R&D progress of high granularity HCAL for CEPC

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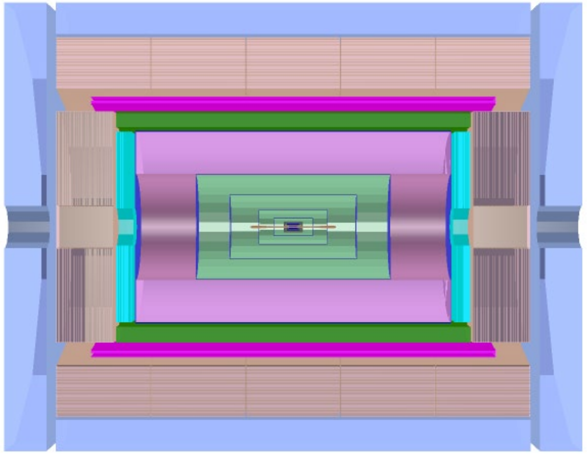
On behalf of the CEPC Calorimeter Working Group

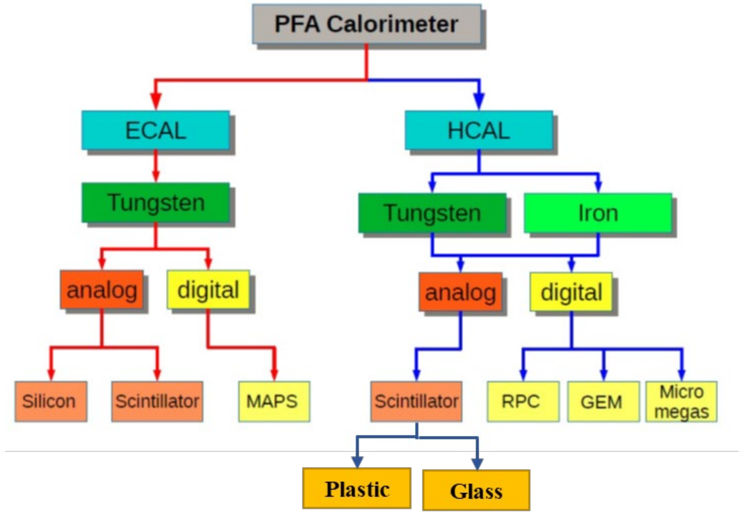
Outline

- Motivation
- Progress of High granularity HCAL based on PFA
  - (Semi-)Digital HCAL
    - GRPC
    - THGEM
  - Analog HCAL
    - Plastic Scintillator + SiPM
    - Glass Scintillator + SiPM (New Option)
- Summary

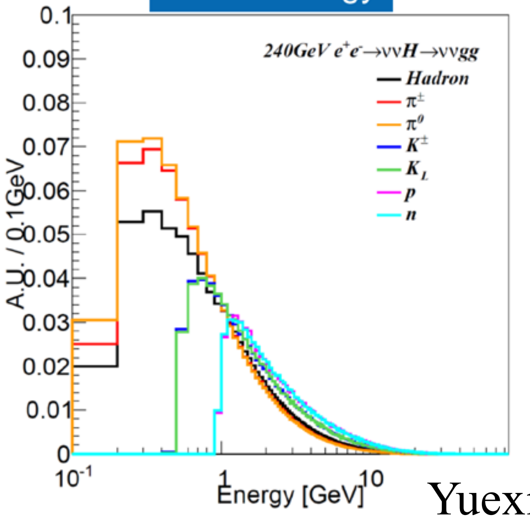
1. Motivation

- CEPC physics benchmarks: Higgs and W/Z bosons
  - ~ 70% Higgs decay directly into jets ($b\bar{b}$, $c\bar{c}$, gg) and ~ 22% indirectly decay into jets (WW^*, ZZ^*), which include abundant hadrons (< 10 GeV)
  - Precision measurement of Higgs/Z/W bosons with jet energy resolution ~ $30\%\sqrt{E}$
- Key Point: high granularity calorimeter + particle flow algorithm (PFA)
  - Semi-digital readout based on RPC or GEM
  - Analog readout based on plastic or glass scintillator



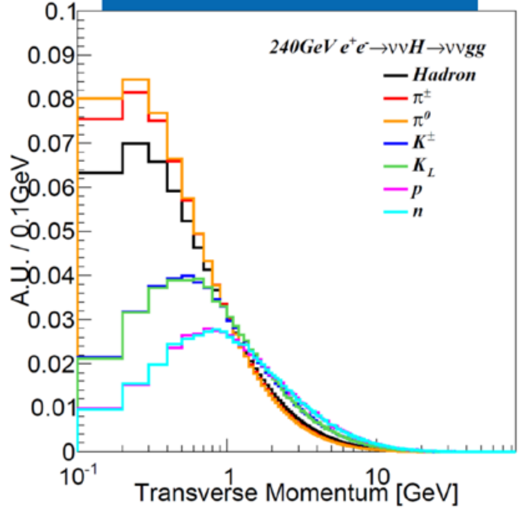


Kinetic energy



Yuexin Wang (IHEP)

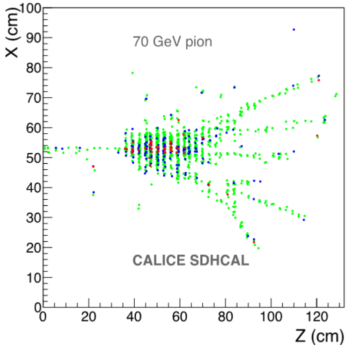
Transverse Momentum

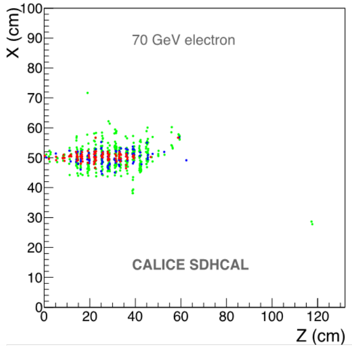


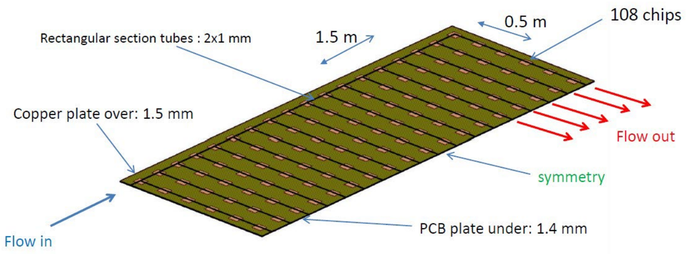
2.1 SDHCAL-GRPC

- Prototype of semi-digital HCAL
  - 48 glass RPC layers with a thickness of 28 mm
  - 1x1 mm^2 cell, ~440k readout channels
  - Semi-digital readout, 3 tunable energy thresholds: 0.1/5/15 MIP
  - Optimize hadronic shower reconstruction via choice of thresholds
  - Better linearity response, improved energy resolution
- Circular colliders (CEPC) expect power consumption 100-200 times larger than ILC
  - Active cooling needed (water cooling using cooper pipes)
  - and/or new readout schemes as woven strips (work in progress)
- RPC-SDHCAL prototype has been exposed to beam particles at CERN PS, SPS in 2012, 2015, 2017 and 2018

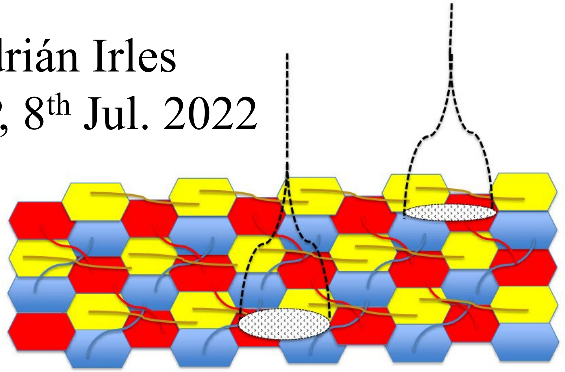
◆ SJTU working with IPNL, Tsinghua and other groups within CALICE on RPC-SDHCAL as part of CEPC detector R&D effort





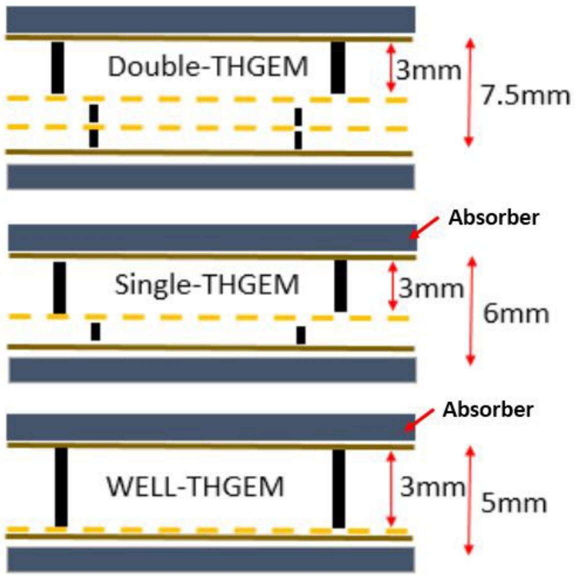


Adrián Irles
ICHEP, 8th Jul. 2022

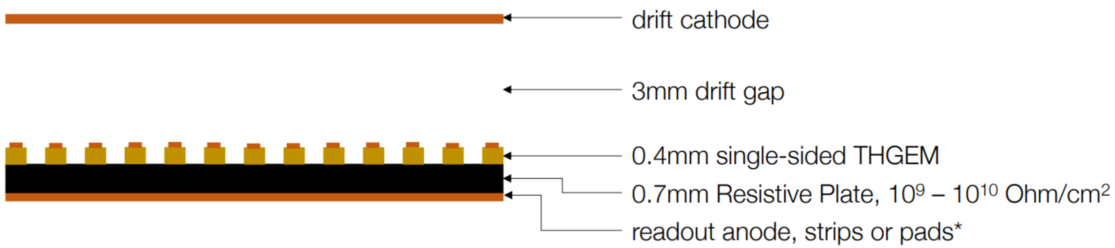


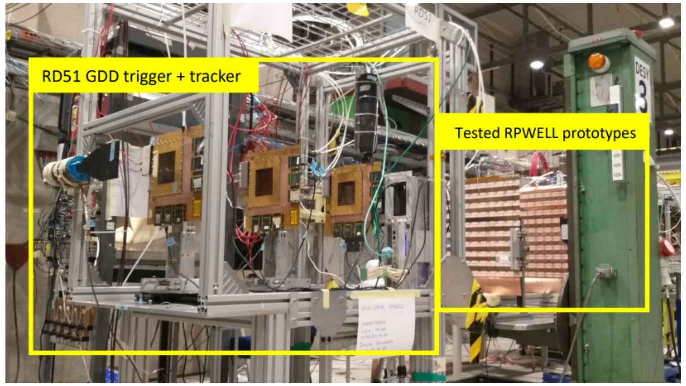
2.2 DHCAL-THGEM

- An alternative option for DHCAL
  - Assembling process is easy and fast, minimum dead area, uniform gas flow
  - Three structure options are available: Single/Double/Well THGEM



- 50x50 cm^2 Resistive Plate WELL (RPWELL) prototypes has been developed and tested in 80 GeV muon beam
  - Detection efficiency and response uniformity were measured



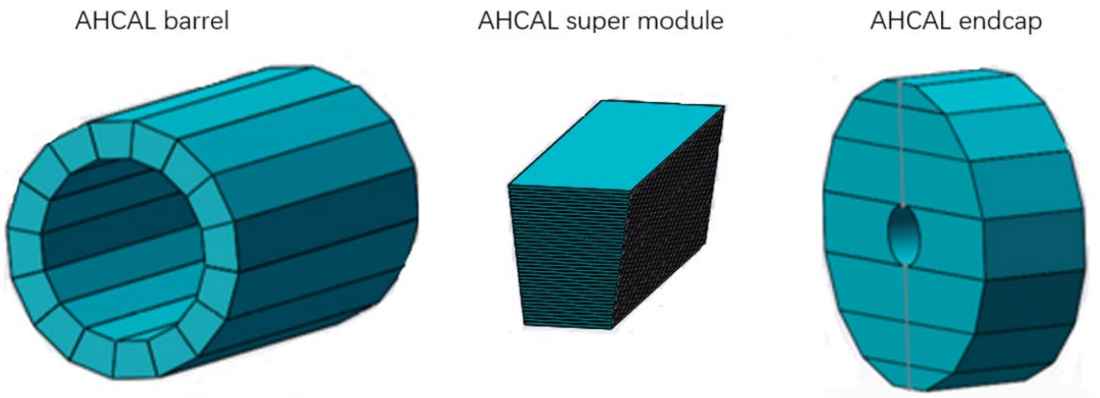


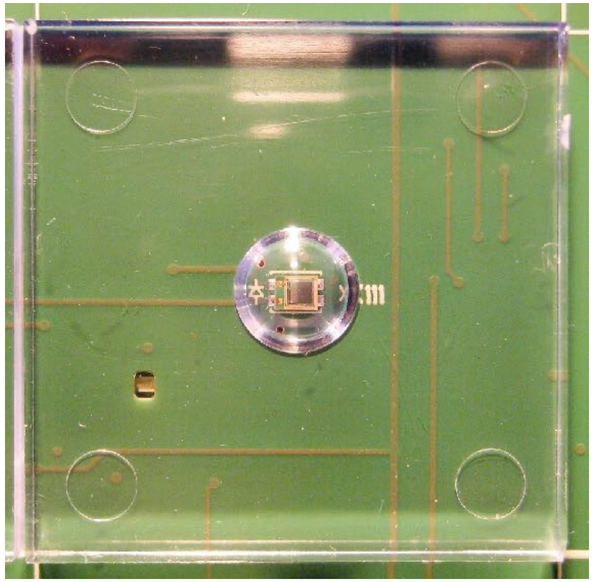
Darina Zavazieva (WIS)

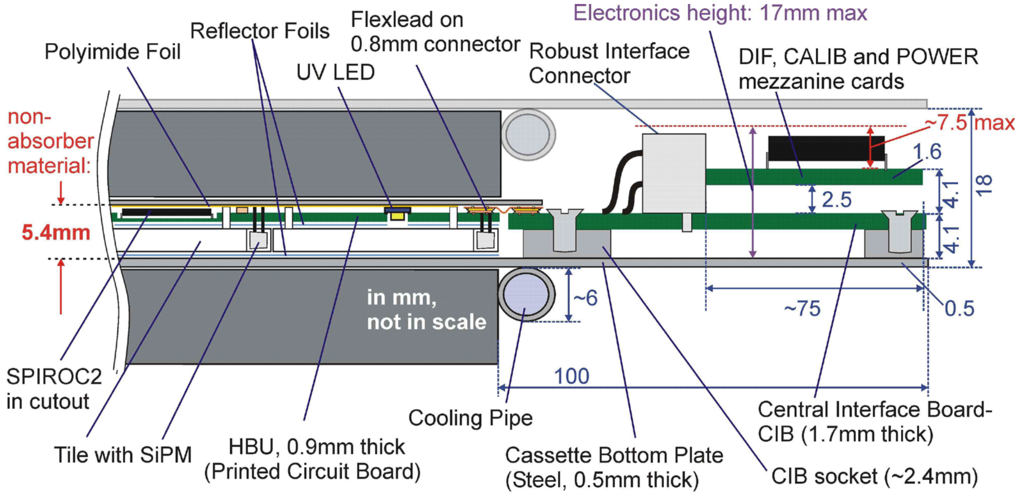
- Muon beam, E = 80GeV;
- RD51 GDD 6cm^2 trigger + tracker: 3 SCs, 3 Micromegas;
- Two 50x50 RPWELL prototypes were tested;
- DAQ: APV25 SRS;
- The goal was to assess the uniformity of the detectors' performance over the entire area;
- 100 points of ≈5cm^2 were scanned

2.3 AHCAL-Plastic Scintillator

- Analog hadronic calorimeter based on plastic scintillator tiles
  - About 40 sampling layer in total
  - Readout with “SiPM-on-Tile” design (Hamamatsu or NDL)
  - Absorber layer: 2 cm stainless steel (0.12 λ_I, 1.14X_0)
  - Transverse segmentation ≥ 3x3 cm^2 (to be optimized)
  - ASIC Readout chip: to be clarified (SPIROC2E, KLauS)





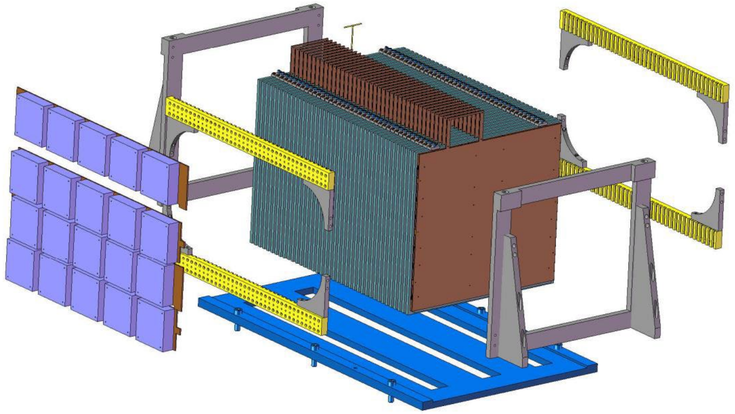


2.3 AHCAL Prototype for CEPC

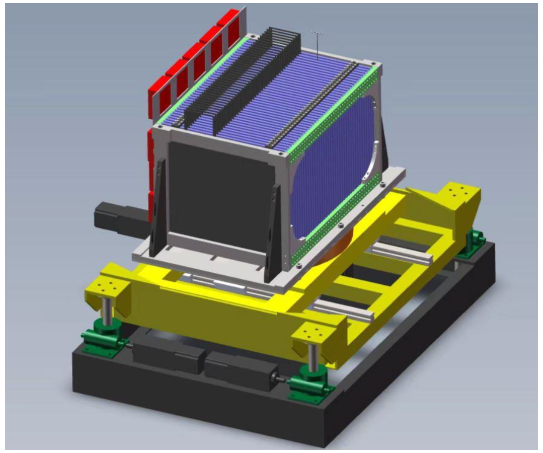
- AHCAL prototype development
  - 40 sampling layers with transverse size 72x72 cm^2
  - Sandwiched structure with steel absorber + scintillator layers
  - Front-end electronics fully integrated
  - Scintillator tile size: 40×40×3 mm3
- Mechanics
  - Single layer: steel cassette to fix flexible PCB and improve stability + light isolation

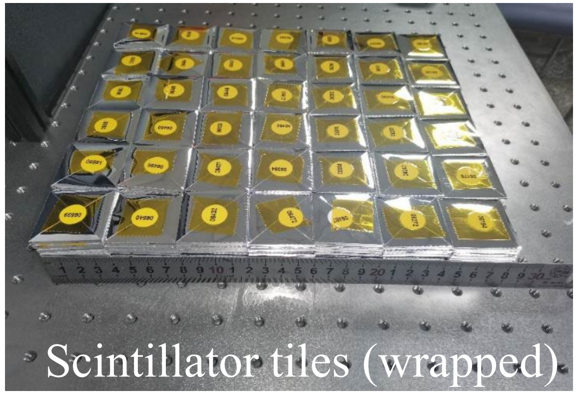
➢ **Preparing for beam test in Oct.**
  - Beam time: 2 weeks at SPS (H8) at CERN
  - ECAL+HCAL prototypes

CEPC-AHCAL prototype structure

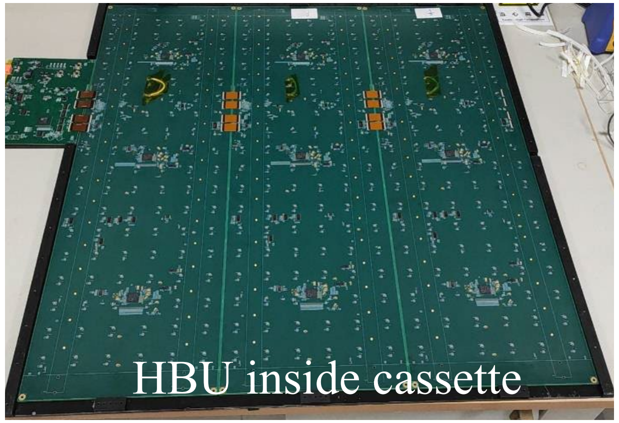


Supporting table designed for beam test





Scintillator tiles (wrapped)



HBU inside cassette

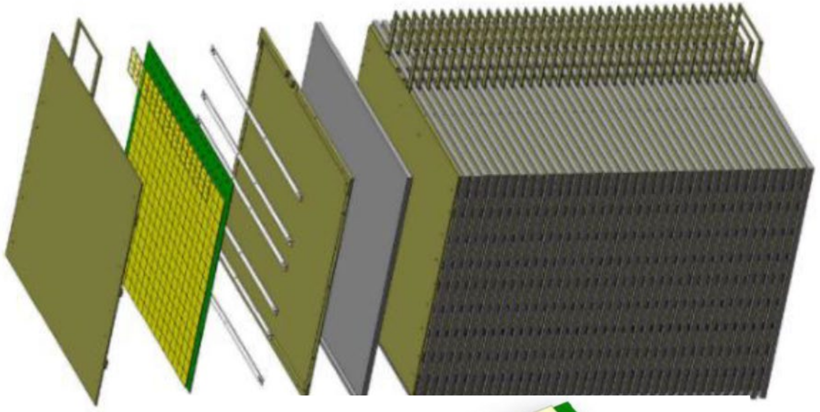
2.4 AHCAL-Glass Scintillator

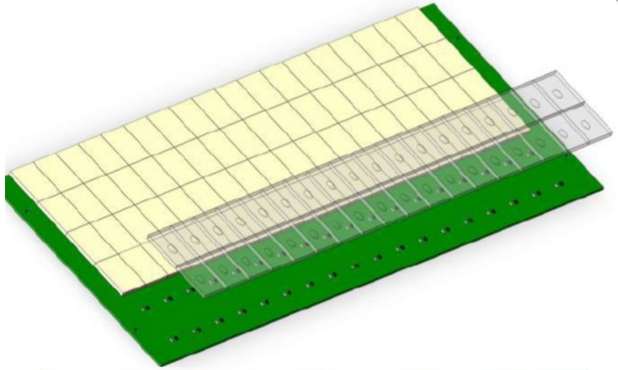
- **Glass Scintillator: An alternative option for AHCAL**

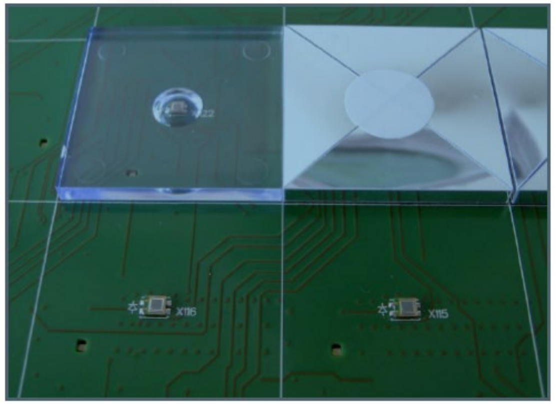
- Advantages of glass scintillator
  - Simple preparation process, low cost, continuously adjustable composition and performance
  - Excellent shaping and processing performance
  - Easy for mass production and large-scale production

- Glass Scintillators are good candidate for the next generation HCAL
  - Higher density provides higher energy sampling fraction excellent shaping and processing performance
  - Certain doping to enhance neutron capture: improve hadronic response (Gd)
  - More compact HCAL layout (given 4~5 nuclear interaction lengths in depth)

- Ongoing R&D
  - Geant4 simulation for the target parameters of glass scintillator
  - Adjusting the composition of glass scintillators to improve the properties





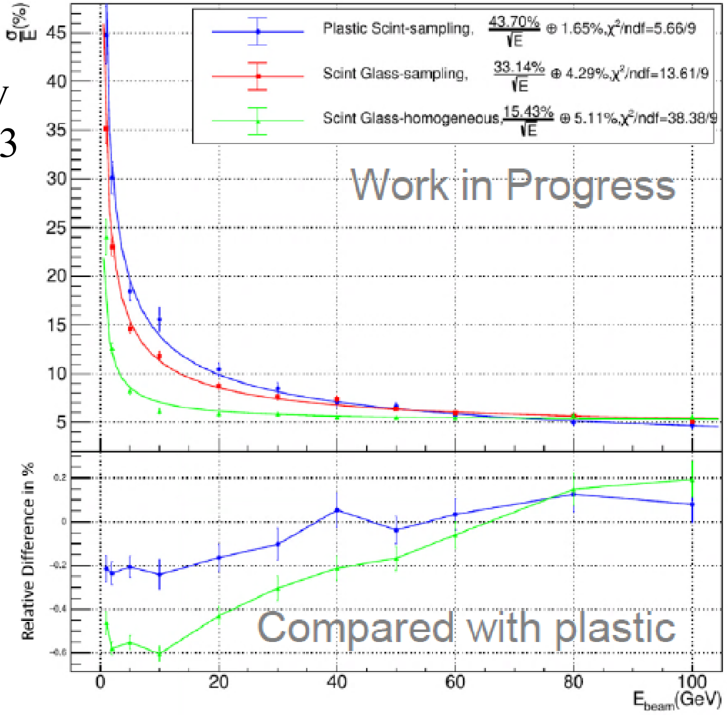


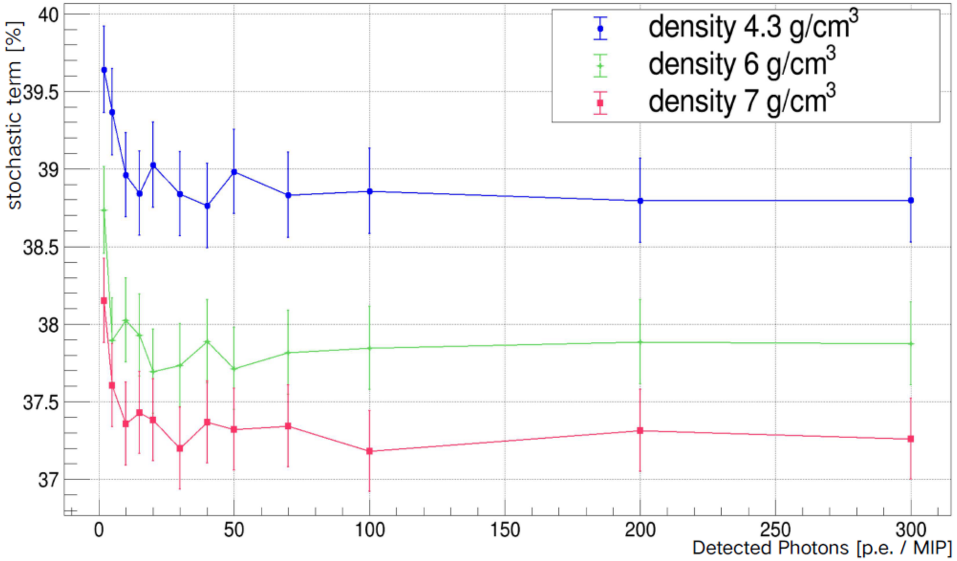
2.4 Simulation with Simplified HCAL Geometry

Dejing Du (IHEP)
LiShuang Ma (IHEP)

- Simplified HCAL Geometry
- transverse 108x108 cm^2, 3x3 cm^2 cell
- 60 longitude layers (3mm scintillator, 2.1mm PCB, 20mm steel)
- incidence with K_L^0 and no threshold applied
- Glass Component: B-Si-Al-Gd:Ce+, 4.94 g/cm^3

An ideal HCAL setup with minimum leakage

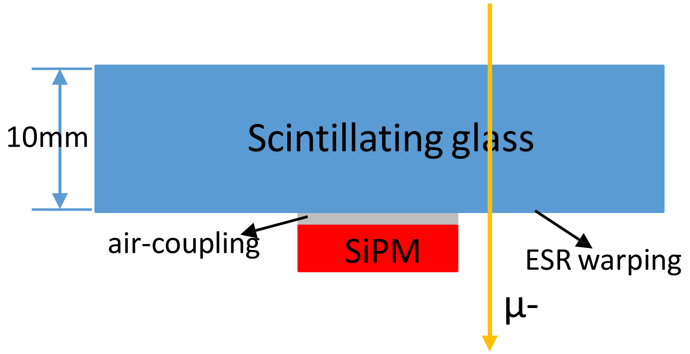




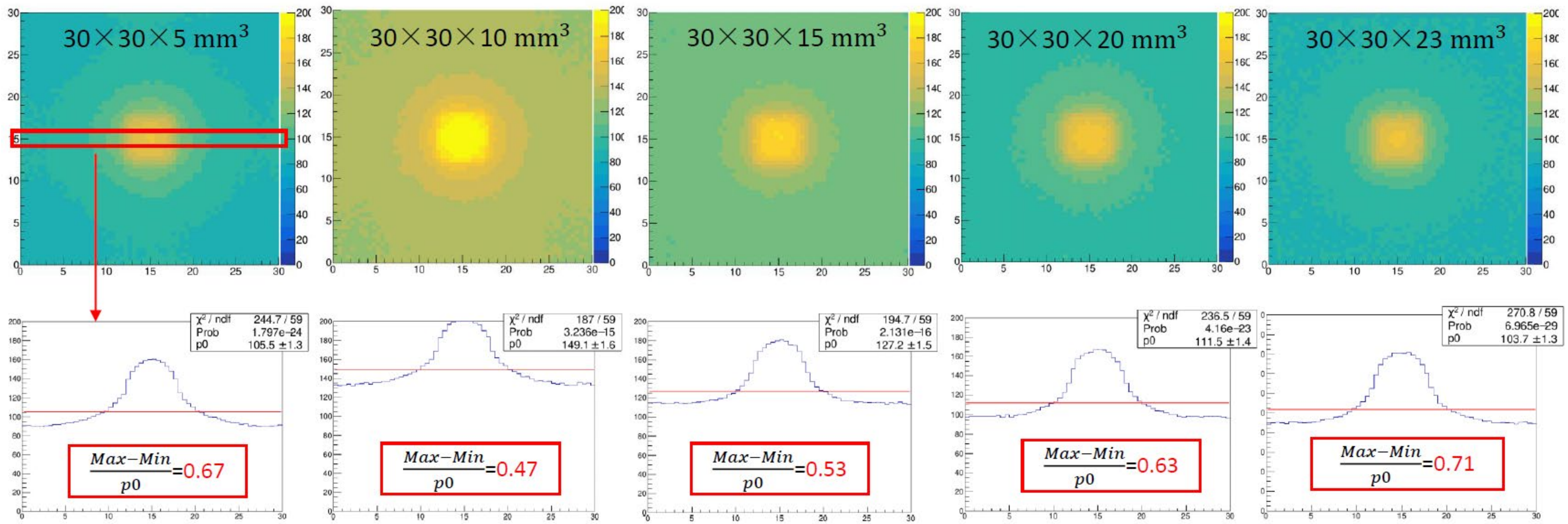
- Comparing HCAL performance of scintillating glass + stainless steel
  - Replace plastic scintillator tiles to increase energy sampling fraction
  - Varying density and light output of glass to search for optimized parameters
- Potentials: Geant4 simulation with single hadrons (preliminary results)
  - Better hadronic energy resolution in low energy region <30GeV

2.4 Glass Cell Simulation

- Response uniformity in different hit position based on Geant4 simulation
  - Assumption: larger tile properties remain the same as small samples
  - Optimal thickness is ~10mm, considering response and uniformity
  - Required to develop scintillating glass tiles with thickness ~10 mm
  - Uniformity can be further optimized with new tile designs



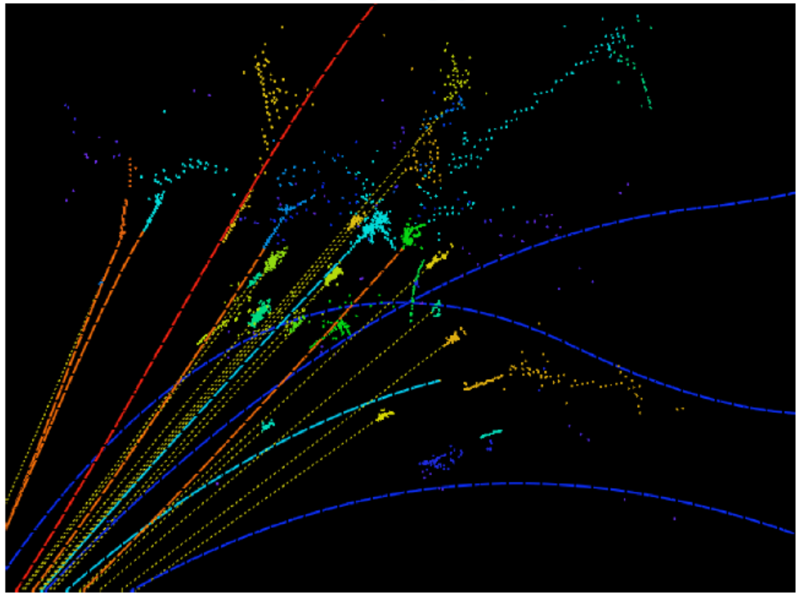
Dejing Du (IHEP)

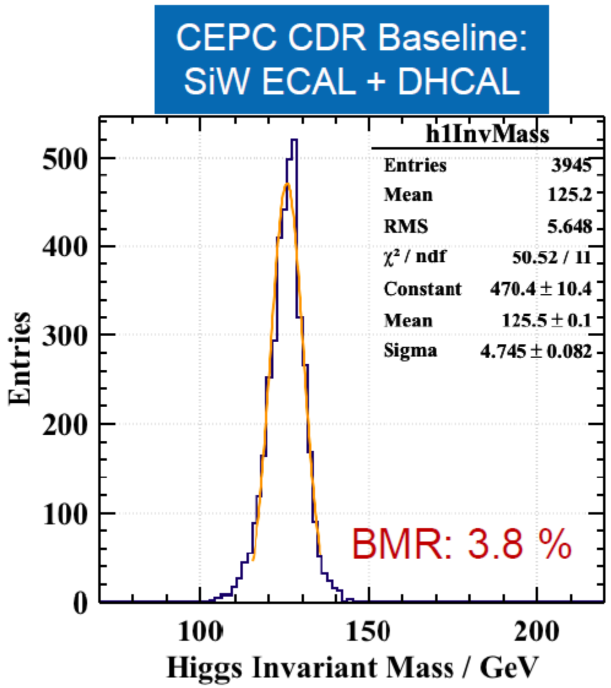


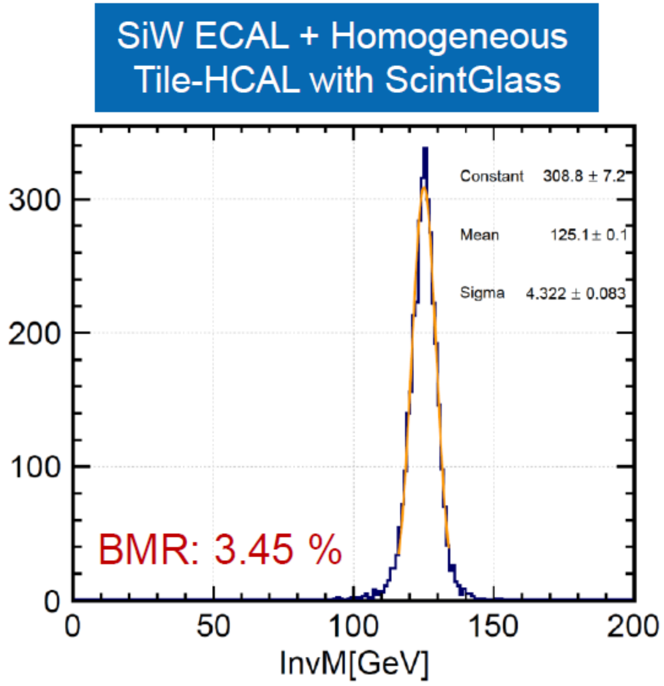
2.4 Simulation within CEPCSoft Framework

Dan Yu (IHEP)

$ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV





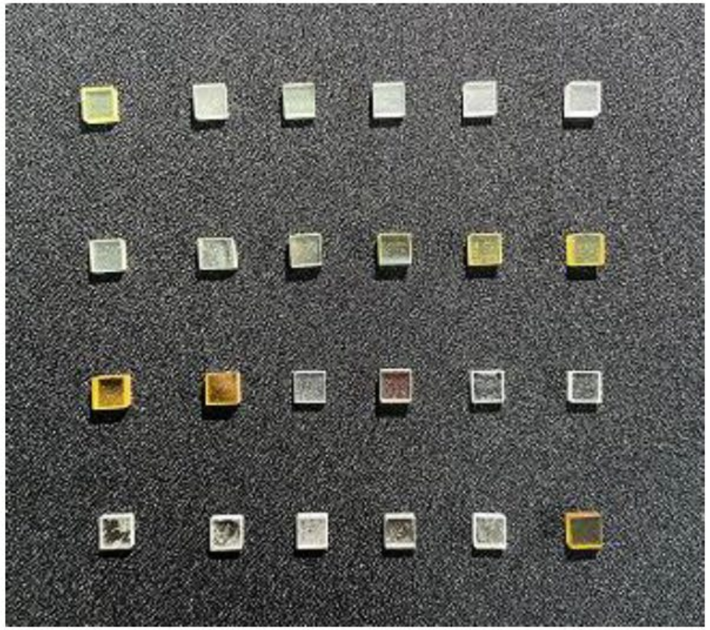


- ☐ Jet performance with an ideal homogenous glass scintillator HCAL within CEPC_v4 (preliminary results)
  - Around 10% improvement of BMR (boson mass resolution) for homogenous glass HCAL (~3.4%), w.r.t baseline HCAL design (~3.8%), through Baseline Arbor with hit energy threshold cut and calibration tuning
  - Expect further improvements: e.g. optimization of PFA, software compensation, etc.

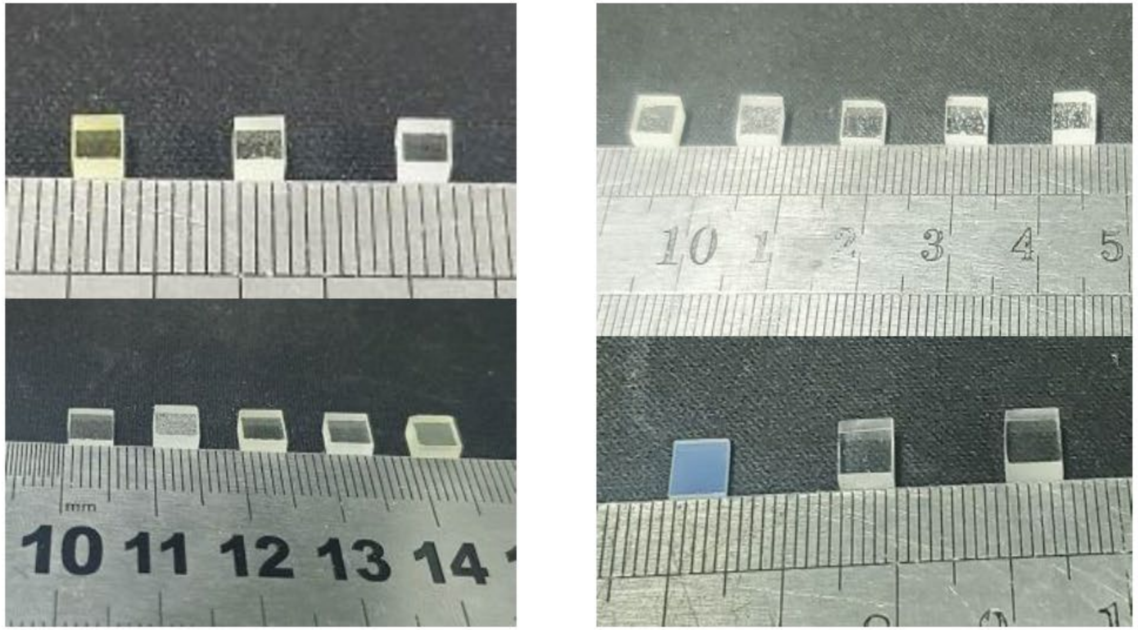
2.4 Key Parameters and Current Design Goals

Key parameters	Value	Remarks
Tile size	$30\times30\ \mathrm{mm}^2\sim40\times40\ \mathrm{mm}^2$	Transverse granularity, number of channels
Tile thickness	~10 mm	Energy resolution, uniformity and MIP response
Density	6-7 $\mathrm{g/cm}^3$	More compact HCAL structure with higher density
Intrinsic light yield	1000-2000 pho./MeV	Higher intrinsic LY can tolerate lower transmittance
Transmittance	~75%	
MIP light yield	~150 p.e./MIP	Needs further optimizations: e.g. SiPM type, SiPM-glass coupling
Energy threshold	~0.1 MIP	Higher light yield: helpful for a lower threshold
Scintillation times	~ 100ns	Pile-up events at high luminosity (e.g. CEPC Z-pole)
Scintillation spectrum	Typically 350-600 nm	To match SiPM PDE and transmittance spectra

2.4 R&D of Glass Scintillator



First stage glass scintillator samples
(2021.11-2022.02)



Second stage glass scintillator samples
(2022.02-2022.04)

- ☐ Over 30 pieces of glass in the first stage have been tested, the scintillating performance of most glasses is poor
- ☐ In the second stage, the research was focused on glass scintillators with better performance
- ☐ In addition to high light yield aluminosilicate glasses, glass ceramics also exhibit very good scintillation properties.

More details in Yao Zhu “Research Progress of The Glass Scintillator” (2022/08/10)

Brief Comparison of HCAL Options

- Better jet energy resolution: better pattern recognition + better intrinsic energy resolution

HCAL Option	GRPC DHCAL	THGEM DHCAL	Plastic Scintillator AHCAL →	Glass Scintillator AHCAL
Advantages	1.Excellent efficiency 2.Good homogeneity 3.Fast timing performance 4.Very fine lateral segmentation		1. Relatively high intrinsic hadronic energy resolution 2.Larger cell size, thus less readout channel and simpler design	1.Higher sampling fraction and better jet energy resolution(<30 GeV) 2.Doping to enhance neutron response 3.More compact structure
Shortages	1.Huge number of electronic channels (complicated readout design) 2. Poor intrinsic hadronic energy resolution		1.Decreased granularity will degrade jet energy resolution	1.Many efforts needed to explore optimal component

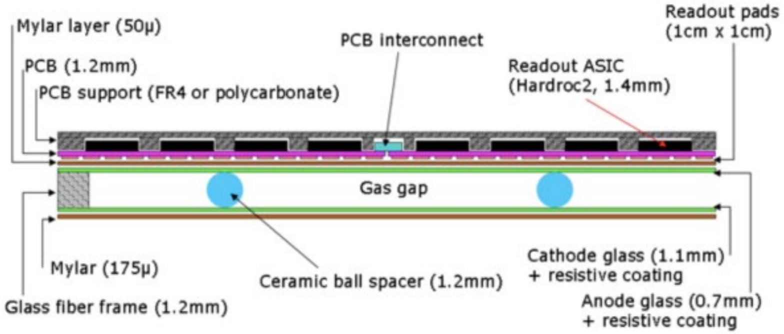
3. Summary

- SDHCAL prototype based on GRPC and THGEM scheme have been constructed and tested in the beam line
  - The excellent performance of CALICE SDHCAL prototype based on GRPC has been confirmed by pion beam
  - SDHCAL prototype based on THGEM was developed by WIS and tested in muon beam, some preliminary results were obtained and further analysis are needed
- Development of AHCAL prototype based on plastic scintillator will be finished and tested in CERN SPS this Oct.
- New AHCAL option based on glass scintillator has been proposed and shows good potential to further improve the BMR
  - Many advantages for AHCAL performance and mass production
  - good potential to further improve the BMR compared with plastic scintillator
  - Ongoing R&D within glass scintillator group

Backup

SDHCAL-GRPC

- CALICE SDHCAL prototype has been exposed to hadron beams in both the CERN PS and the SPS beamlines from 3 GeV to 80 GeV in 2015
  - The BDT-based PID technique was applied to select pure hadron samples by rejecting the muon and electron contamination
  - The response linearity and the energy resolution of the SDHCAL was obtained, which confirms the excellent performance of this prototype



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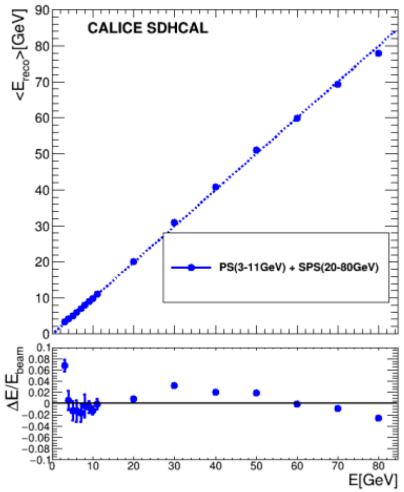
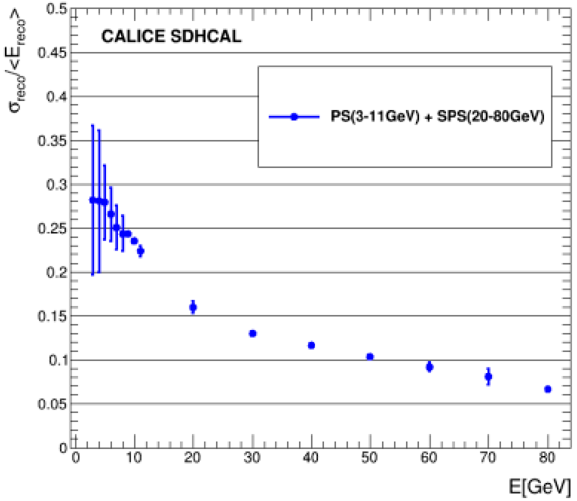
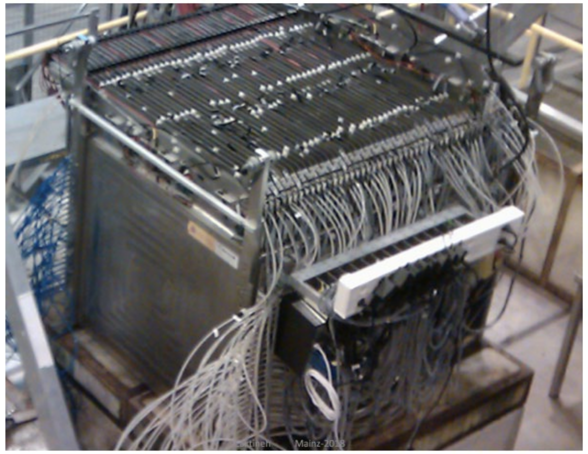


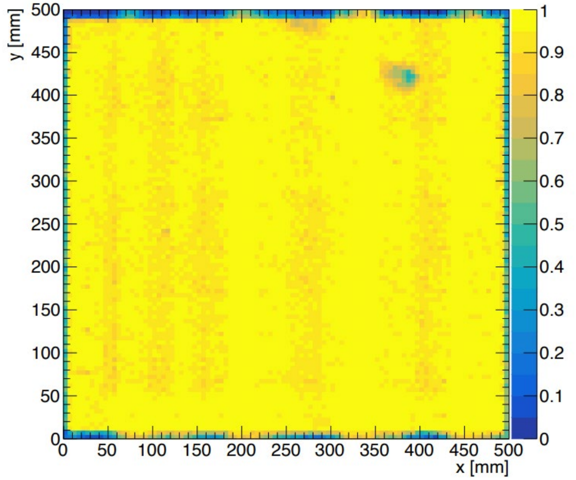


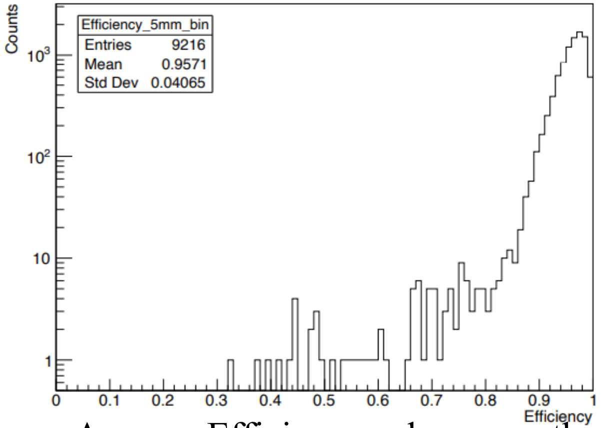


DHCAL-THGEM

Detection Efficiency

From Darina Zavazieva (WIS)



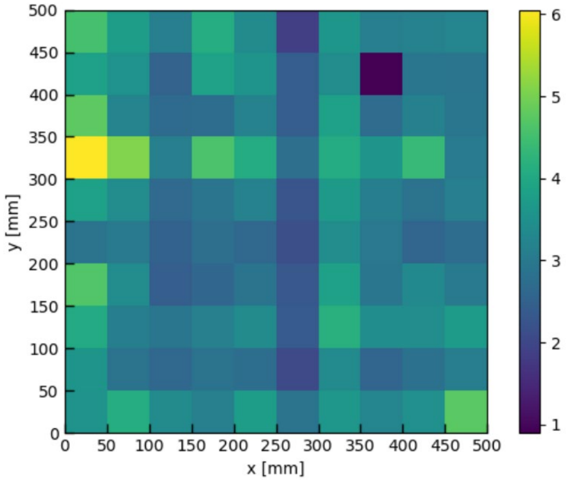


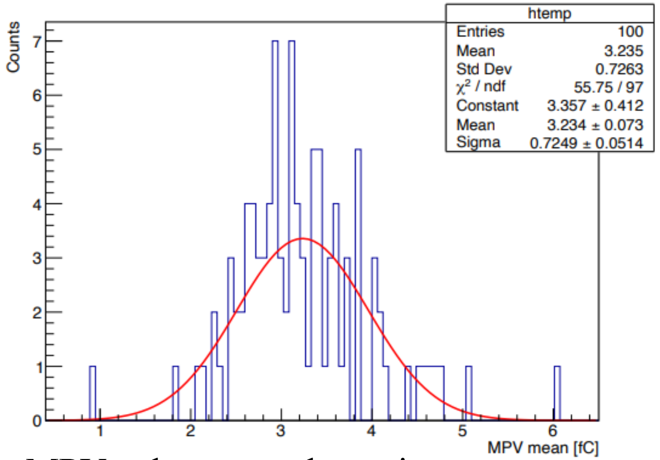
Average Efficiency values over the entire area except for 10mm edges

- Average efficiency ≈ 96%, std (spread) = 4%
- - Low efficiency values (40 – 85%) are measured at the edges and at the low efficiency ”blub” probably related to detached gluing point

Response Uniformity

- Mean ≈ 3.23 fC, sigma = 0.72 fC → 22.3% variation
- THGEM Thickness variation of 5%





MPV values over the entire area except for 10mm edges