The 2021 International Workshop on the High Energy Circular Electron Positron Collider

R&D Highlights of CALICE HCAL Prototypes

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On behalf of

CALICE Collaboration

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

Outline

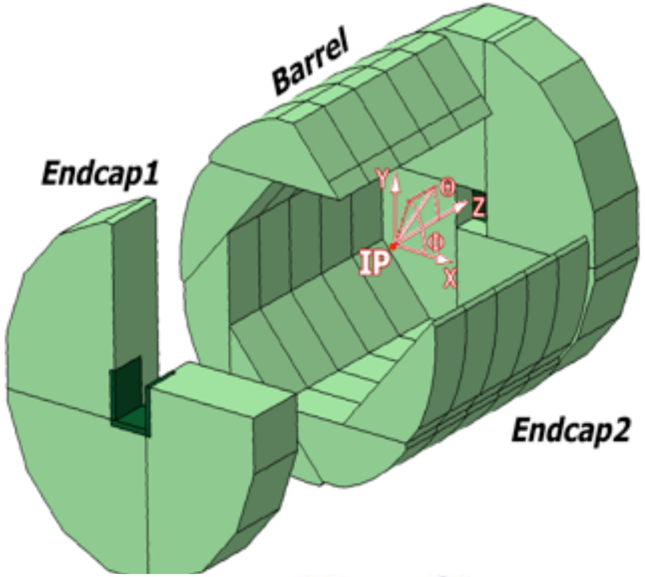
- New developments of the CALICE SDHCAL prototype
- Recent progresses in CALICE AHCAL prototype
- News and status of CEPC AHCAL prototype

01

CALICE SDHCAL (also for CEPC SDHCAL)

SDHCAL in a nutshell

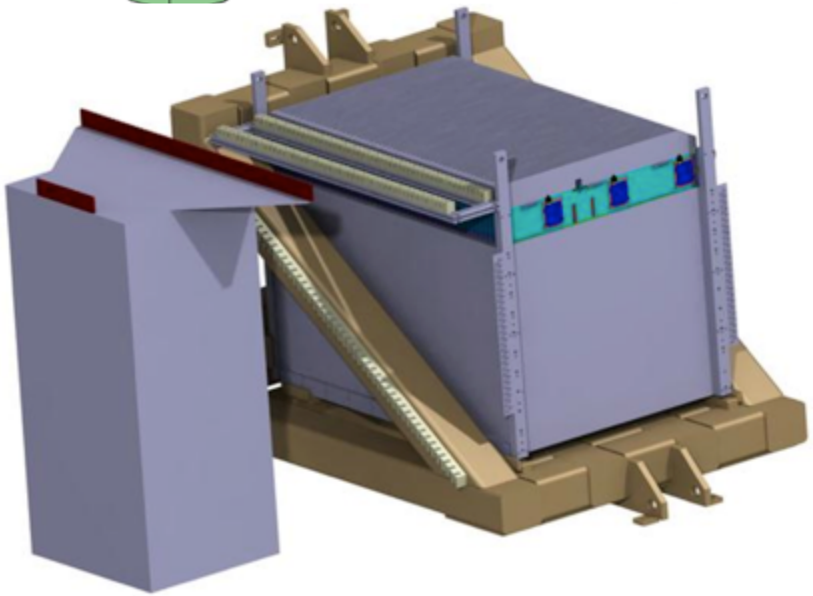
The SDHCAL-GRPC is one of the two HCAL options based on PFA and proposed for **ILD of ILC/CEPC**. Modules are made of 48 RPC chambers (**6λ_I**) equipped with **semi-digital, power-pulsed electronics** readout and placed in **self-supporting mechanical** structure to serve as absorber as well.



The structure proposed for the SDHCAL :

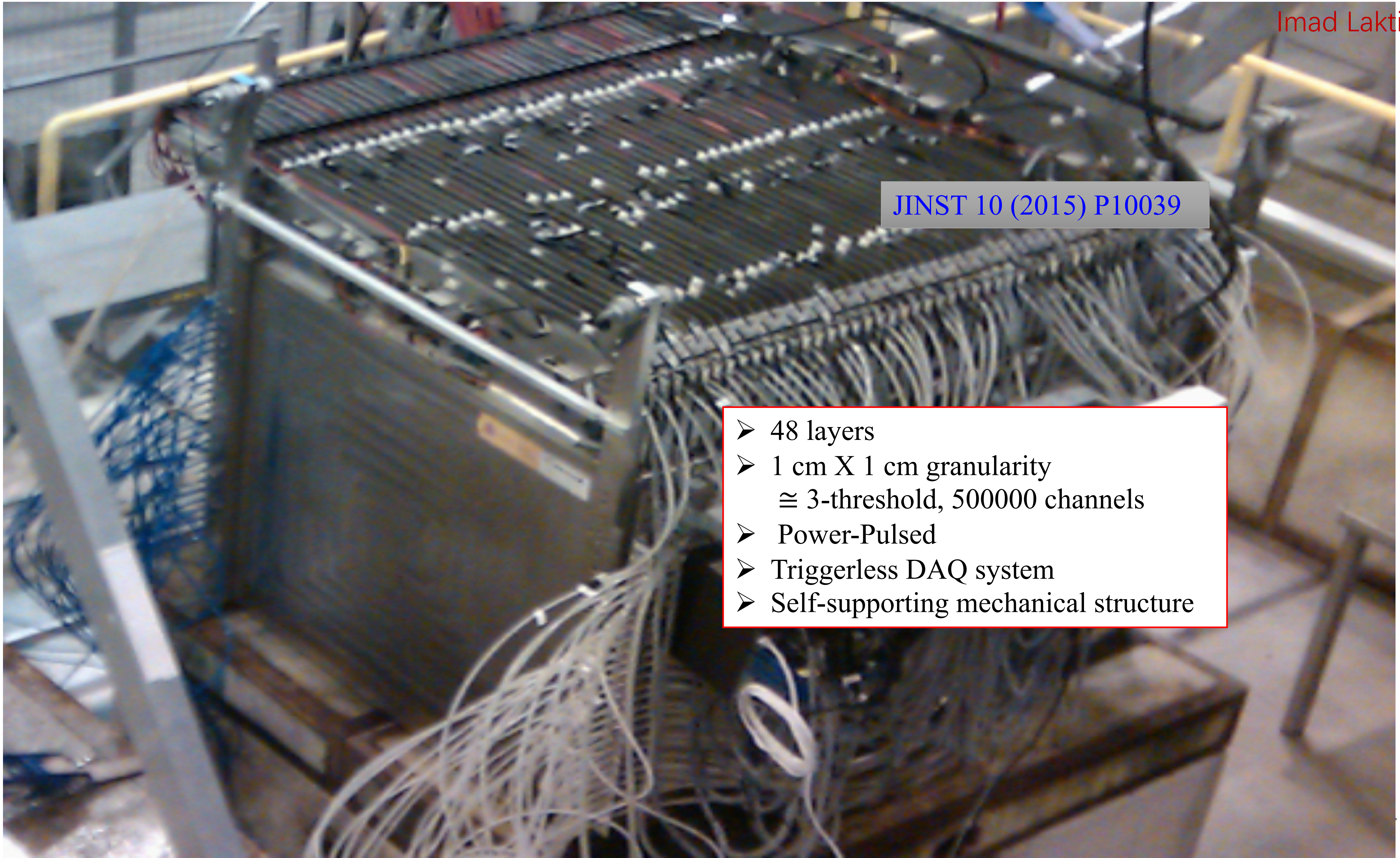
- is very compact with negligible dead zones
- Eliminates projective cracks
- Minimizes barrel / endcap separation (services leaving from the outer radius)

SDHCAL Technological Prototype should be as much as possible similar to the ILD module and able to study **hadronic showers**



Challenges

-Homogeneity for large surfaces
-Thickness of only few mms
-Lateral segmentation of 1 cm X 1 cm
-Services from one side
-Embedded power-cycled electronics
-Self-supporting mechanical structure

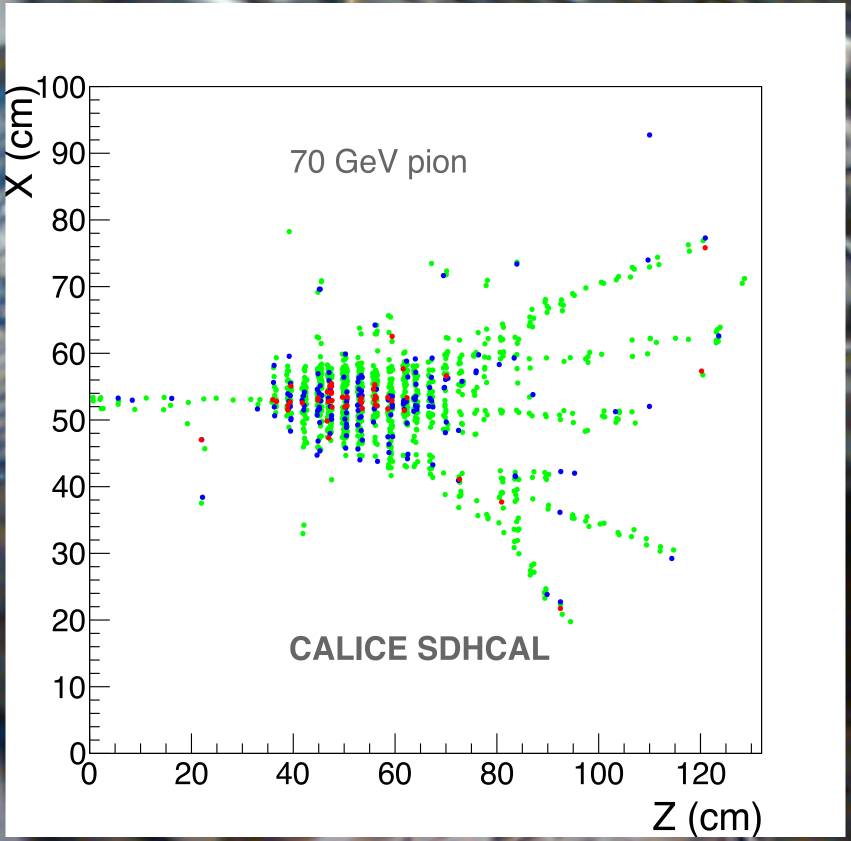


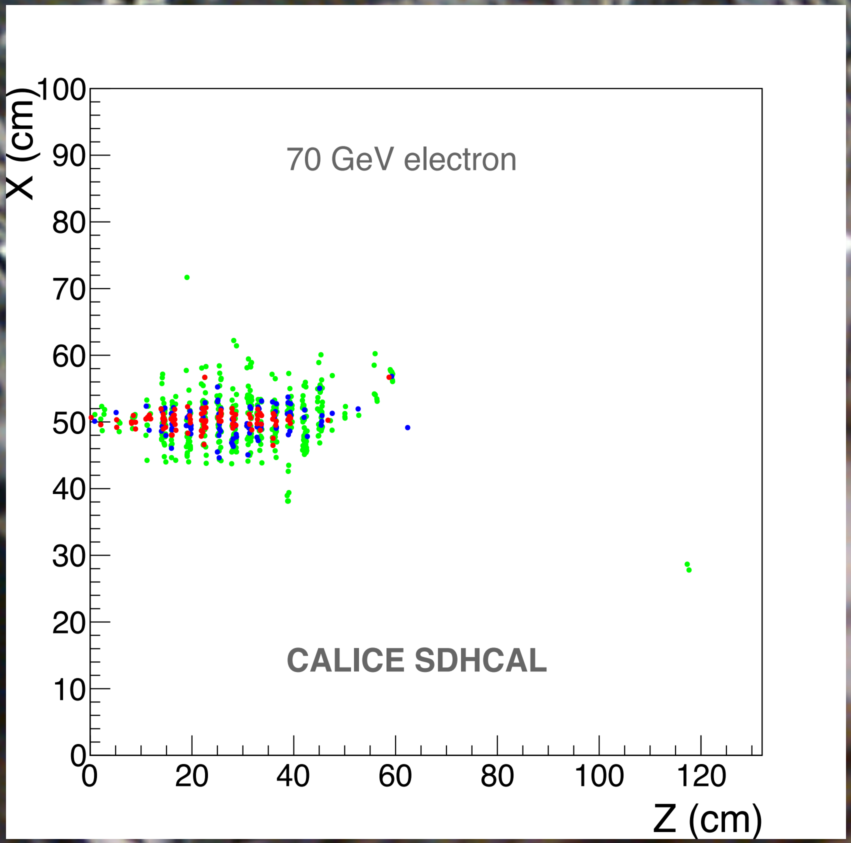
JINST 10 (2015) P10039

- 48 layers
- 1 cm X 1 cm granularity
  ≅ 3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

Imad Laktineh

SDHCAL prototype was exposed to beam particles at CERN PS, SPS in 2012, 2015, 2017 and 2018





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Selected results of the technological SDHCAL prototype

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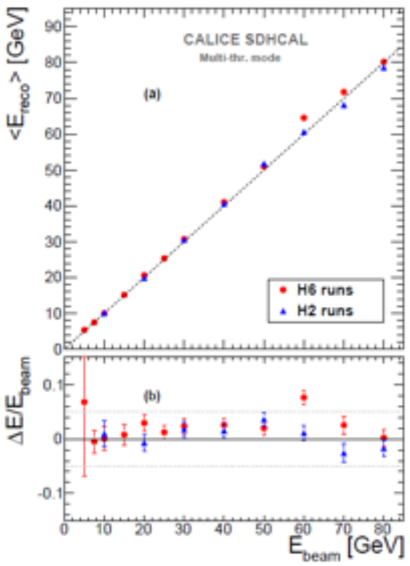
N_1 = Nb. of pads with **first threshold <signal < second threshold**
N_2 = Nb. of pads with **second threshold <signal < third threshold**
N_3 = Nb. of pads with **signal> third threshold**

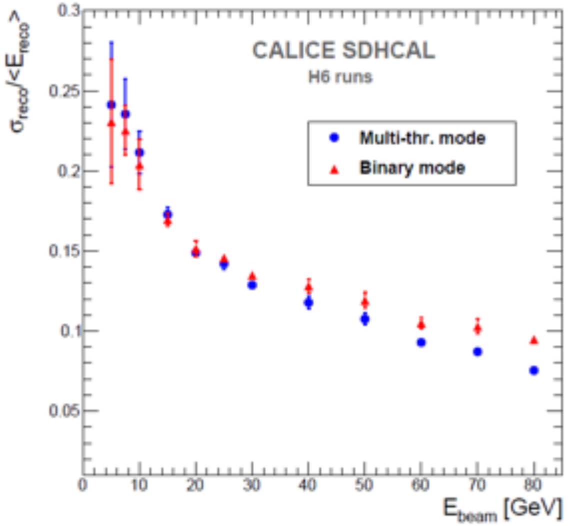
$$E_{rec} = \alpha(N_{tot})\,N_1 + \beta(N_{tot})\,N_2 + \gamma(N_{tot})\,N_3$$

$$N_{tot} = N_1 + N_2 + N_3$$

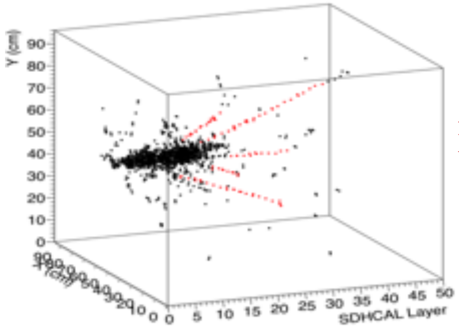
α , β , γ are **quadratic functions** of N_{tot}
They are computed by minimizing

$$\chi^2 = (E_{beam} - E_{rec})^2 / E_{beam}$$





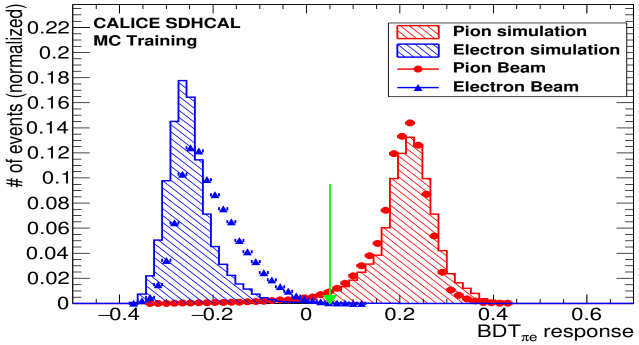
JINST 11 (2016) P04001



Shower track reconstruction Using the Hough Transform for in-situ control

JINST 12 (2017) P05009

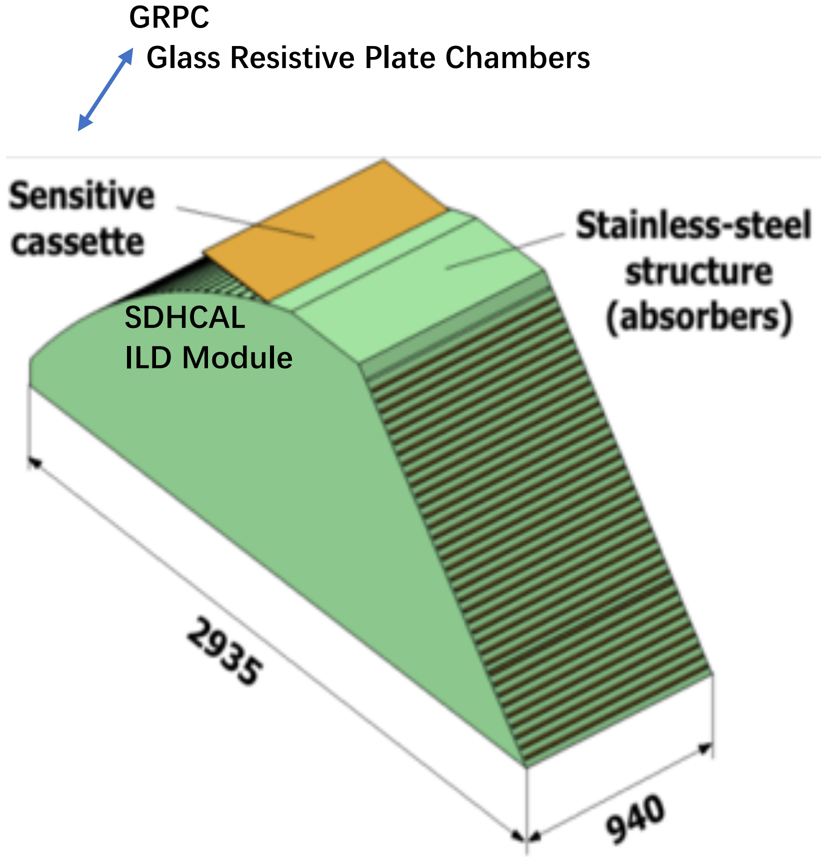
PID based on BDT



JINST 15 (2020) P10009

SDHCAL R&D towards future colliders

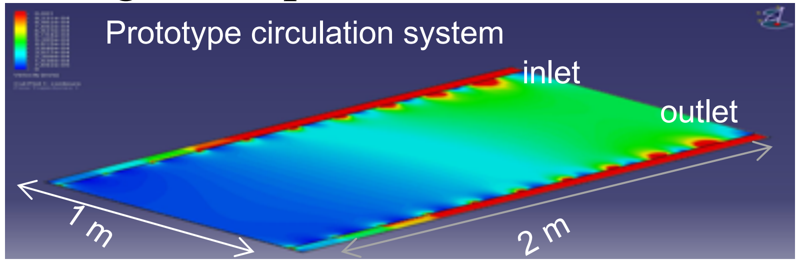
- ❑ Detectors as large as 3m X 1m need to be built
- ❑ Electronic readout should be the most robust with minimal intervention during operation.
- ❑ Mechanical structure with minimal dead zone
- ❑ Include time information **SDHCAL→ T-SDHCAL**

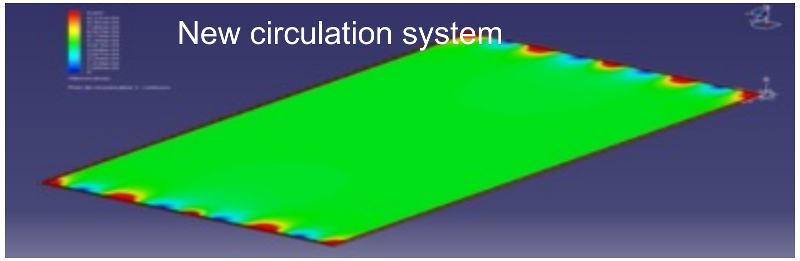


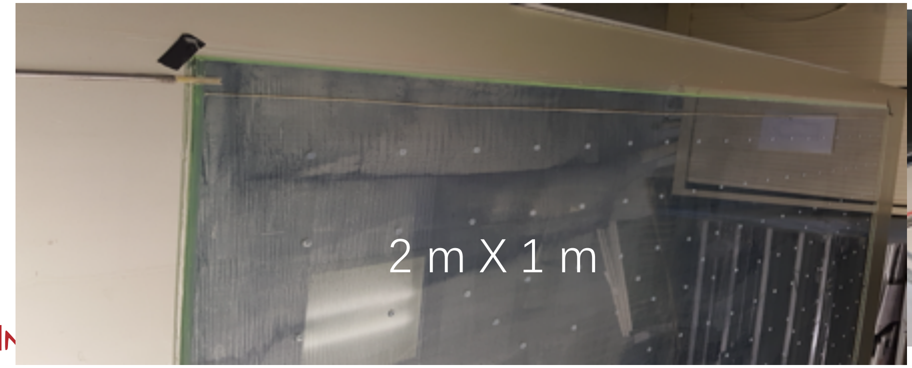
New large RPC design

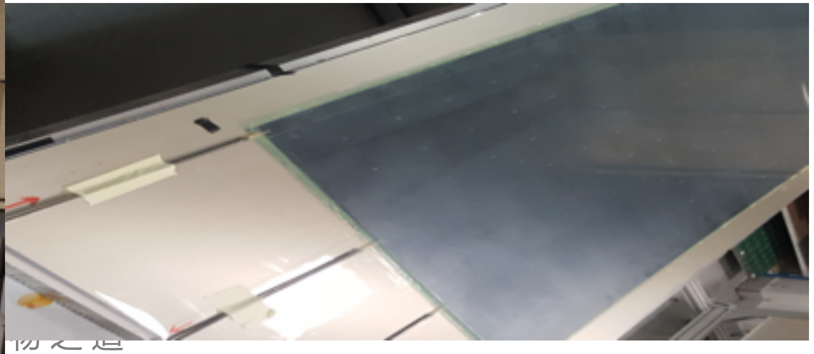
Construction and operation of large GRPC necessitate some improvements with respect to the present scenario.

- Gas distribution: new scheme is adopted
- Gas gap thickness: better control
- Coating: new paints are tested



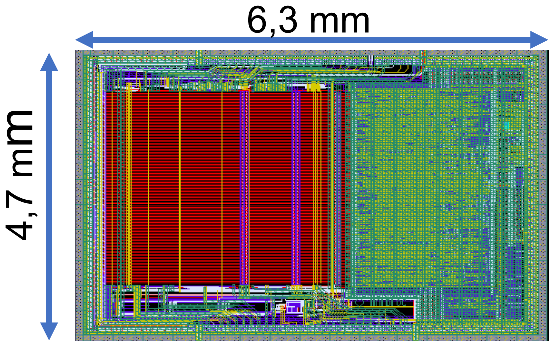




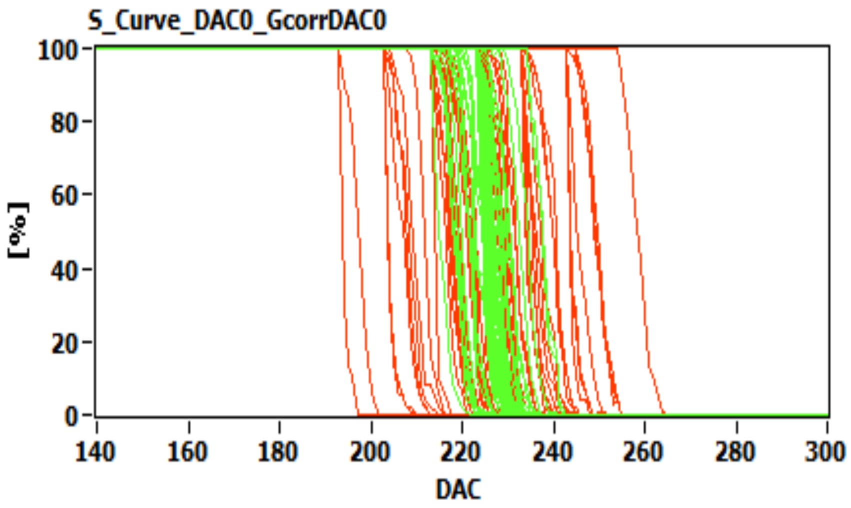


New readout electronics

HR2→HR3

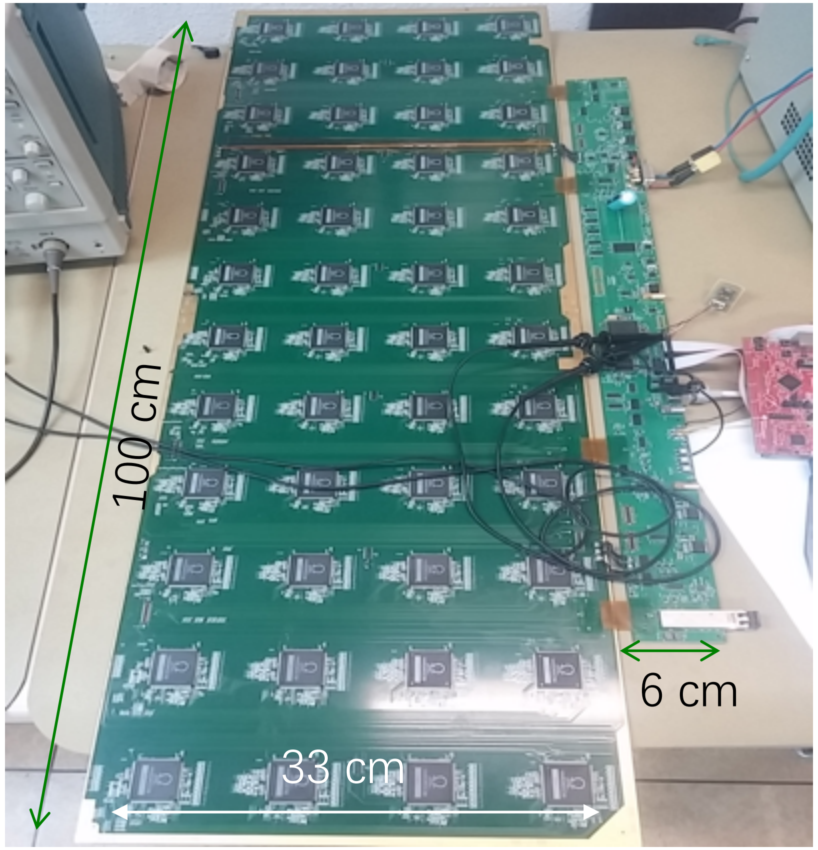


- **Independent channels**
- **Zero suppress**
- Extended dynamic range (up to 50 pC)
- **I2C link with triple voting for slow control parameters**



786 HR3 produced and tested , Yield : 83.3 %

- Larger PCB (**100 cm X 33 cm**)
- Detector InterFace (**DIF**) to read out up to 432 ASICs



13 ASUs & 5 DIF produced and being tested

New mechanical structure design

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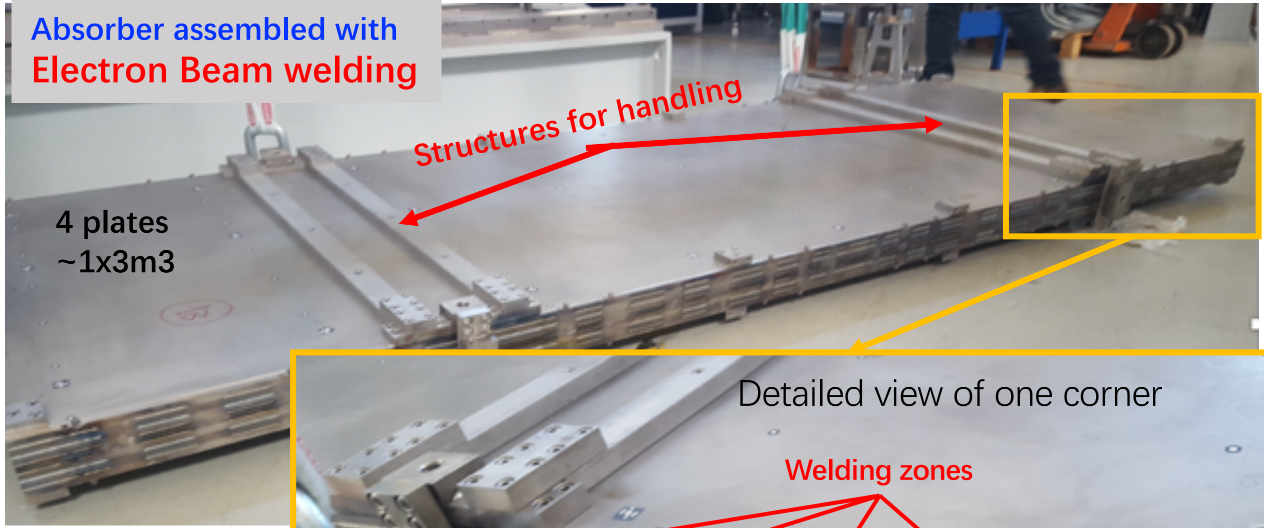
Absorber plates planarity after **roller leveling**

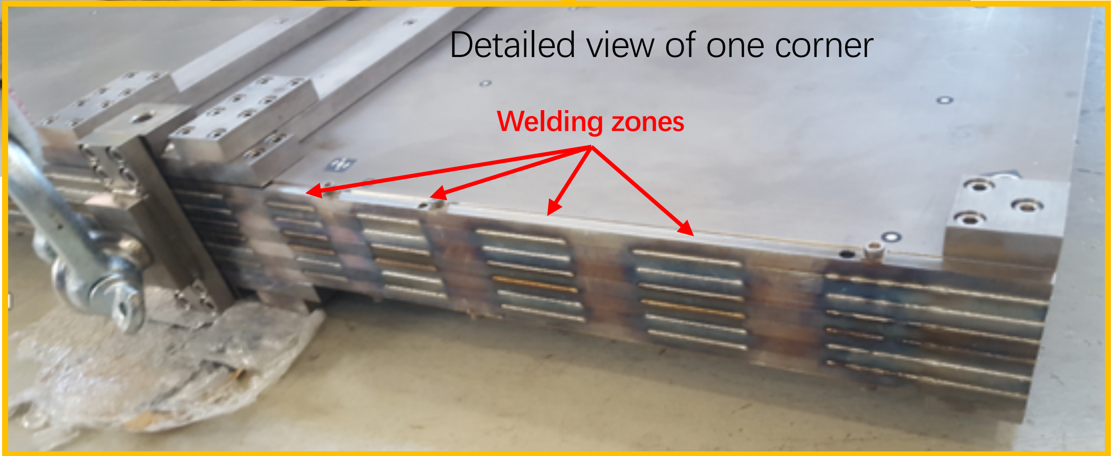
Planarity

Planarity (µm)	Plate A		Plate B		Plate C	
	Side 1 up	Side 2 up	Side 1 up	Side 2 up	Side 1 up	Side 2 up
Average	469,3	852,6	511,6	596,3	983,4	1038,0

Plate D		Plate E	
Side 1 up	Side 2 up	Side 1 up	Side 2 up
458,7	546,1	610,2	521,9

Roller Leveling

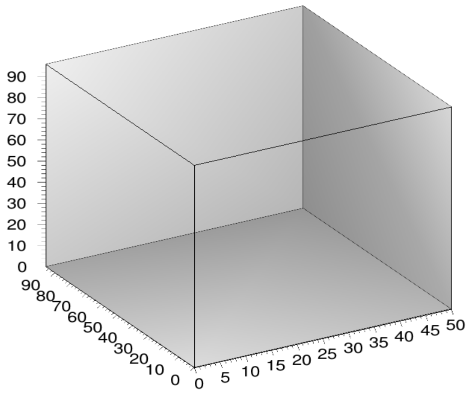


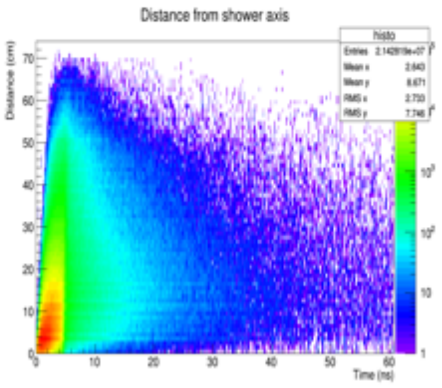


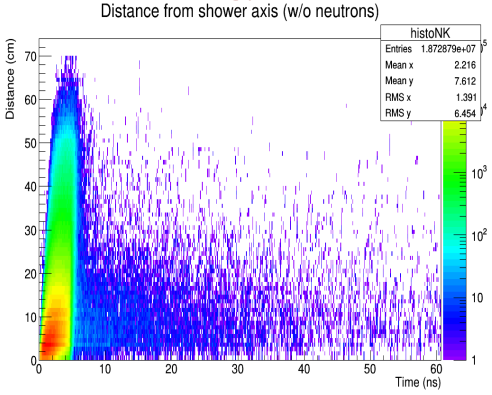
EWB minimizes deformation and reduces dead zones

T-SDHCAL

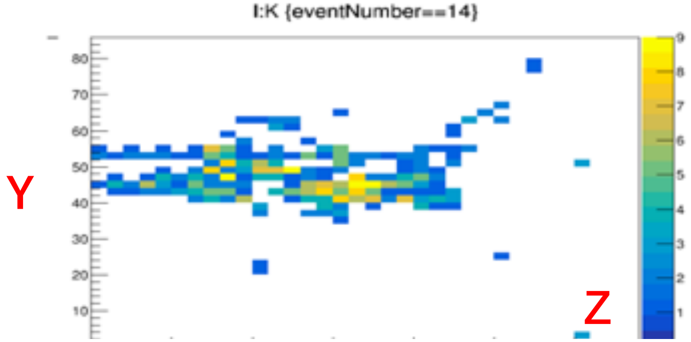
Timing is an important factor to identify delayed neutrons and **better reconstruct their energy**

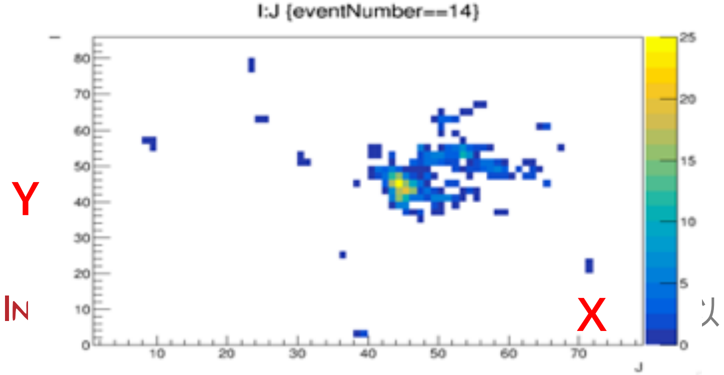


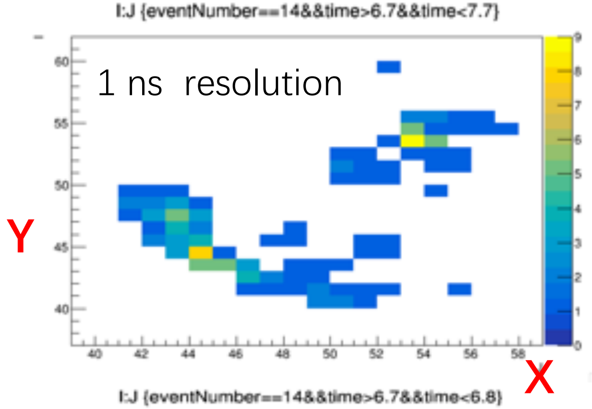


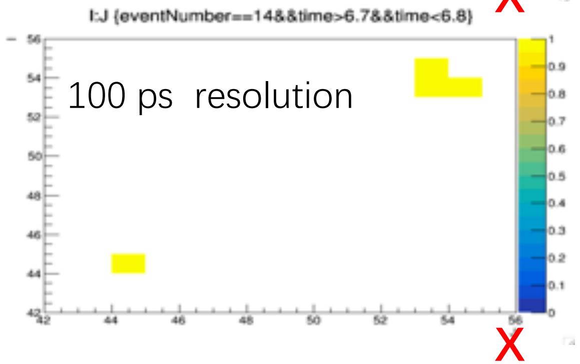


Timing can help to separate closeby showers and reduce the confusion for a better **PFA** application. Example: pi-(20 GeV), K-(10 GeV) separated by 15 cm.

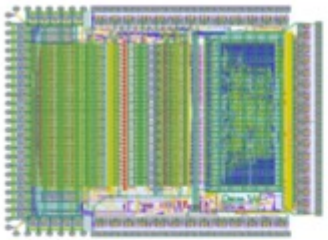








T-SDHCAL

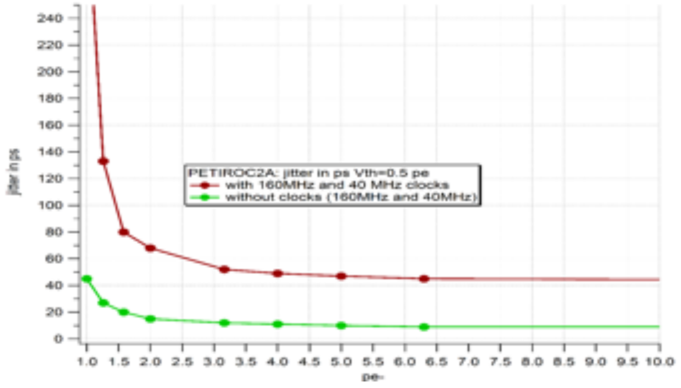


How to achieve an excellent time resolution:

An **ASIC** with a fast preamplifier, precise discriminator and excellent TDC is needed

→**PETIROC** 32-channel, high bandwidth preamp (GBWP> 10 GHz), <3 mW/ch, dual time and charge measurement (Q>50 fC)

jitter < 20 ps rms @ Q>0.3 pC

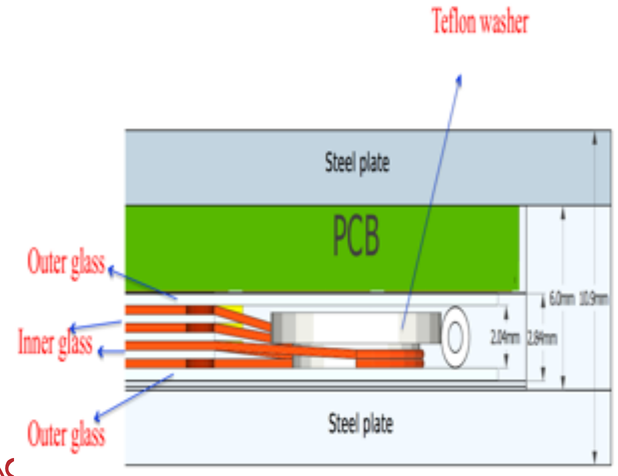


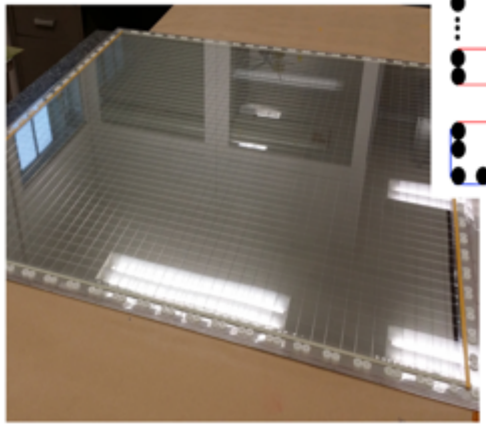
→ TDC either internal or external (delay-line, Vernier,.etc on FPGA as for iRPC CMS upgrade project)

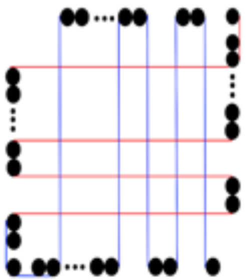
A fast-time **DETECTOR**

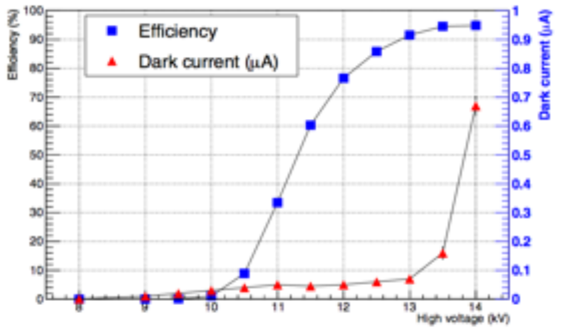
→ **MultiGAP** RPC is an excellent candidate.

4-5 gaps of 250 µm each can provide 100 ps tim resolution



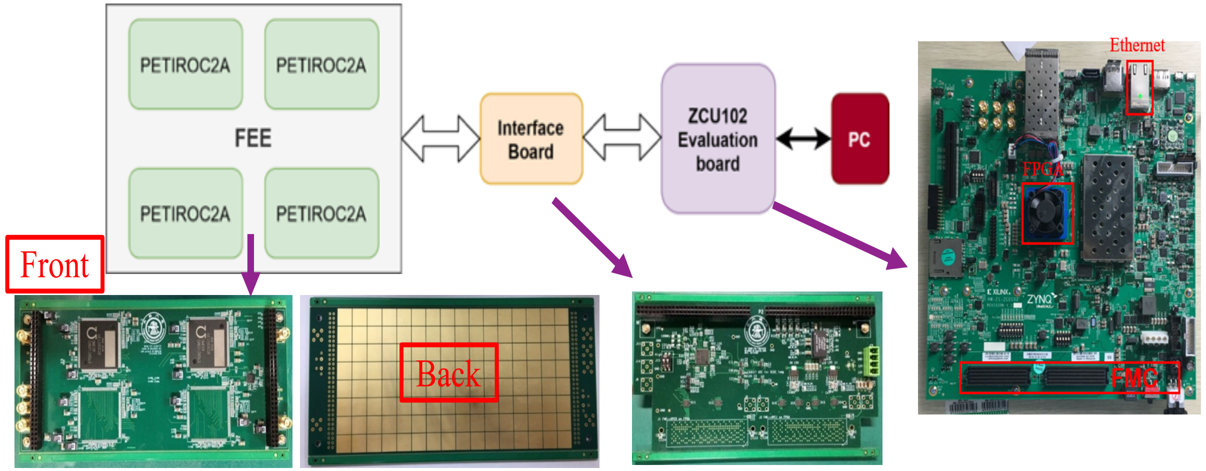






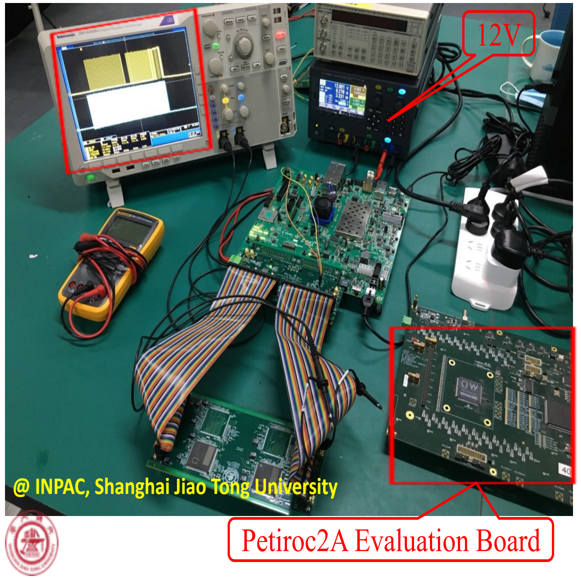
Threshold sets at 114 fC

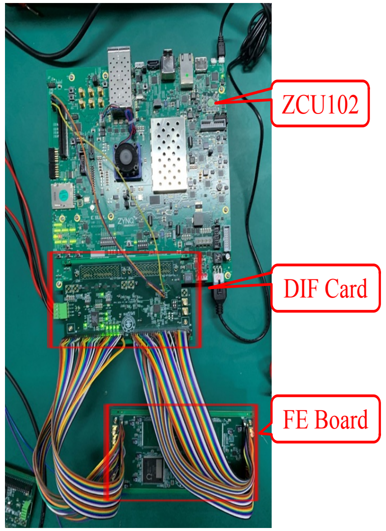
First step towards transforming SDHCAL into T-SDHCAL



- Front-End Electronics for MRPC readout with high timing resolution
- The system includes a front-end board (FEB), a detector interface card (DIF) and a data acquisition system(DAQ) based on ZCU102.

Test System and Setup





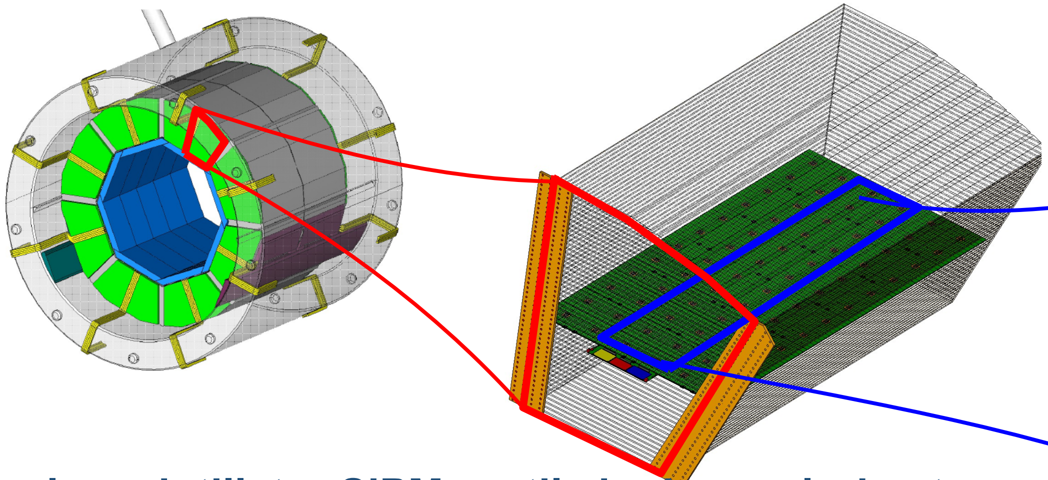
SDHCAL: Conclusions and perspectives

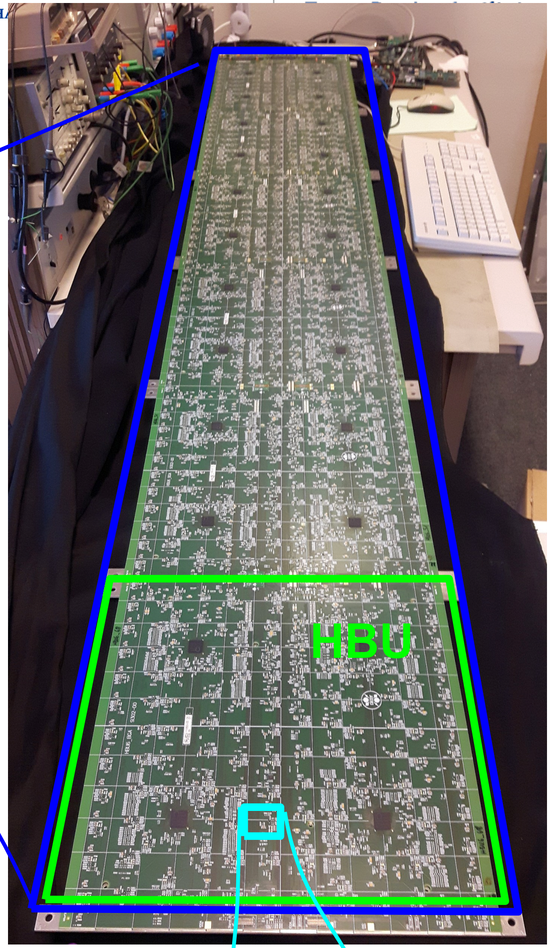
- SDHCAL was the first technological of the CALICE high granular calorimeter prototypes
- Results of beam tests validate the concept. Many results are obtained.
- New prototype with large detectors and improved services is on the rails and in principle could be achieved as soon as funding becomes available.
- New features such as timing will play important role in future R&D for future colliders. SDHCAL with its (M)RPC is an excellent tool to achieve that.

02

CALICE AHCAL

AHCAL Technological Prototype





highly granular scintillator SiPM-on-tile hadron calorimeter,
3*3 cm² scintillator tiles optimised for uniformity

fully integrated design

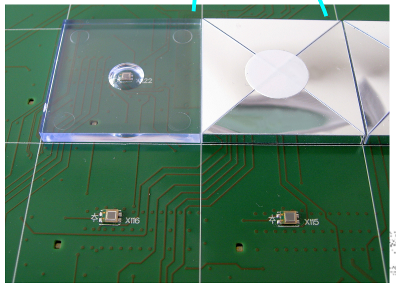
- front-end electronics, readout
- voltage supply, LED system for calibration
- no cooling within active layers -> **power pulsing**

scalable to full detector (~8 million channels)

geometry inspired by ILD, similar to SiD and CLICdp

HCAL Base Unit: 36*36 cm^2, 144 tiles, 4 SPIROC2E ASICs

- slabs of 6 HBUs, up to 3 slabs per laye



AHCAL Technological Testbeam Prototype

Large enough to contain hadron showers

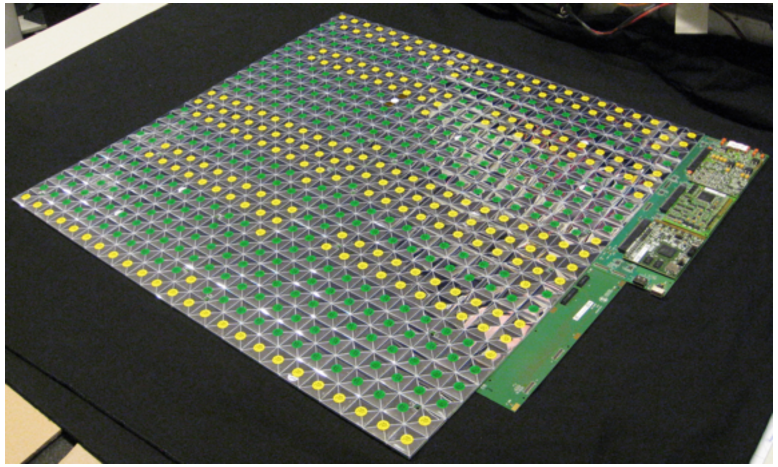
- 38 active layers of 72*72 cm²
- 4 HBUs per module
- in total: 608 SPIROC2E ASICs, ~22000 channels
- SiPMs: Hamamatsu S13360-1325PE

All modules interchangeable

Built with scalable production techniques in ~2 years

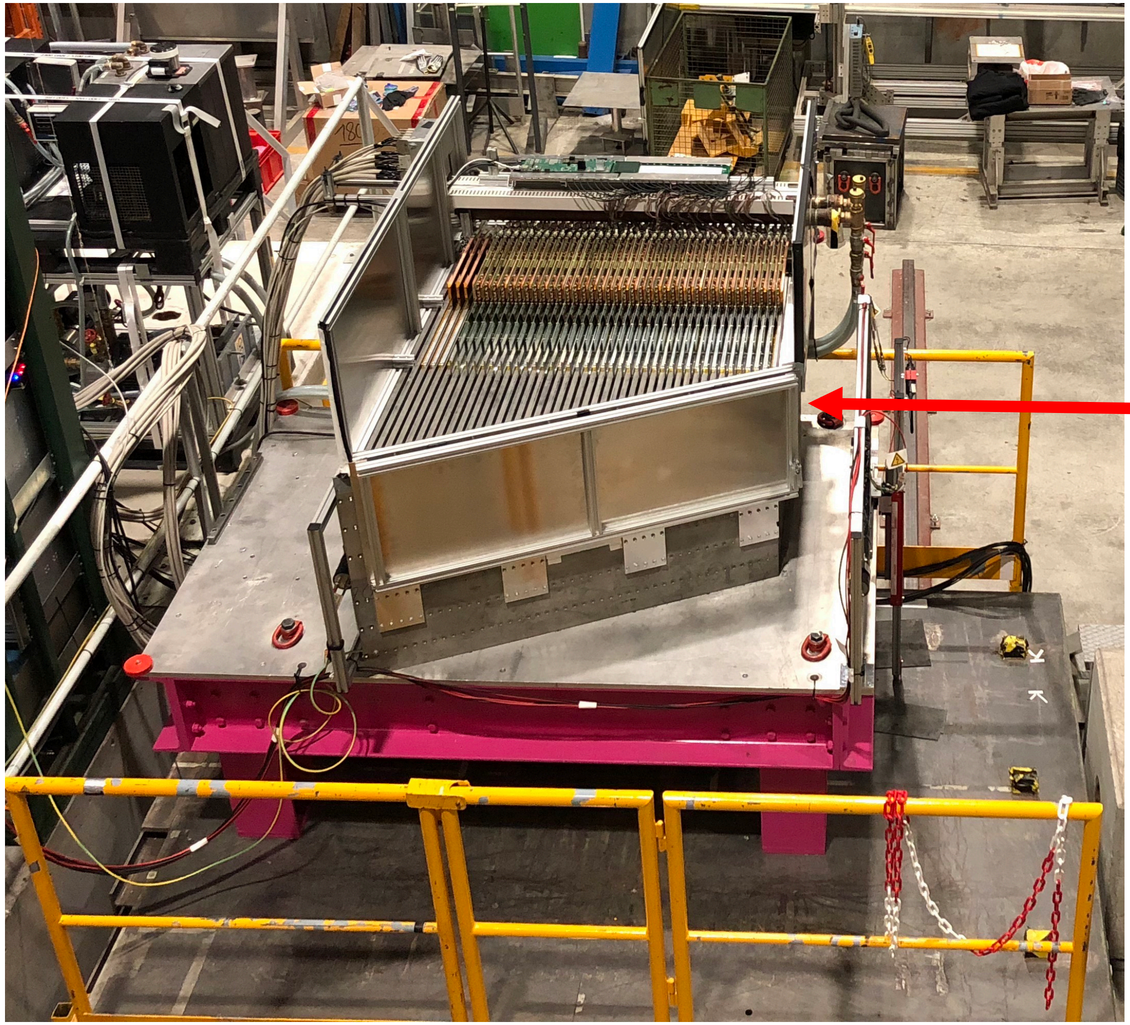
Operated in beam tests with muons, electrons and pions at CERN SPS in 2018

- 3 weeks of beam time
- Collected O(100) mio events
- Very stable running
- Nearly noise free
- < 1 per mille dead channels

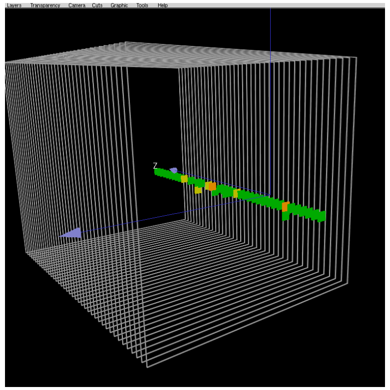


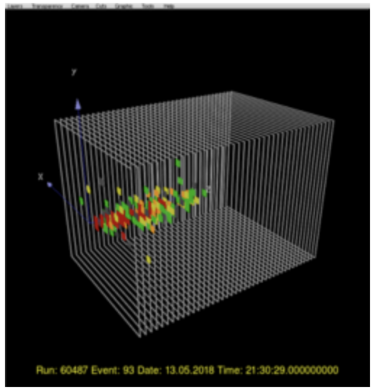
Katja Krüger

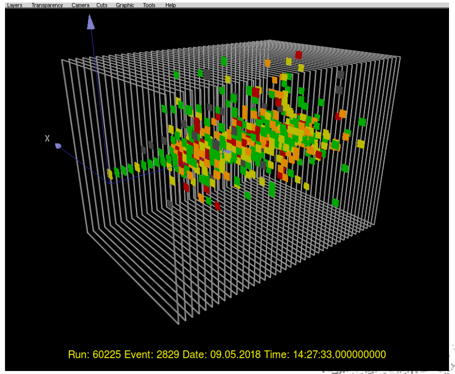
AHCAL Technological Prototype at SPS Testbeam



beam







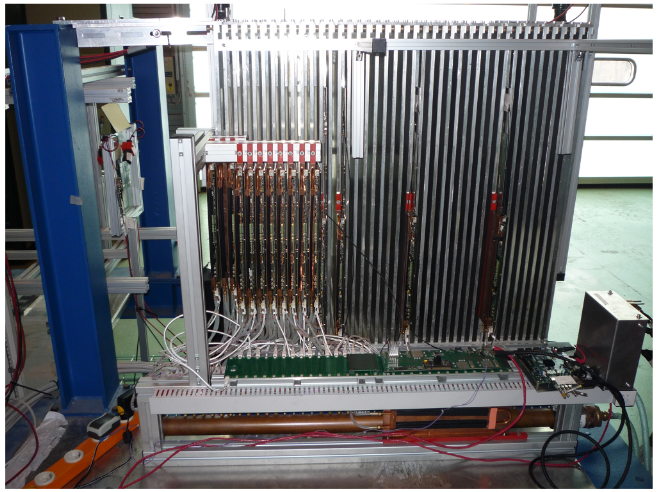
AHCAL Plans: Testbeam Measurements

Fully exploit timing capabilities

- Perform full set of testbeam measurements in ILC mode
- Develop reconstruction algorithms to better use hit time information

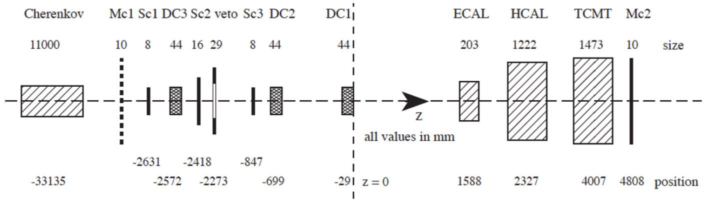
Tungsten Stack

- Data taken so far with steel absorber stack
- Tungsten would offer shorter showers
- Valuable input for hadronic shower models (ECAL)
- Plan to re-use tungsten absorber stack already used for physics protype



Running with ECAL

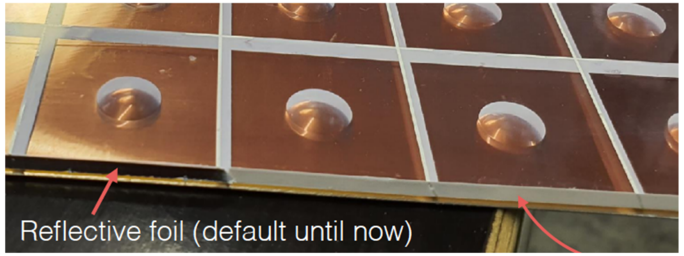
- Performance of a calorimeter system depends on combination of ECAL and HCAL
- Plan to take data together with CALICE silicon-tungsten and/or scintillator-tungsten ECAL



AHCAL Plans: Hardware Developments

Alternative scintillator geometry

- Megatiles would allow larger units for mechanical assembly
- Status: Ongoing effort, optimization of uniformity and cross talk

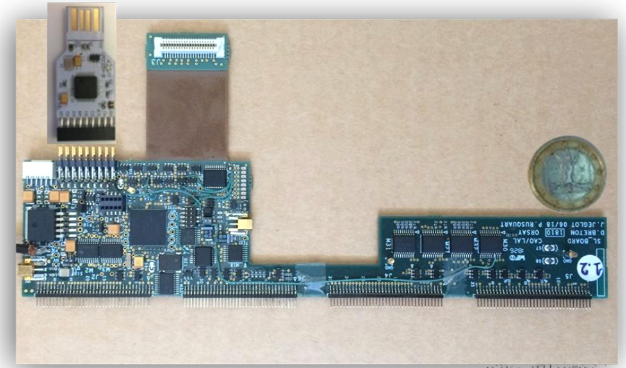


Alternative Readout ASIC (KLauS)

- Wide range of applications
- Possible application at circular Higgs factories
- Optimised for SiPMs with small pixels (10µm) -> possible application in ECAL
- Status: KLauS6 with full functionality available, ongoing effort to integrate into AHCAL DAQ

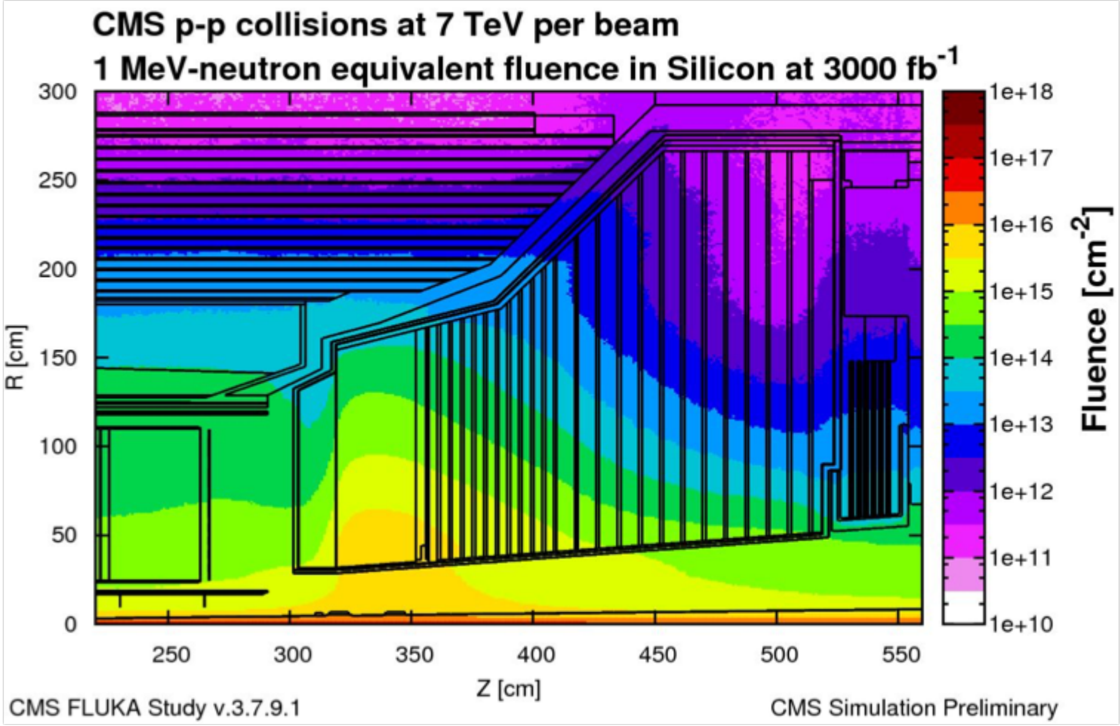
Common Readout

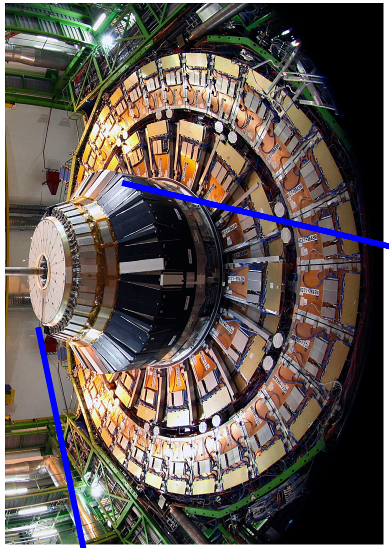
- Harmonize readout between CALICE SiW ECAL and AHCAL
- Status: just started

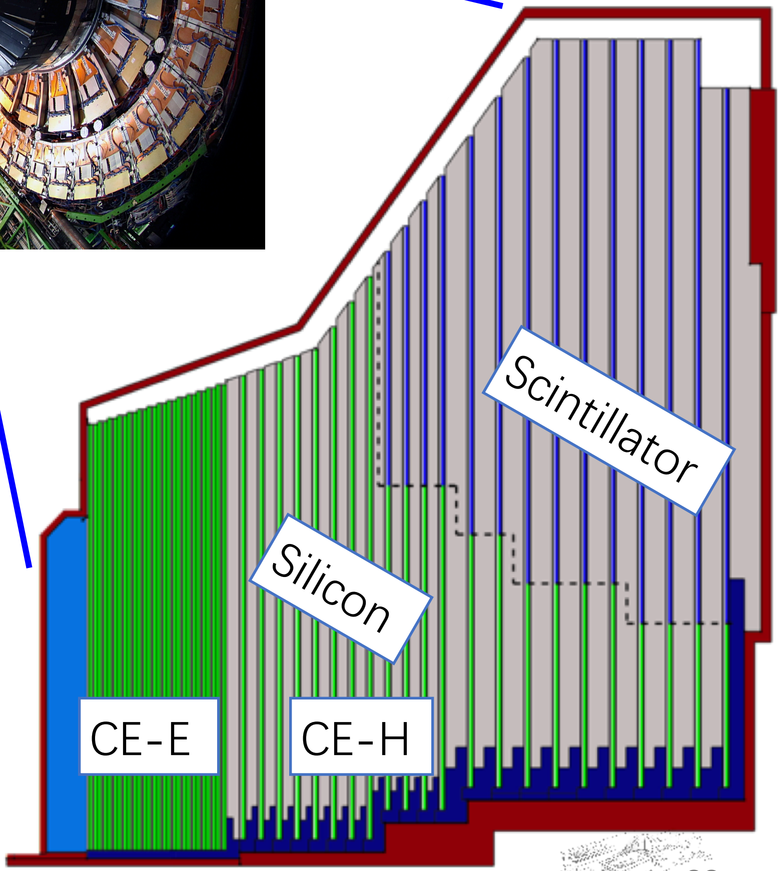


SiPM-on-Tile in CMS HGCAL

- CMS calorimeter endcap will be replaced for HL-LHC by **H**igh-**G**ranularity **cal**orimeter
- synergy with high granularity calorimeter concepts developed for electron-positron colliders
  - Use SiPM-on-tile wherever radiation levels allow



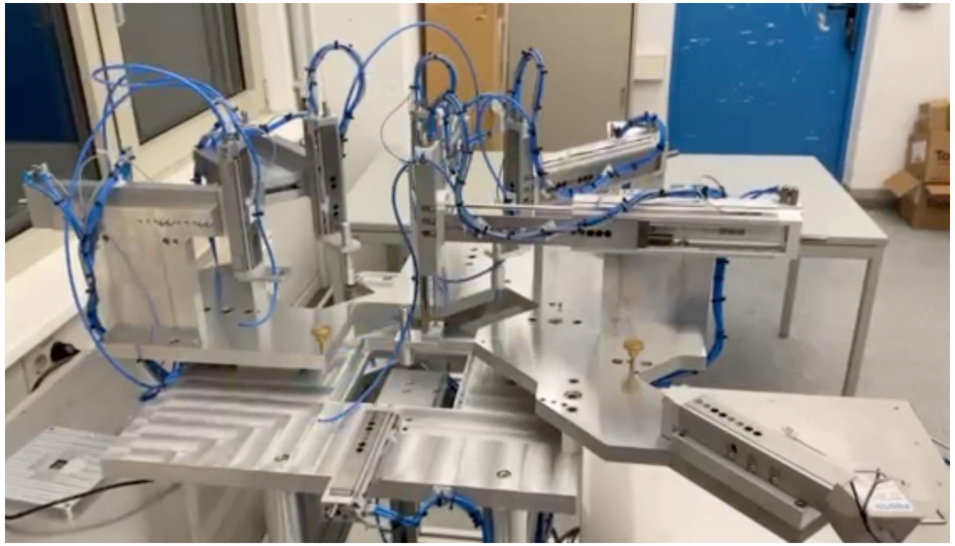


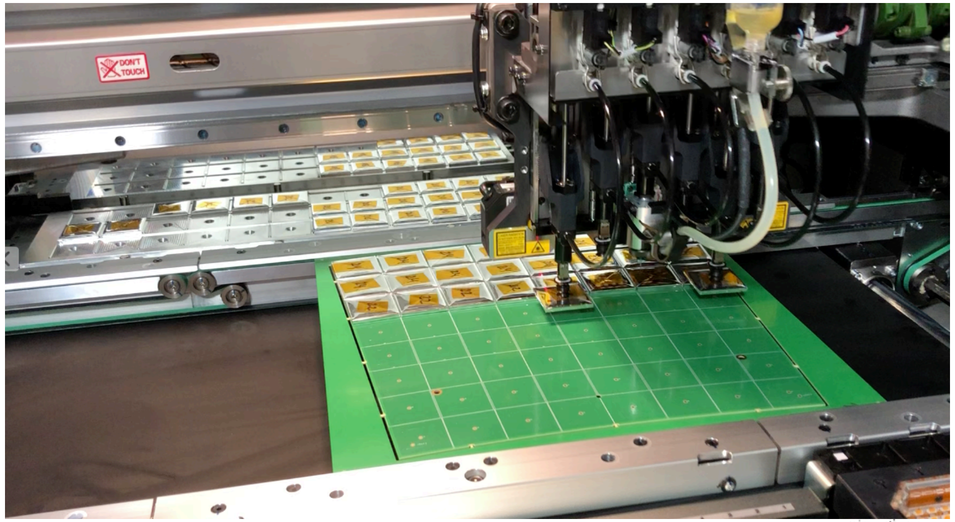


SiPM-on-Tile Technology for HGCAL

- New challenges:
  - radiation levels
  - data rates
  - operation at -30 degrees
  - Many different tile and board sizes

- Adaptation of AHCAL technologies to HGCAL
  - Readout with fast and rad-hard components
  - Careful design for large temperature variations (from assembly to operation)
  - More flexible and robust assembly procedures
    - Tile wrapping
    - Tile glueing





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03

CEPC AHCAL

CEPC Physics goal and PFA

- CEPC Physical Goal
  - Precise measurement of the Higgs particle’ s properties
  - Explores new physics beyond standard model
  - Precise measurement of the electroweak interaction parameters related to W and Z
- Requirements of CEPC calorimeter:
  - high granularity Energy resolution reach 30%/ √ E at jet energy below 100GeV
  - HCal: 60%/ √ E(GeV) ⊕ 4%

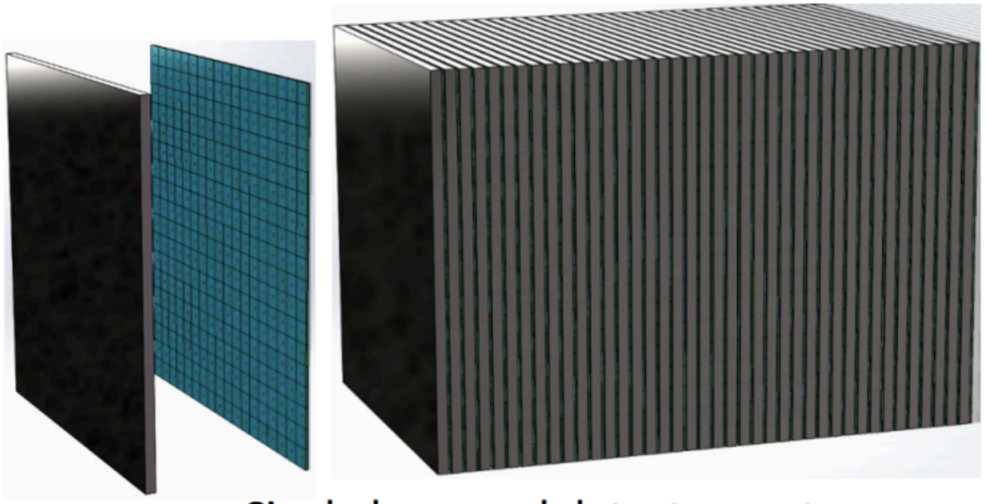
Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	Required for 30%/√E		$\leq 0.24^2\ E_{jet}$

18%/√E

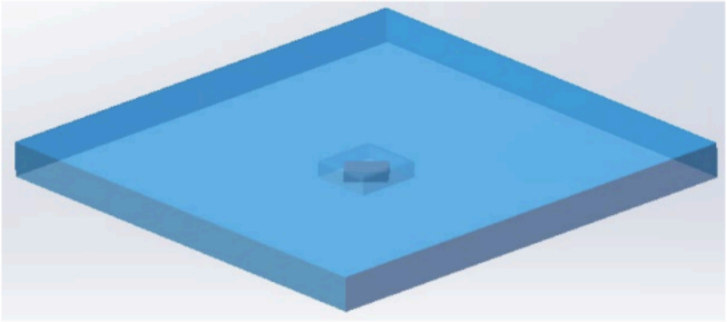
CEPC AHCAL prototype

- The AHCAL task: based on PFA, 60%/ √ E(GeV) ⊕ 4%
  - Designing, building and testing a full AHCAL prototype.

- CEPC AHCAL: SiPM-on-Tile configuration
  - Prototype: 72cm×72cm×100cm with 40 layers
  - PCB: 2mm, with SiPMs, temperature sensors and SPIROC2E based readout system
  - Detector cell size: 40mm×40mm×3mm
  - Detector cell: scintillator made of polystyrene and wrapped in enhanced specular reflector (ESR) films.
  - Active layer: SiPMs + scintillators, 12,960 channel in total Absorber: steel (20mm Fe)



Single layer and detector part



Detector cell of
40mm ×40mm ×3mm

Overall Progress

Participating institutes: USTC+IHEP+SJTU.

Overall Progress:

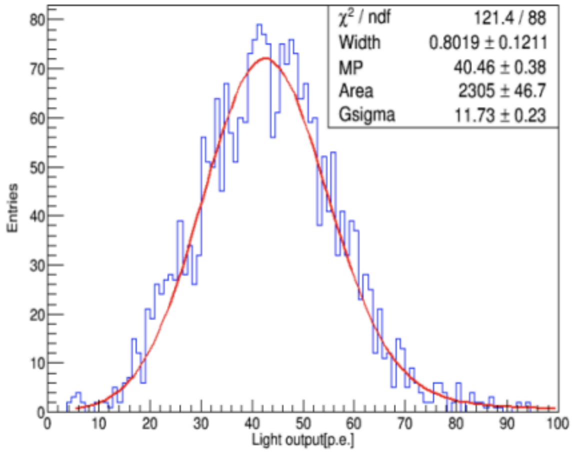
- PFA-based detector simulation tool and completed the design optimization of the AHCAL prototype. (Result from Yukun Shi.) (Finished)
- Boson Mass Resolution: 4%.
- The performance for the AHCAL prototype:
  - Linearity: ±1.5%
  - Resolution: √48% E(GeV) ⊗ 3%
- Injection molding process to produce scintillator tiles. (Finished)
- Scintillator tiles batch testing system. (Finished, more than 14k scintillators qualified)
- SiPMs batch testing system (NDL finished, HAMAMATSU in progress.)
- HBU and DAQ system (in progress.)
- Design of the mechanical structure and cooling (in progress)

Studies on AHCAL sensitive cells

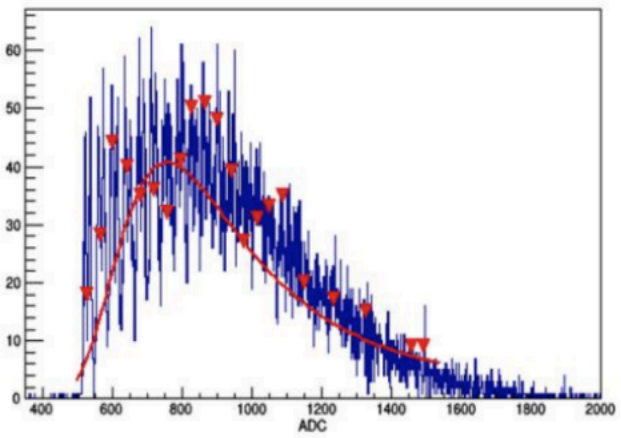
AHCAL sensitive cells progress: (Result from Jiechen Jiang)

- Structure of AHCAL tiles: 4cm × 4cm × 40 layers geometry
- Material of Scintillator: GNKD PS Tiles (injection molding scintillator)
- SiPMs: 35 layer + 5 layer backup HAMAMATSU (S14160-1315PS) + 5 layer NDL (22-1313-15-S)
- 40 sensitive layers, total readout channels: 12,960 (4cm×4cm), 5 backup layers.
- Uniformity testing of AHCAL scintillator tiles: light yield winthin 10%
- deviation Expected the light yield of the scintillator is greater than 40p.e.
- Expected light yield uniformity around ±10%.

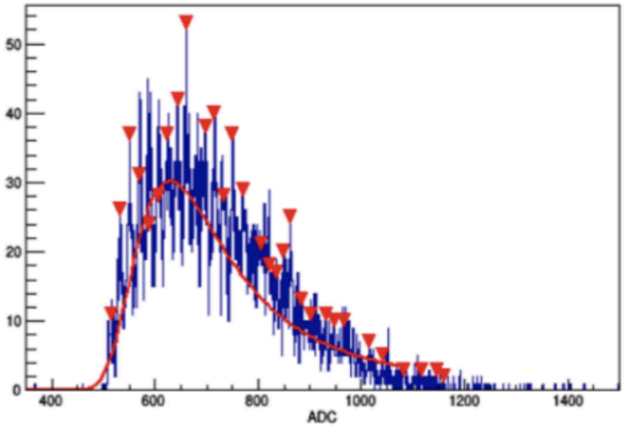
NDL
40 pe/MIP



S13360-1315PE
13 pe/MIP



S14160-1315PS
16 pe/MIP



NIMA 980 (2020) 164481

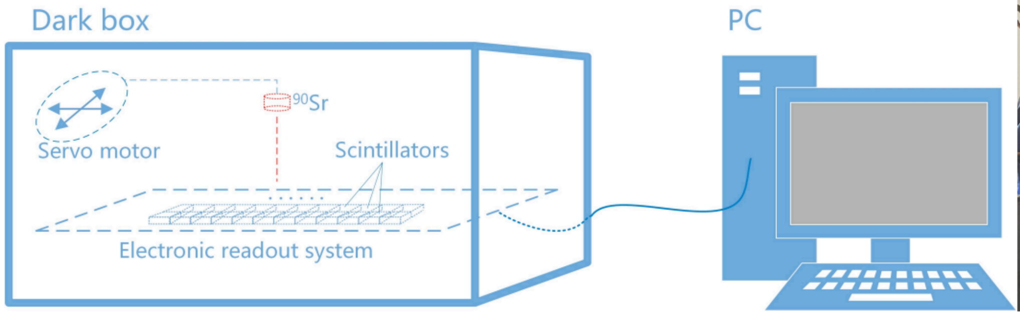
Scintillator tiles batch testing system

JINST15 C10006 (2020)

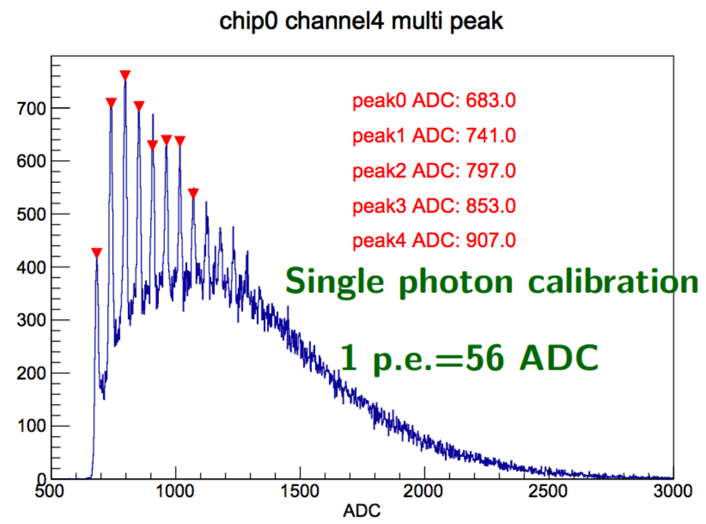
- 3 batch test system in total, USTC + SJTU + IHEP.
- Sr90 (2.28 MeV electron)
- 4 SPIROC2E+ 144 SiPMs (S13360-1325PEs)+FPGA in DIF
- Calibration and light yield measured by batch test system:

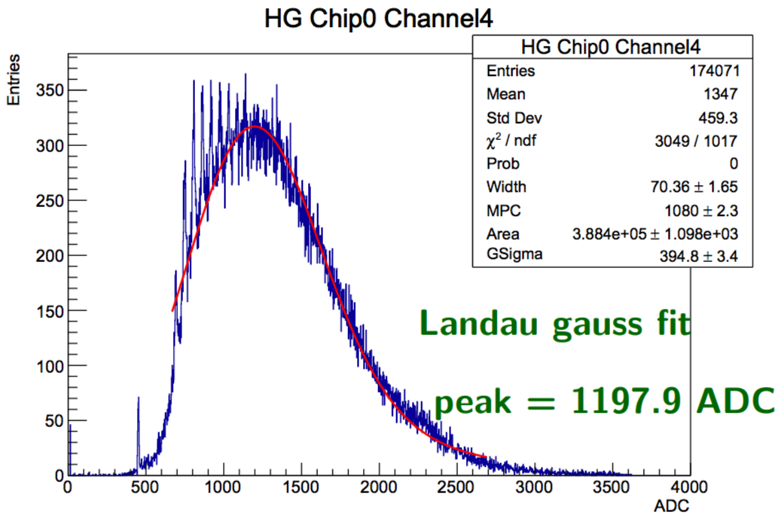
$$LY = \frac{ADC_{MIP} - ADC_{baseline}}{Gain_{SinglePhoton}} (perMIP)$$

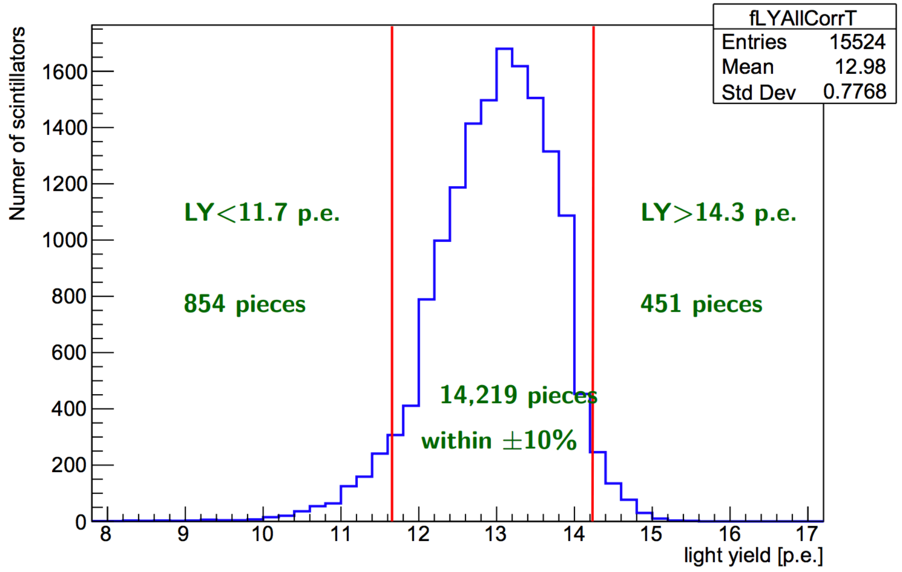
https://arxiv.org/submit/4014265/view

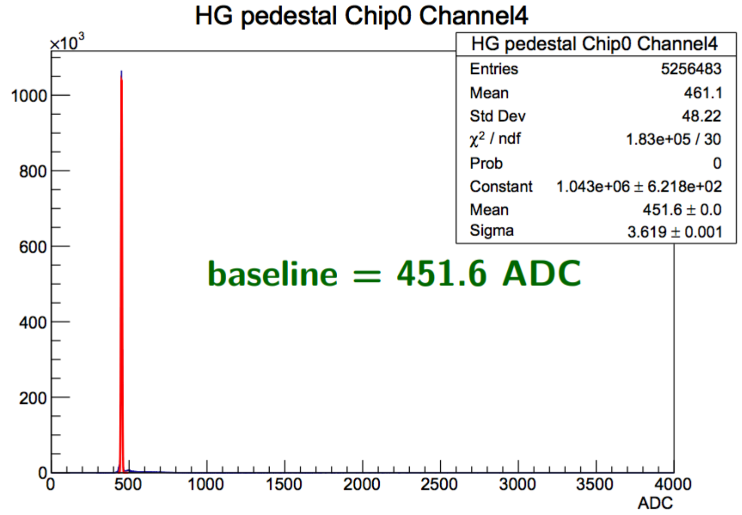


Batch test result - light yield









$$LY = \frac{ADC_{MIP} - ADC_{baseline}}{Gain_{SinglePhoton}}(perMIP) \qquad (2)$$

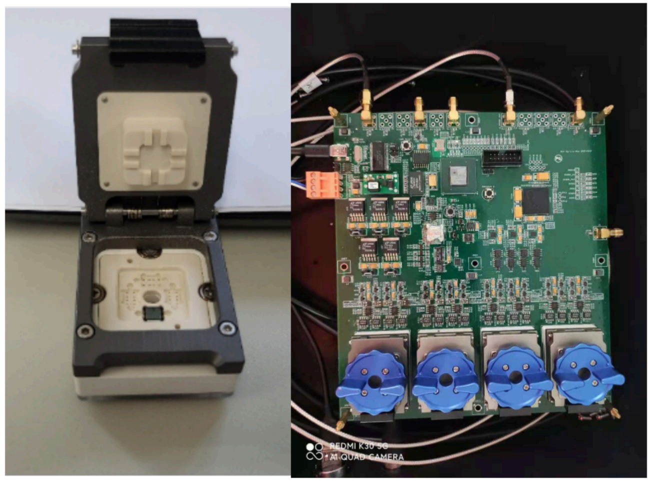
LY=(1197.9-451.6)/56=13.33p.e.

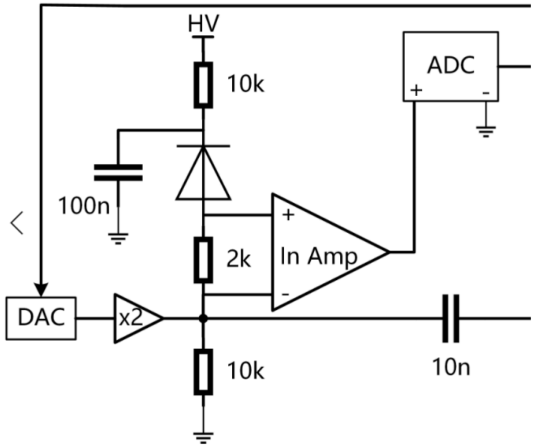
About 91.6% of scintillators are qualified within 10% of LY window.

SiPM Batch Test

SiPM Batch Test: (Result from Yukun Shi)

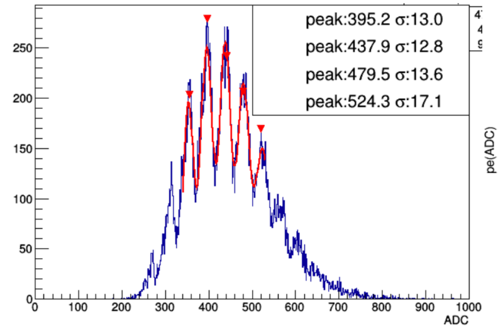
- 16 channels, SKIROC + discrete-circuit readout.
- One LED for 4 SiPMs calibration.
- Determine working voltage:
  - Single photon separation with LED
  - Operating at best SNR
- DCR and gain control
  - SiPM with too high DCR should be abandoned
  - Uniformity of SiPMs’ gain should be controlled
- NDL SiPMs test finished, HAMAMATSU SiPMs in progress.

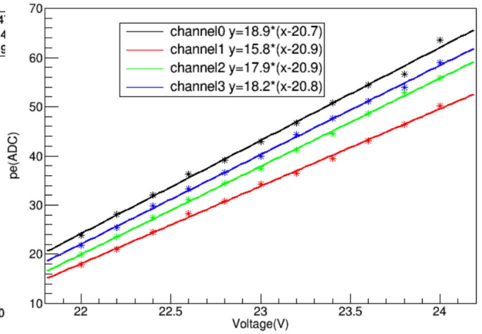




NDL SiPM test: (Result from Yukun Shi)

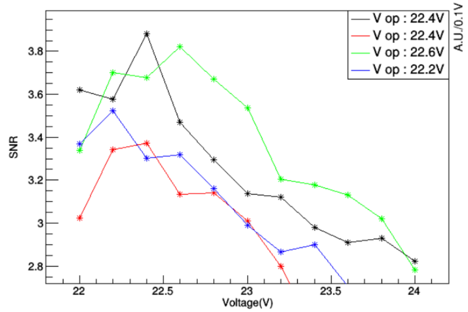
- Different working voltage has been scanned
- Linear fit is used for the V-gain plots
- V break down is defined as the x intercept

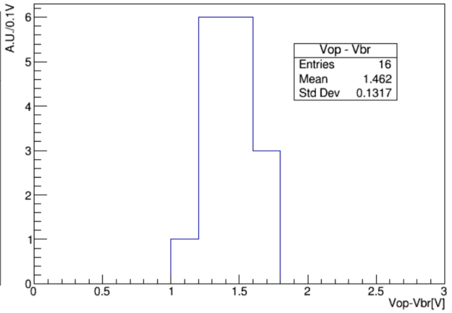




NDL SiPM test: (Result from Yukun Shi)

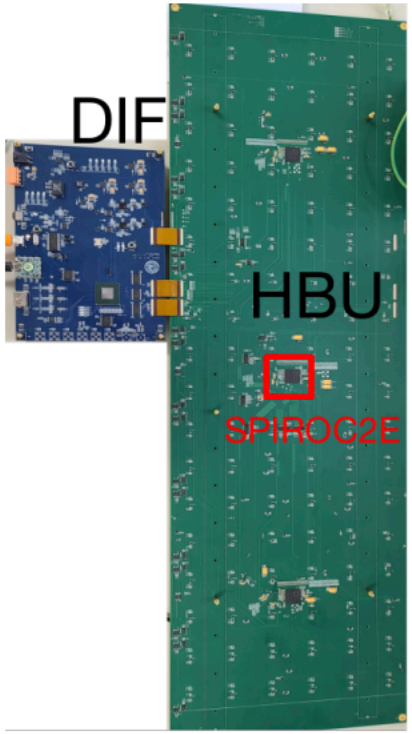
- The SNR is defined as peak/σ
- The V operation is the working voltage with best SNR
- The Vop is generally 1.5V larger than Vbr





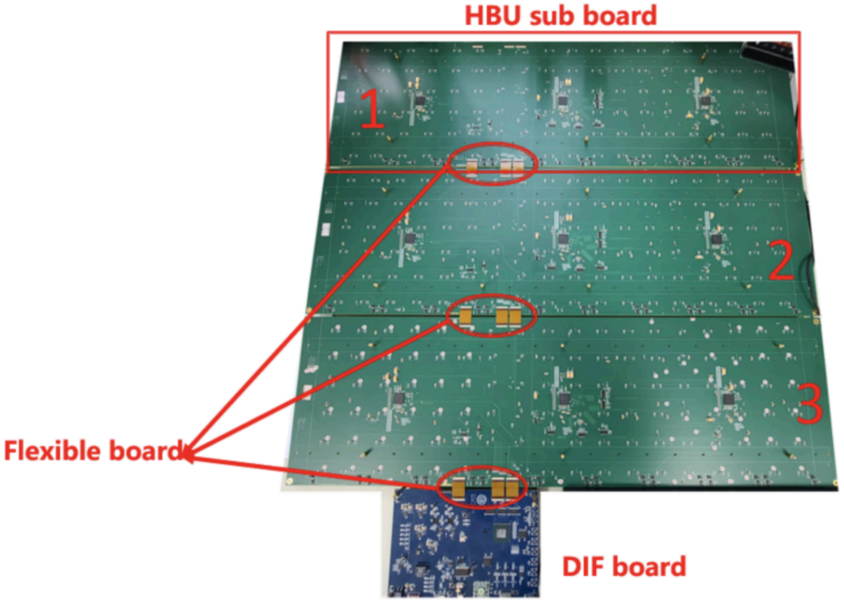
In progress…

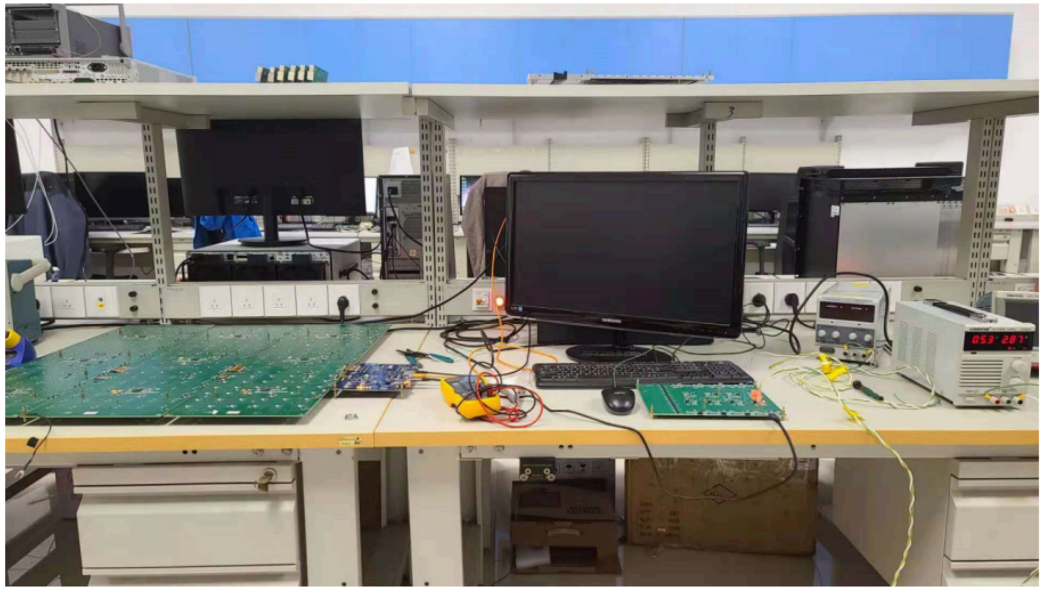
AHCAL readout electronics and DAQ



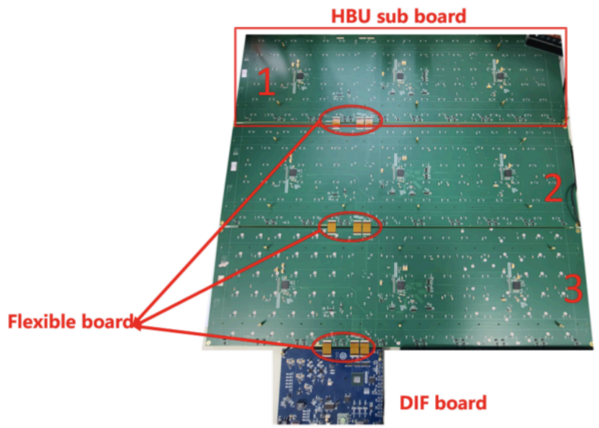
Result from Zhongtao Shen

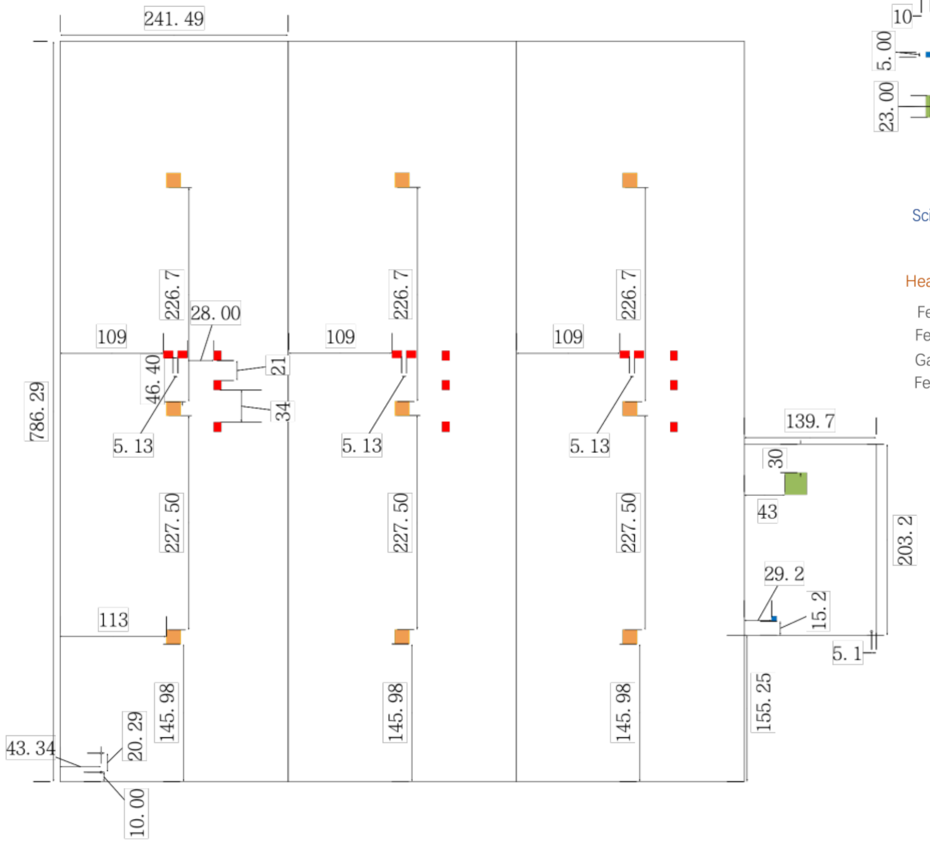
- ASIC design: 9 SPIROC2E HBU design: 18×18 =324 readout channel per layer
  - The function of signal readout, electronics calibration, light calibration and temperature monitor.
- DAQ system development: FELIX card+DAQ board+DIF (Data Interface) boards+HBU

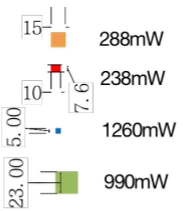


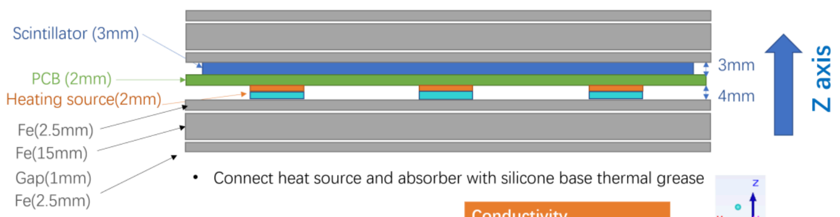


HBU consumption and cooling simulation







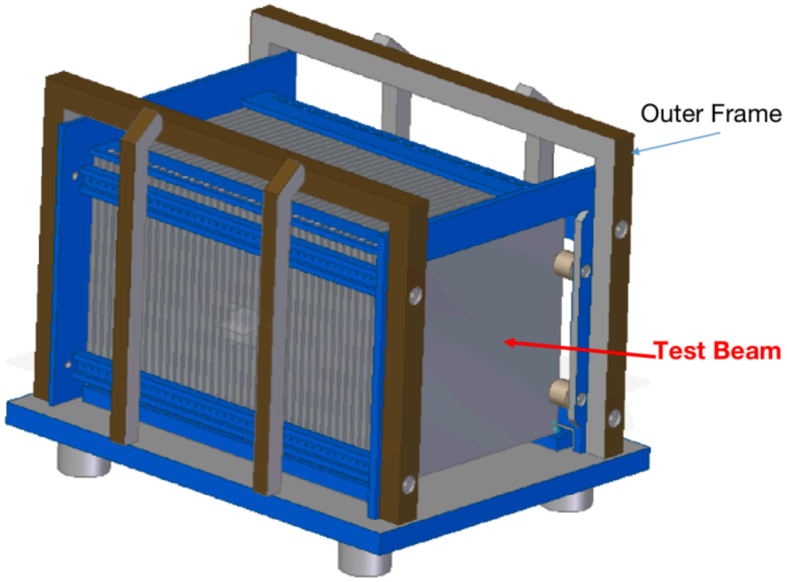


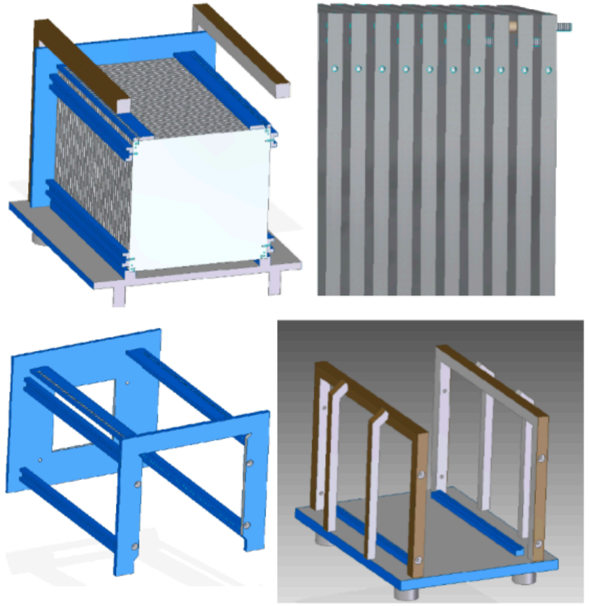
- Connect heat source and absorber with silicone base thermal grease

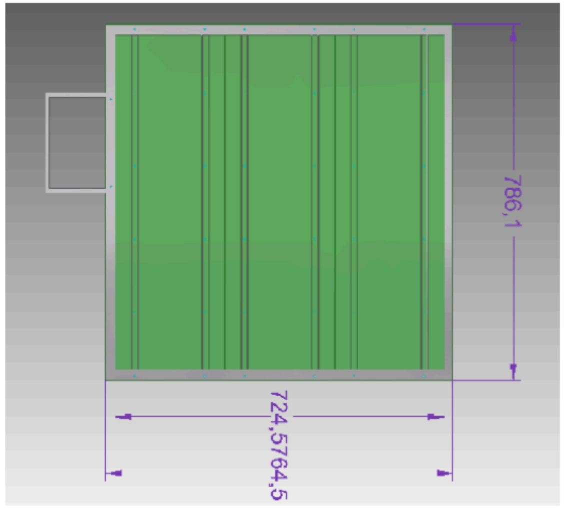
Conductivity
1W/m-K

The power consumption of the current version of HBU is about 10W.

CEPC AHCAL mechanical structure







Summary of CEPC AHCAL Prototyping Progresses

Sensitive cells and Detector:

- Scintillator tile: GNKD PS Tile, batch testing finish, 91.6% pieces are quanlified within 10% of LY window.
- SiPM: 35+5 layer HMAMMATSU (S14160-1315PS) batch testing in progress, 5 layer NDL (22-1313-15-S) batch testing finished.
- Design, assembling and production of sensitive layers in progress.

Electronics:

- Developed HBU.
- Production of HBU and DAQ boards in progress.

Mechanical part:

- Design of absorb layers and supporting structure.
- Design of cooling system based on simulation result.

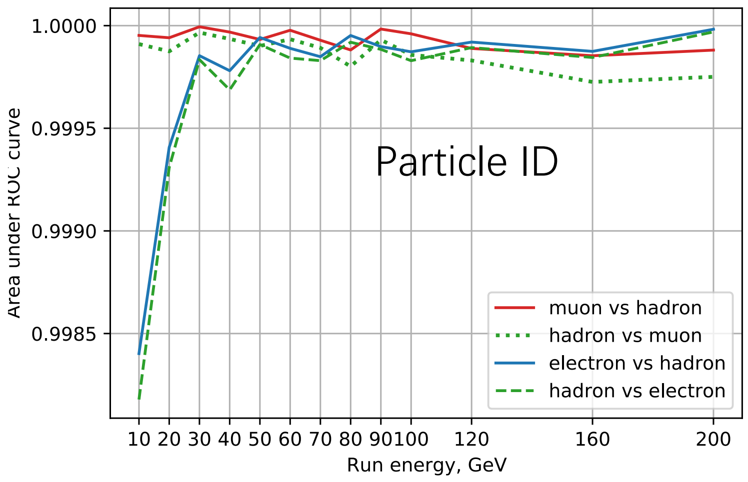
AHCAL Prototype status

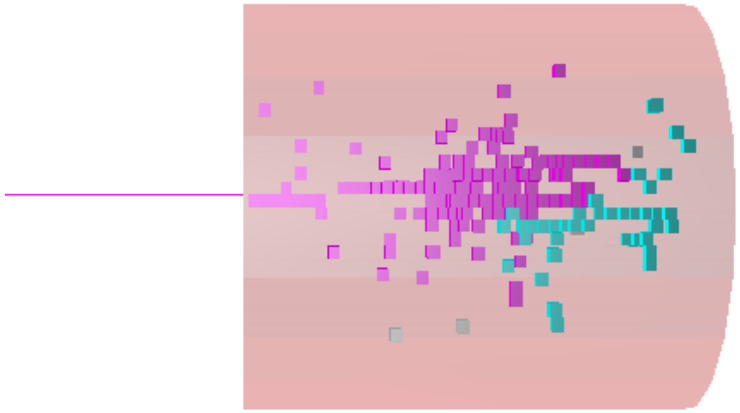
- The prototype construction will start from the end of this year.
- The cosmic and beam test is expected next year.

Backup

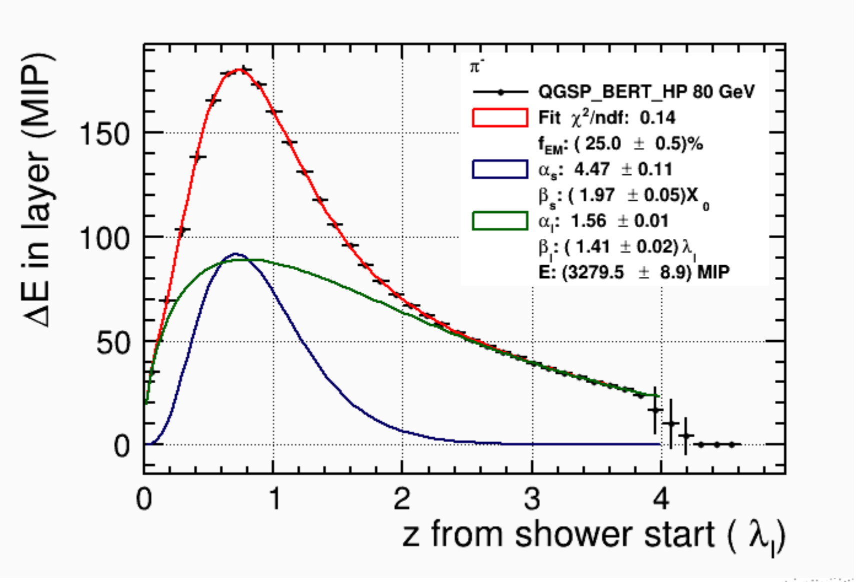
AHCAL Technological Prototype: Ongoing Analyses

- High granularity offers detailed look into hadron showers
- Used in particle ID based on Boosted Decision Trees
- Studies of shower shapes
- Application of the PandoraPFA Particle Flow Algorithm





Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits



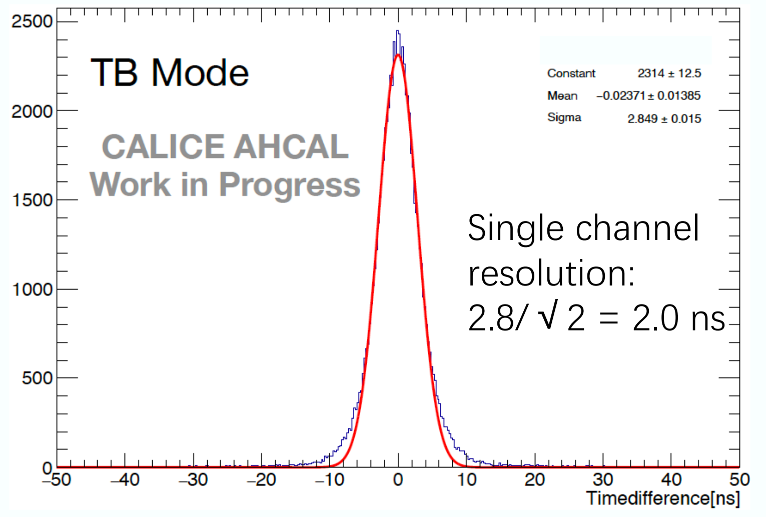
AHCAL Prototype: Hit Time Measurement

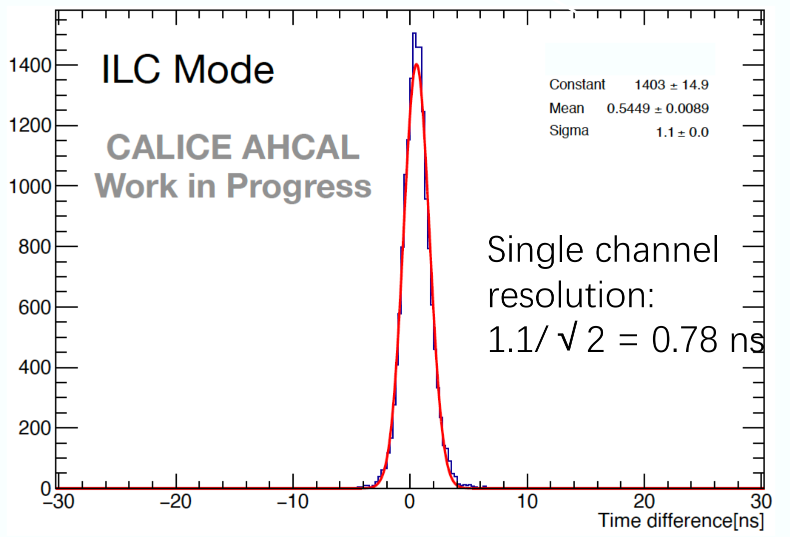
New feature in AHCAL technological prototype: time measurement for individual hits

- Design resolution: ~1 ns
- SPIROC2E readout ASIC supports 2 bunch clock speeds
  - Testbeam mode: 250 kHz clock
    - More efficient for data taking in testbeams
    - Worse hit time resolution: ~2ns
  - ILC mode: 5 MHz
    - Adapted to ILC bunch structure
    - Better hit time resolution: ~0.8 ns

- Full exploitation in data analysis just started

- Most testbeam data so far taken in testbeam mode





CEPC AHCAL HBU Electronics Test

The pedestal and charge calibration results mean that the chips are working normally.