

Electromagnetic Calorimetry Status Report

Alexander Bazilevsky (BNL)

L3/CAM EMCaI

EIC Detector Comprehensive Design Review

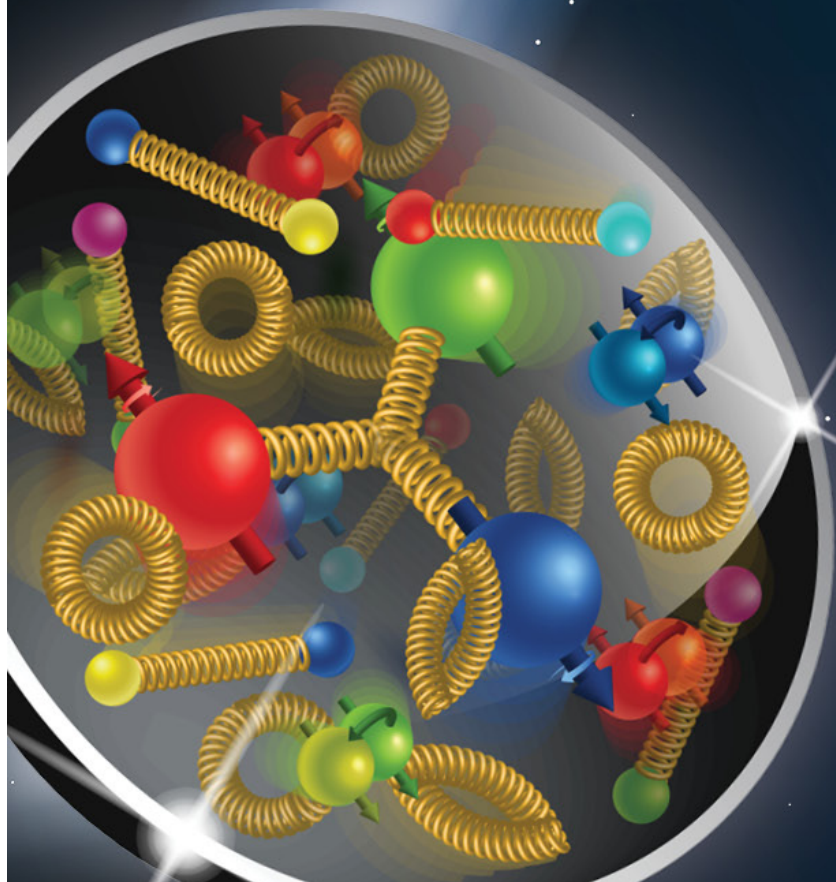
August 29-30, 2023

Electron-Ion Collider

BROOKHAVEN
NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF
ENERGY | Office of
Science

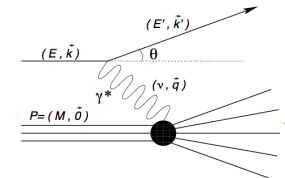


EMCal for an EIC Detector

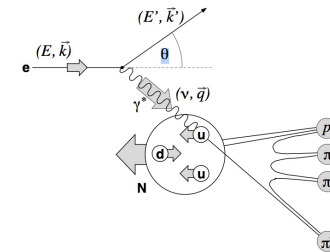
Electron/photon PID, energy, angle/position:

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

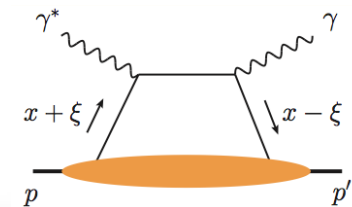
Inclusive DIS: scattered electron



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



Exclusive DIS: DVCS photons, $J/\psi \rightarrow ee$ etc.



Detector Requirements: Summary

As documented in YR and

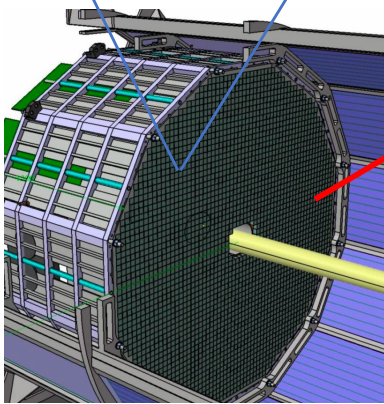
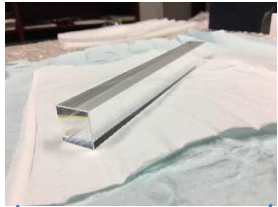
“General, Functional, and Performance Requirements for the EIC Detector Systems”

	Electron endcap	Barrel	Hadron endcap
Energy Resolution	$\frac{(2-3)\%}{\sqrt{E}} \oplus 1\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$
Shower Energy range	0.1–18 GeV	0.1–50 GeV	0.1–100 GeV
π^\pm suppression (helped by other subsystems)	Up to 10^4		
π^0/γ discrimination	Up to 18 GeV/c	Up to 10 GeV/c	Up to 50 GeV/c
Rad dose (includes background) at $10^{34} \text{ sm}^{-2} \text{ sec}^{-1}$	<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 $10^{34} \text{ sm}^{-2} \text{ sec}^{-1}$	$10^{10} / \text{cm}^2 / \text{year}$	$10^{10} / \text{cm}^2 / \text{year}$	$10^{11} / \text{cm}^2 / \text{year}$
Limited space	Compact (small X_0)		
Material on the way	Minimized		

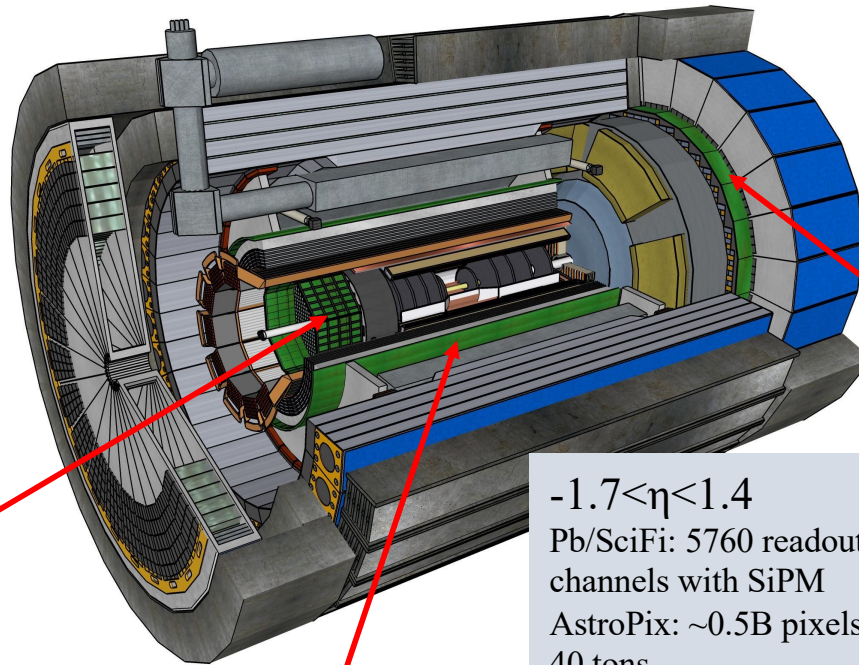
- Continuous acceptance (particularly from e-endcap to barrel)
- Photosensors and FEE tolerate magnetic field

EM Calorimetry in EIC Detector

PbWO₄

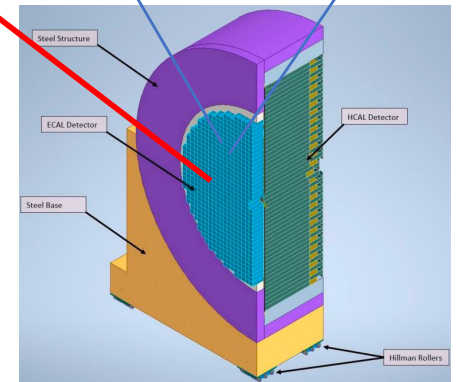
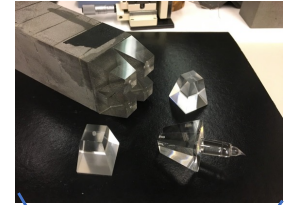


$-3.5 < \eta < -1.7$
~3k crystals
 $R_{\text{outer}} = 64\text{cm}$
SiPM readout
2 tons



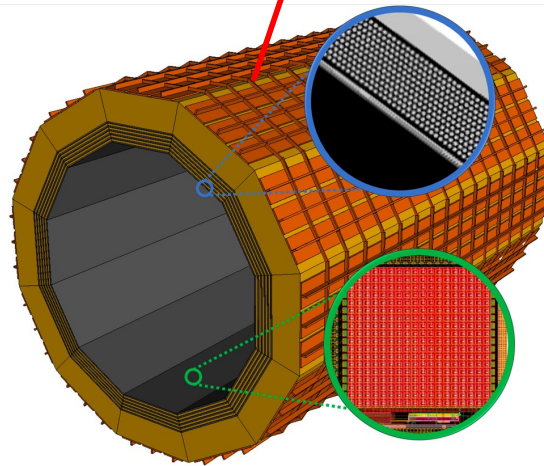
$-1.7 < \eta < 1.4$
Pb/SciFi: 5760 readout channels with SiPM
AstroPix: ~0.5B pixels
40 tons

W/SciFi



$1.4 < \eta < 3.7$
~16k towers
 $R_{\text{outer}} = 160\text{cm}$
SiPM readout
20 tons

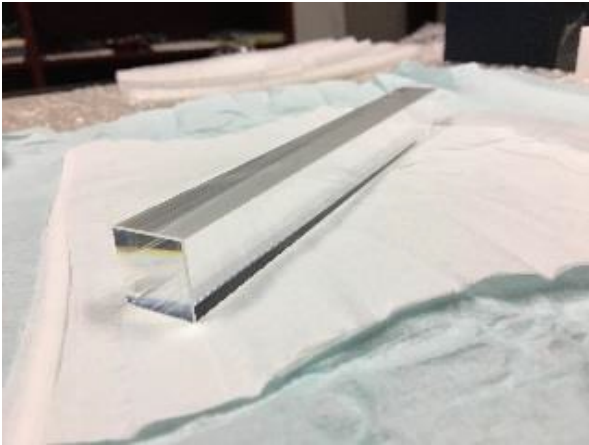
Pb/SciFi



AstroPix

e-endcap: PbWO_4

- High resolution
- High e/π separation for eID



Well established technology

Compact & High granularity: $2 \times 2 \times 20 \text{ cm}^3$

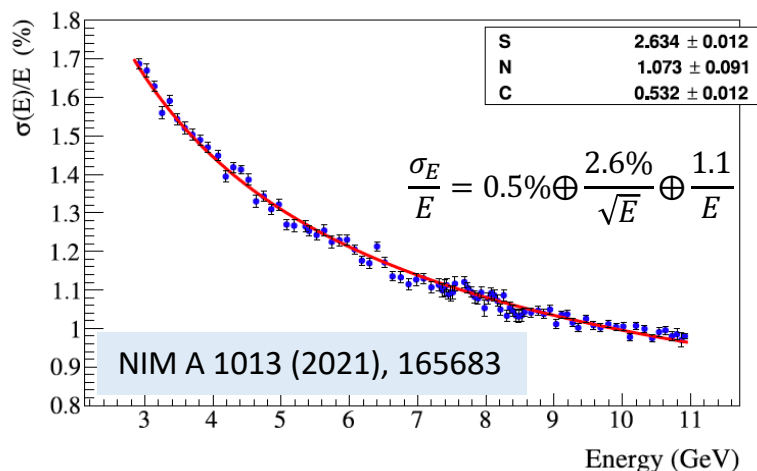
High resolution: $\frac{\sigma_E}{E} = (0.4 - 1)\% \oplus \frac{(2-3)\%}{\sqrt{E}}$

Excellent e/π capabilities: π suppression up to a few 10^3

Radiation hard: $>1000 \text{ krad}$

Temperature sensitive: $d(\text{LY})/dT = -(2-3)\%/^\circ\text{C}$

Jlab-PrimEx eta/NPS PWO EMCal prototype

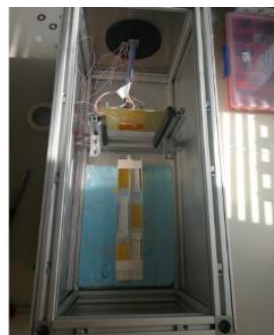
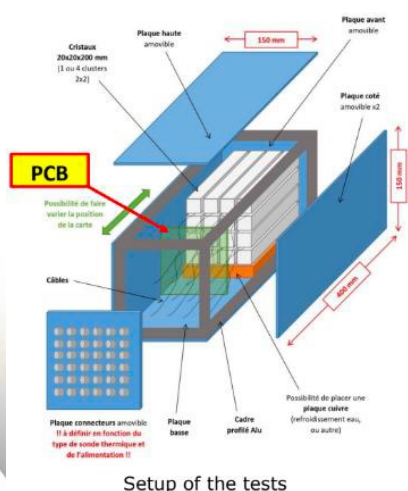
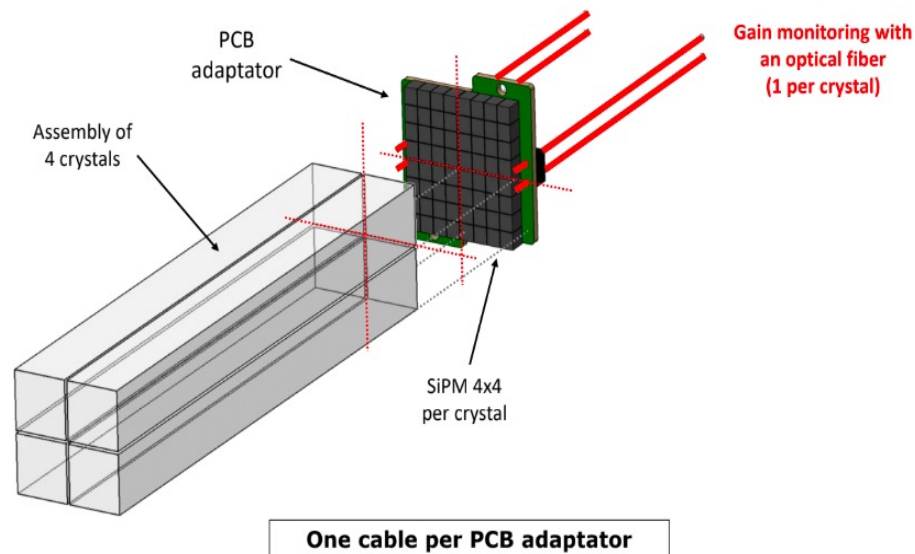


- **Consortium with >10 institutions**
- Synergy with other projects: NPS and FCAL (JLab)
Expertise, Resources, Prototypes, etc
- Extensive experience from recent PANDA (GSI) and CMS (CERN)
- In contact with Vendor (CRYTUR/Czech Republic)
- Ongoing R&D to finalize readout
- NSF MSRI proposal submitted: May 4, 2023

e-endcap: Readout and Cooling



16 $3 \times 3 \text{ mm}^2$ or 4 $6 \times 6 \text{ mm}^2$
SiPM per crystal



11 temperature sensors:

- 6 on crystals
- 3 inside the box (ambient)
- 2 outside the box (ambient)

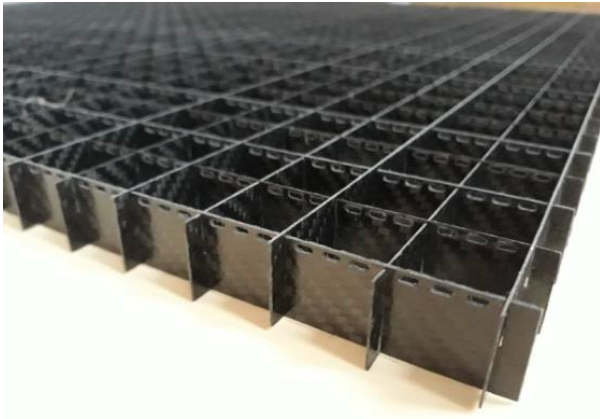
Thermal Design and Test

Operation at room temperature

Simulations to quantify the effect of ambient temperature fluctuation on the crystal temperature

Measurements on a prototype

e-endcap: Mechanics and Integration



0.5-mm-thick C-fiber
between crystals along 2 cm
in the front&back; 0.5 mm of
air elsewhere

**Support
structure for
crystals**
(can be used for
cooling)

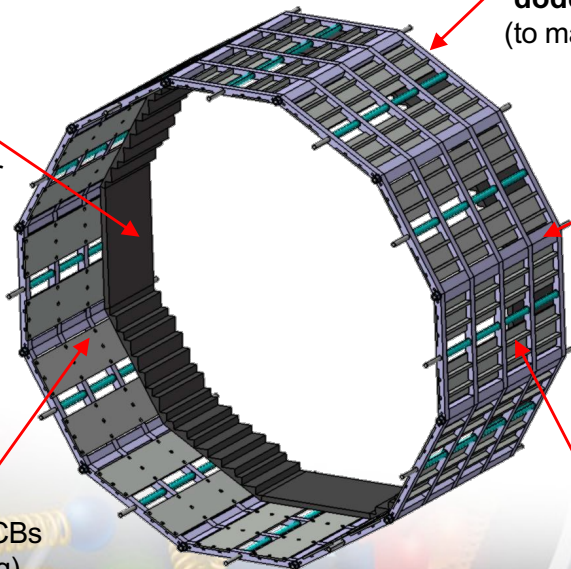
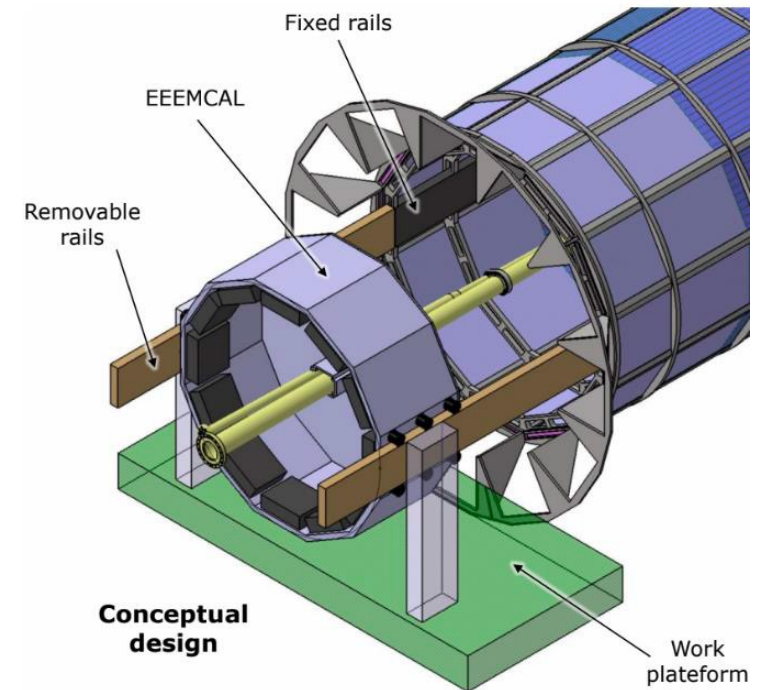


Plate
(to fasten the PCBs
and the cooling)

**5 (at least) strong
dodecagon frames**
(to make the assembly
easier)

Mechanical pieces
(to reinforce the structure
at the angles)

**Threaded rods
and struts**
(to ensure a good
assembly and
reinforce the
structure)

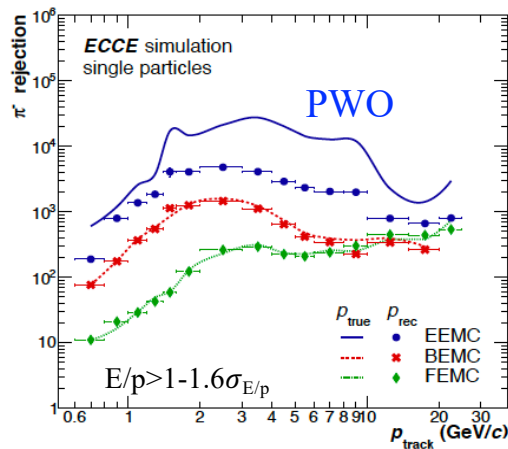


Advanced Preliminary Design

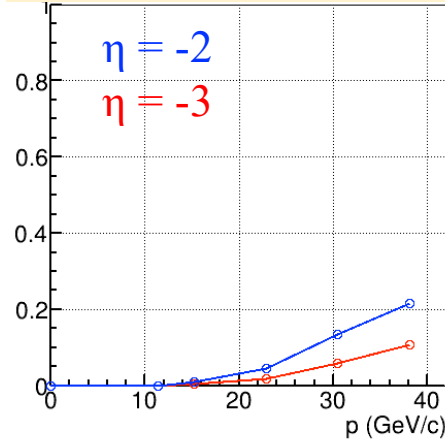
e-endcap: Performance at EIC

Full GEANT simulation with full detector implementation

π^- rejection

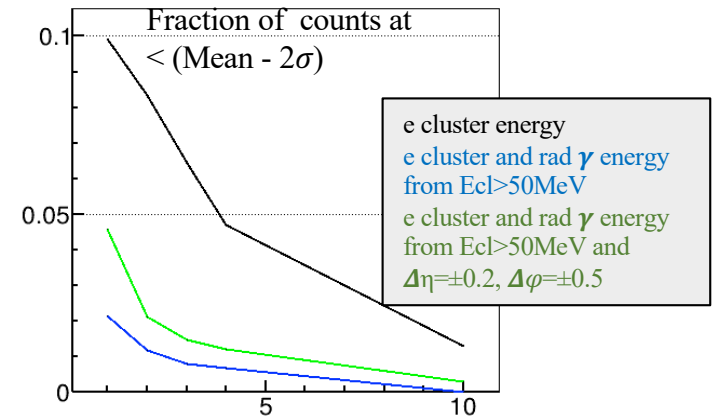


π^0 merging prob (after shower profile analysis)



Material effect

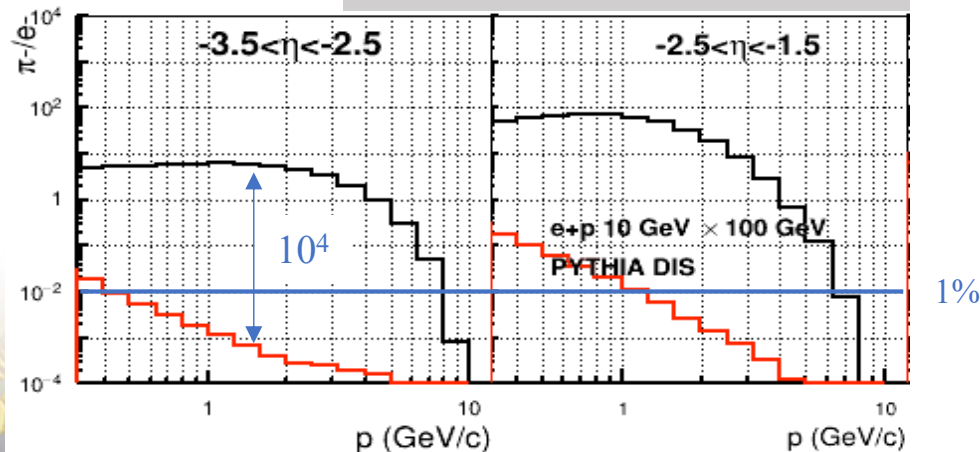
Eff. loss vs E (GeV)



π^-/e^-

No cuts

E/p cut and momentum conservation



* Additional strong suppression of π^- at $< 2.5 \text{ GeV/c}$ is provided by pfRICH

- $\gg 1\%$ π^- contamination is expected for the DIS electron reconstruction
- $\sim 100\%$ eff to discriminate $\pi^0 \rightarrow \gamma\gamma$ over single γ , up to 20 GeV/c
- Material effect within requirements

Fully satisfies the EIC
Detector Requirements

e-endcap: PbWO₄ for LLP

Parameter	Unit	NPS Required
Light Yield (LY) at RT (90% within 100 ns gate at RT, for all sides polished crystals)	pe/MeV	≥15
LY uniformity between blocks	%	10%
LY(100ns)/LY(1μs)	%	>95
Longitudinal Transmission at λ=360 nm	%	≥35
at λ=420 nm	%	≥60
at λ=620 nm	%	≥70
Transverse Transmission and LY uniformity along crystal	%	10
Inhomogeneity of Transverse Transmission Δλ at T=50%	nm	≤5
Induced radiation absorption coefficient Δk at λ=420 nm and RT, for integral dose >100 Gy	m ⁻¹	<1.1
Mean value of dk	m ⁻¹	≤0.75
Tolerance in Length	μm	≤±100 -≤±50
Tolerance in sides	μm	
Surface polished, roughness Ra	μm	≤0.02
Tolerance in Rectangularity (90°)	degree	≤0.1
Purity specific. (raw material)		
Mo contamination	ppm	<10
La, Y, Nb, Lu contamination	ppm	≤40

Based on EIC R&D results and experience from recently built/designed PbWO₄-Crystal EMCals:

- NPS-Jlab
- CMS-CERN
- PANDA-GSI (to be built)

Well established QA protocol

Schedule:

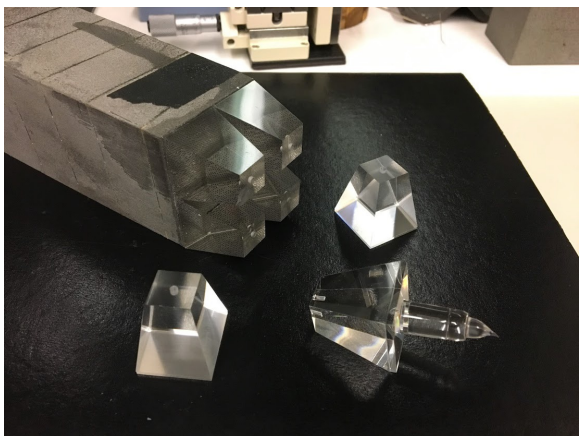
Specs:	Finalized
Final Design Review:	July 21, 2023
Contact award:	Summer 2024
Material Delivery:	Summer 2024 – Summer 2028

Final Design Review:

Fully acknowledged the PbWO₄ readiness for the LLP

h-endcap: W/SciFi

- Good resolution
- High granularity for π^0
- $e/h \sim 1$ for jets



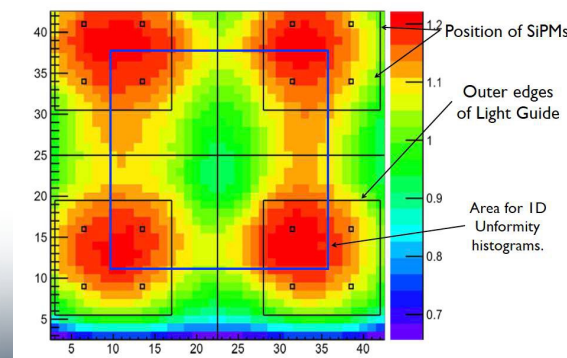
Pioneered by UCLA
sPHENIX EMCal: 25k towers

- Compact: $X_0 = 0.7\text{cm}$
- High granularity: $R_m = 2\text{cm}$
- Sampling fraction: $\sim 2.3\%$
- Good resolution

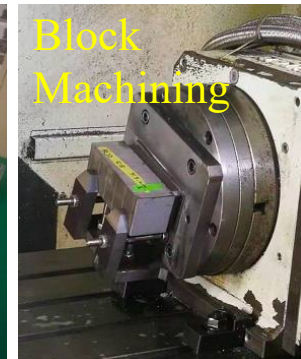
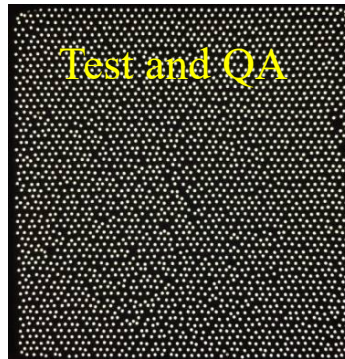
- ~ 10 institutions (USA, China)
- Extensive expertise and capabilities in executing large scale projects (RHIC, JLab, CERN, Super KEKB)
- Participated in building sPHENIX EMCal
- ~ 10 years of EIC R&D

R&D:

- SiPM readout
- Improve light collection eff. and uniformity



h-endcap: Production Chain

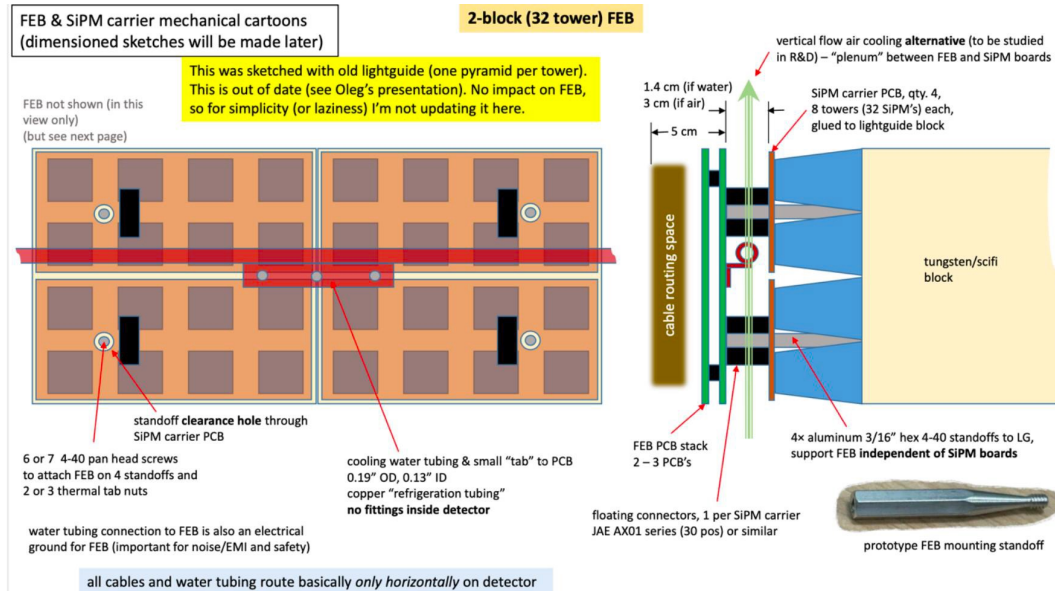


Production chain is fully established

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

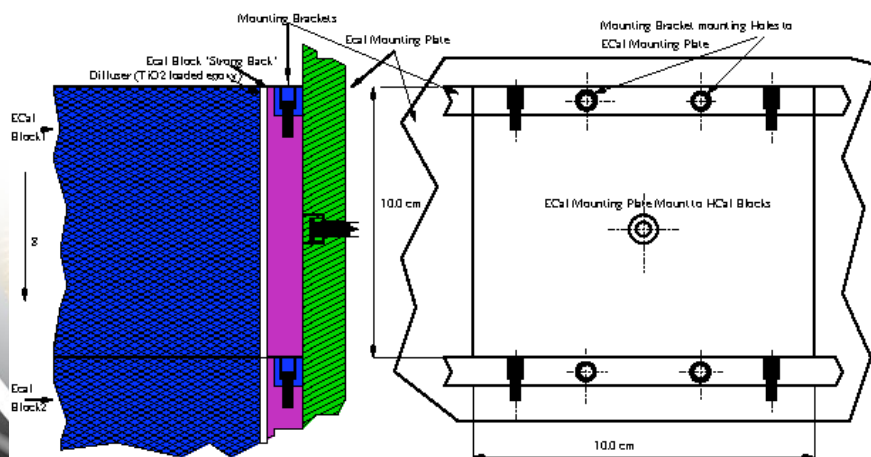
Plan to setup another factory in US

h-endcap: Mechanical Design



Readout, Cooling

4 6x6mm² SiPM per tower



Block installation Design and Structural test

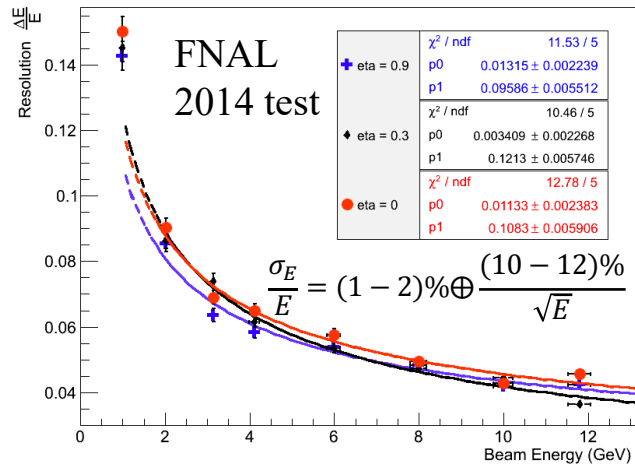


Electron-Ion Collider

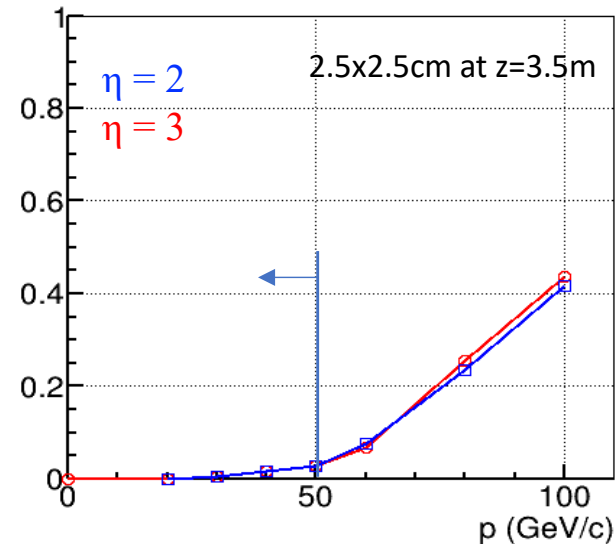
h-endcap: Performance at EIC

Energy Resolution

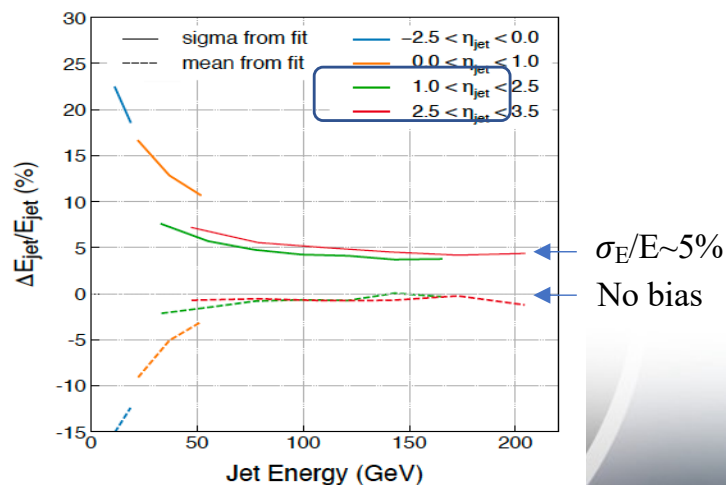
EIC BEMC at eta=0.9, 0.3, 0, Energy Resolution



π^0/γ : merging prob



Jet resolution and bias (ECal+HCal)



- Good energy resolution
- Excellent π^0/γ discrimination capabilities
- Provides high resolution and minimally biased jet measurements (in duet with HCal)

Fully satisfies the EIC Detector Requirements

h-endcap: SciFi for LLP

1. Single clad fibers, round cross section
2. diameter 0.47 mm
3. diameter variation $\pm 2\%$
4. cladding thickness 3% of diameter
5. attenuation length for blue light > 3 m
6. peak emission 450 nm
7. light yield > 7000 ph/MeV
8. scintillation decay time < 3 ns
9. delivered in canes ~ 1 m long, or spools, or both
10. total length 3000 km

Based on sPHENIX experience and ongoing fiber characterization

Well established QA protocol

Schedule:

Specs:	Finalized
Final Design Review:	September 13, 2023
Contact award:	Summer 2024
Material Delivery:	Summer 2024 – Summer 2028

Ready for the LLP in September 2023

Barrel: Pb/SciFi + Imaging

- Good resolution
- High e/π separation for eID

Selected after rigorous review by ePIC in Mar-Apr 2023

Hybrid Concept:

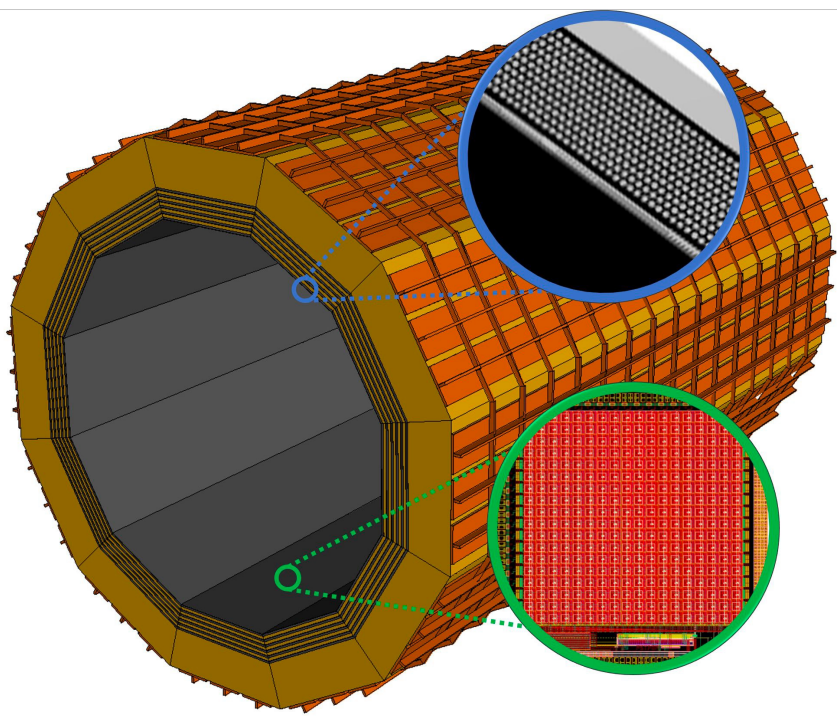
6 imaging Si layers (4 layers in baseline), Interleaved with 5 Pb/SciFi layers, followed by a thick Pb/SciFi layer ($17X_0$ total)

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

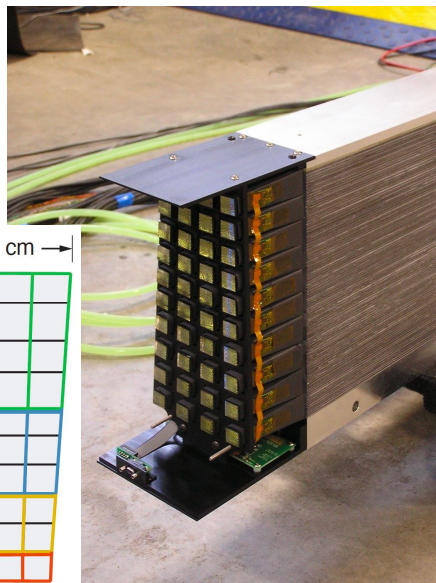
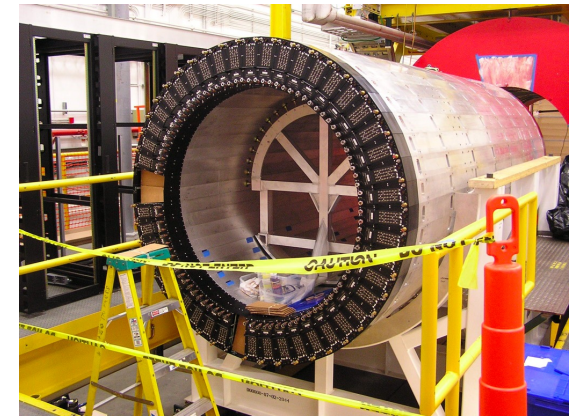
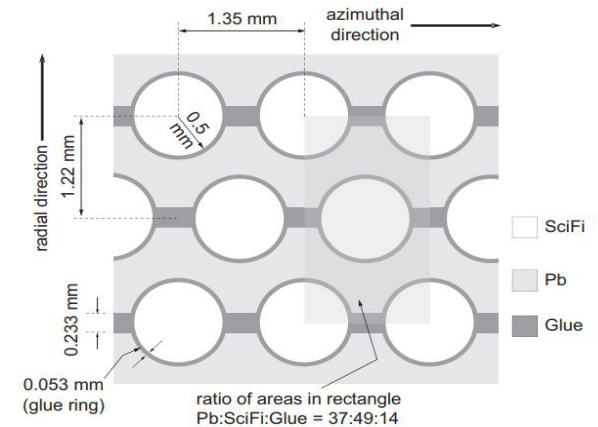
Mature technology (GlueX, KLOE)

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
Study response to electrons/pions/muons to benchmark simulation
Finalize readout

Barrel: Imaging

Based on AstroPix sensors

Developed for AMEGO-X (NASA)

CMOS sensor based on ATLASpix3

4 layers (of 6) in a baseline design

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

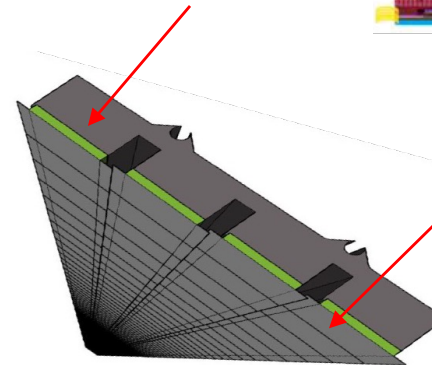
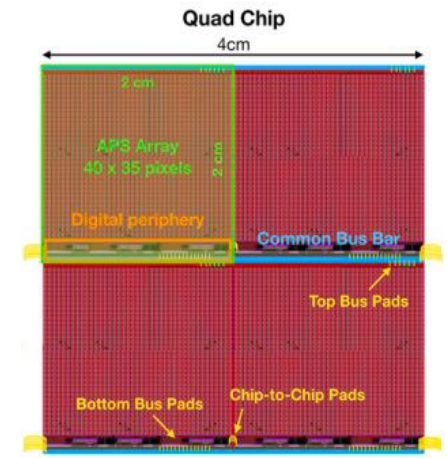
Ongoing R&D in FY23/24 (FNAL)

Multilayer chip test

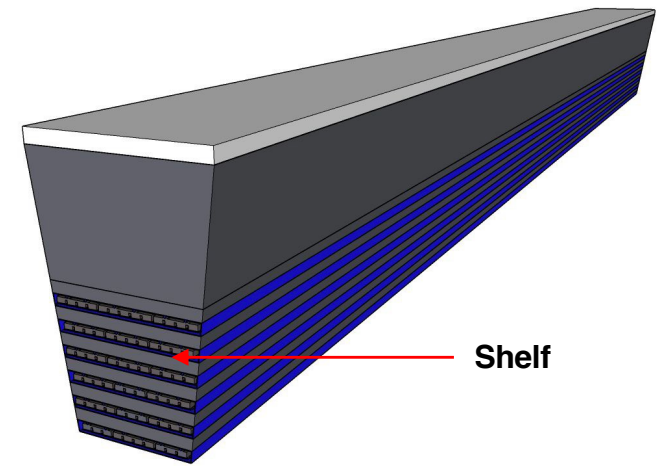
Irradiation test

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

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

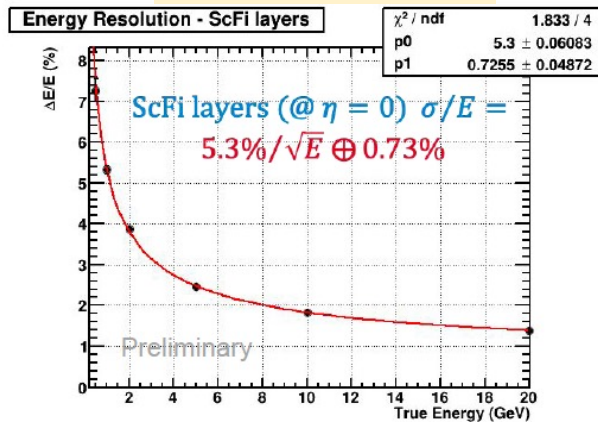


AstroPix Stave
Consists of 1 x 100 chips with the support structure

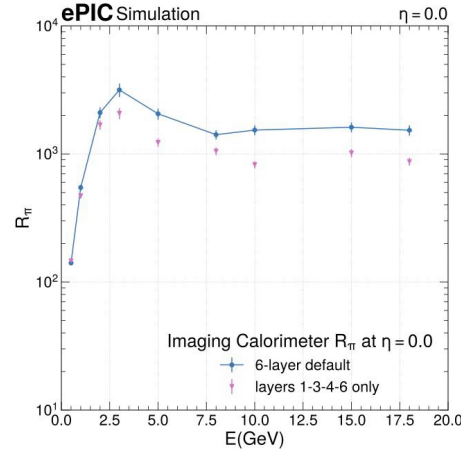


Barrel: Performance at EIC

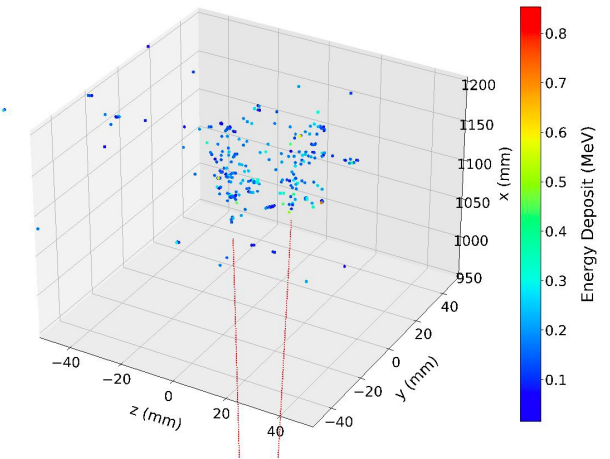
Energy Resolution



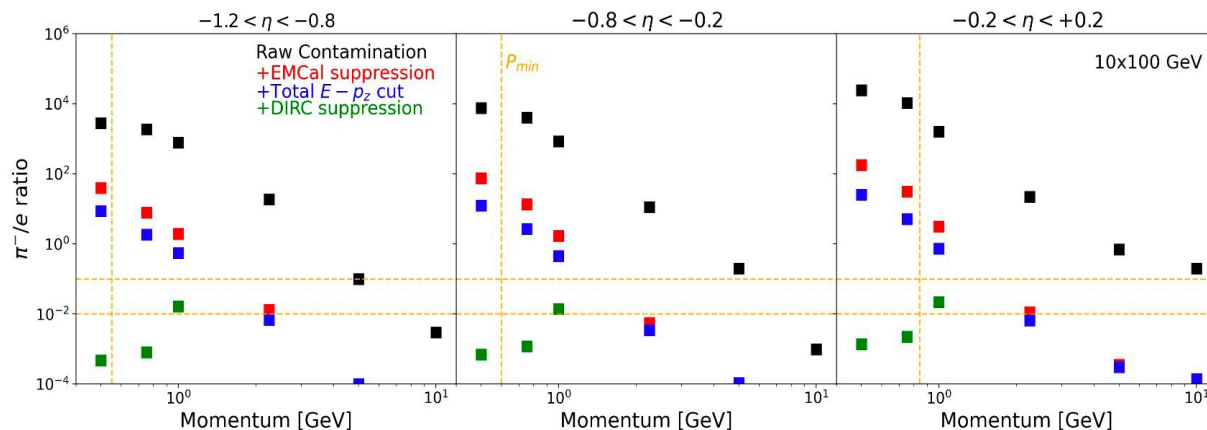
π^- rejection



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

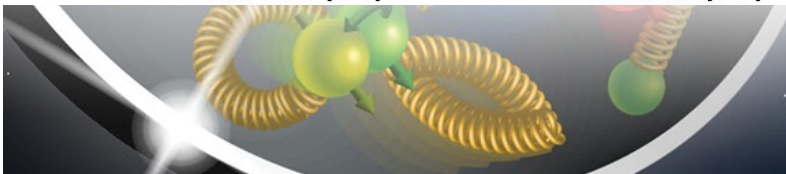


DIS electron purity



- Very good energy resolution
- Strong π^\pm rejection for eID
- DIS electron purity of $\sim 99\%$ or better achieved
- π^0/γ far beyond the required 10 GeV

Fully satisfies the EIC Detector Requirements



Barrel: SciFi for LLP

1. Double or Single clad fibers, round cross section
2. diameter 1.0 mm
3. diameter tolerance shall be less than 2%, so in this case to better than 20 μm .
4. Single clad: cladding thickness $\sim 2\%$ of diameter, Double-clad: cladding thickness $\sim 4\%$ of diameter
5. attenuation length for blue light $> 3.5 \text{ m}$
6. emission spectrum of blue-green light
7. light yield $> 7000\text{-}8000 \text{ ph/MeV}$
8. scintillation decay time $< 3 \text{ ns}$
9. total length 4500 km
10. delivered in spools

Based on GlueX experience and ongoing R&D and fiber characterization

Well established QA protocol

Schedule:

Specs:	~Finalized
Final Design Review:	September 13, 2023
Contact award:	Summer 2024
Material Delivery:	Summer 2024 – Summer 2028

Ready for the LLP in **September 2023**

SiPM for (LL)Procurement

Defined by Light Yield and dynamic range:

$$\frac{N_{pe}^{max}}{N_{pixel}^{max}} \sim 0.2$$

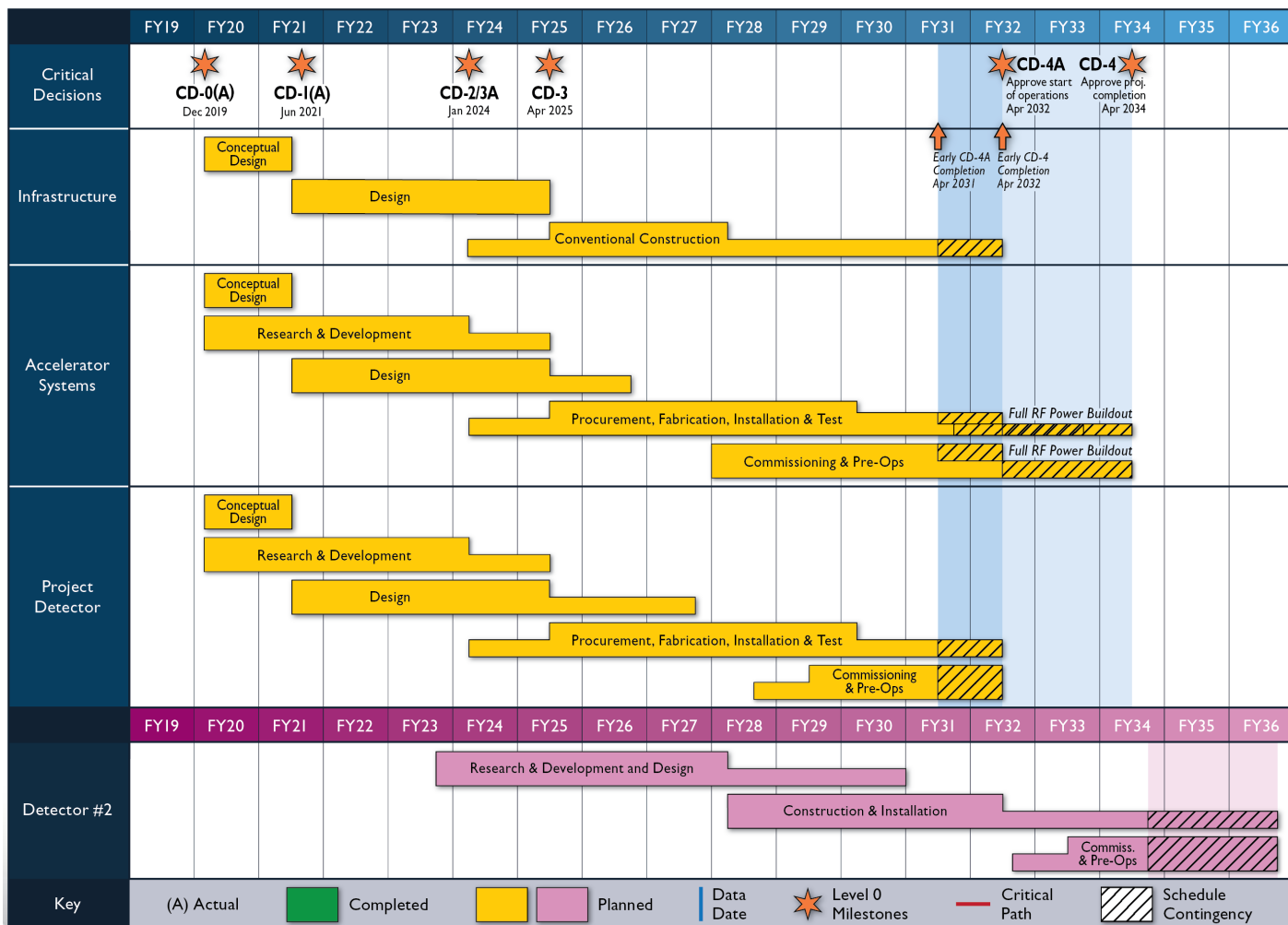
	Backward	Barrel	Forward
Light Yield per GeV	10k	1k	1k
E _{max} per RO channel, GeV	15	10	100
N _{pe} max	150k	10k	100k
SiPM size (4 per RO channel)	6x6 mm ²	6x6 mm ²	6x6 mm ²
SiPM pixel size	15 um	50 um	15 um
SiPM: N pixel max	640k	57k	640k

Final Design Review: **September 14, 2023**

Then we are ready for Procurement

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

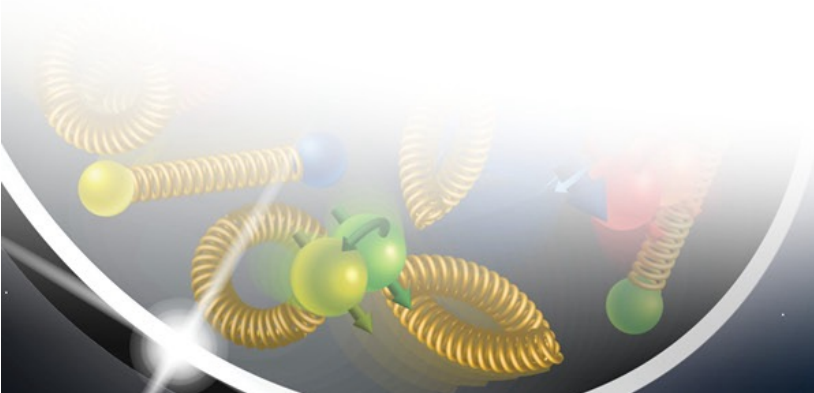
LLP for EMCAL:

- PWO crystal
- Sc. Fibers
- SiPMs

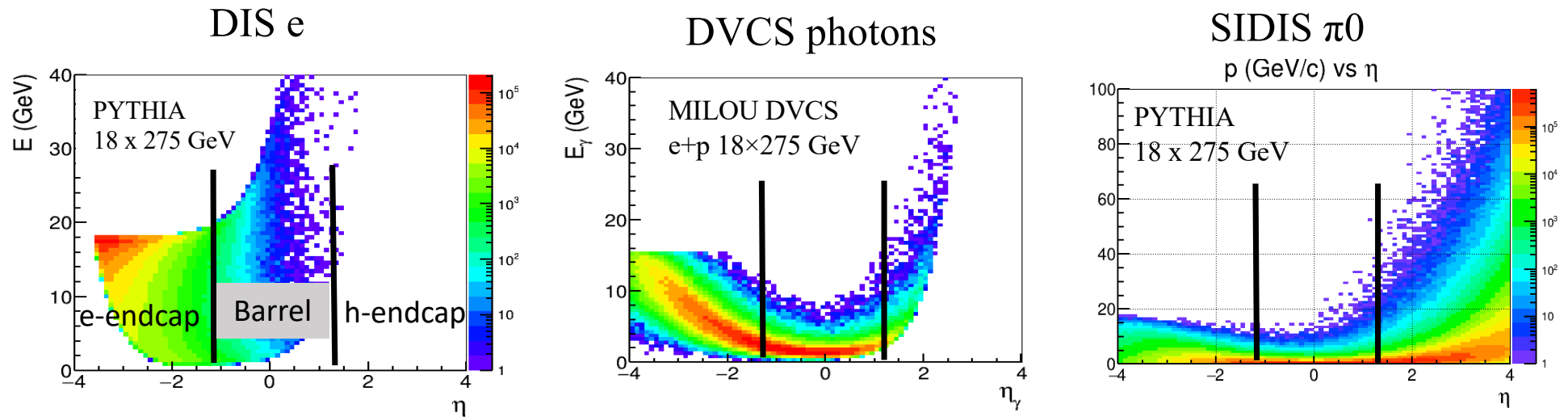
Summary

- Physics requirements are well defined and documented in the YR and “General, Functional, and Performance Requirements for the EIC Detector Systems”
- The selected EMCal technologies satisfy or exceed the requirements
 - e-endcap: PbWO₄ crystal, well established technology
 - Barrel: Pb/SciFi + Imaging (AstroPix), both are well established technologies
 - h-endcap: W/SciFi, well established technology
- Participating groups with extensive expertise and capabilities for selected calorimetry technologies
- Steadily approaching Preliminary Design level
 - Design is mature enough to launch Long Lead Procurement (LLP)
 - LLP item specs are well defined (to be finalized before Oct 2023)
- Fabrication/assembly plans well built in the overall EIC project and Detector schedule

Backup



Coverage, Energy Range



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

Avoid gap, particularly in e-endcap/barrel transition

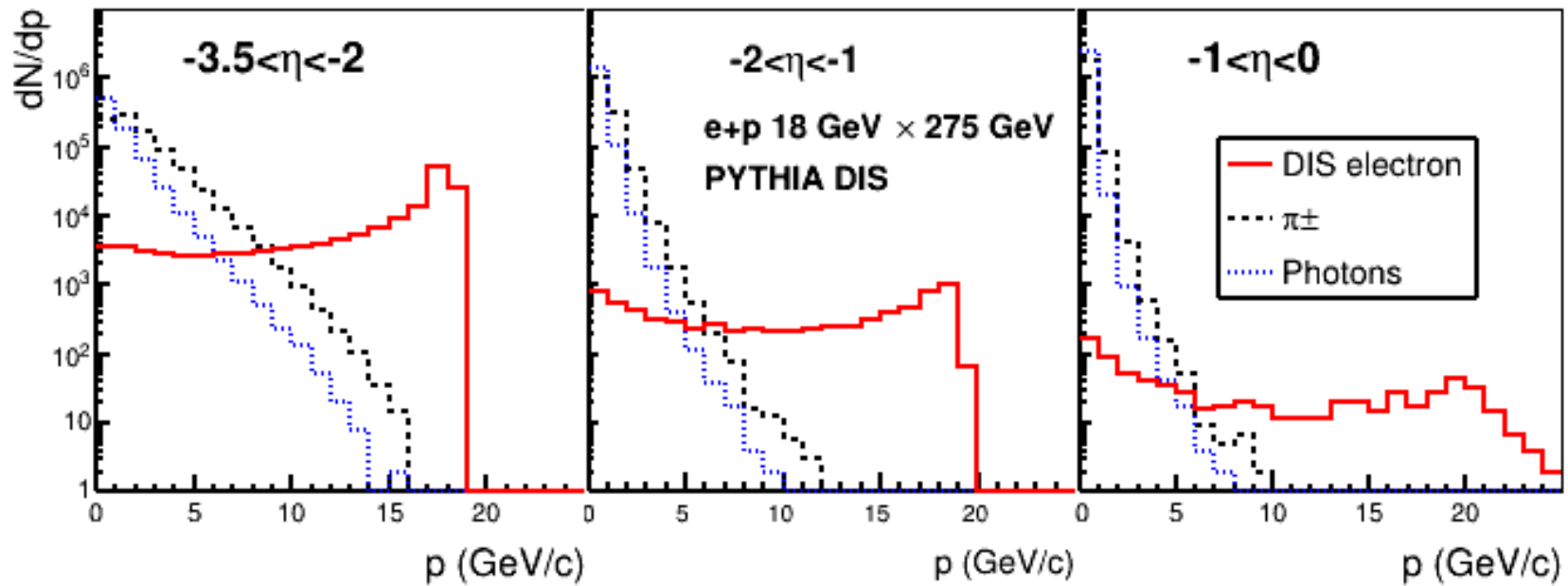
Energy range

e-endcap: up to electron beam energy (up to 18 GeV)

Barrel: up to ~ 50 GeV for DIS e, and ~ 10 GeV for γ and π^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)

Effect of material on the way

➤ Material on the way to EMCal is inevitable

Other detectors, cables, pipes, frames, etc

➤ It degrades the performance of the high resolution EMCal

Photon conversion

Bremsstrahlung radiation by electron

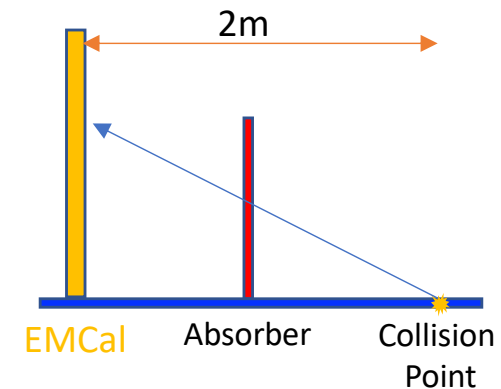
Early shower

➤ Energy gets absorbed in the material

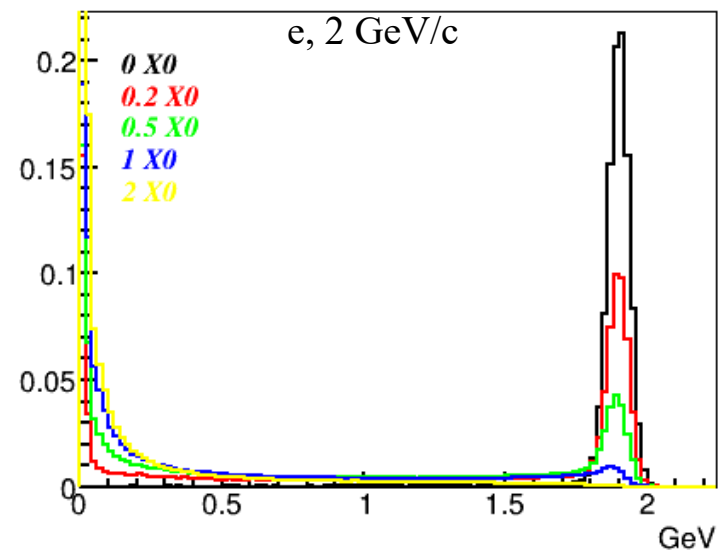
➤ Energy gets distributed in the EMCal, e.g. due to Bremsstrahlung radiation by electron

- Single cluster reco leads to eff. loss
- The eff. can be recovered by radiated photon reco
- The closer to the EMCal the smaller the effect
- The higher Bdl the larger the effect
- Rad. photons are localized in arcs with the same polar angle as a parent electron => topological search window

GEANT simulation for a single electron



Cluster Energy

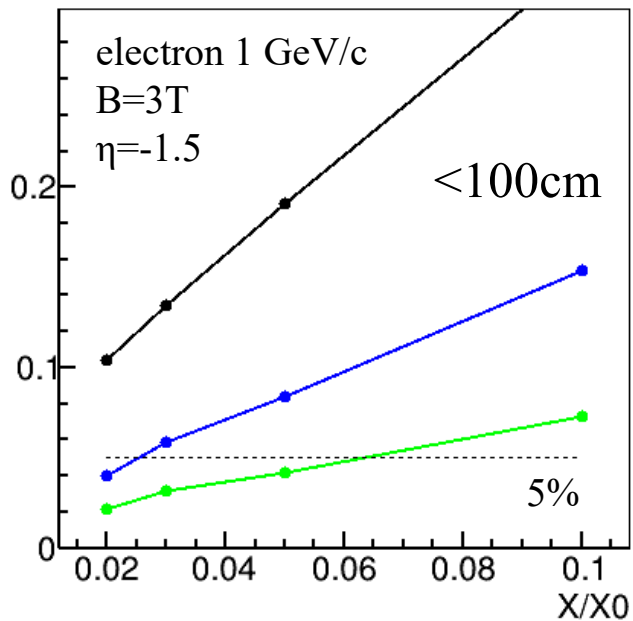


Effect of material on the way

The most extreme case:

Highest Bdl, lowest e momentum, close to coll. point

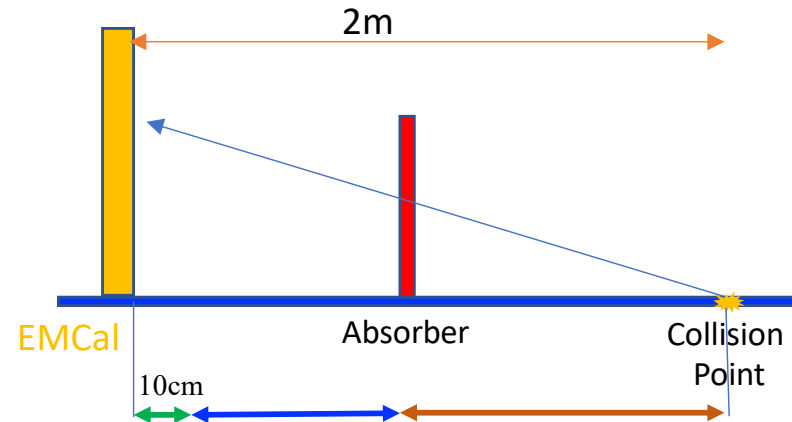
Efficiency loss (with 2σ cut) vs X/X_0



e cluster energy

e cluster and rad γ energy from $E_{cl}>50\text{MeV}$

e cluster and rad γ energy from $E_{cl}>50\text{MeV}$
and $\Delta\eta=\pm 0.2$, $\Delta\phi=\pm 0.5$



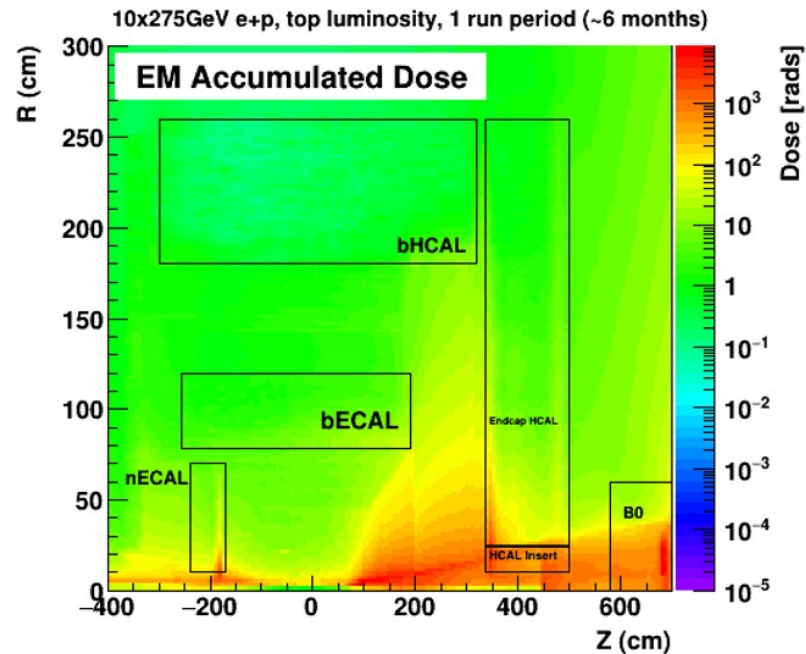
<50% X_0	<20% X_0	<(3-6)% X_0	Electron > 1GeV
<30% X_0	<10% X_0	<10% X_0	Photon > 0.1GeV

Exclusive requirements
(the whole effect assumed from one region)

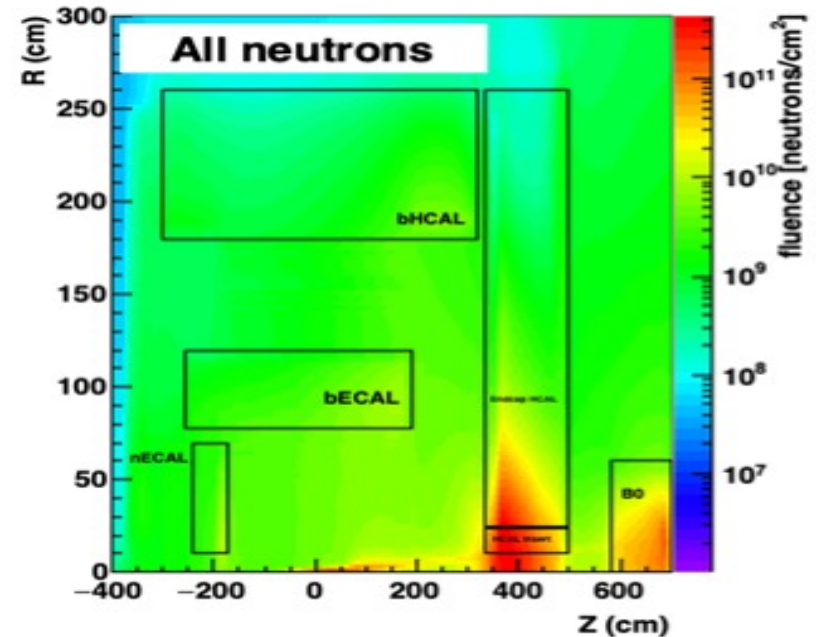
The amount and localization of tolerable material formulated

The requirements are relaxed for $B=1.7-2\text{T}$

Rad Dose and Neutron Flux



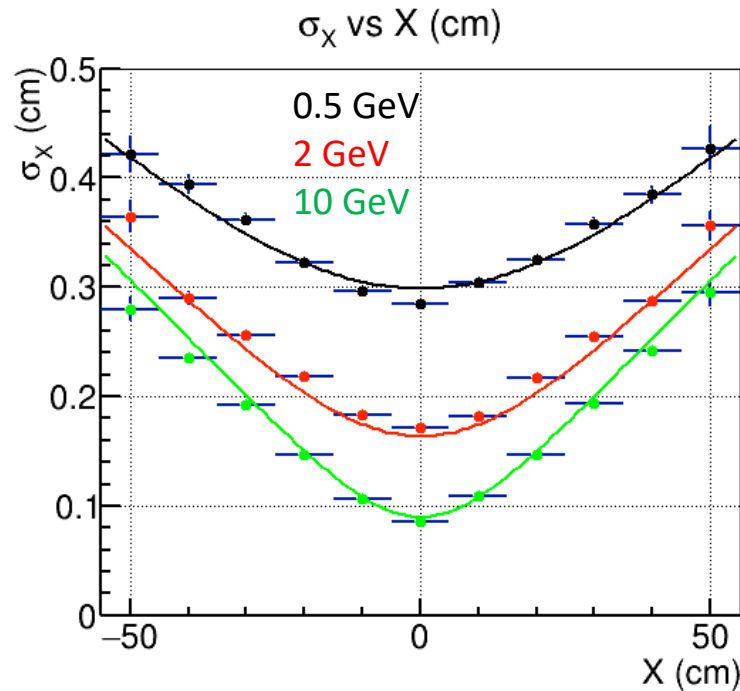
Highest dose in the forw EMCAL
next to the beam pipe:
 $\sim 2.5 \text{ krad/year}$ at $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$



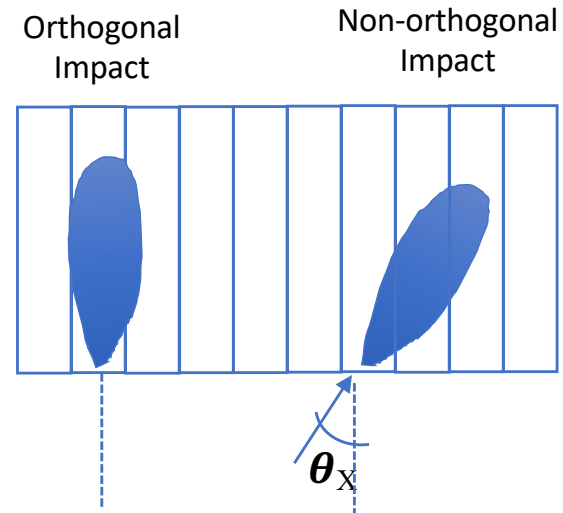
Highest flux in the forw EMCAL next
to the beam pipe:
 $\sim 10^{11} \text{ n/cm}^2\text{/year}$ at $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Non-projectivity and pos. res.

Backward EMCal



Full GEANT simulation with all material



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

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

Maximal non-projectivity term for the backward EMCal is 3mm ($\theta_{\text{max}}=20^\circ$)

Exclusive: DVCS and π^0

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

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

• DVCS: γ

• DVMP π^0 : π^0

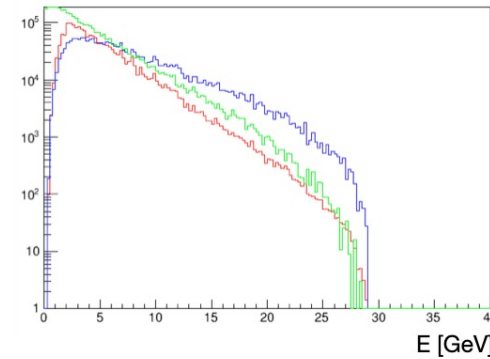
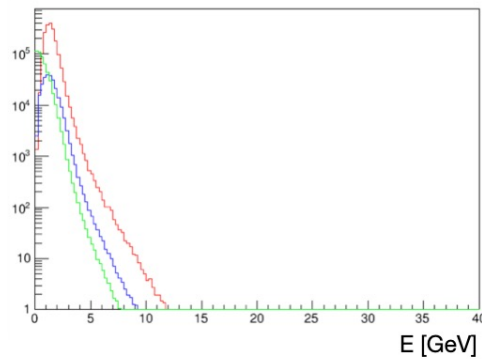
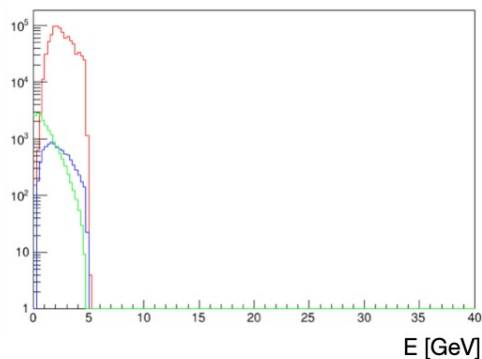
• DVMP π^0 : $\pi^0 \rightarrow \gamma\gamma$

$-3.5 < \eta_\gamma < -1$

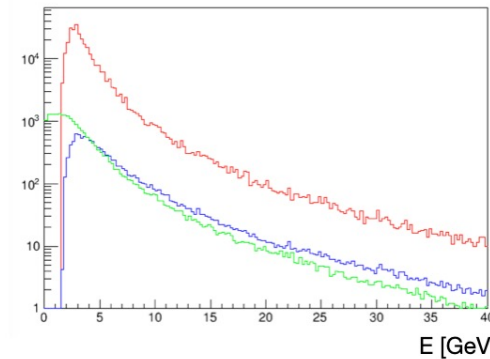
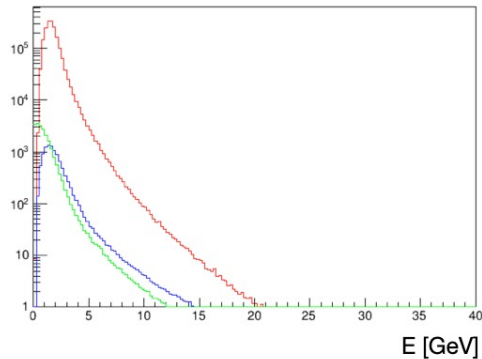
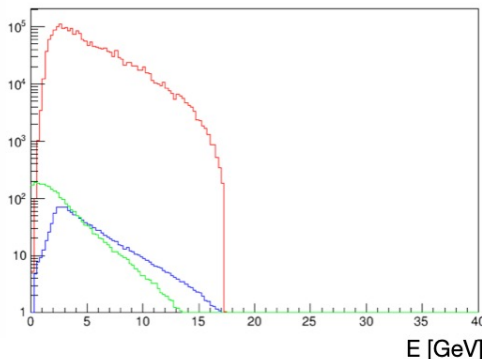
$-1 < \eta_\gamma < 1$

$1 < \eta_\gamma < 3.5$

5 GeV x 41 GeV

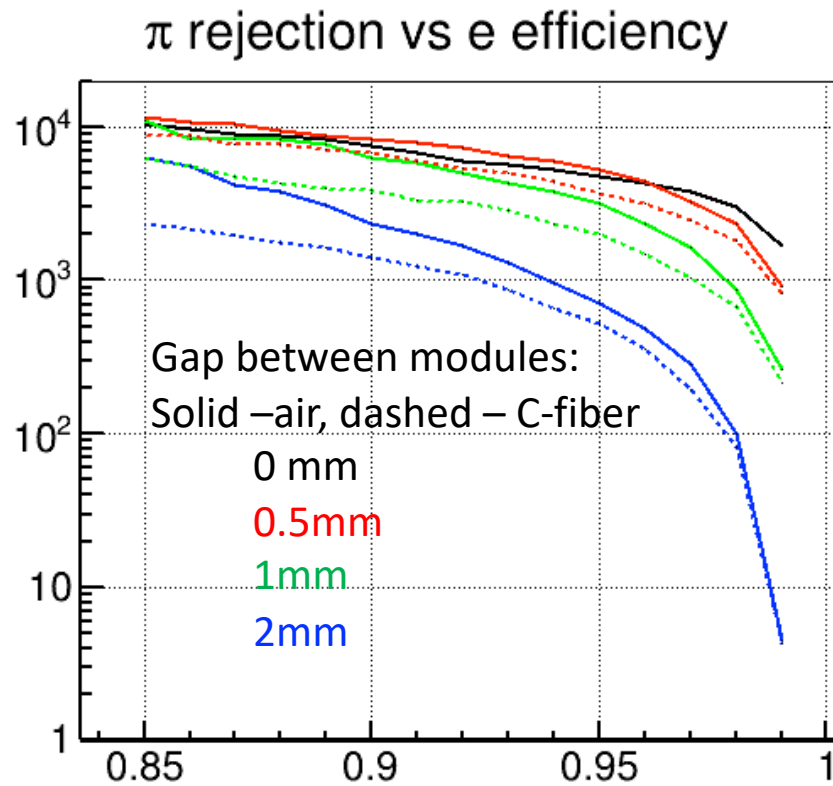


18 GeV x 275 GeV



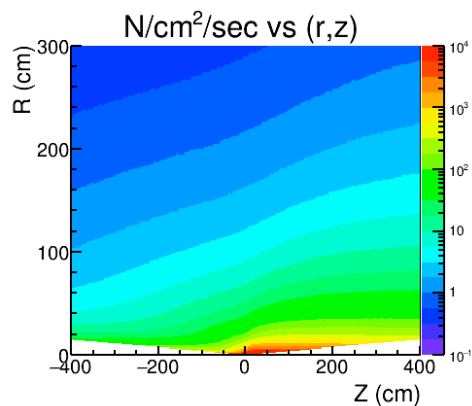
e/π : PWO

For PWO crystals of $2 \times 2 \text{ cm}^2$, $20^\circ \times 0$, $p = 2 \text{ GeV}/c$

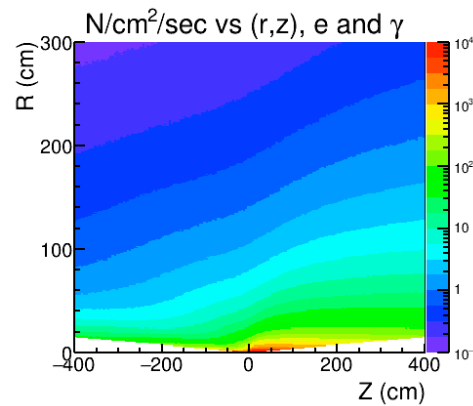


Particle/Energy Flow

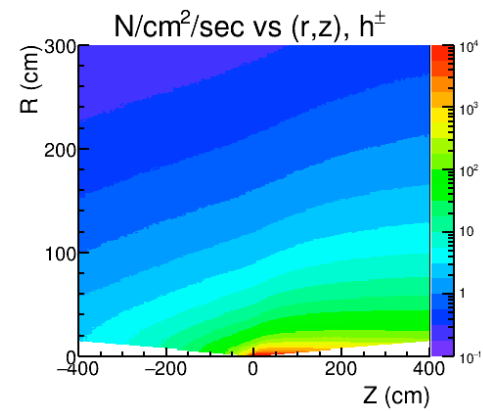
All particles



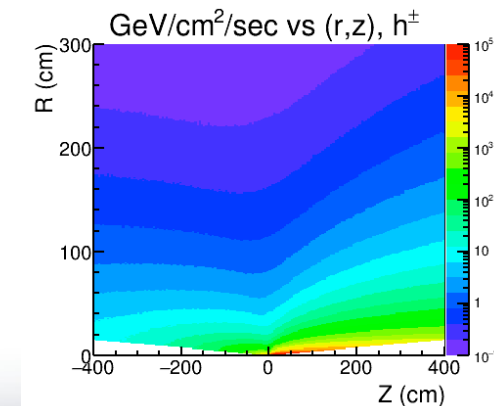
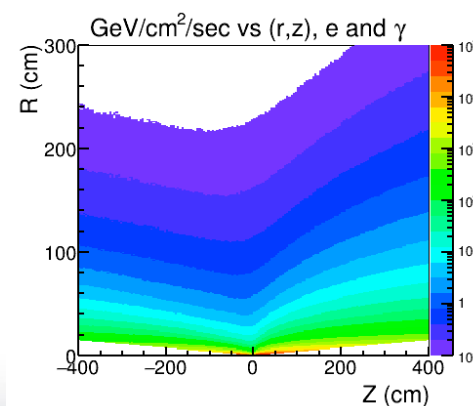
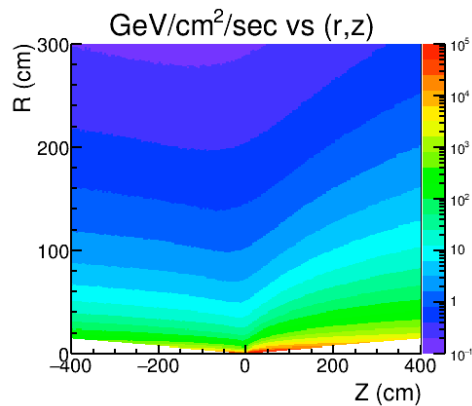
e and γ



h^\pm



Particle
flow



Energy
flow

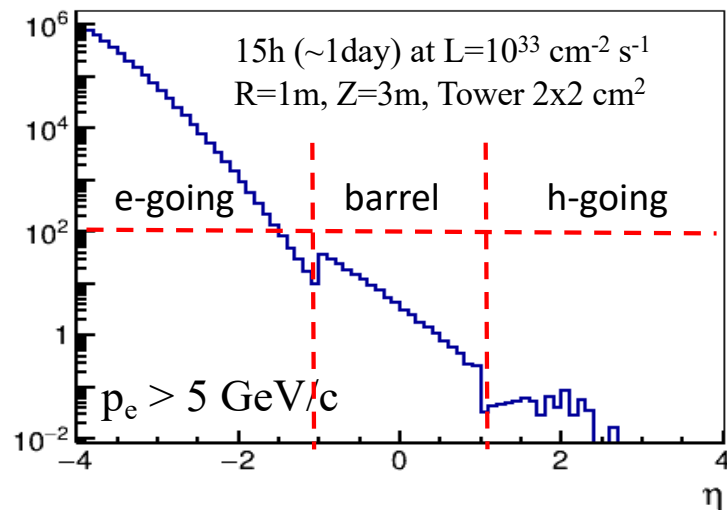
Calibration

“Usually” a few hundred particles per tower needed

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

Electron

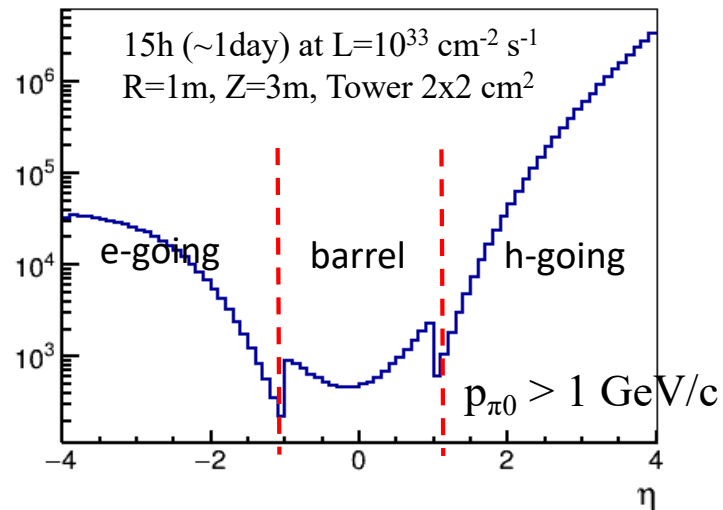
N/Tower vs η



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

$\pi^0 \rightarrow \gamma\gamma$

N/Tower vs η



1-day statistics looks enough for all EMCals

SiPM Specs

Parameter	Specs
Active area	6 mm x 6 mm
Pixel Size	15 μm (50 μm)
Package type	Surface mount
Peak Sensitivity	Max PDE at $\sim 450 \text{ nm}$
PDE	>30% (>50%) @3V overvoltage
Gain	$\sim 2 \times 10^5$ ($\sim 2 \times 10^6$) @3V overvoltage
DCR	< 3000 kcps @ 25C, 0.5 PE threshold, @3V overvoltage
Temperature coefficient of Vop	< 40 mV/C
Direct crosstalk probability	< 1% (<7%)
Terminal capacity	< 3nF @3V overvoltage
Packing granularity	Multiple of 4 per tray
Vop variation within a tray	+/- 0.02V (Forw) and +/- 0.1V (Back and barrel)