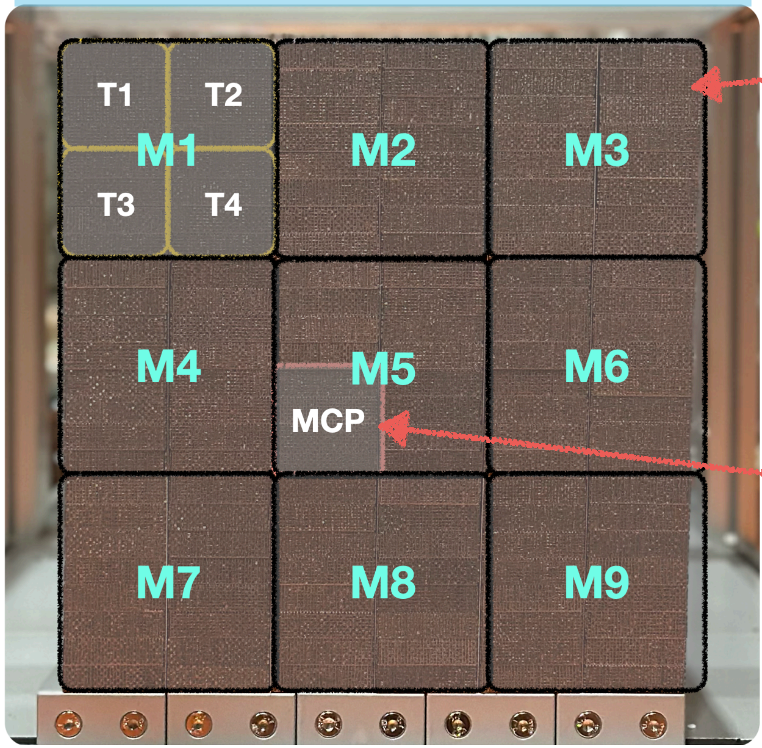
Readout R&D

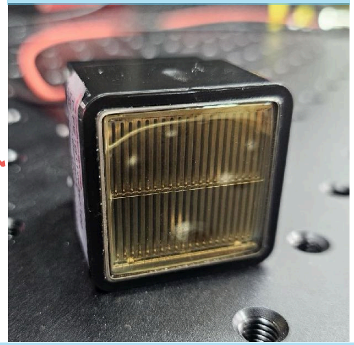
- Readout detectors
  - **Usual** towers: **PMT** for each S and C fiber type
    - 35 towers × 2 fiber type = 70 channels
  - **M5T3**: high-granularity **MCP-PMT** -> 8 fibers / channel (64 channels per fiber type)
    - (64 channels + 1 sum channel) × 2 fiber type = 130 channels
  - Total 70 + 130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

Naming convention for each module & tower

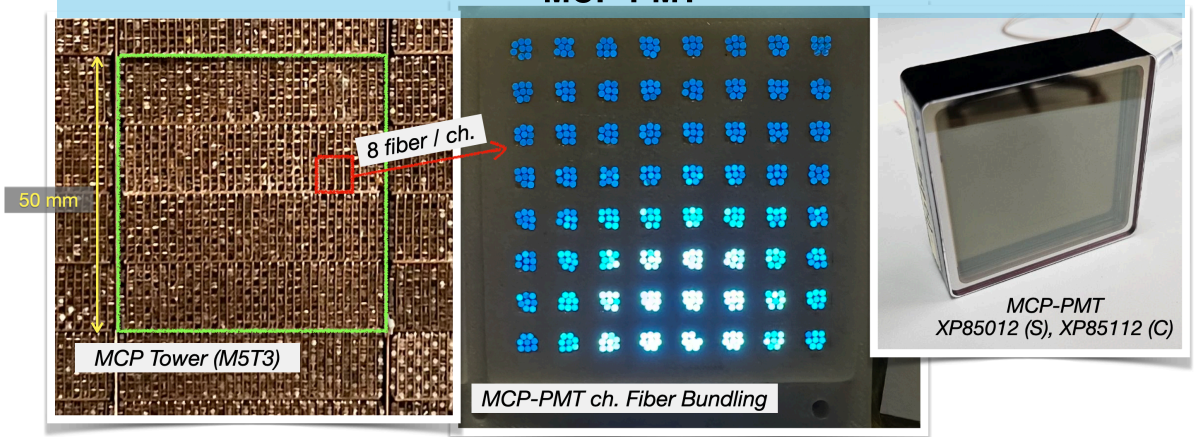


(all towers except for M5T3)

PMT (R11265-100)



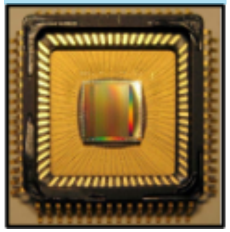
MCP-PMT

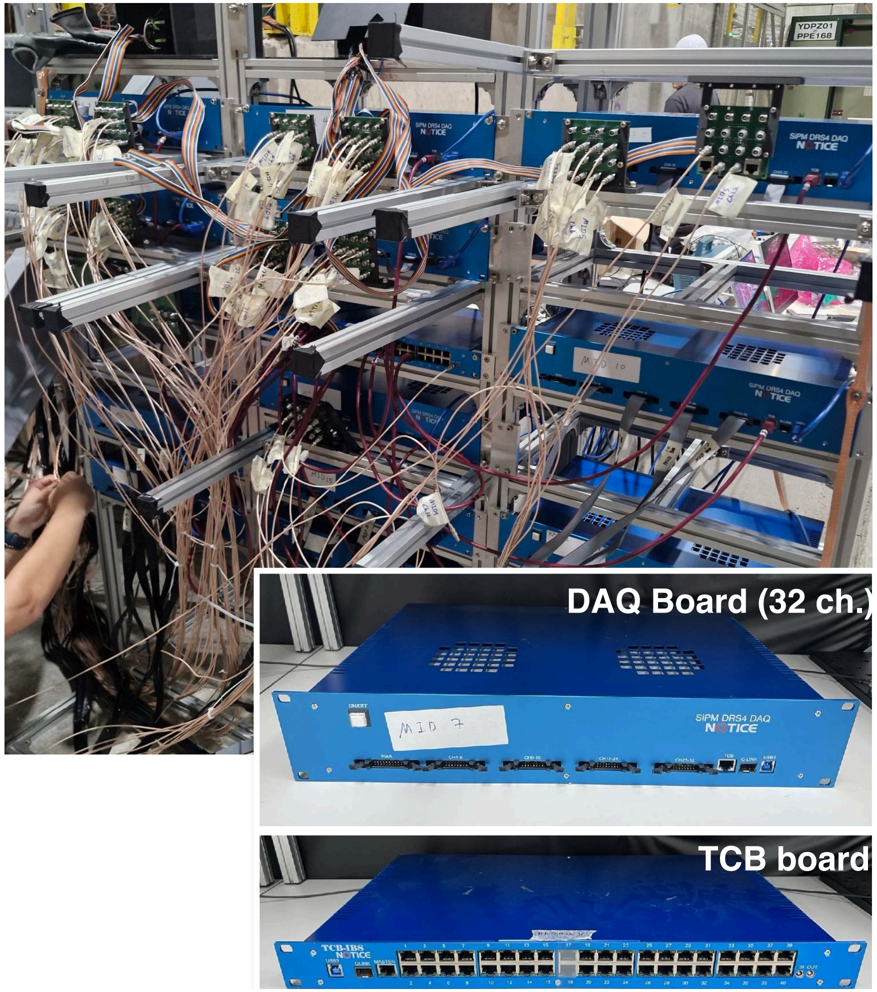


DAQ R&D

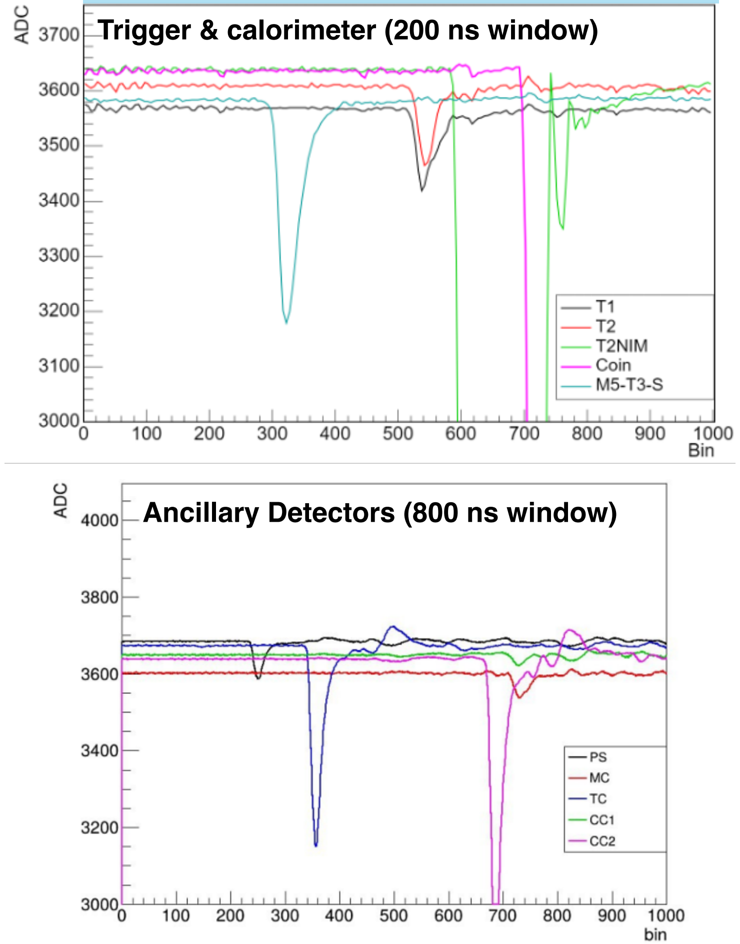
- DAQ system
  - **Customized** DAQ system based on **DRS4** chip
    -> fast sampling rate (5GS/s) & excellent timing resolution
  - Total 13 DAQ boards (32 channels / board) and 1 TCB board

DRS4 chip





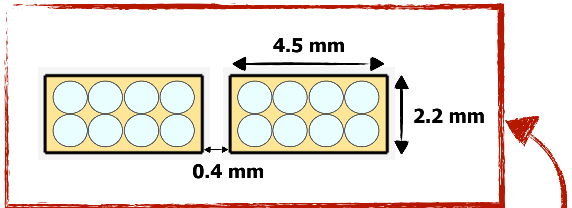
Typical detector signals from DAQ



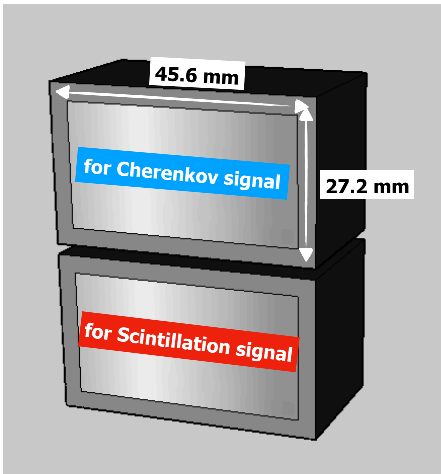
Customized MCP-PMT R&D

- 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)

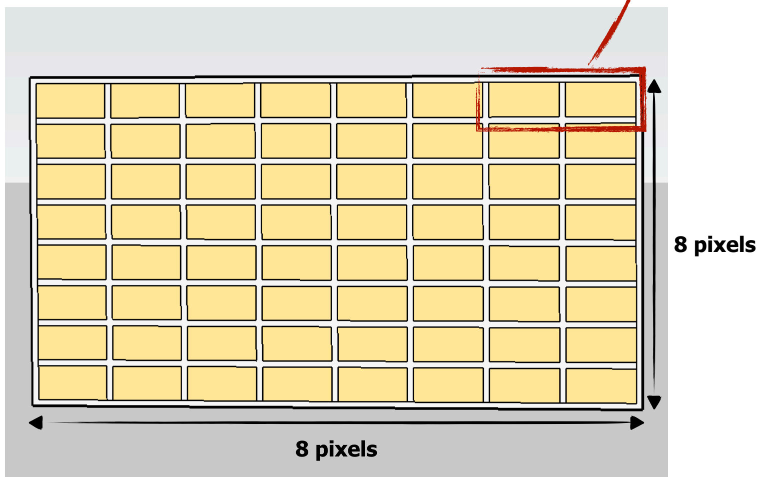
Photonis



- MCP-PMT Fabrication Facility @ANL -



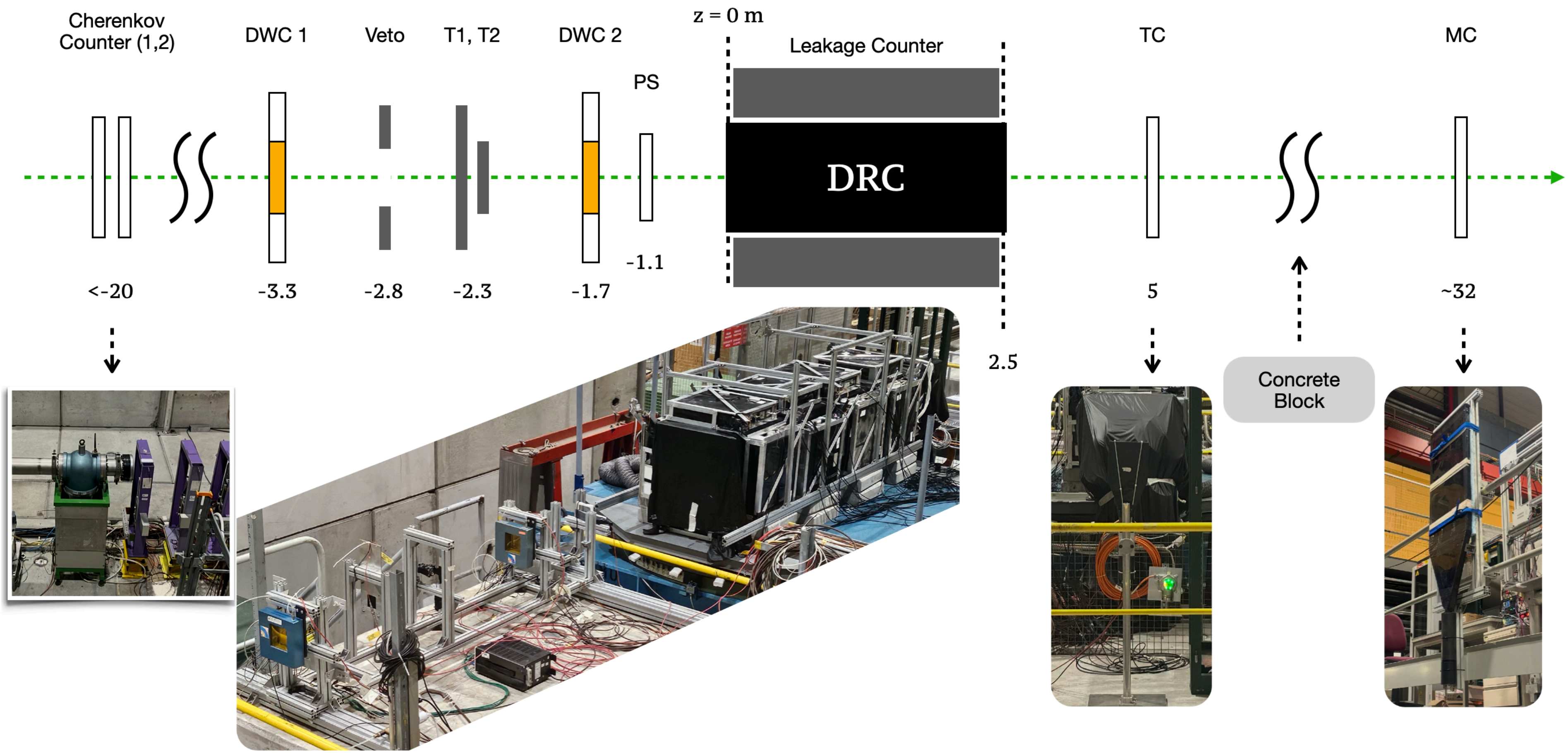
- Front side of two MCP-PMTs -



- Pixel array (ceramic pad) -

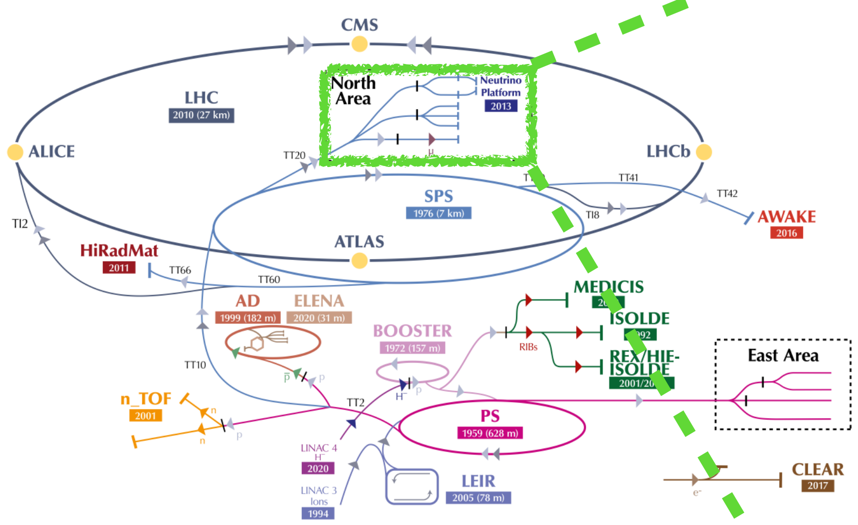
Test-beam Experiments at CERN

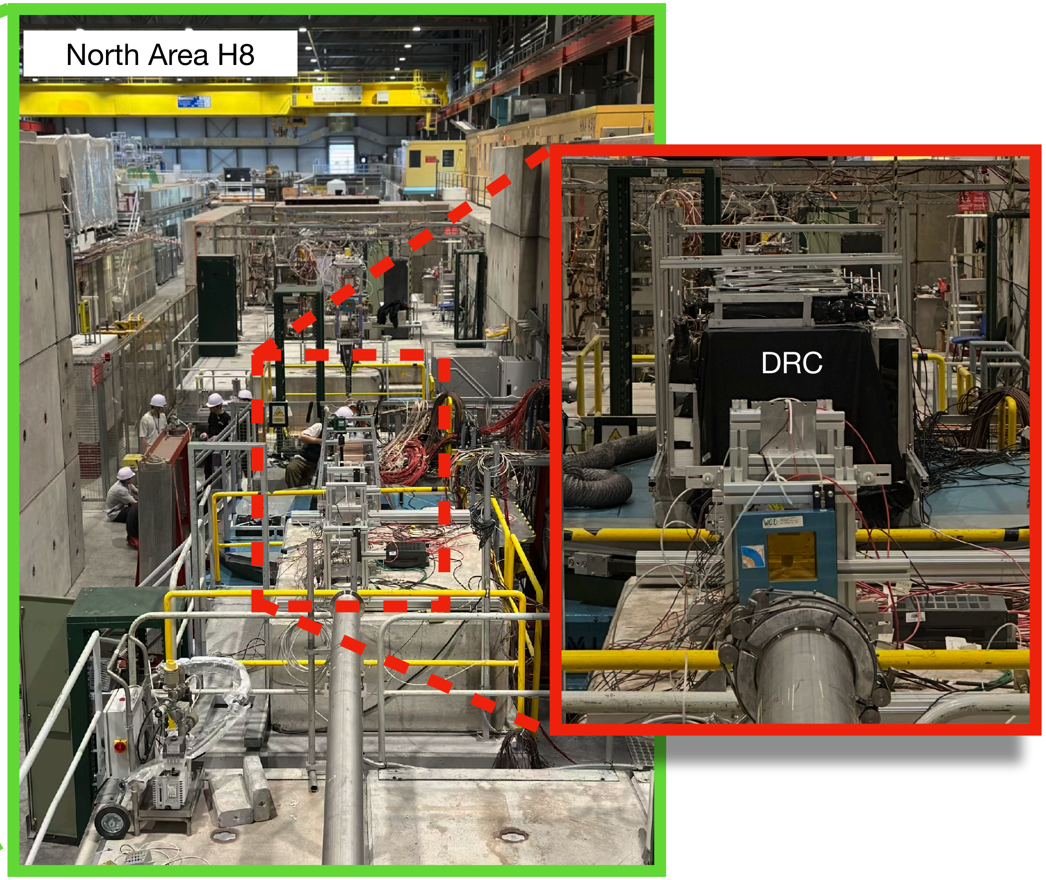
- Experimental setups for 2022, 2024, 2025, and 2026



North Area (SPS H8)

Experimental Hall: CERN SPS H8



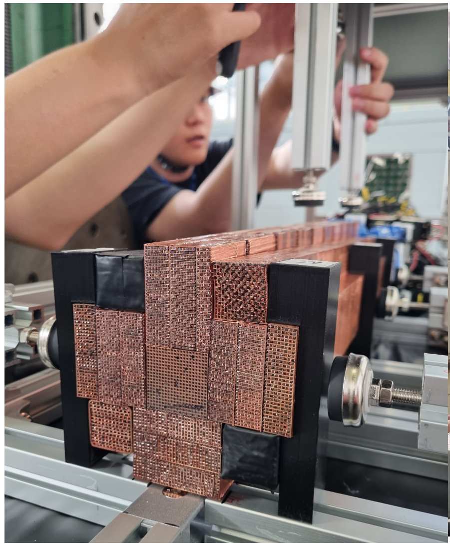


EM : 10 ~ 120 GeV

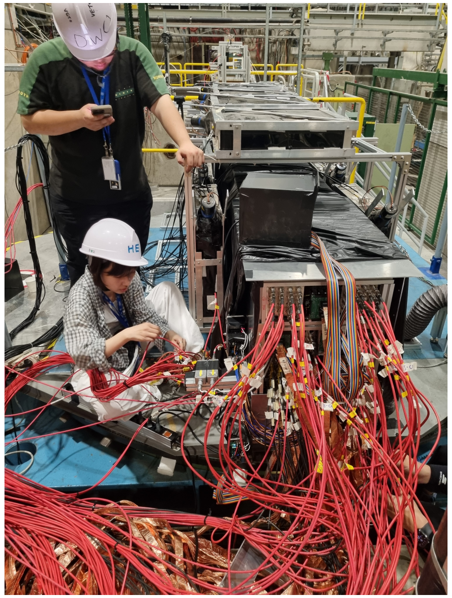
Hadron : 20 ~ 120 GeV

Experimental Setups

TB 2023



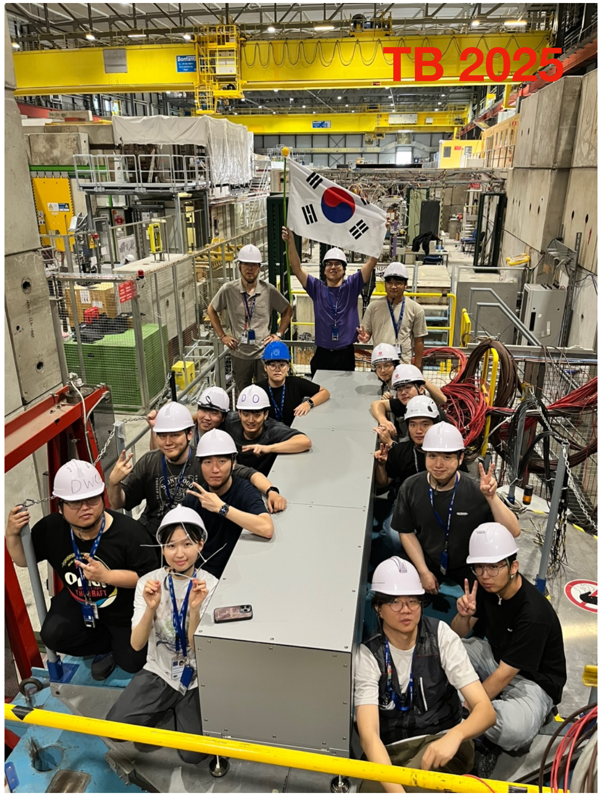
TB 2024



Team-Korea for Future Collider

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

- Training next generation is one of the most important mission



Test-beam Dinners

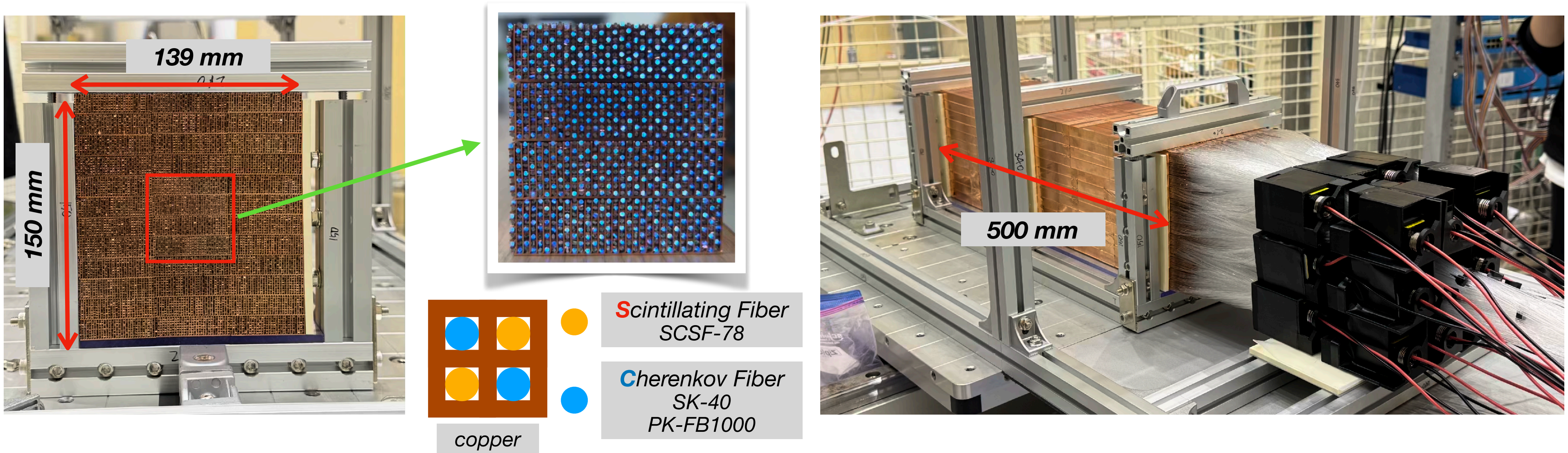
at Les Armures Restaurant, Geneva

Test-beam Campaigns (2022 - 2026)

	Date	Duration (week)	Facility	e Energy (GeV)	Detector Type	Module Size (cm3)	Weight (kg)
CERN	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	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

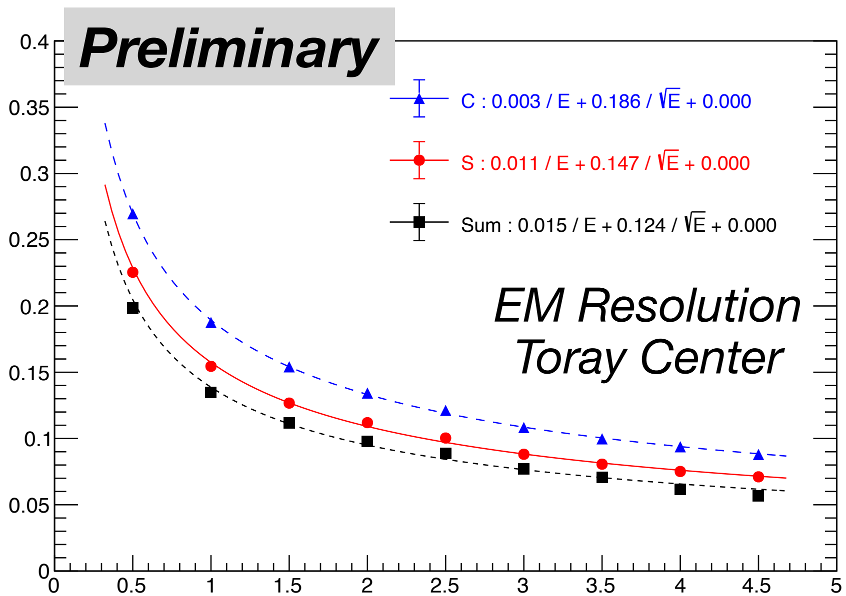
TB Experiments at KEK

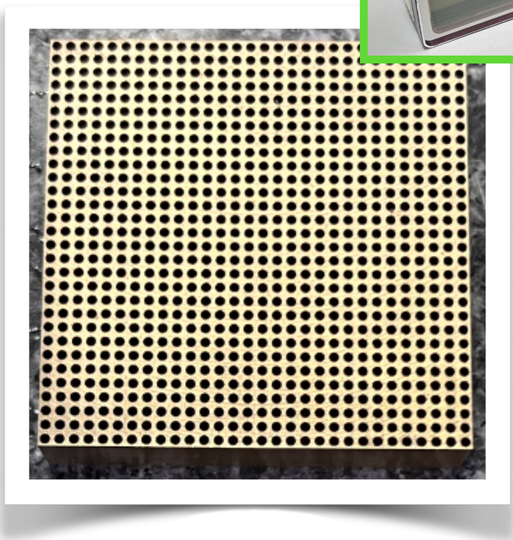
- Compare DRC modules with different configuration in all aspects
  - Fiber model, absorber forming method, readout system
- First TB on November 2025 for DRC
  - Measured & compared performances of two modules consist of different model of optical fibers - both SFHS modules
  - Validated & confirmed response of DRC on energy resolution, angular dependence, and uniformity with low energy electrons (< 5 GeV)

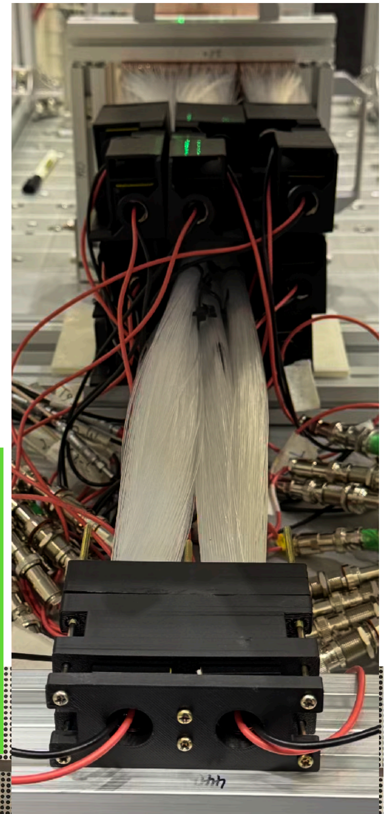


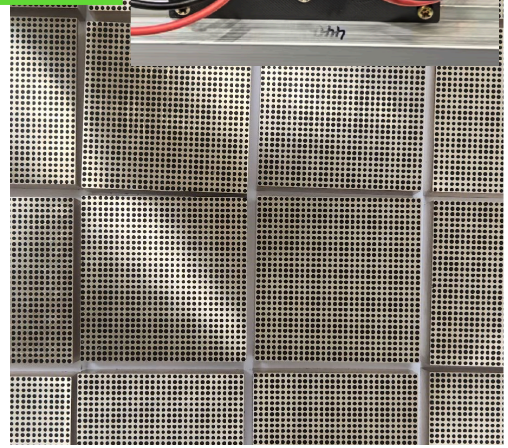
TB Experiments at KEK

- Data analysis on-going between different model of Cherenkov fibers - similar performance found
- Future TB plan
    - Absorber forming method: test drilling-method module (brass)
    - Readout system: test high-granularity module with (customized) MCP-PMT and SiPM
    - Next TB: May 22 - 25









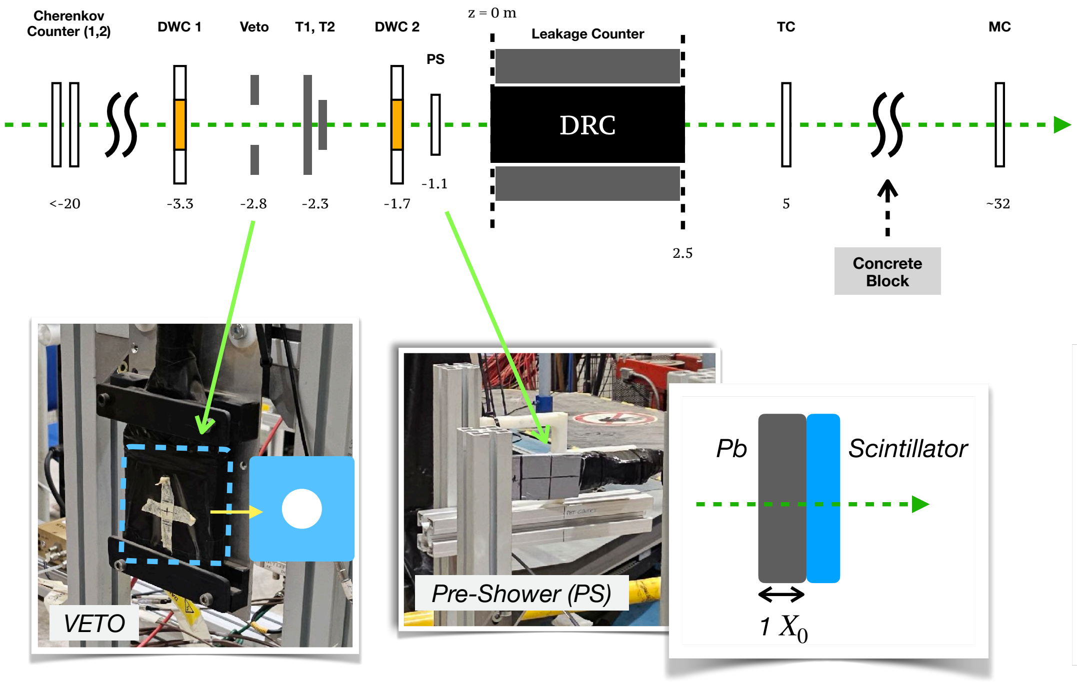
Physics Programs for TBs

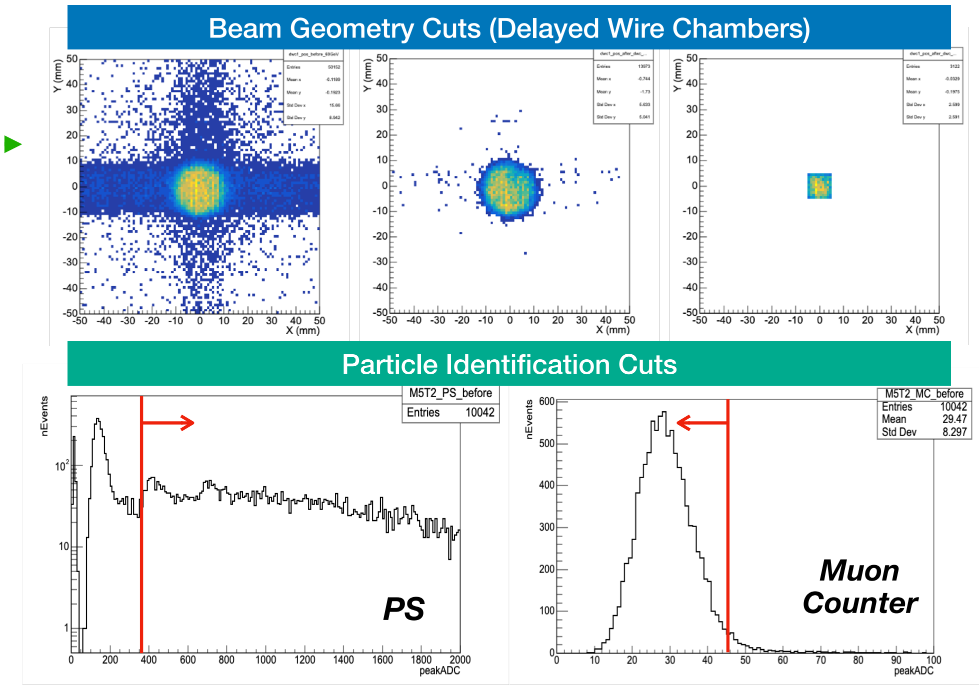
- EM performance: EM response - linearity & resolution
- Uniformity scan (EM)
- Hadron performance: hadron response - linearity, resolution, and features (π^+, p, jet-like)
- Time performance: time resolution
- High granularity test: position resolution

EM Performance

- Particle identification & cuts

- Ancillary detectors were exploited to select pure position and hadron beams





Hadron Reject

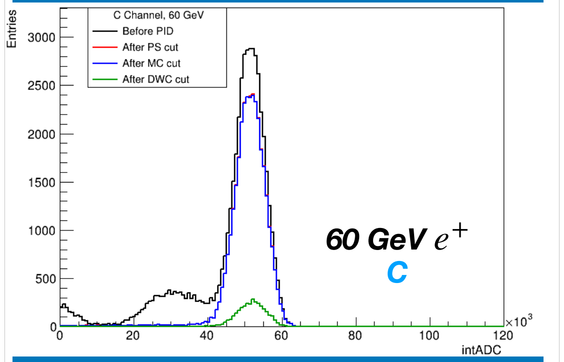
Muon Reject

EM Performance

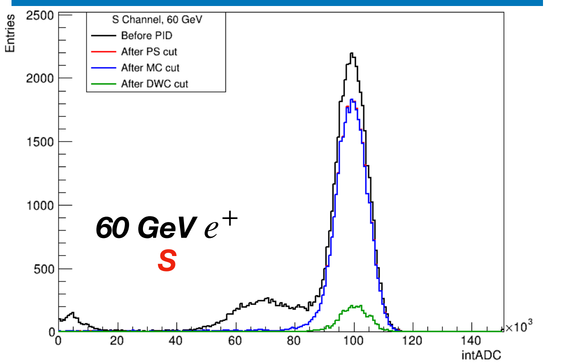
- Particle identification & cuts

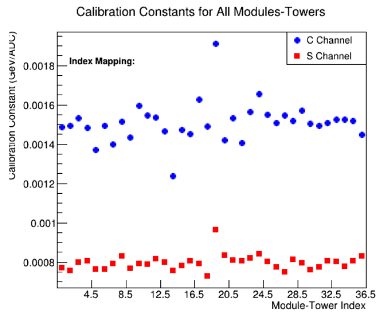
- Ancillary detectors were exploited to select pure position and hadron beams

Distribution after Cuts - C

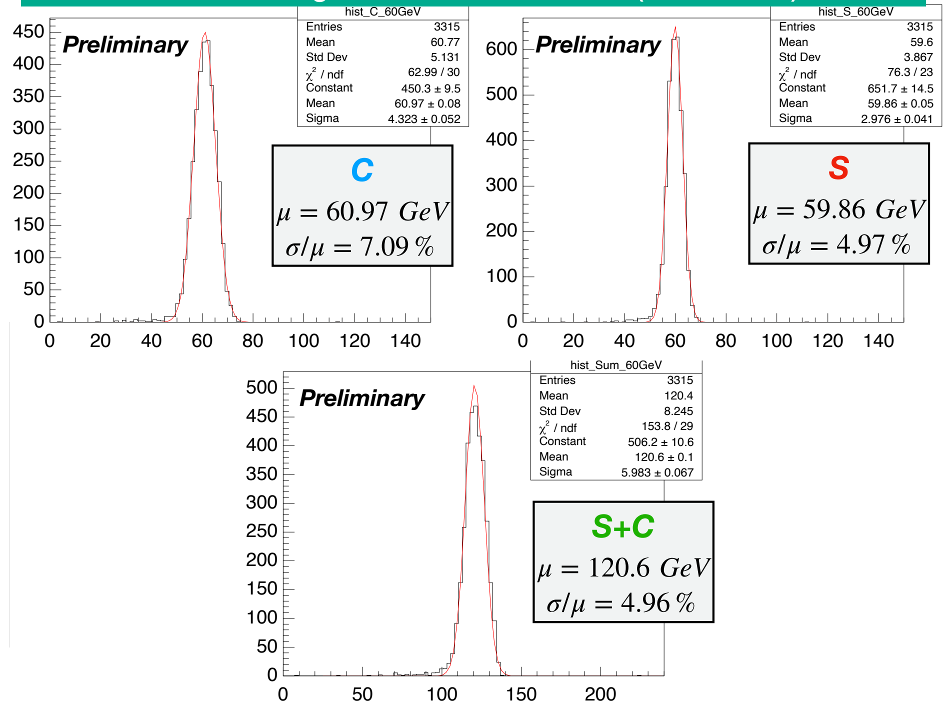


Distribution after Cuts - S





Calibrated Signal of 60 GeV e^+ events (Full Module)



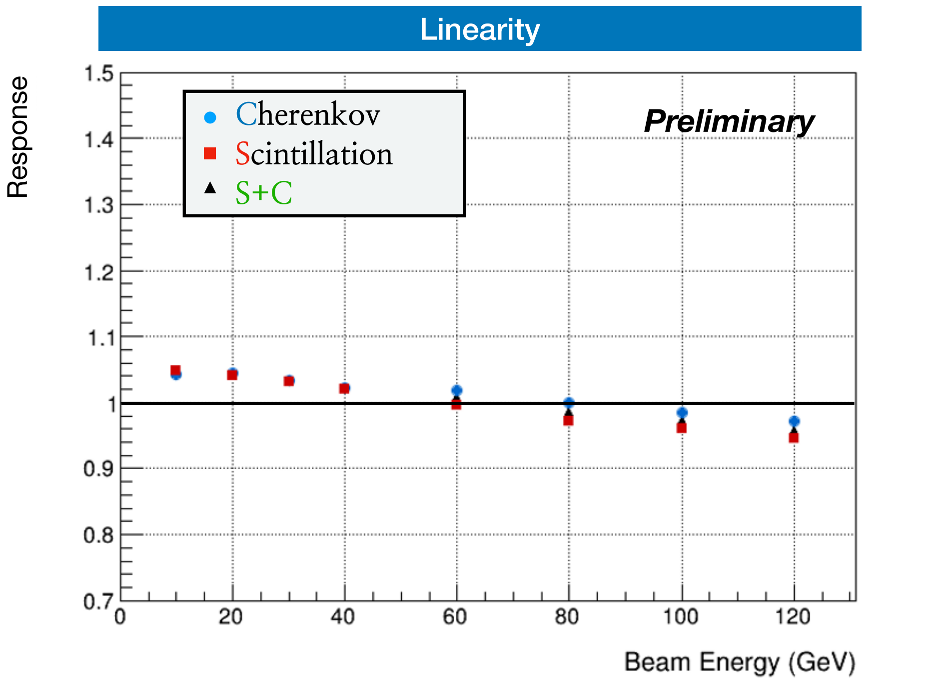
Well calibrated, clear *Gaussian distribution*

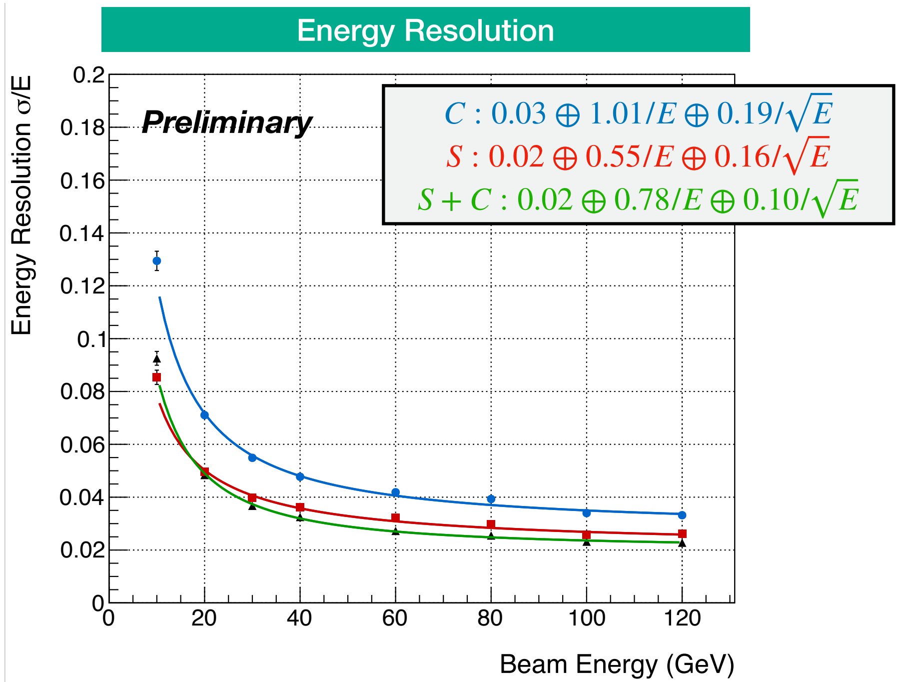
EM Performance

- EM linearity & resolution

~96 % EM deposit

3 x 3 Matrix Response





10, 20, 30, 40, 60, 80, 100, 120 GeV e^+

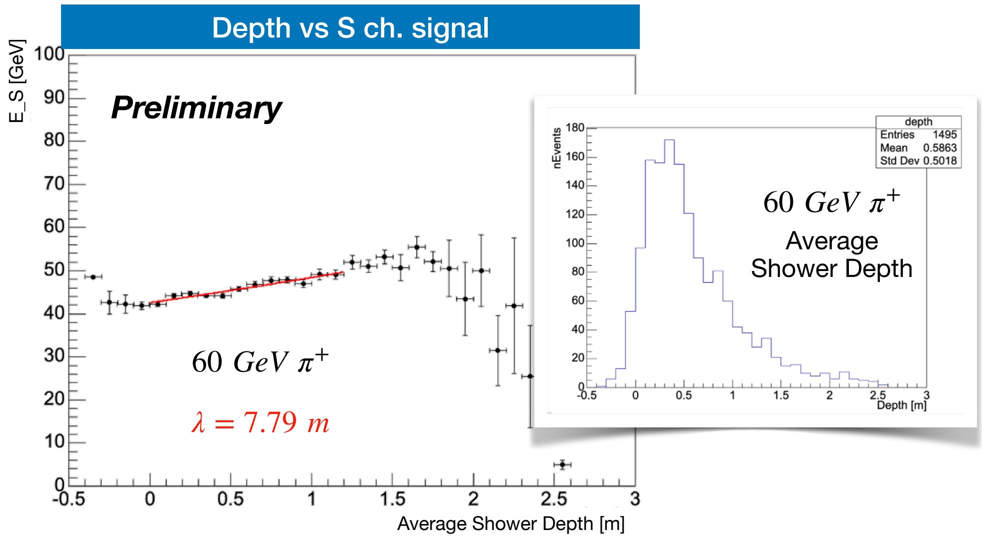
Hadron Performance

- Corrections applied

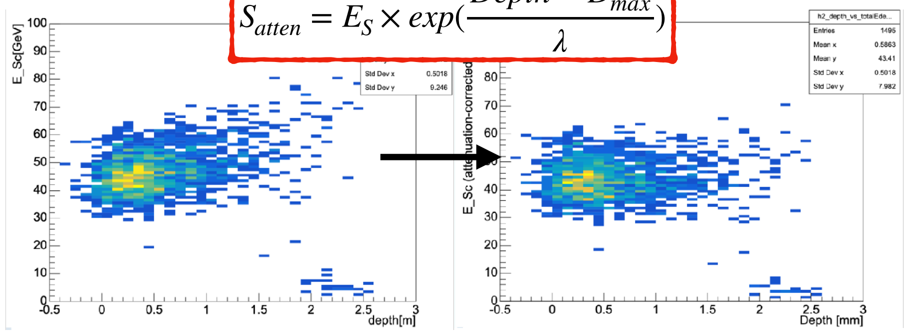
- For hadron signal, additional corrections are applied on Scintillation channel signal

Light Attenuation Correction

- The light attenuation length of scintillating fibers are not negligible compared to our calorimeter geometry.
- By calculating average depth of showers, **measured attenuation length** with π^+ events and **applied attenuation correction on S channel.**



$$S_{atten} = E_S \times exp(\frac{Depth - D_{max}}{\lambda})$$



Before Correction After Correction

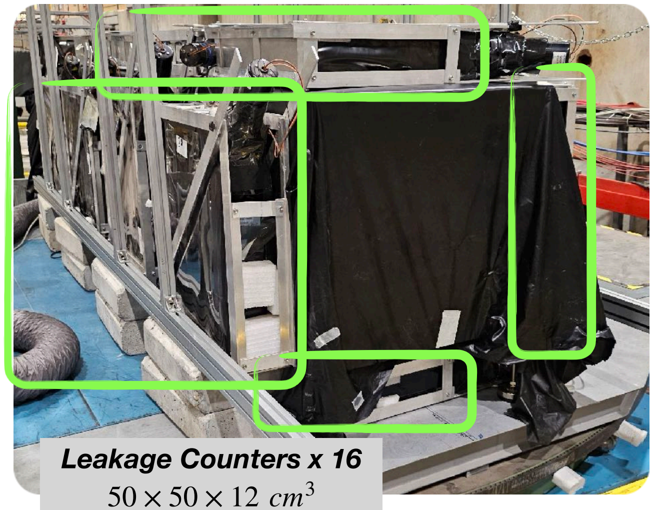
Hadron Performance

- Corrections applied

- For hadron signal, additional corrections are applied on Scintillation channel signal

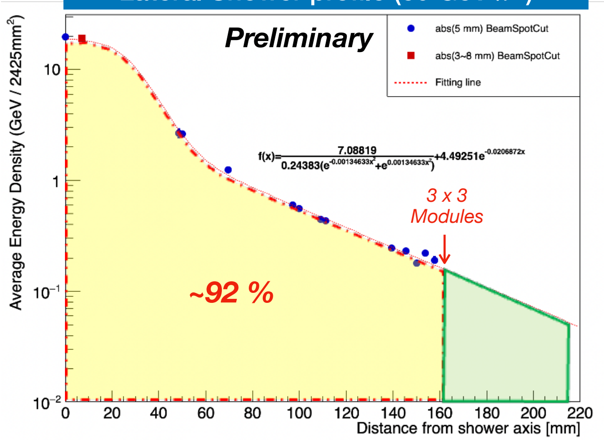
Lateral Leakage Counter Correction

- The calorimeter geometry is not large enough to contain full hadron shower on lateral direction.
- Placed leakage counters (plastic scintillator) around the calorimeter, measured and **corrected lateral leakage on S channel**.



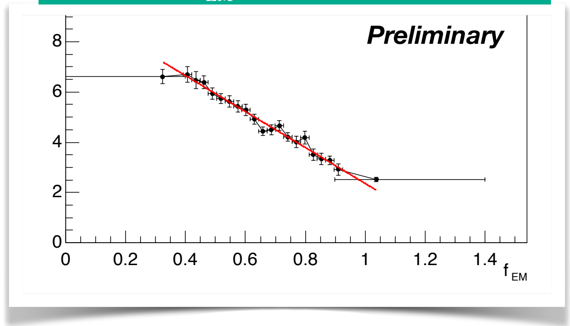
Leakage Counters x 16
$50 \times 50 \times 12\ cm^3$
Plastic Scintillator

Lateral Shower profile (60 GeV π^+)



$$S_{LCcorr} = E_S + E_{LC}$$

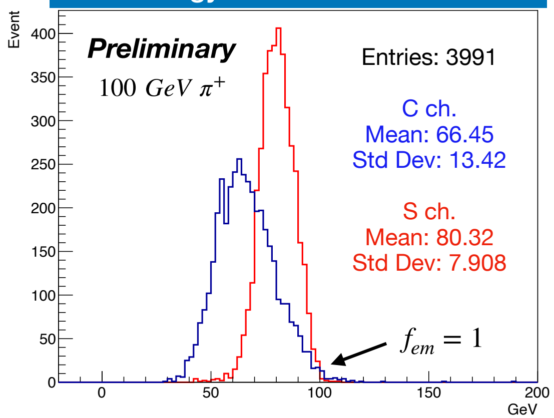
f_{EM} vs LC signal



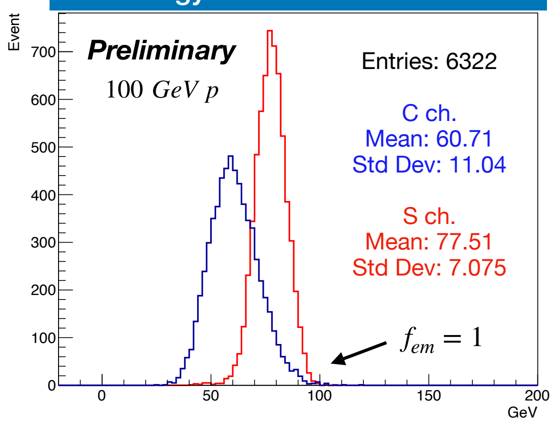
Hadron Performance

- Energy distributions

Energy Distribution - Pion

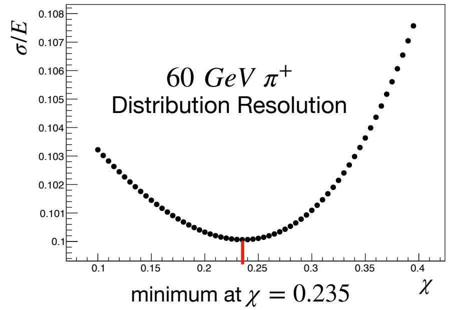


Energy Distribution - Proton

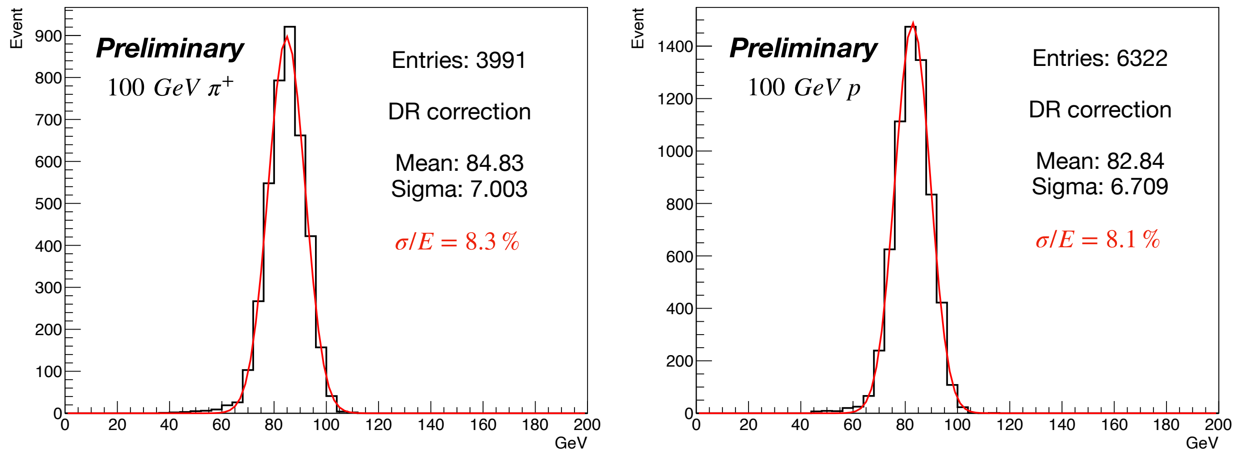


Selected $\chi = 0.235$ to apply DR method, which gives best resolution on scanning χ value

$$E_{DR} = \frac{S - \chi C}{1 - \chi}$$



Dual-Readout Corrected Energy Distribution



Shows clear Gaussian distribution regardless of particle type

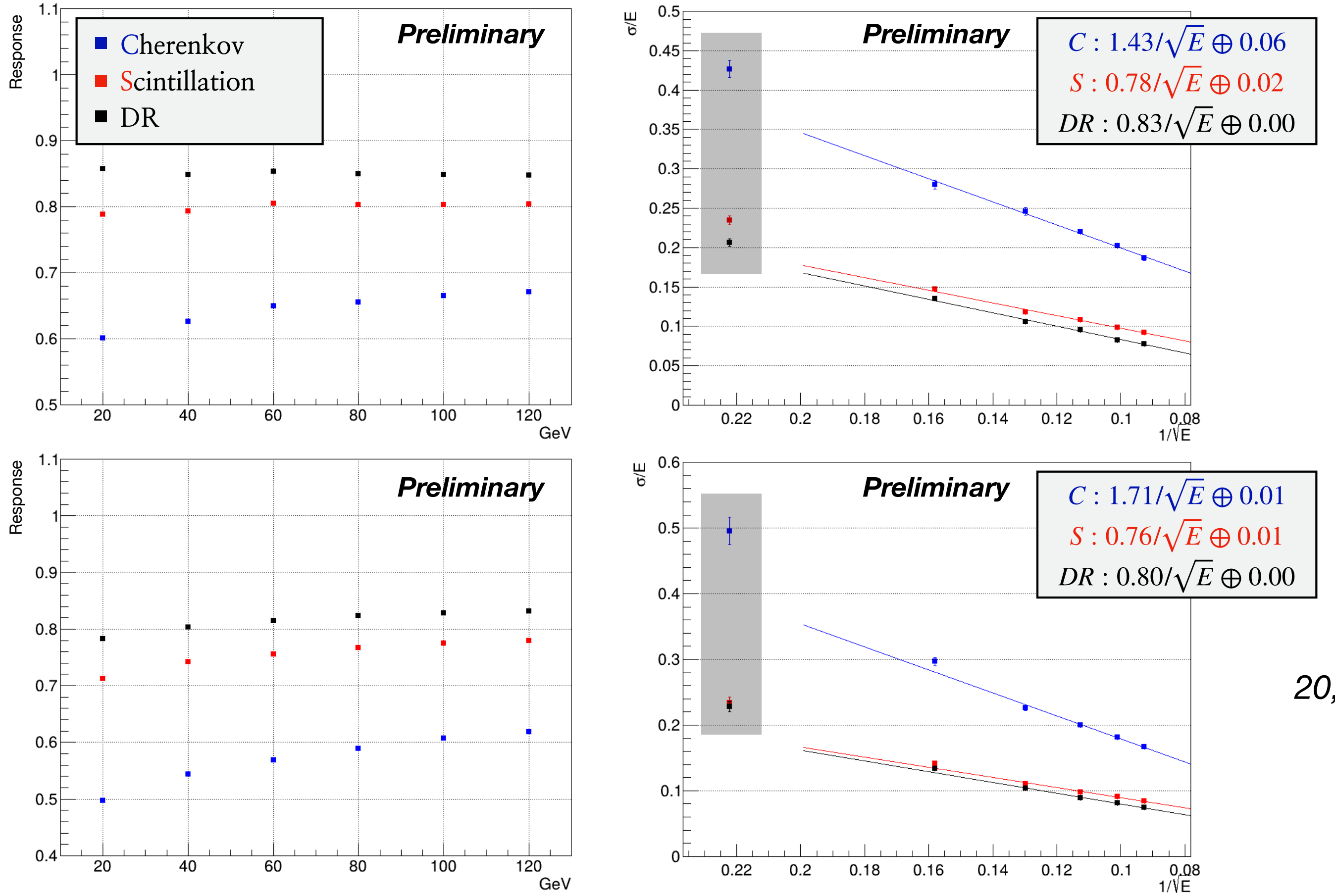
Hadron Performance

- Hadron energy linearity & resolution

π^+

p

Linearity | Energy Resolution



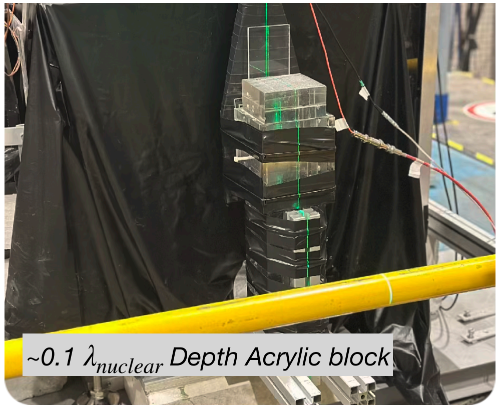
Full Module Response

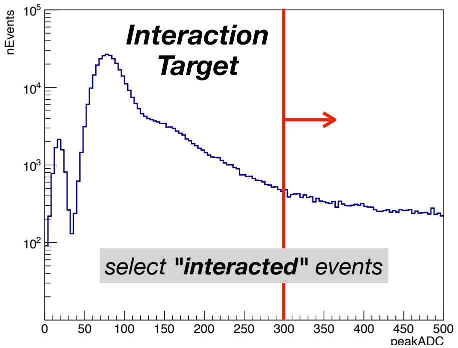
20, 40, 60, 80, 100 and 120 GeV
π^+, p

Hadron Performance

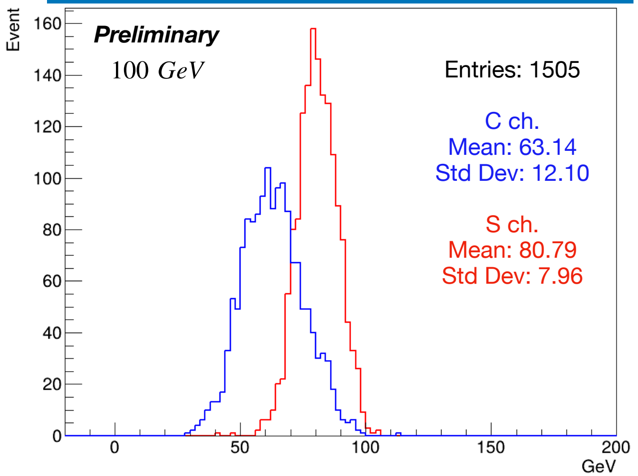
- Jet mimic events

Acrylic block (~0.1 λ_{int}) right front of the calorimeter,
jet-like events were selected by requiring that hadrons interact with the acrylic block (10%)

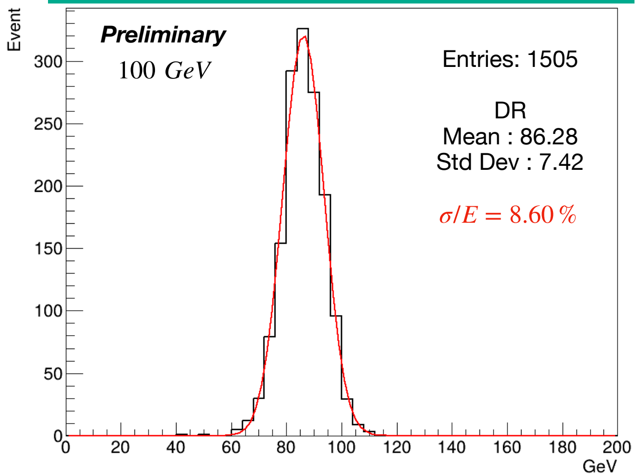




Energy Distribution - Jet-like events



Dual-Readout Corrected Distribution

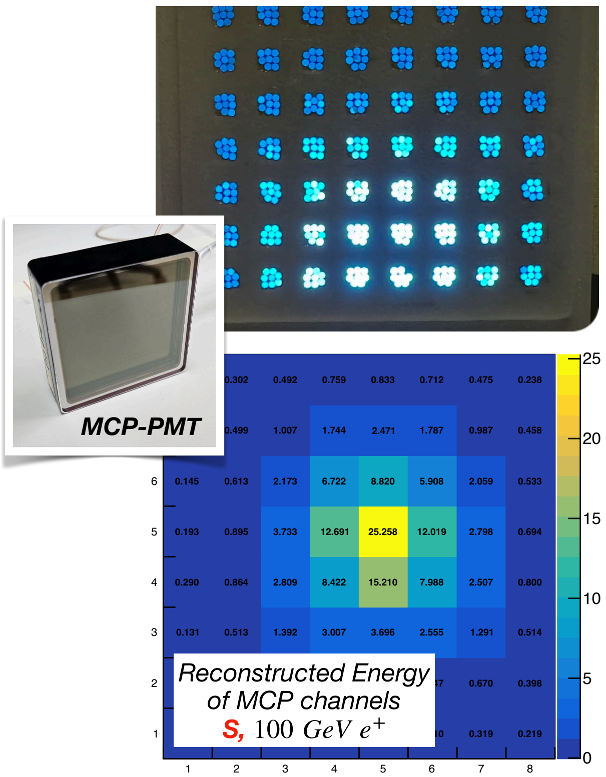


Apply DR method with $\chi = 0.235$

High Granularity

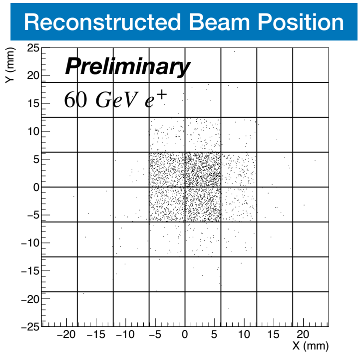
- Position resolution

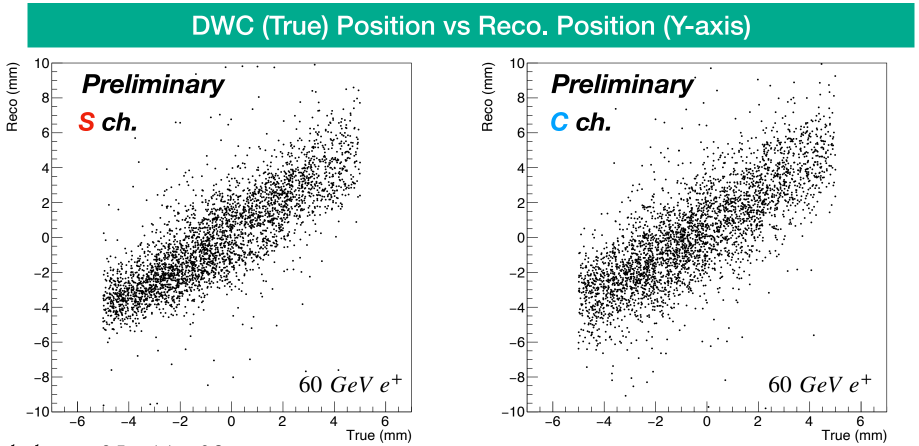
8x8x2, 128 ch.



High Granularity

- Tested High Granularity with MCP-PMT placed at center tower of calorimeter.
- With e^+, using **center-of-gravity method** weighted by energy, reconstructed initial **beam position**.
- Assuming the position measured with DWC is "true" position, measured difference between the DWC and reconstructed position - *sigma as position resolution*

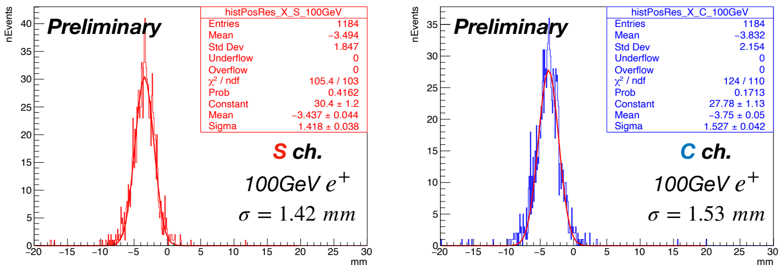




High Granularity

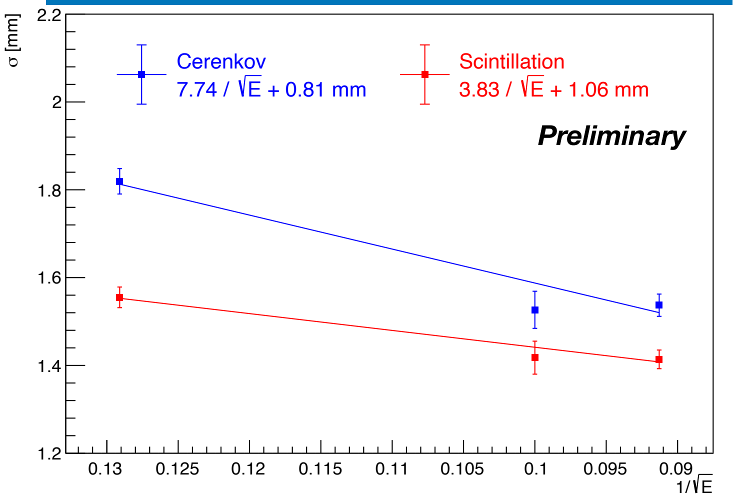
- Position resolution

Reconstructed Position Distribution

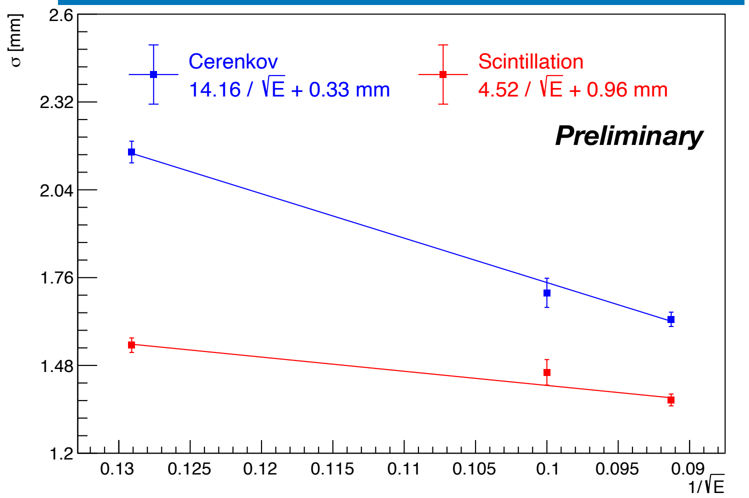


- Measured position resolution for 60, 100, and 120 GeV e^+
- Achieved a resolution of ***~1.5 mm at 100 GeV*** e^+
- Position resolution shows **energy dependence** - improves at high energy

X-axis Position Resolution

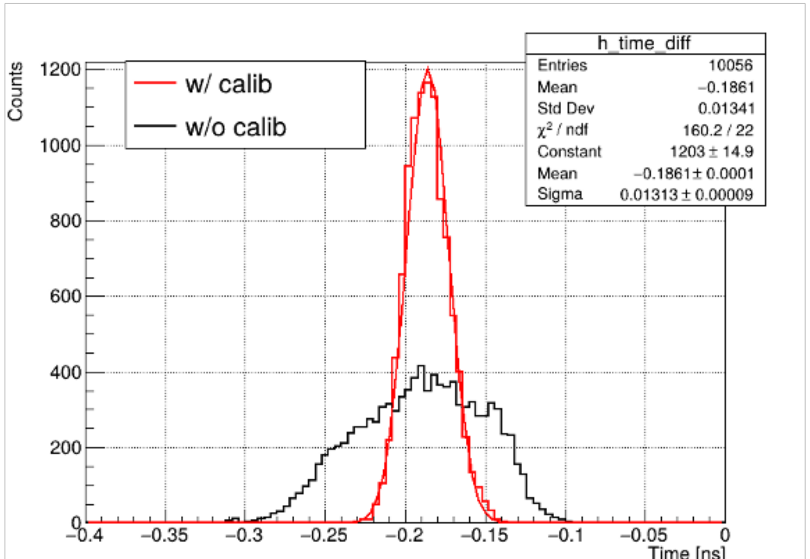


Y-axis Position Resolution

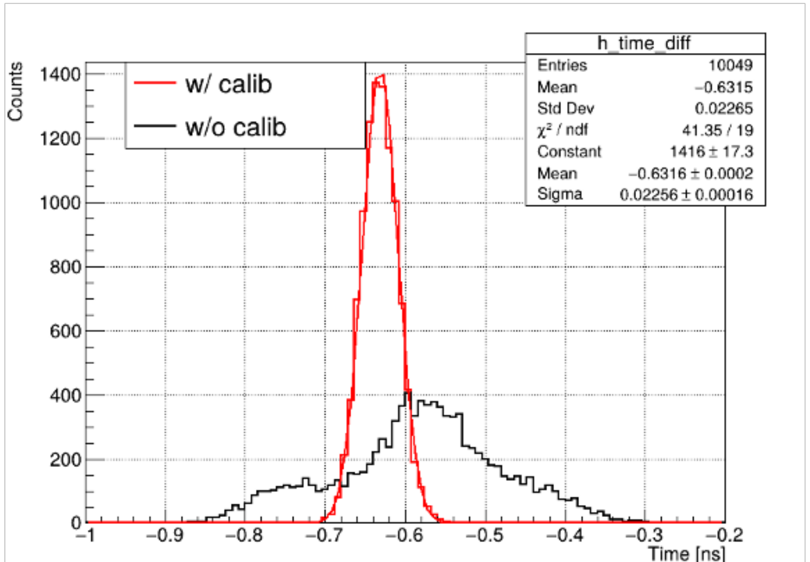


Time Resolution

- DRS4: one of Switched Capacitor Array (SCA)
    - Because of **non-uniform time interval** between each array, the time calibration is required.
    - Time calibration : **measure the time interval** between each array and adjust the measured time interval in waveform. (link)
- **Timing resolution** : The standard deviation of the measured time difference between two channels
- After time calibration, timing resolution of our customized DAQ system is **13 ps** in single DRS4 chip & **23 ps** in multi DRS4 chip



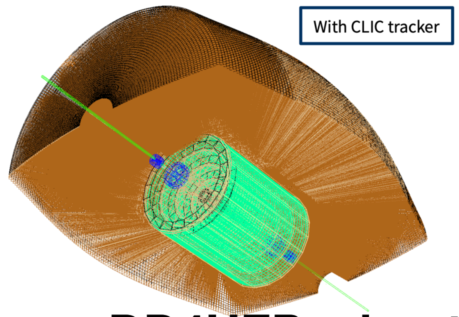
Single DRS4



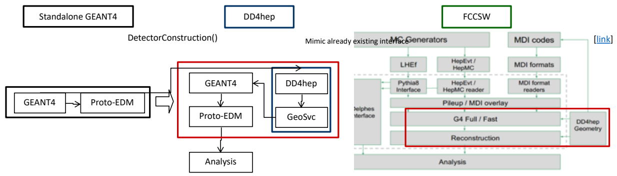
Multi DRS4

Simulation/SW Framework

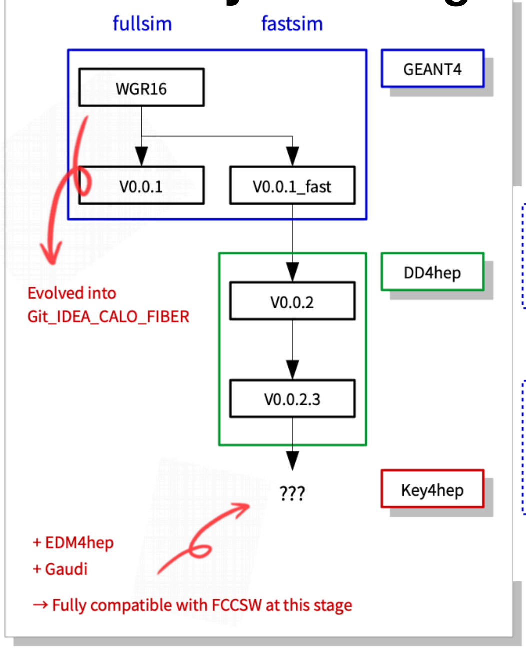
- Contribute on many centralized SW developments
  - Migration to DD4HEP framework
  - Faster simulation: developing optical photon transport in GEANT4 => O(100) times faster
  - Migration to Key4HEP framework
    - Add digitization, reconstruction, calibration, etc.



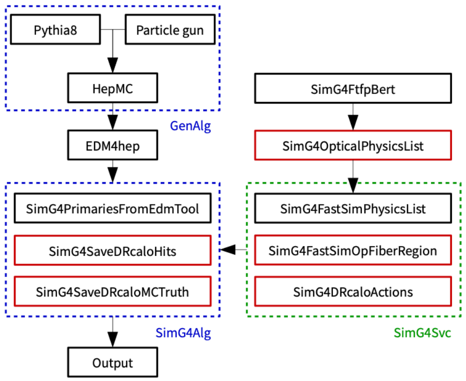
DD4HEP migration



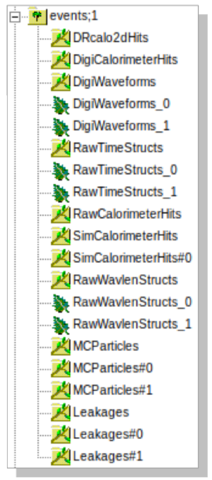
Key4HEP migration



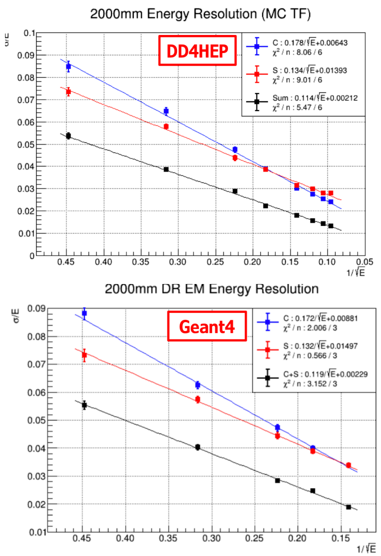
Simulation flow

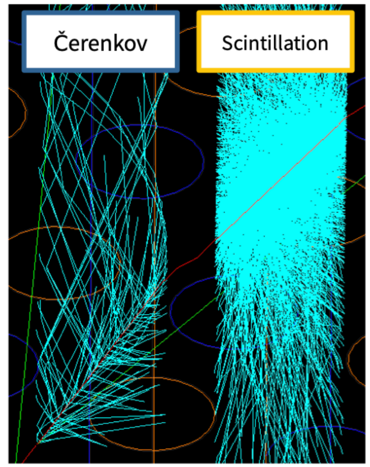


EDM4hep



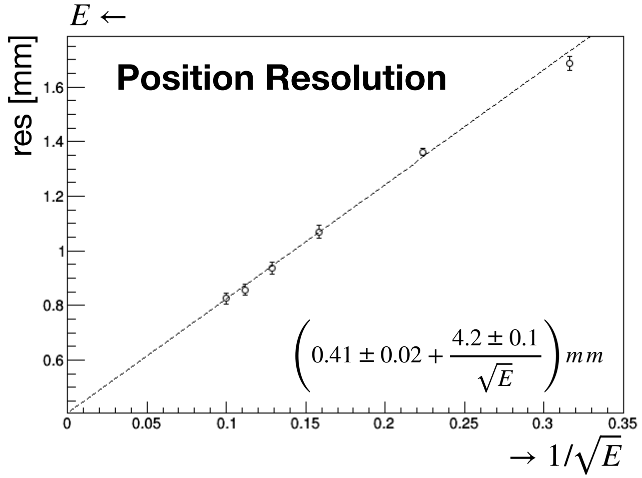
Faster simulation

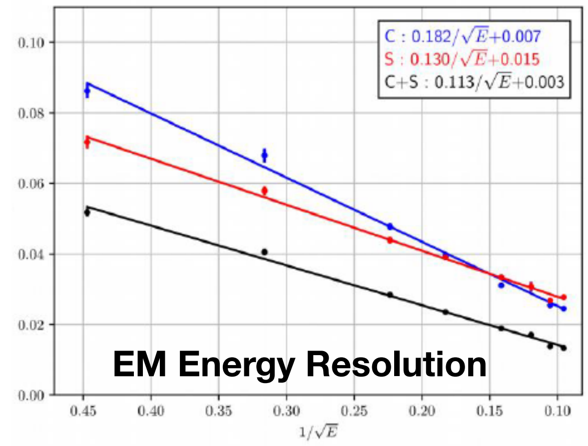


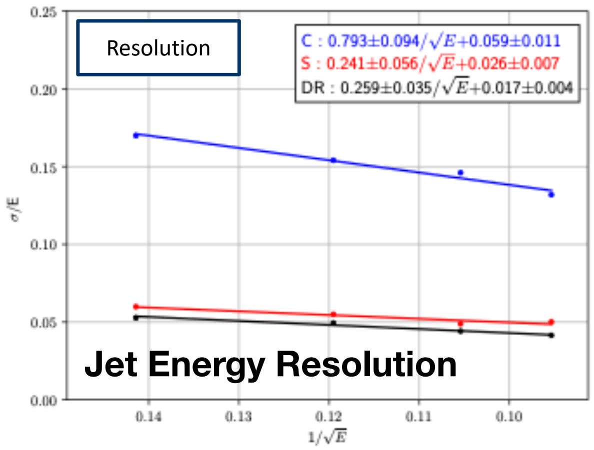


Important for a longitudinally unsegmented calorimeter

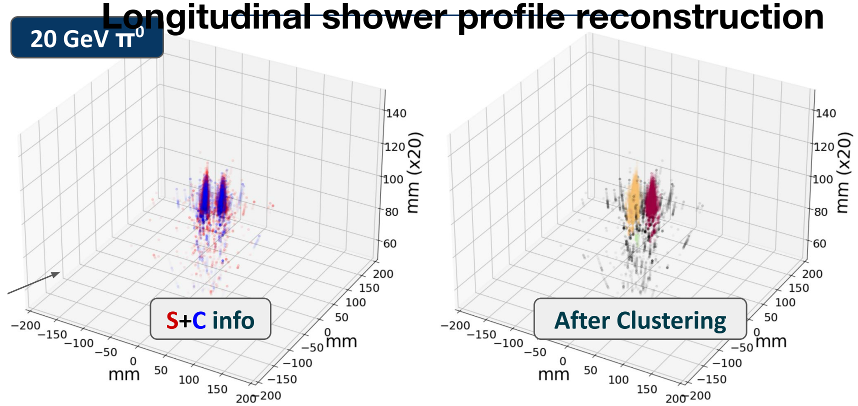
Performance Studies (Simulation)

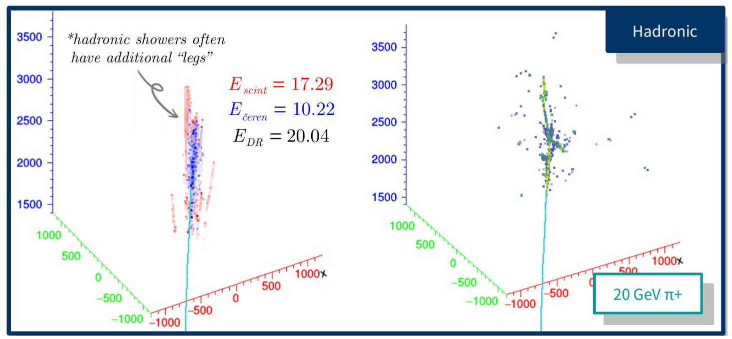


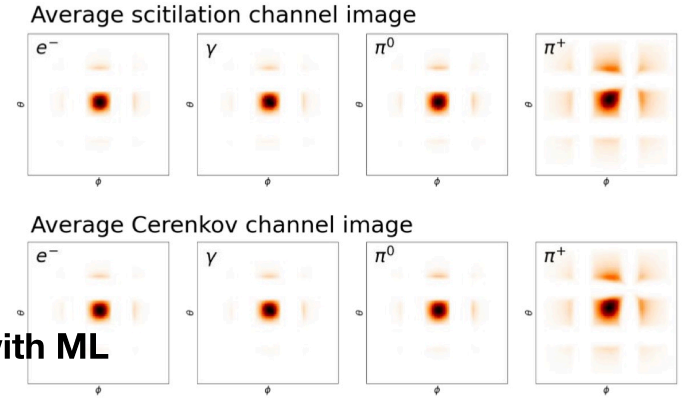




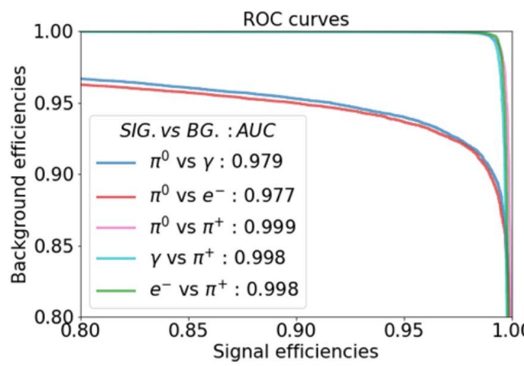
Longitudinal shower profile reconstruction

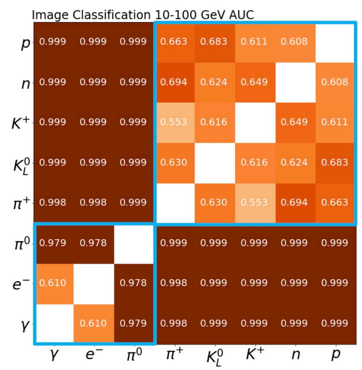






Particle IDs with ML

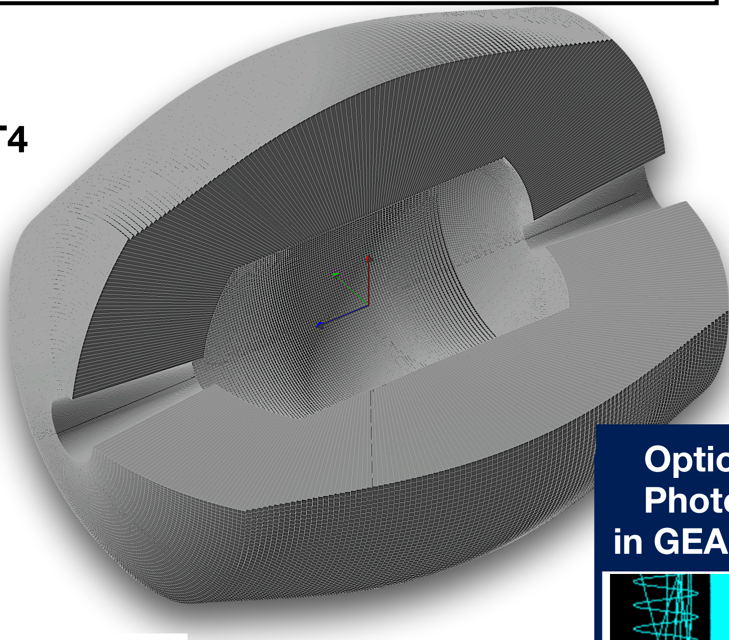


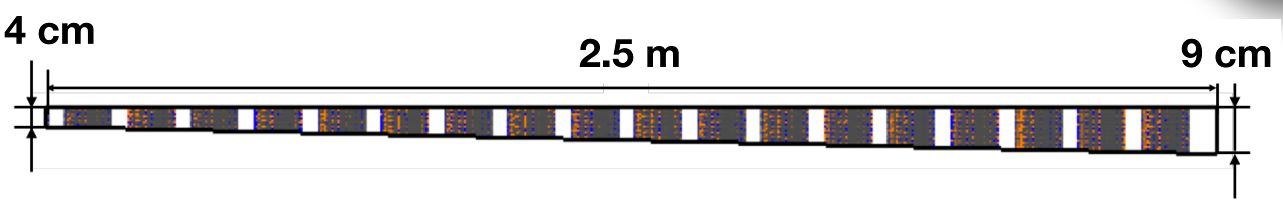


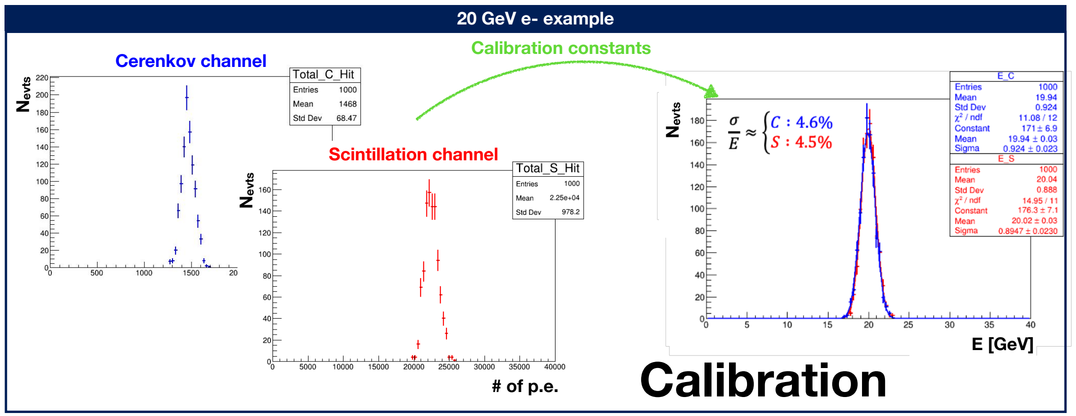
Simulation: 4pi Geometry

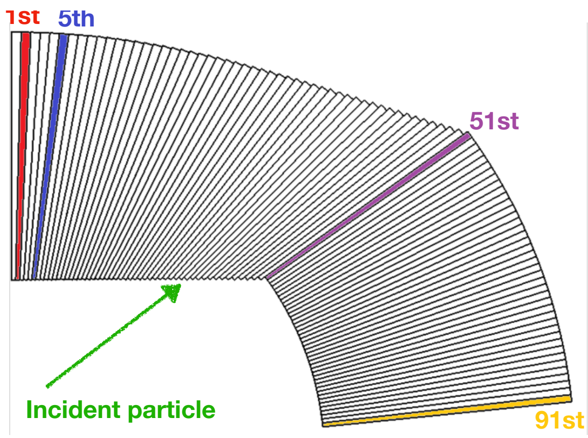
◉ Detector geometry in the GEANT4 simulation

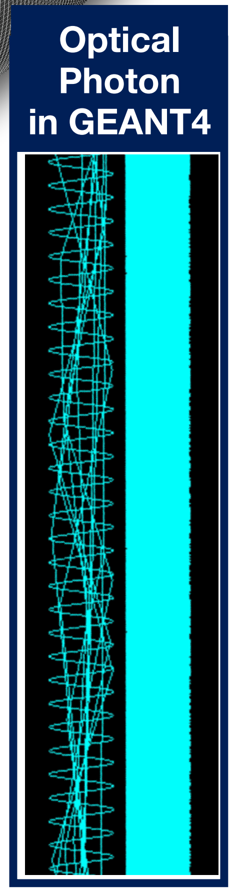
- **4pi full projective DRC** implemented in the **GEANT4**
  - composed with **~ 52000 individual towers**
- **Each tower has 2.5 m length**
  - which corresponds to
    ~ 10 nuclear interaction length
  - allowing us to get **~ 99% energy deposit**
    for EW window
  - **implemented by ~O(1000) fibers**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





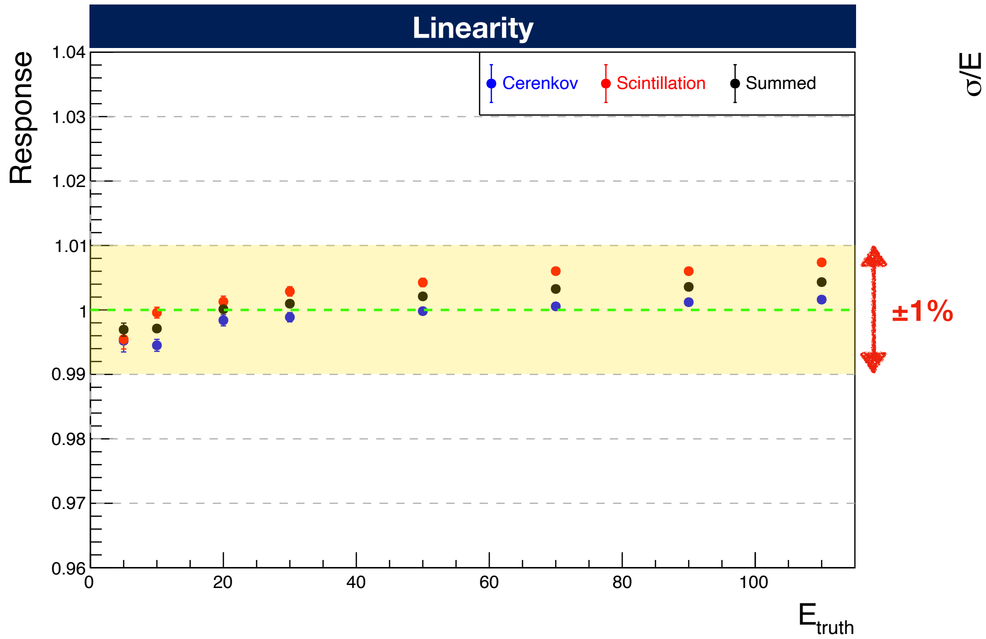


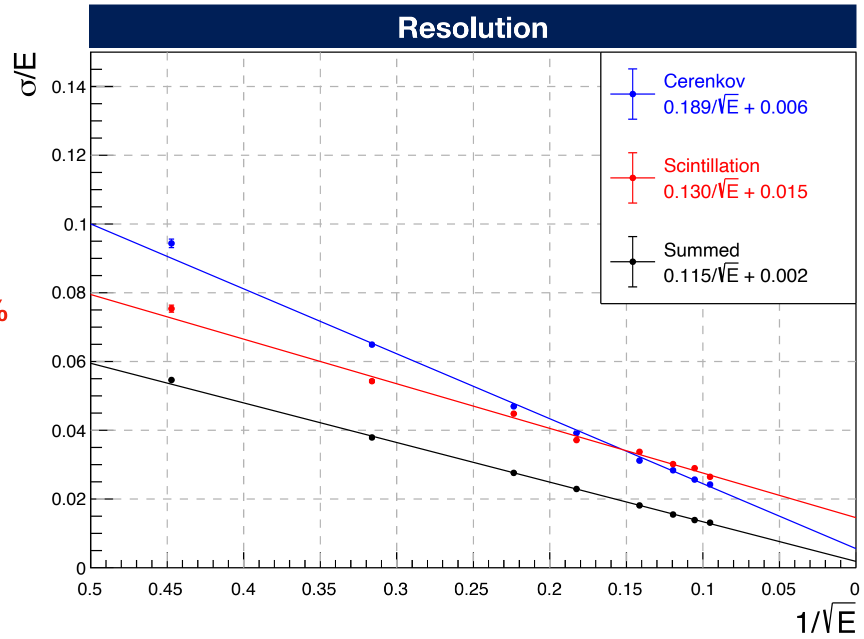




Simulation: 4pi Geometry

- **EM energy resolution with 5 ~ 110 GeV e^- simulation**
  - Resolution result for each energy is **scaled to 1 / √E**
  - **Linearity** is satisfied **within 1% level**
  - **Stochastic term** of the resolution is estimated **~11.5%**



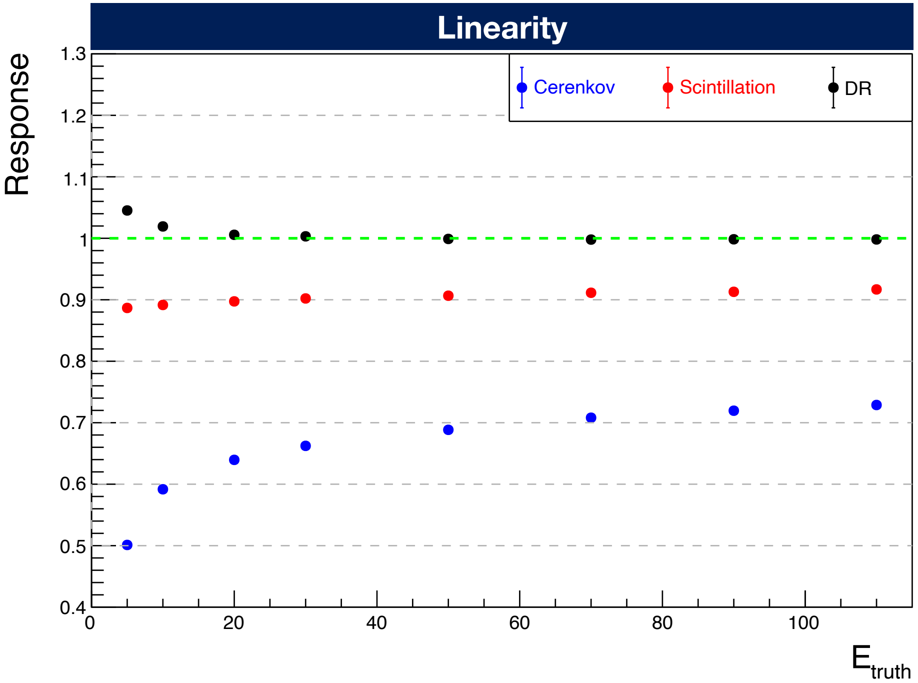


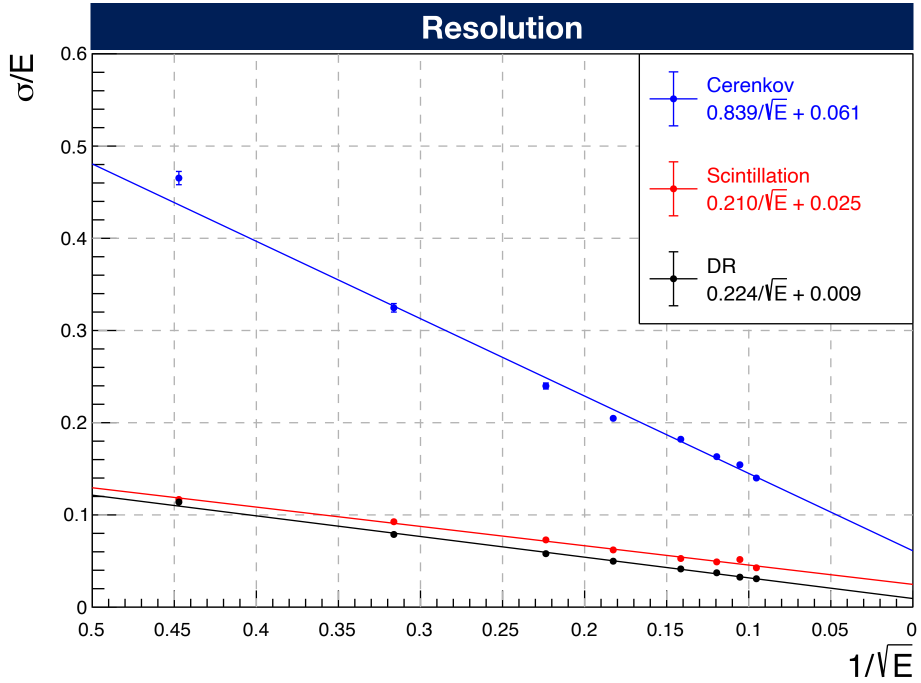
World the most and best precise simulation results!

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

Simulation: 4pi Geometry

- **Hadronic energy resolution with 5 ~ 110 GeV pi+ simulation**
  - Resolution result for each energy is **scaled to 1 / √E**
  - **Attenuation correction** is applied to scintillation channel
  - Dual-Readout correction shows **~ 22.4% stochastic term for the hadronic energy resolution**



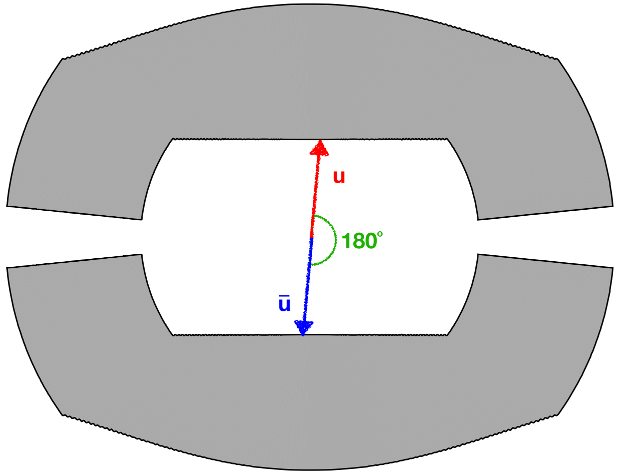


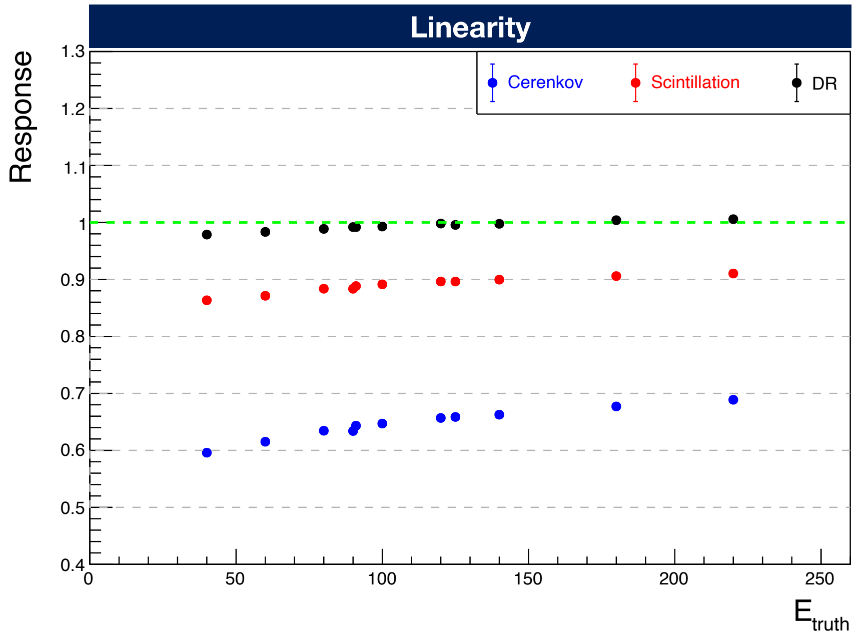
World the most and best precise simulation results!

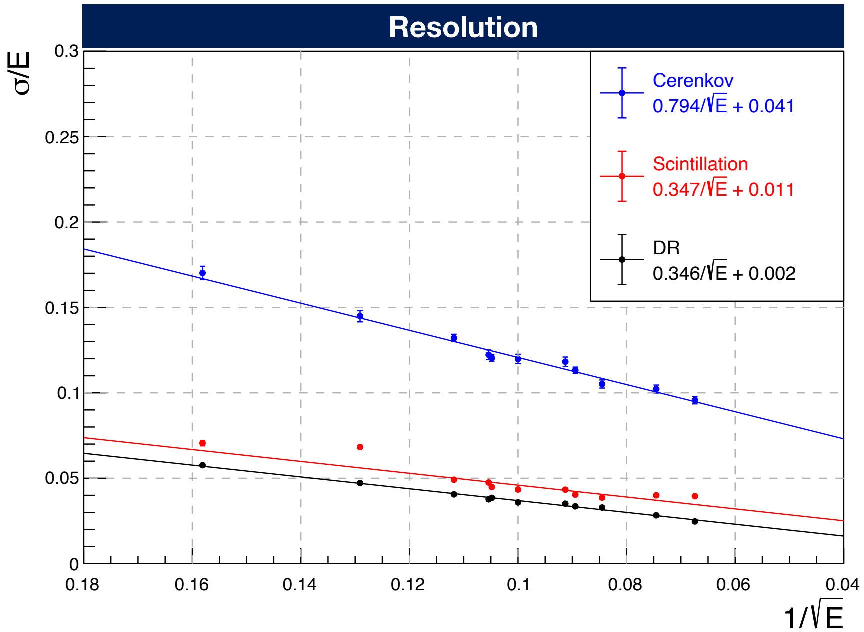
Presented at CALOR 2024 (May 23, 2024) and paper in preparation

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**







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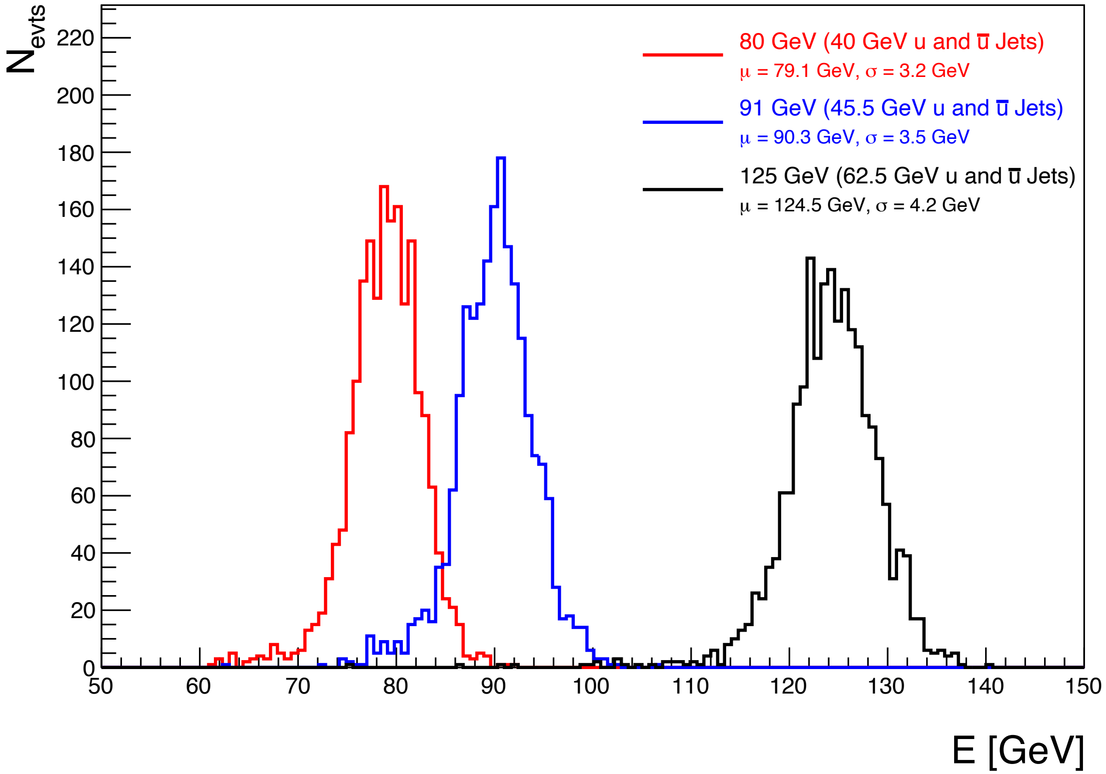
Presented at CALOR 2024 (May 23, 2024) and paper in preparation

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

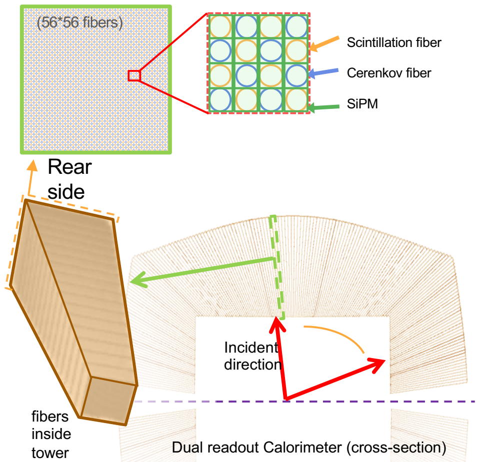


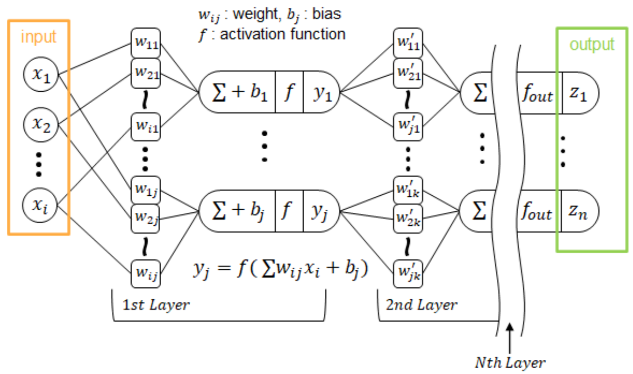
World the most and best precise simulation results!

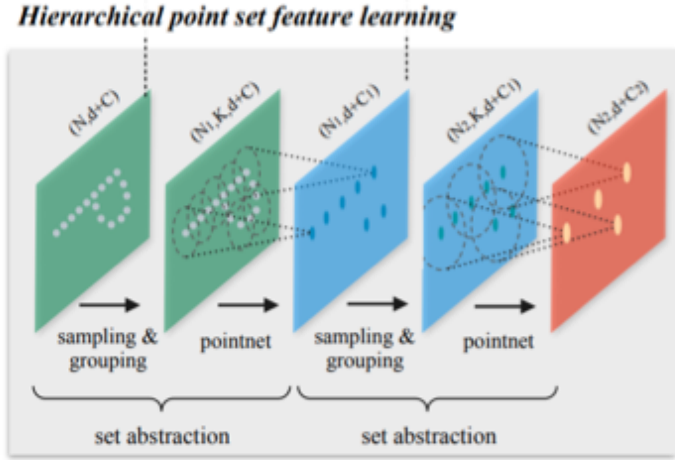
Presented at CALOR 2024 (May 23, 2024) and paper in preparation

Particle ID with ML

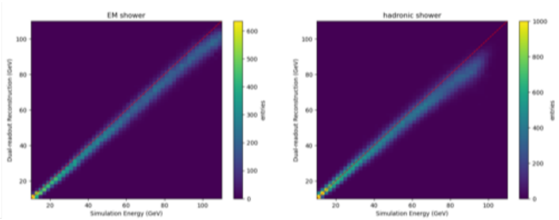
- DL implementation setup for extended particle identification

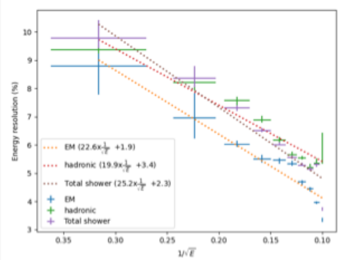


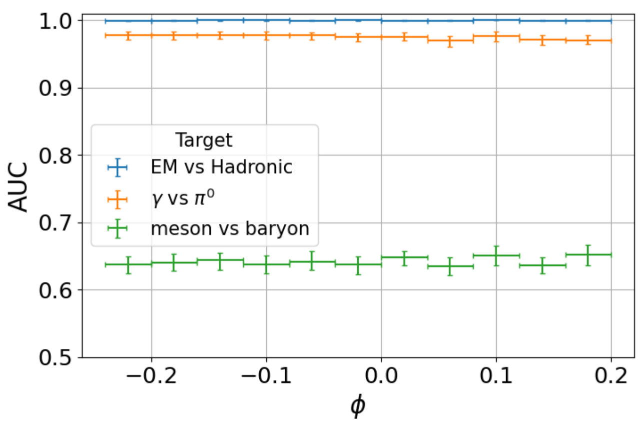


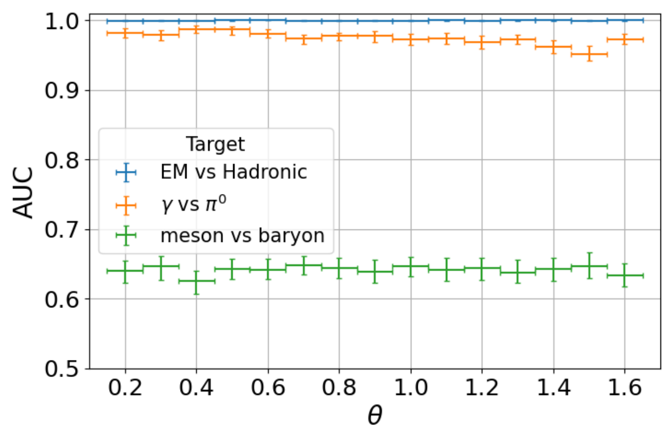


- Performance is quite promising compared to the classical approach









3D Shower Profile

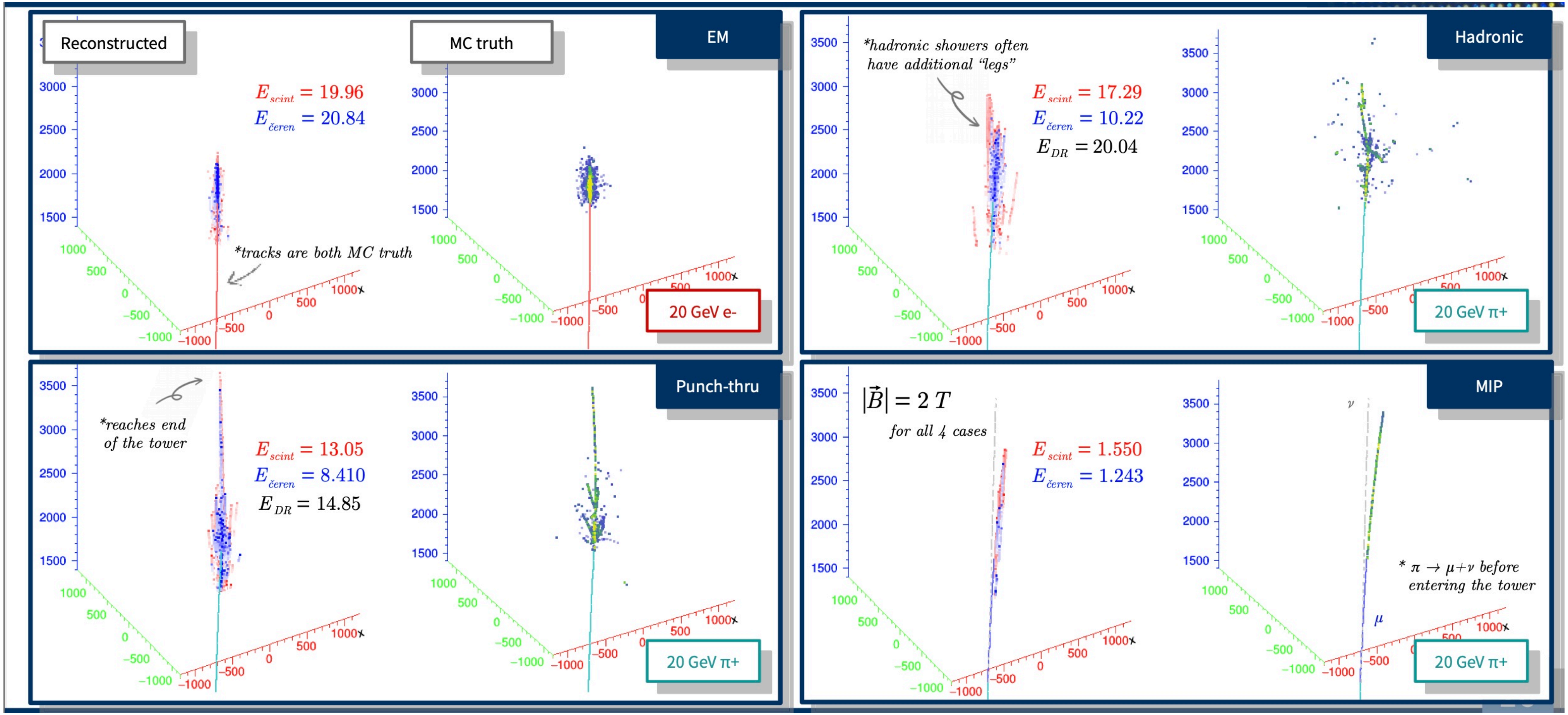
- Develop novel ideas to exploit timing for longitudinal & 3D reconstruction

Signal starting time difference: 2 ns/m

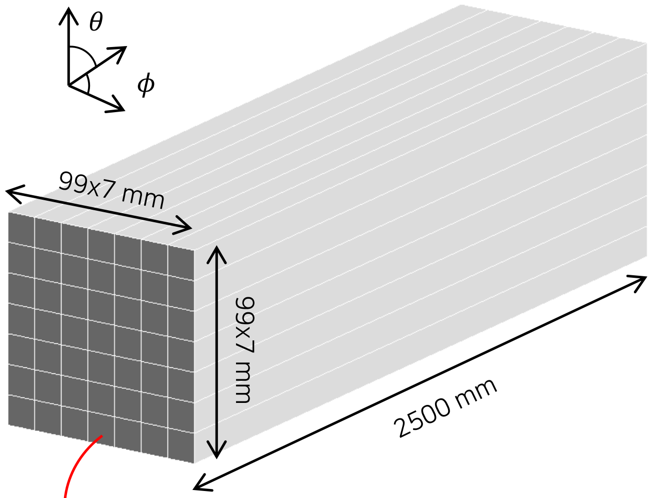
Time resolution: 10 ps —> 5 mm precision

Time resolution: 50 ps —> 25 mm precision

Time resolution: 100 ps —> 50 mm precision



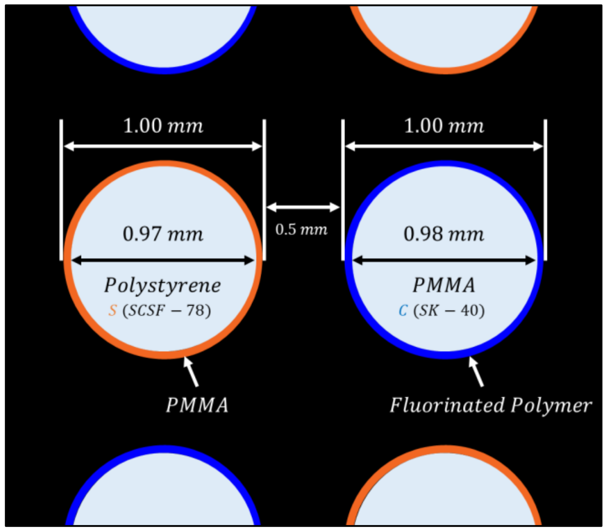
Comparison for Various Absorbers

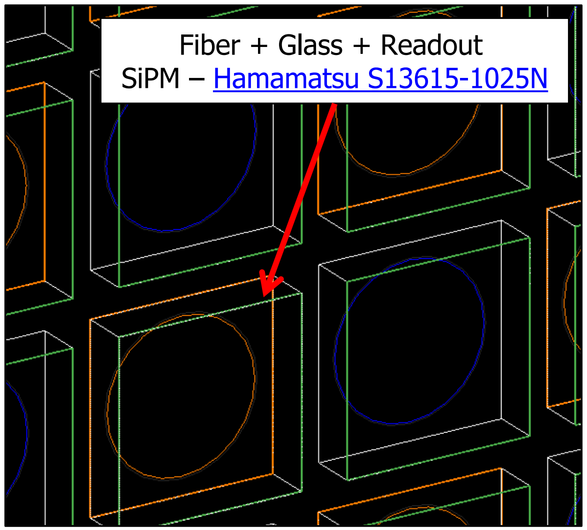


- Simulation setup is based on Geant4 toolkit, 10.5.p01, physics list FTFP-BERT.
- The geometry is **longitudinally unsegmented**, box shape, 7x7 modules.
- 5 different absorbers were used –

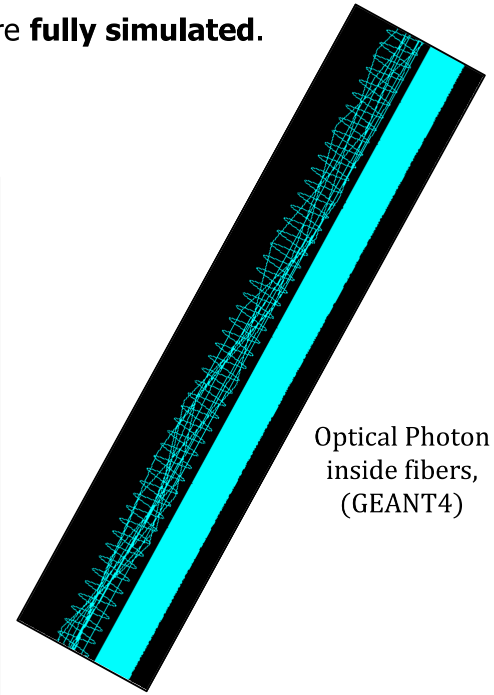
  Copper, Brass (Cu:Zn=7:3), Iron, Lead, Tungsten

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





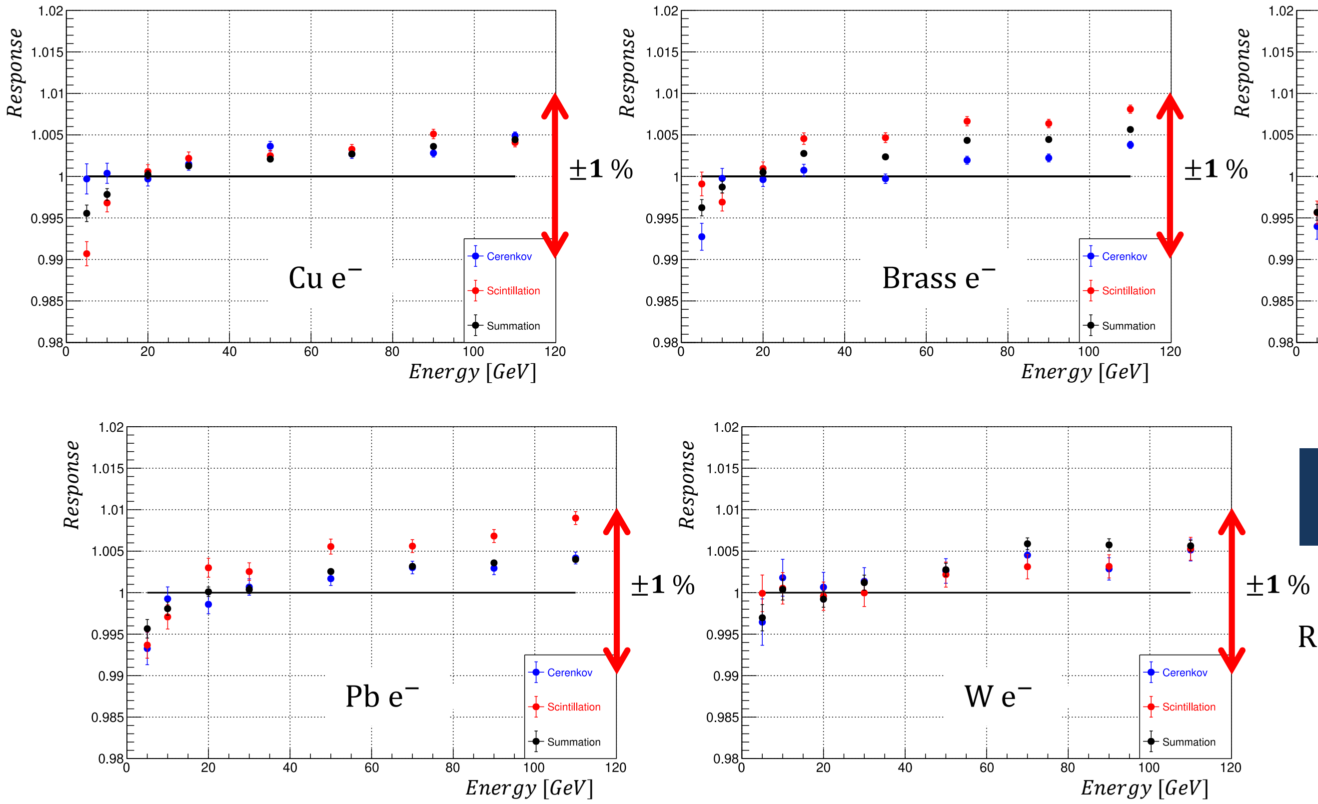
Rearside of module (GEANT4)



Optical Photon inside fibers, (GEANT4)

Submitted to NIM A

Comparison for Various Absorbers



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

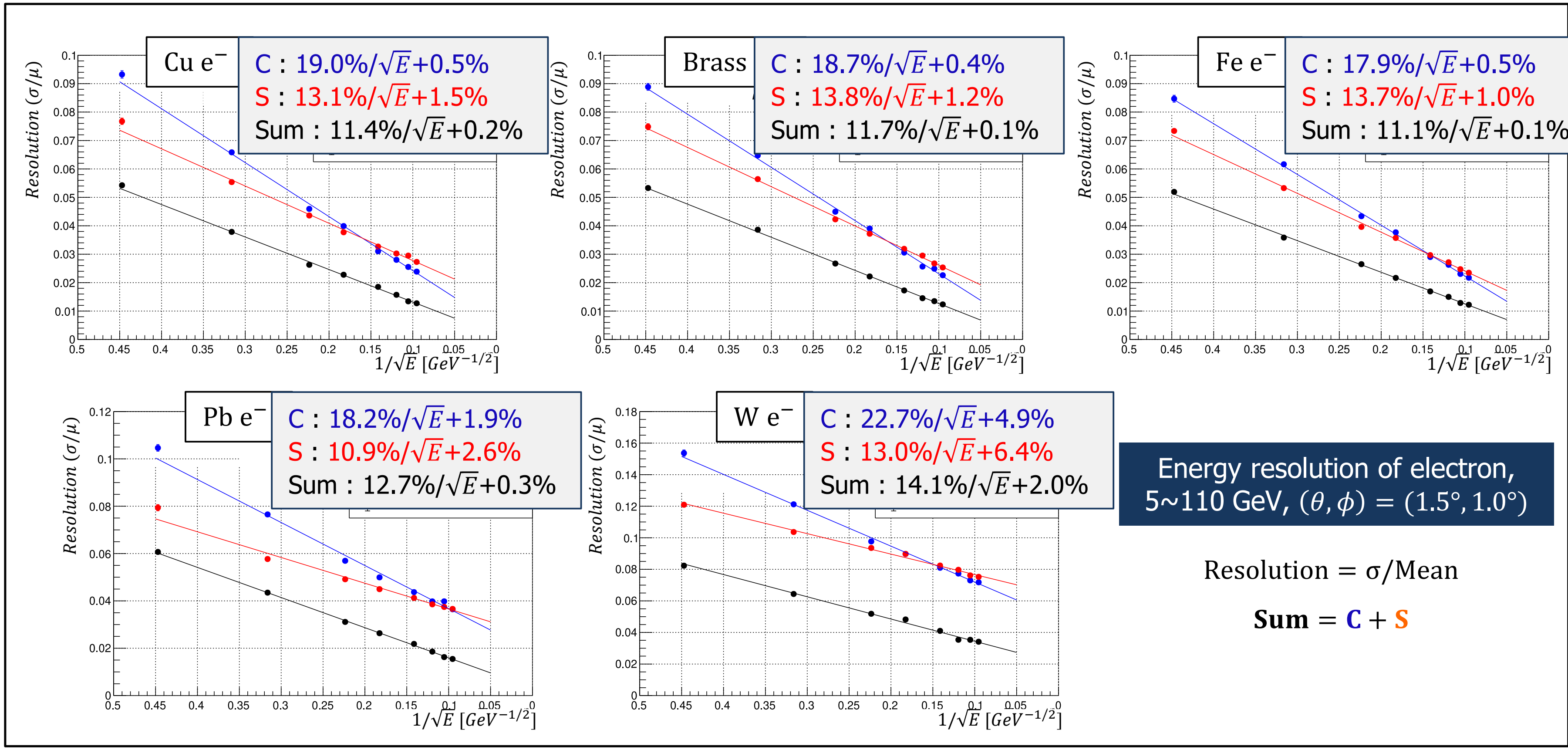
$\mathrm{Response} = \mathrm{Reco.E/Incident\ Energy}$

Summation = C + 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 $\pm 1\%$**

Submitted to NIM A

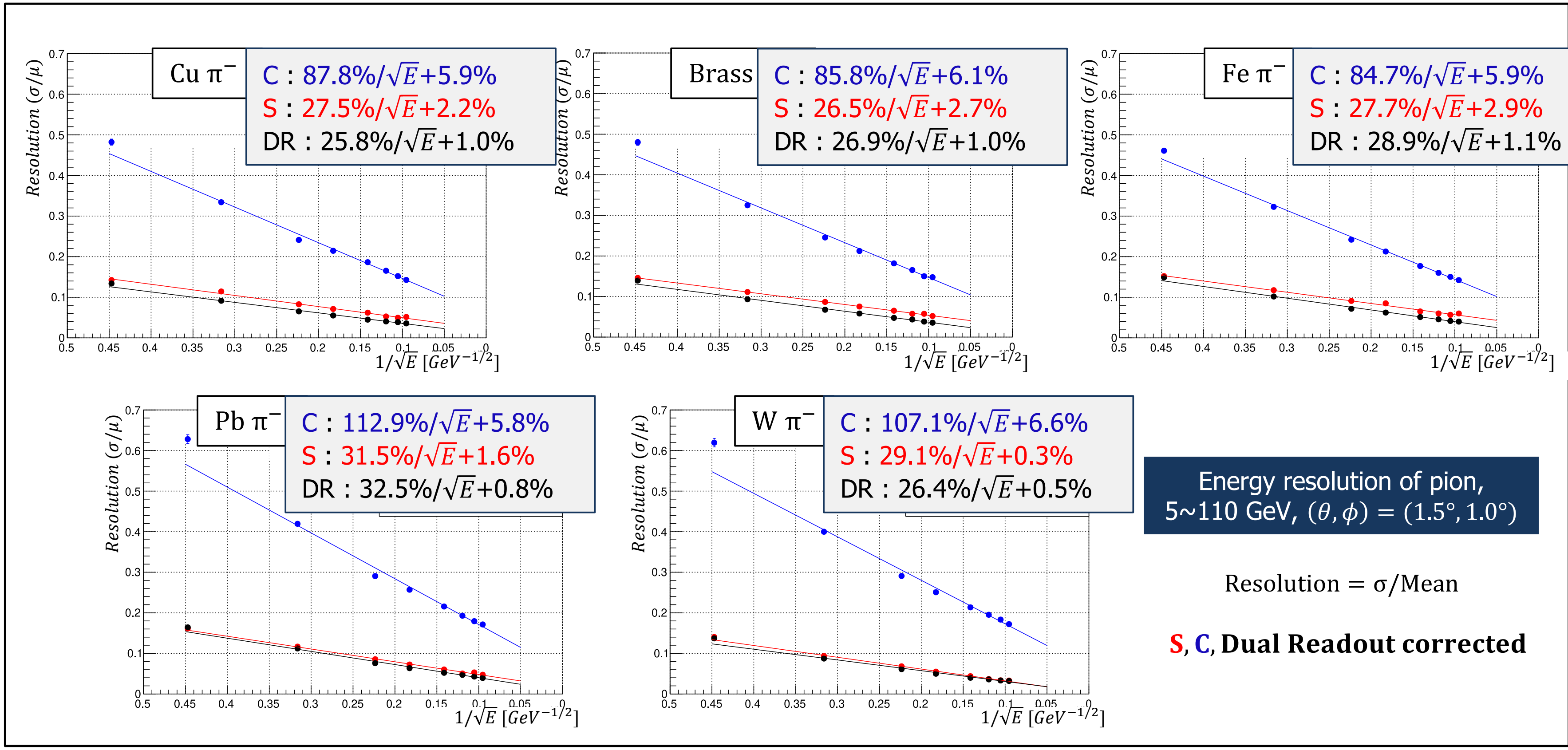
Comparison for Various Absorbers



- 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.**

Submitted to NIM A

Comparison for Various Absorbers



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

Submitted to NIM A

DRC Milestones & Deliverables

Milestone and deliverables: DRCal	
Subtask 3.3.1: DRCal	
D/M Number	**Description**
D3.12	Construction of different options of dual-readout prototypes with hadronic shower containment
M3.15	*Testbeam campaign to assess module performance: result paper*
M3.16	*Continue beam testing with alternative readout elx*

- ✓ The prototype is **already built** & being tested since 2022
  - ✓ depth: **~10** λ_{int}
    lateral hadron shower containment: **>90% (60 GeV,** π**)**
- ✓ Upgrade with larger containment if additional funding is available

- ✓ TB2022: **published** (J.Subatomic Part.Cosmol. 3 (2025) 100021)
- ✓ TB2023: manuscript is under preparation
- ✓ TB2024+25: data analysis is ongoing -> aim to present in CALOR2026 on June
- ✓ TB2026 (expected): 3D shower reconstruction, timing performance, etc

- ✓ Start with square PMTs
- ✓ **High-granularity** readout
  - ✓ Commercial MCP-PMT is being tested
  - ✓ customized MCP-PMT: under development (working with ANL)

Part II: Barrel Imaging Calorimeter for EIC

Detector Requirement

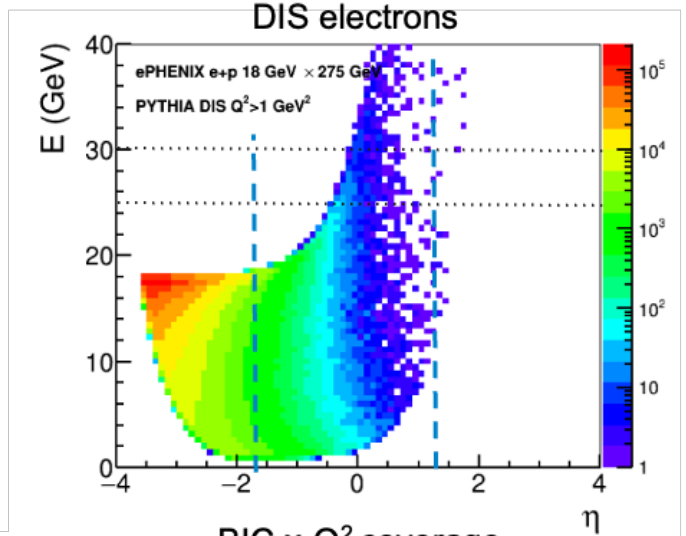
https://eic.jlab.org/Requirements/

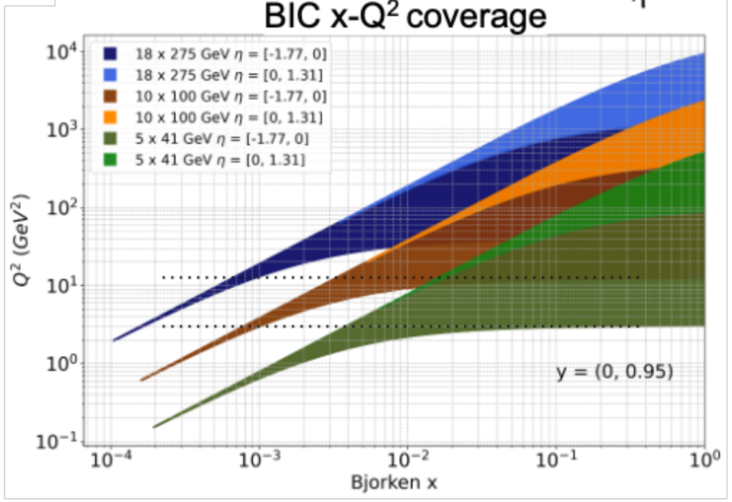
Identify scattered electrons and measure their energy, in high Q^2 events, also decay electrons, e.g., from vector or heavy flavor meson decays, and measure DVCS photons and decay photons

- **Electron ID up to 50 GeV** and down to 1 GeV and below
  - Energy resolution < **10%/√(E) + (2-3)%**
  - High power for **e/π separation down to 1 GeV/c**
- **Photon measurements up to 10 GeV**
- **γ/π⁰ separation up to 10 GeV**
  - Distinguishing two showers with an opening angle down to 30 mrad

Assist with muon identification

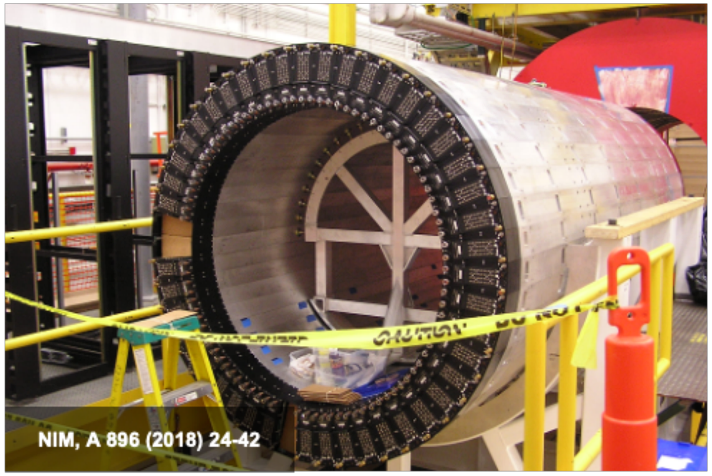
Sufficient dynamic range to **detect MIP** signals in all layers





A Hybrid Imaging Calorimeter

Combination of a high-performance sampling calorimeter with silicon sensors for shower profiling



Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for state-of-the-art sampling calorimeter performance

Insert layers of monolithic AstroPix sensors (ultra-low-power silicon sensor developed for NASA) in the first half of the calorimeter to capture a 3D image of the developing shower

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

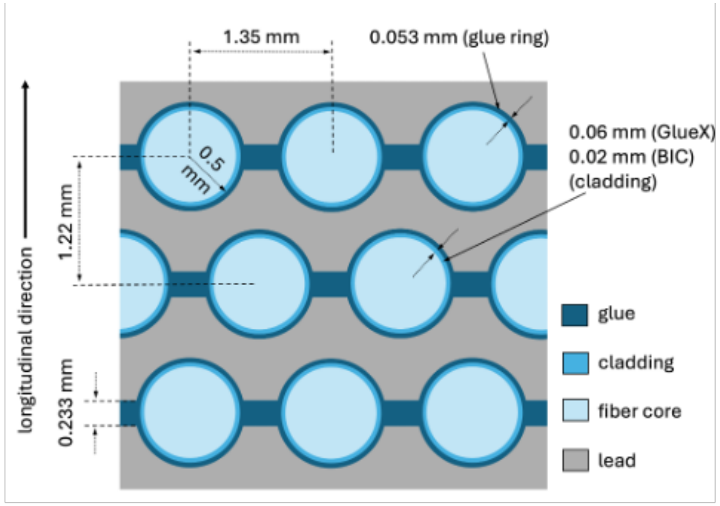
Mature technology used in Barrel ECals (GlueX, KLOE)

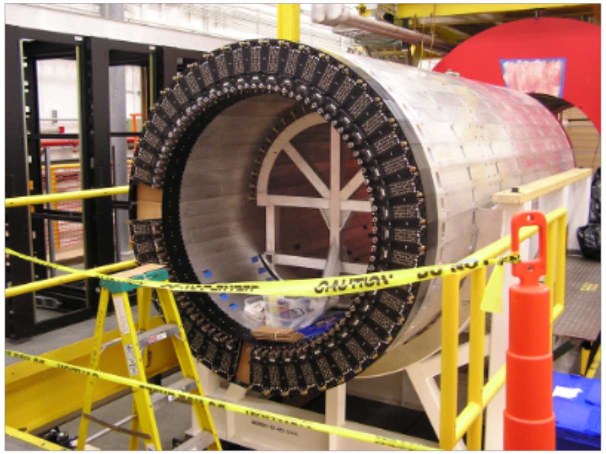
- Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
- **Construction** (lead handling, swaging, Pb/ScFi layers assembly, module machining) is fully developed for GlueX

  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

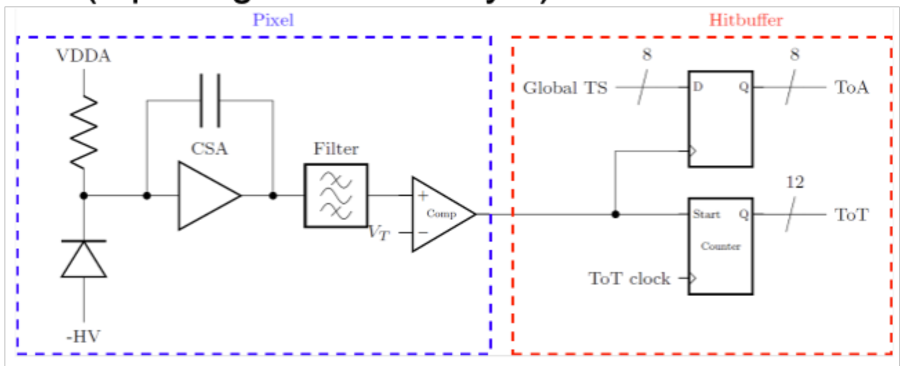
Imaging Layer Technology

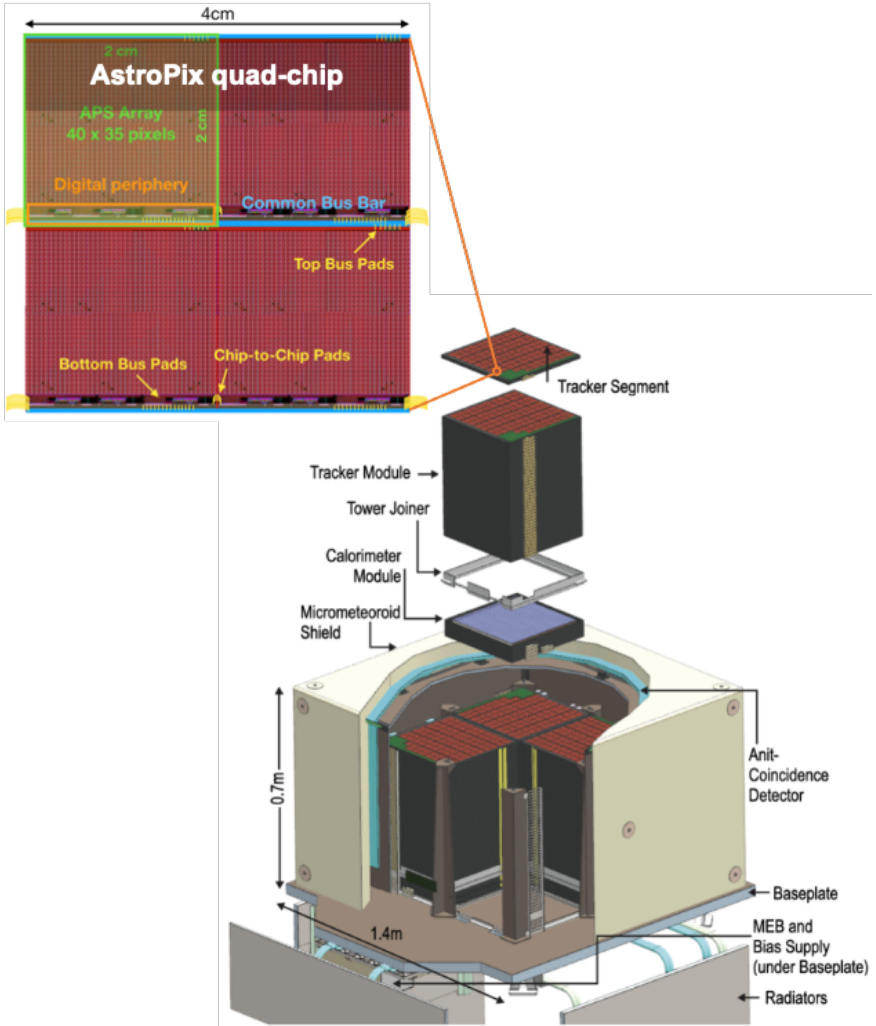
Imaging layers will use the AstroPix sensors

- 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)



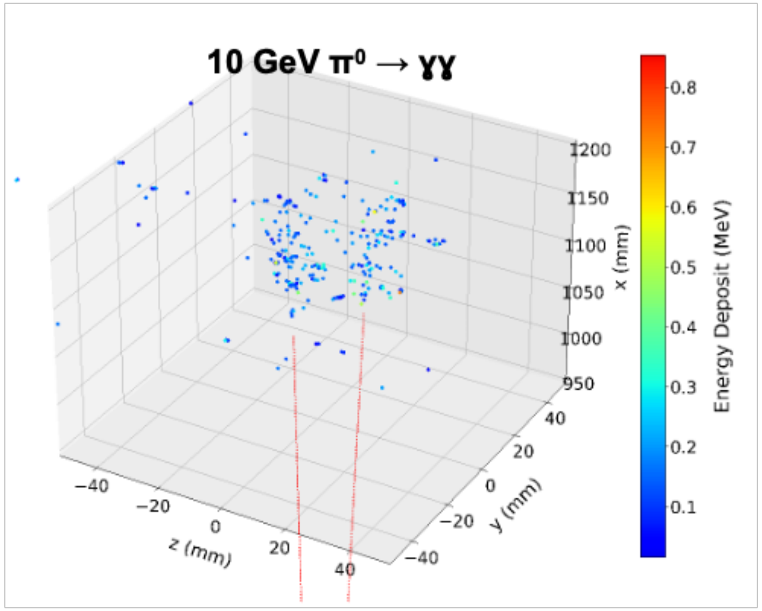


AMEGO-X Detector

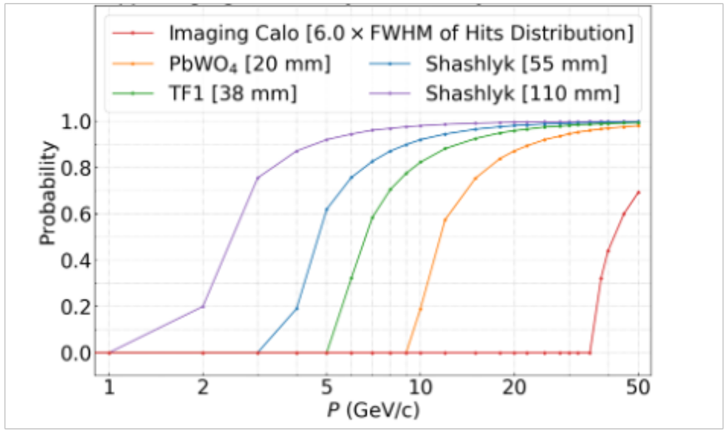
[arXiv:2208.04990 [astro-ph.IM]](arXiv:2208.04990)

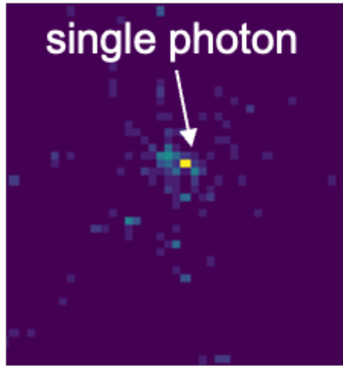
Particle Identification

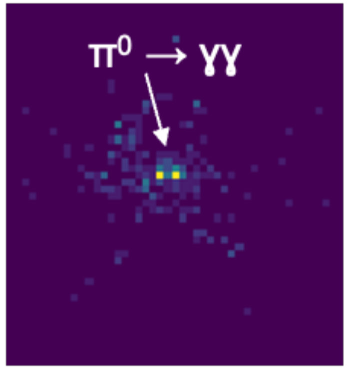
- Photons and neutral pions



Merging probability γ/π^0 (upper limit)



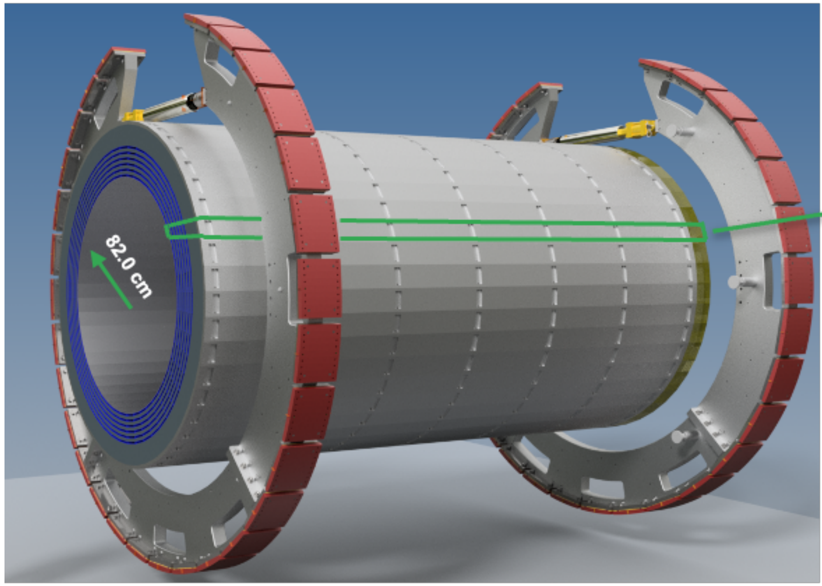




- Precise position resolution and shower imaging allow for excellent separation of γ/π^0 **based on the 3D shower profile**
- Upper limit unticipated from the **AstroPix position resolution and shower profile: well above 10 GeV**
- First insights from a simple **neural network approach**
  (**~82% pion rejection at 90% efficiency above 10 GeV** with the current status of model training - lower limit)

Barrel Imaging Calorimeter

Sector Mechanics

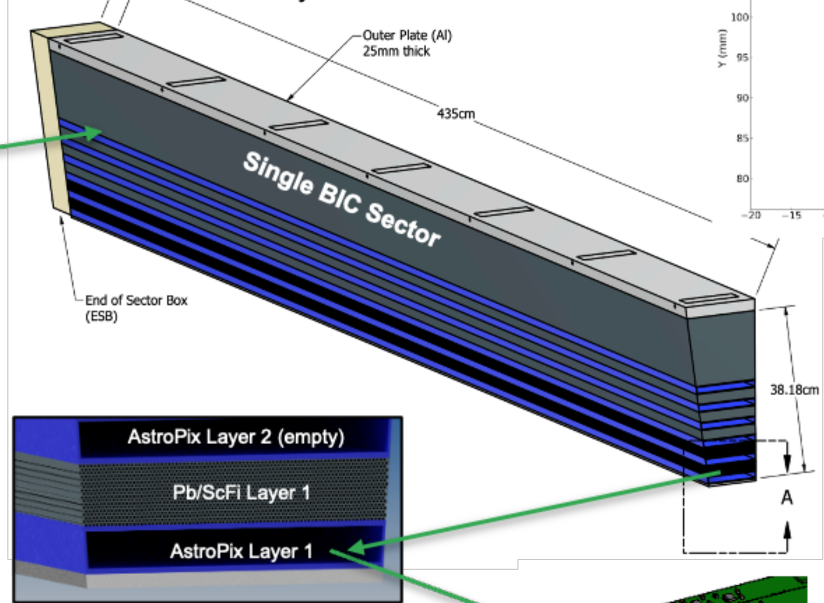


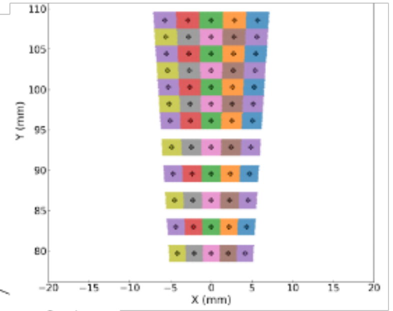
Total BIC weight ~42.5 US tons

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

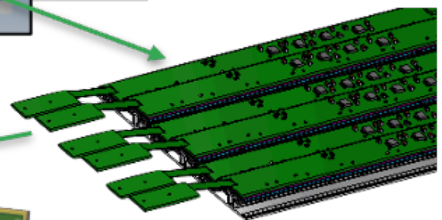
Each sector has 12 Pb/ScFi layers.

Individual light guides divide each layer in 5 readout cells.





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

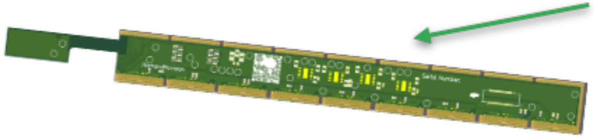


Tray - Structure holding the AstroPix staves for a single layer (217.5 cm long).

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

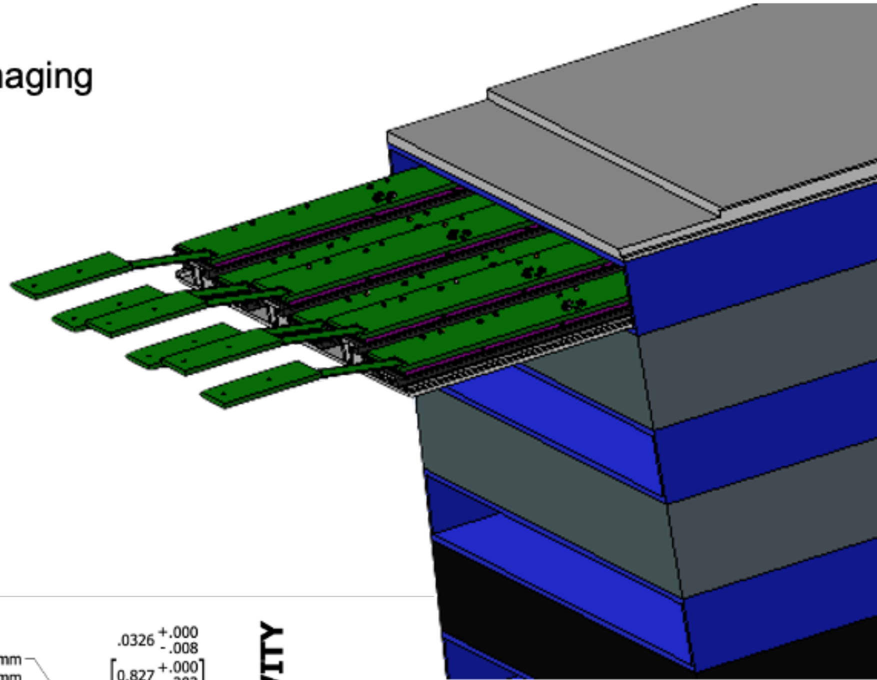
A stave consists of 12 modules.

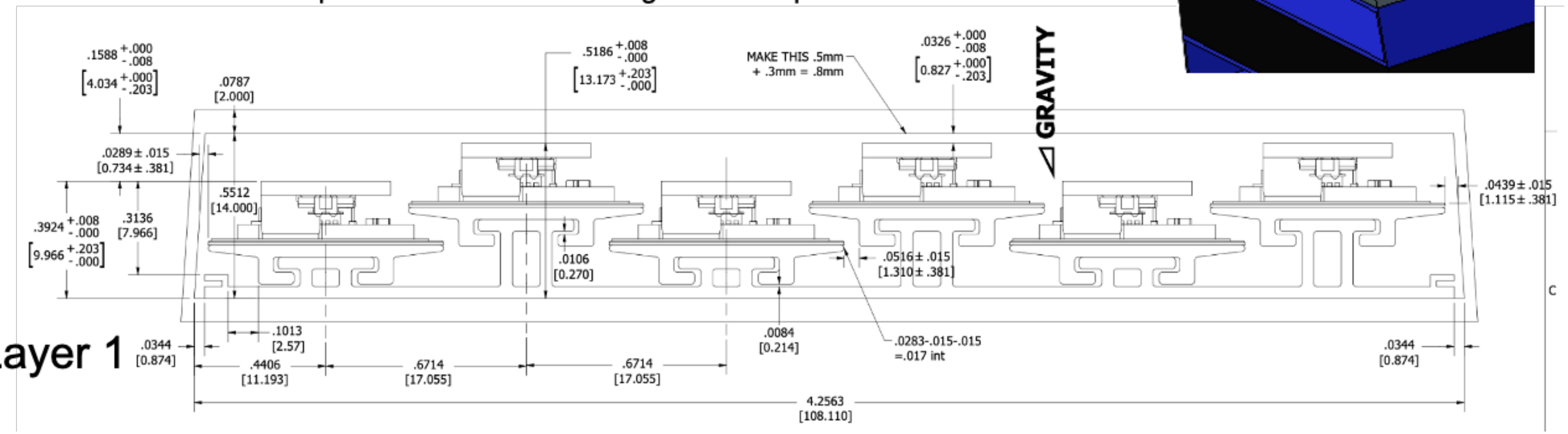
A tray contains of 6-8 staves.



BIC Imaging Layers

- **A Module** is an electrically testable elementary unit for imaging layers
  - **9 AstroPix HV-CMOS chips** - 2 cm X 2 cm
  - Base Plate (Aluminum) slides on Stave rail
  - Rigid(-flex) PCB readout
- 12 modules form a **Stave** and readout at the end of the Sector using End of Tray Card (FPGA) (~217cm)
- **Tray** consists of (6, 7, 7, 8) Staves (56 Staves/Sector)
- There are a total of 48 sectors with a length of ~435 cm
- The BIC is made up of 31104 Modules using ~280k chips





Layer 1

BIC Organization Chart

ePIC Leadership
Spokesperson:
- John Lajoie (ORNL)

Deputy Spokesperson and TC:
- Silvia Dalla Torre (INFN Trieste)

BIC DSC Board
DSC Leadership (DSL)
- Sylvester Joosten (Argonne)
- Hwidong Yoo (Yonsei U)
- Maria Żurek (Argonne)

Other Stakeholders
- Zisis Papandreou (U. Regina)
- Regina Caputo (NASA-GSFC)

BIC Project Manager
- Jessica Metcalfe (Argonne)

BIC Project Management
Project Manager (and DSTC):
- Jessica Metcalfe (Argonne)

Deputy Project Manager
- Sylvester Joosten (Argonne)
- Maria Żurek (Argonne)

EIC Project L3 CAM
L3 CAM for Electromagnetic Calorimetry:
- Alexander Bazilevsky (BNL)

ePIC Technical Coordination
Technical Coordinator:
- Silvia Dalla Torre (INFN Trieste)

Deputy Technical Coordinators
- Prakhar Garg (Yale U.)
- Oskar Hartbrich (ORNL)
- Matt Posik (Temple U.)

AstroPix Wafers / Modules & Staves
TM: Manoj Jadhav (Argonne)
Deputy TM: Sanghoon Lim (PNU)

Chip Support
PoC: Richard Leys
Sites:
- KIT
- NASA-GSFC

Wafer Testing
PoC: Sanghoon Lim
Sites:
- PNU
- Argonne

Wafer Procurement
PoC: Jessica Metcalfe
Sites:
- Argonne
- PNU

Module Design & Assembly
PoC:
- Manoj Jadhav
- Anthony Affolder
- Sanghoon Lim

Sites:
- Argonne
- UCSC
- PNU

Stave Bus
PoC: Steven Welch
Sites:
- Oklahoma State

Mechanics / Sectors
TM: Sylvester Joosten (Argonne)
Deputy TM: Beomkyu Kim (SKKU)

Global Design
PoC: Tom O'Connor
Sites:
- Argonne

Tracker Mechanics
PoC: Vic Guarino
Sites:
- Argonne

CF Engineering
PoC: Andreas Jung
Sites:
- Purdue

Assembly & Install.
PoC:
- Kevin Bailey
- Dan Cacace

Sites:
- Argonne
- BNL (EIC Project)
- ePIC BIC DSC

Sector Production
PoC:
- Kevin Bailey

Sites:
- Argonne
- SKKU
- Yonsei U.

Scintillating Fibers
PoC: Zisis Papandreou
Sites:
- U. Regina
- Argonne

ESB / DAQ & Readout
TM: Zisis Papandreou (U. Regina)
Deputy TM: Shinhyung Kim (KNU)

SiPMs & Light Guides
PoC: Zisis Papandreou
Sites:
- U. Regina
- KNU

Electrical Design
PoC: Aram Teymurazyan
Sites:
- U. Regina

Cooling
PoC: Wouter Deconinck
Sites:
- U. Manitoba
- Argonne

ESB Production
PoC:
- Zisis Papandreou
- Wouter Deconinck
- Shinhyung Kim

Sites:
- U. Regina
- U. Manitoba
- Mt. Allison U.
- KNU

ETC
PoC: Regina Caputo
Sites:
- NASA-GSFC

SiPM FEB & DAQ Integration
PoC: Norbert Novitzky
Sites:
- ORNL
- U. Regina
- U. Manitoba

Slow Controls
PoC: TBD
Sites:
- Argonne
- ORNL
- PNU

System Testing / Software & Sim
TM: Maria Żurek (Argonne)
Deputy TM: Hwidong Yoo (Yonsei U.)

System Demonstration
PoC: Henry Klest
Sites:
- Argonne
- U. Regina
- PNU

Beam Tests
PoC: Bobae Kim
Sites:
- Argonne
- U. Regina
- EIC Korea

System Calibrations
TBD

System QC
PoC: Maria Żurek
Sites:
- Argonne
- U. Regina
- BNL (EIC Project)

Rapid Response
PoC: Maria Żurek
Sites:
- Argonne
- U. Manitoba
- PNU

Development
PoC: Chao Peng
Sites:
- Argonne
- U. Manitoba
- U. Regina
- PNU

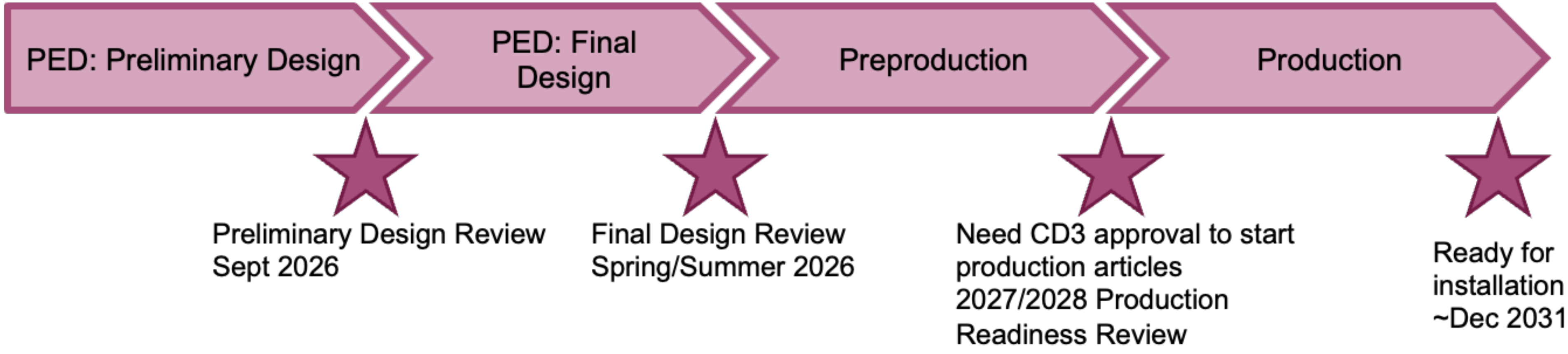
Benchmarks
PoC: TBD
Sites:
- Argonne
- U. Manitoba
- PNU

Glossary
BIC: Barrel Imaging Calorimeter
CAM: Control Account Manager
DSC: Detector Subsystem Collaboration
DSL: Detector Subsystem Lead
DSTC: Detector Subsystem Technical Contact
ESB: End-of-Sector Box
ETC: End-of-Tray Card (AstroPix module RDO)
FEB: Front-End Board
PoC: Point-of-Contact
PM: Project Manager
QC: Quality Control
RDO: Readout board
TBC: To Be Confirmed
TBD: To Be Determined
TM: Technical Manager

BIC ORG Chart v1.0

***Note:** The BIC internal work packages (AstroPix Wafers, Modules & Staves, Mechanics, Sectors, ESB, DAQ & Readout, and System Testing) are integrated under the EIC Project P6 Work Packages*

BIC Project Phase



- Preliminary Design Review, 60% design completion
- AstroPix v3 (and v4)
- BabyBCal & Lanky BCal
- Individual components
- First (second) test articles

- AstroPix v5
- One full sector
- Final designs (90%)
- Production style procedures
- AstroPix v6 validation tests

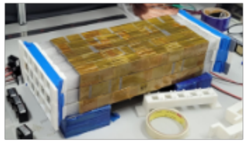
- AstroPix v6
- 48 sectors

Test Beams of Prototypes

May 2024

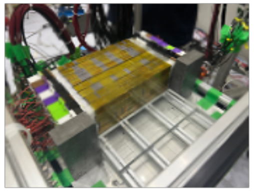
First piece

Aug 2024 CERN PS



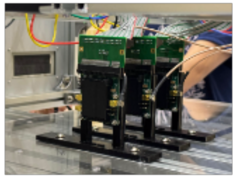
First Pb/SciFi prototype production in Korea
First beam test
Successful data taking

Mar 2025 KEK



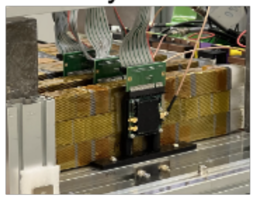
More Pb/SciFi layers
Improved energy resolution
New DAQ, Trigger, Hodoscope, Calibration
Extension cable test

June 2025 KEK



AstroPix synchronization with trigger time

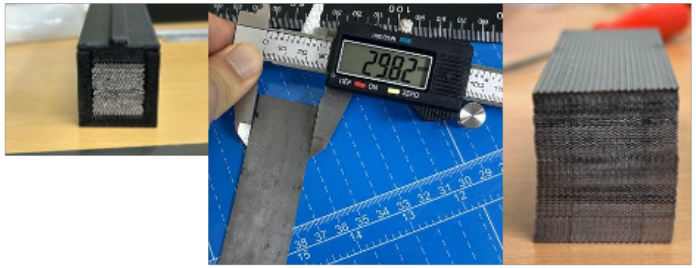
July 2025



synchronized data taking of AstroPix + Pb/SciFi
Proof-of-principle imaging of electrons and pions
Resolution fulfill the EIC requirement

Pb/SciFi Prototype Module

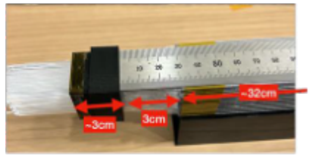
1) Pb plate preparation



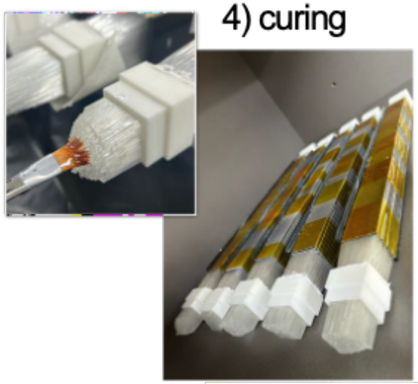
2) Stacking with fiber

Epoxy

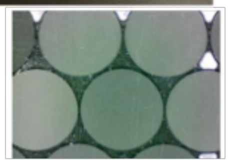
3) Cutting fiber



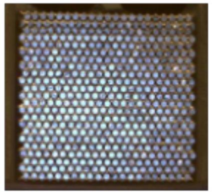
4) curing



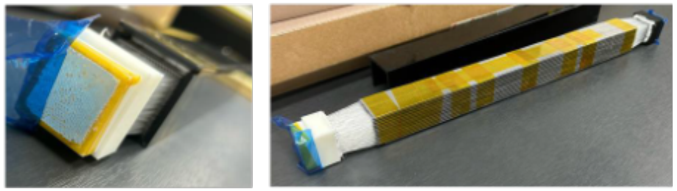
5) polishing



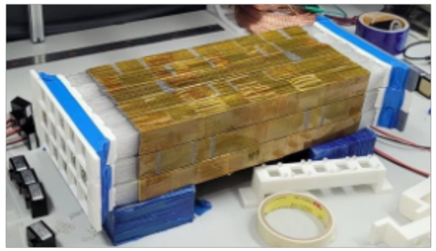
Produced 33 of 32x3x3 cm³ unit modules for beam test



완성본

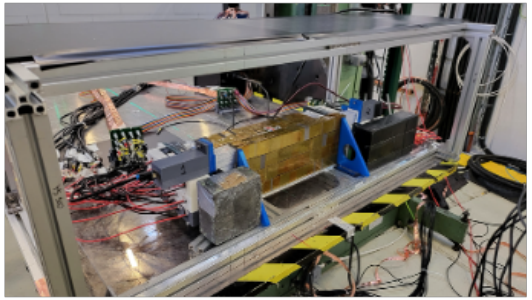
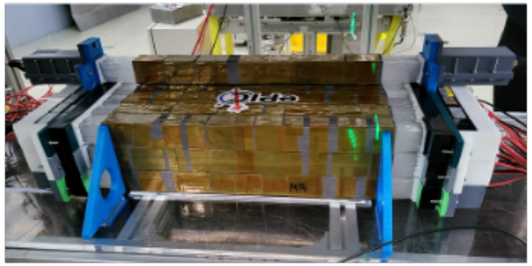
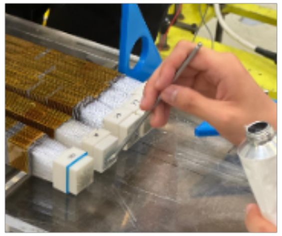
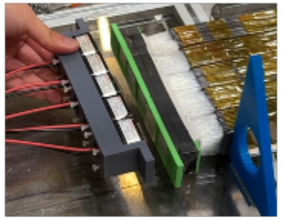
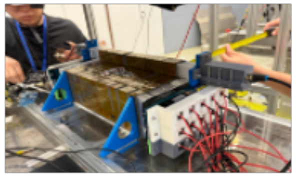
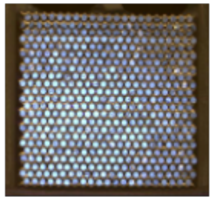
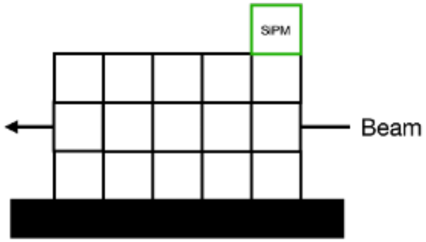


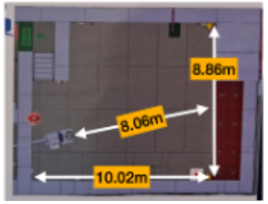
6) Connect with PMT or Light Guide + SiPM



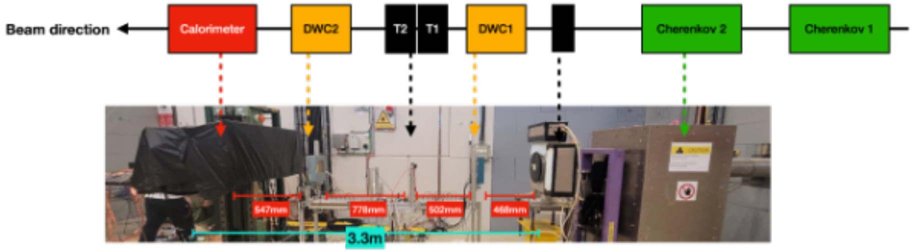
1st Test Beam at CERN

- CERN PS T10 in Aug. 2024

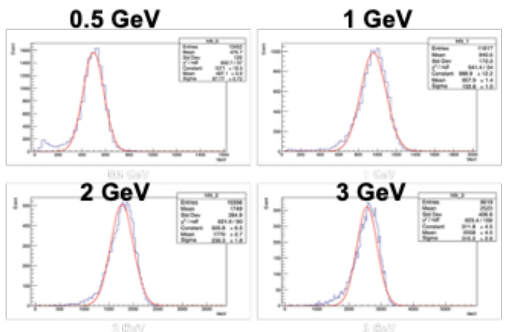












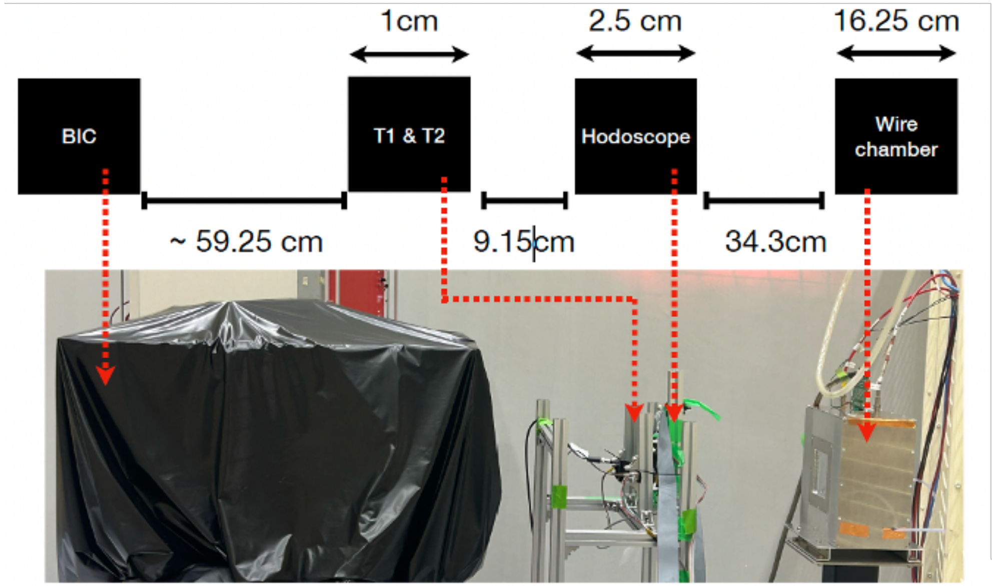


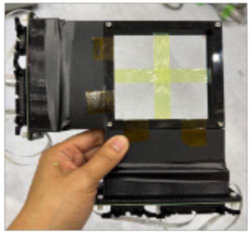
Successfully collected data from the Pb/SciFi calorimeter prototype produced in Korea using our DAQ system with 0.5, 1, 2, and 3 GeV electron beams.

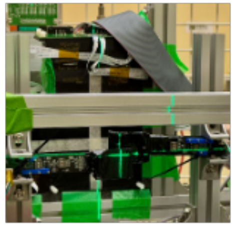


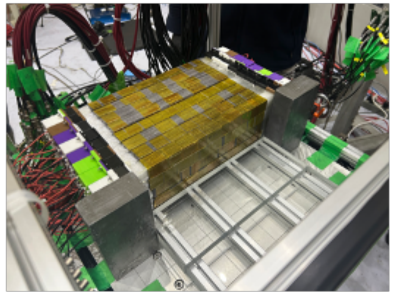
2nd Test Beam at KEK

- KEK PF-AR in March 2025

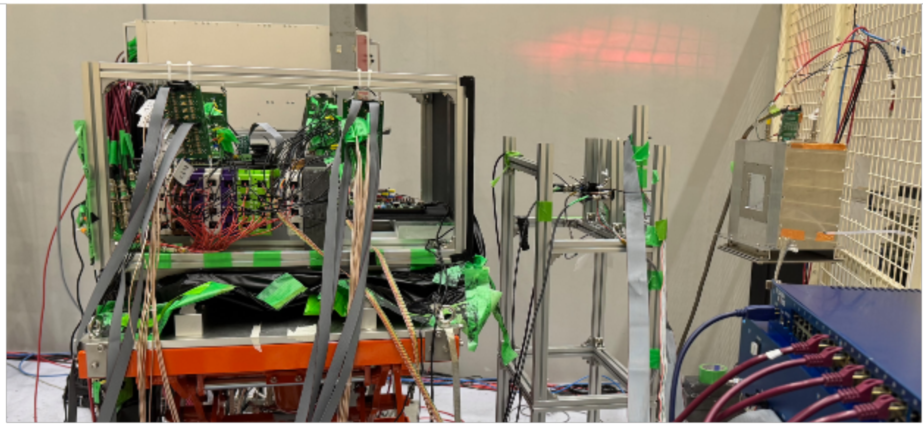


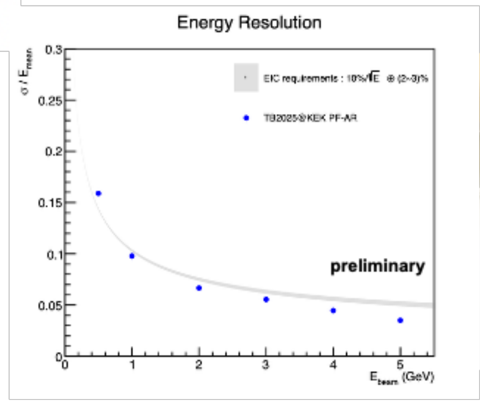


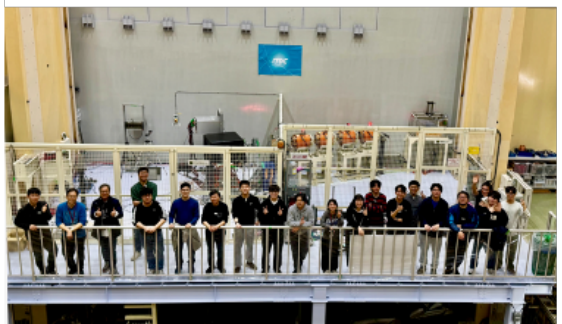




Bigger, Deeper Pb/SciFi setup: 32x12x21cm³
Refine calibration procedure
Smooth operation with new DAQ
Operation of auxiliary detectors: Hodoscope, Trigger

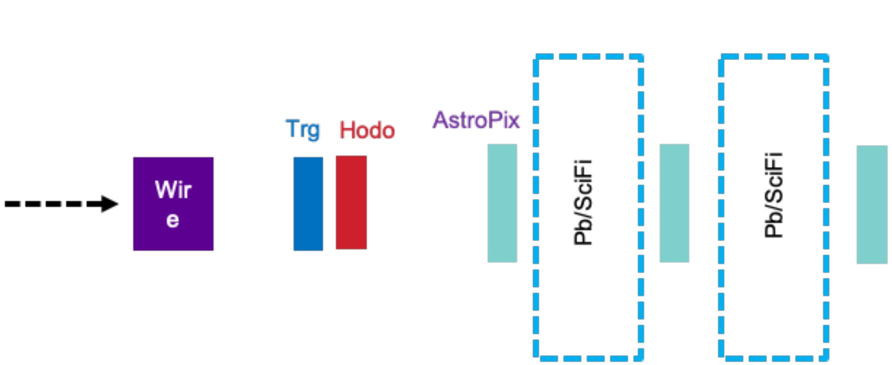


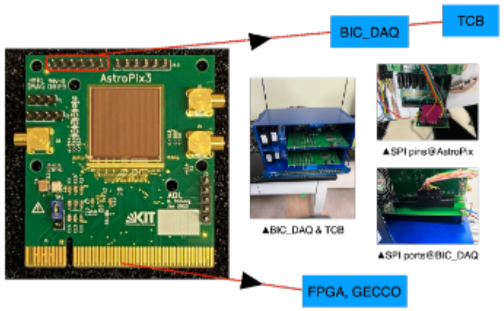


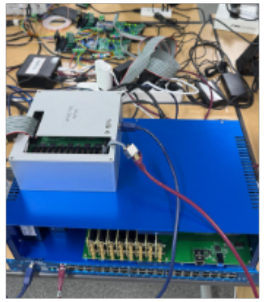


3rd Test Beam at KEK

- KEK PF-AR in June 2025





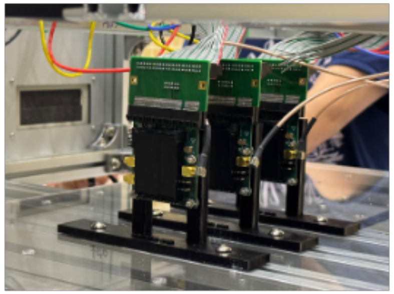


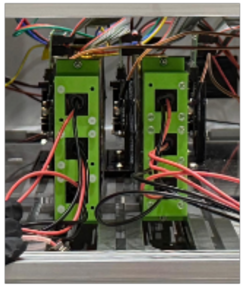
Synchronization between AstroPix and other detectors in the DAQ system produced in Korea

Preparation of the shower profile study.

SiPM and Light Guide test

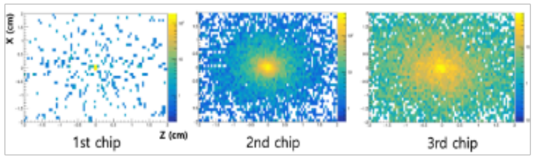
3 AstroPix Layers to be synchronized



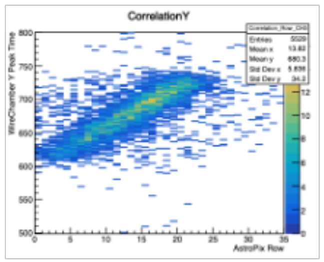


3 AstroPix Layers between Pb/SciFi

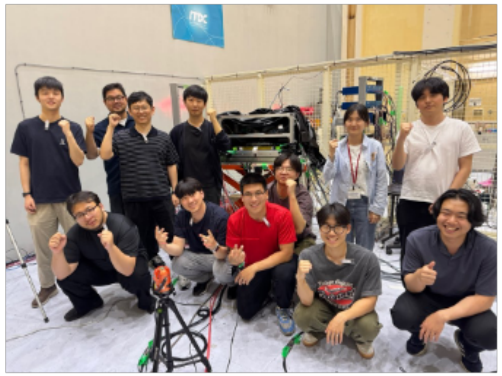
S13,S14 SiPM with LG



Hit distribution from electron beam in GEANT4 simulation

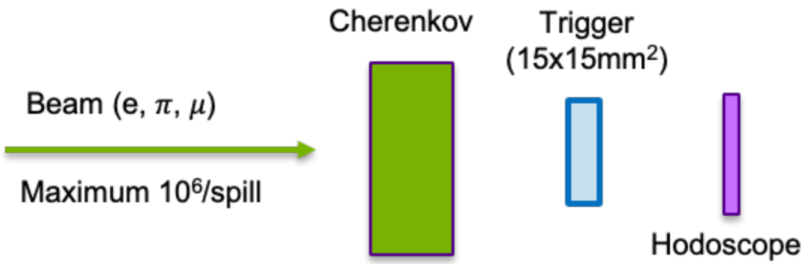


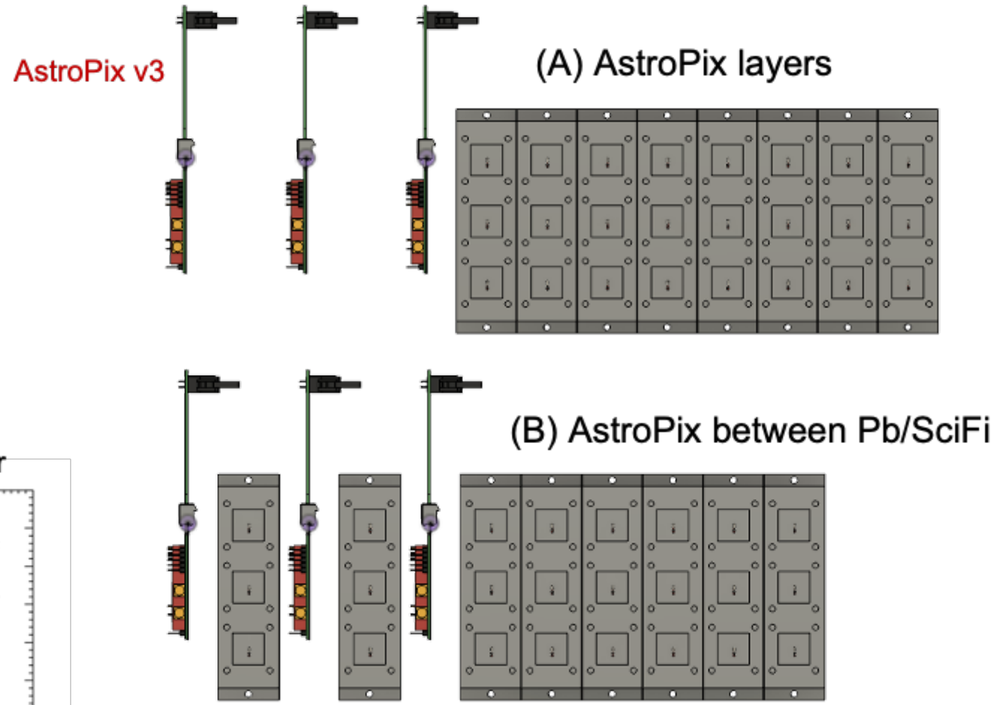
correlation of beam position at AstroPix and drift time at Wire Chamber



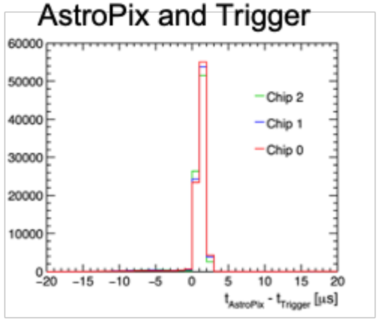
Recent Test Beam at CERN

CERN PS T10 in July 2025





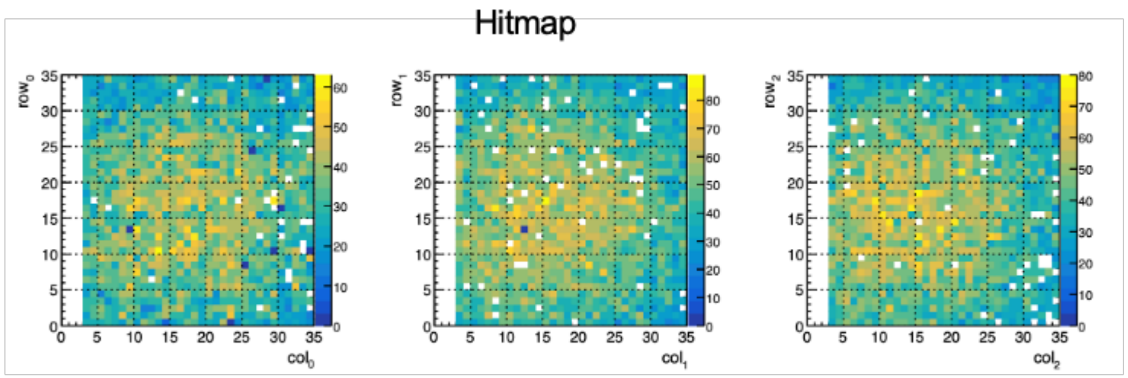
Time between
AstroPix and Trigger

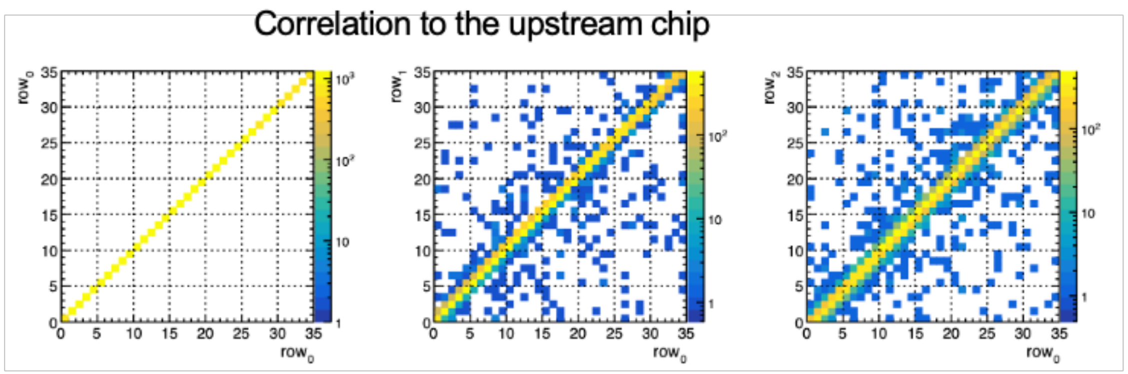


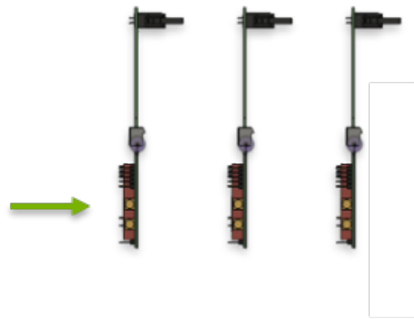
Goal: Proof-of-principle imaging of electrons and pions using a synchronized setup of AstroPix in the beam environment, using synchronized data taking between AstroPix and Pb/SciFi

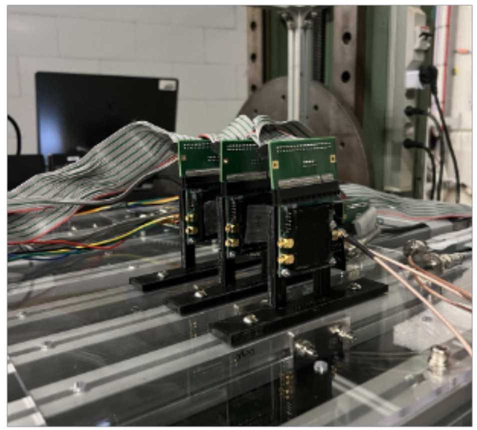
Synchronization of 3 Layers of AstroPix v3

- CERN PS T10 in July 2025





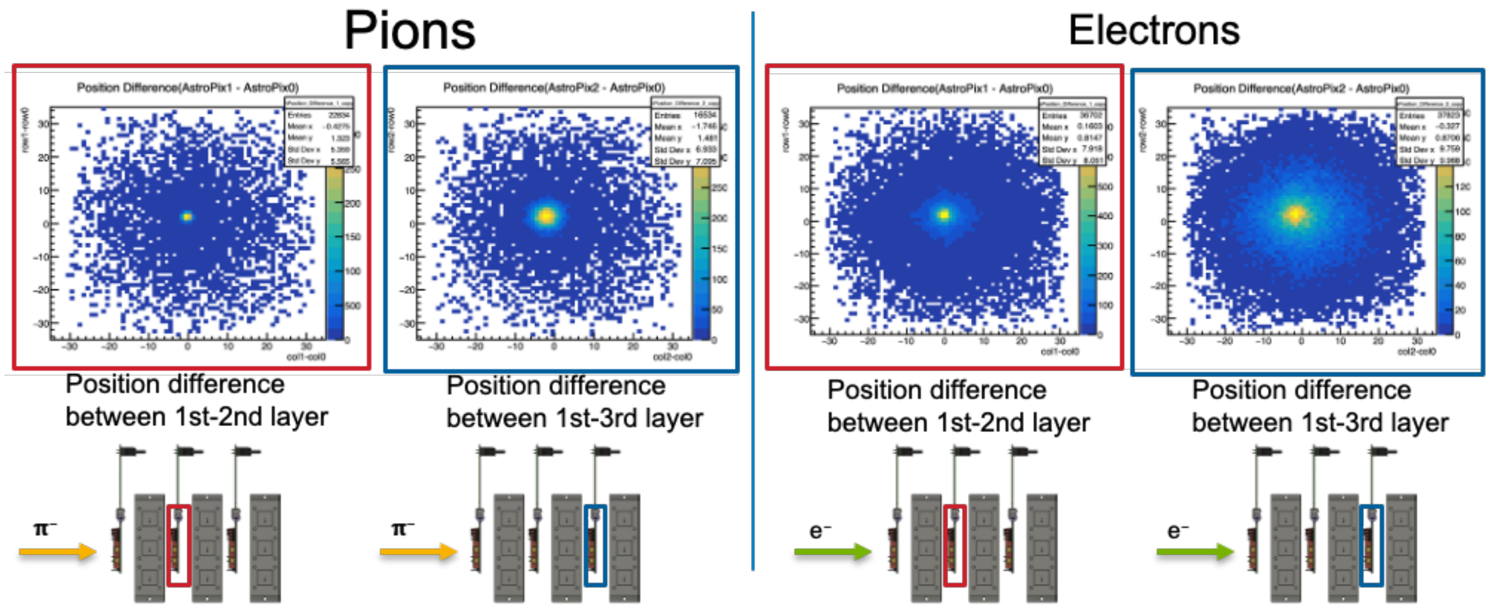


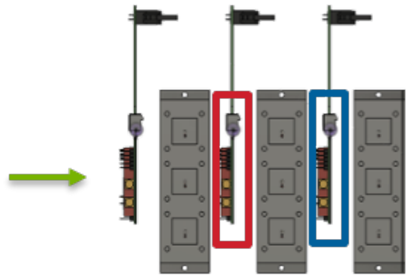


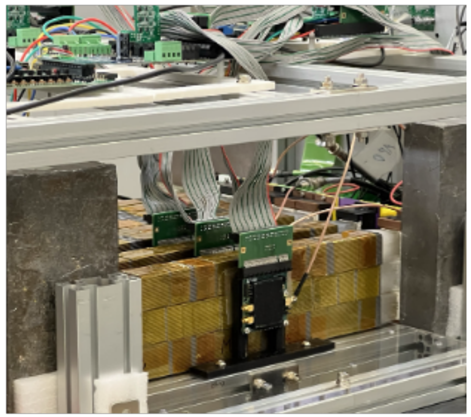
- Three AstroPix v3 layers are tested using the electron/pion beam at CERN PS.
- Correlations to the upstream show good alignment and data synchronization between AstroPix.
- The integrated system works well at a 2.7 kHz trigger rate on the beam. (BIC rate < 1 kHz/chip)

Shower Profiles of electrons and pions

- CERN PS T10 in July 2025

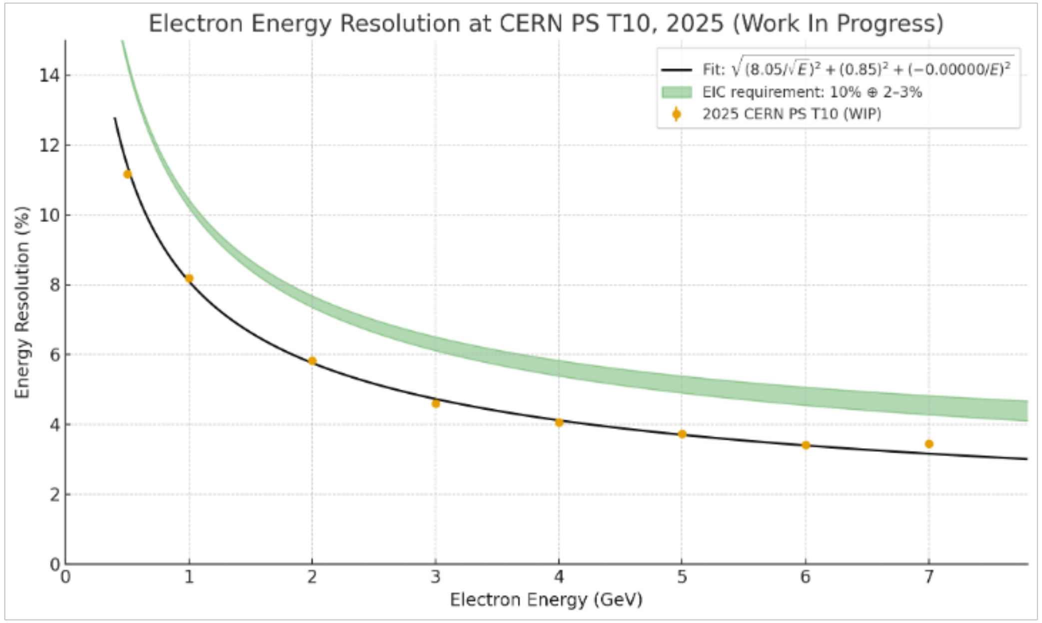


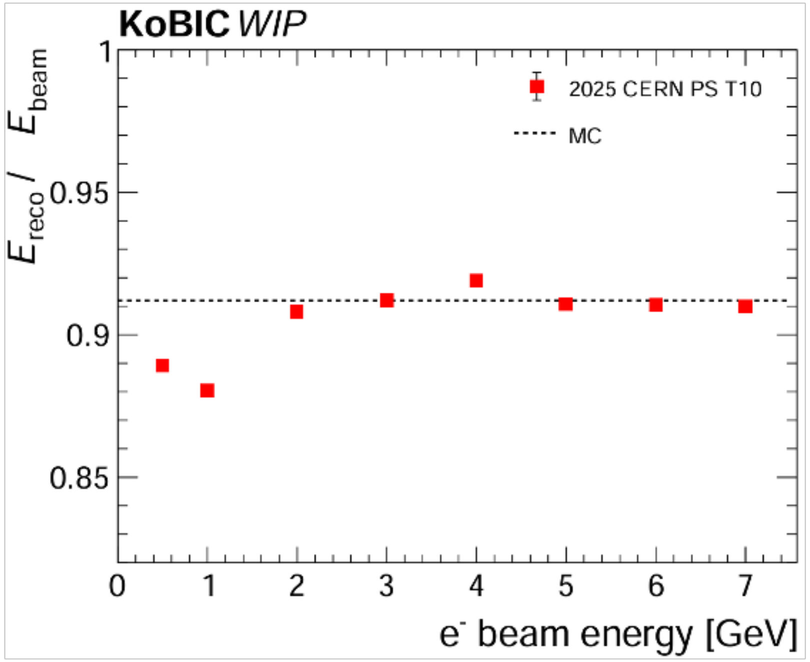




Proof-of-principle imaging of electrons and pions was performed using a synchronized AstroPix setup in the beam environment.

Energy Resolution & Linearity





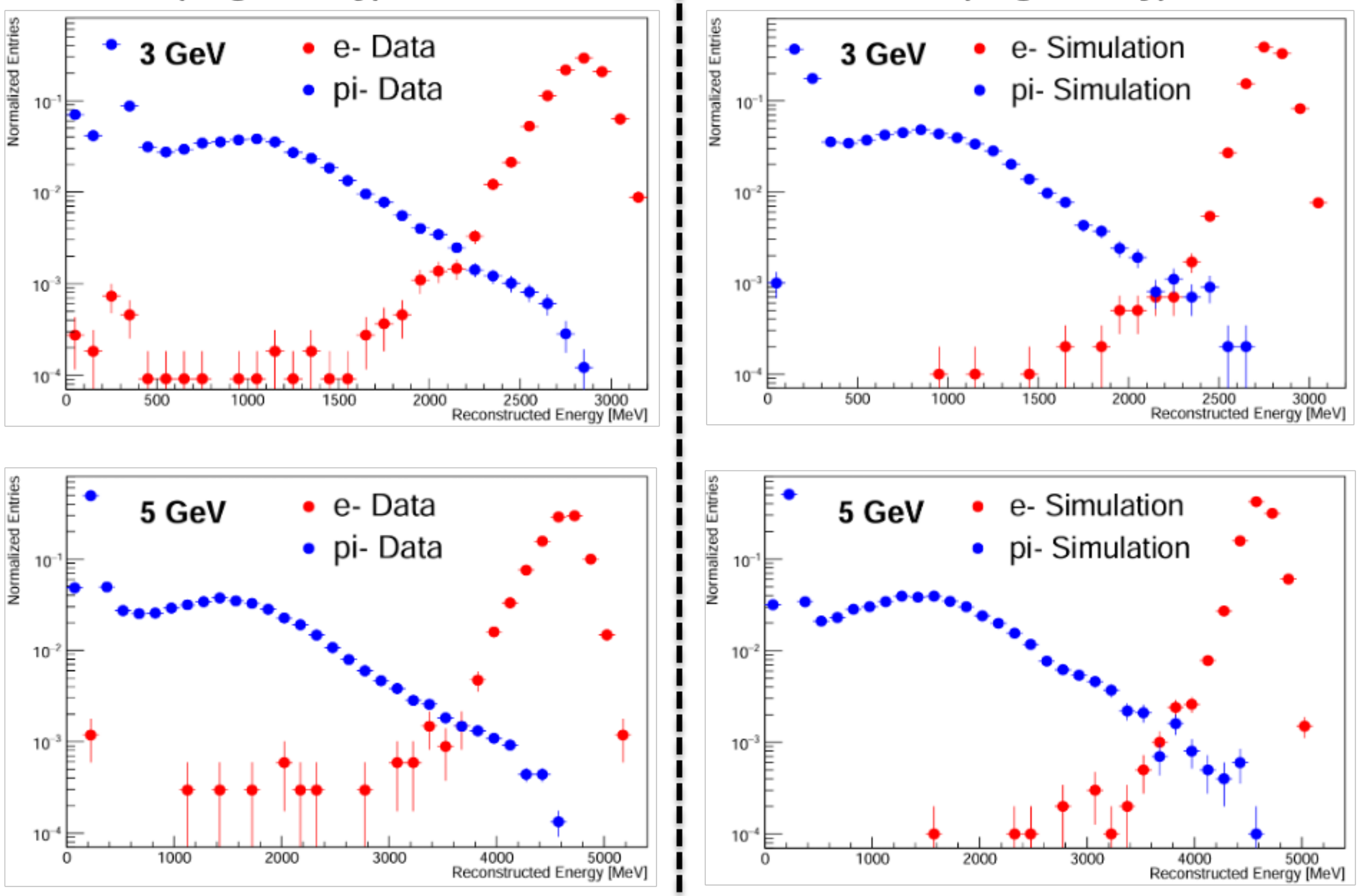
Resolution : (Stochastic) 8.05 %, (Constant) 0.85 %, (Noise) 0.00 %

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

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

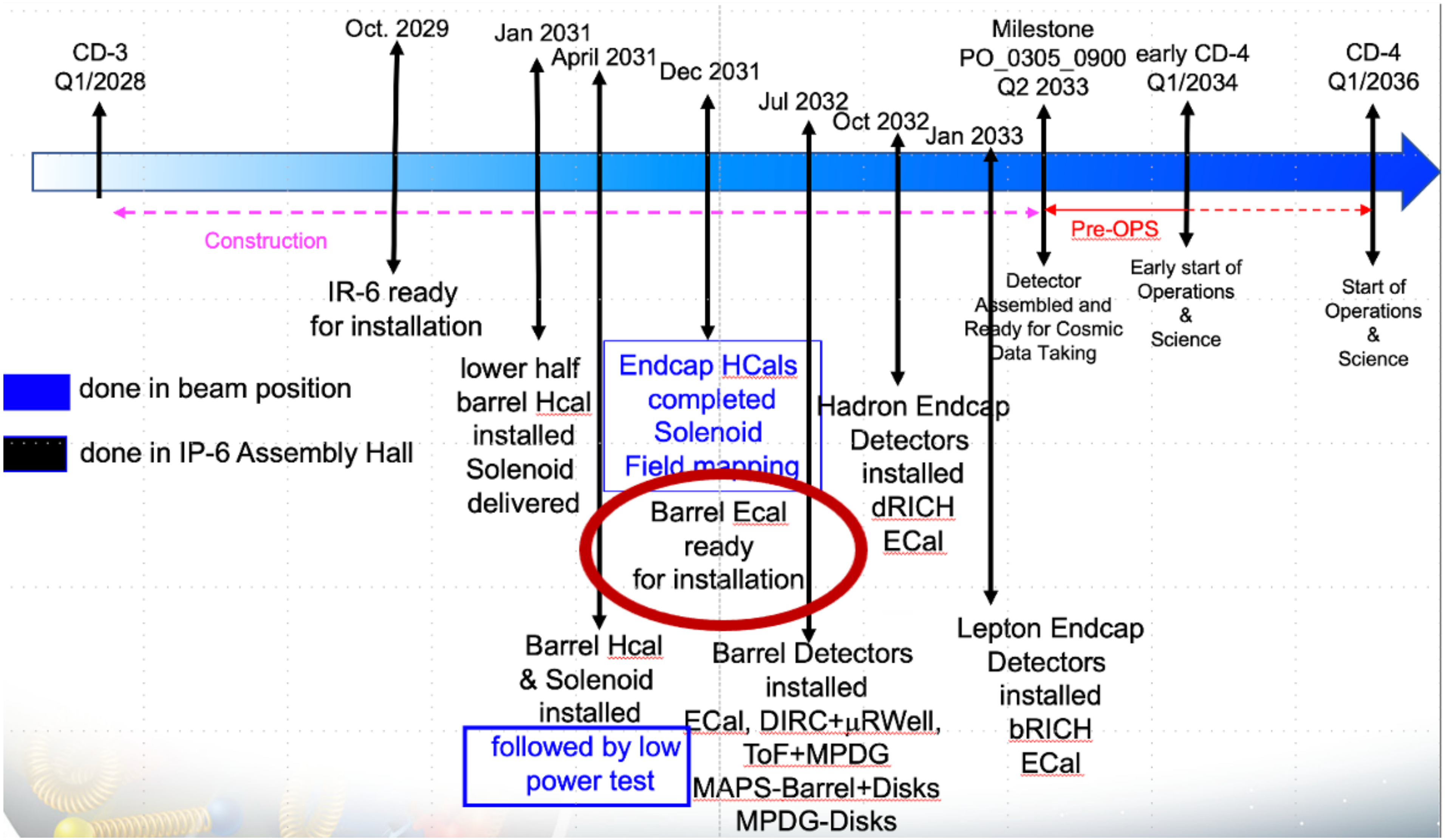
e^-/π^- Separation in Test Beam Data

<Data> (Log scale y) <Simulation> (Log scale y)



- Separating pions from electrons in data using a Cherenkov counter.
- Electron and pion energy distributions in data and simulation show good agreement.
- E/p allows discrimination between electrons and pions entering the calorimeter.

ePIC Schedule



AstroPix v5 Specifications

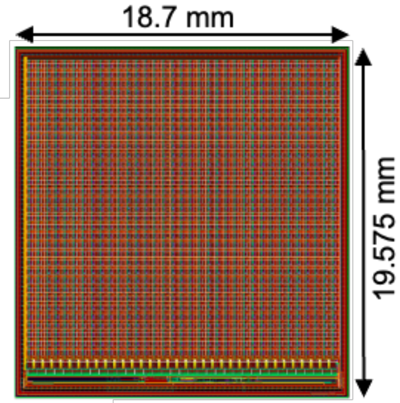
Pixel Matrix:

- 36 cols x 34 rows
  - —32 Columns with Standard NMOS Comparator
  - —2 Columns with dynamic Feedback
  - —1 Column with NMOS Comparator and Resistor Load
  - —1 Column with NMOS Comparator and PMOS Load
- 500u Pixel Pitch
- 3 Tunebits per Pixel
- Pixel Dynamic Range 20 keV - 700 keV
- Noise Floor 5 keV (2%@662 keV)
- Bias Voltage up to 400-500 V to maximize depletion
- Fully NMOS Comparator
- In Pixel amplifier with Dynamic Feedback option for improved Dynamic Range (2 columns)

Power Consumption:

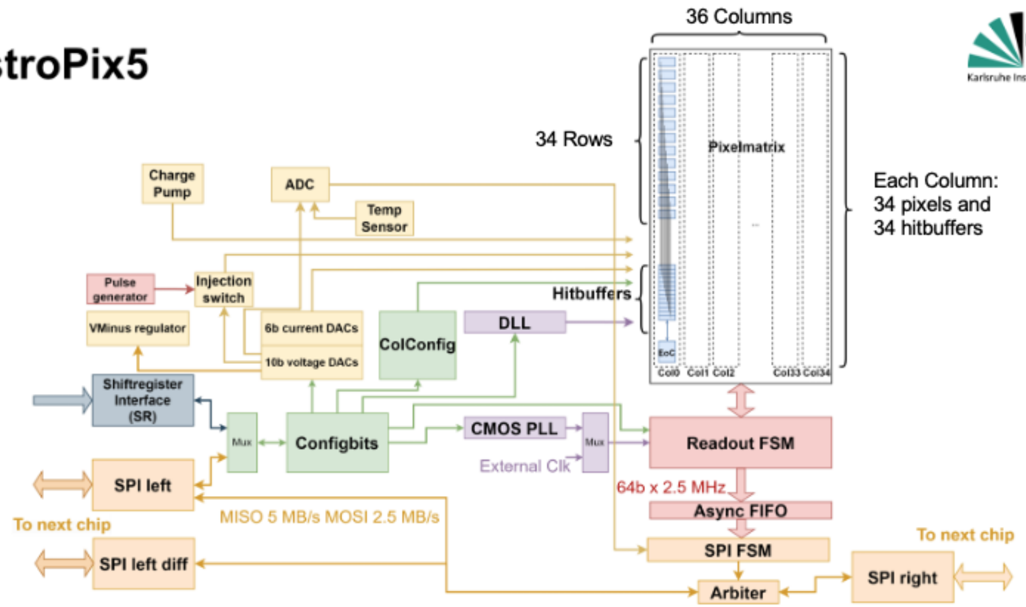
- Pixel 4.6 uW
- Pixel matrix 5.3 mW
- Digital 2.2 mW
  - — 700 uW DigitalTop

Total: ~2 mW/cm^2



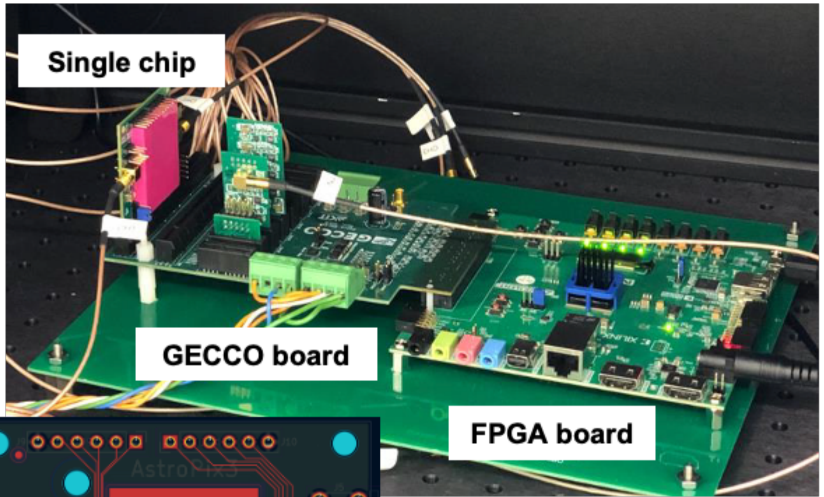
18.7 mm × 19.575 mm chip

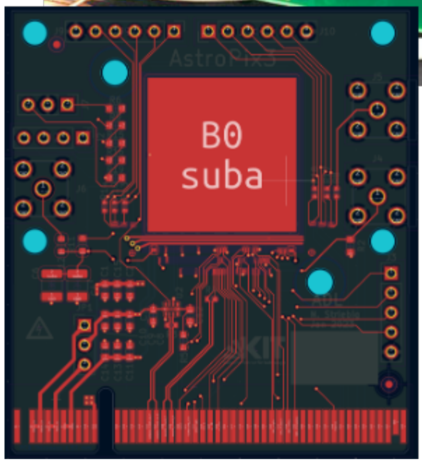
AstroPix5



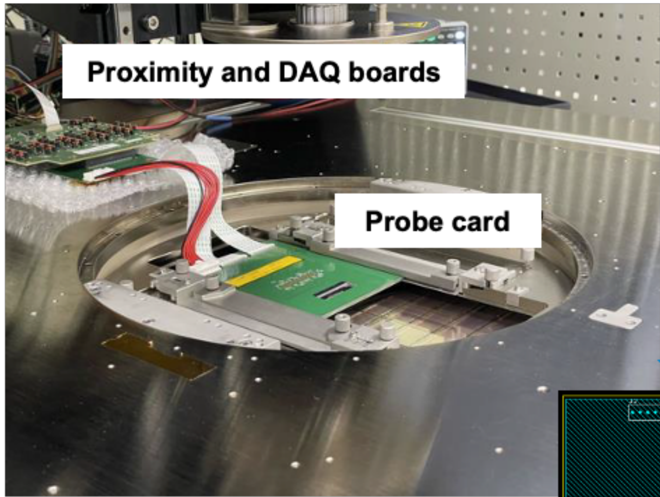
AstroPix Test System

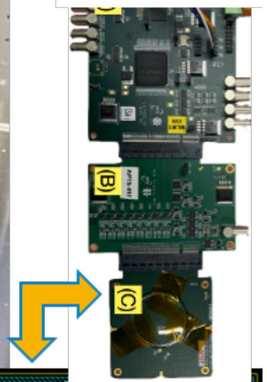
AstroPix v3 lab measurement setup

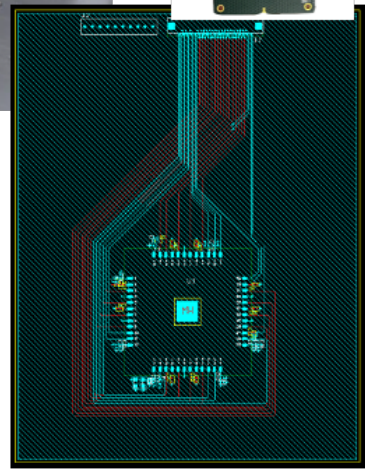




ALICE ITS3 ER1 wafer probing system

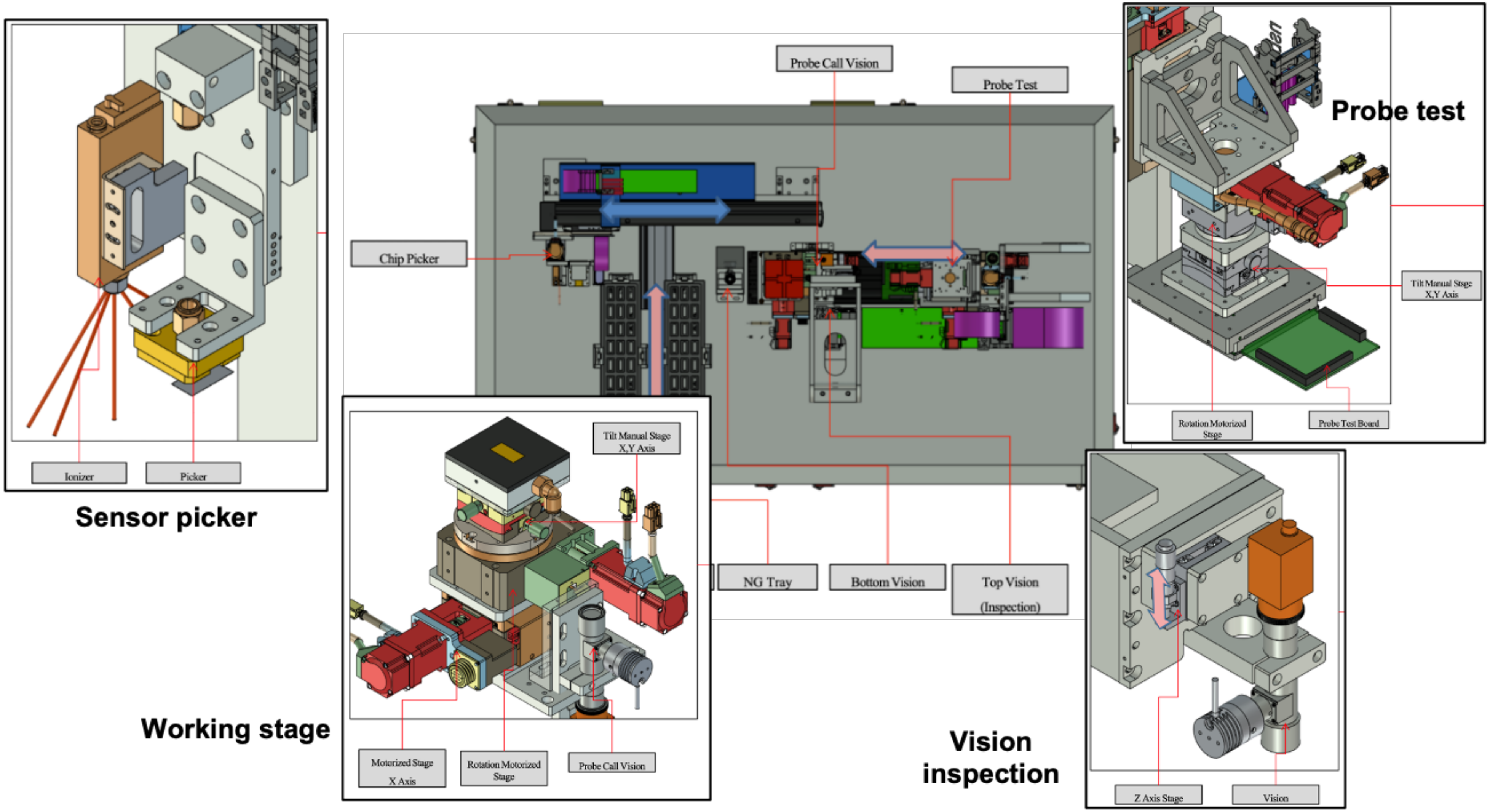






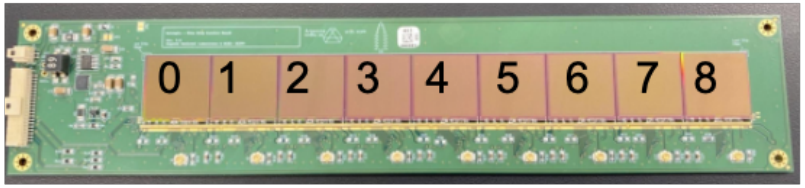
- Initial version of probe card for AstroPix v3: a simple version for the chip carrier board.
- Uses already validated GECCO and FPGA board setup, which will be connected with flexible cables
- Recently, the probe card design for v3 has been done by a local manufacturer in Korea

AstroPix Test System

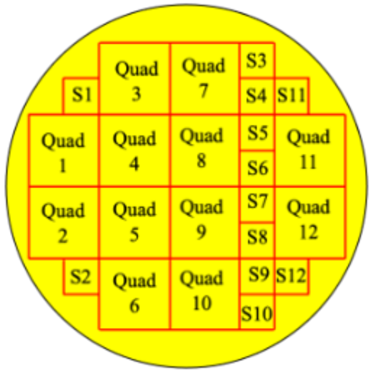


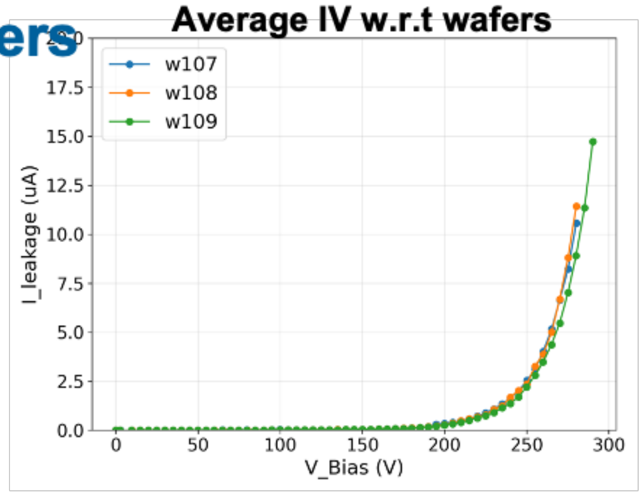
Demonstration of Performance

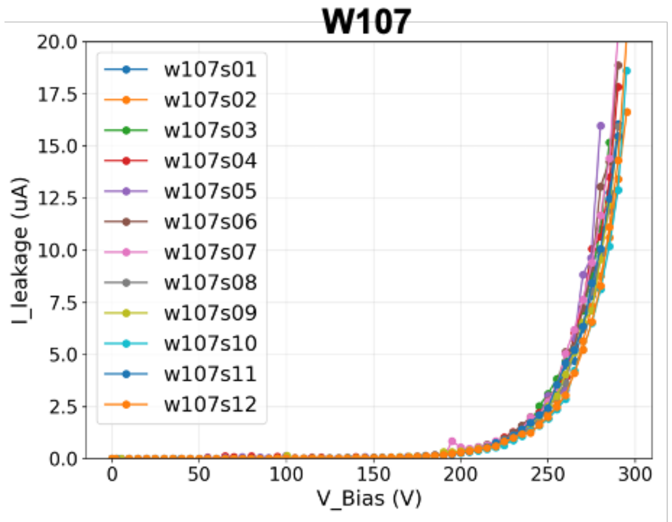
IV trends as function of sensor location on wafers

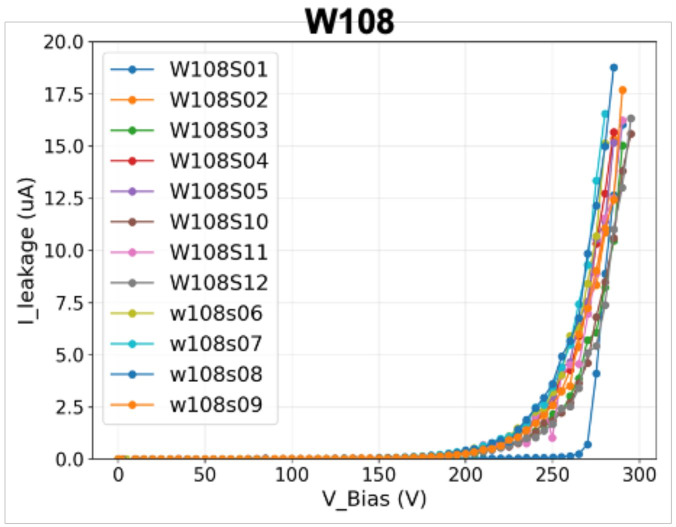


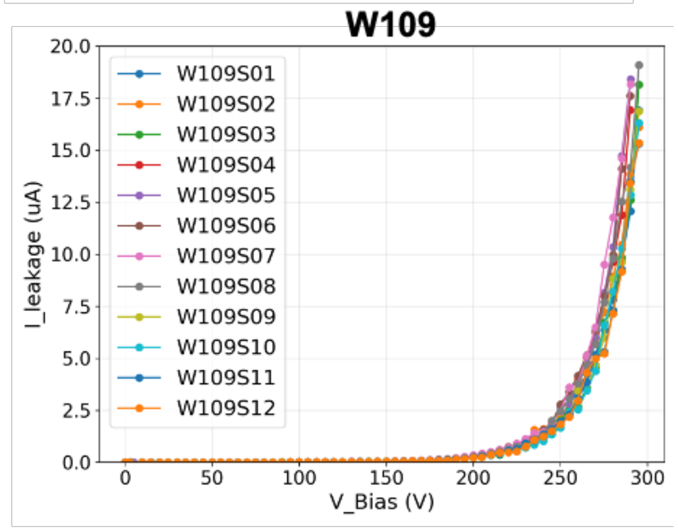
w106s03/04/05/06/07/08/09/10/11 mounted on 9-chip prototype module











Demonstration of Performance

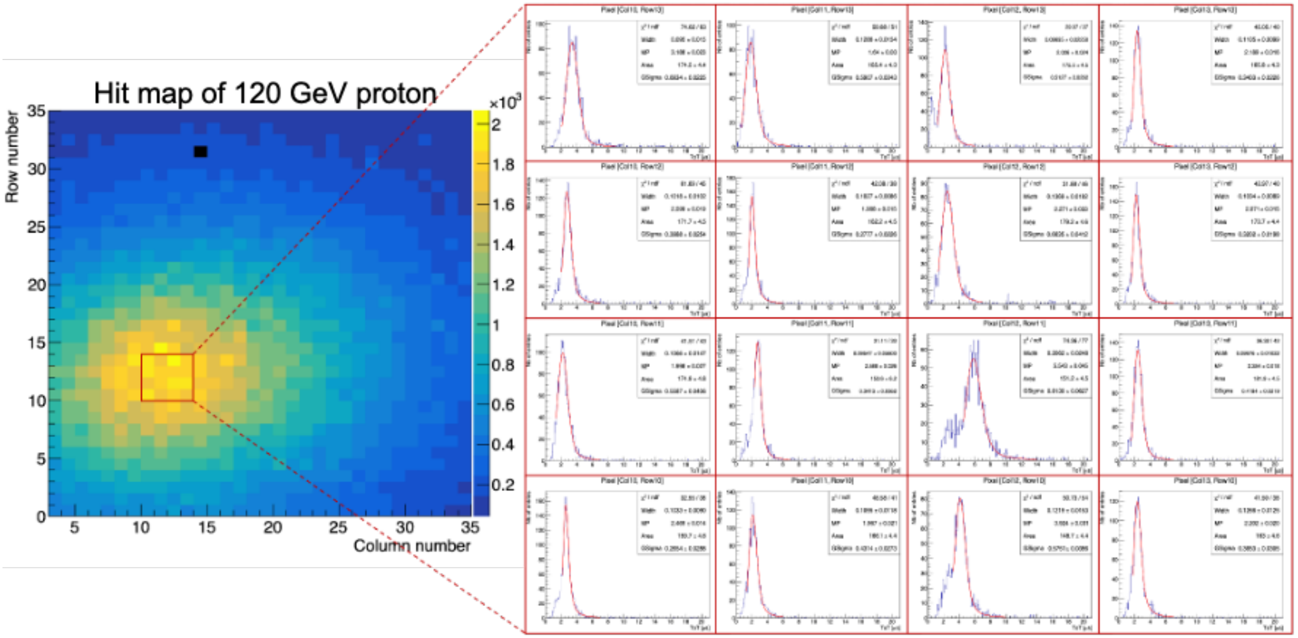
Beam Test of AstroPix v3

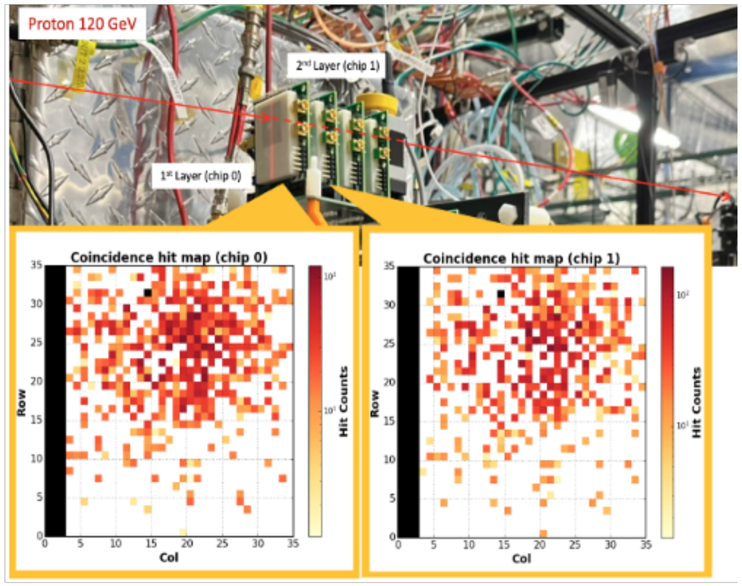
Single layer

- Data collected with a 120 GeV proton beam.
- The hit map reveals the proton beam profile with 500 µm position resolution.
- Histograms of collected ToT values for the marked pixels with MIP response.
- The beam was delivered in 4.2s-long spills every minute, with about 55K particles per spill, resulting in a delivered particle rate of around 13 kHz per spill.

Double layer

- 120 GeV proton beam events from the first two layers, read in coincidence, showing the position of the hit pixel.
- The **proof-of-concept demonstration of the integration of two daisy-chained AstroPix v3 layers in a beam-like environment**





Summary

- In Korea, Calorimeter R&Ds for future collider projects, particularly, FCC-ee and EIC are quite exciting
- We are world-leading group for dual-readout calorimeter for FCC-ee, included in IDEA detector concept
- Korean group is leading the construction of BIC detector in EIC project
  - Construction cost (> $14M) has been approved by government and congress in 2025
  - 7 year construction program will start this year
  - Half of BIC detector will be constructed in Korea!
- If interested, JOIN US!