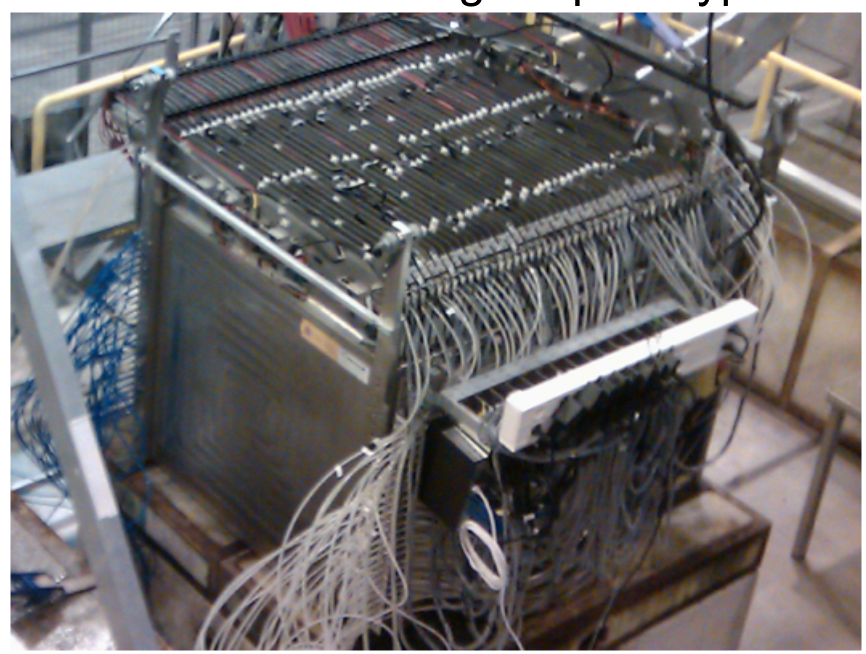
Very compact glass RPC unit



Embedded readout electronics



SDHCAL technological prototype



Reconstruction with digital readout

- Linear (currently used in ILD reconstruction)

$$E_{lin} = \sum_i \alpha_i N_i \qquad i \in \{1,2,3\}$$

- Quadratic :

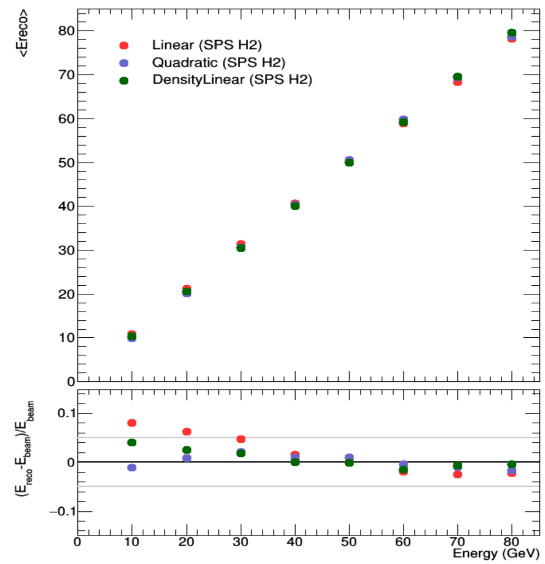
$$E_{quad} = \sum_i \alpha_i N_t \qquad i \in \{1,2,3\}$$

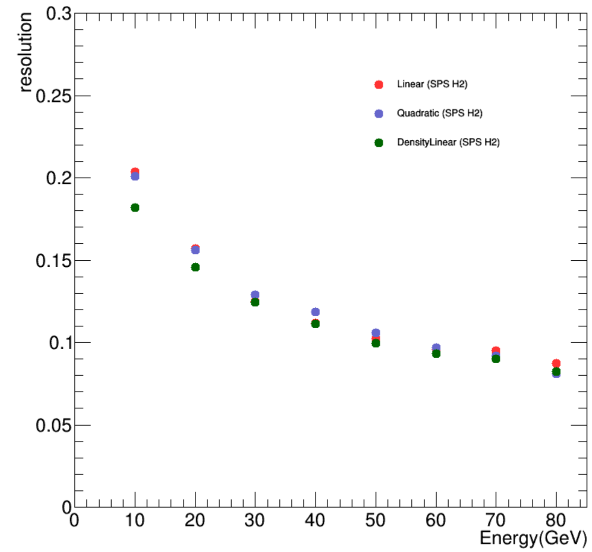
$$\alpha_i = \alpha_{i0} + \alpha_{i1} N_T + \alpha_{i2} N_T^2$$

- Linear formula using density :

$$E_{dens} = \sum_i \sum_d \alpha_{id} N_{id}$$

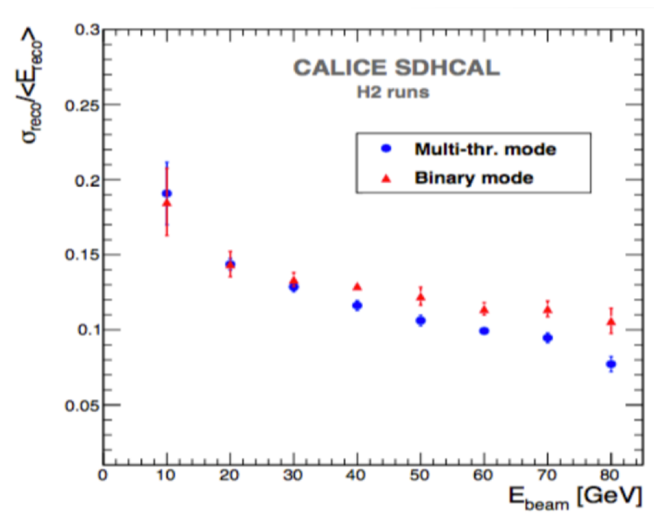
$$i \in \{1,2,3\} \quad d \in \{1 \ldots 9\}$$





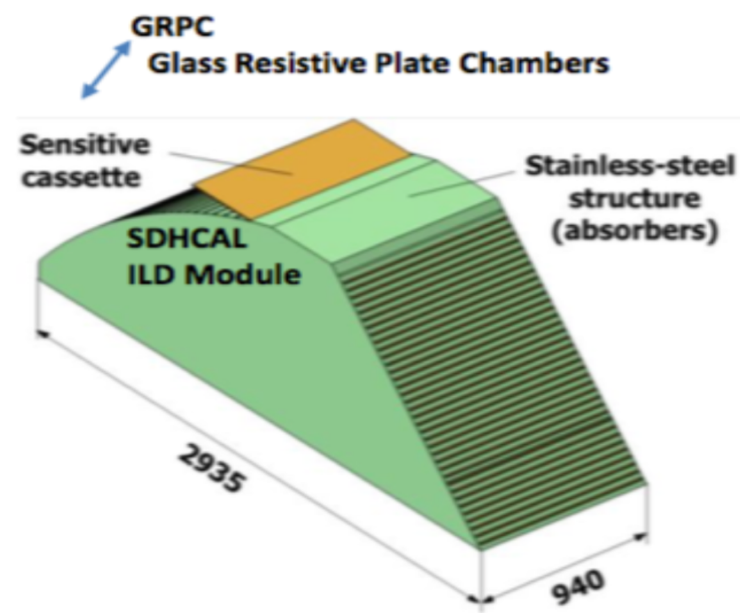
Energy reconstruction approach was optimised to make full use of the multi-threshold information.

Semi-digital readout partially recovers the information lost due to binary readout. It improves measurement of showers with relatively high energy.



New SDHCAL Prototype

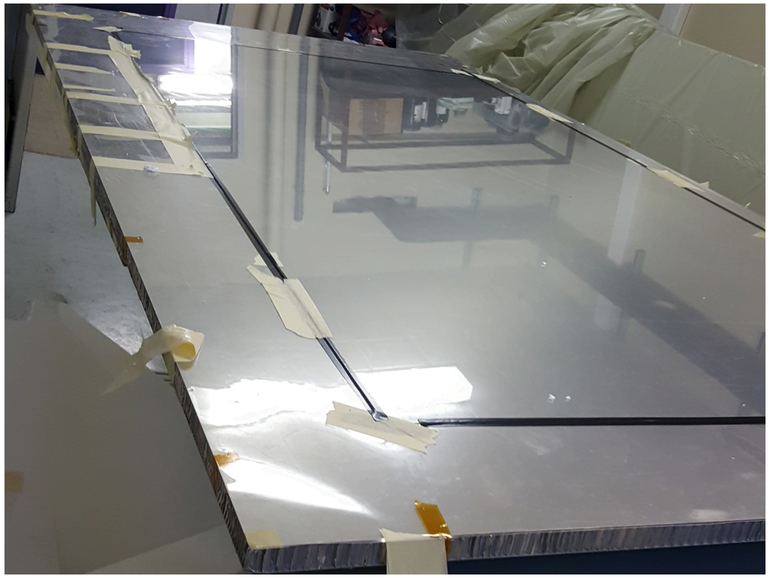
- The previous SDHCAL prototype has validated and characterized the RPC-based SDHCAL technology.
- A new prototype is being built to address real-world challenges/constrains
  - Very large size: 1×3 m
  - Robust and efficient electronics and DAQ
  - little dead area at edges
  - Optional: timing information



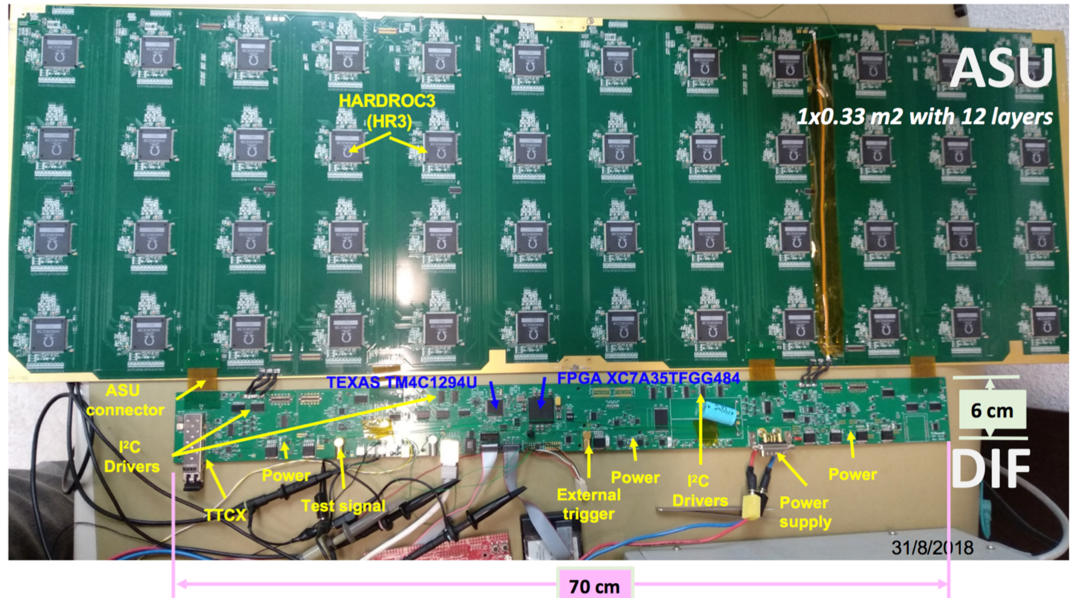
- 1×3m large RPCs equipped with improved electronics are inserted into a mechanical structure of four 1x3m^2 steel plates.

New Features

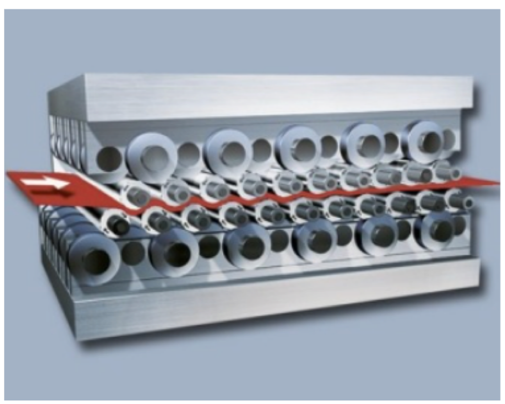
Large size gRPC with optimized design



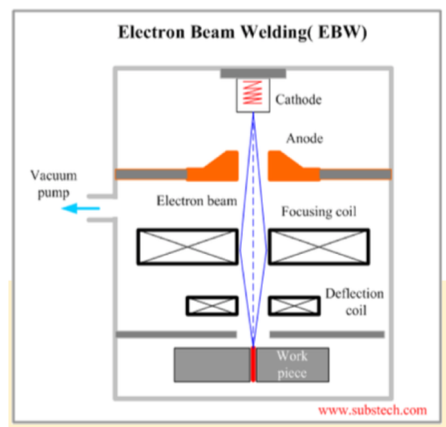
New PCB, new chip, only one DIF …

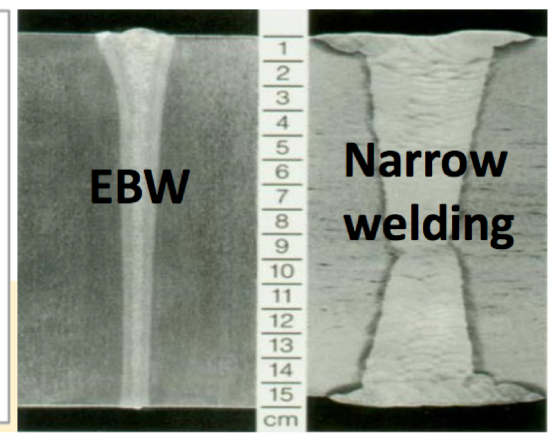


Roller levelling to make steel plates flat



Electron Beam Welding to reduce dead area



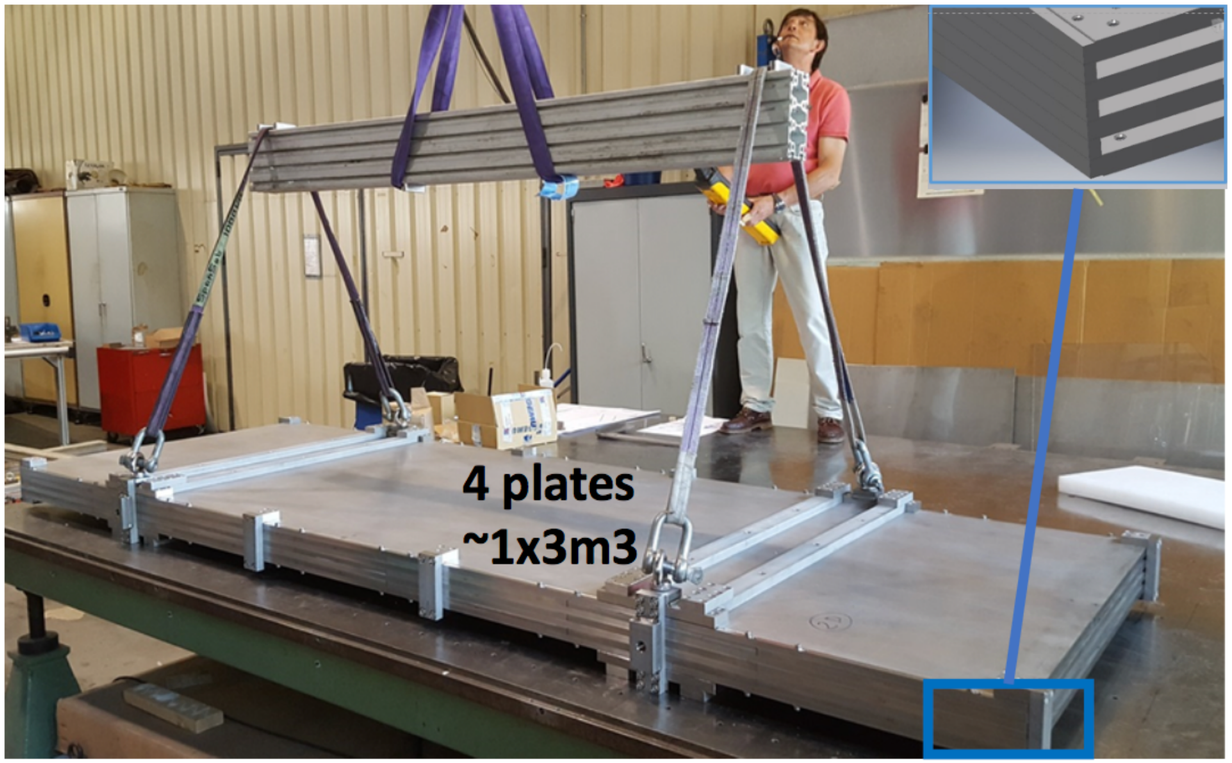


“Status of the Electronics and Mechanics for the new large SDHCAL prototype” by Mary-Cruz Fouz at CALICE collaboration meeting 2018 in Shanghai

Main Structure

Active layer inserting test

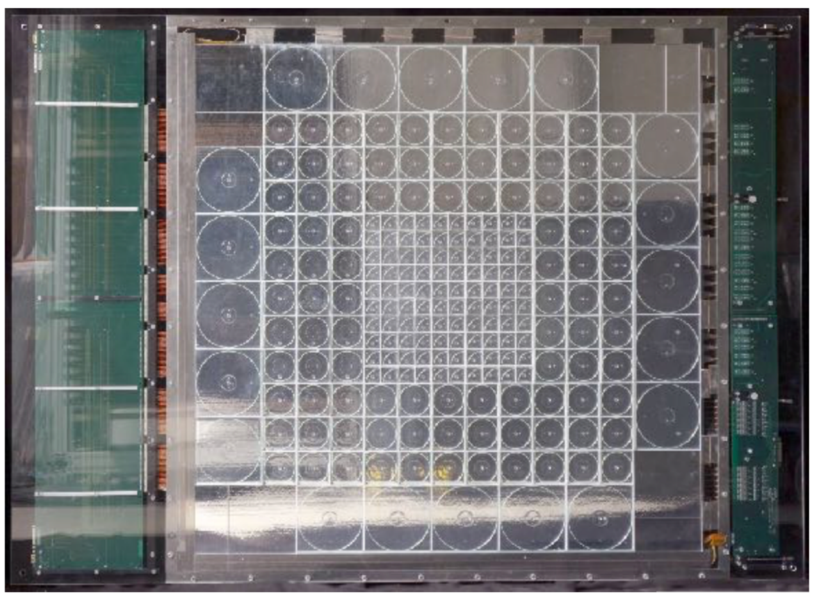
Steel mechanical structure
serving as absorber

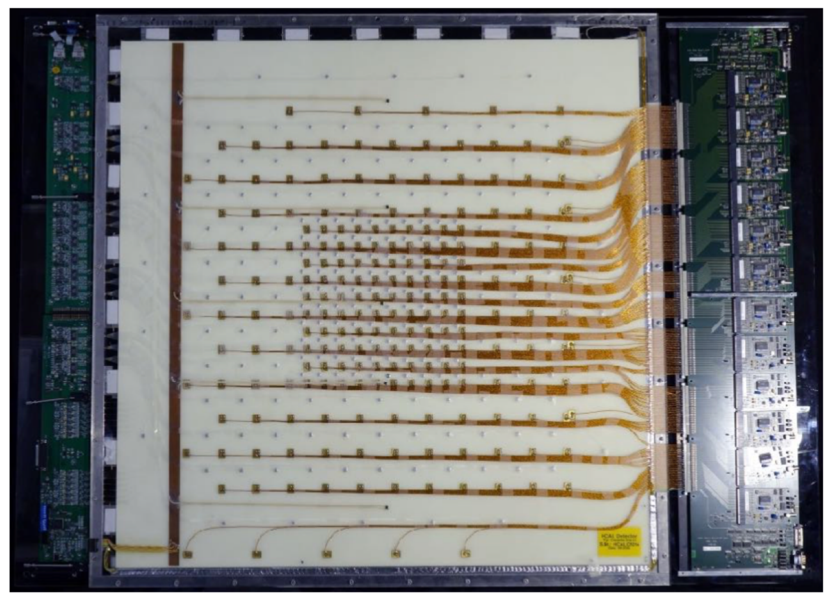


"Status of the Electronics and Mechanics for the new large SDHCAL prototype"
by Mary-Cruz Fouz at CALICE collaboration meeting 2018 in Shanghai

Sci-AHCAL

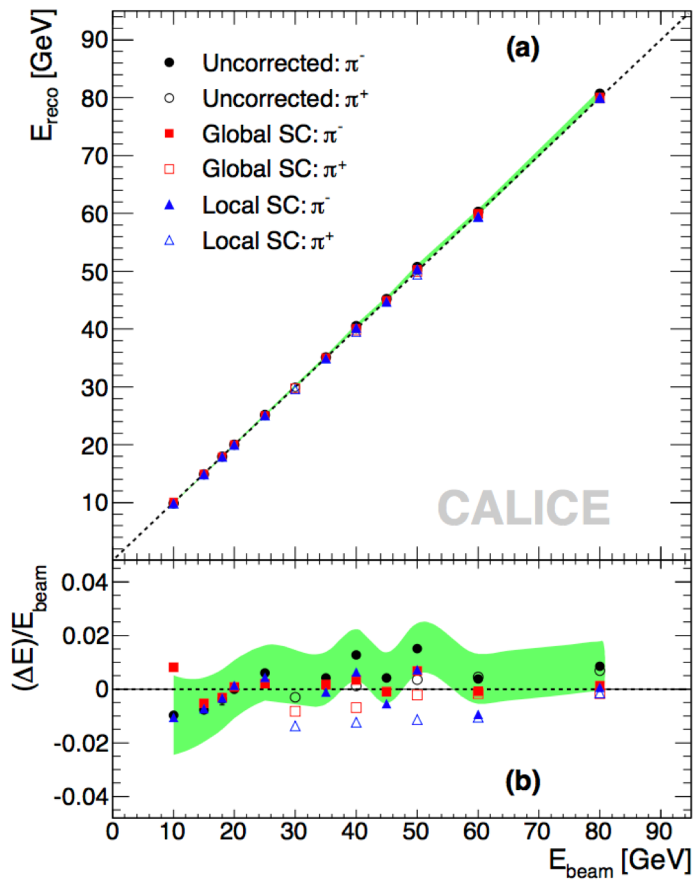
- Rapid development of SiPM technology made a scintillator-based PFA calorimeter possible.
- A large-scale physics prototype was built
  - scintillator tiles in varying size, WLS+SiPM, FEE not imbedded
  - 38 layers, cross-section: $1\times1m^2$, volume: $1m^3$, ~7.6 k channels
  - tested with both tungsten and steel absorber

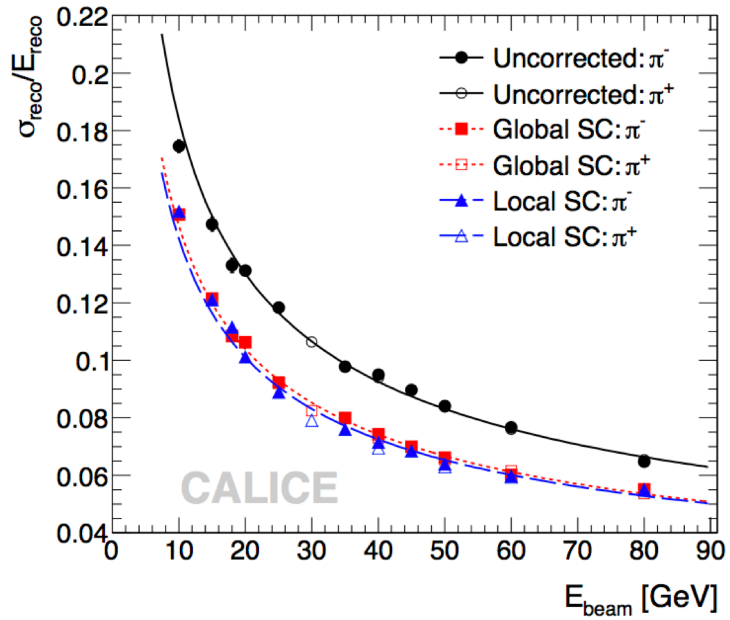




Energy linearity and Resolution

- Software compensation improves energy resolution significantly while preserving linearity.





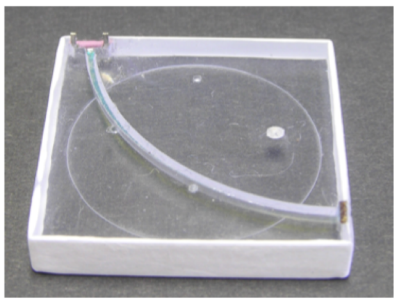
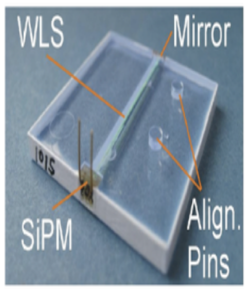
fit results		
	stochastic	constant
initial	57.6%	1.6%
global SC	45.8%	1.6%
local SC	44.3%	1.8%

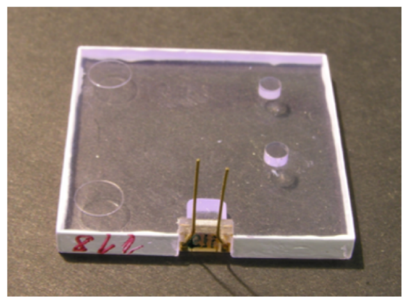
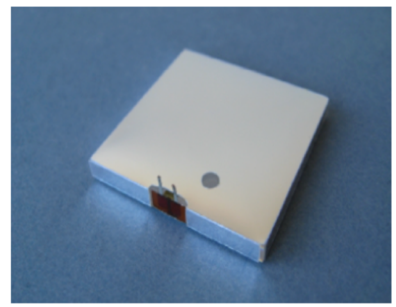
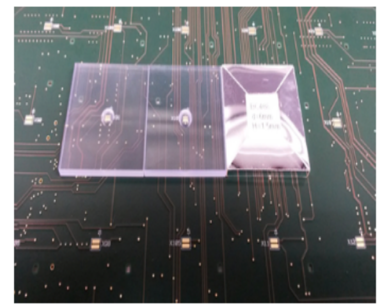
The Sci-AHCAL concept is validated

Scalability: SiPM-on-Tile

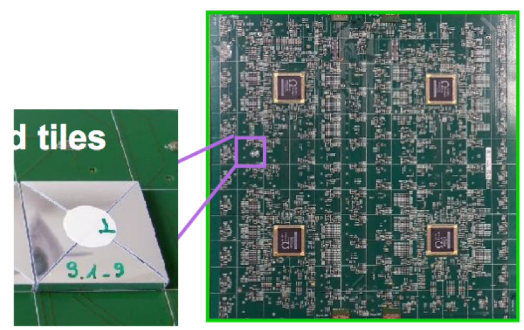
- Must integrate SiPM in the electronics readout board and embed front-end electronics in the detector in an easy way for mass assembling.
  - “SiPM on tile” technology

Evolution of tile-SiPM coupling →

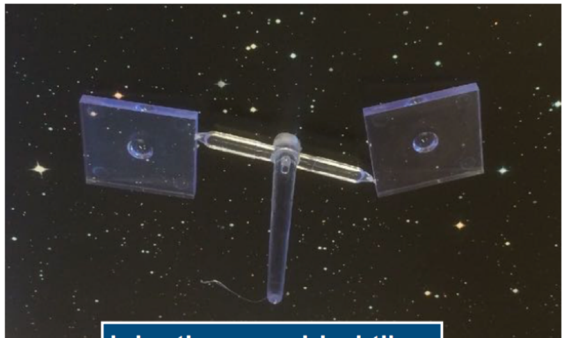



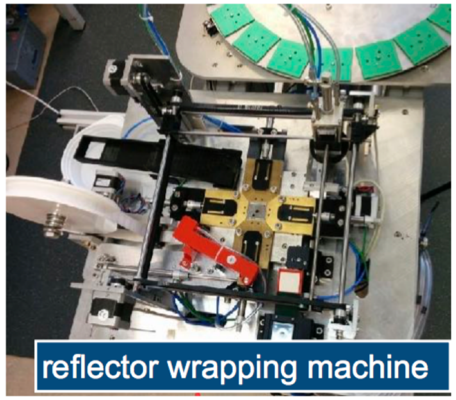




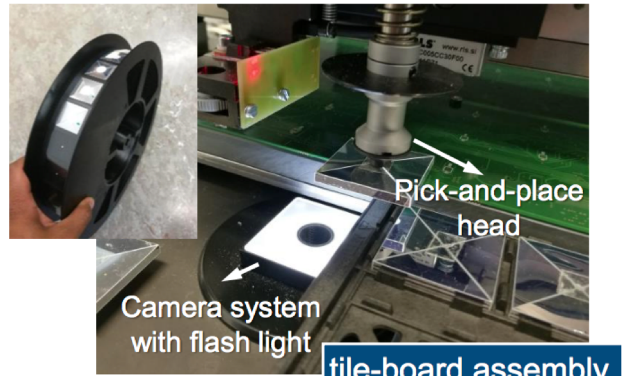
- A technological prototype was built with “SiPM on tile”.
  - HCAL Basic Unit (HBU): 36×36 cm^2, 144 tiles of 3×3cm^2,
  - 38 active layers, each layer made up with 4 HBU
  - ~22 k channels, surface-mounted SiPM: S13360-1325PE
  - Completely scalable to a collider detector by using HBU



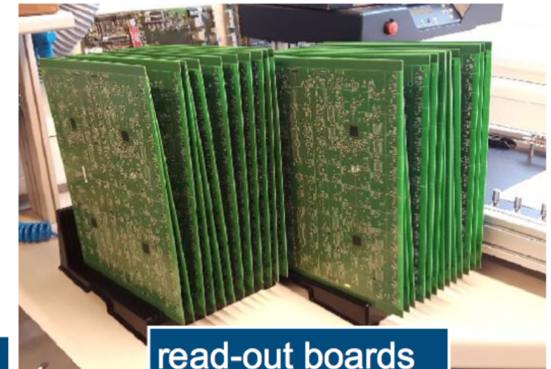
Scalability Established


injection-moulded tiles

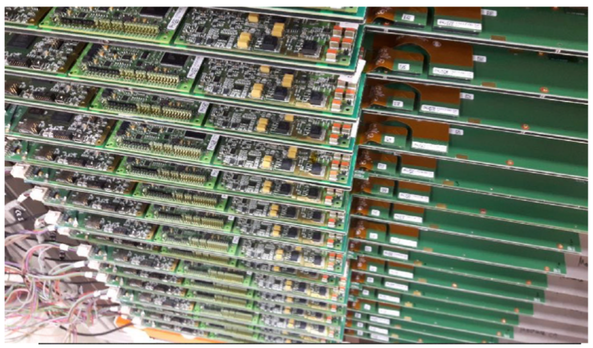

reflector wrapping machine

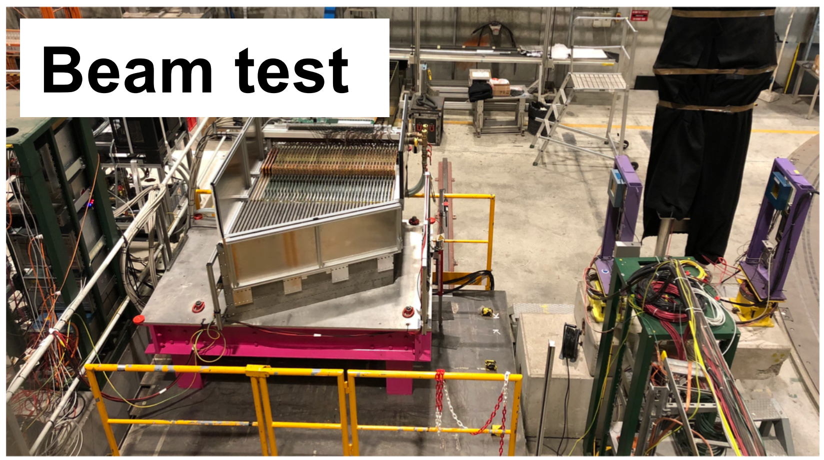


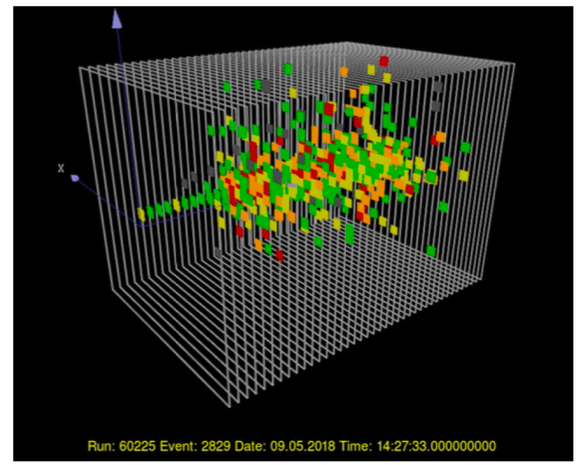
tile-board assembly


read-out boards

“Construction and Commissioning of the CALICE SiPM-on-Tile Calorimeter Prototype” by Felix Sefkow at LCWS 2018


Quality test of active layers


Beam test



A hadronic shower display

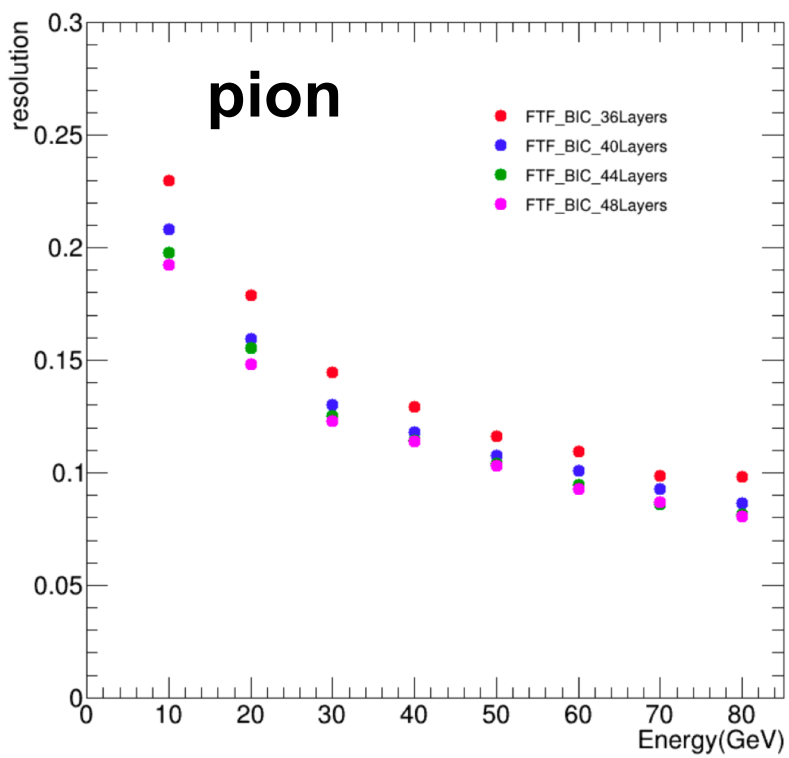
- Scalability to a full collider detector with SiPM-on-Tile technology, automated construction and QA procedures established and validated.
- CMS has adopted the technology for its HGCAL upgrade!

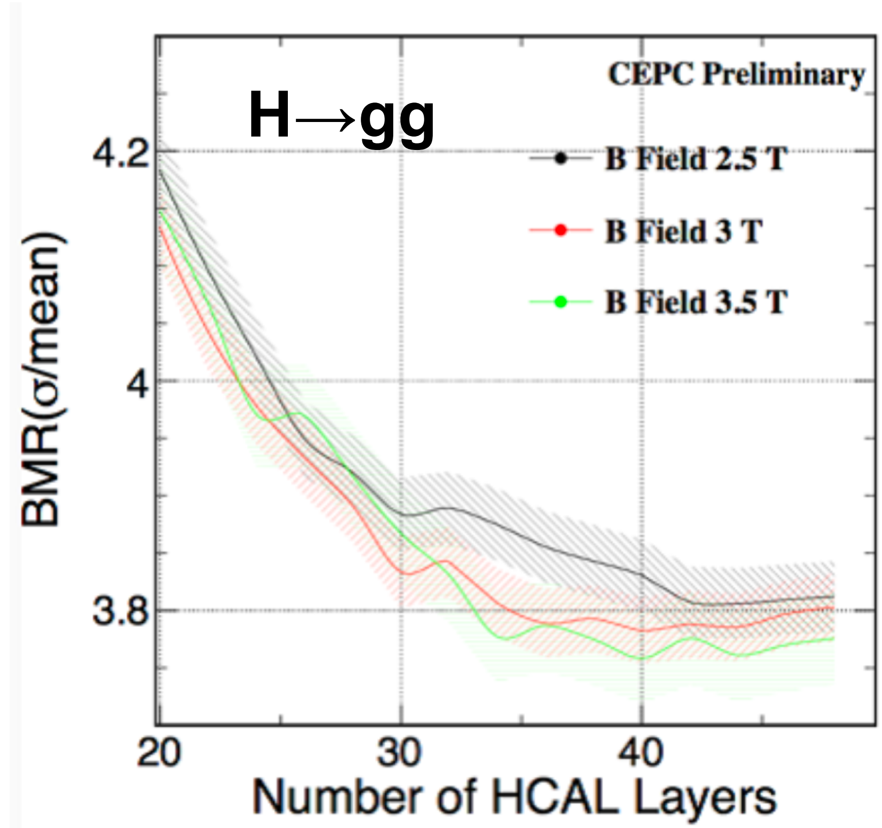
Challenges

- Challenges lie mainly in engineering and operation areas.
- Extremely large scale with a daunting number of channels! All elements have to be scalable in a well-manageable way with the least dead area/zone.
- Electronics must be integrated into active detector elements on a very large scale and in a very compact way. The whole active layer has to stay as compact as possible.
- Reliability, stability and uniformity in a huge number of channels. Operation and maintenance.
- Cooling at circular e+e- colliders with continuous operation !!!

CEPC HCAL Optimization

- Number of sampling layers for SDHCAL
  - 40 layers (1m steel in total) is sufficient. Even less is OK.



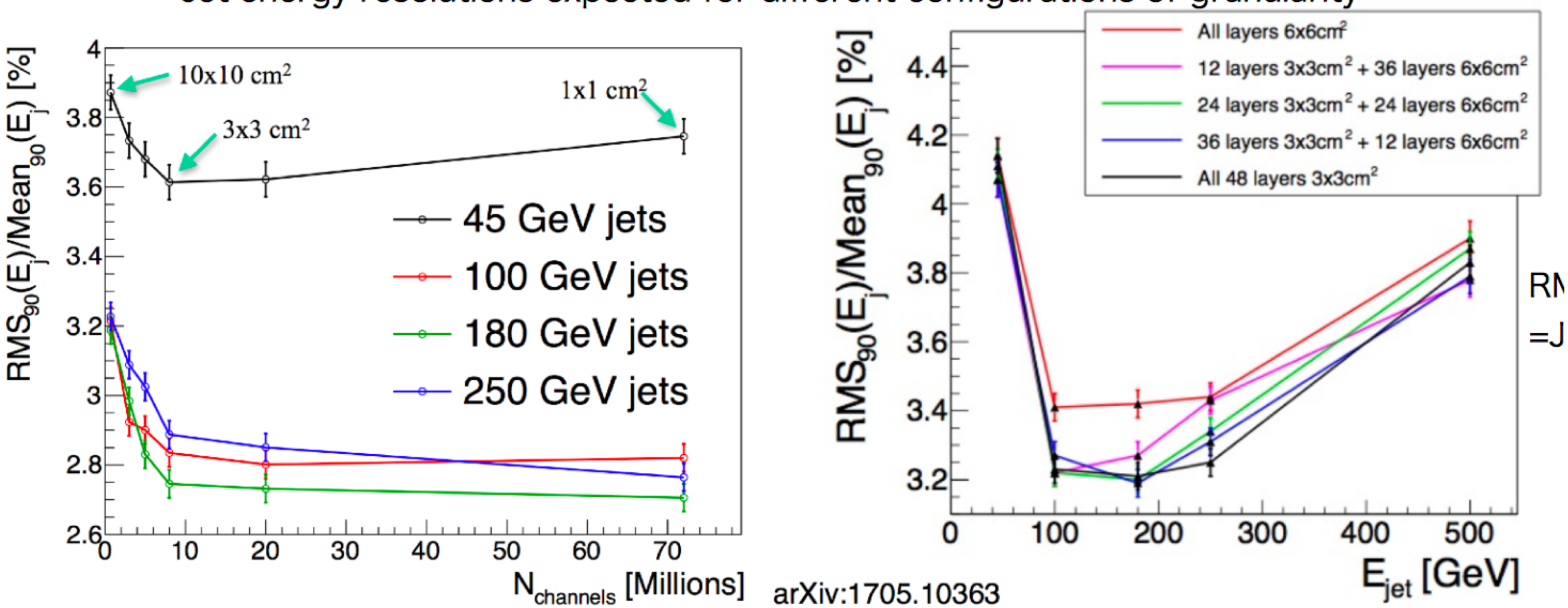


- Cell-size optimization is also ongoing.

One Example of Cell-size Optimization

- Sci-AHCAL with various cell sizes and in non-uniform cell-size configurations.

Jet energy resolutions expected for different configurations of granularity



By Huong Lan Tran etc.

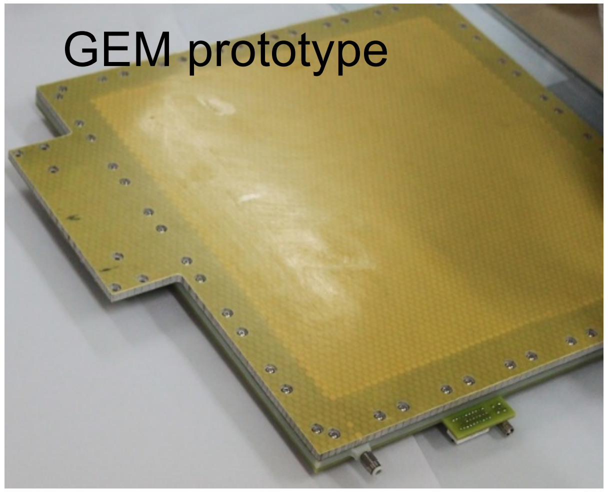
CEPC HCAL R&D

- Supported by two MOST (ministry of science and technology of China) R&D projects
  - DHCAL: technology R&D on active detectors (RPC/MPGD)
  - AHCAL: a prototype with Sci+SiPM
- Institutes being involved in the R&D projects
  - IHEP, SJTU, USTC
  - All joined CALICE

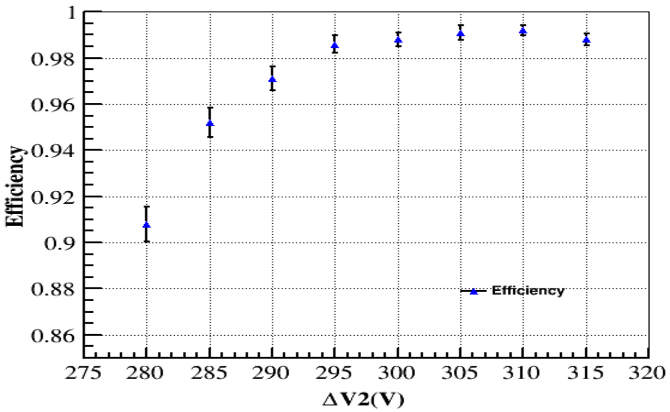
GEM R&D for DHCAL

- Built a 30×30 cm^2 double-GEM prototype and fully characterized it with X-rays and cosmic-rays

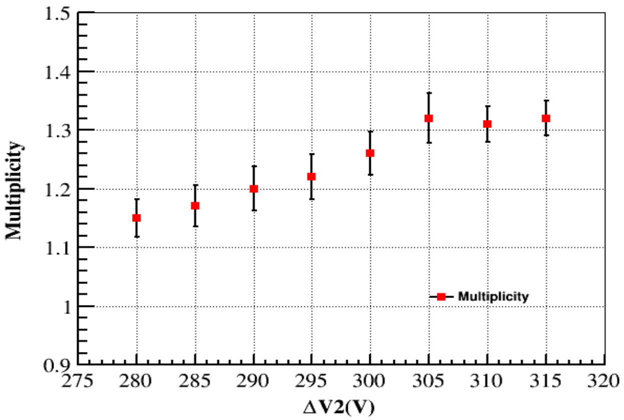
GEM prototype



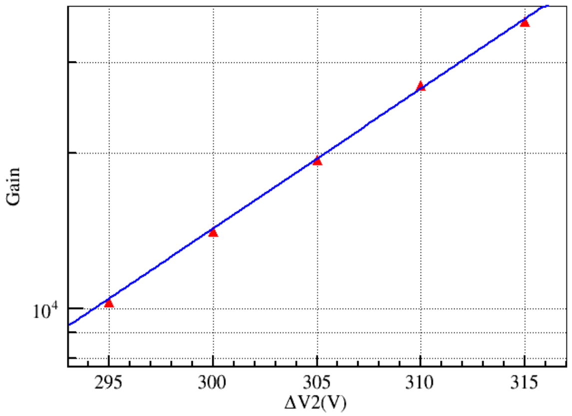
MIP efficiency vs. HV



Pad multiplicity vs. HV



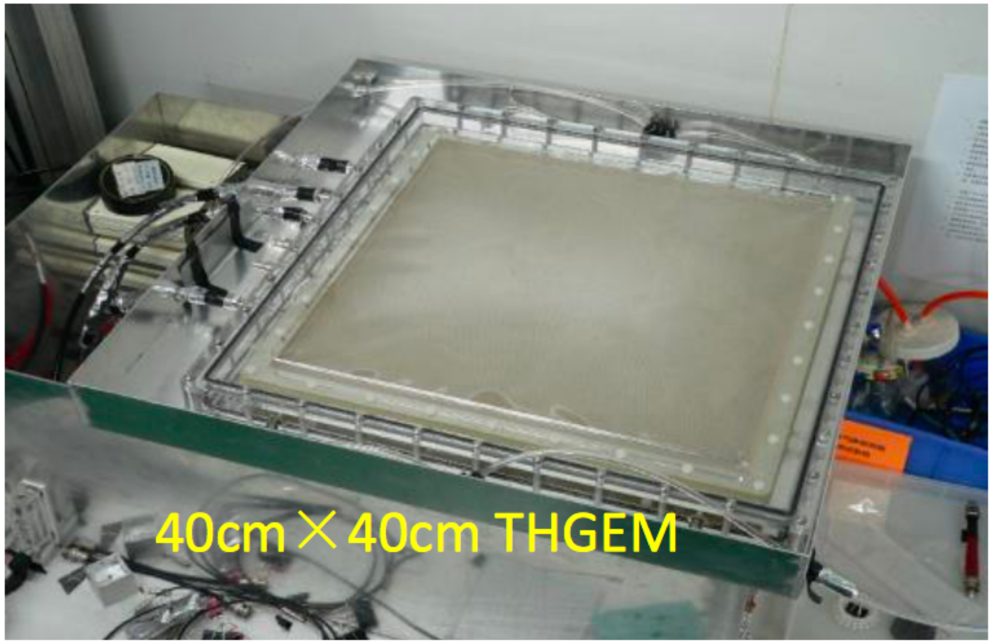
Gain vs. HV



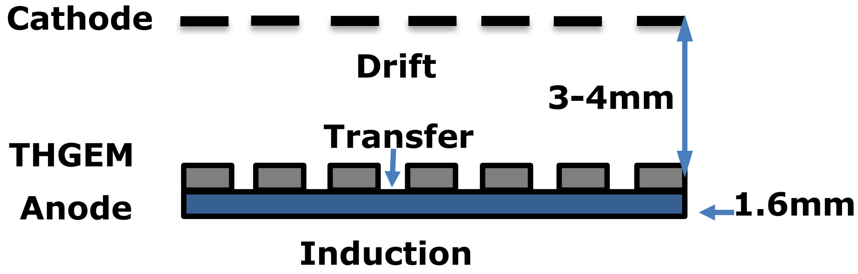
- A gas mixture with a high Ar percentage plus a powerful quenching ingredient, e.g. Ar/iC4H10(95/5), is required to get fully efficient.
- Efficiency > 98% while pad multiplicity ~ 1.3, good performance.
- Unfortunately, this option was abandoned due to large dead area at edges and partly to large gas gap.

THGEM R&D for DHCAL

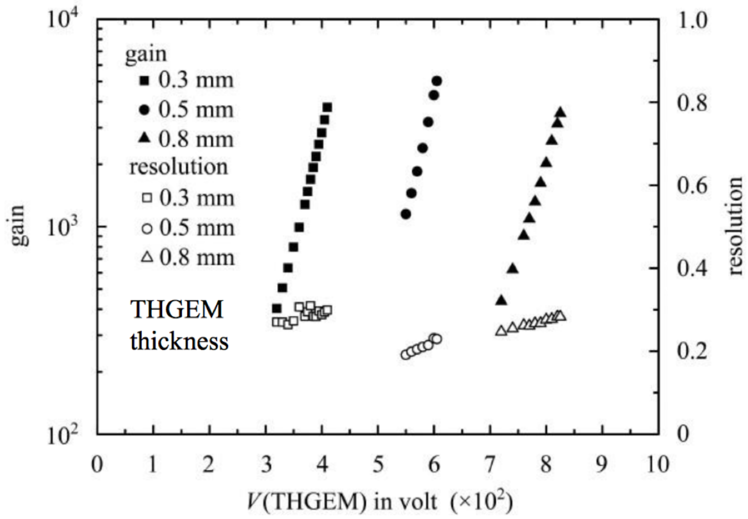
- Then merged effort to be focused on THGEM for the MPGD approach.



WELL-THGEM



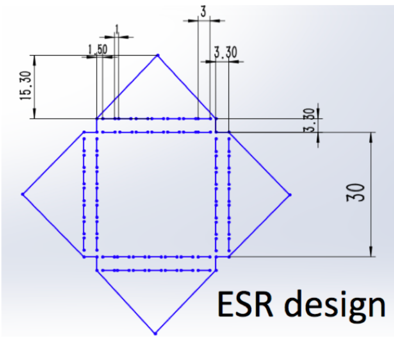
Gain with different THGEM thickness

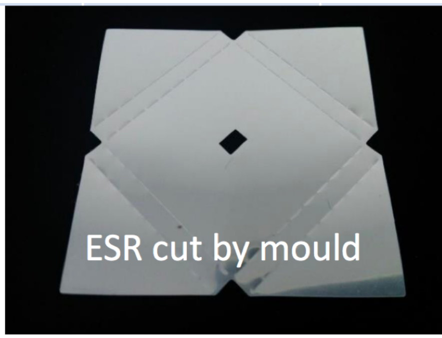


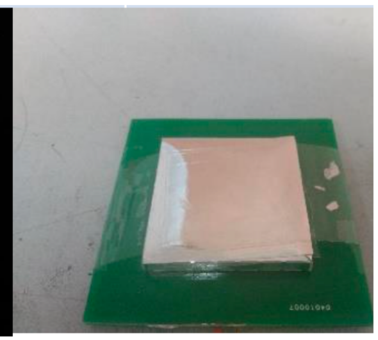
The goal now is to make a detector unit in 50×50 cm2 and can scale to a large active layer by combining such units with little dead area.

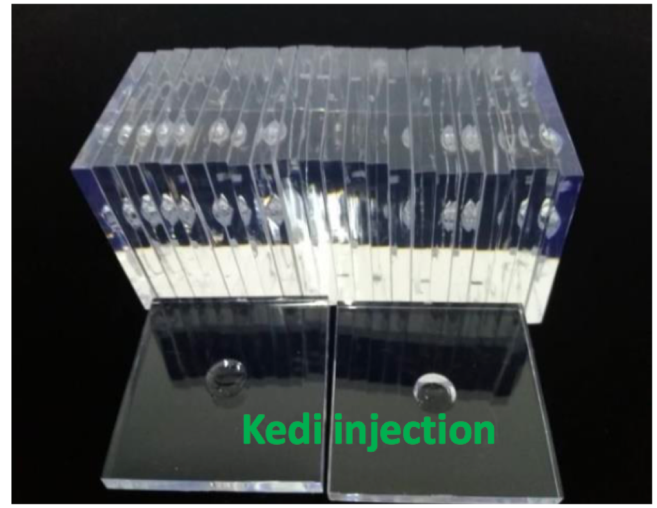
R&D for AHCAL

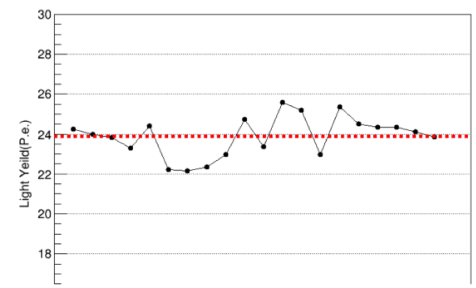
- Scintillator tiles by injection molding
- Wrapping with ESR





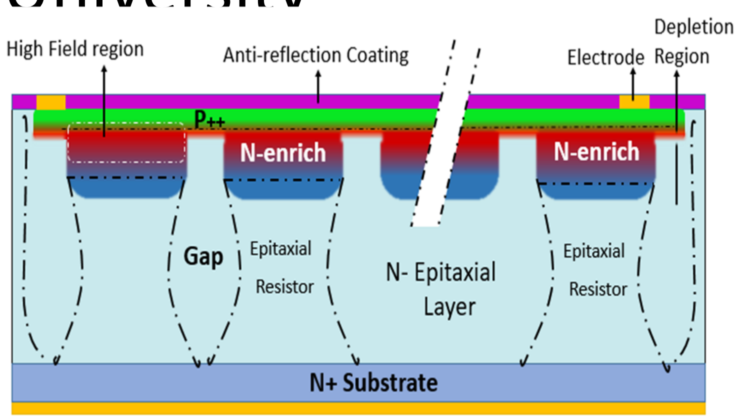






Npe~24 with fairly good uniformity

- SiPM development at Beijing Normal University



A large SiPM-on-Title AHCAL prototype with a customized SiPM and a new SiPM readout chip is envisaged

SiPM with epitaxial quenching resistors (EQR): large fill-factor and low cost

Summary

- PFA is a promising approach to achieving the unprecedented jet energy resolution required by next generation e+e- experiments.
- A highly-granular HCAL plays a crucial role in the PFA approach.
- Various PFA HCAL concepts and technologies.
- Extensive R&D conducted in CALICE.
- Dedicated R&D for CEPC has picked up the pace.
  - Active cooling study started as well
- Very challenging but feasible.