The Barrel Imaging Calorimeter for the ePIC Experiment at EIC

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(on behalf of the ePIC Collaboration)

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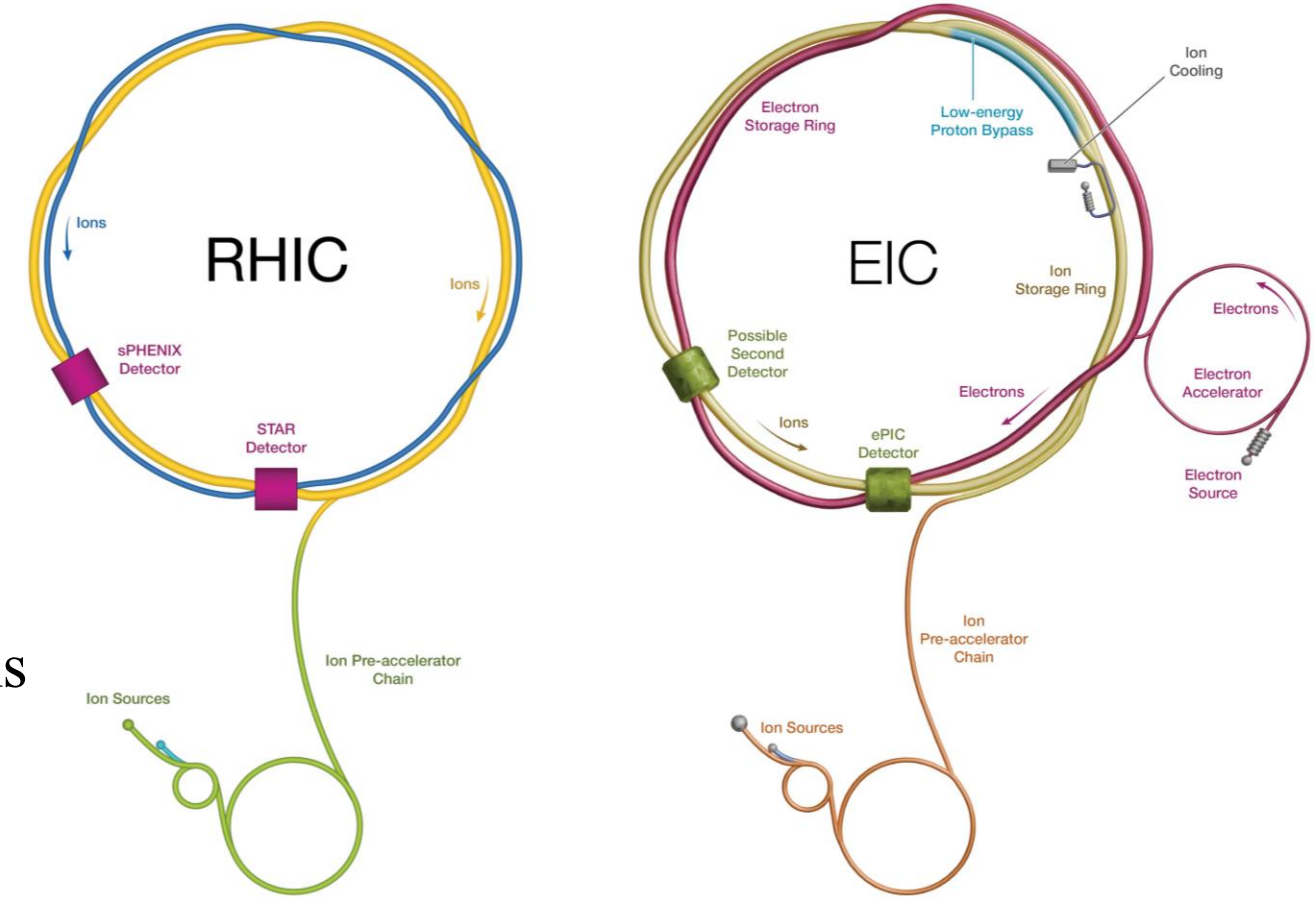
Electron Ion Collider (EIC)

- To be built at Brookhaven National Lab
- Utilizes existing RHIC infrastructure

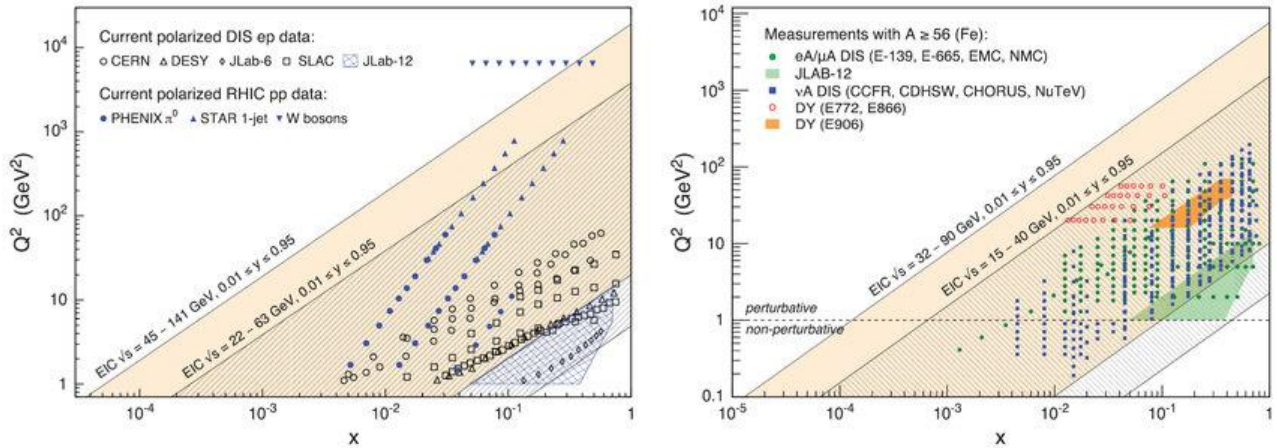
- High luminosity
  - Up to $10^{33\text{-}34}$ cm^{-2} s^{-1}
  - 100x higher than HERA
- Dual beam polarization
  - P > 70% for e, p, light nucleon beams
- Variable center of mass energy
  - ~ 30 – 140 GeV
- Light and heavy ion species
  - RHIC already capable of delivering a variety of heavy nucleon beams



Unique accelerator properties → unique physics opportunities

EIC Physics

Kinematic coverage
e+p (left), e+A (right)
DOI: 10.1088/1361-6633/aaf216



- Access rare interactions/processes
- Study observables vs. x, Q^2, A, etc.

- High luminosity
  - Up to $10^{33\text{-}34}$ cm^{-2} s^{-1}
  - 100x higher than HERA

- Gluon/quark contributions to nucleon spin
- Many polarization observables

- Dual beam polarization
  - P > 70% for e, p, light nucleon beams

- Variable center of mass energy
  - ~ 30 – 140 GeV

- Wide kinematic range in Q^2 and x
- Nucleon imaging in regions dominated by valence quarks and in regions dominated by gluons/sea quarks

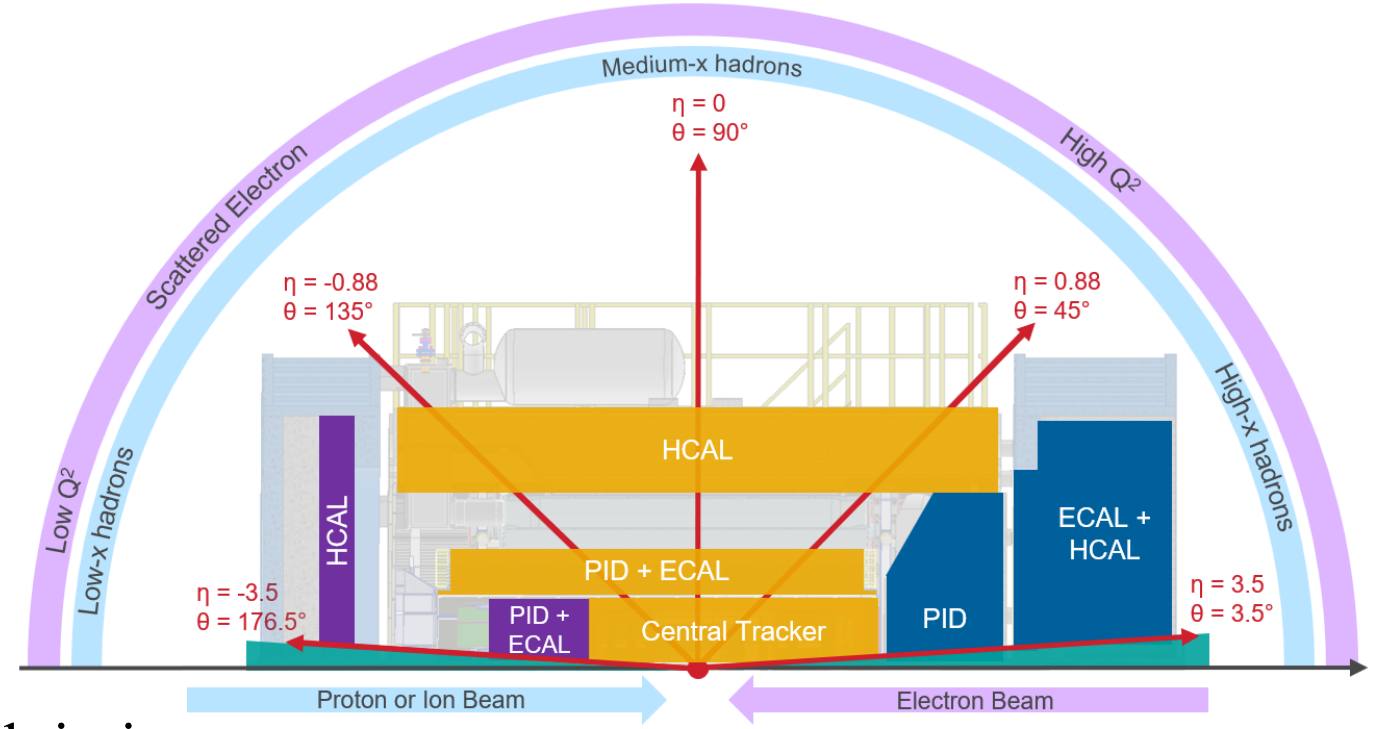
- Light and heavy ion species
  - p, D, He, Al, Cu, Zr, Ru, Au, U

- Collisions at high gluon densities
  - Probe gluon dynamics
- Gluon saturation studies

Stringent particle detector requirements…

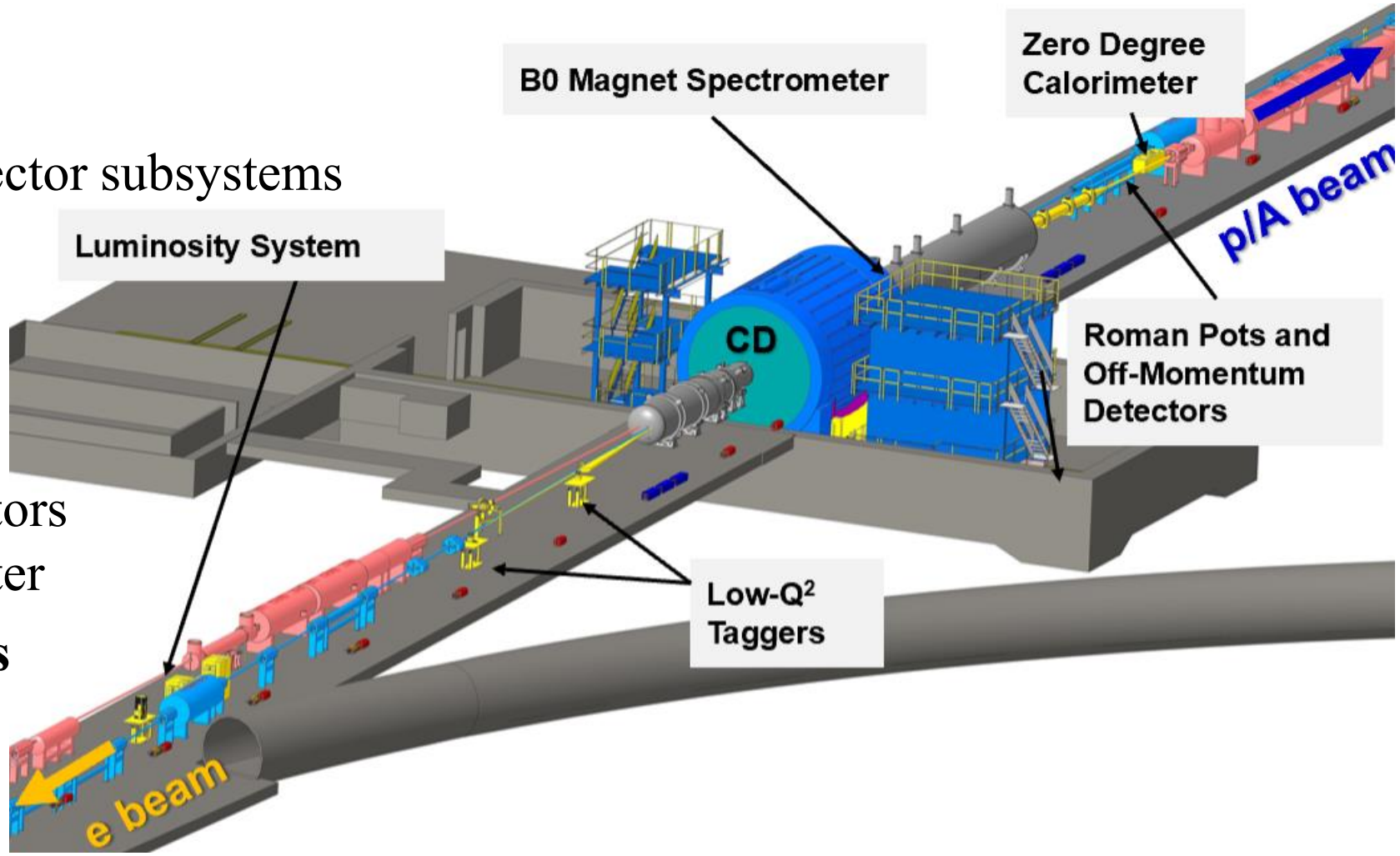
Detector Requirements

- Large angular coverage for detecting DIS products and recoil particles
  - Specialized detector subsystems in each angular region
    - Electromagnetic calorimeters
    - Hadronic calorimeters
    - Tracking systems
    - Particle identification systems
- Electromagnetic calorimetry
  - Lepton/hadron separation
  - High energy resolution
- Hadronic calorimetry
  - π/p/K separation
  - Neutral hadron detection
- High-resolution particle tracking and timing
  - Event vertex reconstruction
- Jet reconstruction and p_T determination
- Extended acceptance for particles at small scattering angles ($|\eta| > 3.5$)



Electron-Proton Ion Collider (ePIC)

- **Central Detector (CD)**
  - $|\eta| < 3.5$
  - Many specialized detector subsystems
- **Far-Forward Detectors**
  - $\eta > 3.5$
  - B0 spectrometer
  - Roman pots
  - Off-momentum detectors
  - Zero-degree calorimeter
- **Far-Backward Detectors**
  - $\eta < -3.5$
  - Low-Q^2 taggers
  - Pair spectrometer
  - Direct photon detector



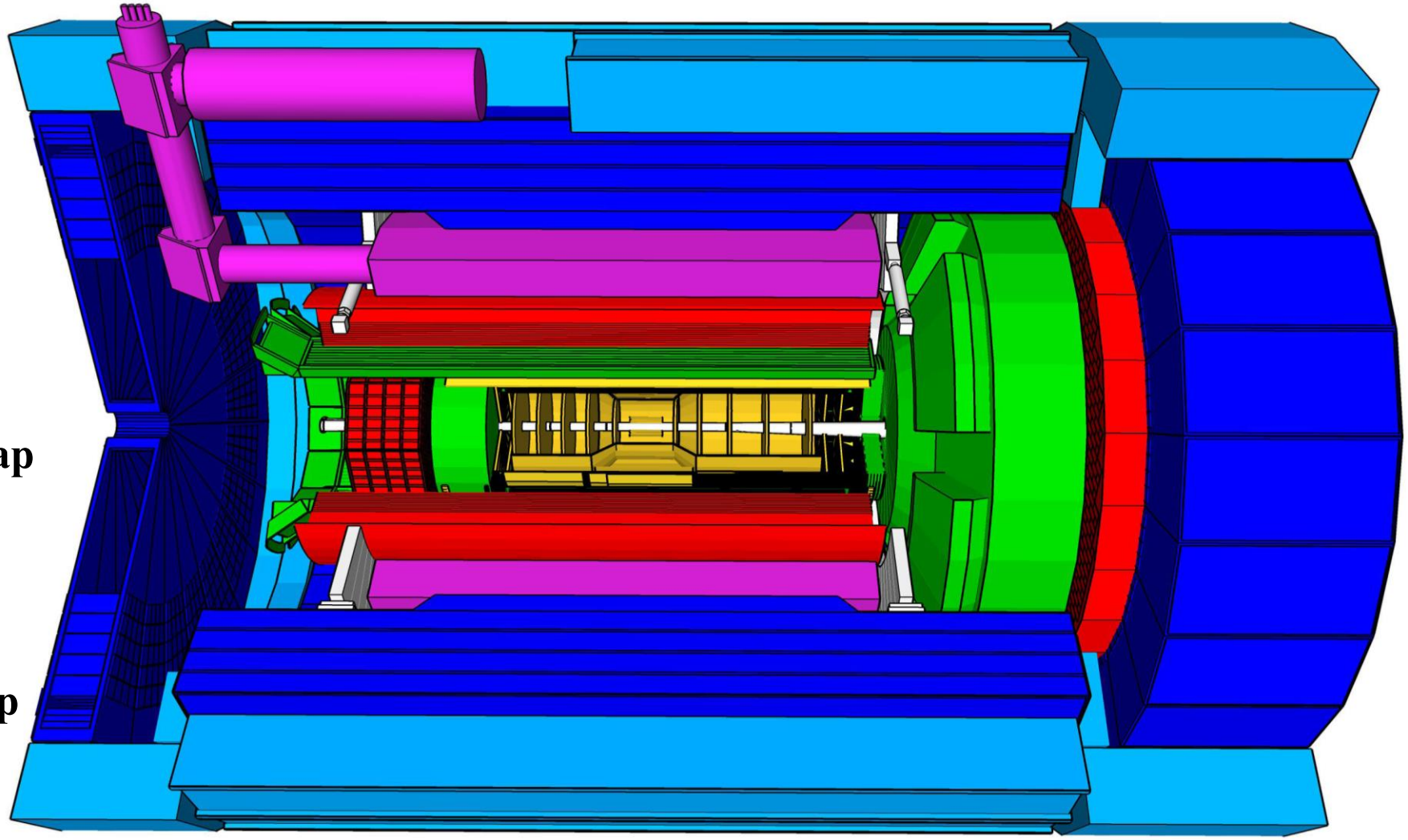
A brief overview of each detector subsystem…

ePIC Detector Systems

TRACKING
PID
EM CALORIMETRY
H CALORIMETRY

Central Detector

- **Barrel Region**
  - SVT inner barrel
  - SVT outer barrel
  - CyMBaL
  - AC-LGAD barrel
  - µRWELL-BOT
  - hpDIRC
  - BIC
  - SC solenoid magnet (1.7 T)
  - Barrel HCAL
- **Lepton (Backward) Endcap**
  - SVT disks
  - µRWELL-ECT
  - pfRICH
  - Backward EMCAL
  - Backward HCAL
- **Hadron (Forward) Endcap**
  - SVT disks
  - µRWELL-ECT
  - AC-LGAD endcap
  - dRICH
  - Forward EMCAL
  - Forward HCAL



Ion Beam

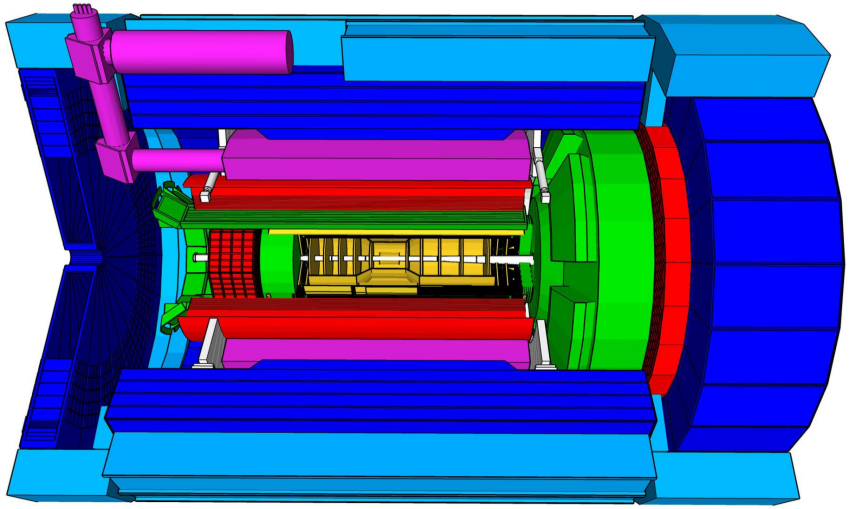
Electron Beam

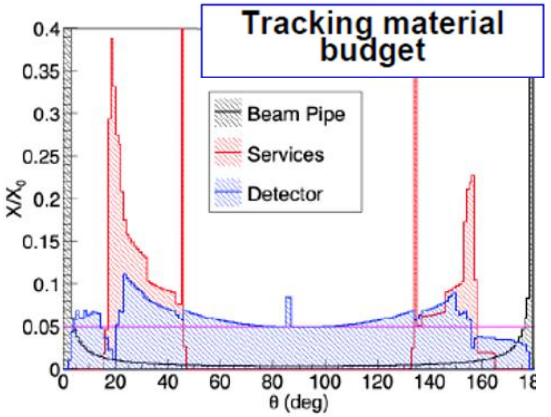
ePIC Detector Systems

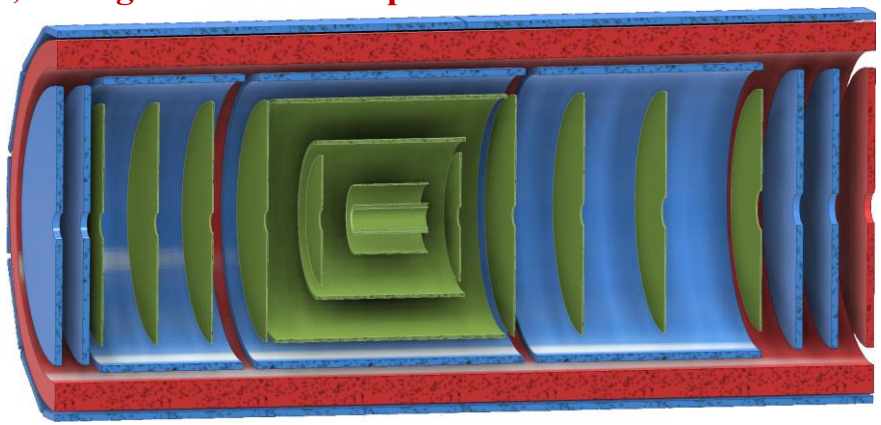
TRACKING | EM CALORIMETRY | PID | H CALORIMETRY

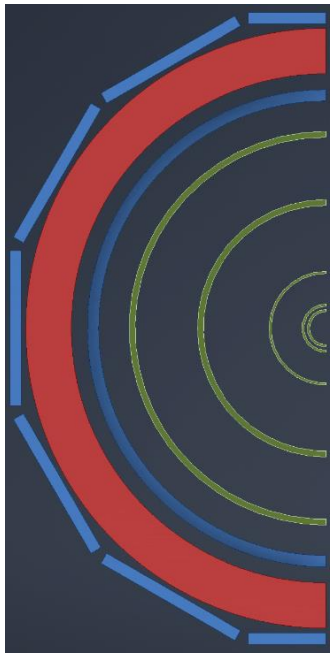
Central Detector

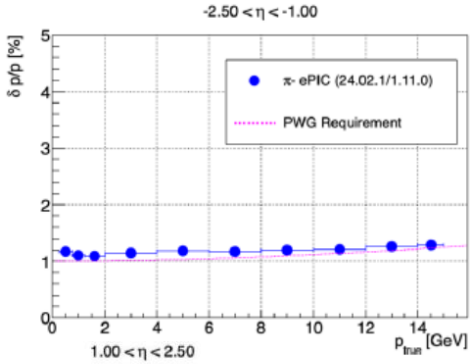
- **General Requirements**
  - Low material budget (small number of radiation lengths, X_0)
  - Good spatial and timing resolution → pattern recognition for event reconstruction
- **Si Vertex Tracker (SVT)**
  - Based on ALICE ITS3 – Monolithic Active Pixel Sensors (MAPS)
  - 5 cylindrical barrel layers, 5 disks in each endcap
  - Spatial resolution < 5 µm
- **Multi-Pattern Gas Detectors (MPGDs)**
  - Cylindrical Micromegas Barrel Layer (CyMBaL)
  - Planar µR-WELL with Gas Electron Multiplier (GEM) pre-amplification
  - Timing resolution ~ 10 ns
- **AC-Coupled Low-Gain Avalanche Diode (AC-LGAD)**
  - Barrel and forward endcap time-of-flight (ToF)
  - Spatial resolution ~ 30 µm, timing resolution ~ 30 ps

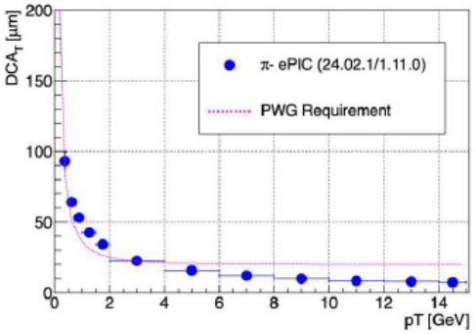










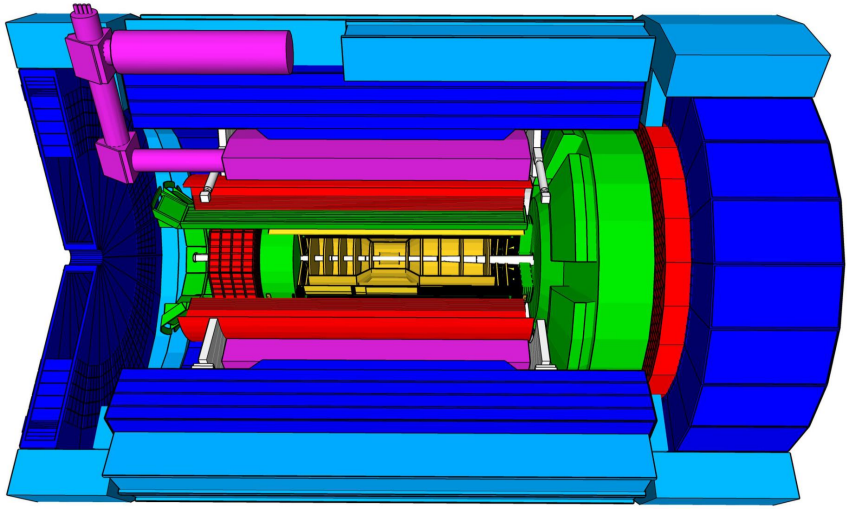


ePIC Detector Systems

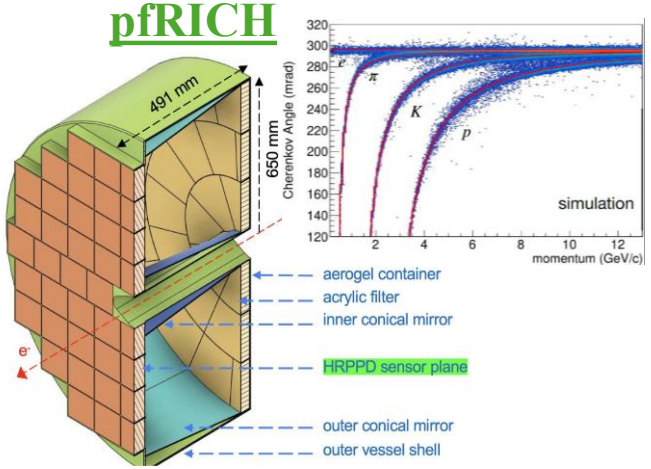
TRACKING EM CALORIMETRY
PID H CALORIMETRY

Central Detector

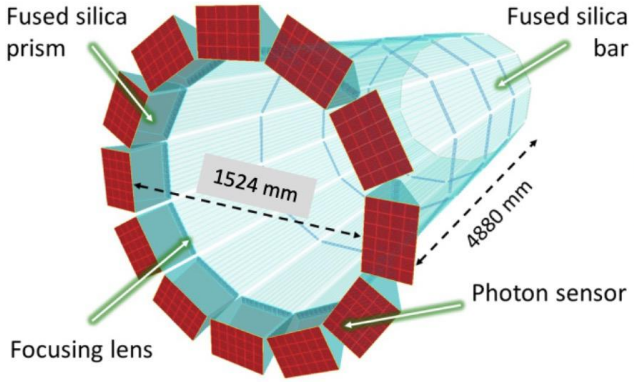
- **Detector Roles**
  - Charged/neutral separation provided by 4π-hermetic tracking
  - Lepton/hadron separation provided mostly by calorimetry and tracking
  - π/K/p separation provided by ToF and Cherenkov
- **Proximity-Focused Ring Imaging Cherenkov (pfRICH)**
  - Backward endcap ($-3.5 < \eta < -1.5$)
  - 3σ hadron separation for $p < 7$ GeV/c, timing resolution ~ 20 ps for backward ToF
  - Backward region hadron identification particularly important for SIDIS
- **Detection of Internally Reflected Cherenkov Light (hpDIRC)**
  - Barrel region ($-1.65 < \eta < 1.65$)
  - Quartz bar radiator (repurposed from BaBar)
  - 3σ hadron separation for $p < 6$ GeV/c, e/π separation for low p
- **Dual-Radiator Ring Imaging Cherenkov (dRICH)**
  - Forward endcap ($1.5 < \eta < 3.5$)
  - Aerogel and C_2F_6 gas for wide momentum coverage
  - 3σ hadron separation up to 50 GeV/c p

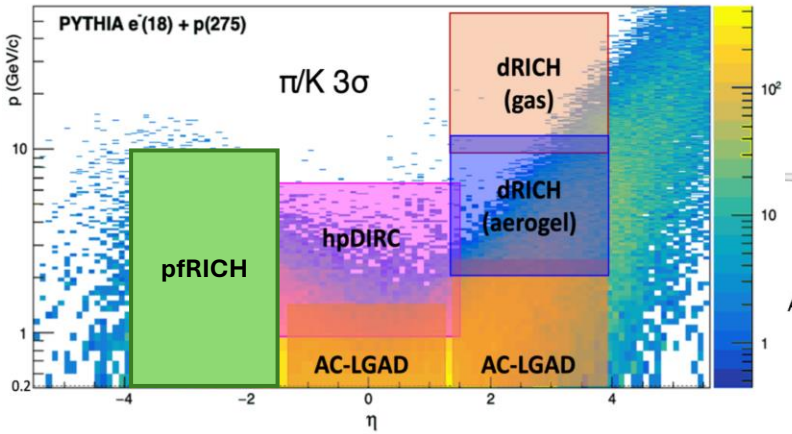


pfRICH

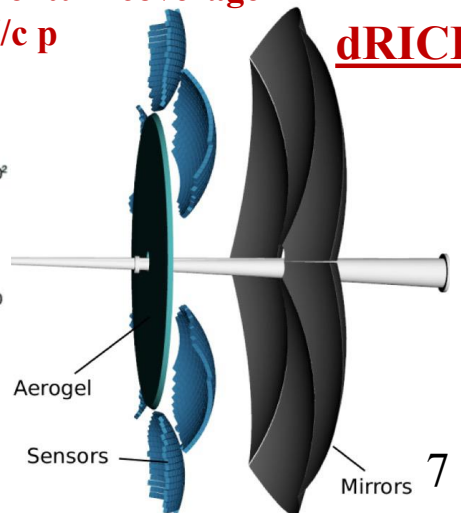


hpDIRC





dRICH

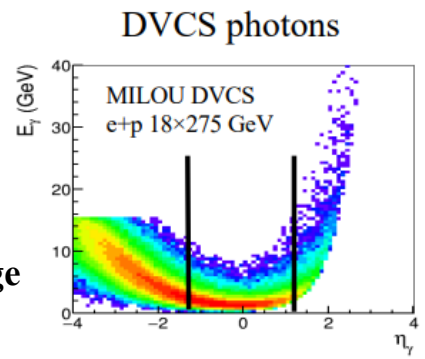


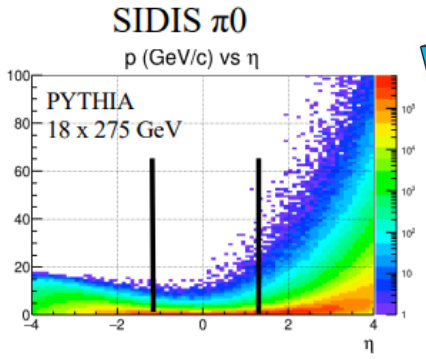
ePIC Detector Systems

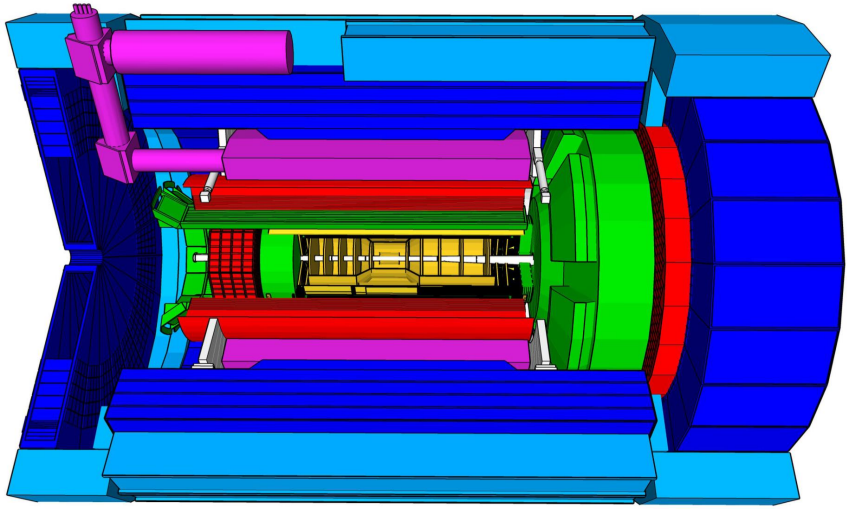
TRACKING
PID
EM CALORIMETRY
H CALORIMETRY

Central Detector

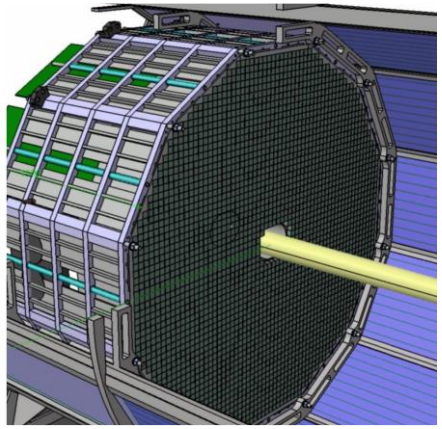
- **General Requirements**
  - Large radiation lengths
  - Good π suppression (10^4)
  - γ/π^0 discrimination
  - Large energy readout range







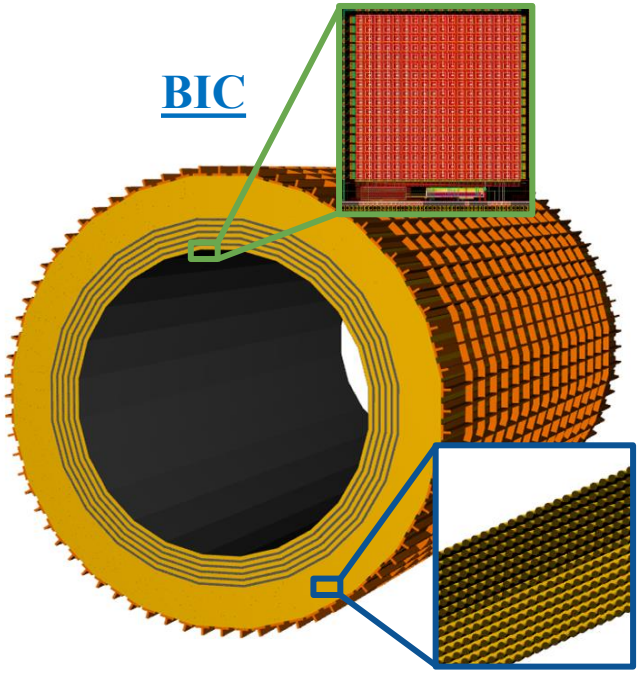
- **Backward EMCal**
  - $-3.5 < \eta < -1.7$, 22 X_0
  - ~ 3000 $PbWO_4$ crystals
  - γ/π^0 discrimination for $p < 7$ GeV/c
  - Expected E resolution $2\%/\sqrt{E} \oplus 1 - 3\%$



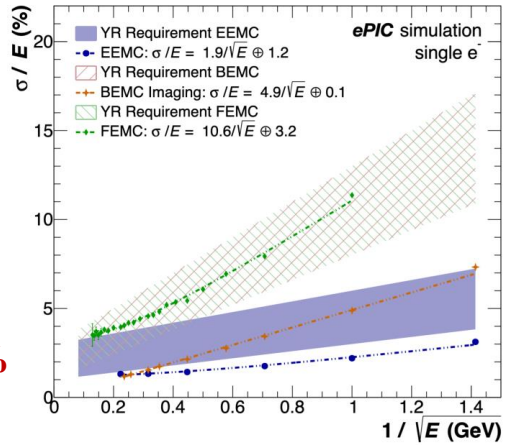
BEMCal

- **Barrel Imaging Calorimeter (BIC)**
  - $-1.7 < \eta < 1.4$, 17 X_0
  - Pb/SciFi matrix with two-ended readout
  - Interleaved AstroPix MAPS layers
  - First AstroPix layer → PID/tracking
  - γ/π^0 discrimination for $p < 10$ GeV/c
  - Expected E resolution $5\%/\sqrt{E} \oplus 1\%$

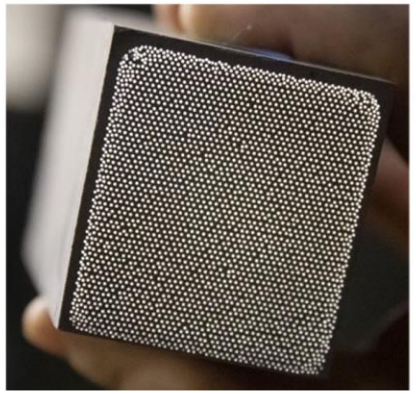
BIC



- **Forward EMCal**
  - $1.4 < \eta < 3.7$, 23 X_0
  - ~ 16000 high-granularity W/SciFi towers
  - γ/π^0 discrimination up to 50 GeV/c p
  - Expected E resolution $10\%/\sqrt{E} \oplus 1 - 3\%$



FEMCal W/SciFi

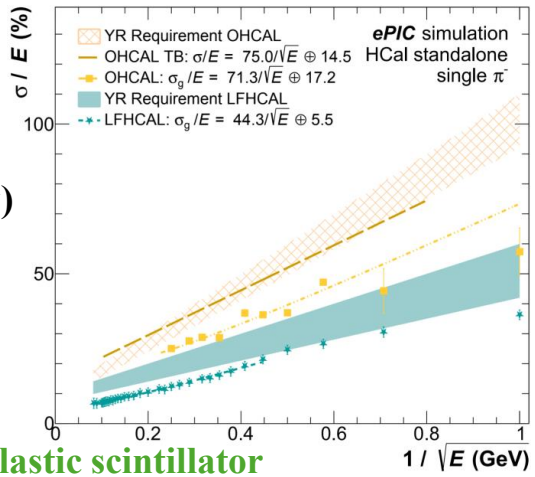


ePIC Detector Systems

TRACKING
PID
EM CALORIMETRY
H CALORIMETRY

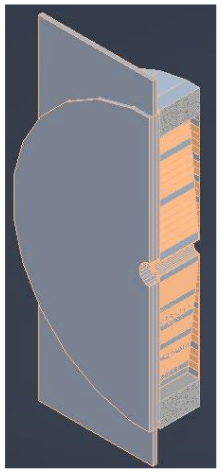
Central Detector

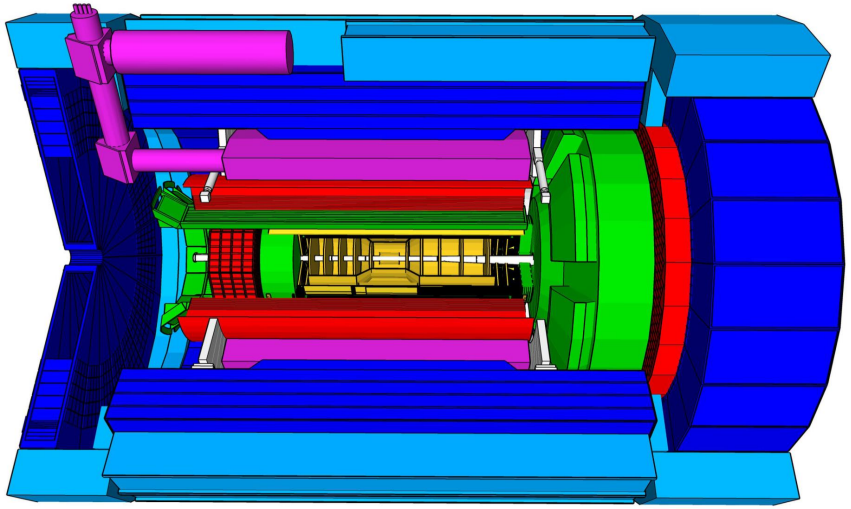
- **General Requirements**
  - Large interaction lengths
  - Jet reconstruction (particle flow)
  - μ identification
  - lepton/hadron separation



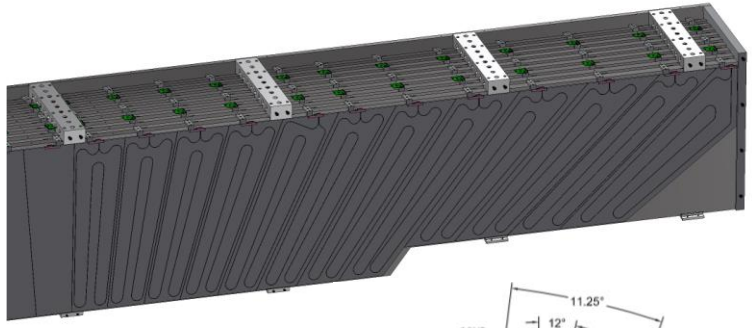
- **Backward HCal**
  - $-3.5 < \eta < -1.7$, 2.4 λ_0
  - Alternating layers of steel and plastic scintillator
  - Low-x hadrons, tail-catcher for BEMCAL
  - Expected E resolution 50%/√E ⊕ 10%

BHCal

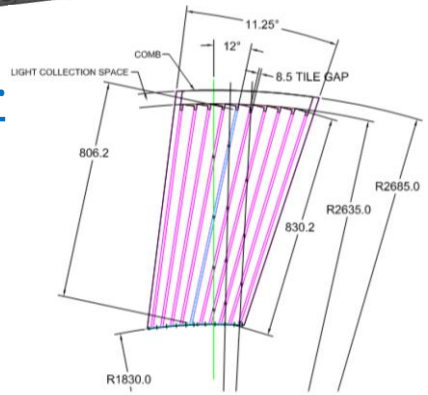




- **Barrel HCal (from sPHENIX)**
  - $-1.7 < \eta < 1.4$, 3.5 λ_0
  - Tilted (in φ) steel/scintillator layers
  - Low E hadrons (E < 5 GeV)
  - J/ψ → μμ
  - Expected E resolution 75%/√E ⊕ 15%

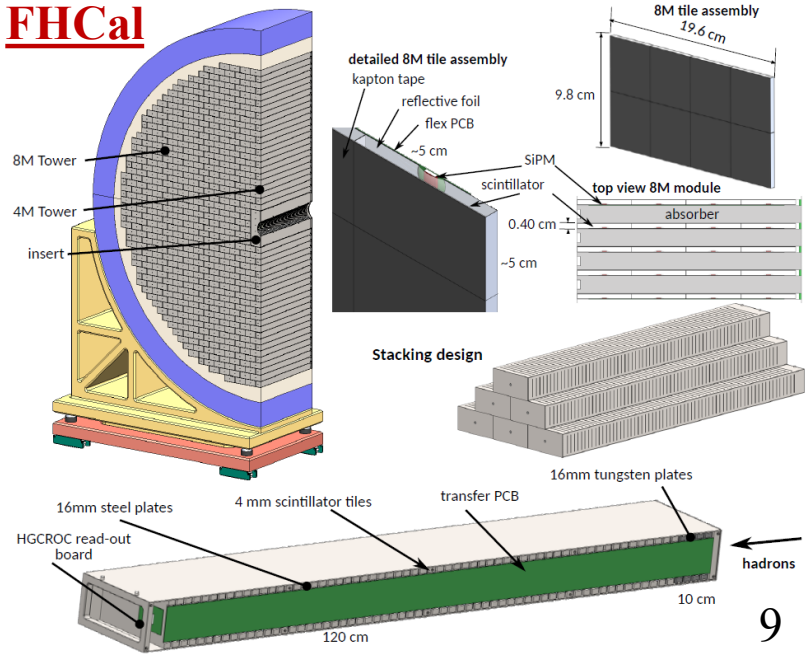


Barrel HCAL Sector



- **Forward HCal**
  - $1.4 < \eta < 4$, 6.5 λ_0
  - High-granularity W/steel/scintillator SiPM-on-tile
    - SiPM on each 4.9 cm x 4.9 cm scintillator tile
  - 65 absorber/scintillator layers in z (7 summed groups)
  - High E forward-going hadrons
  - Expected E resolution ~ 44%/√E ⊕ 6%

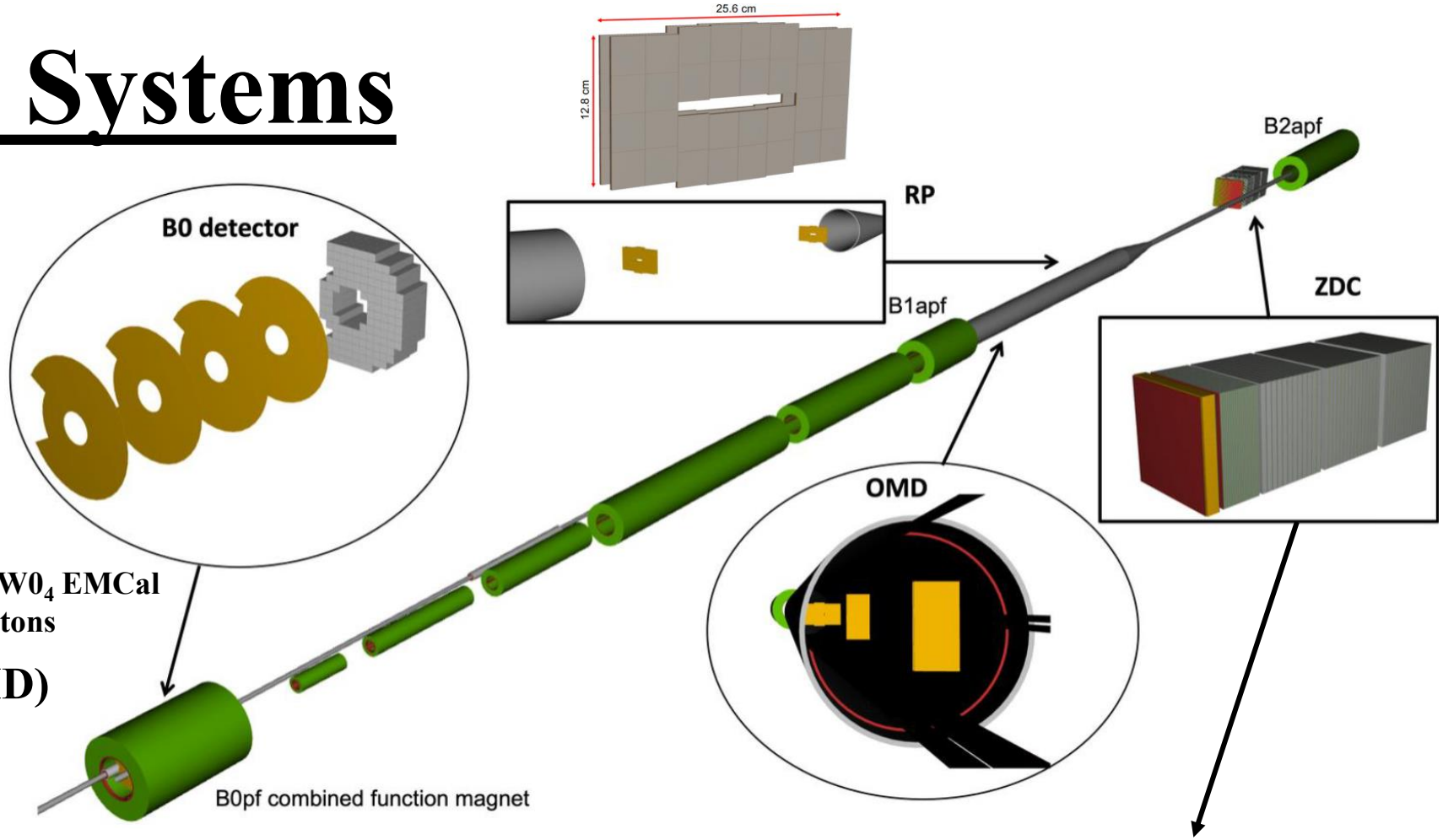
FHCal

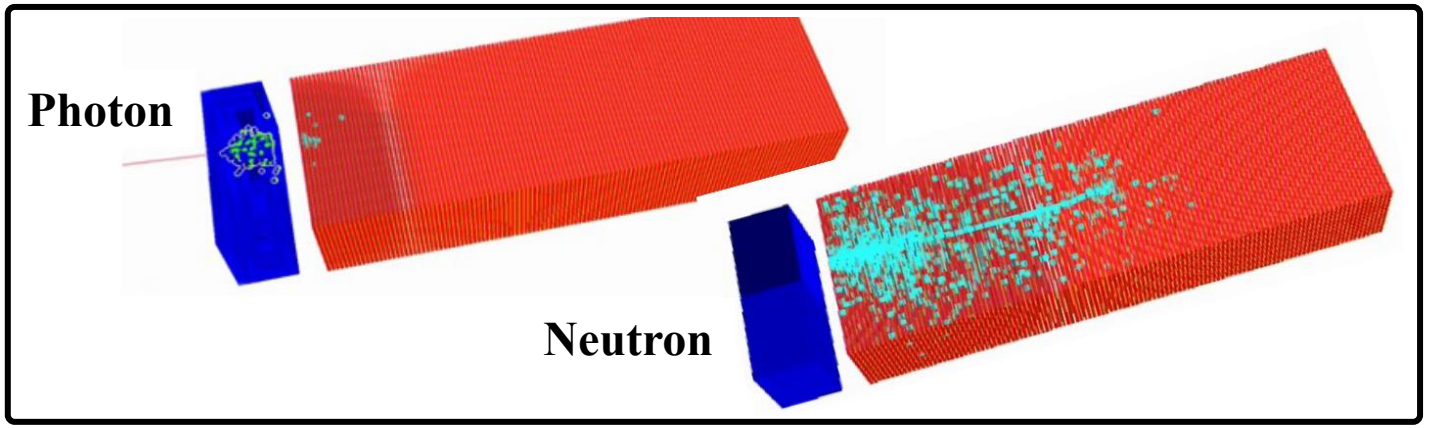


ePIC Detector Systems

Far-Forward Detectors

- **Far-Forward Physics**
  - Exclusive/diffractive reactions
    - π and K form factors
    - Short-range correlations
    - Neutron spin structure
    - Much more…
- **B0 Detector**
  - $5.5 < \theta < 20$ mrad, 6 – 7 m from IP
  - Si tracking layers (AC-LGAD) and $PbW0_4$ EMCal
  - Detection of charged particles and photons
- **Off-Momentum Detectors (OMD)**
  - $\theta < 5$ mrad, 23 – 25 m from IP
  - Two AC-LGAD tracking planes
  - Detection of charged particles
- **Roman Pots (RP)**
  - $\theta < 5$ mrad, 27 – 30 m from IP
  - Two AC-LGAD tracking planes
  - Detection of protons and light nuclei
- **Zero-Degree Calorimeter (ZDC)**
  - $\theta < 5.5$ mrad, 35 m from IP
  - Crystal EMCal for lower energy photons
  - SiPM-on-tile HCal for high energy n/γ/Λ

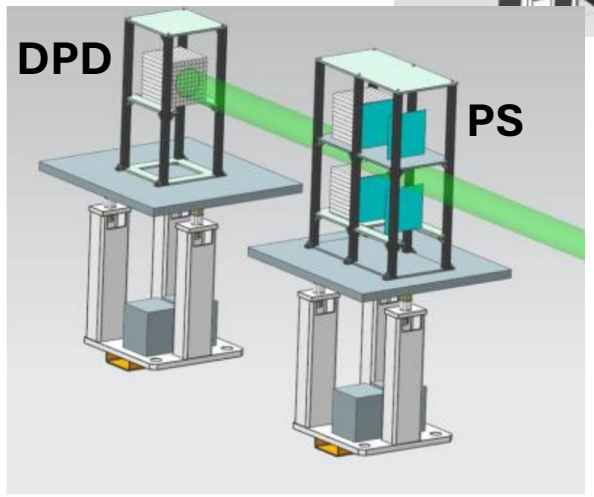


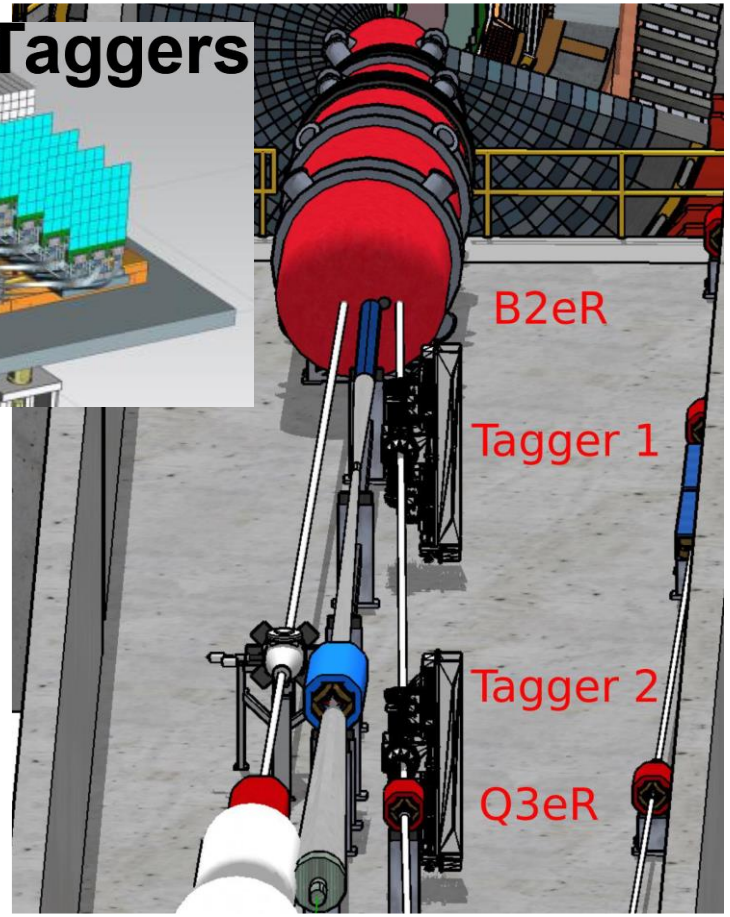


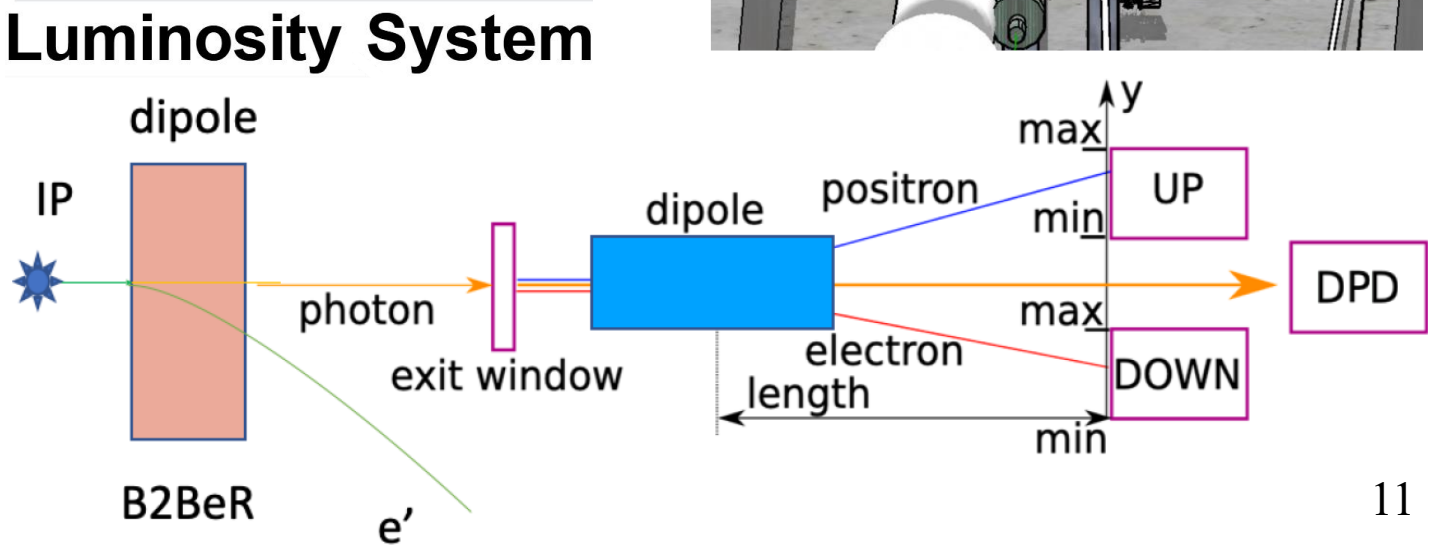
ePIC Detector Systems

Far-Backward Detectors

- **General Requirements**
  - Precise tracking of scattered electrons at $\eta < -4$
  - High-accuracy luminosity measurements
    - Needed for normalization of physics studies
- **Low Q^2 Taggers**
  - Two taggers measure electrons with $Q^2 < 1$ GeV^2
  - Four tracking layers (TimePix4, 55 µm pixel pitch)
  - W/SciFi calorimeter
- **Pair Spectrometer (PS)**
  - Luminosity measurement
  - Al conversion foil: Bremsstrahlung $\gamma \rightarrow e^+ e^-$
  - Tracking layers (AC-LGAD)
  - W/SciFi calorimeter
- **Direct Photon Detector (DPD)**
  - Complimentary luminosity measurement
  - Counts non-converted Bremsstrahlung γ
  - Rough monitoring for high-luminosity running
  - More precision for low-luminosity running



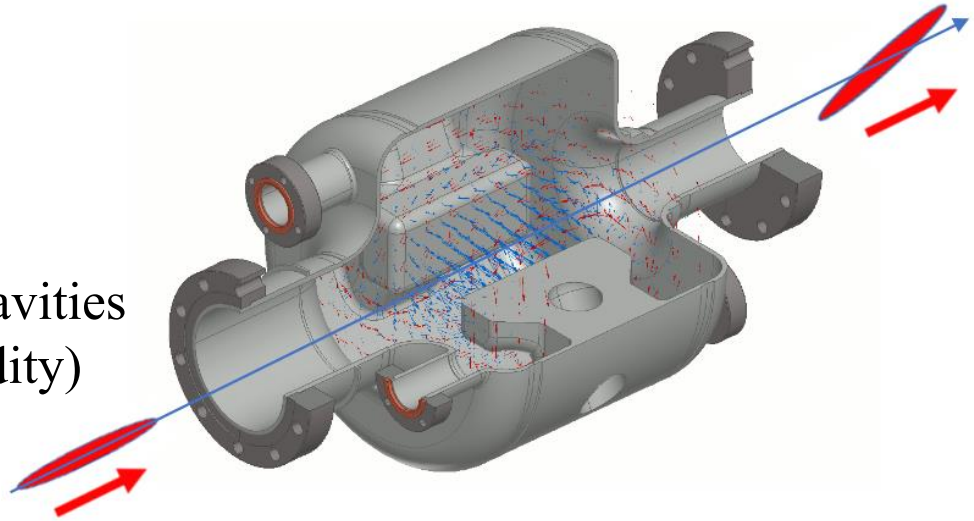


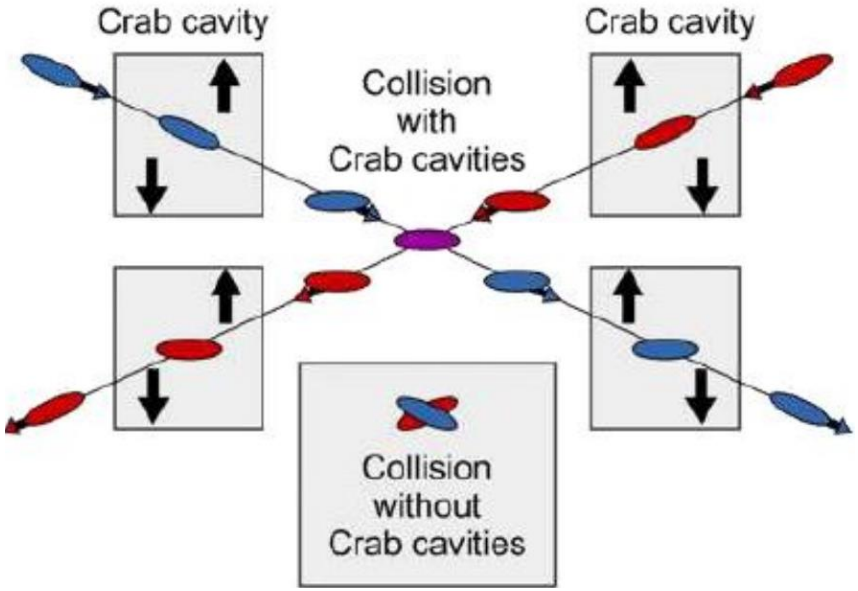


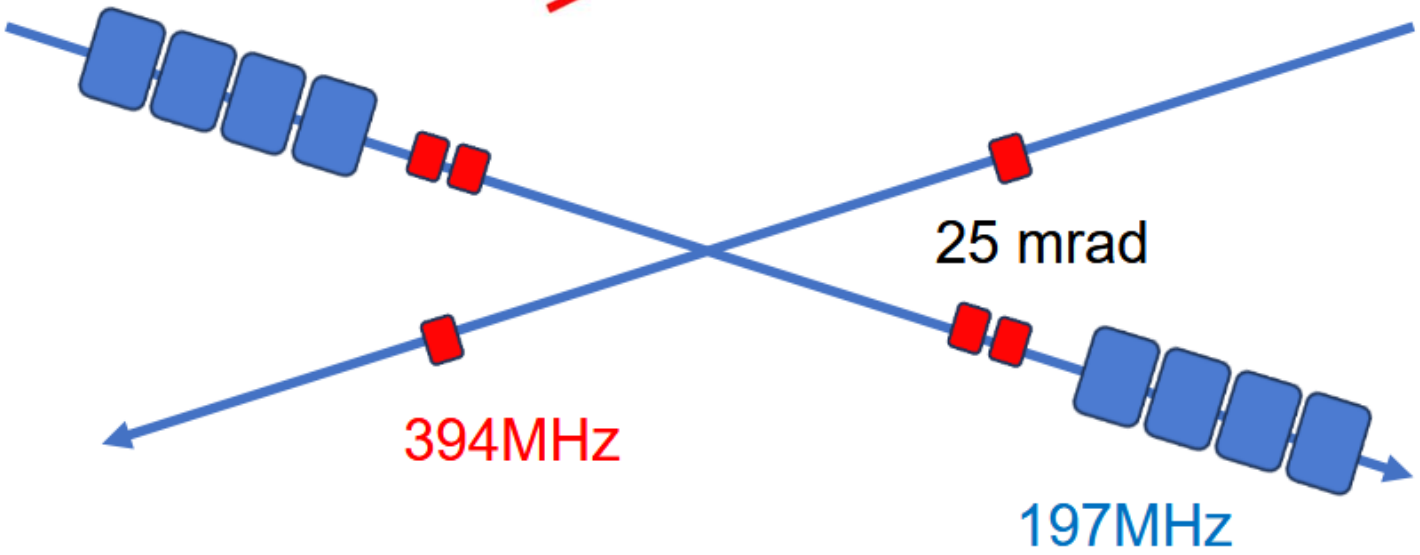
Canadian Contributions to EIC and ePIC

1) Accelerator crab cavities (TRIUMF)

- Beam crossing at an angle
  - Imperfect beam bunch overlap → lower luminosity
- Niobium superconducting RF cavities
- Produces deflecting field, skews beam bunch
- Hadron storage ring: eight 197 MHz cavities, four 394 MHz cavities
- Electron storage ring: two 394 MHz cavities (lower beam rigidity)
- Factor of 10 increase in luminosity





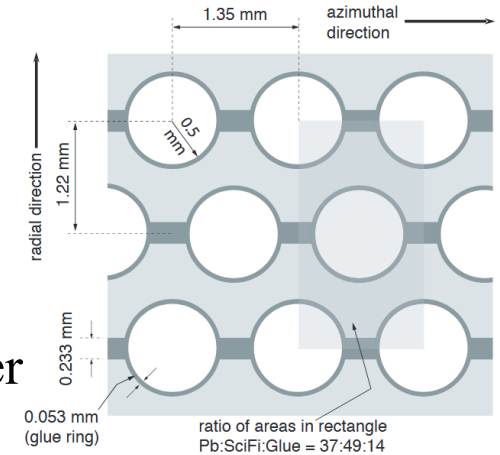


2) BIC (University of Regina, University of Manitoba, Mount Allison University)

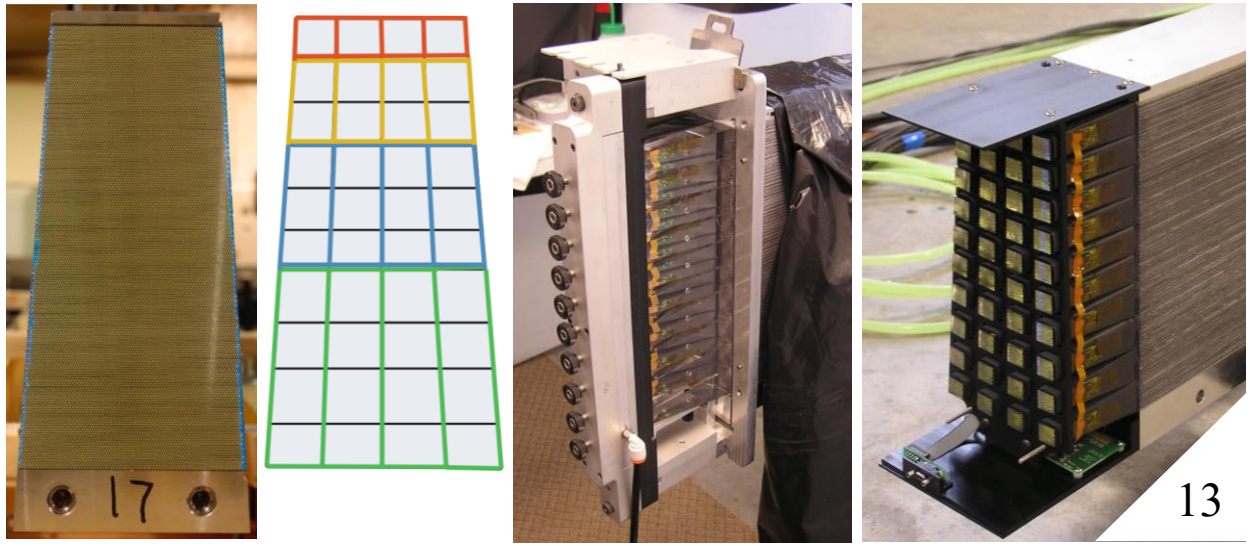
Barrel Imaging Calorimeter (BIC)

Barrel Calorimeter (BCAL) at GlueX

- **BCAL modules**
  - Pb/SciFi matrix
  - Assembled in hydraulic press at UofR
    - Layers of lead, epoxy, and fibers
    - Top and bottom Al plates
  - Machined to trapezoidal cross-section
  - Ends polished



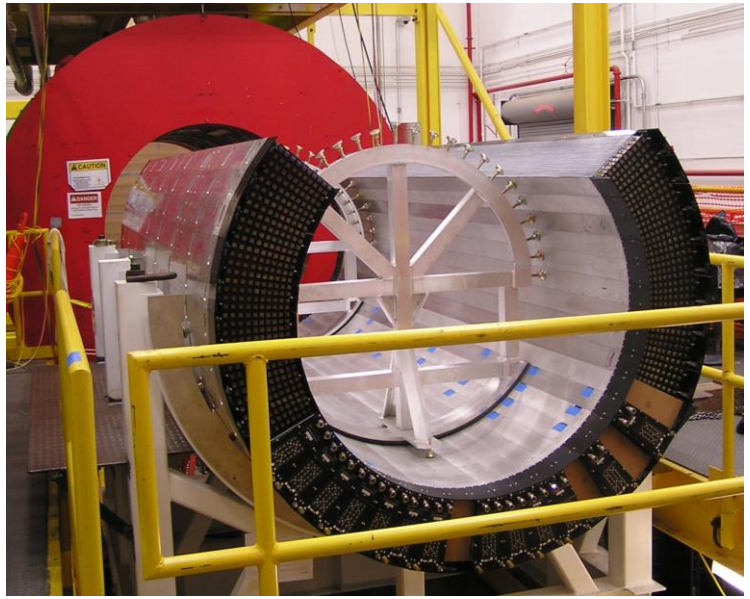
- **Module readout scheme**
  - 40 Hamamatsu S12 SiPMs
  - 10 layers, 4 SiPMs per layer
  - Light guides glued to ends
  - LEDs mounted on each guide
    - SiPM performance monitoring

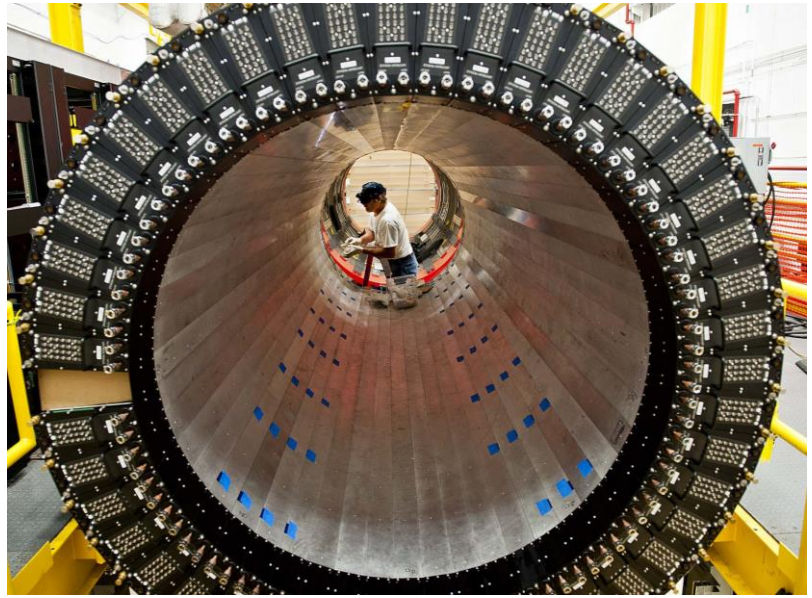


Barrel Imaging Calorimeter (BIC)

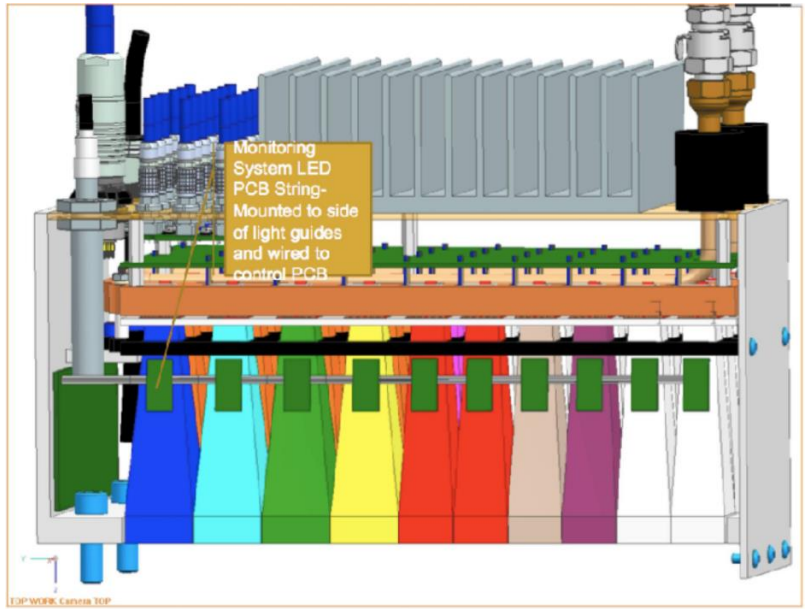
Barrel Calorimeter (BCAL) at GlueX

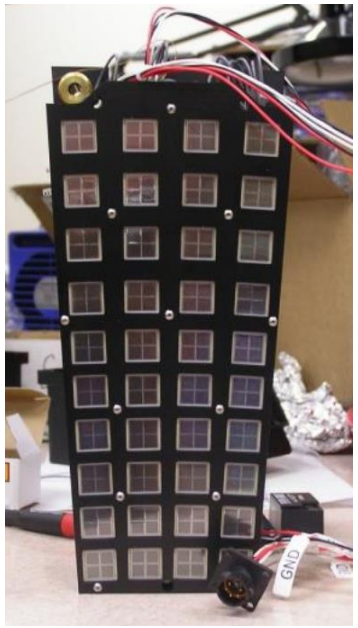
- **BCAL assembly**
  - 48 modules
  - Length = 390 cm
  - Inner radius ~ 65 cm
  - Outer radius ~ 90 cm
  - Pb/SciFi thickness = 15.1 X_0
  - Sampling fraction ~ 10%
  - γ up to ~ 3 GeV
  - e up to ~ 3 GeV





- **Readout wedge design**
  - Attach to module Al plates
  - SiPMs held in dry contact with light guides
  - Thermal plate in contact with each SiPM
  - Copper water-cooling pipes remove heat
  - Amplification/summing PCB board
  - N_2 gas flush for humidity control
  - Back plate (cabling pass-through)

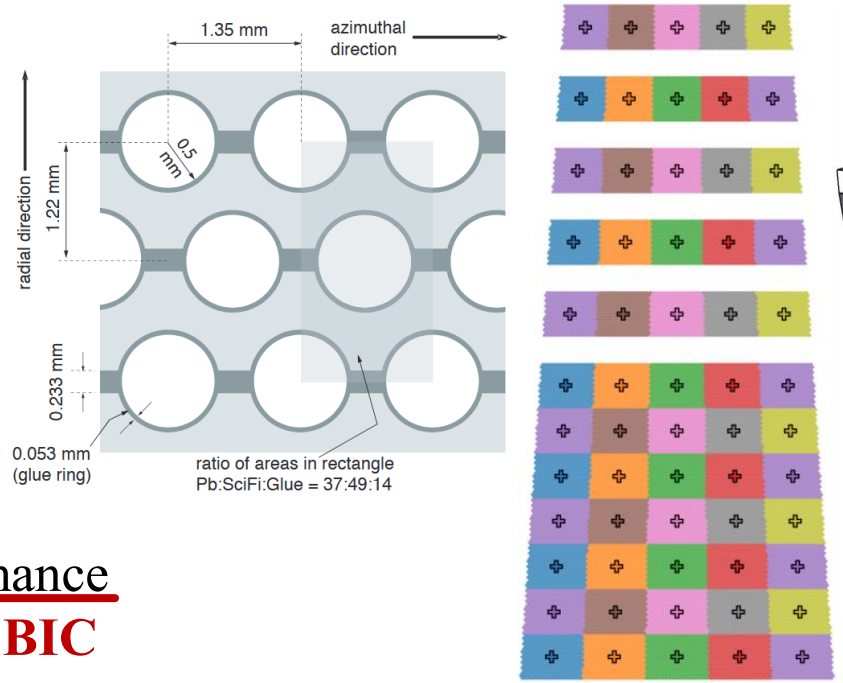


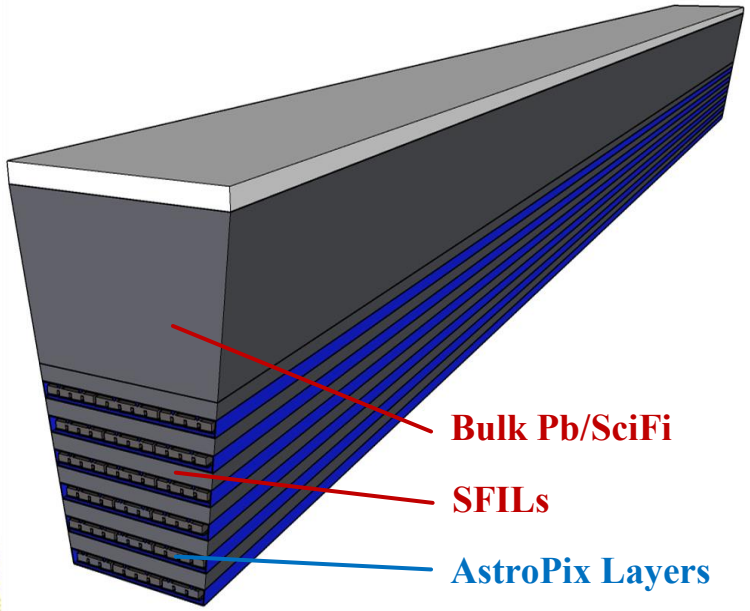


Barrel Imaging Calorimeter (BIC)

Sampling Calorimeter Layers

- ~~BCAL~~ BIC ~~modules~~ sectors
  - Pb/SciFi matrix
  - Assembled in hydraulic press at ~~UofR~~ ANL
    - Layers of swaged lead, epoxy, and fibers
    - Top and bottom Al plates
  - Machined to trapezoidal cross-section
  - Ends polished
  - **Bulk section**
  - **5 SciFi Imaging Layers (SFILs)**

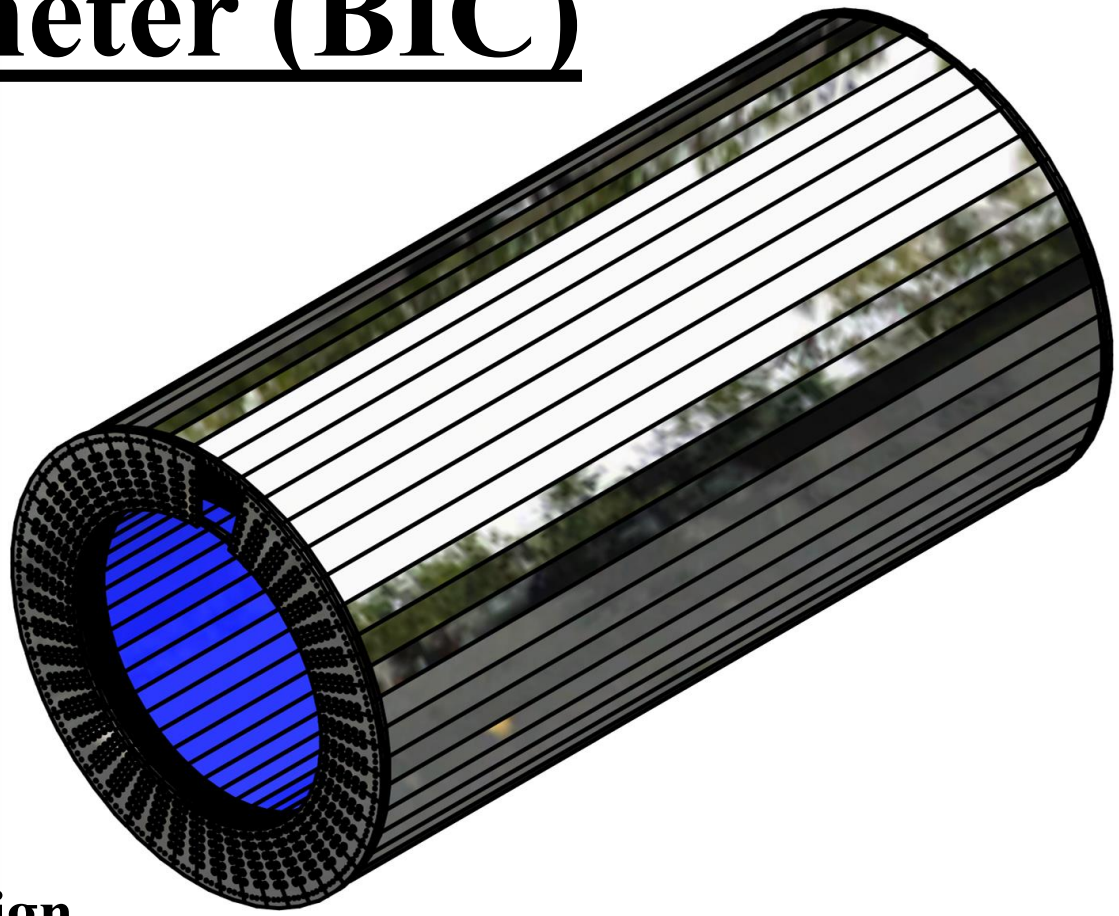




- **Sector readout scheme**
  - ~~40~~ 60 Hamamatsu ~~S12~~ S14 SiPMs
  - ~~10~~ 12 layers, ~~4~~ 5 SiPMs per layer
  - Light guides glued to ends
  - LEDs mounted on each guide
    - Used to monitor SiPM performance
    - **Likely something similar for BIC**

Barrel Imaging Calorimeter (BIC)

Sampling Calorimeter Layers



- **~~BCAL~~ BIC assembly**
  - 48 sectors
  - Length = ~~390~~ **435** cm
  - Inner radius ~ ~~65~~ **82** cm
  - Outer radius ~ ~~90~~ **121** cm
  - Pb/SciFi thickness = ~~15.1~~ **17.1** X_0
  - Sampling fraction ~ 10%
  - γ up to ~ ~~3~~ **10** GeV
  - e up to ~ ~~3~~ **40** GeV

- **~~Readout Wedge~~ End-of-Sector Box (ESB) design**
  - Compared to BCAL wedge:
    - Less physical space → more compact
    - Cooling requirements differ
  - Design currently underway…

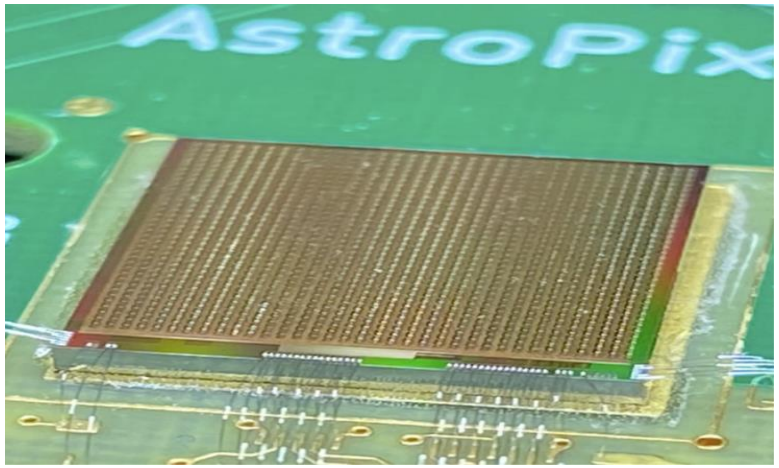
Novel approach: combine proven sampling calorimeter methods with imaging calorimetry **(AstroPix layers)**

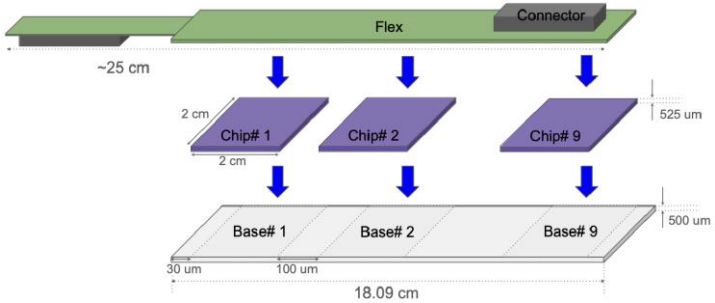
Barrel Imaging Calorimeter (BIC)

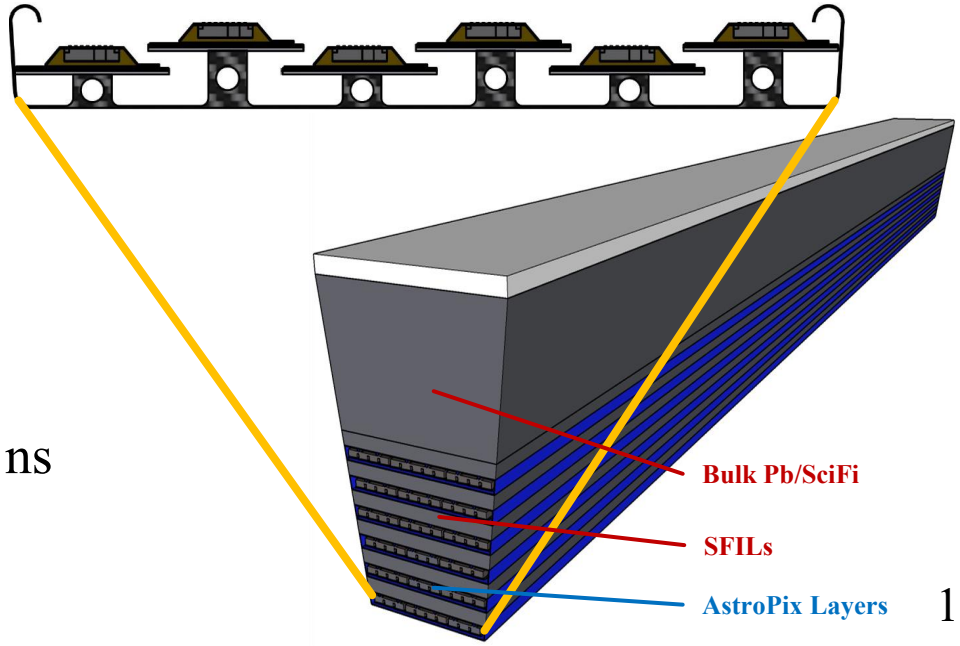
Imaging Calorimeter Layers - AstroPix

9 chips/module
12 modules/stave
6 – 8 staves/tray
8 trays/sector
48 sectors
> 290,000 chips

- **Technology – HV-CMOS MAPS**
  - **H**igh-**V**oltage **C**omplementary **M**etal -**O**xide-**S**emiconductor **M**onolithic **A**ctive **P**ixel **S**ensor
  - Si cells, integrated amplifier circuitry
  - 500 μm pixel size
  - Fast detectors, good timing resolution
  - Decent energy resolution (~ 10% at 60 keV)
  - Designed by NASA for use in space telemetry
    - Very low power dissipation







- **AstroPix v3 (current)**
  - 1.87 cm x 1.96 cm
  - 35 x 35 pixels
  - Timing resolution ~ 25 ns
  - Row/column readout
  - ~ 15 mW / chip
- **AstroPix v6 (final)**
  - 2 cm x 2 cm
  - 39 x 37 pixels
  - Timing resolution ~ 3.25 ns
  - Individual pixel readout
  - ~ 8 mW / chip

Barrel Imaging Calorimeter (BIC)

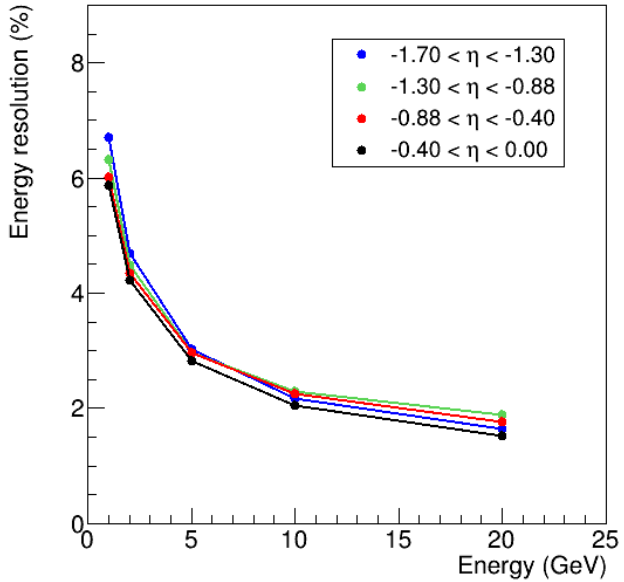
BIC Performance Simulations – Energy and Position Resolution

$$\sigma/E = a/\sqrt{E} \oplus b \ [\%]$$

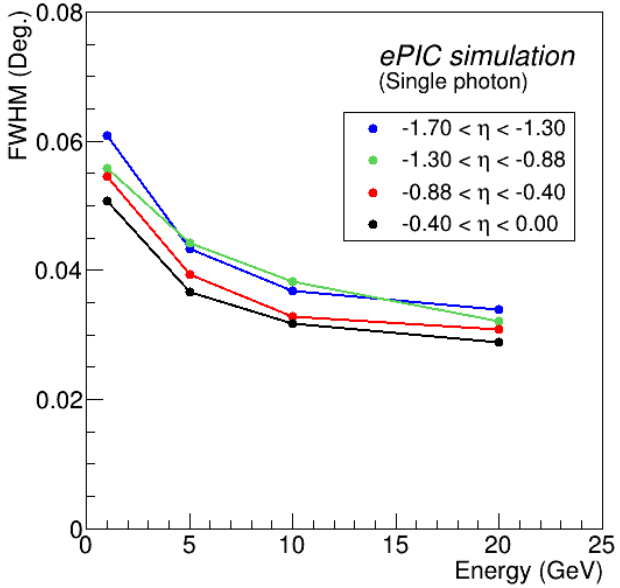
Fit parameters

η	a/√(E) [%]	b [%]
(-1.7, -1.3)	6.60(0.03)	0.66(0.04)
(-1.3, -0.88)	6.11(0.01)	1.24(0.01)
(-0.88, -0.4)	5.91(0.02)	1.24(0.02)
(-0.4, 0)	5.85(0.01)	0.88(0.02)

σ_γ/E_γ vs. E_γ at various η



δφ vs. E_γ at η = 0



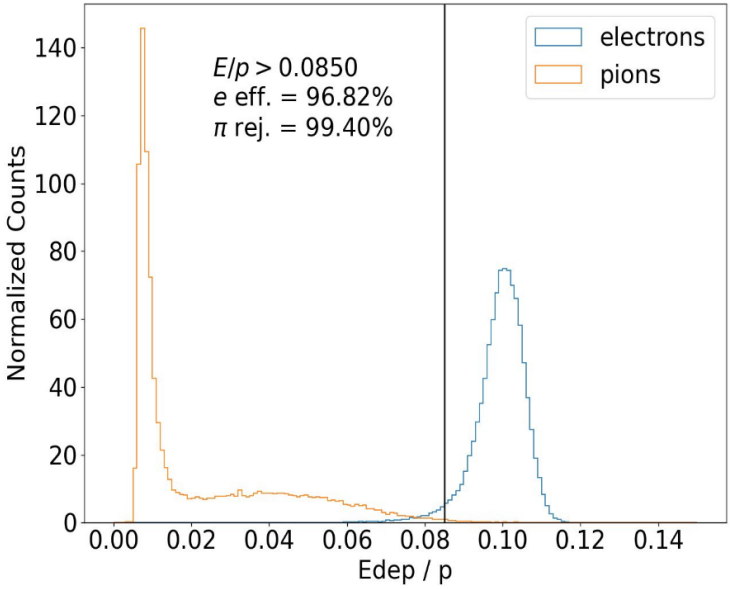
- Simulated E resolution for γ below required 10%/√E ⊕ 2-3% over all η
- Position reconstruction using clustering algorithm with AstroPix layers data
  - Position resolution on the order of the pixel size

- E resolution primarily from Pb/SciFi layers (plus imaging layer energy information)
- Position resolution primarily from AstroPix layers (plus Pb/SciFi two-ended readout)

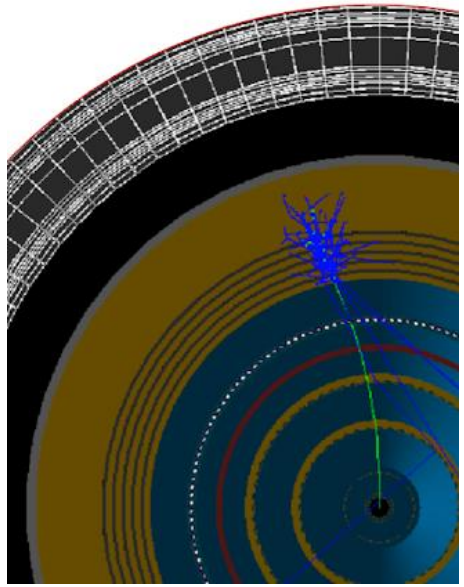
Barrel Imaging Calorimeter (BIC)

BIC Performance Simulations – e/π Separation

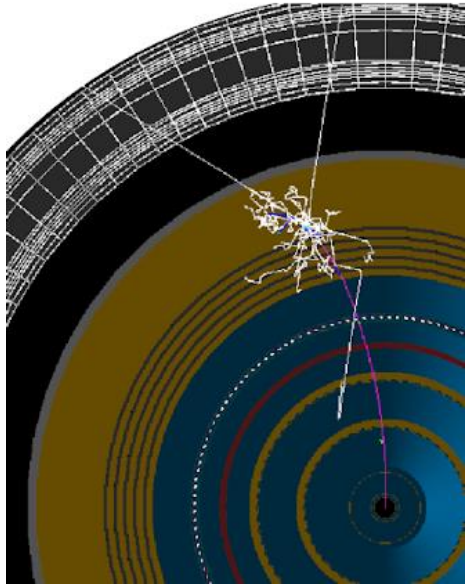
E_{dep}/p in BIC SciFi



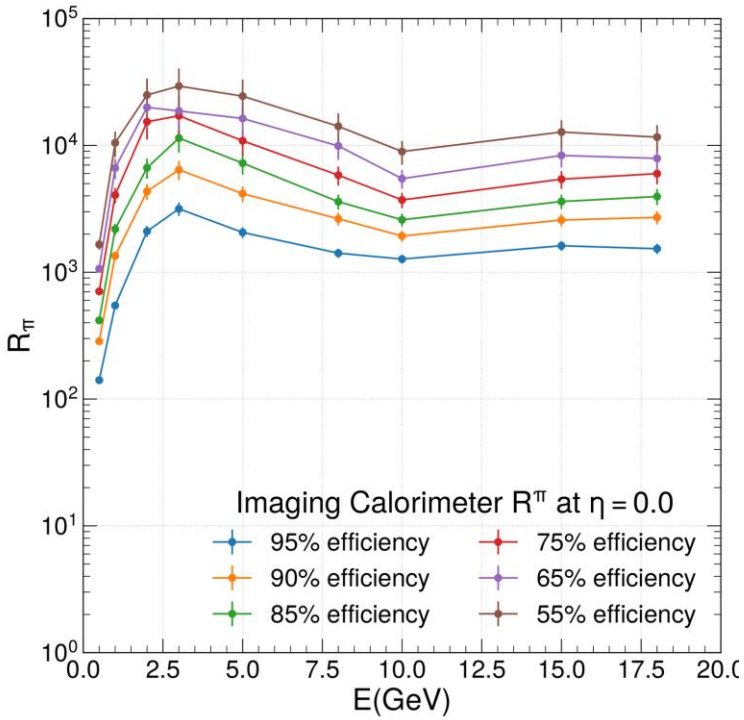
Electron



Pion



R_π vs. E at η = 0



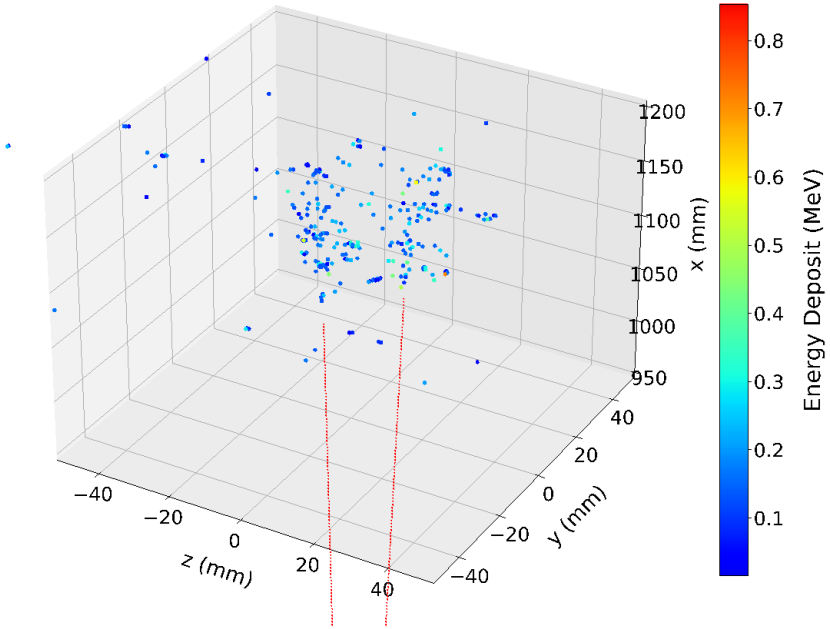
1) Traditional separation: E/p cut using sampling calorimeter layers of BIC
   - > 99% π rejection with 95% e efficiency
2) Shower shape discrimination
   - Neural network using 3D position and energy info from AstroPix layers

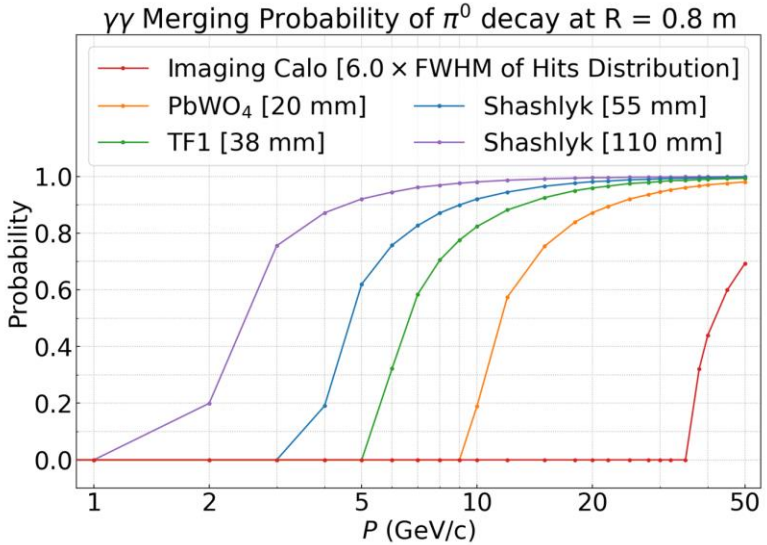
- Expect at least 10^3 in pion suppression at 95% e efficiency for E > 1 GeV

Barrel Imaging Calorimeter (BIC)

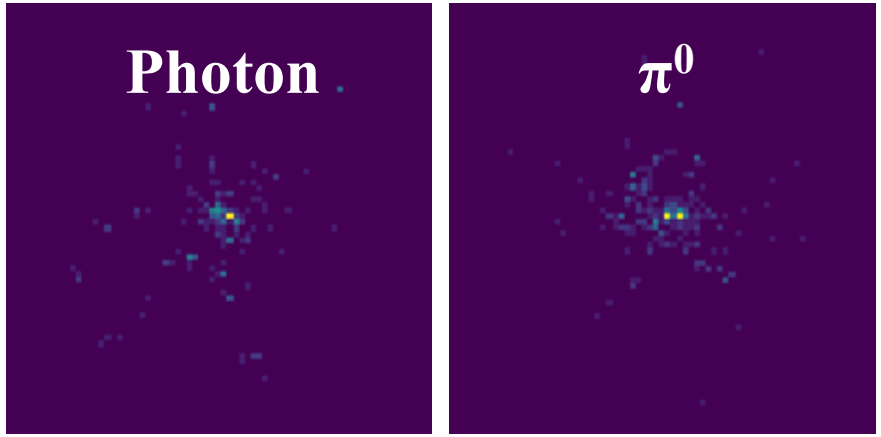
BIC Performance Simulations – γ/π^0 Separation

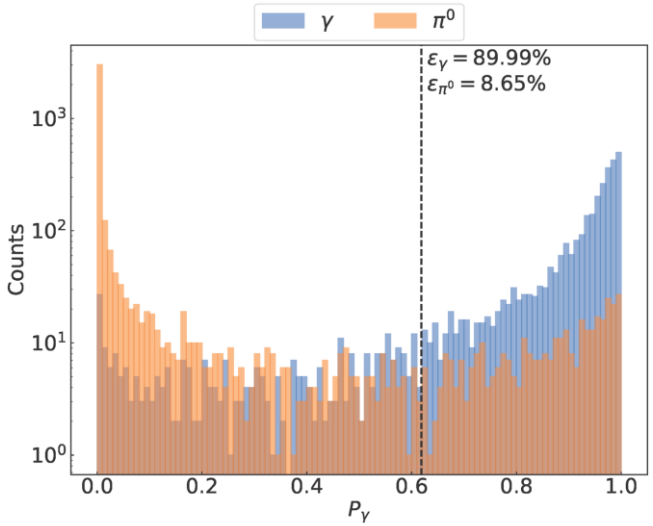
15 GeV/c $\pi^0 \rightarrow \gamma\gamma$





10 GeV/c γ and π^0

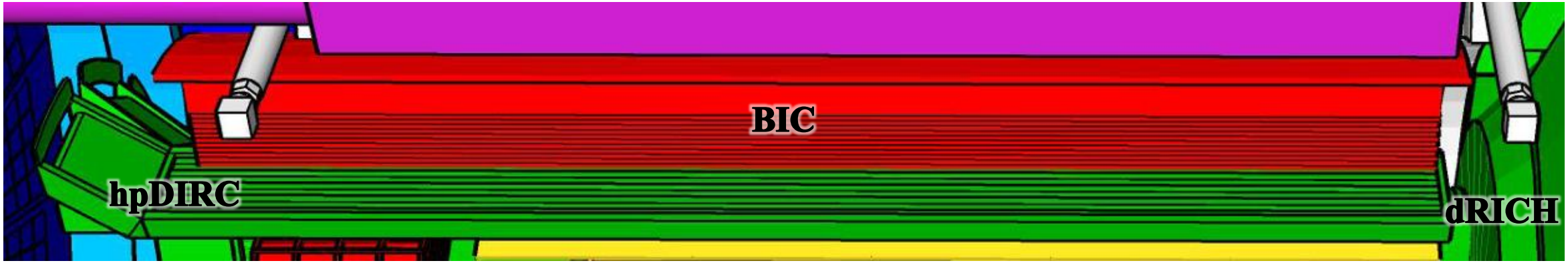


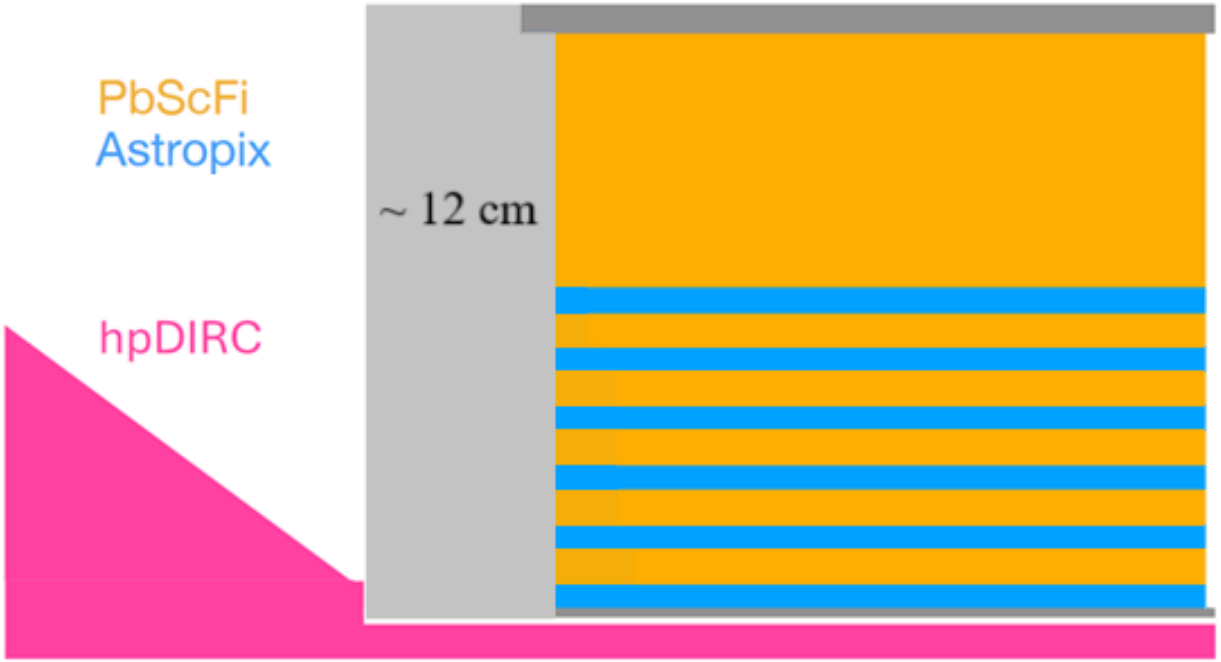


- Great position resolution → π^0 identification and γ/π^0 separation
- $\pi^0 \rightarrow \gamma\gamma$ cluster merging occurs at very high energies
- Convolutional neural network using spatial and energy info from AstroPix layers
  - 10 GeV/c particles at $\eta = 0$ (high-end of required γ/π^0 separation in barrel region)
  - ~ 91% π^0 rejection at ~ 90% γ efficiency

End-of-Sector Box (ESB)

Requirements and design limitations



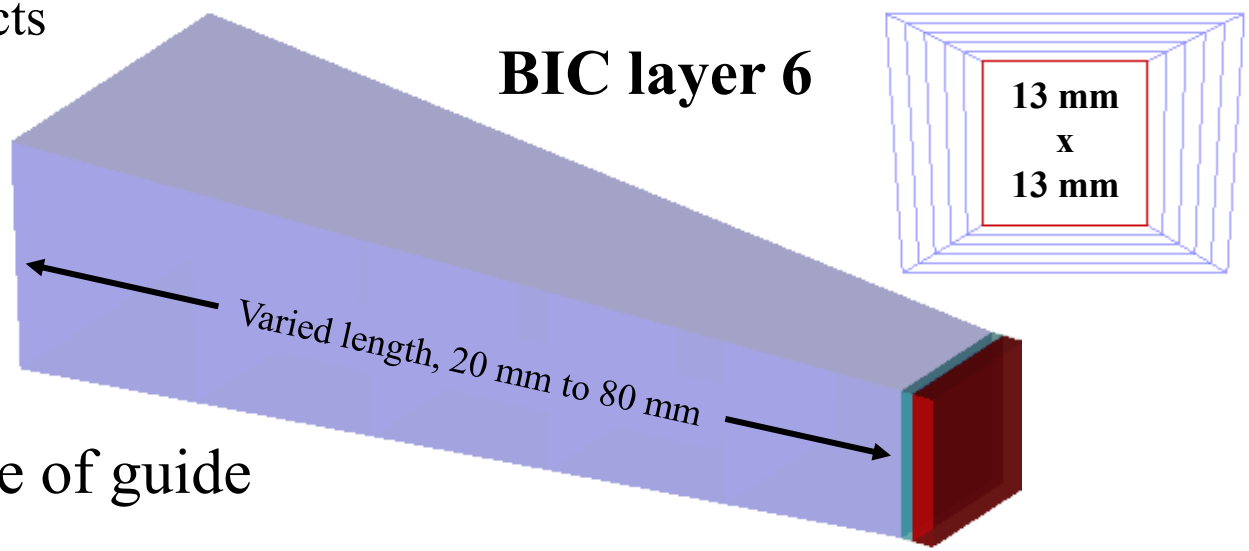


- Limited space for BIC instrumentation
  - ~ 12 cm on e-going side
- *Need to fit:*
  - Light guides
  - SiPMs with optical cookies
  - Cooling system
  - Readout electronics for SiPMs and AstroPix
    - CALOROC and ETC
- Largest element: light guides
  - **How short can we make them?**

End-of-Sector Box (ESB)

Light Guide Simulations

- Geant4 simulation of BIC light guides (all twelve layers) vs. length
- Efficiency: how many photons reach the SiPM face?
- Light mixing: how evenly distributed are photons on the SiPM face?
  - Good light mixing helps avoid saturation effects



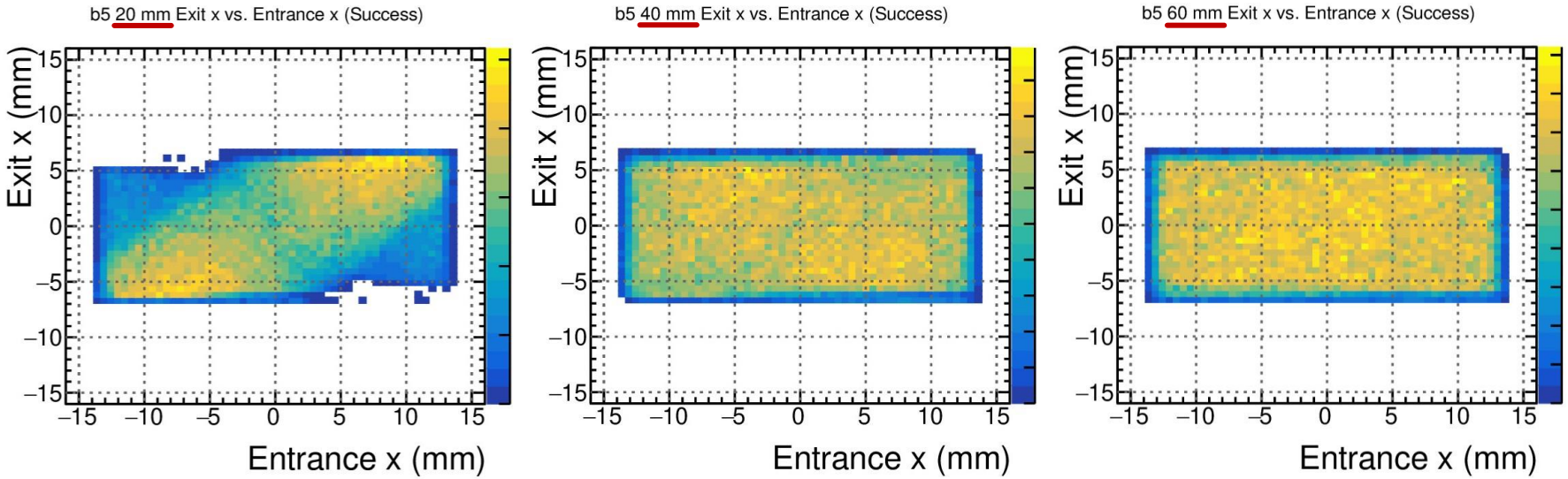
- Light guides: acrylic (n ~ 1.5)
- Optical cookie: silicone (n = 1.43)
- SiPM: Hamamatsu S14 array
  - 0.1 mm epoxy resin window (n = 1.57)

- Generate optical photons uniformly at base of guide
  - Thrown flat in φ, flat in cos(θ)
  - θ_{max} = 20.4 degrees (capture angle for single-clad scintillating fibers)
- Simulate guides with 1-mm-thick optical cookie and with 0.5-mm-thick air gap
- Record thrown ('entrance') coordinates, 'exit' coordinates, and 'detection' coordinates
  - Efficiency = # of 'detected' photons / # of thrown photons

End-of-Sector Box (ESB)

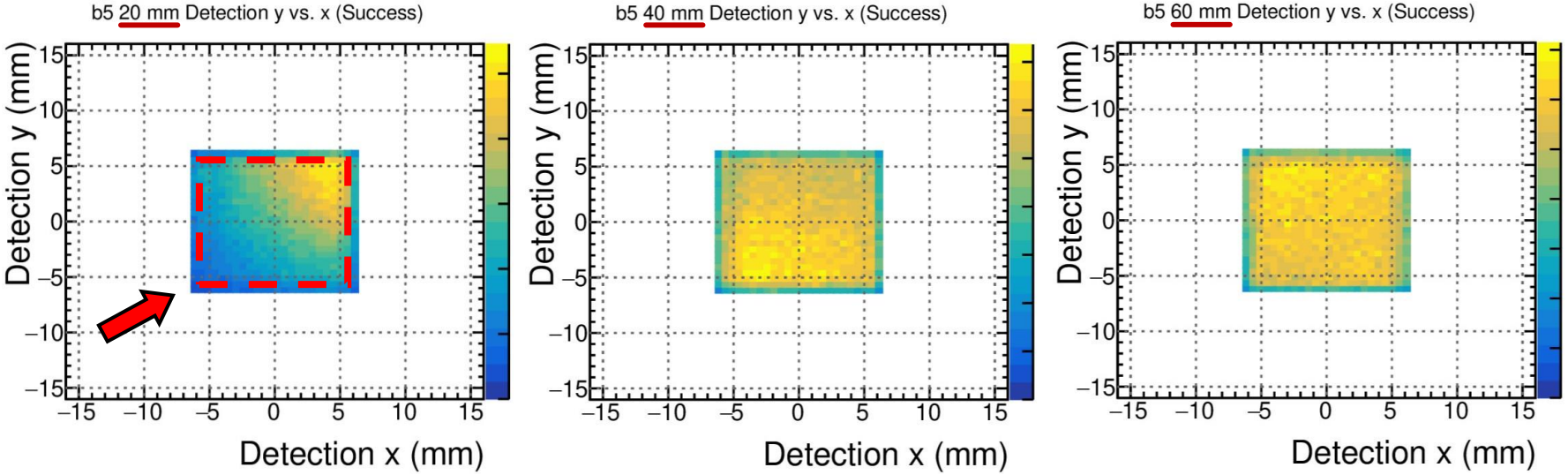
Light Guide Simulations

Light Mixing – Input/Output Correlation



- Exit x vs. entrance x
- Ideal: flat, no obvious pattern
- Correlation clear for low lengths
- Helpful, but fairly subjective…

Light Mixing – SiPM Face Photon Distribution – NAAD



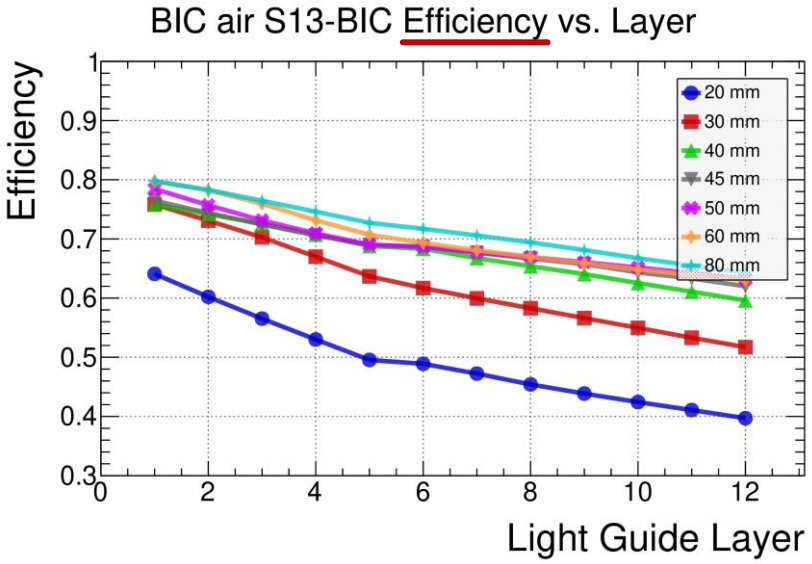
- **N**ormalized **A**bsolute **A**verage **D**eviation
- Metric for flatness of inner SiPM pixels

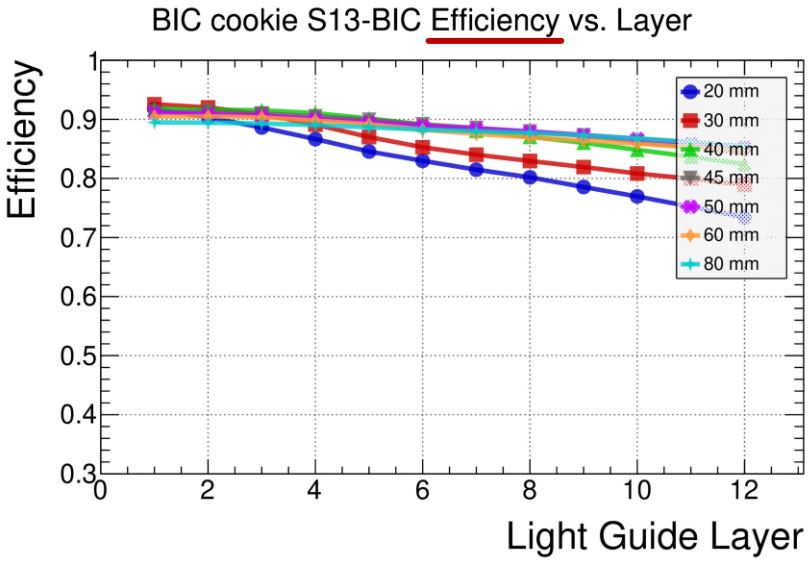
$$1 - \frac{1}{N \cdot \bar{Y}} \sum_{i=1}^{N} \left| Y_i - \bar{Y} \right|$$

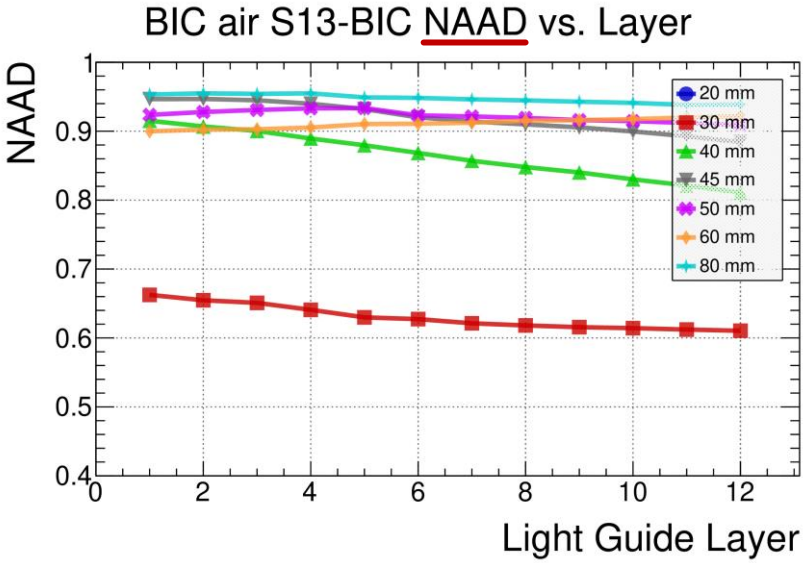
- Detection x vs. detection y
- Quadrant source

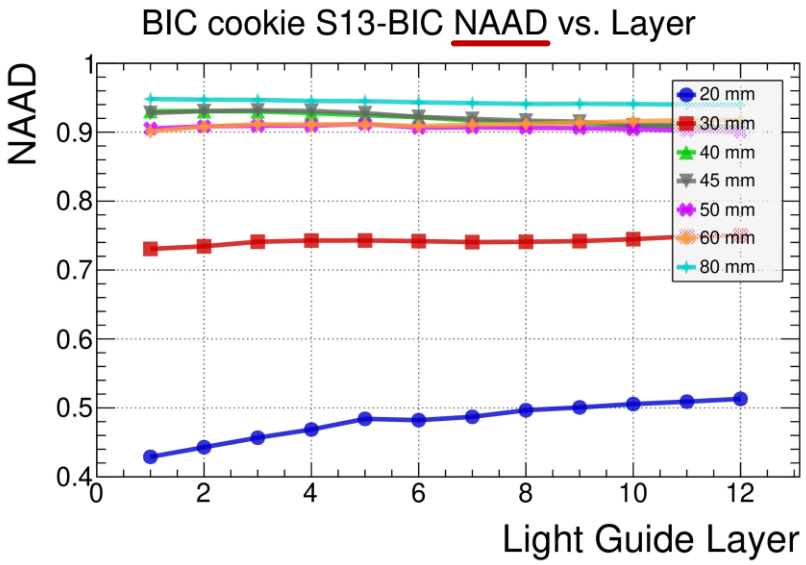
End-of-Sector Box (ESB)

Light Guide Simulations









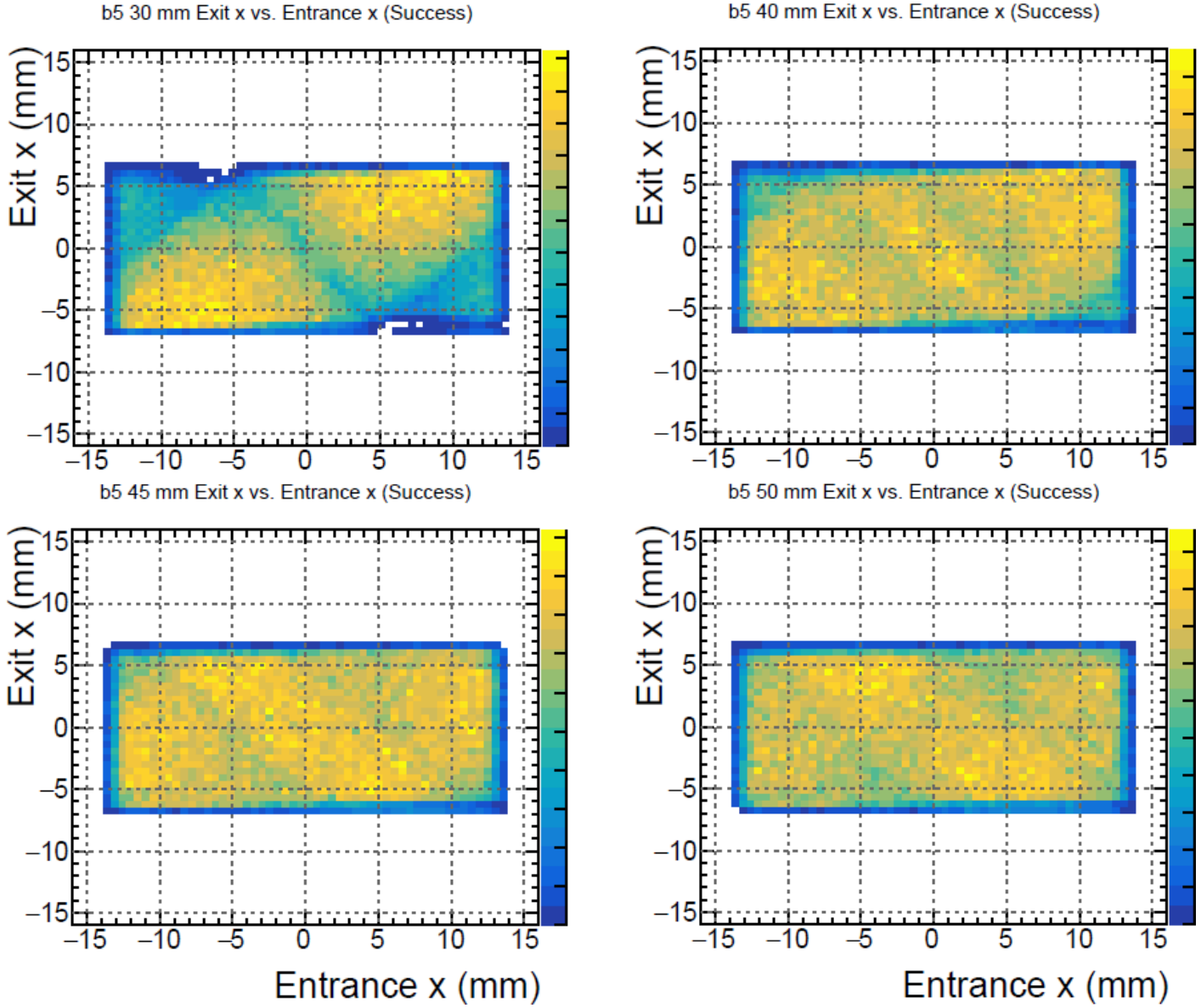
- **Efficiency consistent above 45 mm**
- **20 – 30 % more efficient with cookie**

- **NAAD comparable above 45 mm**
  - **More sporadic with air gap**

- **Optical cookie is important**
- **50 mm guides seem reasonable!**

End-of-Sector Box (ESB)

Light Guide Simulations



- **Efficiency consistent above 45 mm**
- **20 – 30 % more efficient with cookie**

- **NAAD comparable above 45 mm**
  - **More sporadic with air gap**

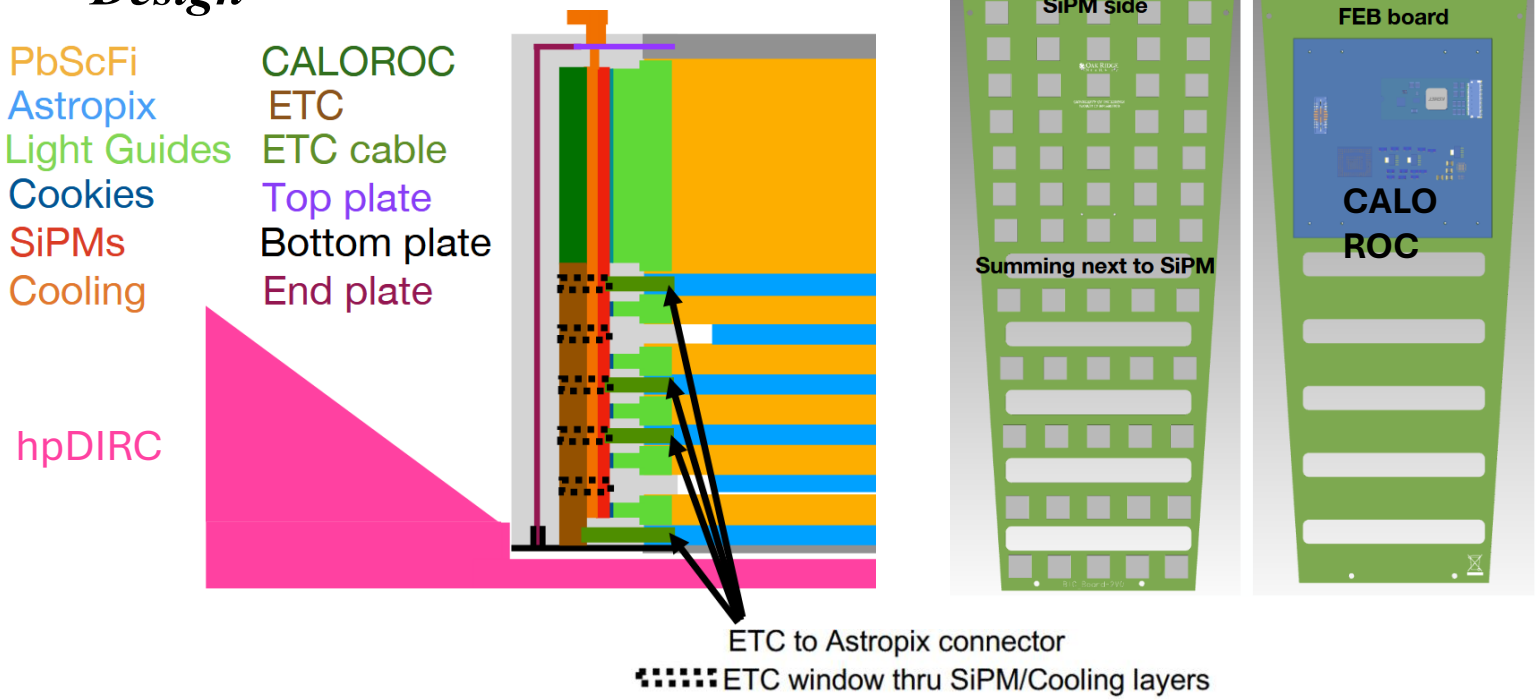
- **Optical cookie is important**
- **50 mm guides seem reasonable!**

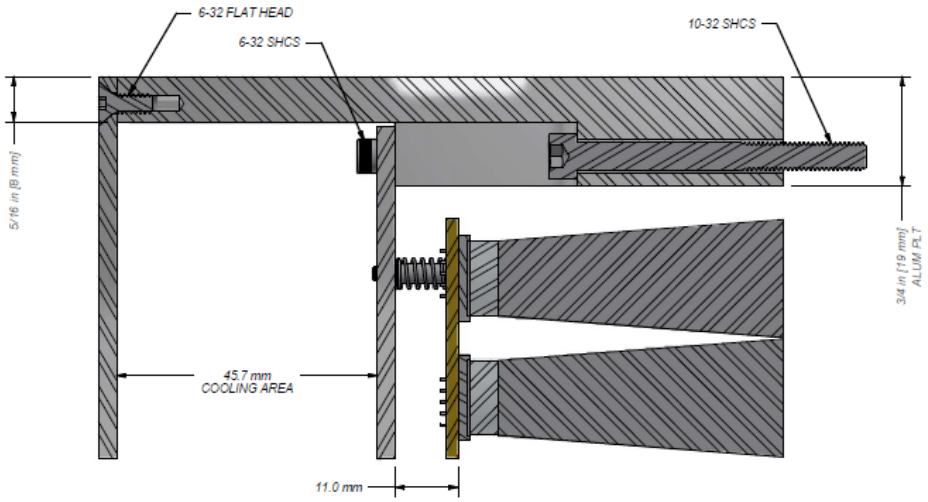
- **Entrance/exit correlations okay, but still visible, at 50 mm**

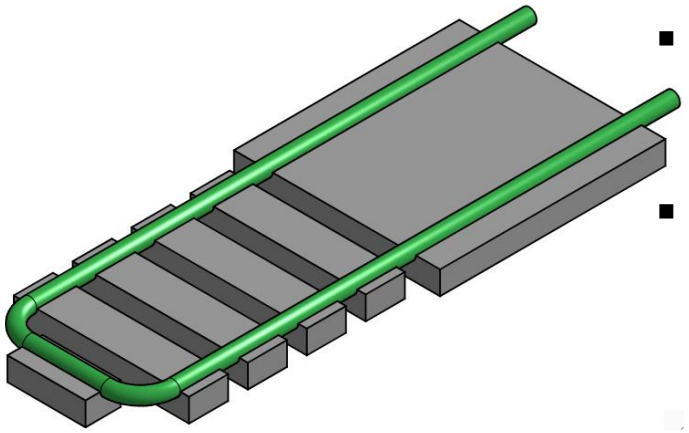
- **Prototype guides being machined**
- **Need to test:**
  - **Cookie vs. air gap transmission**
  - **Level of light mixing required**

End-of-Sector Box (ESB)

Design







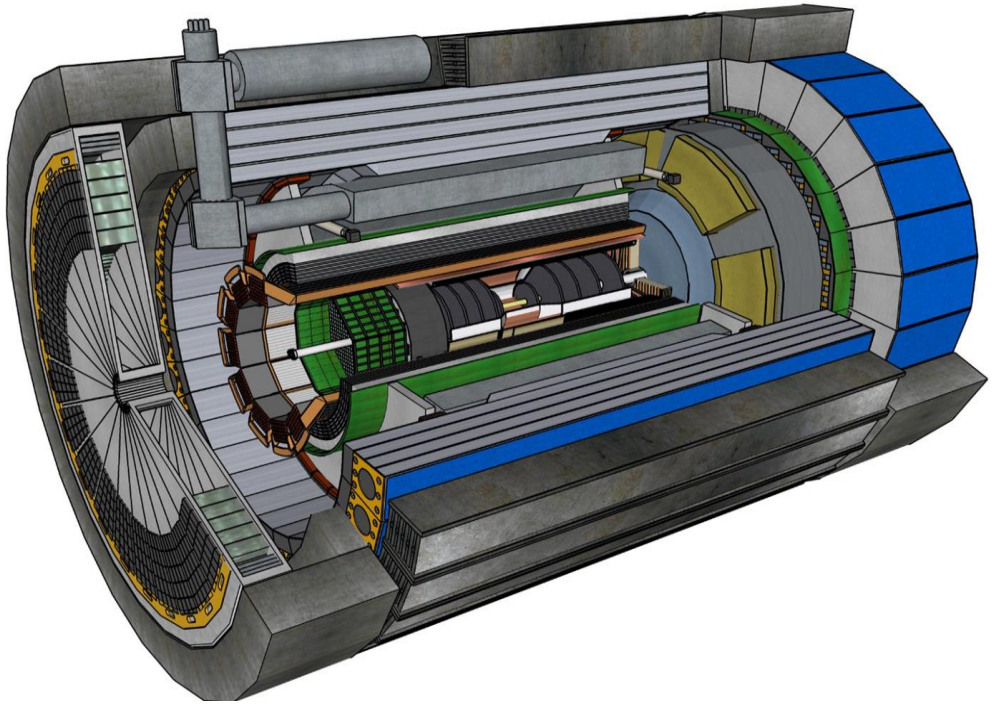
- ✓ 50 mm light guides
- ✓ Optical cookies
- ✓ SiPM readout board
  - ✓ Held under spring tension
- ✓ Front-end board (FEB)
- ❑ Cooling plate between SiPMs and FEB
  - ❑ Chilled water pipe
- ✓ Holes in PCBs and cooling plate
  - ✓ ETC cable pass-through
- ❑ AstroPix readout (ETC)
- ❑ SiPM readout (CALOROC)
- ✓ Space for cabling
- ❑ N_2 gas flush for humidity control
- ✓ ESB removed radially for servicing
  - ✓ Avoids hpDIRC

- ESB cooling requirements
  - SiPMs + RDOs: ~ 20 W (estimate)
    - BCAL wedge was ~ 11 W
- AstroPix heat: 1 W / stave (56 W / sector)
  - Radial heat dissipation?
  - Cooled inner and outer Al plates
  - Simulation studies ongoing

BIC and EIC Timeline

- **BIC R&D**
  - Final designs soon, prototypes by next year
  - ESB
  - Pb/SciFi bulk section
  - SFILs
  - AstroPix v5 and v6
  - Readout Electronics
- **Signal Integration**
  - Beam tests (completed and future)
  - Coincident Pb/SciFi and AstroPix readout
- **Full systems testing**
  - Pb/SciFi + AstroPix + SFILs + ESBs (2026)
- **Full-scale production**
  - Start 2027, BIC delivered to BNL by 2031

- **Broad experiment timeline**
  - RHIC operation ends this year
  - Construction of facilities (2026 – 2029)
  - Installation of detectors (2028 – 2032)
  - Detector commissioning (2031 – 2034)
  - Science starts 2034 – 2035 (hopefully!)



ePIC BIC Detector Subsystem Collaboration

USA

- Argonne National Laboratory
- NASA Goddard Space Flight Center
- Oklahoma 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

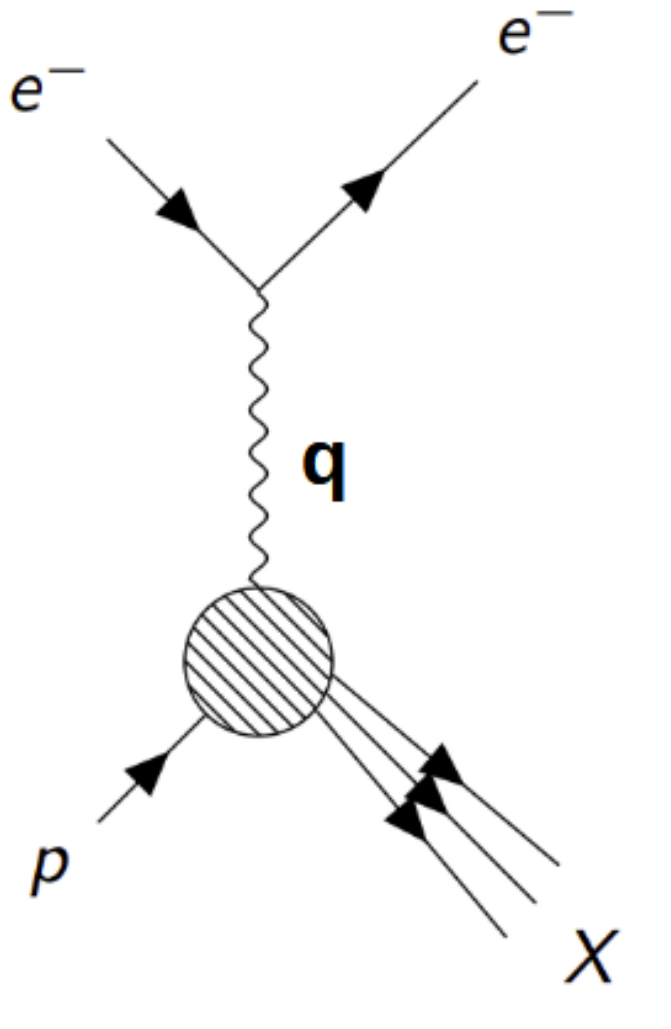
Korea

- 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

Bjorken Scaling

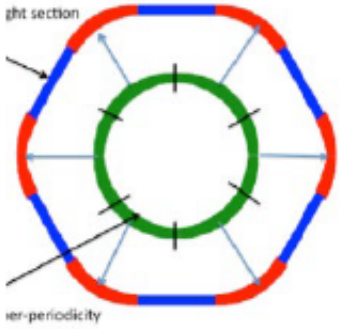


$$Q^2 \equiv -q^2 \qquad x \equiv \frac{Q^2}{2p_2.q} \qquad y \equiv \frac{p_2.q}{p_2.p_1}$$

$$Q^2 = s\,x\,y$$

s: Center-of-mass energy
x: Fraction of nucleon momentum carried by struck parton
y: Fractional energy loss of incoming particle

ABOUT e POLARIZATION



➔ resonance free acceleration up >18 GeV

on average, every bunch refilled in 2.2 min

ABOUT p/ light ion POLARIZATION

presently

Measured RHIC Results:

- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

empowerment

Planned near term improvements:

AGS: Stronger snake, skew quadrupoles, increased injection energy

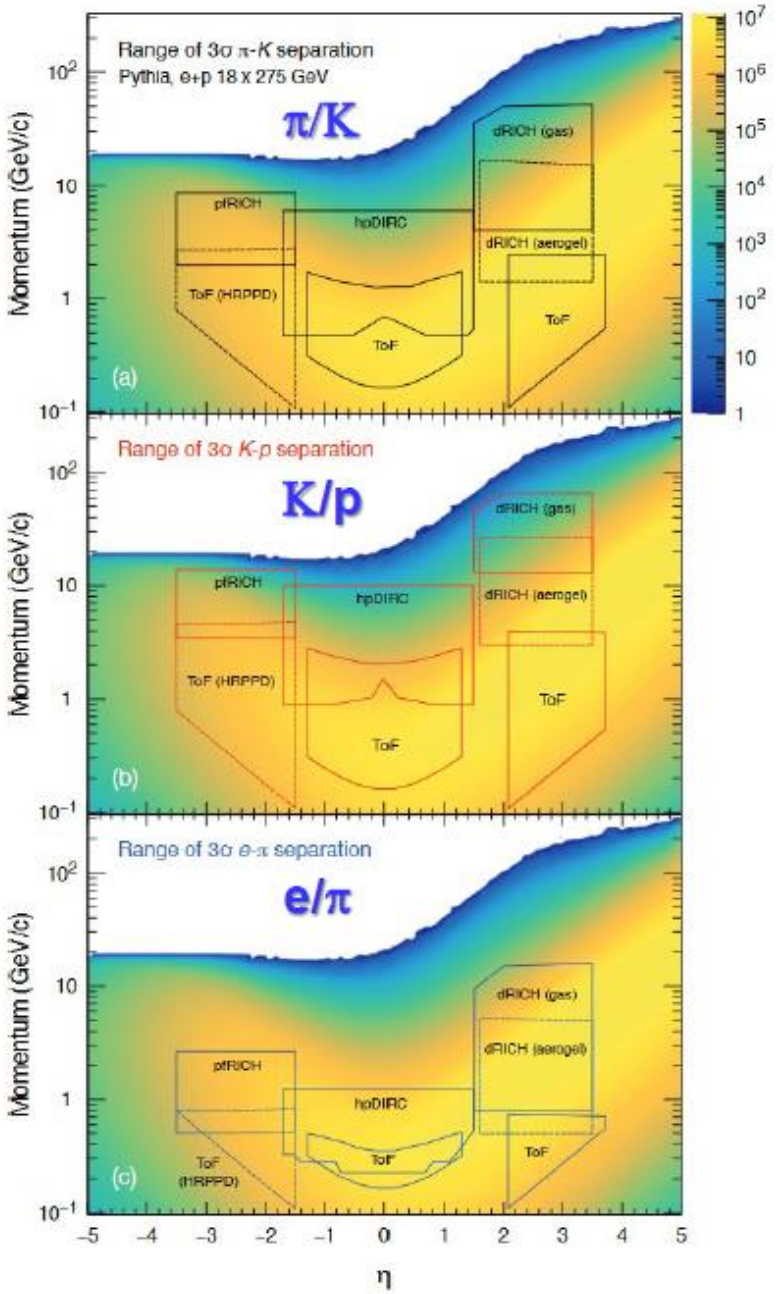
➔expect 80% at extraction of AGS

RHIC: Add 2 snakes to 4 existing no polarization loss

➔ expect 80% in Polarization in RHIC and eRHIC

High polarization ^{3}He and D beams also possible

PID



Detector Requirements

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

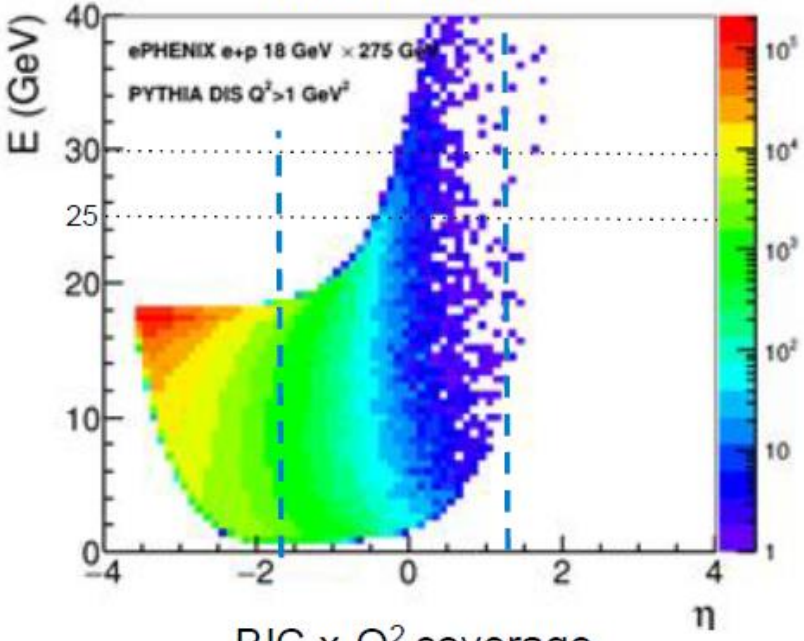
Identify scattered electrons and measure their energy, in high Q^2 events, also decay electrons, e.g. from vector or heavy flavor meson decays, and to measure DVCS photons and decay (G-DET-ECAL-BAR.16.10.05)

- **Electron ID up to 50 GeV** and down to 1 GeV and below (F-DET-ECAL-BAR.16.10.05)
  - Energy resolution < **10%/√(E) + (2-3)%** (P-DET-ECAL-BAR.16.10.05)
  - High power for **e/π separation down to 1 GeV/c** (P-DET-ECAL-BAR.26.10.05)
- **Photon measurements up to 10 GeV** (F-DET-ECAL-BAR.26.10.05
- **γ/π^0 separation up to 10 GeV** (F-DET-ECAL-BAR.36.10.05)
  - Distinguishing two showers with opening angle down to 30 mrad (P-DET-ECAL-BAR.36.10.05)

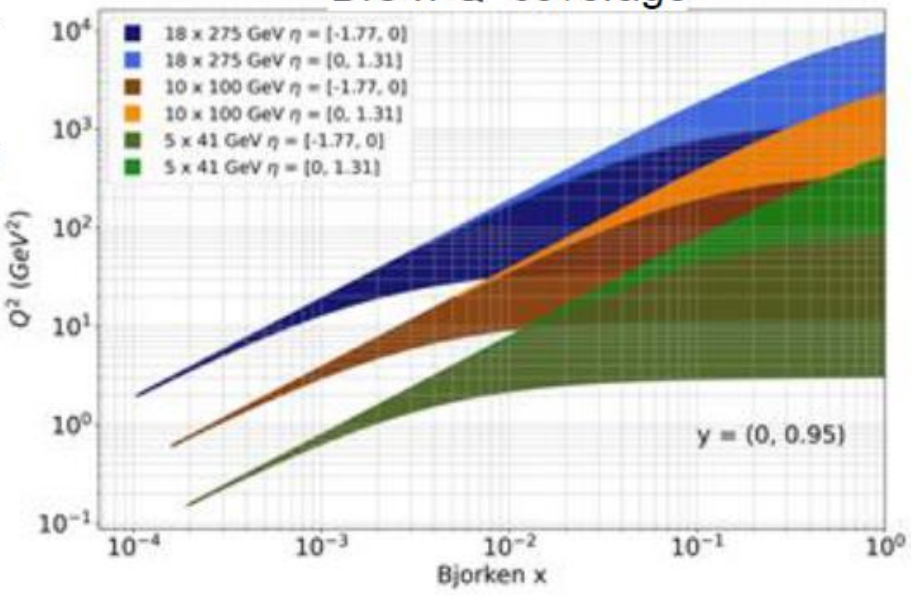
Assist with muon identification (G-DET-ECAL-BAR.36.10.05)

Sufficient dynamic range to **detect MIP** signals in all layers (P-DET-ECAL-BAR.56.10.05)

DIS electrons

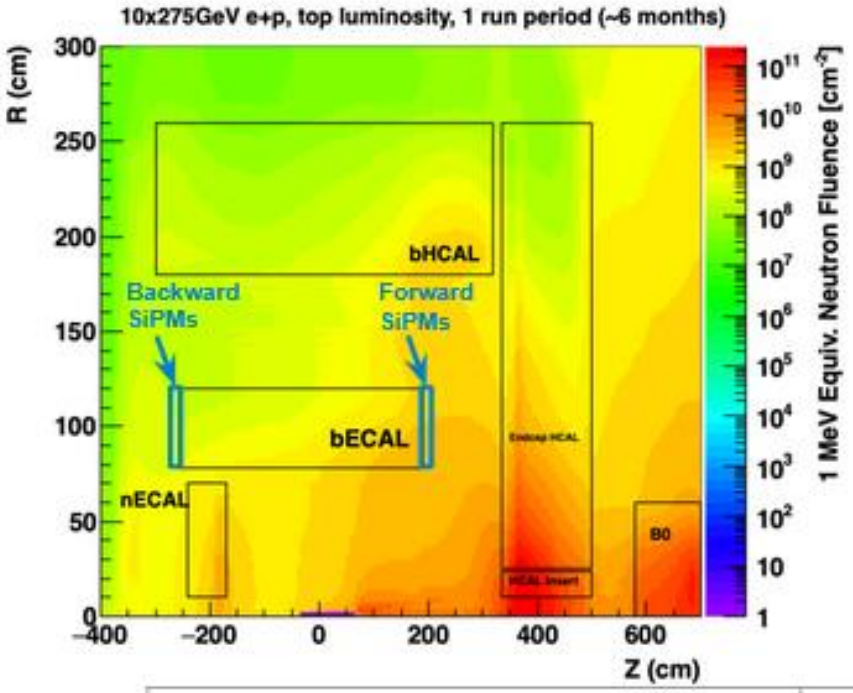


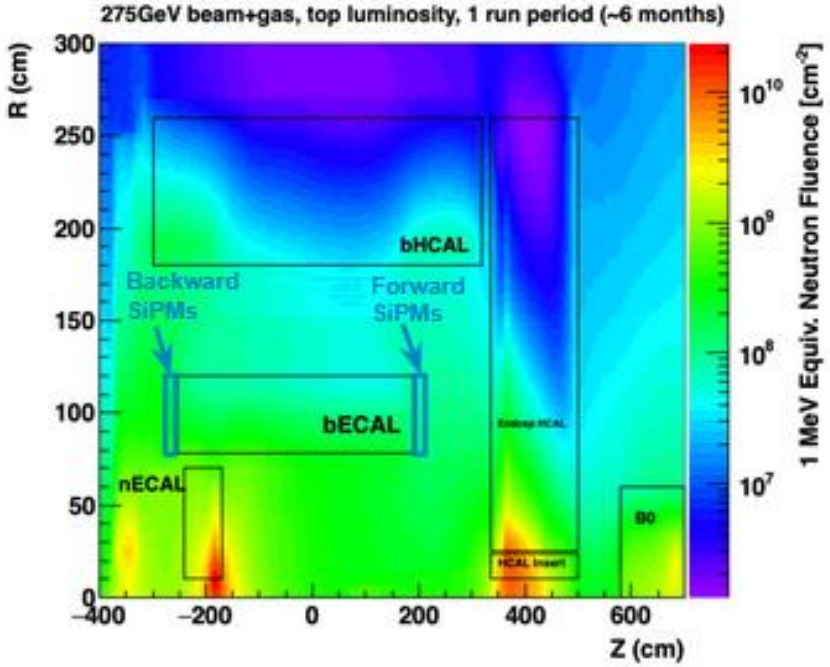
BIC x-Q^2 coverage



Radiation dose at the Barrel ECal SiPMs

https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses





1 MeV equivalent neutron fluence for minimum-bias PYTHIA e+p events at 10x275 GeV @ top machine luminosity for 6 months of running at 100% machine and detector efficiency.

	Forward SiPMs (+z)	Backward SiPMs (-z)
Dose from physics*	~ 3 x 10^{10} / cm^2	~ 6 x 10^9 / cm^2
Dose from beam + gas*	~ 9 x 10^9 / cm^2	~ 5 x 10^9 / cm^2

***In 1 MeV equivalent neutron flux for 10 year-periods of running with top luminosity**

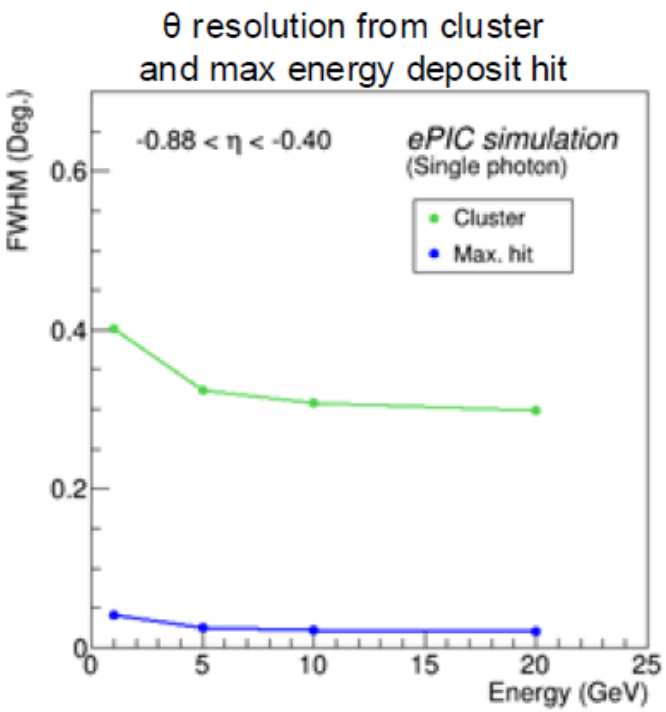
AstroPix

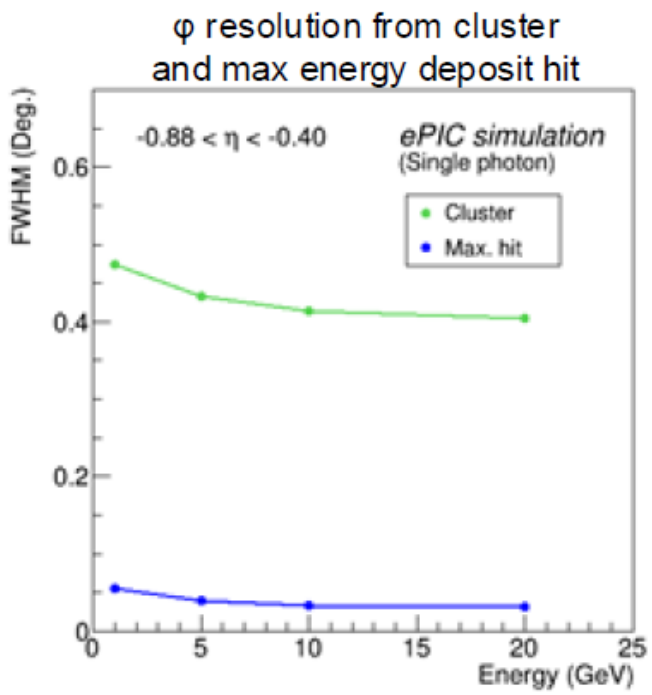
Position Resolution

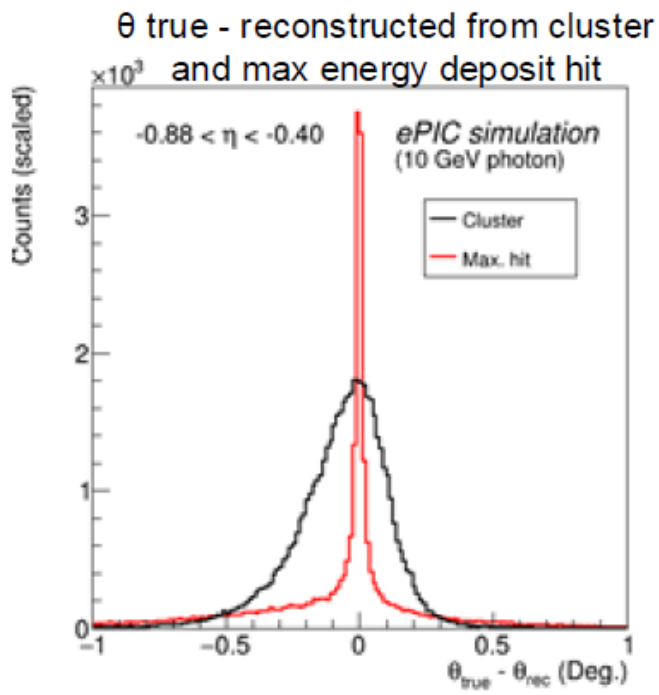
- Maximum energy deposit hit (Max. hit) on the imaging layer where the shower started used to reconstruct θ and ϕ
  - Compared to cluster's θ and ϕ from imaging layers reconstructed with 3D topological algorithm

- Cluster level information: **σ_θ = (0.274 ± 0.006) deg/√E ⊕ (0.295 ± 0.002) mm at -0.88 < η < -0.4**
- First-layer hit information added: **σ_θ= (0.040 ± 0.004) deg/√E ⊕ (0.016 ± 0.003) mm**

- The hit level method shows one **order better** angle resolutions (corresponding ~single pixel resolution) than the ones obtained by cluster (~0.5 Deg.)

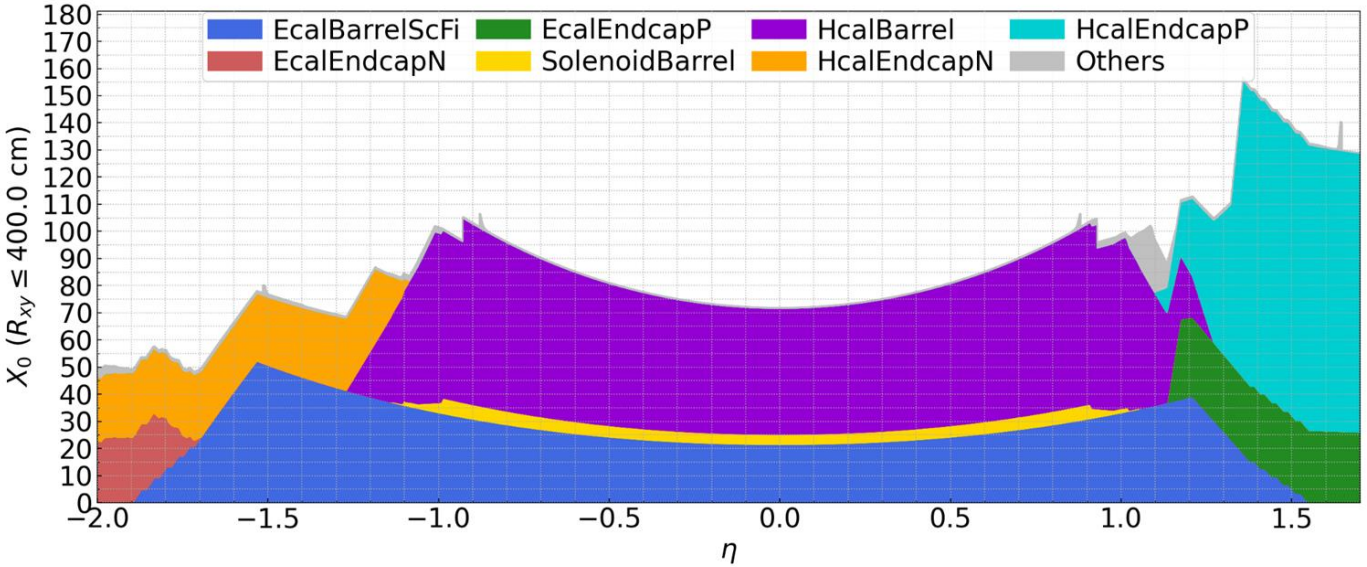




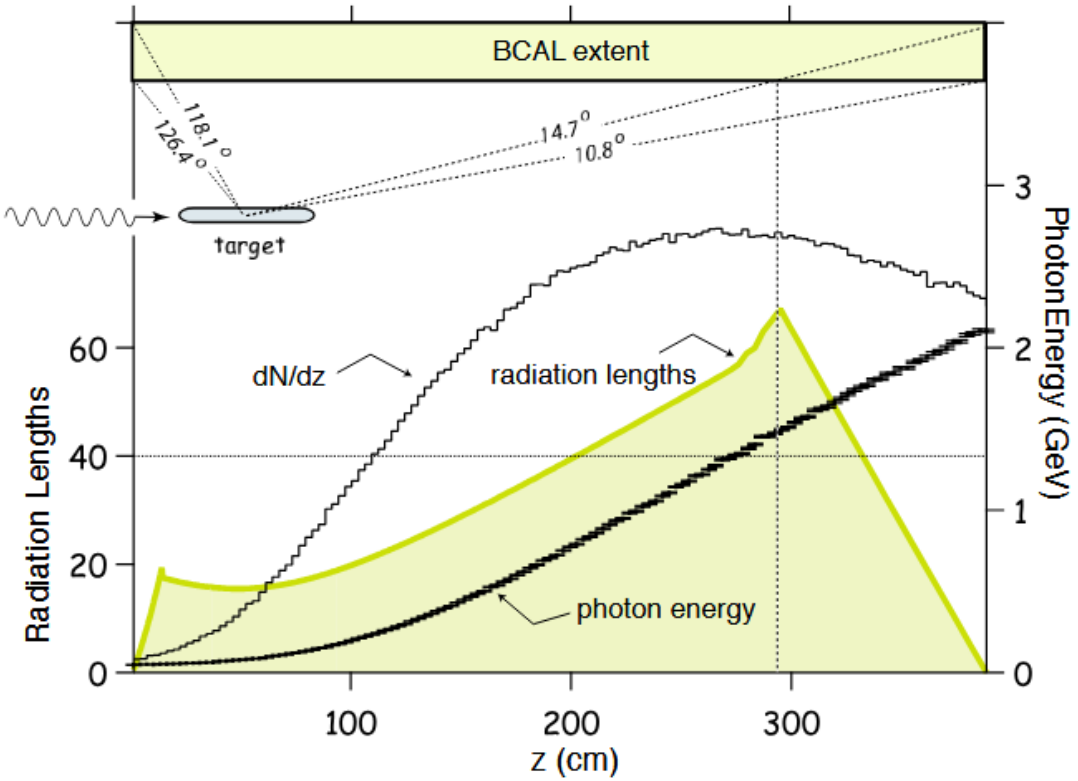


Detector Radiation Lengths

ePIC Components



GlueX BCAL



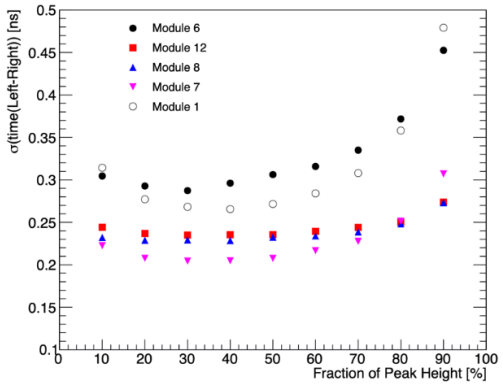
Classification Neural Network

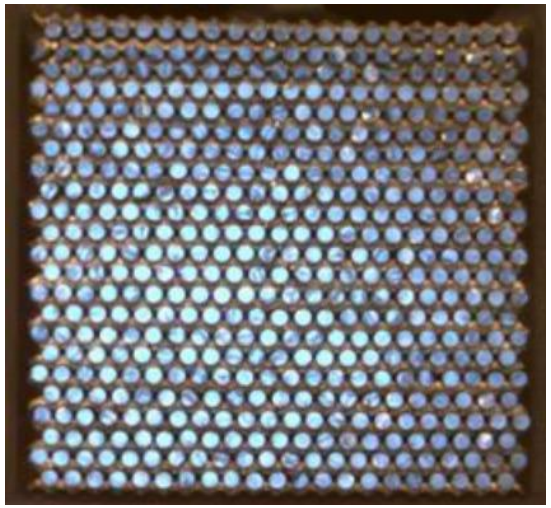
- 10-layer VGG-style **convolutional neural network** (CNN)
  - Combined data from AstroPix and Pb/ScFi
  - 5+2 convolutional and pooling layers, and 3 dense layers
  - Data formatted for each event to N_layers x N_hits x N_features
  - 4 features (Edep, Rc, eta, phi), energy and spatial information for shower
- **Supervised training**
  - Used all official singles productions with 10:1 pion to electron samples (to ensure enough remaining pions after E/P cut. Typically 100-200k events in the AI training sample. Processed over 2TB of simulation results.
  - 20 epochs per training cycle, data split 70-10-20 for training, validation, and testing
  - All uncertainties are based on binomial statistics
- Similar (but somewhat simplified) approach used for neutral pion identification
- Expect further increases in performance through algorithmic improvement, e.g. using GNNs or Point Clouds.

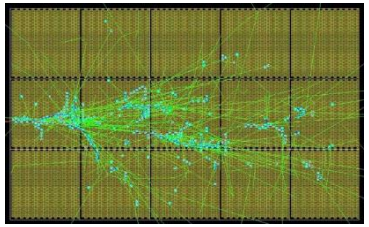
Barrel Imaging Calorimeter (BIC)

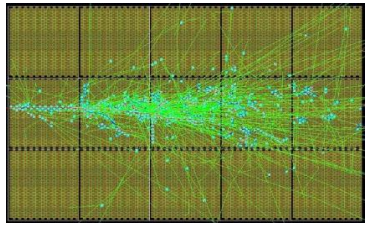
Bench Tests, Beam Tests, and Technology Integration – Korean BIC Collaborators

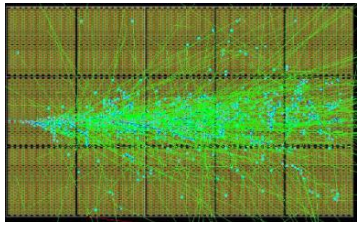
- Beam tests at CERN PS T10: 0.5 – 3 GeV e beam
  - Stacked Pb/SciFi prototype bricks (3 x 5, 10.4 X_0)
  - Longitudinal shower profile and timing resolution (200 – 300 ns)
  - DAQ development and general calibration
- Beam tests at KEK: 0.5 – 5 GeV e beam
  - Stacked bricks (4 x 8, 16.7 X_0), AstroPix chip
  - Test calorimeter and AstroPix signal integration
  - E resolution ~ 5.9% at 3 GeV

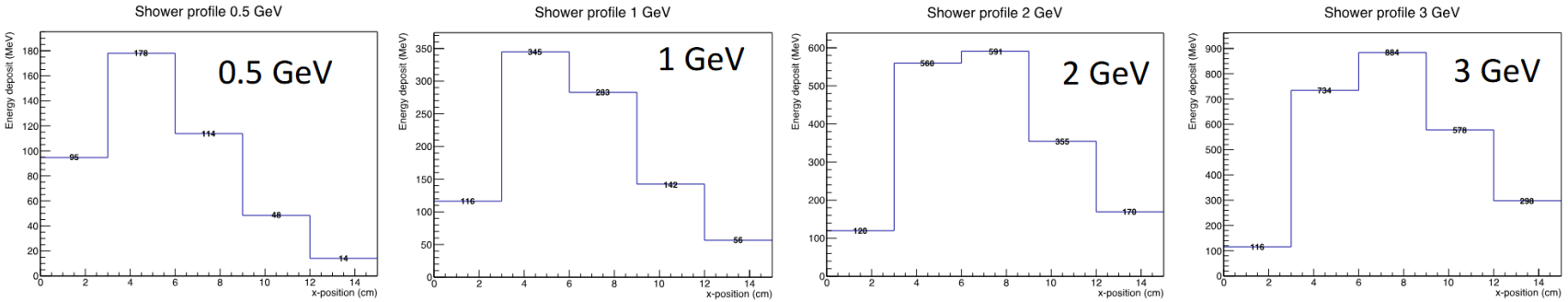


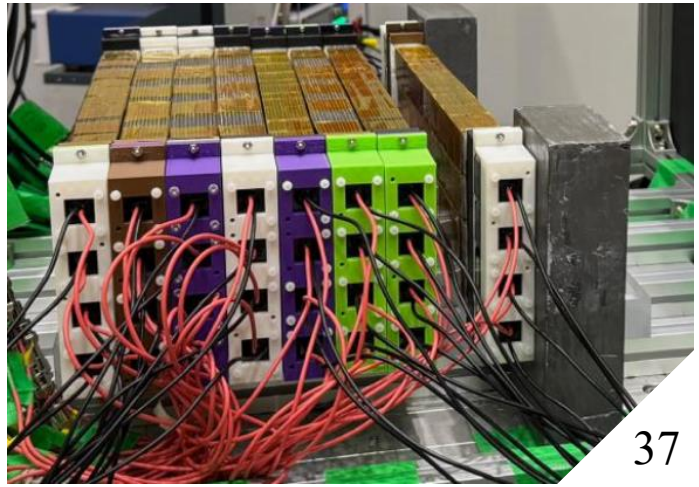








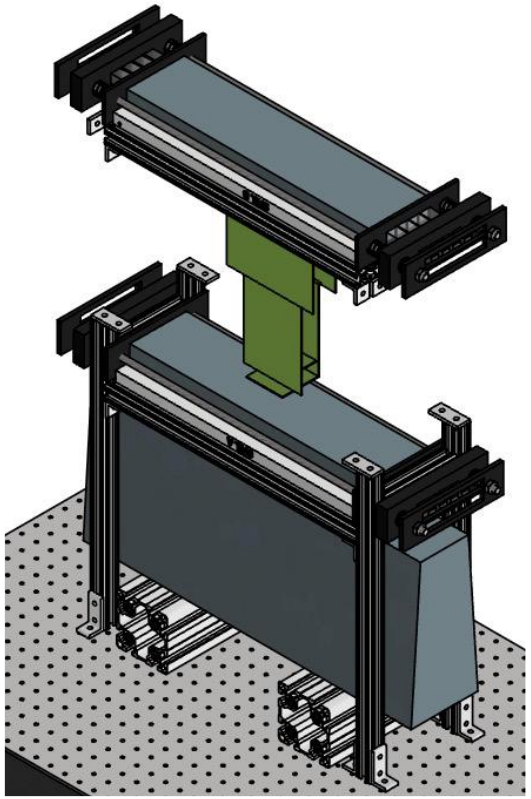


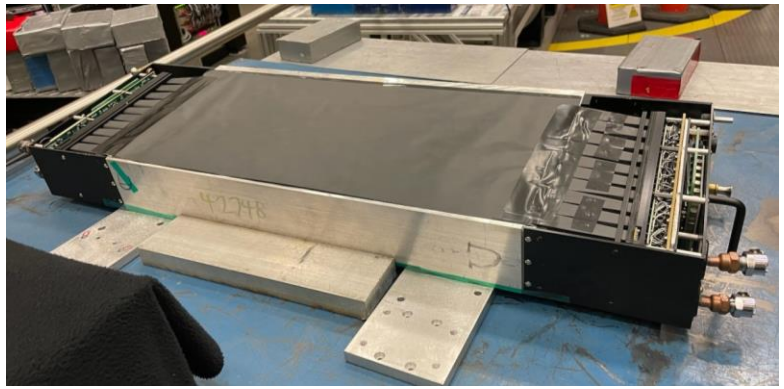


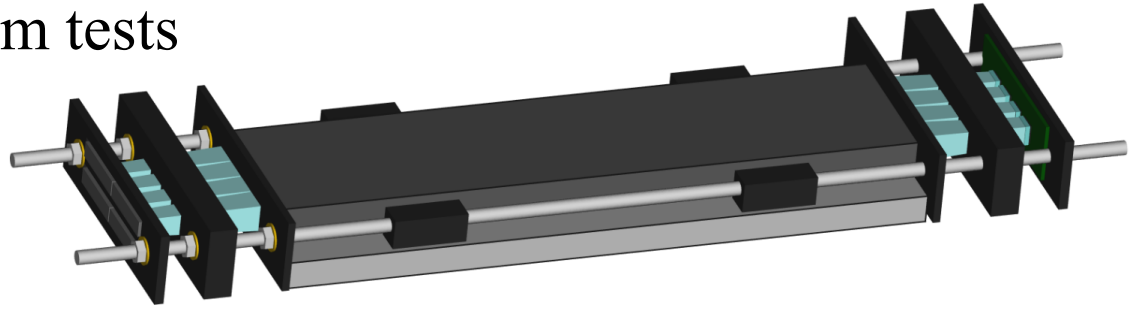
Barrel Imaging Calorimeter (BIC)

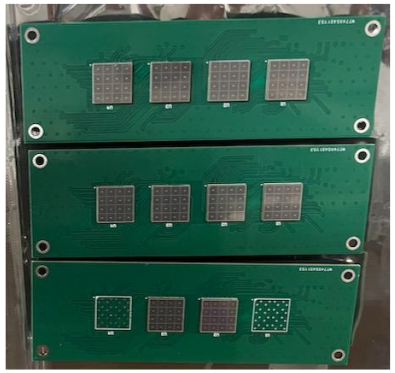
Bench Tests, Beam Tests, and Technology Integration – Argonne and Regina

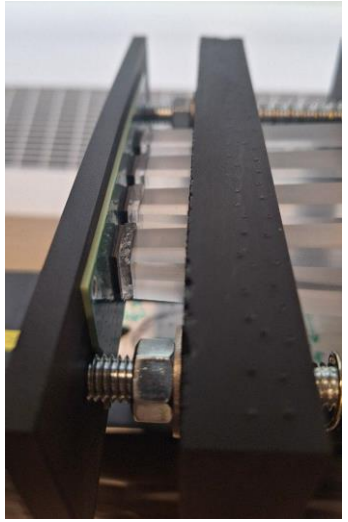
- Cosmics at Argonne: SFIL/bulk section/AstroPix technology integration
  - Bulk: baby BCAL (58 cm prototype BCAL module) + readout wedge
  - SFILs: old prototype 1-inch-thick Pb/SciFi layers + custom readout
    - 3D-printed parts hold light guides and SiPMs in place
    - Ready for future beam tests

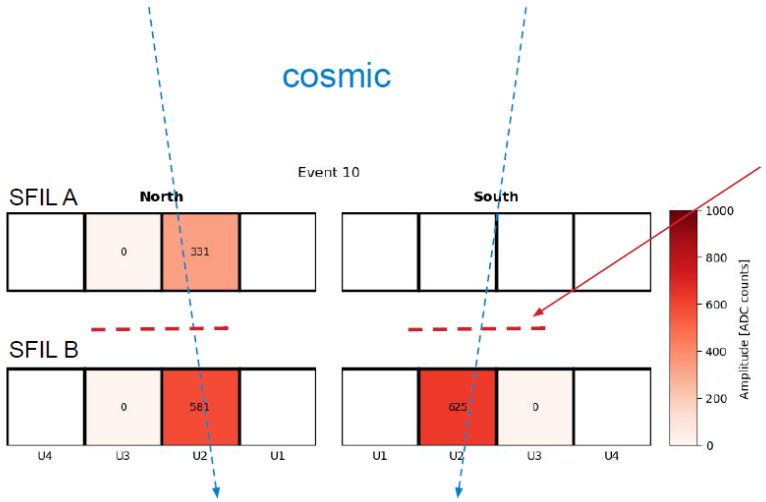


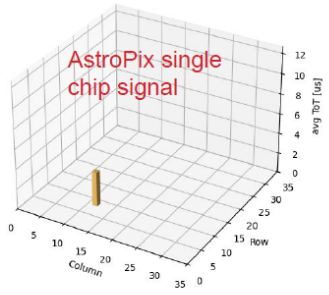








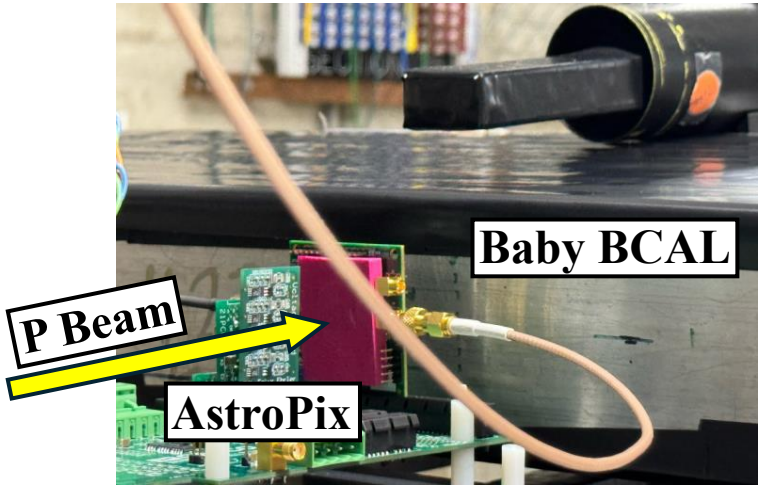


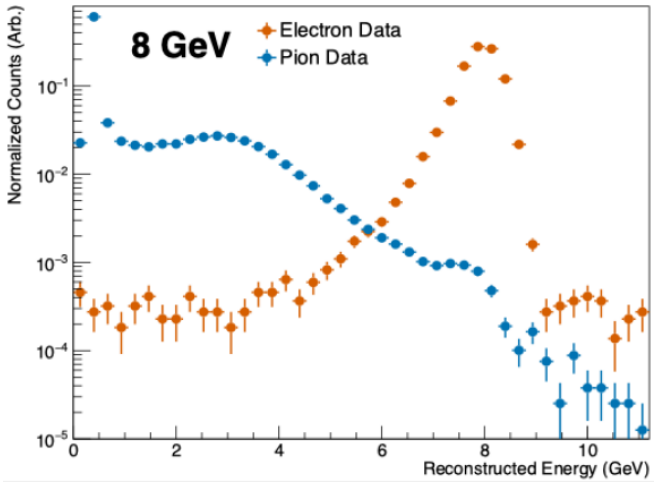


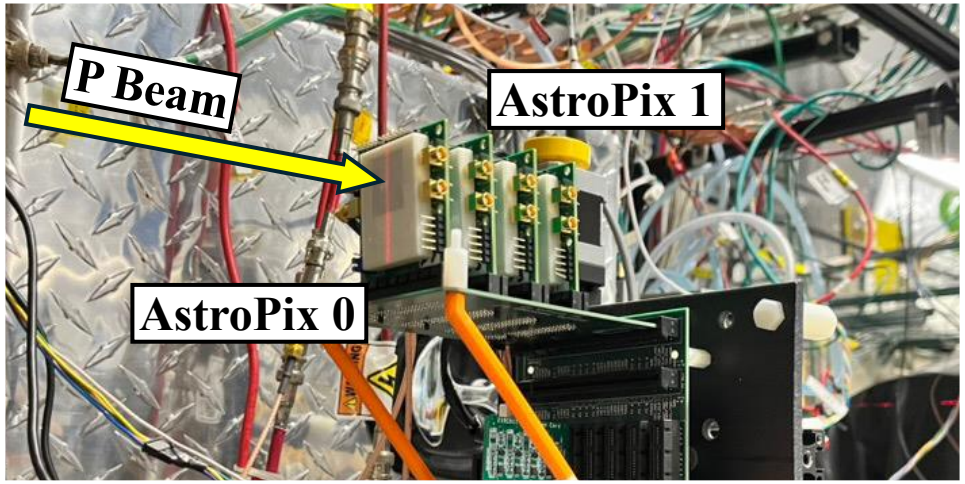
Barrel Imaging Calorimeter (BIC)

Bench Tests, Beam Tests, and Technology Integration – Argonne BIC Collaborators

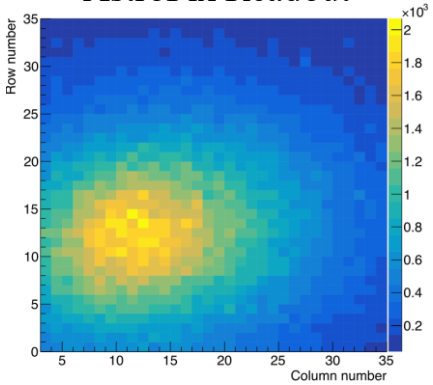
- Beam tests at Fermilab: 120 GeV/c proton beam, lower energy secondary particle beams
  - AstroPix chip plus baby BCAL – beam profile imaging, e/π separation
  - Two stacked AstroPix chips – coincidence between tracking layers



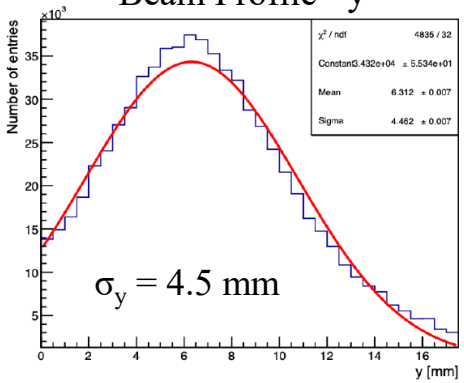




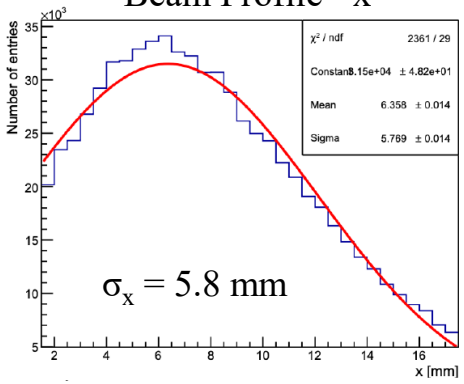
AstroPix Readout

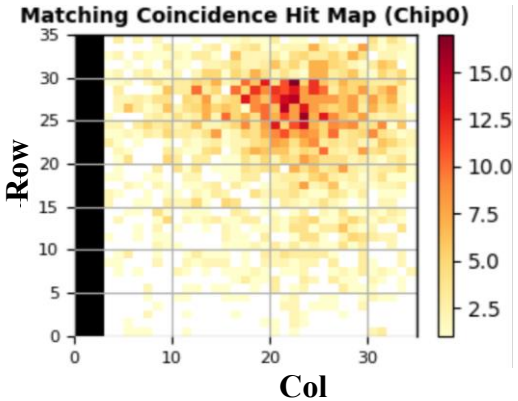


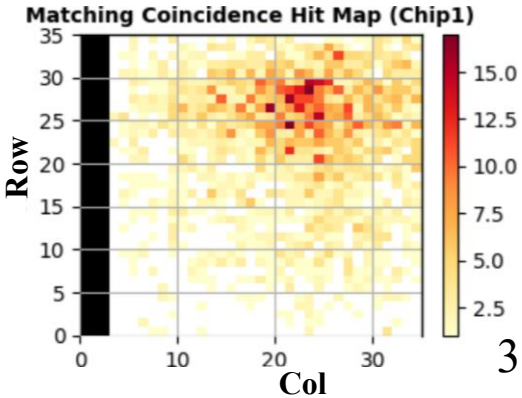
Beam Profile - y



Beam Profile - x





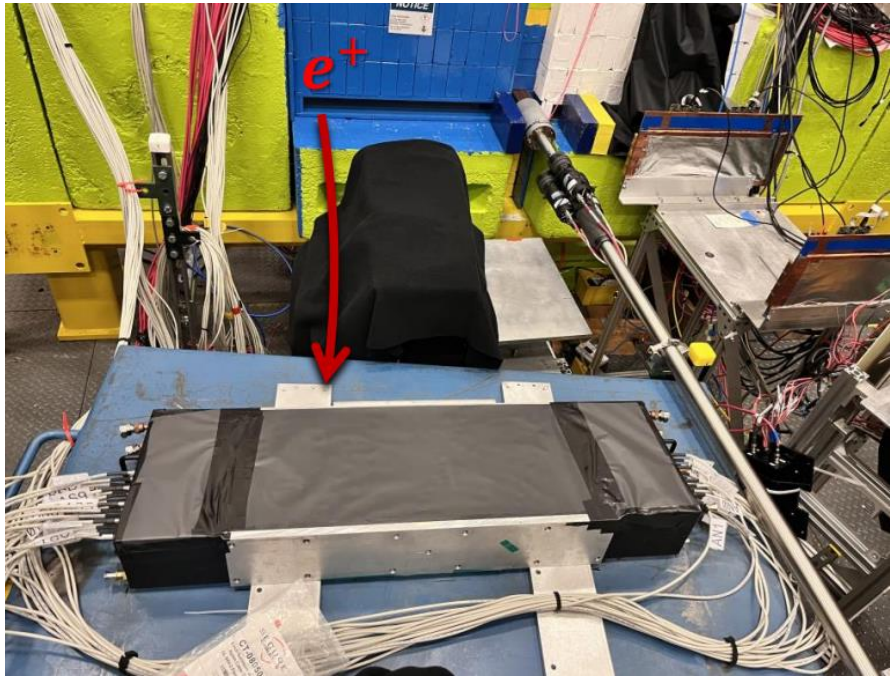


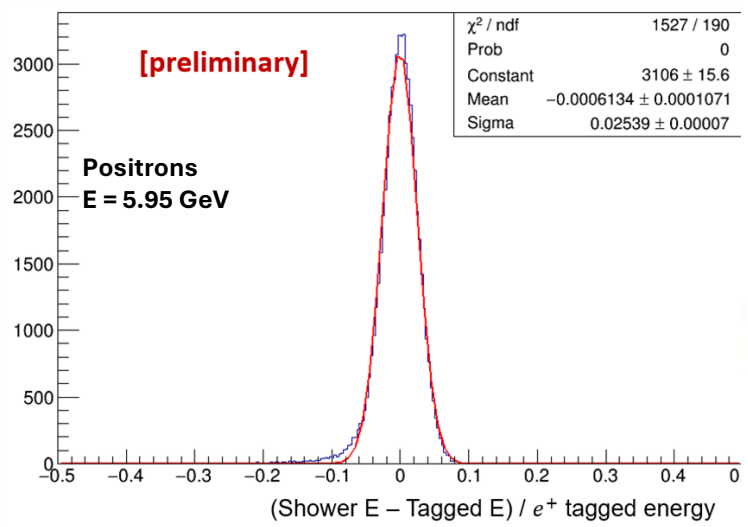
Barrel Imaging Calorimeter (BIC)

Bench Tests, Beam Tests, and Technology Integration – Jefferson Lab Tests

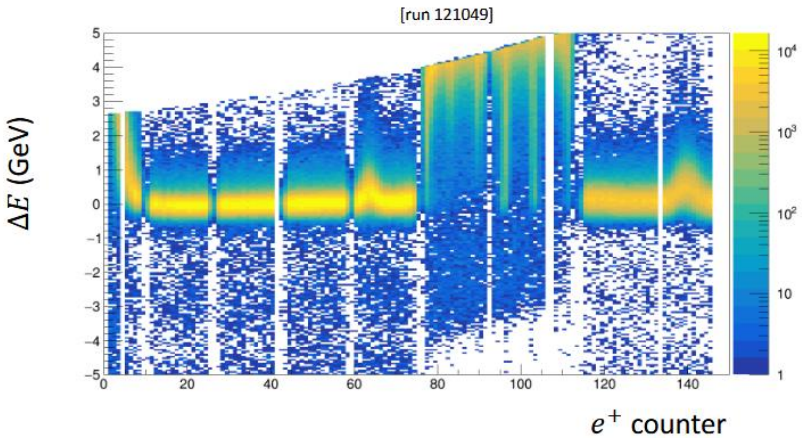
Baby BCAL
59 cm long
15.5 X0

Tested with e+ E ~ 3.6-6 GeV





- Plot $\Delta E = E_{tag} - E_{BCAL}$
- Appears good in non-shadowed regions



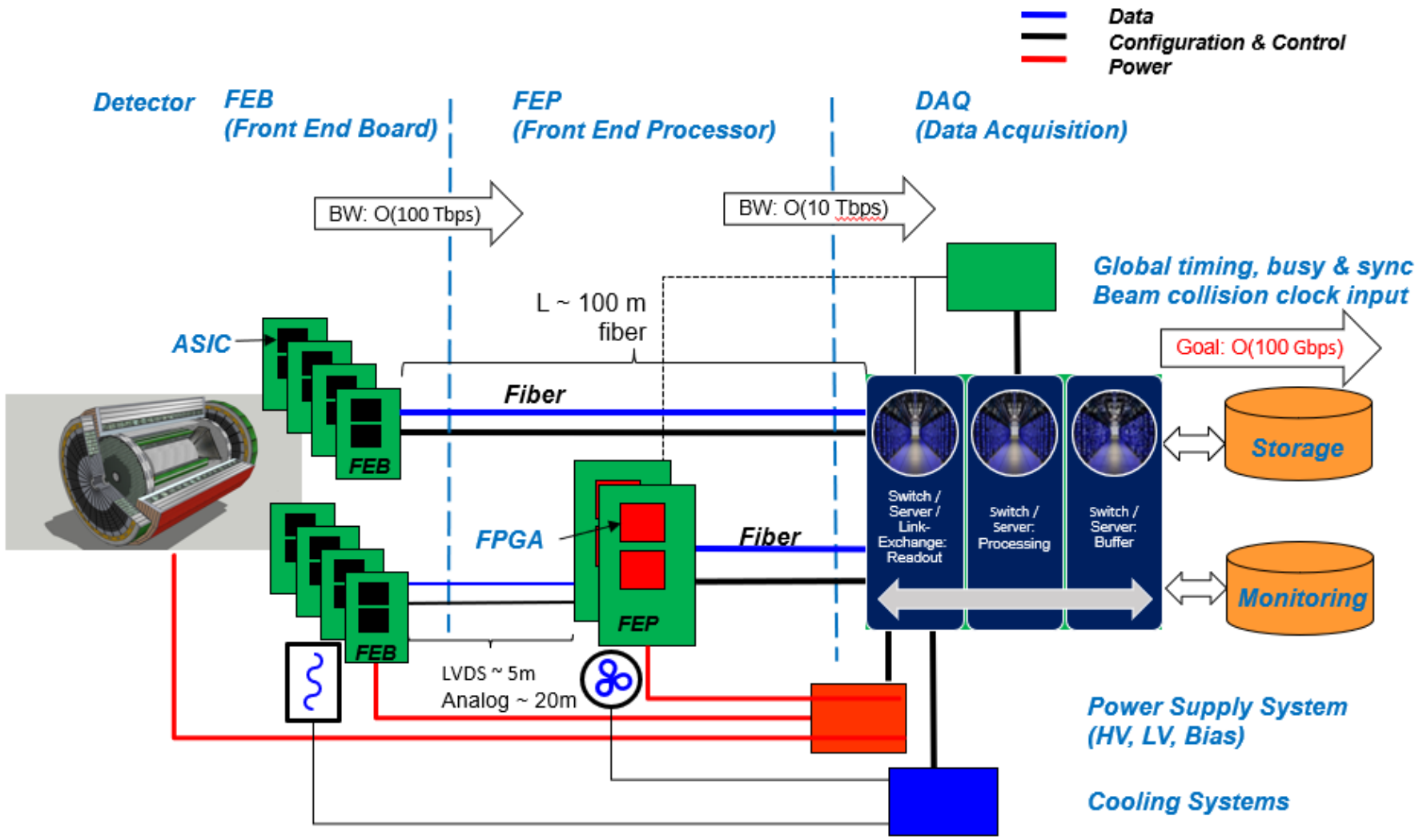
March 2023 beam test

Measured
Resolution: ~ 2.5%

Extrapolated
GlueX NIM[1)]: ~4.2%

Trends well below a 2% constant term!

ePIC Streaming DAQ



- No External trigger
- All collision data digitized but aggressively zero suppressed at FEB
- Low / zero deadtime
- Event selection can be based upon full data from all detectors (in real time, or later)
- Collision data flow is independent and unidirectional-> no global latency requirements
- Avoiding hardware trigger avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage

BIC Light Guide Dimensions

Table 1: Input and output face dimensions of BIC light guides of various shapes and layers. Trapezoid dimensions are given as 'bottom length - top length × height.'

Light Guide Designation	Input Dimensions (mm)	Output Dimensions (mm)
b1 & bh1	20.691-23.505 x 21.463	13.00-13.00 x 13.00
b2 & bh2	21.707-24.521 x 21.463	13.00-13.00 x 13.00
b3 & bh3	22.723-25.537 x 21.463	13.00-13.00 x 13.00
b4 & bh4	23.739-26.553 x 21.463	13.00-13.00 x 13.00
b5 & bh5	24.755-27.569 x 21.463	13.00-13.00 x 13.00
b6 & bh6	25.801-28.504 x 20.625	13.00-13.00 x 13.00
b7 & bh7	26.360-29.063 x 20.625	13.00-13.00 x 13.00
b8 & bh8	26.893-29.597 x 20.625	13.00-13.00 x 13.00
b9 & bh9	27.452-30.155 x 20.625	13.00-13.00 x 13.00
b10 & bh10	28.011-30.714 x 20.625	13.00-13.00 x 13.00
b11 & bh11	28.544-31.248 x 20.625	13.00-13.00 x 13.00
b12 & bh12	29.103-31.806 x 20.625	13.00-13.00 x 13.00
bt1	20.691-23.505 x 21.463	13.00-14.7044 x 13.00
bt2	21.707-24.521 x 21.463	13.00-14.7044 x 13.00
bt3	22.723-25.537 x 21.463	13.00-14.7044 x 13.00
bt4	23.739-26.553 x 21.463	13.00-14.7044 x 13.00
bt5	24.755-27.569 x 21.463	13.00-14.7044 x 13.00
bt6	25.801-28.504 x 20.625	13.00-14.7037 x 13.00
bt7	26.360-29.063 x 20.625	13.00-14.7037 x 13.00
bt8	26.893-29.597 x 20.625	13.00-14.7037 x 13.00
bt9	27.452-30.155 x 20.625	13.00-14.7037 x 13.00
bt10	28.011-30.714 x 20.625	13.00-14.7037 x 13.00
bt11	28.544-31.248 x 20.625	13.00-14.7037 x 13.00
bt12	29.103-31.806 x 20.625	13.00-14.7037 x 13.00

Photoelectron statistics

From our 2023 Hall D tests using GlueX SiPMs and double-clad Kuraray fibers: **1000 phe/GeV** per side for showers at the center of the Baby BCAL prototype

- Corrected for attenuation: **1077 phe/GeV*** per side

We can scale these results for the **ePIC Barrel ECal*:**

- x 1.5 factor improvement in **SiPM photon detection efficiency**
- x 1.16 factor to account for **better optical coupling**
- x 0.69 reduction accounting for **single-clad** Kuraray fibers

This gives ~ **1239 phe/GeV** per side (fully corrected for attenuation)

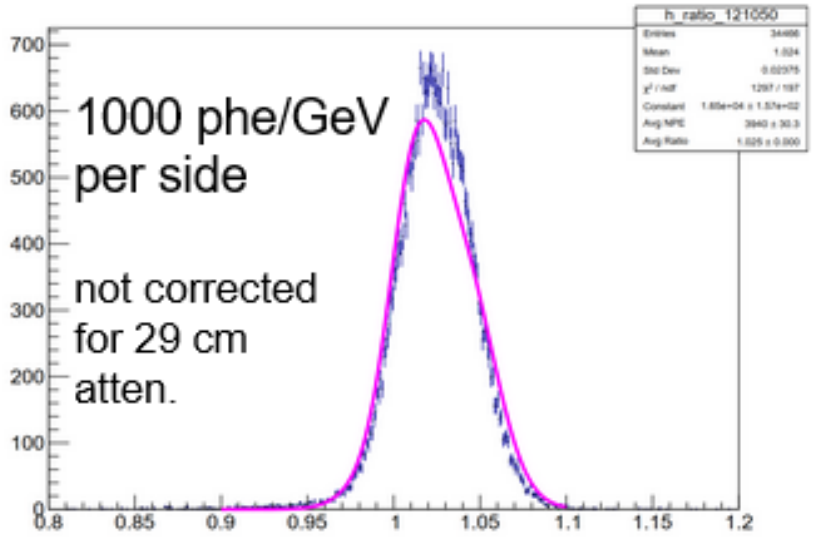
- **10 GeV γ at η ~ -1.7:** 5560 phe → **9.8 % max SiPM occupancy**
- **19 GeV e^- at η ~ -1.7:** 9181 phe → **16.1 % max SiPM occupancy**
- **50 GeV e^- at η ~ 1.4 (most extreme case):** 17456 phe → **30.1% max SiPM occupancy**

Well below the region where large nonlinearities in the SiPM response are expected in almost all cases.

Small non-linear effects possible for some ultra-high energy electrons, which is acceptable (e-π separation straightforward).

* See backup slide for the attenuation length measurement and extraction of those factors

2023 Hall D, Baby BCal, 3.9 GeV e^+



2008 Hall B beam test, photons

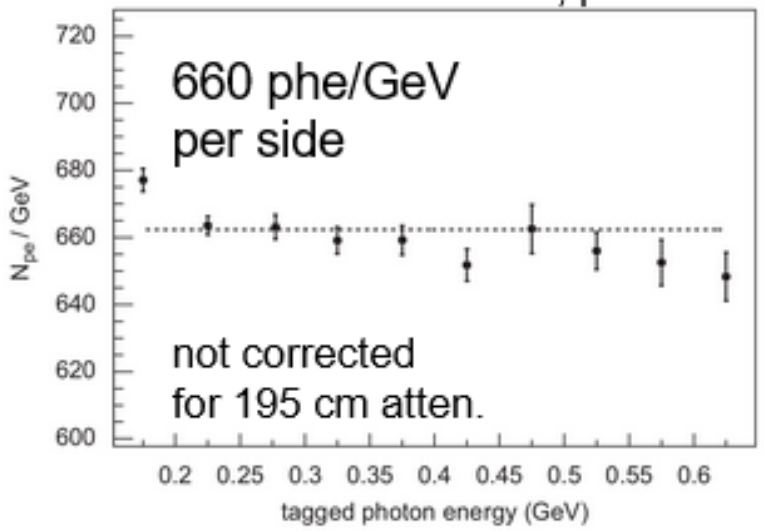
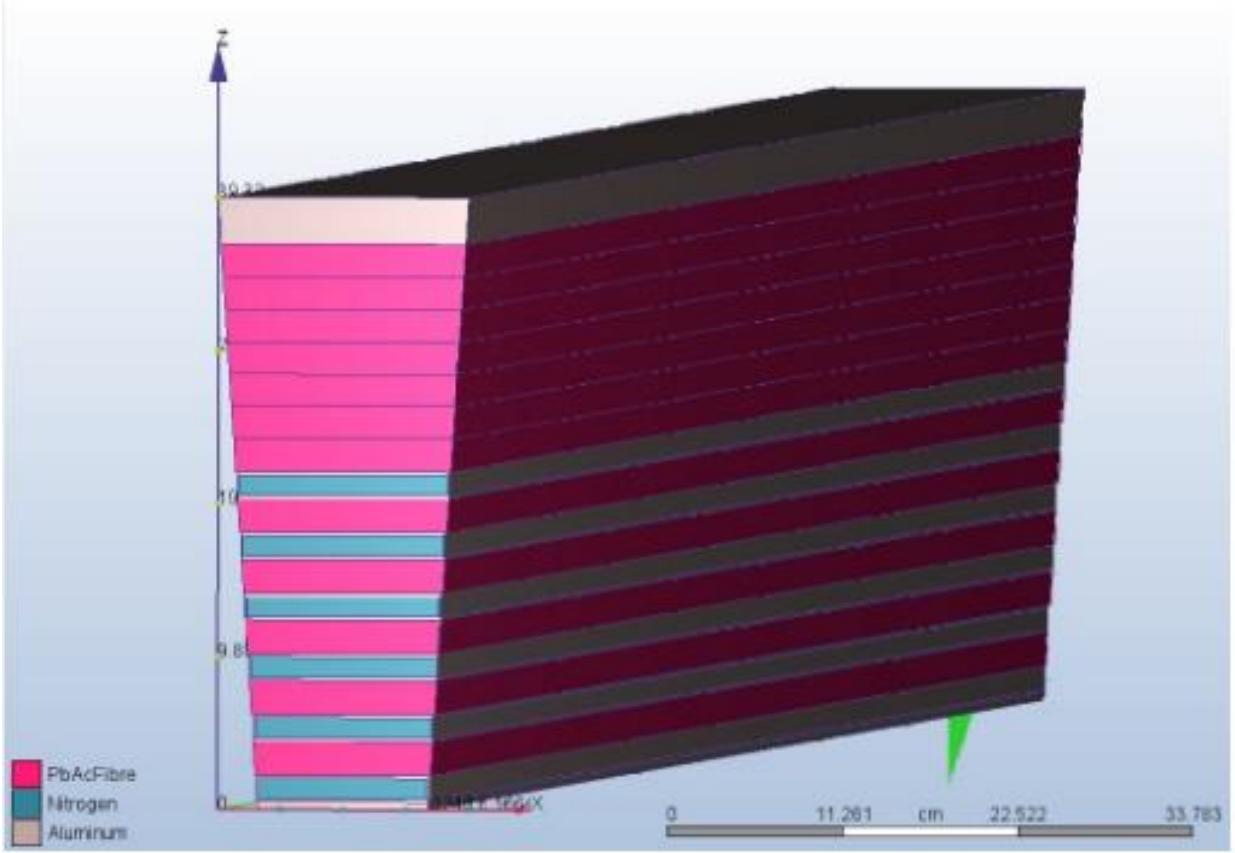


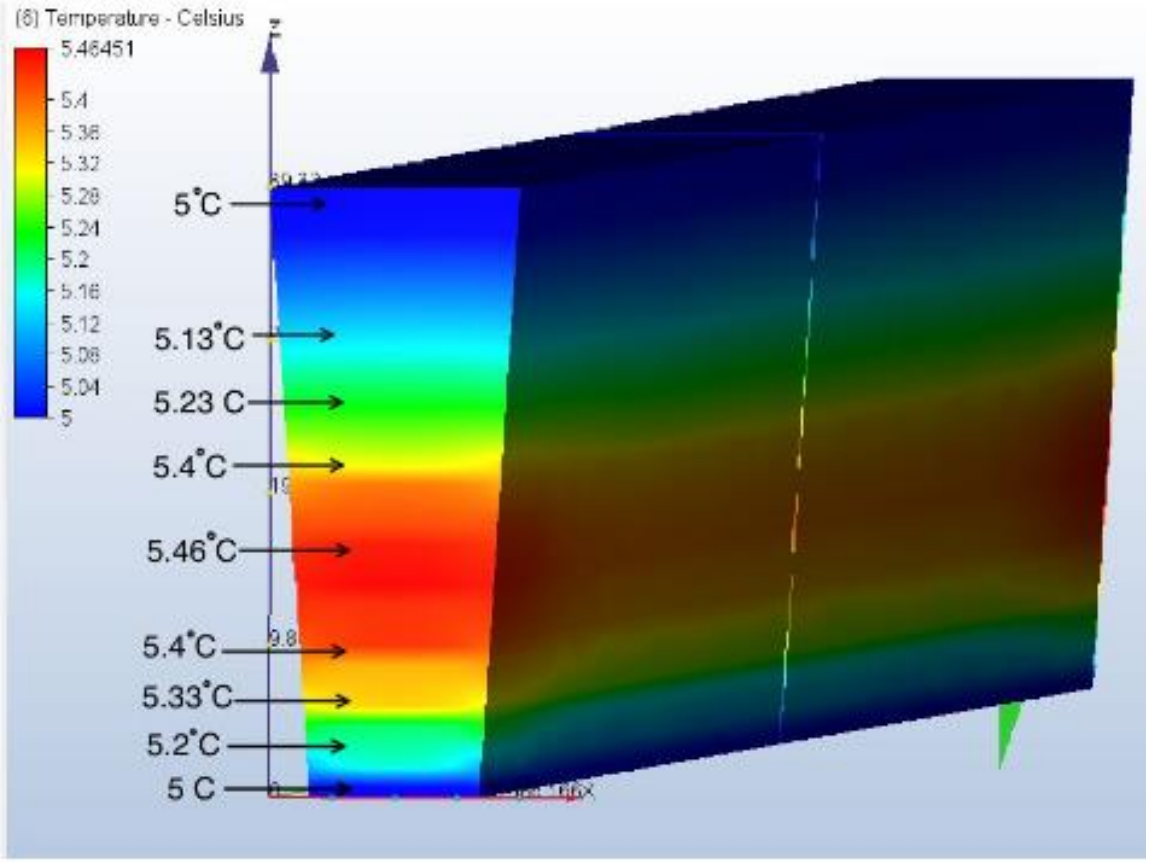
Fig. 16. The number of photoelectrons per GeV per end of the BCAL module is shown as a function of energy. A one parameter fit is plotted (dashed line). For more details see the text.

Sector Cooling Simulations

Material distrubution



Temperature with cooling



Detector Requirements

η	θ	Nomenclature			Tracking						Electrons and Photons			π/K/p		HCAL		Muons
					Resolution	Relative Momentum	Allowed X/X_0	Minimum-pT	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range (GeV/c)	Separation	Resolution σ_E/E	Energy	
< -4.6		↓ p/A	Far Backward Detectors	low-Q2 tagger														
-4.6 to -4.0					Not Accessible													
-4.0 to -3.5						Reduced Performance												
-3.5 to -3.0			Central Detector	Backward Detector		σ_p/p ~0.2%×p⊕5%	~5% or less X	70-150 MeV/c (B=1.5 T)			1%/E ⊕ 2.5%/√E ⊕ 1%	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ	50%/ √E⊕10%	~500MeV	Muons useful for bkg, improve resolution
-3.0 to -2.5																		
-2.5 to -2.0						σ_p/p~ 0.04%×p⊕2%												
-2.0 to -1.5									dca(xy) ~ 40/pT μm ⊕ 10 μm	dca(z) ~ 100/pT μm ⊕ 20 μm	2%/E ⊕(4-8)%/ √E ⊕ 2%	π suppression up to 1:(1E-3 - 1E-2)	50 MeV					
-1.5 to -1.0																		
-1.0 to -0.5				Barrel		σ_p/p ~0.04%×p⊕1%		200 MeV/c	dca(xy) ~ 30/pT μm ⊕ 5 μm	dca(z) ~ 30/pT μm ⊕ 5 μm	2%/E ⊕(12-14)%/ √E ⊕ (2-3)%	π suppression up to 1:1E-2	100 MeV	≤ 6 GeV/c		100%/ √E+10%		
-0.5 to 0.0																		
0.0 to 0.5																		
0.5 to 1.0																		
1.0 to 1.5				Forward Detectors		σ_p/p ~0.04%×p⊕2%		70 - 150 MeV/c (B = 1.5 T)	dca(xy) ~ 40/pT μm ⊕ 10 μm	dca(z) ~ 100/pT μm ⊕ 20 μm	2%/E ⊕ (4*-12)%/ √E ⊕ 2%	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		50%/√E+10%		
1.5 to 2.0																		
2.0 to 2.5																		
2.5 to 3.0						σ_p/p ~0.2%×p⊕5%												
3.0 to 3.5																		
3.5 to 4.0		↑ e		Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5					Not Accessible													
> 4.6			Far Forward Detectors	Proton Spectrometer														
				Zero Degree Neutral Detection														