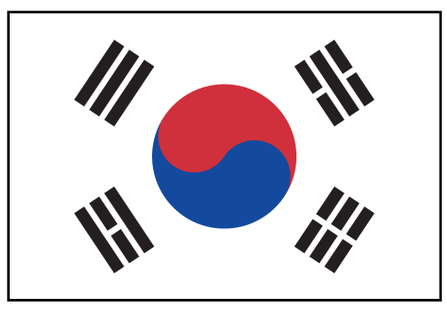
Detector R&D in Korea for the FCC and future collider projects (2020 - present)

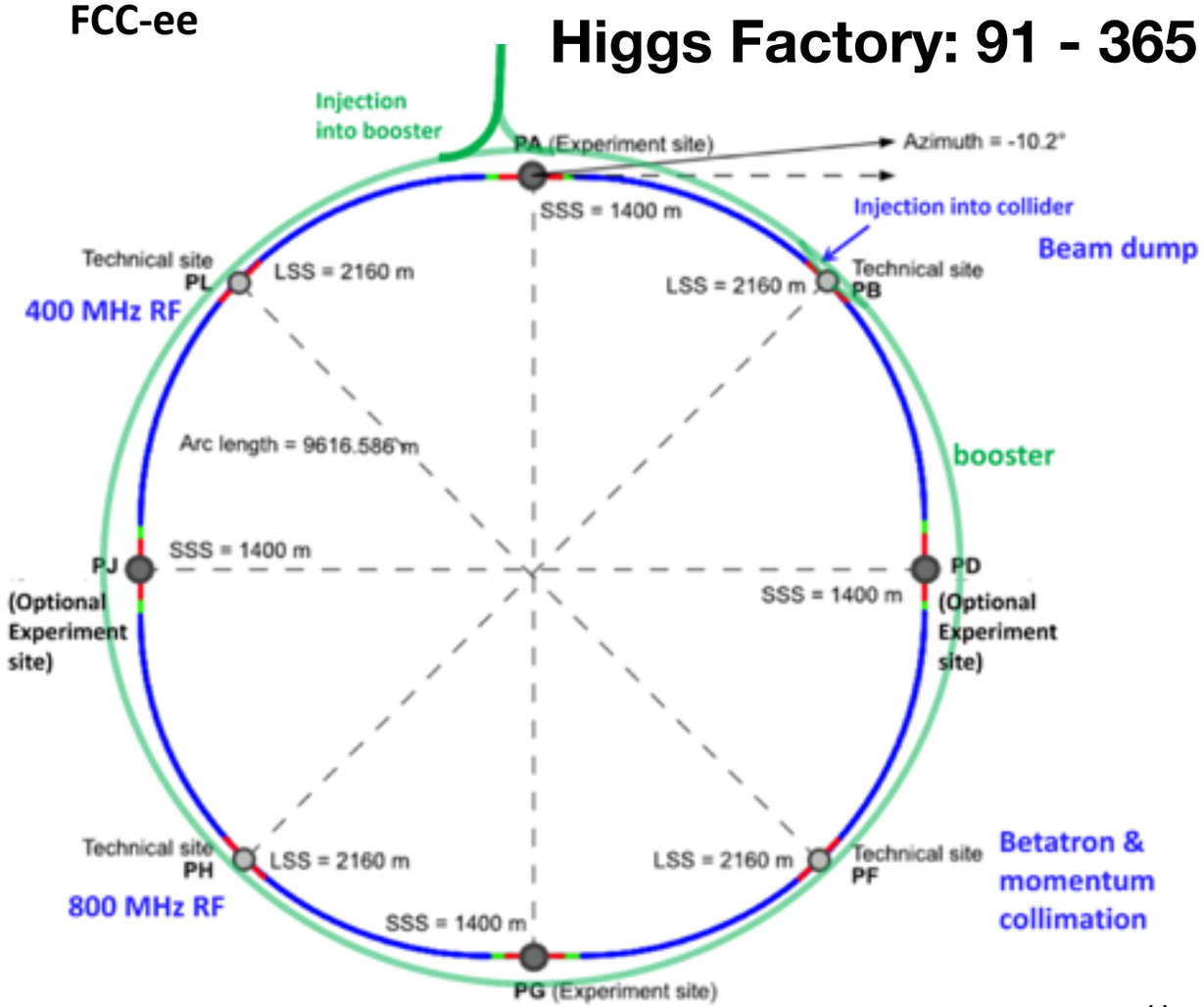
Hwidong Yoo (Yonsei Univ.)

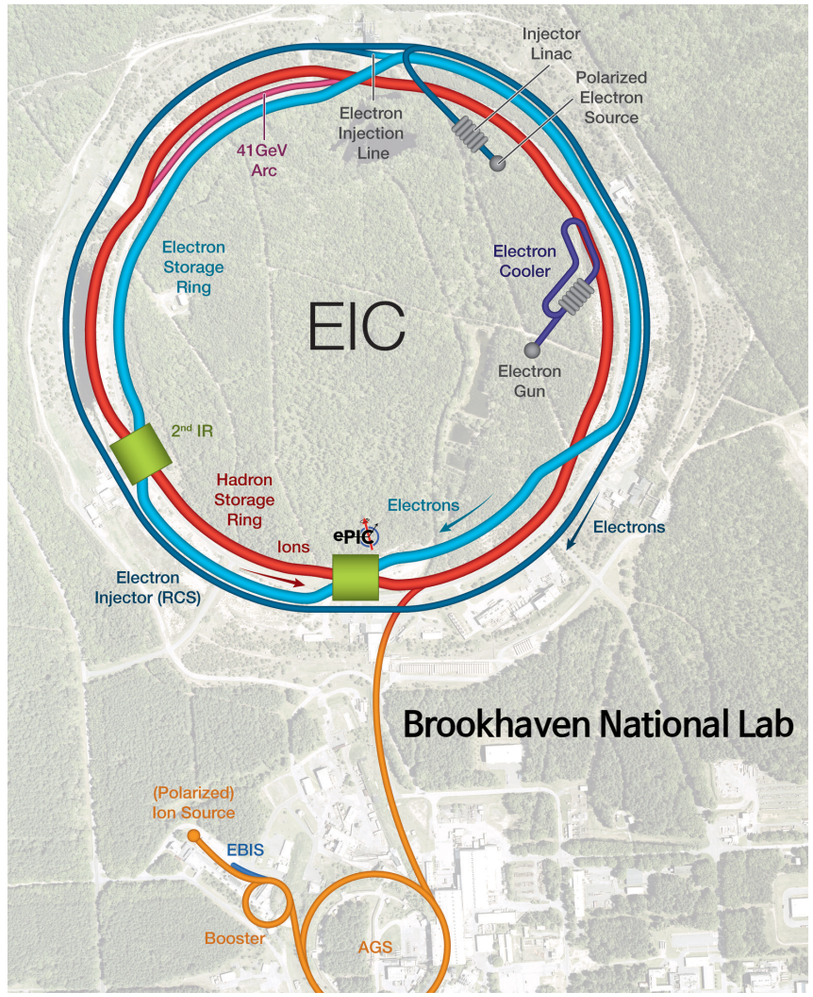


Introduction

- Calorimeter R&D projects in Korea: optical fiber-based calorimeter
  - FCC-ee (+CEPC) IDEA detector: **Dual-Readout Calorimeter**
  - EIC ePIC detector: **Barrel Imaging Calorimeter**

FCC-ee



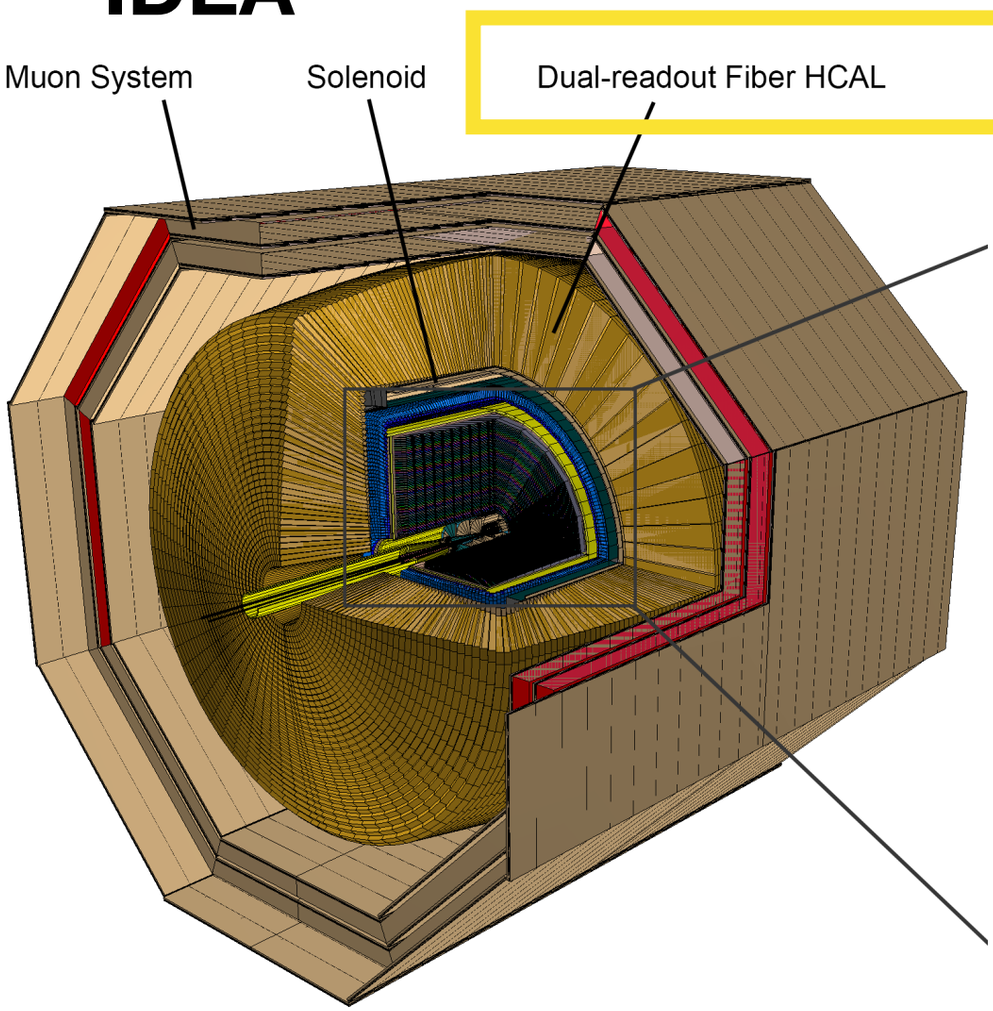


41 GeV, 100 to 275 GeV — p/A beam → ← e beam — 5 GeV to 18 GeV

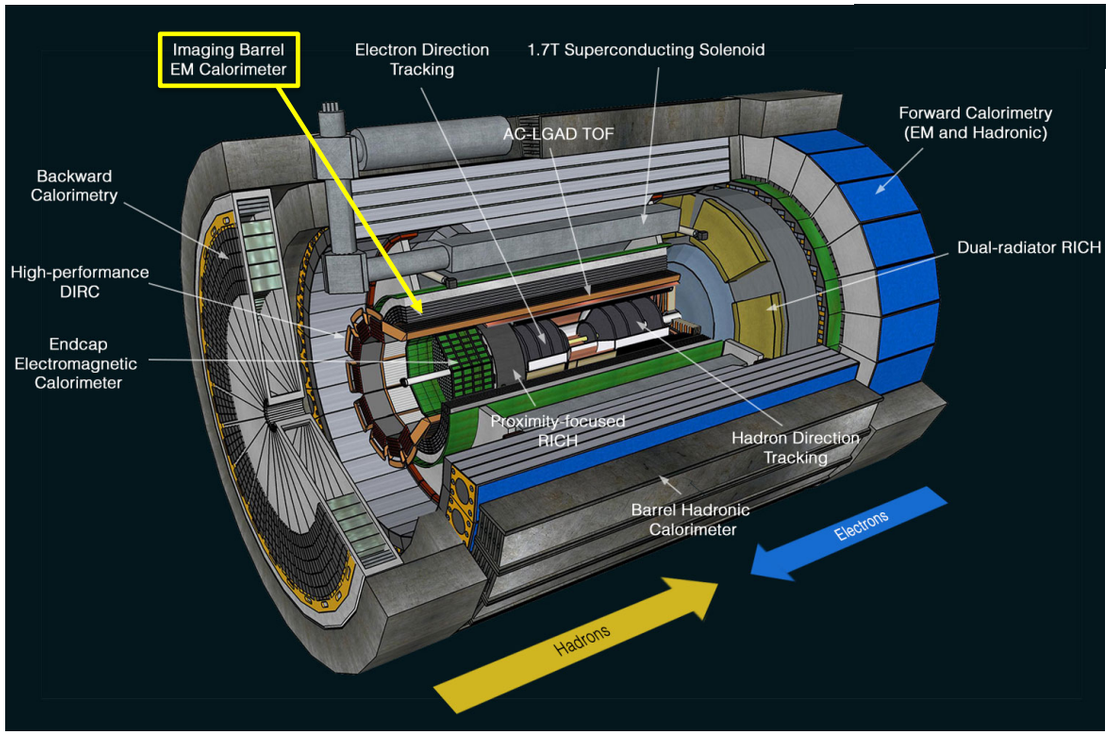
Introduction

- Calorimeter R&D projects in Korea: optical fiber-based calorimeter
  - FCC-ee (+CEPC) IDEA detector: Dual-Readout Calorimeter
  - EIC ePIC detector: Barrel Imaging Calorimeter

IDEA



ePIC

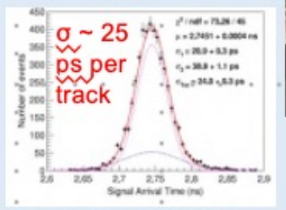


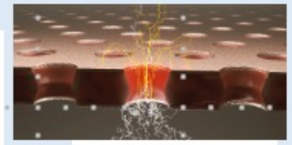
R&D on Detector Technologies

Implemented through Detector R&D (DRD) collaborations hosted at CERN, with review and oversight provided by DRD Committee (DRDC) and ECFA Detector Panel

DRD1: Gaseous Detectors

Large · Fast · eco-friendly gases · MPGD, e.g. GEMs

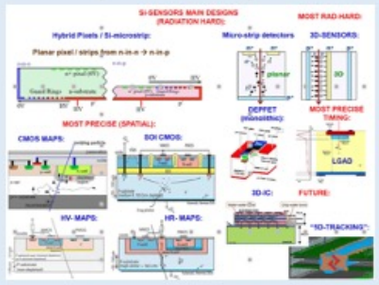




PICOSEC: NIMA903 (2018) 317

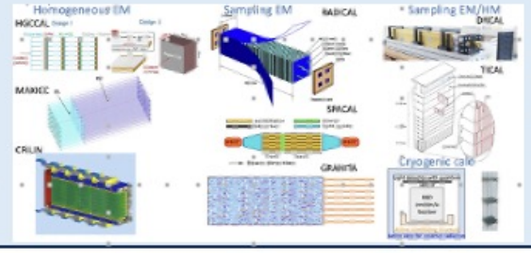
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs · radiation hardness · interconns.



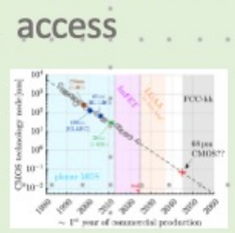
DRD6: Calorimetry

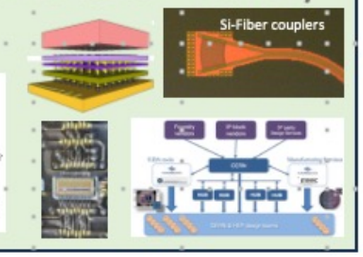
Energy resolution · High granularity · dual readout · particle flow · sandwich · optical



DRD7: Electronics

ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access

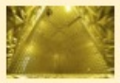




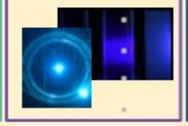
DRD2: Liquid Detectors

for Neutrinos · Dark Matter · 0vbb

Noble Elements
- Argon & Xenon
- Ionisation charge & transport
- VUV Scintillation, light propagation & detection



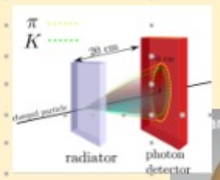
Liquid Scintillators
- Visible Scintillation, light propagation
- Scintillator properties
- Isotope loading

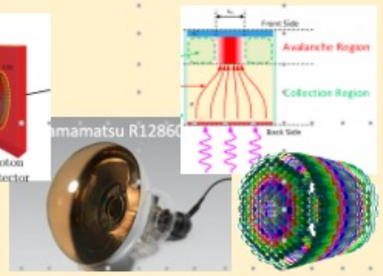


Water Cherenkov
- Cherenkov light, light propagation
- Doping for n-capture

DRD4: Photon detectors

vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID and RICH

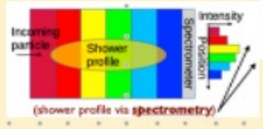


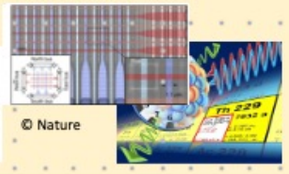


DRD5: Quantum Sensors

Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks

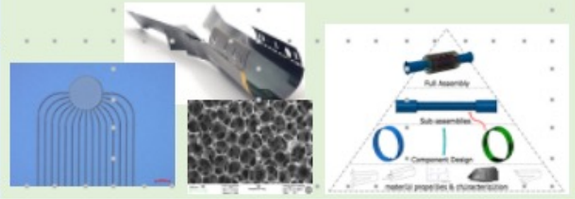
First applications for DM, first projects in HEPP happening





DRD8: Mechanics

Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality



Courtesy T. Bergauer

Status of Participations in Korea

	Institute	PI
DRD1	Osong Medical Innovation Foundation	Won-Kyu Lee
	DGIST	Gain Kim
	Hanyang University	Tae Jeong Kim
	Seoul National University	Do Won Kim
	University of Seoul	Ian Watson
	Yonsei Cancer Center	Dong Wook Kim
DRD3	Kyungpook National University	Chang Seong Moon
DRD6	Kangwon National University-Gangneung	Minsuk Kim
	Hanyang University	Byunggu Chun
	Korea University	Jae Hyeok Yoo
	Kyungpook National University	Sehwook Lee
	Sungkyunkwan University	Beomkyu Kim
	Yonsei Cancer Center	Dong Wook Kim
	Yonsei University	Hwidong Yoo
		Jason Lee
		Sanghoon Lim

DRDCalo Activities in Korea

- Huge participation in the DRD-Calo collaboration from the beginning

ECFA

DRD Calo - Proposal Team

European Strategy Update

Coordinators: Roberto Ferrari, Gabriella Gaudio (INFN-Pavia), R.P. (IJCLab)

Representative from ECFA Detector R&D Roadmap Coordination Team: Felix Sefkow (DESY)

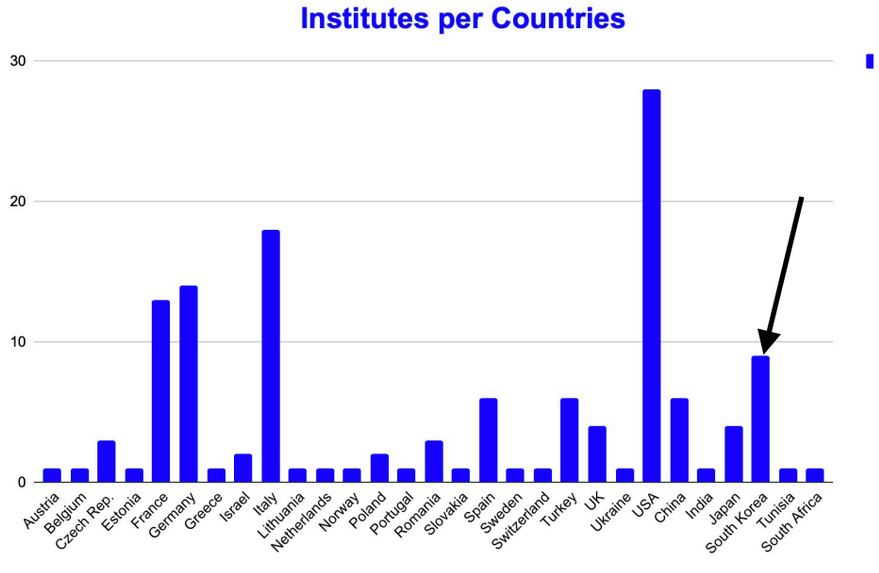
WP 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters
Conveners: Adrian Irles (IFIC, adrian.irles@ific.uv.es), Frank Simon (KIT, frank.simon@kit.edu), Jim Brau (University of Oregon, jimbrau@uoregon.edu), Wataru Ootani (University of Tokyo, wataru@icepp.s.u-tokyo.ac.jp), Imad Laktineh (I2PI, imad.laktineh@in2p3.fr)

WP 2: Liquified Noble Gas Calorimeters
Conveners: Martin Aleksa (CERN, martin.aleksa@cern.ch), Nicolas Morange (IJCLab, nicolas.morange@ijclab.in2p3.fr), Marc-Andre Pleier (mpleier@bnl.gov)

WP 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
Conveners: Etiennette Auffray (CERN, etiennette.auffray@cern.ch), Macro Lucchini (University and INFN Milano-Bicocca, marco.toliman.lucchini@cern.ch), Philipp Roloff (CERN, philipp.roloff@cern.ch), Sarah Eno (University of Maryland, eno@umd.edu), Hwidong Yoo (Yonsei University, hdyoo@cern.ch)

WP 4: Electronics and DAQ
Christophe de la Taille (OMEGA, taille@in2p3.fr)

Transve
Photode



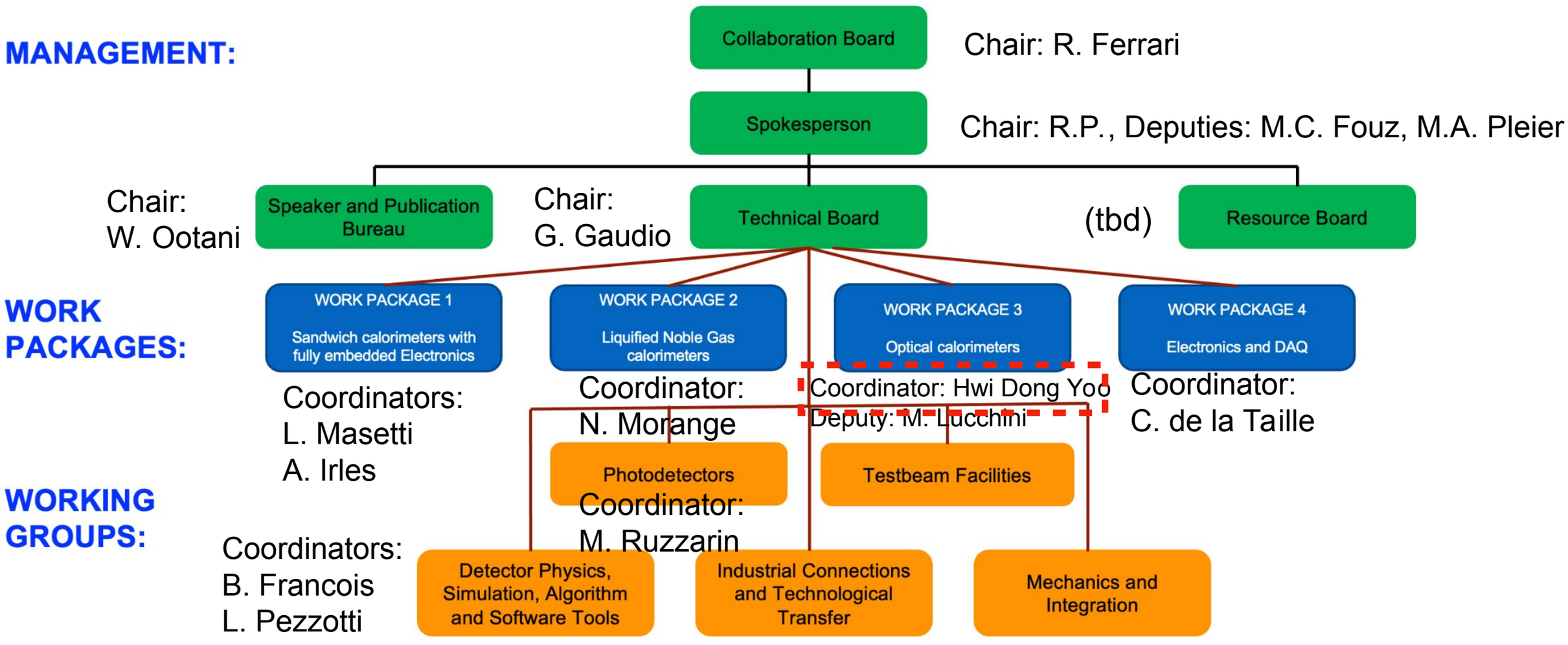
1st collaboration meeting (4/9-11, 2024)

DRDCalo Activities in Korea

- Hwidong Yoo

  - Current WP3 coordinator (elected)

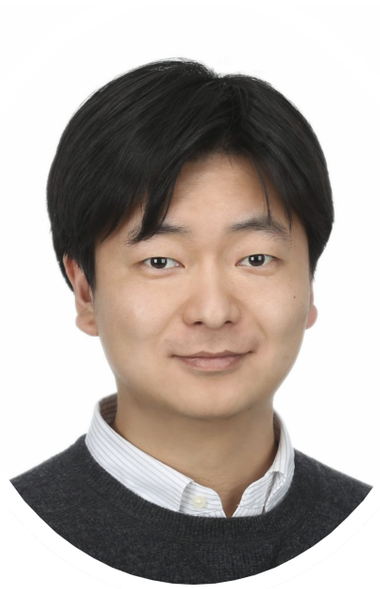
  - Calorimetry group co-coordinators in FCC Detector Concept Group



All CMS members!

Part I: Dual-Readout Calorimeter for FCC-ee

Prof. Kyeongpil Lee



Prof. Jason S.H. Lee

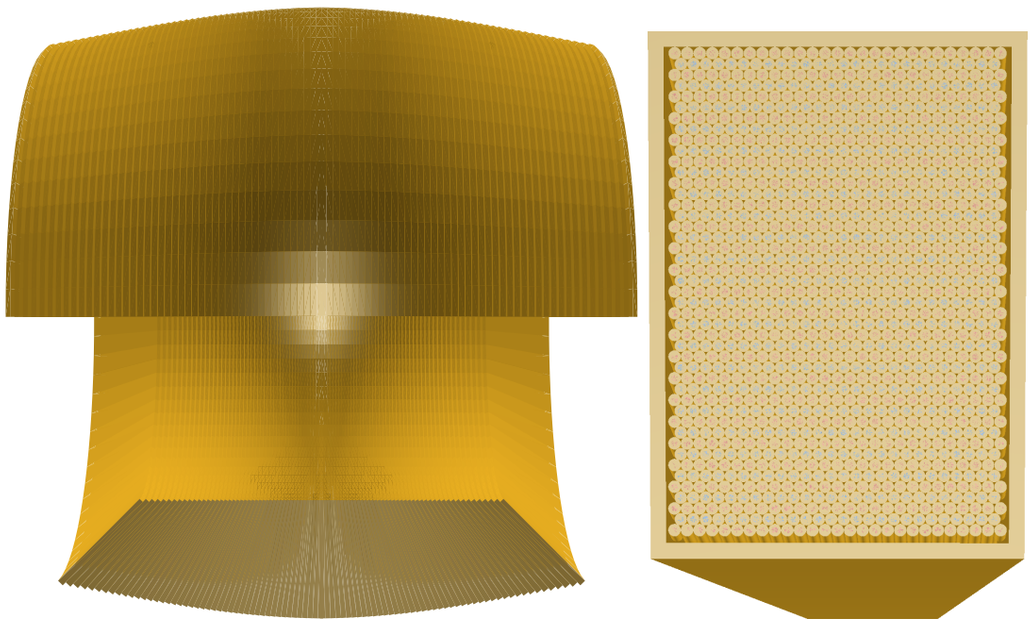
Prof. Sehwook Lee

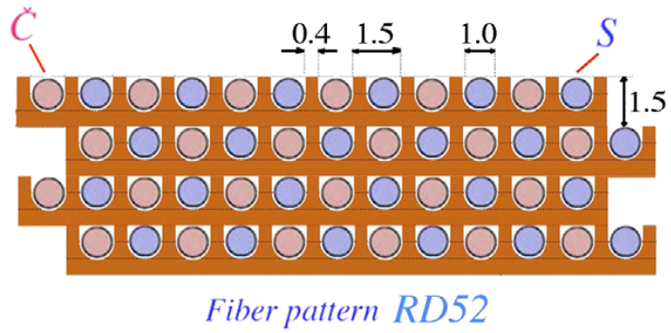
Prof. Ian Watson

Prof. Minsuk Kim

Dual-Readout Calorimeter (DRC)

- FCC-ee (+CEPC) IDEA detector: Dual-Readout Calorimeter

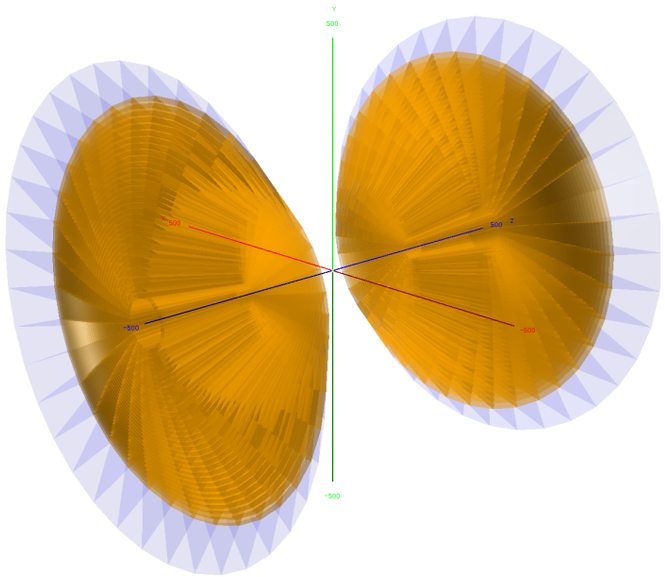


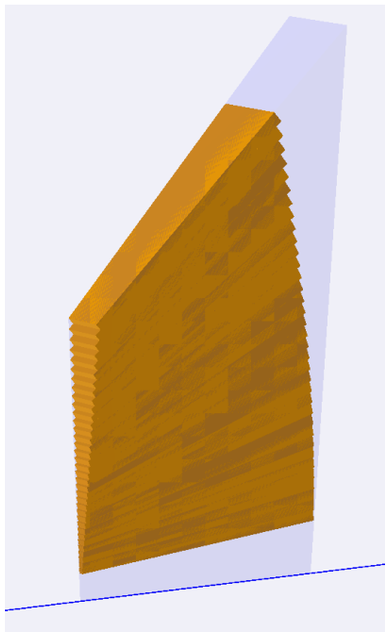


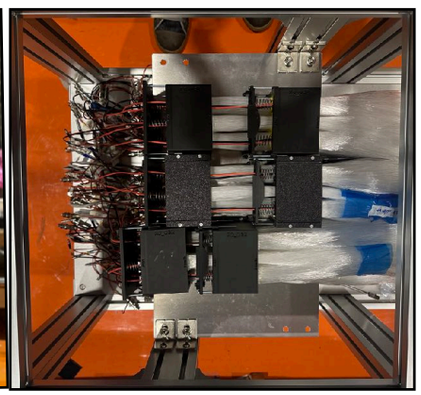
Fiber pattern RD52

S: Kurary SCSF-78
C: Mitsubishi SK-40

gure 29: Barrel region of the dual-readout calorimeter, with a few towers tal
t for visualization purposes (left). Backside of one tower with the assembly of tul
d the support structure around them, forming one tower (right).

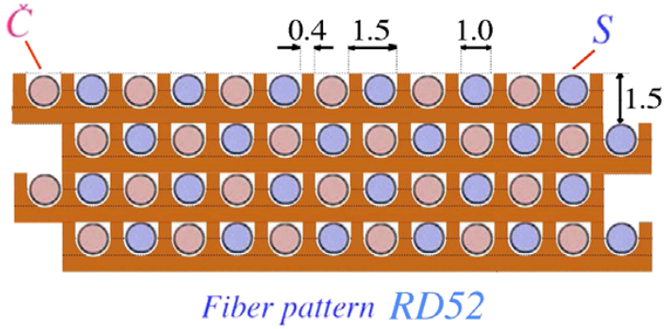






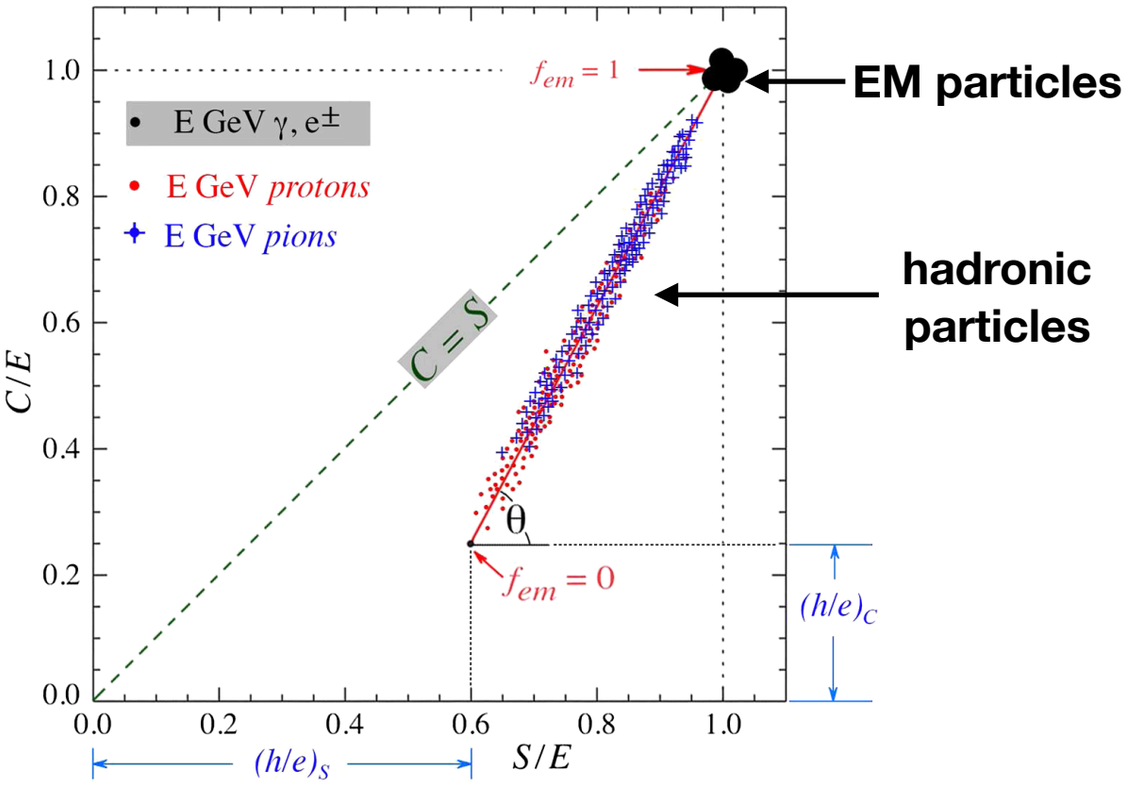
Dual-Readout Calorimeter (DRC)

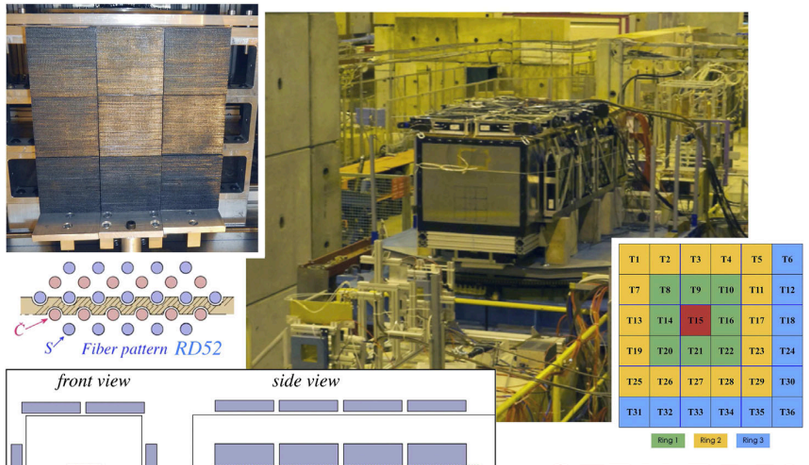
- DRC offers high-quality energy measurement for both EM particles and hadrons
  - DRC consists of two different optical fibers (S, C) in a single component
  - The main culprit of poor hadronic energy resolution is fluctuations of the EM shower components of hadron showers (f_{em})
  - f_{em} can be determined using the measured values of scintillation and Cerenkov signals
- Excellent hadron energy resolution can be achieved by correcting the energy of hadron event-by-event



Fiber pattern RD52

$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_S}(1 - f_{\rm em})\right],$$
$$C = E\left[f_{\rm em} + \frac{1}{(e/h)_C}(1 - f_{\rm em})\right],$$
$$f_{\rm em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}.$$



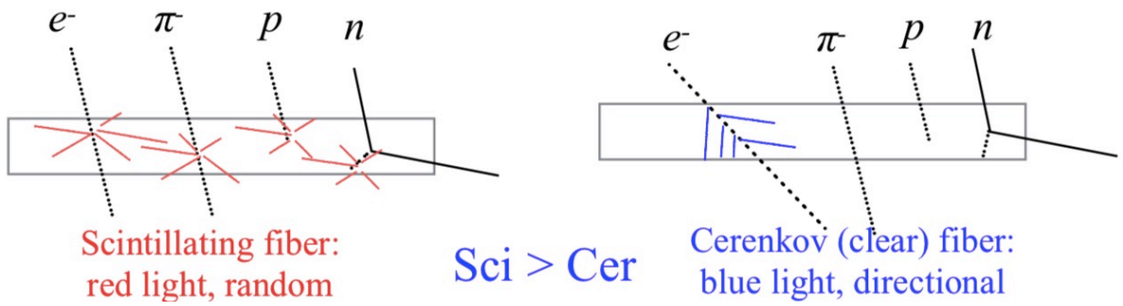


CERN RD52 experiment

$$E = \frac{S - \chi C}{1 - \chi}.$$

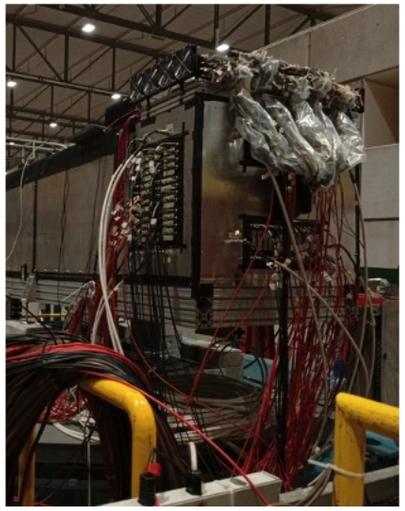
$$\cot\theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \chi,$$

Signal generation: Scintillating & Cerenkov fibers

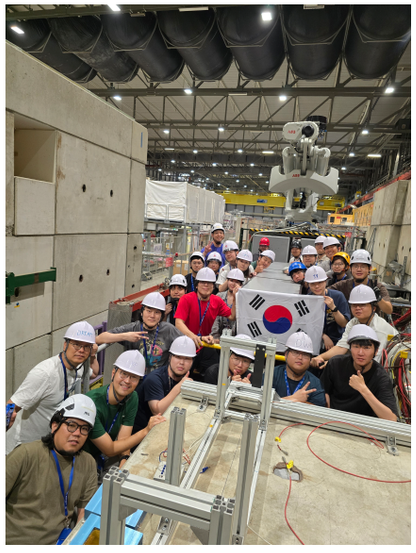


World-Wide Collaboration

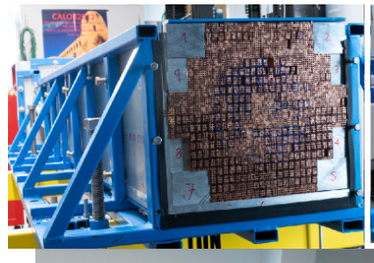
EU HiDra

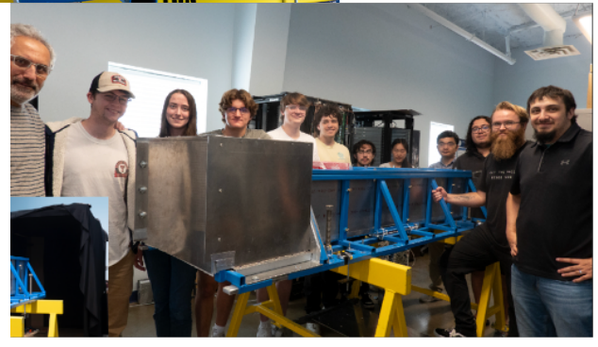


Korea FC-DREAM



US HG-DREAM

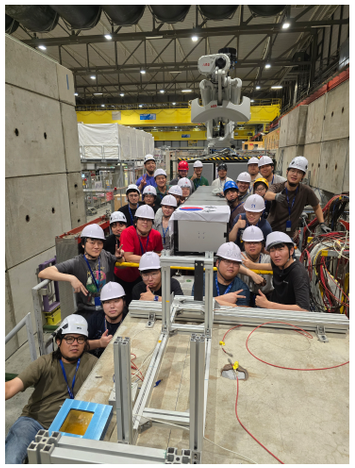




2023.May, DRC barbecue party

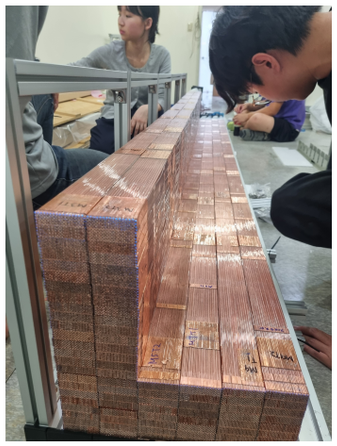
What Team Korea has done since 2020

- All aspects of the DRC R&D toward FCC-ee detector design (TDR)

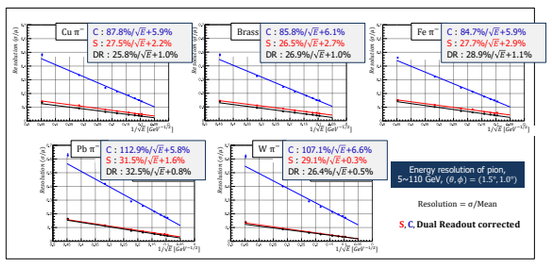


Training next generation

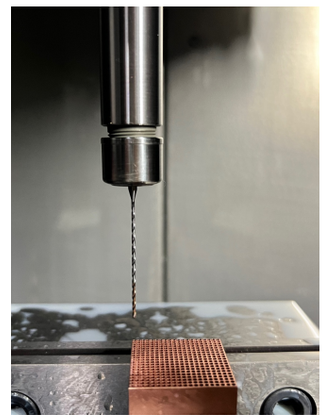
Module building



GEANT4 simulation / data analysis

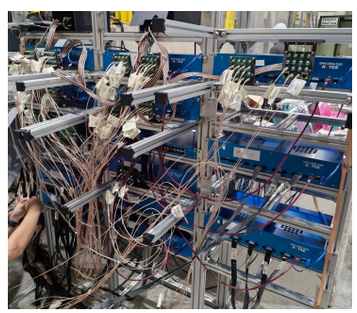


Cu forming



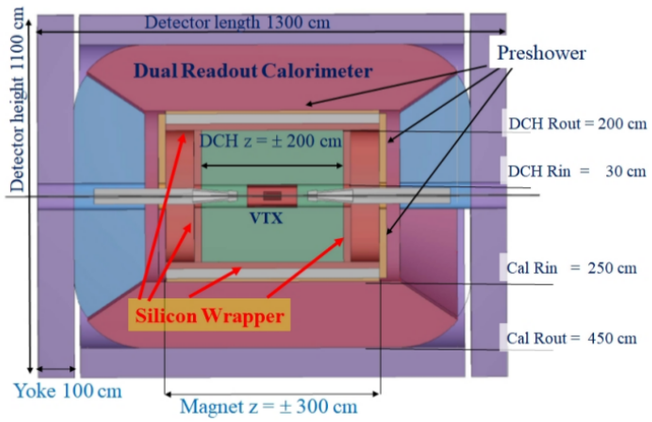
Test-beam experiment

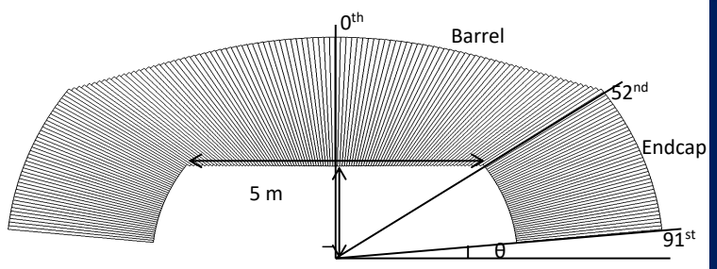
Readout/DAQ

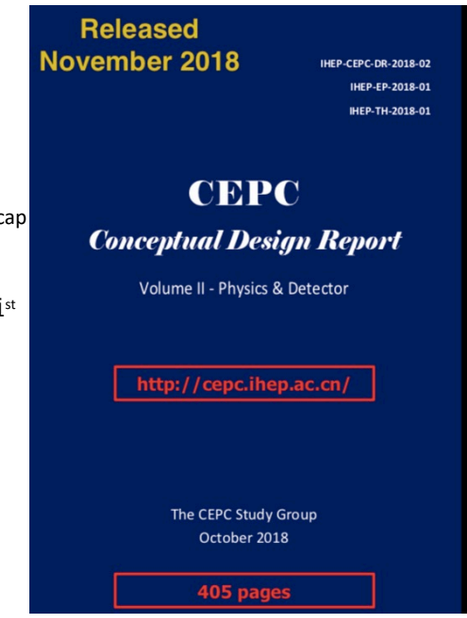


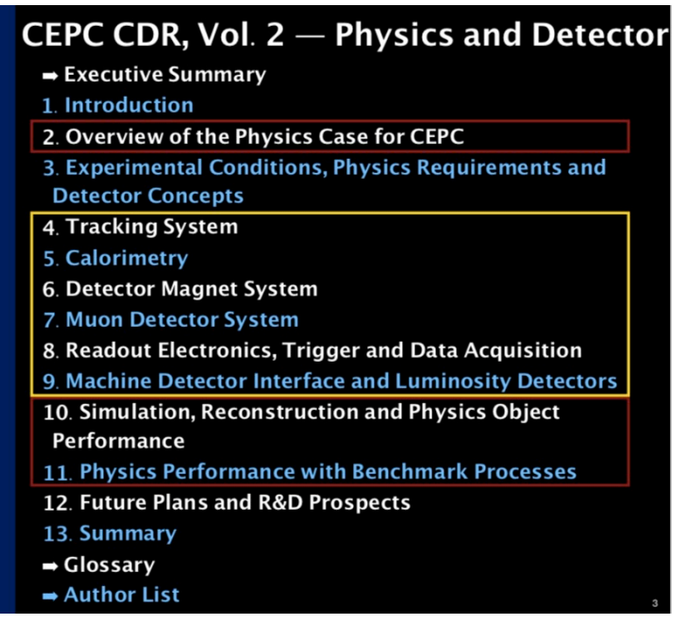
Initial Contributions for CDR

- Dual-readout calorimeter R&D team has contributed major role for CDRs of both CEPC and FCC projects (published in 2018)

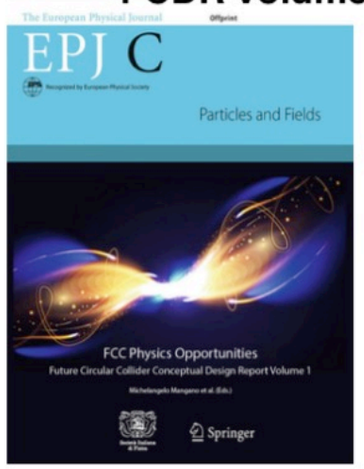




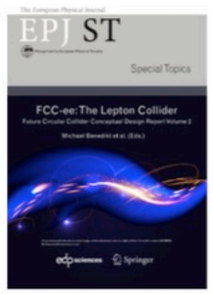




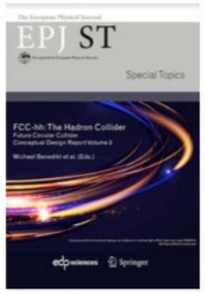
4 CDR volumes submitted to EPJ in December 2018.



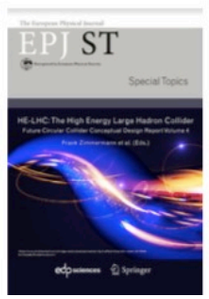
FCC Physics Opportunities



FCC-ee: The Lepton Collider



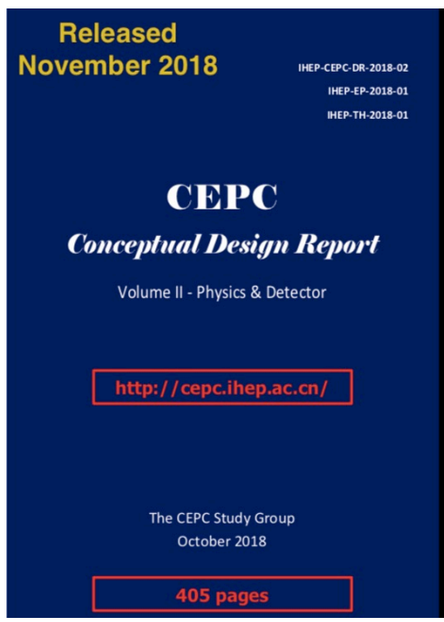
FCC-hh: The Hadron Collider



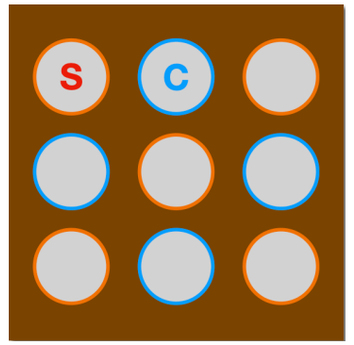
HE-LHC: The High Energy Large Hadron Collider

Copies can be requested at http://get-fcc-cdr.web.cern.ch

5

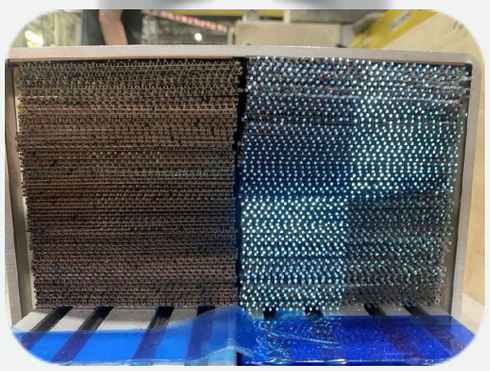


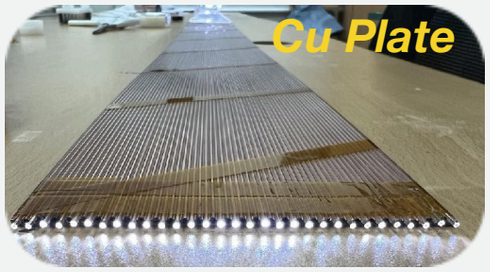
Module Building



- Dual-readout calorimeter (DRC) from Korea DRC group:
  Two optical fibers (S and C) with **Cu absorber**
  - Various Cu forming was studied and tested for the last few years
  - Test beam experiment has been performed at CERN SPS or PS **since 2022**

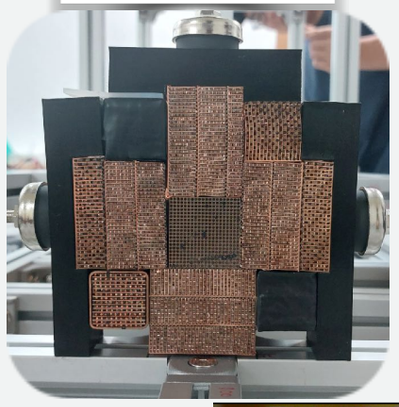
TB2022

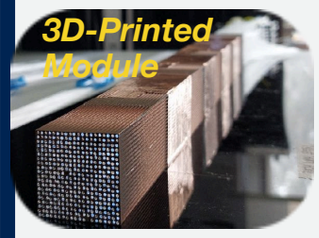




EM Performance Study
Cu Plate
~3.5 ρ_M, > 30 X_0
PMT, SiPM
10 ~ 120 GeV e^+
@SPS H8

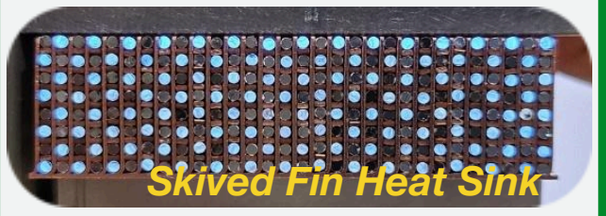
TB2023





Low Energy
EM Performance Study
3D-Printed Module,
SFHS, Lego-Like
~3 ρ_M, ~17 X_0
PMT, MCP-PMT
0.5 ~ 5 GeV e^+
@PS T9

TB2024



EM&Hadron Performance Study
SFHS, Cu Plate
~90% lateral hadron deposit, ~10 λ_{int}
PMT, MCP-PMT, SiPM
10~120 GeV e^+, 20~120 GeV π^+
@SPS H8

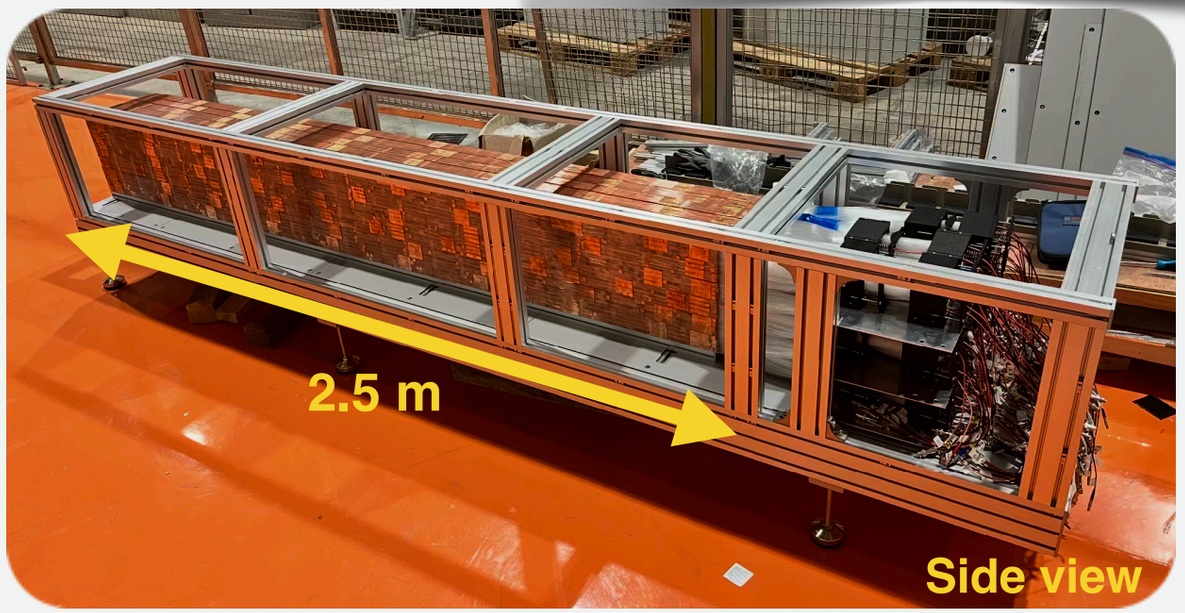
TB2025

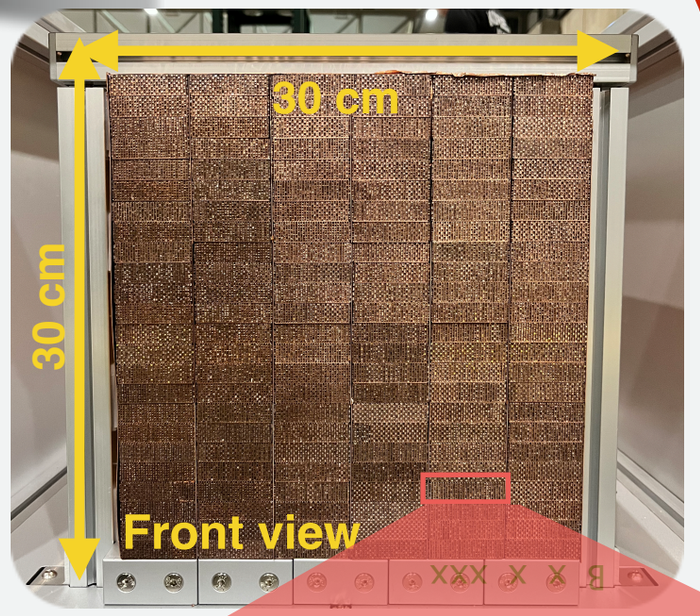
EM&Hadron Performance Study
SFHS, Cu Plate
~90% lateral hadron deposit, ~10 λ_{int}
PMT, MCP-PMT
Frame & DAQ upgrade from TB2024
10~120 GeV e^+, 20~120 GeV π^+/p
@SPS H8

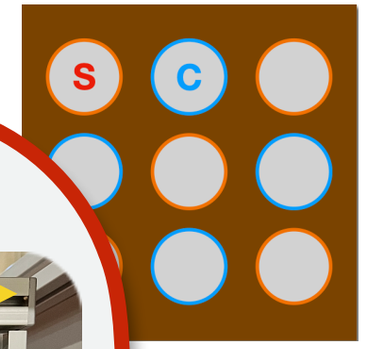
Module Building

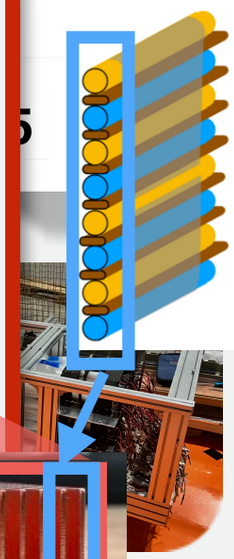
Latest result:
TB2026@CERN SPS
(27 July - 03 August, 2026)

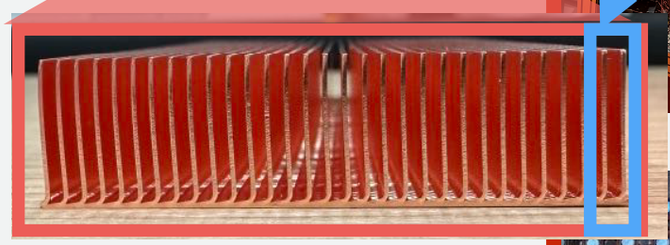
- Dual-readout calorim… …oup:
  Tw…

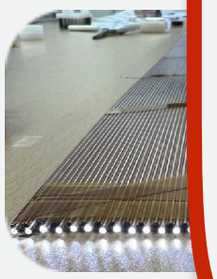












- ◎ **Module**: Skived Fin Heat Sink (SFHS) Module
  - Depth: 2.5 m (~10 λ_{int})
  - Effective radius: 17 cm
- ◎ **Readout & DAQ**: PMT, MCP-PMT with custom DAQ boards (DRS4)
- ◎ **Program**: EM & hadronic performance
  - e⁺: 6 - 120 GeV beams
  - hadron (π^+,p): 20 - 120 GeV beams

EM Perfor…
Cu F…
~3.5 ρ_M, > 3…
PMT, SiPM
10 ~ 120 GeV e^+
@SPS H8

…
PMT, MCP-PMT
0.5 ~ 5 GeV e^+
@PS T9

…
10~120 GeV e^+, 20~120 GeV π
@SPS H8

…mance Study
…Plate
…n deposit, ~10 λ_{int}
…, MCP-PMT
…rame & DAQ upgrade from TB2024
10~120 GeV e^+, 20~120 GeV π^+/p
@SPS H8

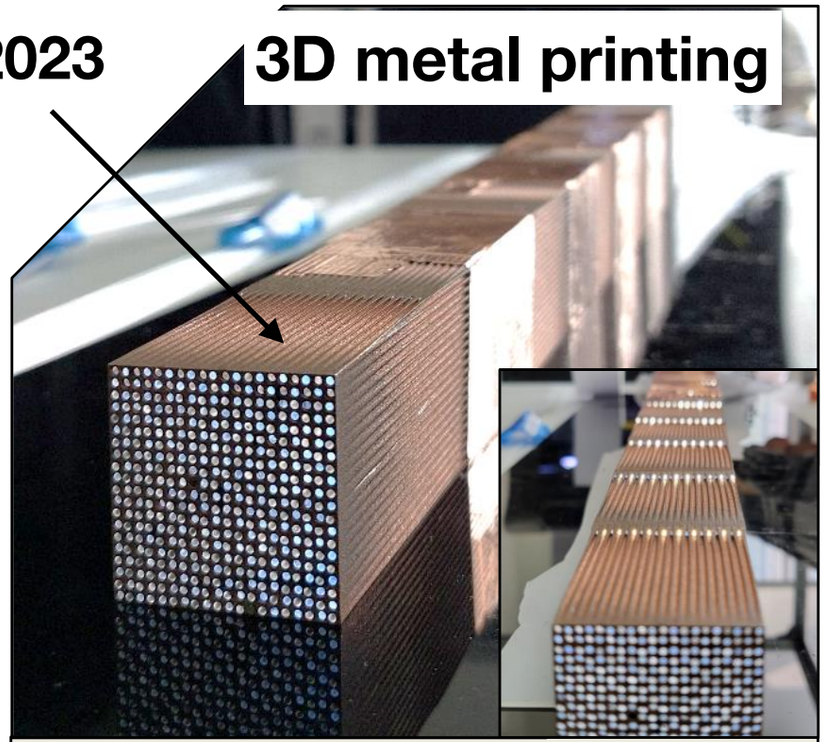
Cu Forming R&D

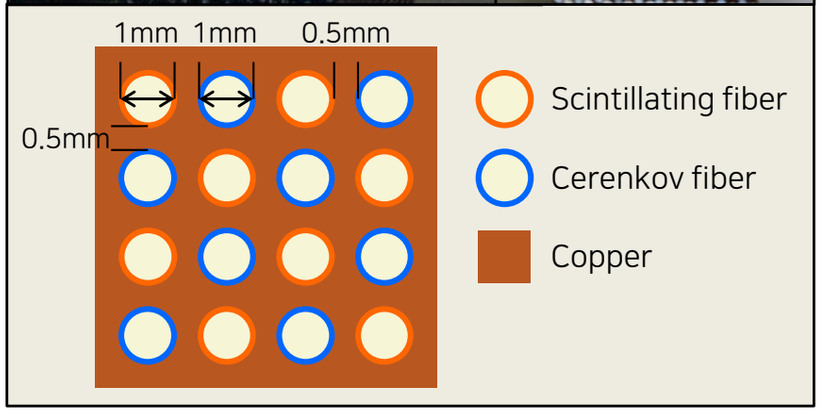
- Try to find a solution for mass production with local mechanical engineering experts and manufacturers

  - Skiving fin heatsink, 3D metal printing, drilling, etc.

TB2023

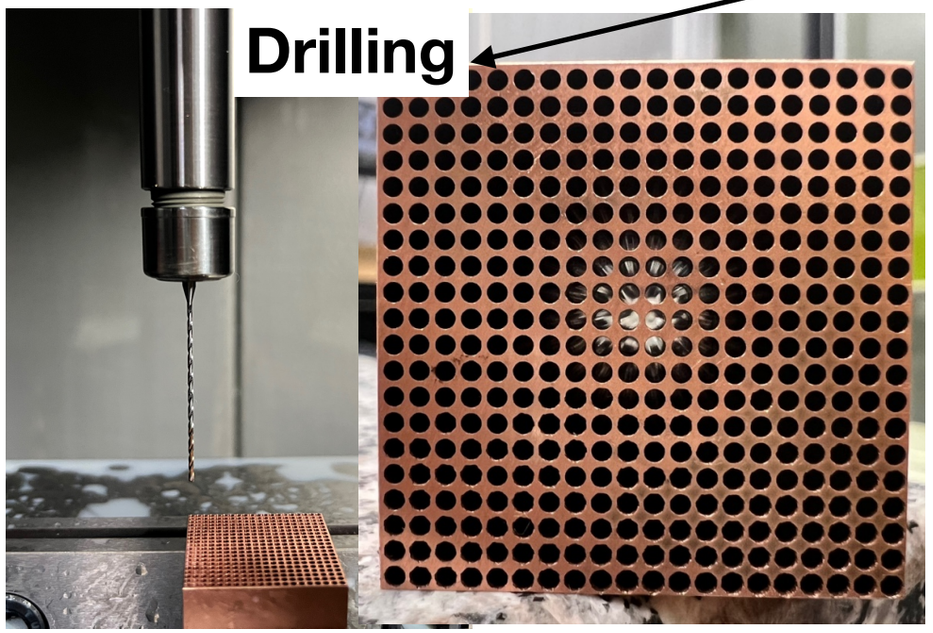
3D metal printing



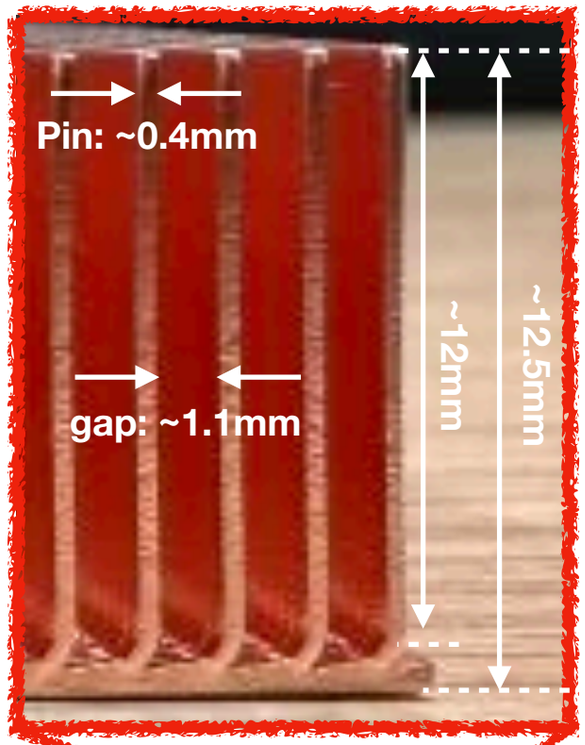


Structure of 3D-Printed Module

Drilling

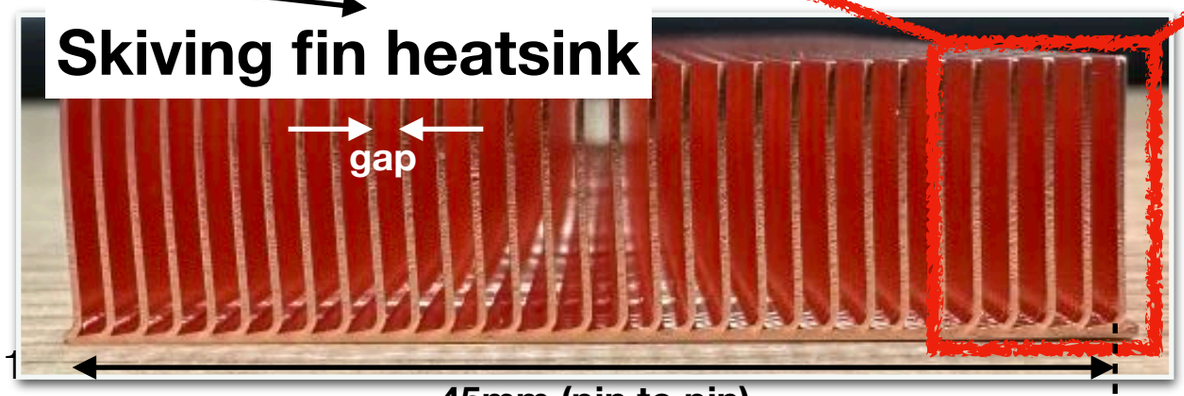


Prototype at 2026



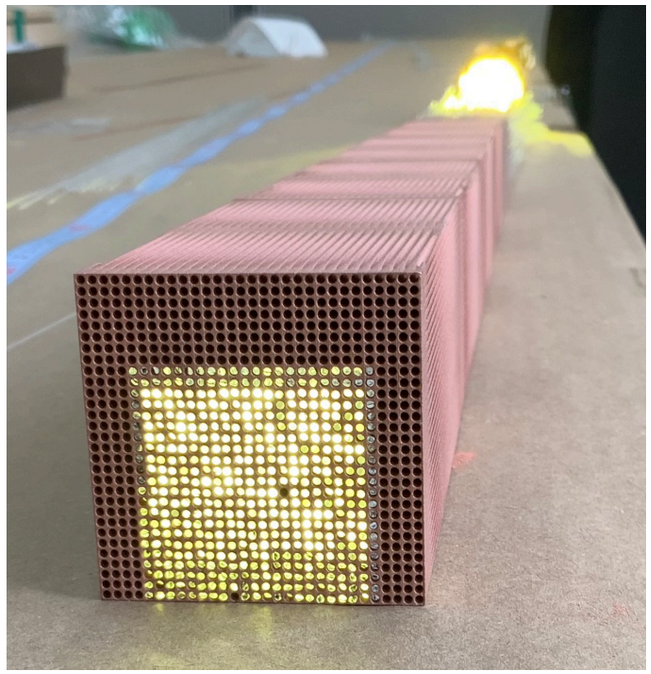
TB2024-2026

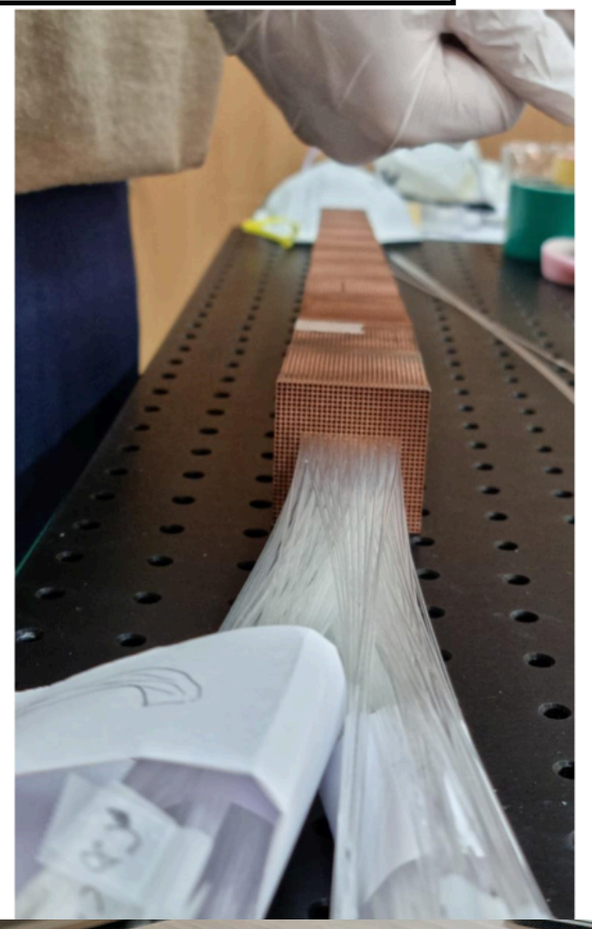
Skiving fin heatsink

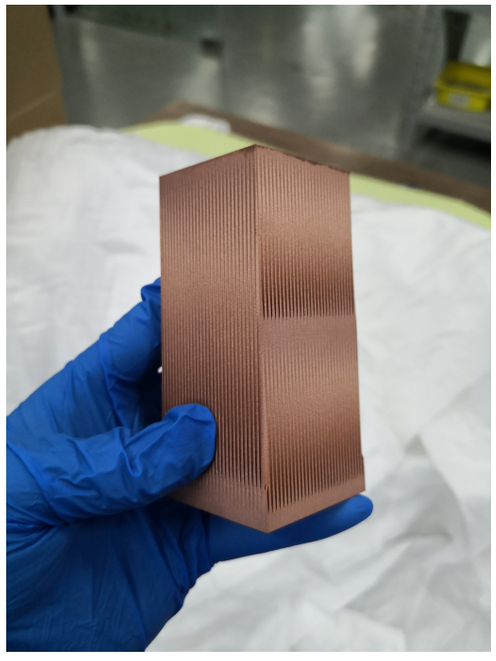


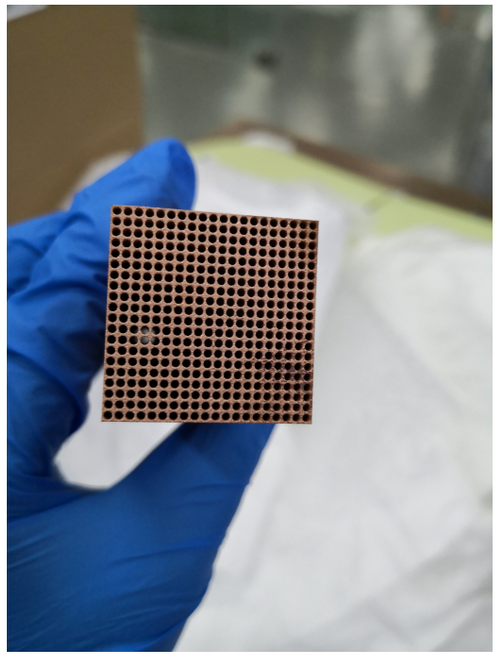
3D Metal Printing with Harvestance

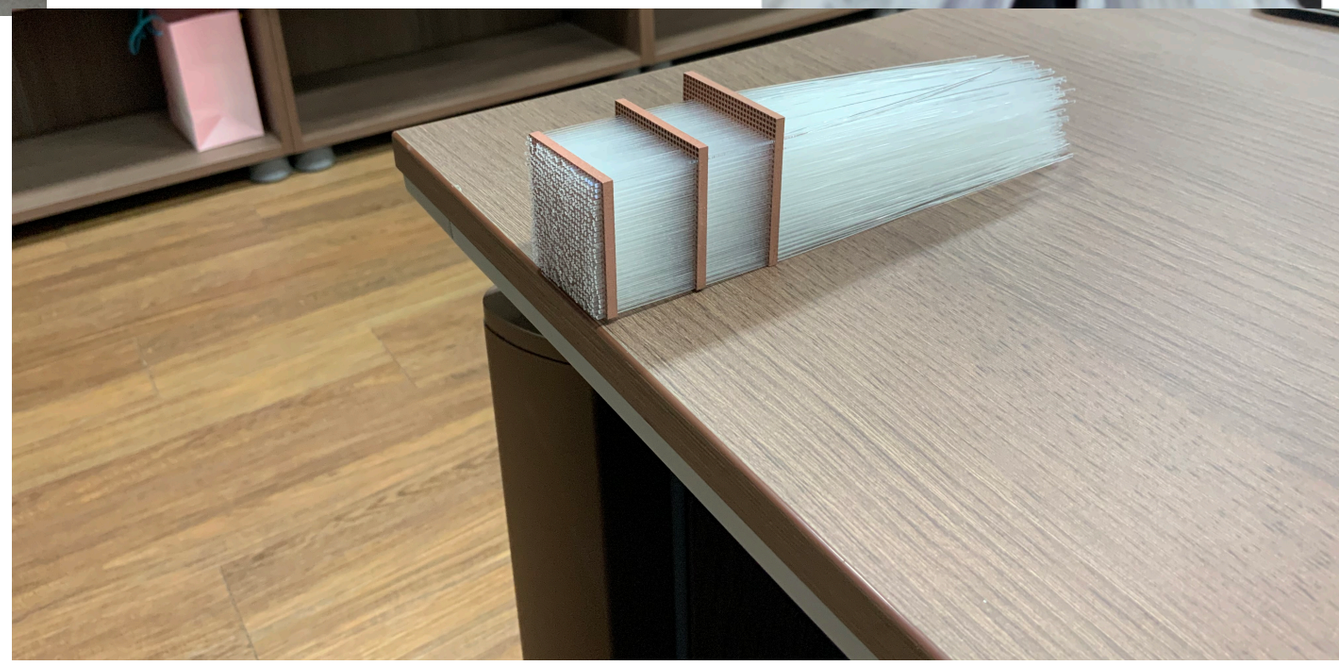
- 1st projective DRC module!







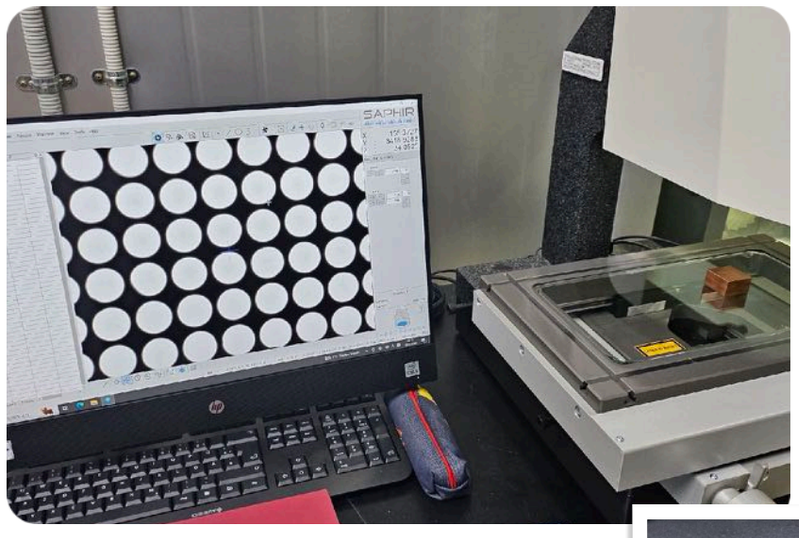


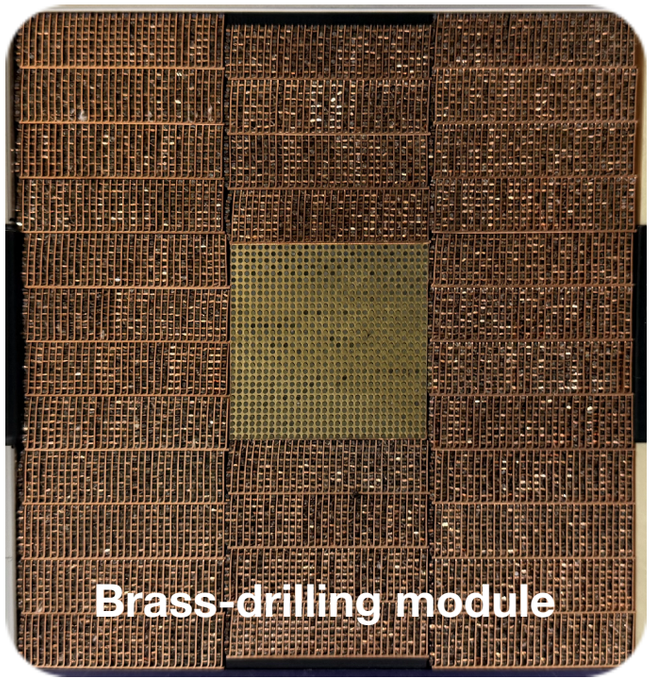


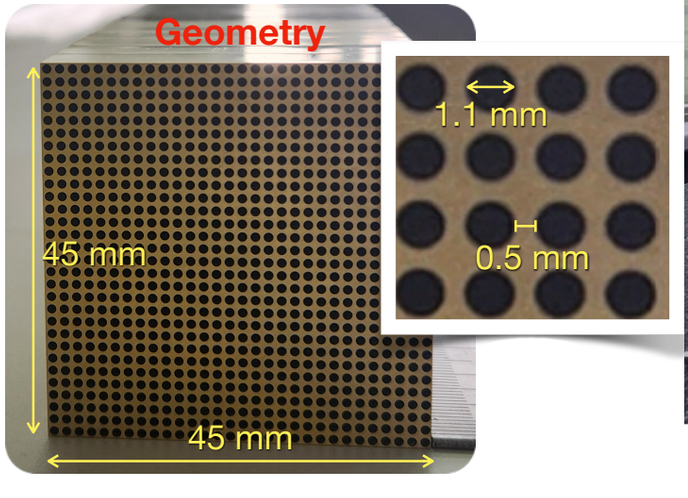
Drilling Module

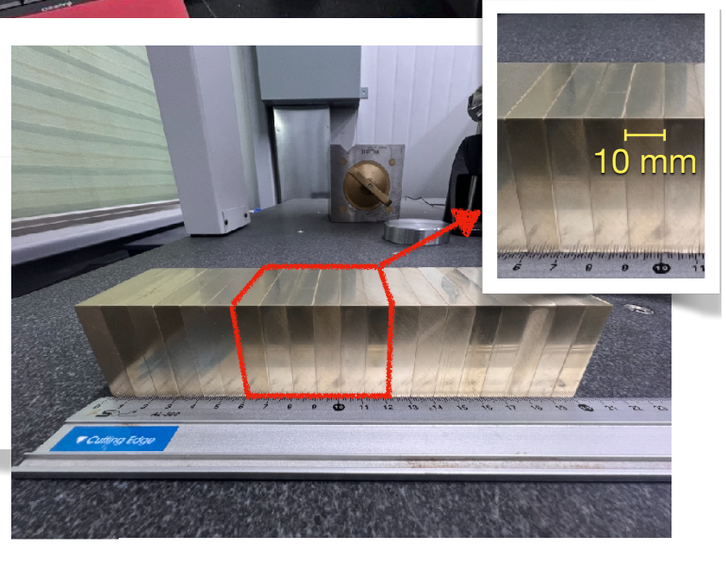
- “Drilling” might be another good option for copper forming to build full 4pi detector

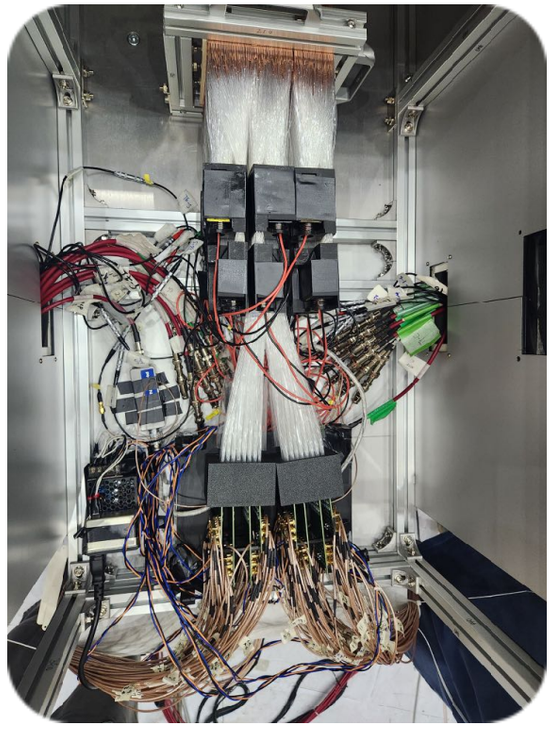
- Prototype has been tested at KEK PF-AR











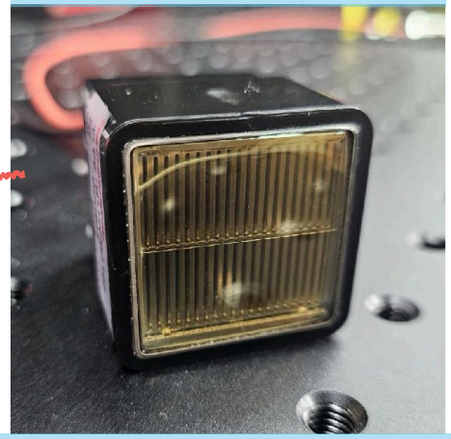
Readout R&D

- Readout detectors
  - **Usual** towers: **PMT** for each S and C fiber type
    - 35 towers × 2 fiber type = 70 channels
  - **M5T3**: high-granularity **MCP-PMT** -> 8 fibers / channel (64 channels per fiber type)
    - (64 channels + 1 sum channel) × 2 fiber type = 130 channels
  - Total 70 + 130 = **200 channels**

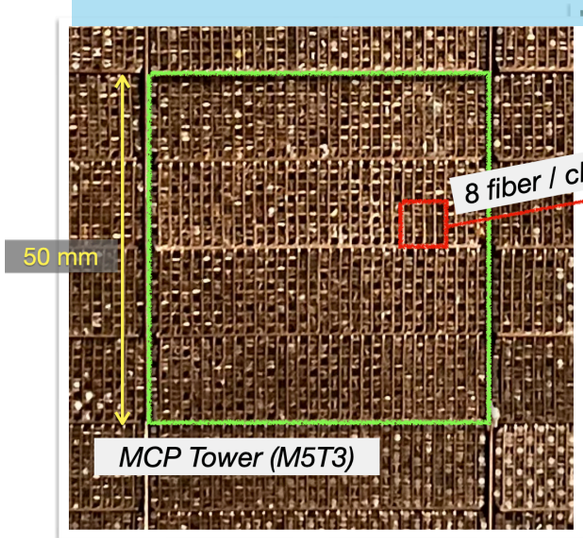
Naming convention for each module & tower

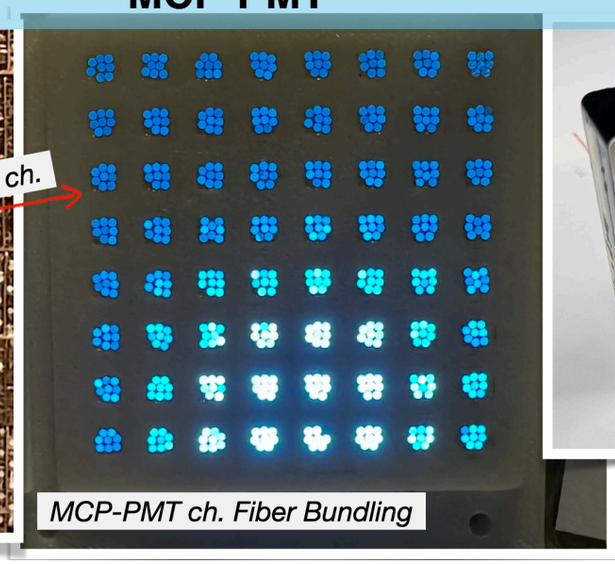
(all towers except for M5T3)

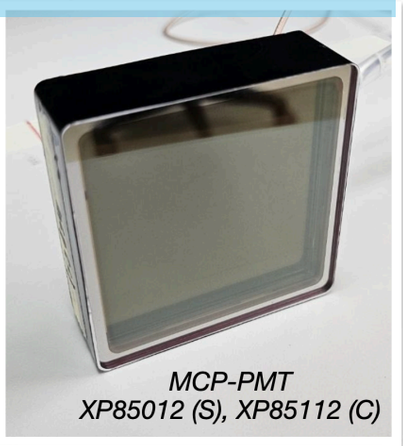
PMT (R11265-100)



MCP-PMT







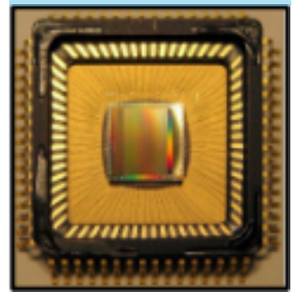
MCP-PMT
XP85012 (S), XP85112 (C)

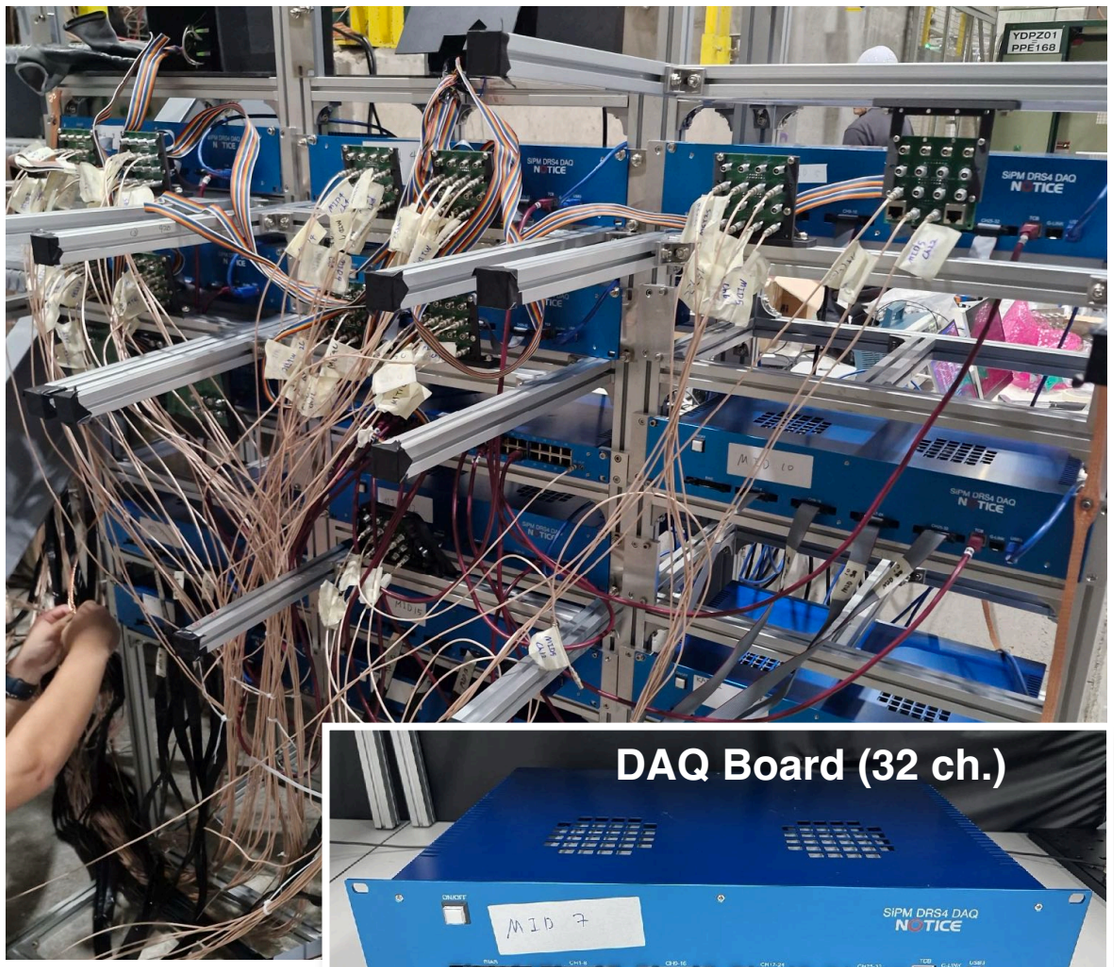
DAQ R&D

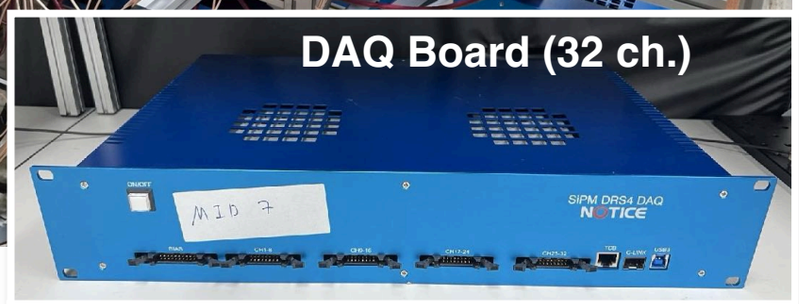
- DAQ system

  - **Customized** DAQ system based on **DRS4** chip
    -> fast sampling rate (5GS/s) & excellent timing resolution
  - Total 13 DAQ boards (32 channels / board) and 1 TCB board

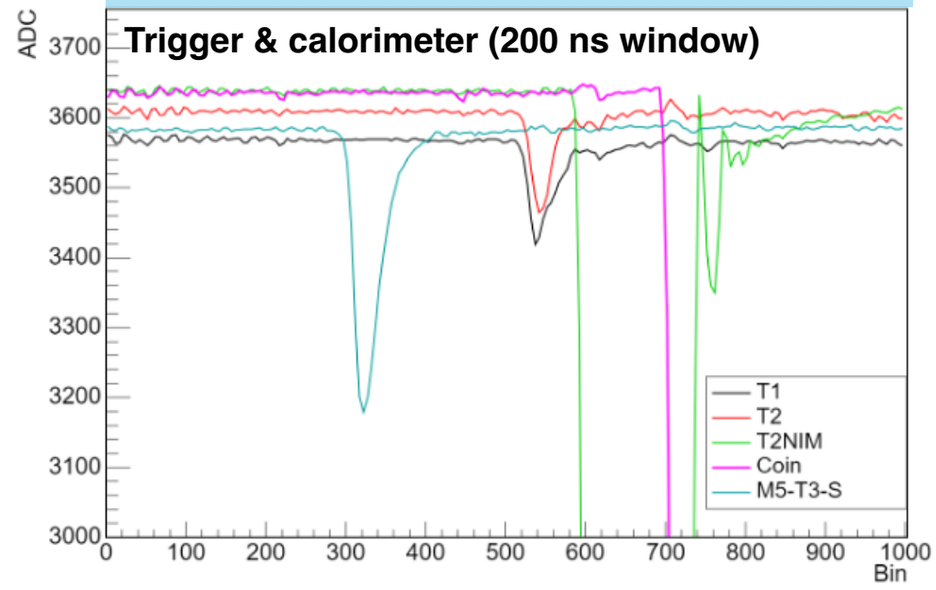
DRS4 chip

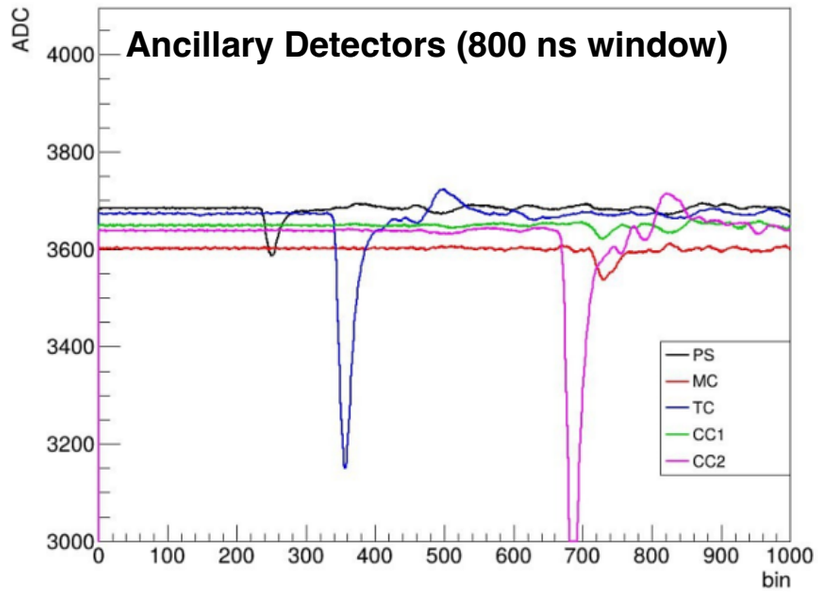






Typical detector signals from DAQ

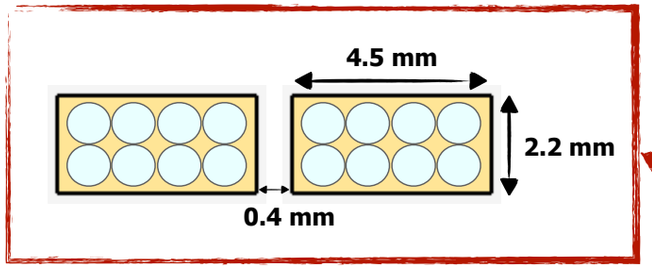


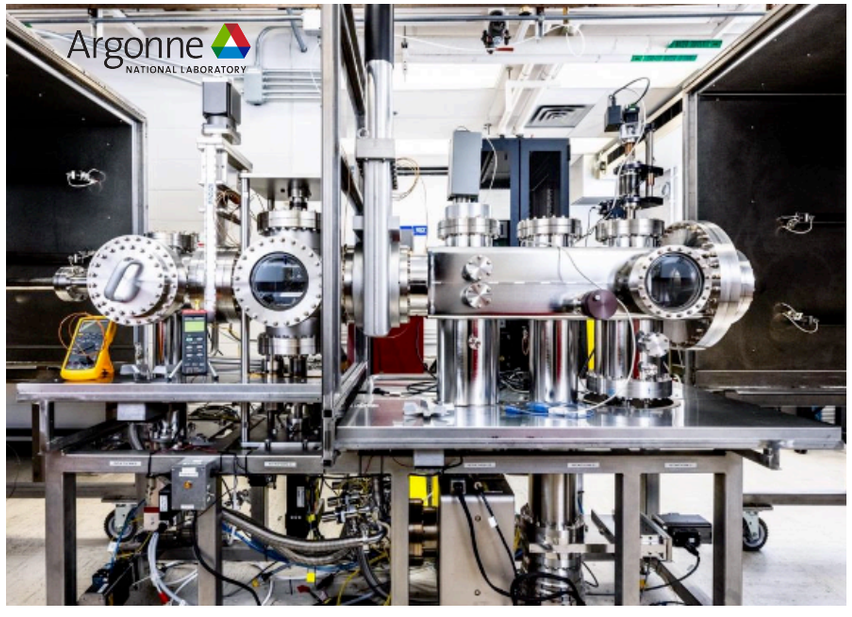


Customized MCP-PMT R&D

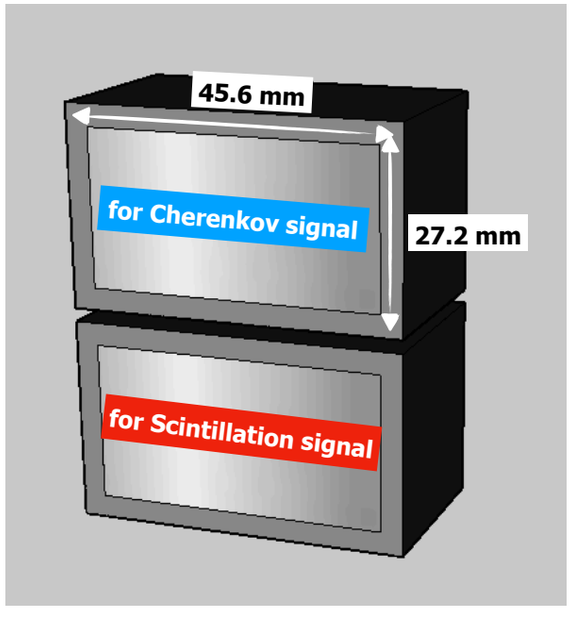
- SiPM based high granularity system R&D: DRC-EU, DRC-US teams
- MCP-PMT based high granularity system R&D: DRC-Korea
  - Collaborating with Argonne Nat. Lab. Medium Energy team
- Achieve readout dimensions comparable to the module front face -> compact design
- Enable evaluation of smaller pixel sizes with alternative pixel geometries (e.g. rectangular shapes)

Photonis

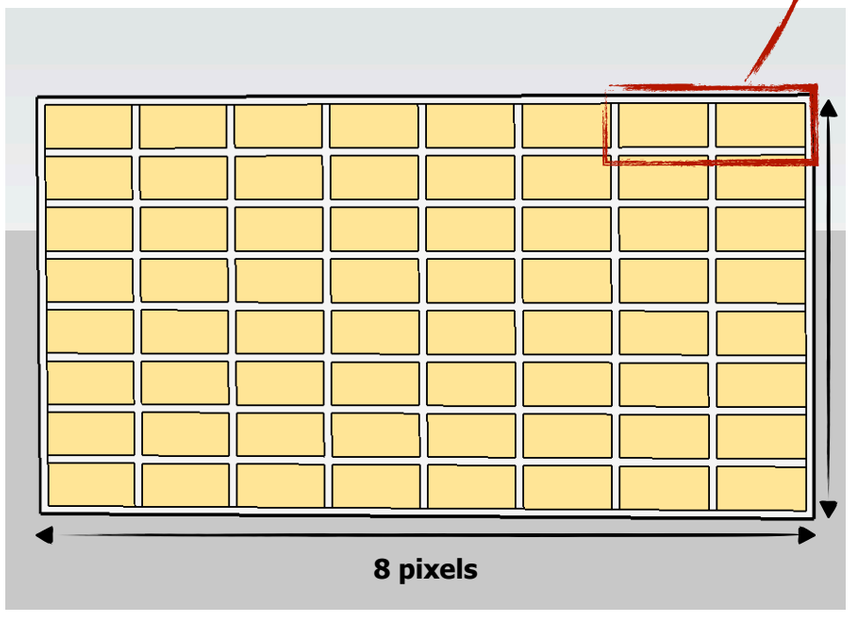




- MCP-PMT Fabrication Facility @ANL -



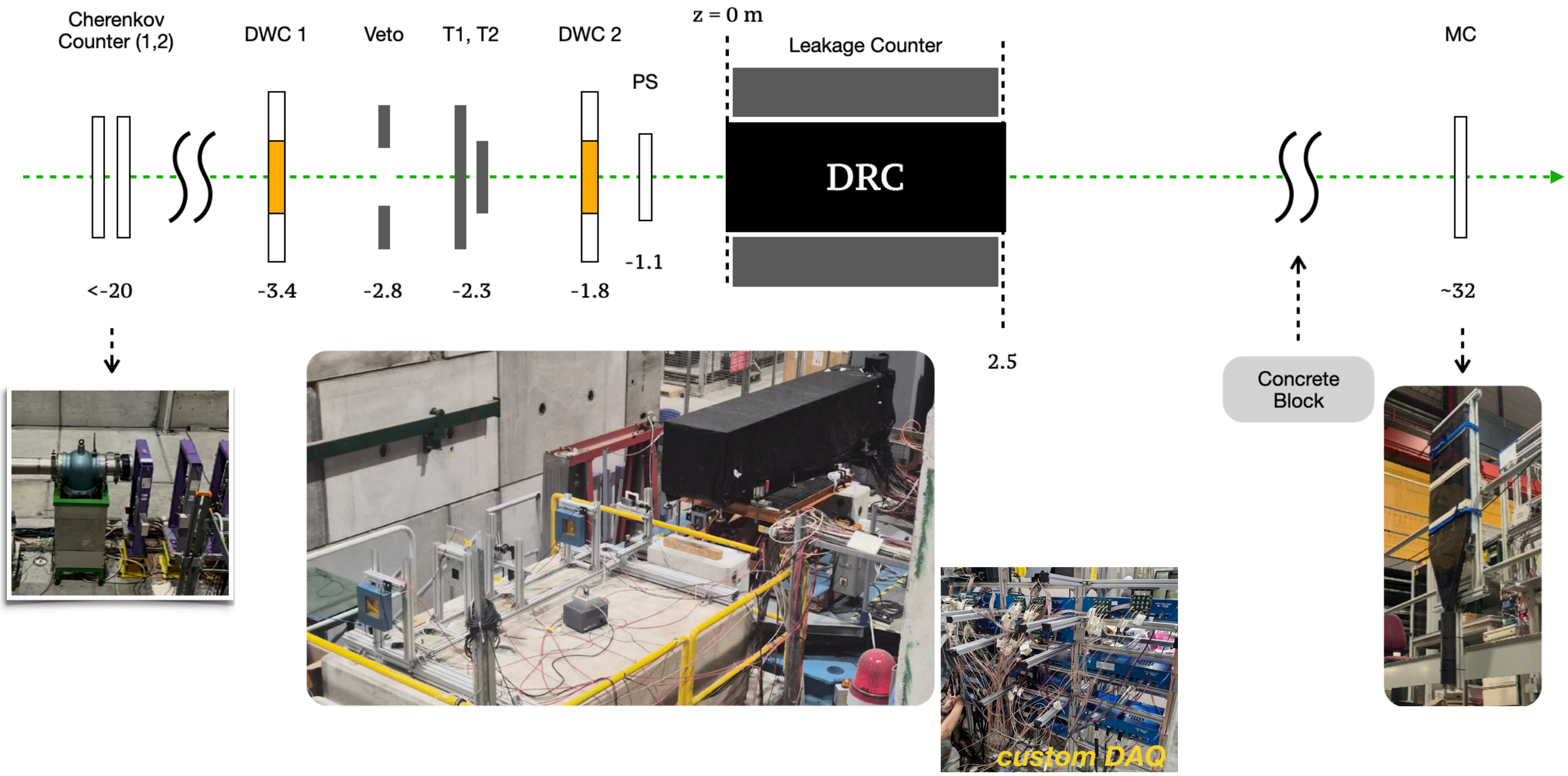
- Front side of two MCP-PMTs -



- Pixel array (ceramic pad) -

Test-beam Experiments at SPS

- Experimental setups for 2022, 2024, 2025, and 2026 (2023 at PS)

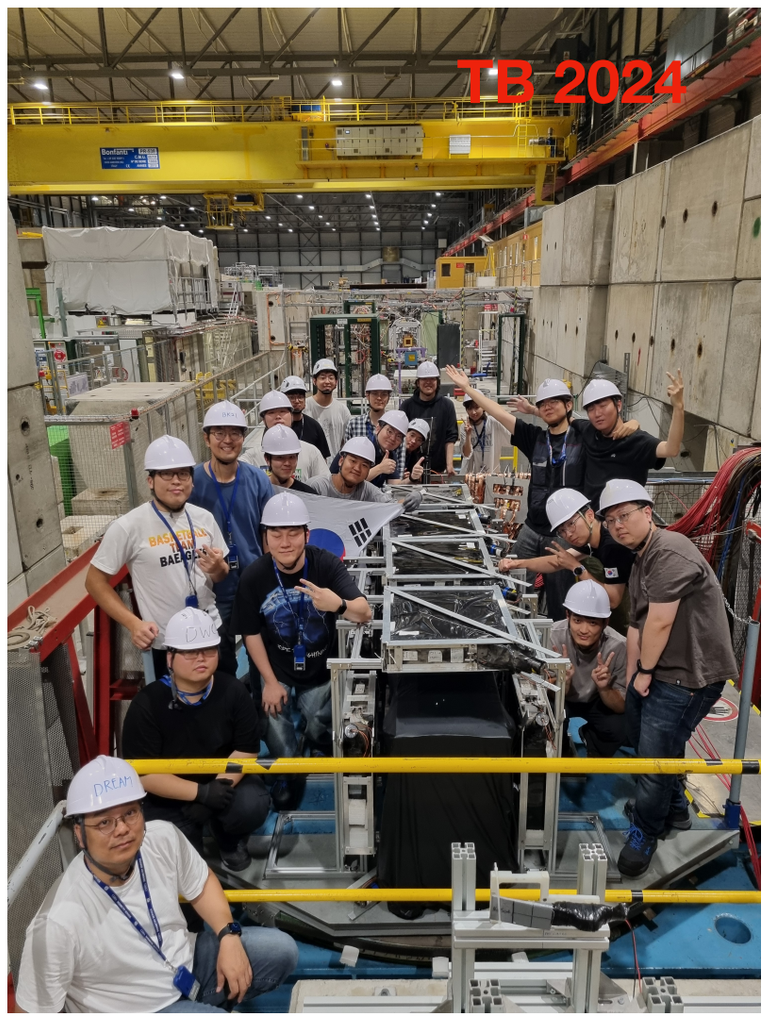


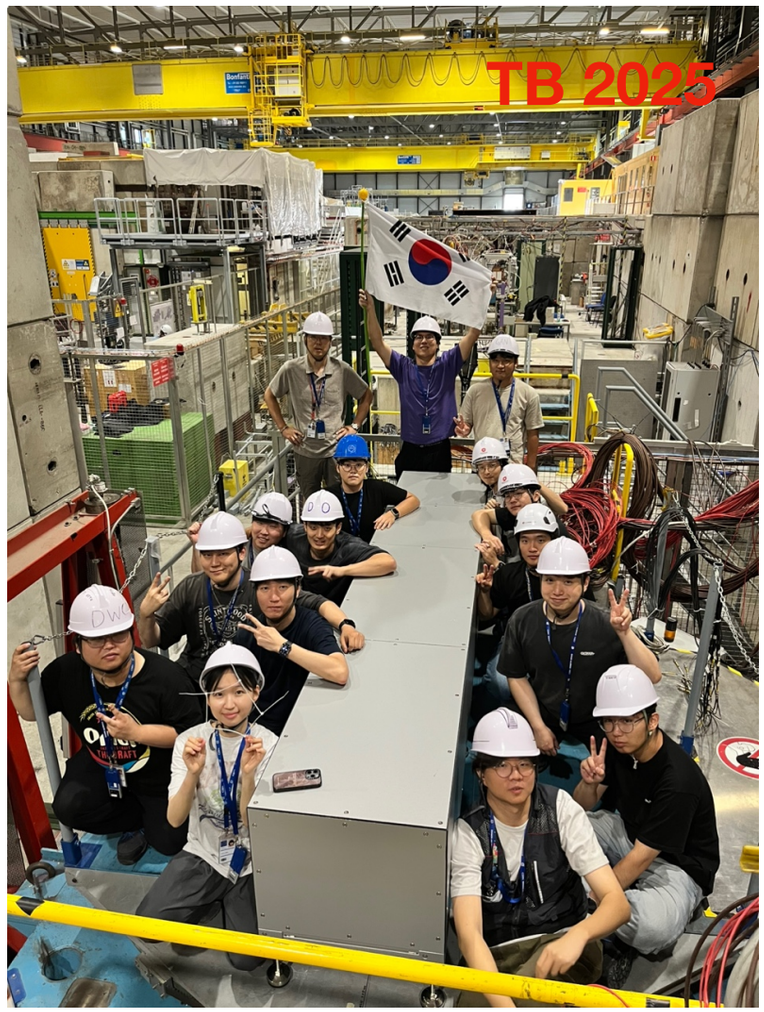
North Area (SPS H8)

Team-Korea for Future Collider

- Students participation: TB 2022 (23), TB 2023 (15), TB 2024 (25), TB 2025 (20), 2026 (28)

- Training next generation is one of the most important missions





Team-Korea for Future Collider

- Students participation: TB 2022 (23), TB 2023 (15), TB 2024 (25), TB 2025 (20), 2026 (28)

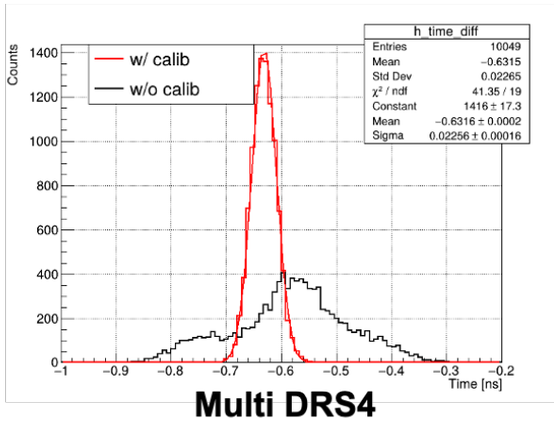
- Training next generation is one of the most important missions

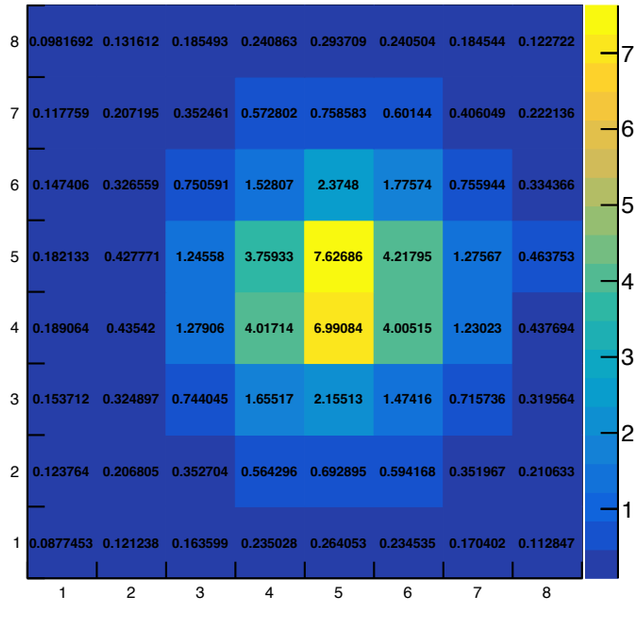
Test-beam Campaigns (2022 - 2026)

	Date	Duration (week)	Facility	e Energy (GeV)	Detector Type	Module Size (cm3)	Weight (kg)
CERN (8)	08/17/2022	1	SPS	10 - 120	DRC	10x20x250	300
	07/05/2023	1	PS	0.5 - 5	DRC	10x10x50	30
	08/07/2024	1	PS	0.5 - 3	BIC	15x9x32	15
	08/07/2024	3	SPS	10 - 120	DRC	30x30x250	1500
	07/23/2025	1	PS	0.5 - 5	BIC	32x15x24	30
	08/06/2025	1	SPS	10 - 120	DRC	30x30x250	1500
	07/27/2026	1	SPS	10 - 120	DRC	30x30x250	1500
	08/24/2026	1	PS	0.5 - 5	BIC	40x40x100	100
KEK (5)	03/19/2025	1	PF-AR	0.5 - 5	BIC	32x12x24	30
	06/12/2025	1	PF-AR	0.5 - 5	BIC	32x15x24	30
	11/27/2025	<1	PF-AR	0.5 - 5	DRC	15x15x50	50
	05/14/2026	1	PF-AR	0.5 - 5	BIC	40x40x100	100
	05/22/2026	<1	PF-AR	0.5 - 5	DRC	15x15x50	50

Physics Programs for TBs

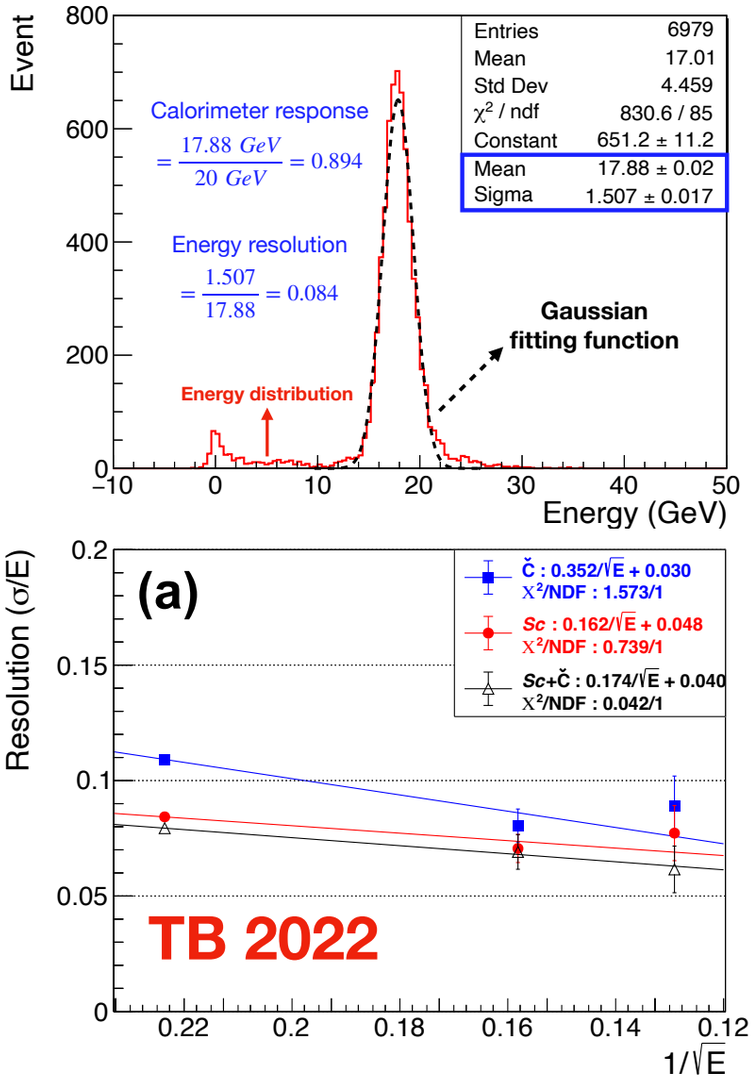
- EM performance: EM response - linearity & resolution
- Uniformity scan (EM)
- Hadron performance: hadron response - linearity, resolution, and features (π^+, p, jet-like)
- Time performance: time resolution
- High granularity test: position resolution



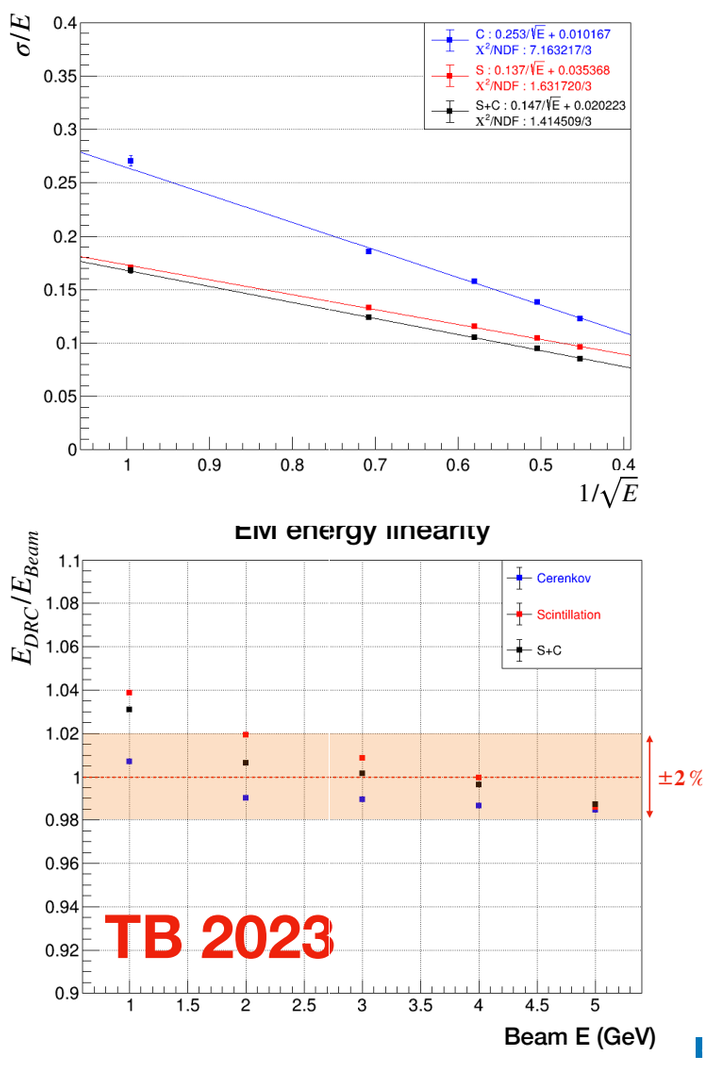


Test-beam Results

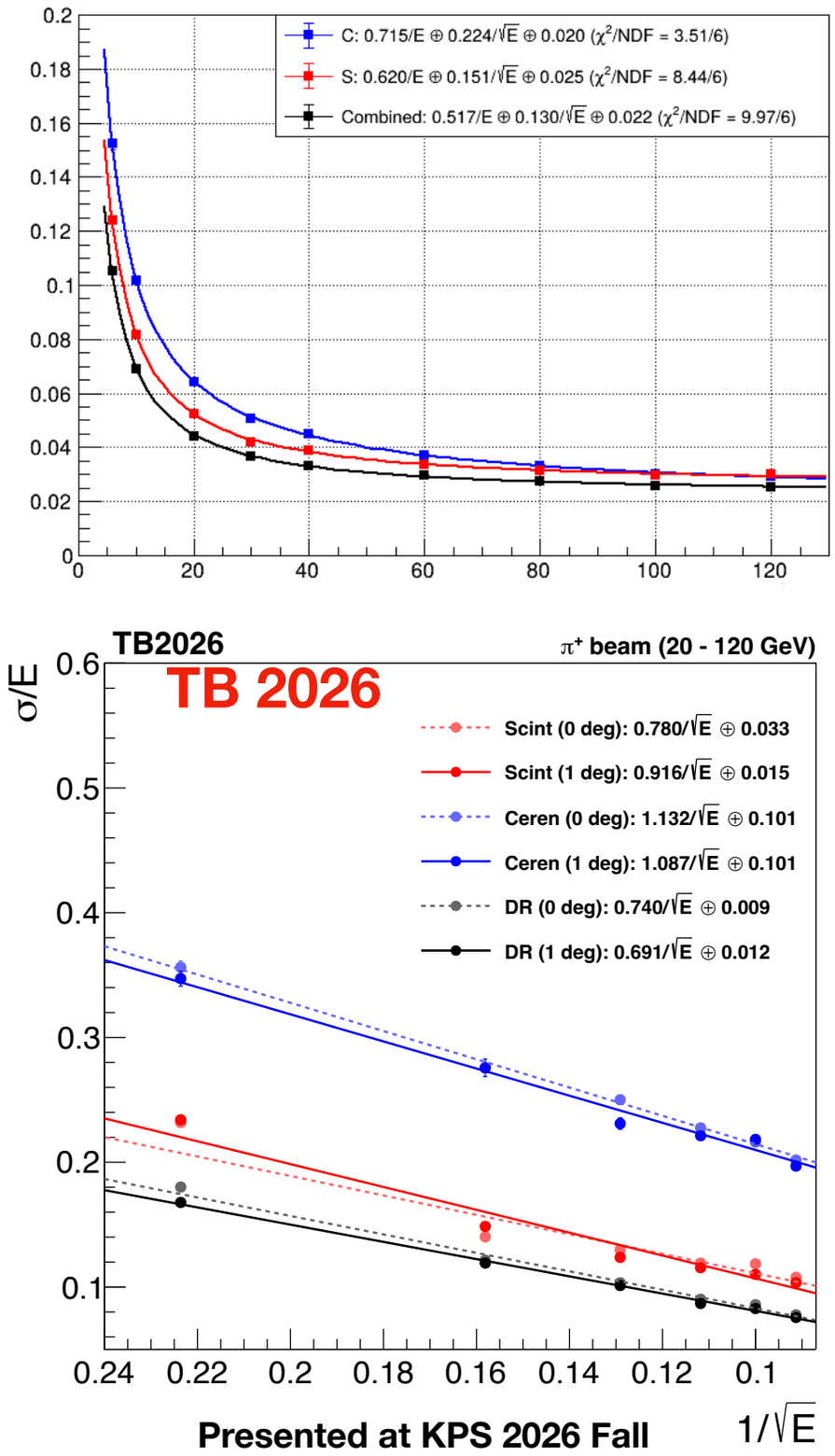
- Analyses and paper preparations are on-going



Published at Journal of Subatomic Particles and Cosmology (Elsevier)



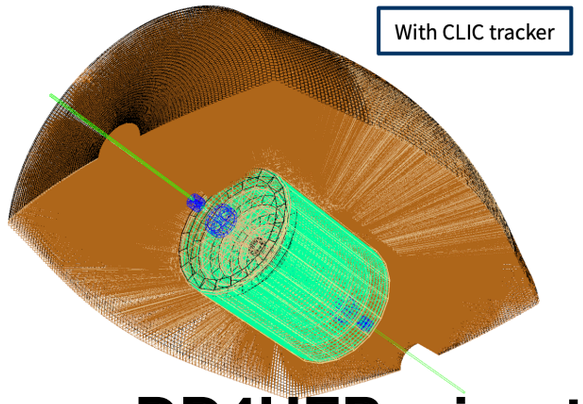
Presented at CALOR 2024



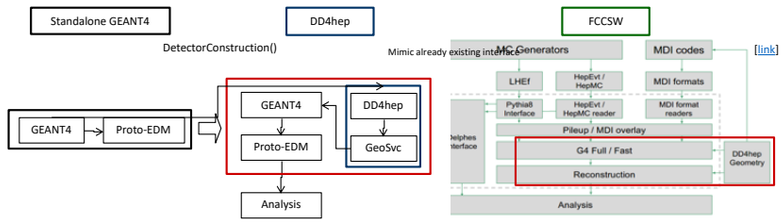
Presented at KPS 2026 Fall

Simulation/SW Framework

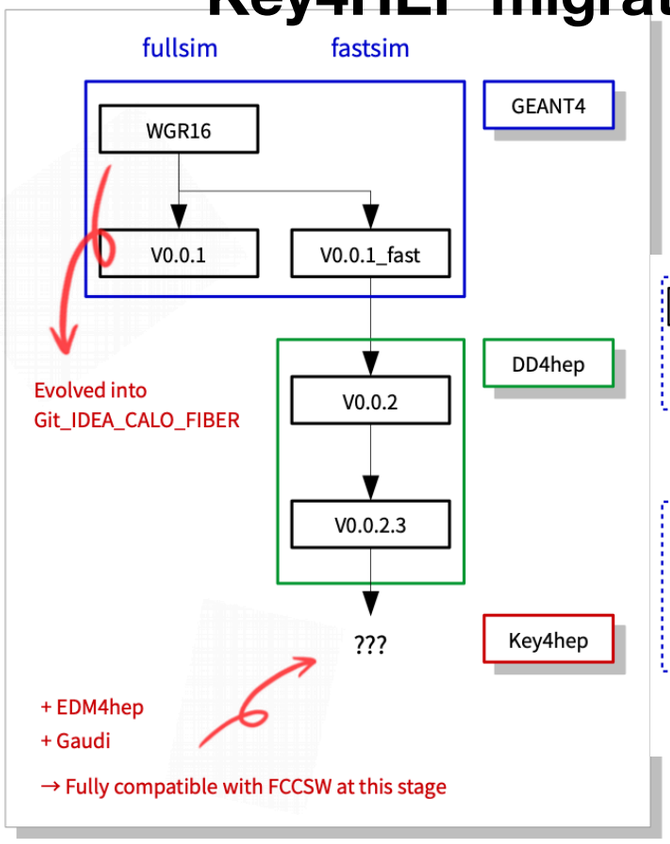
- Contribute on many centralized SW developments
  - Migration to DD4HEP framework
  - Faster simulation: developing optical photon transport in GEANT4 => O(100) times faster
  - Migration to Key4HEP framework
    - Add digitization, reconstruction, calibration, etc.



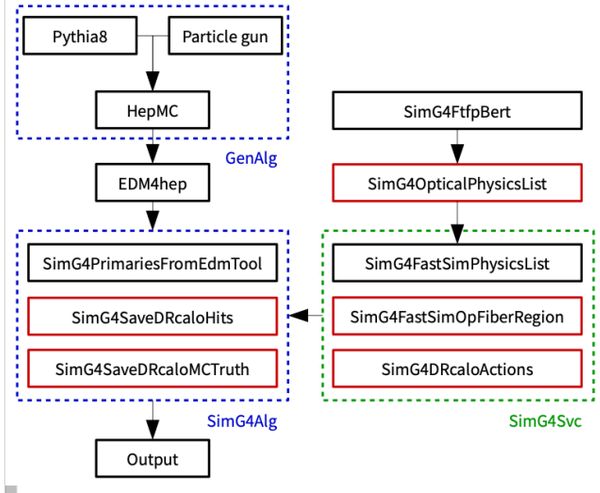
DD4HEP migration



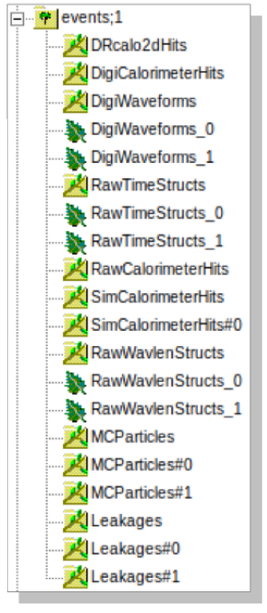
Key4HEP migration



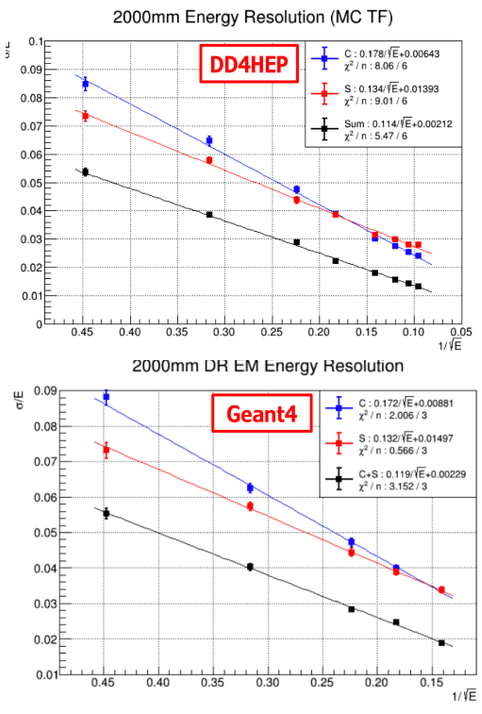
Simulation flow

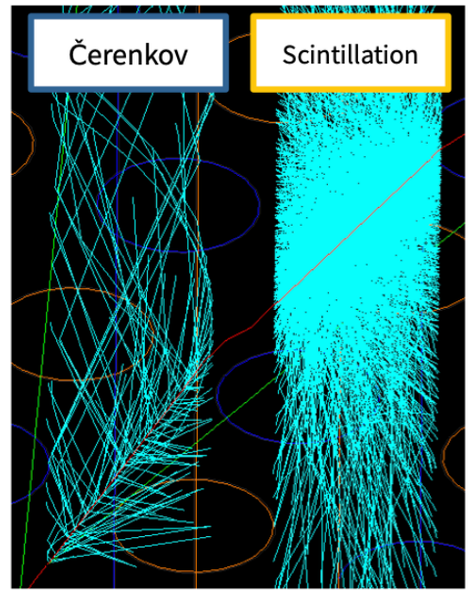


EDM4hep



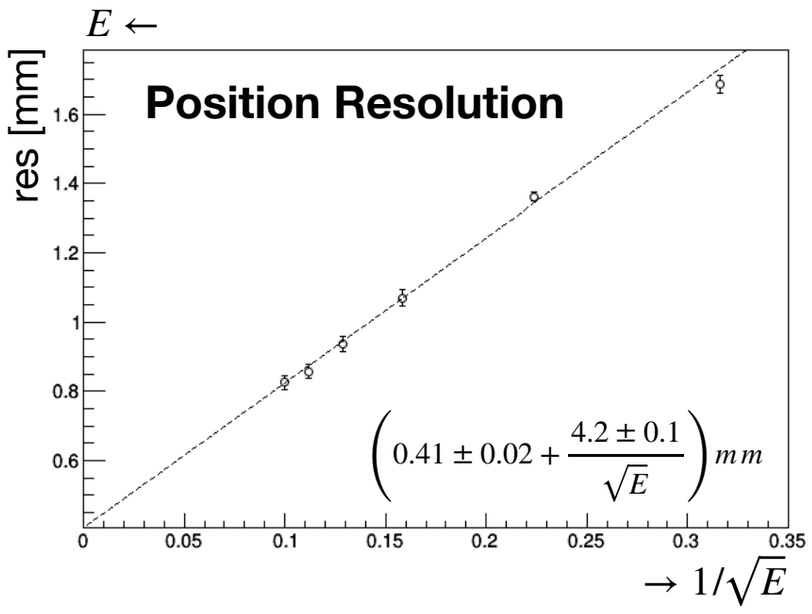
Faster simulation

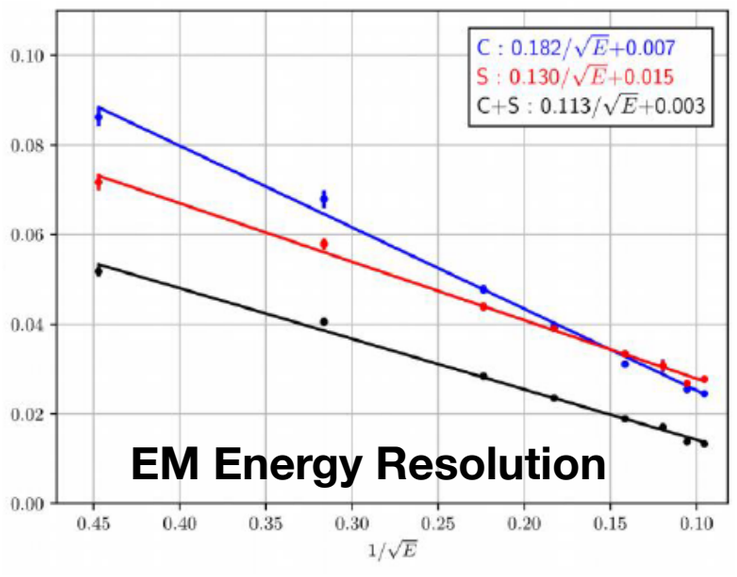


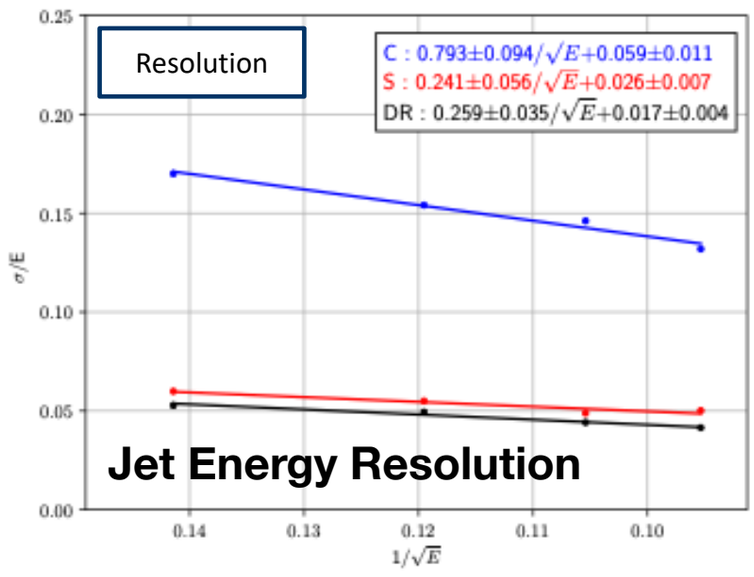


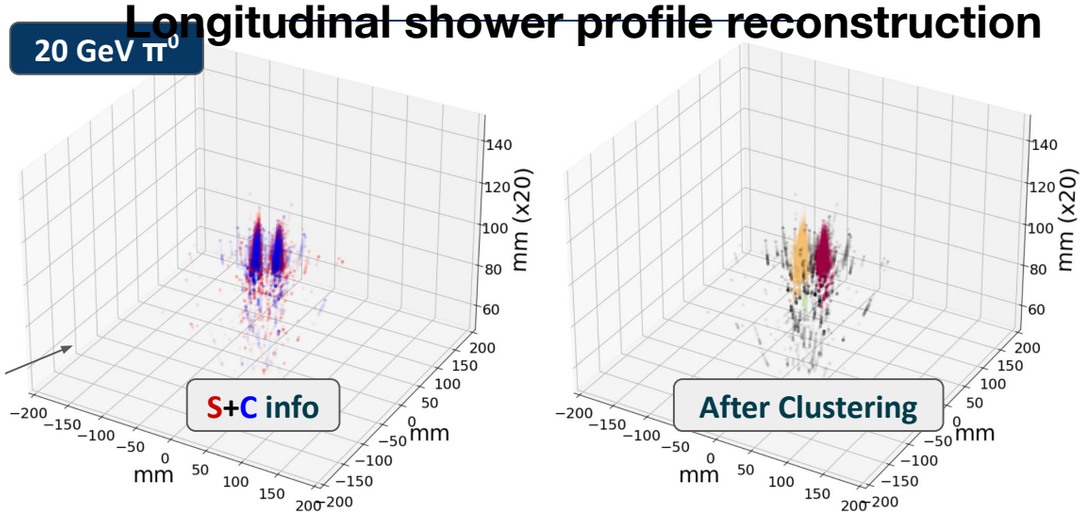
Important for a longitudinally unsegmented calorimeter

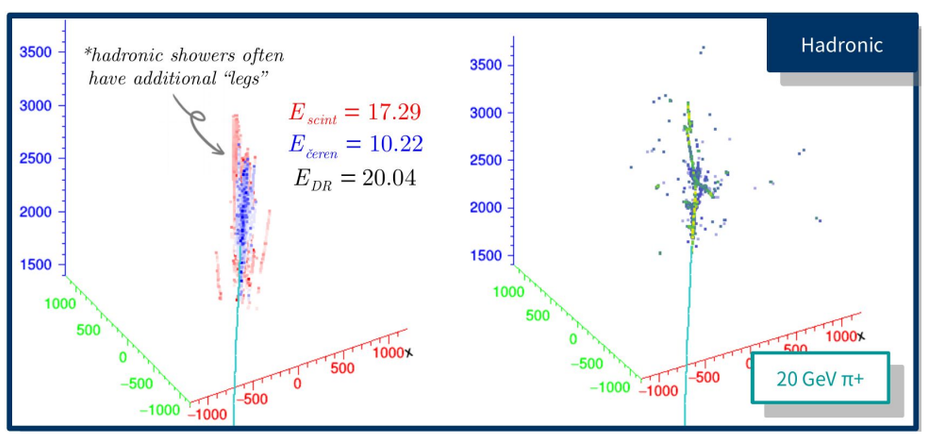
Performance Studies (Simulation)

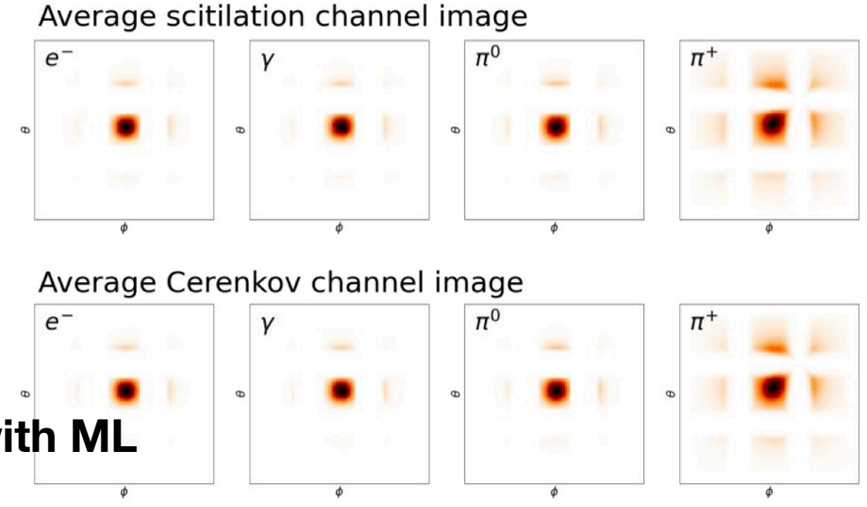




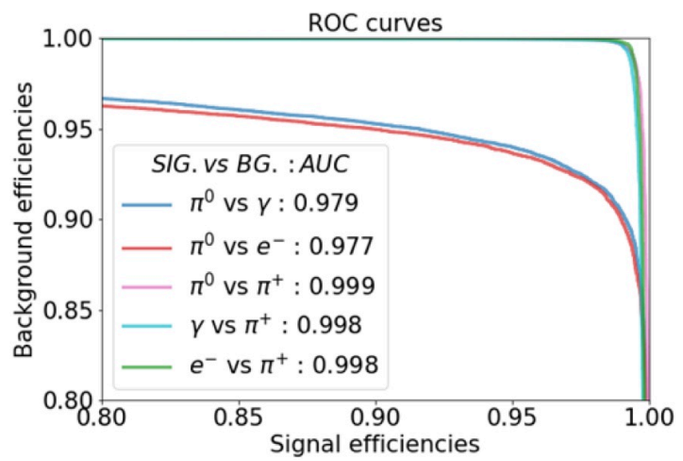


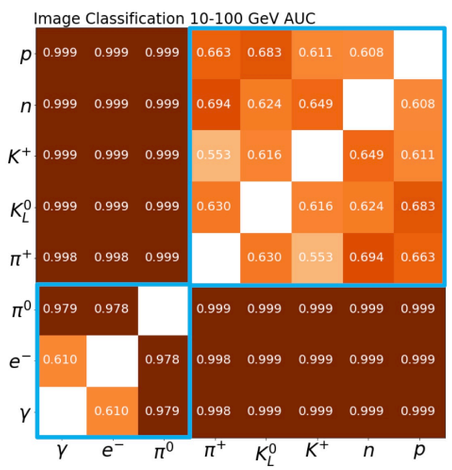






Particle IDs with ML

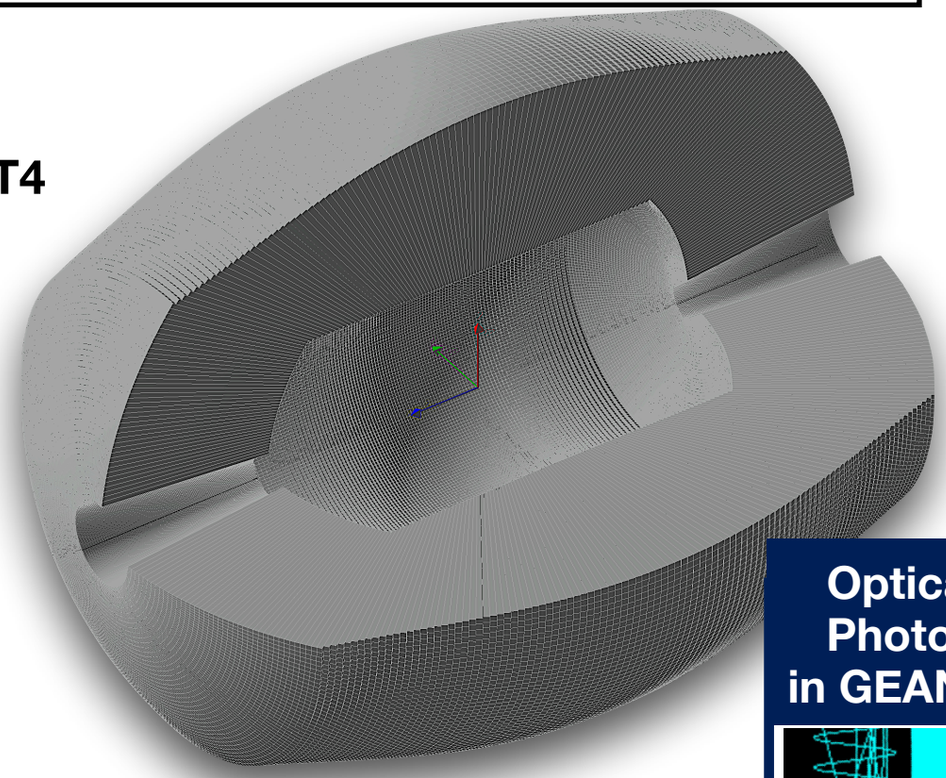


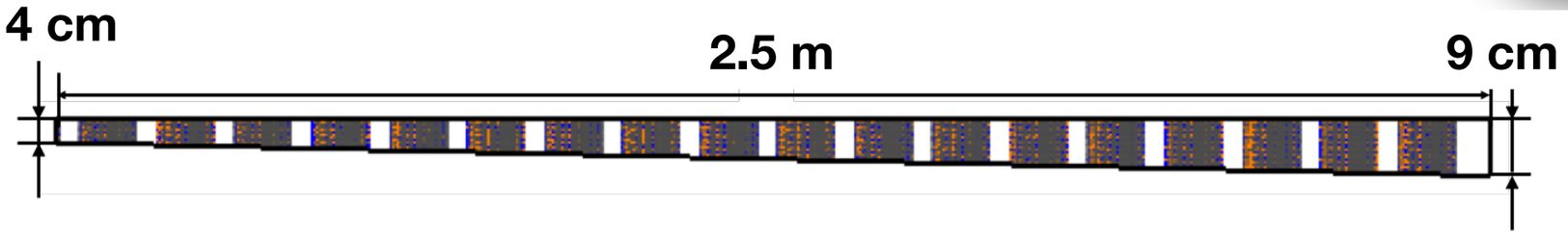


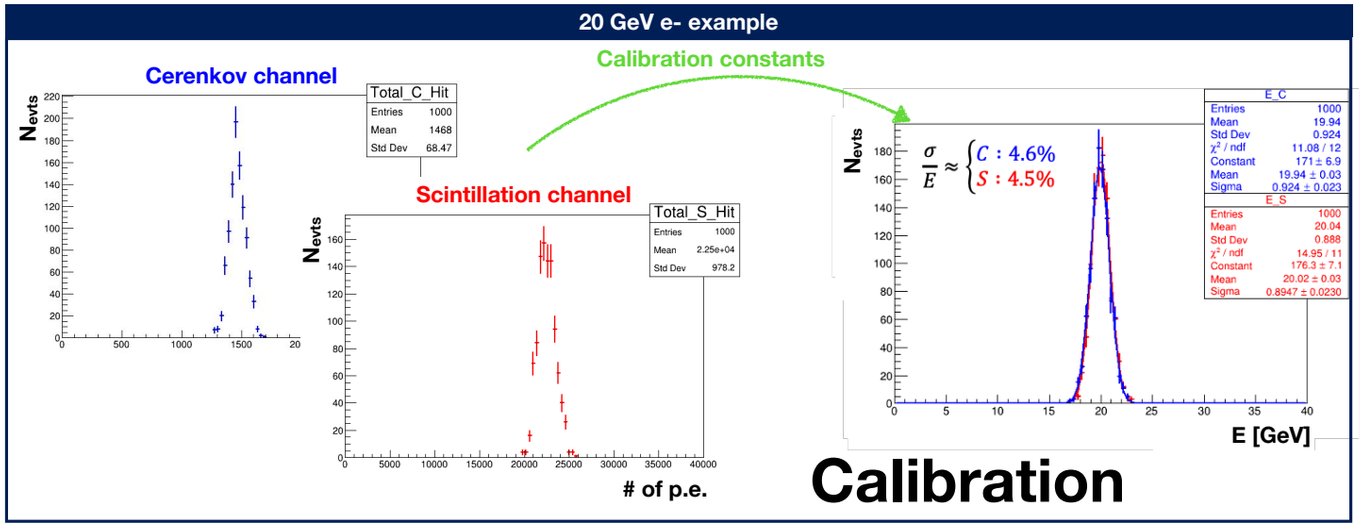
Simulation: 4pi Geometry

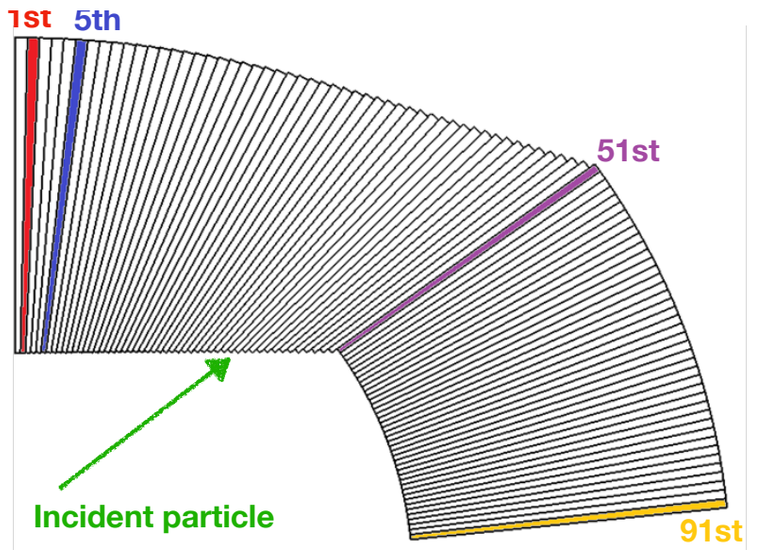
◉ Detector geometry in the GEANT4 simulation

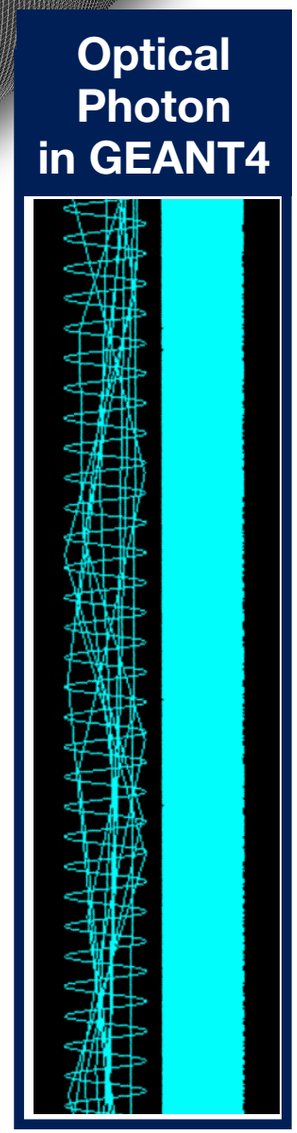
- **4pi full projective DRC** implemented in the **GEANT4**
  - composed with **~ 52000 individual towers**
- **Each tower has 2.5 m length**
  - which corresponds to **~ 10 nuclear interaction length**
  - allowing us to get **~ 99% energy deposit for EW window**
  - **implemented by ~O(1000) fibers in copper absorber**





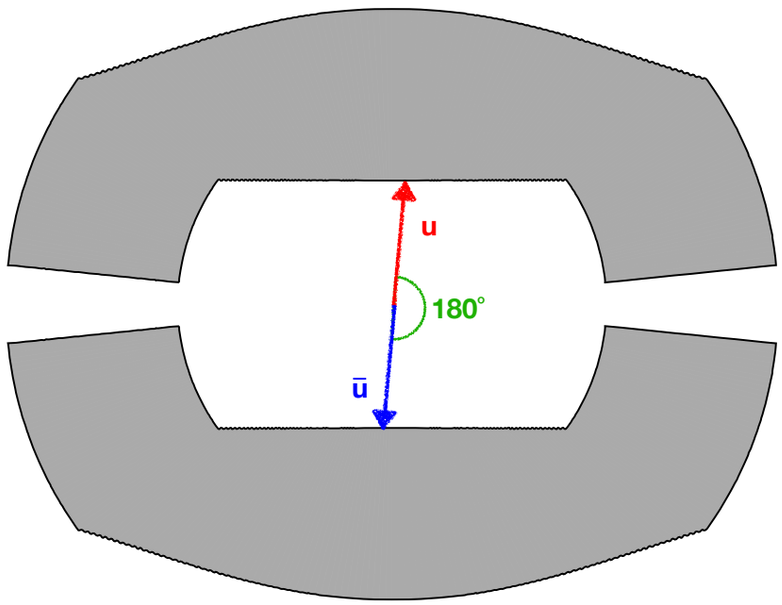




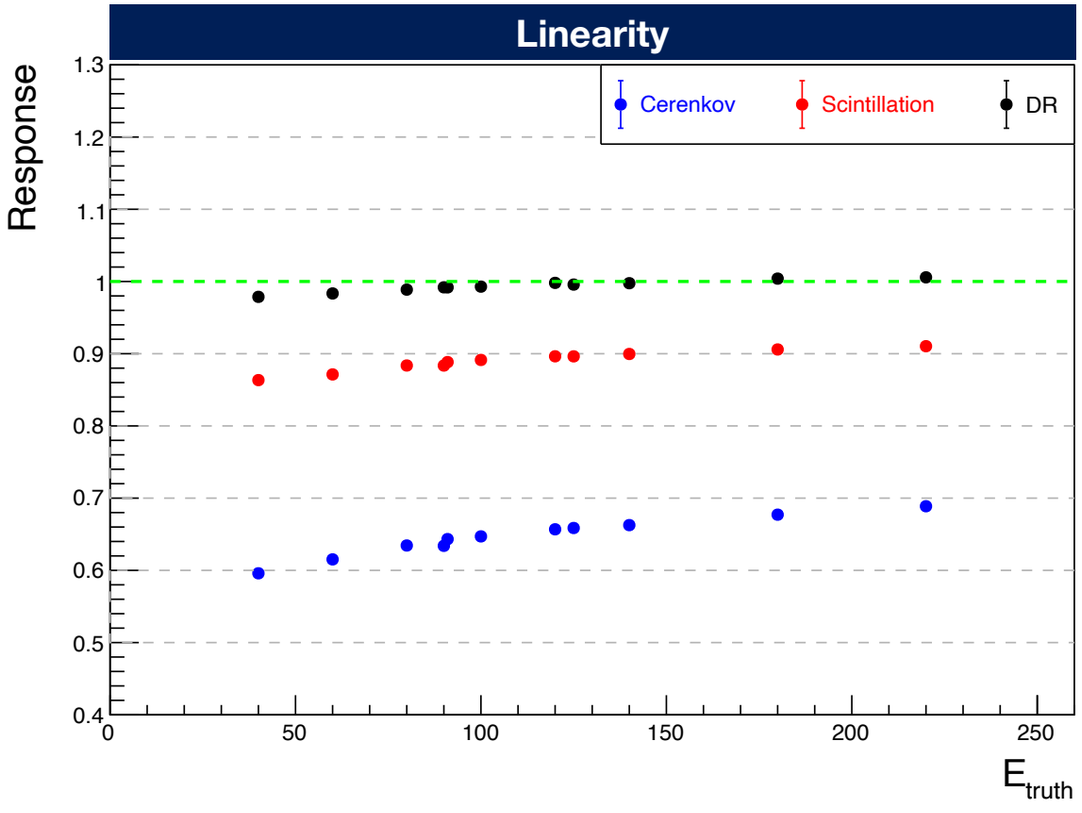


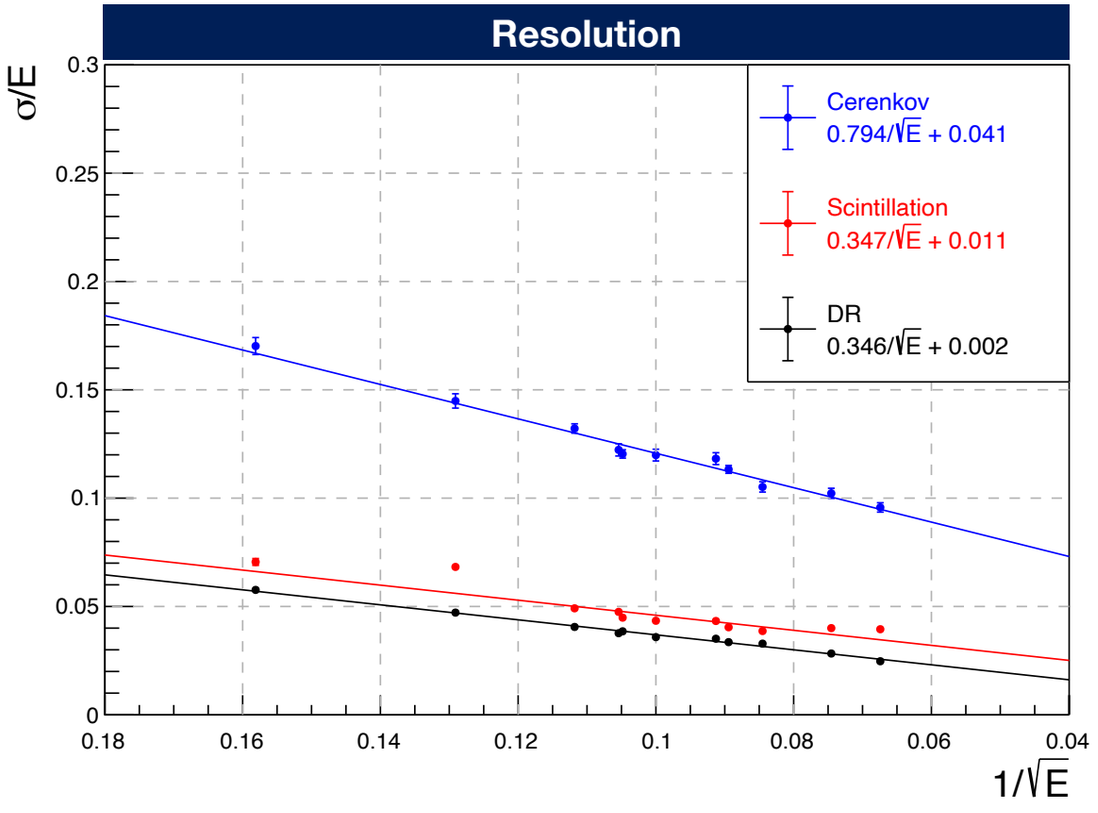
Simulation: 4pi Geometry

- **Energy reconstruction with Jet events**
  - **Obtain energy response from whole detector**
    - e.g) **40 GeV** u and ubar quark event
      - ➡ corresponding energy is **80 GeV**



- **Estimation of Jet energy resolution with u quark jet simulation**
  - Generated u and ubar quarks have the energy from 20 GeV to 110 GeV
  - Resolution result for each energy is **scaled to 1 / √E**
  - Stochastic term of resolution: **34.6% stochastic term** → **with 100 GeV: 3.7% res**





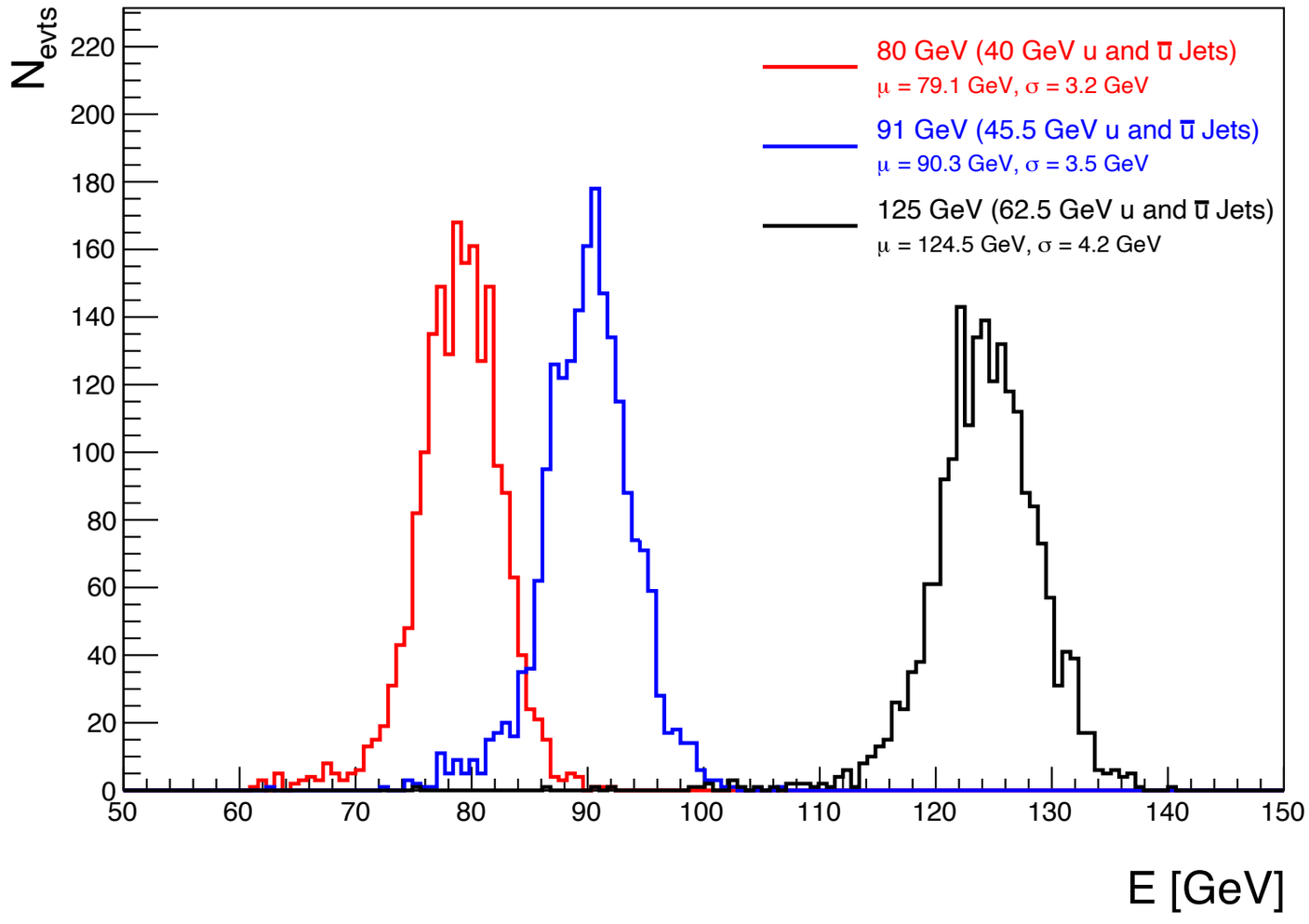
World the most and best precise simulation results!

Presented at CALOR 2024 (May 23, 2024) and paper in preparation

Simulation: 4pi Geometry

- **Energy separation between the events with 80, 91 and 125 GeV u and ubar quark jets simulation**
  - As future collider experiment aiming to see Higgs, **mass separation between bosons is the most important aspect**
  - The **DRC** shows **good separation** between the energies that correspond **the mass of bosons**

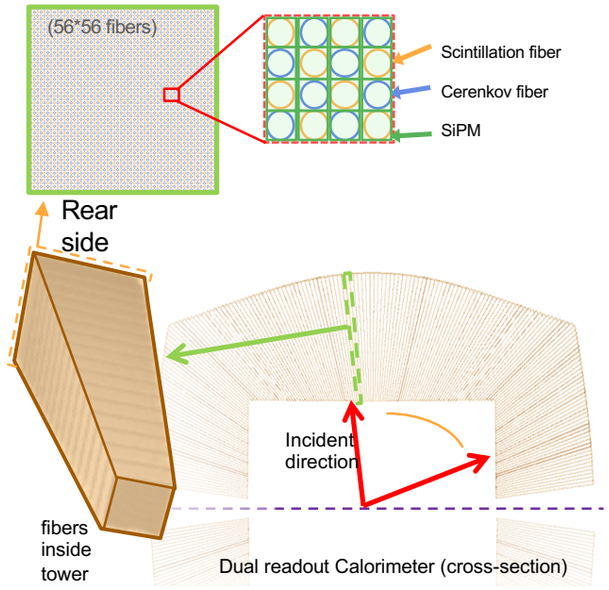
- **Each simulation correspond to the invariant mass of bosons**
  - e.g) 40 GeV u and ubar jet events
    - ➡ 80 GeV ~ W inv. mass

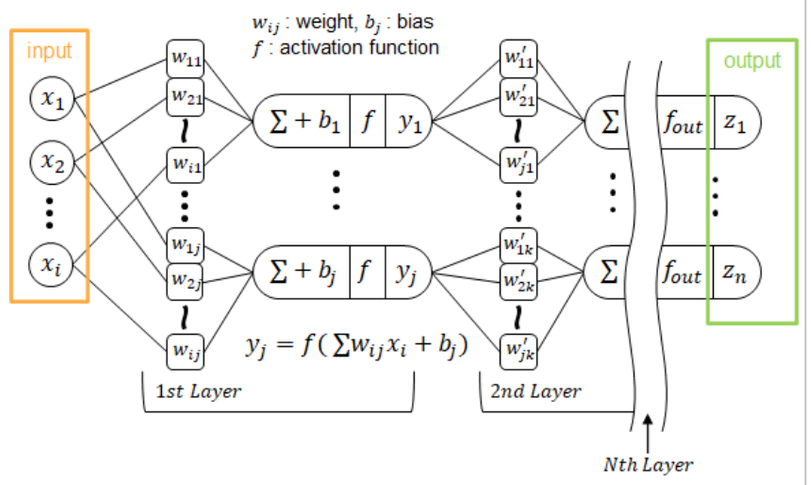


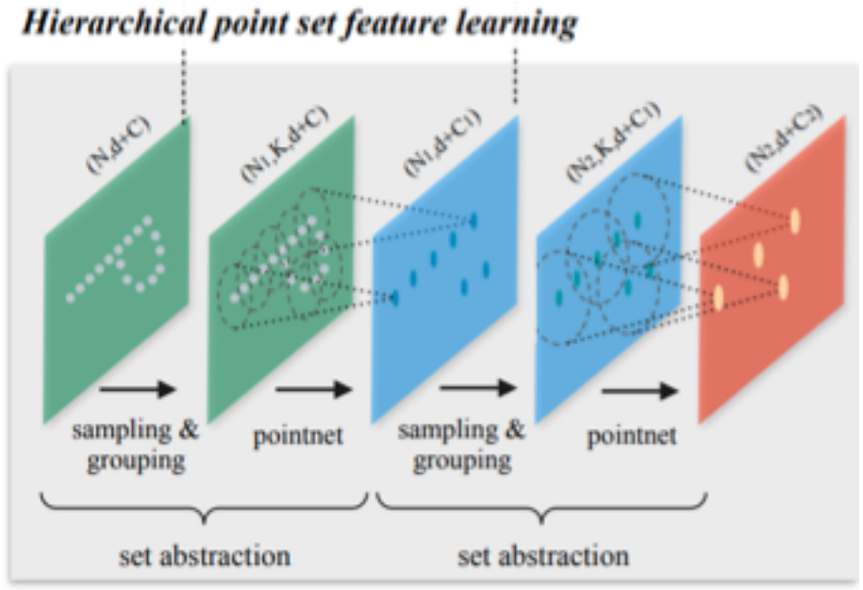
Presented at CALOR 2024 (May 23, 2024) and paper in preparation

Particle ID with ML

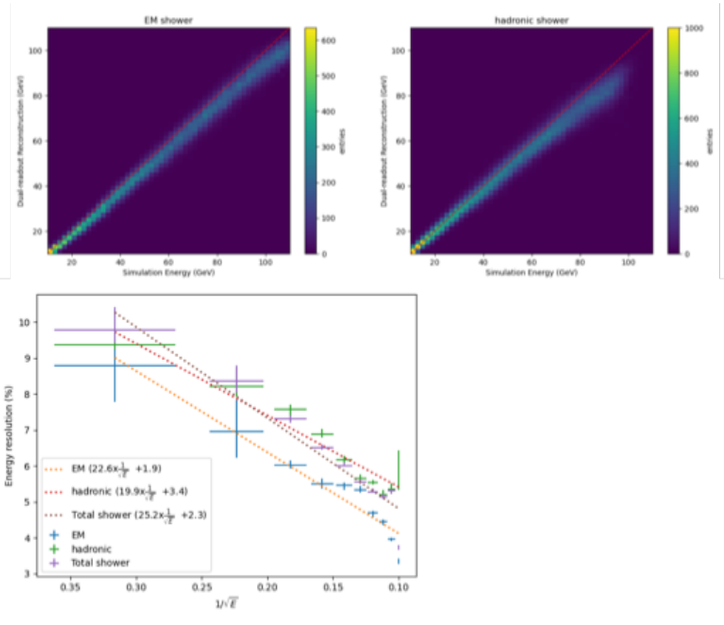
- DL implementation setup for extended particle identification

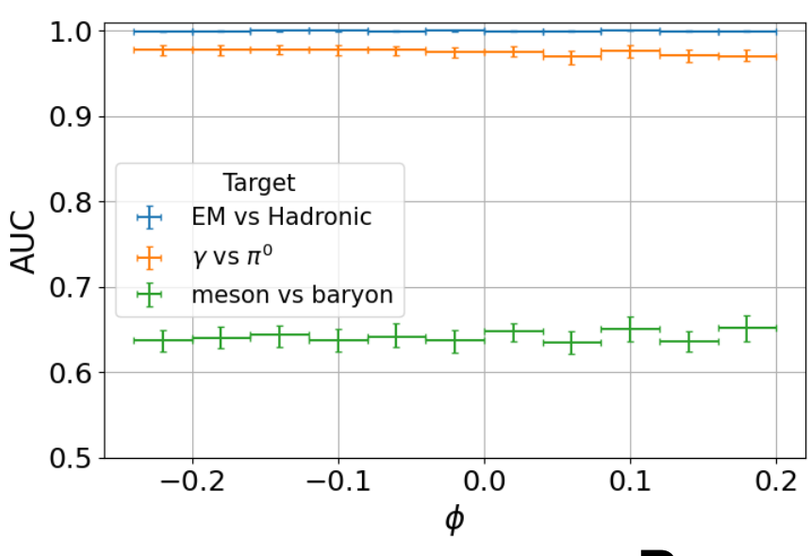


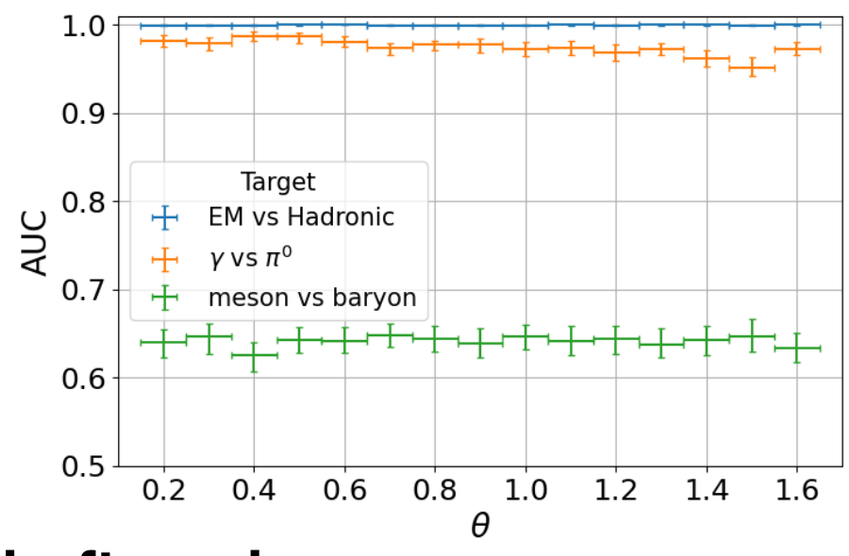




- Performance is quite promising compared to the classical approach

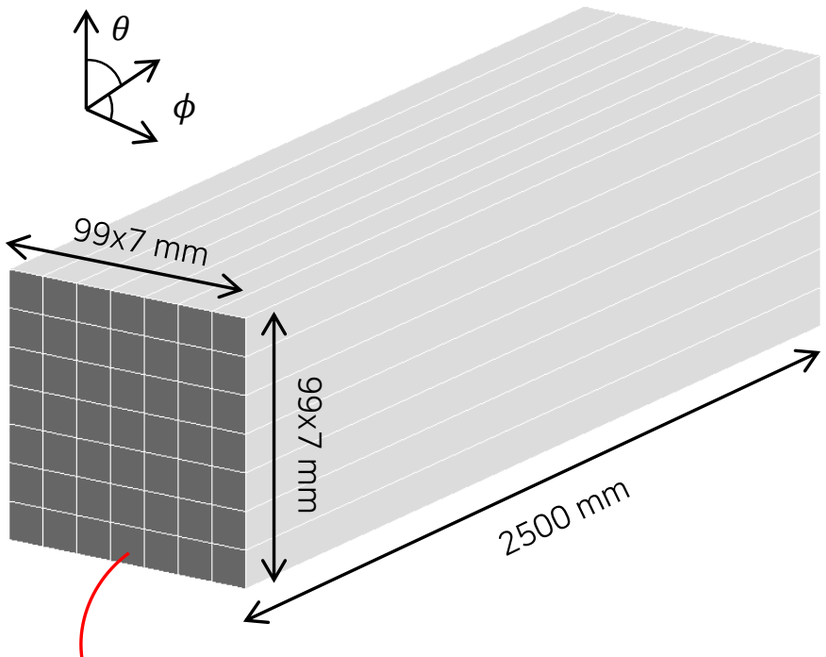






Paper draft ready

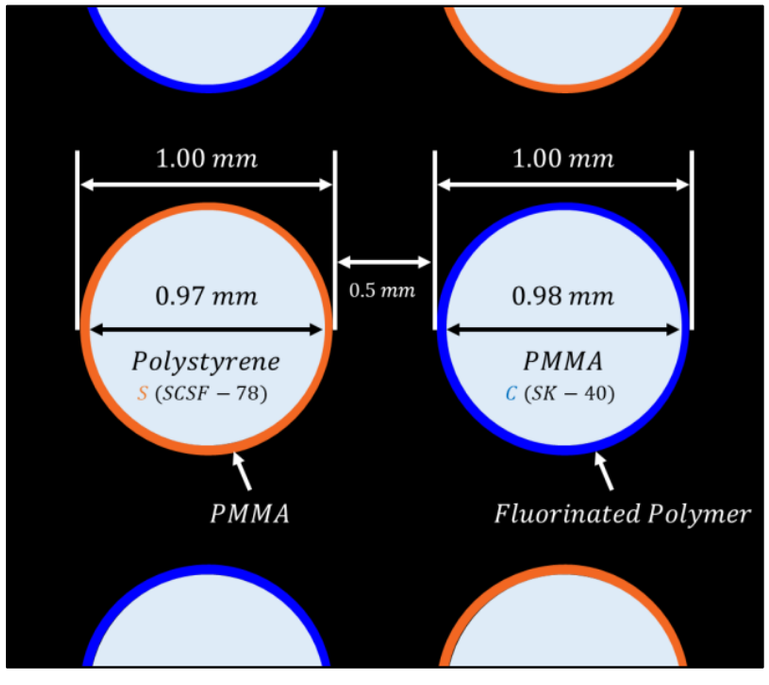
Comparison for Various Absorbers

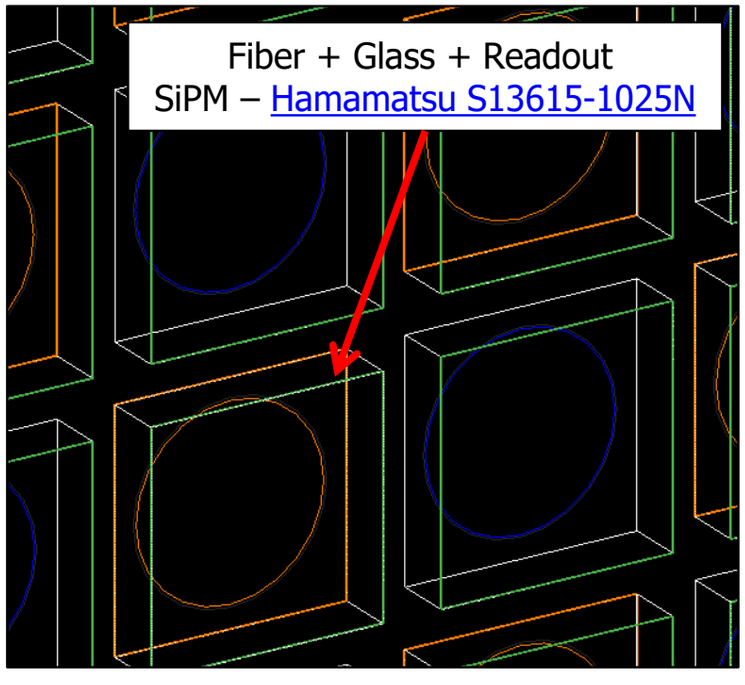


- Simulation setup is based on Geant4 toolkit, 10.5.p01, physics list FTFP-BERT.
- The geometry is **longitudinally unsegmented**, box shape, 7x7 modules.
- 5 different absorbers were used –

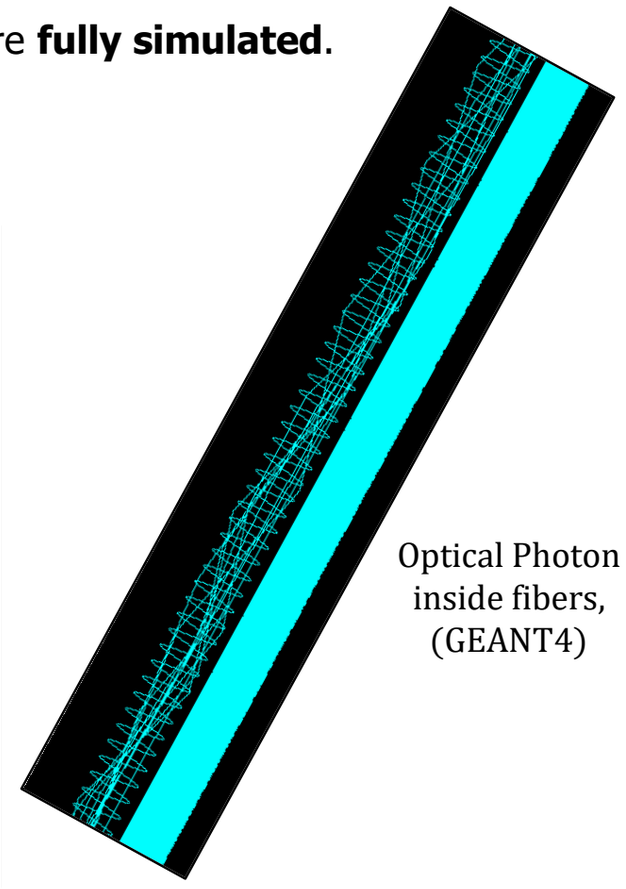
  Copper, Brass (Cu:Zn=7:3), Iron, Lead, Tungsten

- 1mm diameter scintillating & Cherenkov (Clear) optical fibers are implemented.
- **Optical physics process** inside fibers are **fully simulated**.
- SiPM is attached for each single fibers.





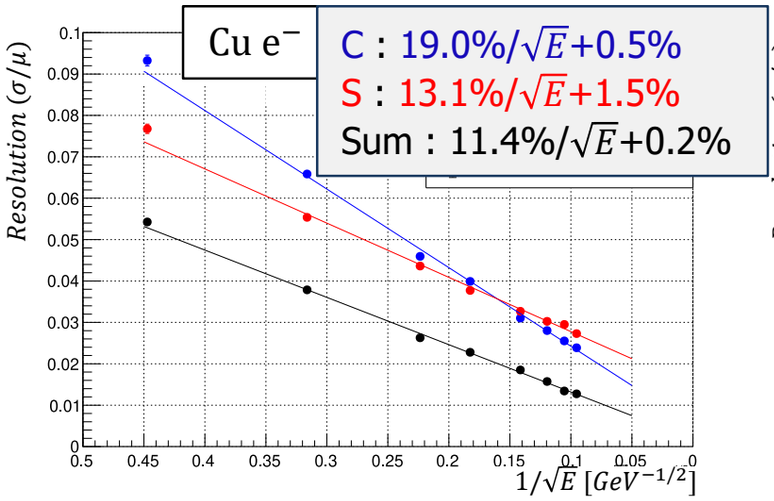
Rearside of module (GEANT4)

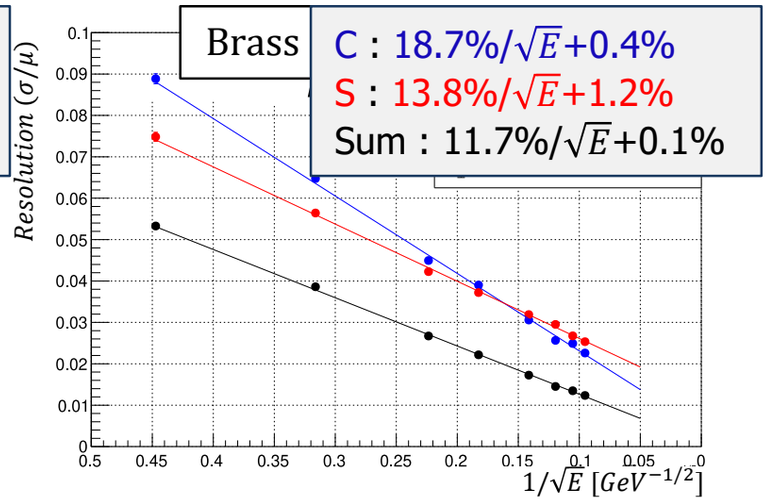


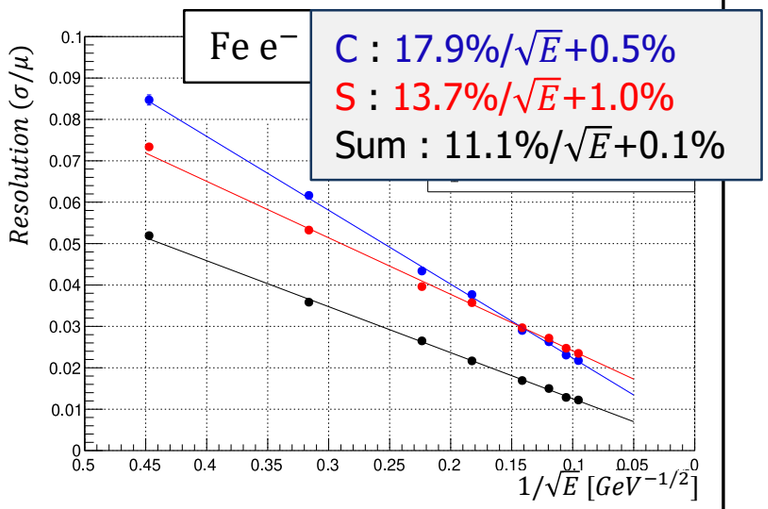
Optical Photon inside fibers, (GEANT4)

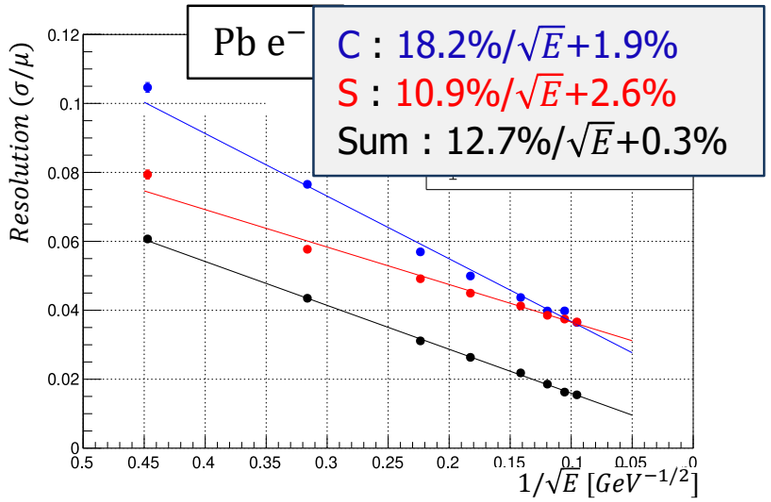
NIM A 1090 (2026)

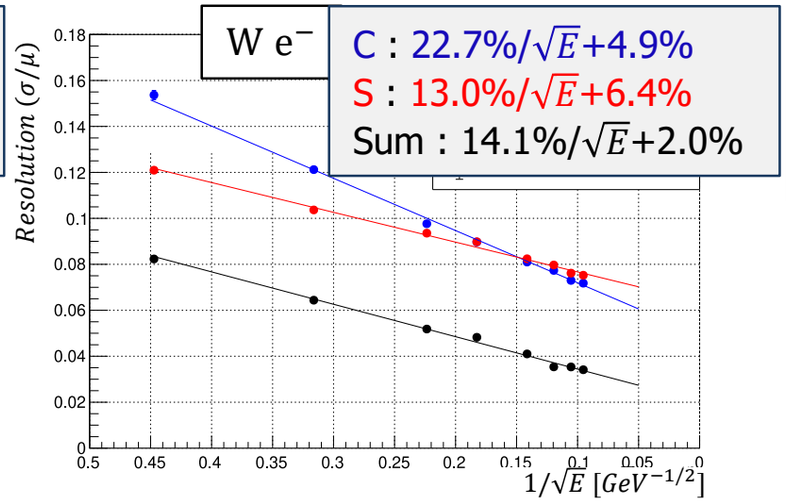
Comparison for Various Absorbers











Energy resolution of electron, 5~110 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

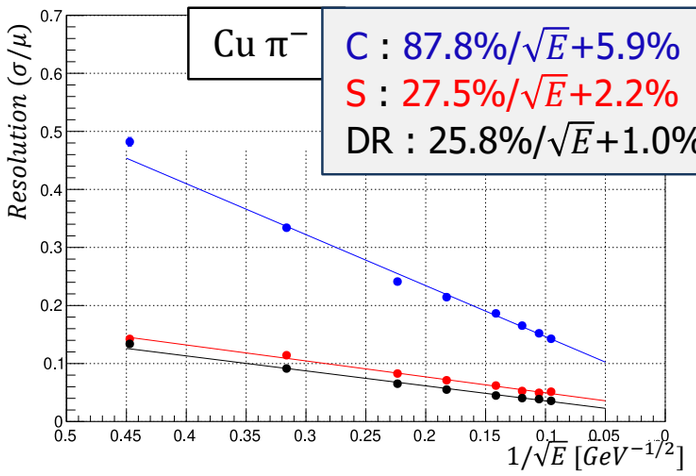
$\text{Resolution} = \sigma/\text{Mean}$

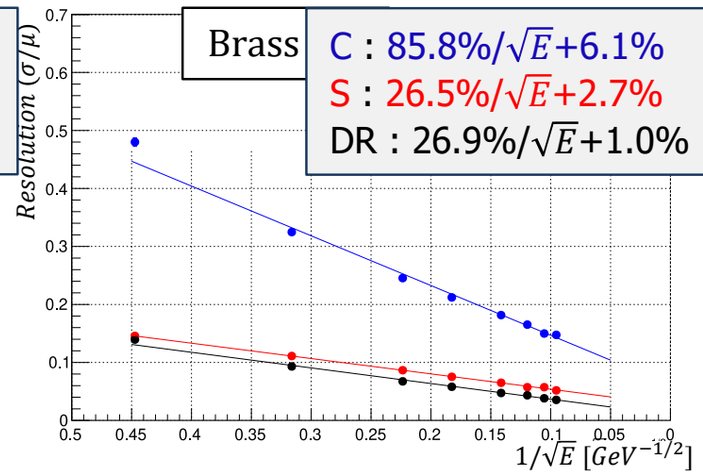
$\textbf{Sum} = \textbf{C} + \textbf{S}$

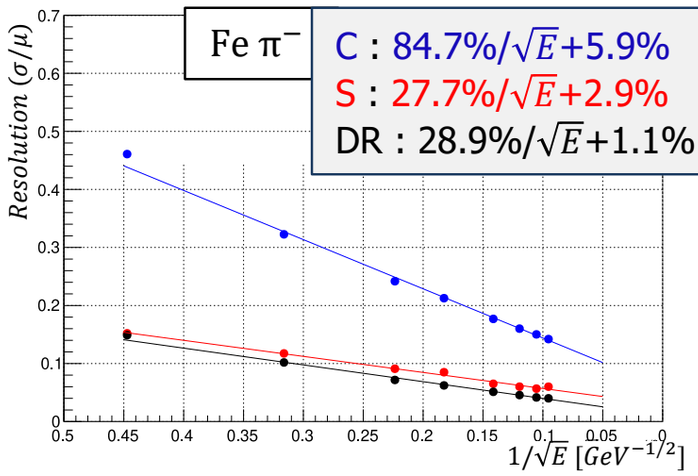
- Used mean & RMS of guassian fit function of reconstructed energy – Scintillation Cherenkov, and Summation channel.
- Energy resolution of electrons, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- **Low Z absorbers show relatively better resolution than Pb, W – 11~12% of stochastic term.**

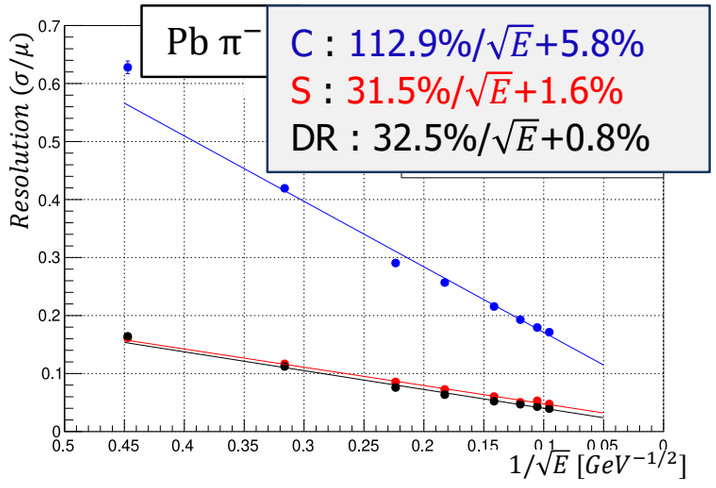
NIM A 1090 (2026)

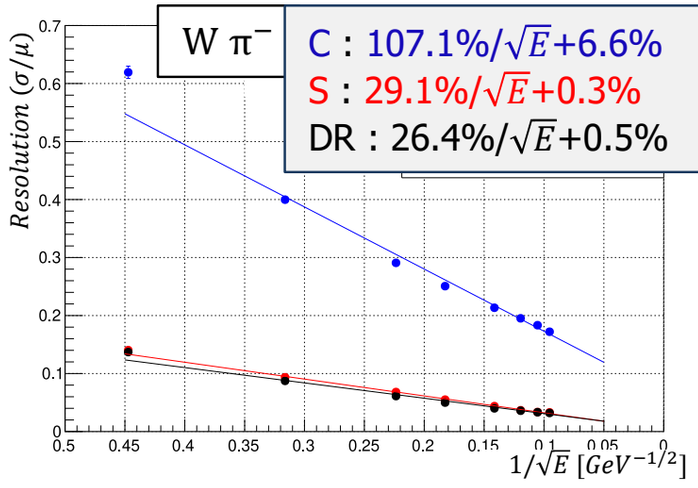
Comparison for Various Absorbers











Energy resolution of pion,
5~110 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

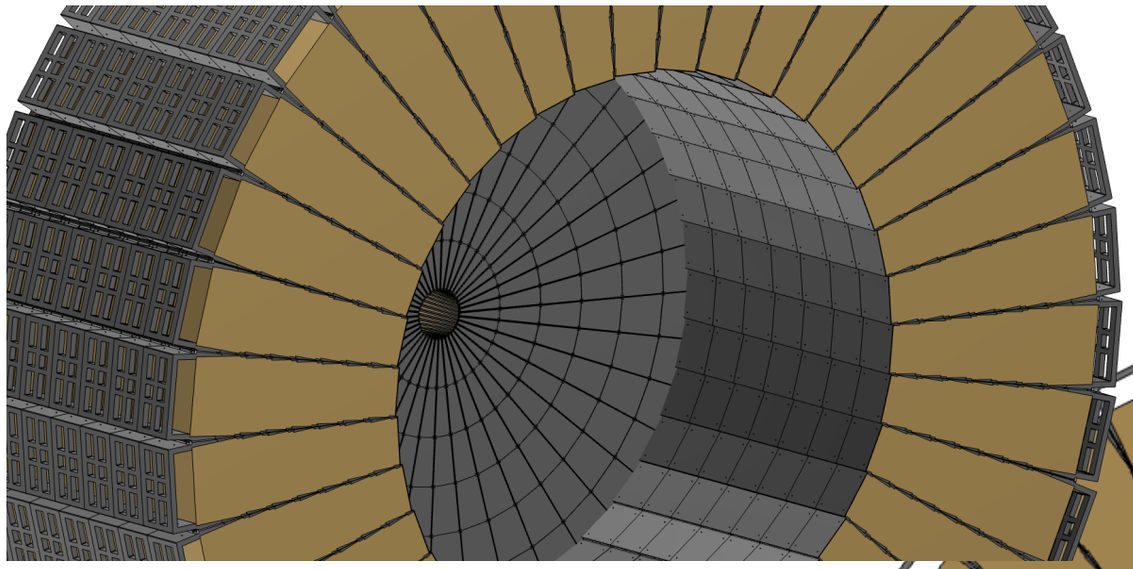
$\text{Resolution} = \sigma/\text{Mean}$

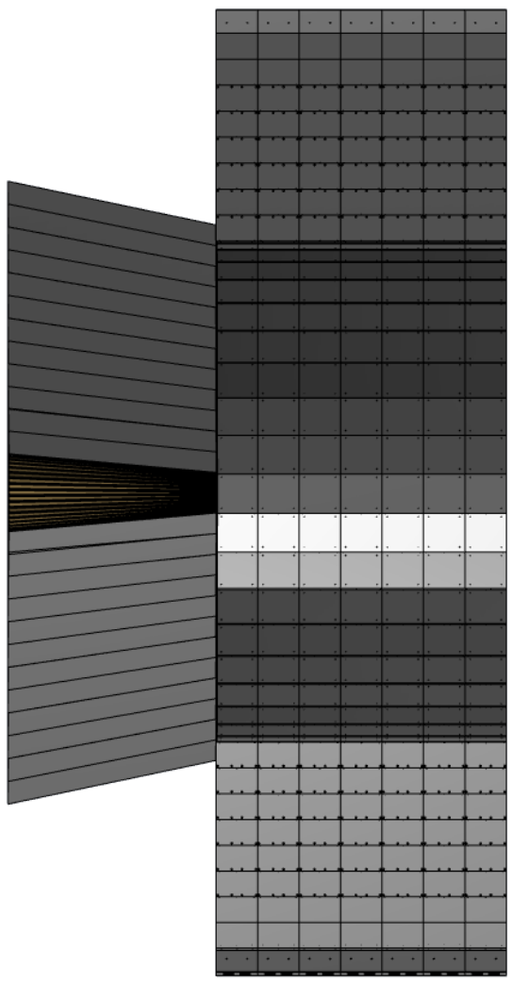
S, C, Dual Readout corrected

- Used mean & RMS of distribution of reconstructed energy – Scintillation Cherenkov, and gaussain fit for DR corrected ch.
- Energy resolution of pions, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- **Low Z absorbers show stochastic term of corrected channel under 30%,** for **copper – 25.8%/$\sqrt{E}$**

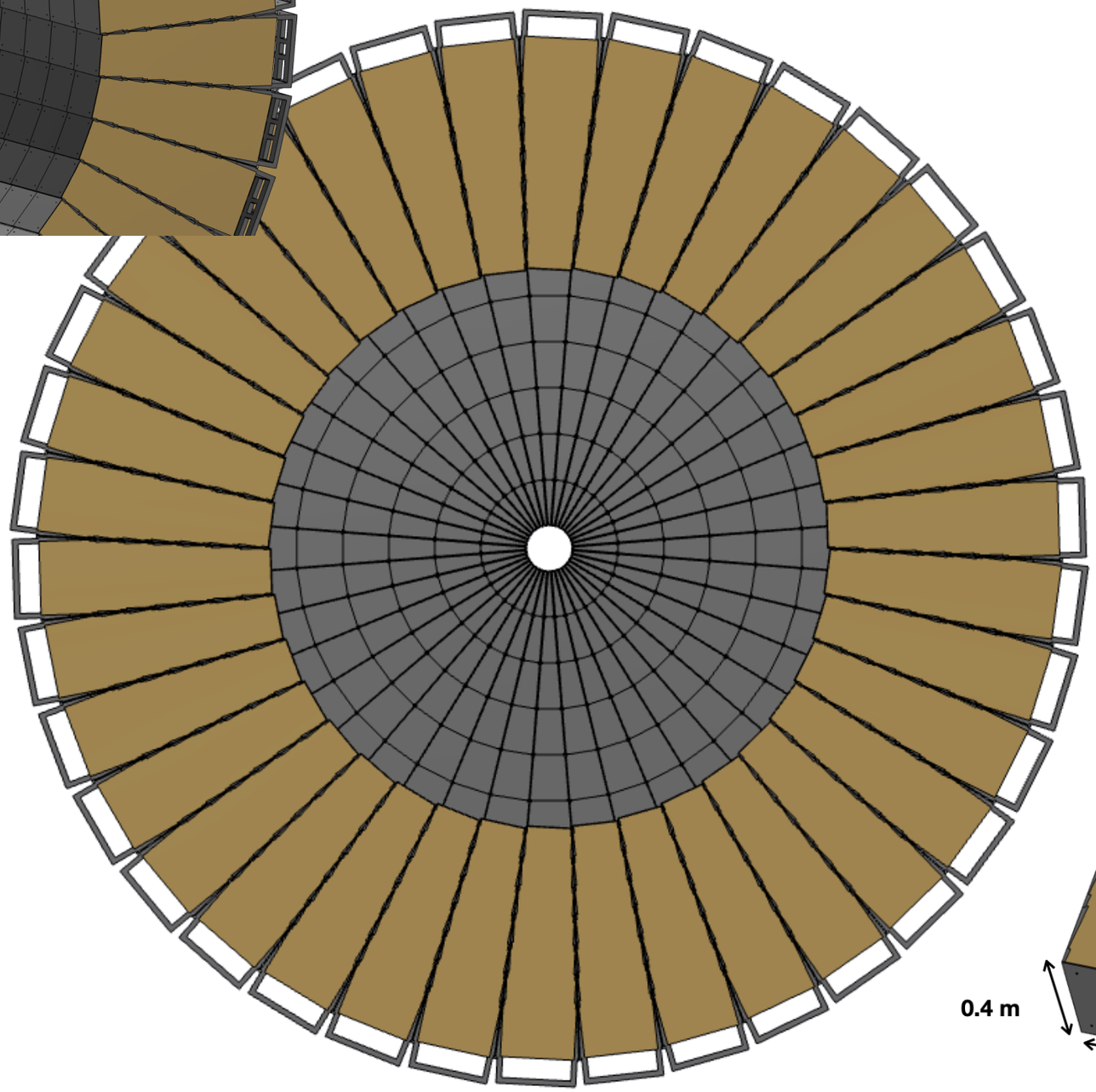
NIM A 1090 (2026)

Toward Engineering Design

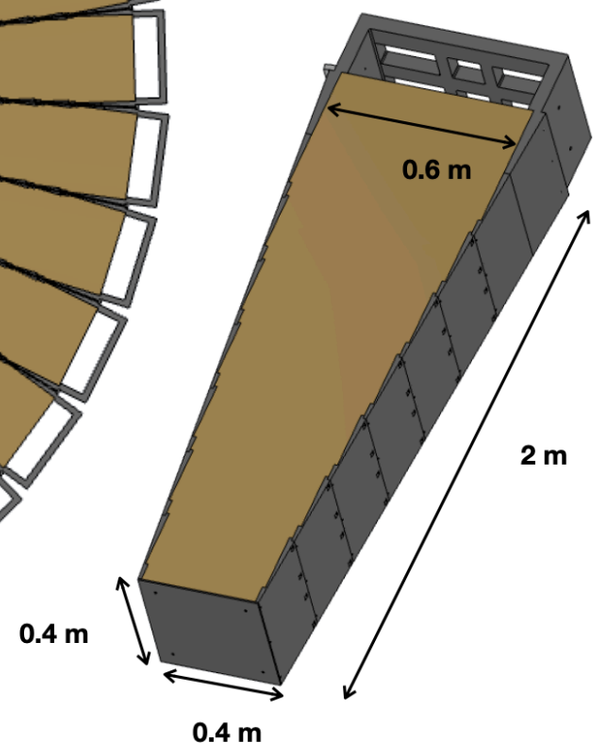




39 modules / wheel
14 wheels for barrel (5.6 m)



Single unit module

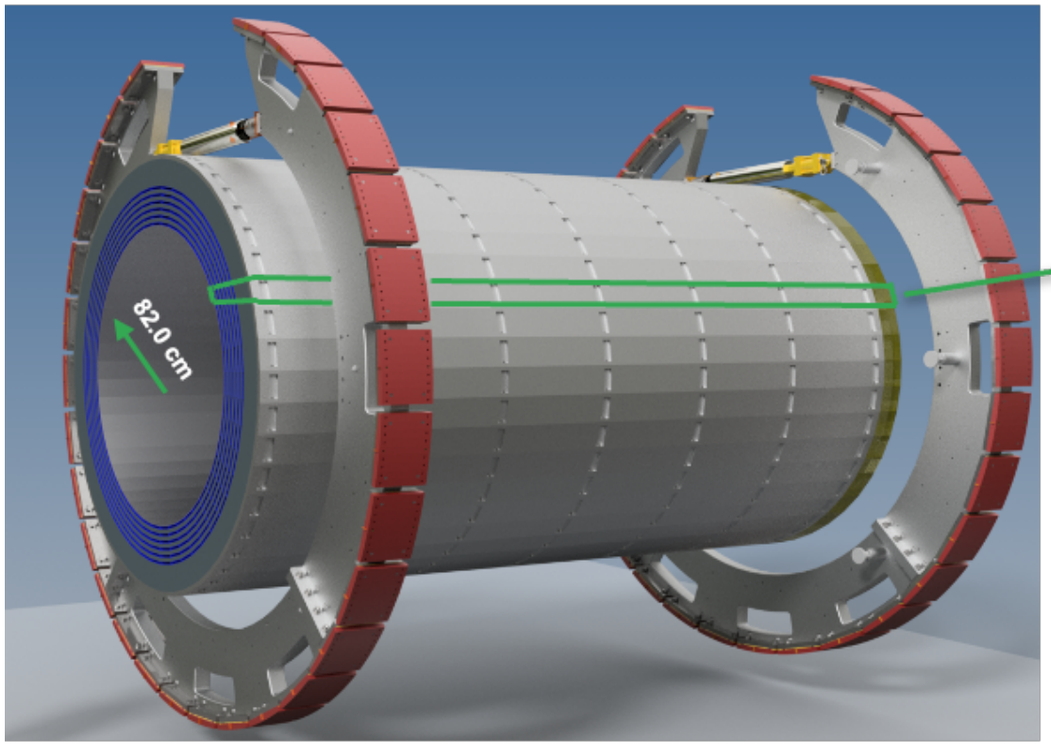


Part II: Barrel Imaging Calorimeter for EIC

Barrel Imaging Calorimeter

- Korea-BIC group will construct 50% of BIC detector at EIC project
  - 2026-2033 (7 years), ~$13M, PI (Hwidong Yoo)

Sector Mechanics

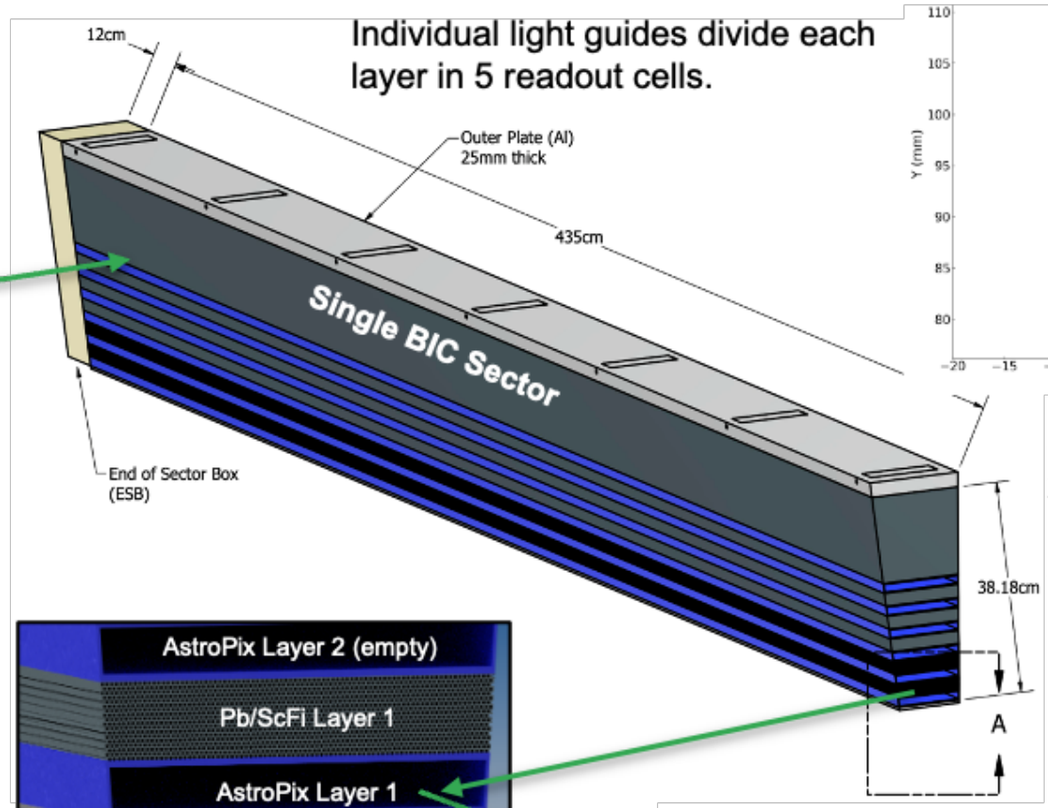


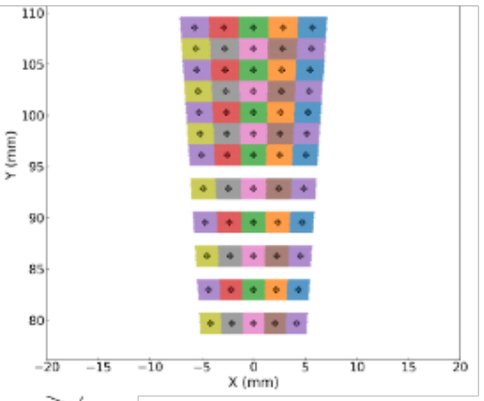
Total BIC weight ~42.5 US tons

Pb/SciFi Layers - 17 rows of fiber between corrugated lead.

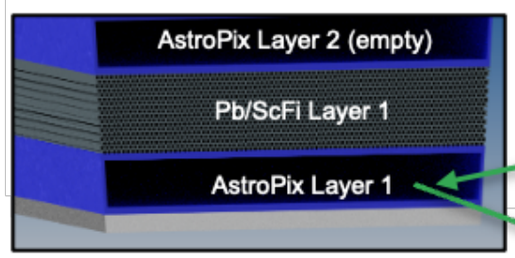
Each sector has 12 Pb/ScFi layers.

Individual light guides divide each layer in 5 readout cells.





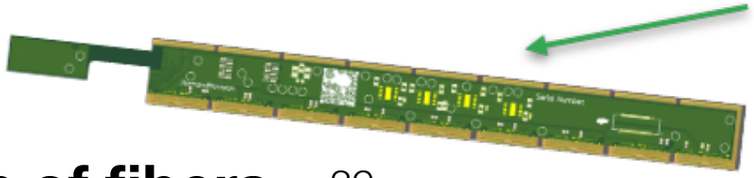
SiPMs - 5 per layer x 12 layers = 60 (Hamamatsu S14161-3050)

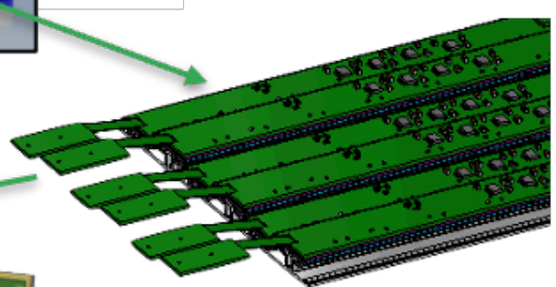


AstroPix Module - Nine AstroPix sensors daisy-chained together on Flex PCB.

A stave consists of 12 modules.

A tray contains of 6-8 staves.





Tray - Structure holding the AstroPix staves for a single layer (217.5 cm long).

~100 m² of silicons / ~5,000 km of fibers

Pb/SciFi Layer Technology

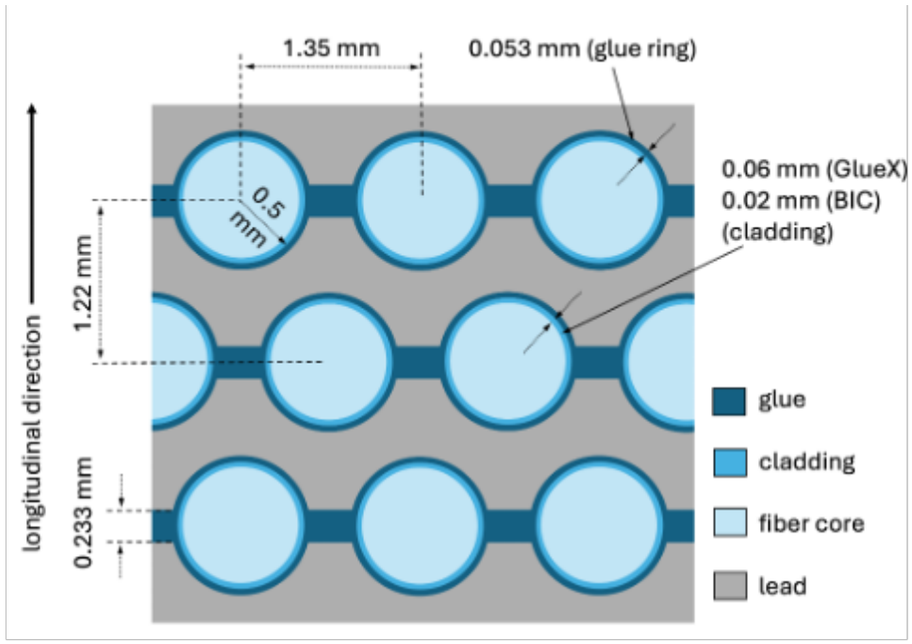
Our Pb/ScFi layers follow the GlueX Design

Energy resolution at GlueX: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ [1)]

- GlueX has 15.5 X_0, and could not constrain the constant term (due to low energies) → fixed in FTBF/CERN Beam Test (< 2%)

Position resolution in z: $1.1\text{cm}/\sqrt{E}$ [2)]

- 2-side SiPM readout, Δt measurement



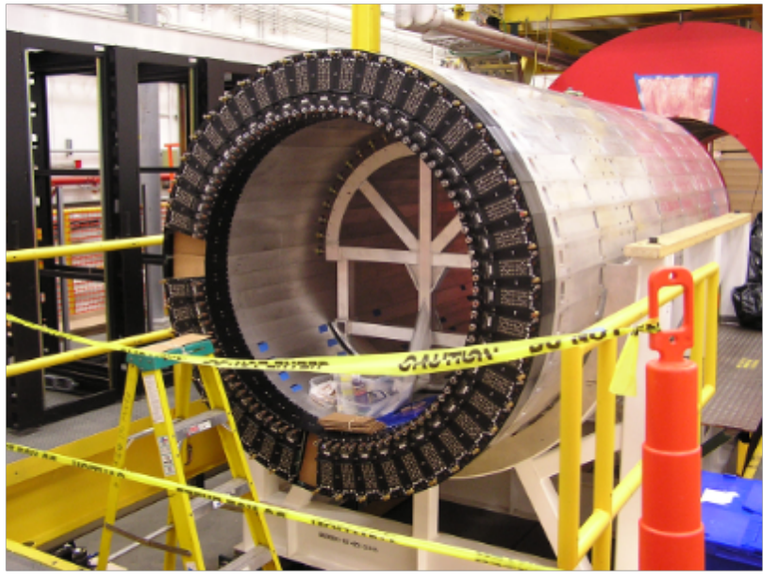
Mature technology used in Barrel ECals (GlueX, KLOE)

- Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
- **Construction** (lead handling, swaging, Pb/ScFi layers assembly, module machining) is fully developed for GlueX

  Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/

Long-lead procurement items are ongoing for BIC (past FDR)

- SiPMs 1.2 x 1.2 mm^2 arrays, 50 um pitch (Hamamatsu S14160-6050-04 or similar)
- Single Clad Kuraray (SCSF-78, ø 1mm)



1) Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018
2) Nucl. Instrum. Meth. A, vol. 596, pp. 327–337, 2008

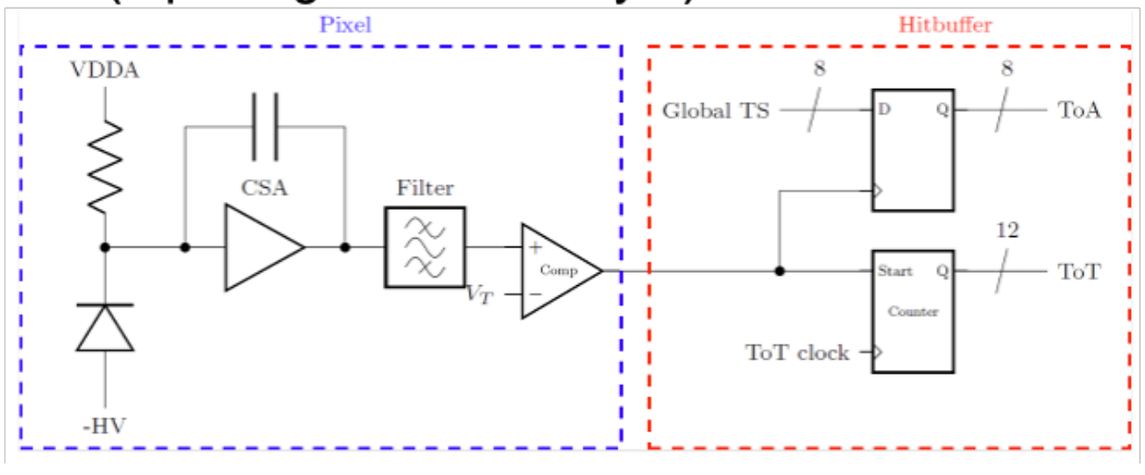
Imaging Layer Technology

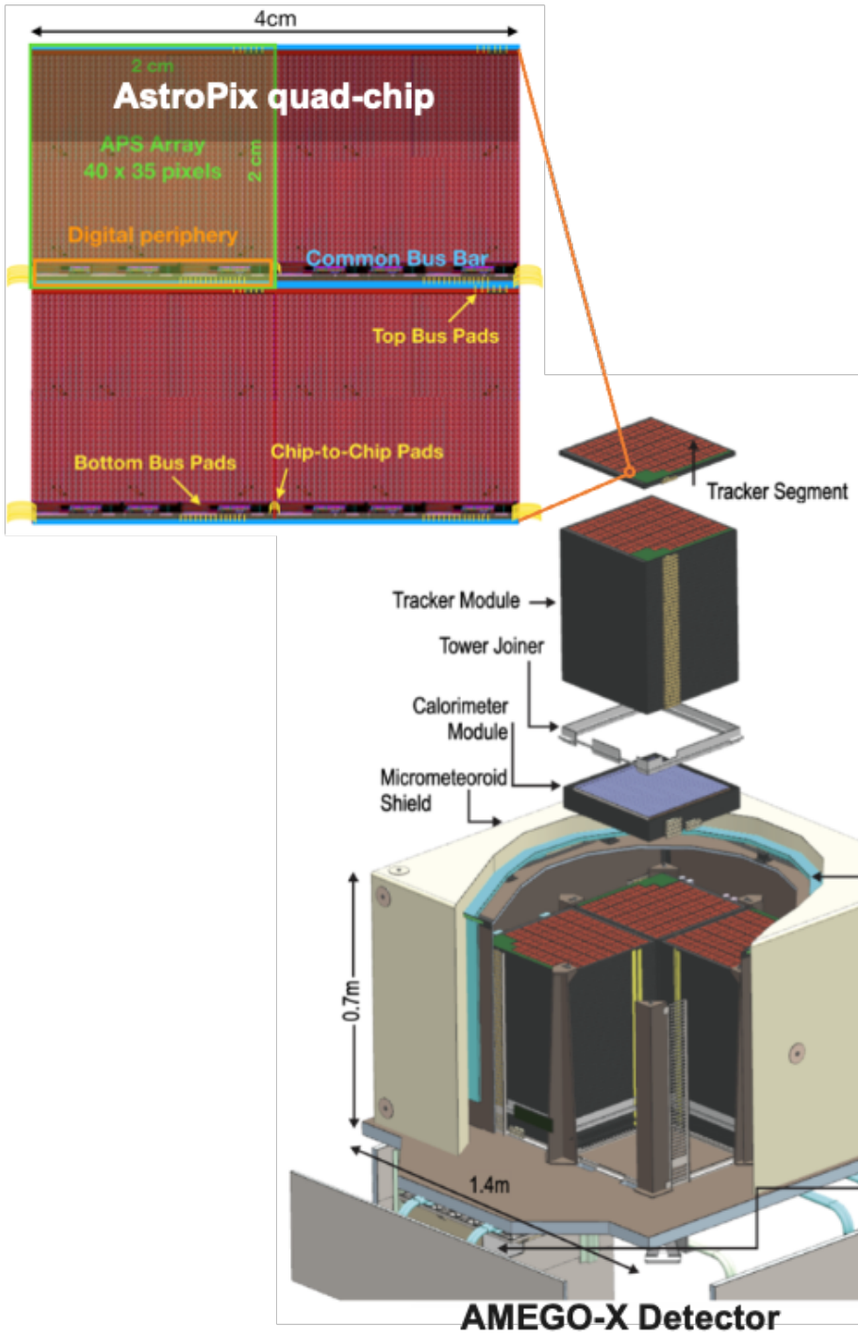
Imaging layers will use the AstroPix sensors

- Developed for NASA AMEGO-X space mission arXiv:2109.13409 [astro-ph.IM]

Key features:

- Very low power dissipation - will be used in space!
- Good energy resolution (thick silicon sensor)
- 500 μm pixel size (~144 μm resolution)
- First silicon layer has sufficient resolution to be used as a tracking layer behind the DIRC (replacing the MPGD layer)

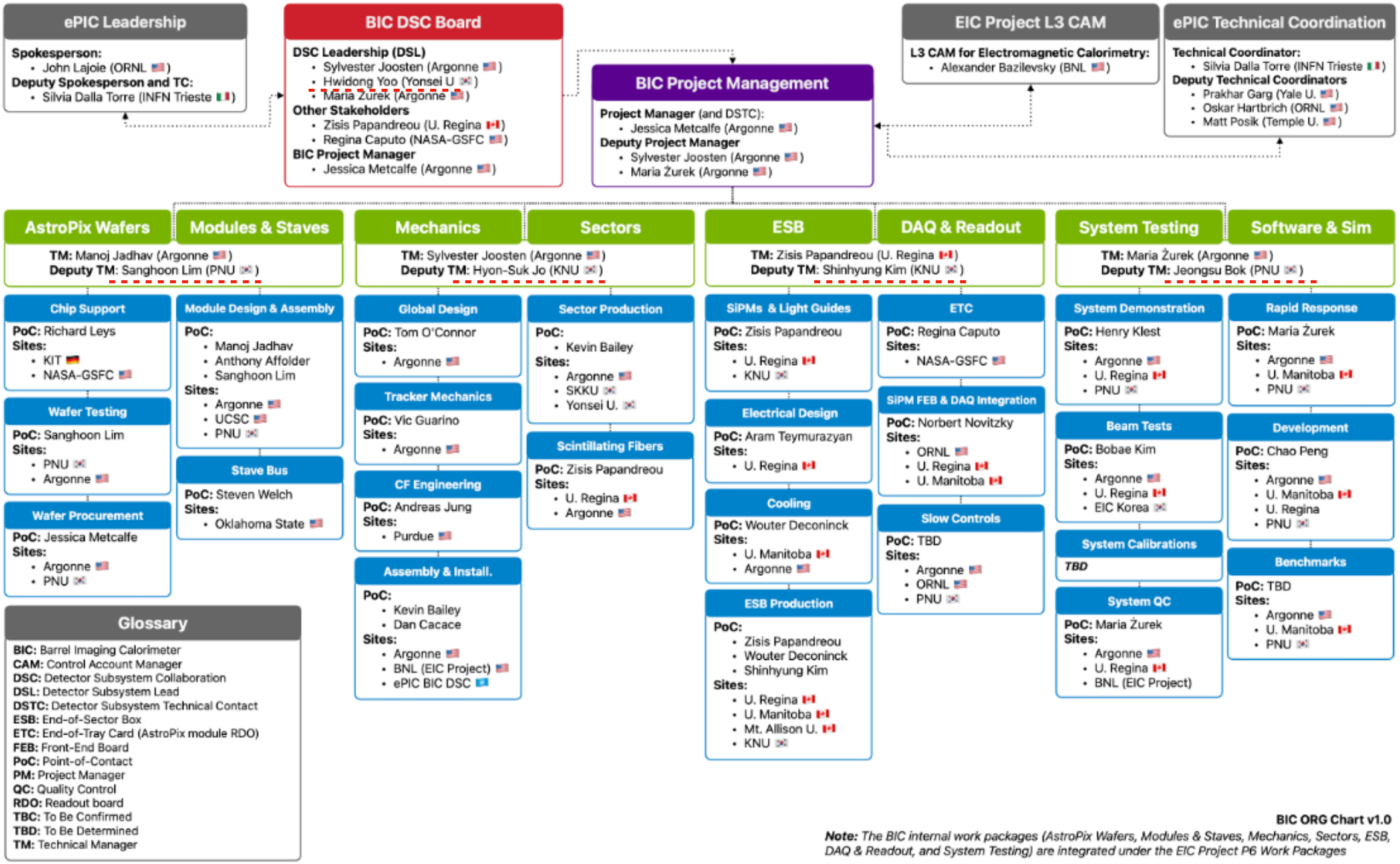




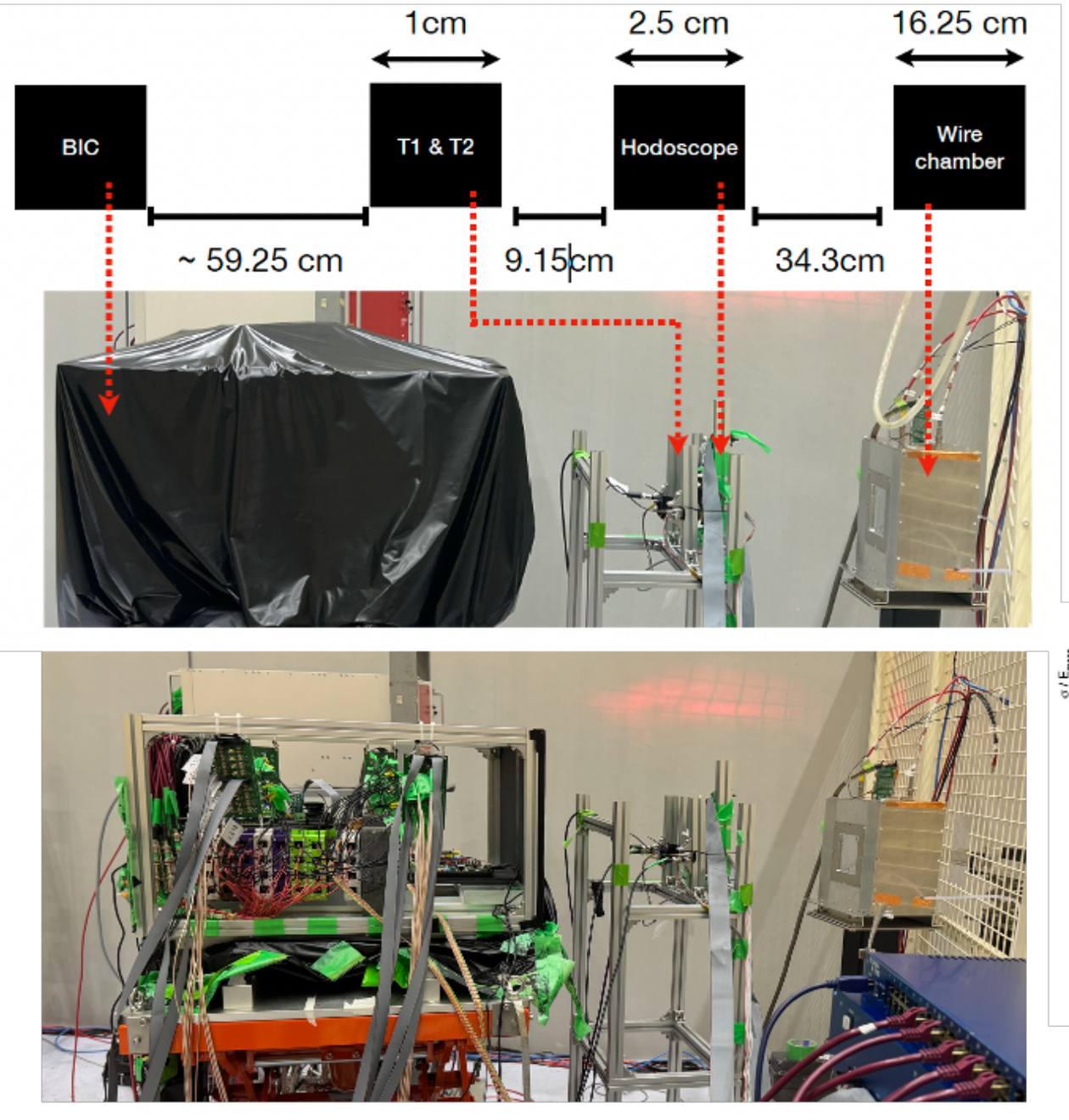
AMEGO-X Detector

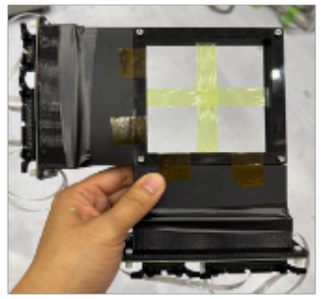
arXiv:2208.04990 [astro-ph.IM]

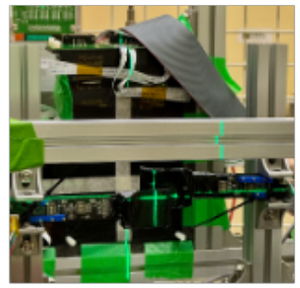
BIC Organization Chart

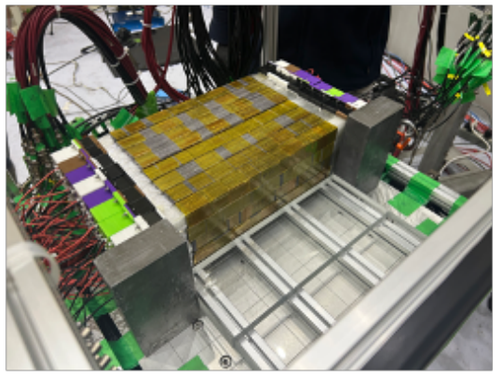


Test beam Experiments







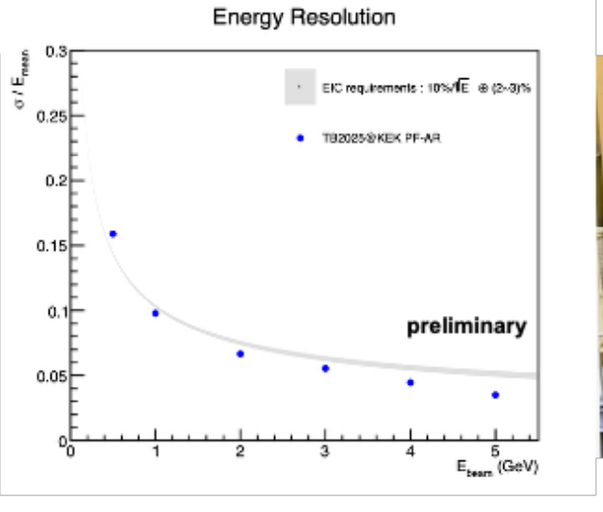


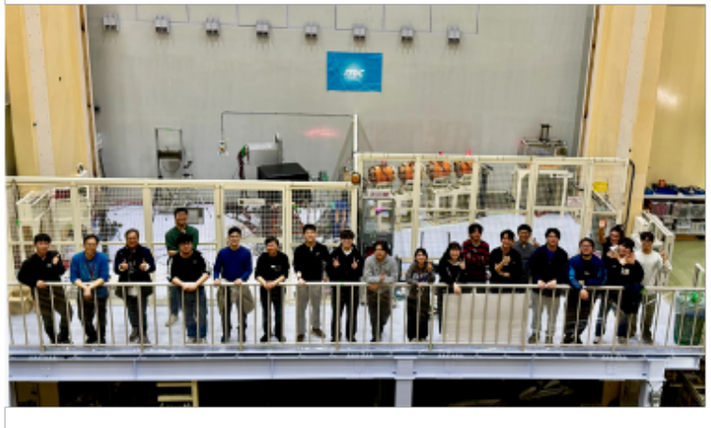
Bigger, Deeper Pb/SciFi setup: 32x12x21cm³

Refine calibration procedure

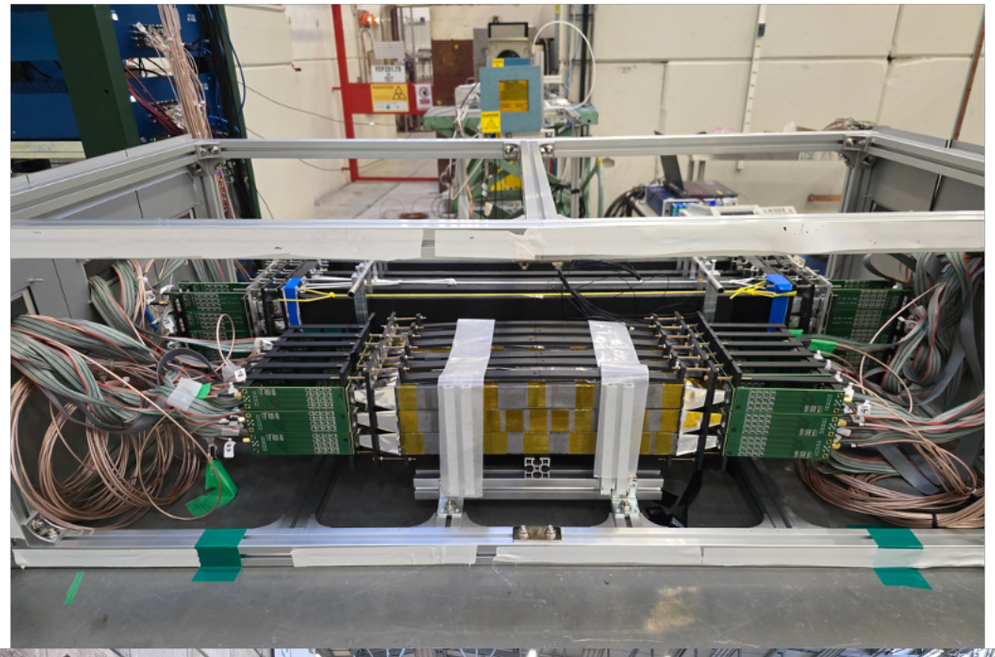
Smooth operation with new DAQ

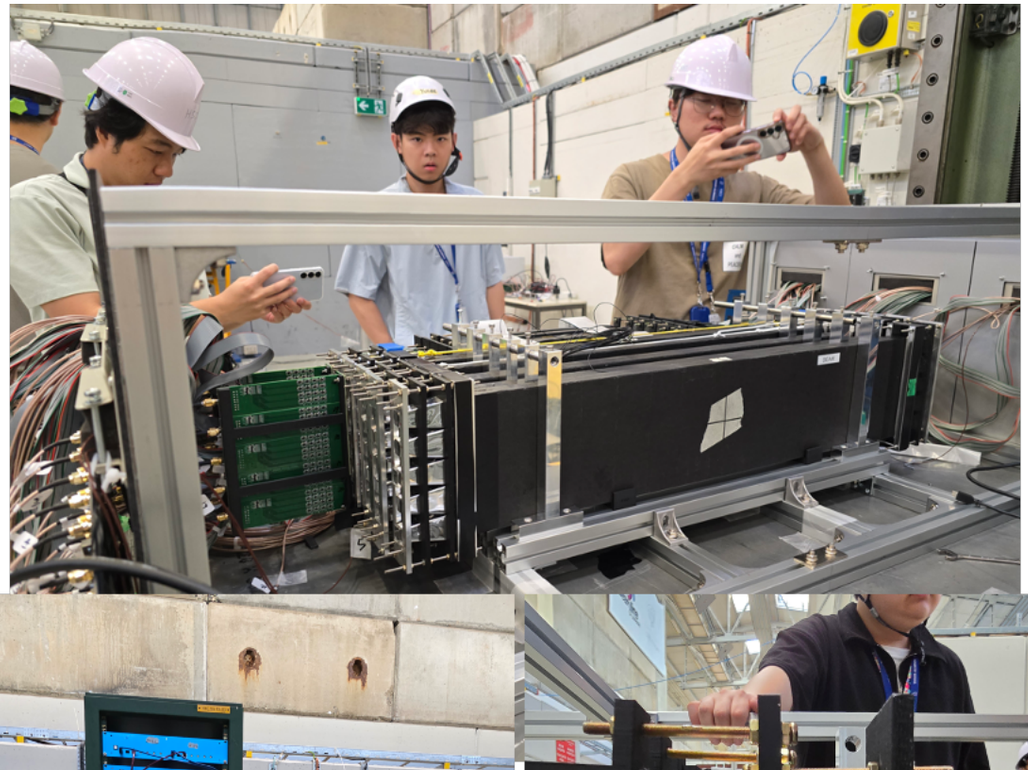
Operation of auxiliary detectors: Hodoscope, Trigger

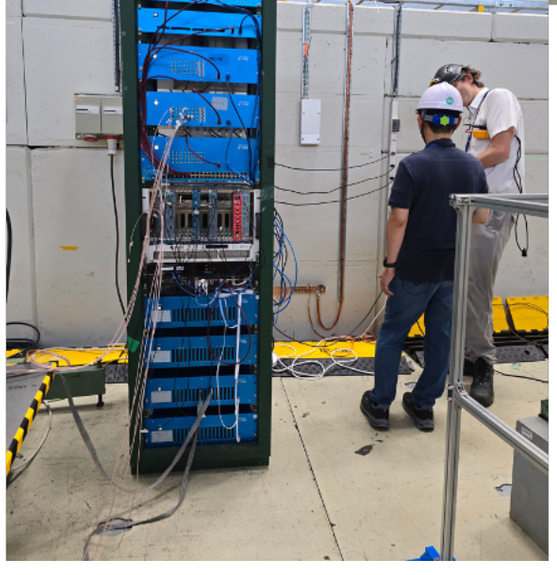


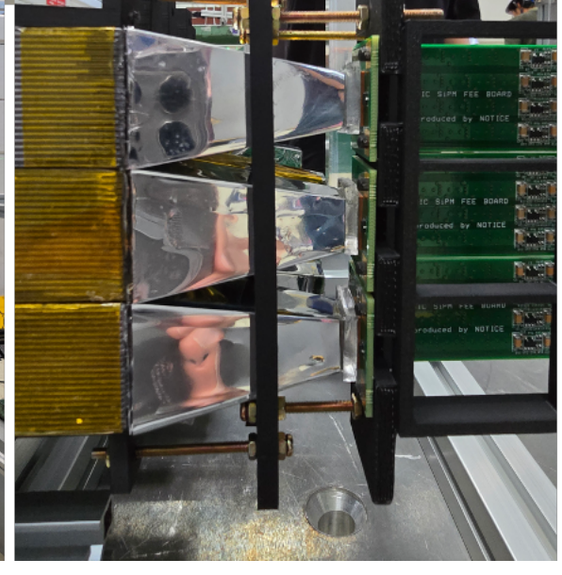


Beam-test at CERN (8/24-31)



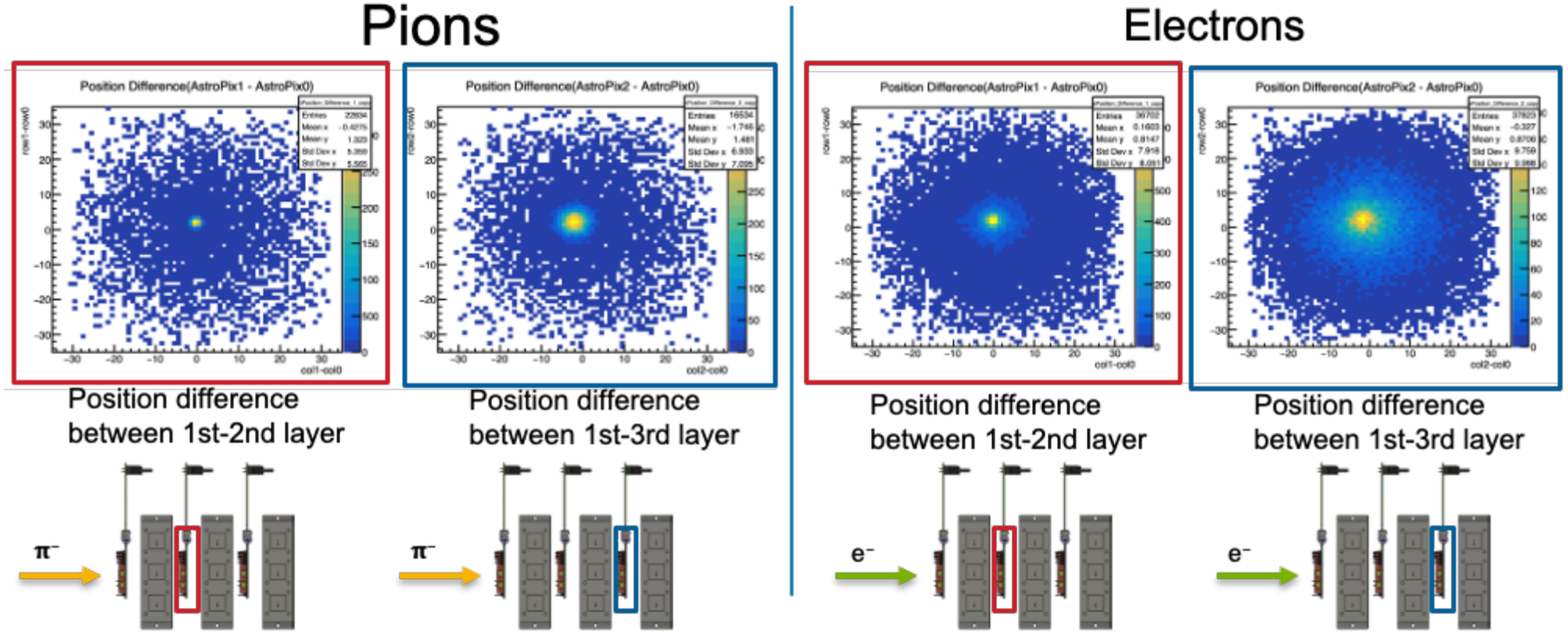


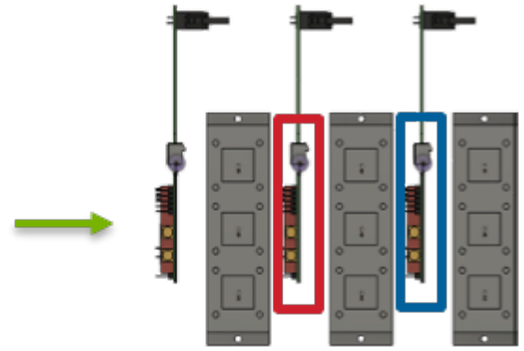


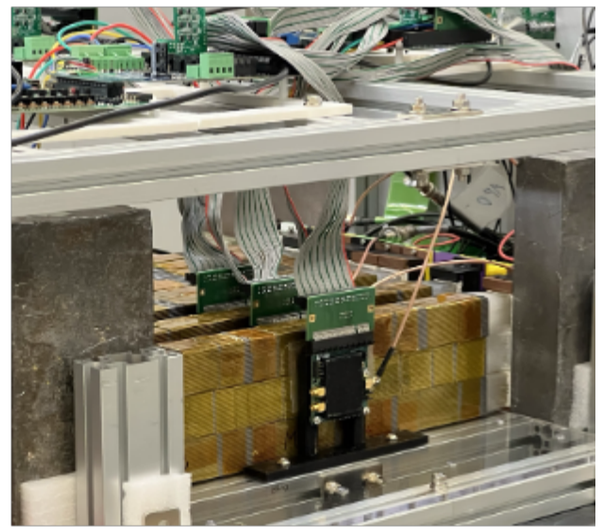


Shower Profiles of electrons and pions

- CERN PS T10 in July 2025







Proof-of-principle imaging of electrons and pions was performed using a synchronized AstroPix setup in the beam environment.

Proof-of-principle imaging of electrons and pions was performed using a synchronized AstroPix setup in the beam environment.

Test-Beam Performance of the AstroPix Silicon Sensor for Imaging Calorimetry

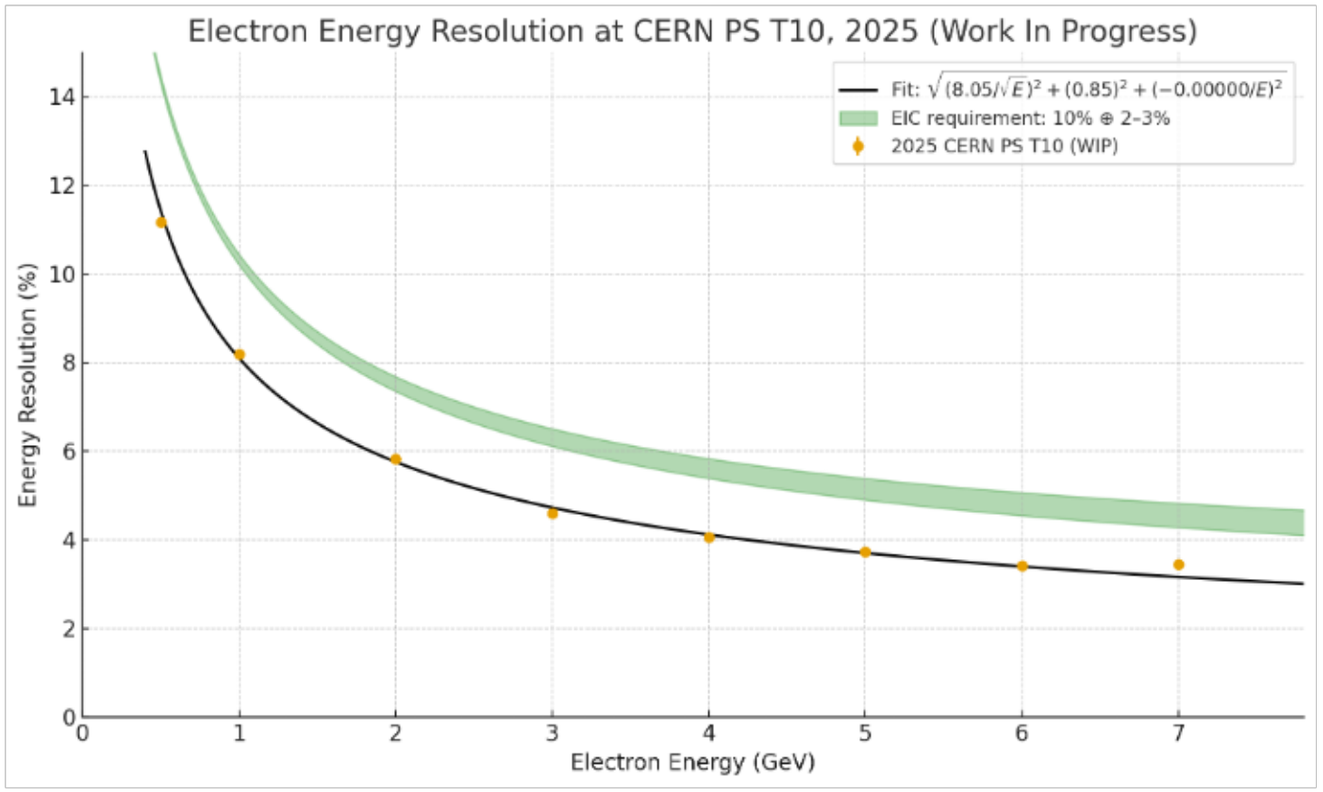
Yoonha Hong[c,1], Jeongsu Bok[c,1], Geunpil An[d], Joonsuk Bae[a], Yunseul Bae[a], Regina Caputo[i], Yun Eo[c], Wooseok Ham[a], Woohyeon Heo[g], Manoj Jadhav[b], Seo Yun Jang[a], Jinryong Jeong[d], Hyon-Suk Jo[b], Sylvester Joosten[h], Beomkyu Kim[a], Bobae Kim[b], Chong Kim[c], Dongguk Kim[a], Minsuk Kim[d], Shin Hyung Kim[b], Woojong Kim[g], Wonjun Ko[b], Changhui Lee[b], Hyungjun Lee[a], Jason Sang Hun Lee[e], Jongwon Lee[c], Kyeongpil Lee[f], Sehwook Lee[b], Sangwoo Park[a], Jaehyeok Ryu[c], Bogyeong Seo[b], Jessica Metcalfe[h], Minsub Shim[b], Junseop Shin[b], Hwidong Yoo[c], Maria Żurek[h], Sanghoon Lim[c,·]

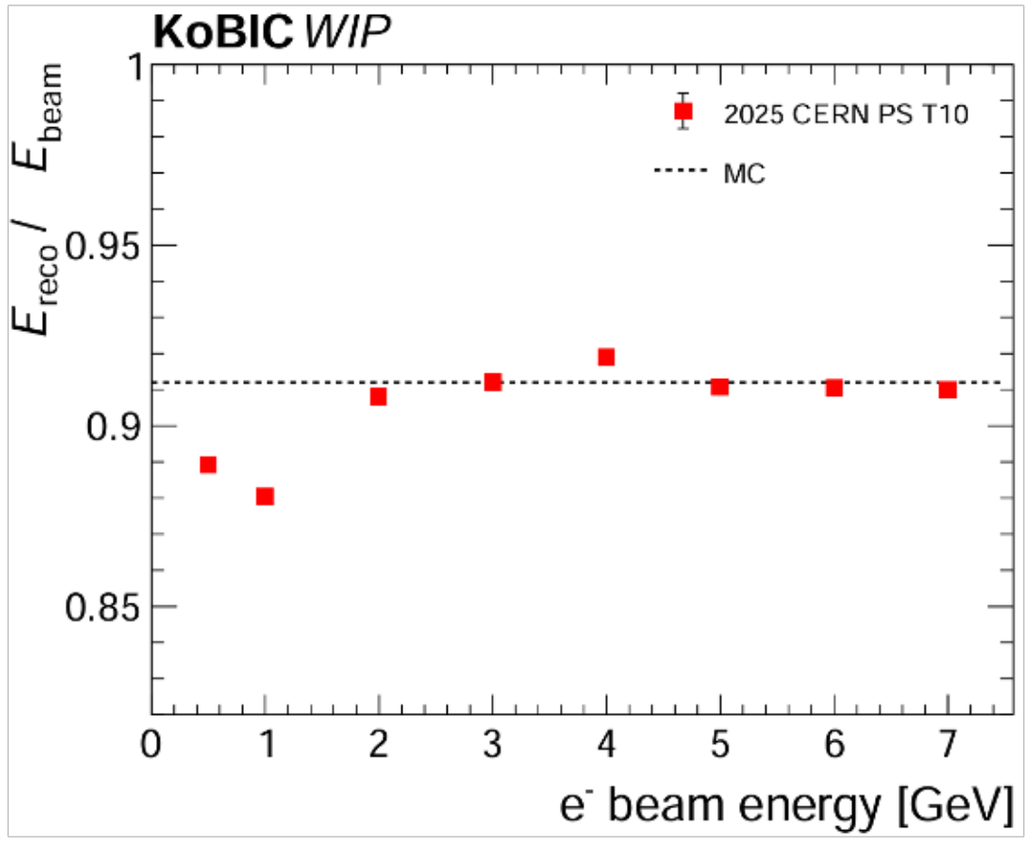
[a]Department of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea
[b]Department of Physics, Kyungpook National University, Daegu 41566, Republic of Korea
[c]Department of Physics, Pusan National University, Busan 46241, Republic of Korea
[d]Department of Physics, Kangwon National University, Gangneung 25457, Republic of Korea
[e]Department of Physics, Yonsei University, Seoul 03722, Republic of Korea
[f]Department of Physics, Chung-Ang University, Seoul 06974, Republic of Korea
[g]Department of Physics, University of Seoul, Seoul 02504, Republic of Korea
[h]Argonne National Laboratory, Lemont, IL 60439, U.S.A.
[i]NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

May 2026

arXiv: 2605.07681, accepted by NIM A

Energy Resolution & Linearity



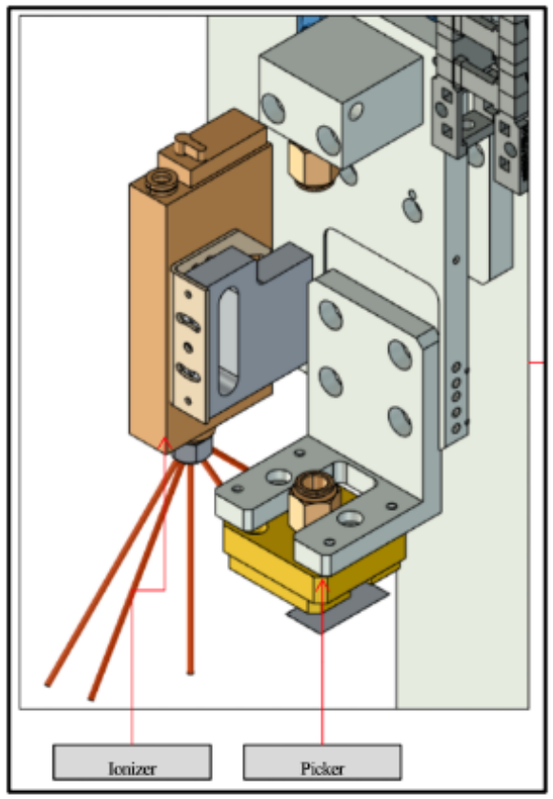


Resolution : (Stochastic) 8.05 %, (Constant) 0.85 %, (Noise) 0.00 %

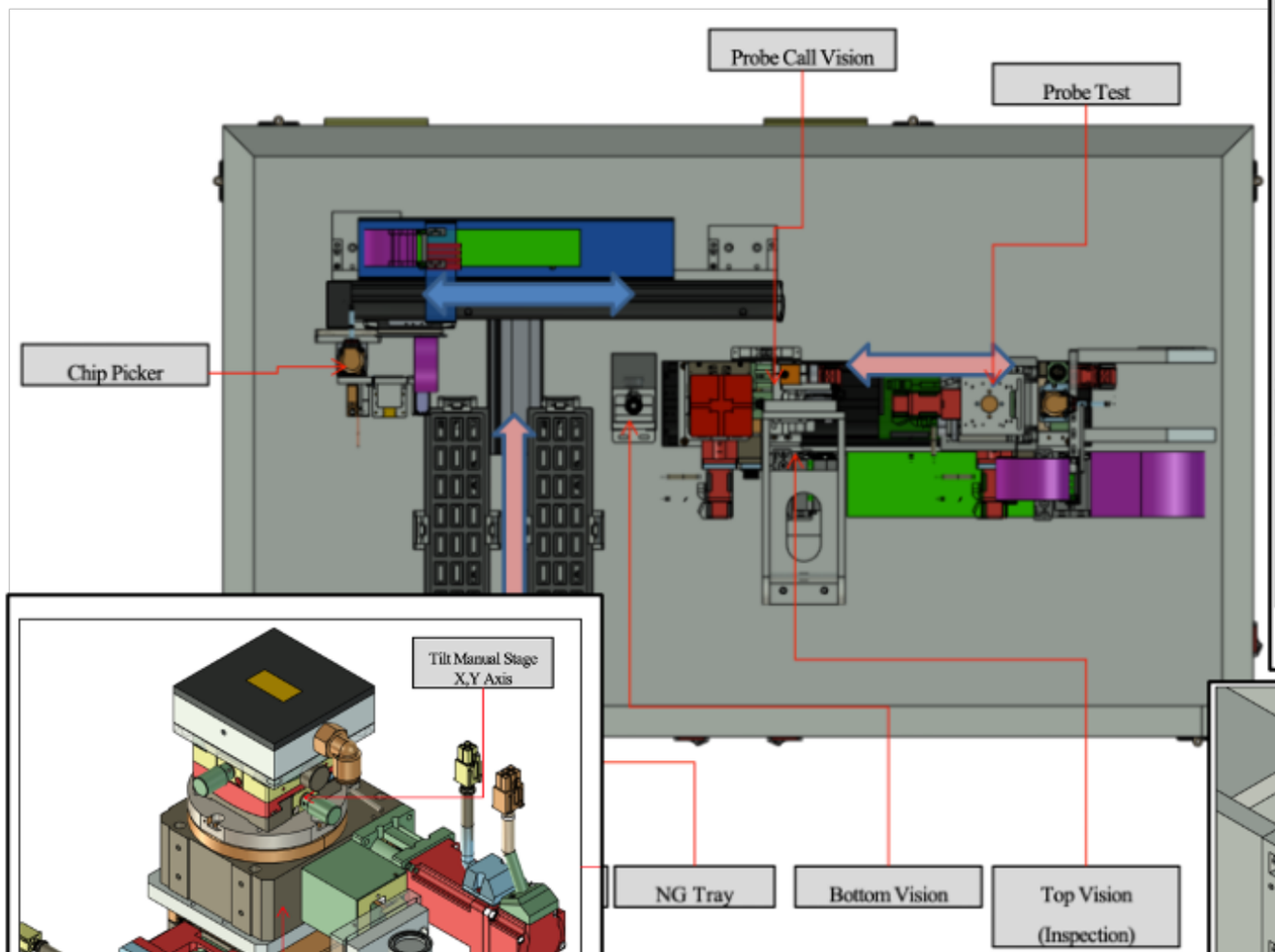
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus c/E$$

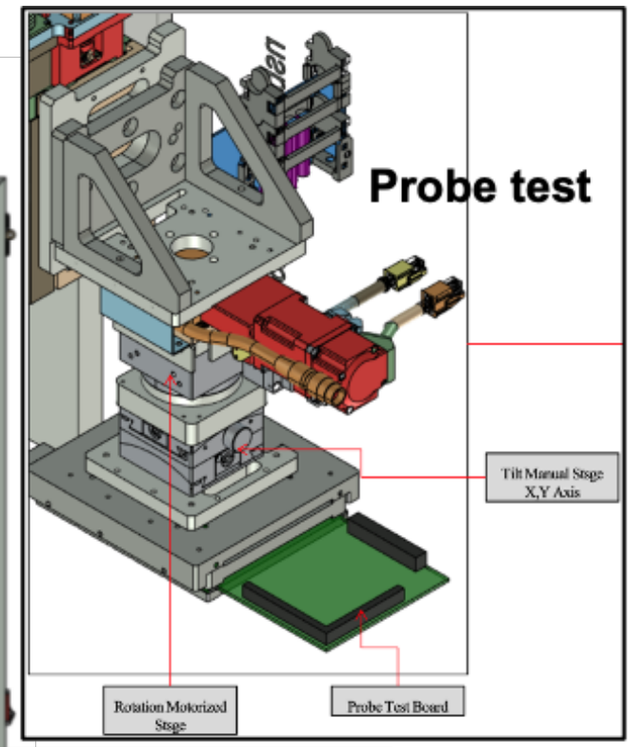
- The energy resolution has been progressively improved, achieving the best performance in this beam test.

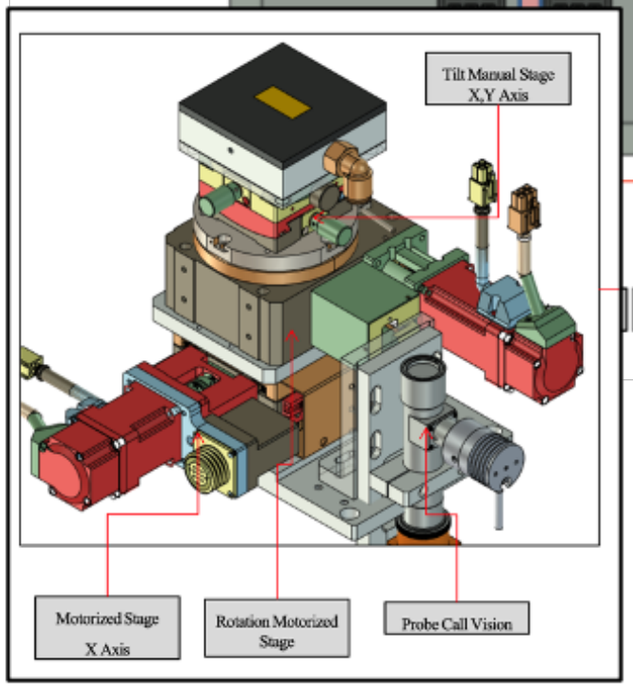
AstroPix Test System



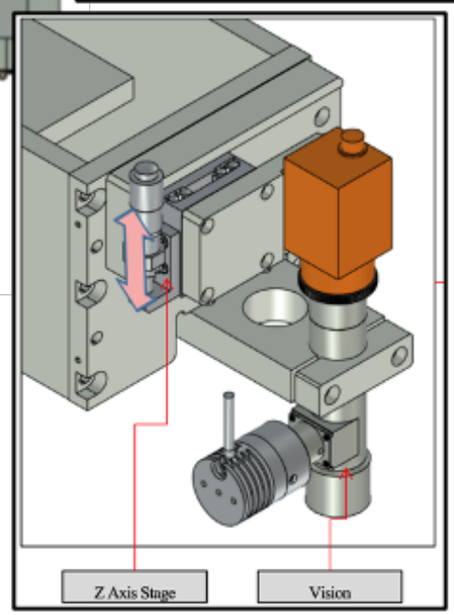
Sensor picker







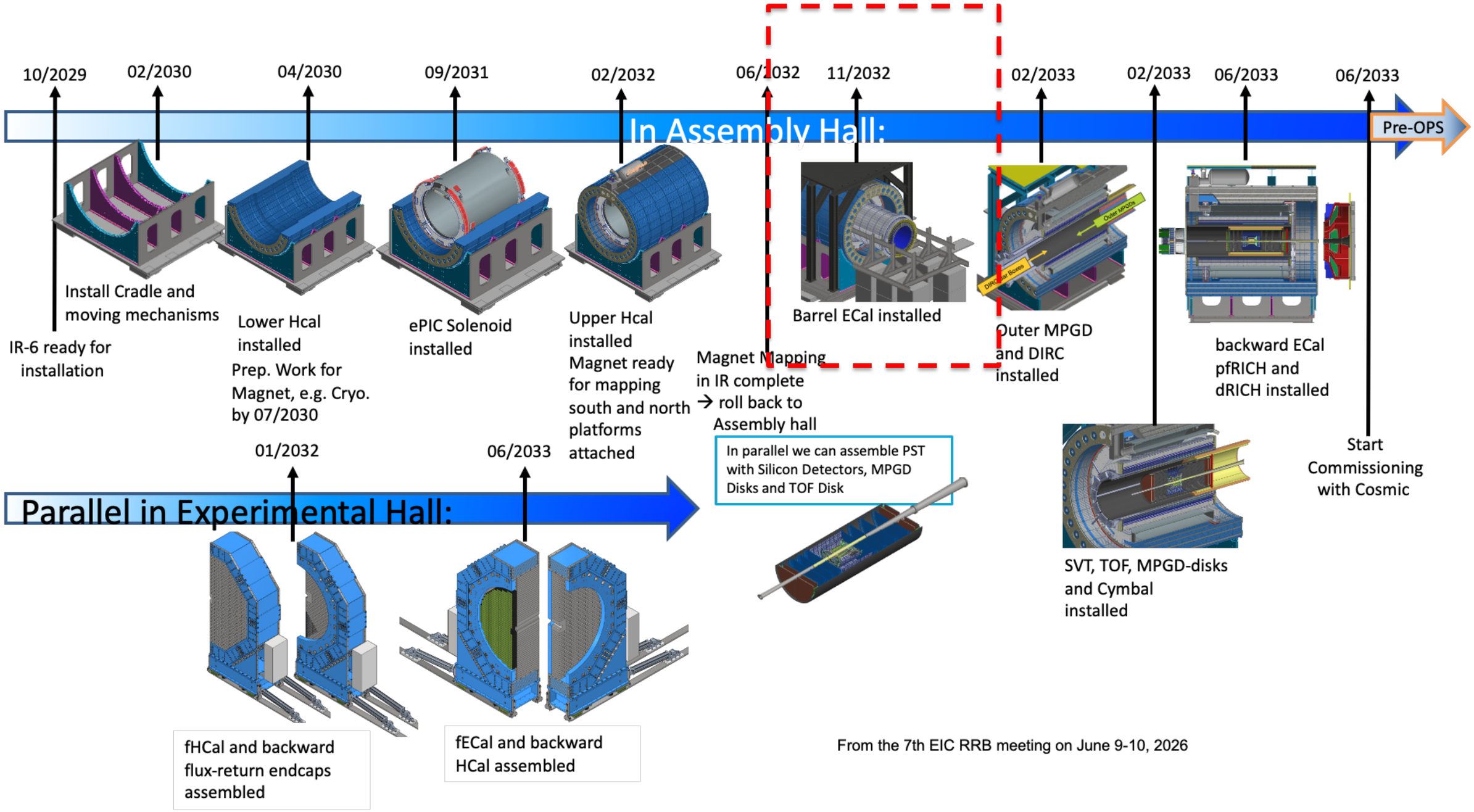
Working stage



Vision
inspection

Cooperate with wide semiconductor industry infrastructure in Korea

Schedule



From the 7th EIC RRB meeting on June 9-10, 2026

Summary

- In Korea, Calorimeter R&Ds for future collider projects, particularly, FCC-ee and EIC are quite active and exciting moments are on-going
  - We successfully launch two major projects for FCC-ee and EIC
- We are world-leading group for dual-readout calorimeter for FCC-ee
- Korean group is leading the construction of BIC detector in EIC project
  - Construction cost (> $13M) has been approved by government and congress in 2025
  - 7 year construction program starts this summer!
  - Half of BIC detector will be fully constructed in Korea!

Bright future for next generation and stay tuned!