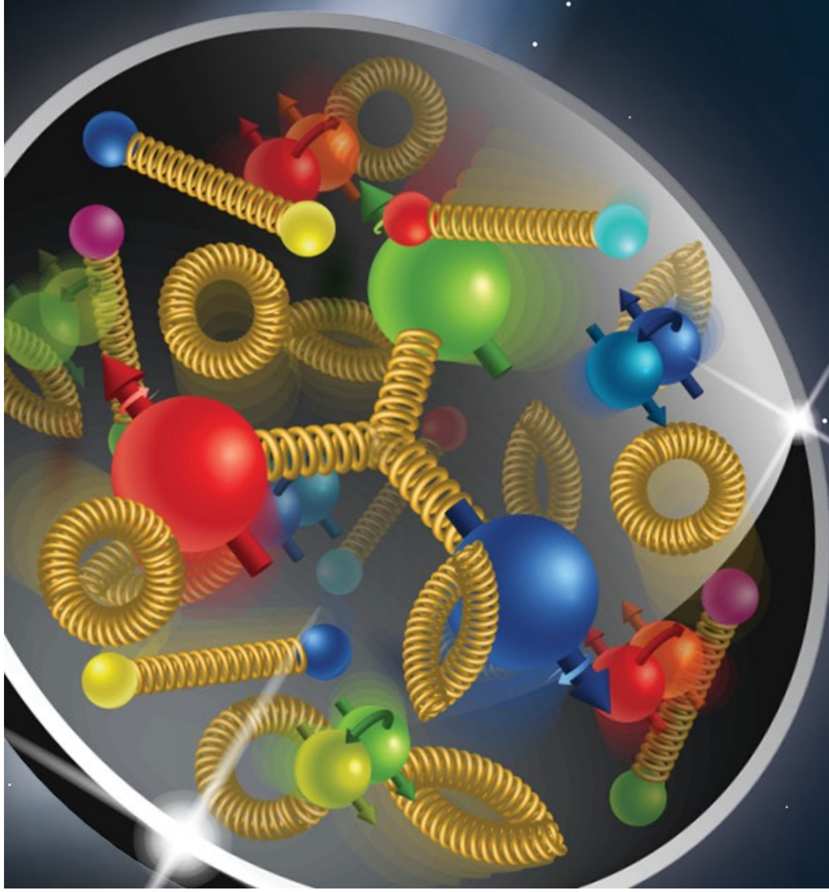
Electromagnetic Calorimetry Status Report

Alexander Bazilevsky (BNL)

L3/CAM EMCal

EIC Detector Comprehensive Design Review

August 29-30, 2023



Electron-Ion Collider

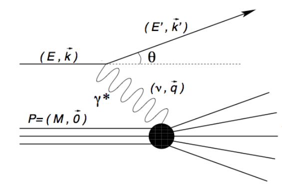
BROOKHAVEN NATIONAL LABORATORY   Jefferson Lab   U.S. DEPARTMENT OF ENERGY | Office of Science

EMCal for an EIC Detector

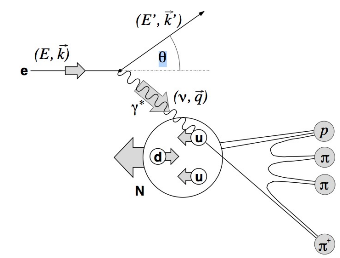
Electron/photon PID, energy, angle/position:

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

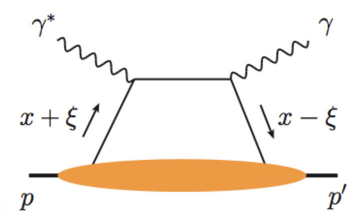
Inclusive DIS: scattered electron



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



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



Detector Requirements: Summary

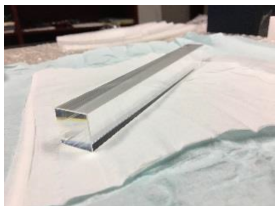
As documented in YR and
"General, Functional, and Performance Requirements for the EIC Detector Systems"

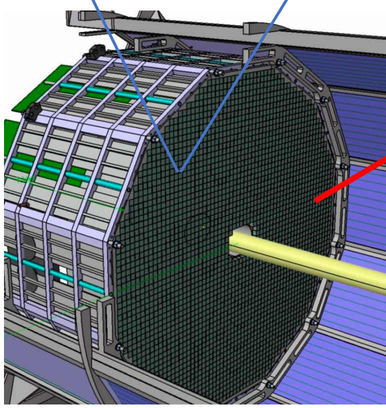
	Electron endcap	Barrel	Hadron endcap
Energy Resolution	$\frac{(2-3)\%}{\sqrt{E}} \oplus 1\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$
Shower Energy range	0.1−18 GeV	0.1−50 GeV	0.1−100 GeV
$\pi\pm$ suppression (helped by other subsystems)	Up to 10^4		
$\pi^0/\boldsymbol{\gamma}$ 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} /cm²/year	10^{10} /cm²/year	10^{11} /cm²/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

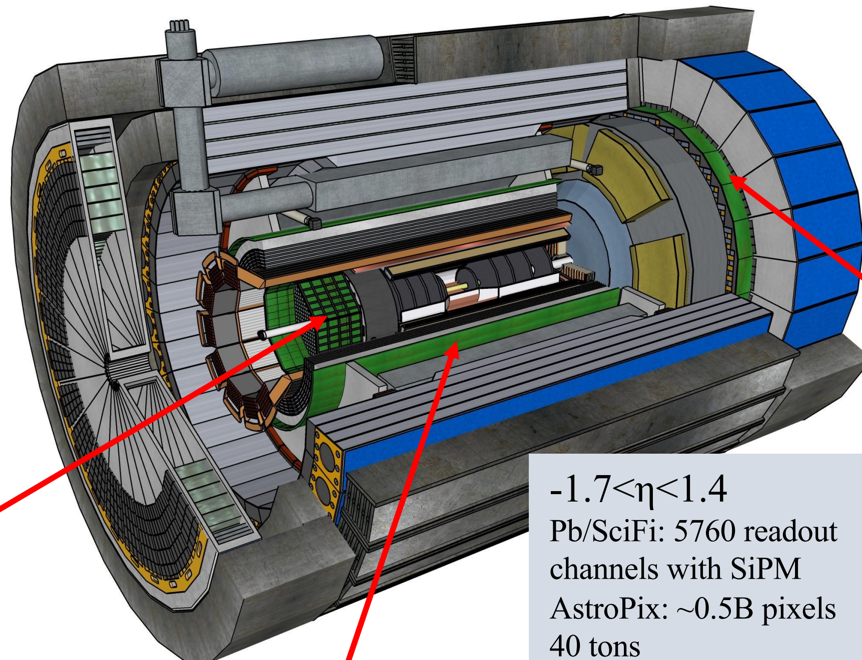
EM Calorimetry in EIC Detector

PbWO4

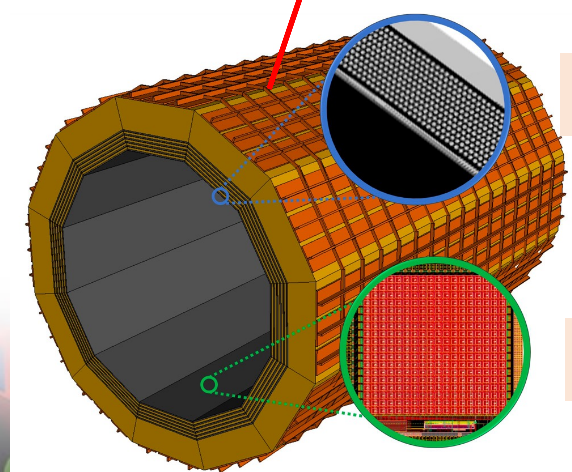




$-3.5<\eta<-1.7$
~3k crystals
R_{outer}=64cm
SiPM readout
2 tons



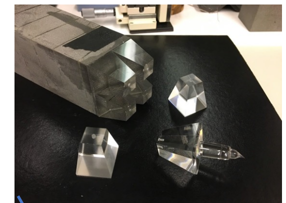
$-1.7<\eta<1.4$
Pb/SciFi: 5760 readout channels with SiPM
AstroPix: ~0.5B pixels
40 tons

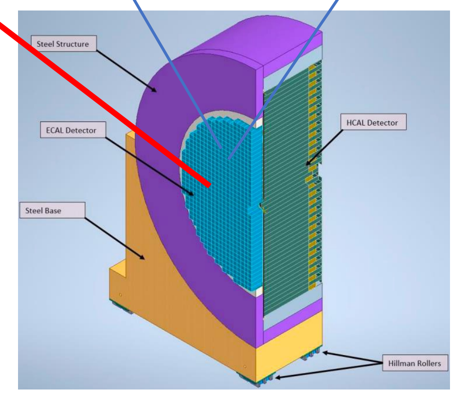


Pb/SciFi

AstroPix

W/SciFi

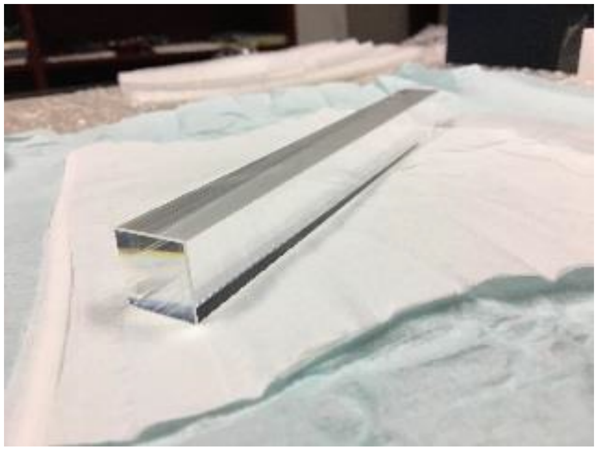




$1.4<\eta<3.7$
~16k towers
R_{outer}=160cm
SiPM readout
20 tons

e-endcap: $PbWO_4$

- High resolution
- High e/π separation for eID



Well established technology

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

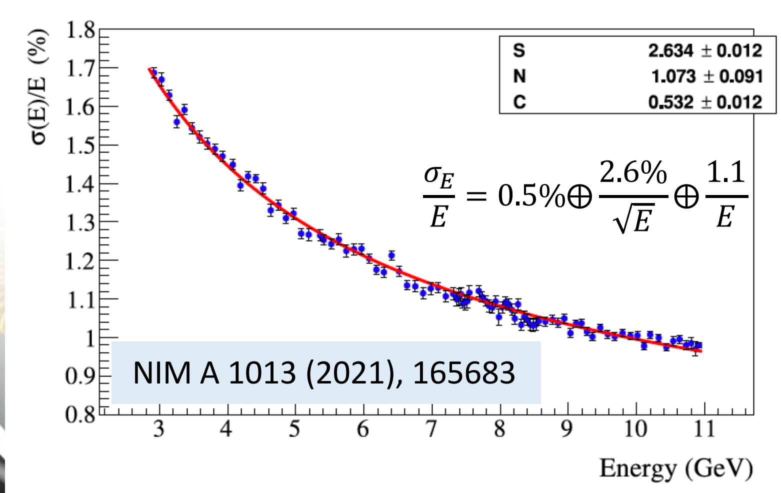
High resolution: $\frac{\sigma_E}{E} = (0.4-1)\%\oplus\frac{(2-3)\%}{\sqrt{E}}$

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

Radiation hard: >1000 krad

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

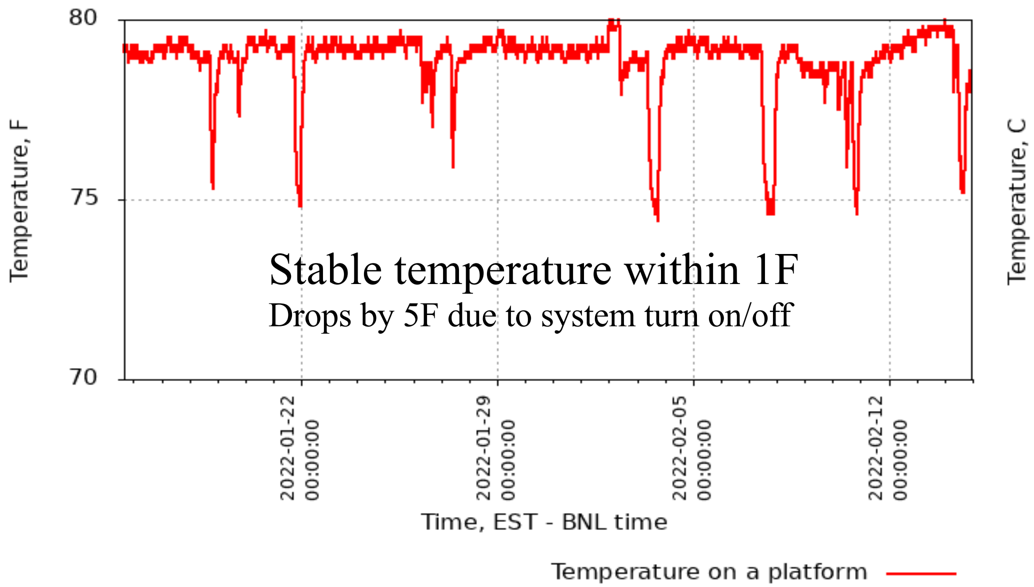
Jlab-PrimEx eta/NPS PWO EMCal prototype



- **Consortium with >10 institutions** (USA, Armenia, Czech Republic, France)
- Synergy with other projects: NPS and FCAL (JLab)

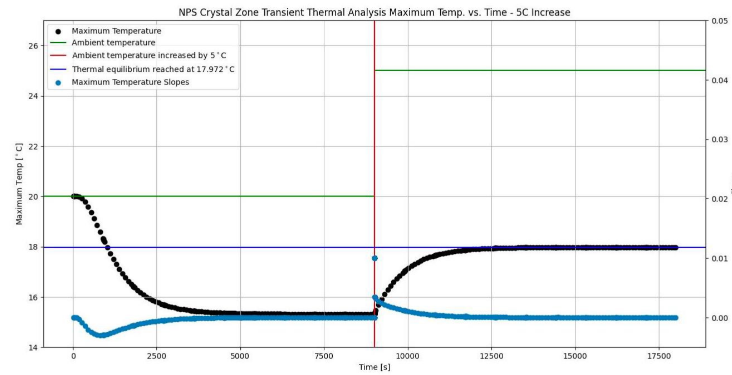
  Expertise, Resources, Prototypes, etc
- Extensive experience from recent PANDA (GSI) and CMS (CERN)
- In contact with Vendor (CRYTUR/Czech Republic)
- Ongoing R&D to finalize readout
- NSF MSRI proposal submitted: May 4, 2023

e-endcap: T^0 stabilization



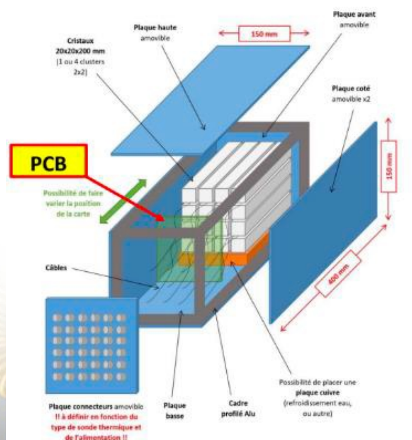
Stable temperature within 1F

Drops by 5F due to system turn on/off

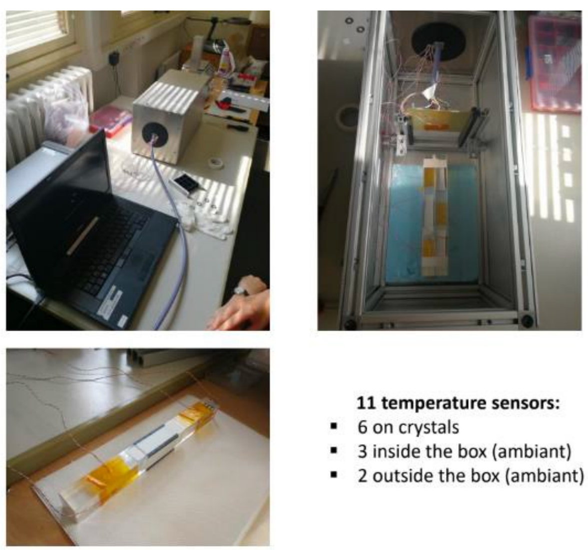


ANSYS simulation

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)

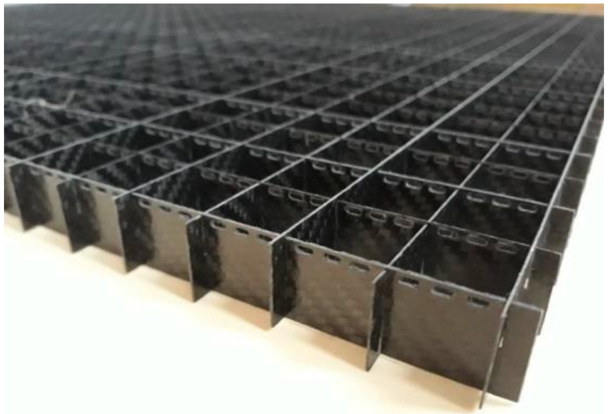
Thermal Design and Test

Operation at room temperature

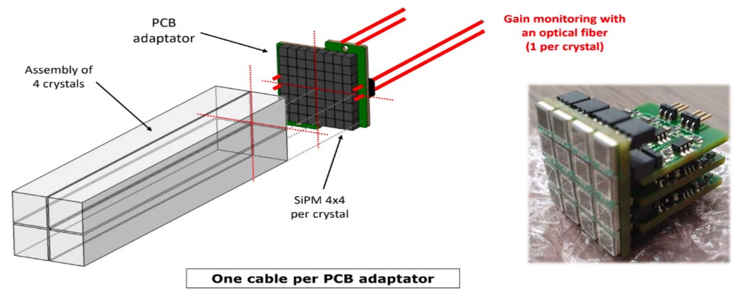
Simulations to quantify the effect of ambient temperature fluctuation on the crystal temperature

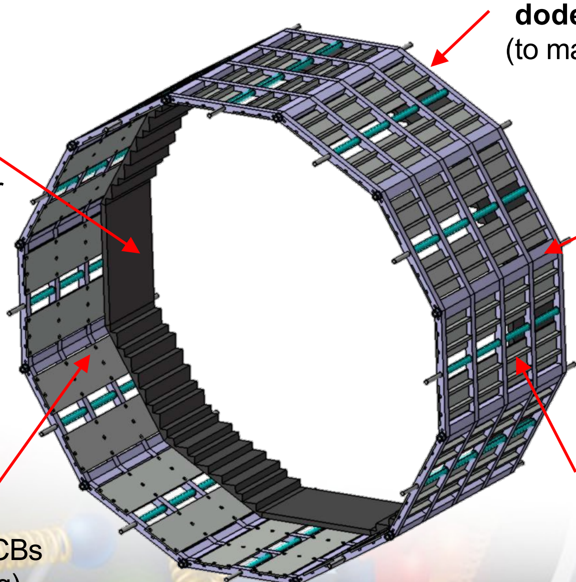
Measurements on a prototype

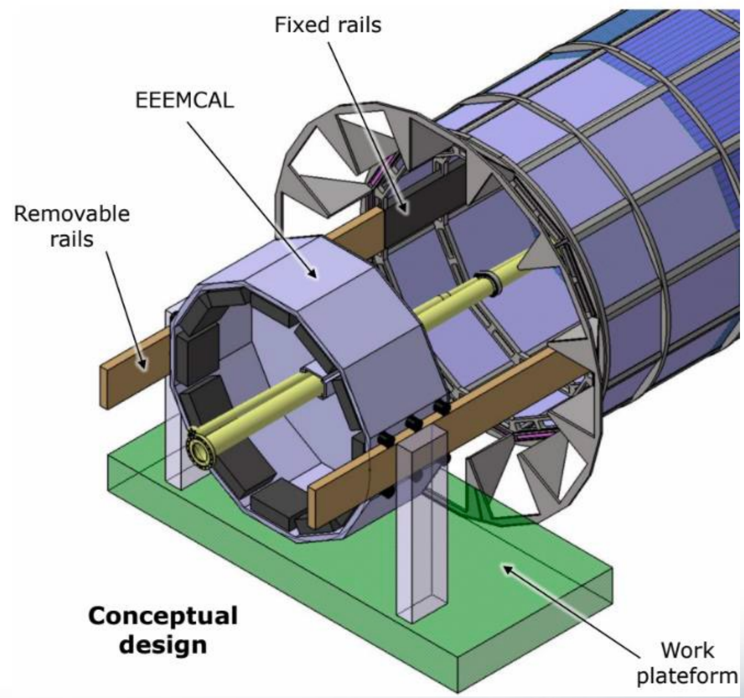
e-endcap: Mechanics and Integration



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





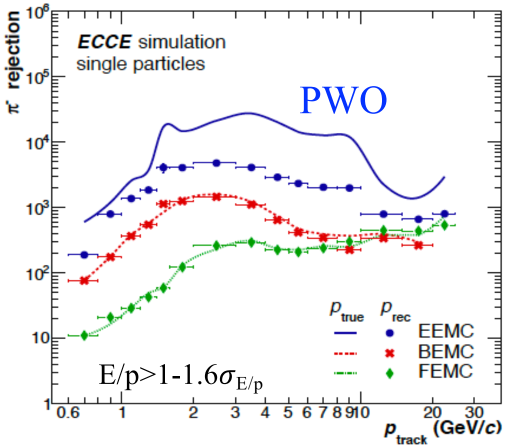


Advanced Preliminary Design

e-endcap: Performance at EIC

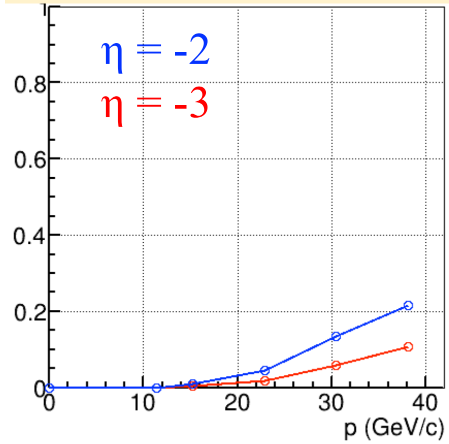
Full GEANT simulation with full detector implementation

π- rejection



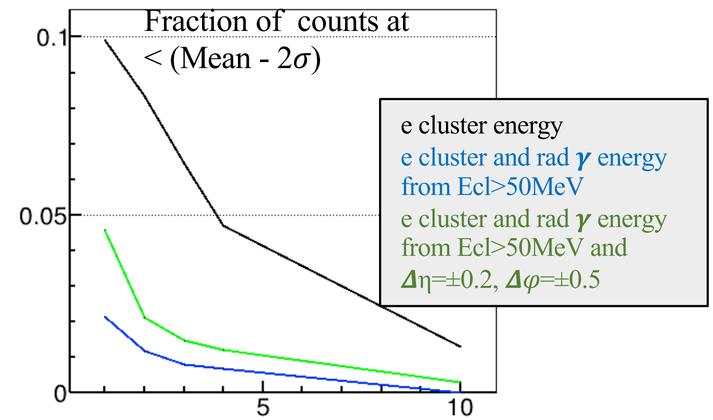
π0 merging prob

(after shower profile analysis)

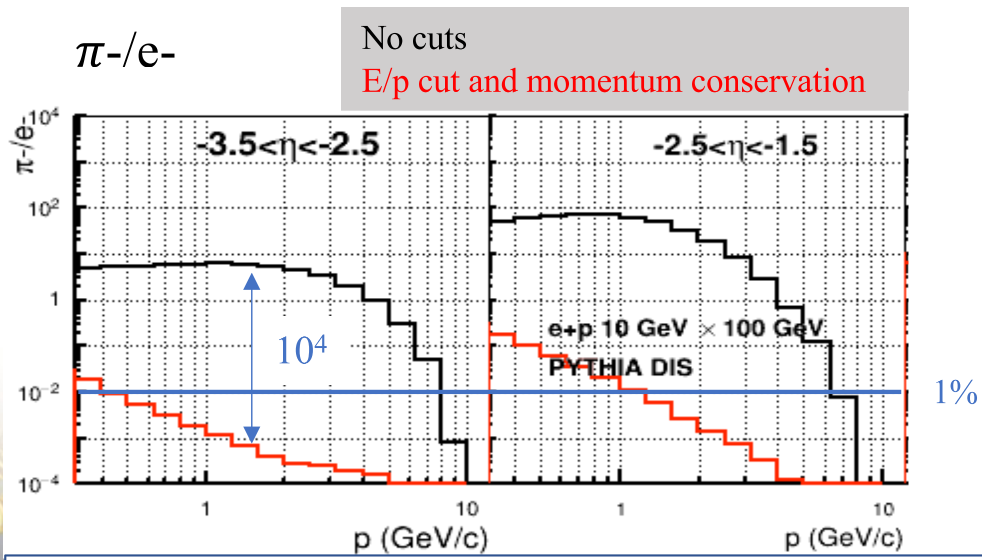


Material effect

Eff. loss vs E (GeV)



π-/e-



* 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

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:

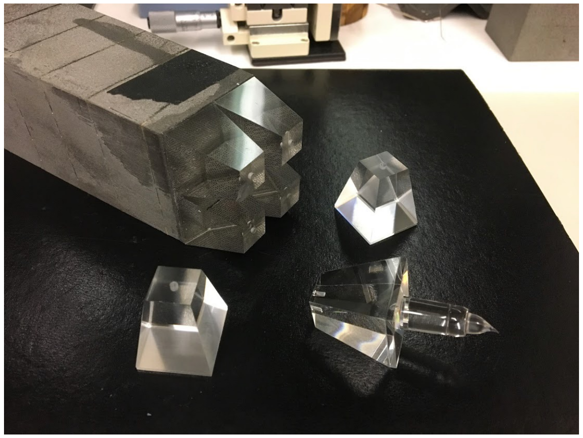
Specs:	Finalized
Final Design Review:	July 21, 2023
Contact award:	Summer 2024
Material Delivery:	Summer 2024 – Summer 2028

Final Design Review:

Fully acknowledged the PbWO4 readiness for the LLP

h-endcap: W/SciFi

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

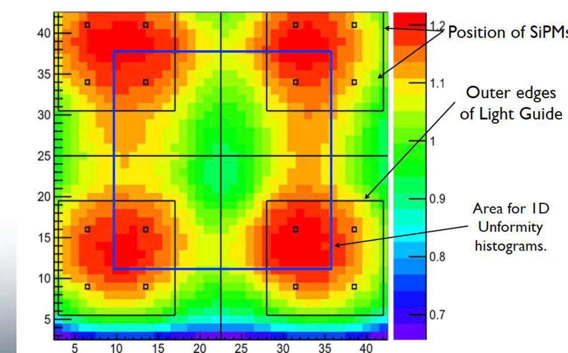


Pioneered by UCLA
sPHENIX EMCal: 25k towers

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

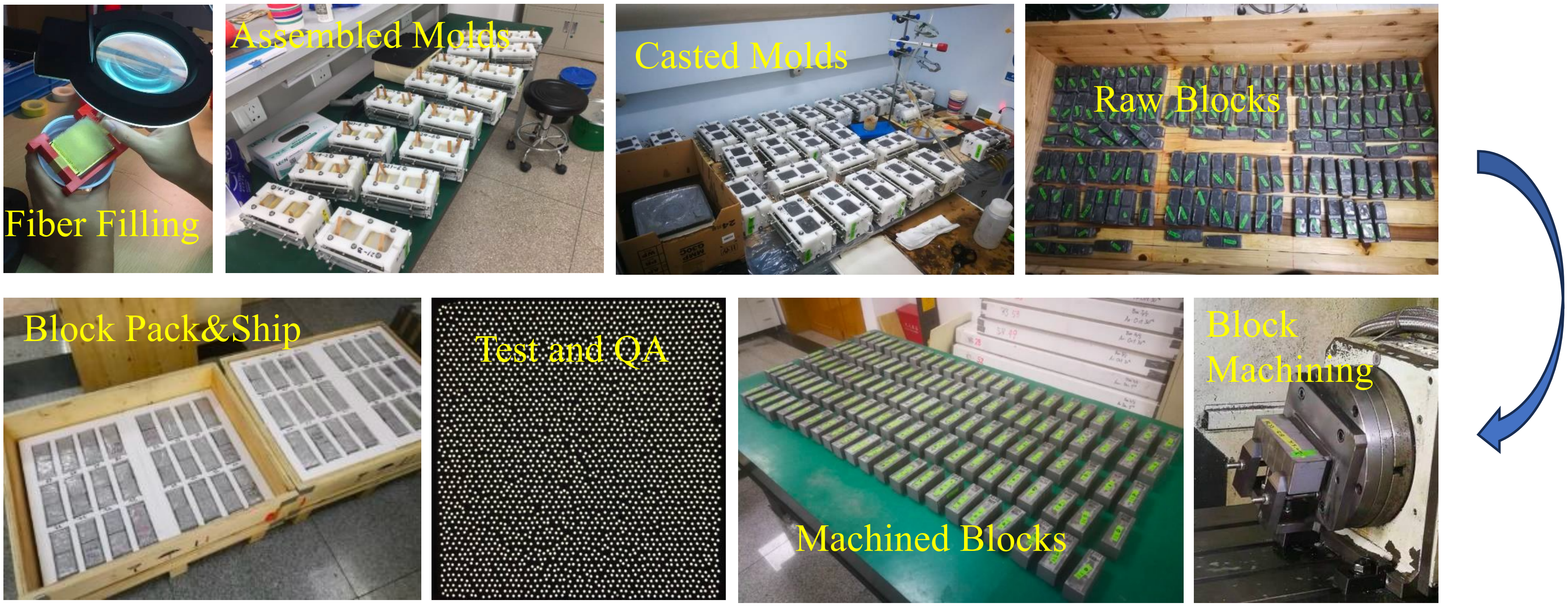
R&D:

- SiPM readout
- Improve light collection eff. and uniformity



- ~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

h-endcap: Production Chain

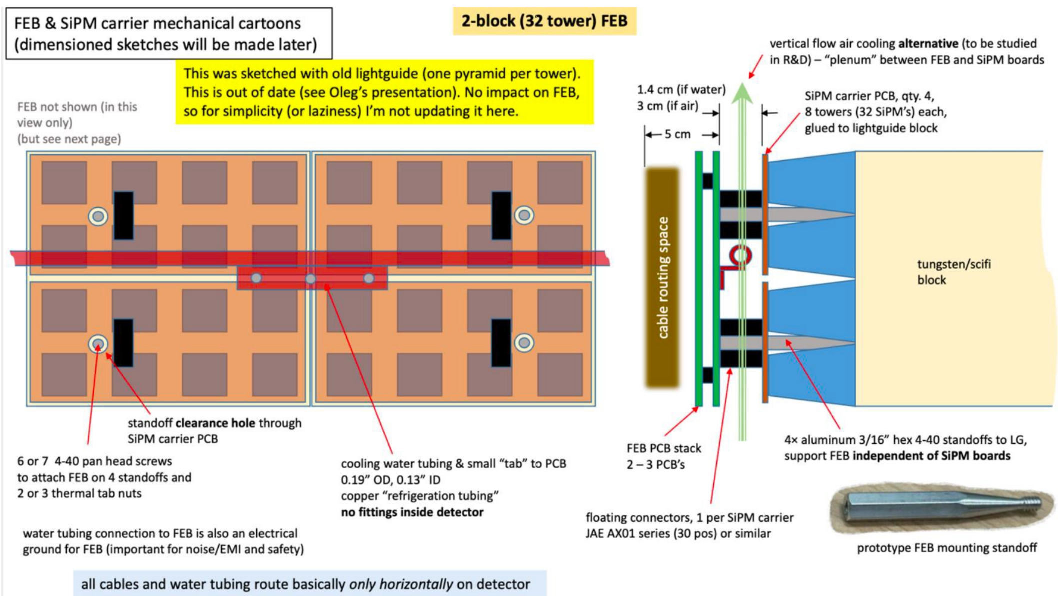


Production chain is fully established

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

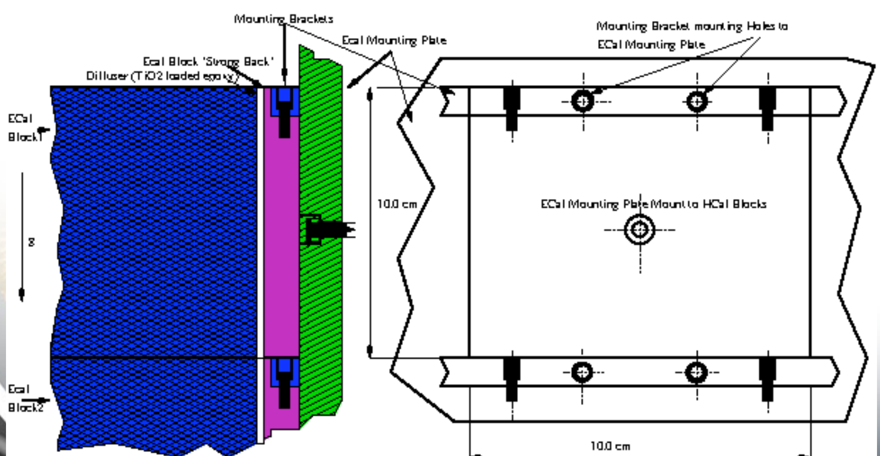
If US-China S&T agreement is not extended, we'll setup another factory in US

h-endcap: Mechanical Design



Readout, Cooling

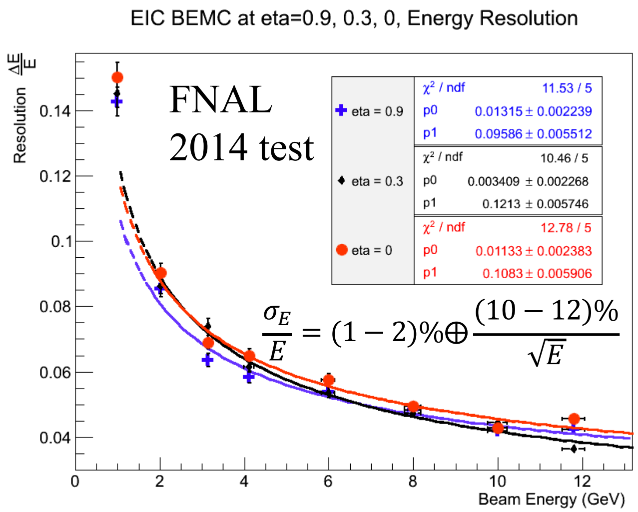
4 6x6mm^2 SiPM per tower



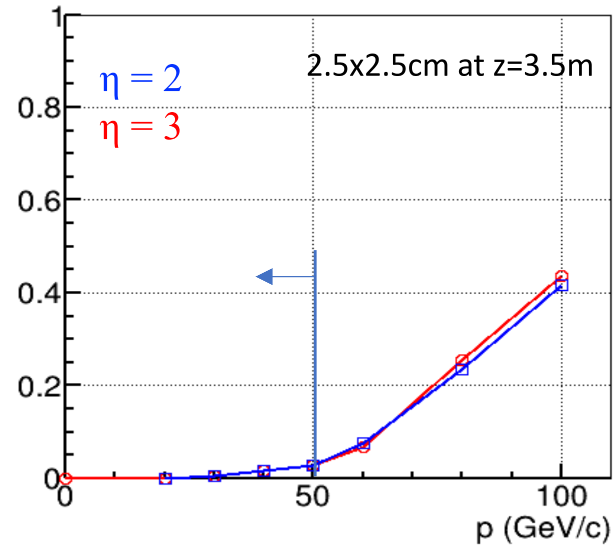
Block installation Design
and
Structural test

h-endcap: Performance at EIC

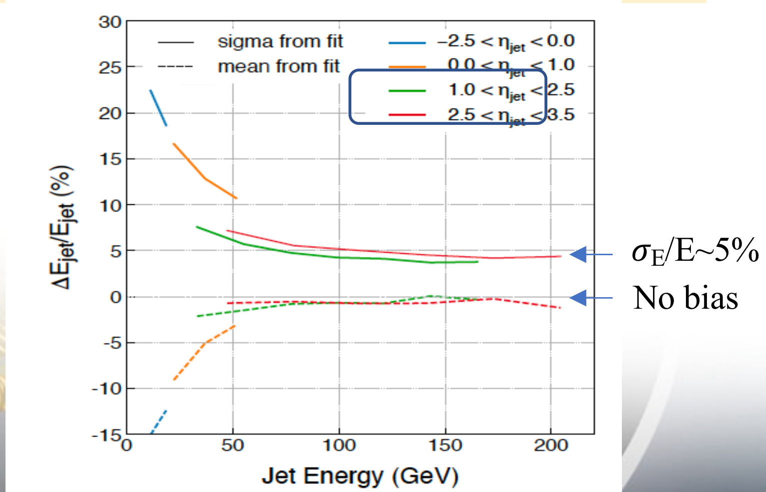
Energy Resolution



$\pi 0/\gamma$: 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

h-endcap: SciFi for LLP

1. Single clad fibers, round cross section
2. diameter 0.47 mm
3. diameter variation ±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 < 3ns
9. delivered in canes ~ 1m 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

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

Hybrid Concept:

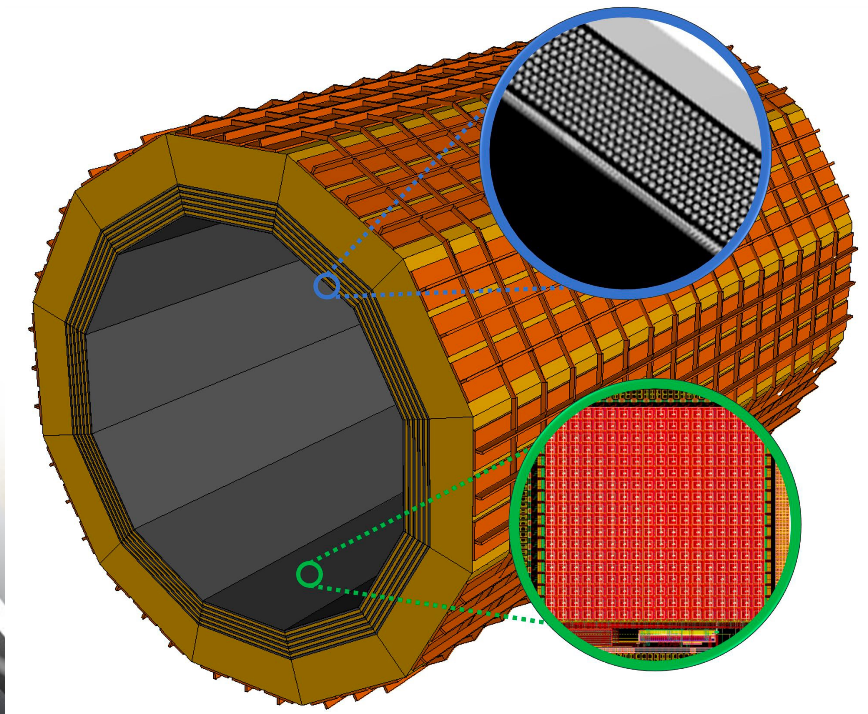
6 imaging Si layers (4 layers in baseline), Interleaved with 5 Pb/SciFi layers, followed by a thick Pb/SciFi layer ($17X_0$ total)

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

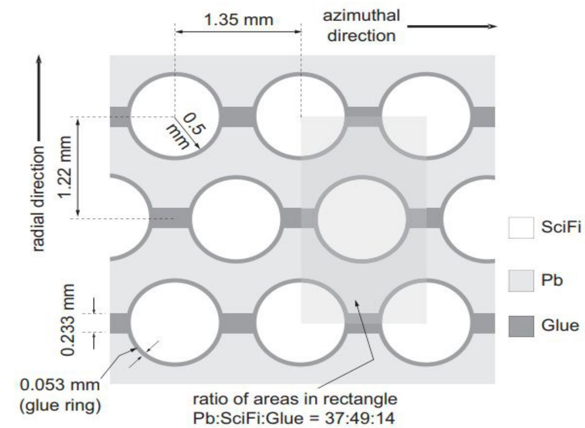
Pb/SciFi part follows GlueX barrel EMCal

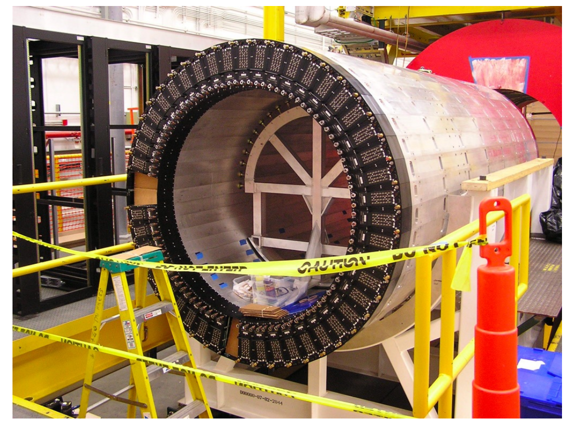
2-side SiPM readout

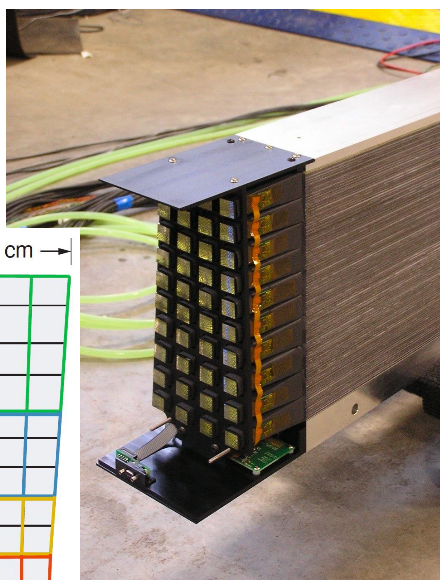
Mature technology (GlueX, KLOE)

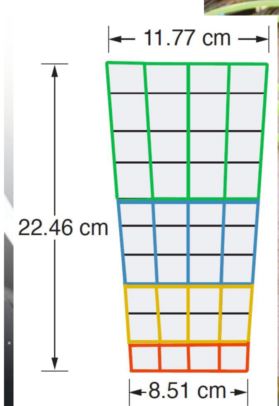
- Module construction fully developed
- GlueX module construction equipment available
- Calorimeter performance well studied

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
- 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

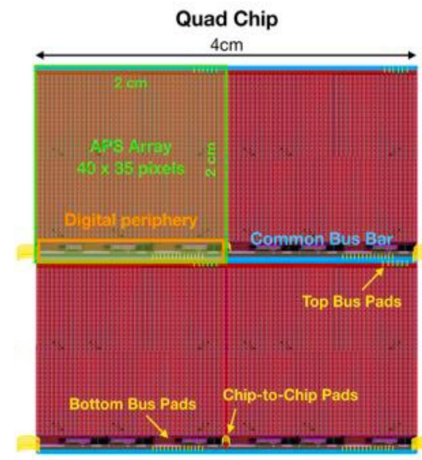
- Developed for AMEGO-X (NASA)
- CMOS sensor based on ATLASpix3

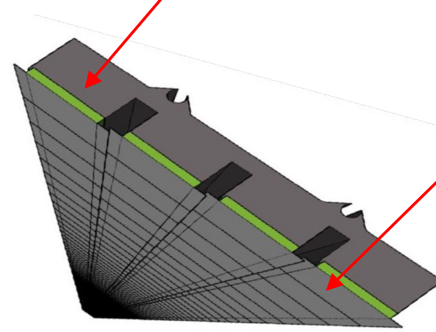
4 layers (of 6) in a baseline design

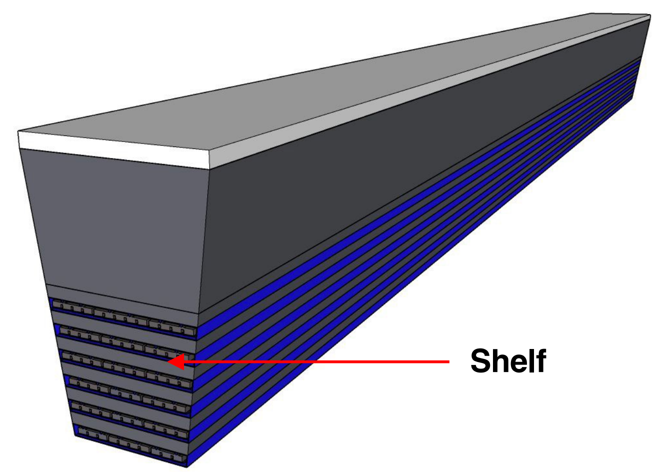
Pixel size	$500\,\mu m \times 500\,\mu m$
Power usage	< 1 mW/cm^2
Energy resolution	10% @ 60 keV (based on the noise floor of 5 keV)
Dynamic range	$\sim$ 700 keV
Passive material	$< 5\%$ on the active area of Si
Time resolution	25 ns
Si Thickness	$500\,\mu m$

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)

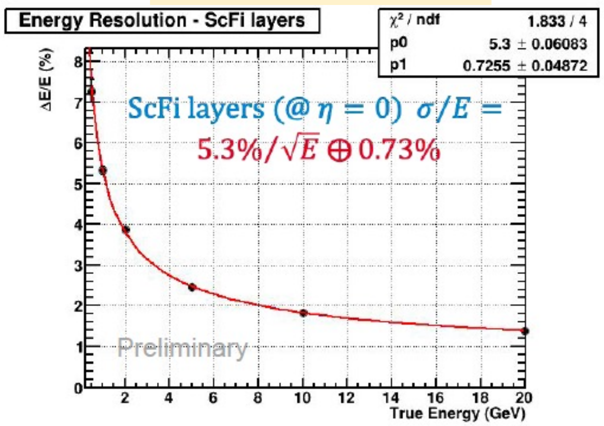




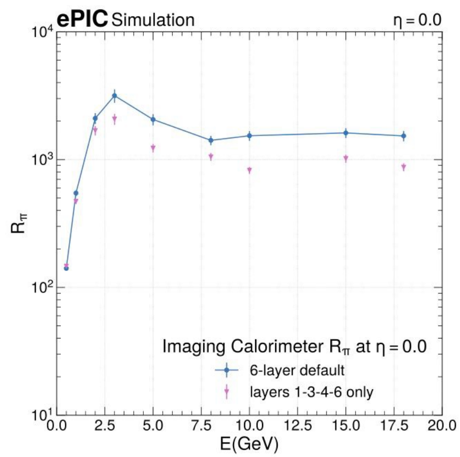


Barrel: Performance at EIC

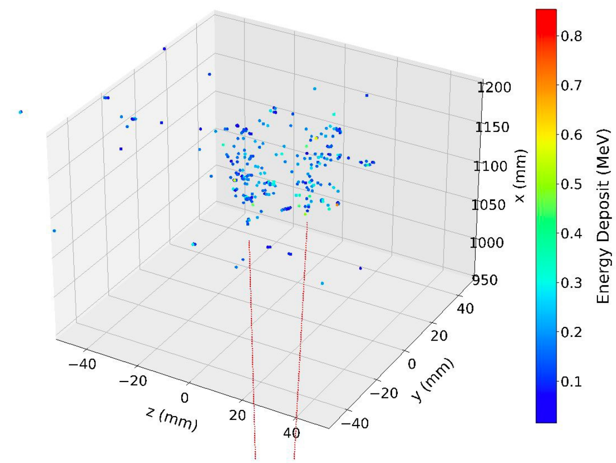
Energy Resolution



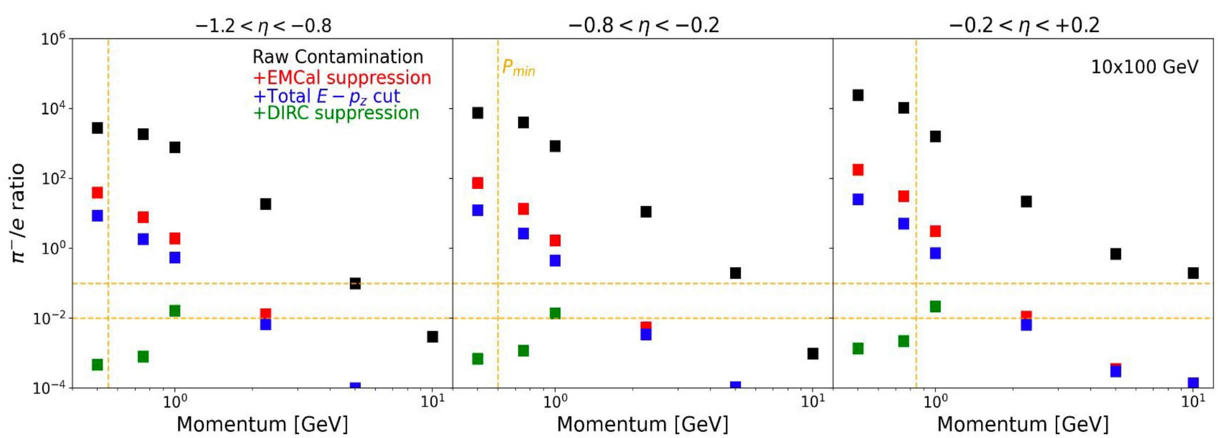
π- rejection



15 GeV $\pi0 \rightarrow \boldsymbol{\gamma\gamma}$



DIS electron purity



- Very good energy resolution
- Strong $\pi\pm$ rejection for eID
- DIS electron purity of ~99% or better achieved
- $\pi0/\boldsymbol{\gamma}$ 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 um.
4. Single clad: cladding thickness ~2% of diameter, Double-clad: cladding thickness ~4% of diameter
5. attenuation length for blue light >3.5 m
6. emission spectrum of blue-green light
7. light yield > 7000-8000 ph/MeV
8. scintillation decay time < 3ns
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:

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

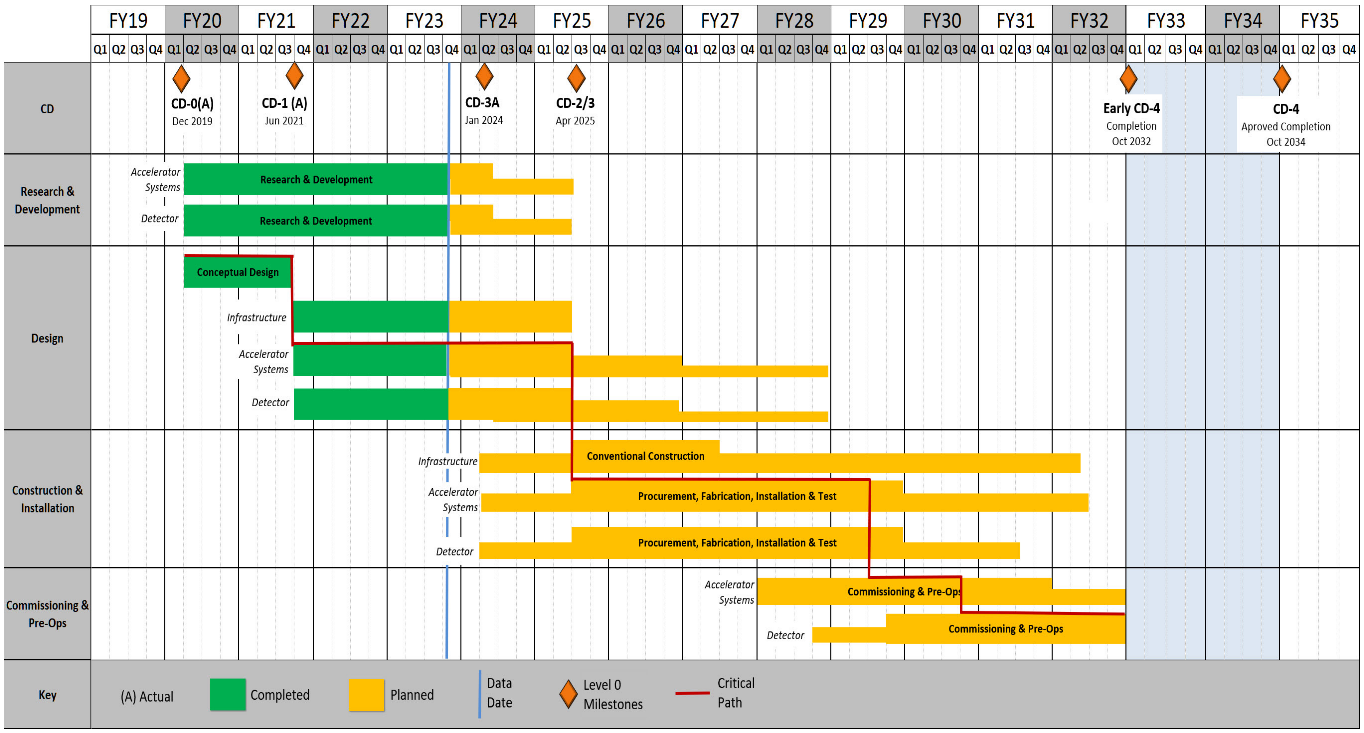
	Backward	Barrel	Forward
Light Yield per GeV	10k	1k	1k
E_{max} per RO channel, GeV	15	10	100
N_{pe} max	150k	10k	100k
SiPM size (4 per RO channel)	6x6 mm^2	6x6 mm^2	6x6 mm^2
SiPM pixel size	15 um	50 um	15 um
SiPM: N pixel max	640k	57k	640k

Final Design Review: September 14, 2023

Then we are ready for Procurement

Schedule

Detector subsystem schedule matches EIC Project Critical Decision path



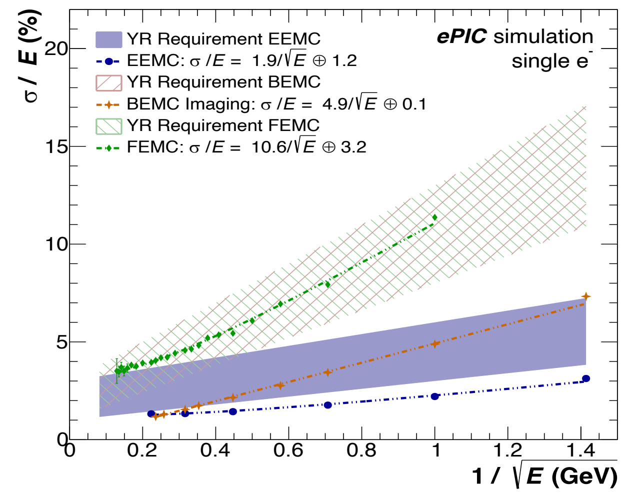
EIC Project Critical Decision and Detector Milestone Path

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



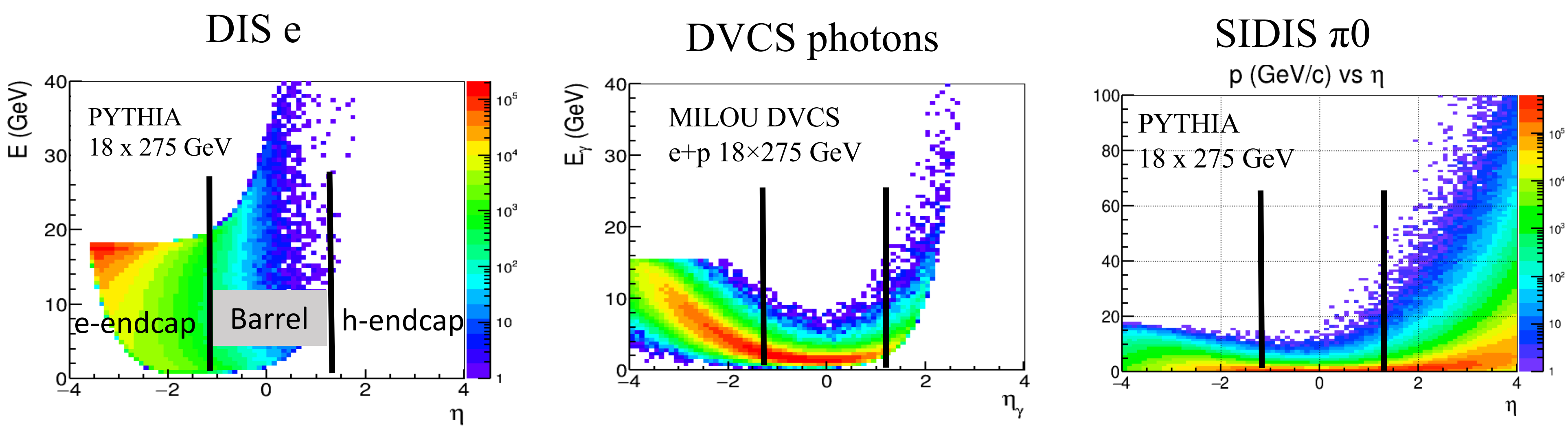
- Physics requirements are well defined and documented in the YR and “General, Functional, and Performance Requirements for the EIC Detector Systems”
- The selected EMCal technologies satisfy or exceed the requirements
  - e-endcap: PbWO4 crystal, well established technology
  - Barrel: Pb/SciFi + Imaging (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
  - Advanced preliminary design for e-endcap EMCal
  - 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

Conclusion

1. Given the detector progress over the last two years and the status of the ePIC detector, are the projected timelines of the Electron-Ion Collider detector feasible? Do there remain significant open detector technology questions?
   - Yes, the detector technologies are defined, the production timeline for such technologies is well established and matches well the EIC project schedule
2. Are the requirements for the detector and their flow down sufficiently comprehensive for this stage of the project to complete the design of the various detector technologies?
   - Yes, the detector requirements are defined and documents; the selected technologies satisfy or exceed the requirements.
3. Are the interfaces between the elements of the design adequately defined for this stage of the project and to proceed with the detector long-lead procurement items?
   - Yes; little interference of the LLP items with the other elements of the design
4. Is the design of these long-lead procurement items sufficiently advanced and mature to start procurement in 2024? Are the technical specifications complete?
   - Yes, the design and specifications for LLP items are complete
   - Successful FDR for PbWO4 on Jul 21; FDR for SciFi on Sep 13, and for SiPM on Sep 14
5. Is the projected design maturity of the further detector components likely to be accomplished by the end of 2024 for CD-2 and CD-3?
   - Yes, all technologies are defined and are well established; engineering design progressing quickly
6. Is the overall schedule for completion of the design, production, and installation of detector components realistic?
   - Yes, based on experience from the recently completed projects

Backup

Coverage, Energy Range



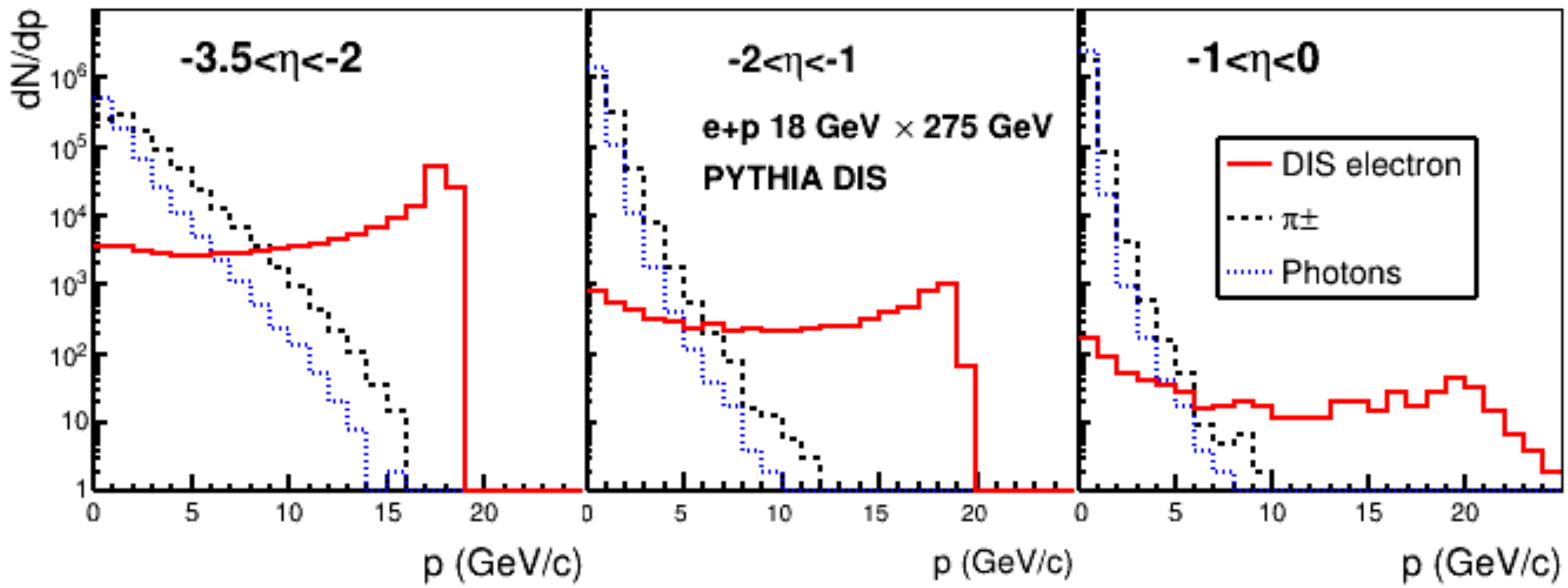
Continuous acceptance coverage: at least $|\eta|<3.5$

- 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 $\pi0$
- h-endcap: up to ~100 GeV

DIS kinematics: ePID



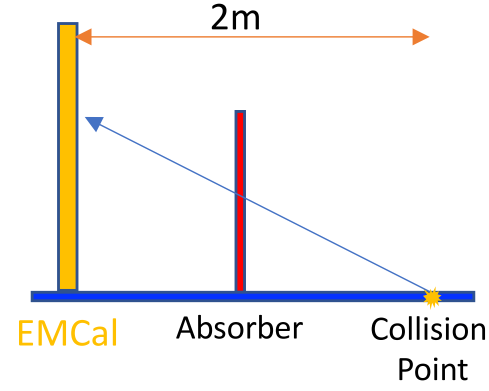
Charged hadron high suppression power is required

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

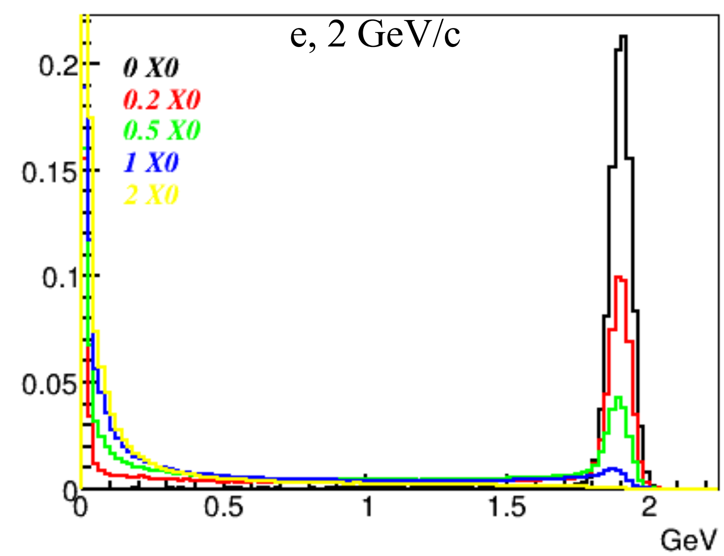
Effect of material on the way

- 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

GEANT simulation for a single electron



Cluster Energy

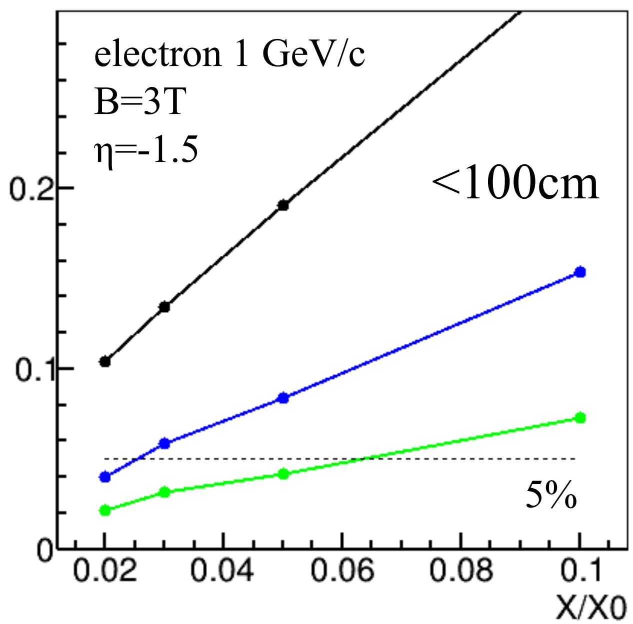


- Energy gets absorbed in the material
- Energy gets distributed in the EMCal, e.g. due to Bremsstrahlung radiation by electron
  - Single cluster reco leads to eff. loss
  - The eff. can be recovered by radiated photon reco
  - The closer to the EMCal the smaller the effect
  - The higher Bdl the larger the effect
  - Rad. photons are localized in arcs with the same polar angle as a parent electron => topological search window

Effect of material on the way

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

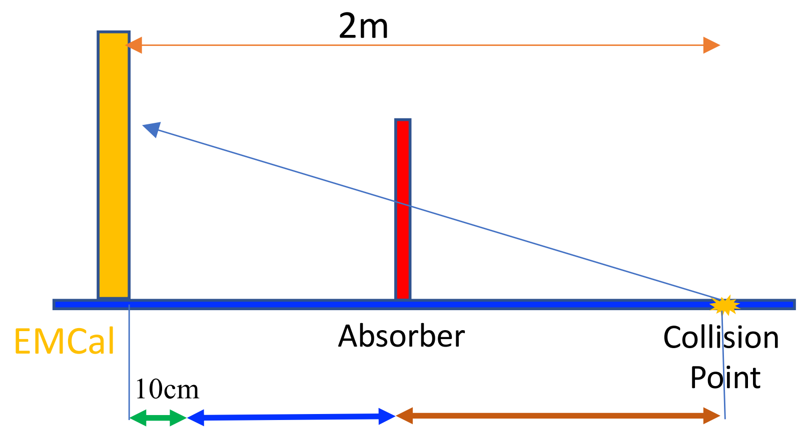
Efficiency loss (with 2σ cut) vs X/X_0



e cluster energy

e cluster and rad γ energy from Ecl>50MeV

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



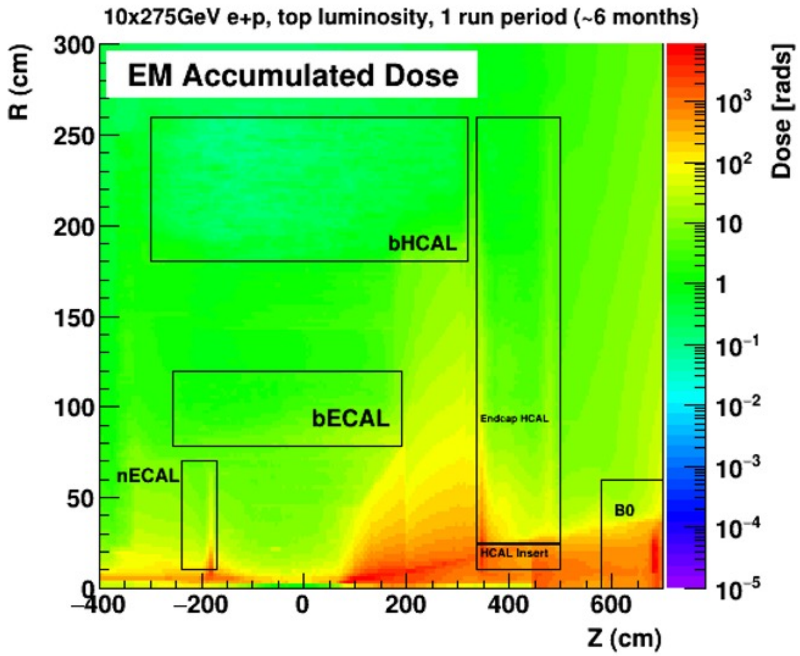
$<50\%X_0$	$<20\%X_0$	$<(3\text{-}6)\%X_0$	Electron > 1GeV
$<30\%X_0$	$<10\%X_0$	$<10\%X_0$	Photon > 0.1GeV

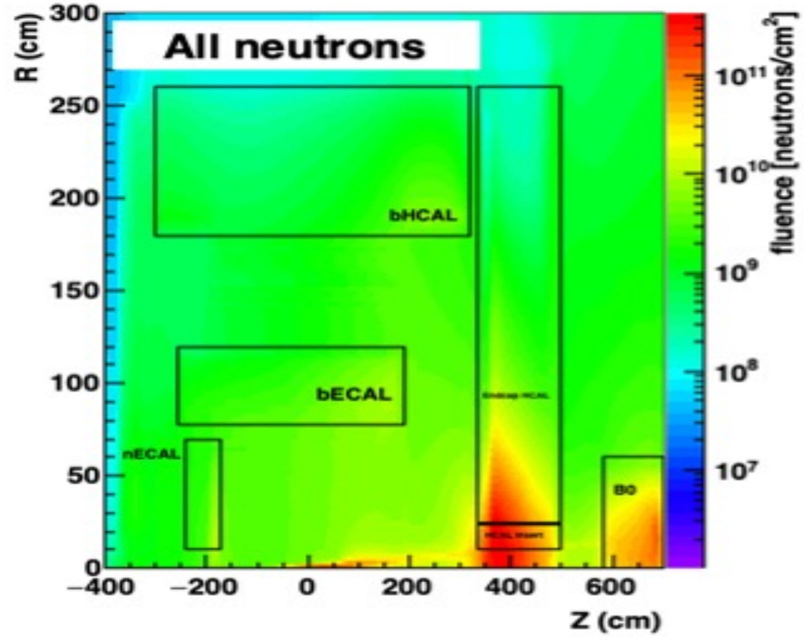
Exclusive requirements
(the whole effect assumed from one region)

The amount and localization of tolerable material formulated

The requirements are relaxed for B=1.7-2T

Rad Dose and Neutron Flux



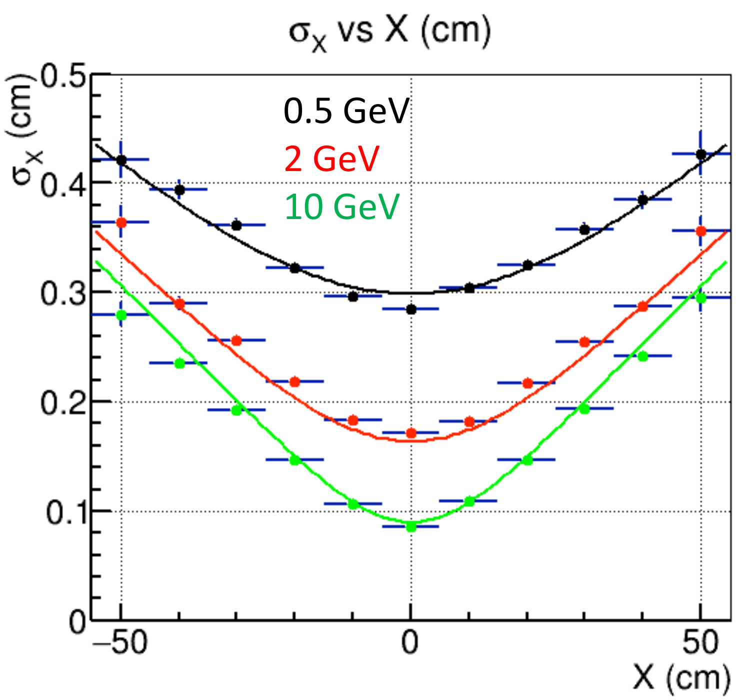


Highest dose in the forw EMCal next to the beam pipe:
~2.5 krad/year at L=10^{34} $cm^{-2}s^{-1}$

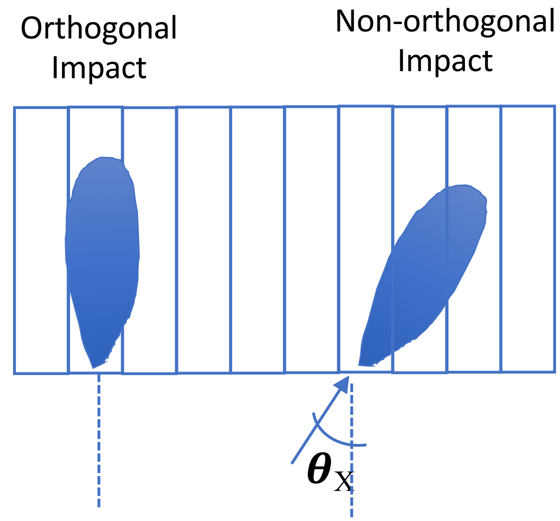
Highest flux in the forw EMCal next to the beam pipe:
~10^{11} n/cm^2/year at L=10^{34} $cm^{-2}s^{-1}$

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)

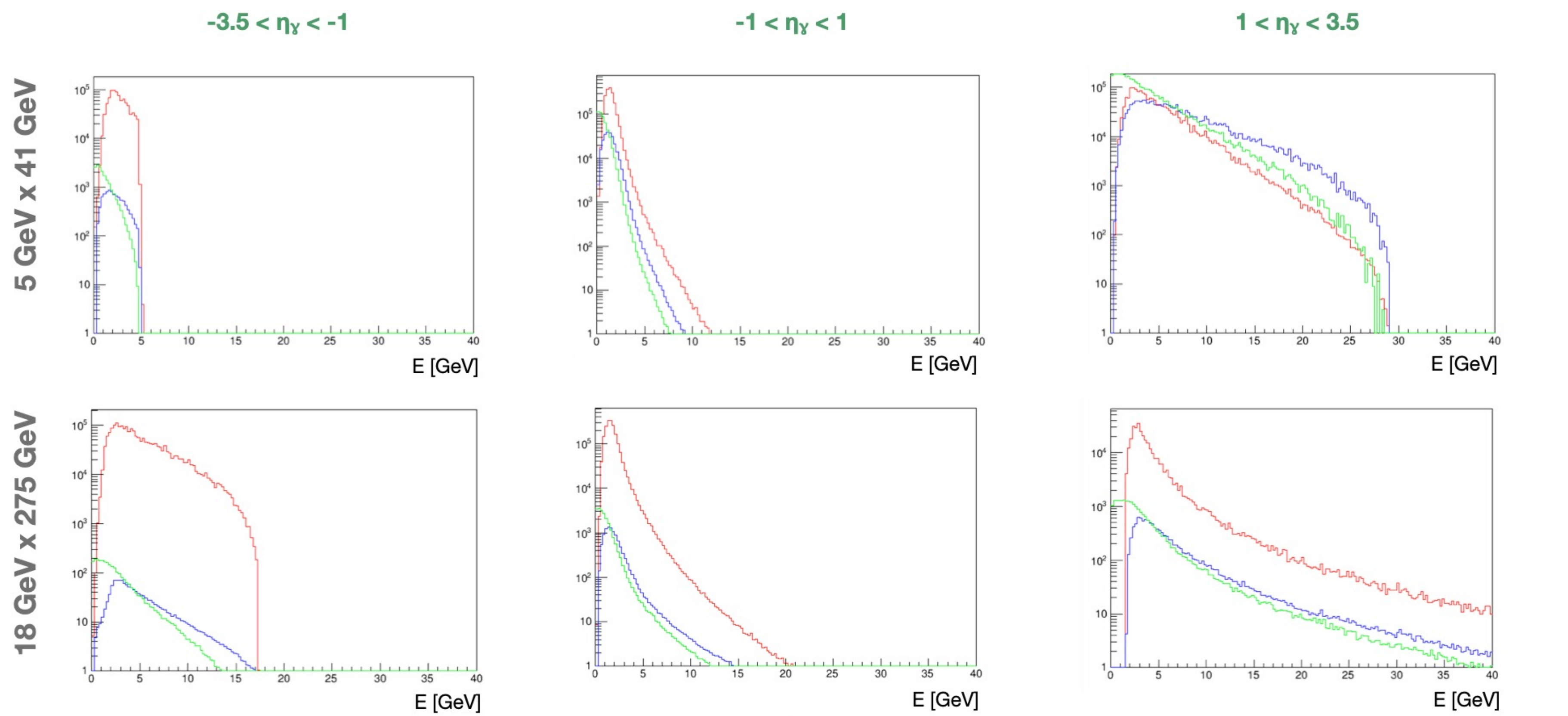
Maximal non-projectivity term for the backward EMCal is 3mm ($\boldsymbol{\theta}_{max}=20^0$)

Exclusive: DVCS and pi0

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

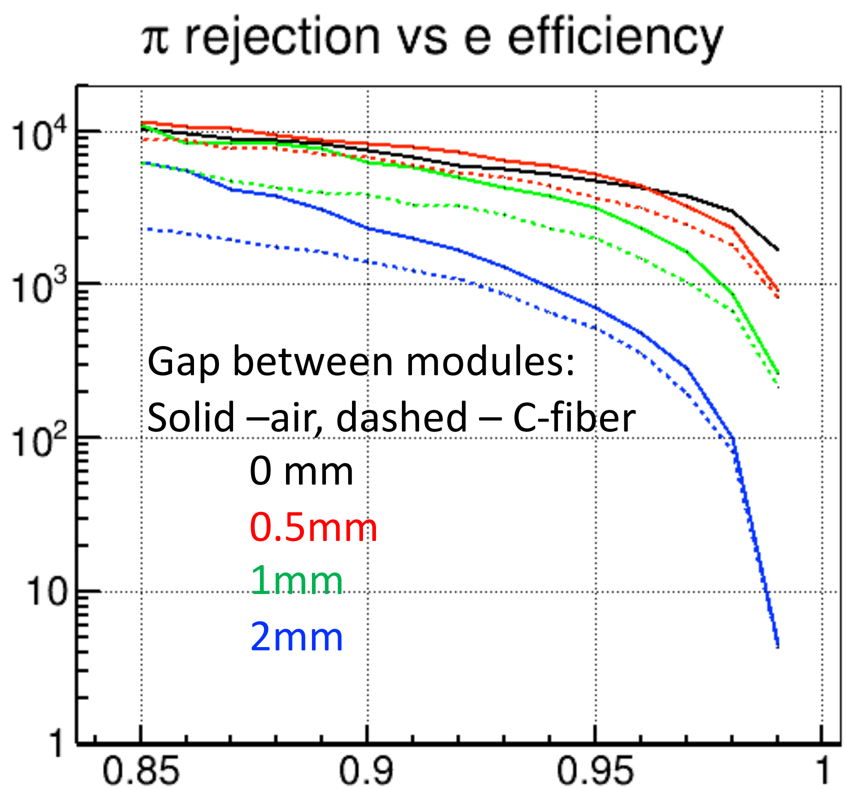
$Q^2 > 1$ GeV^2
$0.01 < y < 0.95$
$|\eta_{e^-}| < 3.5$
$L = 10$ fb^{-1}

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



e/π: PWO

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



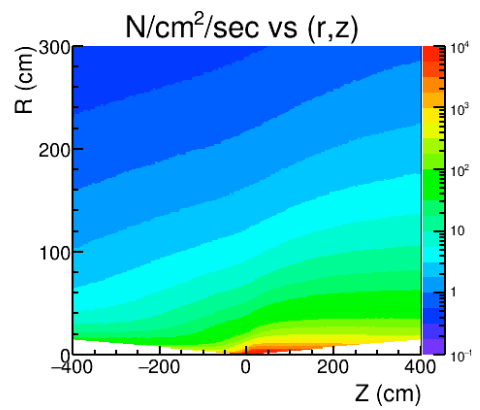
Particle/Energy Flow

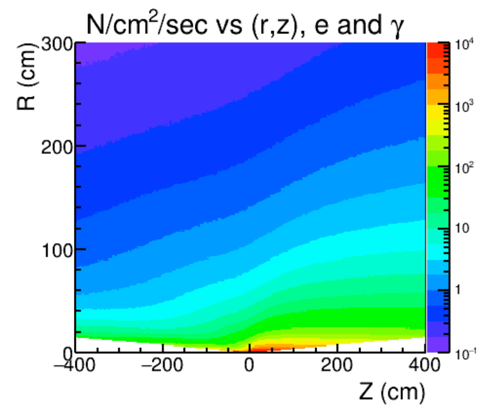
All particles

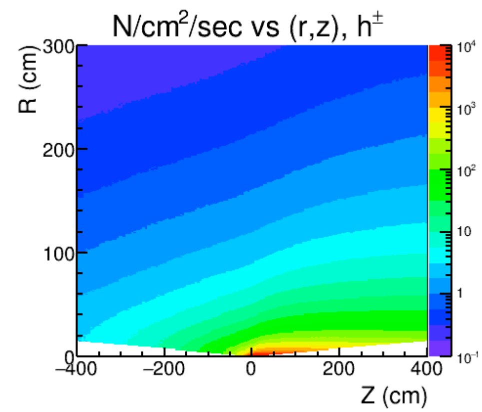
e and γ

h±

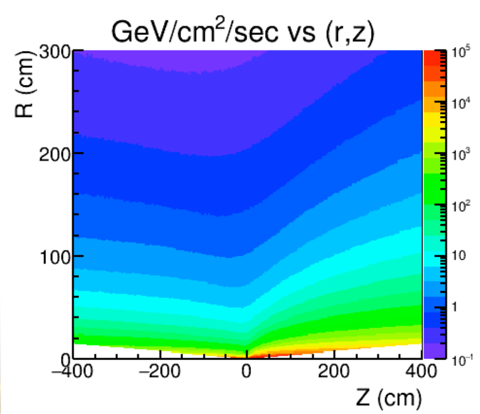
Particle flow

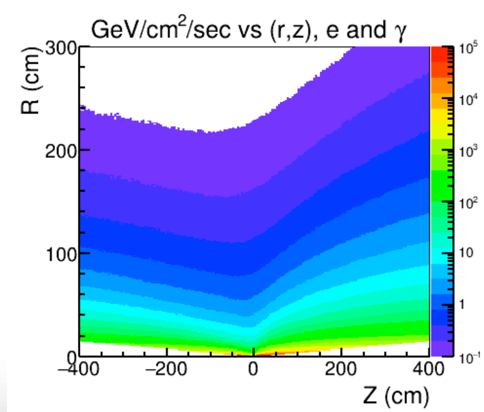


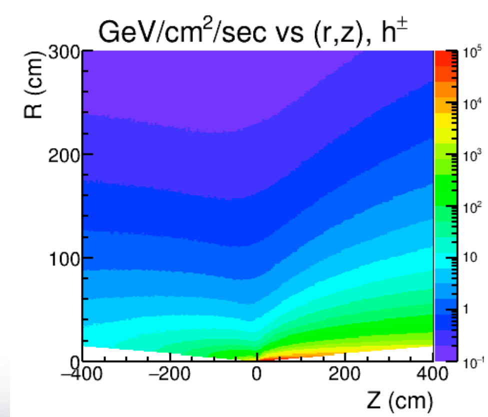




Energy flow





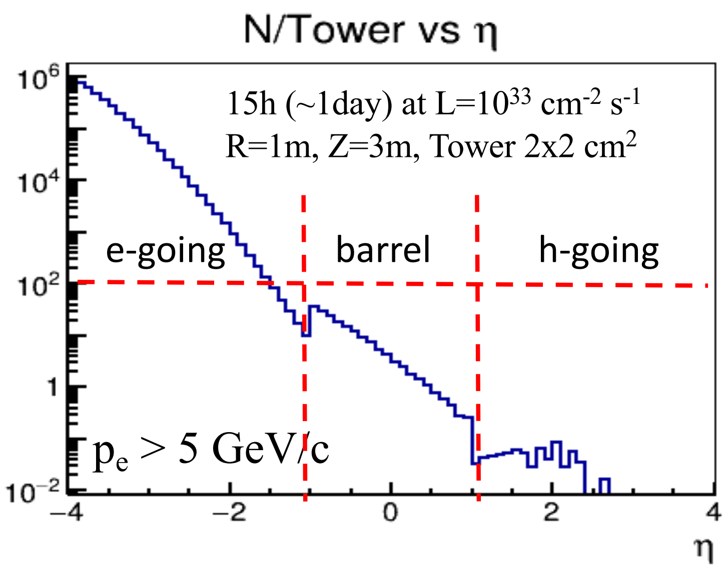


Calibration

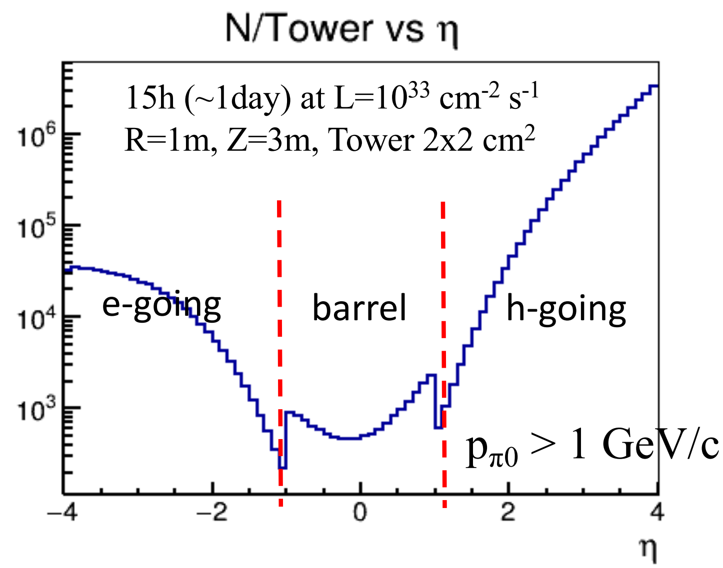
"Usually" a few hundred particles per tower needed

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

Electron



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

SiPM Specs

Parameter	Specs
Active area	6 mm x 6 mm
Pixel Size	15 um (50 um)
Package type	Surface mount
Peak Sensitivity	Max PDE at ~ 450 nm
PDE	>30% (>50%) @3V overvoltage
Gain	~2x 10^5 (~2x 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)