Energy Analysis for Barrel Imaging Calorimeter Prototype

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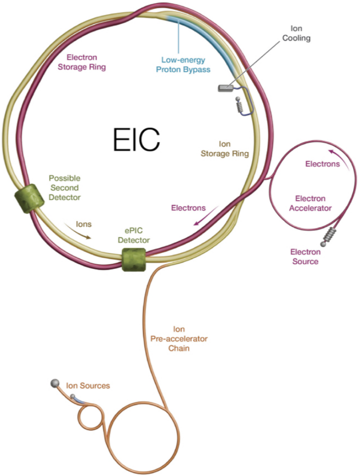
EICUG Early Career Workshop

July 11, 2025

Overview of BIC's Role for EIC



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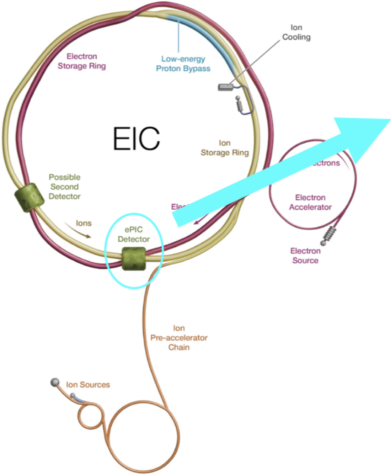

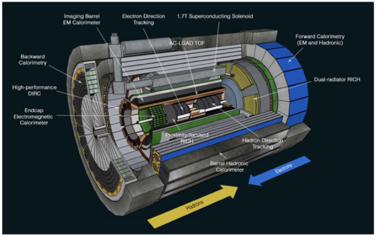

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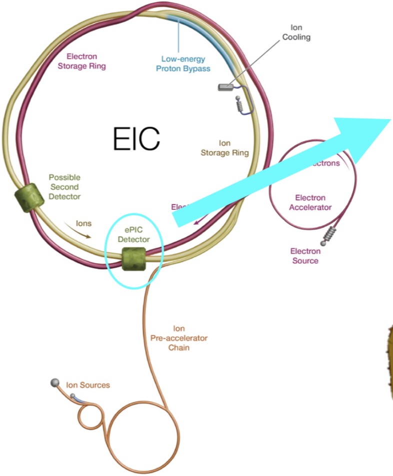
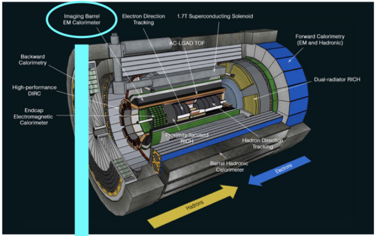
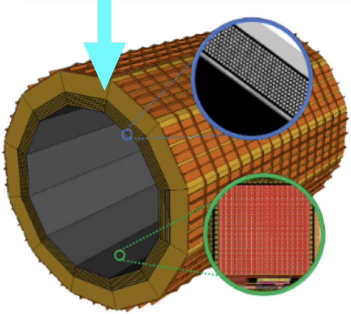






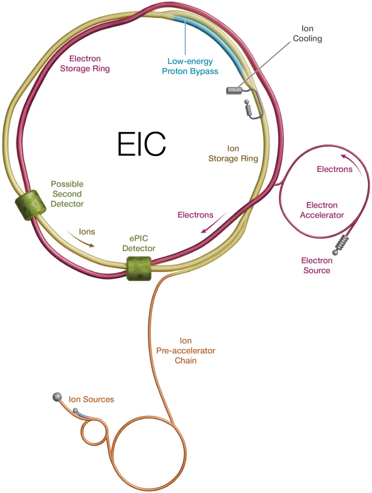
Outline

1. Background
2. Gain Calibrations
3. Energy Resolution
4. Conclusions

Background

Locations of this Work

The Electron-Ion Collider (EIC) Project



- Facility to investigate **quantum chromodynamics**

https://www.bnl.gov/eic/ (2025)

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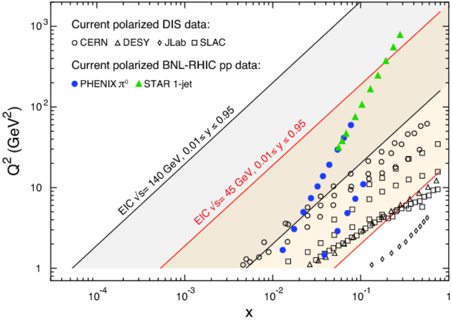

- Facility to investigate **quantum chromodynamics**
- Unique machine parameters enable exploration of **new regions** in Q^2/x phase space

A. Accardi et al., Eur. Phys. J. A **52** (2016)

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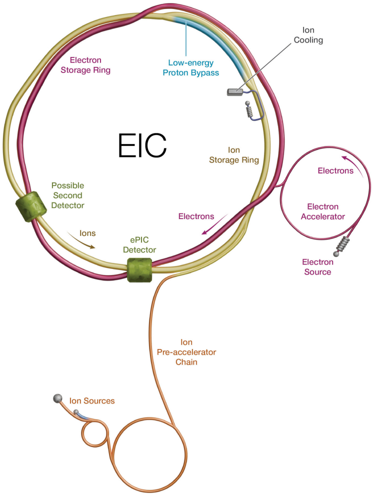
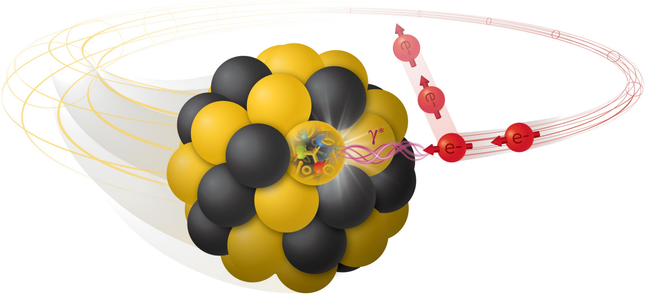


- Facility to investigate **quantum chromodynamics**
- Unique machine parameters enable exploration of **new regions** in Q^2/x phase space
- Broad agenda of **physics goals**

https://www.bnl.gov/eic/ (2025)

Reaction

We use $e^- p/A$ collisions between polarized electron and ion rings as a probe for these physics studies.



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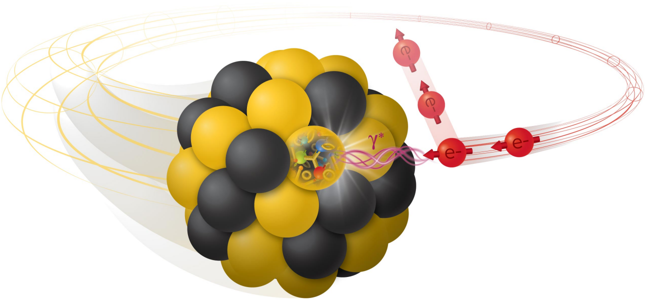
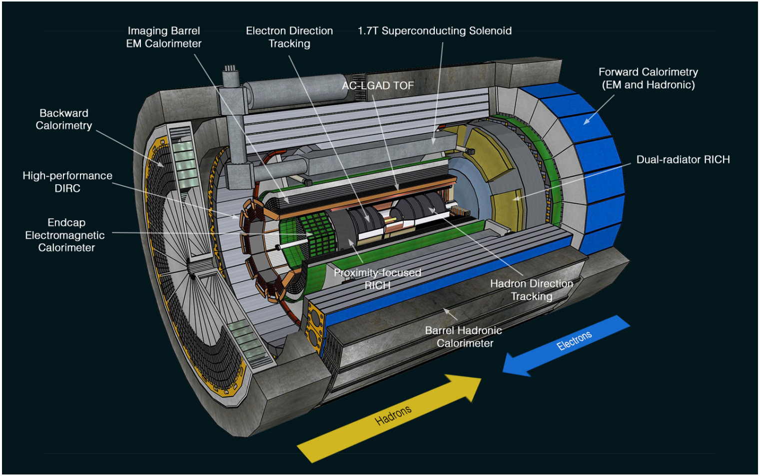


Requires extensive and largely new detector system to detect and reconstruct collisions $\rightarrow$ **significant R&D project**.

https://www.bnl.gov/eic/ (2025)

ePIC Detector System



https://www.bnl.gov/eic/epic.php (2025)

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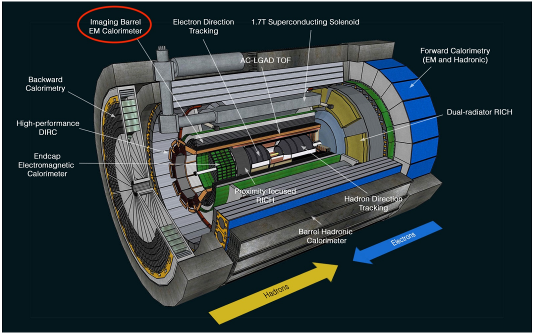

- EM calorimetry significant component of ePIC detector

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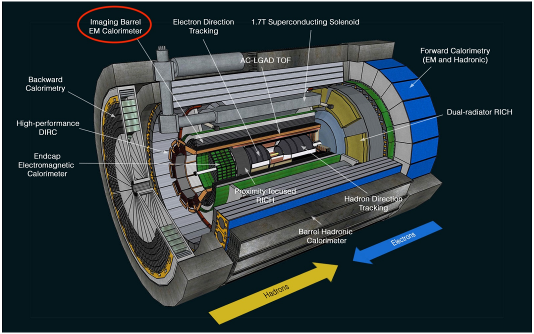
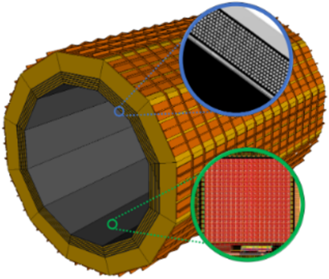


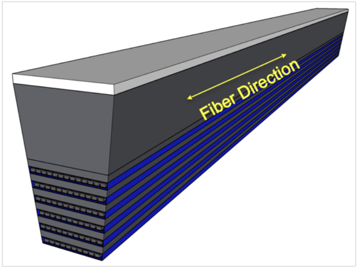
- EM calorimetry significant component of ePIC detector
- This works focuses on R&D for the **Barrel Imaging Calorimeter** (BIC) segment

https://www.bnl.gov/eic/epic.php (2025)

Barrel Imaging Calorimeter (BIC)

- **Electromagnetic solenoidal** detector with 48 segments

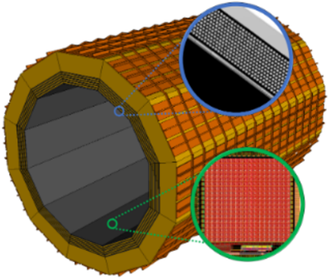


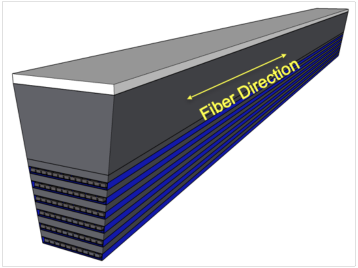


J. Adam et al., JINST **17** (2022)
https://www.bnl.gov/eic/epic.php (2024)

Barrel Imaging Calorimeter (BIC)

- **Electromagnetic solenoidal** detector with 48 segments
- 6 **detector** layers
  - Pb/SciFi lattice
  - Longitudinal EM shower profile, deposit position & energy





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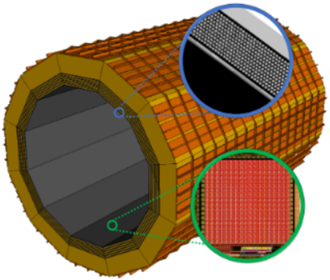
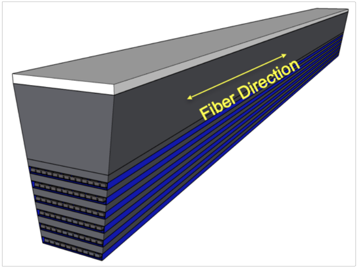
  - AstroPix sensor arrays
  - 3D shower profile & position resolution





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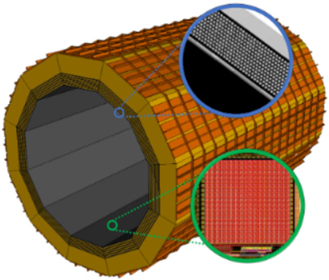
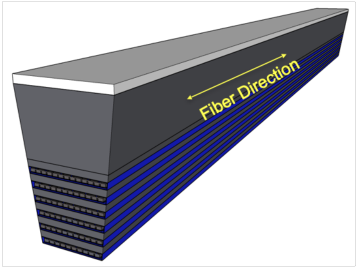
- 6 **tracking** layers
  - AstroPix sensor arrays
  - 3D shower profile & position resolution
- Detector layer design similar to **JLab Hall D BCAL**, but tracker layers make this a **unique instrument**





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EIC Specifications

Main BIC Tasks:

- **Detection** (position, momentum, energy)
- **Particle identification**, specifically $e^{\pm}/\pi^{\pm}$ and $\gamma/\pi^{0} \to \gamma\gamma$ separation

R. Abdul Khalek et al., Nucl. Phys. A **1026** (2022)
M. Zurek, The Imaging Barrel Electromagnetic Calorimeter, in *ePIC Collaboration Meeting* (2023)

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To accomplish these tasks for EIC, BIC should:

- **have energy resolution of** $(7-10)\%/\sqrt{E} \oplus (1-3)\%$
- identify pions suppressed up to 10^4 at momenta as low as 4 GeV/c
- have spatial resolution to distinguish π^0 decay products up to 10–15 GeV/c
- detect particles in energy range 0.1–10 GeV
- fit within geometric constraints of detector system

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This work: detector layer energy resolution analysis

R. Abdul Khalek et al., Nucl. Phys. A **1026** (2022)
M. Zurek, The Imaging Barrel Electromagnetic Calorimeter, in *ePIC Collaboration Meeting* (2023)

Experimental Goals

Hall D BCAL Detector:

- Energy resolution of $5.2\%/\sqrt{E} \oplus 3.6\%$ at $E_\gamma < 2.5$ GeV

M. Zurek, The Imaging Barrel Electromagnetic Calorimeter, in *ePIC Collaboration Meeting* (2023)
Beattie et al., Nucl. Instrum. Meth. A, **896** (2018)
Leverington et al., Nucl. Instrum. Meth. A, **596** (2008)

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Hall D BCAL Detector:

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This work: Using miniature barrel calorimeter segment (BBCAL) to investigate energy resolution at e^- energies comparable to EIC

M. Zurek, The Imaging Barrel Electromagnetic Calorimeter, in *ePIC Collaboration Meeting* (2023)
Beattie et al., Nucl. Instrum. Meth. A, **896** (2018)
Leverington et al., Nucl. Instrum. Meth. A, **596** (2008)
Baby BCAL at JLab, in GlueX Wiki (2024)

Experimental Setup

Ran at various biases and tilts using **Jefferson Lab Hall D** beam line for 12 days in March 2023.

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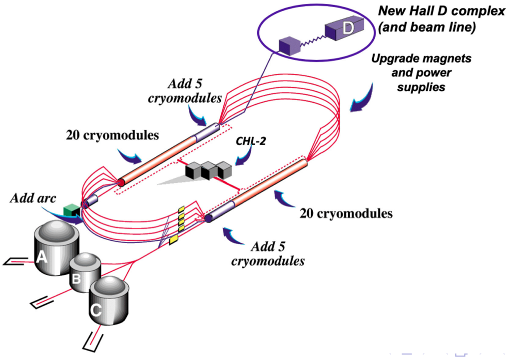
1. Continuous Electron Beam Accelerator Facility (CEBAF)

- "Racetrack" accelerator
- Accelerates e^- to $\approx$ 12 GeV thorough 5.5 passes



S. Adhikari et al., Nucl. Instr. and Meth. A **987** (2021)

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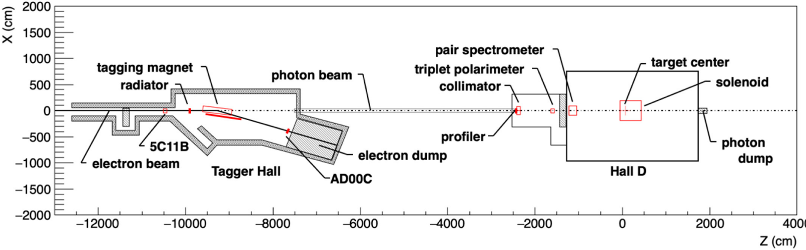
2. Hall D Beamline

- e^- beam $\rightarrow$ linearly polarized γ beam $\rightarrow$ γ beam & e^-e^+ pairs
- Applied **B** field: e^+e^- beams bend into PS



S. Adhikari et al., Nucl. Instr. and Meth. A **987** (2021)

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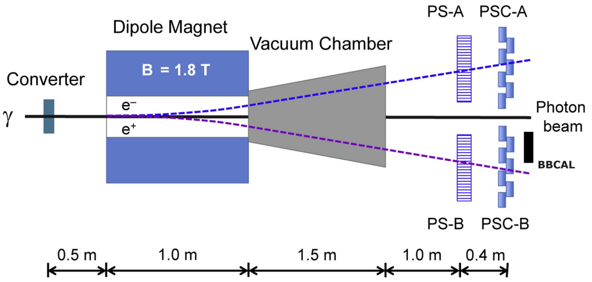
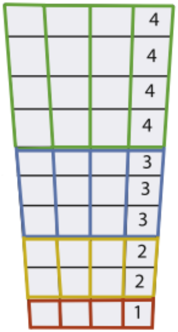
3. BBCAL Setup

- 16 North and 16 South channels in 4 layers
- Channels connected to fADCs, measure detector read-out





F. Barbosa et al., Nucl. Instr. and Meth. A **795** (2015) T. D. Beattie et al., Nucl. Instr. and Meth. A **896** (2018)

Gain Calibrations

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Converting **fADC channels** to **energy** requires **calibration**

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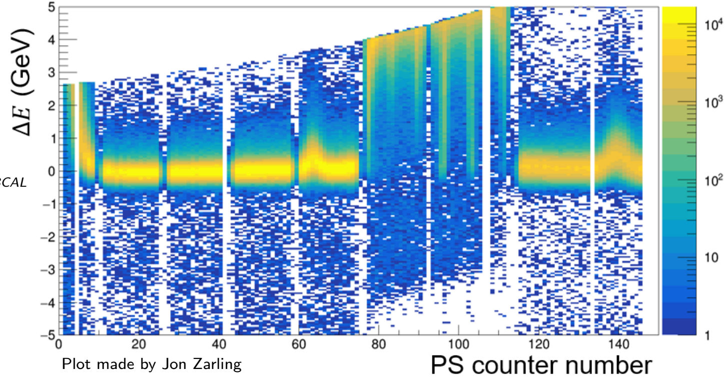
3) Calculate **fine-grain** (energy-dependent) calibrations for channels 1, 2, 5, 6, 7, 9, 10, 11, 13, 14, 15

Event Selection

- **PS counter number range**

$\Delta E =$
$E_{PS} - E_{BBCAL}$



Plot made by Jon Zarling

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  - Visible leakage
  - Unexpected behaviour

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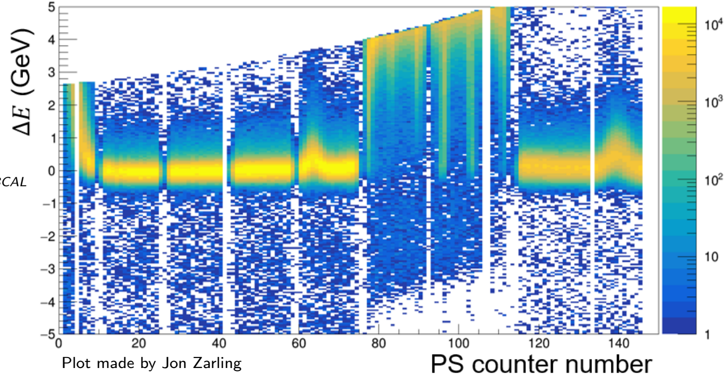

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Event Selection

- **PS counter number range**
  - SciGlass blocking
  - Visible leakage
  - Unexpected behaviour
- **Minimum energy** requirement to remove noise

$\Delta E =$
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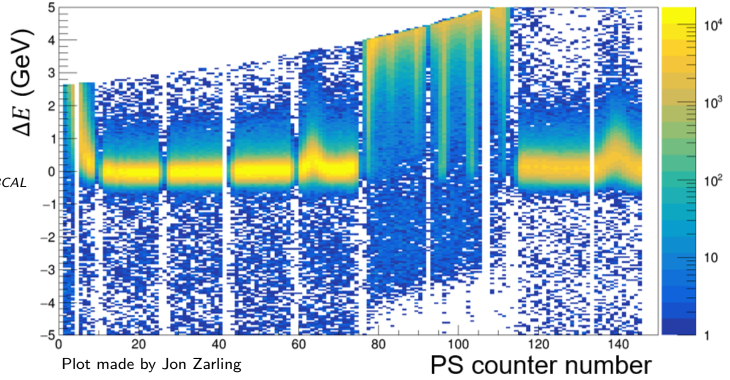

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Quality and Slow Checks

Testing data **reliability** and **consistency over time**

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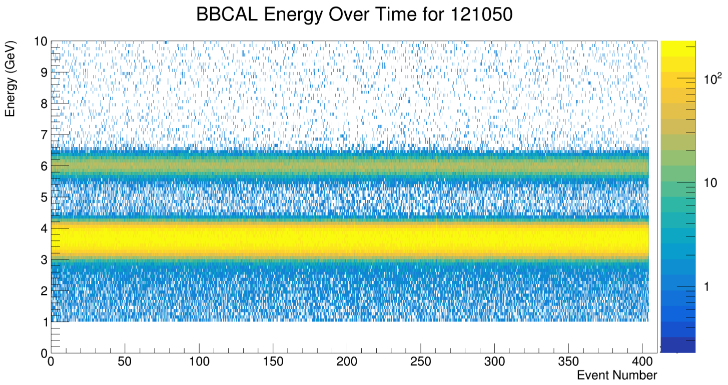
BBCAL E versus Time (Event #)

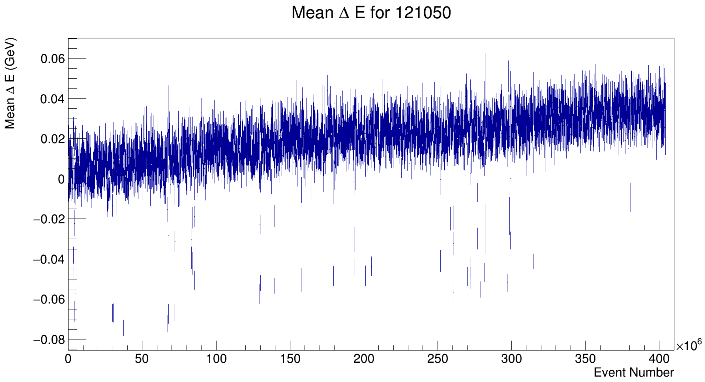


Quality and Slow Checks

Testing data **reliability** and **consistency over time**

Mean $\Delta E = E_{PS} - E_{BBCAL}$ versus Time

- Slow time dependence (negligible)



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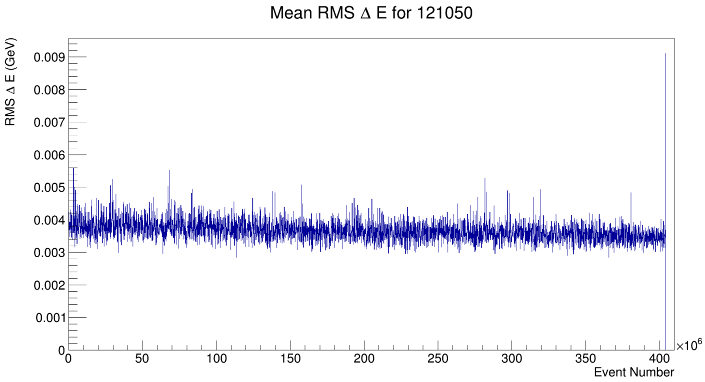
Mean RMS $\Delta E = E_{PS} - E_{BBCAL}$ versus Time

- Spike consequence of ending run



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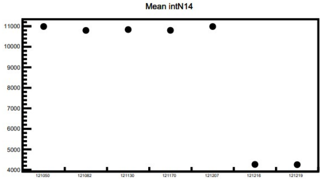
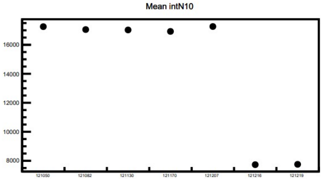
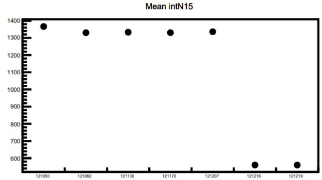
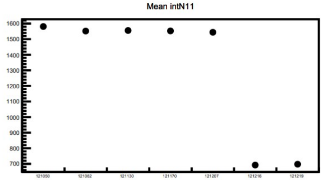
Slow Time Checks

- No evidence of radiation, longer-scale time damage







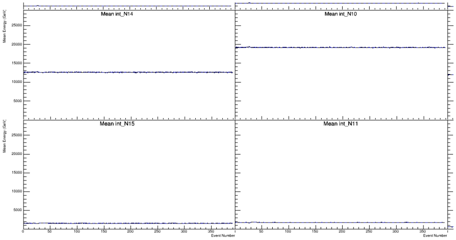


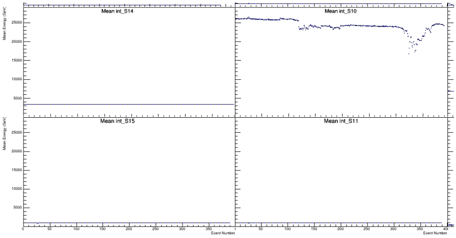
Quality and Slow Checks

Testing data **reliability** and **consistency over time**

S10 Channel

- Too noisy for analysis in later runs (> 121051)
- Can zero and redistribute N10 energy
- ... but accounts for $\sim 40\%$ of total energy deposited





Energy Resolution

EM Calorimeter Energy Resolution

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- $b \rightarrow$ **floor** term
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- a → **stochastic** term
  - fluctuations in shower process rates
- b → **floor** term
  - systematic, equipment uncertainties
- c → **noise** term
  - electronic noise, signal readout uncertainties
  - negligible for BBCAL/BIC

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- $a \rightarrow$ **stochastic** term
  - fluctuations in shower process rates
- $b \rightarrow$ **floor** term
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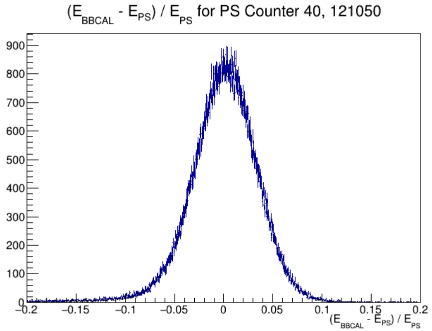
Energy Resolution Extraction

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

1) Plot $\frac{E_{BBCAL} - E_{PS}}{E_{PS}}$ for acceptable PS counter numbers
→ each counter yields data for an energy value

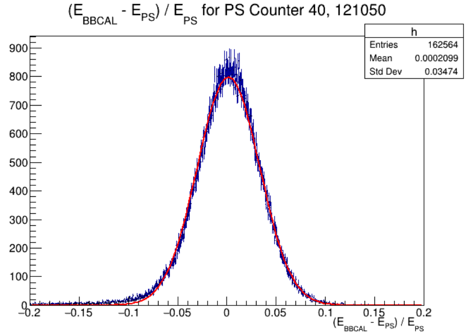


Energy Resolution Extraction

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

2) Fit with Gaussian function, extract standard deviation:

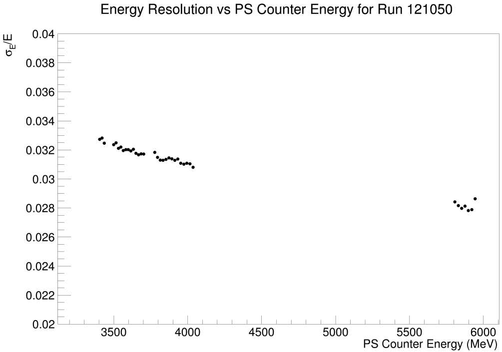
$$\text{std dev}\left(\frac{E_{PS} - E_{BBCAL}}{E_{PS}}\right)\Bigg|_{PS=i} = \frac{\sigma_E}{E}\Bigg|_{PS=i}$$



Energy Resolution Extraction

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

3) Plot $\frac{\sigma_E}{E}$ terms from Gaussian fits as a function of their mean PS counter energy



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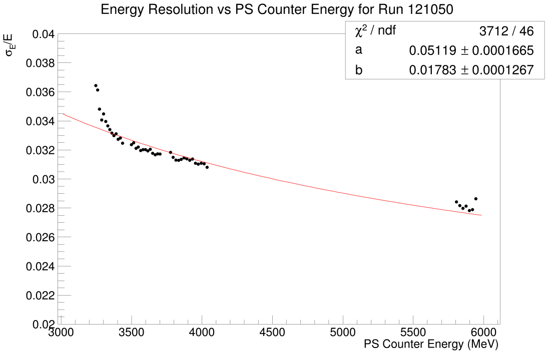
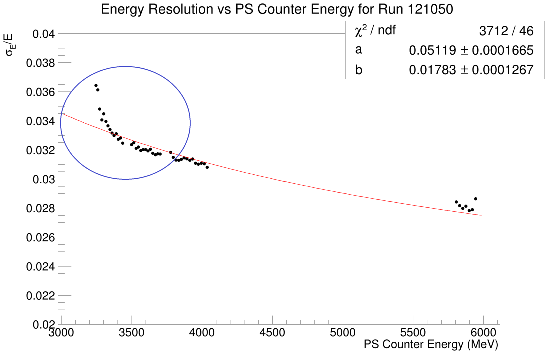
4) Fit with energy resolution function



Energy Resolution Extraction

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

4) Fit with energy resolution function
$\rightarrow$ issues, especially in **low energy range** (< 3400 MeV)



Energy Leakage

- **Lower energy** $\frac{\sigma_E}{E}$ modeled **poorly** across all runs

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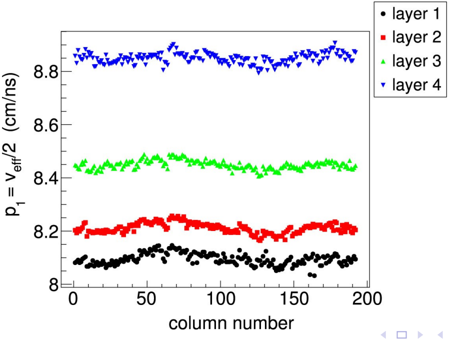
1) **Reconstructed Hit Position**

- $x = \frac{d}{2} - v_l \Delta t$

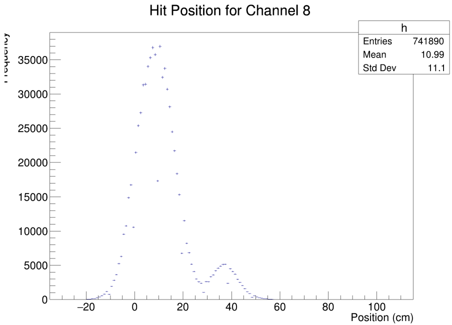


Energy Leakage

- **Lower energy** $\frac{\sigma_E}{E}$ modeled **poorly** across all runs
- Potential **energy leakage** out the BBCAL

1) Reconstructed Hit Position

- $x = \frac{d}{2} - v_l \Delta t$
- *Should* be between 0 and 58 cm → otherwise implies energy leakage

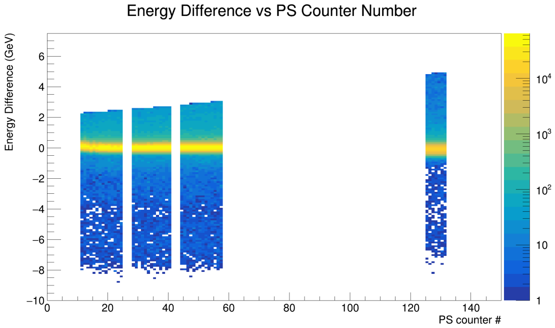


Energy Leakage

- **Lower energy** $\frac{\sigma_E}{E}$ modeled **poorly** across all runs
- Potential **energy leakage** out the BBCAL

2) **Energy Difference**

- Identifies leakage at specific PS counters (energies)
- Low energies display leakage



Energy Leakage

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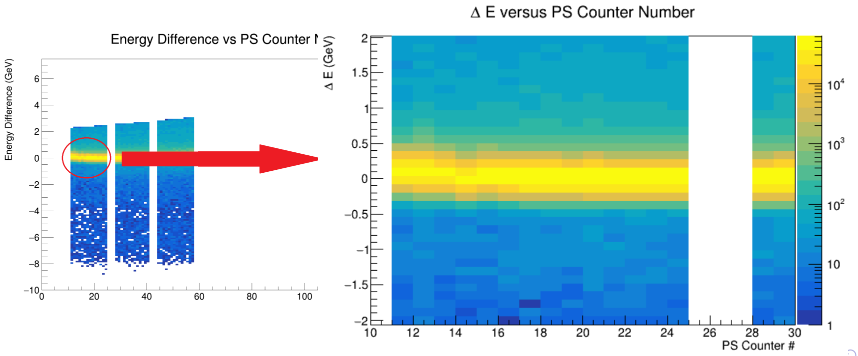


Energy Leakage Modifications

Updated PS counter number ranges to **exclude** counters corresponding with **energies displaying leakage**

Runs	Old PS Counter Numbers	Modified PS Counter Numbers
121050–121186	**11**–24, 28–40, 44–57, 125–131	**22**–24, 28–40, 44–57, 125–131
121197–121206	**11**-24, 28–40, 61–73, 78–83	**22**–24, 28–40, 44–57, 125–13
121216–121223	**11-24**, 35–40, 61–73, 78–83	**35–40**, 61–73, 78–83

Energy Resolution Results

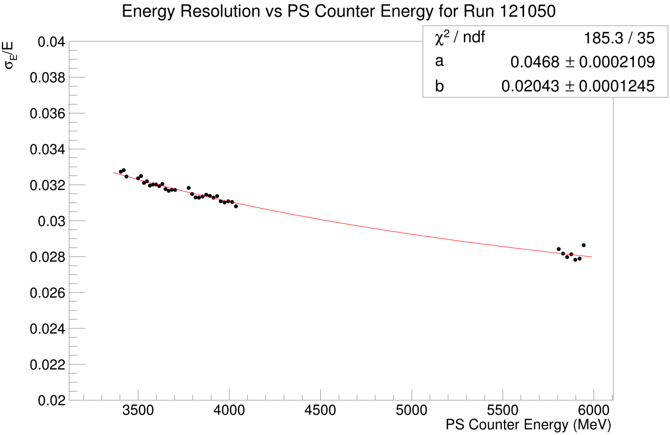
Overall Summary

Run #	$a \pm \delta a$ (%)	$b \pm \delta b$ (%)
121050	4.68 ± 0.02	2.04 ± 0.01
121051	4.66 ± 0.02	2.05 ± 0.01
121128	4.42 ± 0.02	2.28 ± 0.01
121129	4.27 ± 0.03	2.35 ± 0.01
121185	4.34 ± 0.02	2.34 ± 0.01
121186	4.24 ± 0.03	2.38 ± 0.01
121197	4.64 ± 0.03	2.10 ± 0.01
121199	4.72 ± 0.03	2.05 ± 0.01
121200	4.72 ± 0.03	2.05 ± 0.01
121201	4.66 ± 0.03	2.09 ± 0.01
121204	4.56 ± 0.03	2.14 ± 0.01
121206	4.72 ± 0.03	2.06 ± 0.01
121216–121219	5.71 ± 0.01	0.00 ± 4.65
121221–121223	5.43 ± 0.00	0.8 ± 0.3

Energy Resolution Results

Runs 121050–121051

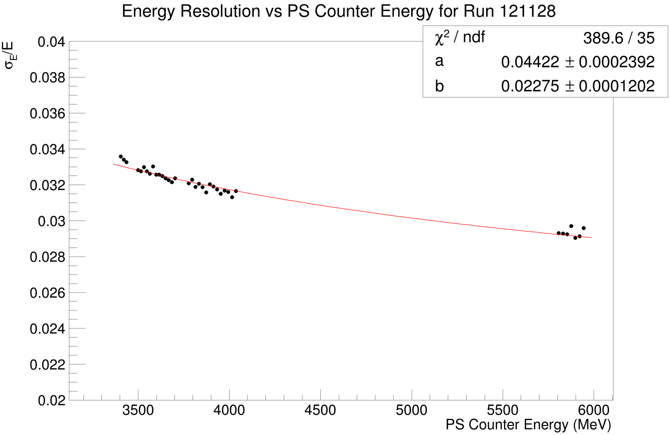
- S10 on



Energy Resolution Results

Runs 121128–121186

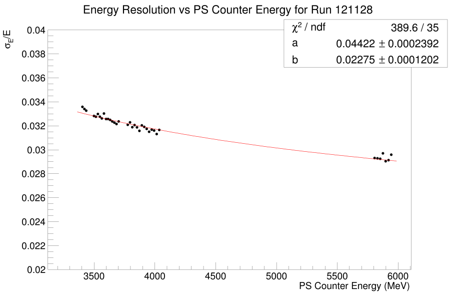
- S10 off
- Lower *a*, higher *b*

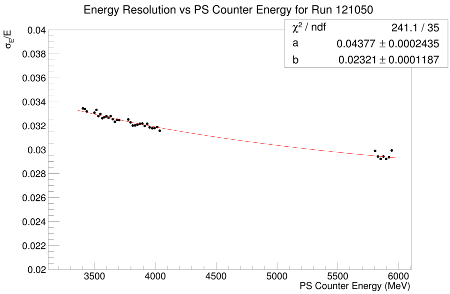


Energy Resolution Results

Runs 121128–121186

- S10 off
- Lower a, higher b $\rightarrow$ compare to 121050 with S10 off

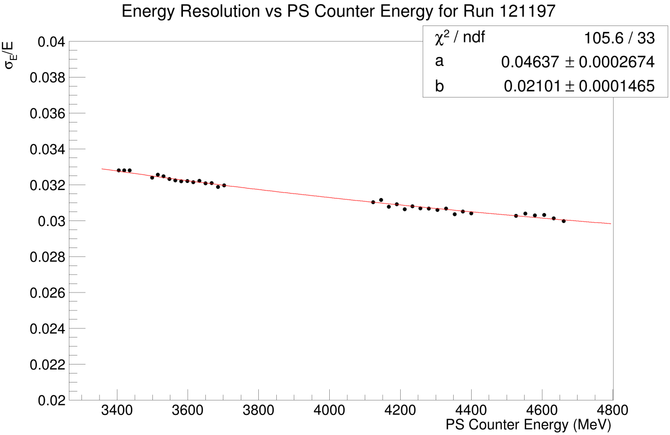




Energy Resolution Results

Runs 121197–121206

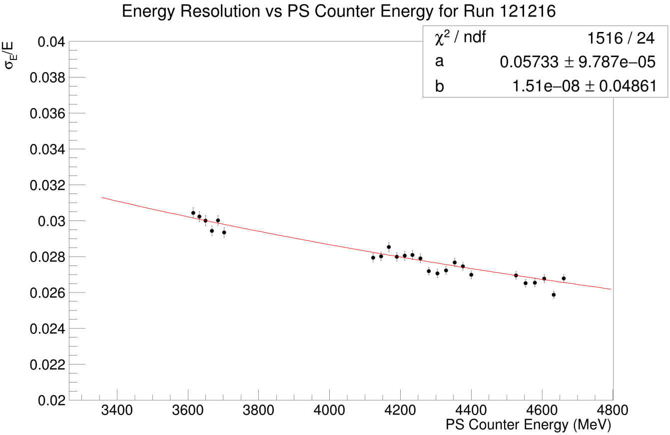
- S10 off
- *a*, *b* $\sim$ to 121050



Energy Resolution Results

Runs 121216–121223

- S10 off, rotated BBCAL
- Lower statistics



Energy Resolution Results

- Conservative energy resolution range of

$$\frac{\sigma_E}{E} = \frac{(4.2 - 4.7)\%}{\sqrt{E}} \oplus (2.0 - 2.4)\%$$

- Omitting S10 effects, $a = (4.6 - 4.7)\%$ & $b = (2.0 - 2.1)\%$
- **Improvement** on b term compared to JLab's BCAL results

$$\frac{\sigma_E}{E} = \frac{5.2\%}{\sqrt{E}} \oplus 3.6\%$$

- a less than EIC specs, b in EIC specs range $\rightarrow$ **higher energies resolve as expected!**

T. D. Beattie et al., Nucl. Instr. and Meth. A **896** (2018)

Conclusions

Conclusions

- BBCAL is effective and calibrated for future R&D (Argonne National Laboratory) $\rightarrow$ energy leakage and rotation important considerations

- BBCAL energy resolution meets and exceeds EIC requirements, although statistical precision (# of events) stronger than systematic precision (understanding of equipment's functionality)

Thank you, questions?