Calorimetry with the ePIC Project

And Canadian Contributions to the EIC Effort

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15th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei

Paphos, Cyprus

October 31, 2023

MountAllison UNIVERSITY

University of Regina

NSERC CRSNG

Mount Allison University

New Brunswick

Population: 840,000
Area: 72,908 km²

English and French

Lobster, Lumber, and High Tides

Mount Allison University

- 2,250 students
- Undergrads only

Bay of Fundy

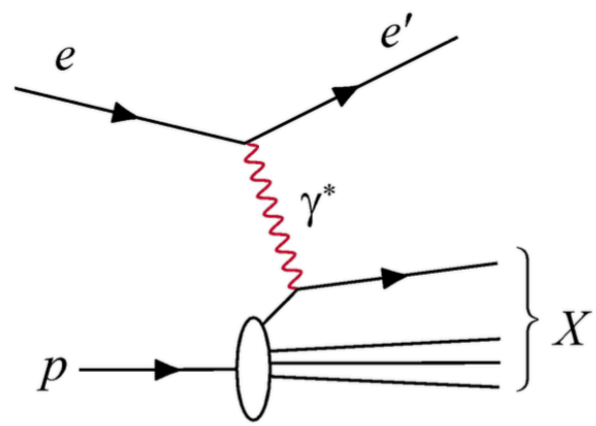
Highest tides in the world — 16 m!

$$\tau \approx 12.5 - 12.7 \text{ h}$$
Bay

$$N_2 \approx 12.66 \text{ h}$$
Moon

DIS: Accessing Quarks in Electron-Ion Collisions

Key variables x and Q^2 in DIS along with η



Four-momentum transfer of the virtual photon

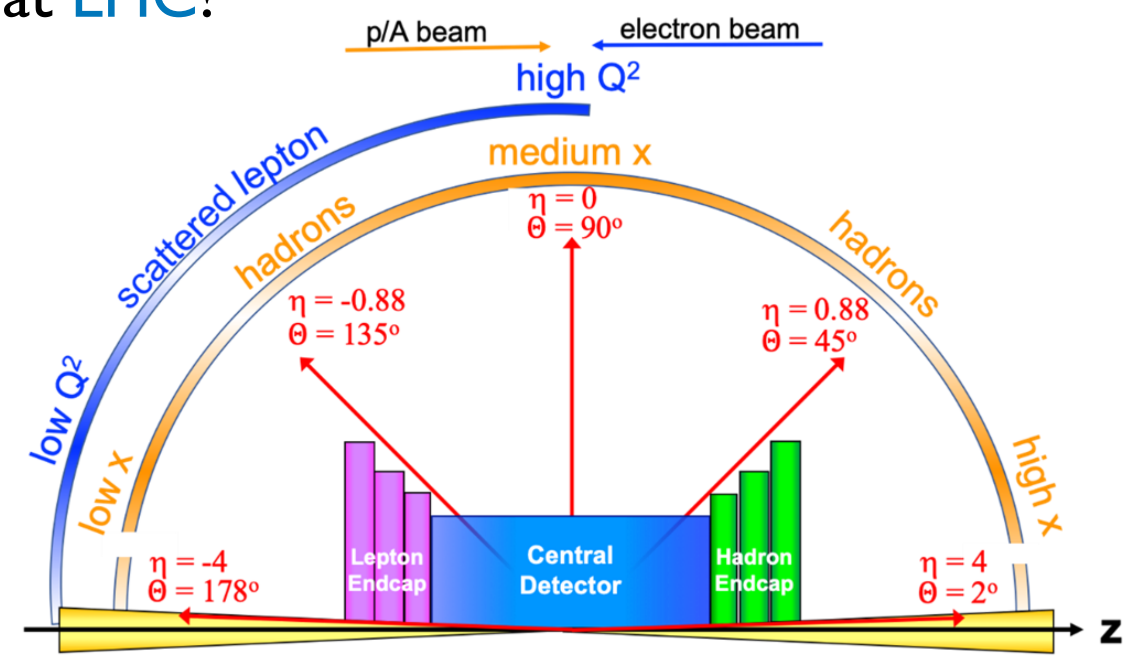
$$Q^2 = -q^2 = -(k - k')^2$$ resolution of probe

Momentum fraction of struck quark $x = \dfrac{Q^2}{2M\nu}$

Pseudo rapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Asymmetric reaction unlike pp at LHC!



Electrons in backward direction

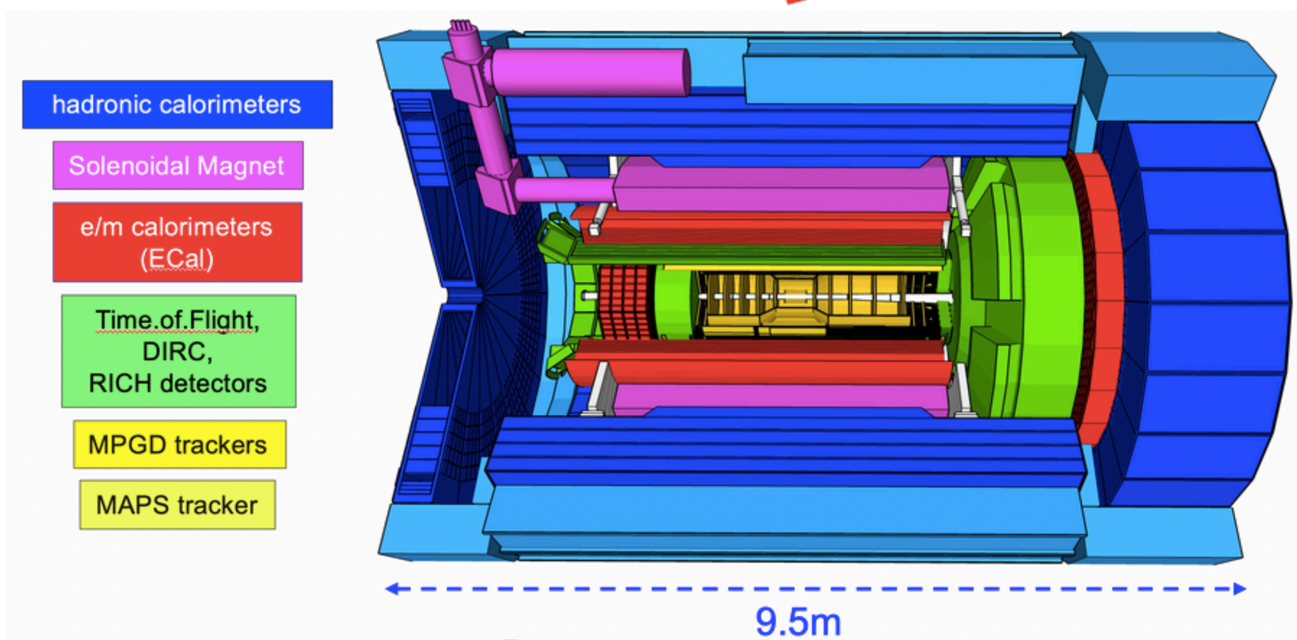
Hadrons go in every direction

ePIC Detector for the EIC

ECCE + ATHENA = ePIC

Lepton Endcap

Hadron Endcap



p/A Beam

e^- Beam

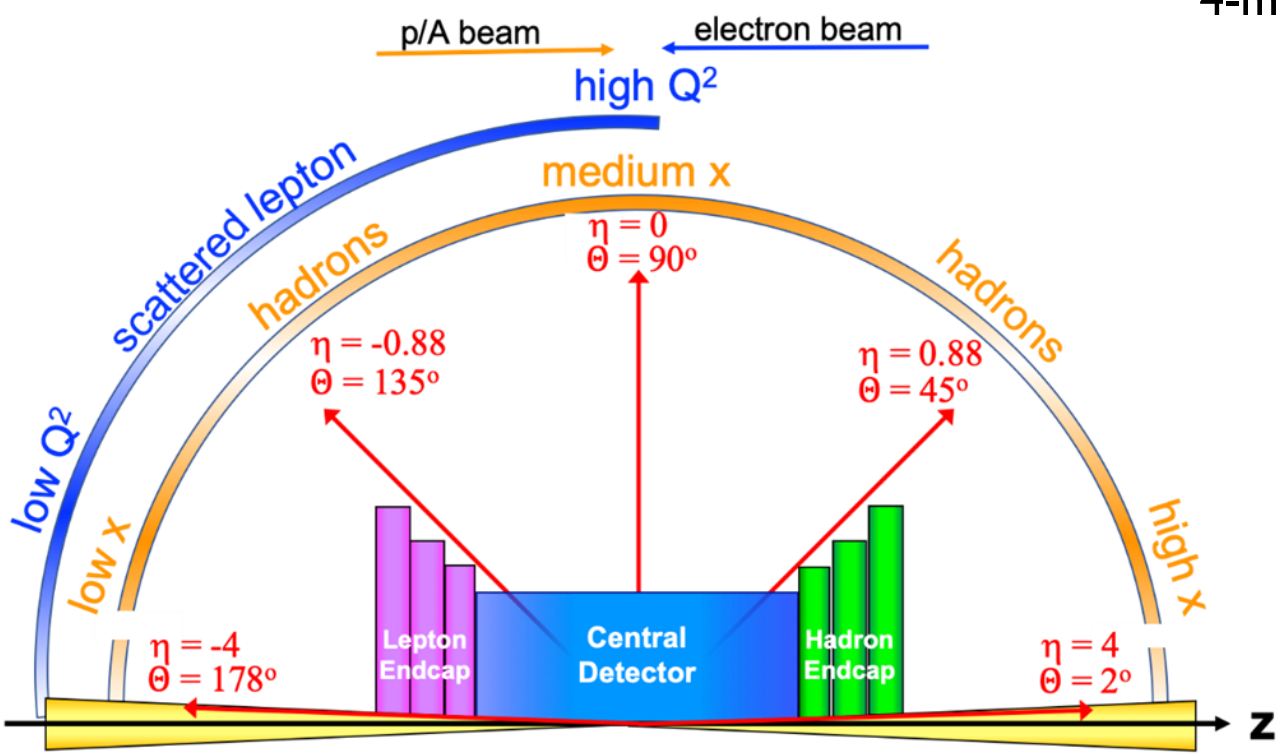
Calorimetry for the ePIC Detector

Electromagnetic calorimeter:

- Measure E, θ for photons and identify electrons.
- Backward: $PbWO_4$ Crystals
- Forward: W/SciFi
- Barrel: Pb/SciFi + Imaging

Hadronic calorimeter:

- Measure energy and position of charged hadrons, neutrons, and K_L^0
- Main challenge is resolution for low-E hadrons
- Fe/Scintillator sandwich with longitudinal segmentation



4-mom transfer of virtual photon

$$Q^2 = -q^2 = -(k - k')^2$$

Momentum fraction

$$x = \frac{Q^2}{2M\nu}$$

Pseudo rapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Note: The Barrel has a very wide kinematic coverage!

Hadronic Calorimetry

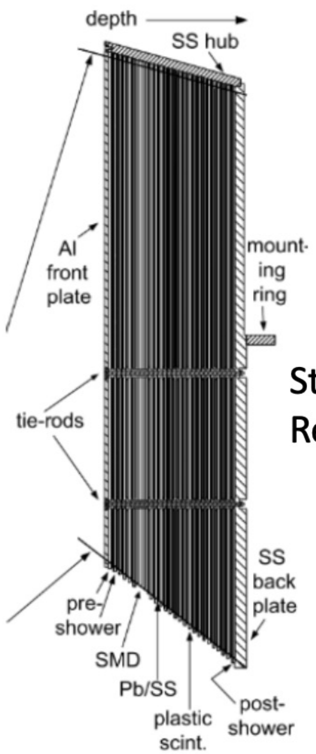
Backward (electron) Endcap
Barrel
Forward (hadron) Endcap
Forward Insert

Barrel HCal

sPHENIX barrel calorimeter with new SiPMs

Upgrade electronics

Electron Endcap HCal



Steel/Scint. Sandwich (10 layers)
Reuse of STAR Scint. tiles

Hadronic Calorimetry

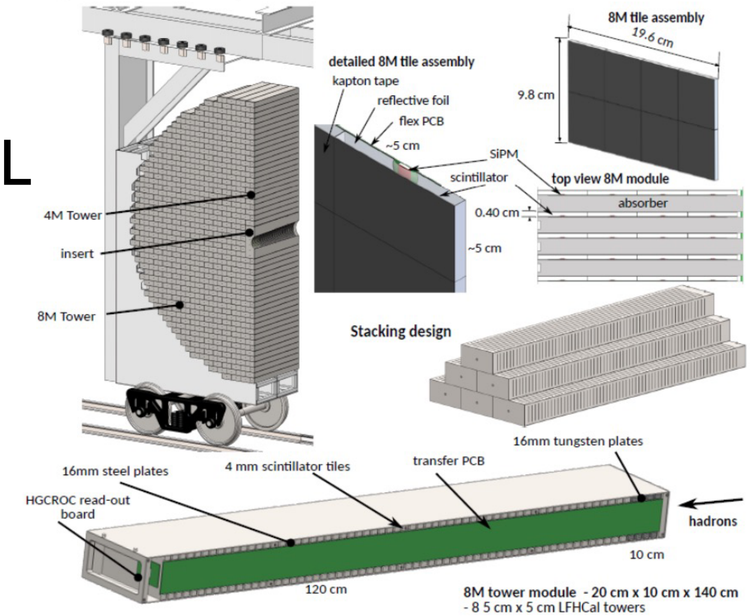
Backward (electron) Endcap
Barrel
Forward (hadron) Endcap
Forward Insert

Hadron Endcap HCal

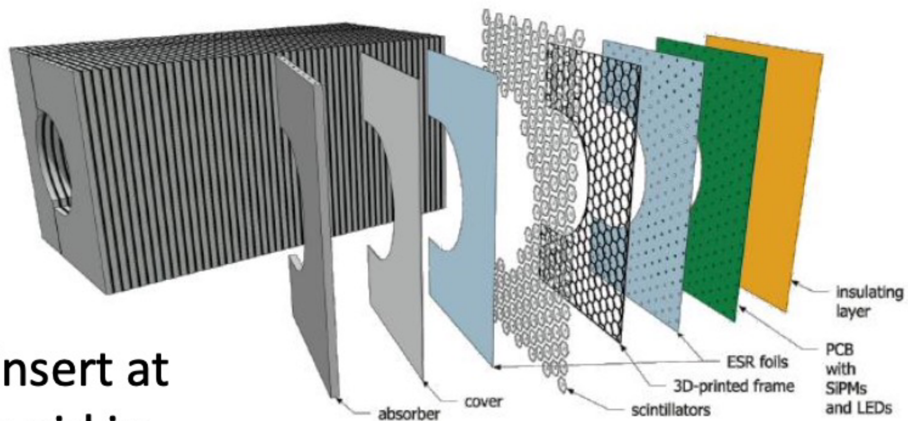
Longitudinally separated HCAL
Steel/Scint. & W/Scint. sandwich

SiPM-on-tile
readout

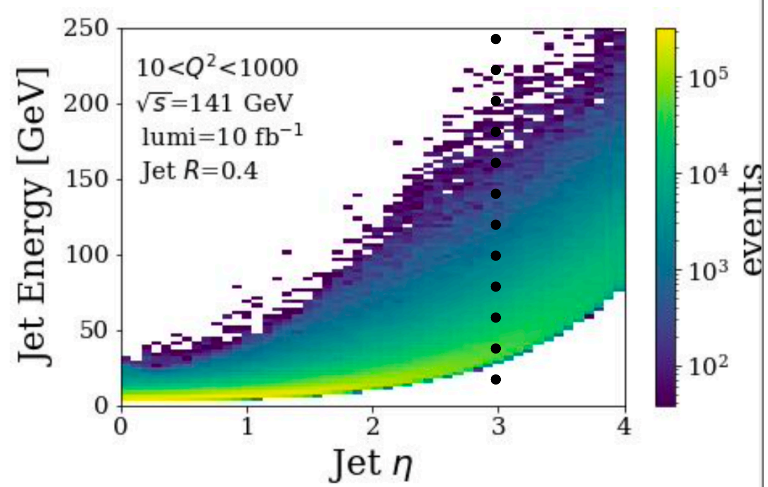
LFHCAL



Tracking degrades rapidly
at very forward angles, i.e. $3 < \eta < 4$



High-granularity insert at
most forward η to aid in
reconstruction of HFS

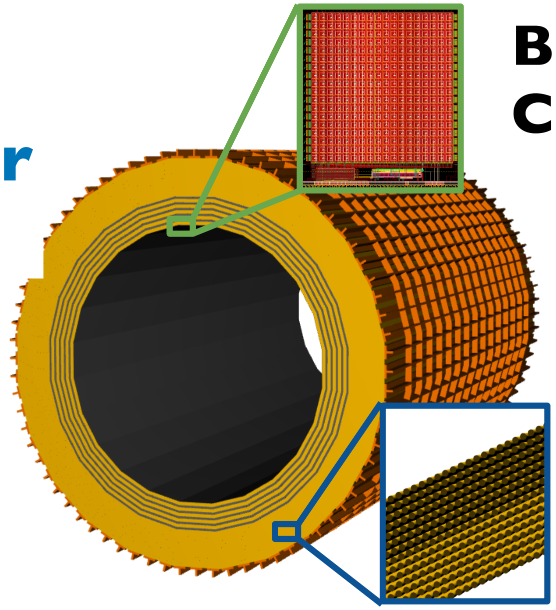


Electromagnetic Calorimetry

Backward (electron) Endcap

Barrel Imaging Calorimeter

Forward (hadron) Endcap



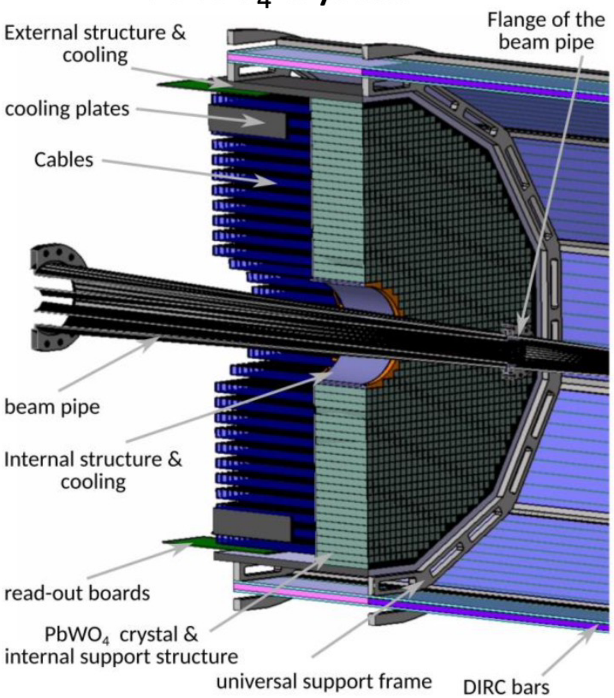
Barrel Imaging Calorimeter

Formerly known as the bECAL…

High-resolution sampling calorimeter interleaved with high-granularity silicon sensors.

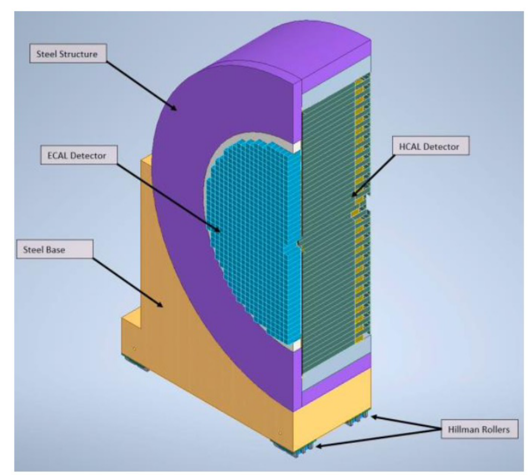
Electron Endcap EMCal

$PbWO_4$ crystals



High granularity
High rates
High resolution
Compact
Radiation hard
Good PID

Hadron Endcap EMCal

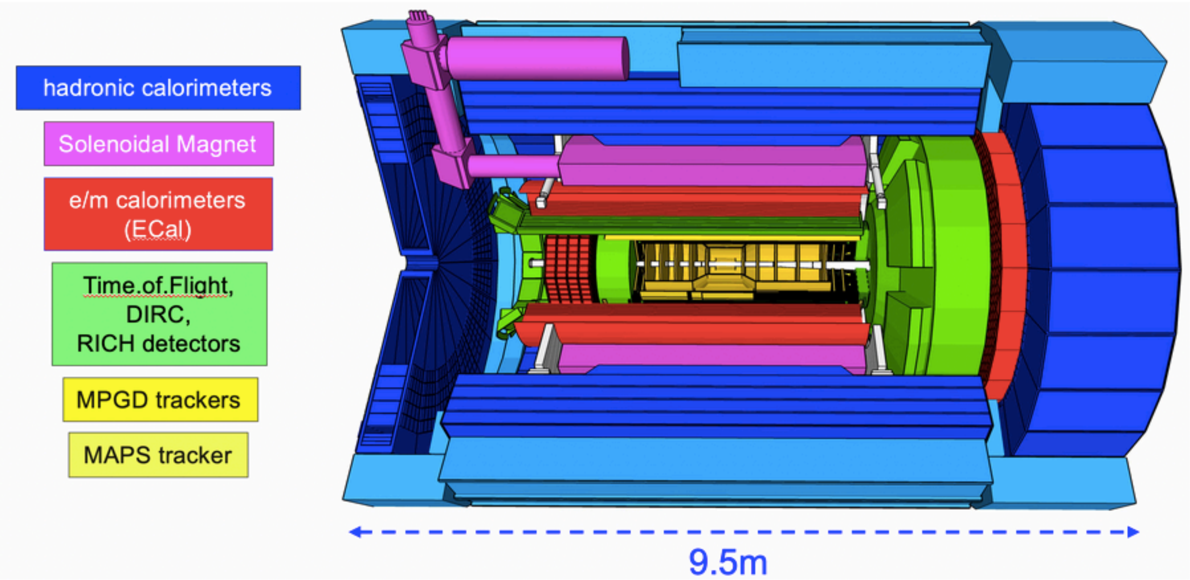


High granularity W-powder/SciFi EMCal

"Spacal" design, similar to sPHENIX barrel

Barrel Imaging Calorimeter for ePIC

- BIC Consortium
- Design Constraints
- Performance Requirements
- SciFi Technology
- SciFi Assessment



BIC Consortium

USA

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

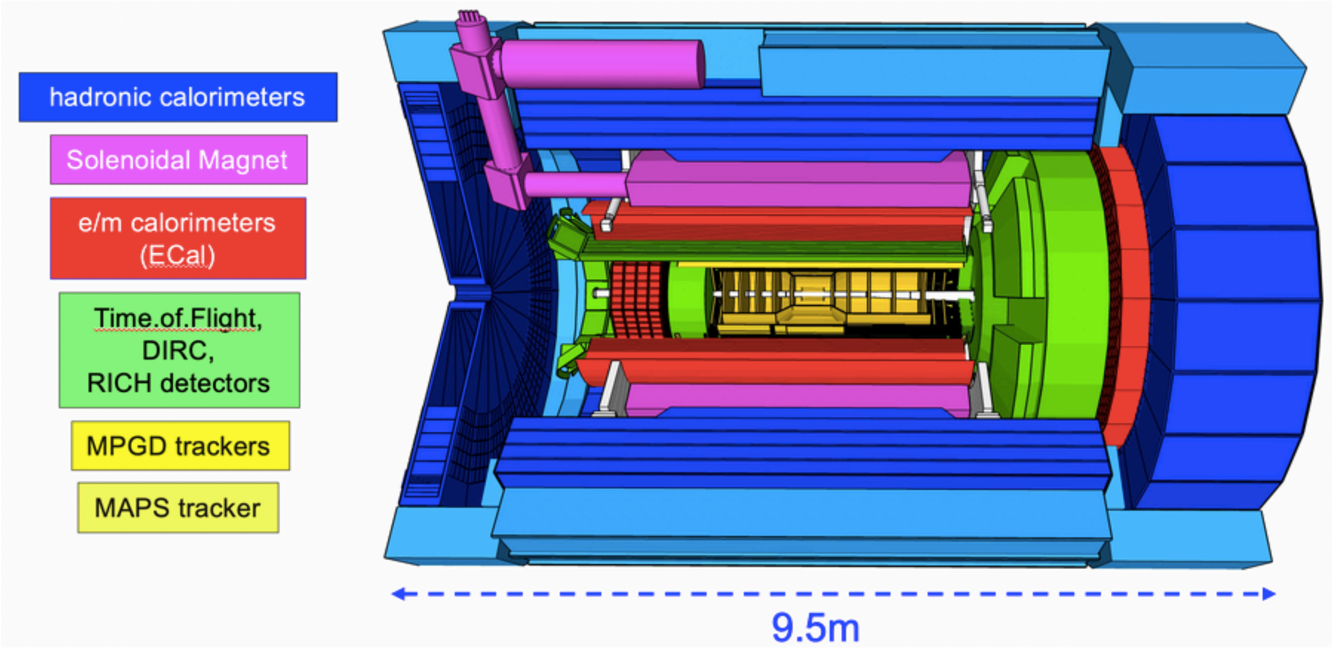
Germany

- Karlsruhe Institute of Technology
- University of Giessen

ePIC BIC Detector Subsystem Collaboration

BIC Design Constraints

- Size/Shape
- Cost
- Performance



Calorimetry Requirements for BIC

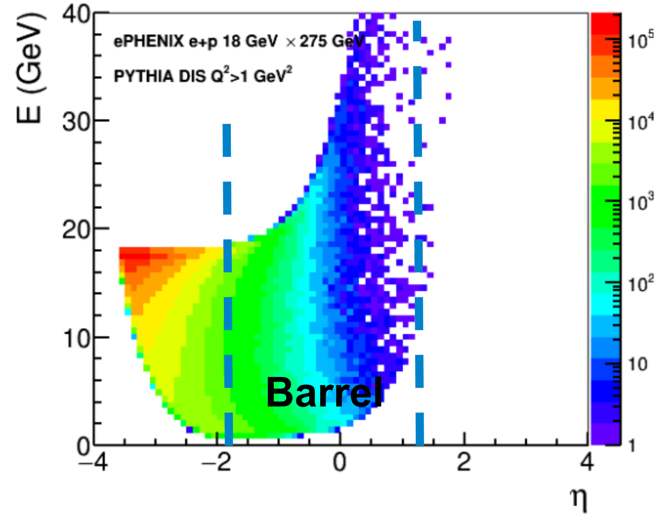
EIC Yellow Report:

- Detection of **e** and **γ** to measure **energy** and **position**
- Require **moderate energy resolution** $(7-10)\%/\sqrt{E} \oplus (1-3\%)$
- Require **e/π separation** up to **10⁴** at low momenta in combination with other detectors
- Discriminate between **π⁰ decays** and **single γs** up to **~10 GeV**
- **Low-energy photon** reconstruction **~100 MeV**

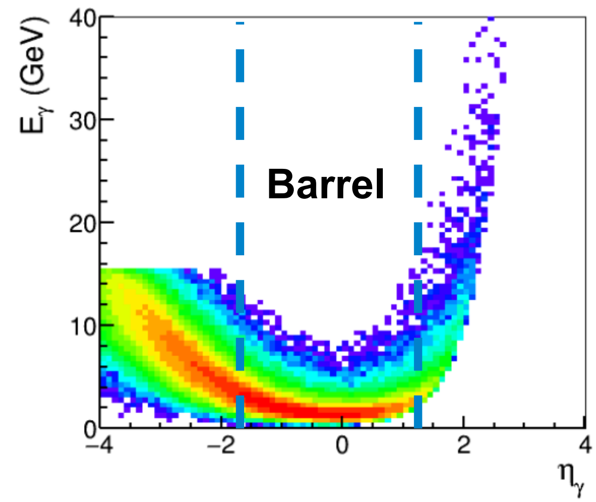
Challenges:

- **e/π** PID
- **γ/π⁰** discrimination
- Dynamic range of sensors
- Available space

DIS electrons



DVCS photons

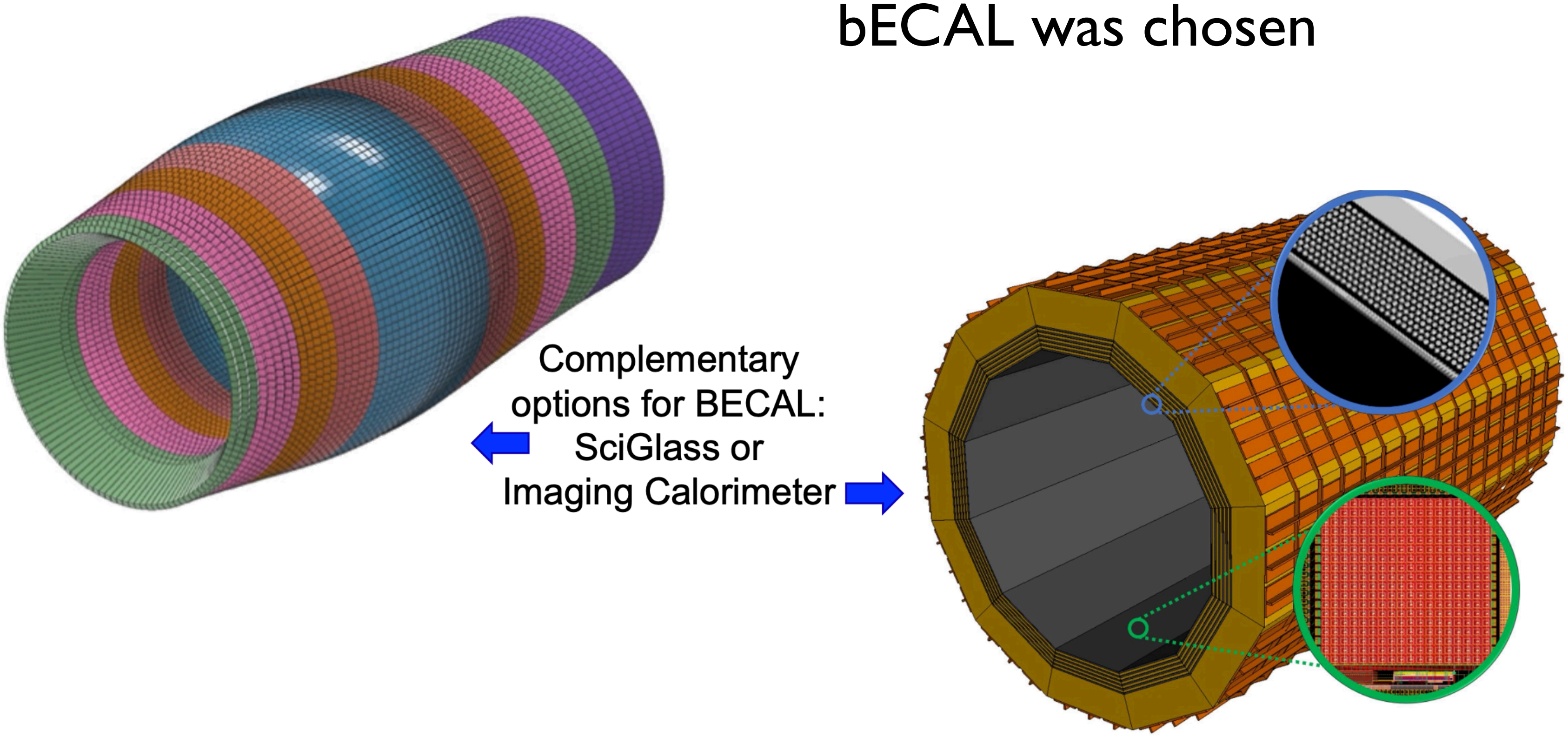


Barrel Review

2 possible options:

SciGlass or bECAL

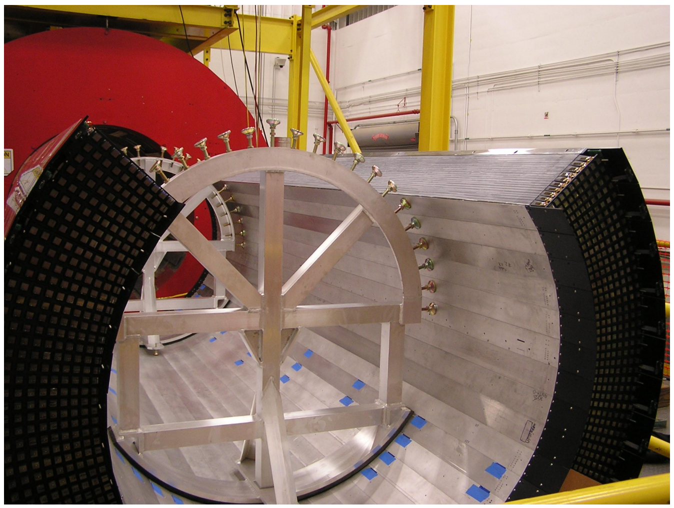
bECAL was chosen

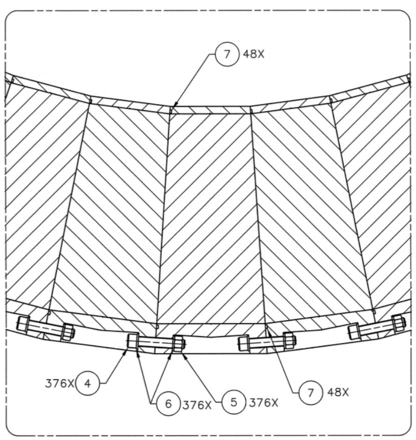


EM Barrel: ePIC vs GlueX

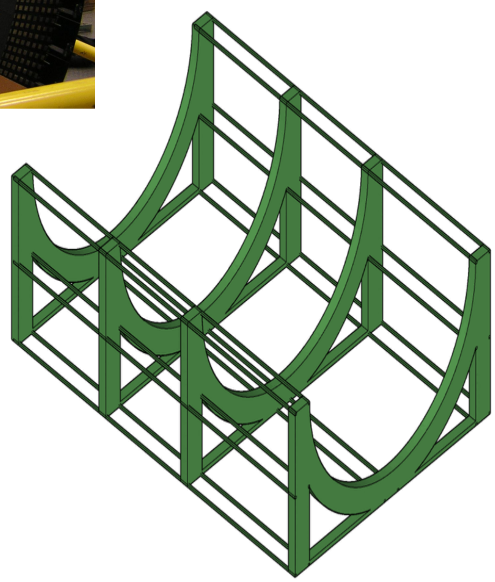
Based on GlueX design — University of Regina

GlueX self-supporting Arch





GlueX Stave Interconnections



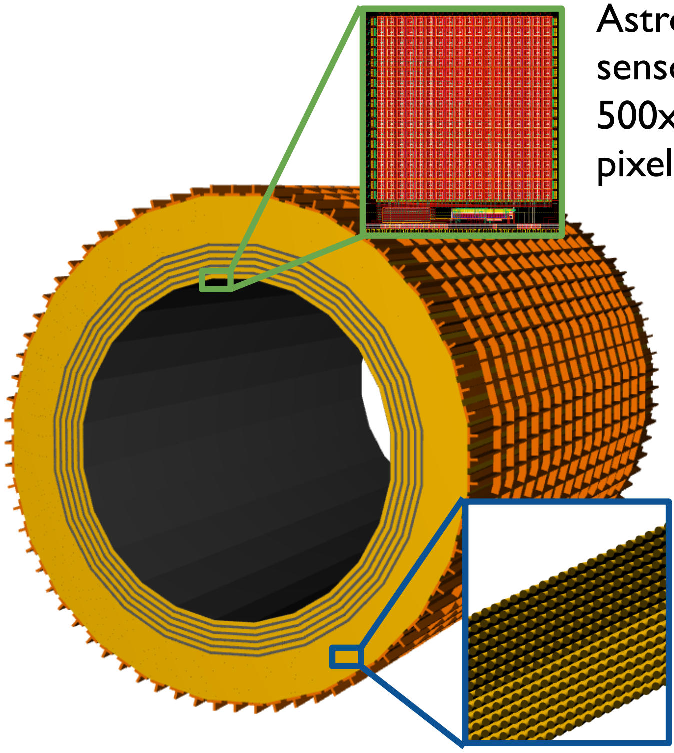
		ePIC	GlueX
Diameter (m)			
	Inner	1.62	1.3
	Outer	2.6	1.8
Length (m)		4.35	3.90
# Staves		48	48
Mass/stave (T)		1.1	0.58
Weight		36 tons	23 tons

ePIC/bECAL & GlueX/BCAL

- Pb/SciFi construction
- 4,500 km vs 3,300 km
- Hybrid vs Monolithic

BIC Performance

Hybrid imaging calorimeter
3D Shower Imaging



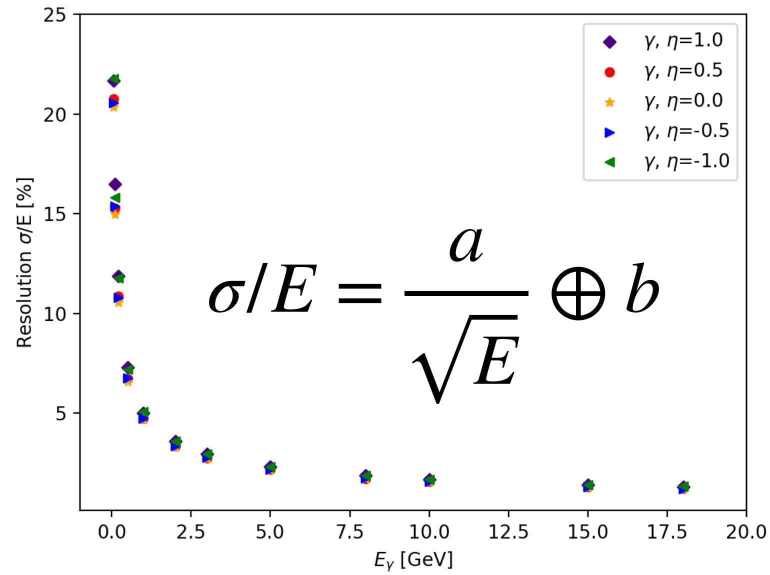
AstroPix: silicon sensor with 500x500μm[2] pixel size

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

Covers $-1.71 < \eta < 1.31$

Total radiation thickness at $\eta = 0 \approx 17X_0$

Sampling fraction $\sum E_{fibers}/E_{thrown} \approx 10\,\%$



Fit parameters

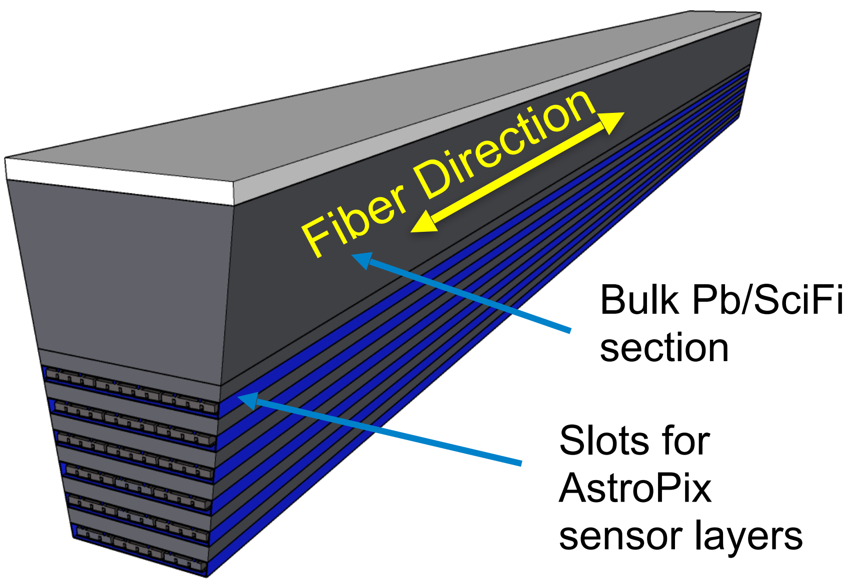
η	a [%]	b [%]
0	4.75(0.01)	1.02(0.02)

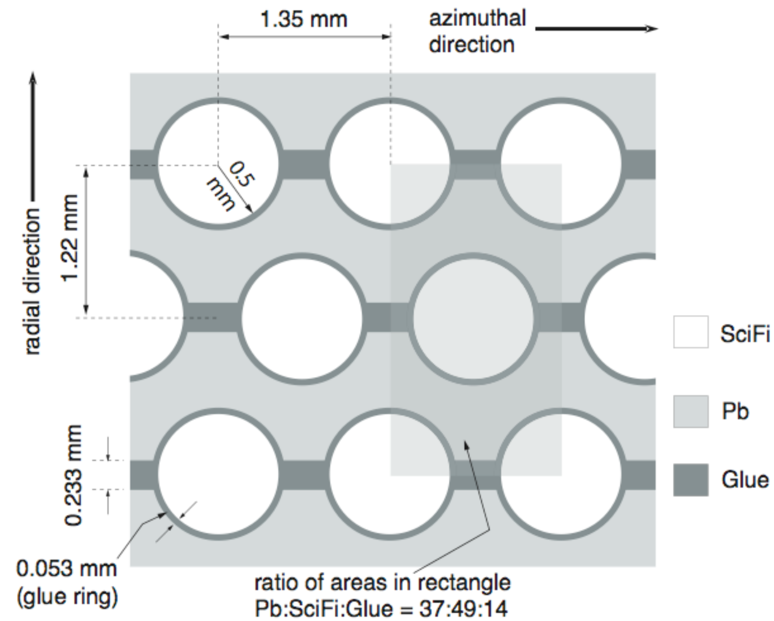
Energy resolution - Primarily from Pb/SciFi layers (+ Imaging pixels energy information)

Position resolution - Primarily from Imaging Layers (+ 2-side Pb/SciFi readout)

BIC Sector

Calorimeter Sector





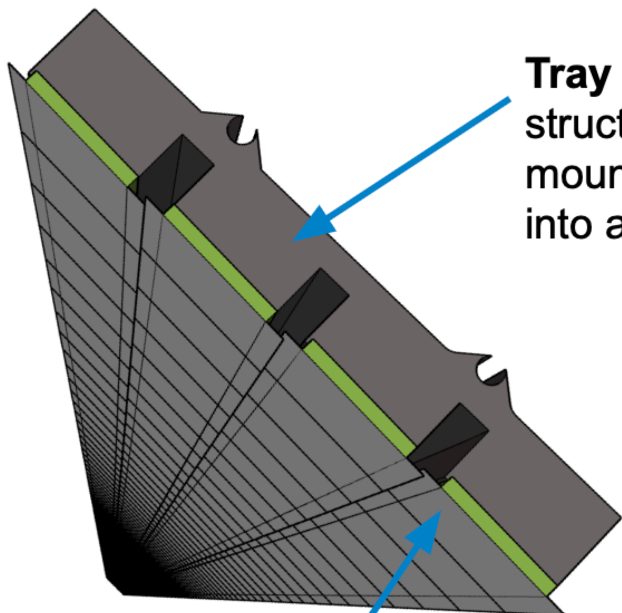
48 sectors:

Main Site

Satellite Site

- Inner: interleaved layers of imaging Si sensors with PbSciFi (SFIL- SciFi Imaging Layers)
- Outer: bulk Pb/SciFi section
- Light guides; optical cookies
- SiPMs as sensors on each end

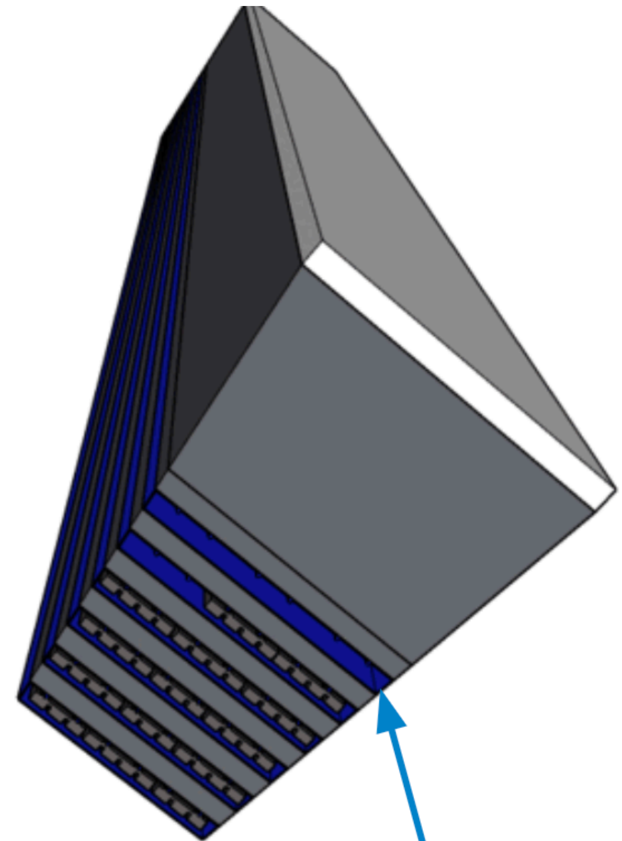
BIC Sector — Imaging Layers



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

AstroPix **Stave**
Consists of 1 x 108 chips with the support structure

AstroPix **Module**
Subset of chips that will be mounted on one stave support structure

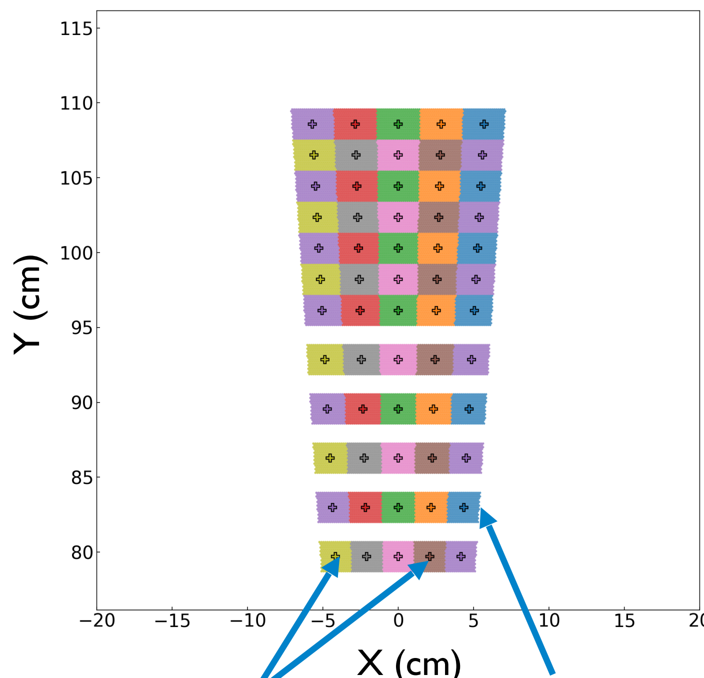


Shelf - a carbon fiber structure that is glued to the Pb/ScFi layers, that we will slide trays with AstroPix staves on.

SiPM Readout

- **2-sided SiPM readout**
- **Light guides** on 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 X_0

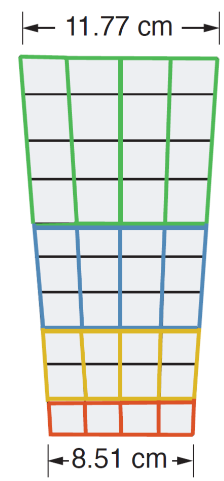


Readout **Cell**
The area 1 light guide is attached to
Layer = 5 cells

Pb/SciFi **Layer**

1 sector = 12 layers
1 layer = 17 fiber rows

GlueX Sector End View, 15.5 X_0



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

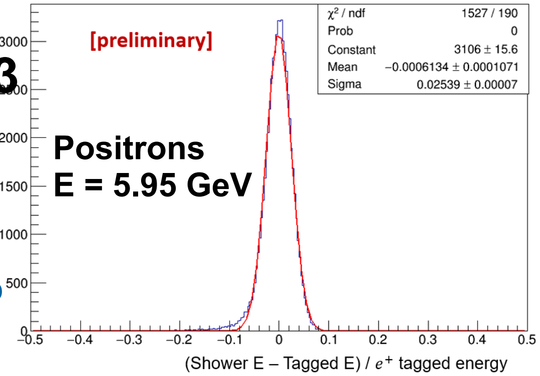
16 FADC per side
12 TDC per side

SciFi Technology

- Mature Technology: **GlueX**, KLOE EMCals
- Tested extensively for electromagnetic response in energies **E_γ < 2.5 GeV**
- **Energy resolution: σ = 5.2% /$\sqrt{E} \oplus$ 3.6%**[1)]
  - New results from Baby BCAL prototype in Hall D extend coverage to **6 GeV** and show that **constant term is < 2%**

Hall D, March 2023
Baby BCAL Test

Measured Resolution: ~ 2.5%

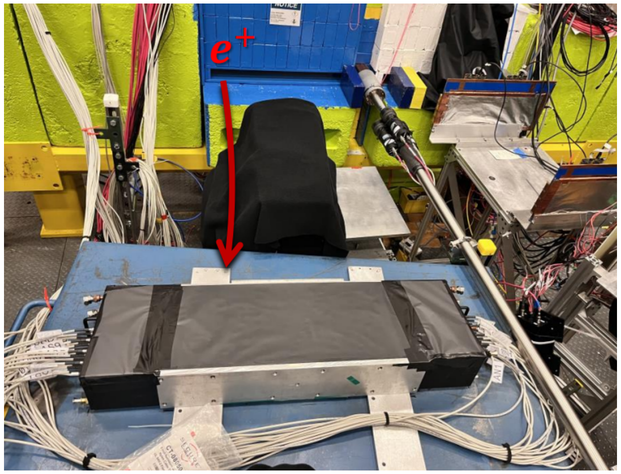


GlueX BCAL parameters

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



Baby BCAL 60 cm long, 15.5 X_0, tested with e^+, E ~3.6-6 GeV

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

Fiber Measurements

Photodiode Station

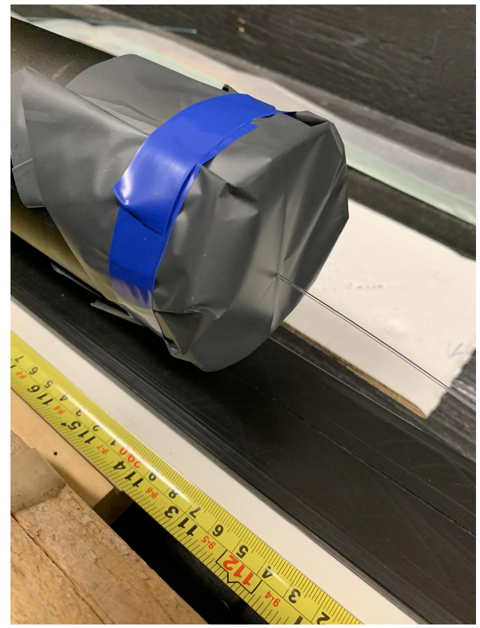
HAMAMATSU
PHOTON IS OUR BUSINESS

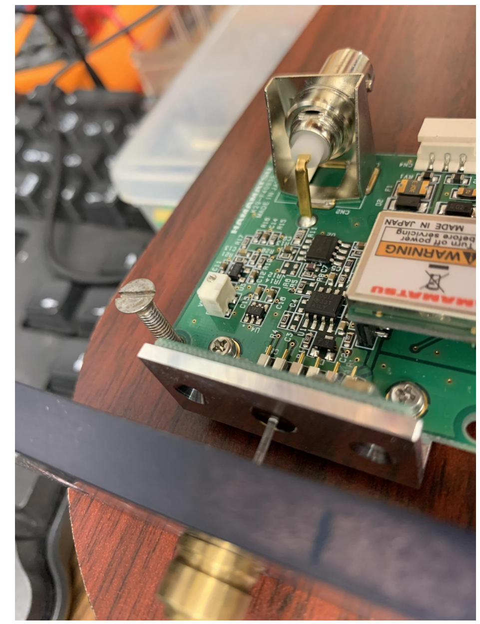
Si photodiodes

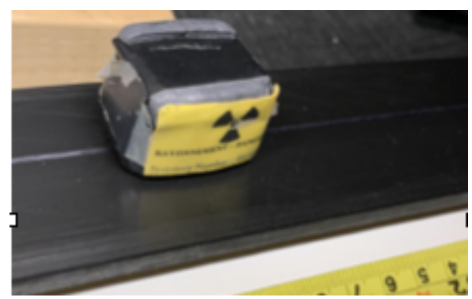
S2281 series

Si photodiodes with BNC connector

N_{pe} Station

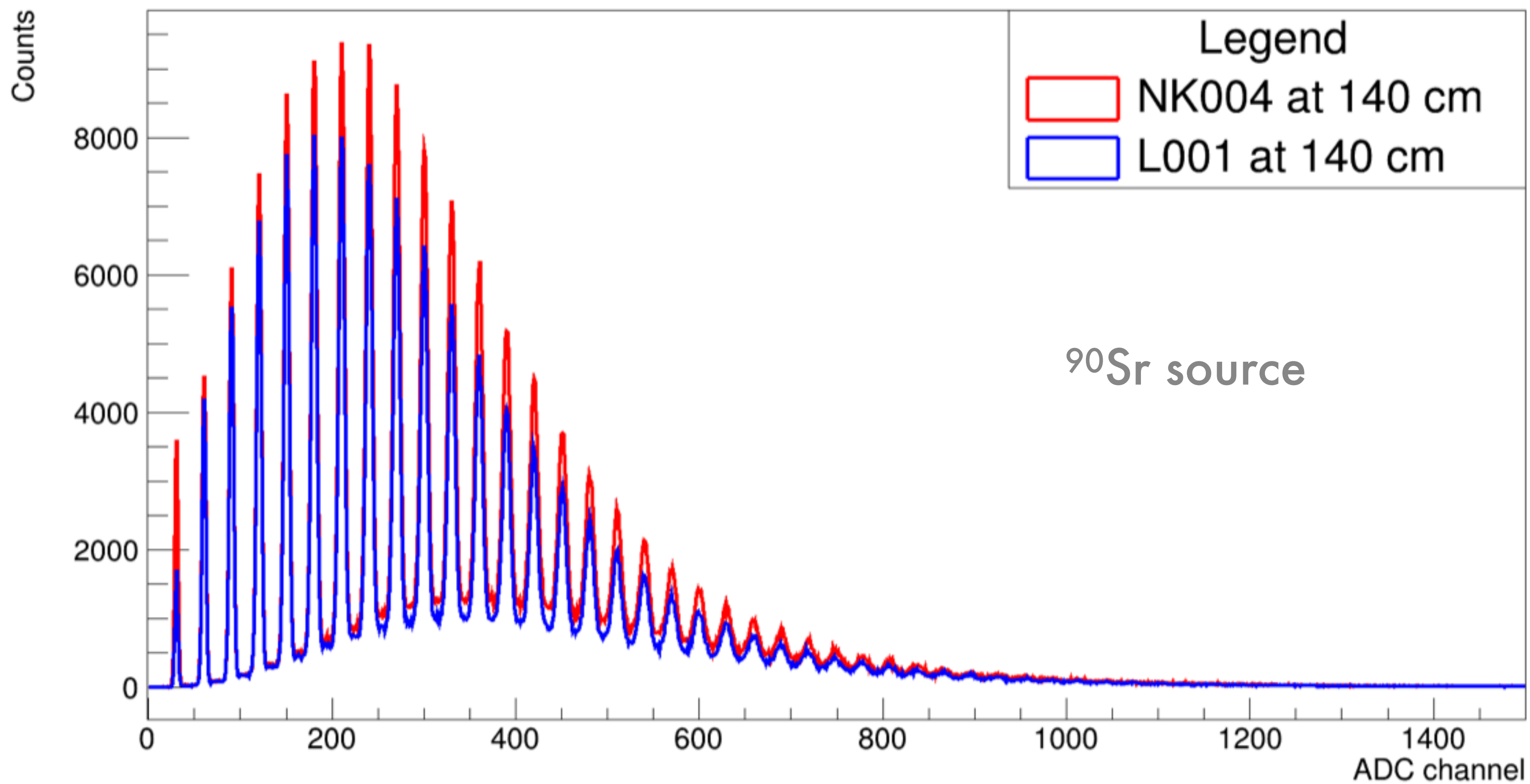






90Sr source
SiPM-PMT
coincidence

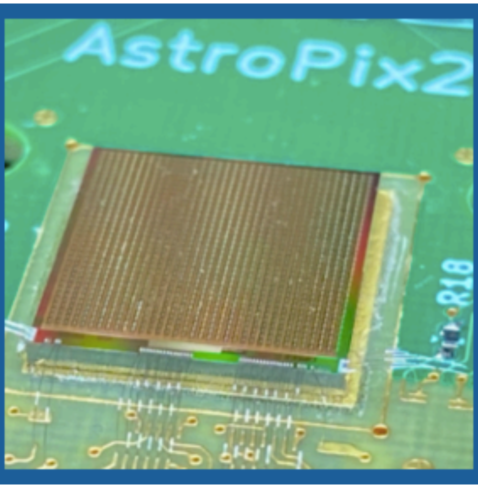
Fiber Measurements

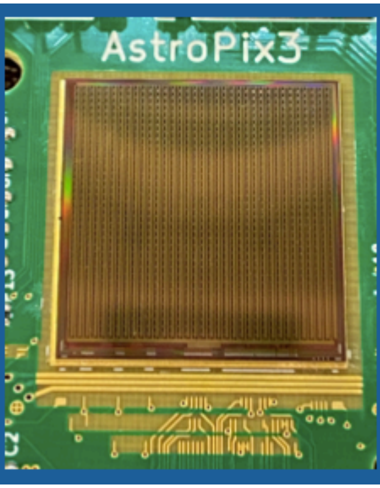


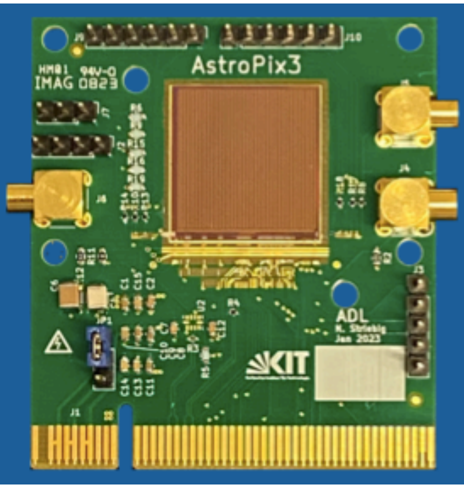
N_{pe} = number of photo-electrons from the fibers
Measurements with high-resolution SiPMs in coincidence with a PMT

AstroPix

BIC - AstroPix

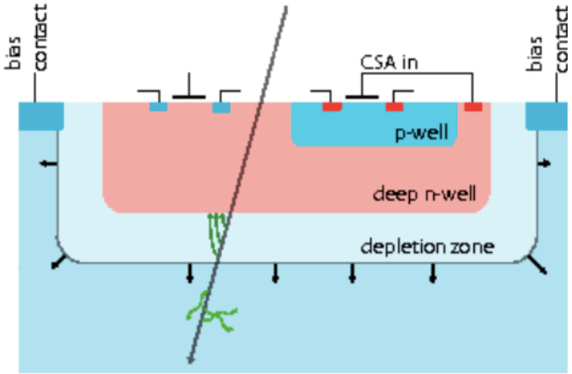






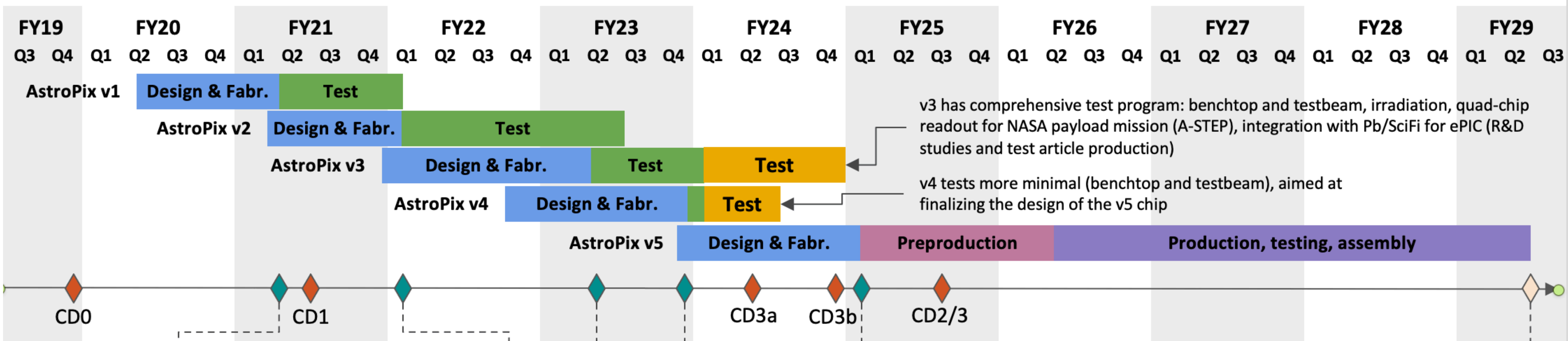
HV-CMOS Monolithic Active Pixel Sensor (MAPS):

- Combination of silicon pixel & Front-End ASIC
- On-pixel charge amplification and digitization
- Technology uses more typical CMOS wafer processing for cost effective mass production

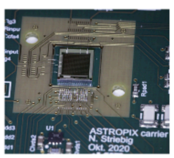


AstroPix Development

Not shown:
Early CD4 (Oct 2032)
CD4 (Oct 2034)

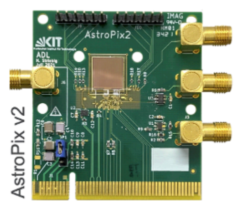


Start of BIC installation at BNL



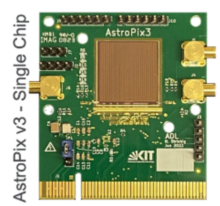
AstroPix v1
HV-CMOS MAPS based on ATLASPix3, designed for the AMEGO-X GSFC/NASA mission, optimized for power dissipation and energy resolution Nucl.Instrum.Meth.A 1019 (2021) 165795

0.45 x 0.45 cm² chip, 175 µm pixel pitch
18 x 18 pixel matrix
Power dissipation 14.7 mW/cm²



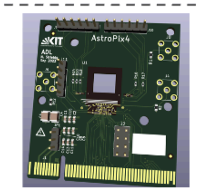
AstroPix v2

1 x 1 cm² chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm²



AstroPix v3
First full-size chip

2 x 2 cm² ch... pixel pitch
Row/colum
Power dissipation <1 mW/cm²
2.5 MHz timestamp, 200 MHz ToT
10 byte data frame per hit



AstroPix v4
Final design but smaller size

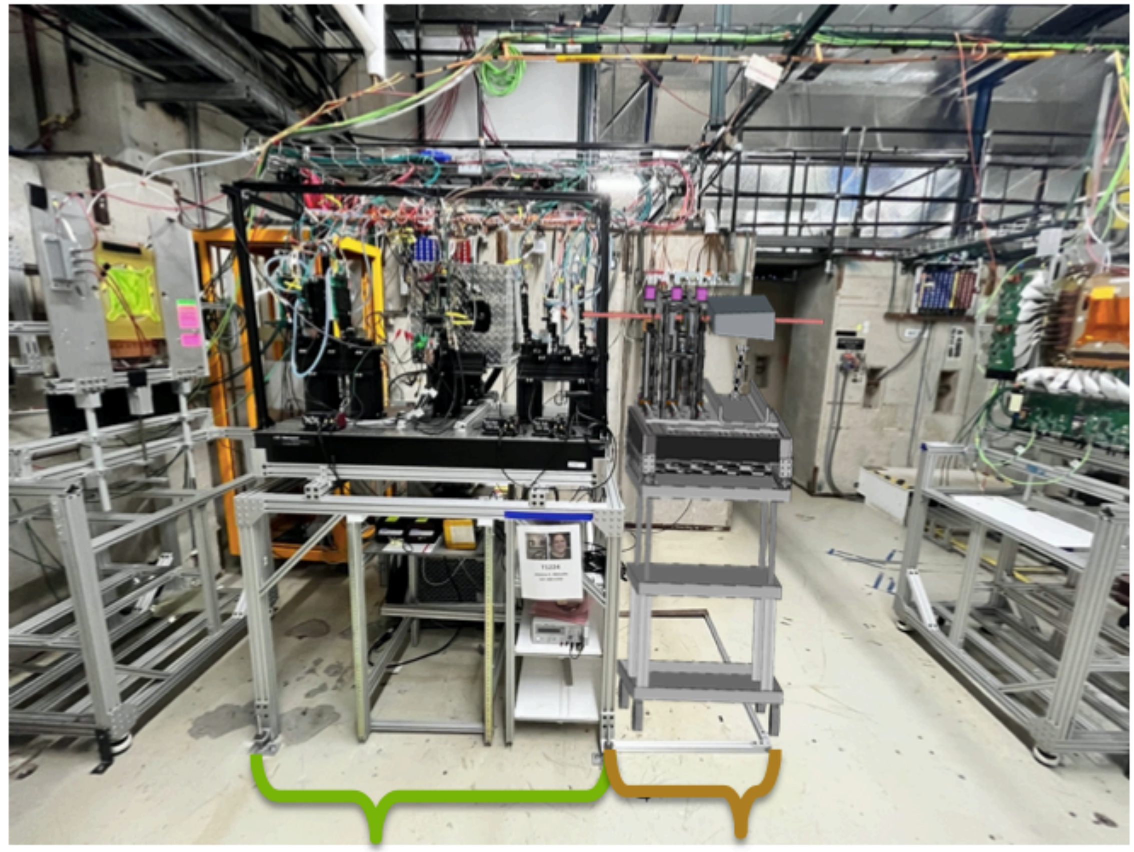
1 x 1 cm² chip, 500 µm pixel pitch
Individual pixel readout
3 timestamps, 3.25ns time resolution
TuneDAC for pixel-by-pixel thresholds
Self-triggered

AstroPix v5
Full-size production chip

2 x 2 cm² chip, 500 µm pixel pitch
Design identical to v4 ...

Integrating Imaging and Calorimetry

- Add BIC prototype calorimeter behind existing AstroPix setup at MTest
- Rotating stage to simulate particles incident at angles up to 45° ($\eta \sim 1$)
- Ability to lower BIC setup out of the beam, no need to uninstall for other experiments to run
  - Proximity to Argonne enables occasional opportunistic running



Current AstroPix Setup

Planned BIC Setup

U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

3

Drawings by Tom O'Connor

Argonne NATIONAL LABORATORY

BIC Summary

Things are moving along quickly!

- Fiber testing is being done at Regina
  - Attenuation length and light output
  - Kuraray and Luxium fibers
  - Decision about single- vs. double-clad fibers coming soon
- Astropix work proceeding smoothly — v4 chip ready in early 2024
- R&D prototype (Baby BCAL + one Astropix layer) will be tested in the beam at FNAL — integrate readouts and check $\mathbf{e/\pi}$ suppression

Electron-Ion Collider Collaboration Canada

University of Manitoba

- Wouter Deconinck
- Michael Gericke
- Juliette Mammei
- Savino Longo

University of Regina

- Garth Huber
- Zisis Papandreou

Mount Allison University

- DLH

TRIUMF

Also presently 4 PDFs, 14 grad students, and one undergrad.

Collaboration is growing!

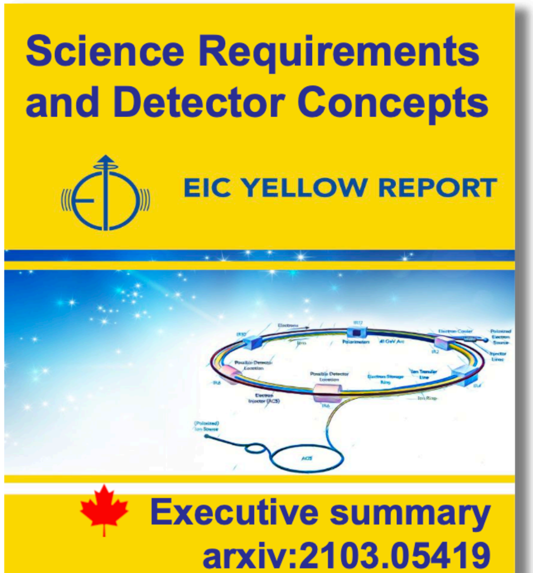
EIC User Group

- 31 members from Canada, including theoretical, experimental, and accelerator physicists.
- 7 institutions from Canada.
- 8th largest country by member count
- Deconinck elected as international representative on global Steering Committee (2020–2021).

EIC Canada Collaboration

- **Coordinating the Canadian participation in the Electron Ion Collider.**
- Chartered in 2020 after EIC Project CD-0 decision and BNL site selection.
- Current initiatives:
  - Input to the 2022-2036 Canadian Subatomic Physics Long Range Plan
  - NSERC Subatomic Physics Project Research Grants (2021-2025: funding of 8 HQP)
  - Interfacing with partner and funding organizations:
    - National funding agencies and research facilities (NSERC, CFI, TRIUMF
    - International partners (EIC User Group, BNL, JLab, working groups and consortia)
  - Participation in the ePIC collaboration (working group conveners)
- Current membership:
  - PIs at three institutions U. Regina, U. Manitoba, Mt. Allison U.
  - First step to joining: institutions and PI must join the EIC User Group
- Management plan, members, leadership and further details at eic-canada.org

Canadian Involvement in EIC Yellow Report, Proposals



2021: From Yellow Report…

…to two large collaboration detector proposals with Canadian involvement

2022: proposal selection

…to one large EIC Project detector collaboration

2024: Construction/Installation

2030: First Beam/Operations

ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

EIC Canada focus areas:

- Calo: Si-pixel imaging + SciFi hybrid barrel, PbWO + SciGlass hybrid endcaps
- Software: CERN-oriented (dd4hep, gaudi, ACTS)

EIC Canada leadership roles:

- U Manitoba (W. Deconinck: software WG co-convener)

ECCE *EIC Comprehensive Chromodynamics Experiment*

EIC Canada focus areas:

- Calo: Barrel, e-/Hadron endcap, far forward region: roman pots, ZDC, B0

EIC Canada leadership roles:

- U Regina: G. Huber (meson form factors at high Q2); Z. Papandreou (spectroscopy of XYZ states)
- Event generators, far forward studies

Combined Canadian hardware effort now concentrating on BIC lead by Z. Papandreou!

University of Manitoba   Mount Allison University   University of Regina

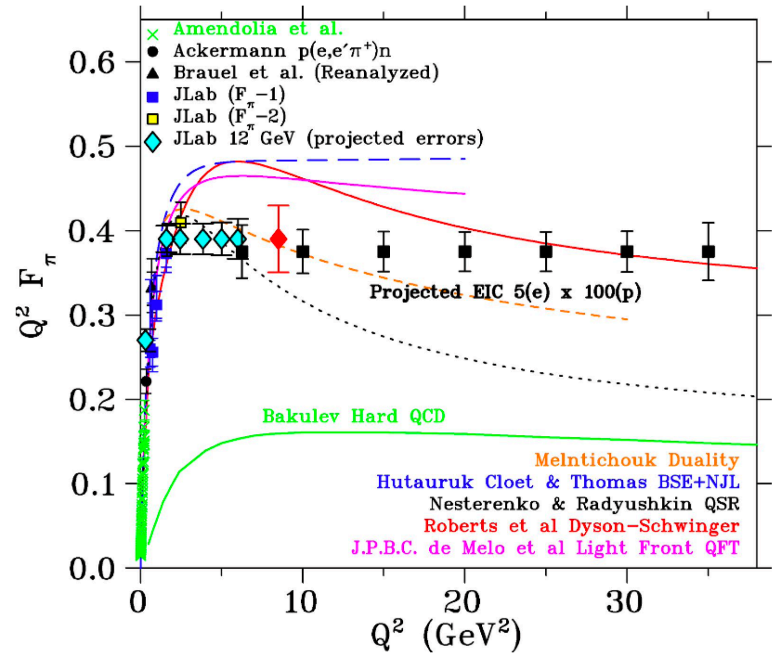
Supported in part by NSERC SAPIN-2020-00049, SAPPJ-2021-00026.

Canadian Interests/Contributions at the EIC near term

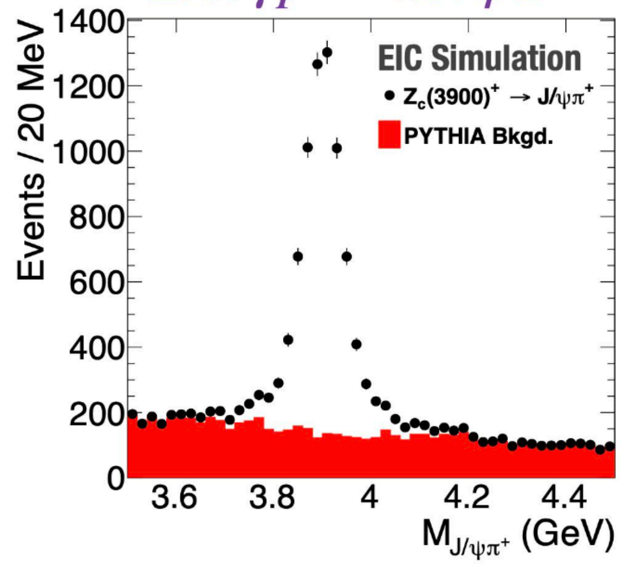
- Extend Pion and Kaon Form-Factor Studies
- *XYZ* Spectroscopy
- Extend Studies of Leptoquark sensitivity
- PVES to determine interference structure functions
- Machine Learning for calorimeter design optimization
- Compton polarimetry
- HV-MAPS electron detector
- BIC

Contributions: U. Regina / Mt. Allison

- Pion form factors as probe of emergent mass generation in hadrons.
  - Precision at high momentum transfers.
- Light and heavy quark spectroscopy.
  - Hadron Spectroscopy has components in: Semi-inclusive, Heavy Flavour and Exclusive.
  - Explore underlying degrees of freedom in Charmonium states.
  - Explore Bottomonium Exotic Sector.
- Artificial intelligence detector co-design.
- Detector development (ongoing with ANL, UM).
  - EM barrel calorimeter based on GlueX Pb SciFi design, with AstroPix (low-power ATLASPix) silicon imaging layers for shower profile measurements.



EIC: $\gamma p \to nJ/\psi\pi^+$



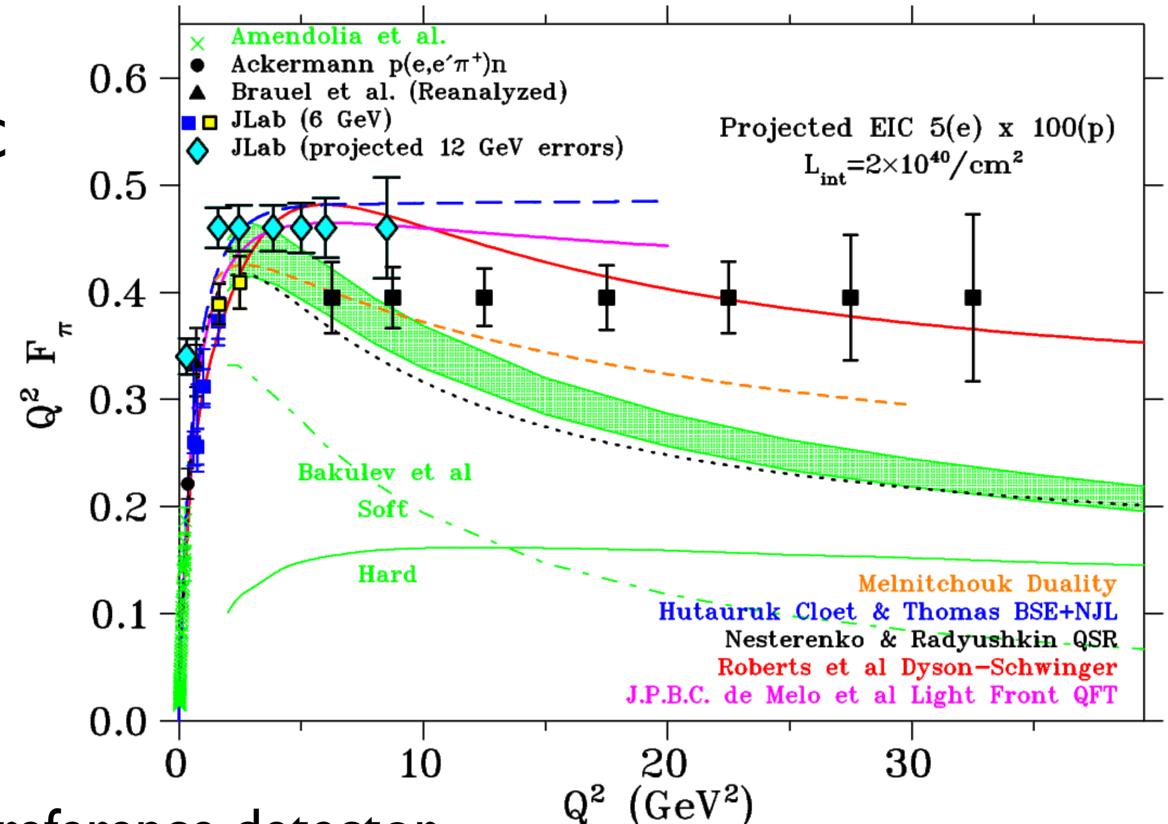
Pion and Kaon FF Measurements

Rich insights into hadron structure → Dynamical Chiral Symmetry Breaking

Exclusive reaction $p(e, e'\pi^{+}n)$ at EIC can possibly extend Q^2 reach of $F_{\pi}(Q^2)$

- Triple coincidence.
- Need model help — LT separation not possible.

Kaon is even more challenging.



Projected $F_{\pi}(Q^2)$ results for ECCE reference detector.

Work continues on $F_{K}(Q^2)$ simulations.

Extension of JLab 6- and 12-GeV programs.

Heavy and Light Quark Spectroscopy

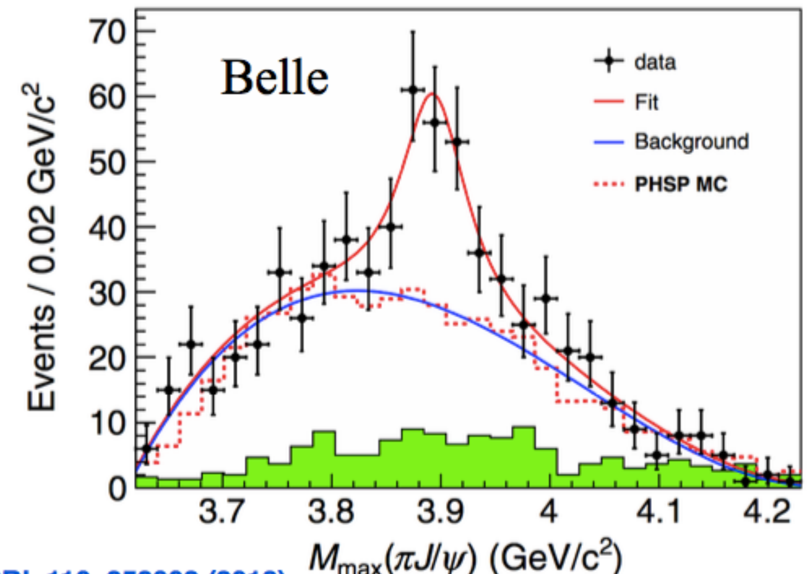
Recent evidence for *non-standard* exotic heavy mesons.

The so called ***XYZ* states**.

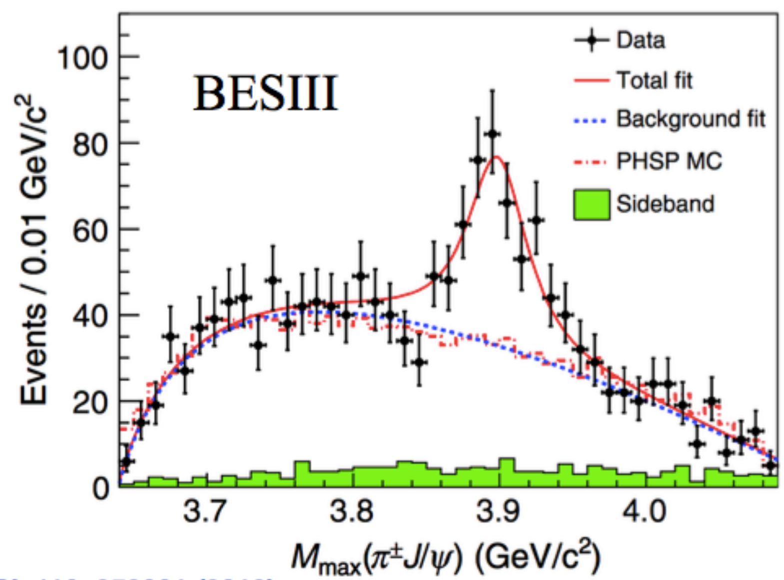
- ***Y* states:** same quantum numbers as the photon. $J_{PC} = 1^{--}$
- ***Z* states:** all exotic charge states. Decay into quarkonium state and a light charged meson.
- ***X* states:** all other neutral states with quantum numbers NOT $J_{PC} = 1^{--}$

Charmonium structure discovered at Belle and observed at both BESIII and LHCb in the decay of the $\Upsilon(4260)$, given the name $X(3872)$.

Superposition of exotic and conventional $c\bar{c}$ states??



PRL 110, 252002 (2013)



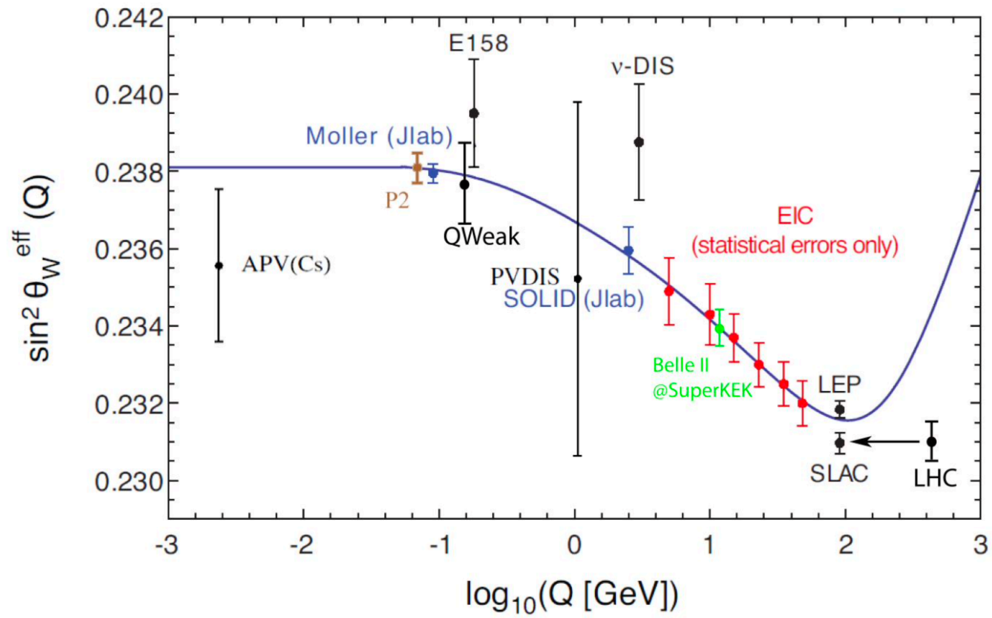
PRL 110, 252001 (2013)

Some EIC advantages:

Well controlled initial state
High luminosity
"Clean" environment
Flexibility in tuning kinematics

Contributions: U. Manitoba

- Exploiting parity-violation in weak interaction to access observables:
    - Strangeness in nucleon (fixed target).
    - Precision searches for new physics.
- CC and NC program of precision $\sin^2\theta_W$ measurements at the EIC span unexplored region between low energy and Z-pole (LHC).
- BSM: leptoquark, CLFV.
- Polarimetry detector development:
    - Electron spectrometer with HV-MAPS.
- Core software development efforts.

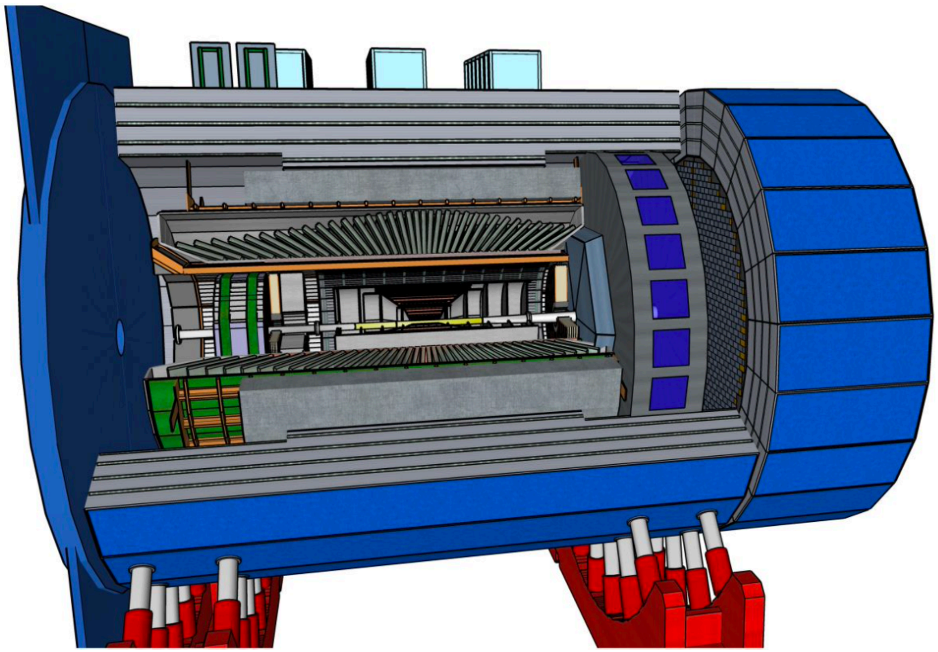


Ref: YX Zhao, Eur.Phys.J.A (2017) 53:55

Projected Involvement by Canadian University PIs

- EIC logically follows extensive physics programs at JLab, BNL, and connects to other existing Canadian programs.
- EIC Canada contributing to a M**ajor Detector Construction Effort** (calorimetry, polarimetry).
- A community similar in size to the Canadian Belle II Collaboration is our goal.
  - PI FTEs: growth to **~10 PIs** by start of operations in 2029.
  - HQP: growth to **~20 HQP** by start of operations 2029.
  - Detailed projections in EIC SAP LRP brief (at eic-canada.org).

Major Detector Construction In Canada



Electromagnetic Calorimetry:

- Major components of the ePIC Barrel Imaging Calorimeter will be built by U. Regina (end-of-sector readout box) and U. Manitoba (Pb/SciFi layers)
- Calorimeter pulse-shape discrimination in the electron endcap (PbWO4 technology).
- Positioning for CFI IF 2025 application for calorimeter construction.

Compton Polarimetry for EIC Electron Beam:

- HV-MAPS technology at U. Manitoba for Compton polarimeters at JLab, KEK.
- Photon polarimetry based on MOLLER and Belle II experience (U. Manitoba).

Online/Offline Production Software:

- Experience throughout JLab and EIC programs, including proposal stages.

Much of this work will be undertaken with help from TRIUMF.

Thank You

Special shout out to Zisis Papandreou and Sylvester Joosten for slides and feedback.