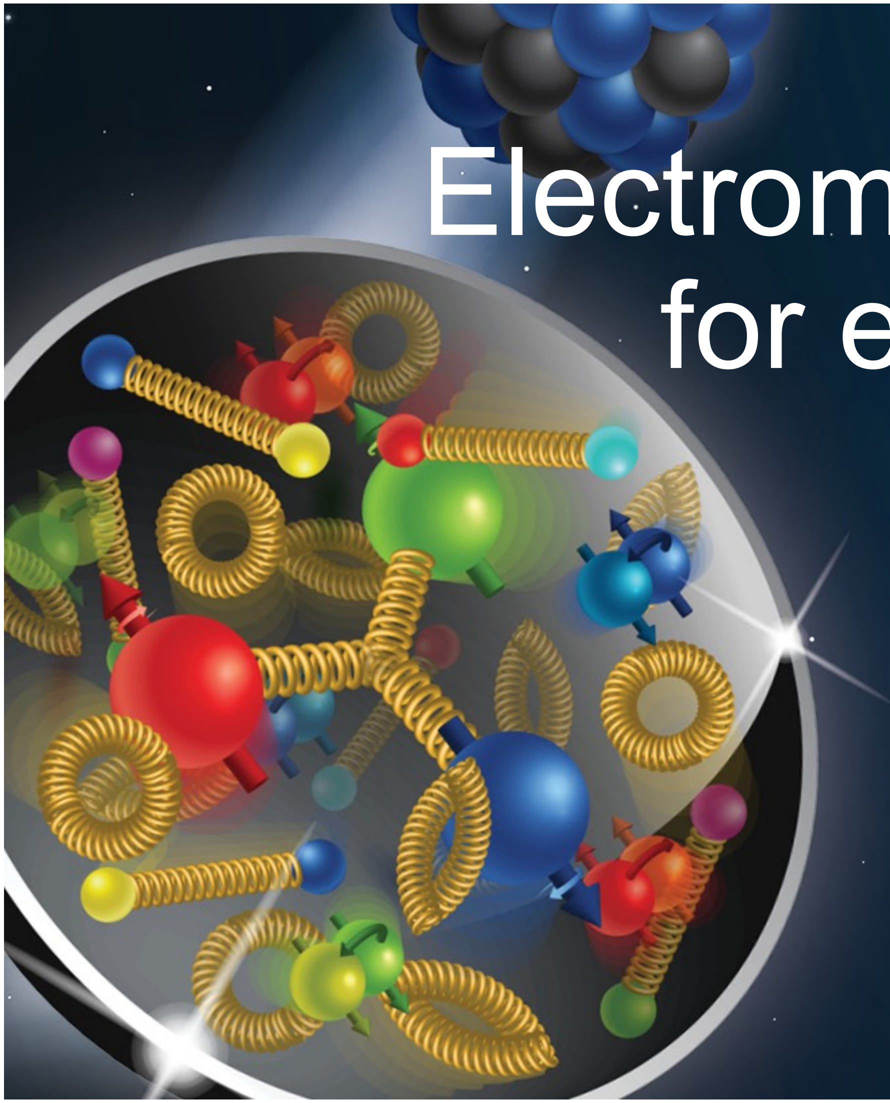
CALOR 2024 Tsukuba



Electromagnetic Calorimetry for ePIC detector at EIC

Alexander Bazilevsky (BNL)

For ePIC Collaboration

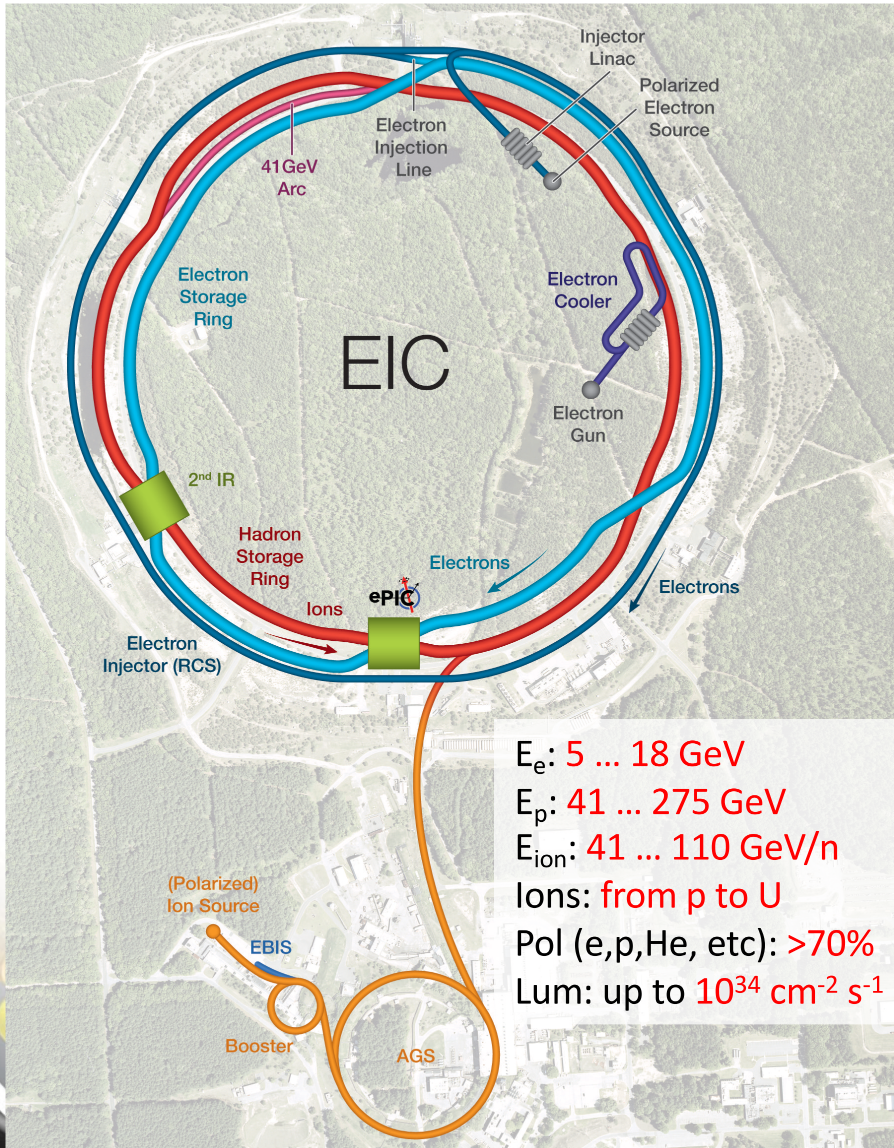
May 19-24, 2024

Electron-Ion Collider

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

Electron Ion Collider (EIC)

Based on RHIC Complex (BNL)



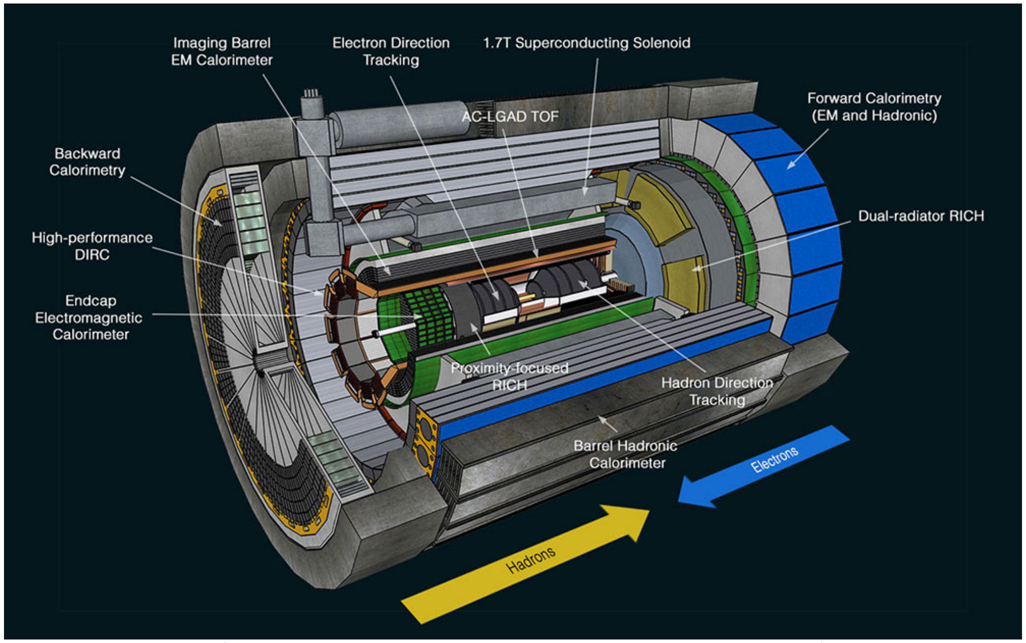
E_e: 5 … 18 GeV
E_p: 41 … 275 GeV
E_{ion}: 41 … 110 GeV/n
Ions: from p to U
Pol (e,p,He, etc): >70%
Lum: up to 10^{34} cm^{-2} s^{-1}

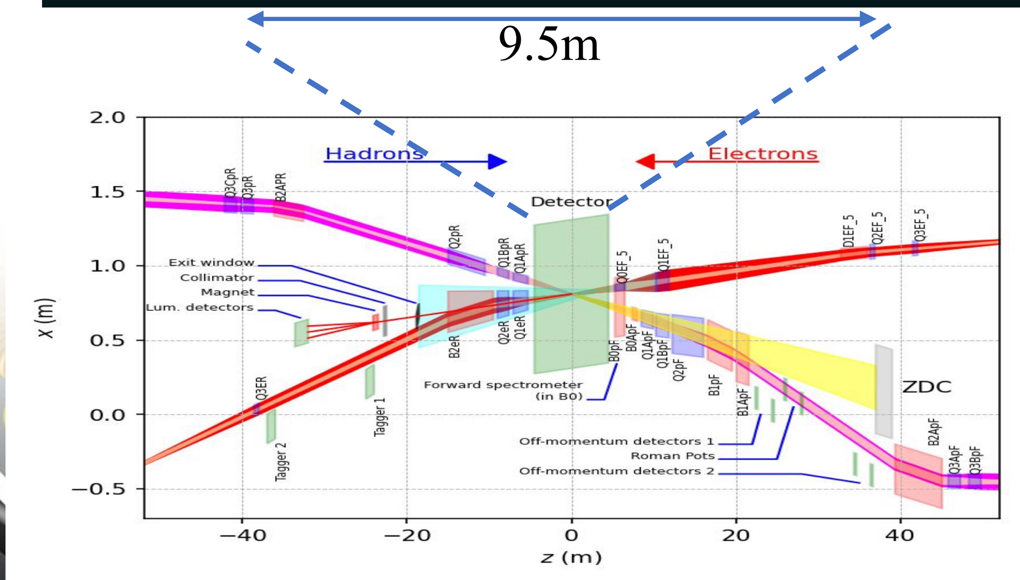
EIC Project Critical Decision		
CD-0 (Mission need)	Dec 2019	✓
CD-1 (Conceptual Design)	Jun 2021	✓
CD-3a (Long Lead Procur.)	Mar 2024	✓
CD-2 (Baseline)	~2025	
CD-3 (Construction)	~2026	
CD-4 (Operation)	2034	

"An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:

- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?"**

ePIC Detector





- Asymmetric beams (species, energy) => Asymmetric capabilities
- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (μ-vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - also need good e/π separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

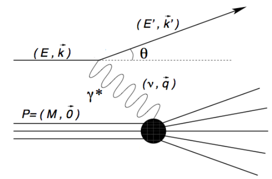
EMCal for an EIC Detector

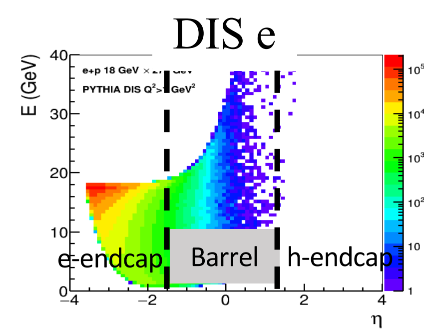
18 x 275 GeV

Electron/photon PID, energy, angle/position:

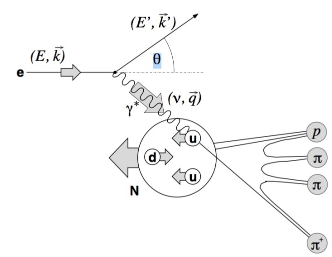
Coverage (in rapidity and energy), resolution, e/π, granularity

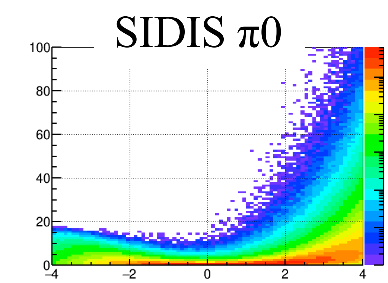
Inclusive DIS: scattered electron



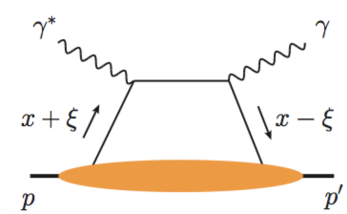


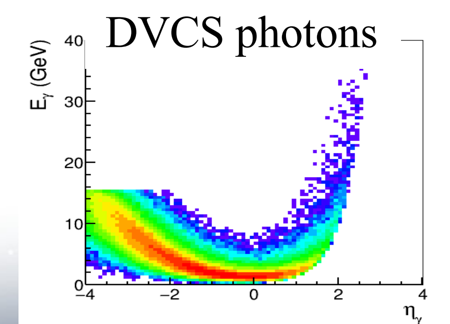
Semi-Inclusive DIS: $\pi 0 \rightarrow \gamma\gamma$, HF $\rightarrow$ e





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





EMCal Requirements: Summary

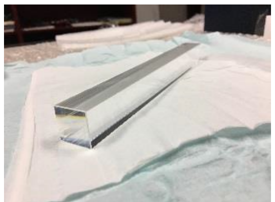
As documented in Yellow Report (arXiv:2103.05419) and
"General, Functional, and Performance Requirements for the EIC Detector Systems"

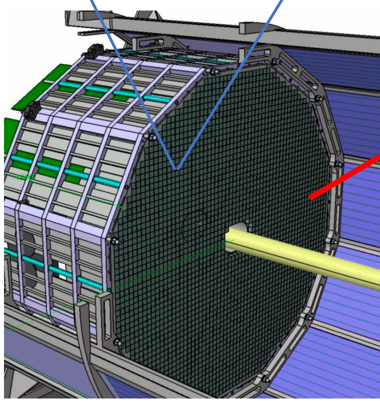
	Electron endcap (Backward)	Barrel	Hadron endcap (Forward)
Energy Resolution	$\frac{(2-3)\%}{\sqrt{E}} \oplus 1\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$
Shower Energy range	0.1−18 GeV	0.1−50 GeV	0.1−100 GeV
$\pi\pm$ suppression (helped by other subsystems)	Up 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)	50 kHz	5 kHz	20 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

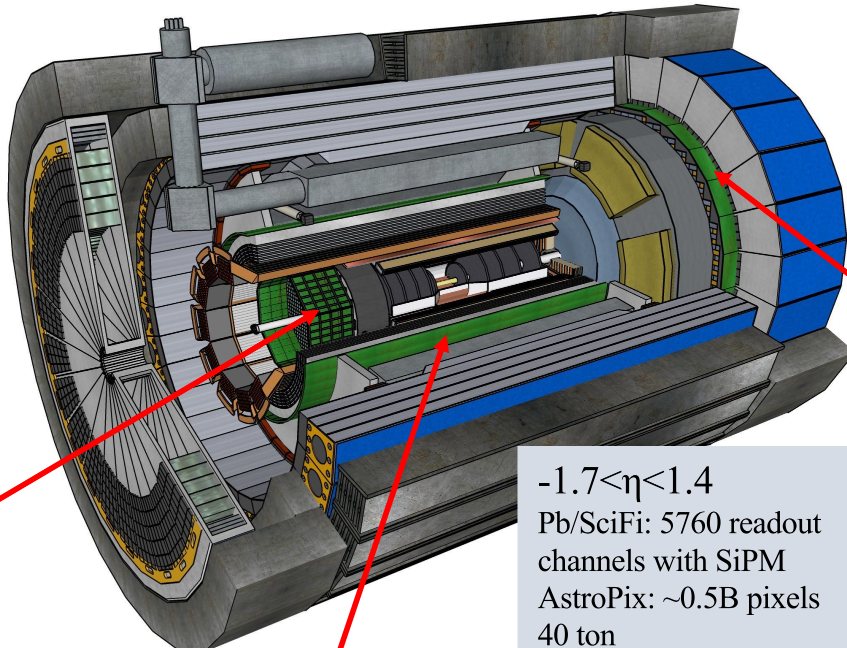
EM Calorimetry in ePIC

PbWO4

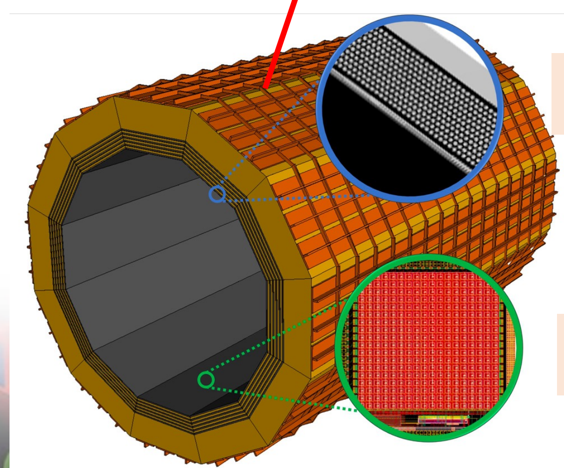




-3.5<η<-1.7
~3k crystals
R_{outer}=64cm
SiPM readout
2 ton



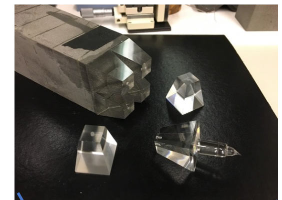
-1.7<η<1.4
Pb/SciFi: 5760 readout channels with SiPM
AstroPix: ~0.5B pixels
40 ton

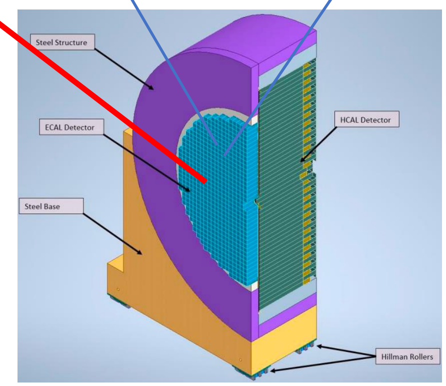


Pb/SciFi

AstroPix

W/SciFi

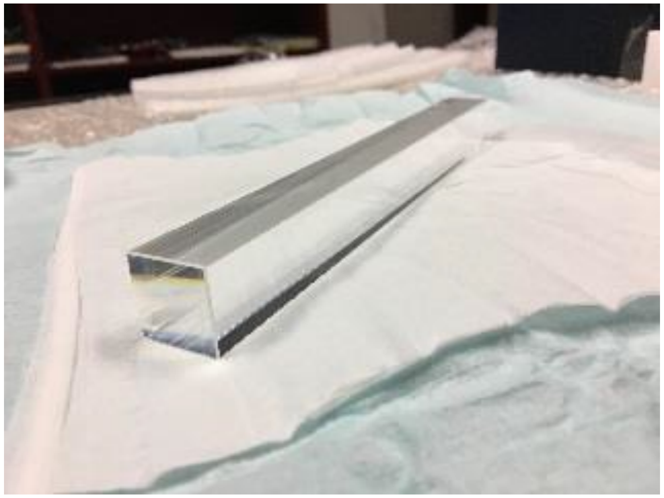




1.4<η<3.7
~19k towers
R_{outer}=190cm
SiPM readout
20 ton

e-endcap: $PbWO_4$

- ➢ High resolution
- ➢ High e/π separation for eID



DIS electron

Defines DIS kinematics

High resolutions, particularly at small angles

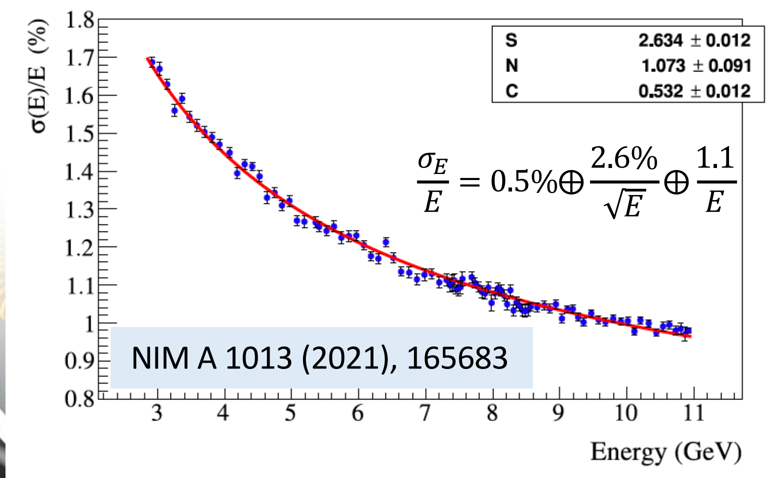
Strong hadron background suppression

Radiated $\boldsymbol{\gamma}$ measurements down to 100 MeV

DVCS photons

Also decay photons ($\pi 0/\boldsymbol{\gamma}$) and decay e

Jlab-PrimEx eta/NPS PWO EMCal prototype



PbWO4 - Well established technology

Compact & High granularity: $2 \times 2 \times 20$ cm^3 ($22X_0$)

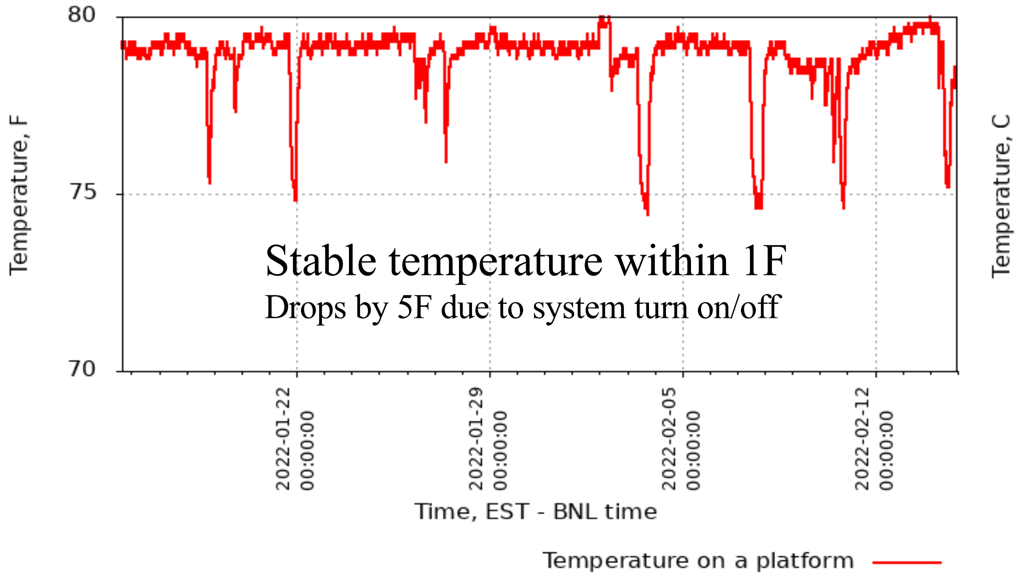
High resolution: $\frac{\sigma_E}{E} = (0.4-1)\% \oplus \frac{(2-3)\%}{\sqrt{E}}$

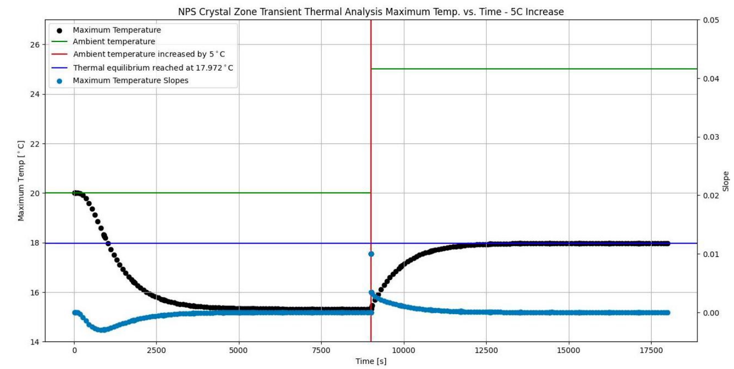
Excellent e/π capabilities: π suppression up to a few 10^3

Radiation hard: >1000 krad

Temperature sensitive: d(LY)/dT = -(2-3)%/°C

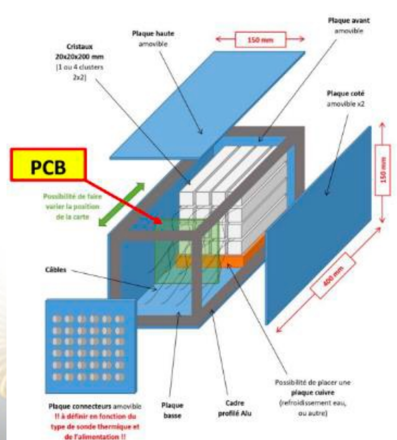
e-endcap: T^0 stabilization



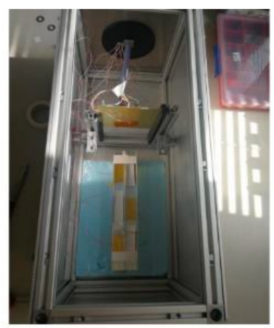


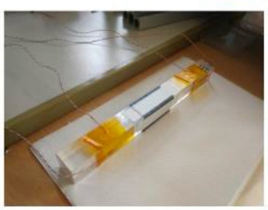
ANSYS simulation

Temperature stabilizes after ~1 h



Setup of the tests





11 temperature sensors:

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

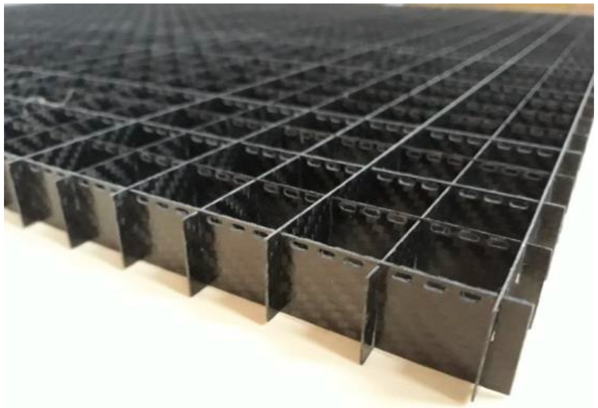
Thermal Design and Test

Operation at room temperature

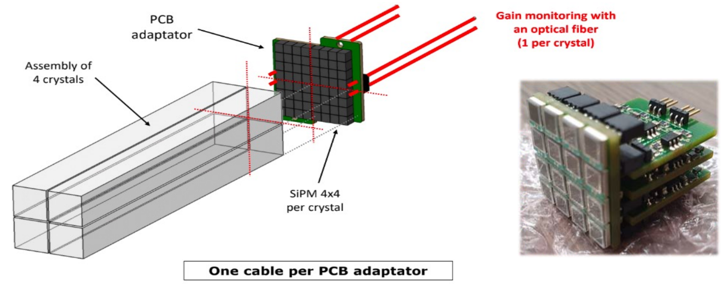
Simulations to quantify the effect of ambient temperature fluctuation on the crystal temperature

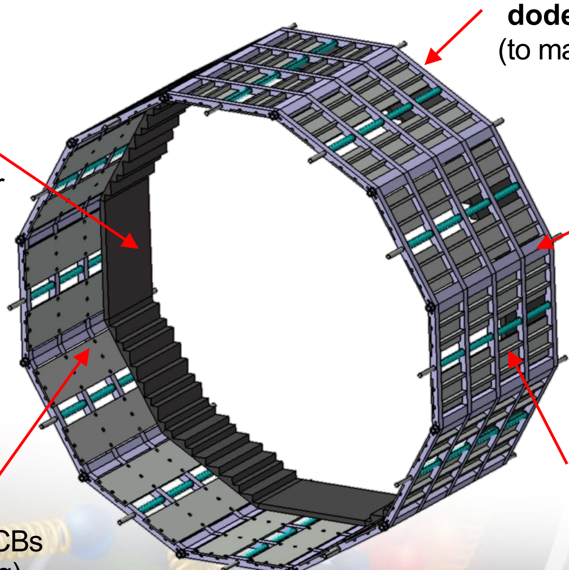
Measurements on a prototype

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





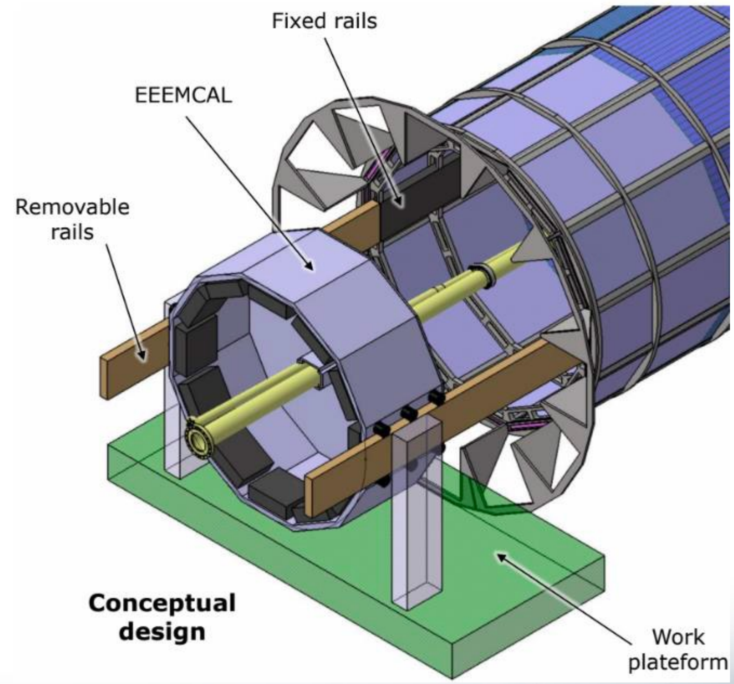
5 (at least) strong dodecagon frames
(to make the assembly easier)

Support structure for crystals
(can be used for cooling)

Mechanical pieces
(to reinforce the structure at the angles)

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

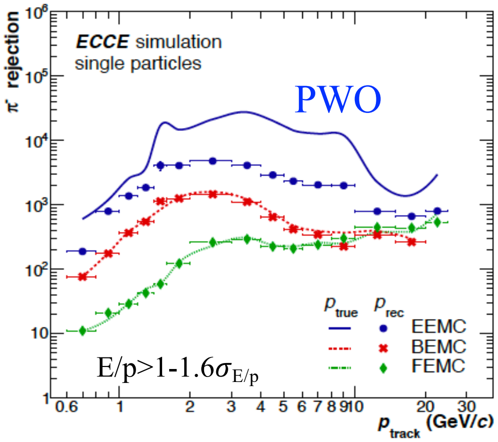
Plate
(to fasten the PCBs and the cooling)



e-endcap: Performance

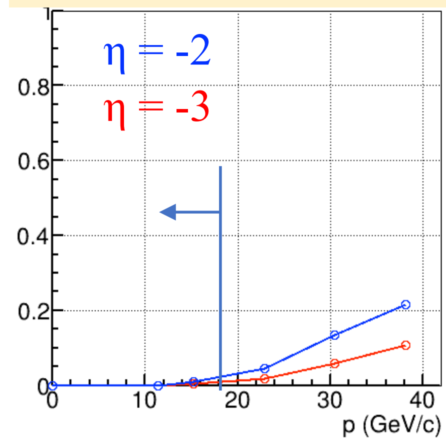
Full GEANT simulation with full detector implementation

π- rejection



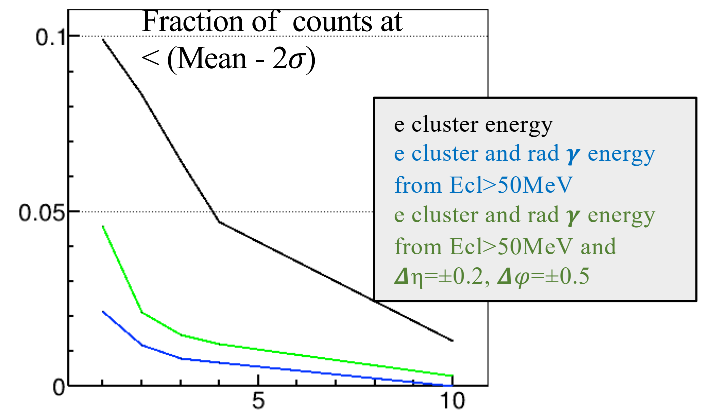
π0 merging prob

(after shower profile analysis)



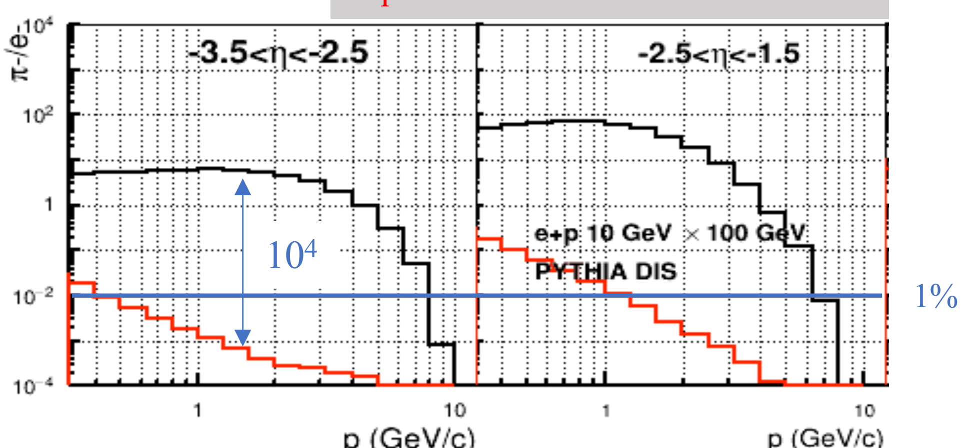
Material effect

Eff. loss vs E (GeV)



π-/e-

No cuts
E/p cut and momentum conservation



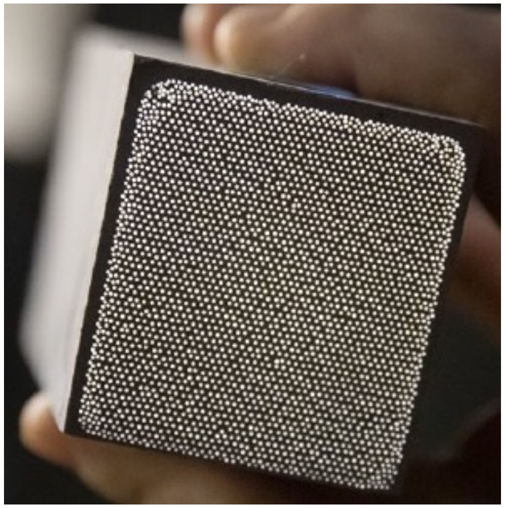
* Additional strong suppression of π^- at < 2.5 GeV/c is provided by pfRICH

- <<1% π- contamination is expected for the DIS electron reconstruction
- ~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

h-endcap: W/SciFi

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



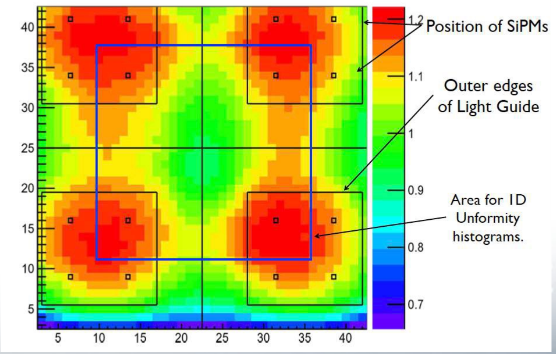
Jets up to energies ~100 GeV
$\pi 0/\gamma$ discrimination up to 50 GeV
Decay electrons

W + SciFi SPACAL Design
sPHENIX EMCal: 25k towers

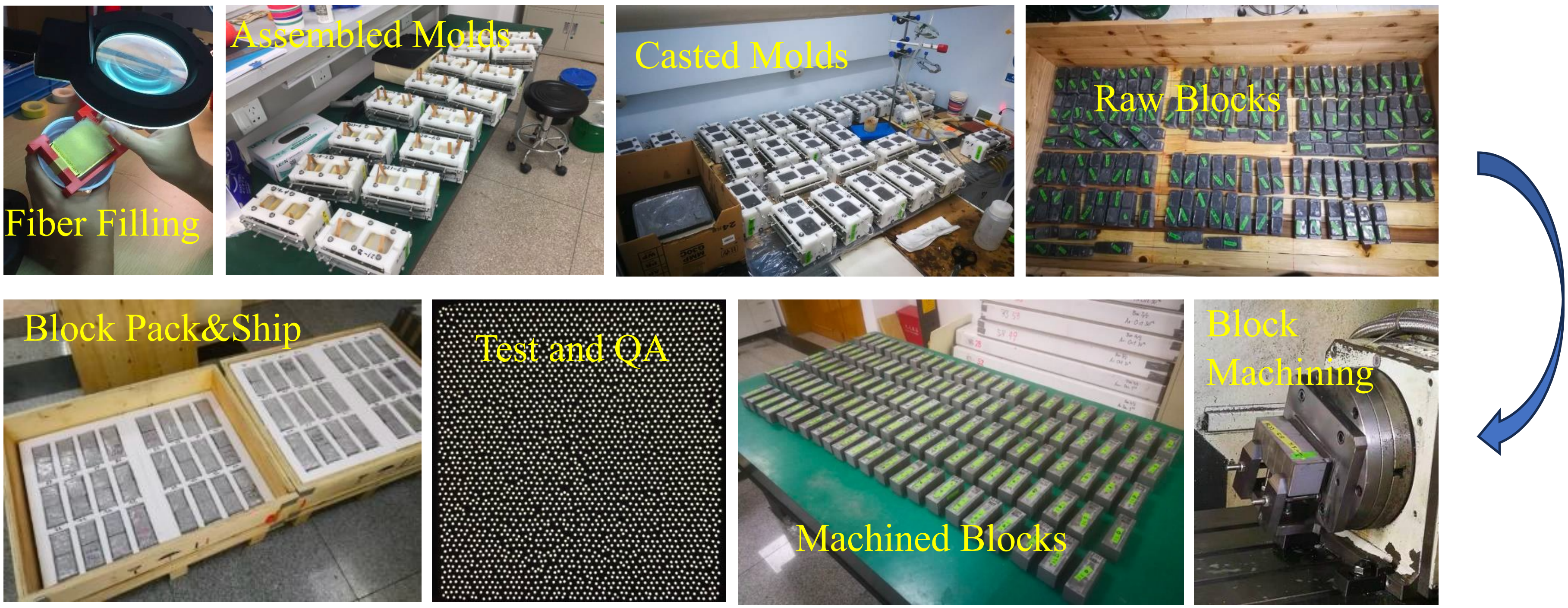
- Compact: X_0 = 0.7cm
- High granularity: R_m = 2cm
- Sampling fraction: ~2.3%
- Good resolution

R&D:

- SiPM readout
- Improve light collection eff. and uniformity

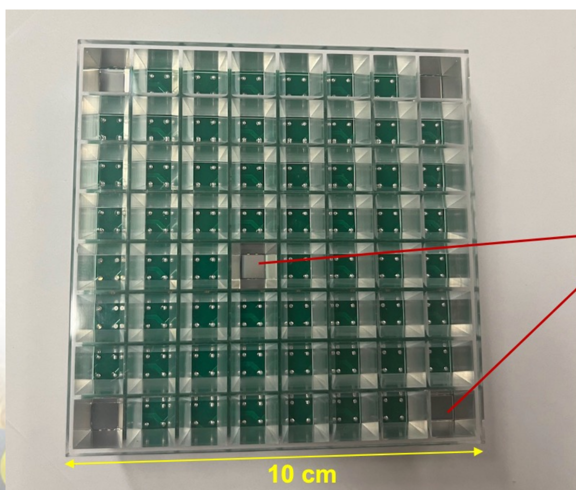


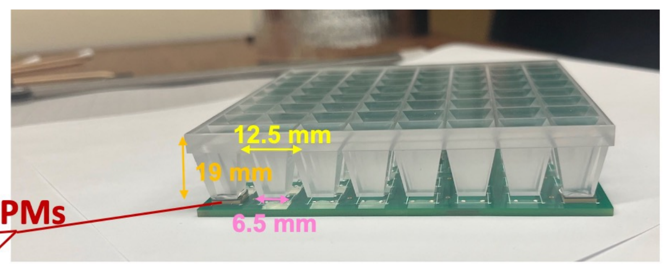
h-endcap: Production Chain

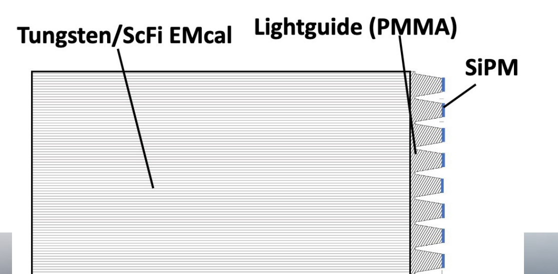


Production chain is fully established in US and China

h-endcap: Mechanical Design and RO





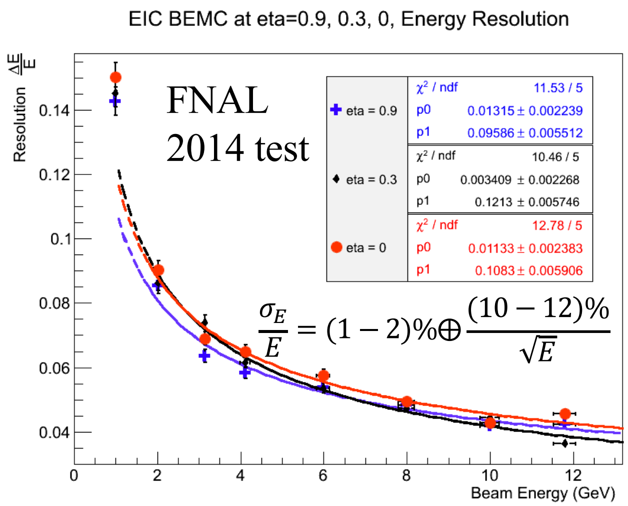


One Light Guide panel for each installation block:

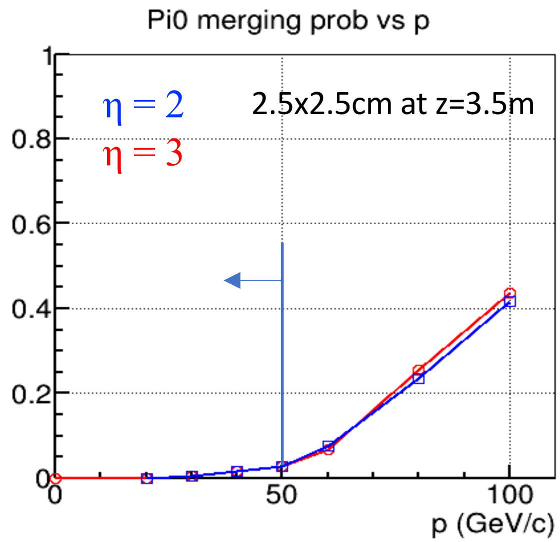
- 8x8 prisms, each readout by a $6x6mm^2$ SiPM
- 4 SiPMs per tower ($2.5x2.5\ cm^2$)

h-endcap: Performance at EIC

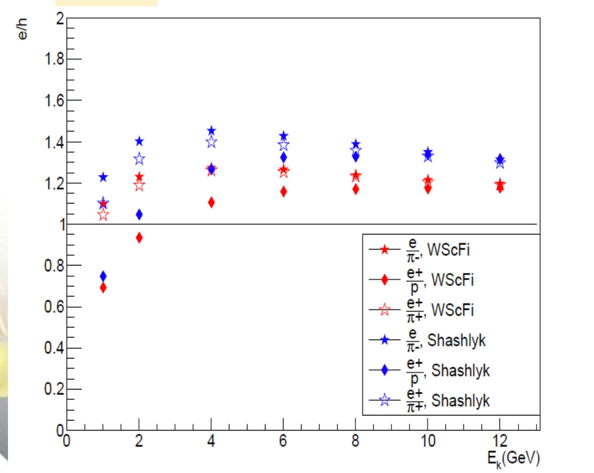
Energy Resolution



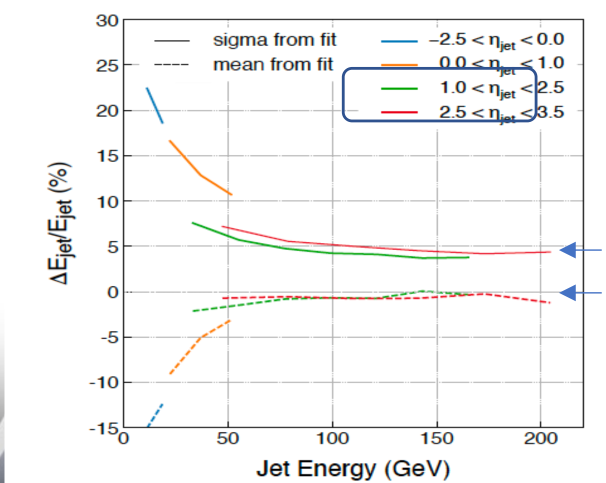
$\pi0/\gamma$: merging prob



e/h



Jet resolution and bias (ECal+HCal)



σ_E/E~5%

No bias

- Good energy resolution
- Excellent $\pi0/\boldsymbol{\gamma}$ discrimination capabilities
- Provides high resolution and minimally biased jet measurements (in duet with HCal)

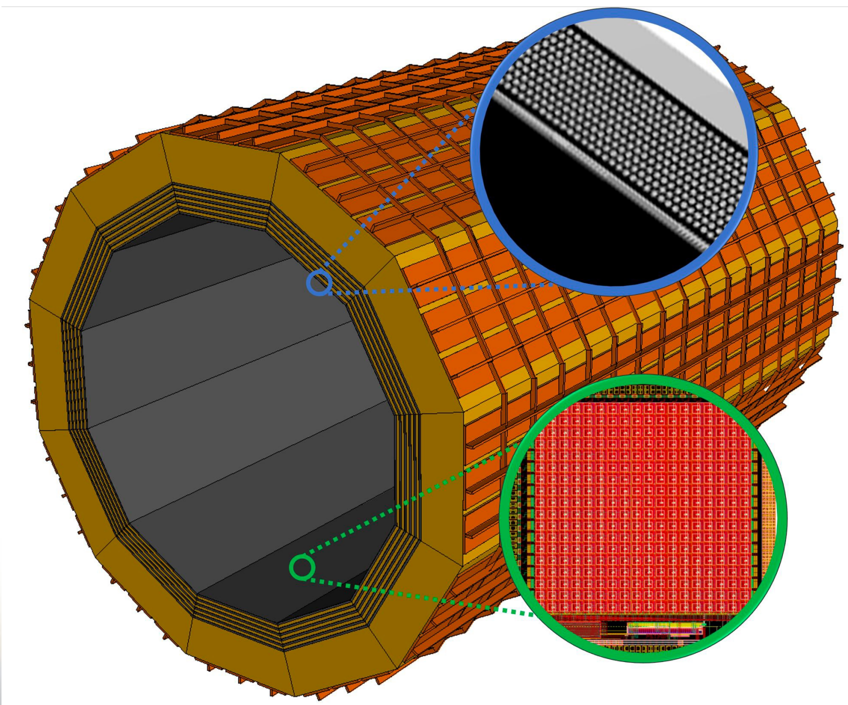
Fully satisfies the EIC Detector Requirements

Barrel: Pb/SciFi + Imaging

- ➢ Good resolution
- ➢ High e/π separation for eID

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)



Pb/SciFi:

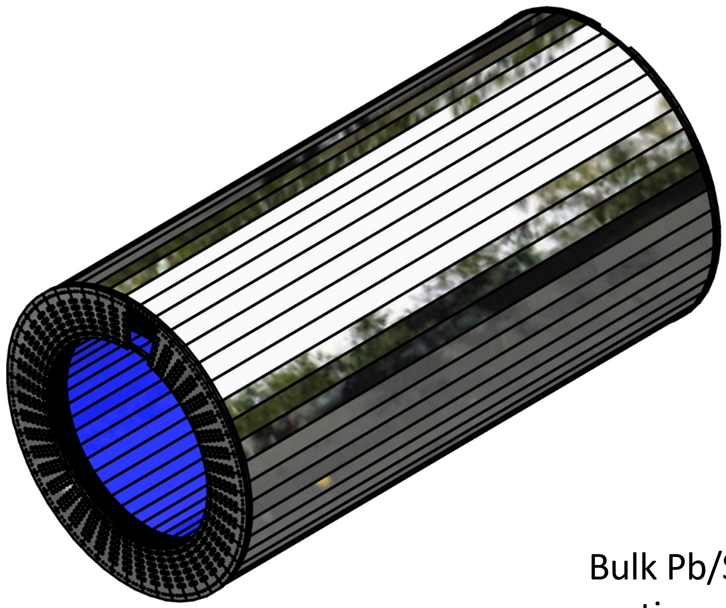
Scintillating fibers embedded in Pb (Similar to GlueX barrel EMCal)

Imaging:

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

Barrel: Structure

Barrel = 48 Sectors



Length: ~435 cm

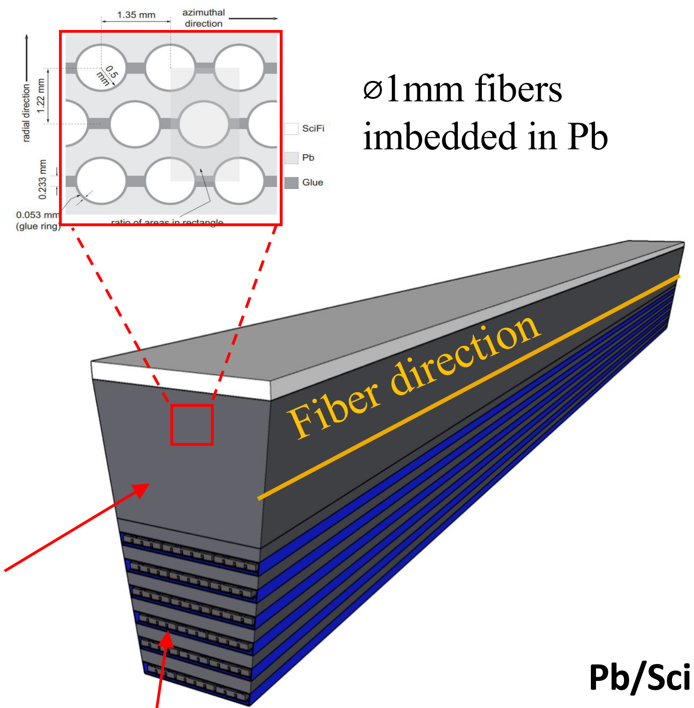
Inner Radius: ~ 82 cm

η Coverage: $-1.7 < \eta < 1.3$

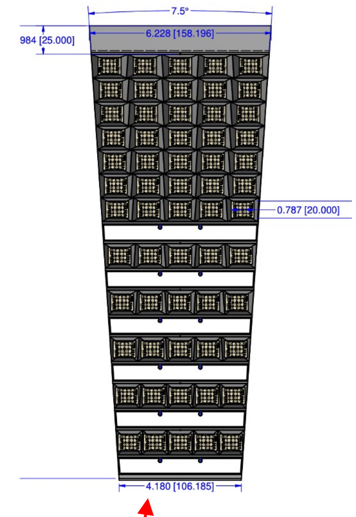
Depth: 17.1X0 at η = 0

Sampling fraction ~10%

Pb/SciFi technology as GlueX



Sector end view



Pb/SciFi Layer (1.4X0)

- 5 readout cells per layer
- 1 light-guide per cell
- Two side readout
- Each readout by 4x4 SiPMs of $3x3mm^2$

Barrel: Imaging Layers

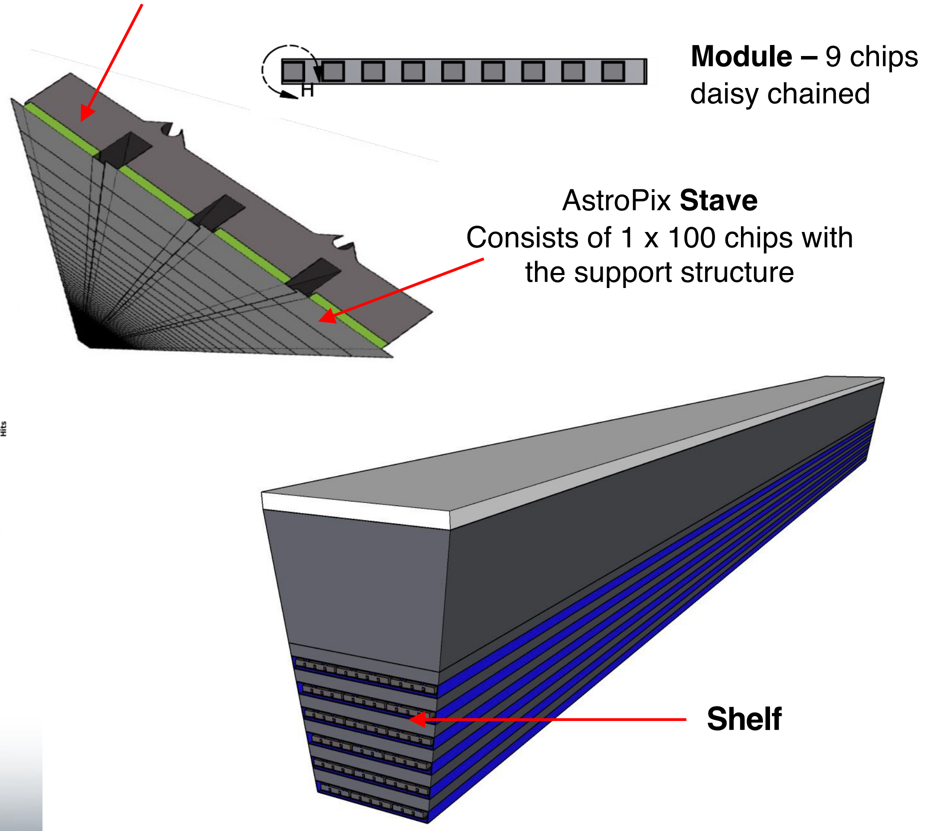
Based on AstroPix sensors

- Developed for AMEGO-X (NASA)
- CMOS sensor based on ATLASpix3

4 layers (of 6) in a baseline design

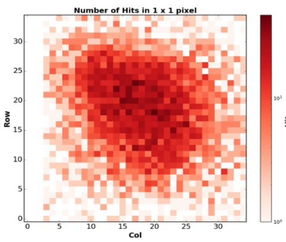
Key characteristics

- ✓ 500 μm pixel size
- ✓ Energy resolution 10%@60keV
- ✓ Time resolution 3.25 ns
- ✓ Low power dissipation (~1.5mW/cm2)



FY23 tests (FNAL):

Performs well in much harsher conditions than EIC

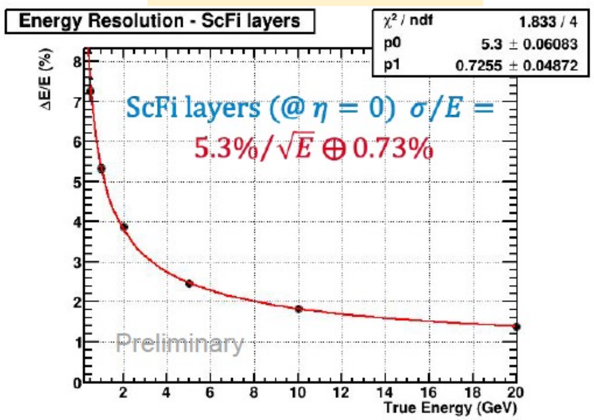


Ongoing tests in FY24 (FNAL)

- Multilayer chip test
- Irradiation test
- Response to e and π with AstroPix prototype integrated with Pb/SciFi (GlueX prototype)

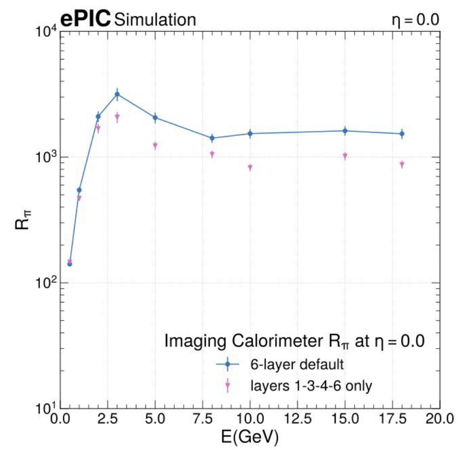
Barrel: Performance at EIC

Energy Resolution

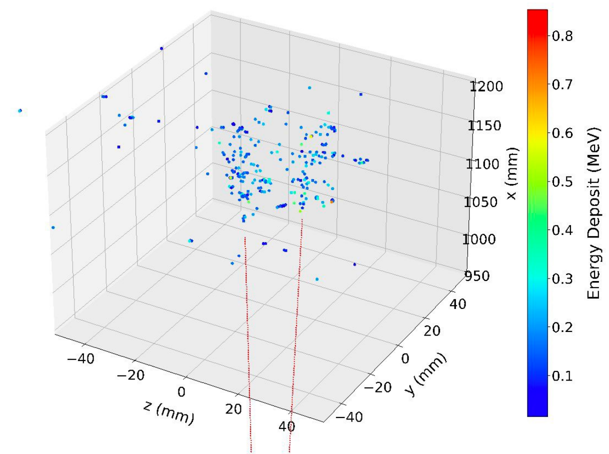


Test Beam: $\sigma/E \sim 5.2\%/\sqrt{E} \oplus 2\%$

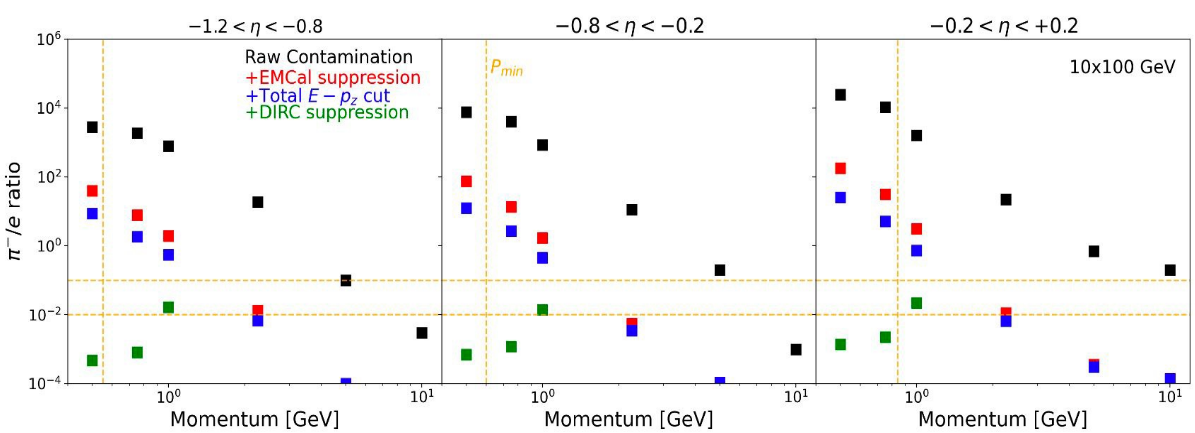
π- rejection



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



DIS electron purity



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

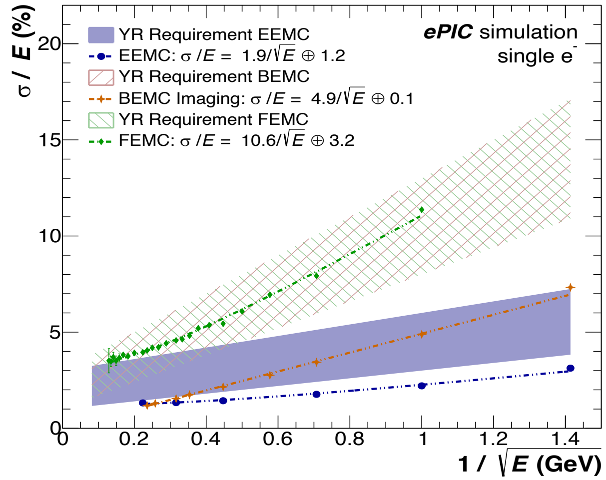
Fully satisfies the EIC Detector Requirements

SiPM

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 of 6x6 mm^2	16 of 3x3 mm^2	4 of 6x6 mm^2
SiPM pixel size	15 um	50 um	15 um
SiPM: N pixel max	640k	57k	640k

Summary

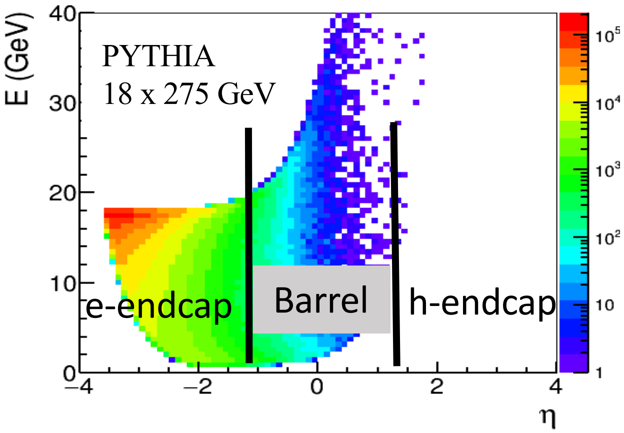


- ➢ Physics requirements are well defined
- ➢ The selected EMCal technologies satisfy or exceed the requirements
  - e-endcap: PbWO4 crystal, well established technology
  - Barrel: Pb/SciFi + Imaging (AstroPix), both are well established technologies
  - h-endcap: W/SciFi, well established technology
- ➢ Participating groups with extensive expertise and capabilities for selected calorimetry technologies
- ➢ Designs are in advanced stage; construction ~2026 – 2030

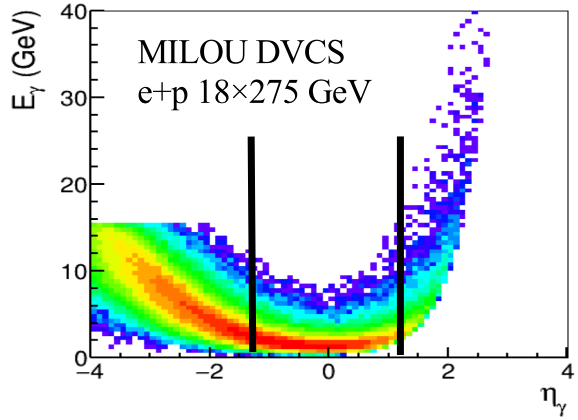
Backup

Coverage, Energy Range

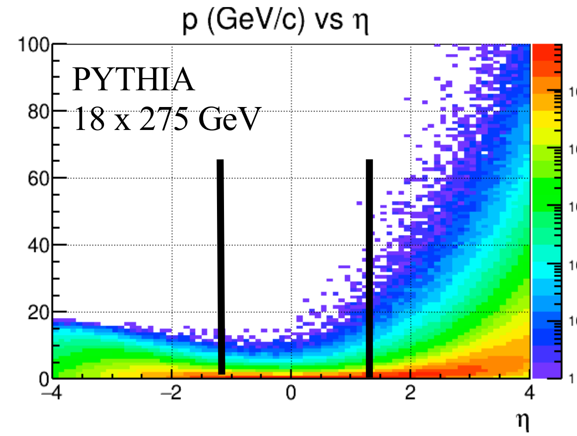
DIS e



DVCS photons



SIDIS π0



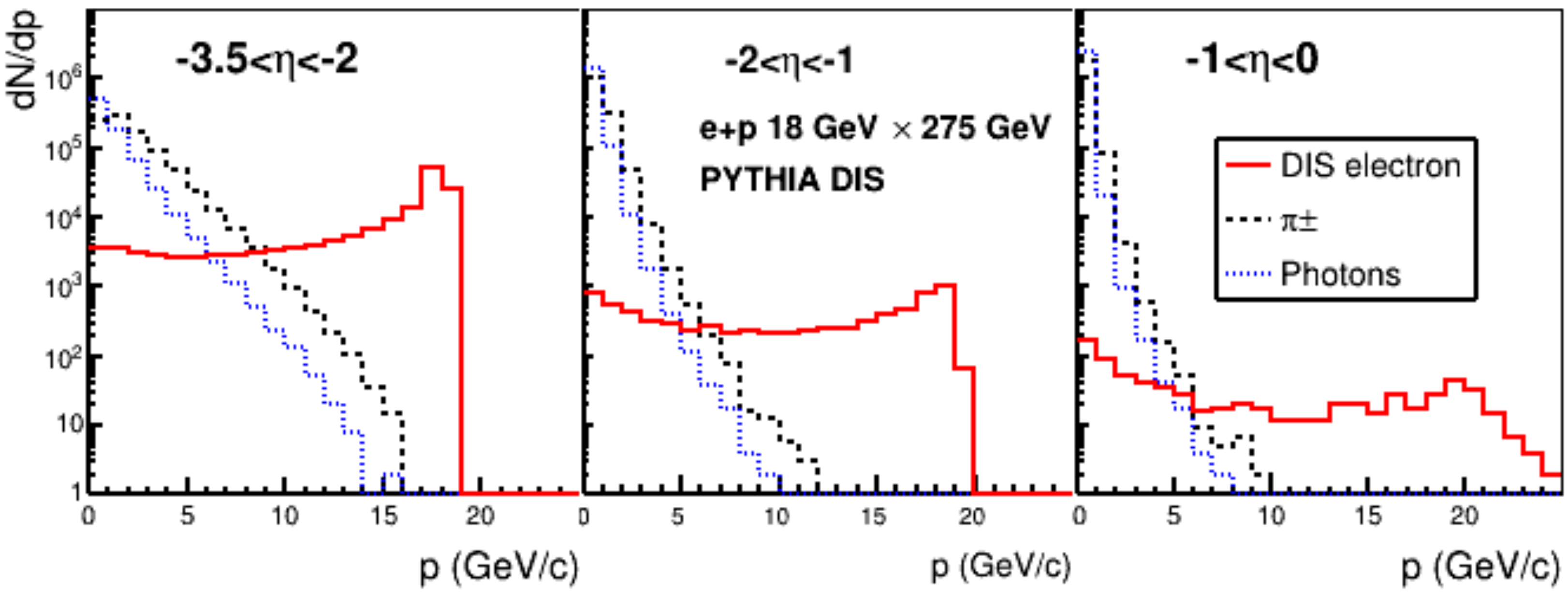
Continuous acceptance coverage: at least |η|<3.5

- 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 $\pi0$
- 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

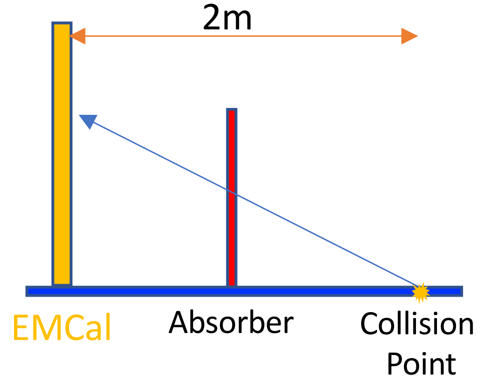
  Photon conversion

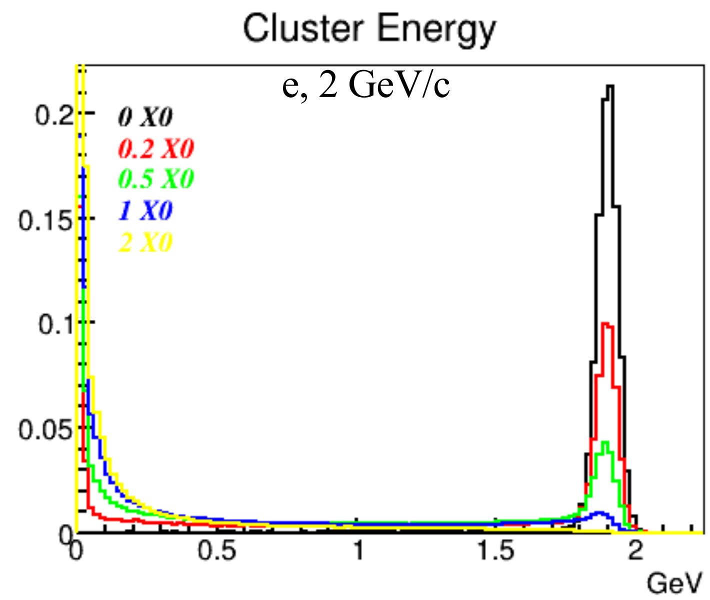
  Bremsstrahlung radiation by electron

  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

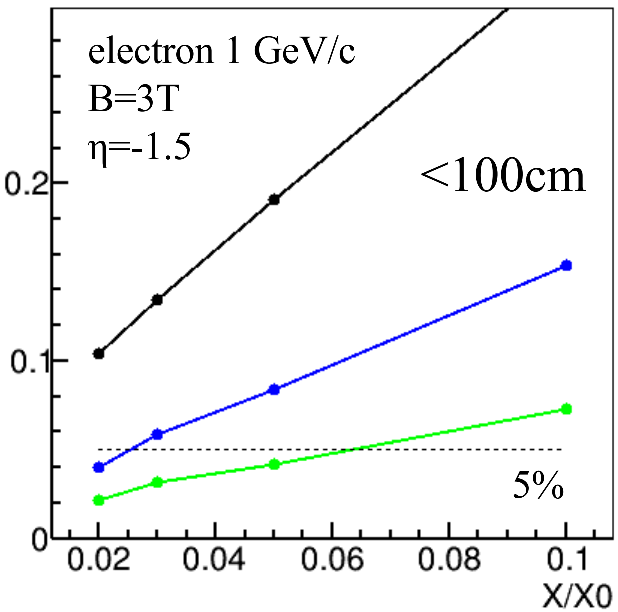




Effect of material on the way

The most extreme case:
Highest Bdl, lowest *e* momentum, close to coll. point

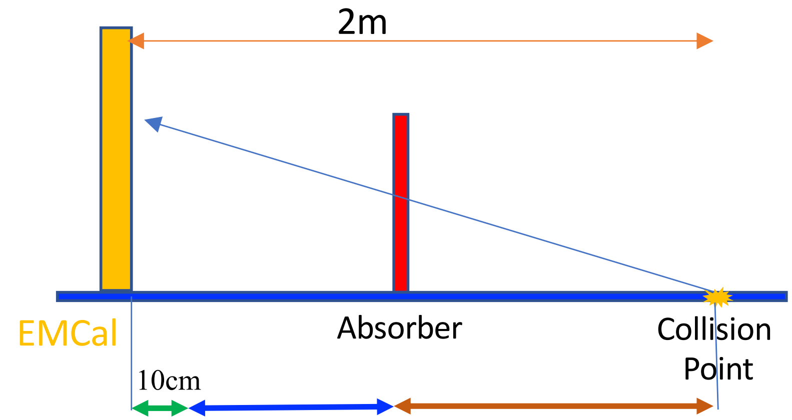
Efficiency loss (with 2σ cut) vs X/X_0



e cluster energy

e cluster and rad γ energy from Ecl>50MeV

e cluster and rad γ energy from Ecl>50MeV and $\Delta\eta=\pm0.2$, $\Delta\varphi=\pm0.5$



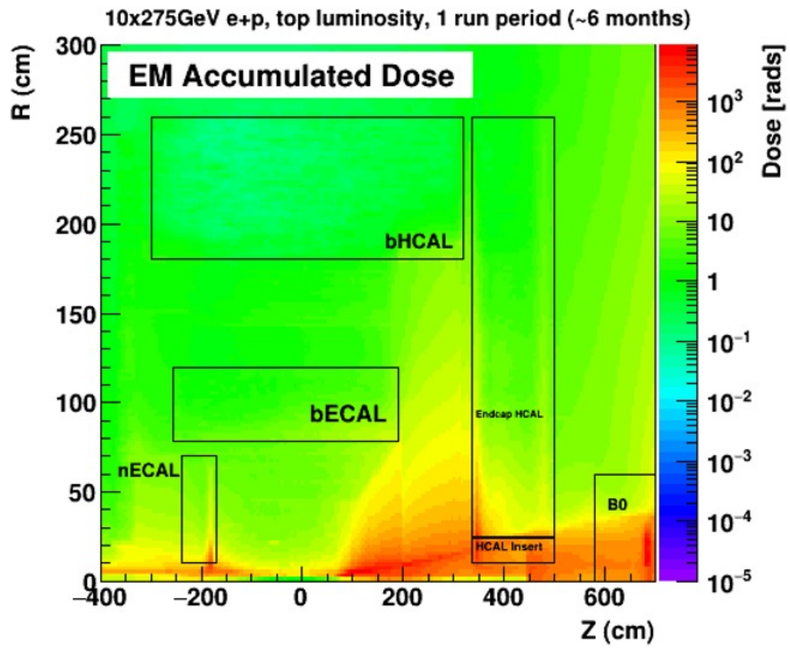
<50%X_0	<20%X_0	<(3-6)%X_0	Electron > 1GeV
<30%X_0	<10%X_0	<10%X_0	Photon > 0.1GeV

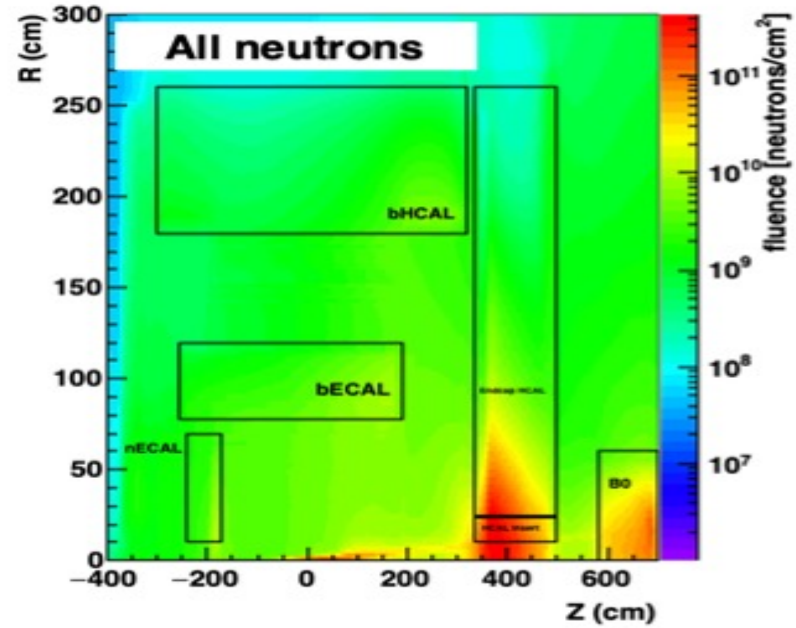
Exclusive requirements
(the whole effect assumed from one region)

The amount and localization of tolerable material formulated

The requirements are relaxed for B=1.7-2T

Rad Dose and Neutron Flux



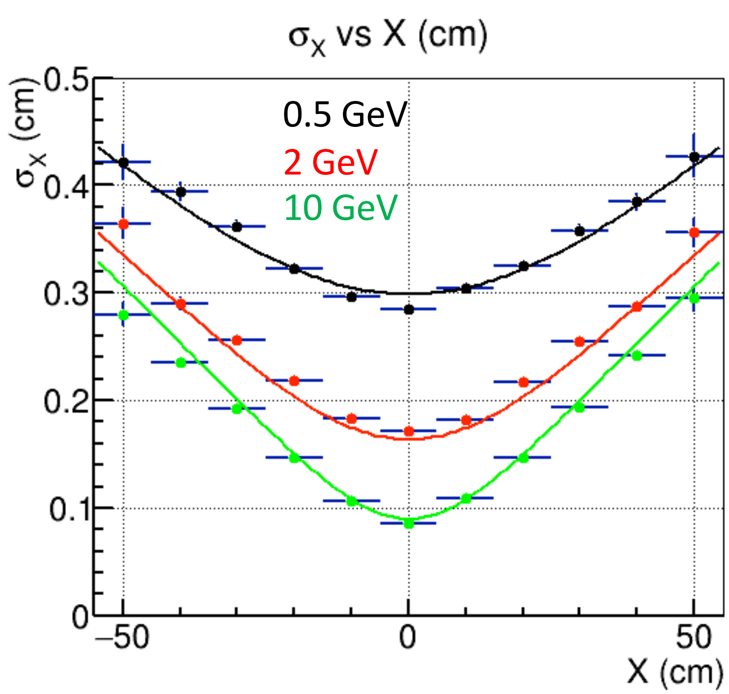


Highest dose in the forw EMCal next to the beam pipe:
~2.5 krad/year at L=10^{34} cm^{-2}s^{-1}

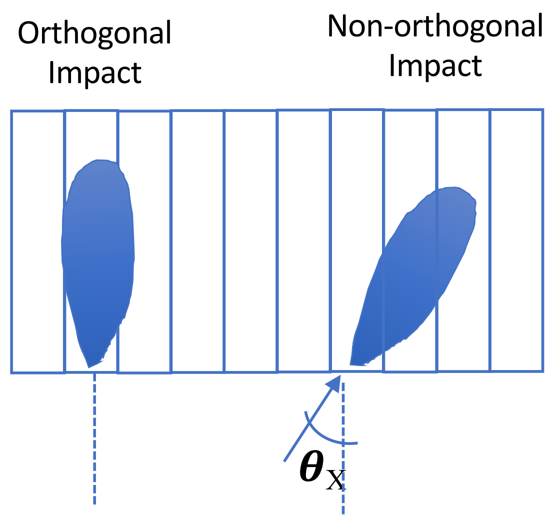
Highest flux in the forw EMCal next to the beam pipe:
~10^{11} n/cm^{2}/year at L=10^{34} cm^{-2}s^{-1}

Non-projectivity and pos. res.

Backward EMCal



Full GEANT simulation with all material



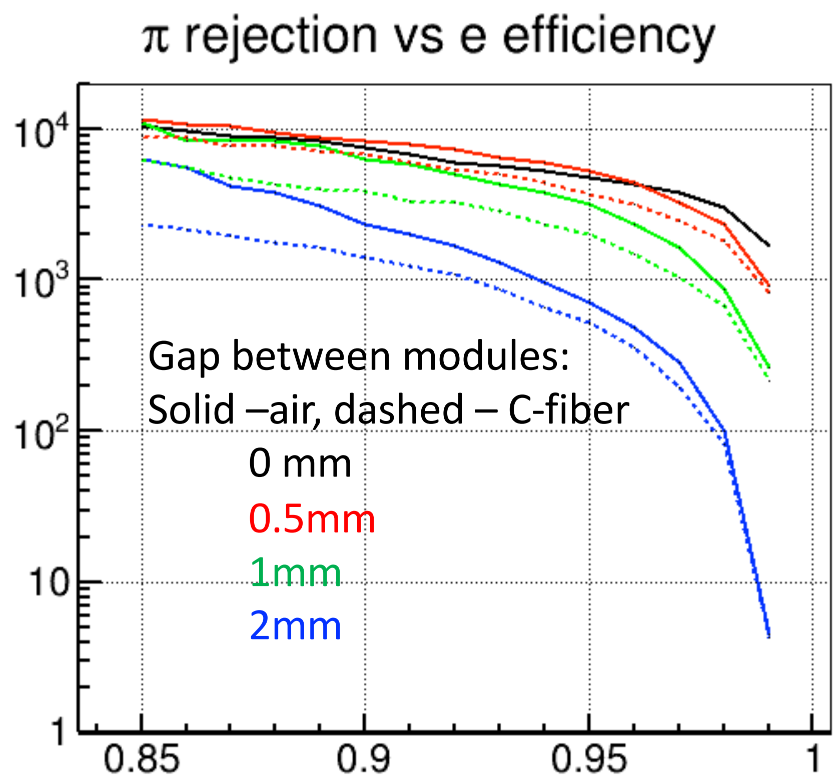
$$\sigma_X = \left(\frac{2mm}{\sqrt{E[GeV]}} + 0.3\text{mm} \right) \oplus (X_0 \sin\theta_X)$$

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

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

e/π: PWO

For PWO crystals of 2x2 cm2 , 20*X0, p = 2 GeV/c



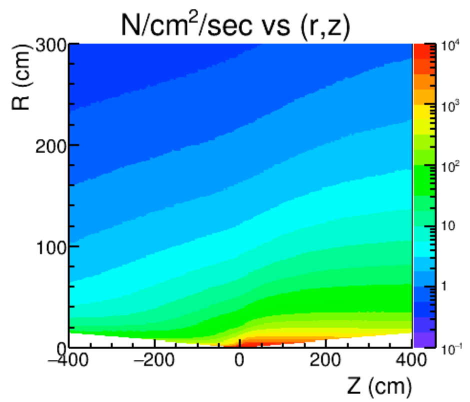
Particle/Energy Flow

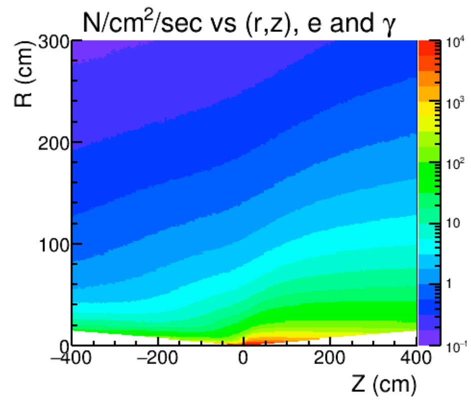
All particles

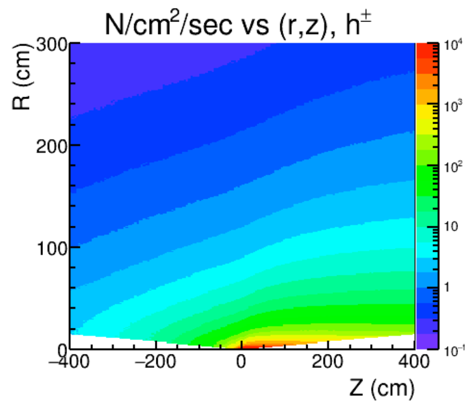
e and γ

h±

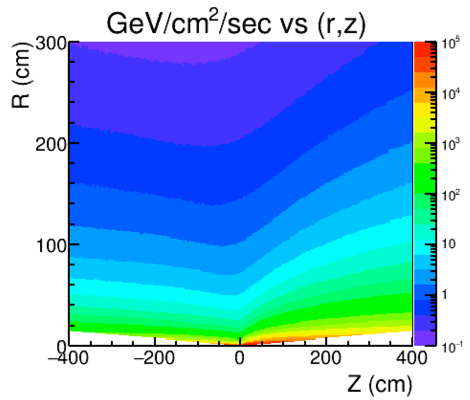
Particle flow

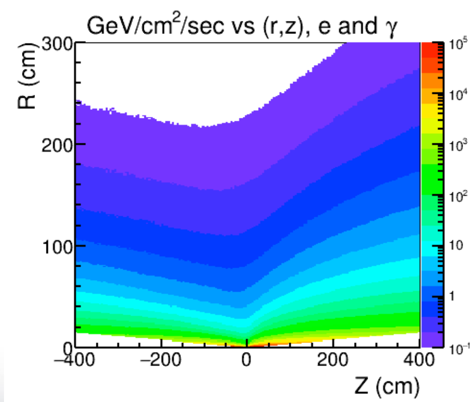


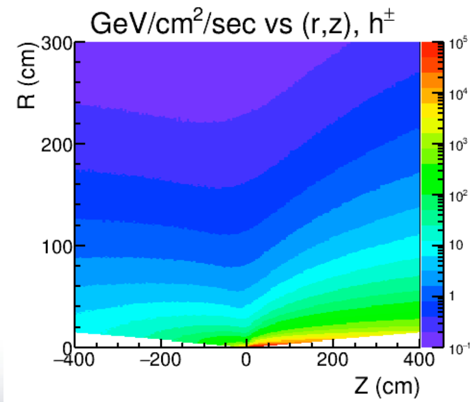




Energy flow





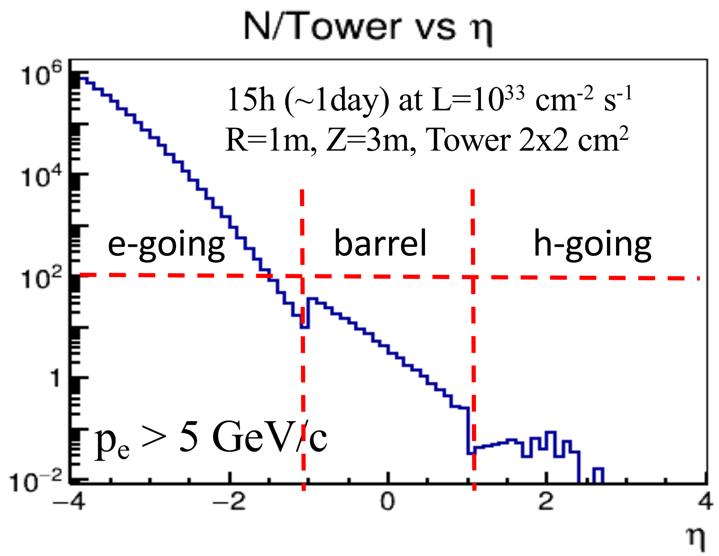


Calibration

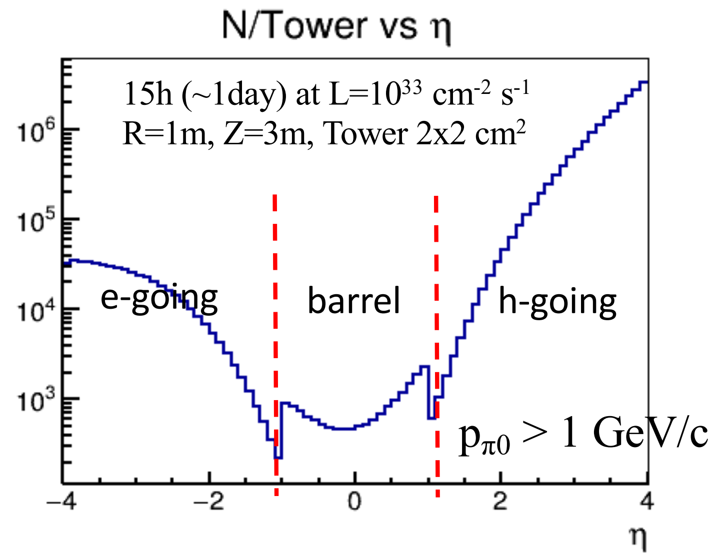
"Usually" a few hundred particles per tower needed

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

Electron



$\pi 0 \rightarrow \gamma\gamma$



- ✓ 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

Central Detector Package

Length x Radius = 9.5m x 3.3m

ePIC detector geometry database: https://eic.jlab.org/Geometry/Detector/

Tracking: MAPS, MPGD, AC-LGAD*, BIC*
PID: dRICH, pfRICH, DIRC, AC-LGAD
Calorimeter: EMCAL, HCAL