Barrel Imaging Calorimeter for ePIC experiment at the Electron-Ion Collider

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NUCLEAR PHYSICS LAB

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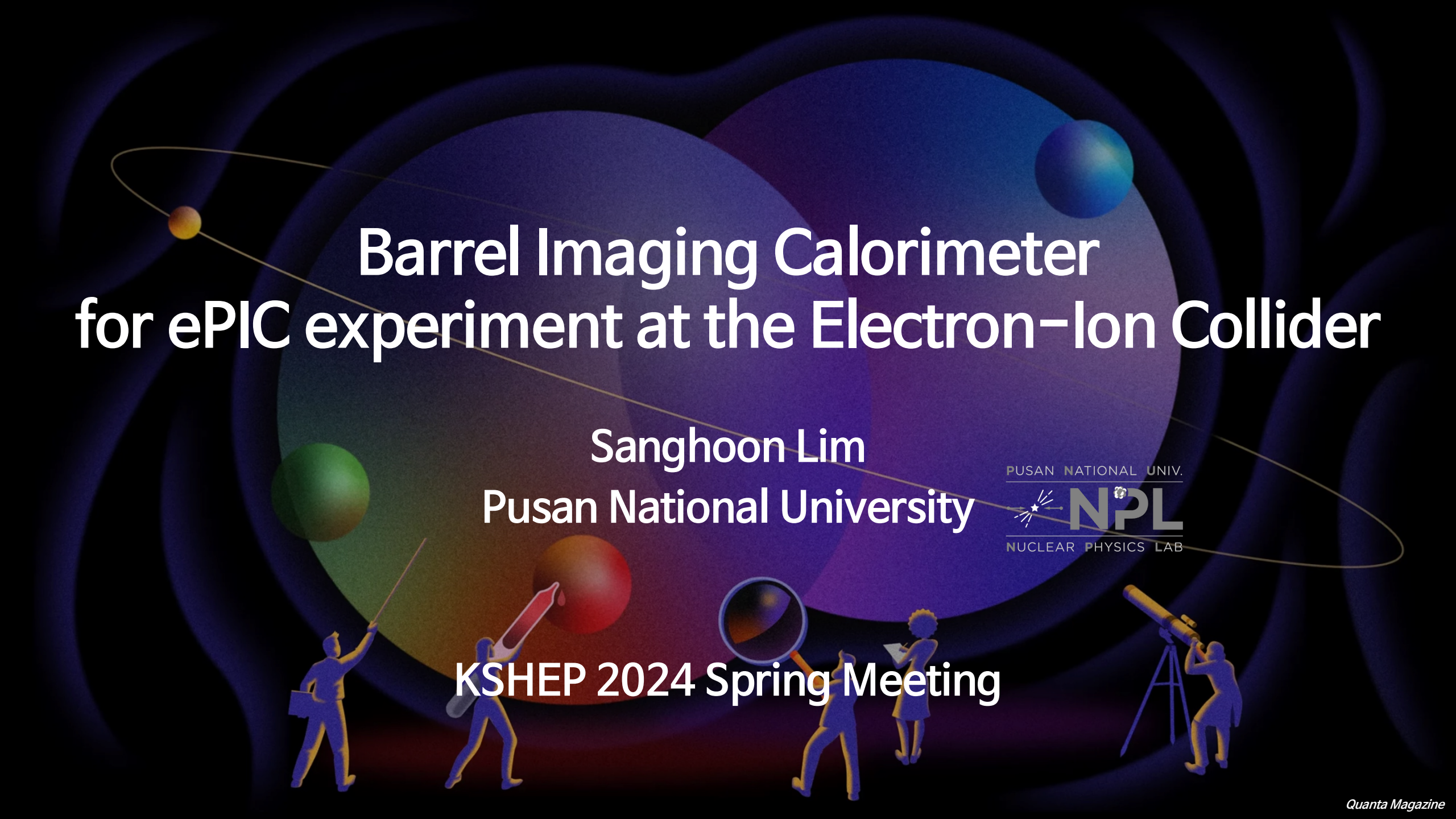
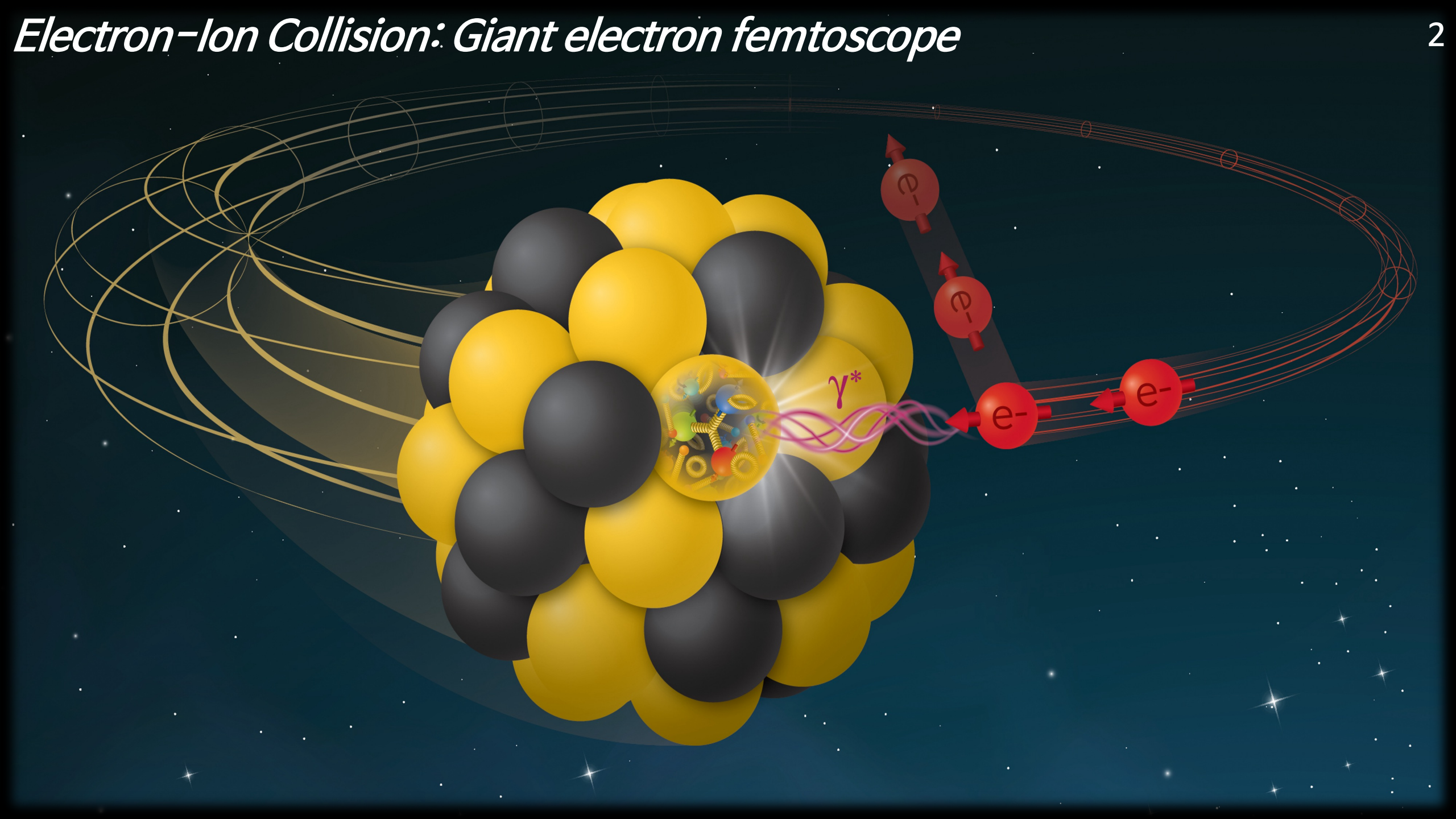
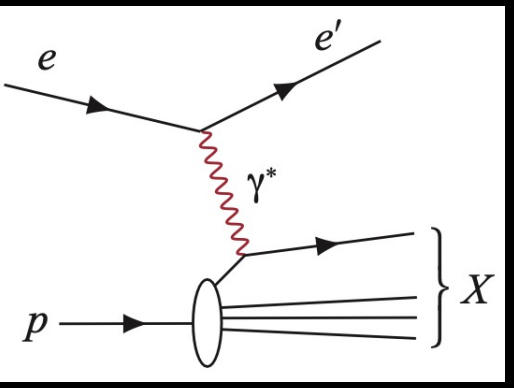


Quanta Magazine

Electron-Ion Collision: Giant electron femtoscope

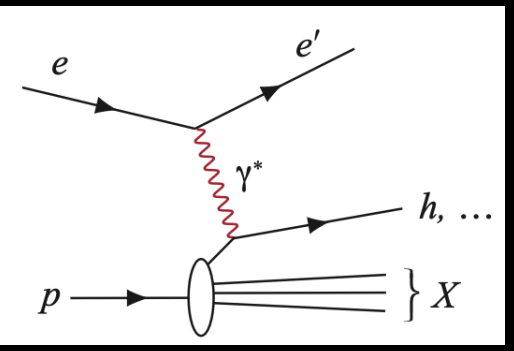


Electron-Ion Collision: Giant electron femtoscope



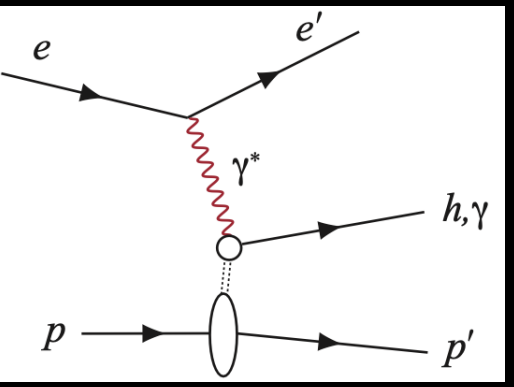
Inclusive DIS

$e + p/A \rightarrow e' + X$



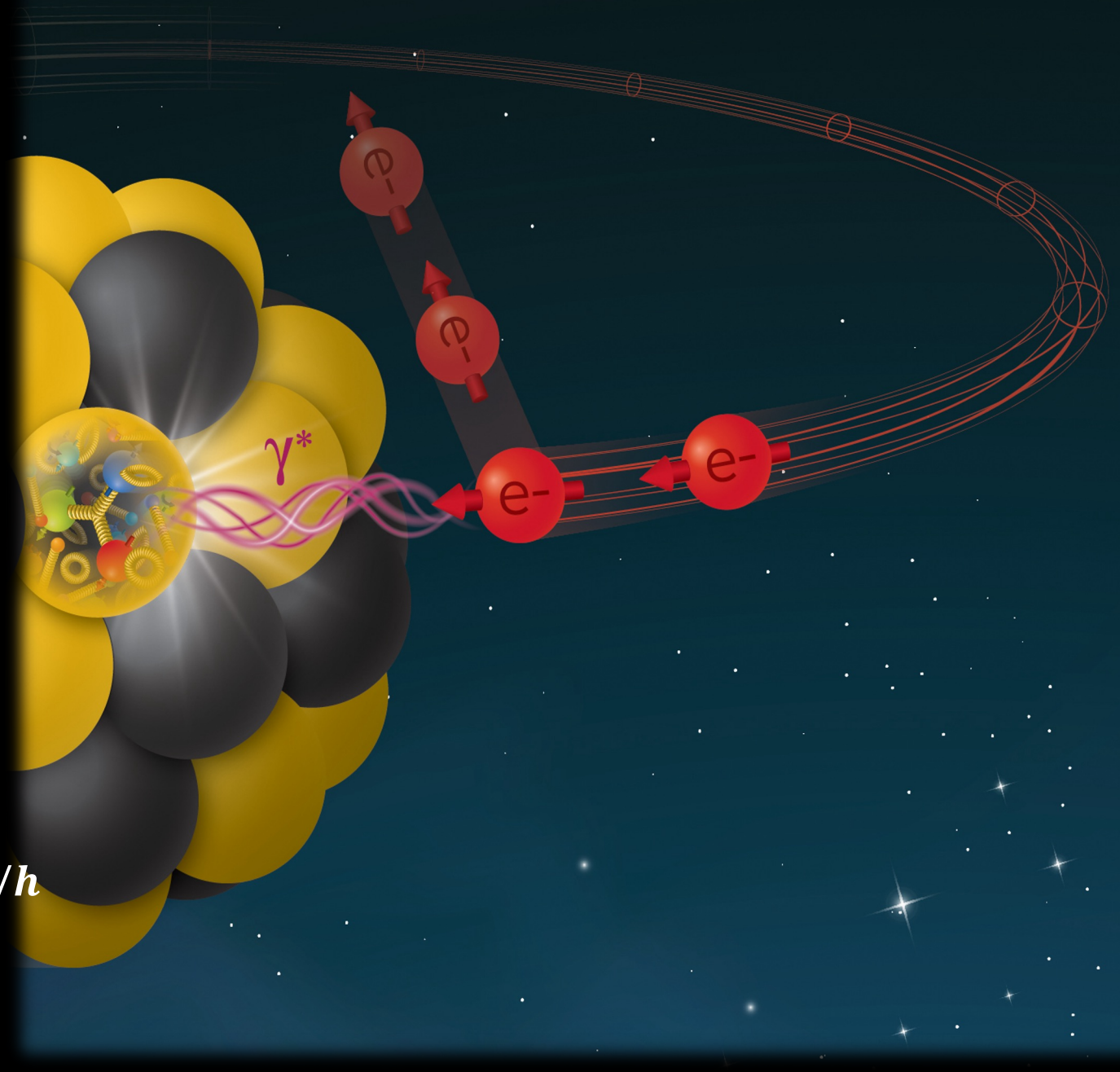
Semi-inclusive DIS

$e + p/A \rightarrow e' + h + X$

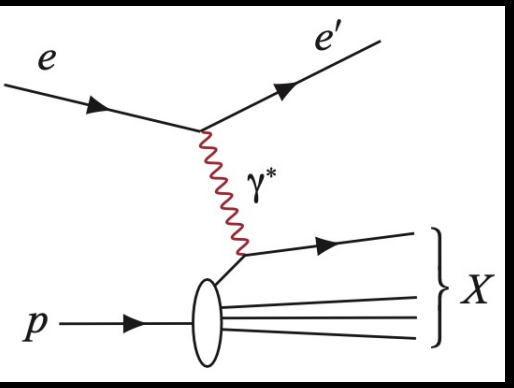


Exclusive DIS

$e + p/A \rightarrow e' + p'/A' + \gamma/h$

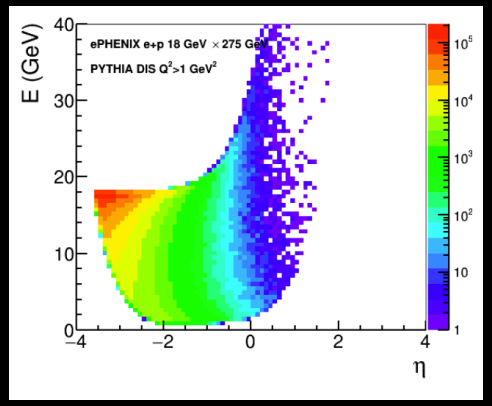


Critical measurements: electron and photon



Inclusive DIS

$e + p/A \rightarrow e' + X$



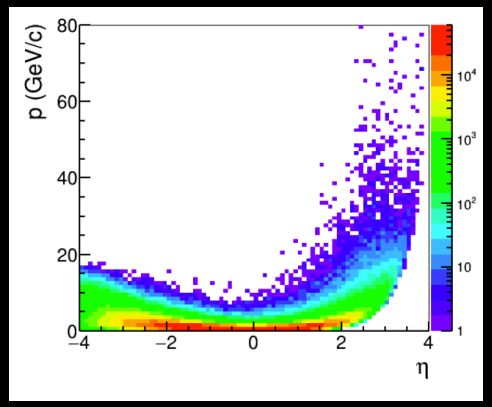
DIS electrons

Inclusive DIS

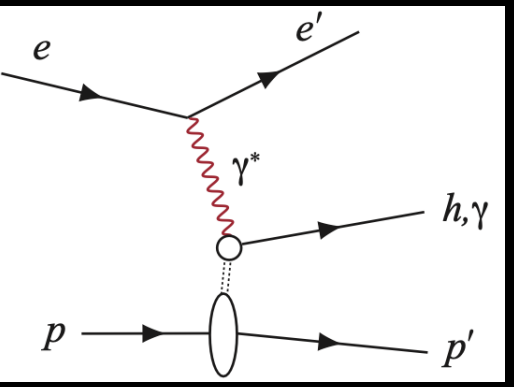
$e + p/A \rightarrow e' + X$

Semi−inclusive DIS

$e + p/A \rightarrow e' + h + X$

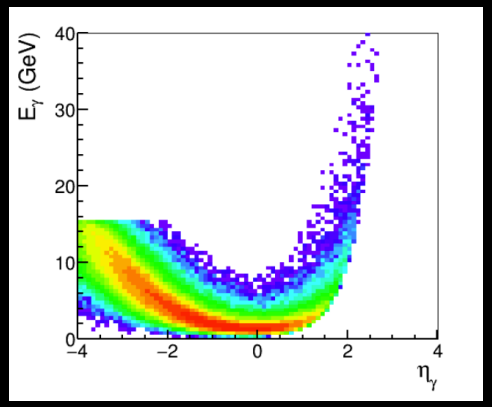


SIDIS π^0



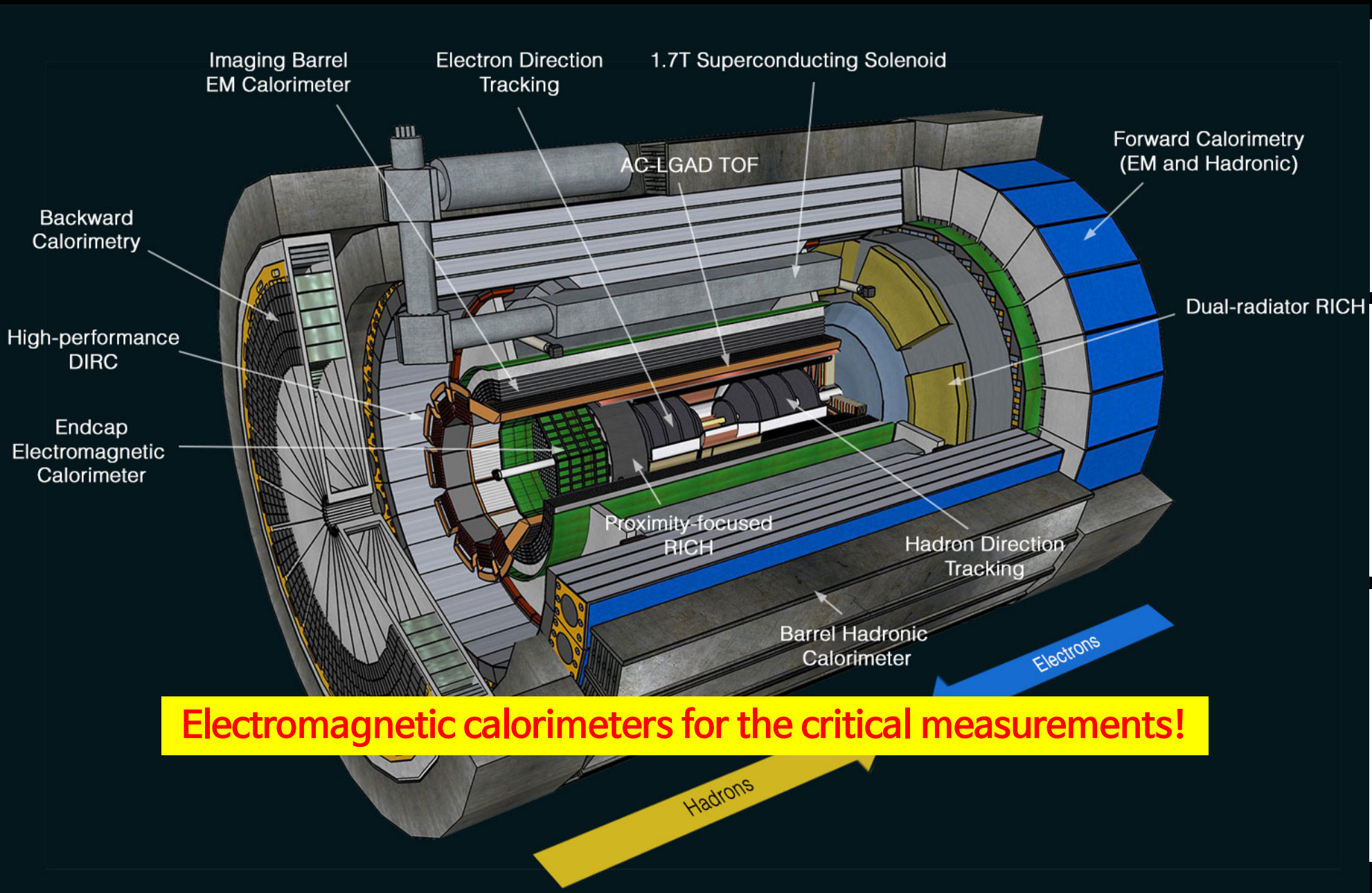
Exclusive DIS

$e + p/A \rightarrow e' + p'/A' + \gamma/h$

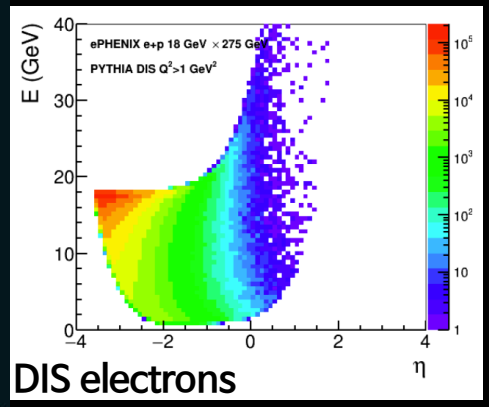


DVCS photons

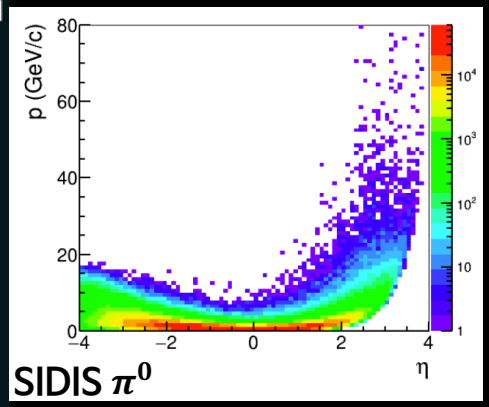
Detector for the EIC: ePIC



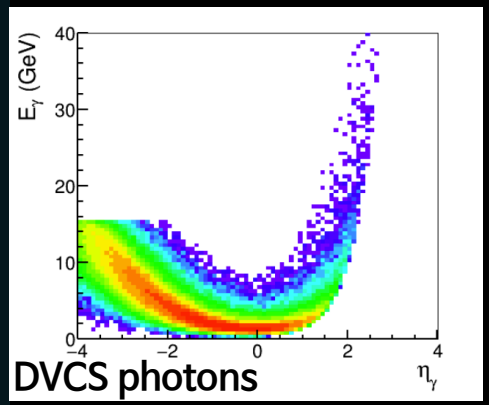
Electromagnetic calorimeters for the critical measurements!



DIS electrons

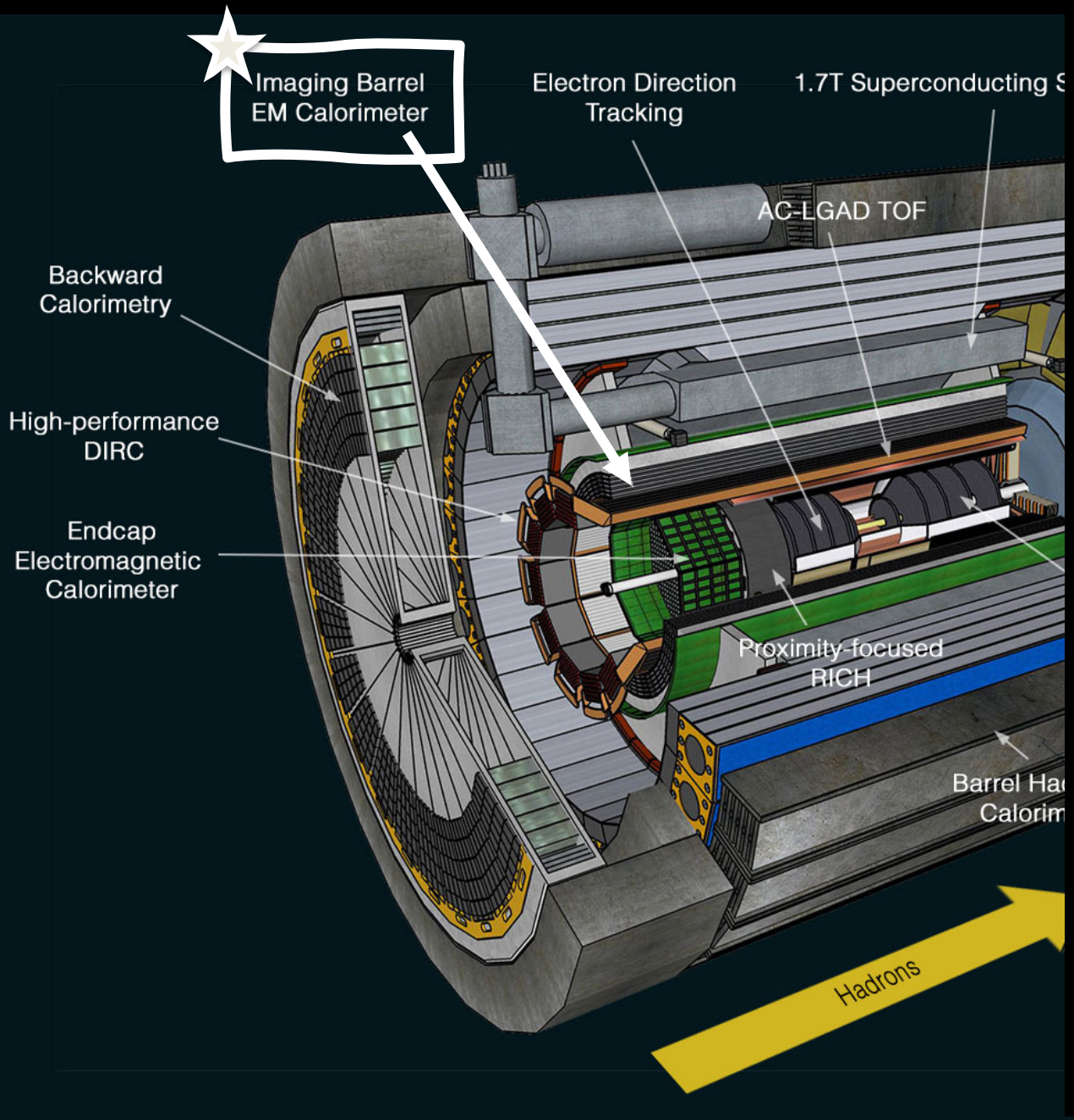


SIDIS π^0

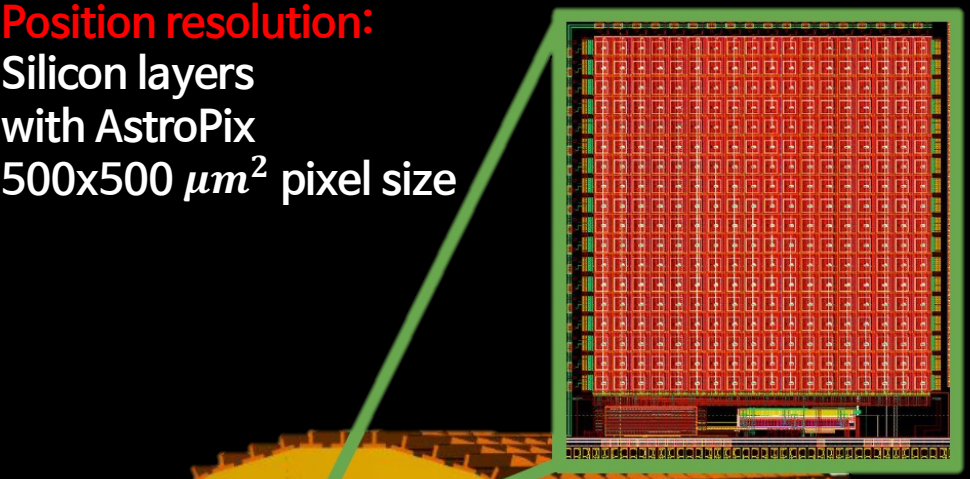


DVCS photons

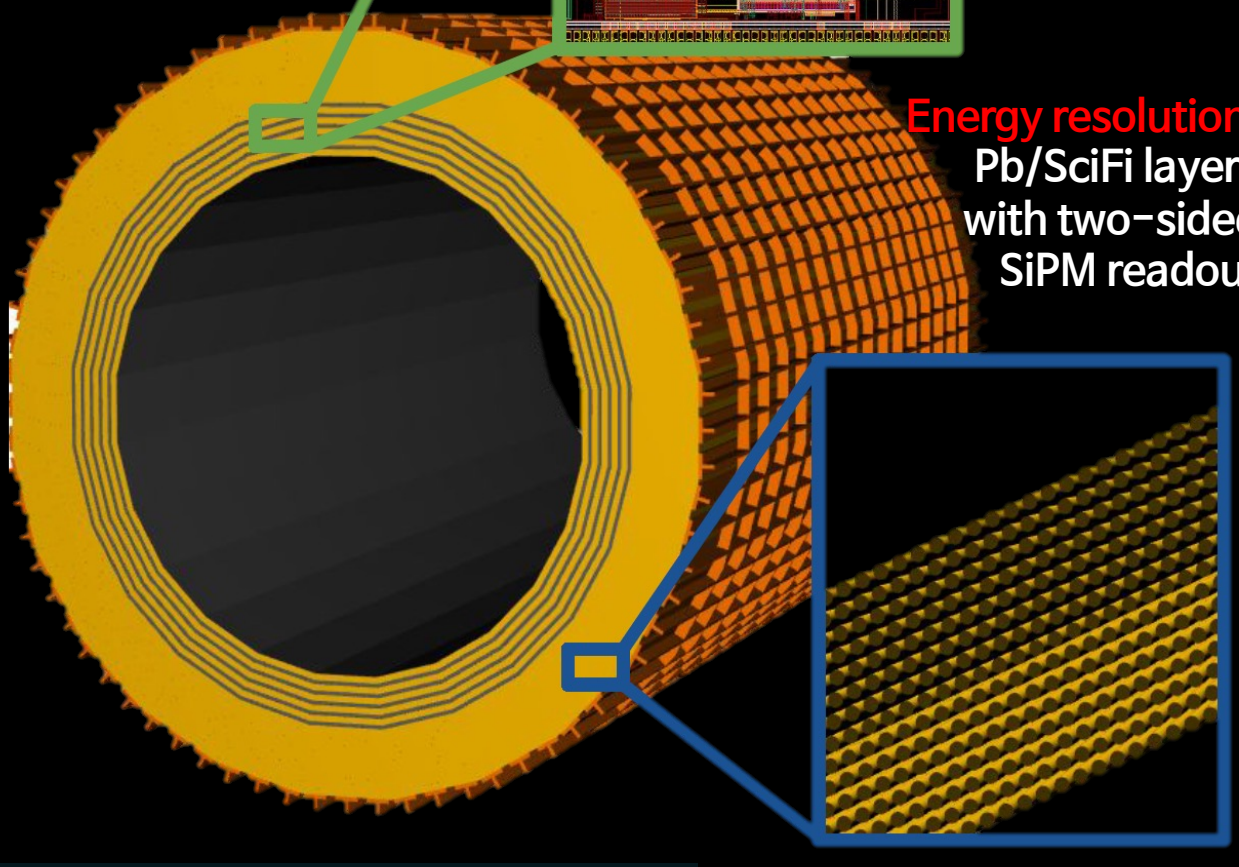
Barrel Imaging Calorimeter



Position resolution:
Silicon layers
with AstroPix
500x500 μm^2 pixel size

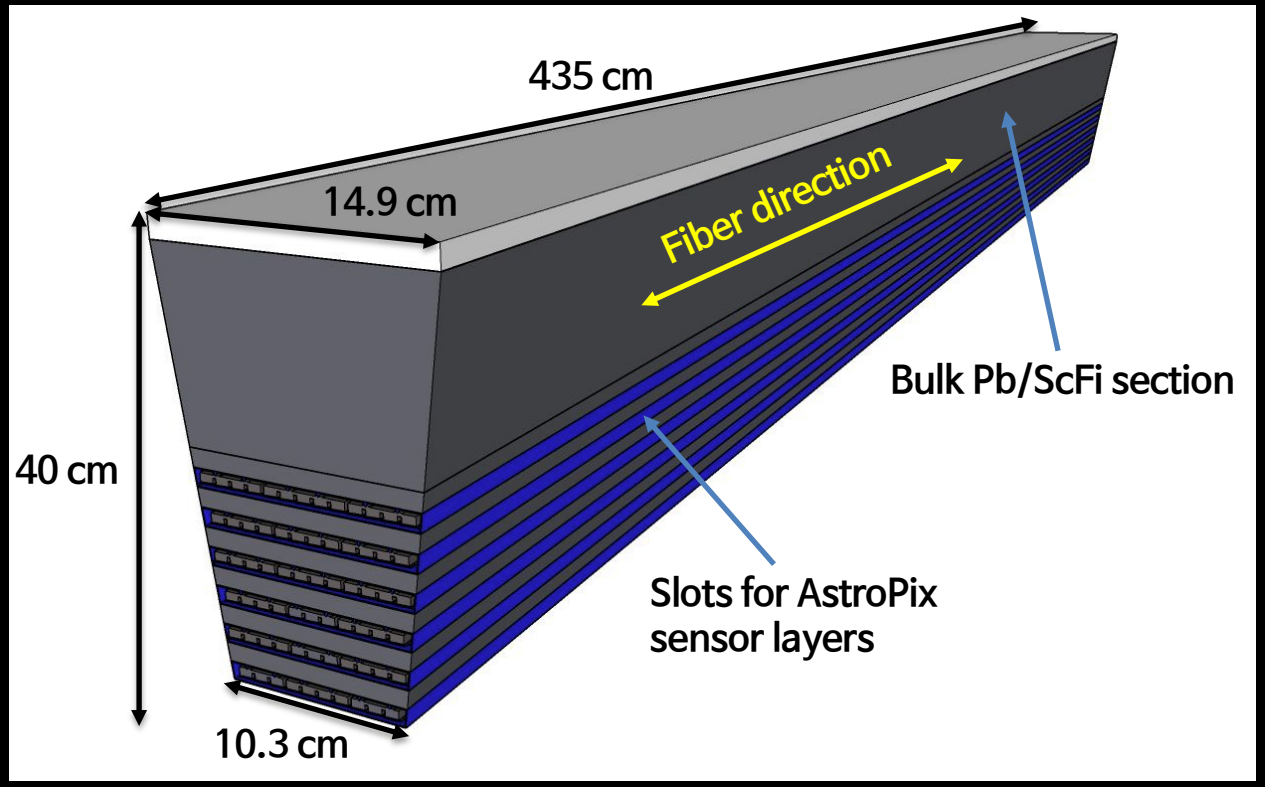


Energy resolution:
Pb/SciFi layers
with two-sided
SiPM readout



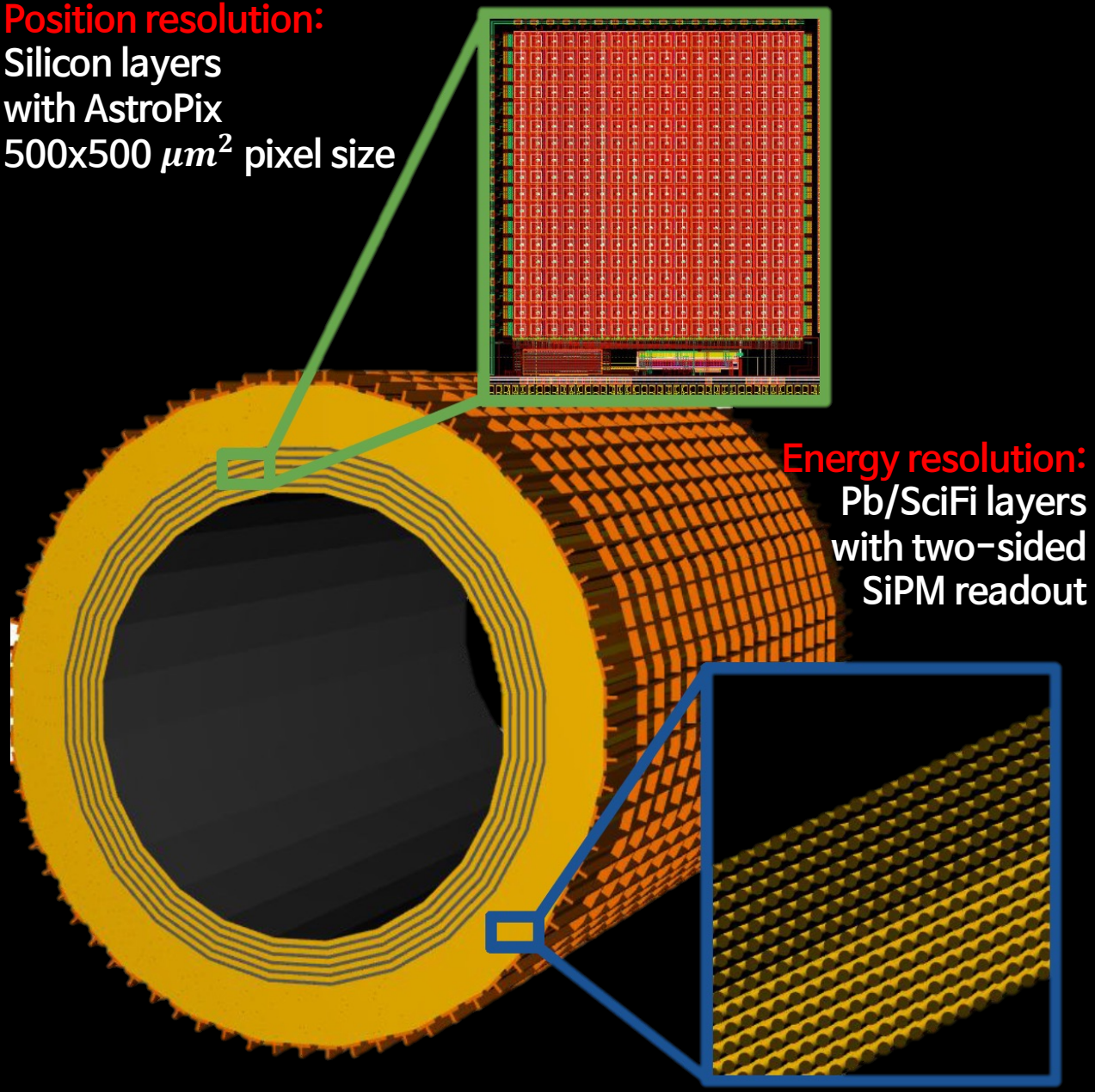
Barrel Imaging Calorimeter

BIC Sector (total 48 sectors)



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

Position resolution:
Silicon layers
with AstroPix
500x500 μm^2 pixel size



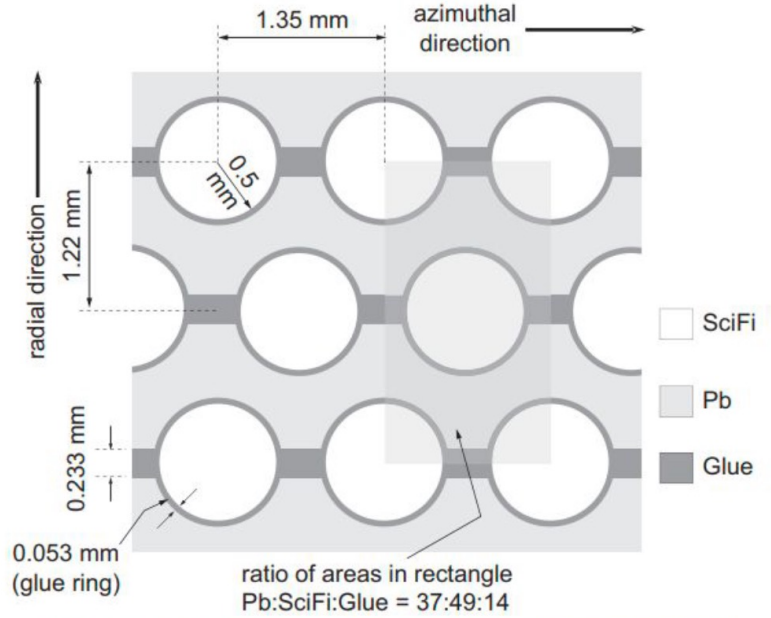
Energy resolution:
Pb/SciFi layers
with two-sided
SiPM readout

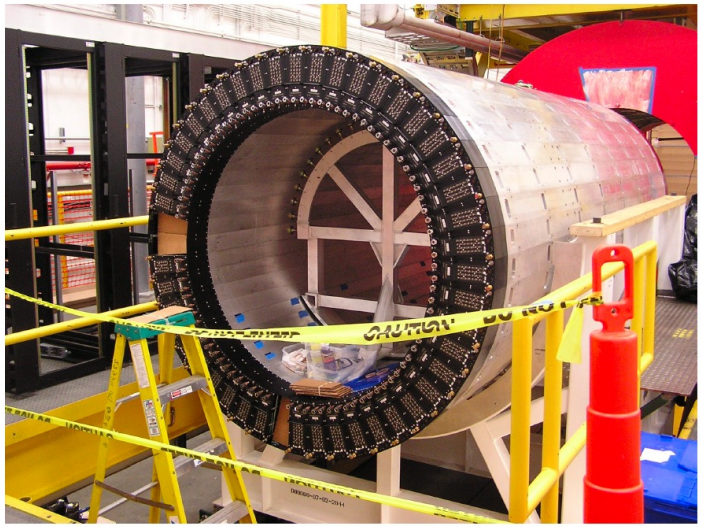
Barrel Imaging Calorimeter: Pb/SciFi layers

- **SciFi/Pb layers follow the GlueX Barrel Calorimeter**
  Energy resolution: $5.2\%/\sqrt{E} \oplus 3.6\%$
- **Position resolution in z: 1.1 cm/$\sqrt{E}$**
  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.
  -Module construction (lead handling, swaging, Pb/SciFi layers assembly, module machining) fully developed for GlueX

	ePIC	GlueX
Diameter (m)		
Inner	1.62	1.3
Outer	2.6	1.8
Length (m)	4.35	3.90
# Sectors	48	48
Mass/sector (T)	1.1	0.58
Weight	36 tons	23 tons

- Design hybrid vs monolithic
- 4,500 km vs 3,300 km
- Si cookies + Light guides
- Large area SiPMs





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

Barrel Imaging Calorimeter: Pb/SciFi layers (R&D)

- **R&D goals with GlueX Baby BCal prototype**
  - Pb/SciFi tested extensively for energies $E_\gamma < 2.5$ GeV
  - ➔**higher-energy data** is essential to constrain **the constant term** of energy resolution

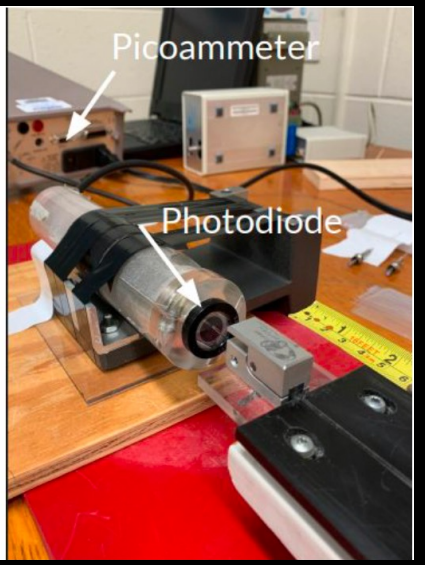
  - **Obtain responses to EM showers** to benchmark simulations and provide input to the realistic waveform analysis (Hall D, electrons up to 6.2 GeV)

  - **Test with hadronic beams** in the integrated system with AstroPix sensor and thin Pb/SciFi layers to benchmark response to hadronic showers

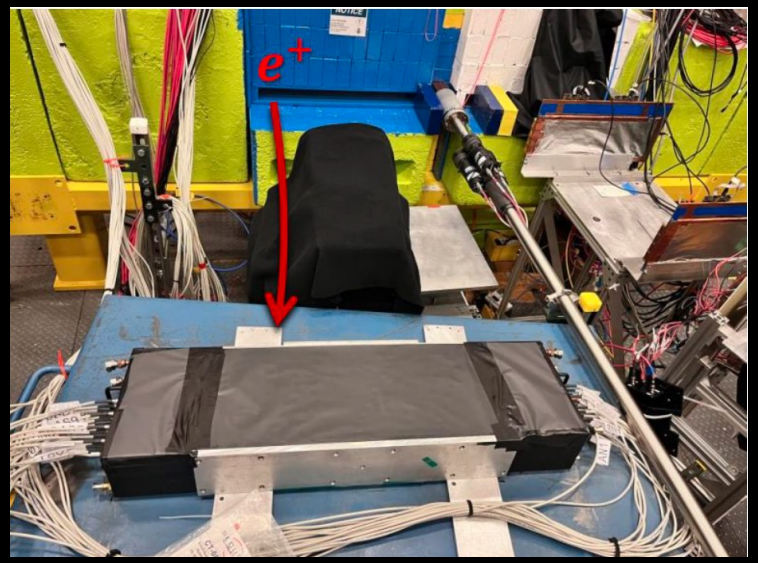
- **R&D goals with fibers**
  Light output and attenuation length measurements with single- and double-clad fibers from Kuraray and Luxium

Baby BCal ~15.5 X_0

Attenuation length study



Test beam at Hall D, JLab



Barrel Imaging Calorimeter: Imaging layers

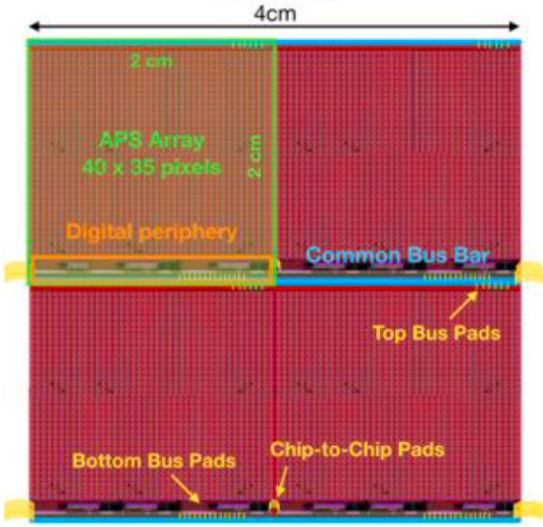
- **Imaging layers based on AstroPix sensors**
  Developed for AMEGO-X NASA mission
  CMOS sensor based on ATLASpix3 (arXiv:2109.13409)

- **Key features:**
  Very low power dissipation (<1 mW/cm^2)
  500 μm pixel size
  Time resolution ~3.25 ns

- **AstroPix chip R&D:**
  v1 (4.5×4.5 mm^2, 200 μm pixel)
  v2 (1×1 cm^2, 250 μm pixel)
  -Tested with γ, β sources, and 120 GeV proton beam
  v3 (2×2 cm^2, 500 μm pixel, quad chip)
  -Ongoing bench and beam test
  -Main prototyping with this chip version
  v4 (1×1 cm^2, 500 μm pixel)
  -Engineering run

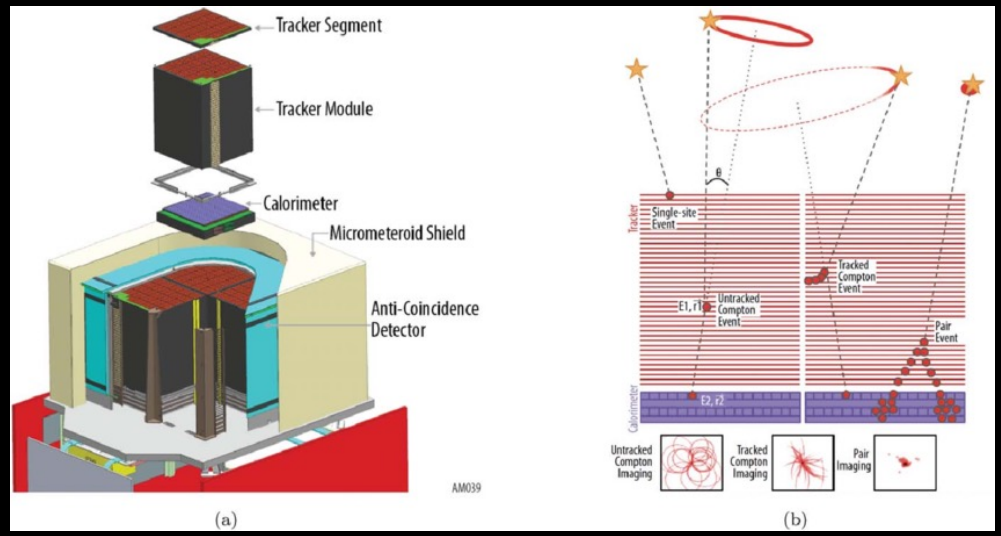
- **Total number of 2x2 cm^2 chips: ~250,000**
  ➔ ~100 m^2

Quad chip v3



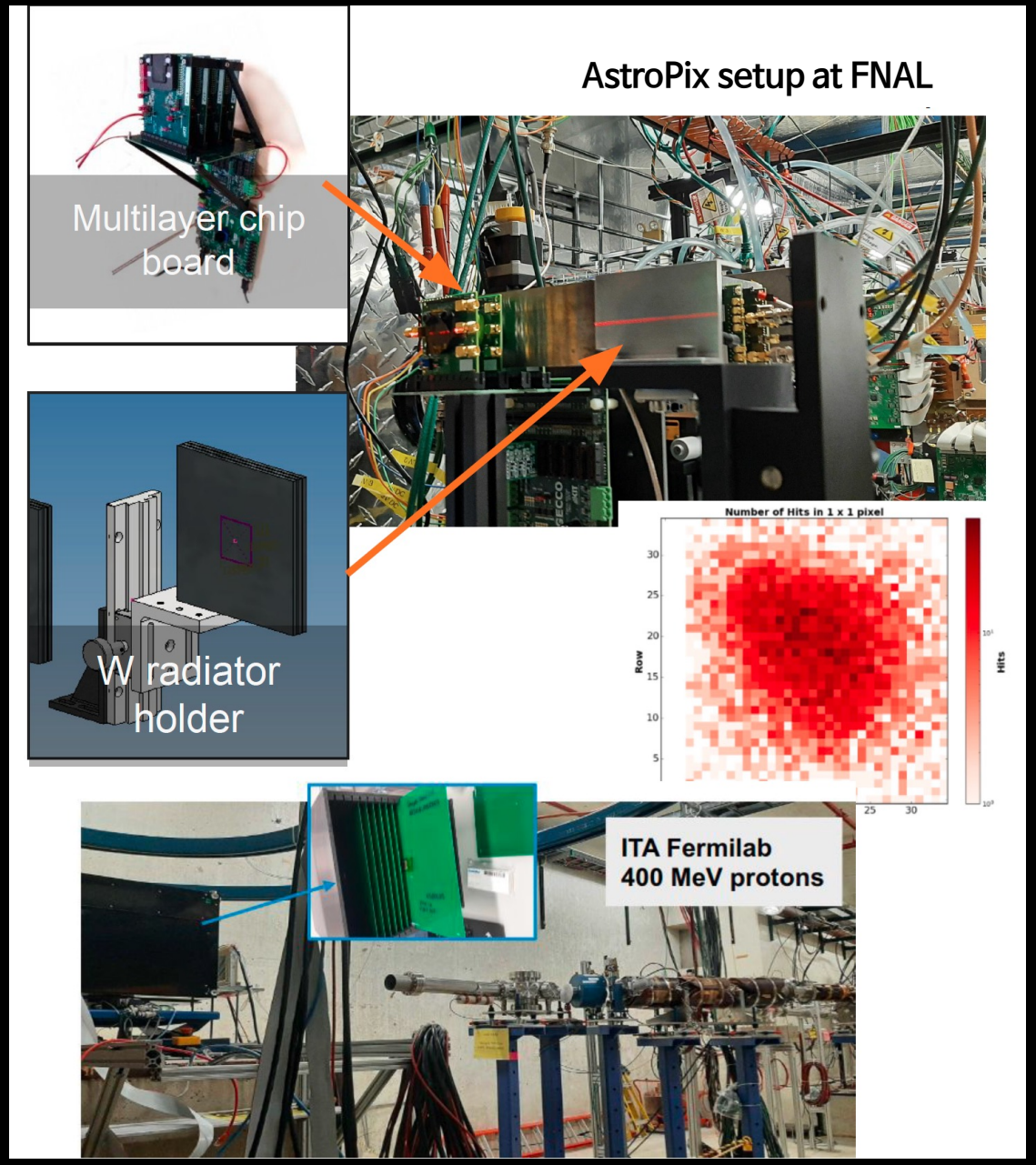
v3 carrier board

AMEGO-X gamma ray telescope



Barrel Imaging Calorimeter: Imaging layers (R&D)

- **Tests of AstroPix v2/v3 sensor**
  - –Multilayer chip tests in FNAL with protons, pions, and electrons, tests with W radiator, readout aspects (Beam tests in February and May 2023)
  - –Irradiation test in the FNAL ITA Facility
- **Plan:**
  - –Study response to electromagnetic/hadronic shower with multilayer AstroPix v3 prototype integrated with the Pb/SciFi layers
  - –Investigate the overall procedure for mass production (chip test and module assembly)



Organization

Co-DSL
Sylvester Joosten

Co-DSL
Hwidong Yoo

Deputy-DSL
Maria Żurek

North America

DSTC (Silicon)
Jessica Metcalfe

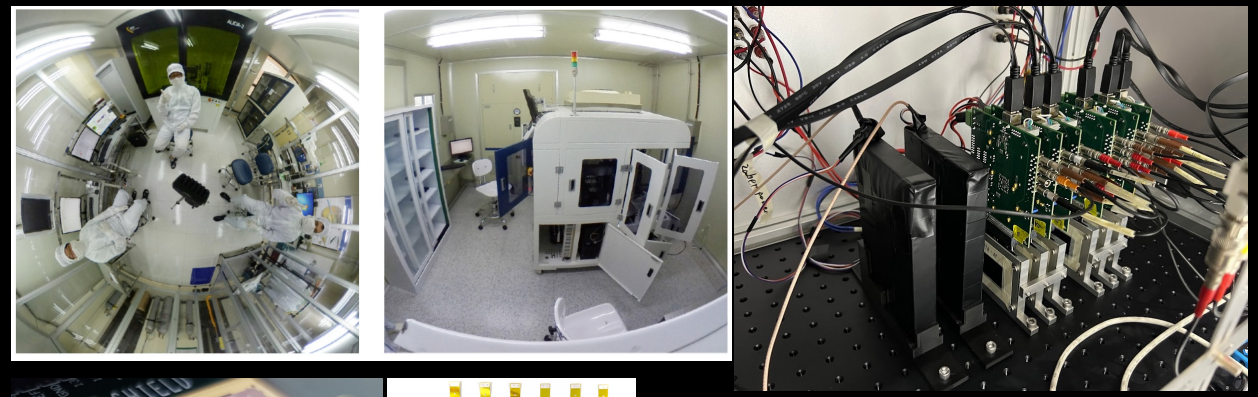
DSTC (Pb/ScFi)
Zisis Papandreou

Korea

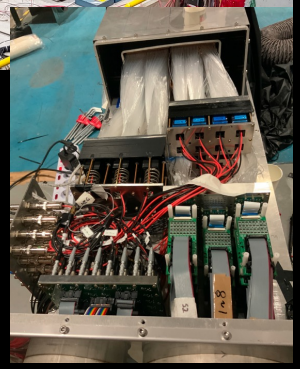
DSTC (Silicon)
Sanghoon Lim

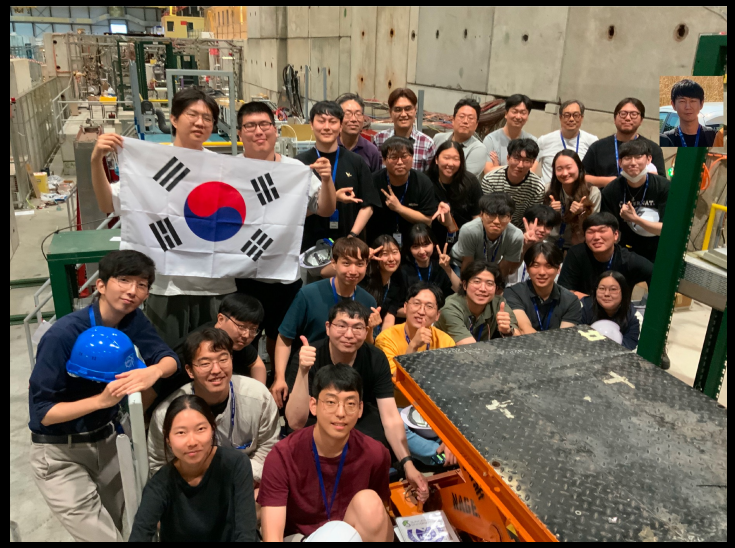
DSTC (Pb/ScFi)
Hyon-Suk Jo

- Silicon tracker for ALICE at the LHC



- Dual readout calorimeter for IDEA at the FCC





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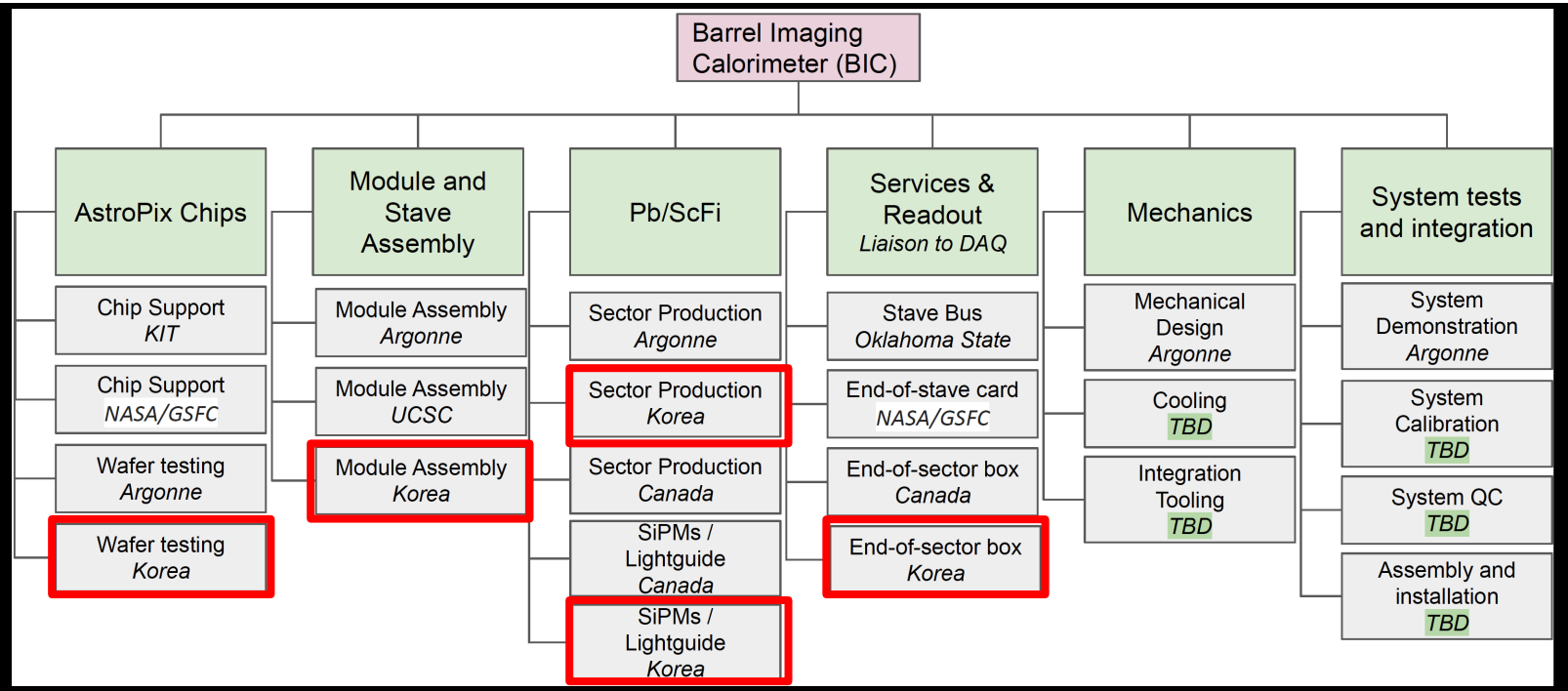
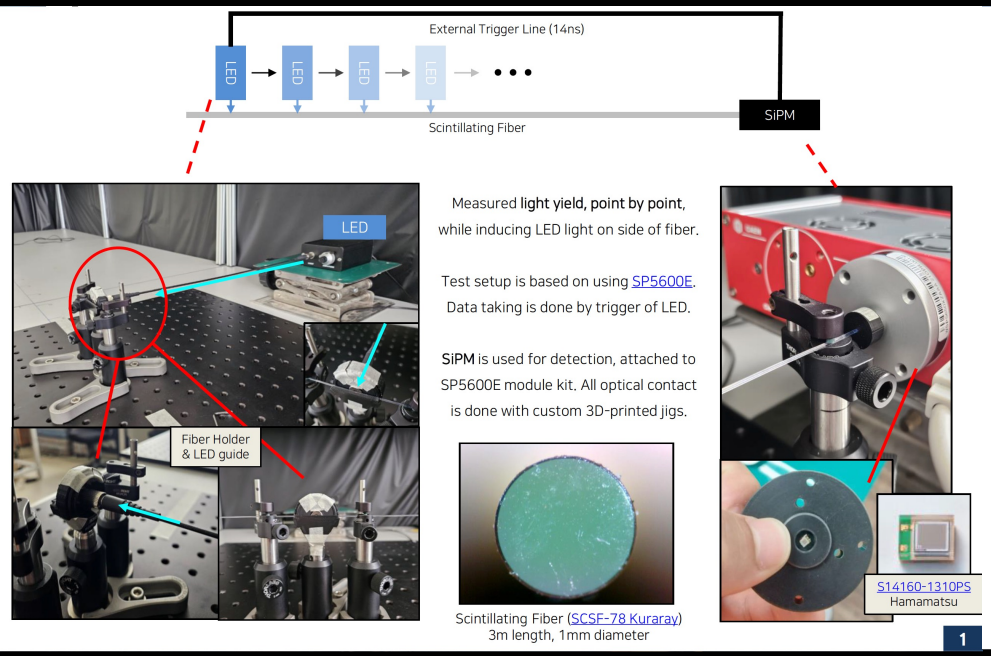


Activity & plan from Korean group

○ Fiber attenuation measurement

Comparison between single and double cladding



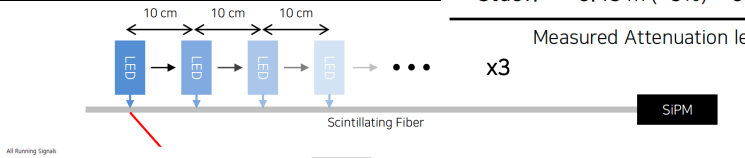
Measured **light yield, point by point**, while inducing LED light on side of fiber.

Test setup is based on using SP5600E. Data taking is done by trigger of LED.

SiPM is used for detection, attached to SP5600E module kit. All optical contact is done with custom 3D-printed jigs.

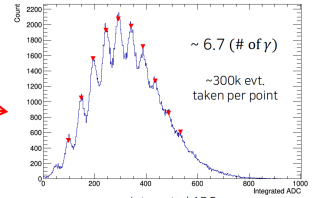
Scintillating Fiber (SCSF-78 Kuraray)
3m length, 1mm diameter

1

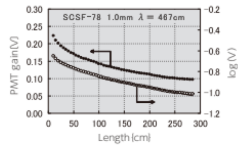


x3

Single waveform from HERA (LINK)



- Used HERA, which software is provided by CAEN, for controlling SiPM & data taking.
- Measured 1.0~2.4m, 10cm interval 15 points | 3 measurement per points
- Made 3 iterations of measurement, each following through guide line.
- Used #of γ as light yield, which can be obtained from multi-photon peak of integrated ADC plot.
- Used average of 3 measurements as value, RMS as error of the points.
- Fit points using single exponential function - $\text{Light Yield}(x) = I_0 \exp(-\frac{1}{\lambda}x)$, ($\lambda$: Attenuation length)

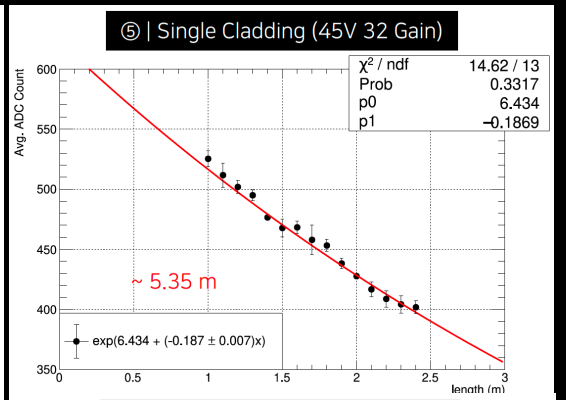


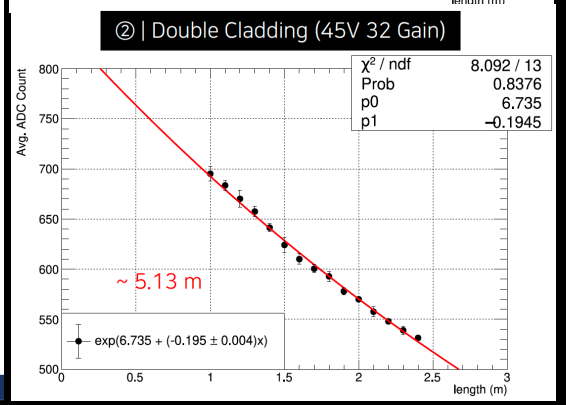
Attenuation measurement from SCSF-78 spec. sheet

2

	SC	DC
Avg.	5.19 m	4.87 m
Stdev.	0.45 m (~9%)	0.18 m (~4%)

Measured Attenuation length



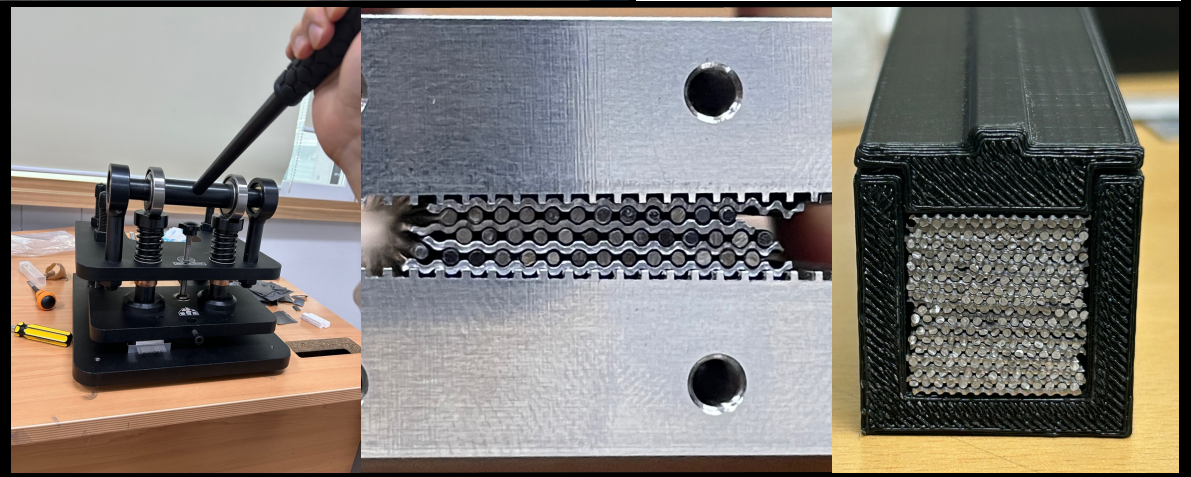


○ Prototype Pb/SciFi production

A similar design to the GlueX prototype

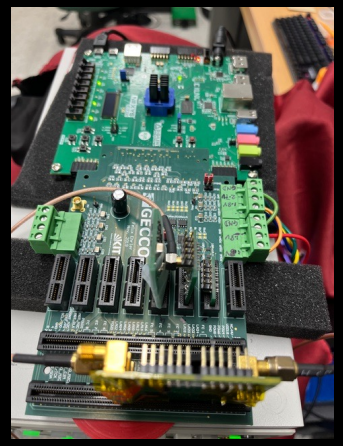
Under development of procedure for the prototype production

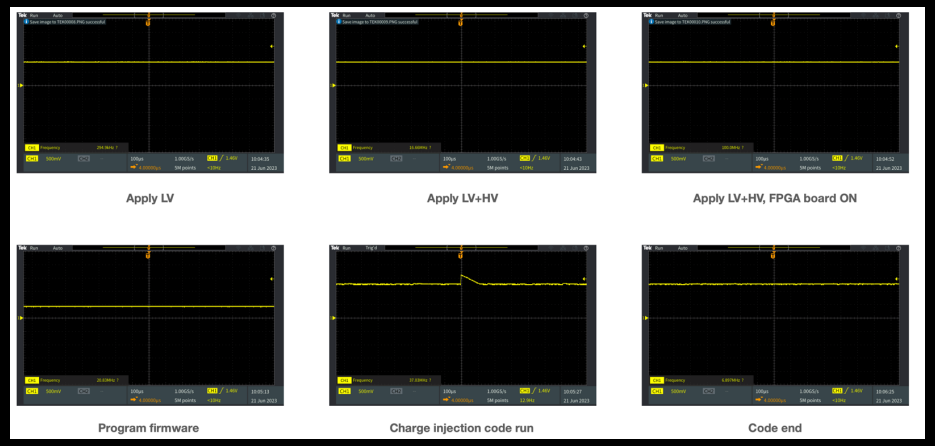
Plan to perform a test beam at PS or SPS in August



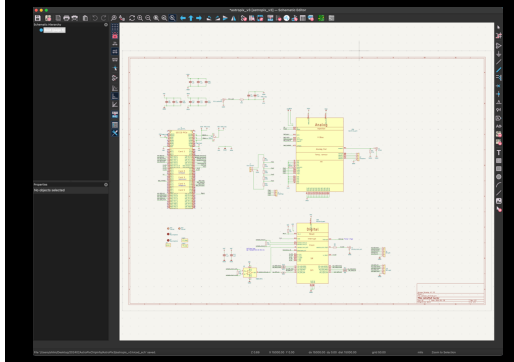
Activity & plan from Korean group

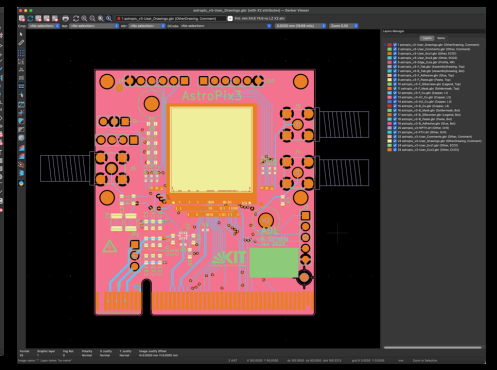
- **Testbench with AstroPix v2 and v3**
  Built a testbench and performed a basic operation with charge injection

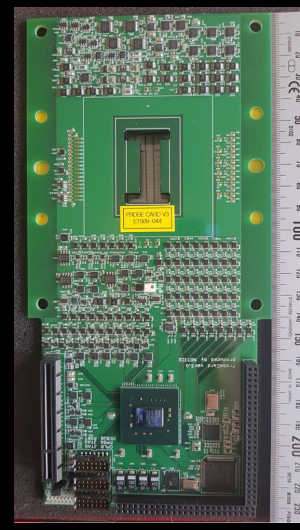




- **Chip test machine**
  Based on the design files of the single-chip carrier board of AstroPix v3, a probe card design is ongoing
  Plan to utilize the chip test equipment for the ALICE ITS2

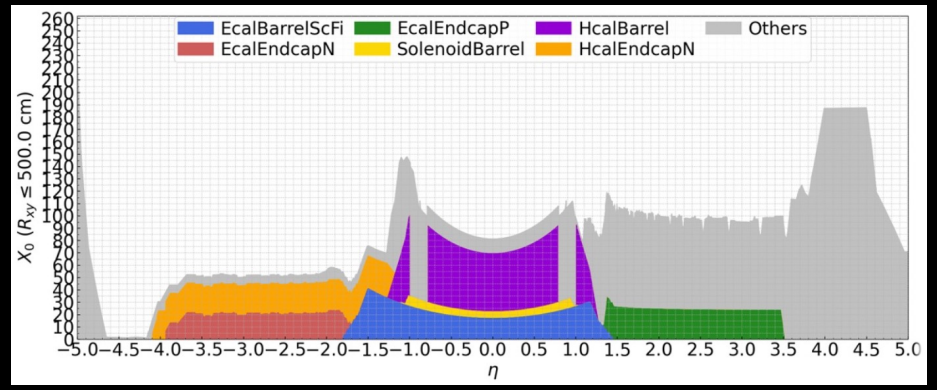




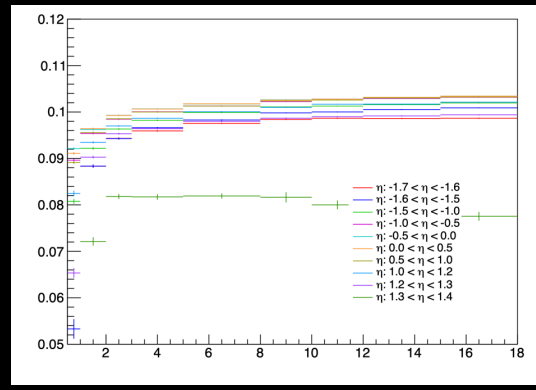


- **Simulation development for TDR**
  Detailed geometry implementation and performance study

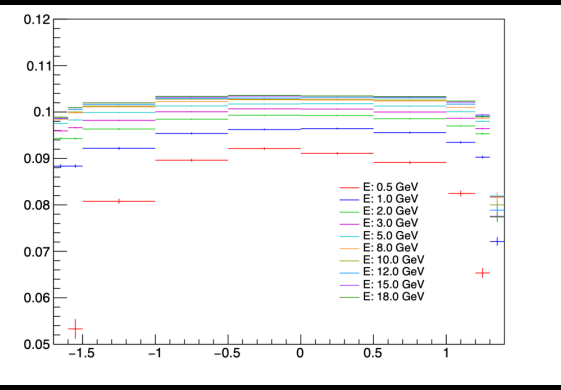
Material scan



Sampling fraction vs. E



Sampling fraction vs. η



Timeline

ePIC decision about Barrel ECAL
April 23

CD-3a
Jan 24

CD-3
Apr 25

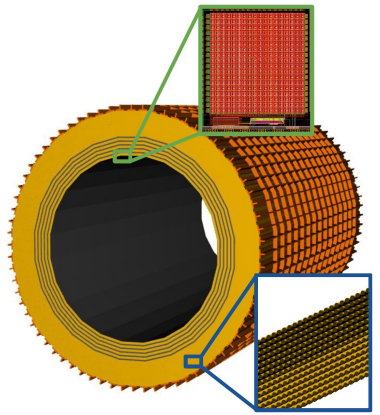
Barrel Installation in BNL
Jun 29

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

Chip v3 Feb 2023

Chip v4 Nov 2023

Chip v5 Nov 2024



- **Prototype R&D**
- **Final Design/PED**
- **Pre-production**
- **Scintillating Fiber Fabrication**
- **Production SciFi/local support layers and testing**
- **Production wafer fabrication v5**
- **Wafer testing**
- **Sectors/Trays production assembly and testing**
- **Integration**
- **Delivery**
- **Sector Assembly in a Barrel and Integration with Si Trays**

Summary

From the EIC Yellow Report: stringent requirements

EIC is an **electron scattering** machine and identifying scattered electrons mainly depends on the electromagnetic calorimetry.

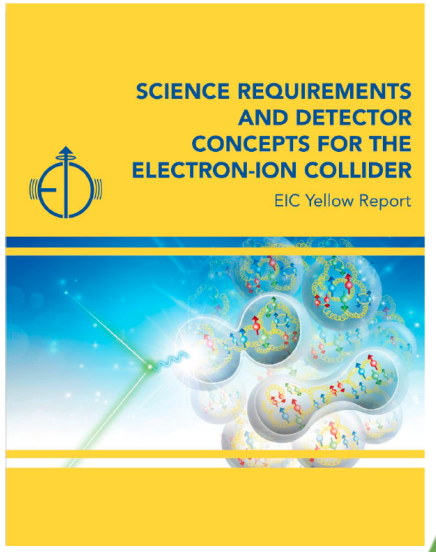
The electromagnetic calorimeter is the main detector for **electron-pion separation**. The inclusive physics program requires up to 10^4 pion suppression at low momenta in the barrel.

The exclusive program requires **decent energy resolution** ($< 7\%/\sqrt{E} \oplus 1\%$) **for photon energy reconstruction, and also the fine granularity for good** π^0-γ separation up to 10 GeV/c.

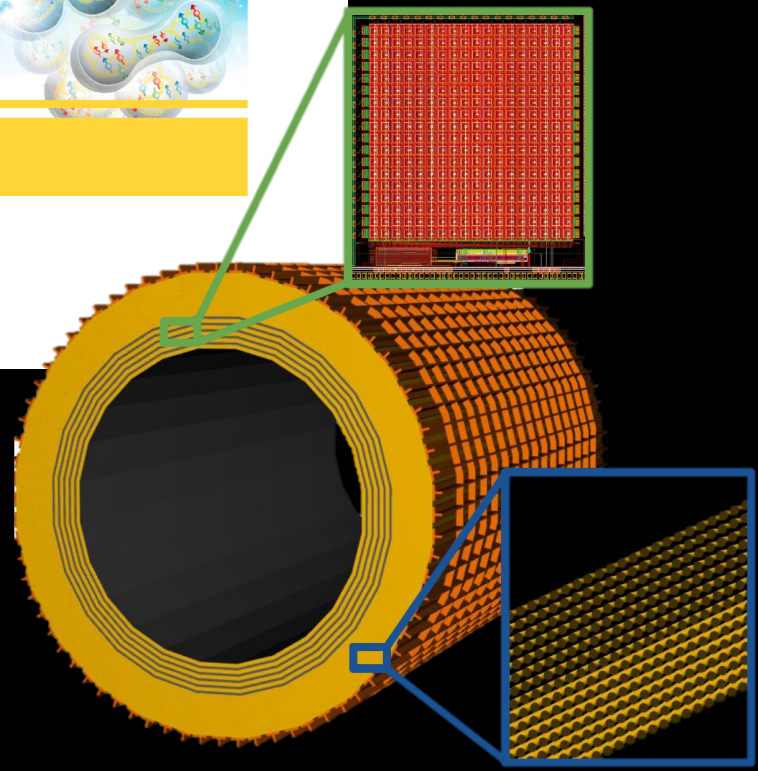
The bECal should be capable of measuring **low energy photons** down to 100 MeV, while having the range to measure energies well above 10 GeV

The system is space-constrained to very **limited space** inside the solenoid.

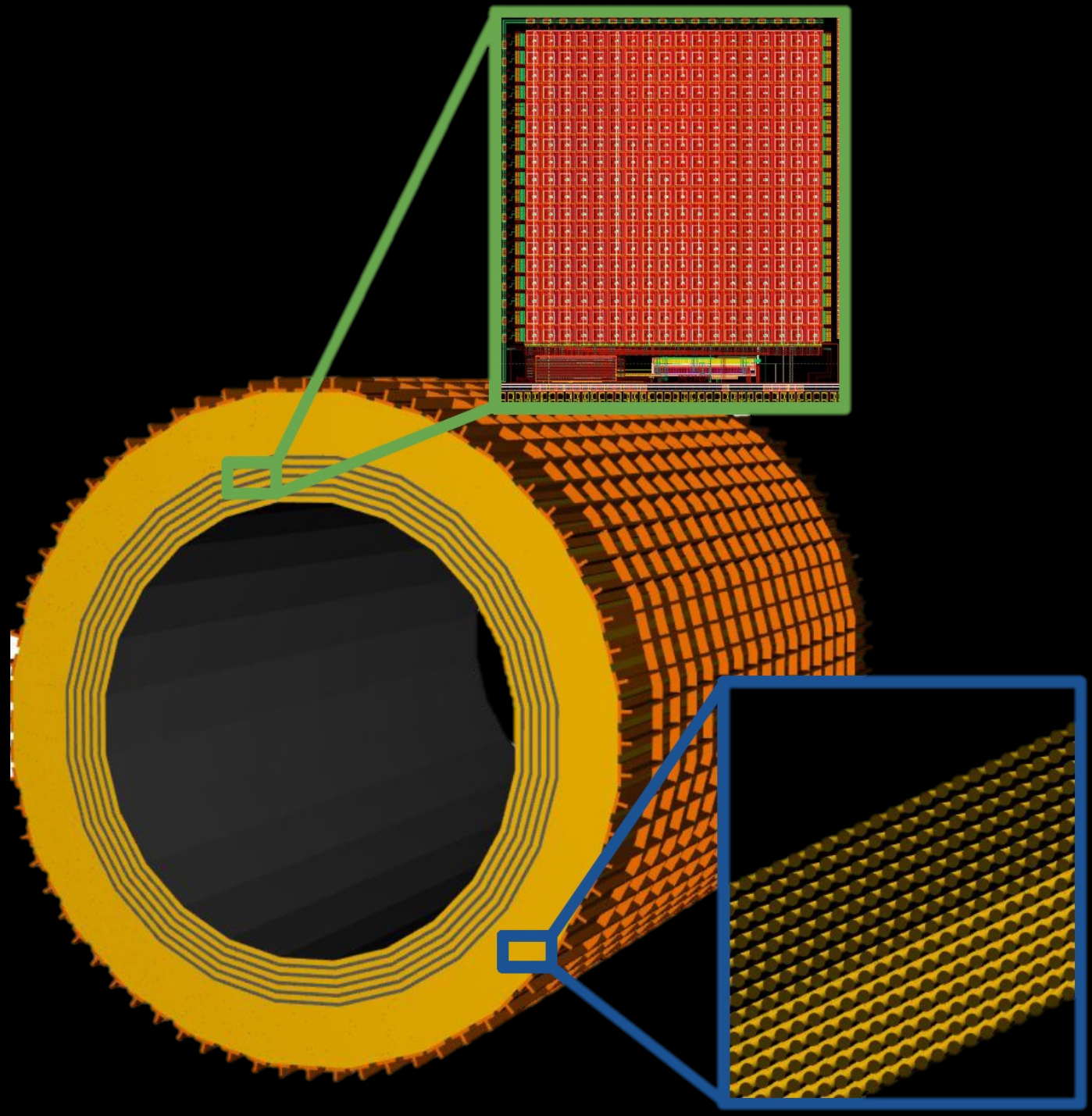
EIC Yellow Report
arXiv:2103.05419



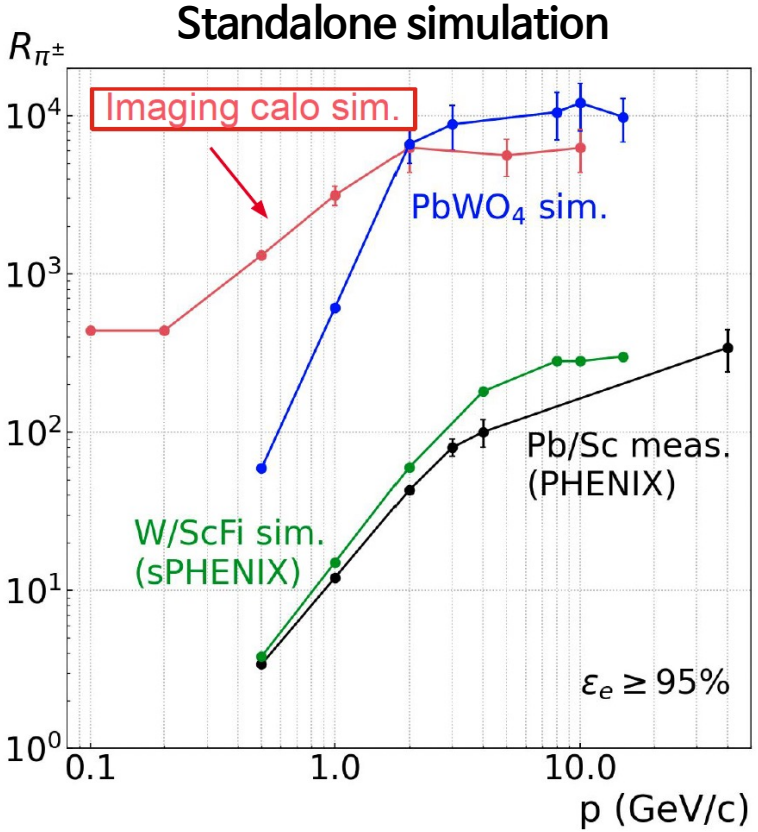
Korean institutions will make a significant contribution to the Barrel Imaging Calorimeter of the ePIC experiment at the EIC!

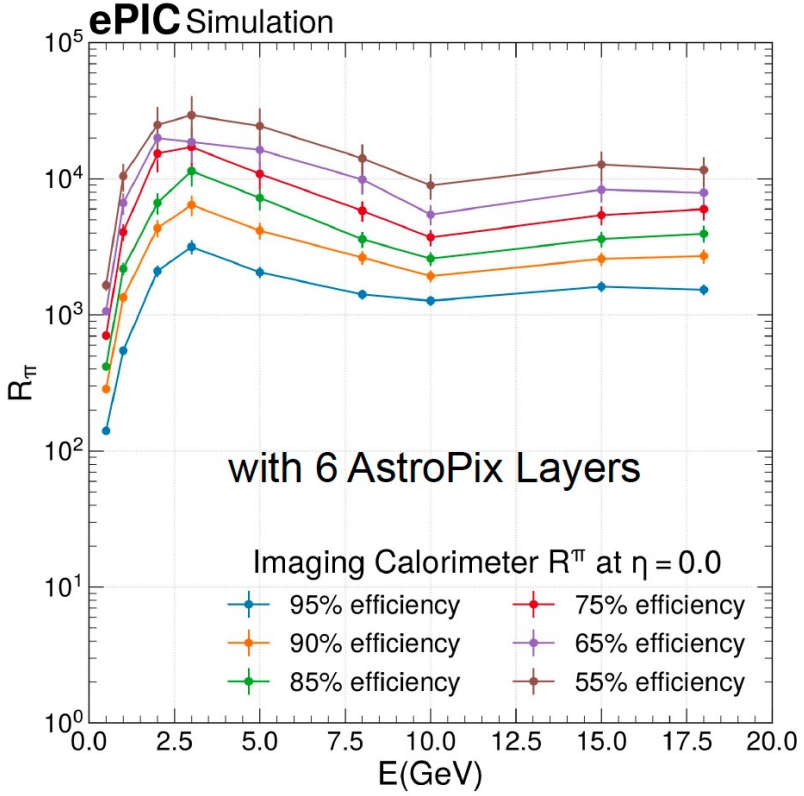


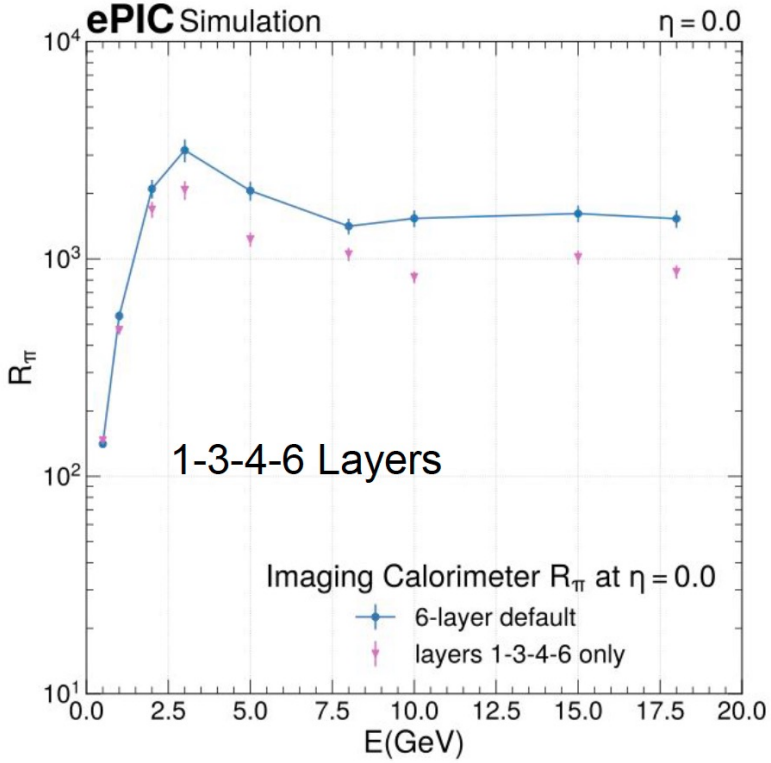
BACKUP



Performance: electron identification





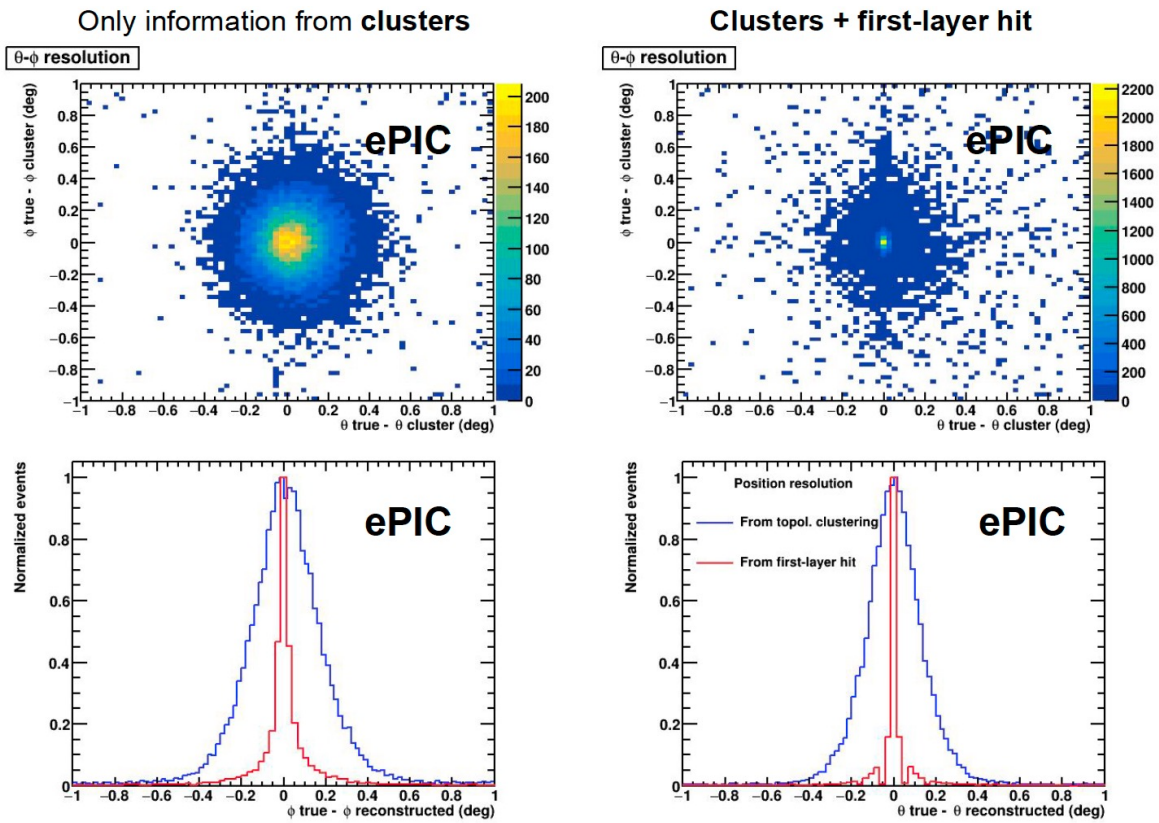


- **Goal:** Separation of electrons from the background in Deep Inelastic Scattering (DIS) processes
- **Method:** E/p cut (Pb/SciFi) + Neural Network using 3D position and energy info from imaging layers

- **e/π separation exceeds 10^3 in pion suppression at 95% efficiency above 1 GeV in realistic conditions!**

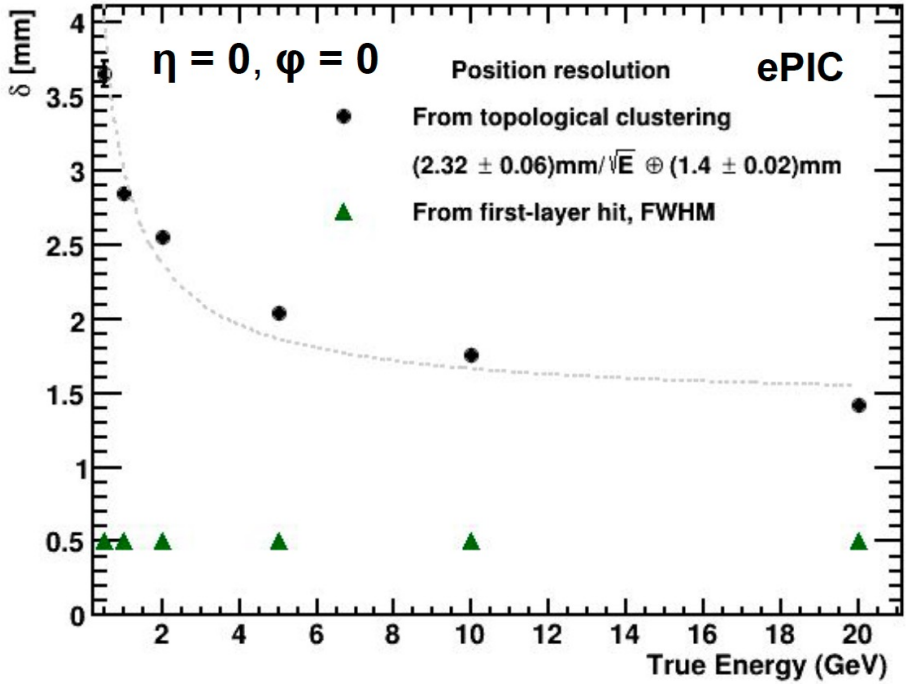
Performance: position resolution

Example $\theta-\varphi$ resolution for 5 GeV photons



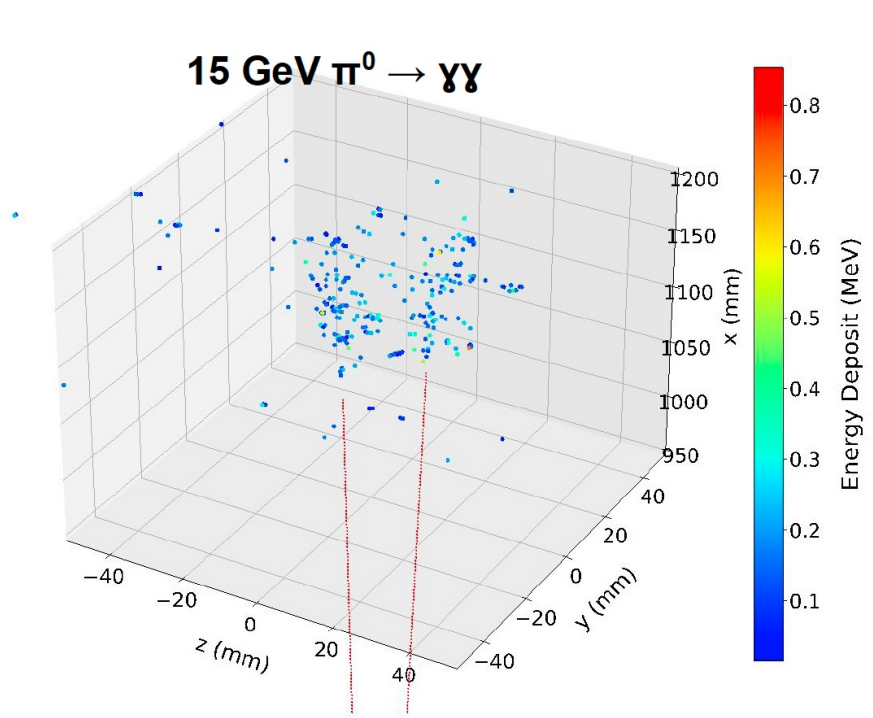
Position resolution for photons

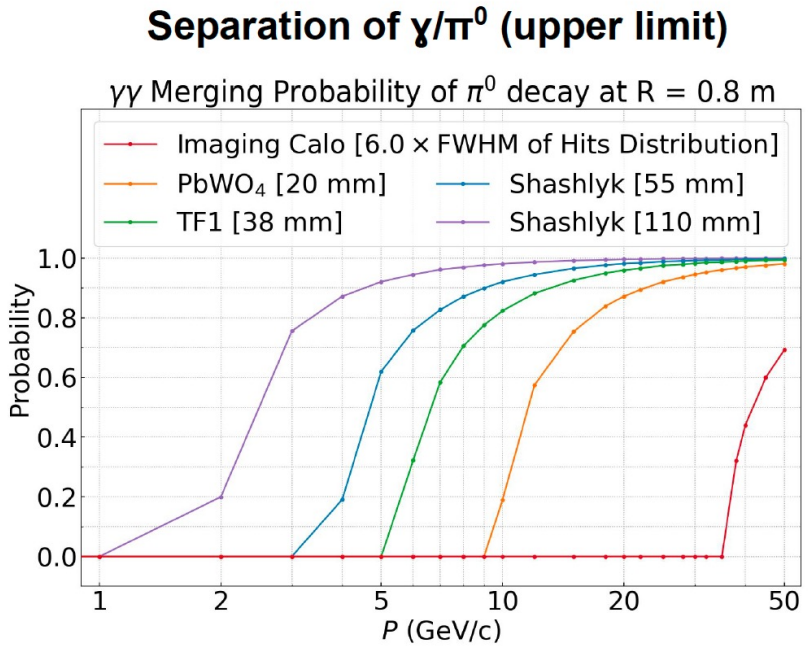
Particles thrown perpendicular to the calo surface

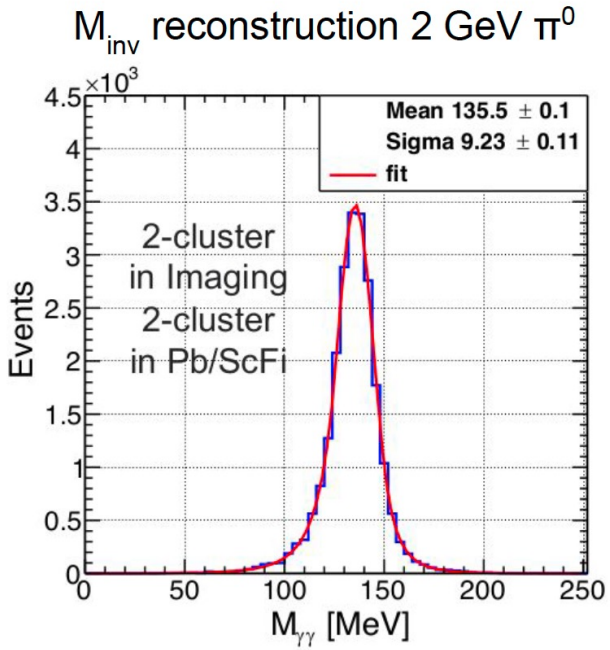


- Clusters from Imaging Si layers reconstructed with a 3D topological algorithm
- Cluster level information: $\sigma_{position}$= (2.32 ± 0.06) mm/$\sqrt{E} \oplus (1.4 \pm 0.02)$ mm at $\eta = 0$
- First-layer hit information added: : $\sigma_{position}$= ~0.5 mm (pixel size)

Performance: Neutral pion identification



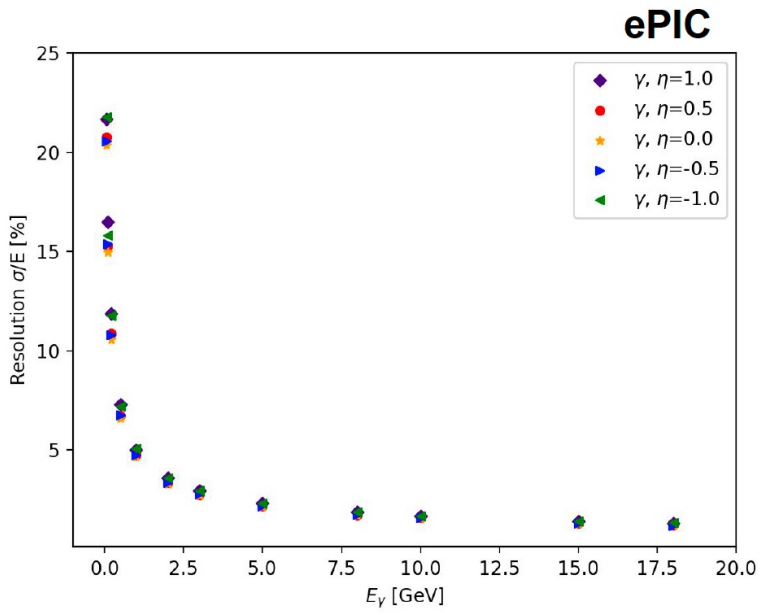


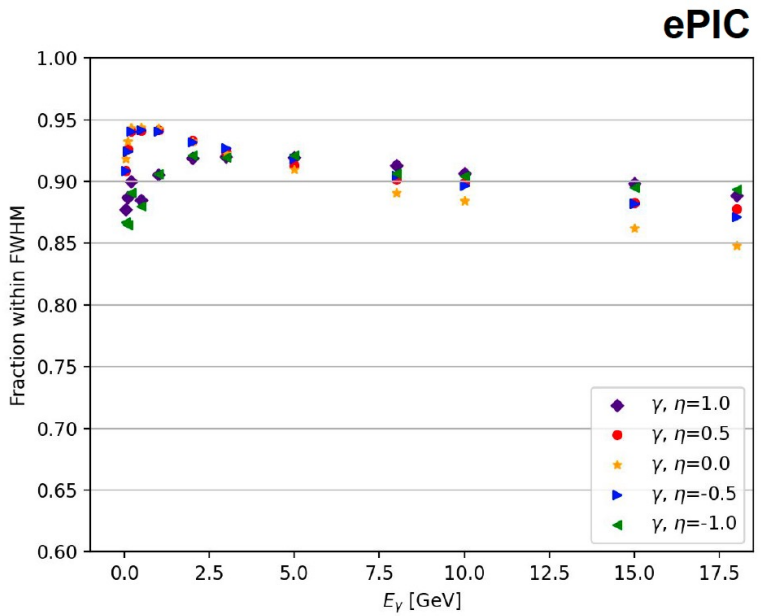


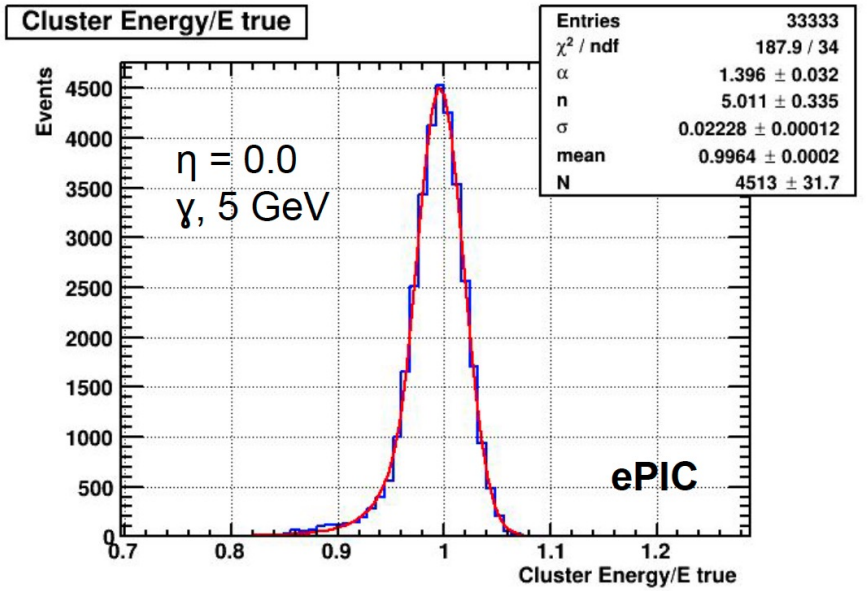
- **Goal:** Discriminate between π^0 decays and single γ from DVCS, neutral pion identification
- Precise position resolution allows for excellent separation of γ/π^0 based on the 3D shower profile
  Reconstruction of 2 GeV π^0 invariant mass as a testing ground for cluster energy splitting

- **Separation of two gammas from neutral pion well above required 10 GeV**

Performance: Energy resolution (photons)



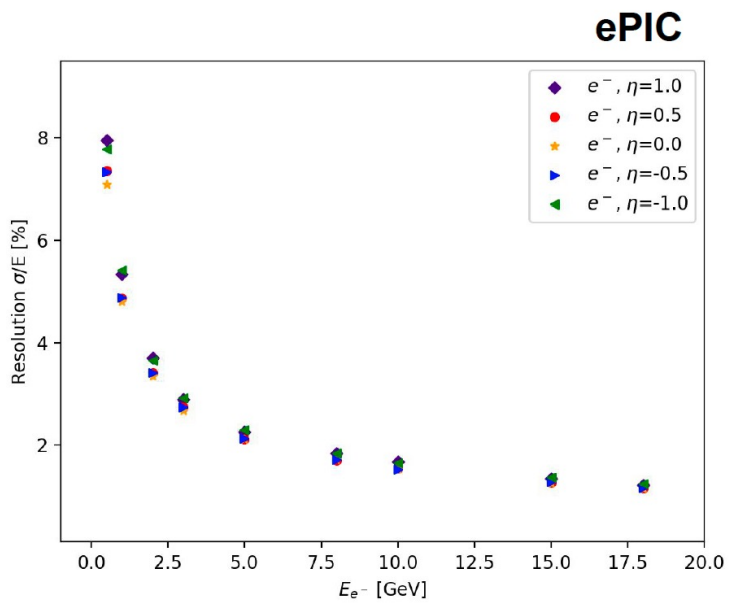


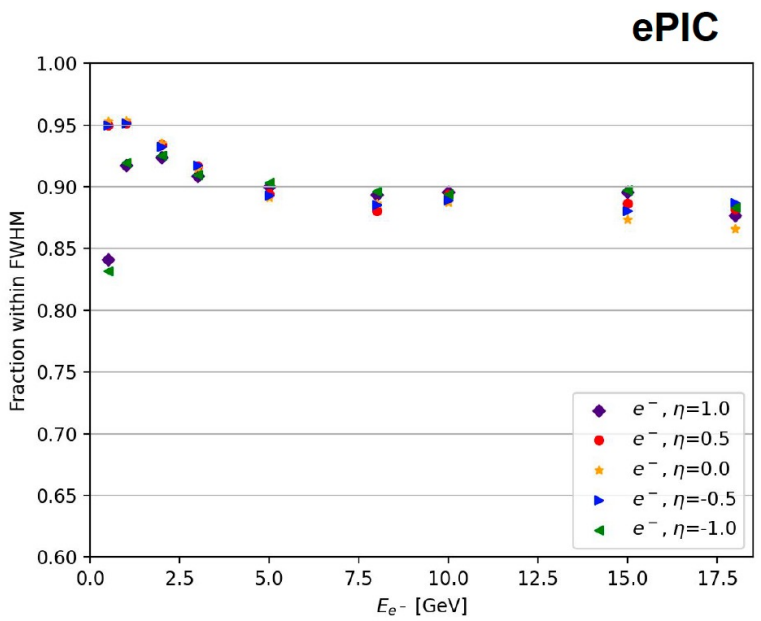


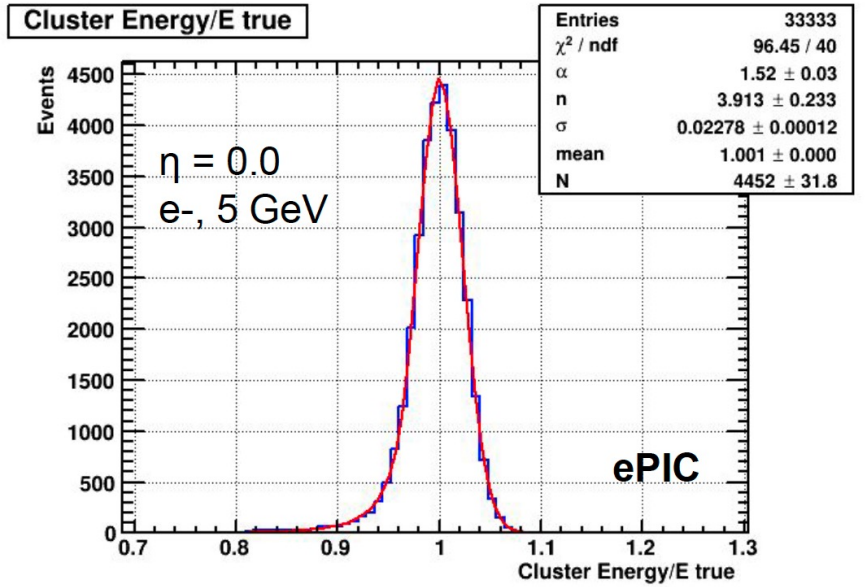
- Based on the Pb/SciFi part of the calorimeter
- Resolution extracted from a Crystal Ball fit σ

- GlueX Pb/SciFi Ecal: $5.2\%/\sqrt{E} \oplus 3.6\%$
  15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ=0.5−2.5 GeV)

Performance: Energy resolution (electrons)



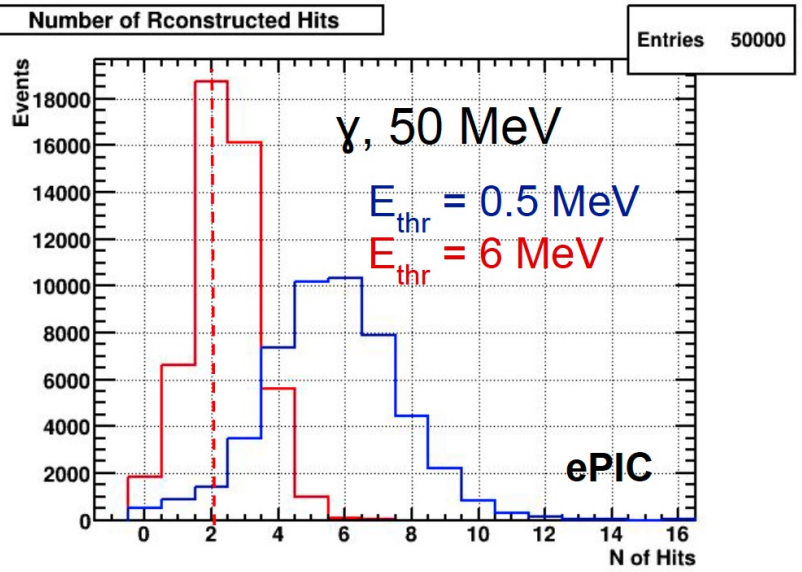




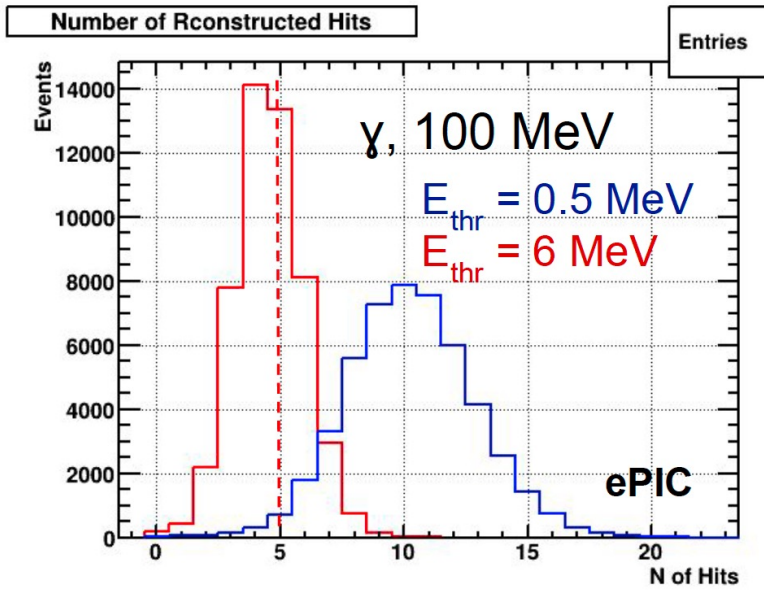
- Based on the Pb/SciFi part of the calorimeter
- Resolution extracted from a Crystal Ball fit σ

- GlueX Pb/SciFi Ecal: $5.2\%/\sqrt{E} \oplus 3.6\%$
  15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ=0.5−2.5 GeV)

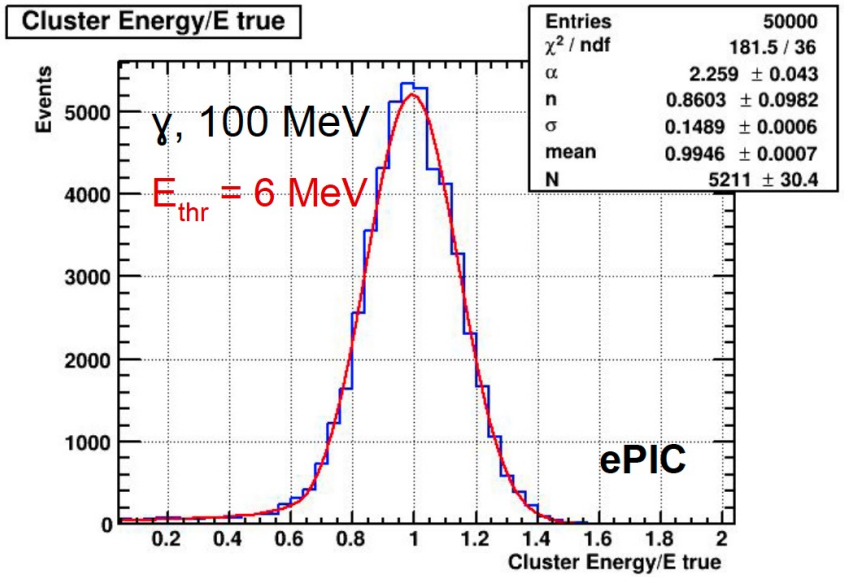
Performance: Low – energy particles



Thresholds corrected for f_{sam}



Blue threshold very low just to illustrate the distribution shape



- For electrons: cut out because of the 1.7 T field to reach the calorimeter (p <~408 MeV)
- For photons: the number of fired readout cells with different thresholds at $\eta = 0$

- From GlueX studies: cluster/shower threshold is 100 MeV nominal (down to 50 MeV for some analyses, with mostly two cells per event only).