Dual-Readout Calorimeter Activities in Asia

Hwidong Yoo (Yonsei Univ.)

CEPC workshop,
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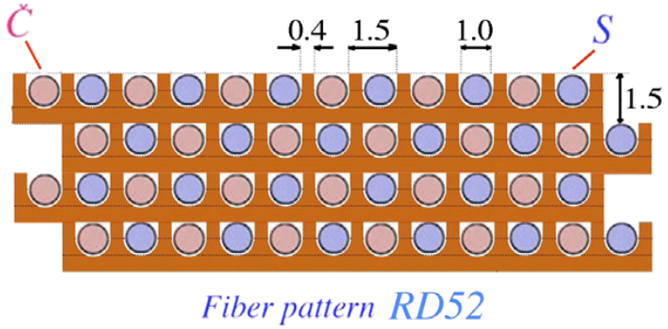
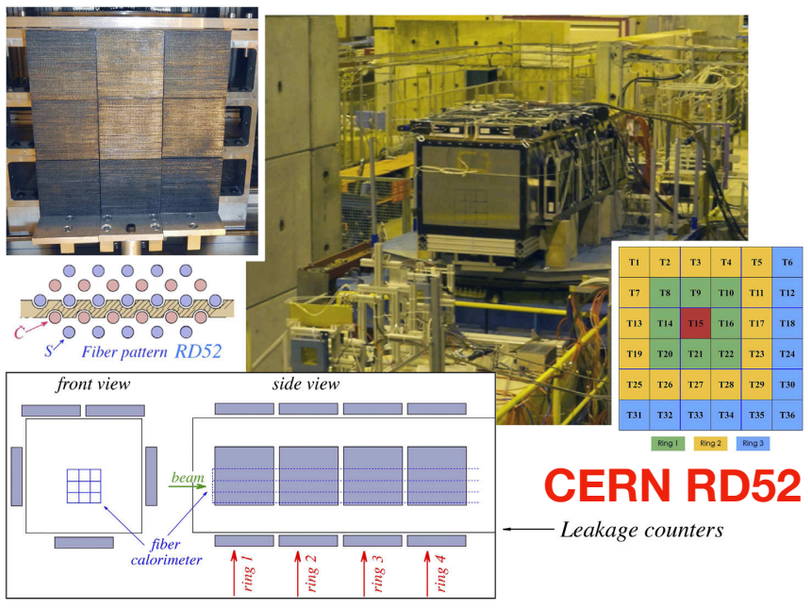
Dual-Readout Calorimeter (DRC)

- 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



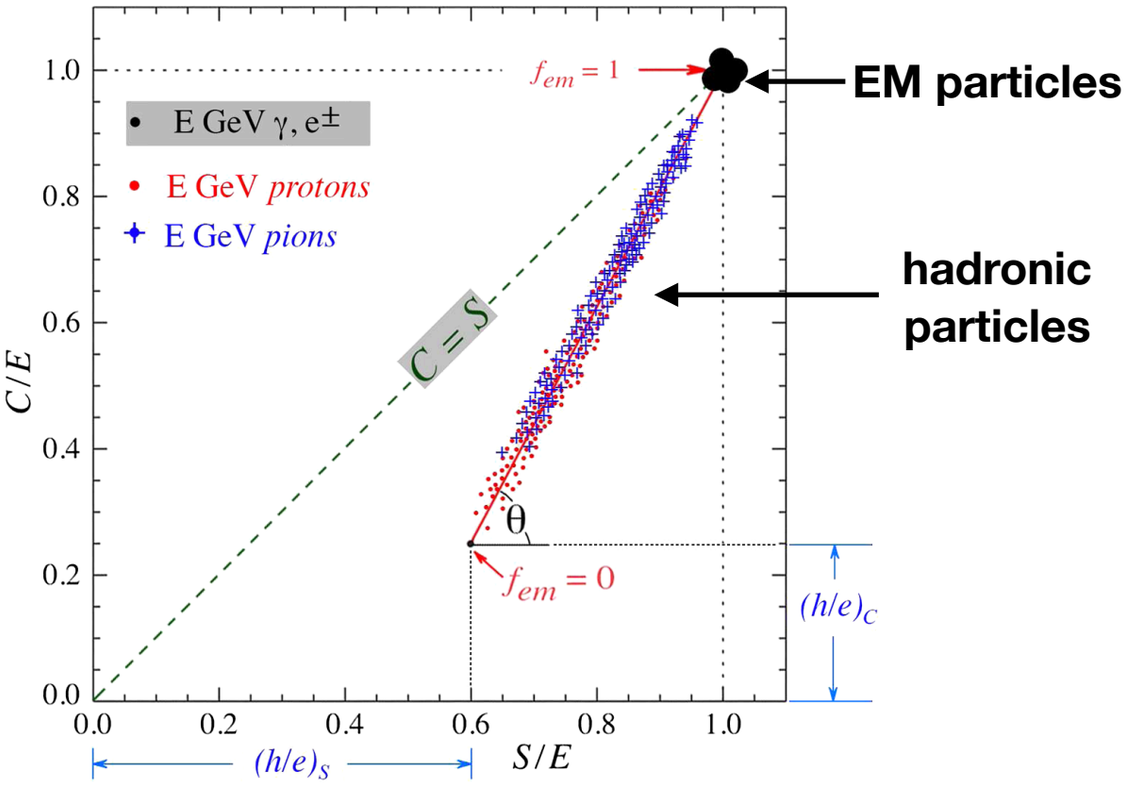
Fiber pattern RD52

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

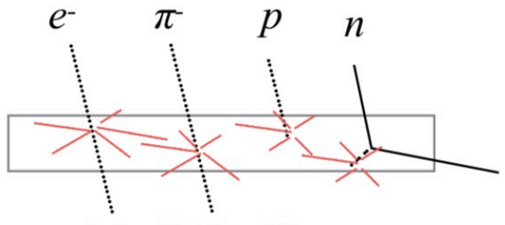


CERN RD52 experiment

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

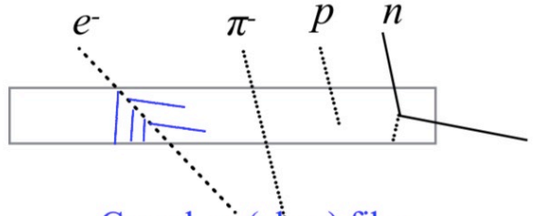


Signal generation: Scintillating & Cerenkov fibers



Scintillating fiber: red light, random

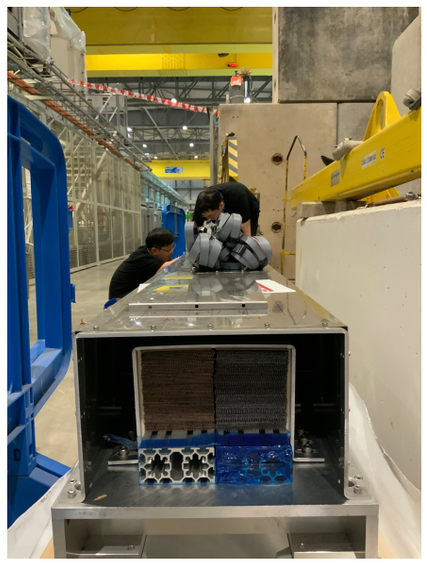
Sci > Cer

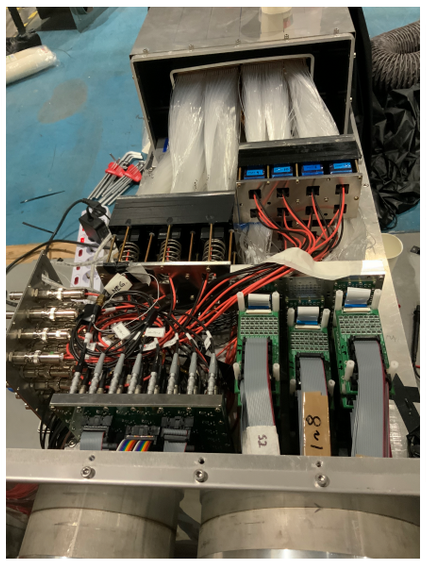


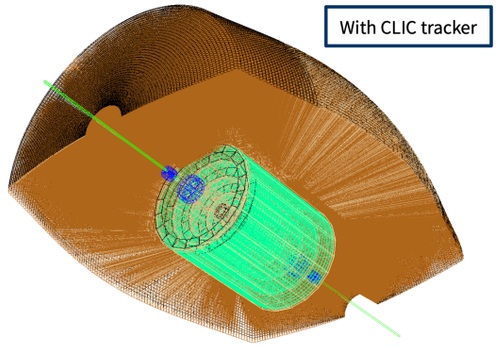
Cerenkov (clear) fiber: blue light, directional

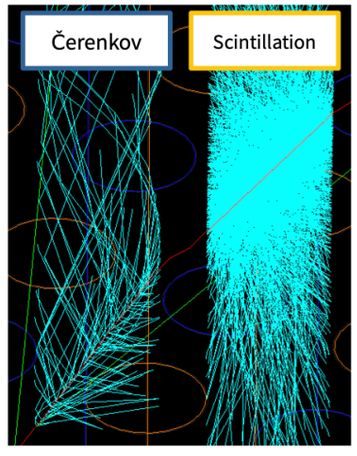
Status of DRC R&D in Korea

- We are doing all aspects of the DRC R&D
  - Module building
  - Electronics system
  - DAQ system
  - Data analysis framework
  - Test-beam experiments at CERN
  - Full/fast GEANT4 simulation framework (standalone, key4hep)
  - Performance studies using simulation
- We expand our activities to barrel ECAL construction for Electron-Ion Collider project (BNL)







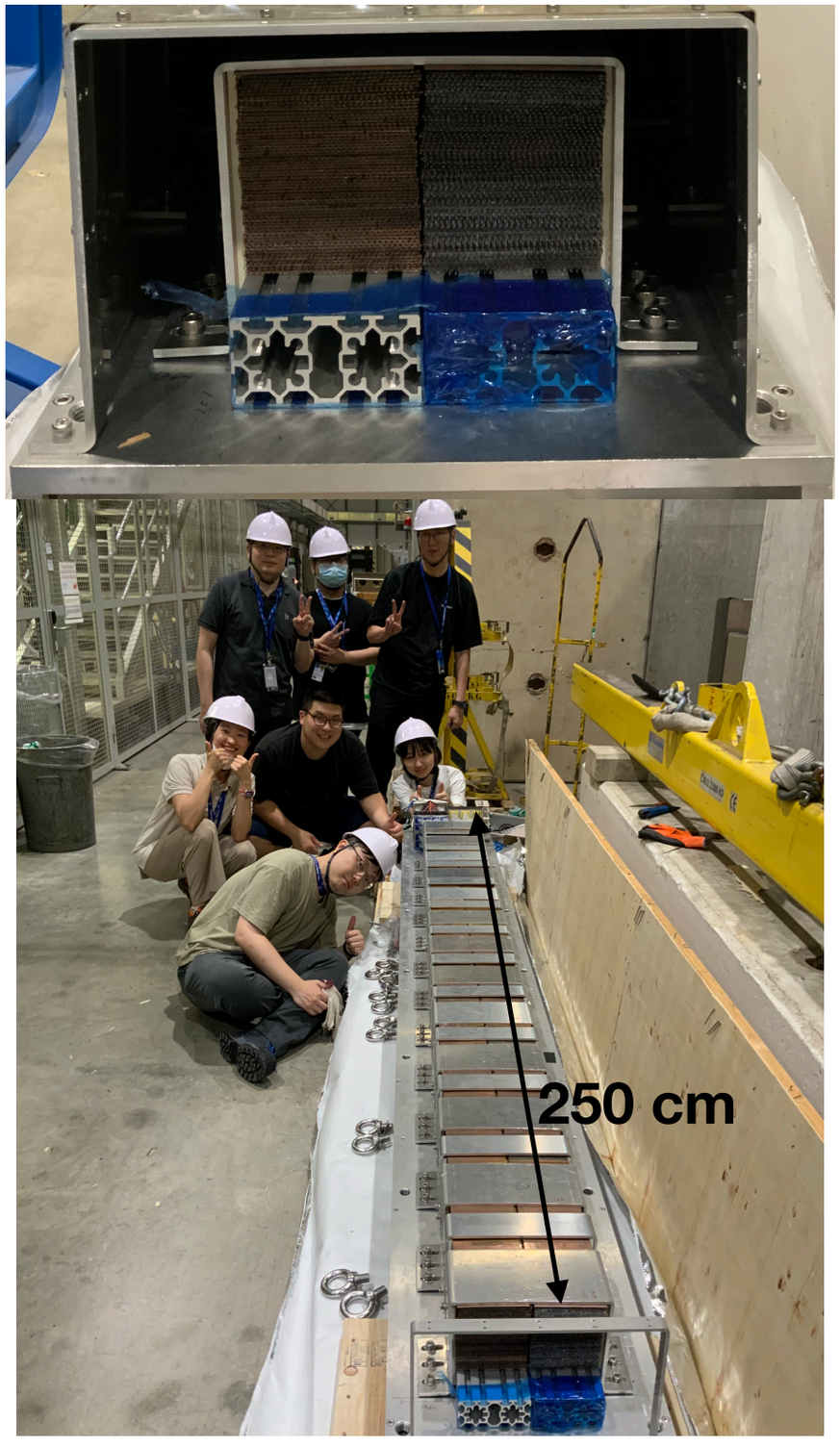


Important for a longitudinally unsegmented calorimeter

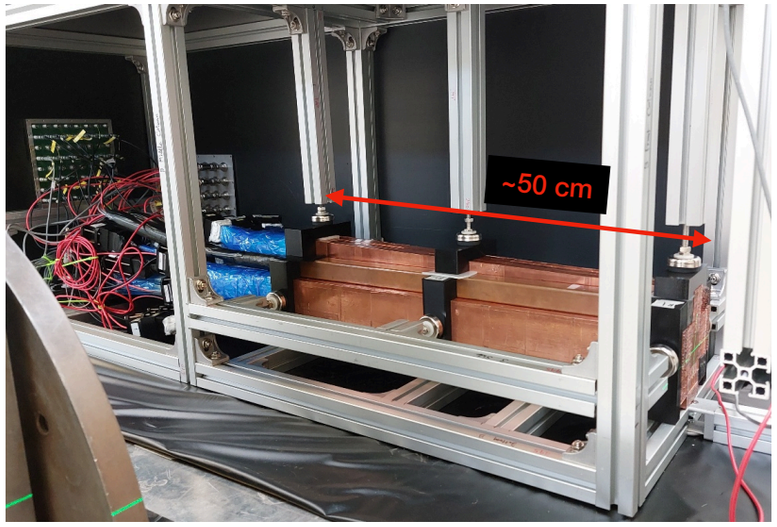
8 institutes participates DRC projects in Korea

Module Building

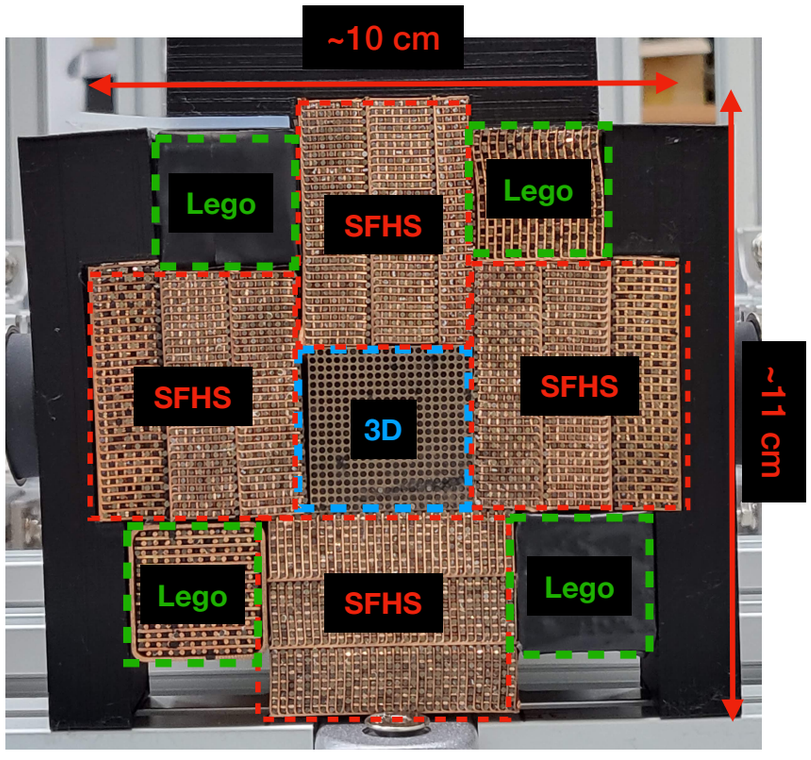
TB 2022



TB 2023



Side view of DRC module



Upstream view of DRC module

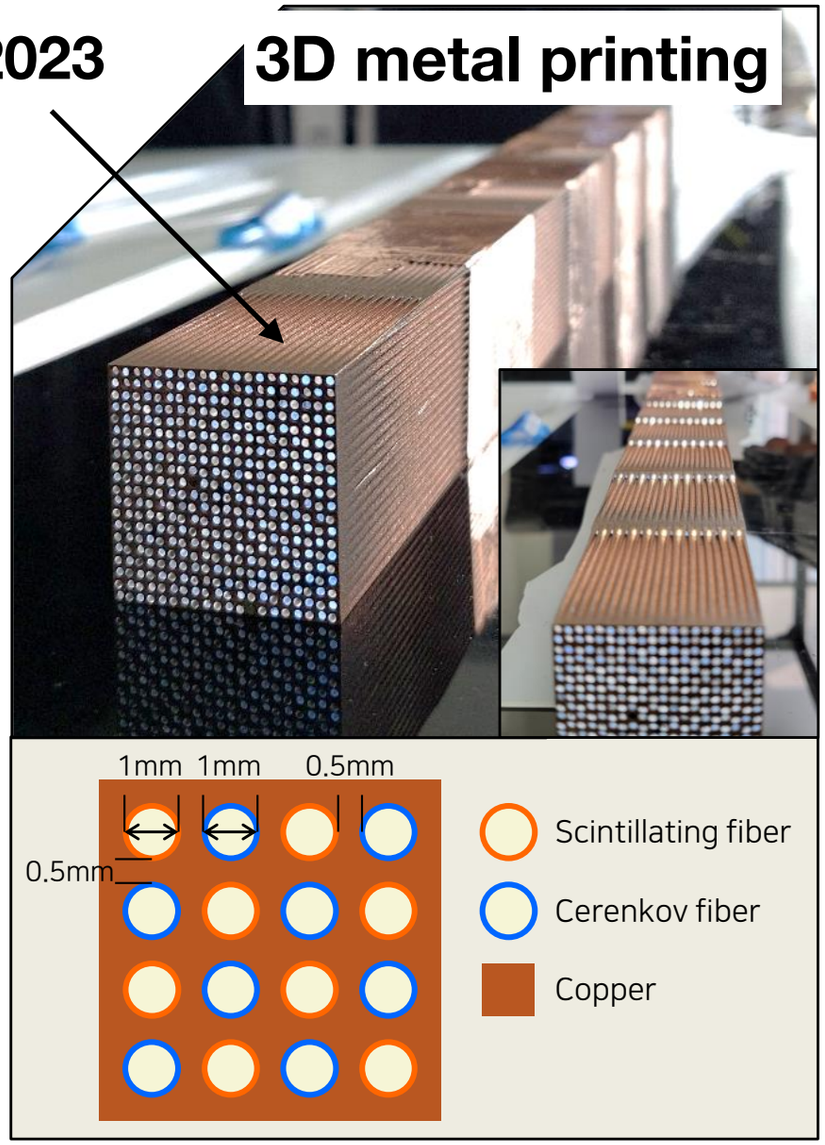
30x30x250 cm

TB 2022 module

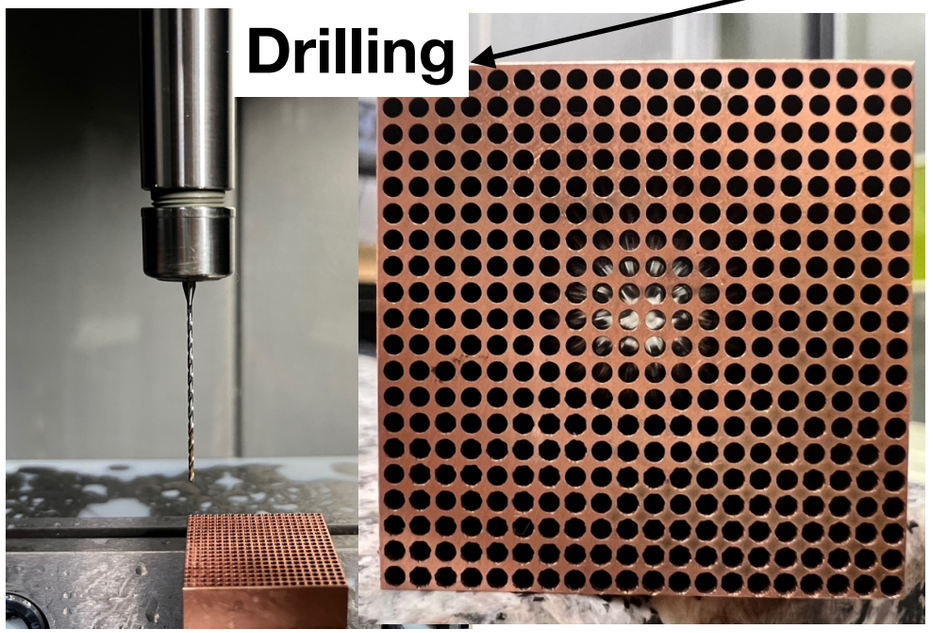
Cu Forming R&D

- Try to find a solution for mass production with local mechanical engineering experts and manufacturers
  - Skiving fin heatsink, 3D metal printing, drilling, etc.

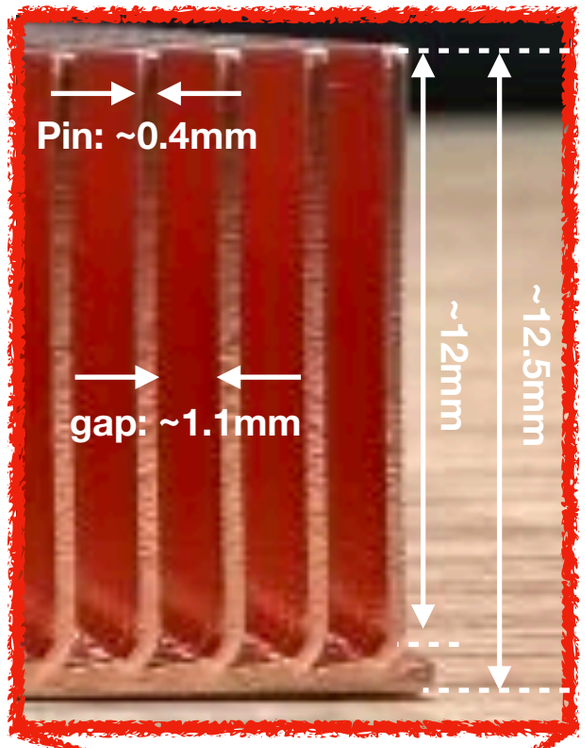
TB2023



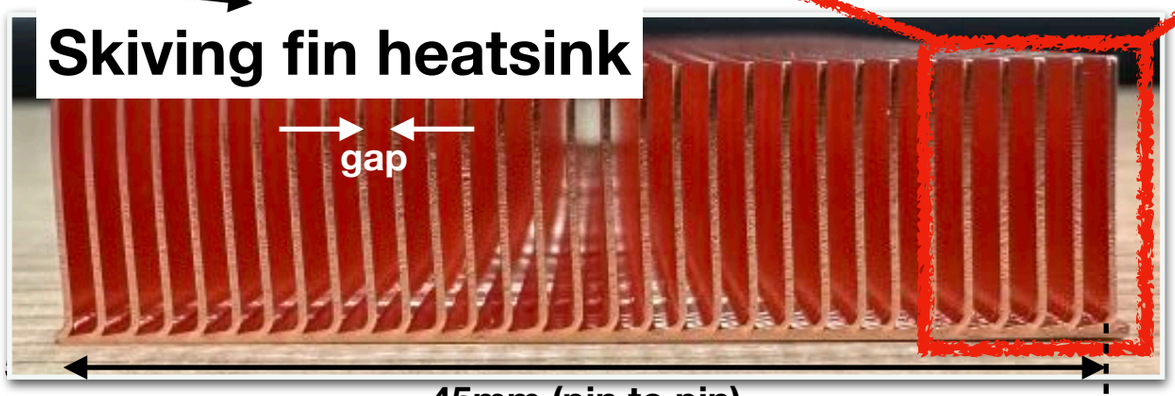
Structure of 3D-Printed Module



Future TB

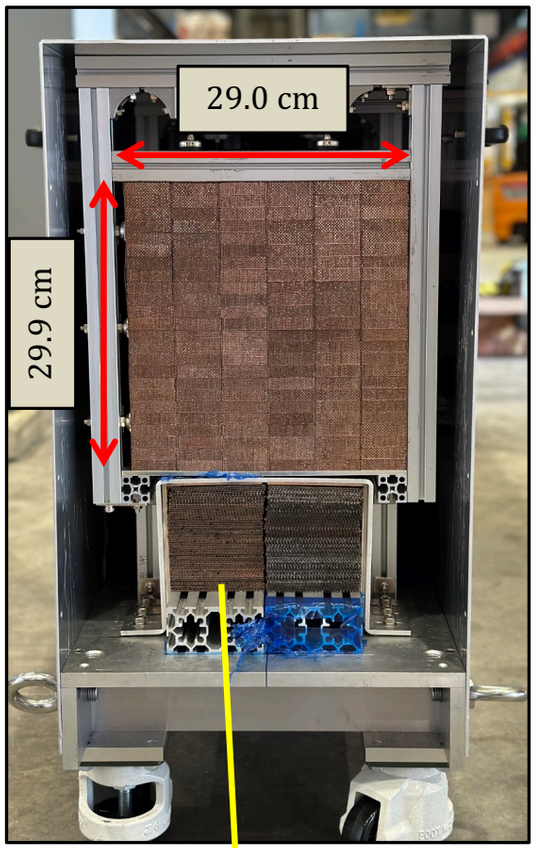


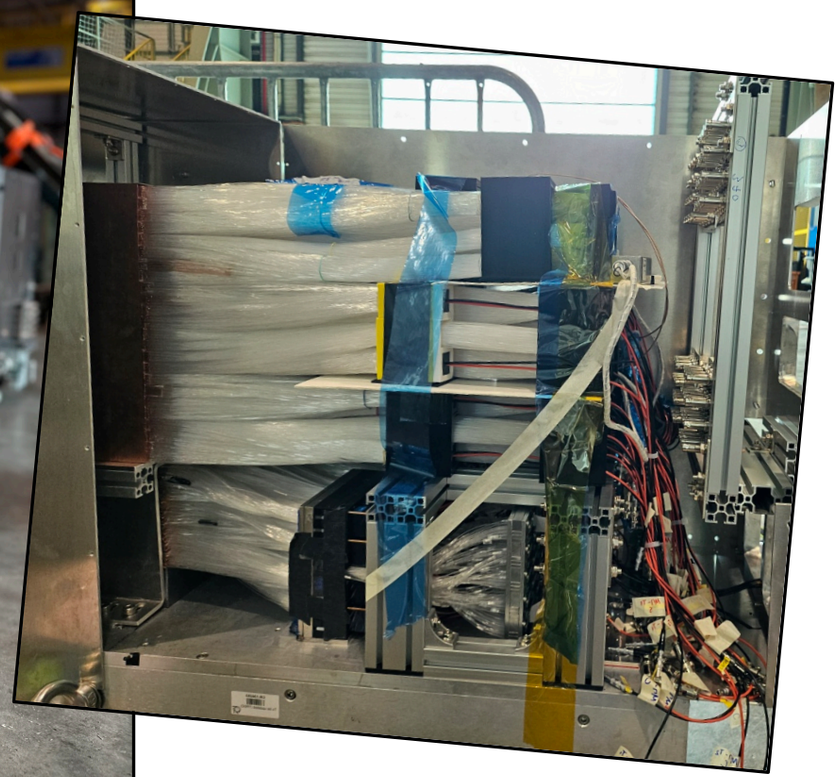
TB2024

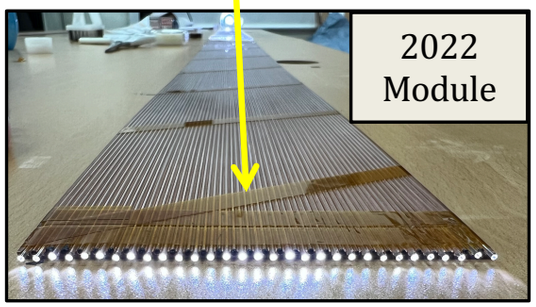


Module for TB2024

- Biggest prototype DRC module with copper-based





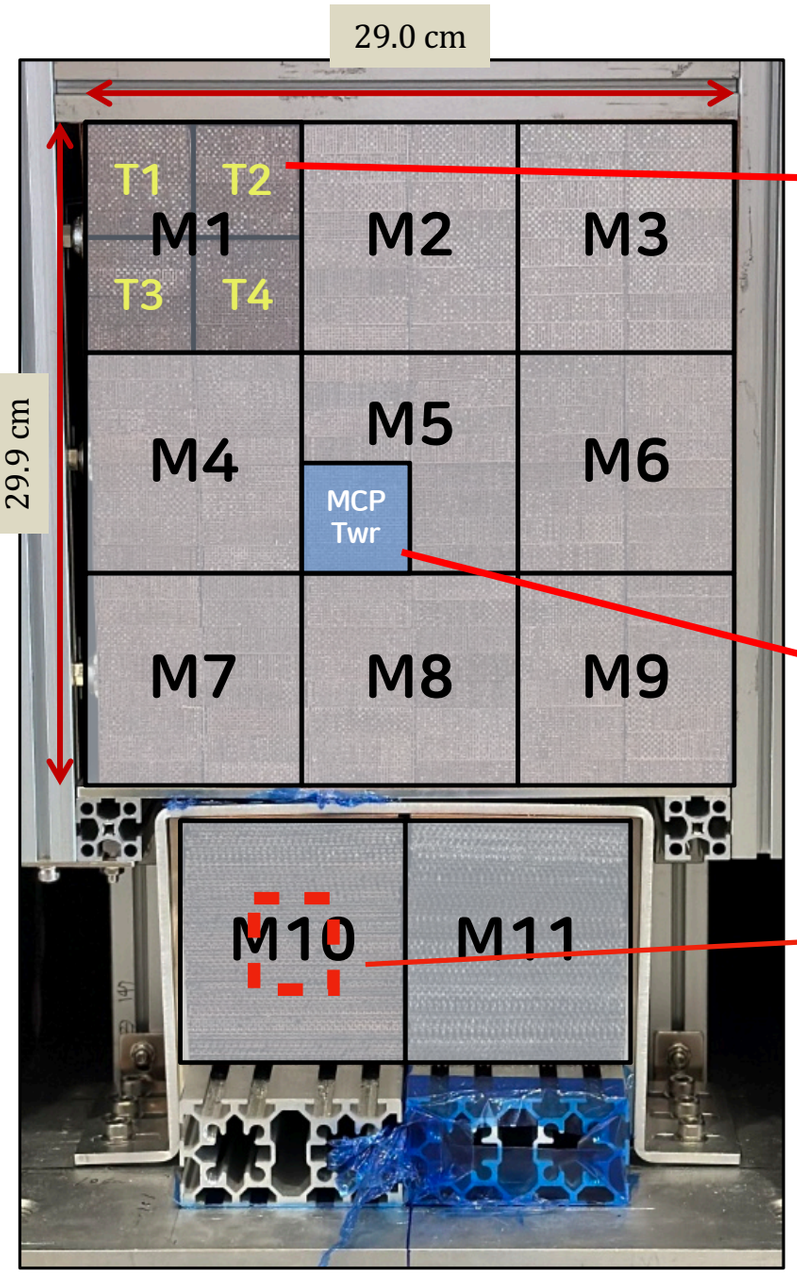


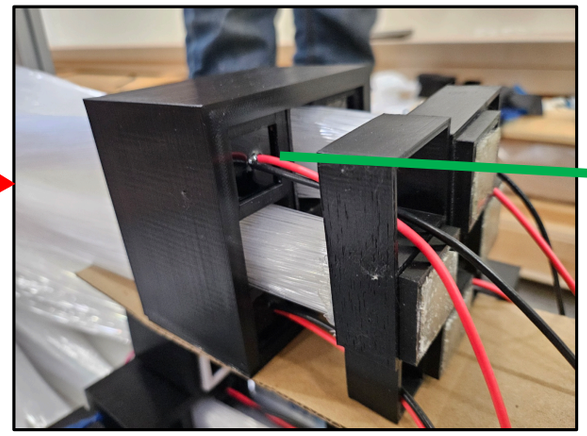
- Arrived module was assembled with another prototype module, which was used in TB2022.
- The total geometry gave more than **90%** of lateral shower deposit of hadronic particles, and length of **10 nuclear interaction length**.

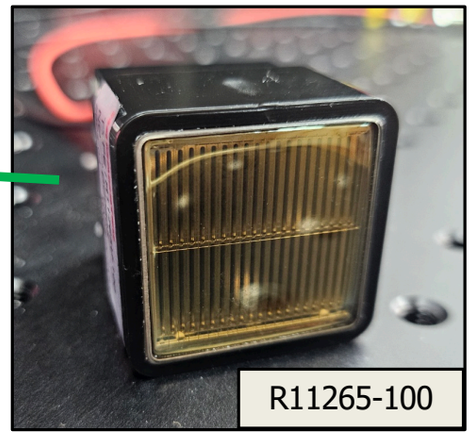
X_0	λ_I	Sampling Fraction
2.92 cm	27.91 cm	S=5.10%, C=5.77%

Electronics R&D

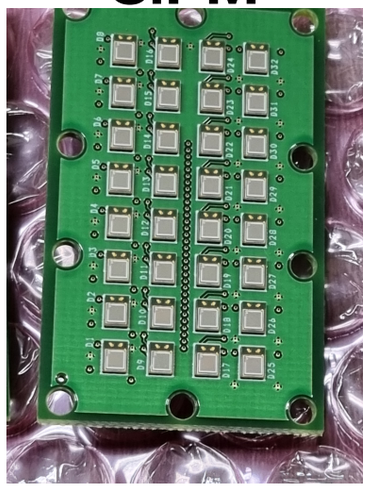
- High granularity solutions: MCP-PMT (128 ch) vs SiPM (400 ch)

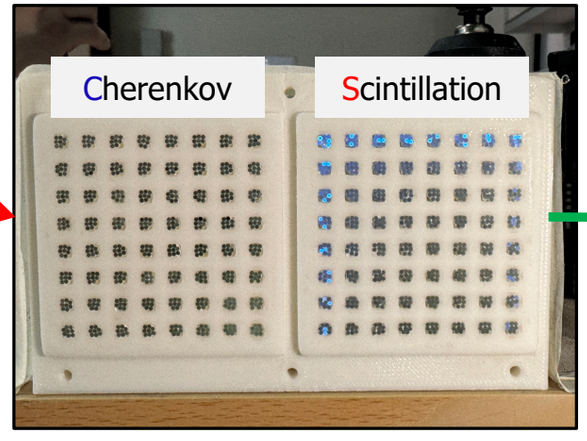


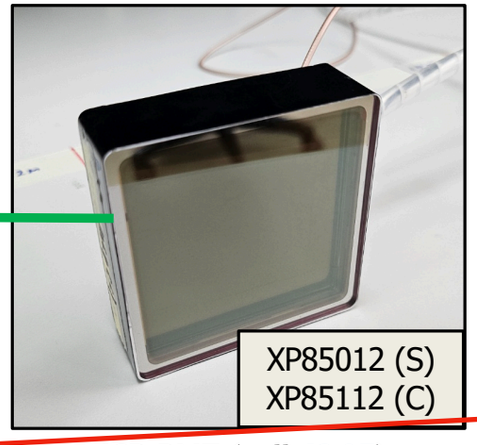




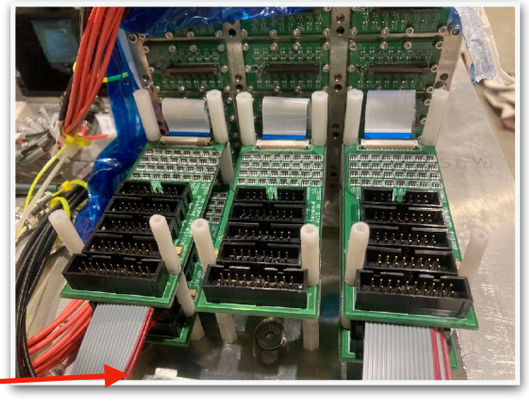
SiPM







MCP-PMT (talk J2.07)



S-ch: 200
C-ch: 200
on the center of M10

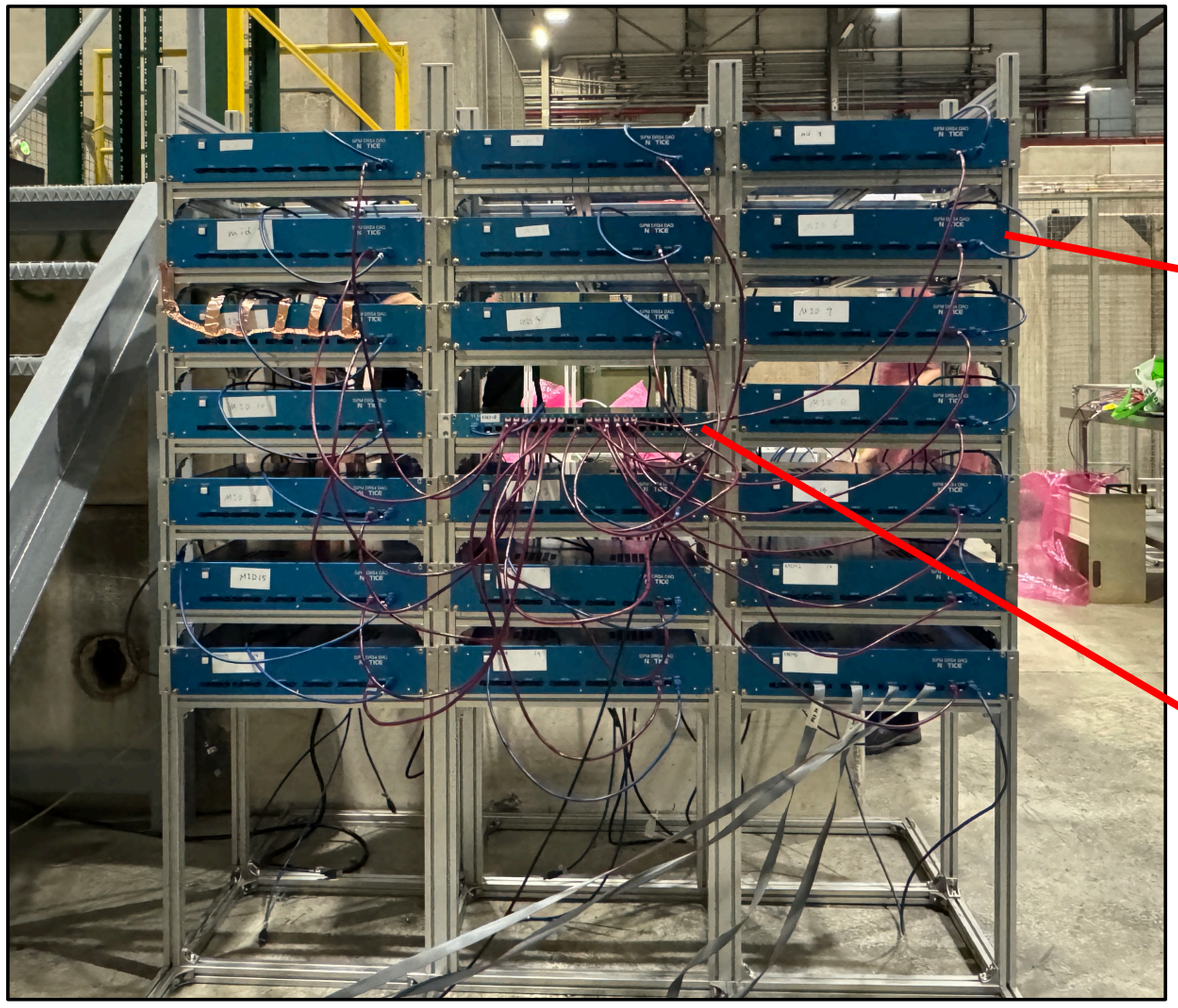
- The DRC module is divided to '**tower**' unit, each tower is bundled to single readout channel. (Square type PMT, Hamamatsu R11265-100)
- On M5-T3, **MCP-PMT** is attached, which provides high granularity, dividing single tower into 64 channels. (XP85012, XP85112)

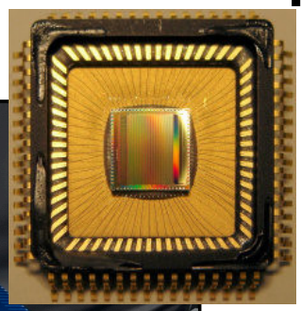
DAQ R&D

- Customized DAQ system is designed: 20 DAQ boards and 1 TCB board (to control multi DAQ boards)
  - DAQ board is based on DRS4 chip for fast timing resolution (32 channel / board)
- Very powerful performance during test-beam experiments
- Upgrade plan is under discussion for faster timing resolution

200-400 ps with MCP-PMTs

DRS4 chip

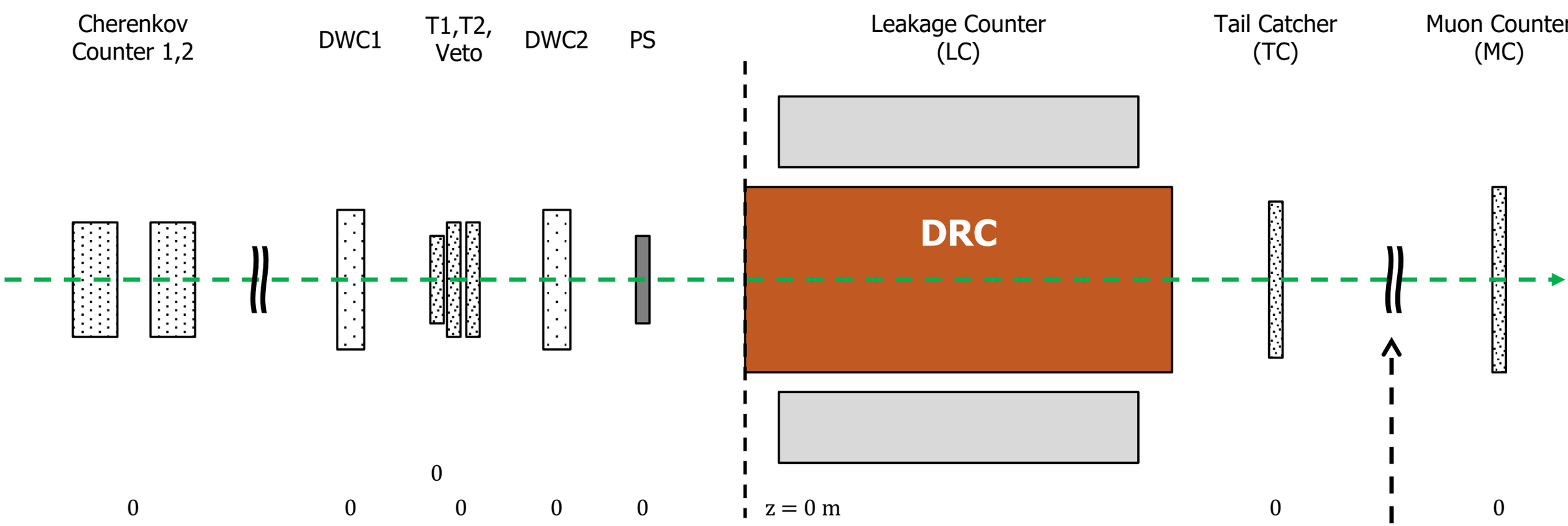


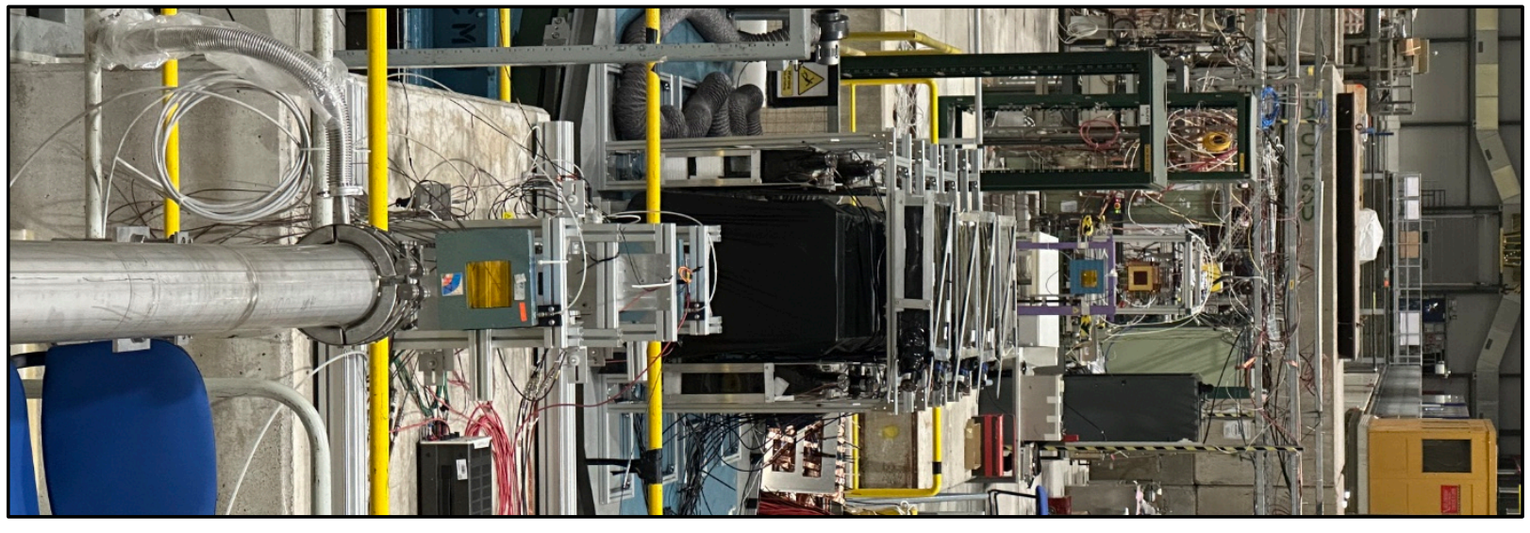


DAQ Board

TCB Board

Test-beam Experiments at CERN

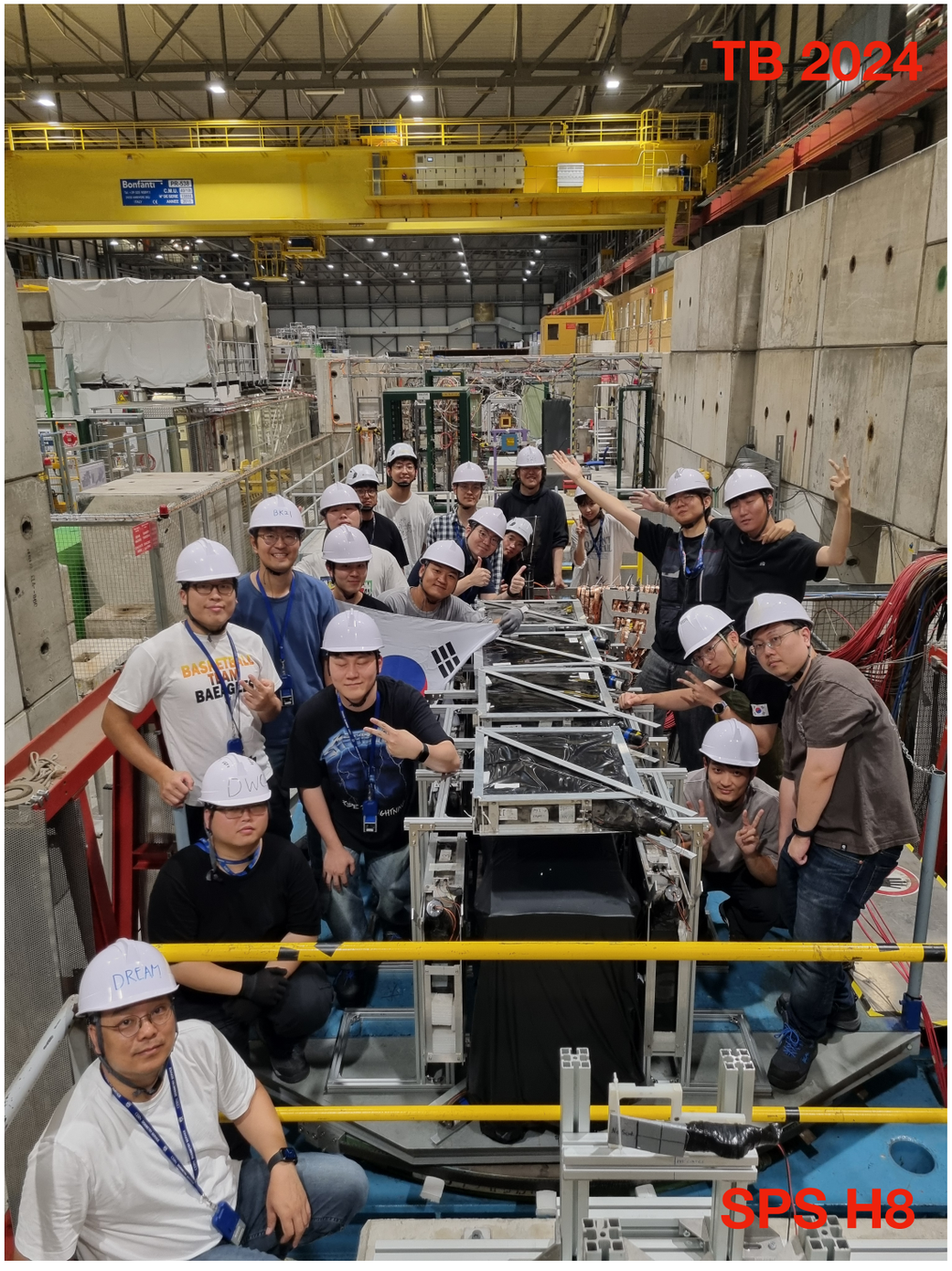




North Area (SPS H8)

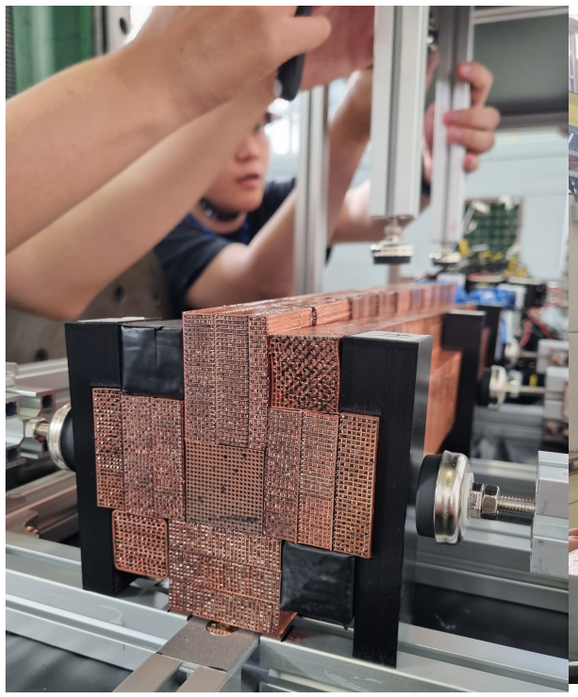
Training Young Generation

- Students participation: TB 2022 (23), TB 2023 (15), TB 2024 (25)

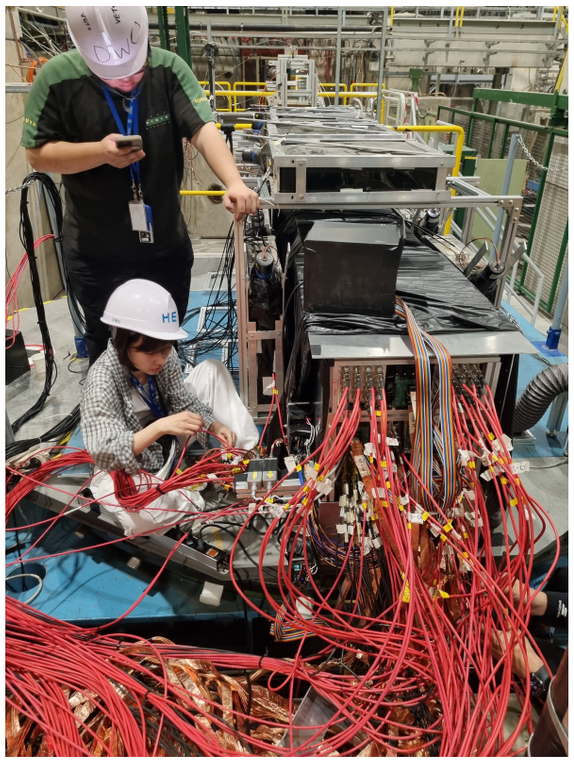


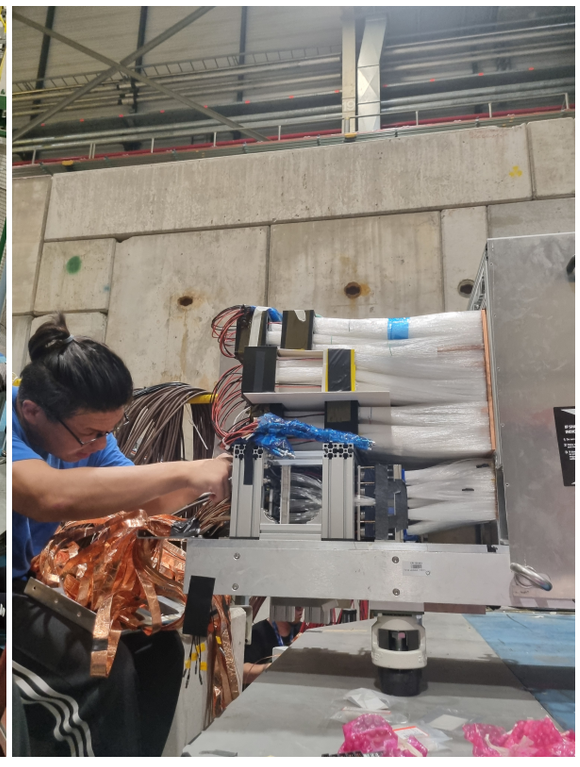
Experimental Setups

TB 2023



TB 2024

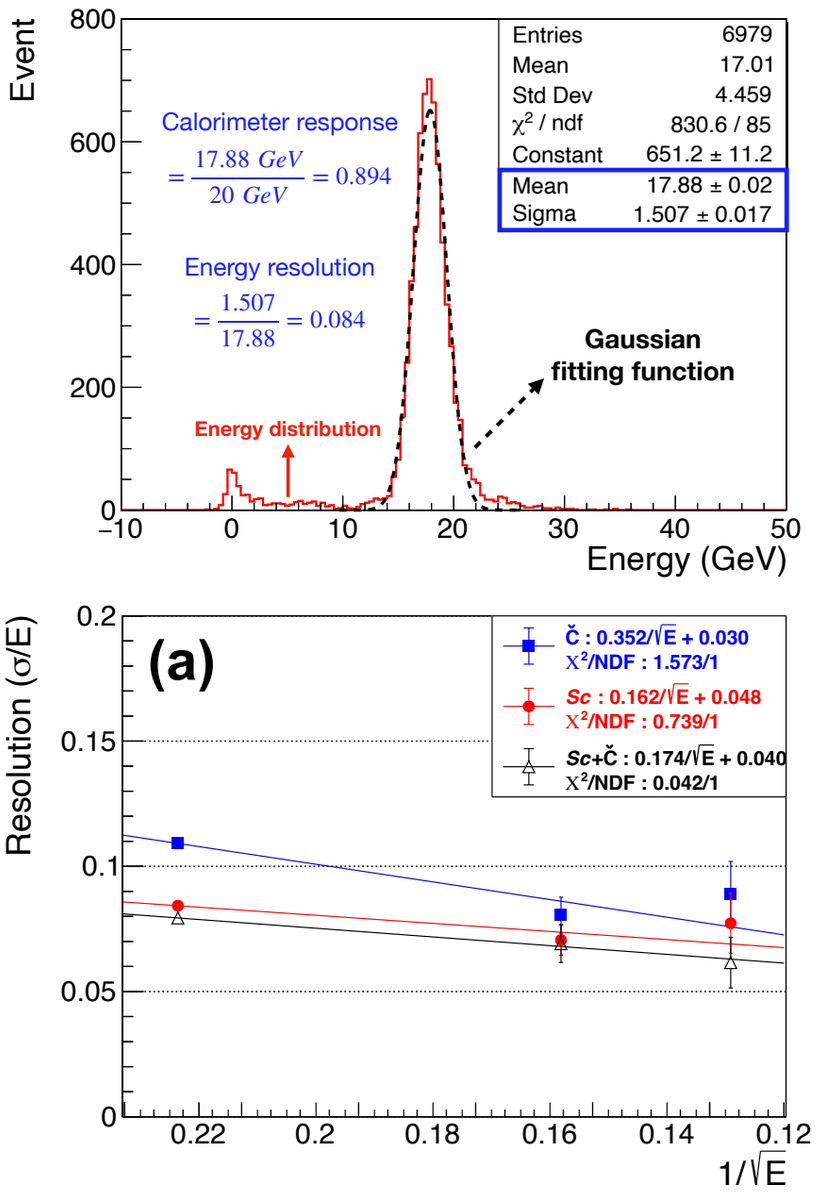




Results of Test-beam Exp.

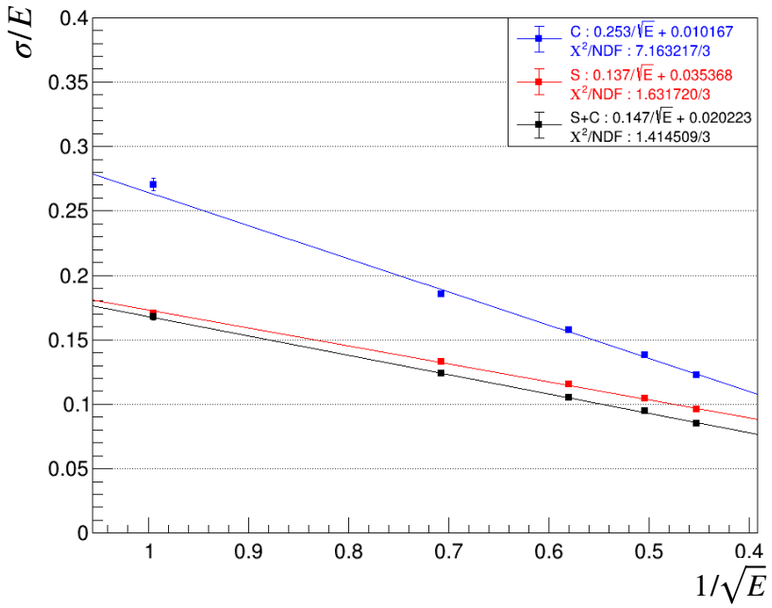
- Analyses and paper preparation are on-going

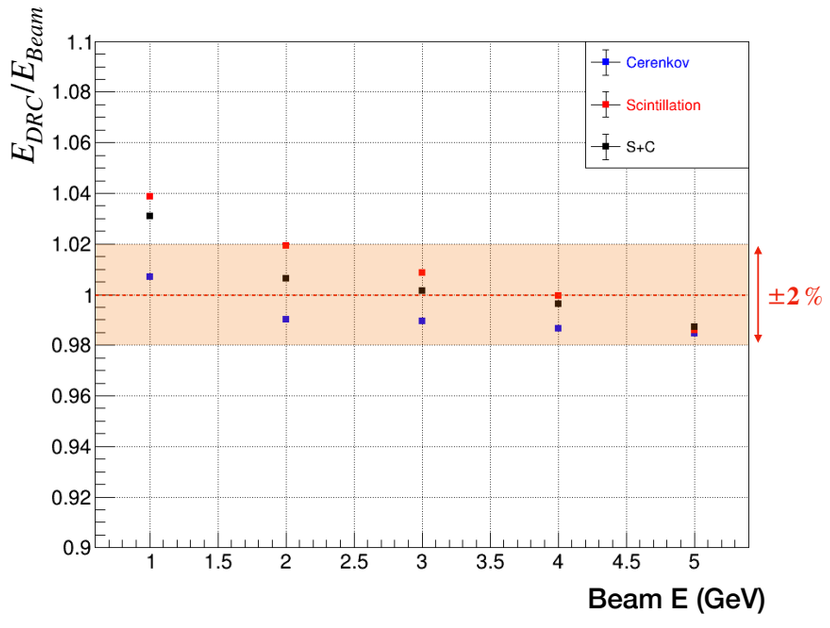
TB 2022



Submitted to Journal of Subatomic Particles and Cosmology (Elsevier)

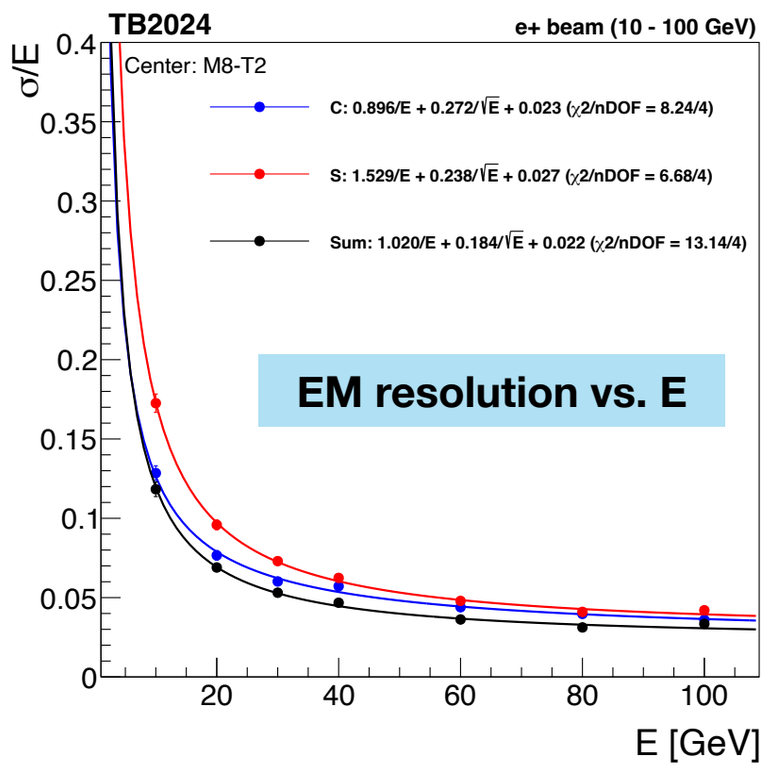
TB 2023

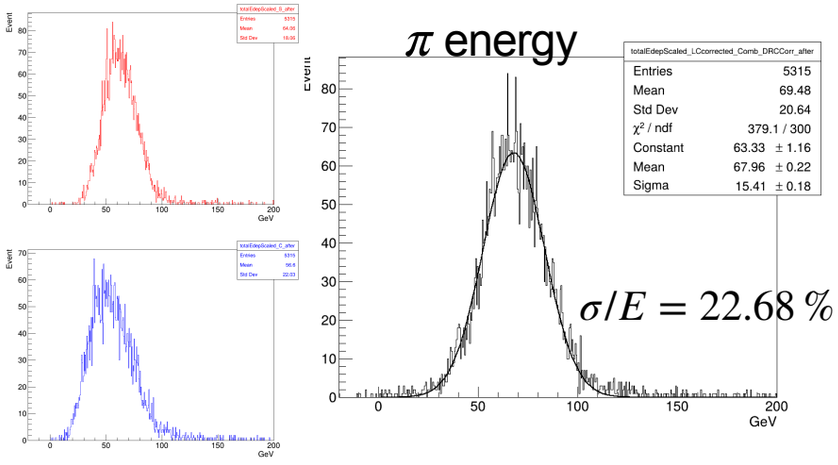




Presented at CALOR 2024

TB 2024

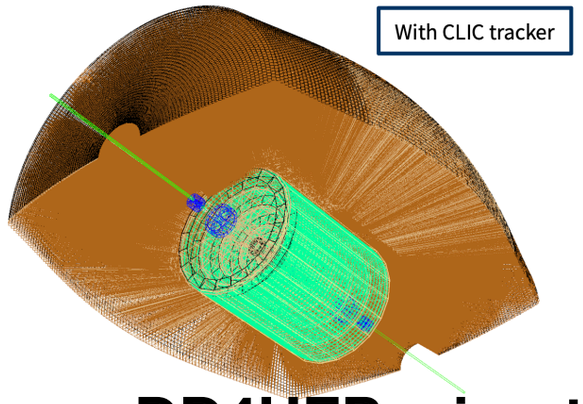




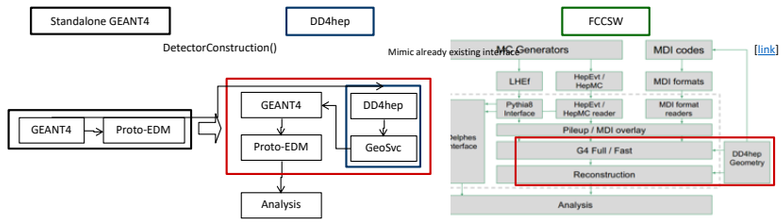
Very Preliminary

Simulation/SW Framework

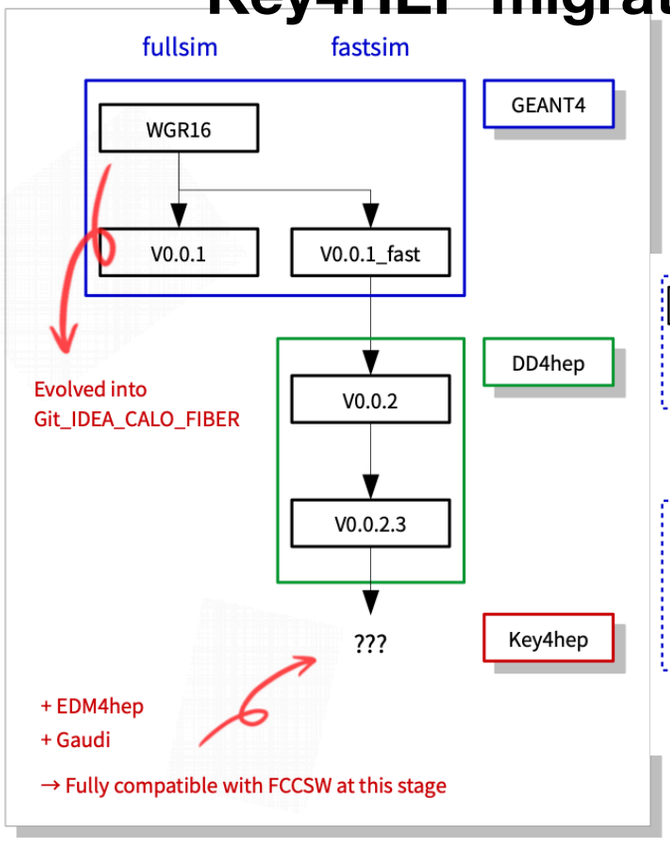
- Contribute on many centralized SW developments
  - Migration to DD4HEP framework
  - Faster simulation: developing optical photon transport in GEANT4 => O(100) times faster
  - Migration to Key4HEP framework
    - Add digitization, reconstruction, calibration, etc.



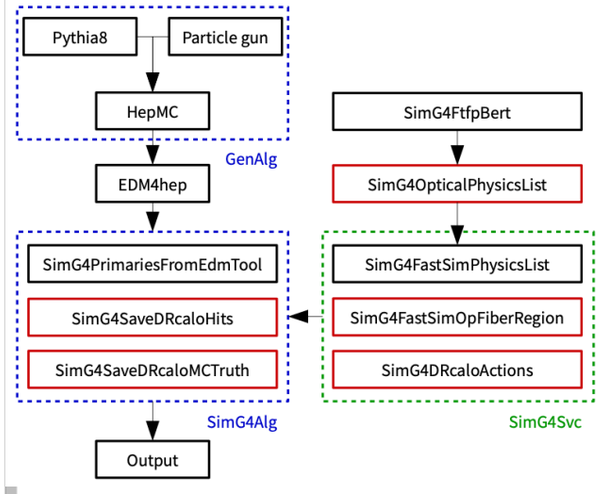
DD4HEP migration



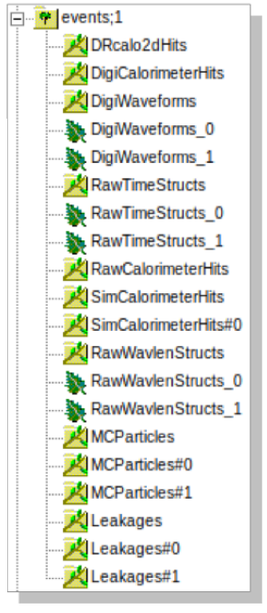
Key4HEP migration



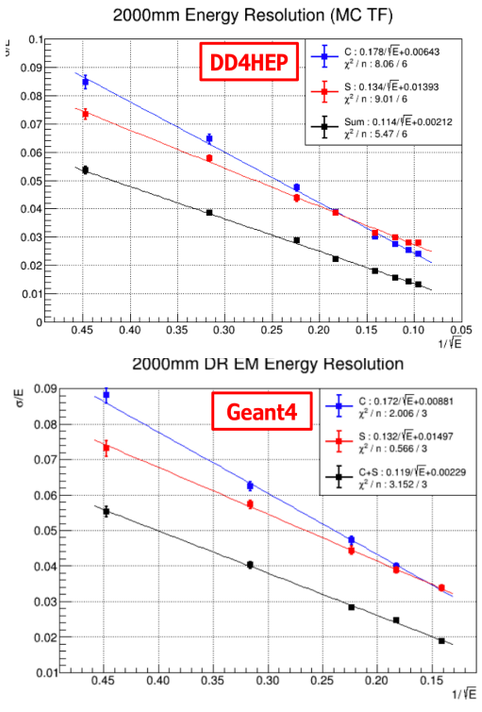
Simulation flow

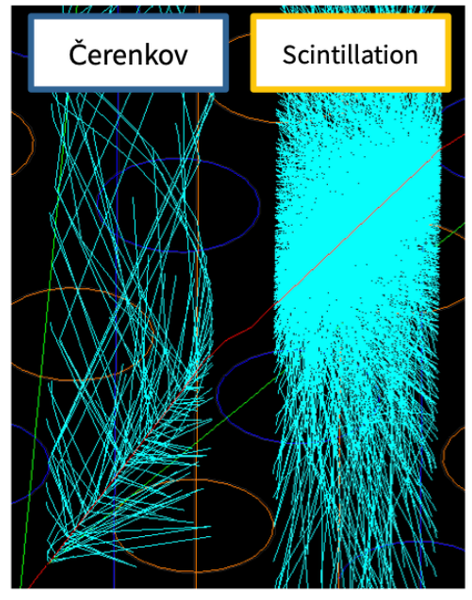


EDM4hep



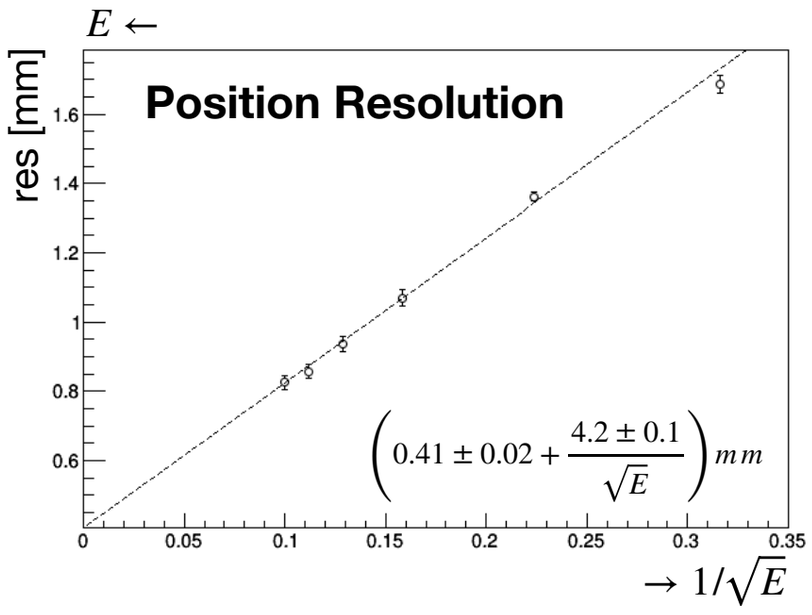
Faster simulation

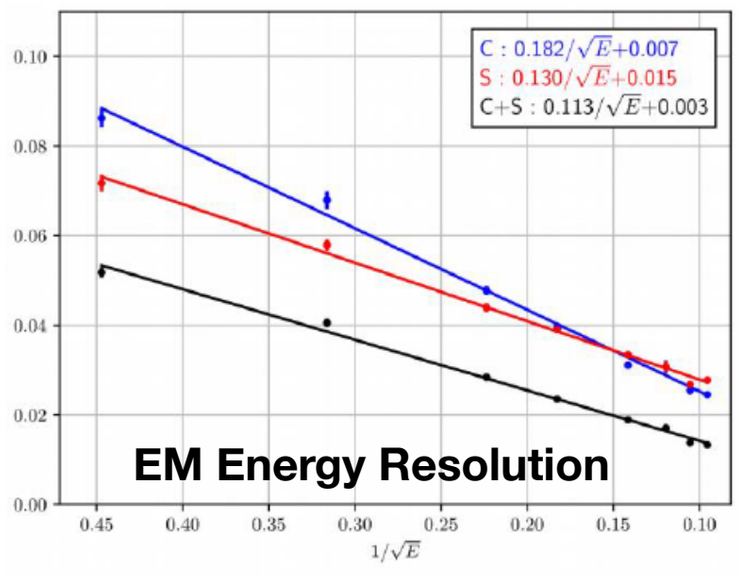


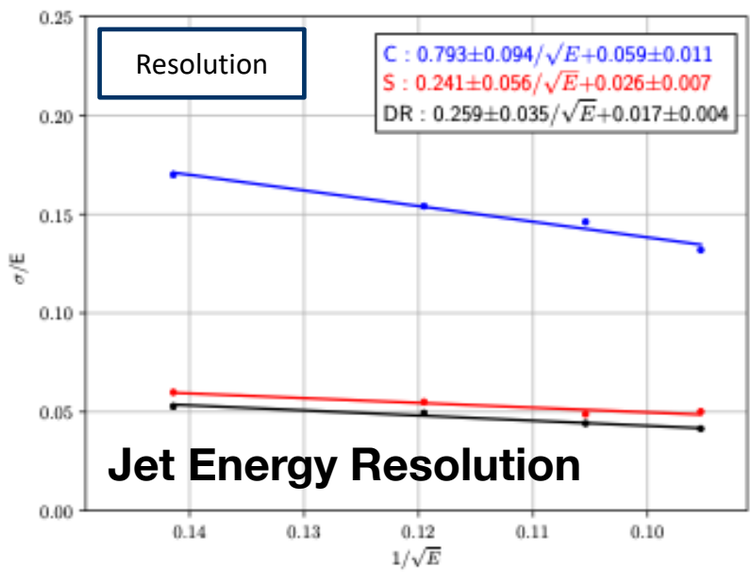


Important for a longitudinally unsegmented calorimeter

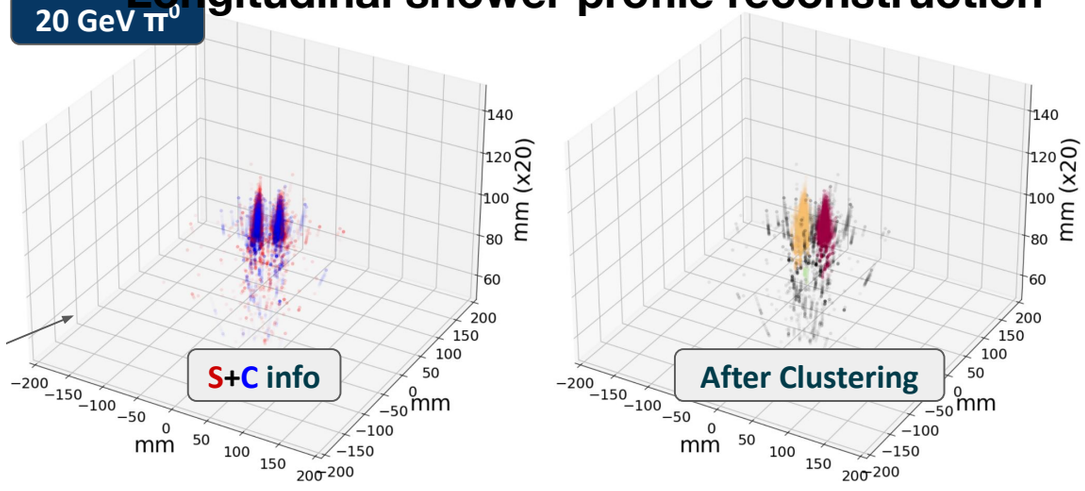
Performance Studies (Simulation)

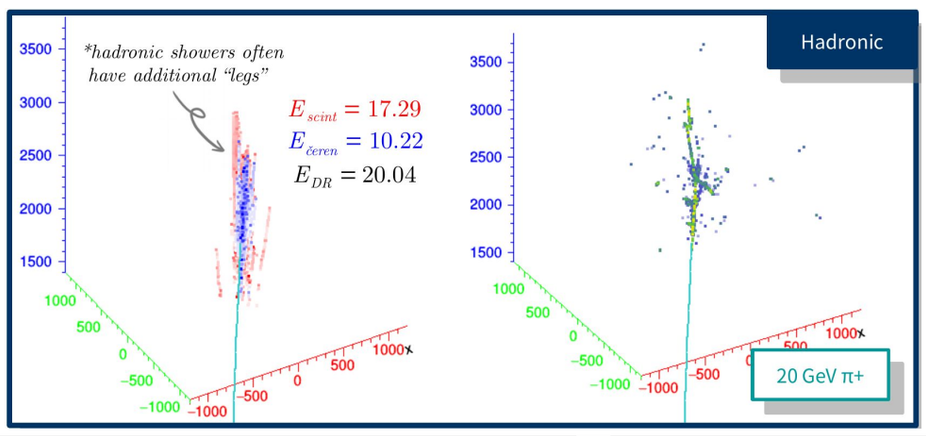




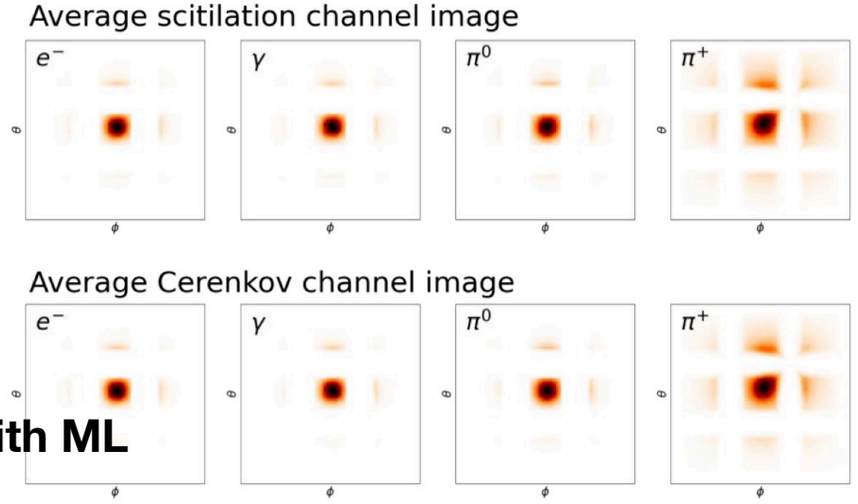


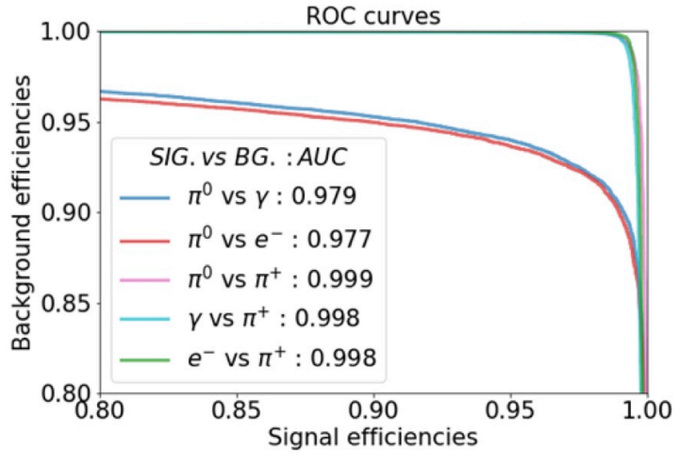
Longitudinal shower profile reconstruction

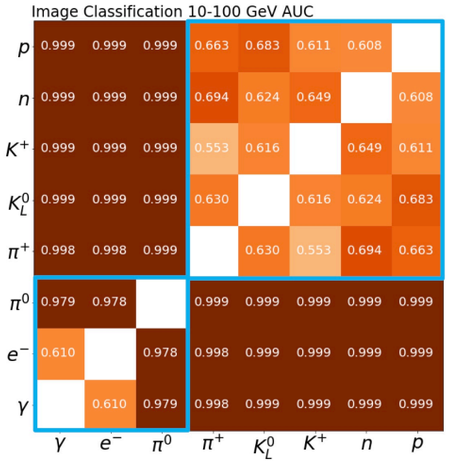




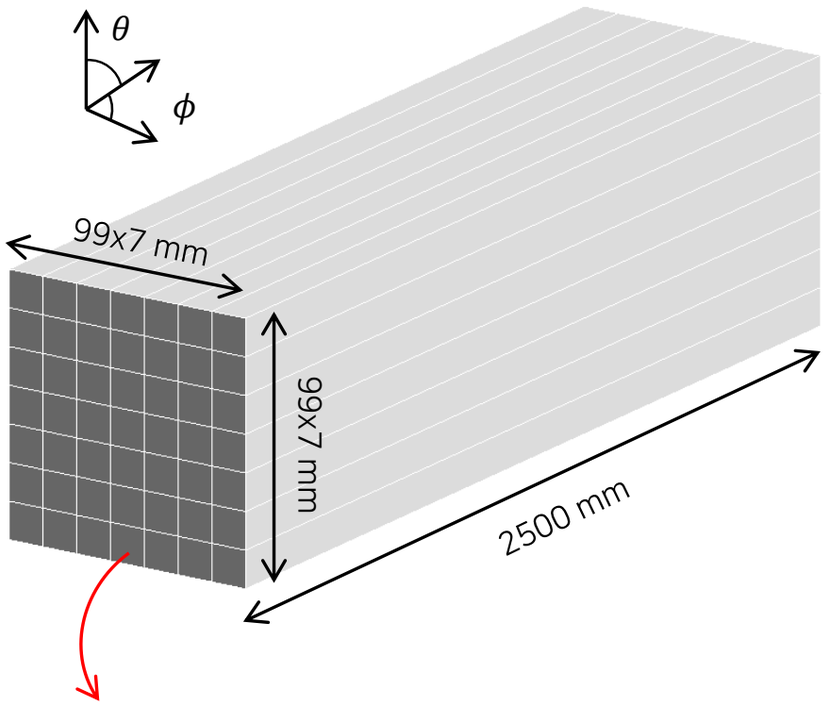
Particle IDs with ML





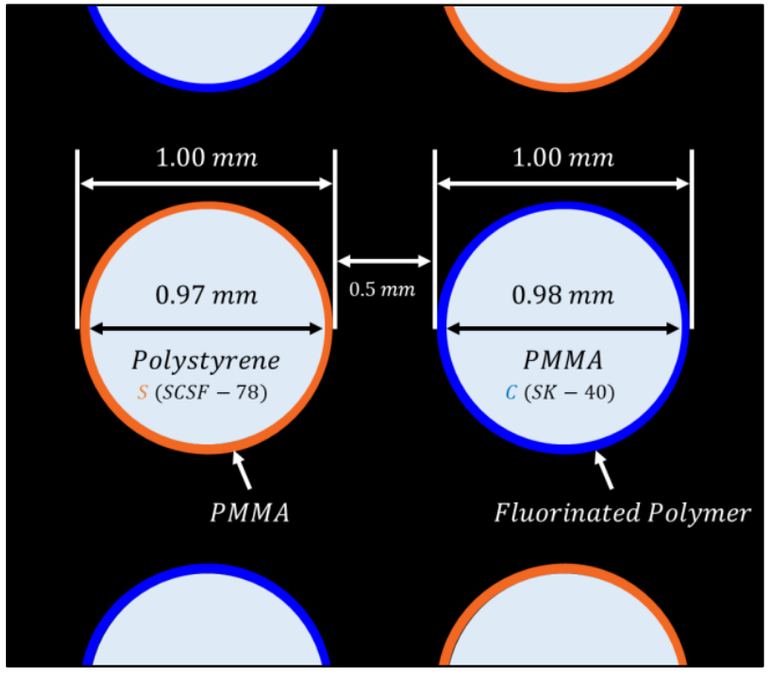


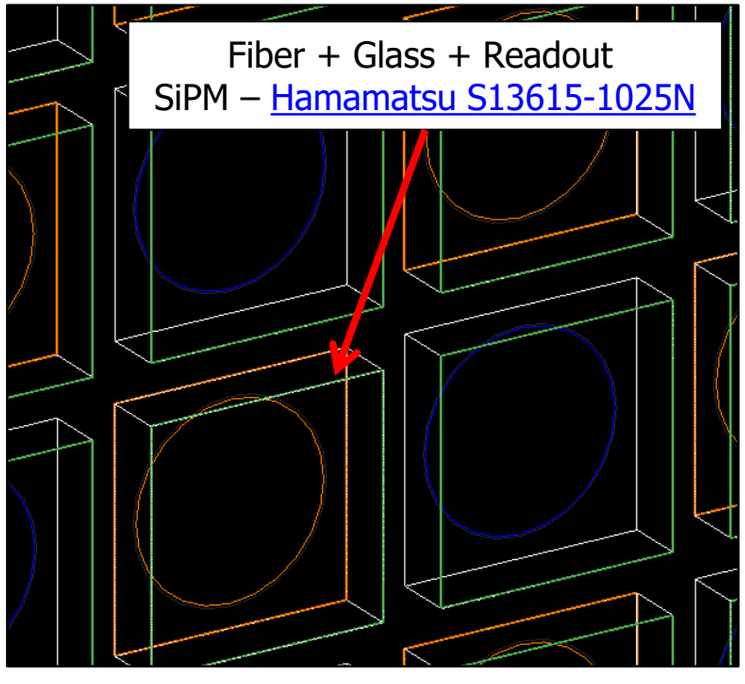
Comparison for Various Absorbers



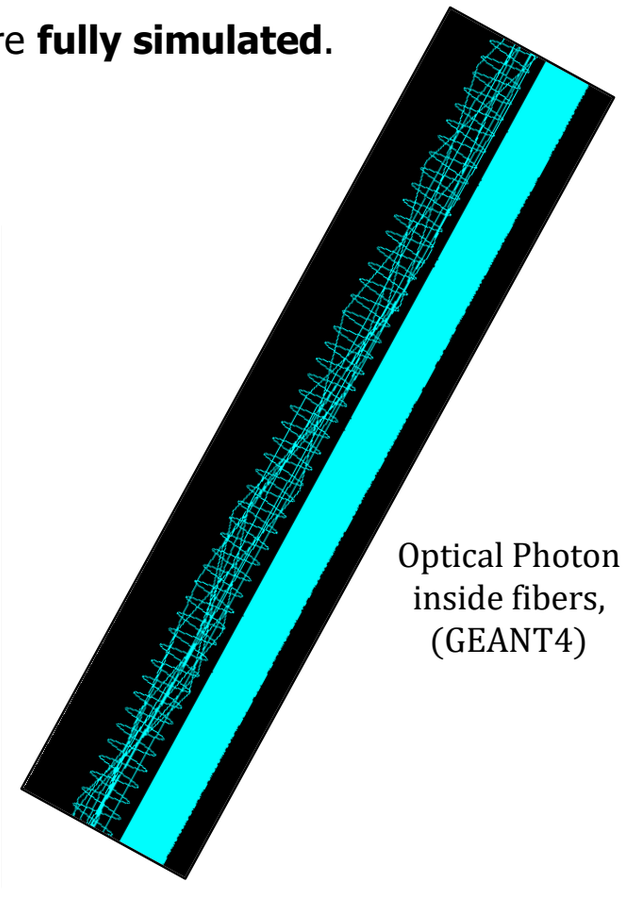
- Simulation setup is based on Geant4 toolkit, 10.5.p01, physics list FTFP-BERT.
- The geometry is **longitudinally unsegmented**, box shape, 7x7 modules.
- 5 different absorbers were used –

  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.





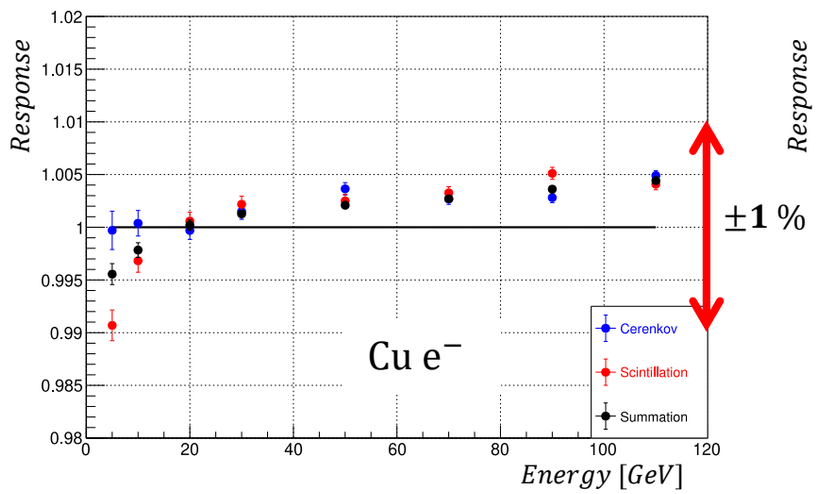
Rearside of module (GEANT4)

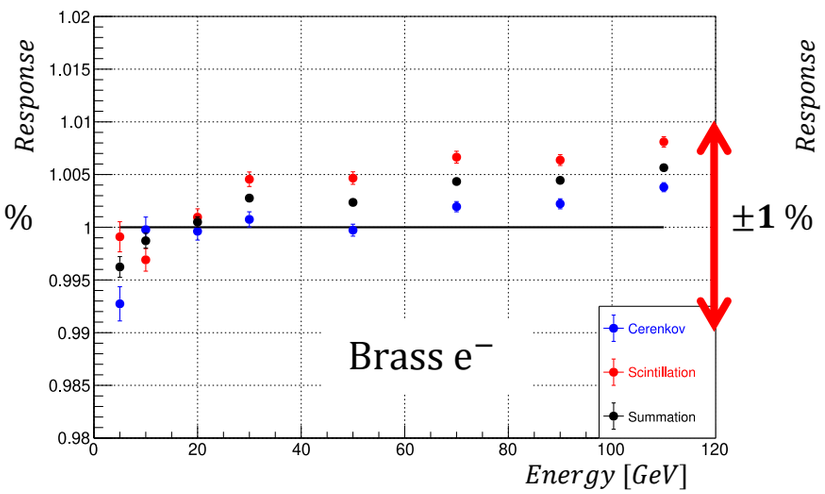


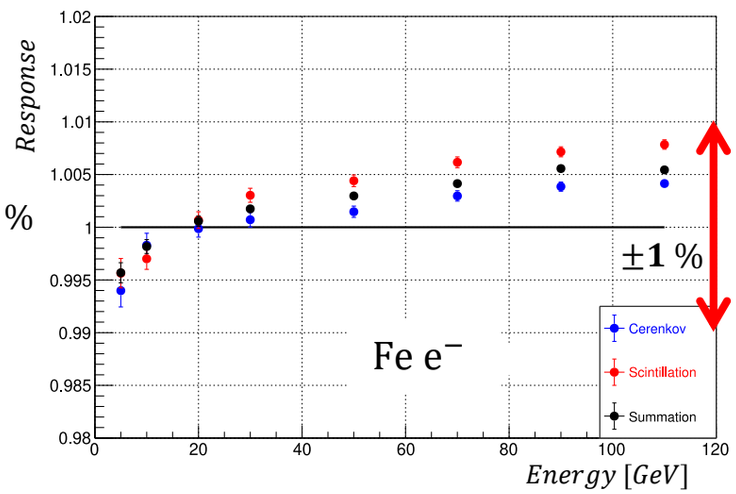
Optical Photon inside fibers, (GEANT4)

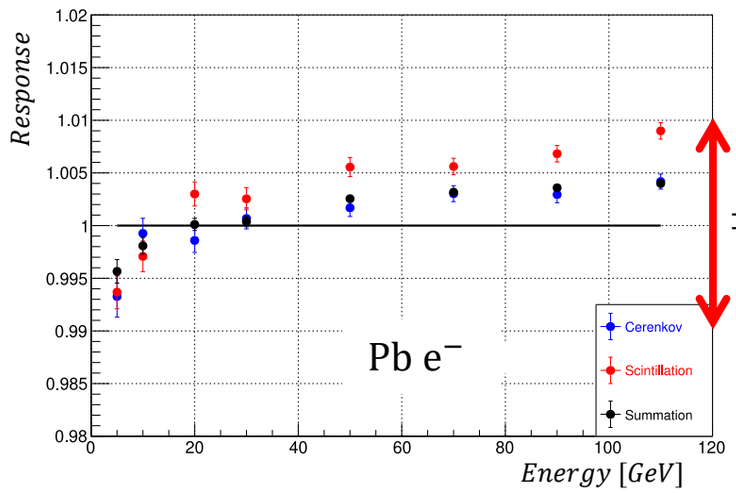
Presented at CALOR 2024 and paper in preparation

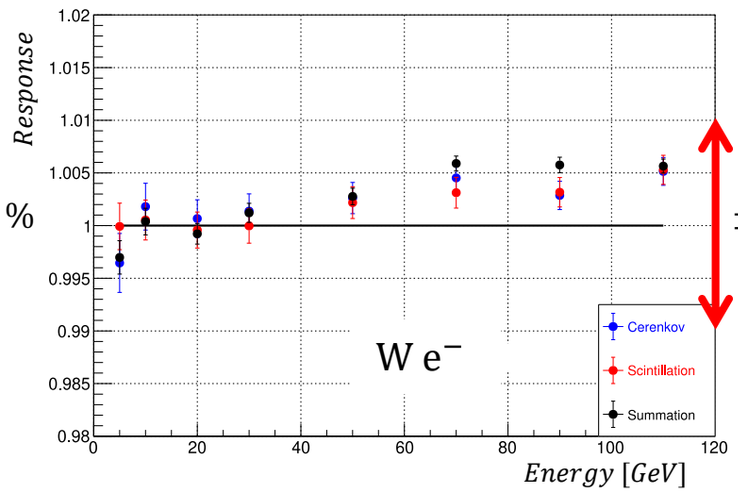
Comparison for Various Absorbers











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

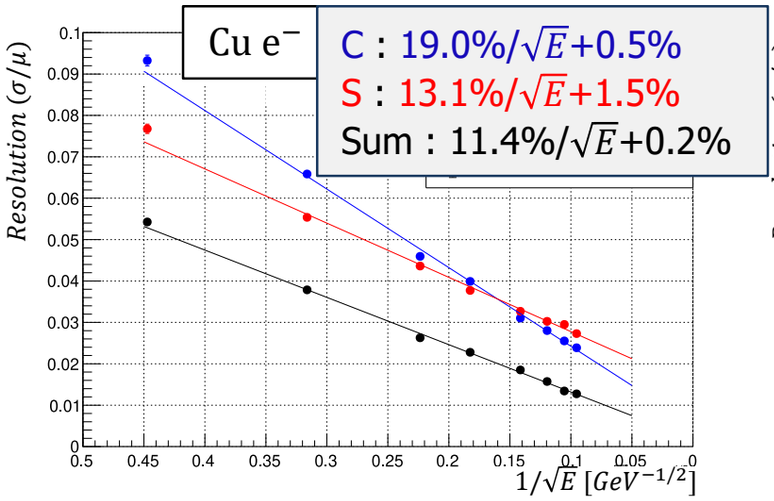
$\text{Response} = \text{Reco. E/Incident Energy}$

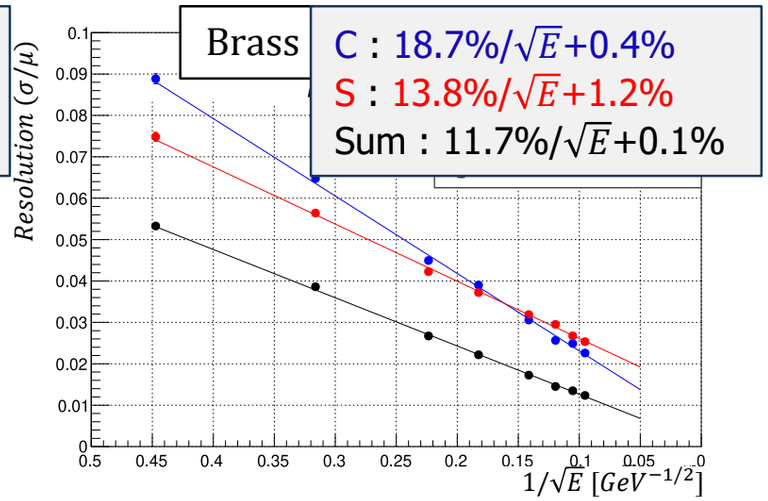
$\textbf{Summation} = \mathbf{C} + \mathbf{S}$

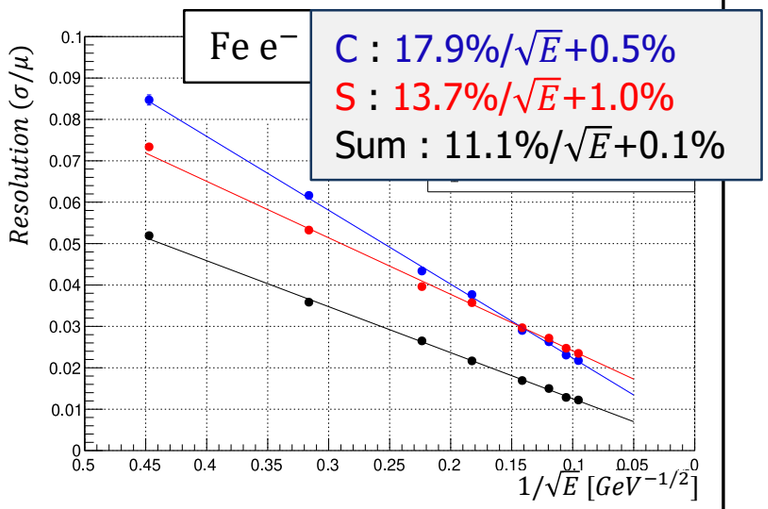
- Used mean & RMS of guassian fit function of reconstructed energy – Scintillation, Cherenkov, and Summation channel.
- Energy linearity of electrons, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- Regardless of energy or absorber, **energy linearity matches in** $\pm 1\%$

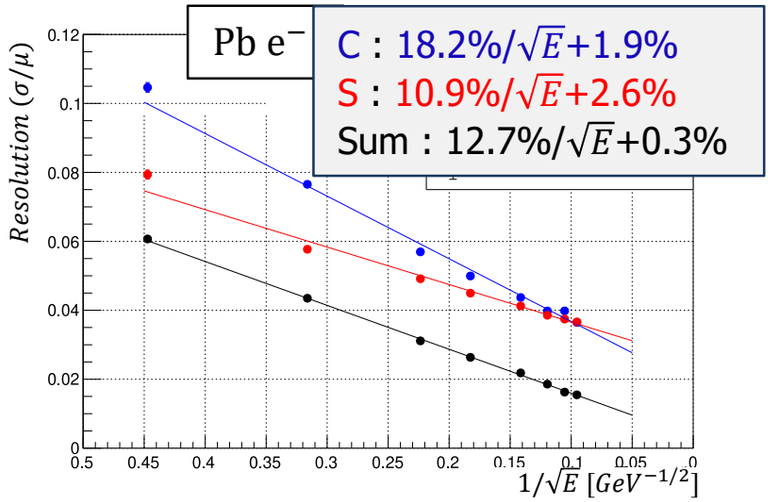
Presented at CALOR 2024 and paper in preparation

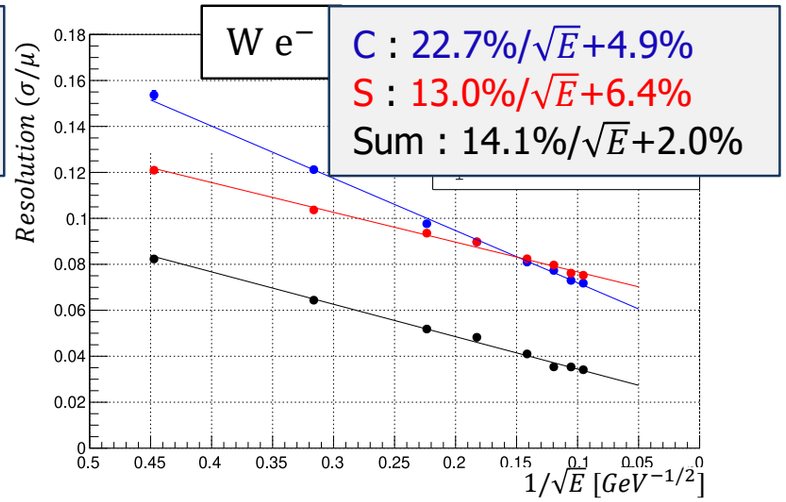
Comparison for Various Absorbers











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.**

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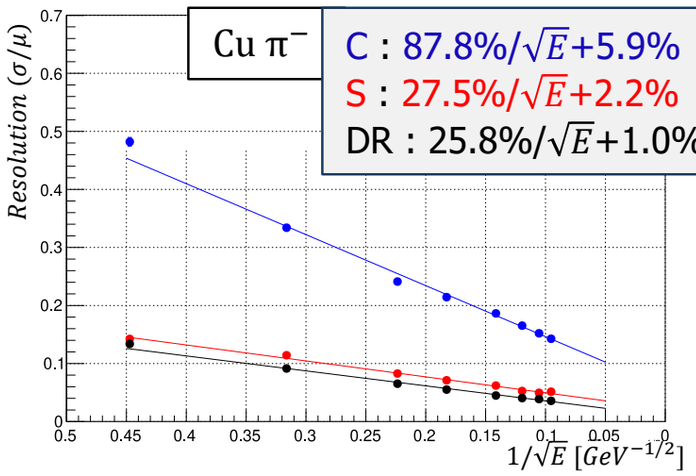
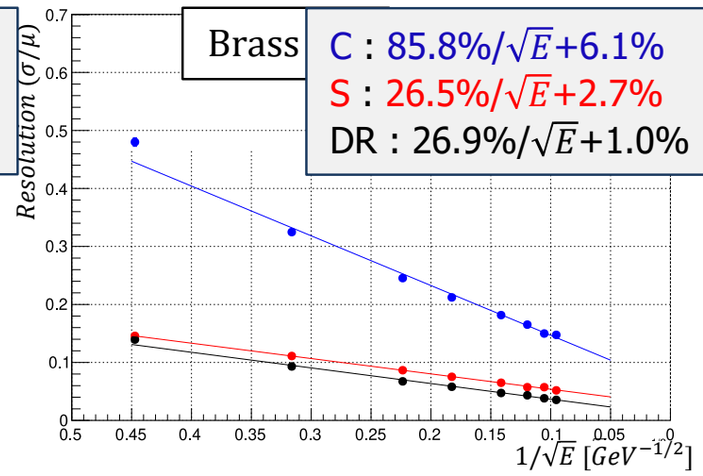
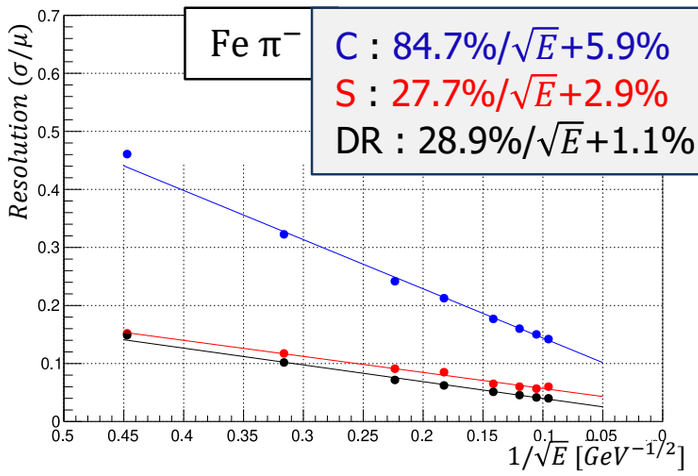
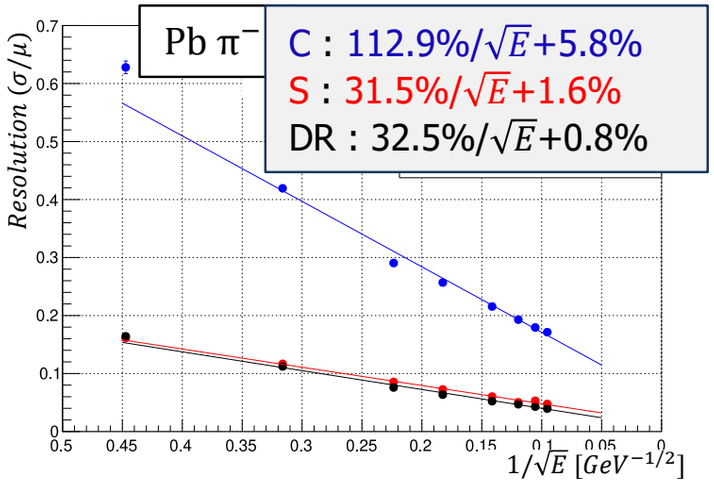
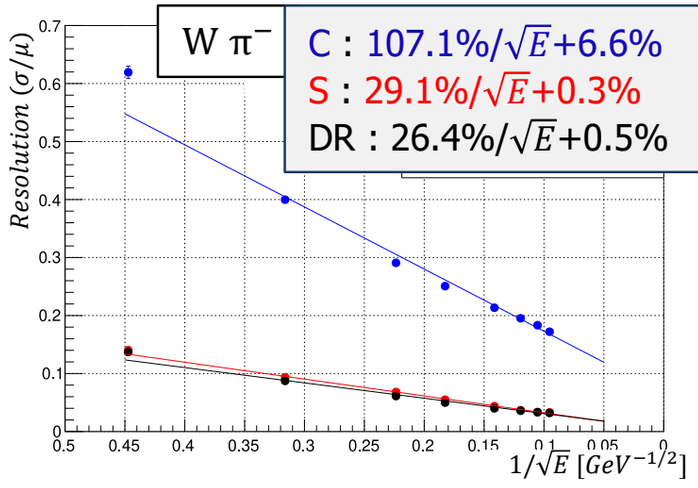
Comparison for Various Absorbers











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

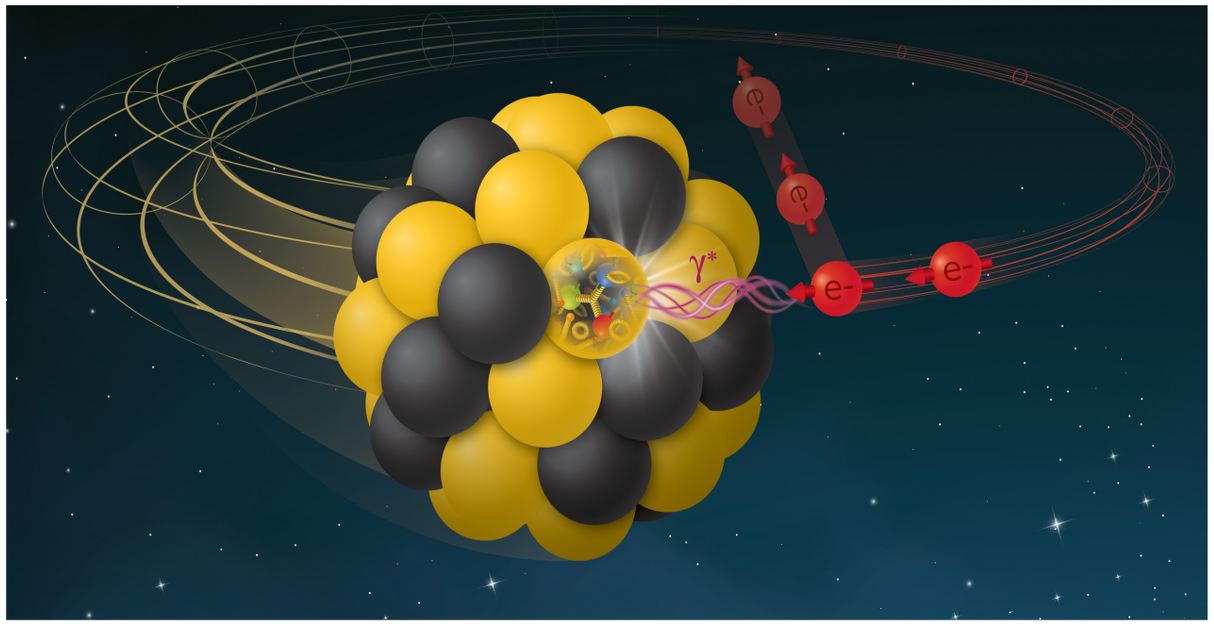
Resolution = σ/Mean

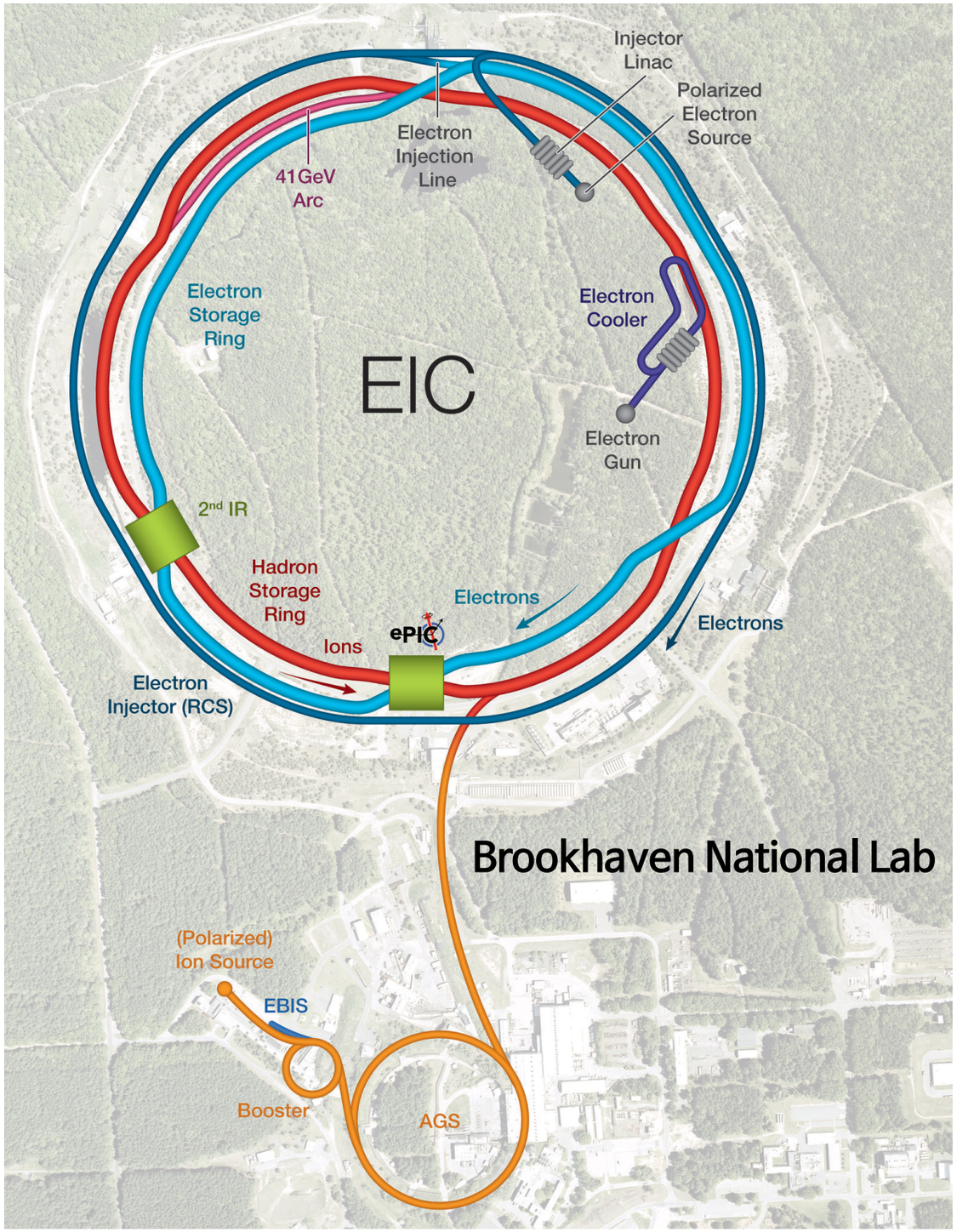
S, C, Dual Readout corrected

- 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%/$\sqrt{E}$**

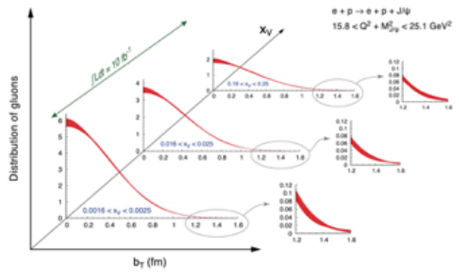
Presented at CALOR 2024 and paper in preparation

Electron-Ion Collider

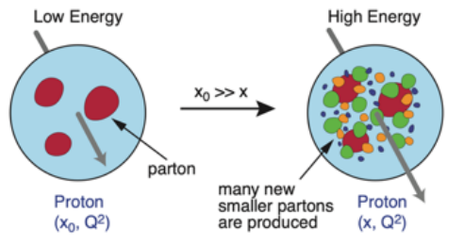




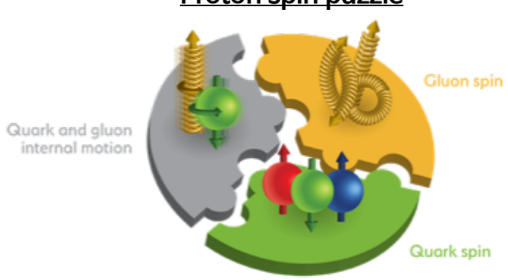
3D structure of protons and nuclei



Gluon saturation



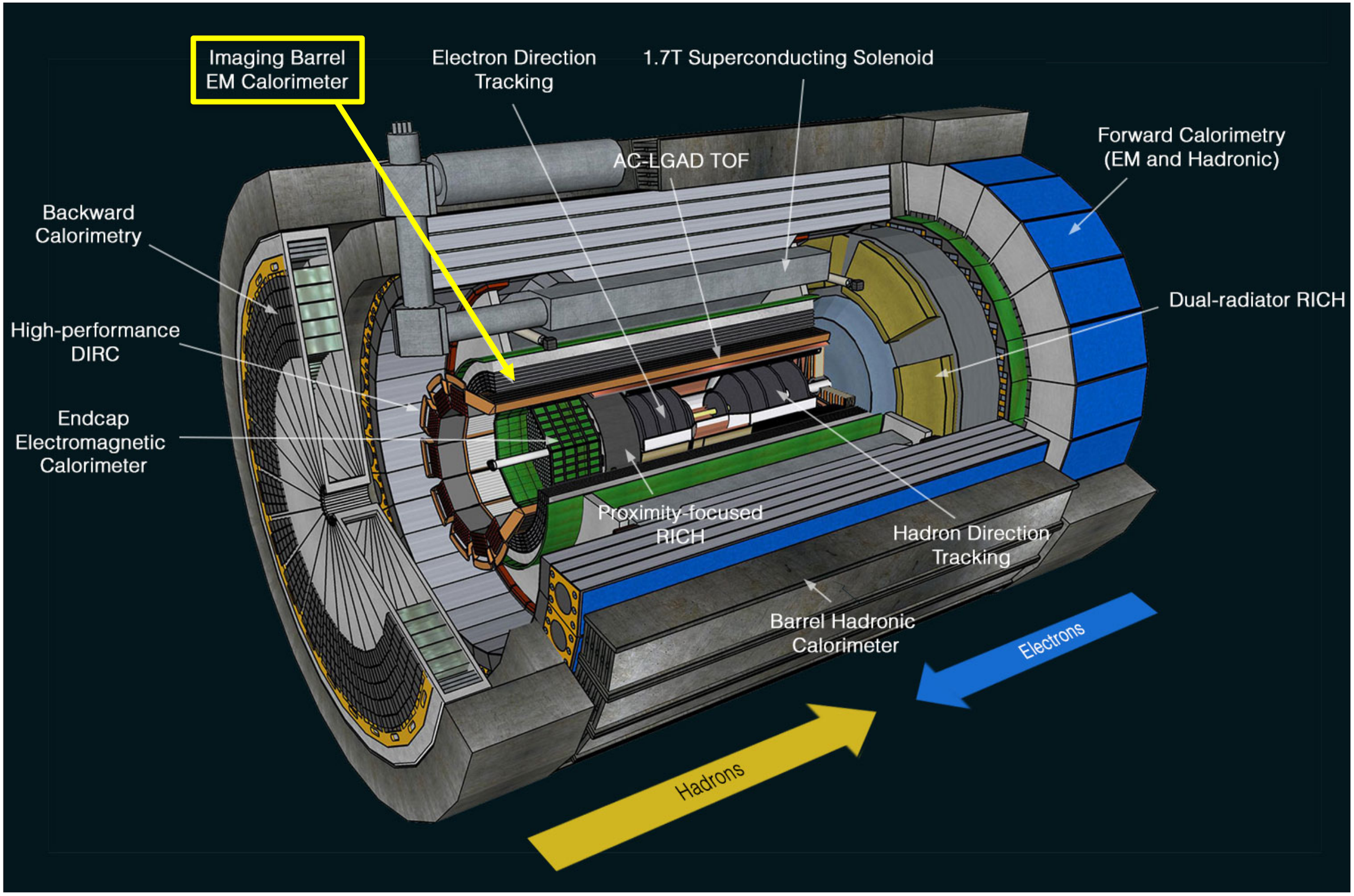
Proton spin puzzle



Quark gluon confinement

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

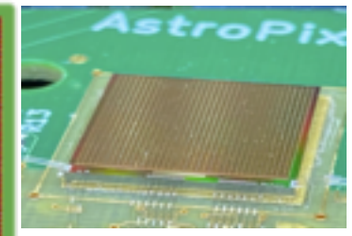
ePIC Detector

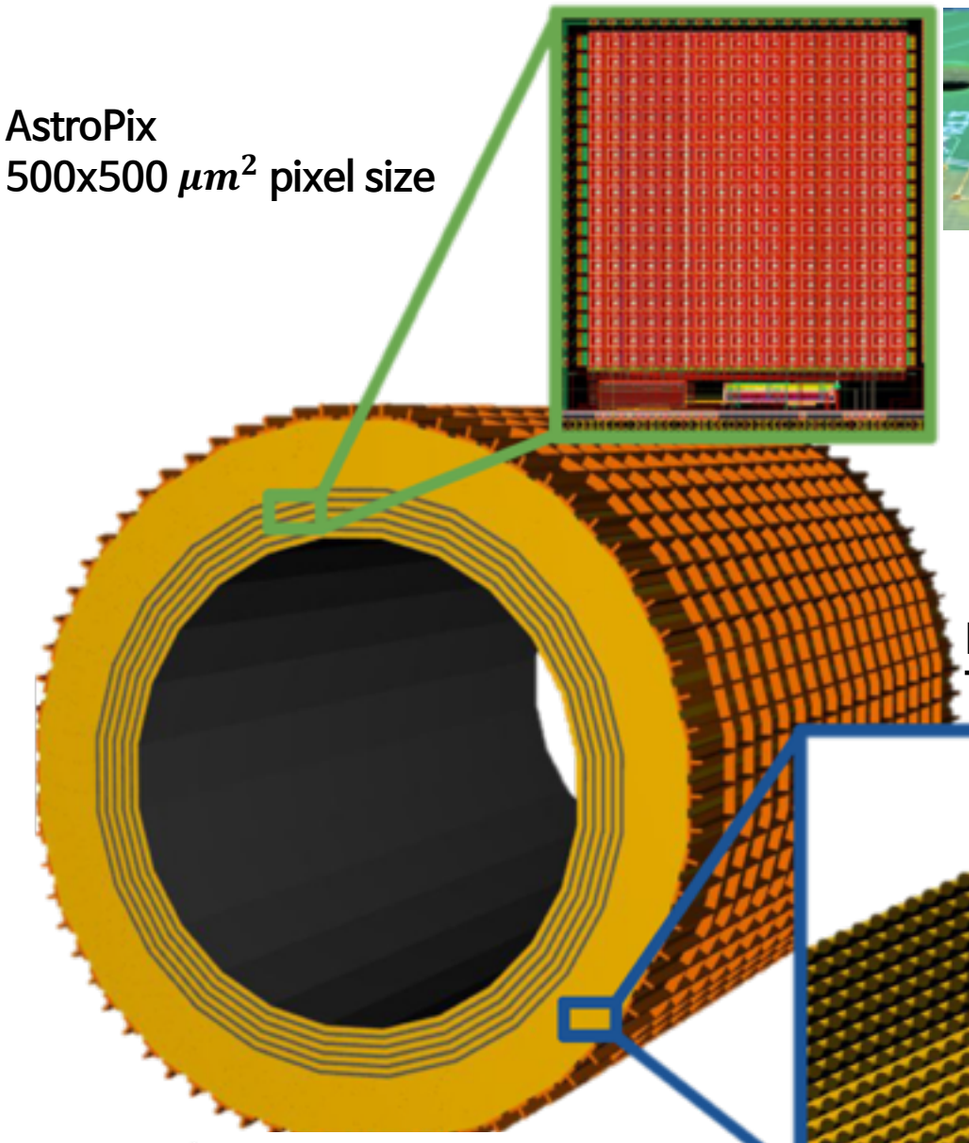


Korean group is responsible for 50% of construction of EM calorimeter

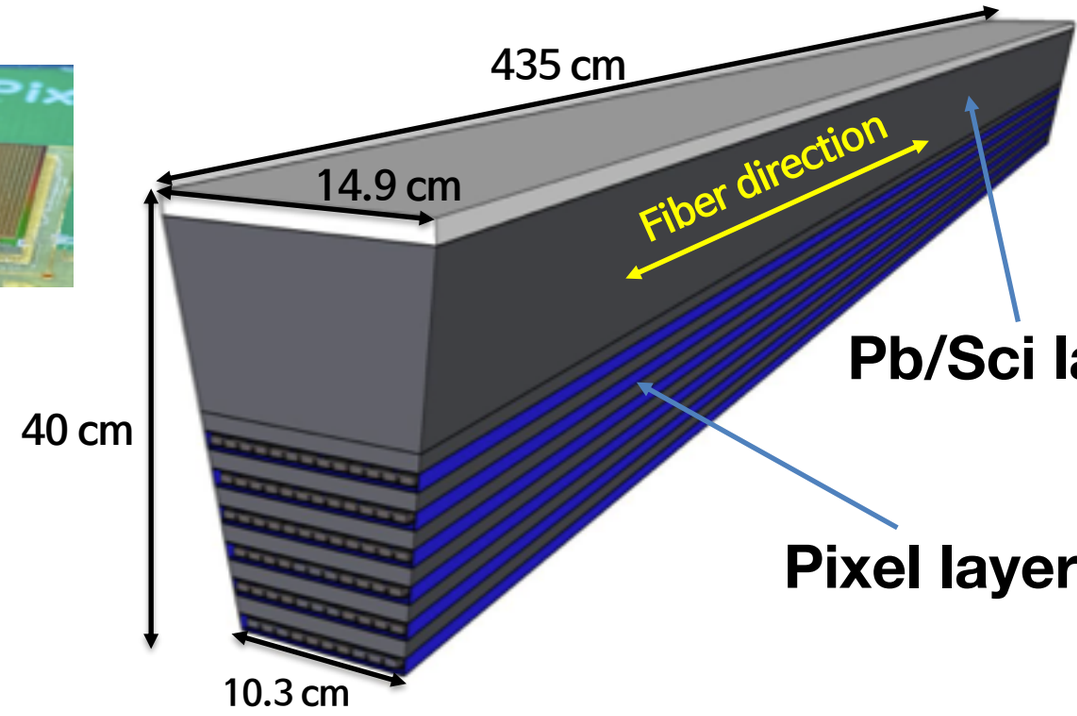
EIC (BNL) Activities in Korea

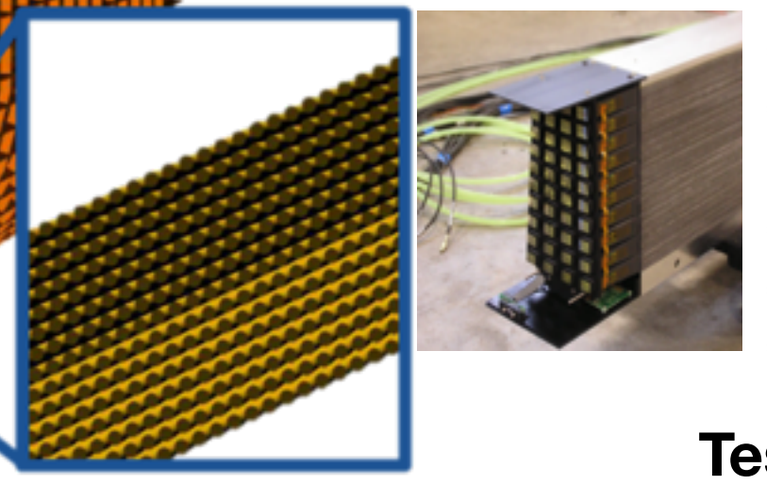
AstroPix
500x500 μm^2 pixel size



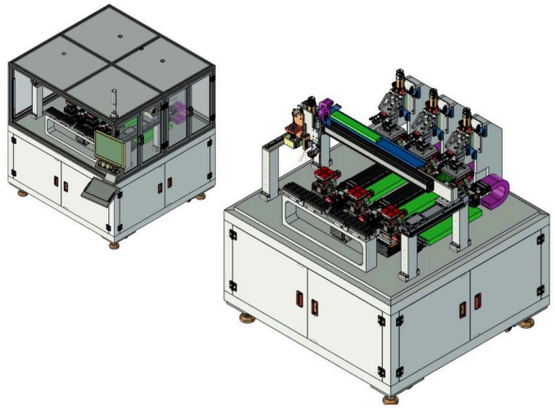


Pb/SciFi
Two-sided SiPM readout

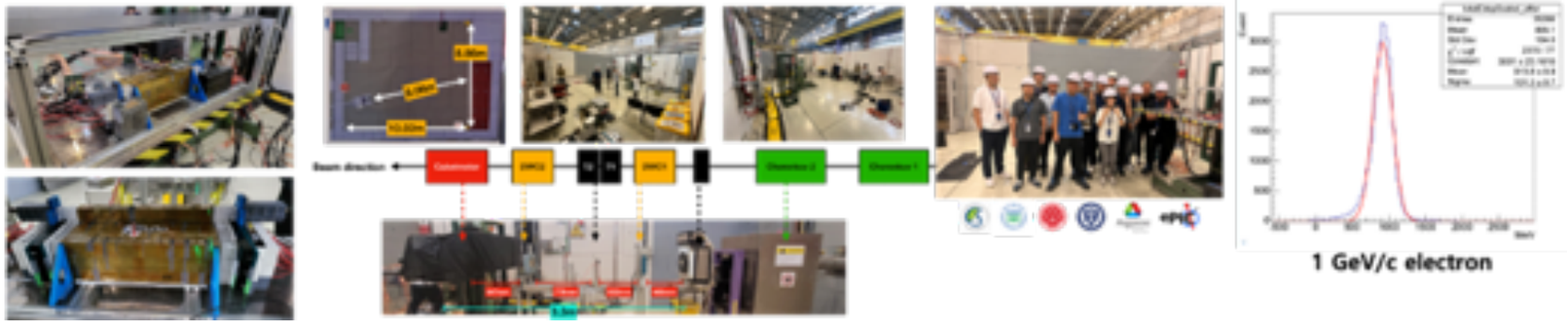




- Barrel Imaging Calorimeter
- 4(+2) layers of imaging Si sensors interleaved with 5 Pb/SciFi layers
- Followed by a bulk section of Pb/SciFi
- Total radiation thickness ~17.1 X_0
- Sampling fraction ~10%



Test-beam at CERN PS T9 (24.8)



BIC Collaboration

Korean institutions for the BIC

USA

Argonne National Laboratory

NASA Goddard Space Flight Center

Oklahome State University

University of Connecticut

University of California Santa Cruz

Canada

University of Manitoba

University of Regina

Mount Allison University

NSERC

Canada Fund for Innovation

Korea

Kyungpook National University

Yonsei University

University of Seoul

Pusan National University

Korea University

Sungkyunkwan University

Hanyang University

Gangneung-Wonju National University

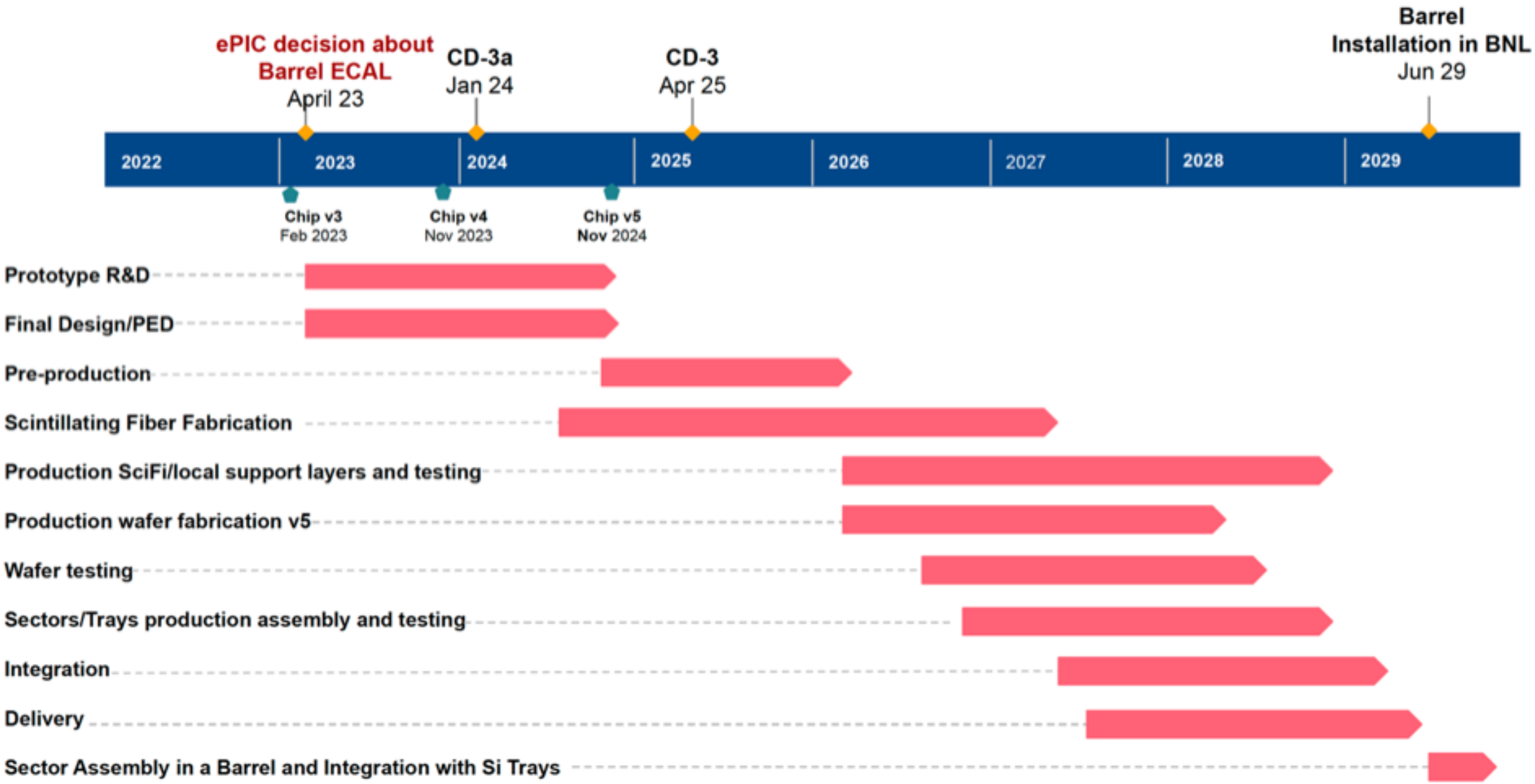
Germany

Karlsruhe Institute of Technology

University of Giessen

ePIC BIC Detector Subsystem Collaboration

Roadmap of BIC Construction



Summary

- Dual-Readout Calorimeter R&D project for future e^+e^- collider in Korea is very active
  - All aspects of the DRC detector R&D have been done
  - Innovative R&D approaches for HW systems such as copper forming, electronics readout, DAQ
  - Wide contribution to next generation of SW framework development under global organization
  - Various performance studies using GEANT4 simulation
  - Training next generation of calorimeter experts
- Expand our activities to barrel ECAL construction for Electron-Ion Collider project (BNL)

TB dinner at Les Armures Geneva (24.8)