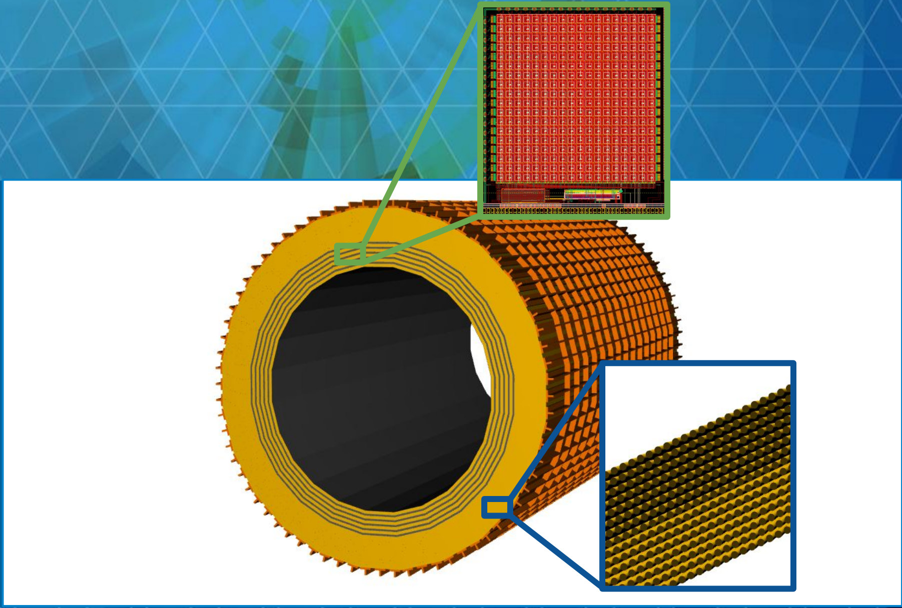
EIC SiPM FDR

September 14, 2023

ePIC Barrel Imaging Calorimeter SiPMs



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On behalf of the Barrel Imaging Calorimeter DSC

U.S. DEPARTMENT OF ENERGY
ePIC
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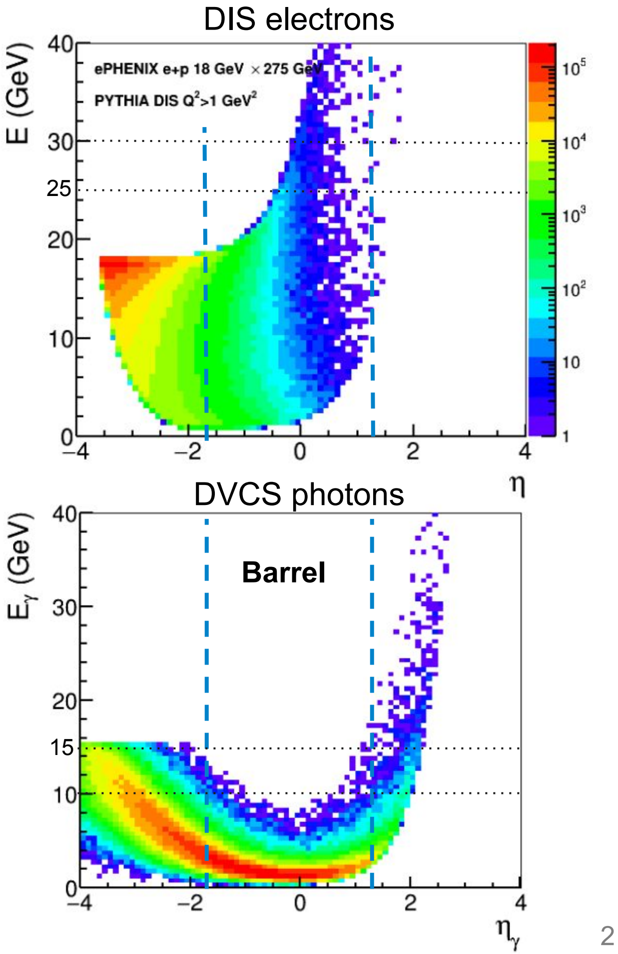
EIC Calorimetry Requirements

Barrel ECAL in EIC Yellow Report

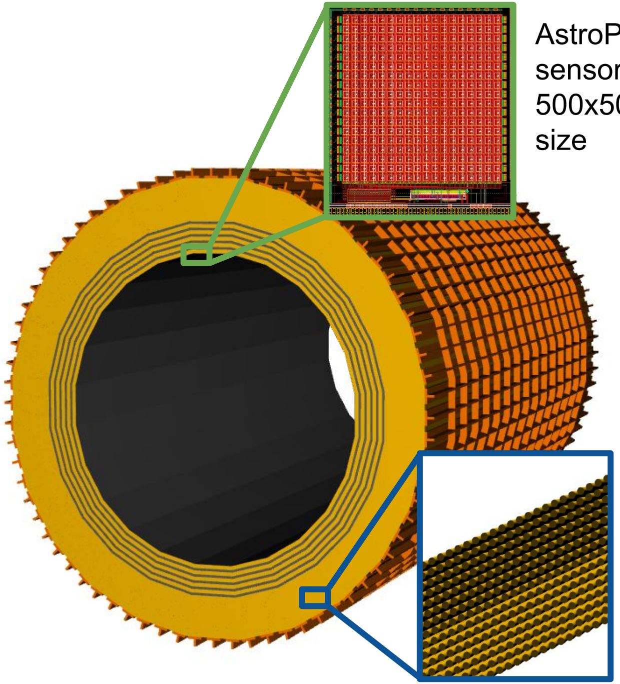
EIC Yellow Report requirements for Barrel EM Cal:

- Detection of electrons/photons to measure **energy and position**
- Require **moderate energy resolution** $(7-10)\%/\sqrt{E} \oplus (1-3)\%$
- Require **electron-pion separation up to 10^4** at low momenta in combination with other detectors
- Discriminate between **π^0 decays and single γ up to ~10 GeV**
- **Low energy photon** reconstruction ~100 MeV

Challenges: e/π PID, γ/π^0 discrimination, available space



Barrel Imaging ECal: General Overview



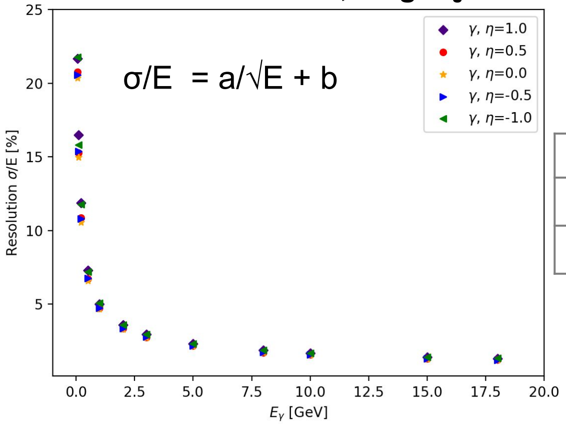
AstroPix: silicon sensor with $500 \times 500 \mu m^2$ pixel size

SciFi Layers with **two-sided SiPM readout**

- **4(+2) layers of imaging Si sensors** interleaved with **5 Pb/ScFi layers**
- Followed by a **bulk Pb/SciFi section**

- Total radiation thickness at $\eta=0$ ~17.1 X_0
- Sampling fraction (ΣE_{fibers} / E_{thrown}) ~10.3%

ePIC full simulation, single ɣ



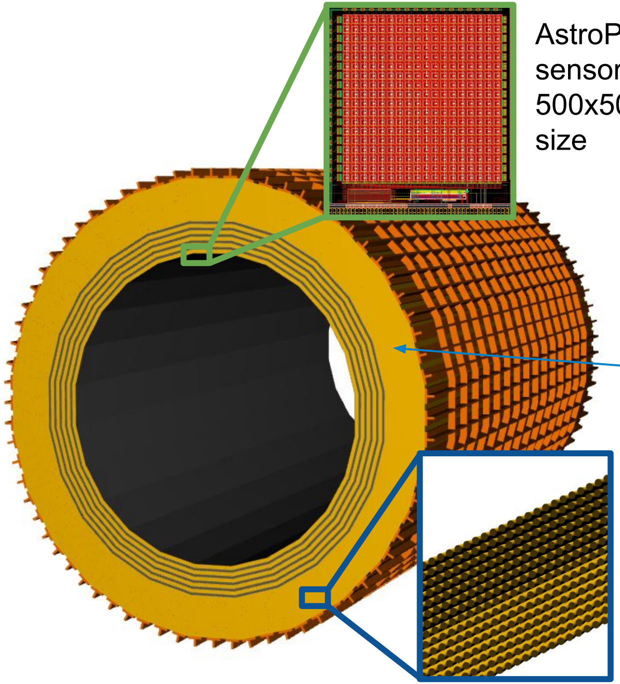
Fit parameters

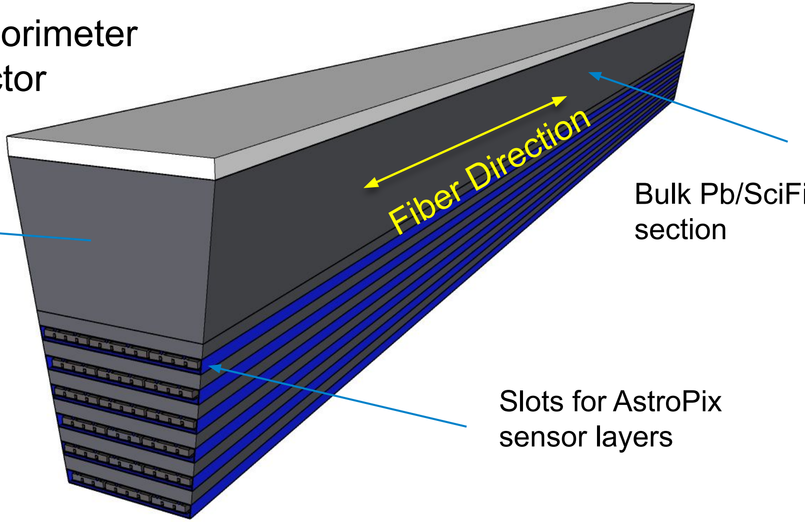
η	a/√(E) [%]	b [%]
0	4.67(0.01)	0.40(0.02)
1	5.1(0.01)	0.41(0.02)

Energy resolution - Primarily from Pb/SciFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/SciFi readout)

Barrel Imaging ECal: General Overview

- **4(+2) layers of imaging Si sensors** interleaved with **5 Pb/SciFi layers**
- Followed by a **large section of Pb/SciFi section**

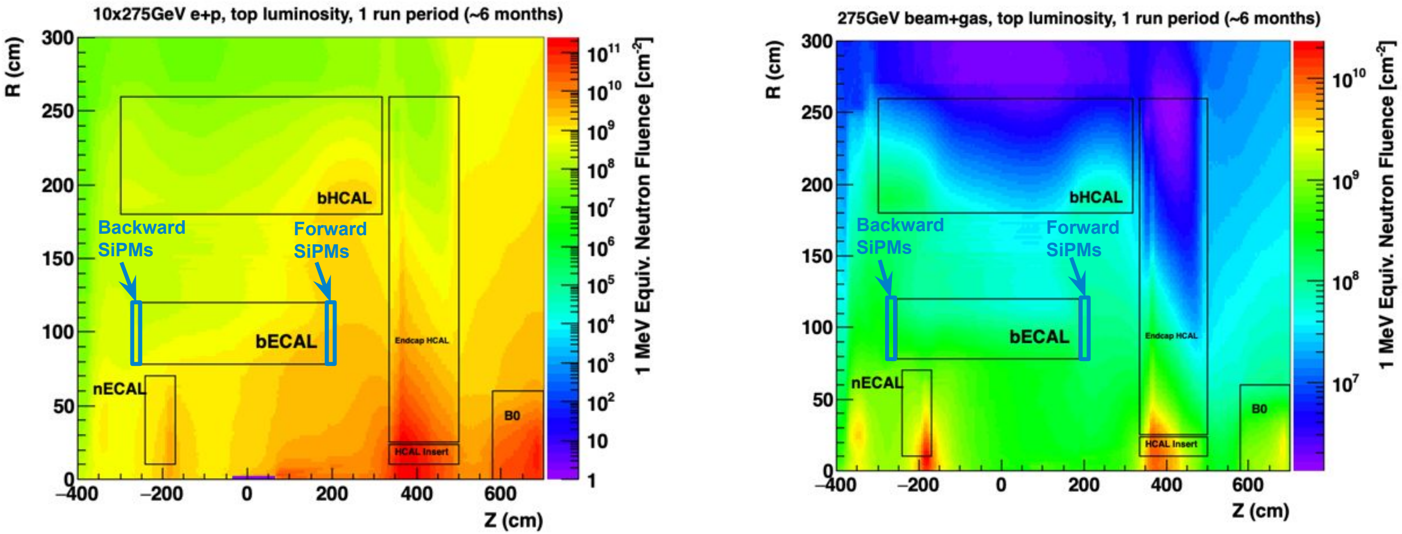




- 432.5 cm in length and 80 cm radius, 48 sectors
- Covers $-1.71 < \eta < 1.31$

Radiation dose at the Barrel ECal SiPMs

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



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

*In 1 MeV equivalent neutron flux for 10 year of running

SciFi/Pb Technology

- Mature Technology: **GlueX**, KLOE EMCals
- Tested extensively for electromagnetic response in energies **E_γ < 2.5 GeV**
- **Energy resolution:** $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$[1)]
  - 15.5 X_0, GlueX could not constrain the constant term due to low energies
  - New results from Hall D with Baby BCal show that constant term < 2%

GlueX BECal parameters:
SiPMs: S12045(X) 4×4 array of 3×3 mm^2, 50µm pixel
https://ieeexplore.ieee.org/document/7161418,
https://www.sciencedirect.com/science/article/pii/S0168900213009042,
https://www.sciencedirect.com/science/article/pii/S0168900213017233.

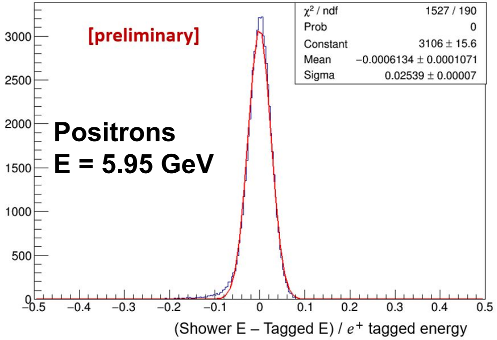
Lightguides: 8 cm long attached to the sector sides
https://halldweb.jlab.org/doc-public/DocDB/ShowDocument?docid=1784

Fibers: double-clad SCSF-78MJ

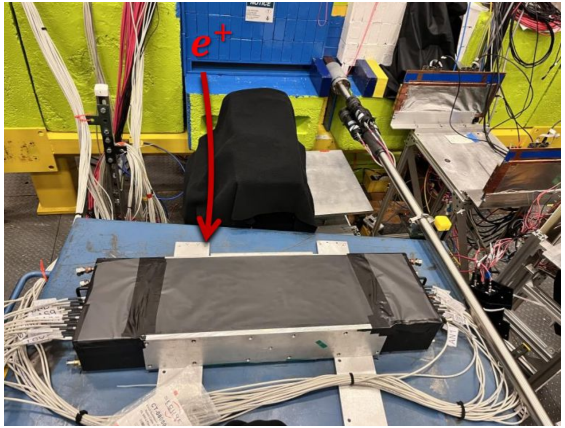
Hall D, March 2023
Baby BCAL Test

Measured Resolution: ~ 2.5%

Extrapolated GlueX NIM[1)]: ~4.2%



Trends well below a 2% constant term!



Baby BCAL
60 cm long
15.5 X0

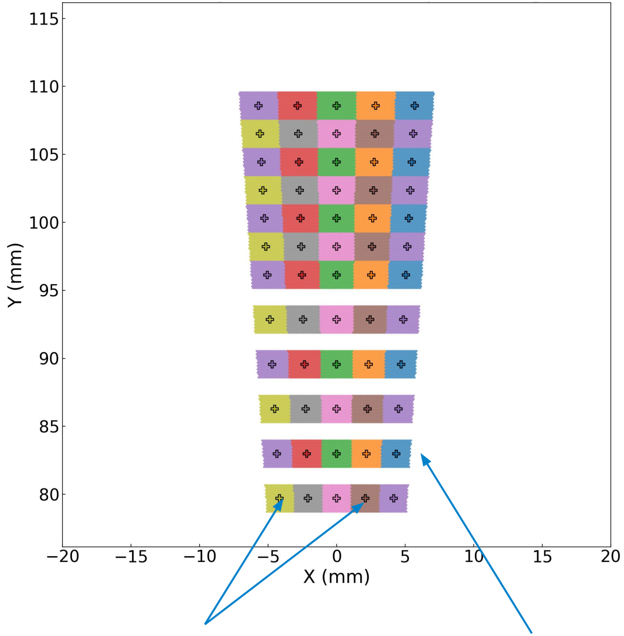
tested with e+
E ~ 3.6-6 GeV

1) GlueX, Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018

SiPM Readout

- **2-side SiPM readout**
- **Lightguides** attached to the sector sides
  - inner surface ~2×2 cm^2
  - output face 1.3×1.3 cm^2
- SiPMs that meet our requirements:
  - 4 x 6×6 mm^2 SiPMs (or equivalent) with 50 µm pixels (e.g. 4 x S14160-6050, or a pre-assembled S14161-3050-04 array)
  - same dimensions as GlueX but with better performance*:
    - PDE = 50% (GlueX 33%)
    - Lower noise
- 12 layers x 5 cells x 2 sides x 48 sectors = **5760 channels**

ePIC Sector End View (x-y plane view), 17.1 X0



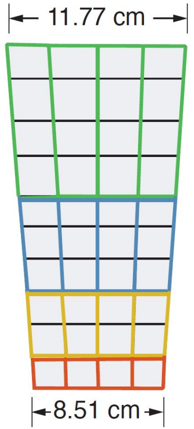
Readout **Cell**
The area 1 light guide is attached to

Layer = 5 cells

Pb/Scii **Layer**

1 sector = 12 layers
1 layer = 17 rows of fiber

GlueX Sector End View, 15.5 X0



Hamamatsu S12045(X)
4×4 array of 3×3 mm^2
50×50µm^2 pixels

16 FADC per side
12 TDC per side

* See backup slides for documentation

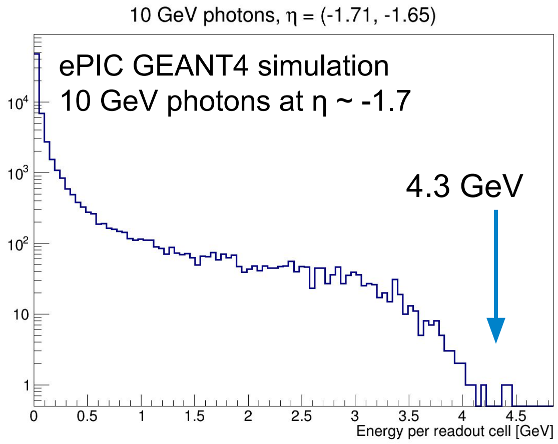
Pixel Size and Number of Pixels

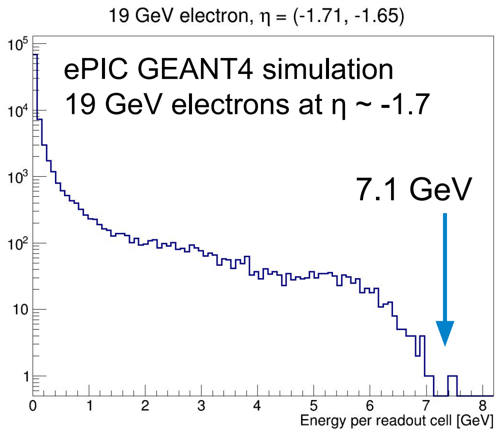
Defined by photoelectron statistics and energy range to be measured

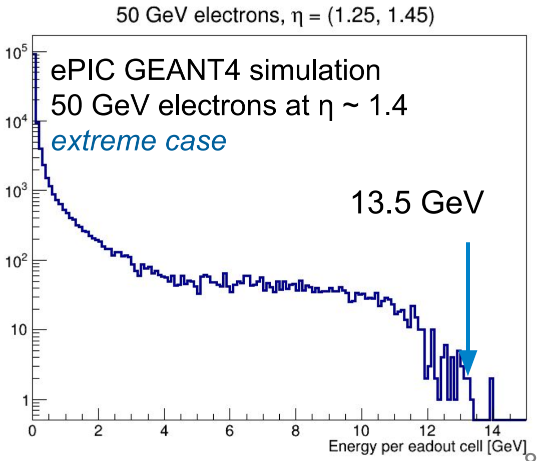
Energy measurement ranges in BECal:

- *Shall provide photon measurements up to 10 GeV* (F-DET-ECAL-BAR.2) *and down to 100 MeV* (F-DET-ECAL.9)
- *Shall provide electron ID up to 50 GeV and down to 1 GeV and below* (F-DET-ECAL-BAR.1)
  - Electron energy measurement needed for e/π separation only (straightforward at high energies)
- Reasonable performance for MIPs needed for calibration and for muon ID

Largest energy deposit occurs for particles at large η (steep angle) where the pathlength in a cell is maximal and the attenuation is minimal.







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)

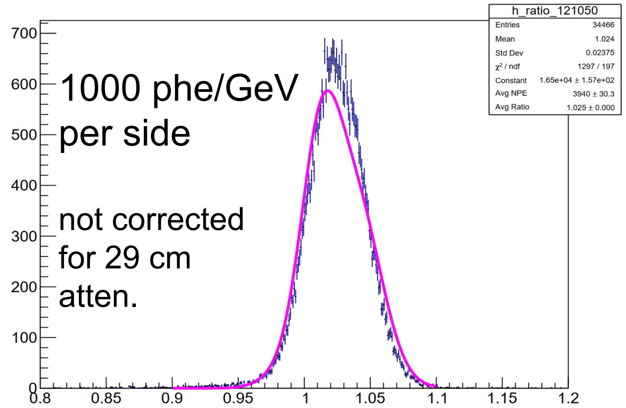
- **10 GeV ɣ at η ~ -1.7:** 5560 phe → **9.8 % max SiPM occupancy**
- **19 GeV e^- at η ~ -1.7:** 9181 phe → **16.1 % max SiPM occupancy**
- **50 GeV e^- at η ~ 1.4 (most extreme case):** 17456 phe → **30.1% max SiPM occupancy**

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

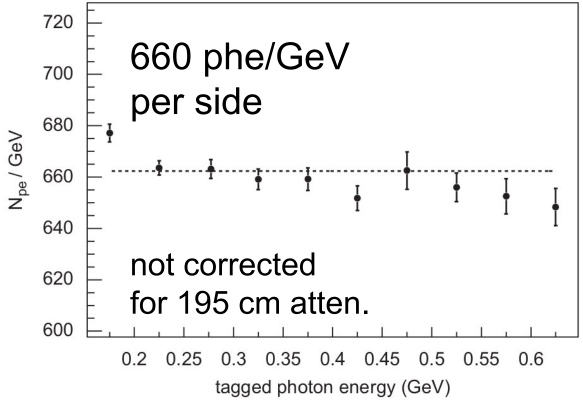


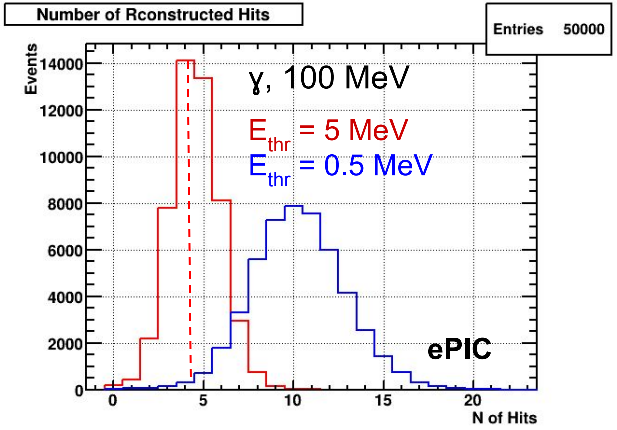
Fig. 16. The number of photoelectrons per GeV per end of the BCAL module is shown as a function of energy. A one parameter fit is plotted (dashed line). For more details see the text.

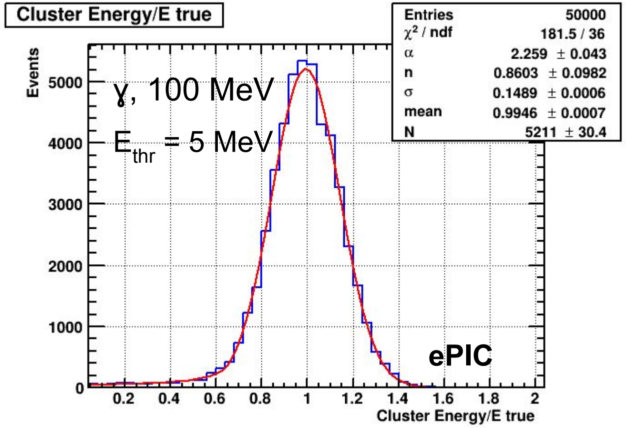
Low energy performance

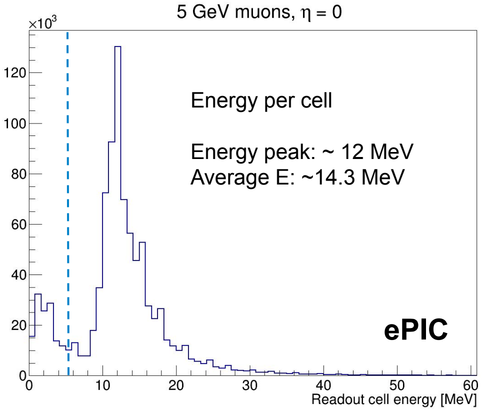
GlueX capabilities (NIM, A 896 (2018) 24-42):

- Cluster/shower threshold is **100 MeV nominal** (down to 50 MeV for some analyses, with mostly 2-3 cells per event only). Low energy detection threshold studied also with Michel electrons.
- Capability of **measuring MIPs**.
- Readout channel threshold **~ 17 MeV** (note: GlueX sums cells radially with the scheme 1-2-3-4)

Results from full ePIC GEANT4 simulation: 5 MeV threshold per channel







Extreme case - MIPs at η = 0:
Energy per cell = 12 MeV (peak) ➡ 15-16 phe at η = 0 ➡ ~ 7-8 phe per side (factor ~ 2 from atten. loss, assuming single-clad Kuraray fibers)

Low-energy measurements favor a larger PDE, matches well with 50μm pixel pitch SiPMs

QA procedure

- We will follow the same QA procedure as GlueX ([Nucl.Instrum.Meth.A 732 (2013) 431-436])
  - The scope for testing is similar (comparable number of readout cells)
- We will test the entire readout array:
  - Visual inspection
  - Measure PDE
  - Measure gain, breakdown voltage, optical crosstalk, dark rate

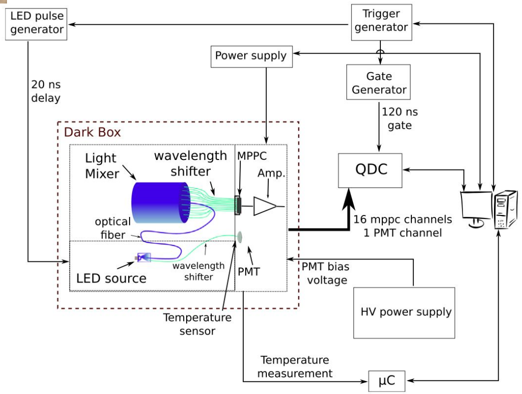
Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Characterization of novel Hamamatsu Multi Pixel Photon Counter (MPPC) arrays for the GlueX experiment

Orlando Soto*, Rimsky Rojas, Sergey Kuleshov, Hayk Hakobyan, Alam Toro, William K. Brooks



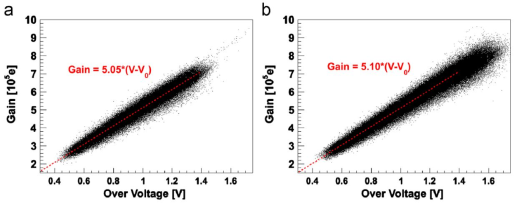
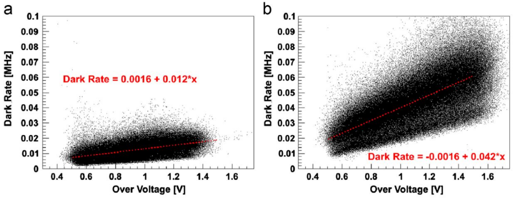
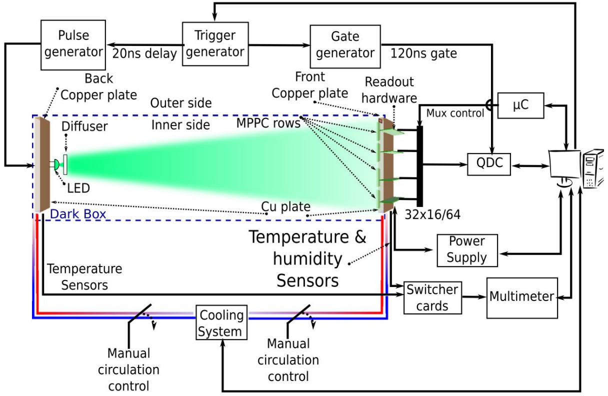


Fig. 11. Gain vs. voltage for 1700 MPPCs: (a) 5 °C; (b) 20,°C.





Summary

- The design of the Pb/SciFi portion of the ePIC Barrel Imaging Calorimeter is derived from the GlueX Barrel Calorimeter
- The requirements for ePIC are not identical to those for GlueX: At ePIC we reach higher energies, have a larger average particle multiplicities, and need to measure the full energy profile of the developing shower
- We determined our SiPM requirements through a combination of full simulation studies, prototype measurements, and experience with the GlueX Barrel Calorimeter.
    - Major departures from GlueX:
        - Higher SiPM PDE, different fiber cladding (single instead of double), improved optical coupling (optical cookies instead of air gap)
        - Readout scheme without summing (impacts thresholds)

SiPM Preference: 4 x 6×6 mm^2, 50 µm pixel SiPMs (4 x S14160-6050) or equivalently a 4x4 pre-assembled array of 3×3 mm^2, 50 µm pixel SiPMs (S14161-6050-04 array) per channel are a good match for the physics performance requirements of the ePIC Barrel Imaging Calorimeter

Parameter	Specification
Active area per readout cell*	1.2 x 1.2 cm^2
Pixel size	50 um
Peak sensitivity wavelength	450 nm
PDE	> ~ 50%
Gain	> ~ 10^6
Temperature coefficient of Vop	~ 34 mV/C
Terminal capacity	~ 8000 pF per 1.44 cm^2
Vop variation	~ 0.1 V
Fill Factor	~ 74%

* This corresponds either to 2x2 6 mm^2 SiPMs or a 4x4 array of 3 mm^2 SiPMs

1. Are the technical performance requirements complete for all detector systems that employ SiPMs, documented, and understood?
   Slide 2 and slide 8

2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project? (I.e., are they commensurate with the initiation of the SiPM procurement?)
   Slides 3-4, 8-10, (Backup slides 25-28, 30-34), construction timeline in overview talk

3. Do the present detector system designs and the resulting SiPM specifications meet the performance requirements with a low risk of cost increases, schedule delays, and technical problems?
   The current detector design is based on the existing GlueX barrel calorimeter (slide 6-7), with modifications to accommodate different needs for EIC (slide 11). Both the existing Hamamatsu S14160-6050 and S14161-6050-04 SiPMs meet our specifications. Due to the maturity of the design, and the relatively small amount of SiPMs needed for this system compared with other calorimeters in ePIC, there is a low risk of cost increases, schedule delays, and technical problems.

4. Are the fabrication and assembly plans for the detector systems consistent with the overall project and detector schedule and sufficiently developed to initiate the SiPM procurement?
   The SiPMs sit in readout boxes at either end of each sector. The readout box will be assembled separately for each sector and installed during final detector assembly and integration at BNL. This is accounted for in the schedule presented in the introduction talk.

5. Are the plans for detector integration in the EIC detector appropriately developed to initiate the SiPM procurement
   The number of SiPMs and their specifications is determined by the total number of radiation lengths of the detector, the inner radius of the detector, and the required physics performance (see slides reference in answer to question 2). The total number of radiation lengths is driven by physics, while the inner radius is driven by the integration with the other subsystems in the EIC detector that sit inside the barrel Ecal, and the need to fit within the inner radius of the solenoid magnet. The integration between all of these subsystems (see backup slide 30, overview talk) is understood well enough to initiate SiPM procurement.

6. Have previous review recommendations been adequately addressed to initiate the SiPM procurement?
   N/A

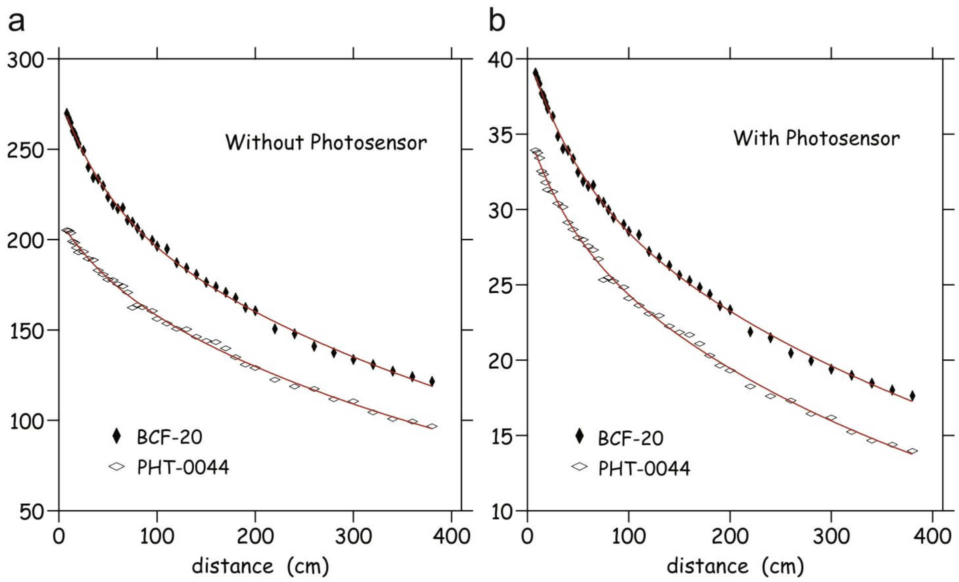
7. Have ES&H and QA considerations been adequately incorporated in the SiPM procurement planning? (This includes a quality assurance plan for receipt of material meeting specifications.)
   See slide 11

8. Is the procurement approach sound and the procurement schedule credible?
   The procurement schedule was presented in the overview talk.

Backup

Attenuation length measurements from GlueX

Source: Nucl.Instrum.Meth.A 596 (2008) 338-346



Double-exponential fits to the PHT-0044 and BCF-20 data without and with the convolution of the photosensor. The photosensor in the case of PHT-0044 is the XP2020 and in the case of BCF20 is the SiPM.

Table 1
Short and long attenuation length components for the PHT-0044 and BCF-20 fibers, as extracted from a double-exponential fit

	Without photosensor		With photosensor	
Component	PHT-0044	BCF-20	PHT-0044	BCF-20
Short (cm)	50 ± 14	48 ± 8	43 ± 8	50 ± 9
Long (cm)	478 ± 21	481 ± 21	414 ± 14	491 ± 21
Weighted (cm)	428 ± 23	400 ± 23	353 ± 18	408 ± 25

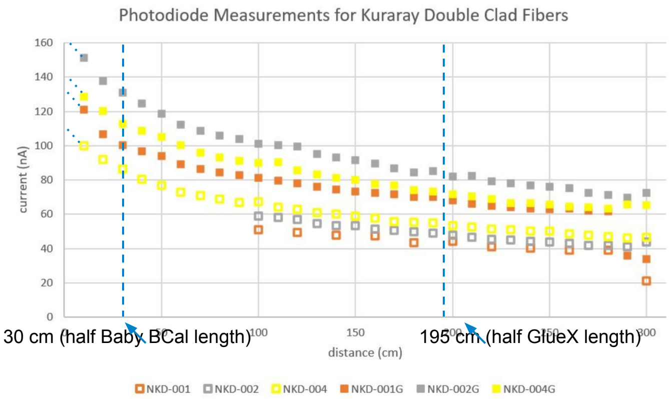
The weighted attenuation length is based on the relative amplitudes of the two exponentials. The photosensor in the case of PHT-0044 is the XP2020 and in the case of BCF-20 is the SiPM.

$$I(\Delta) = I_0(\alpha e^{\Delta/\lambda_1} + (1-\alpha)e^{\Delta/\lambda_2})$$

These are the results from an early GlueX prototype test. To account for the attenuation in the Baby BCAL prototype, we used similar measurements from the actual GlueX BCAL. The resulting attenuation is close to the these prototype results.

Attenuation length measurements

Source: bECAL Fiber Tests @Regina - Update 5



Kuraray Double Clad

30cm - 0cm correction factor: 1.3

- NKD-004: 110/85 ~1.3
- NKD-001G: 130/100 ~1.3
- NKD-002G: 165/130 ~ 1.27
- NKD-004G: 140/112 ~ 1.25

195cm - 0cm correction factor: 2

- NKD-004: 110/55 ~2
- NKD-001G: 130/67 ~1.94
- NKD-002G: 165/85 ~ 1.94
- NKD-004G: 140/70 ~ 2

2008 Hall B beam test, photons

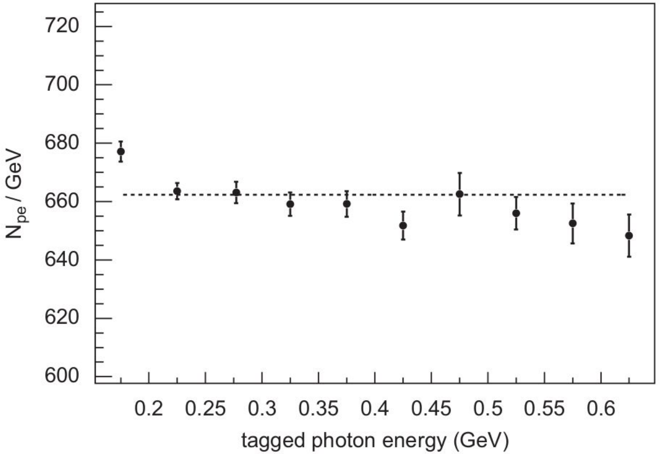
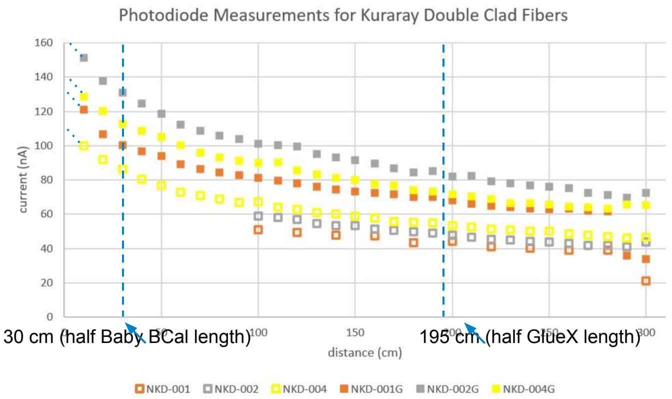


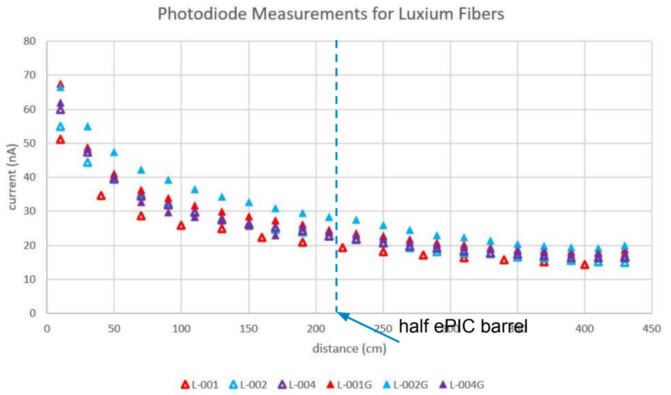
Fig. 16. The number of photoelectrons per GeV per end of the BCAL module is shown as a function of energy. A one parameter fit is plotted (dashed line). For more details see the text.

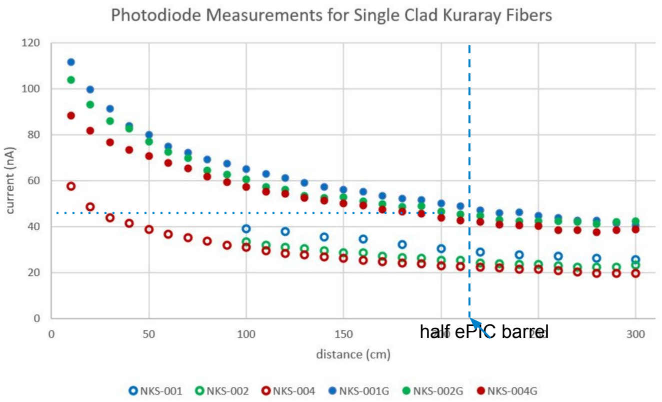
- GlueX full length (390 cm) prototype **with PMTs**
- Measured 660 phe/GeV per end (for events striking the center of the prototype)
- Corrected for attenuation (@195 cm): 660 phe/GeV x 1.57 (from GlueX) = **1036 phe/GeV**

Attenuation length measurements

Source: bECAL Fiber Tests @Regina - Update 5







Kuraray double-clad/Kuraray single-clad with grease

- at 10 cm: (122+130+155)÷3 / (88+102+112)÷3 = 135.7/100.7 **~ 1.4**
- at 200 cm: (70+71+82)÷3 / (47+45+43)÷3 ~ 74.33/45 **~ 1.65**

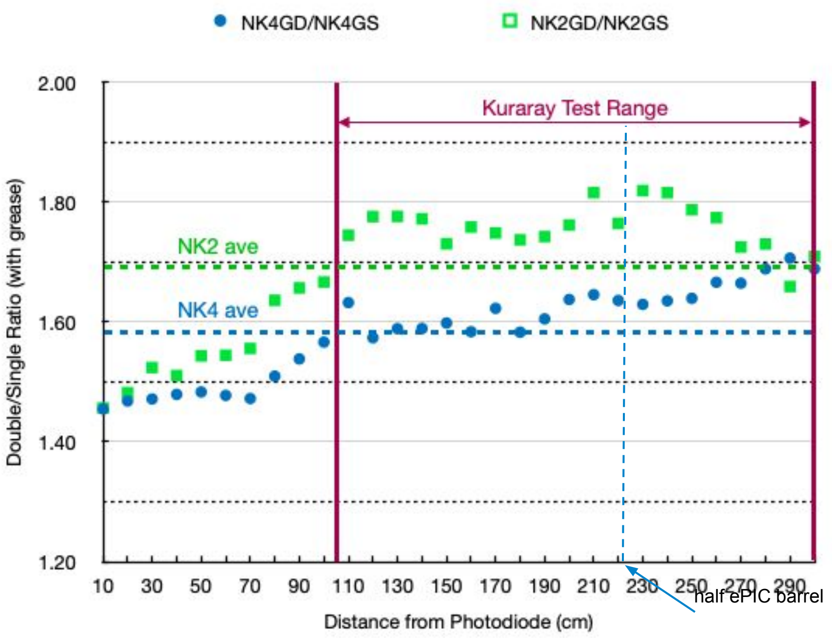
Kuraray double-clad/Luxium single-clad with grease

- at 10 cm: 135.7 / (62+66+67)÷3 = 135.7/65 **~ 2.01**
- at 200 cm: 74.33 / (29+25+25)÷3 ~ 74.33/26.33 **~ 2.8**

Kuraray single-clad 0cm - 216 cm: ~108/45 = **2.4 (NKS-004G: ~2)**
Luxium single-clad 0cm - 216 cm: ~68/25 = **2.7**

Attenuation length measurements

Source: bECAL Fiber Tests @Regina - Update 5



GlueX light guides

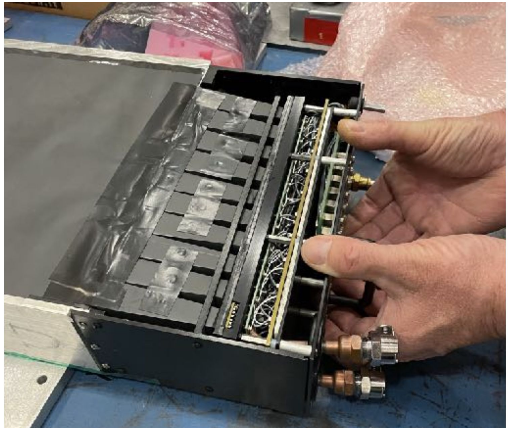
Source: https://halldweb.jlab.org/doc-public/DocDB/ShowDocument?docid=1784

Table 1: Collection efficiency for various trapezoidal configurations for the nominal guide length of 8 cm. The attenuation length in the light guide was set to 240 cm. The ratio of output to input areas is 29% for the rectangle and 23% for the circular output. For reference a Winston Cone shape calculation is also given.

Configuration	Top (cm)	Side (cm)	Bottom (cm)	Length (cm)	Output Square (cm)	Gap (mm)	Eff (%)
SiPM rect Inner outside top	2.525	2.0	2.4026	8	1.2×1.2	Lucite (2mm)	87.1
SiPM rect Inner outside top	2.525	2.0	2.4026	8	1.2×1.2	Air Gap 2 (1mm)	69.1
SiPM rect Inner outside top	2.525	2.0	2.4026	8	1.2×1.2	Air Gap1 (1mm)	52.5
SiPM WC inner outside top	2.525	2.0	2.4026	2+6+2.13	circle R=0.6	None	81.2 [3]

Lucite approx. for optical cookie

Table source:



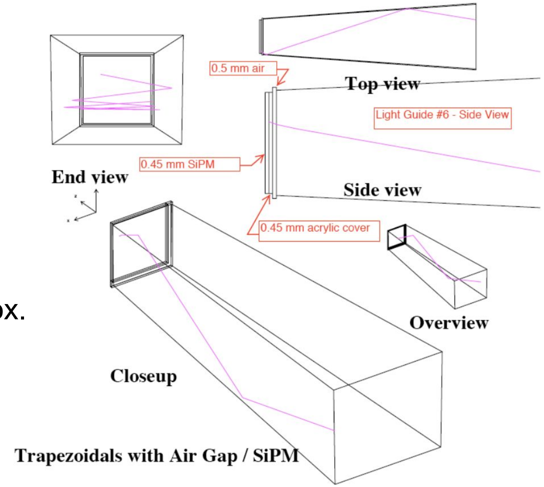


Table 1: Sizes of the ten production light guides for the Bcal. The trapezoid dimensions are denoted using the notation (bottom-top × height).

Configuration	Input Trapezoid (mm^2)	Length (cm)	Output Trapezoid (mm^2)	Eff (%)
g1	20.96-21.64 × 20.57	8	13.19-13.61 × 13.19	0.748
g2	21.64-22.30 × 20.57	8	13.19-13.61 × 13.19	0.723
g3	22.30-22.99 × 20.57	8	13.19-13.61 × 13.19	0.701
g4	22.99-23.65 × 20.57	8	13.19-13.61 × 13.19	0.683
g5	23.67-24.33 × 20.57	8	13.19-13.61 × 13.19	0.662
g6	24.33-25.02 × 20.57	8	13.19-13.61 × 13.19	0.643
g7	25.02-25.83 × 24.64	8	13.19-13.61 × 13.19	0.516
g8	25.83-26.62 × 24.64	8	13.19-13.61 × 13.19	0.503
g9	26.64-27.43 × 24.64	8	13.19-13.61 × 13.19	0.488
g10	27.46-27.84 × 24.64	8	13.19-13.61 × 13.19	0.477

final 0.5-mm air gap

PDE: GlueX SiPM Parameters

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 4, AUGUST 2015 1865

Methodology for the Determination of the Photon Detection Efficiency of Large-Area Multi-Pixel Photon Counters

T. Beattie, G. J. Lolos, Z. Papandreou, A. Yu. Semenov, and L. A. Teigrob

***Abstract*—Large-area, multi-pixel photon counters will be used for the electromagnetic Barrel Calorimeter of the GlueX experiment at Jefferson Lab. These photo sensors are based on a 3 × 3 mm^2 cell populated by 50 μm pixels, with 16 such cells tiled in a 4 × 4 arrangement in the array. The 16 cells are summed electronically and the signals are amplified. The photon detection efficiency of a group of first-article units at room temperature under conditions similar to those of the experiment was extracted to be $(28 \pm 2(stat) \pm 2(syst))\%$, by employing an analysis methodology based on Poisson statistics carried out on the summed energy signals from the units.**

***Index Terms*—Multi-photon pixel counters, photon detection efficiency, silicon photomultipliers.**

I. Introduction

MODERN particle physics experiments and medical applications have placed technical demands that cannot often be met by photomultipliers (PMTs). Indeed, there has been a flurry of activity in the development and application of silicon photomultipliers (SiPMs). These offer immunity to Tesla-level magnetic fields, compactness, high (≈ 20%) photon detection efficiency (PDE) and operation below 100 V, while preserving many of the PMT's other attributes. In addition, SiPMs provide excellent photoelectron peak separation provided that dark current is kept low, the latter reduced either by using mm^2-sized or by cooling cm^2-sized devices. The evolution of the field, including large-scale applications of SiPMs in particle physics detectors and applications to related fields, is available in a comprehensive review [1].

SiPMs are known by other acronyms with a common one being Hamamatsu's (Hamamatsu Corporation, Bridgewater, NJ 08807, USA (sales.hamamatsu.com)) Multi-Pixel Photon Counters (MPPCs). These devices are comprised of an array of limited Geiger-mode avalanche photodiodes on a silicon substrate. The electronic circuit of an MPPC is the parallel sum of its individual pixels/diodes. Each pixel is a silicon Avalanche Photo Diode (APD) typically based on "n on p" structure. The avalanche in these APDs is quenched by a silicon resistor that is in series with the pixel [2]. A common inverse bias voltage is provided to all APDs, so as to operate the device at a few volts above the break down point, V_{br} and the signals may include after-pulsing and cross talk [3].

II. Large-Area MPPCs for the GlueX BCAL

The GlueX Experiment aims to elucidate the confinement property of quantum chromodynamics by mapping out the spectrum of exotic hybrid mesons [4], [5]. A hermetic detector is needed for this task, a key sub-system of which is the electromagnetic barrel calorimeter (BCAL) [6]. The BCAL is a lead-scintillating-fibre sampling calorimeter that will reside inside a 2 T superconducting solenoid.

Our collaboration investigated various solutions for the BCAL readout, among them hybrid photodiodes [7]. None of those, however, could satisfy the simultaneous requirements of magnetic field tolerance, minimization of light losses from calorimeter to sensor, high gain and compactness. In addition, the BCAL readout granularity demanded readout cell areas of ≈ 1.3 cm^2. To this end, we focused our attention on SiPMs and embarked on a multi-year collaboration with a photonics firm (SensL - Ireland, 6800 Airport Business Park Cork, Ireland (sensl.com)) that eventually led to the development of the very first large-area tiling based on a 3 × 3 mm^2 cell with 35 μm pixel size [8]. The potential of such a device in particle physics applications and in related fields was apparent, as evidenced by other companies eventually producing similar devices. The GlueX configuration is one of the standards now available commercially from several firms.

In the end, Hamamatsu was selected to produce MPPC arrays for the BCAL. The chosen S12045(X) units were configured in 4 × 4 array of 3 × 3 mm^2 cells based on a 50 μm pixel, which yields 57,600 pixels per array. These devices deliver a nominal gain of 6×10^5 at 25°C; a schematic is reproduced in Fig. 1. The BCAL's 3840 units are fully operational and are currently being gain-calibrated using cosmic rays and high-energy photons from π° decays.

III. Evaluation and Quality Control

A detailed description of "first-article" (first 80 units from the production) MPPC arrays and initial evaluation tests on gain, dark noise, cross talk, temperature dependence and radiation hardness have been published by our colleagues at Jefferson Lab [9]. The devices will be cooled to +5° in order to reduce their

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNS.2015.2442262

PDE value for 11 SiPM units from our measurements of 28% ± 2% (stat) ± 2% (syst), for these Hamamatsu large-area arrays for 0.9 V and at 460 nm.

The average PDE of (24 ± 2)% for 3000 units measured by USM at 0.9 V was extracted at a wavelength of 518 nm. The PDE varies as a function of wavelength, with it being larger by a factor of 1.11 in going from 518 nm to 460 nm according to the manufacturer. This correction increases the USM number to ~27% at 460 nm, consistent with the result reported herein.

https://ieeexplore.ieee.org/document/7161418

Measurements at USM:

Characterization of novel Hamamatsu Multi Pixel Photon Counter (MPPC) arrays for the GlueX experiment:
https://www.sciencedirect.com/science/article/pii/S0168900213009042

Novel Hamamatsu Multi-Pixel Photon Counter (MPPC) array studies for the GlueX experiment: New results
https://www.sciencedirect.com/science/article/pii/S0168900213017233

PDE: GlueX SiPM Parameters

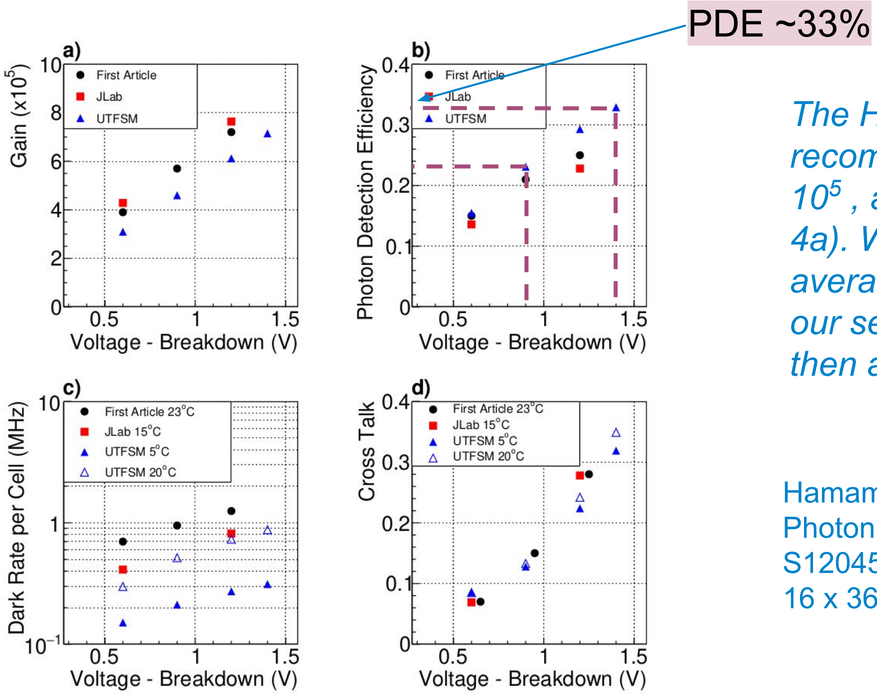

Figure 4: Measurements of the first-article samples (black circles) [20, 25], production samples at JLab (red squares) and production samples at UTFSM (triangles) [21, 22] of four basic SiPM parameters as a function of the voltage over breakdown. a) gain, b) photon detection efficiency, c) dark rate per tile (the dark rate for the array is 16 times higher) and d) cross talk determined from deviations of the single-pixel distributions from a pure Poisson function. As long as the voltage over breakdown is kept constant, the dark rate is the only parameter that has a significant temperature dependence. The nominal operating voltage for the GlueX experiment is 1.4 V above breakdown. (Color online)

The Hamamatsu specification sheets provide the recommended operating voltage for a nominal gain of 7.5 × 10^5 , although our measurements indicate lower gains (Fig. 4a). We determined that this operational voltage on average corresponds to 0.9 V above breakdown; to obtain our setting at an overvoltage of 1.4 V, we added 0.5 V and then adjusted for temperature.

Hamamatsu Multi-Pixel Photon Counter (MPPC) S12045(X):
16 x 3600 pixels (50 um)

arXiv:1801.03088v2 [physics.ins-det] 20 Apr 2018

Construction and Performance
of the Barrel Electromagnetic Calorimeter
for the GlueX Experiment

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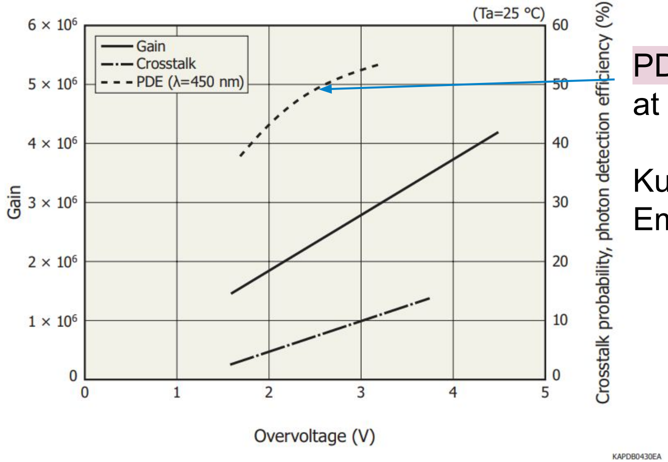
Abstract

The barrel calorimeter is part of the new spectrometer installed in Hall D at Jefferson Lab for the GlueX experiment. The calorimeter was installed in 2013, commissioned in 2014 and has been operating routinely since early 2015. The detector configuration, associated Monte Carlo simulations, calibration and operational performance are described herein. The calorimeter records the time and energy deposited by charged and neutral particles created by a multi-GeV photon beam. It is constructed as a lead and scintillating-fiber calorimeter and read out with 3840 large-area silicon photomultiplier arrays. Particles impinge on the detector over a wide range of angles, from normal incidence at 90 degrees down to 11.5 degrees, which defines a geometry that is fairly unique among calorimeters. The response of the calorimeter has been measured during a running experiment and performs as expected for electromagnetic showers below 2.5 GeV. We characterize the performance of the BCAL using the energy resolution integrated over typical angular distributions for π^0 and η production of $\sigma_E/E=5.2\%/\sqrt{E(\mathrm{GeV})}\oplus 3.6\%$ and a timing resolution of $\sigma = 150\,\mathrm{ps}$ at 1 GeV.

https://arxiv.org/abs/1801.03088

PDE: Hamamatsu s14160/14161

Overvoltage vs. gain, crosstalk probability, photon detection efficiency (typical example)

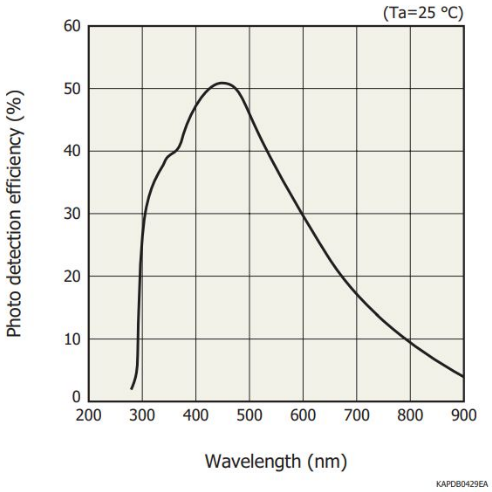


PDE = ~50%
at 2.7 V, λ = 450 nm

Kuraray SCSF-78
Emission peak = 450 nm

MPPC characteristics vary with the operating voltage. Although increasing the operating voltage improves the photon detection efficiency and time resolution, it also increases the dark count and crosstalk at the same time, so an optimum operating voltage must be selected to match the application.

Photon detection efficiency vs. wavelength (typical example)



Photon detection efficiency does not include crosstalk and afterpulses.

50%/33% = ~1.51

- https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf
- https://www.kuraray.com/uploads/5a717515df6f5/PR0150_psf01.pdf

Hamamatsu: s14160/14161 series - 50 um pixel

Electrical and optical characteristics (Typ. Ta=25 °C, Vover=2.7 V, unless otherwise noted)

Parameter		Symbol	S14160/S14161 -3050HS-04, -08	S14160/S14161 -4050HS-06	S14160/S14161 -6050HS-04	unit
Spectral response range		λ		270 to 900		nm
Peak sensitivity wavelength		λp		450		nm
Photon detection efficiency at λp*3		PDE		50		%
Breakdown voltage		V_{BR}		38		V
Recommended operating voltage*4		Vop		V_{BR} + 2.7		V
Vop variation between channels in one product*5	Typ.	-		0.1		V
	Max.			0.2		
Dark current	Typ.	I_D	0.6	1.1	2.5	μA
	Max.		1.8	3.3	7.5	
Crosstalk probability		-		7		%
Terminal capacitance		Ct	500	900	2000	pF
Gain		M		2.5×10^6		-
Temperature coefficient of recommended reverse voltage		ΔTVop		34		mV/°C

*3: Photon detection efficiency does not include crosstalk and afterpulses.
*4: Refer to the data attached for each product.
*5: The parameter is for the S14161 series (multichannel type)

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf

Hamamatsu: s14160/14161 series - 50 um pixel

Structure

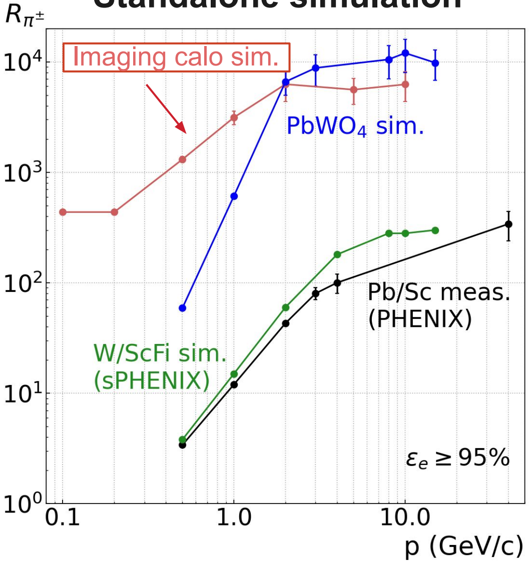
Typ. no.	Number of channels (ch)	Effective photosensitive area/channel (mm^2)	Pixel pitch (μm)	Number of pixels/channel	Package	Window	Window refractive index	Geometrical fill factor (%)
S14160-3050HS	1	3.0 × 3.0	50	3531	Surface mount type	Silicone	1.57	74
S14160-4050HS		4.0 × 4.0		6331				
S14160-6050HS		6.0 × 6.0		14331				
S14161-3050HS-04	16 (4 × 4)	3.0 × 3.0		3531				
S14161-3050HS-08	64 (8 × 8)	3.0 × 3.0		3531				
S14161-4050HS-06	36 (6 × 6)	4.0 × 4.0		6331				
S14161-6050HS-04	16 (4 × 4)	6.0 × 6.0		14331				

Note:
3050HS-04 array has 16 x 3531 pixels = 56496 pixels (98.5% of below)
4 x 6050HS has 4 x 14331 pixels = 57324 pixels

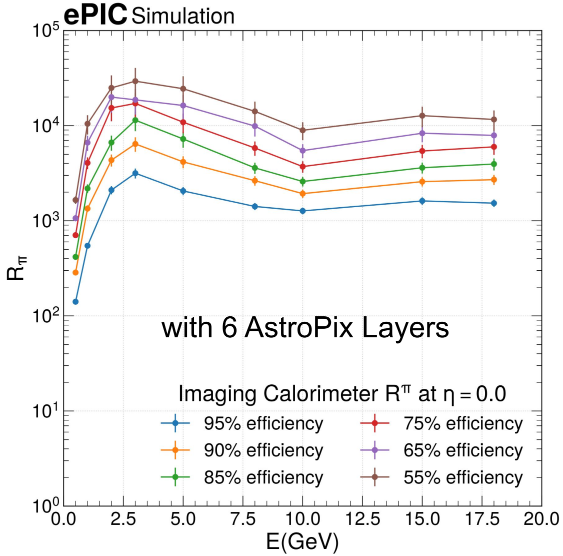
https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf

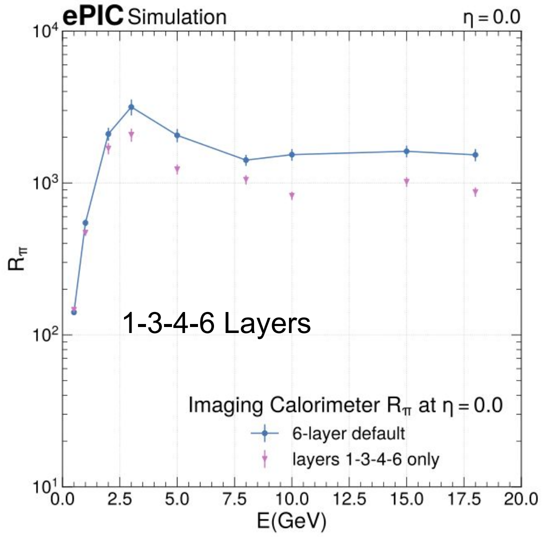
Barrel Imaging ECal: Performance Example

Standalone simulation



Realistic ePIC simulation





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

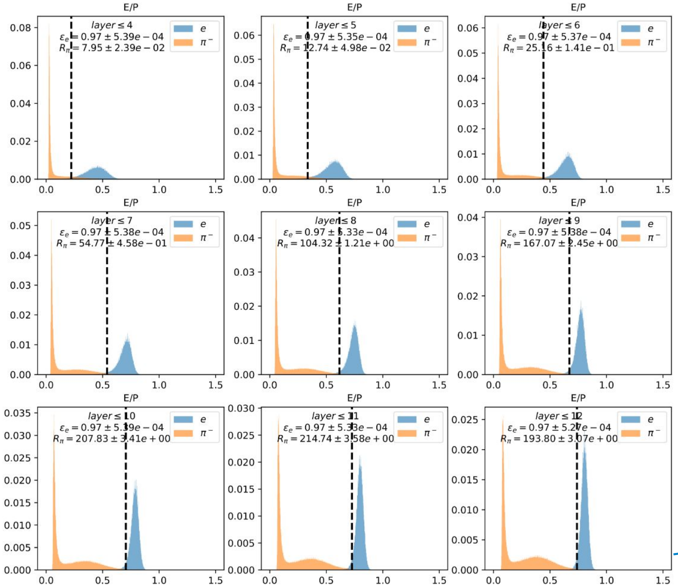
- e-π separation exceeds $\mathbf{10^3}$ in pion suppression at **95% efficiency** above 1 GeV in realistic conditions!

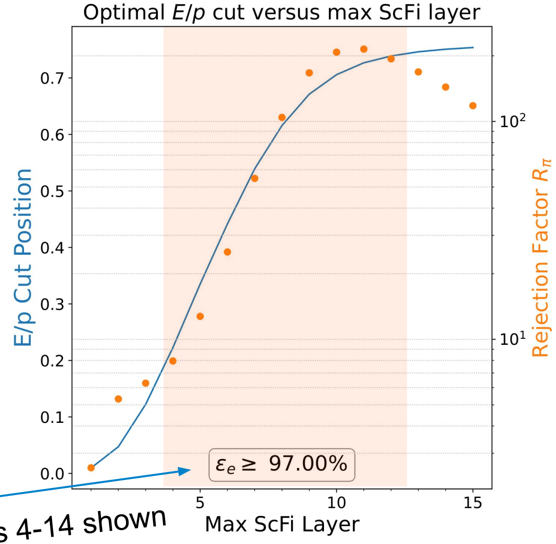
e/π Separation in Barrel ECal - Method

Steps:

1. **Optimized cut on E/p** from different depth of Pb/ScFi layers at very high electron efficiency
2. **Convolutional neural network** utilizing energy and spatial information for shower (see backup slides for details)

Example for 2 GeV e/π

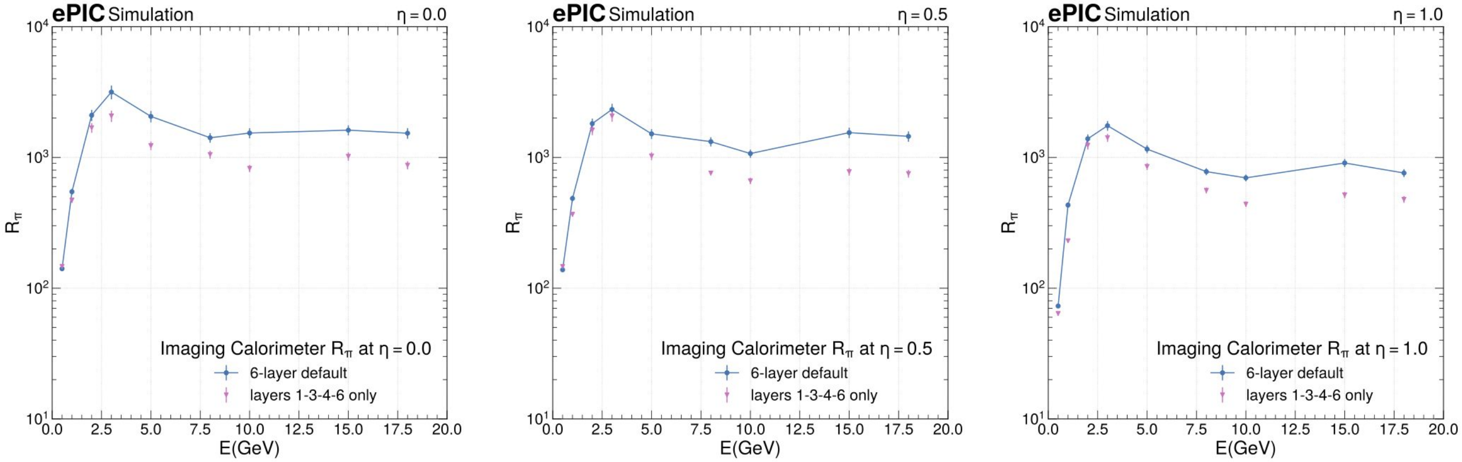




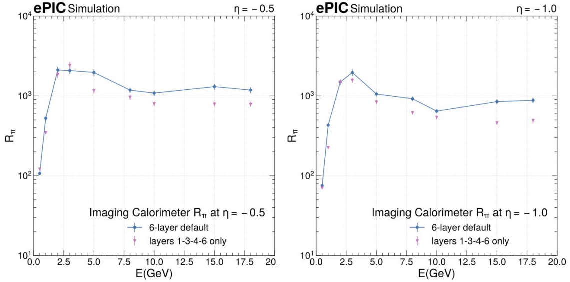
ScFi layers 4-14 shown

Performance with reduced number of layers

e/π separation at 95% efficiency



4-layer alternate:
layers 1-3-4-6

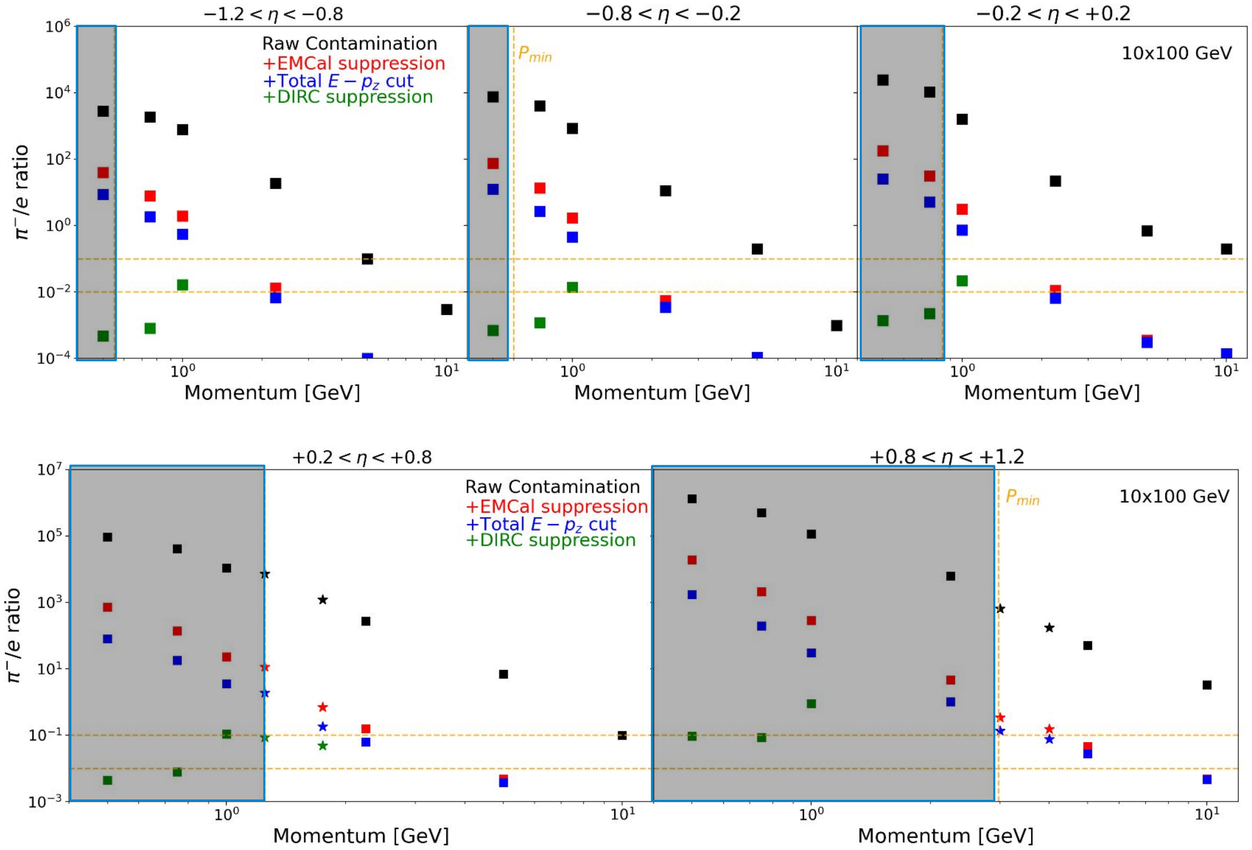


Default configuration exceeds 10^3 pion rejection almost everywhere

4-layer alternate still performs relatively well at lower energies (where most rejection is needed), larger degradation at higher energies

4-layer alternate seems workable compromise.

Performance for 10 x 100 GeV



Studies on π contamination performed by B. Schmookler (UCR)

- See ePIC Collaboration Meeting contribution (link)

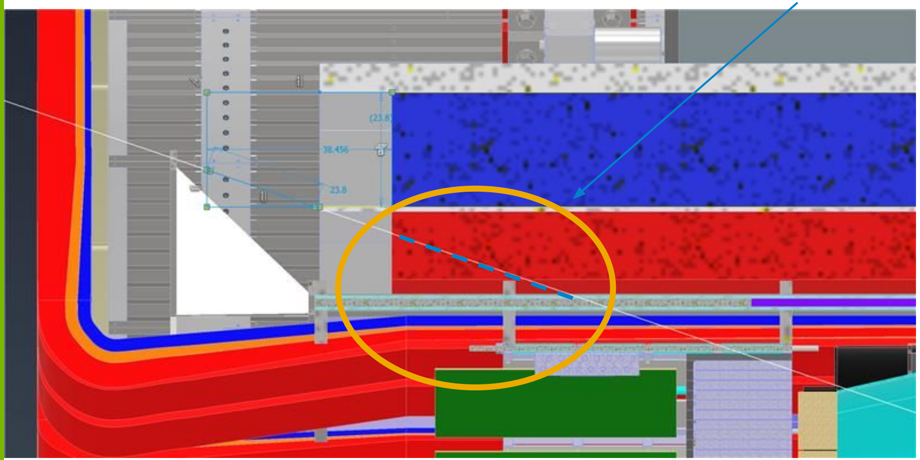
Challenging goal: Achieve 90% electron purity from the combined detector performance (ECAL + DIRC)

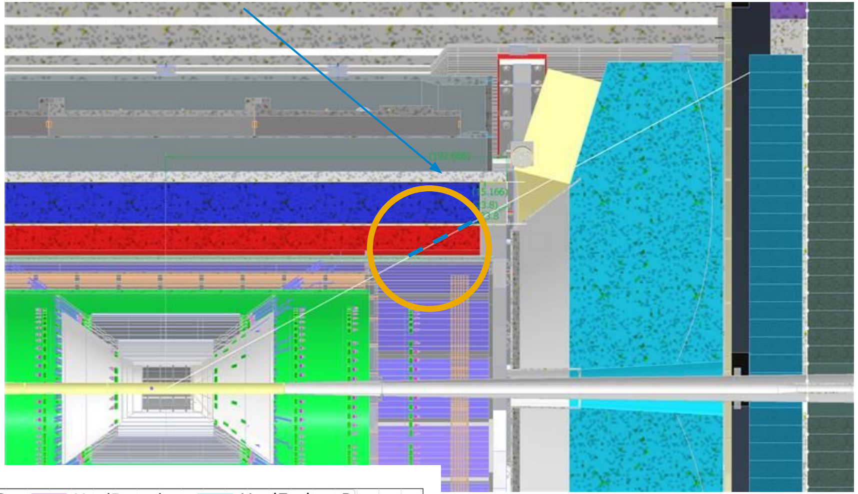
- To keep pion contamination systematic uncertainty to required 1% level

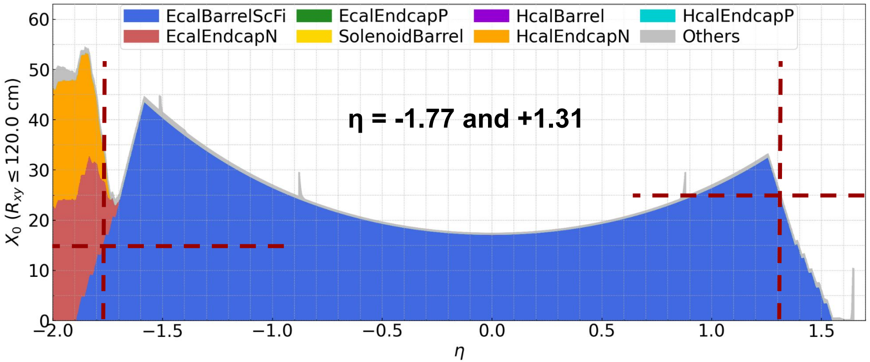
Imaging calorimeter fulfills the requirement in all η ranges

Integration

η = -1.77 and +1.31 for those lines assuming *one block size less than maximum radius*







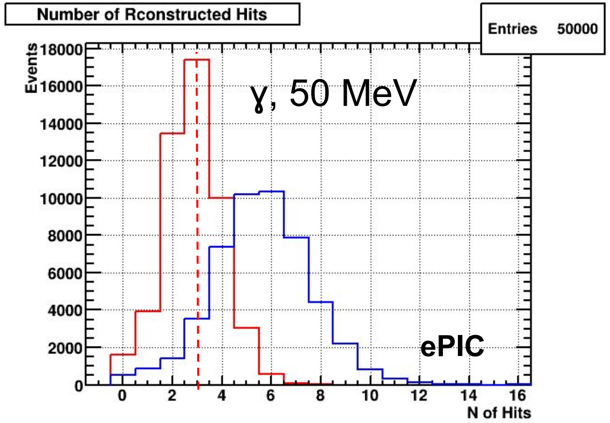
Low Energy Particles

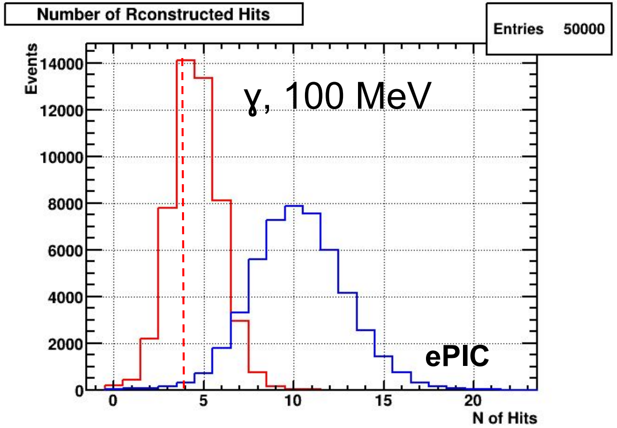
Threshold corrected for f_{sam}

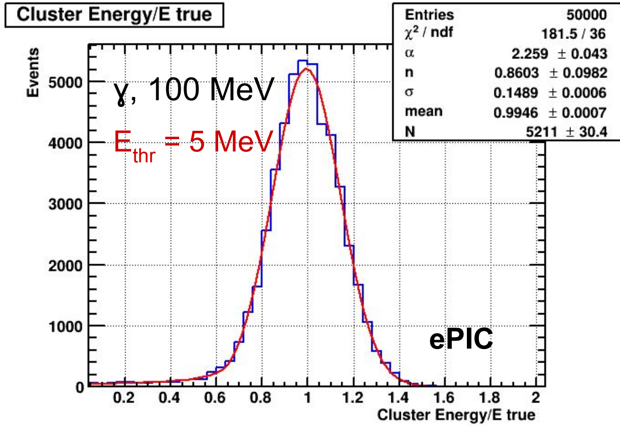
E_{thr} = 0.5 MeV

E_{thr} = 5 MeV

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





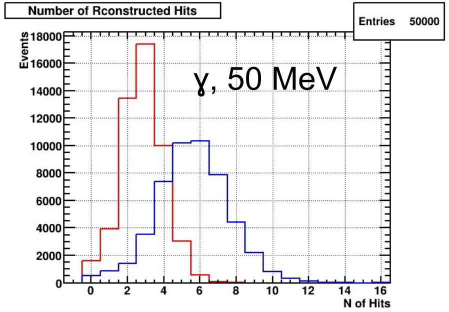


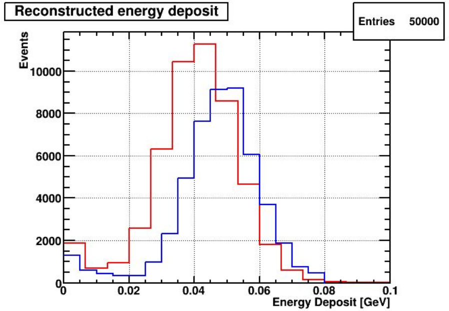
Blue threshold very low just to illustrate the distribution shape

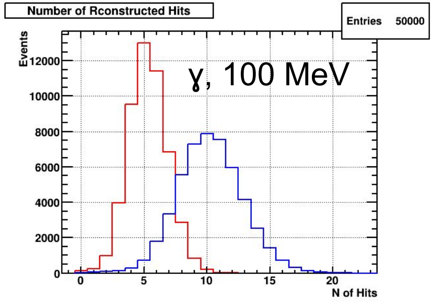
- **From GlueX** studies: cluster/shower threshold is 100 MeV nominal (down to 50 MeV for some analyses, with mostly two cells per event only). Low energy detection threshold studied also with Michel electrons. (NIM, A 896 (2018) 24-42)

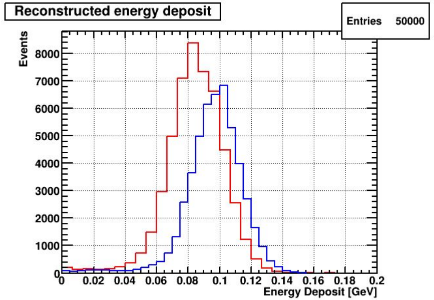
Low Energy - Gammas

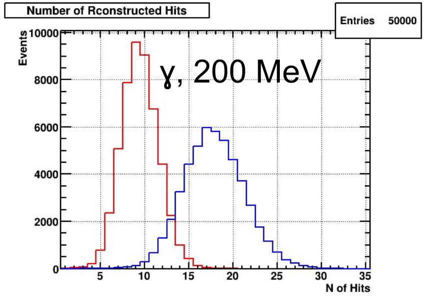
Threshold corrected for f_{sam}
E_{thr} = 0.5 MeV
E_{thr} = 5 MeV

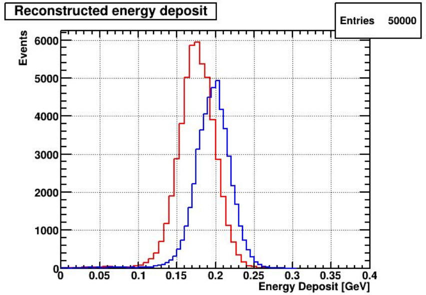


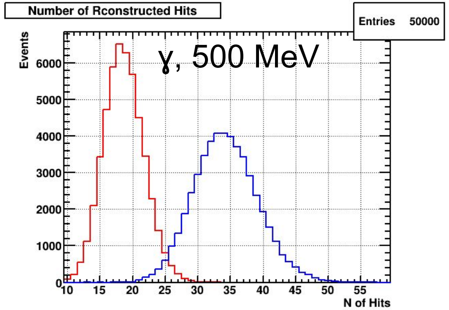


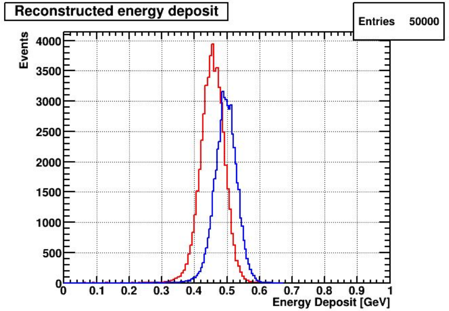






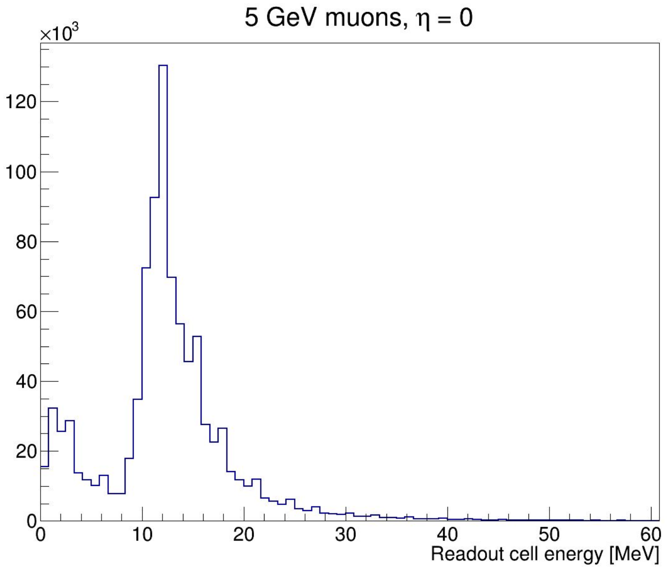


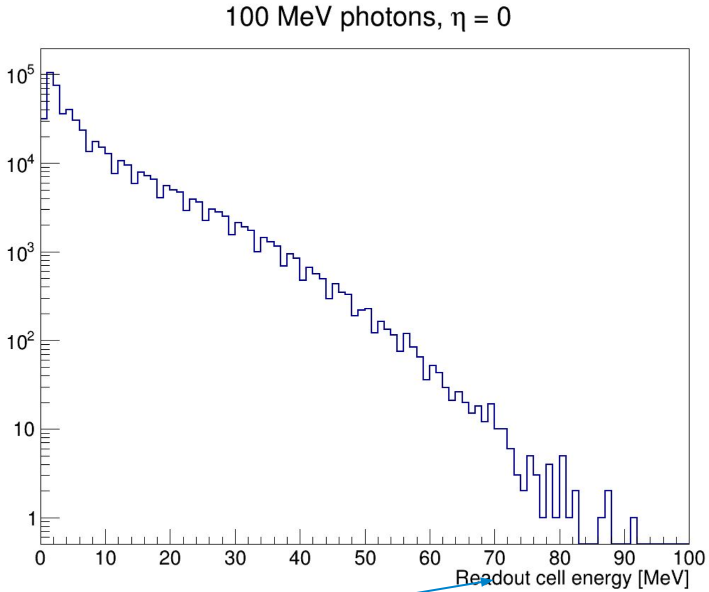




N of Hits: Number of cells above the threshold
Energy Deposit: Energy deposited with particular threshold

Low Energy Particles - Energy per readout cell

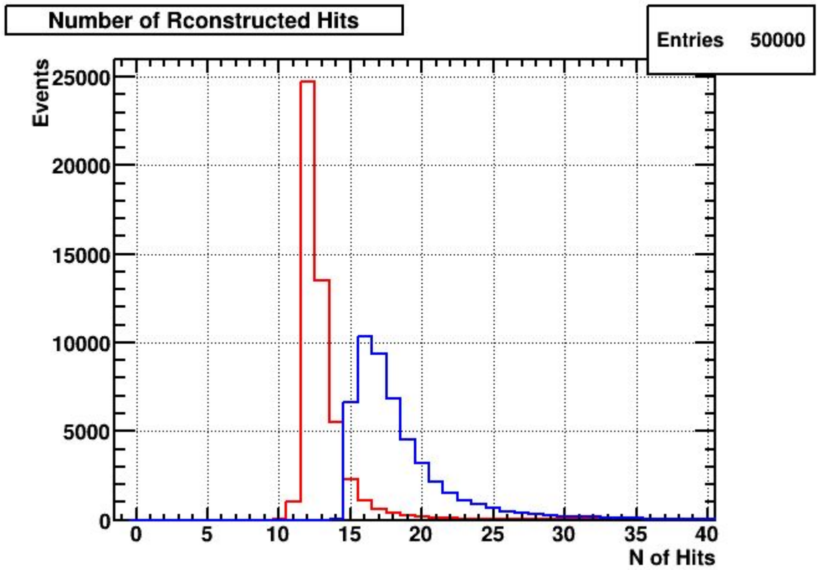


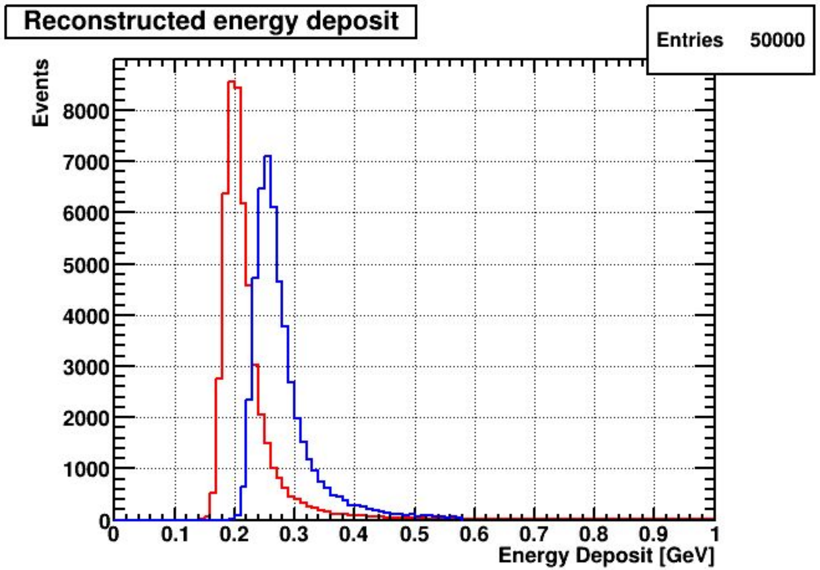


- Energy corrected for 10% sampling fraction in readout cells
- Studies at η = 0 to look at the lowest dE
- Threshold set very low = 0.05 MeV to study the energy distribution of readout cells

Low Energy Particles - MIPs

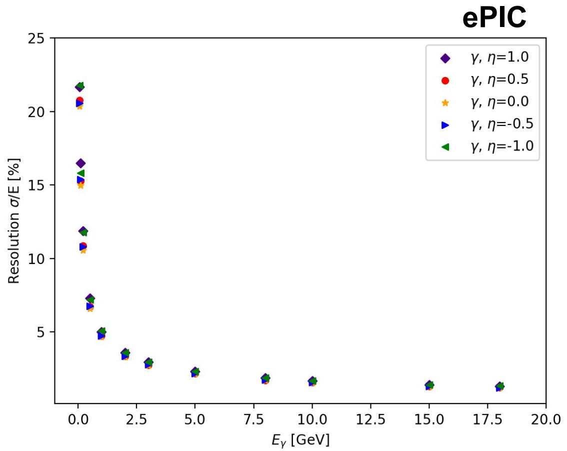
Threshold corrected for f_{sam}
E_{thr} = 0.5 MeV
E_{thr} = 5 MeV

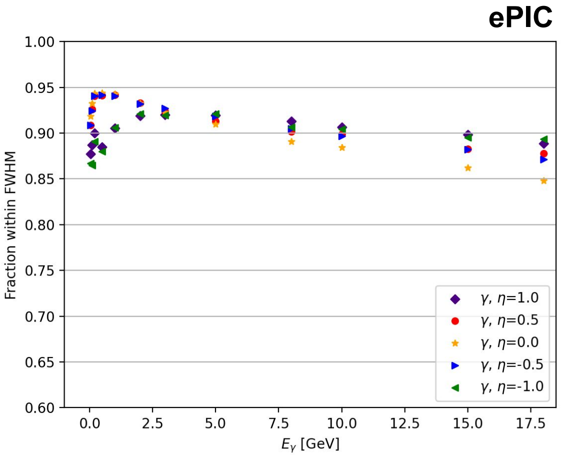


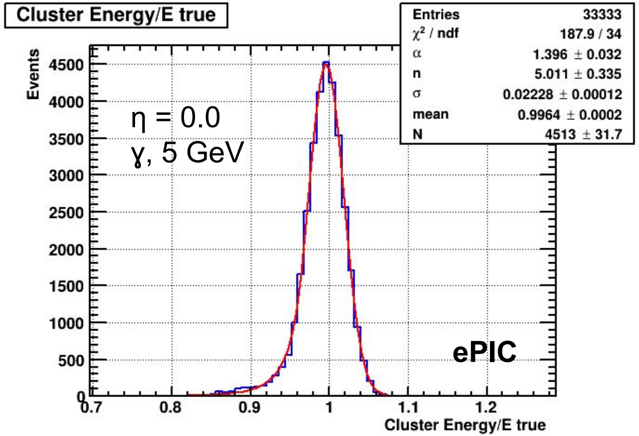


- 5 GeV Muons
- Studies at $\eta = 0$ to look at the lowest dE
- Threshold set very low = 0.05 MeV to study the energy distribution of readout cells

Energy Resolution - Photons







Fit parameters

η	a/√(E) [%]	b [%]
-1	5.1(0.01)	0.47(0.03)
-0.5	4.77(0.01)	0.38(0.02)
0	4.67(0.01)	0.40(0.02)
0.5	4.75(0.01)	0.39(0.02)
1	5.1(0.01)	0.41(0.02)

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

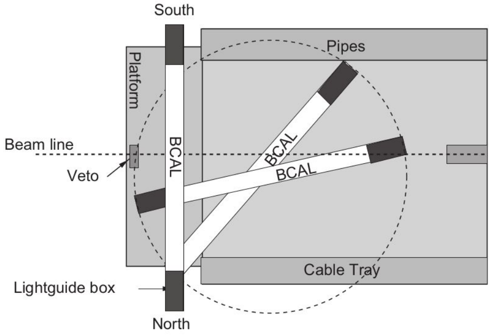
GlueX Pb/ScFi ECal: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ NIM, A 896 (2018) 24-42

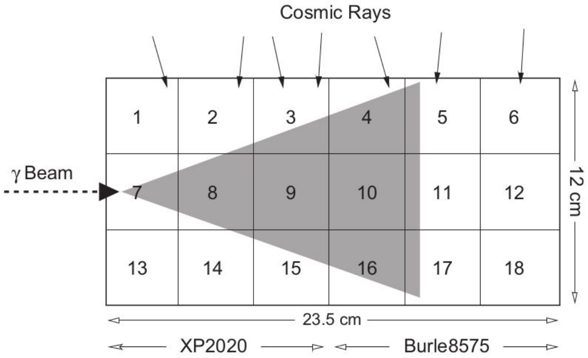
- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

Simulations of **GlueX prototype** in ePIC environment agree with data at E_γ < 0.5 NIM, 596 (2008) 327−337

Comparison with GlueX prototype data

Test at JLab Hall B with **full size one stave prototype**, secondary **photon beam**, **~0.15-0.6 GeV**, **90º angle**
NIM, 596 (2008) 327–337, Performance of the prototype module of the GlueX electromagnetic barrel calorimeter





Hall B, 2008 beam test with full length GlueX BCAL Prototype

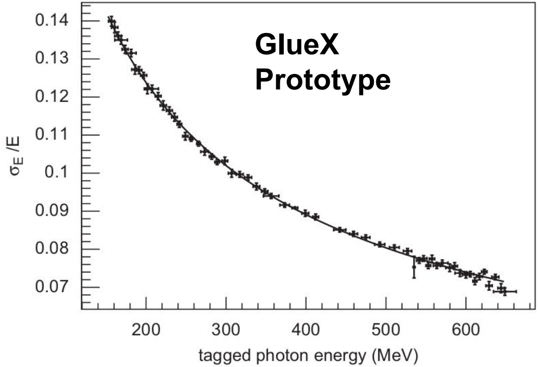


Fig. 11. Energy resolution vs. E_{BEAM} for photons for $\theta = 90^\circ$ and $z = 0$ cm. The fit gives $\sigma_E/E = 5.4\%/\sqrt{E(\mathrm{GeV})} \oplus 2.3\%$. The fit of Fig. 10 corresponds to the 40th datum from the right (19th from the left) in this figure.

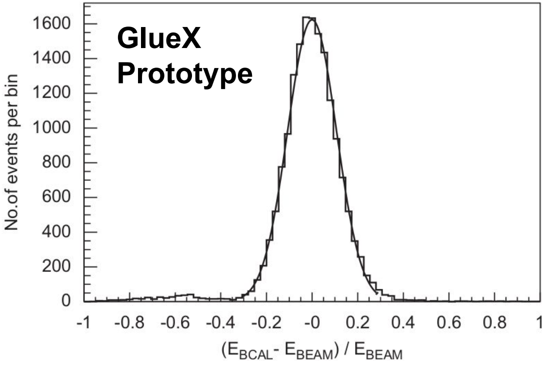
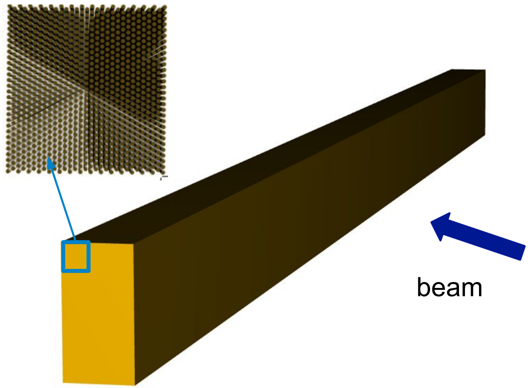
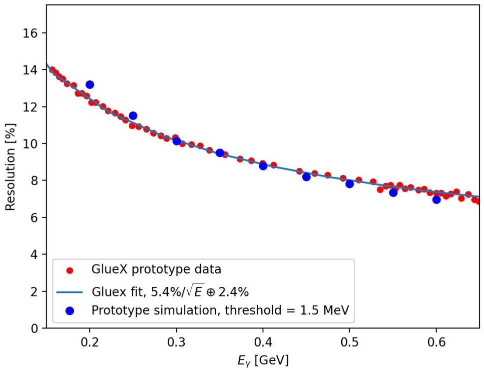


Fig. 10. The calibrated spectrum for D is shown for timing counter 40, corresponding to a beam energy of 273 MeV. The solid line is a Gaussian fit to the data.

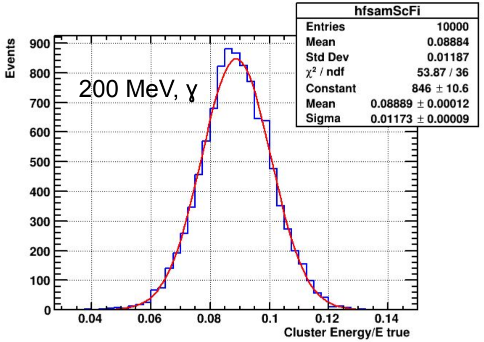
Comparison with GlueX prototype data

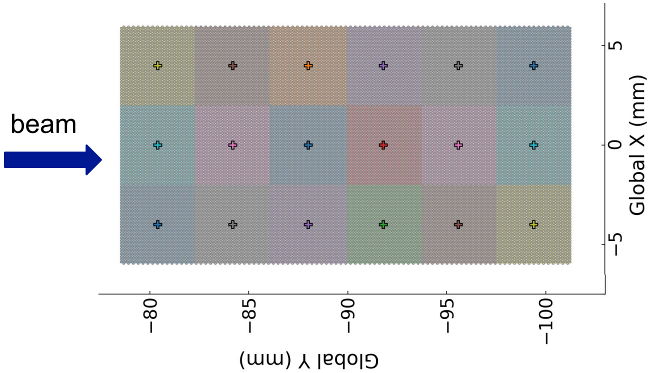
Simulation of GlueX prototype and readout scheme in **ePIC simulation environment**





Reconstructed Energy/True energy

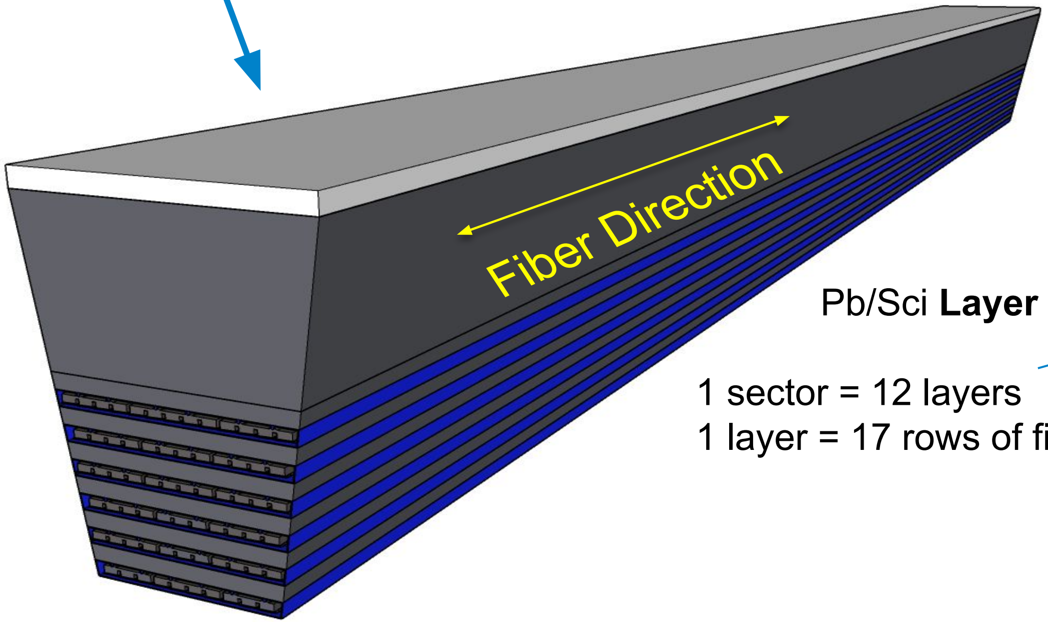




- Realistic geometry implementation and simulation of the prototype and readout
- Low energy data described quite well by the simulation
- Energies up to ~6 GeV tested in the ongoing test at Hall D

Geometry and Naming Scheme

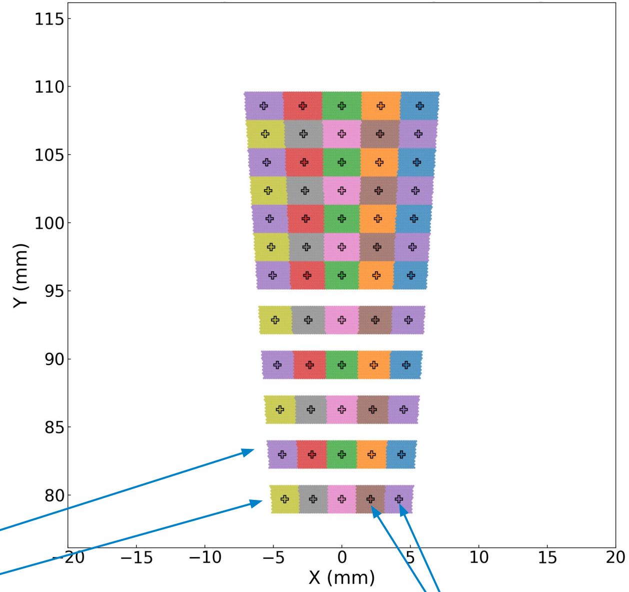
Sector
Whole Barrel: 48 Sectors



Pb/Sci **Layer**

1 sector = 12 layers
1 layer = 17 rows of fiber

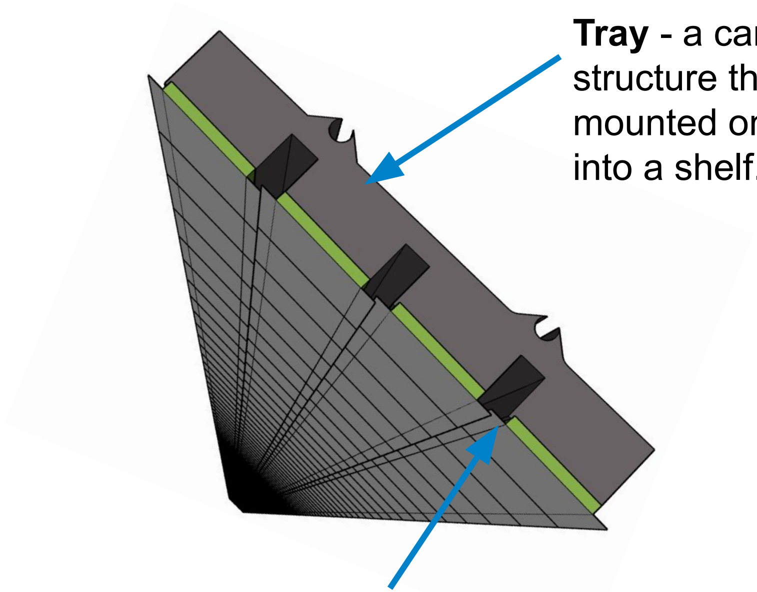
Sector End View
(x-y plane view)



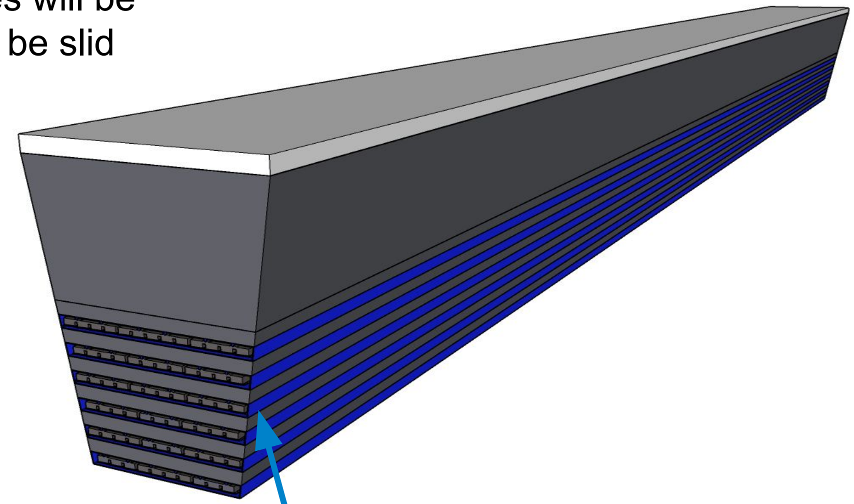
Readout **Cell**
Layer = 5 cells

The area 1 light guide is attached

Geometry and Naming Scheme



Tray - a carbon fiber structure the staves will be mounted on. It will be slid into a shelf.



AstroPix **Stave**

Consists of 1 x 100 chips with the support structure

AstroPix **Module**

Subset of 10 chips that will be mounted on one stave support structure

Shelf - a carbon fiber structure that is glued to the Pb/ScFi layers, that we will slide trays with AstroPix staves on.

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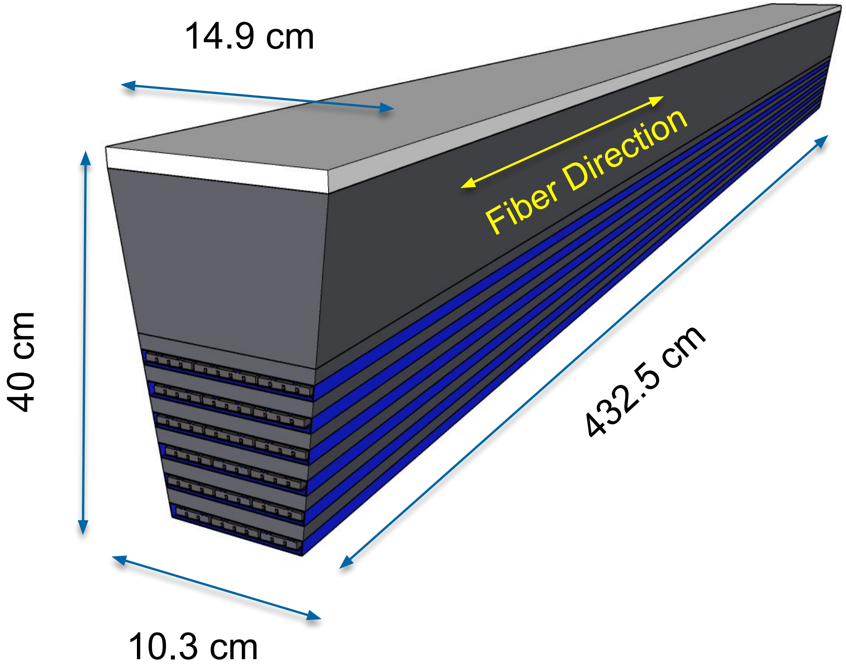
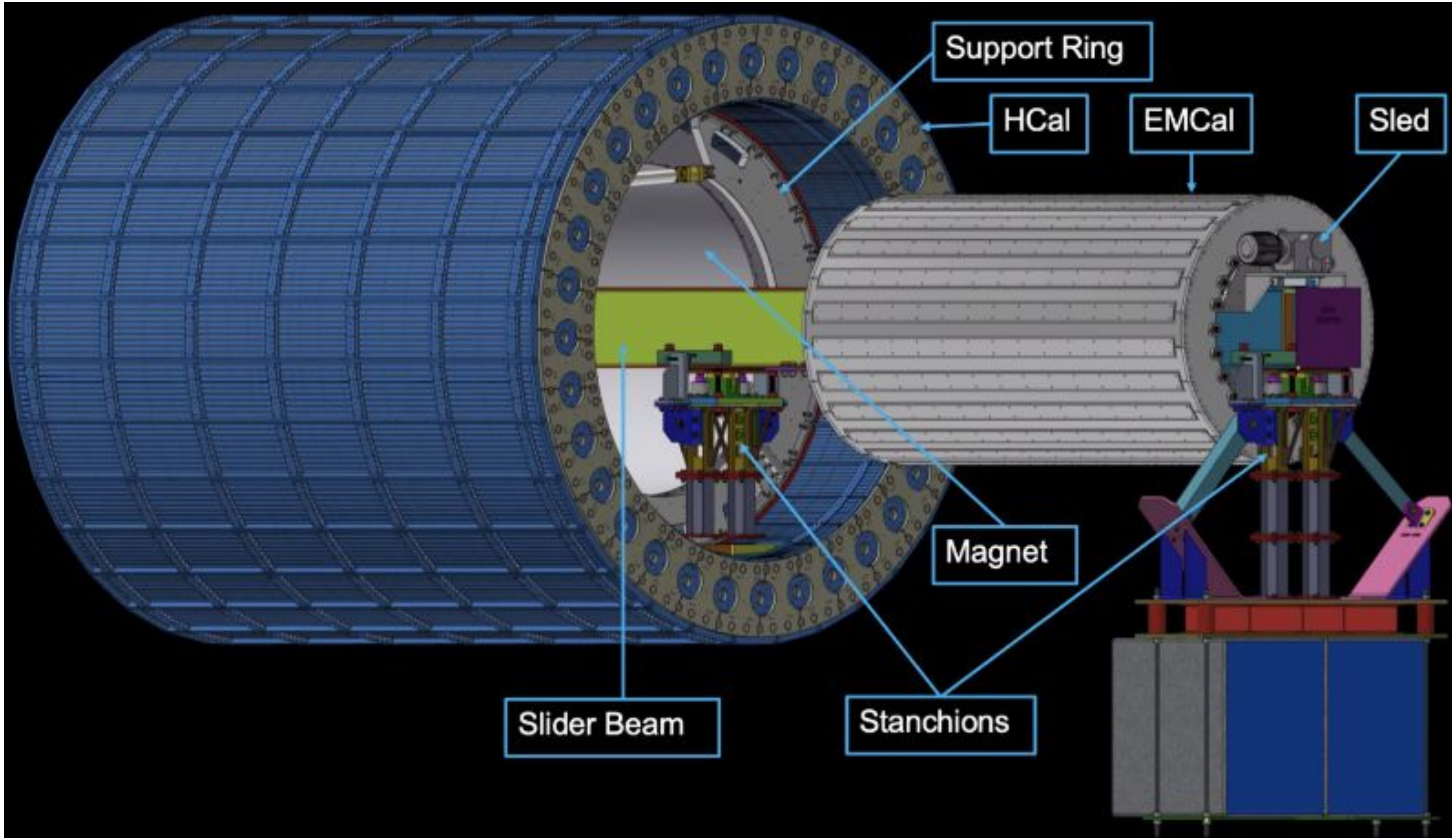
Dimensions



Dimensions a the current stage of the design

inner barrel radius	78.3 cm
nb of sectors	48
length	432.5 cm
AstroPix slot thickness	1.5 cm
SciFi/Pb Layer 1-5 thickness	2 cm
Total weight	~36 t
1 sector weight	~750 kg

Assembly tooling



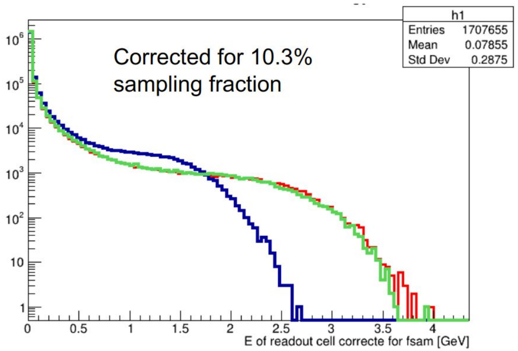
Pixel Size and Number of Pixels

Defined by photoelectron statistics and maximal energy to be measured

- Maximal fraction of the total shower energy deposited in a longitudinal layer of **~1.5 X0 size** (approximately the readout layer depth) will be **~15%** (from longitudinal shower profile) **at η = 0**
- With a steeper impact angle, the effective thickness of one SciFi/Pb layer will be longer, so the energy deposit per layer will be larger.
- The most extreme case for us would be **50 GeV electrons at +1.31** (30 deg impact)
- Assuming that we have ~30% (15%/sin(30 deg)) of max deposit for 50 GeV electrons at eta = 1.31 this gives us **~15 GeV**

dE of the single readout cell for 18 GeV particles

- e- (green) at eta = 1
- photons (blue) at eta = 0
- photons (red) at eta = 1



dE in single readout cell
Example for 18 GeV photons at η = 0 and η = 1 (~41 deg impact)

- Max dE at η = 0: ~2.7 GeV (18 GeV * 15%)
- Max dE at η = 1: ~4.1 GeV (18 GeV * 15%/sin(41 deg))