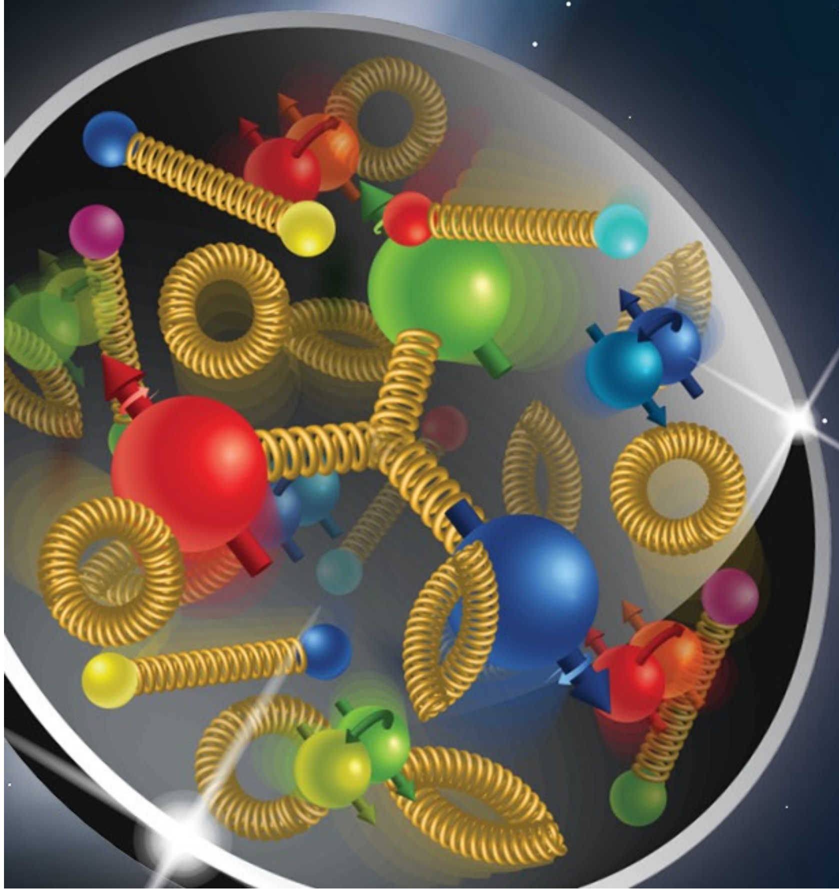
Barrel and Forward EMCal:
Physics Goals, Detector Requirements, Expected Performance

Alexander Bazilevsky (BNL)

L3/CAM EMCal

Scintillating Fiber FDR

September 13, 2023



Electron-Ion Collider

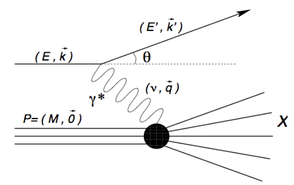
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

EMCal for an EIC Detector

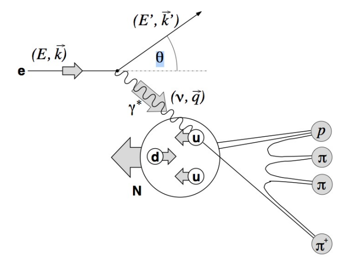
Electron/photon PID, energy, angle/position:

Coverage (in rapidity and energy), resolution, e/π, granularity

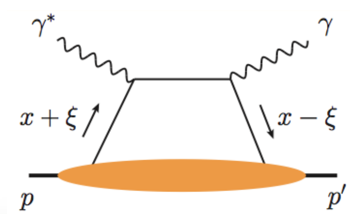
Inclusive DIS: scattered electron



Semi-Inclusive DIS: $\pi 0 \rightarrow \gamma\gamma$, HF $\rightarrow$ e



Exclusive DIS: DVCS photons, J/ψ→ee etc.



Detector Requirements: Summary

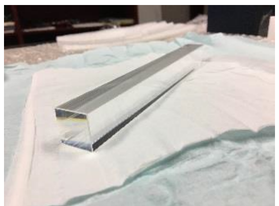
As documented in YR and
"General, Functional, and Performance Requirements for the EIC Detector Systems"

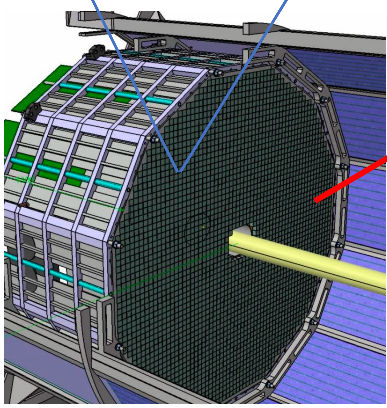
	Electron endcap (Backward)	Barrel	Hadron endcap (Forward)
Energy Resolution	$\frac{(2-3)\%}{\sqrt{E}} \oplus 1\%$	$< \frac{10\%}{\sqrt{E}} \oplus 2\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$
Shower Energy range	0.1−18 GeV	0.1−50 GeV	0.1−100 GeV
$\pi\pm$ suppression (helped by other subsystems)		Up to 10^4	
$\pi^0/\boldsymbol{\gamma}$ discrimination	Up to 18 GeV/c	Up to 10 GeV/c	Up to 50 GeV/c
Rad dose (includes background) at 10^{34} sm^{-2} sec^{-1}	<3 krad/year	<0.1 krad/year	<4 krad/year
Max hit rate per tower (includes background)	10 kHz	5 kHz	50 kHz
Neutron flux, at 10^{34} sm^{-2} sec^{-1}	10^{10} /cm^2/year	10^{10} /cm^2/year	10^{11} /cm^2/year
Limited space		Compact (small X_0)	
Material on the way		Minimized	

- Continuous acceptance (particularly from e-endcap to barrel)
- Photosensors and FEE tolerate magnetic field

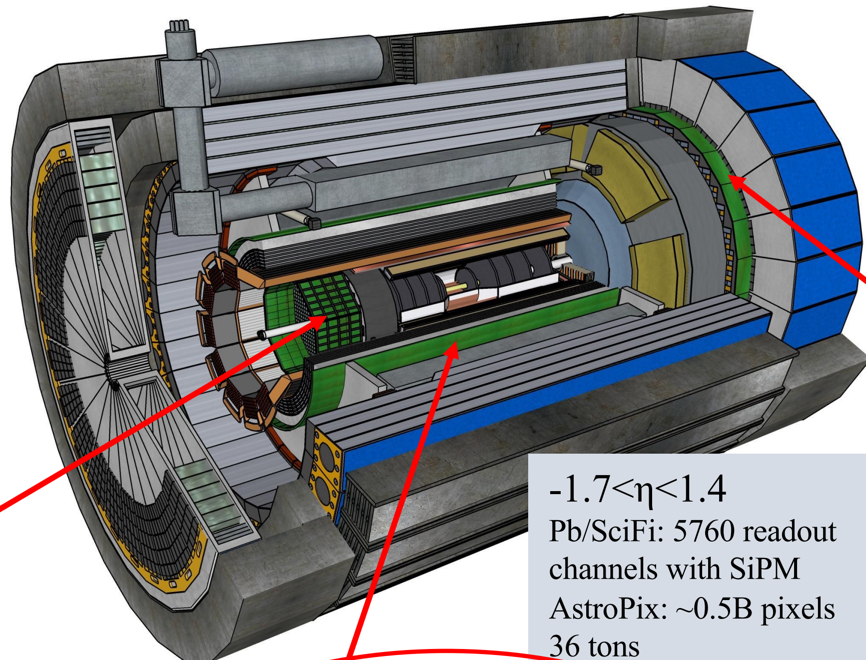
EM Calorimetry in EIC Detector

PbWO4

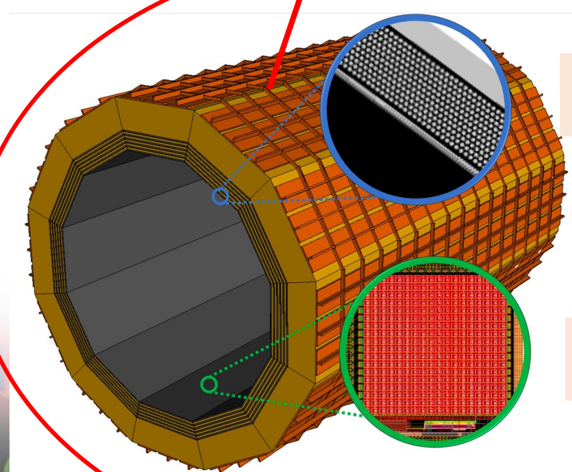




-3.5<η<-1.7
~3k crystals
R_{outer}=64cm
SiPM readout
2 tons



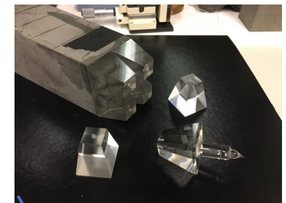
-1.7<η<1.4
Pb/SciFi: 5760 readout channels with SiPM
AstroPix: ~0.5B pixels
36 tons

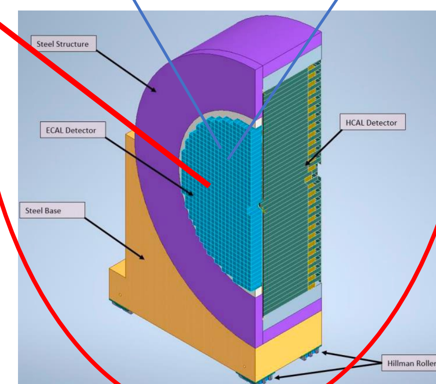


Pb/SciFi

AstroPix

W/SciFi

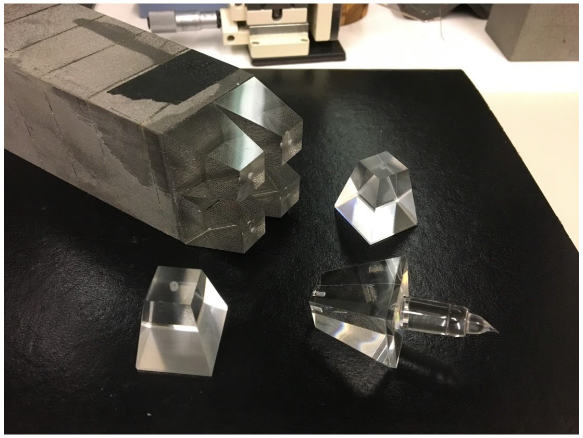




1.4<η<3.7
~16k towers
R_{outer}=170cm
SiPM readout
18 tons

h-endcap: W/SciFi

- Good resolution
- High granularity for $\pi 0$
- e/h~1 for jets



Pioneered by UCLA
sPHENIX EMCal: 25k towers

- Compact: X_0 = 0.7cm
- High granularity: R_m = 2cm
- Sampling fraction: ~2.3%
- Good resolution

- ~10 institutions (USA, China)
- Extensive expertise and capabilities in executing large scale projects (RHIC, JLab, CERN, Super KEKB)
- Participated in building sPHENIX EMCal
- ~10 years of EIC R&D

sPHENIX (trapezoidal blocks): $\frac{\sigma_E}{E} \sim 3\% \oplus \frac{13\%}{\sqrt{E}}$

EIC R&D (rectangular blocks): $\frac{\sigma_E}{E} = \sim 2\% \oplus \frac{(10-12)\%}{\sqrt{E}}$

Already satisfies the EIC detector requirements

More improvement expected from ongoing R&D:

Higher eff. for light collection

Better uniformity

h-endcap: Production Chain

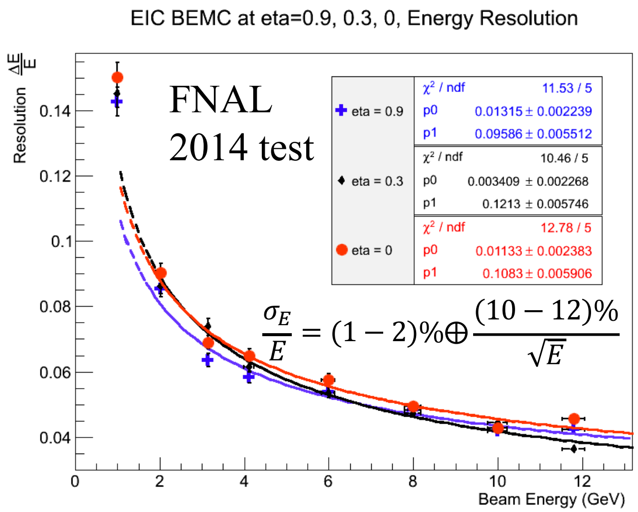
Production chain is fully established

Production factory is setup and ready to go at Fudan U. (China)

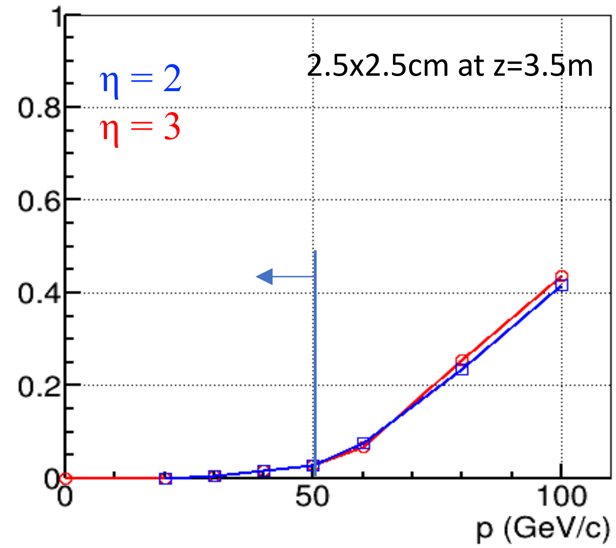
- If US-China S&T agreement is not extended, we’ll setup another factory in US

h-endcap: Performance at EIC

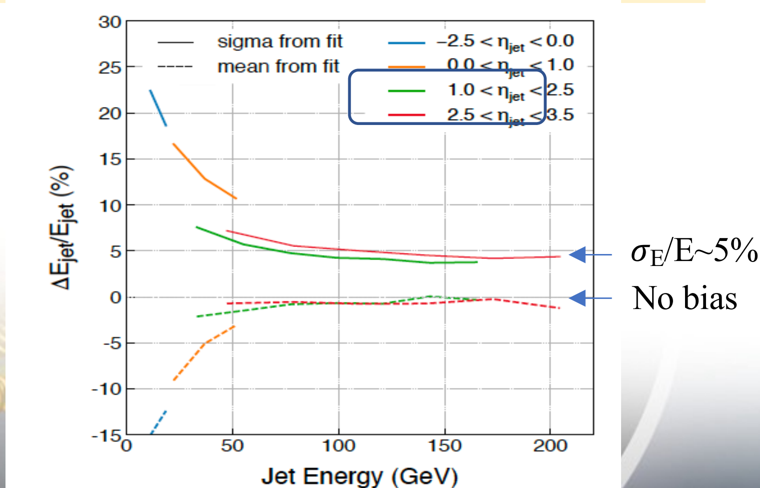
Energy Resolution



$\pi 0/\gamma$: merging prob



Jet resolution and bias (ECal+HCal)



- Good energy resolution
- Excellent $\pi 0/\boldsymbol{\gamma}$ discrimination capabilities
- Provides high resolution and minimally biased jet measurements (in duet with HCal)

Fully satisfies the EIC Detector Requirements

Barrel: Pb/SciFi + Imaging

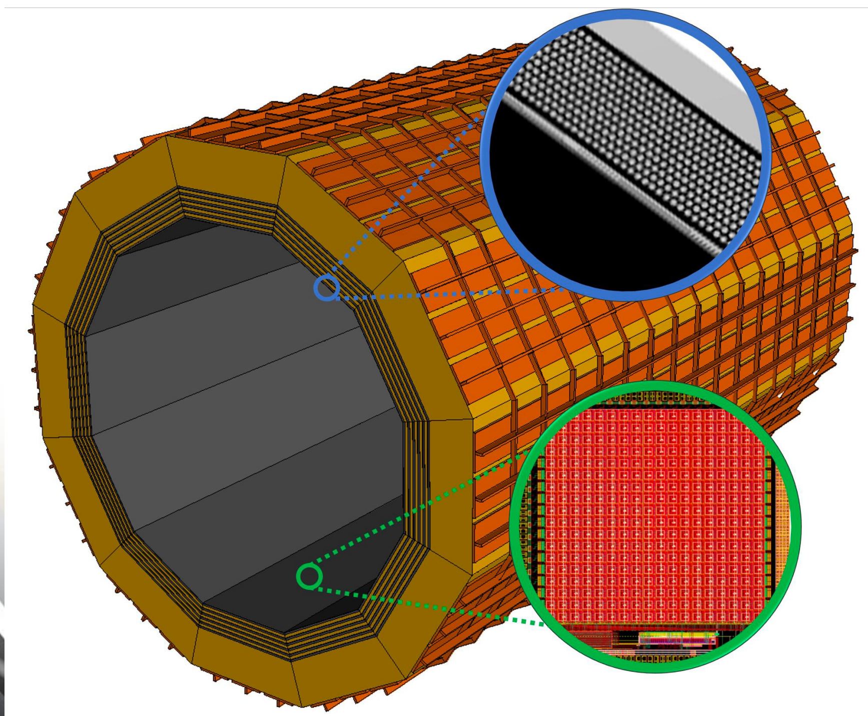
- Good resolution
- High e/π separation for eID

Selected after rigorous review by ePIC in Mar-Apr 2023

Barrel EMCal Workshop in Argon (June 12-16, 2023): *https://indico.bnl.gov/event/19689*

Hybrid Concept:

6 imaging Si layers (4 layers in baseline), Interleaved with 5 Pb/SciFi layers, followed by a thick Pb/SciFi layer ($17X_0$ total)



Imaging:

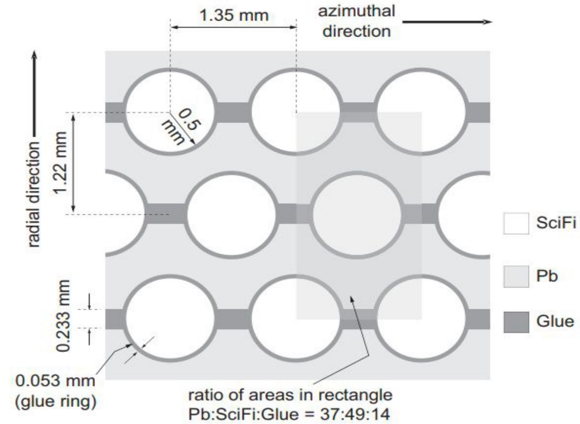
Monolithic silicon sensor AstroPix (NASA's AMEGO-X mission)

Pb/SciFi:

Scintillating fibers embedded in Pb (Similar to GlueX barrel EMCal)

- ~20 institutions (US, Korea, Canada, Germany)
- Extensive expertise and capabilities in calorimetry, Si sensors, large detector systems
- Broad experience with large projects at RHIC, Jlab, CERN
- Generous in-kind contributions anticipated

Barrel: Pb/SciFi



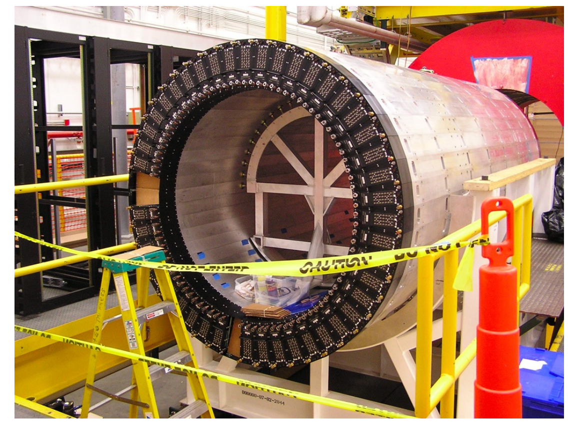
Pb/SciFi part follows GlueX barrel EMCal

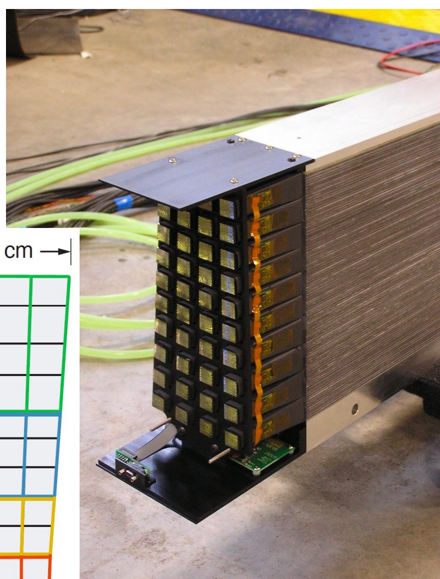
2-side SiPM readout

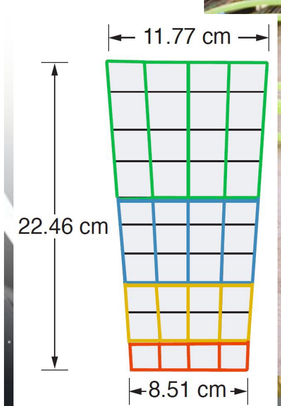
Mature technology (GlueX, KLOE)

- Module construction fully developed
- GlueX module construction equipment available
- Calorimeter performance well studied

Assembly and installation re-using sPHENIX equipment







GlueX small prototype (15.5X_0, 70 cm long)

- Tests with beam at Jlab (FY23) and FNAL (FY24), and cosmic
- Resolution: $\frac{\sigma_E}{E} \sim \frac{5.2\%}{\sqrt{E(GeV)}} \oplus 2\%$ - already exceeds the EIC detector requirements; more improvements expected
- Study response to electrons/pions/muons to benchmark simulation
- Finalize readout

Barrel: Imaging

Barrel EMCal Workshop in Argon (June 12-16, 2023):
https://indico.bnl.gov/event/19689

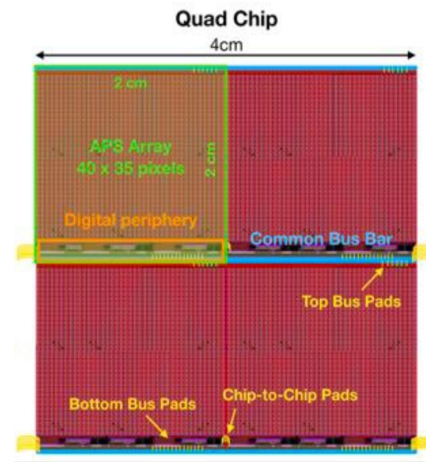
Based on AstroPix sensors

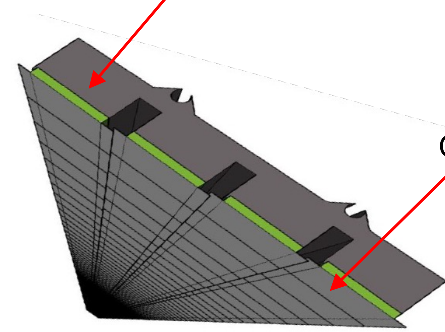
Developed for AMEGO-X (NASA)

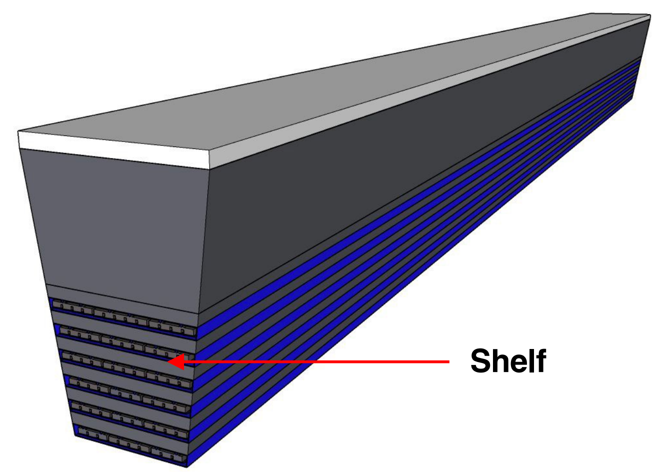
CMOS sensor based on ATLASpix3

4 layers (of 6) in a baseline design

Pixel size	$500\,\mu m \times 500\,\mu m$
Power usage	< 1 mW/cm^2
Energy resolution	10% @ 60 keV (based on the noise floor of 5 keV)
Dynamic range	~ 700 keV
Passive material	$< 5\%$ on the active area of Si
Time resolution	25 ns
Si Thickness	$500\,\mu m$







Ongoing tests in FY23/24 (FNAL)

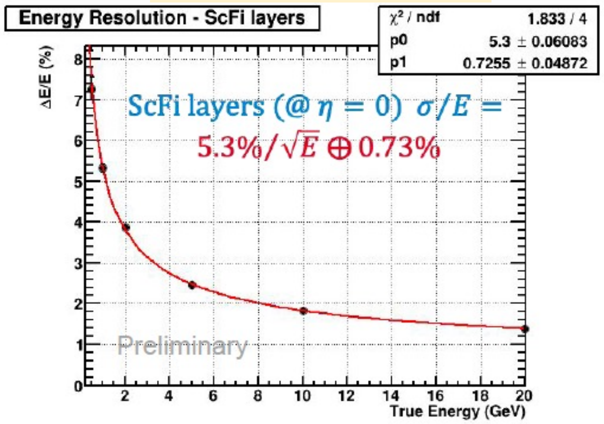
Multilayer chip test

Irradiation test

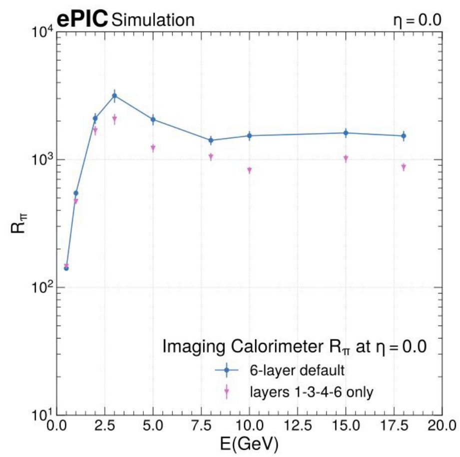
Response to e and π with AstroPix prototype integrated with Pb/SciFi (GlueX prototype)

Barrel: Performance at EIC

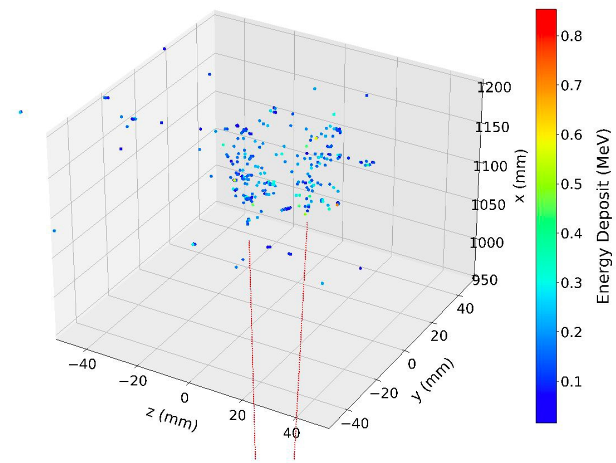
Energy Resolution



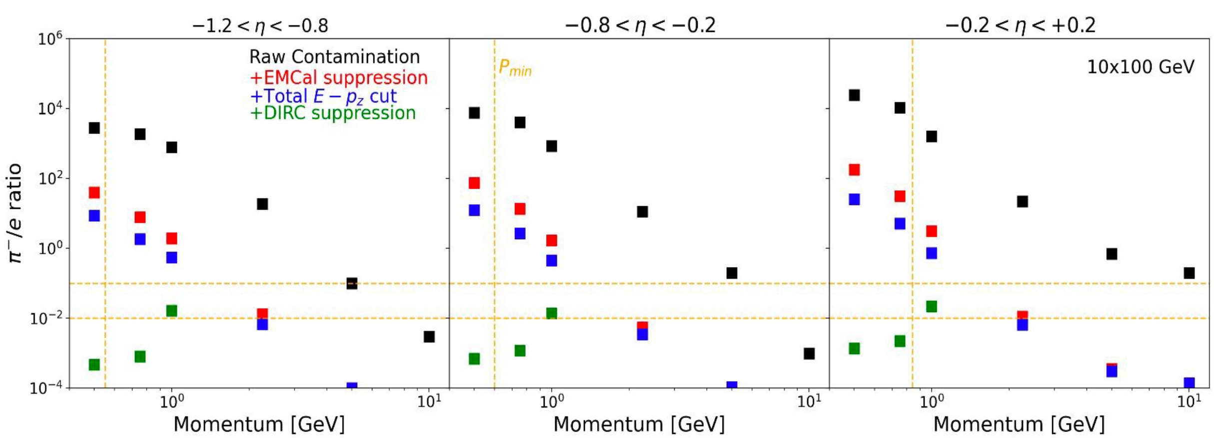
π- rejection



15 GeV $\pi 0 \rightarrow \boldsymbol{\gamma\gamma}$



DIS electron purity



- Very good energy resolution
- Strong $\pi\pm$ rejection for eID
- DIS electron purity of ~99% or better achieved
- $\pi 0/\boldsymbol{\gamma}$ far beyond the required 10 GeV

Fully satisfies the EIC Detector Requirements

SciFi for LLP: Cost Estimate

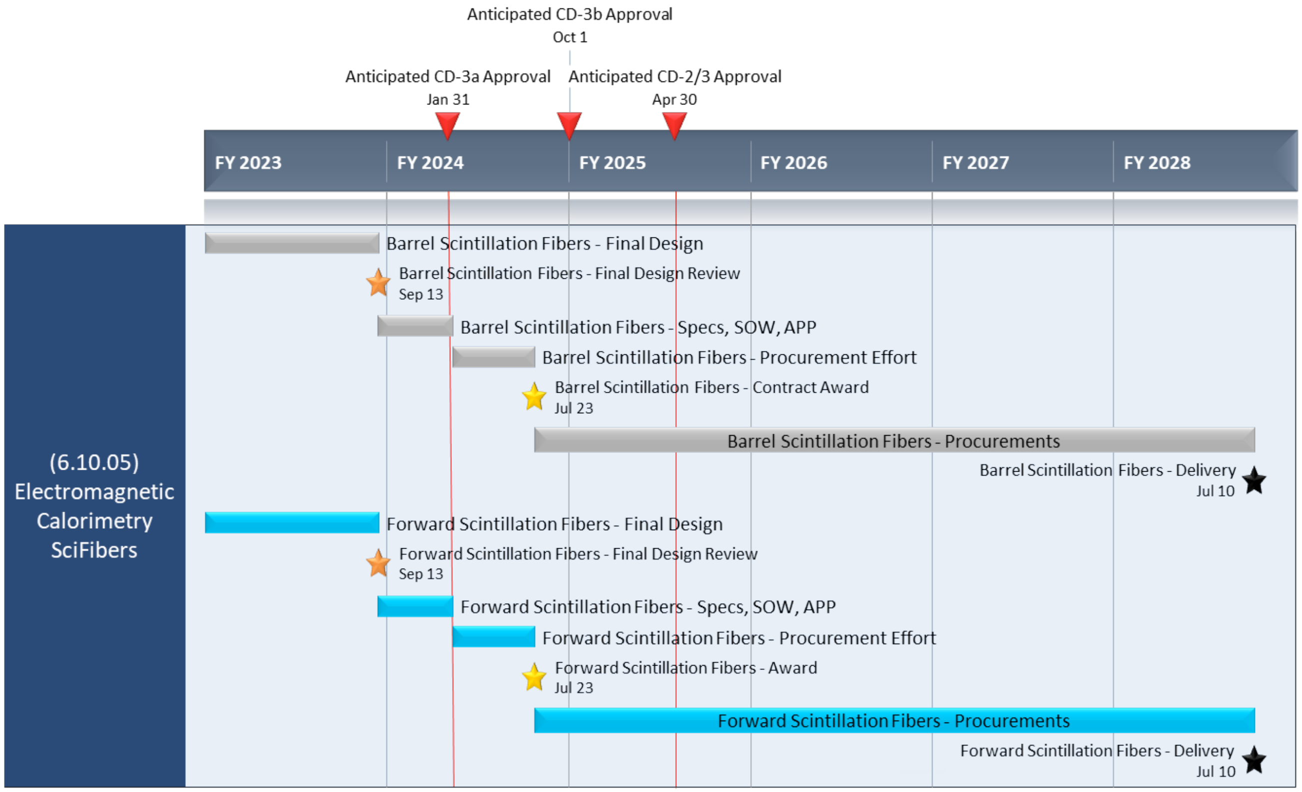
Barrel EMCal: ~4,500 km of ⌀1mm fibers
Forward EMCal: ~3,000 km of ⌀0.47mm fibers

L3 WBS	L4 WBS	Activity ID	EXPECTED AWARD DATE	CAM / ESTIMATOR	LAB	PMC REP	LABOR HOURS	DIRECT MATERIAL COST	Budgeted Labor Cost	Budgeted Nonlabor Cost	Total Cost (Burd&Esc)
		CD-3A Scope and Design									
		Scintillating Fibers					104	1,659,000	$16,800.26	$1,768,642.41	$1,785,442.67
6.10.05	6.10.05.03	Hadron Endcap EMCal Fibers	23-Jul-24	A. Bazilevsky	BNL	T. Lewis	48	384,000	$7,768.29	$398,208.01	$405,976.30
6.10.05	6.10.05.02	Barrel EMCal Fibers	17-Oct-24	A. Bazilevsky	BNL	T. Lewis	56	1,275,000	$9,031.97	$1,370,434.40	$1,379,466.37
		CD-3B Scope and Design									
		Scintillating Fibers					12	4,369,700	$2,323.61	$4,891,300.15	$4,893,623.76
6.10.05	6.10.05.03	Hadron Endcap EMCal Fibers	4-Feb-25	A. Bazilevsky	BNL	T. Lewis	6	979,571	$1,146.50	$1,075,003.14	$1,076,149.64
6.10.05	6.10.05.02	Barrel EMCal Fibers	11-Jul-25	A. Bazilevsky	BNL	T. Lewis	6	3,390,129	$1,177.11	$3,816,297.01	$3,817,474.12

Basis of Estimates:

- The current cost estimates are based on a vendor quote from 2023 (St.Gobain/Luxium for barrel and Kuraray for forward)

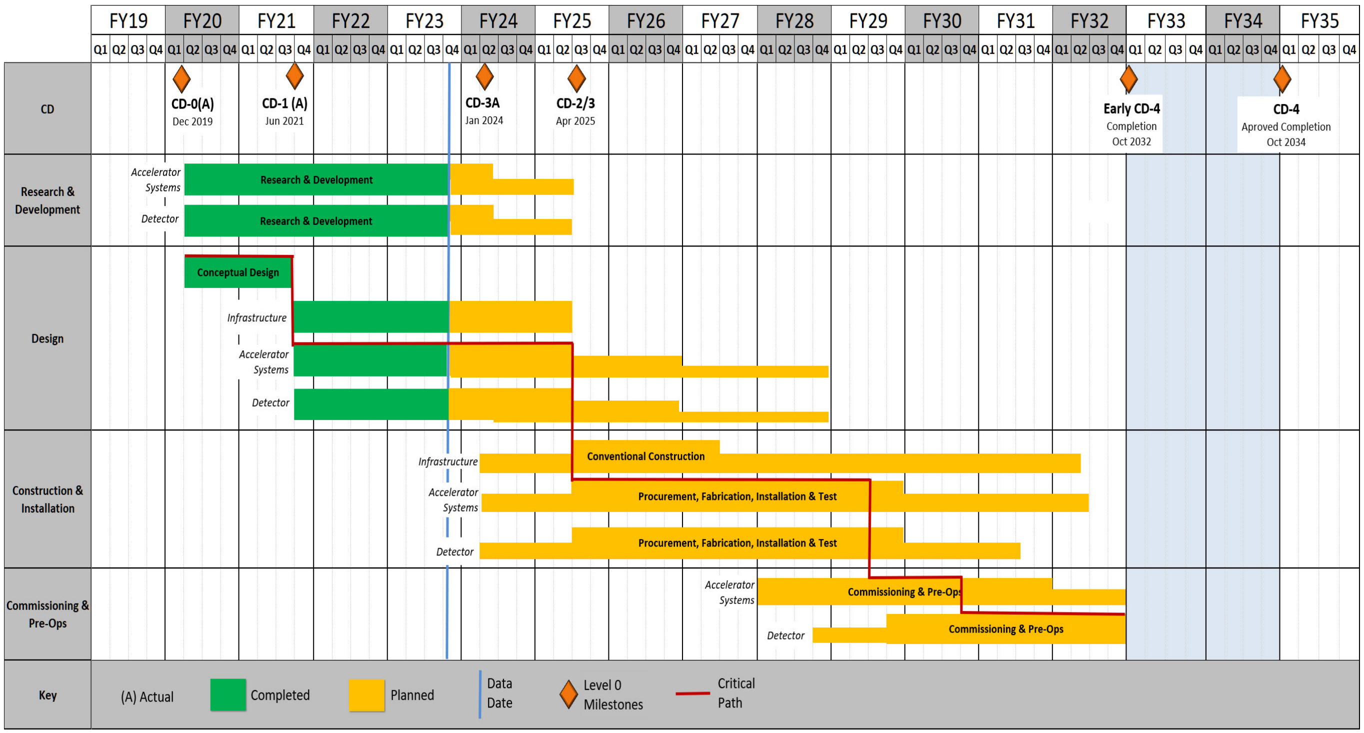
SciFi for LLP: Schedule



Specs finalized:	Now
Final Design Review:	Now
Contract award:	Summer 2024
Material delivery:	Summer 2024 – Summer 2028

EIC Schedule

Detector subsystem schedule matches EIC Project Critical Decision path



EIC Project Critical Decision and Detector Milestone Path

CD1 (Conceptual Design)	**Jun 2021**
Final Design for LLP	Fall 2023
CD-3a (LLP)	**Jan 2024**
Contract Award for LLP	Summer 2024
Preliminary Design	Spring 2024
Final Design	Fall 2024
CD-2/3 (Construction)	**Apr 2025**
Contract Award	Winter 2026
Production/Assembly	…
Ready for Installation	2030
Accelerator and Detector integrated system completed	**Apr 2031**

Conclusion

1. Are the EMCAL technical performance requirements complete, documented, and understood?

   Yes, the detector requirements are defined and documents; the selected technologies satisfy or exceed the requirements.

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 scintillating fiber procurement?)

   The design and specifications for SciFi are complete; little interference with the other elements of the design

3. Do the present EMCAL design and the resulting scintillating fiber specifications meet the performance requirements with a low risk of cost increases, schedule delays, and technical problems?

   Yes, based on the experience from similar EMCals (of sPHENIX and GlueX) and ongoing R&D and tests

4. Are the fabrication and assembly plans for the EMCAL consistent with the overall project and detector schedule and appropriately developed to initiate the scintillating fiber procurement?

   Yes, EMCal schedule matches the overall EIC schedule

5. Are the plans for detector integration in the EIC detector appropriately developed to initiate the scintillating fiber procurement?

   Yes, see R.Wimmer's presentation

6. Have previous review recommendations been adequately addressed to initiate the scintillating fiber procurement?

   N/A

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

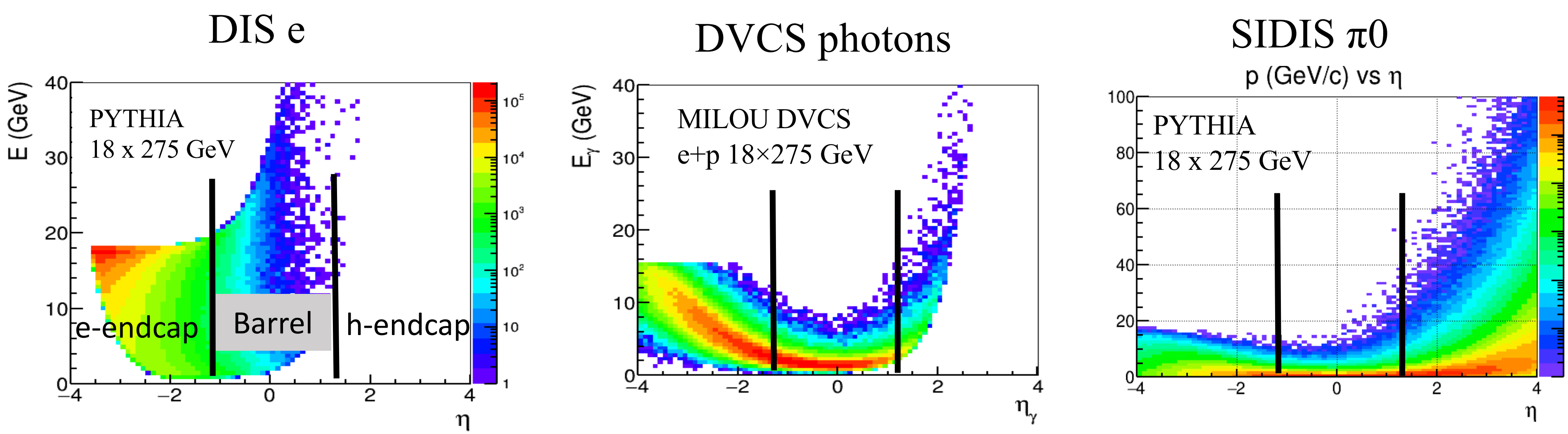
   Yes, see Z.Papandreou and O.Tsai's presentation

8. Is the procurement approach sound and the procurement schedule credible?

   Yes, based on the experience from similar EMCals (of sPHENIX and GlueX)

Backup

Coverage, Energy Range



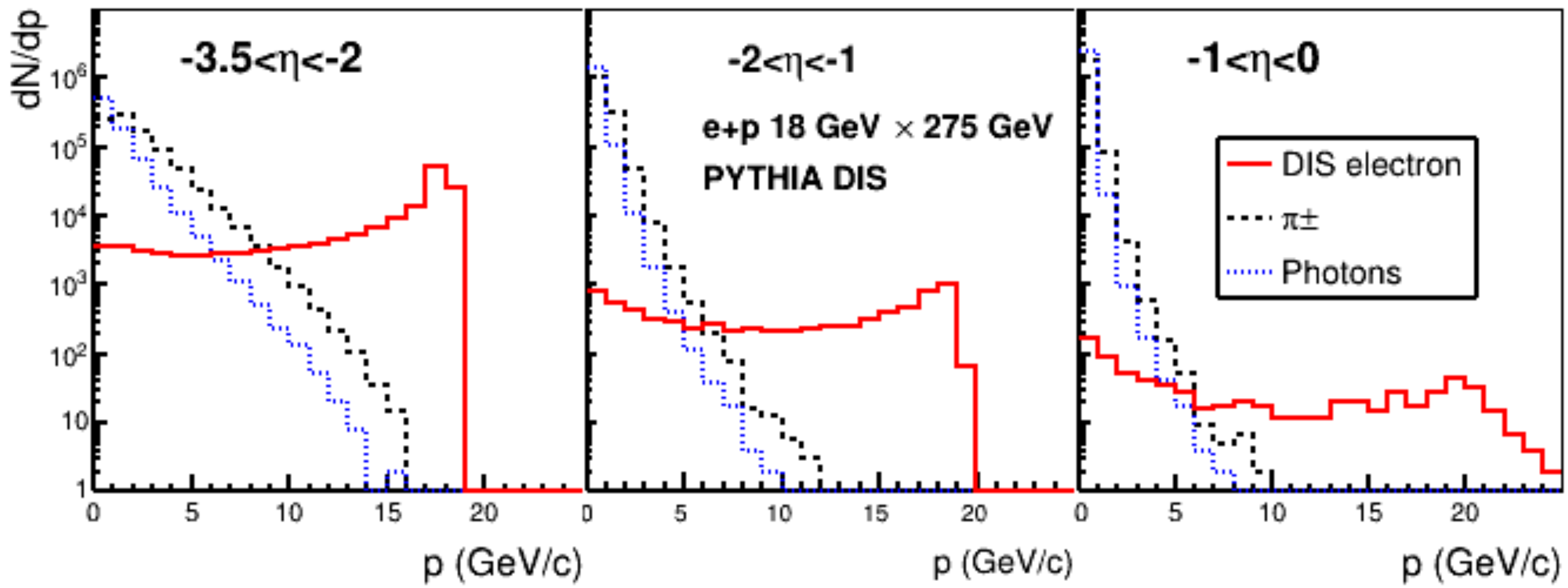
Continuous acceptance coverage: at least $|\eta|<3.5$

- Avoid gap, particularly in e-endcap/barrel transition

Energy range

- e-endcap: up to electron beam energy (up to 18 GeV)
- Barrel: up to ~50 GeV for DIS e, and ~10 GeV for $\boldsymbol{\gamma}$ and $\pi 0$
- h-endcap: up to ~100 GeV

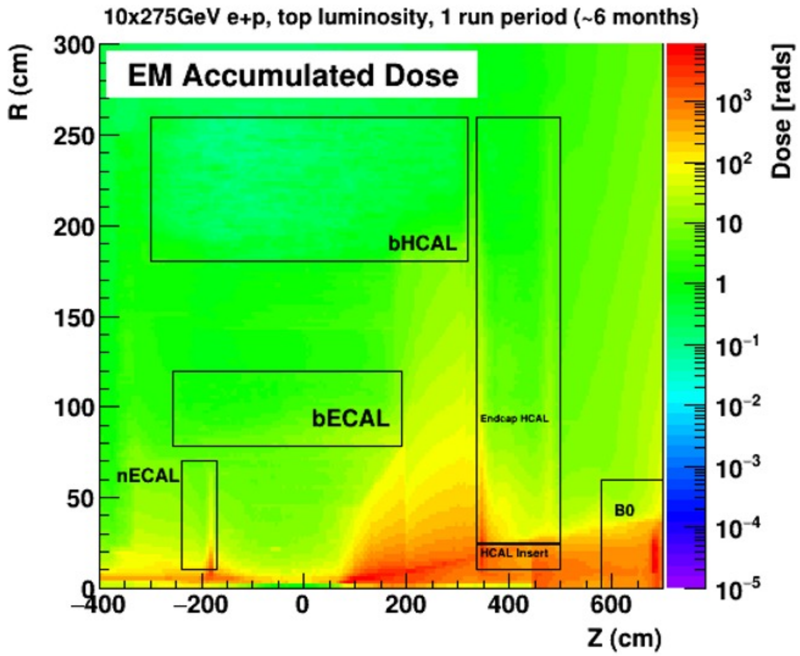
DIS kinematics: ePID

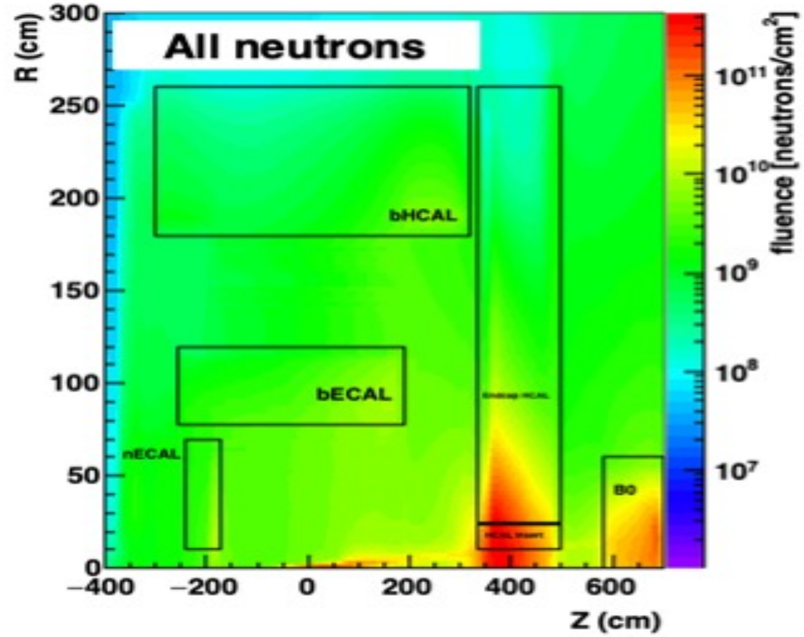


Charged hadron high suppression power is required

Particularly at low momenta (up to 10^4 , in combination with other subsystems)

Rad Dose and Neutron Flux



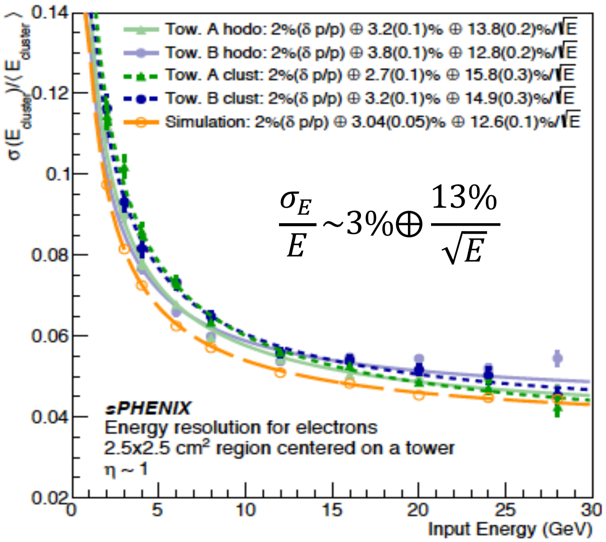


Highest dose in the forw EMCal next to the beam pipe:
~2.5 krad/year at L=10^{34} $cm^{-2}s^{-1}$

Highest flux in the forw EMCal next to the beam pipe:
~10^{11} n/cm^2/year at L=10^{34} $cm^{-2}s^{-1}$

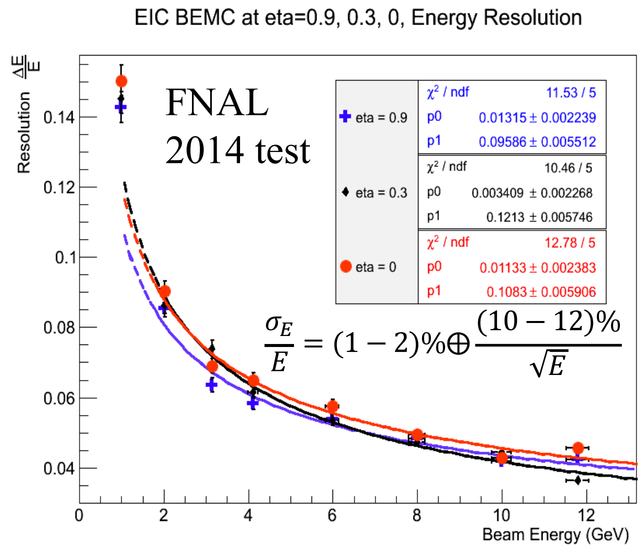
W/SciFi: sPHENIX → EIC

sPHENIX



Trapezoidal blocks

EIC R&D



Rectangular blocks

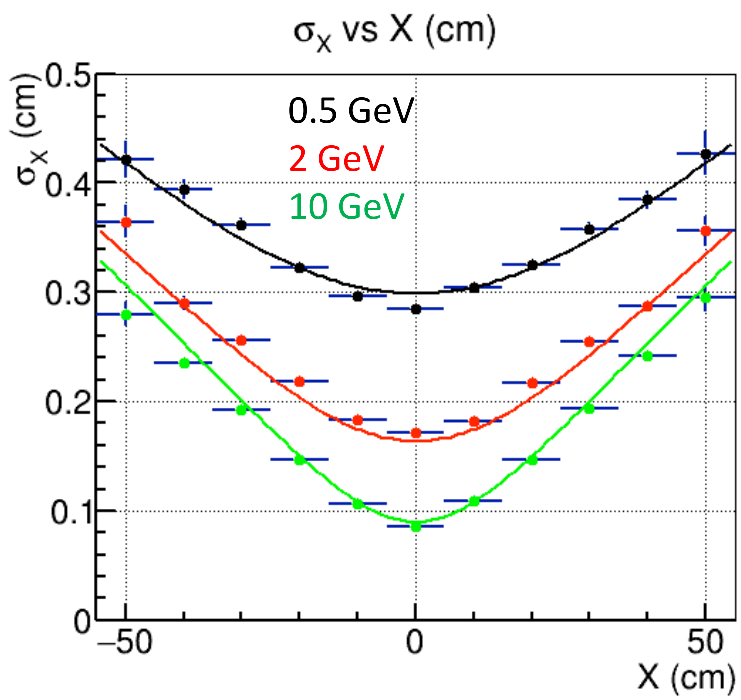
Already satisfies the EIC Detector requirements

Further improvements:

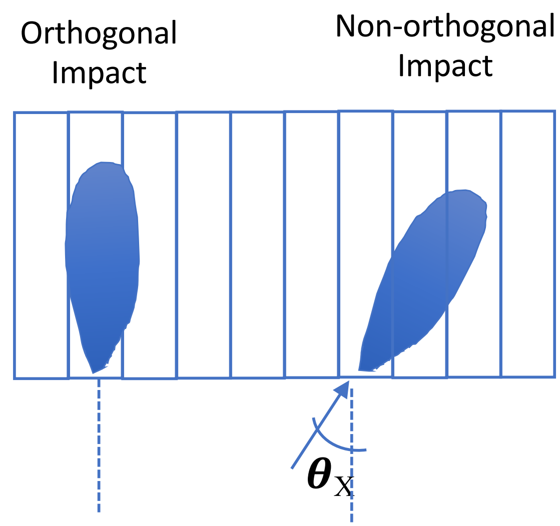
- Higher eff. for light collection
- Improved uniformity

Non-projectivity and pos. res.

Backward EMCal



Full GEANT simulation with all material



$$\sigma_X = \left(\frac{2mm}{\sqrt{E[GeV]}} + 0.3\text{mm}\right) \oplus (X_0 \sin\theta_X)$$

Non-projectivity term
(due to long. shower fluct)

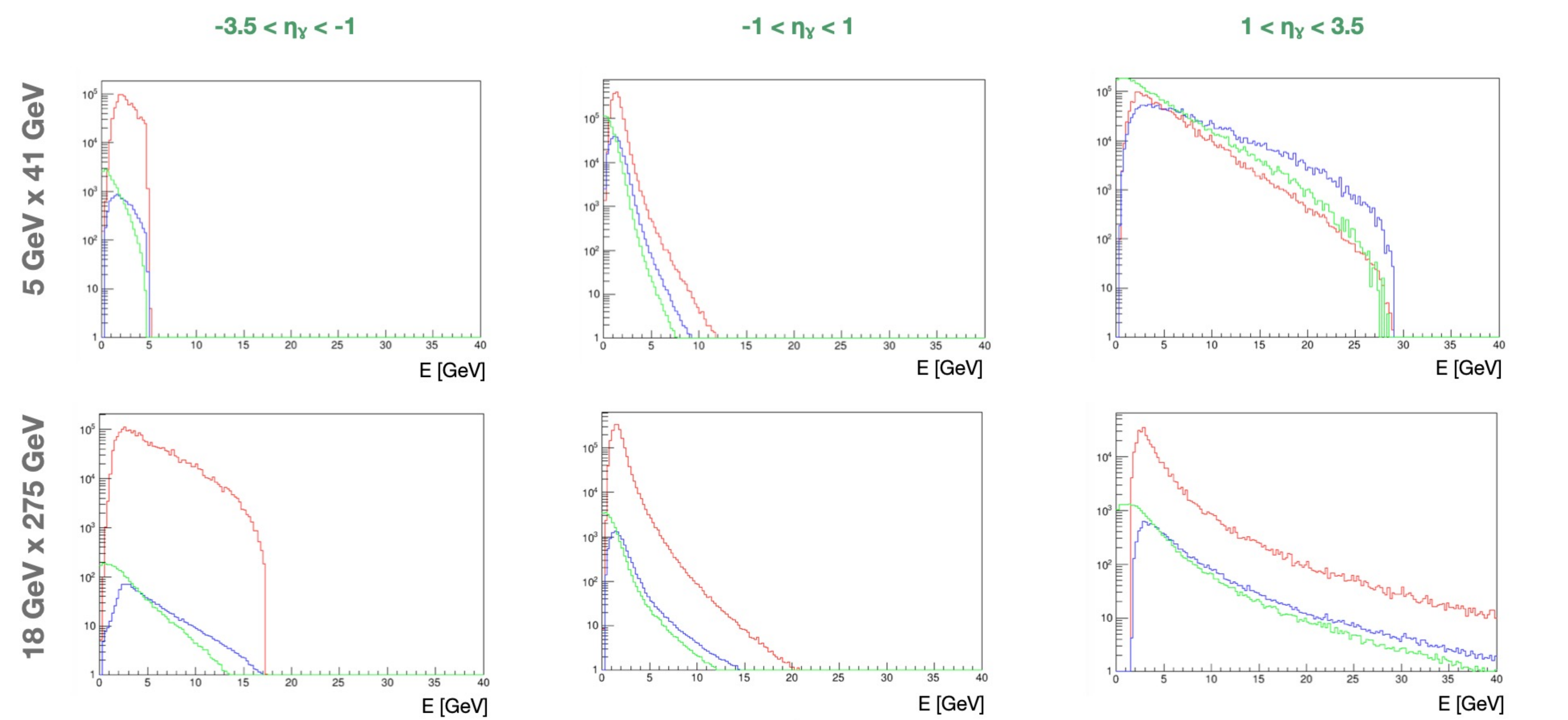
Maximal non-projectivity term for the backward EMCal is 3mm ($\boldsymbol{\theta}_{max}=20^0$)

Exclusive: DVCS and pi0

distributions of energy for two beam energies and various ranges of eta

$Q^2 > 1$ GeV^2
$0.01 < y < 0.95$
$|\eta_{e^-}| < 3.5$
$L = 10$ fb^{-1}

- DVCS: γ
- DVMP π^0: π^0
- DVMP π^0: $\pi^0 \to \gamma\gamma$



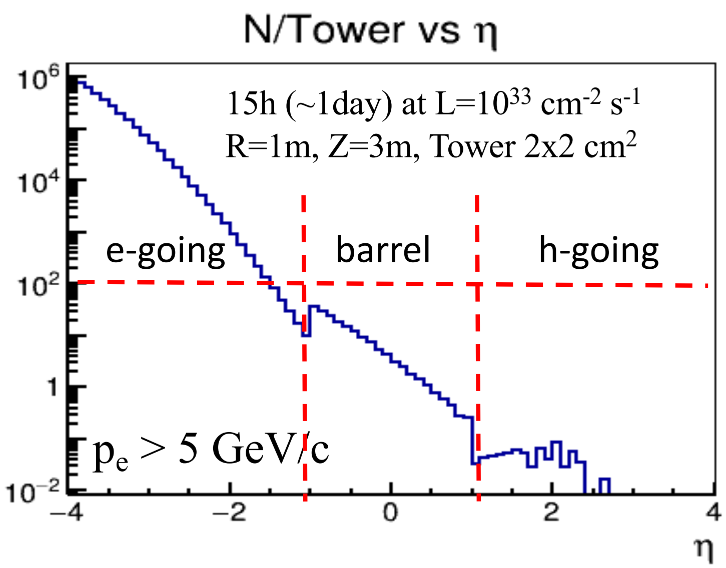
Electron-Ion Collider

Calibration

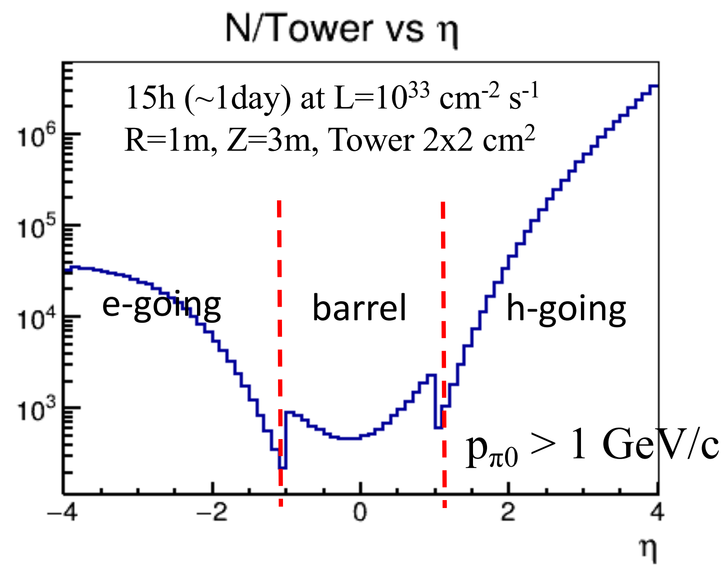
"Usually" a few hundred particles per tower needed

Depends on resolution, gain alignment, background, other syst. effects

Electron



π0 → γγ



- ✓ 1-day statistics is enough for e-endcup
- ✓ Barrel needs more data
- ✓ Not enough for h-endcup

1-day statistics looks enough for all EMCals