Calorimetry for the Electron Ion Collider

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CPAD Instrumentation Frontier Workshop 2022

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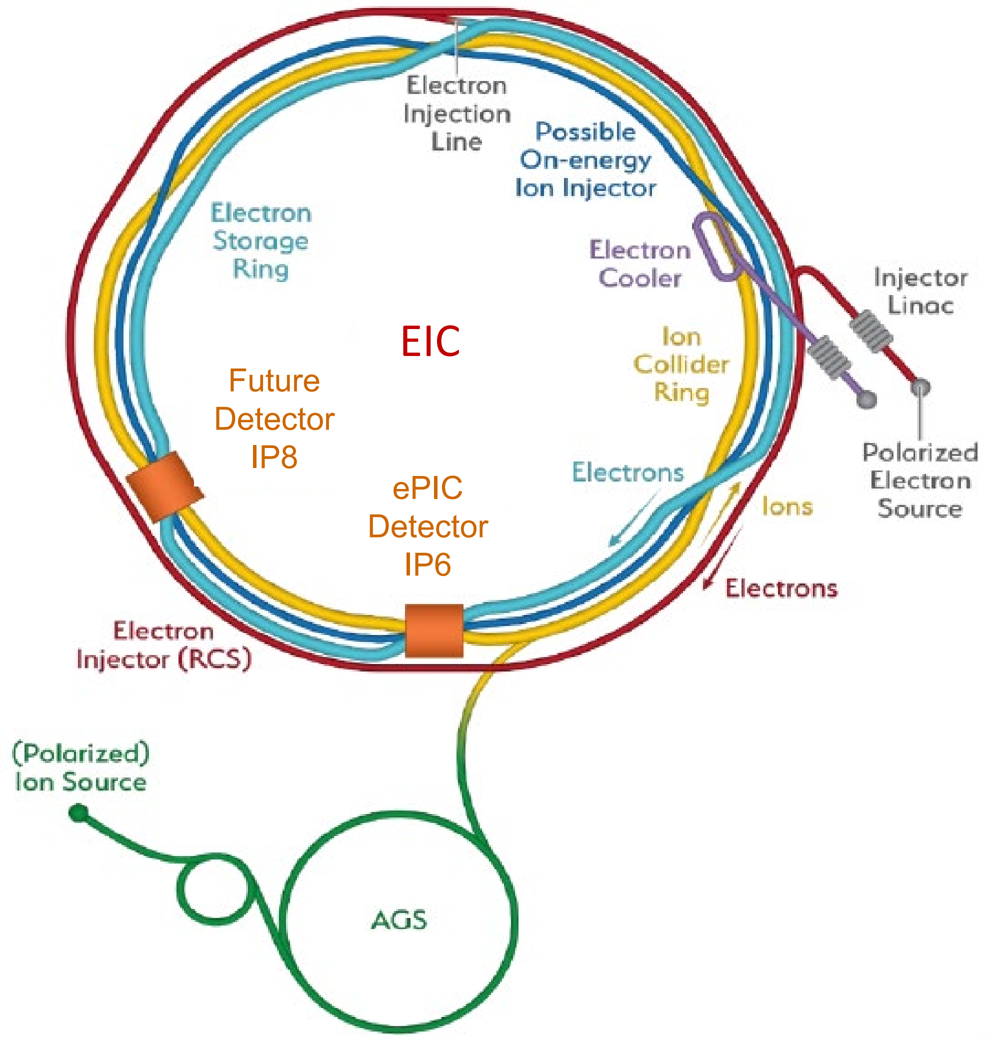
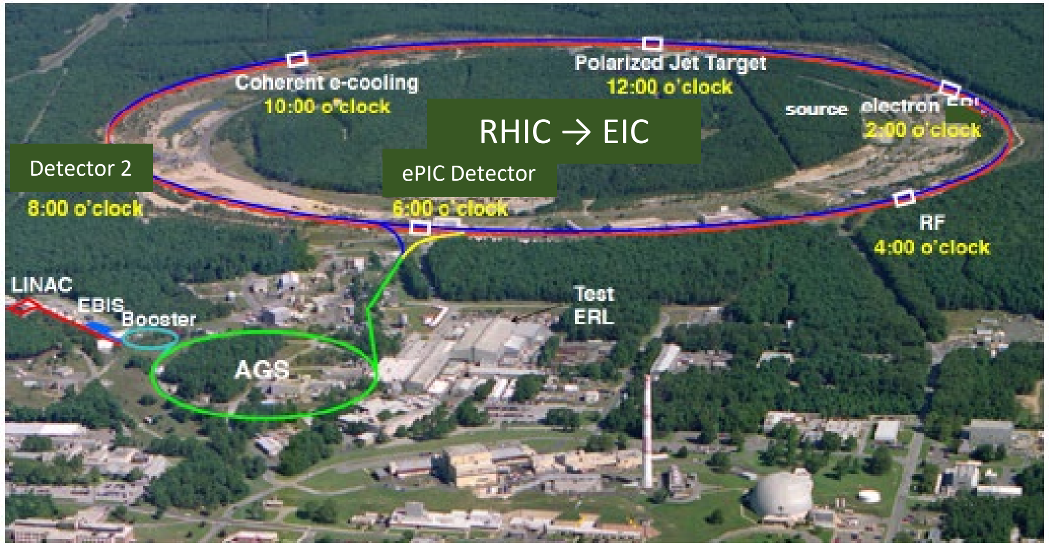
Overview

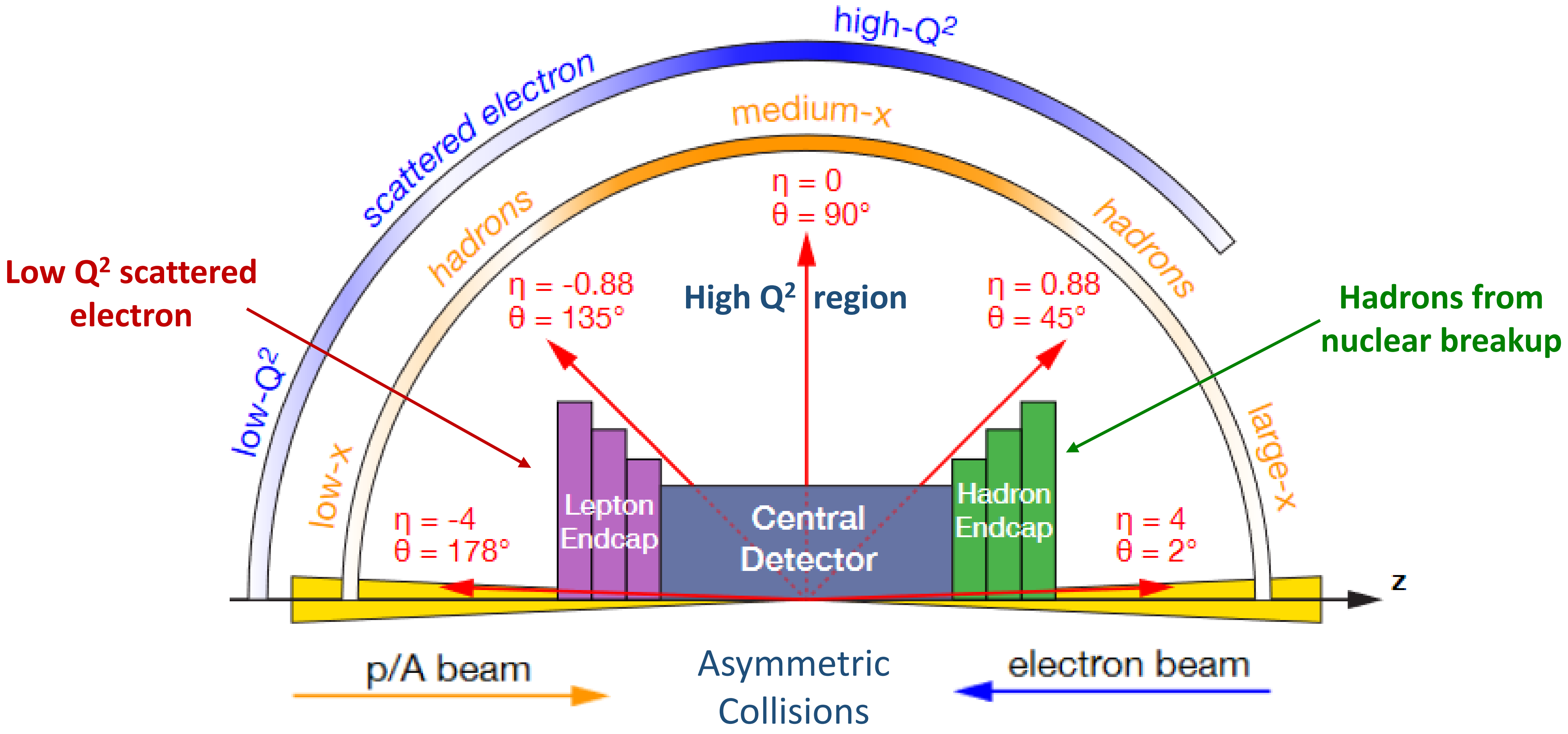
The Electron Ion Collider at BNL





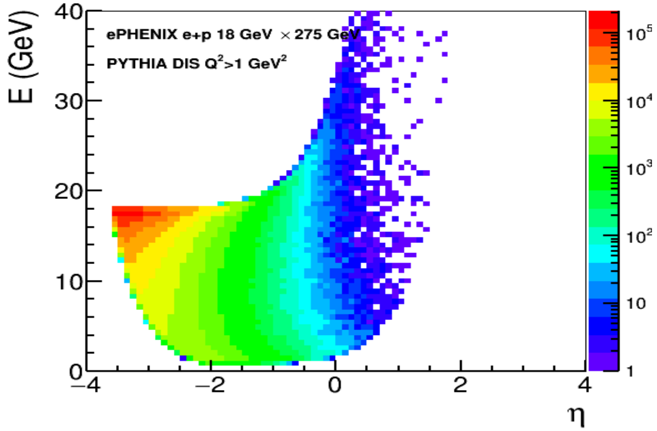
- Calorimeter requirements for EIC.
- Calorimeter technologies being considered for the ePIC detector.
- Other calorimeter technologies for a possible 2nd EIC detector.

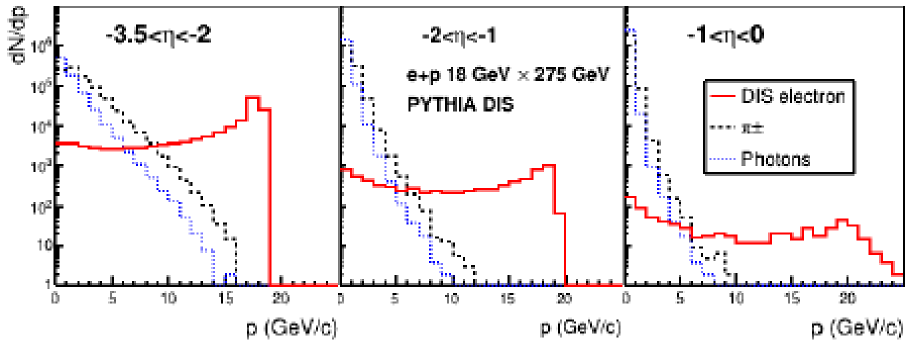
EIC Detector Conceptual Design



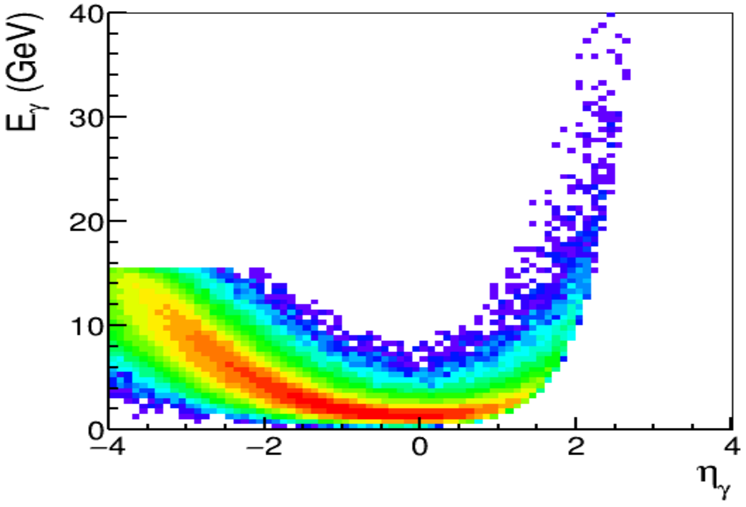
EMCAL

DIS e

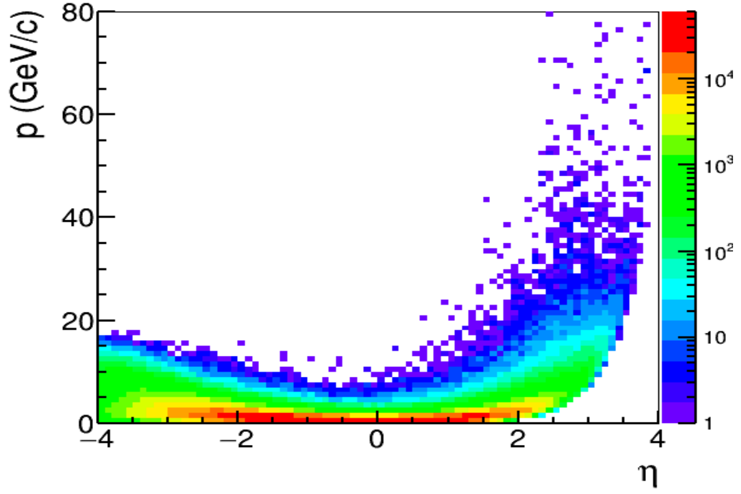




DVCS γ



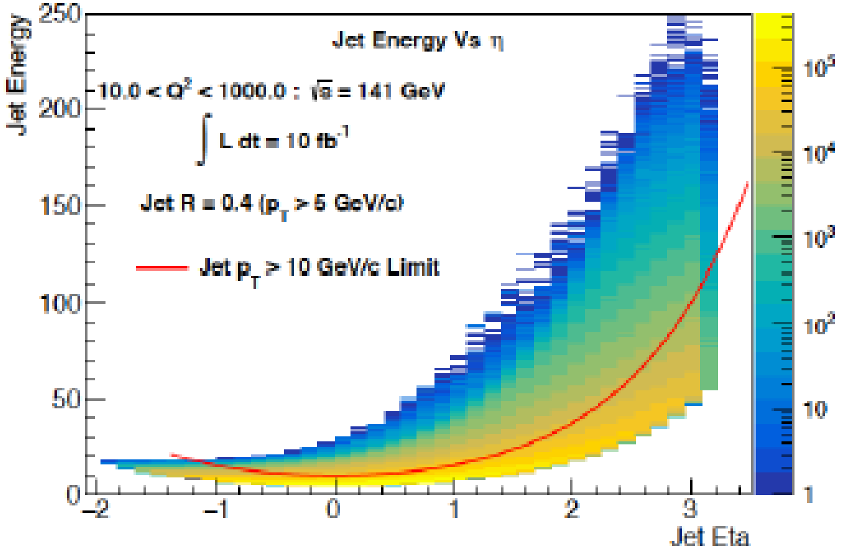
SIDIS π^0s

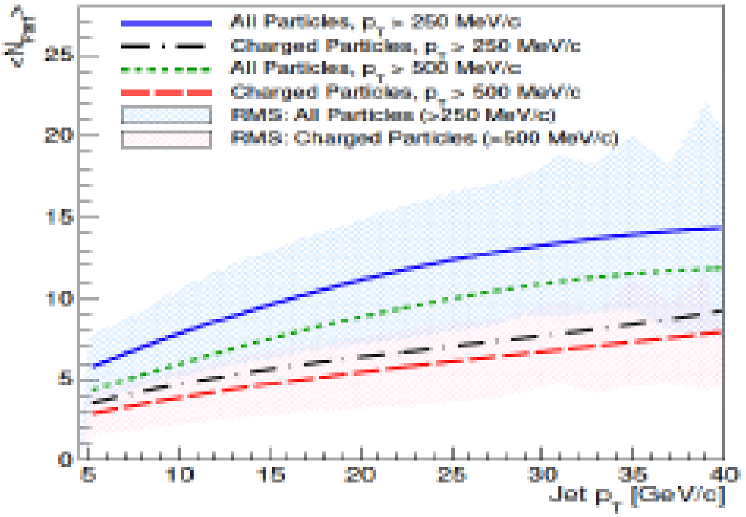


Requirements from EIC Yellow Report

	Backward -4 < η < -2	Backward -2 < η < -1	Barrel -1 < η < -1	Forward 1 < η < 4	
Resolution σ_E/E	2%/√E ⊕ (1-3)%	7%/√E ⊕ (1-3)%	(10-12)%/√E ⊕ (1-3)%	(10-12)%/√E ⊕ (1-3)%	Need to measure the scattered electron with good resolution and provide e/h separation
Min E (MeV)	20	50	100	100	Require low E_{min} to measure decays
Granularity (Δθ)	< 0.02	< 0.02	< 0.025	< 0.01	γ/π^0, e/h discrimination (~ 10^{-3} – 10^{-4})
Space	ΔZ = 60 cm	ΔZ = 60 cm	ΔZ = 30 cm	ΔZ = 40 cm	Including all services

HCAL



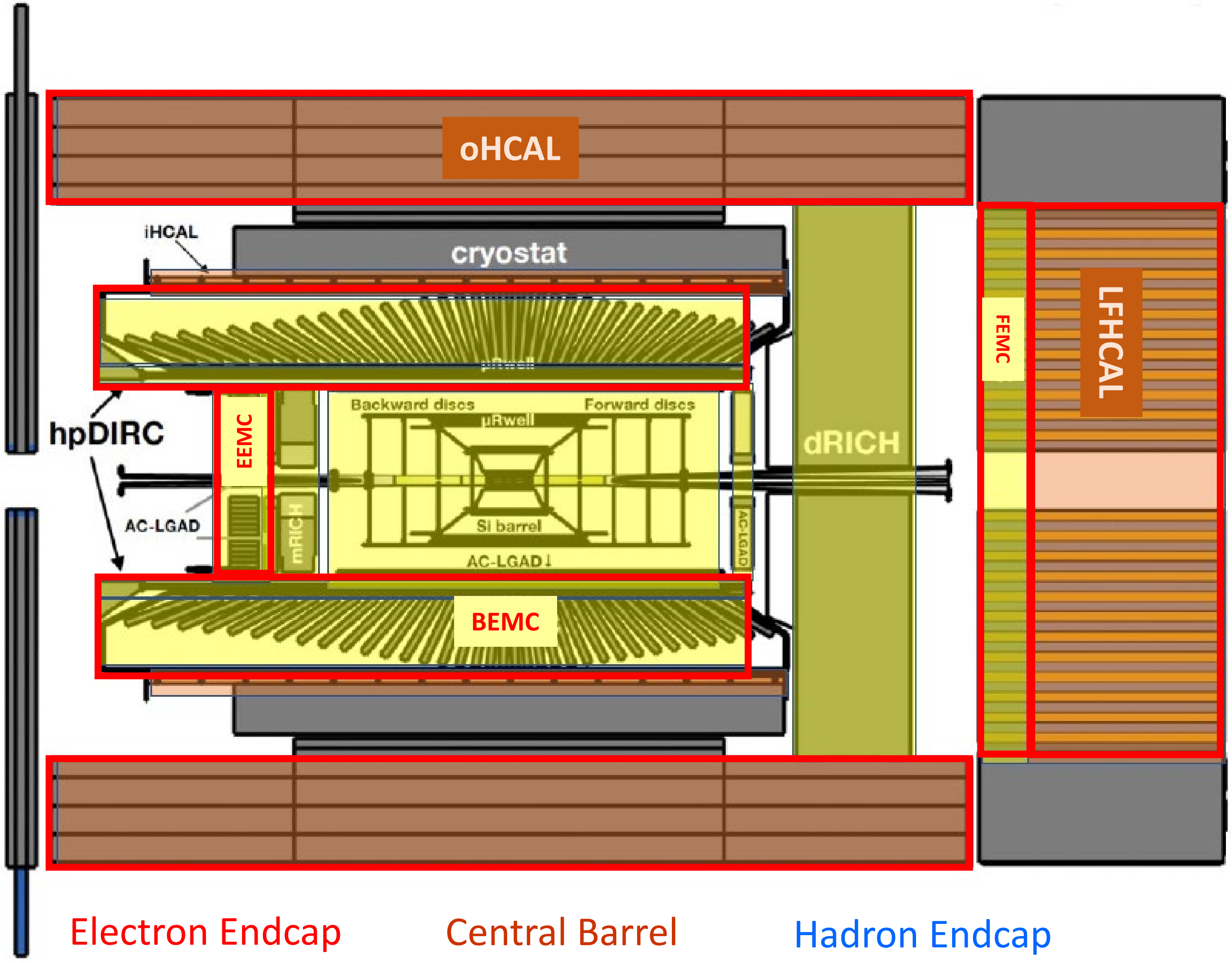


- Jet energies typically < 50 GeV
- Particle multiplicity within a jet is typically ~ 10

Requirements from EIC Yellow Report

	Backward Endcap $-4 < \eta < -1$	Barrel $-1 < \eta < -1$	Forward Endcap $1 < \eta < 2.5$	Forward Endcap $2.5 < \eta < 4$	
Resolution σ_E/E	$50\%/\sqrt{E} \oplus 6\%$	$85\%/\sqrt{E} \oplus 7\%$	$50\%/\sqrt{E} \oplus 6\%$	$35\%/\sqrt{E} \oplus 5\%$	Would benefit from better calorimeter resolution for $\eta > 2.5$ due to degradation of tracking resolution
Min E (GeV)	0.5	0.5	0.5	0.5	Would like to measure all hadrons (including neutrals) to minimize bias for jets and for determining event kinematics using Jacquet-Blondel method
Granularity (cm^2)	10 x 10	10 x 10	10 x 10	10 x 10	Separate charged from neutral
Space	ΔZ = 100 cm	ΔZ = 120 cm	ΔZ = 120 cm	ΔZ = 120 cm	Including all services

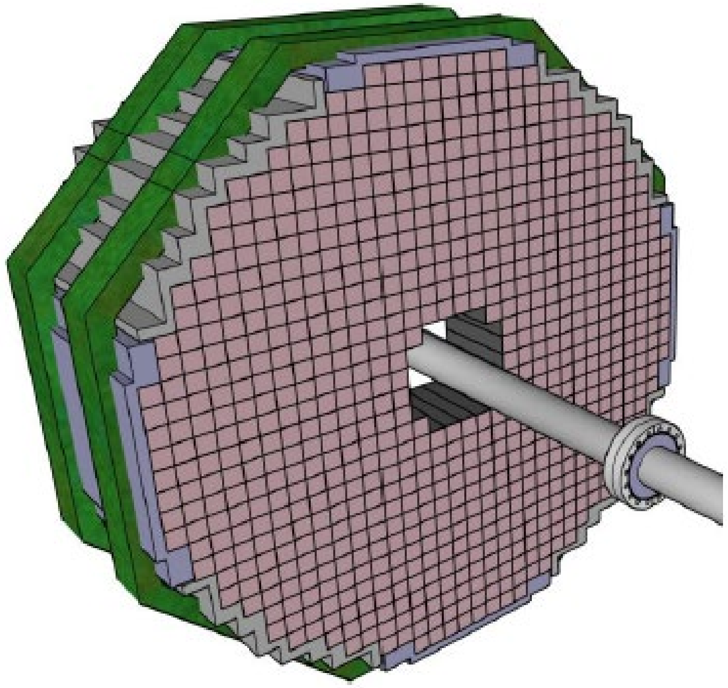
The ePIC Detector



ePIC Calorimeter Systems

- Electron End Cap EMCAL (EEMC)
  - PWO
- Barrel EMCal (BEMC)
  - Scintillating Glass (Option 1)
  - Pb/SciFi/Si "Imaging" (Option 2)
    (see talk by J.Kim)
- Outer HCal (oHCAL)
  - Fe/Scint tile (sPHENIX re-use)
- Forward EMCAL (FEMC)
  - W/SciFi (similar to sPHENIX)
    (see talk by Z.Ji)
- Longitudinally Segmented Forward HCAL (LFHCAL)
  - Fe/W/Scint tile
    (see talk by N.Novitzky)

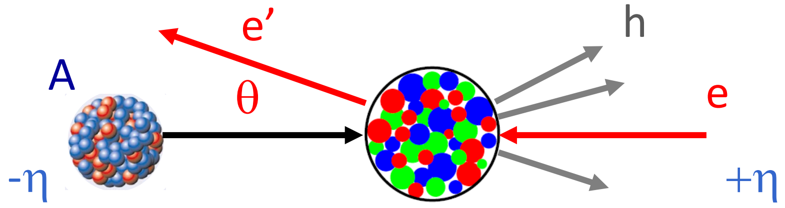
PWO Endcap Calorimeter



Must measure energy/momentum and angle of the scattered electron

Similar in design to the PANDA Endcap

- Coverage: ($-3.4 < \eta < -1.5$)
  (possibly extended to $\eta = -3.7$)
- Consists of ~ 3000 PWO crystals
- 2 x 2 x 20 cm^3 (Rectangular non-projective)
- Read out with SiPMs (3x3 mm2)
  (either 4 or 16 per crystal)
- Energy Resolution : $2\%/\sqrt{E} \oplus (1\text{-}3)\%$
- Angular Resolution < 1°

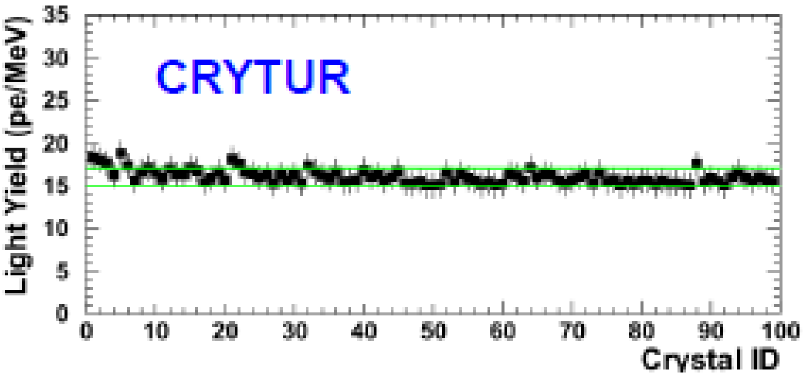


$$Q_e^2 = 2E_eE'_e(1+\cos\theta'_e) = 4E_eE'_e\cos^2\left(\frac{\theta'_e}{2}\right)$$

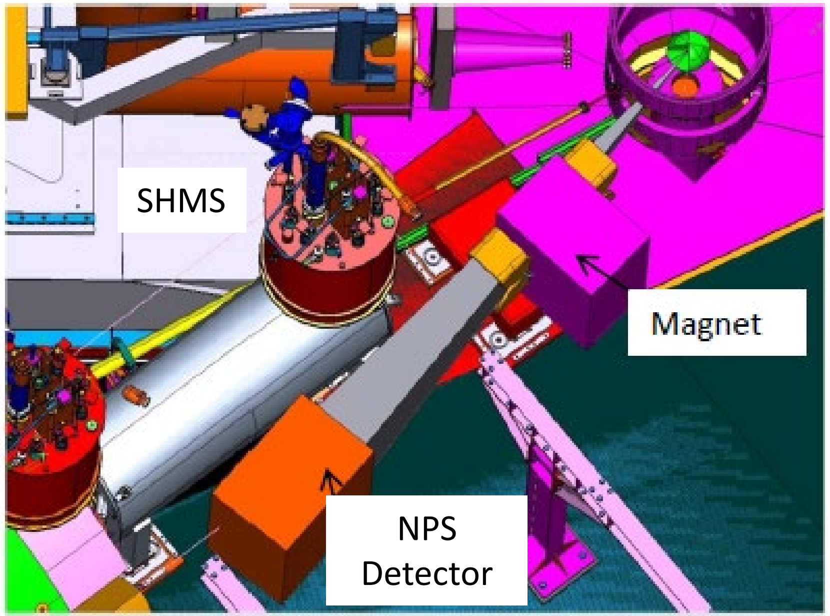
Measuring E'_e and θ_e determine Q^2

Status of PWO Crystals

Crystals for EIC are expected to be supplied by Crytur (Czech Republic)



CRYTUR can currently produce up to ~ 60 crystals/month



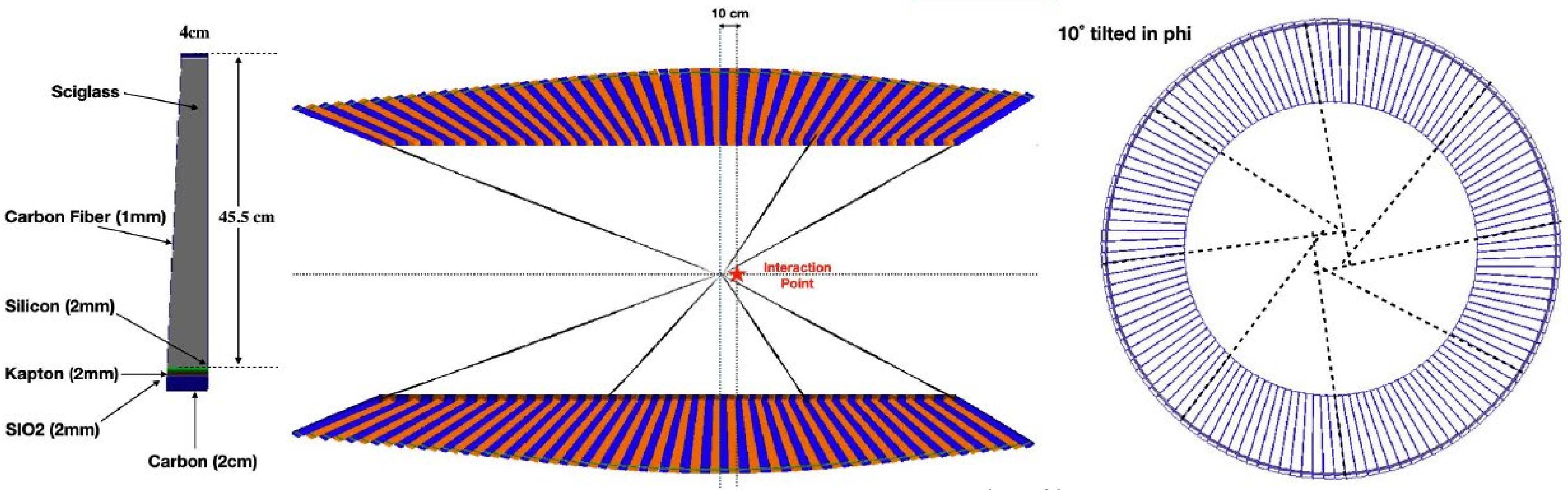
~ 25 msr detector with 1080 PWO crystals

"Precursor" to EIC

Neutral Particle Spectrometer (NPS) detector in the Super High Momentum Spectrometer (SHMS) in Hall C at JLAB

T. Horn CUA/JLAB

Scintillating Glass Barrel EMCAL



Carbon fiber support

- Coverage: $(-1.7 < \eta < 1.3)$
- Consists of ~ 9000 blocks of *new* Scintillating Glass (SciGlass)
- 2 x 2 cm^2 inner area, 5 x 5 cm^2 $\rightarrow$ 6 x 6 cm^2 outer, 45.5 cm long (17 X0)
- Projective in η and ϕ (but not pointing to the vertex)
- Read out with SiPMs (3x3 mm^2) (4 or 16 per crystal)
- Expected energy Resolution : $2.5\%/\sqrt{E} \oplus 1.6\%$ (similar to PWO)

Status of Scintillating Glass

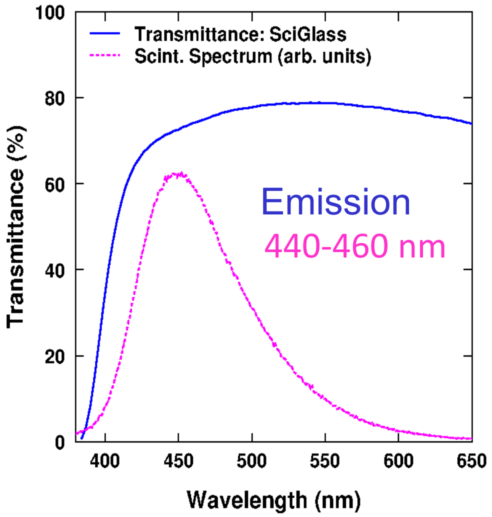
A new type of Scintillating Glass is being developed at Catholic University and the Vitreous State Laboratory

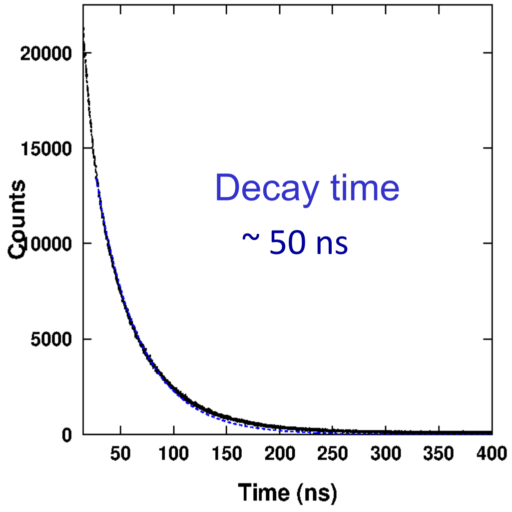
Info provided by T. Horn CUA/JLAB

Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
($BaO*2SiO_2$):Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass loaded with Gd	4.7-5.4 **4.22**	2.2 **2.7**	**3.6**	~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

GEANT 4

Also: ($BaO*2SiO_2$):Ce shows no temperature dependence

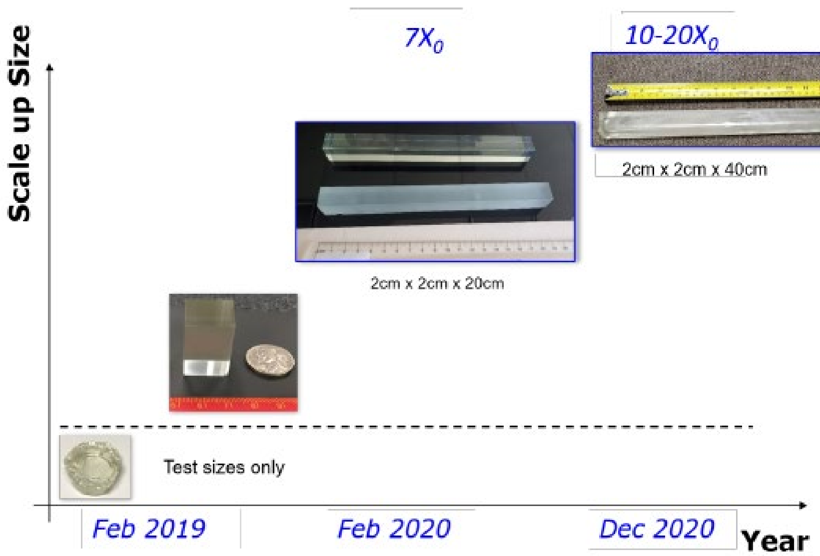




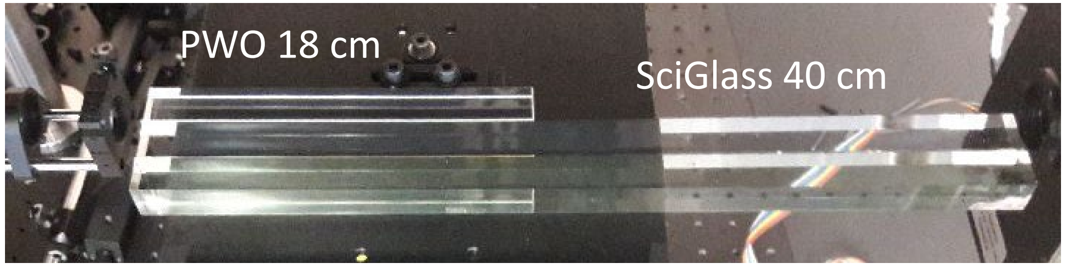
- Light Yield comparable to PWO (> 100 γ/MeV)
- Lower density than PWO ⇒ longer blocks (17 X0 > 45 cm)

Scaling up to Produce 45 cm Blocks for EIC

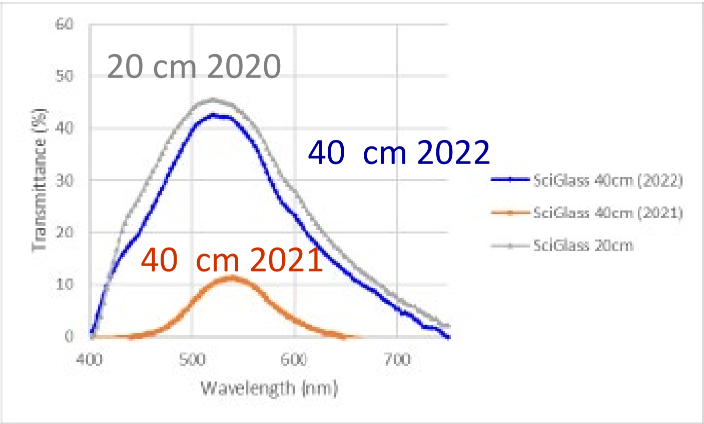
A Joint Collaboration was formed between Catholic University/Vitreous State Laboratory and a new startup company SCINTILEX



Significant improvement in the quality of 40 cm blocks was made from 2021 to 2022



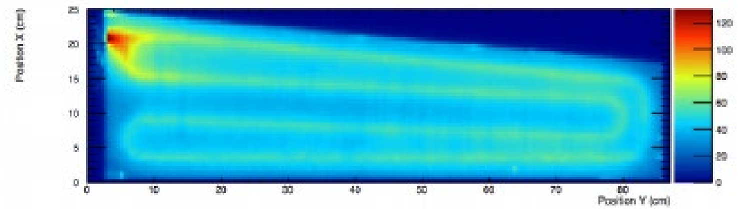
- Scintilex is now able to routinely produce good quality 40 cm blocks.
- Plans to test 3x3 prototype of 40 cm blocks this fall at JLAB.
- Challenge is to scale up production in order to produce the ~ 9000 blocks that are needed for EIC.



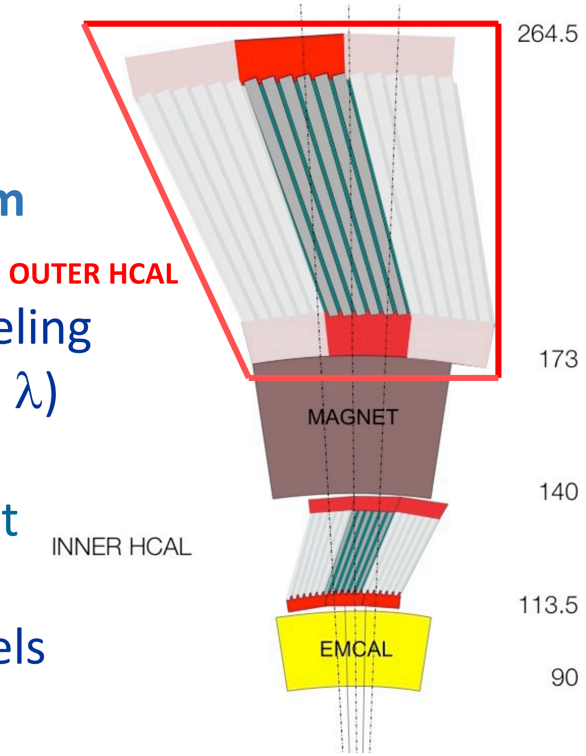
Outer HCAL

Reuses the sPHENIX Outer Hadronic Barrel Calorimeter

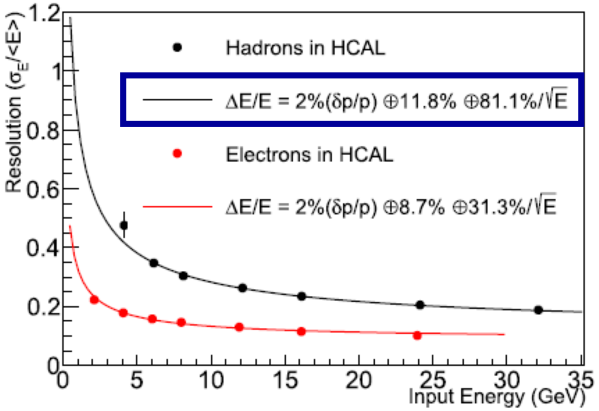
- Steel plates + scintillating tiles with WLS fiber readout
- **Plates oriented parallel to beam**
- **Iron serves as flux return**
- Plates are tilted to avoid channeling
- Two longitudinal sections (~ 4.5 λ)
  - Inner HCAL inside magnet
  - Outer HCAL outside magnet
- $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$
- 2x24x64 = 3072 readout channels



Scintillating tile with WLS fiber



sPHENIX Calorimeter System



Test Beam 2016

Hadronic resolution ~81%/√E ⊕ 12%

Outer HCAL installed in sPHENIX outside the solenoid magnet in March 2022

W/SciFi Calorimetry

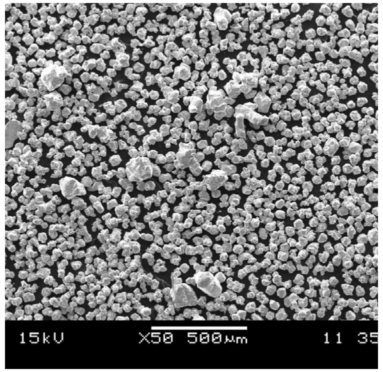
- The Forward EMCAL is based on the technology developed for the sPHENIX EMCAL.
- It is a W/SciFi SPACAL consisting of a matrix of tungsten powder and epoxy with embedded scintillating fibers.
  - 0.47 mm dia. fibers, spacing 1 mm, SF ~ 2%
  - Density ~ 9.0 g/cm^3, X0 = ~ 7 mm, ~ 20 X0 total, R_M ~ 2.3 cm

Energy Resolution ~ (13-15)%/√E ⊕ 3%
Large area (8x8 tower) prototype

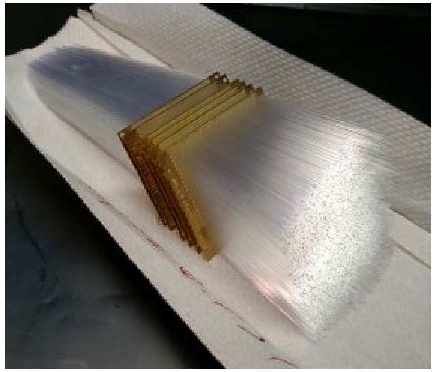
- W/SciFi modules consist of 4 towers, each with its own light guide that is read out on the front with a 2x2 array of 3x3 mm^2 SiPMs.

6144 Modules (24,576 towers)

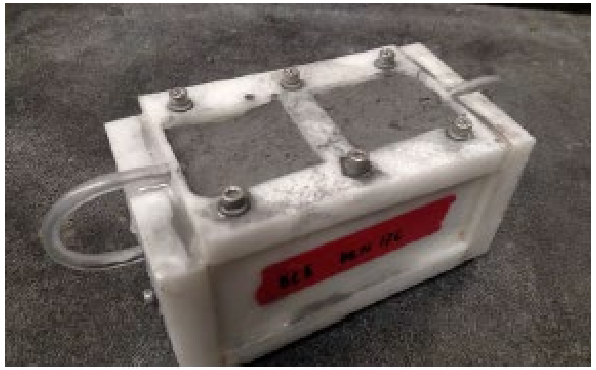
W Powder ~ 50 μm

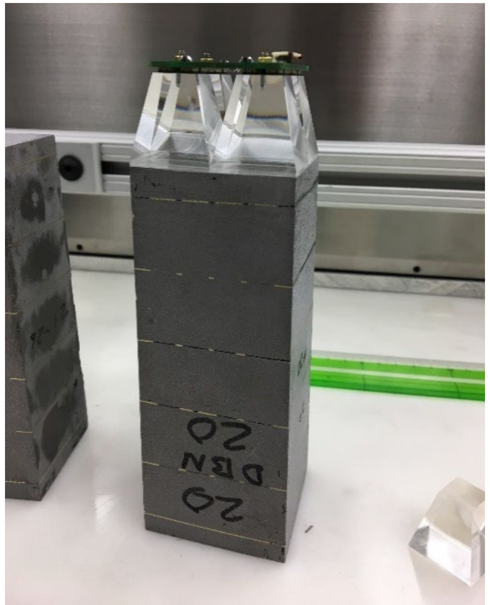


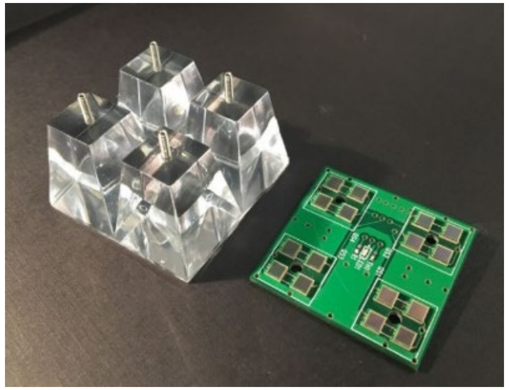
Fiber Assembly



Mold with W powder, fibers + epoxy





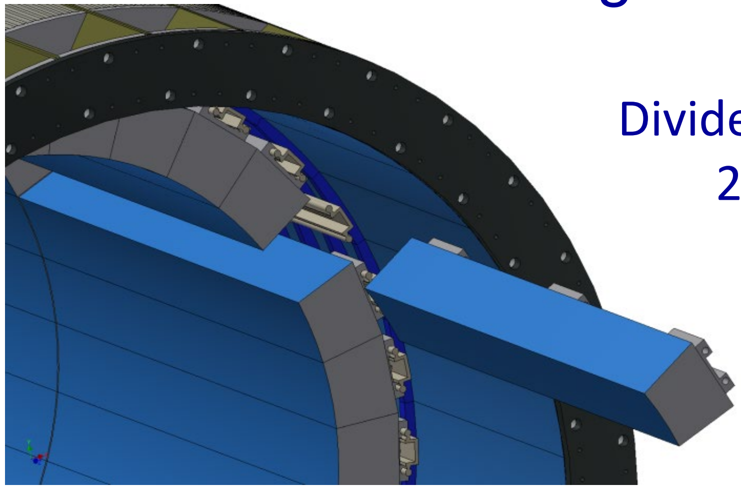


Readout with light guides (1") and SiPMs

~ 100K SiPMs
Hamamatsu S12572-015P

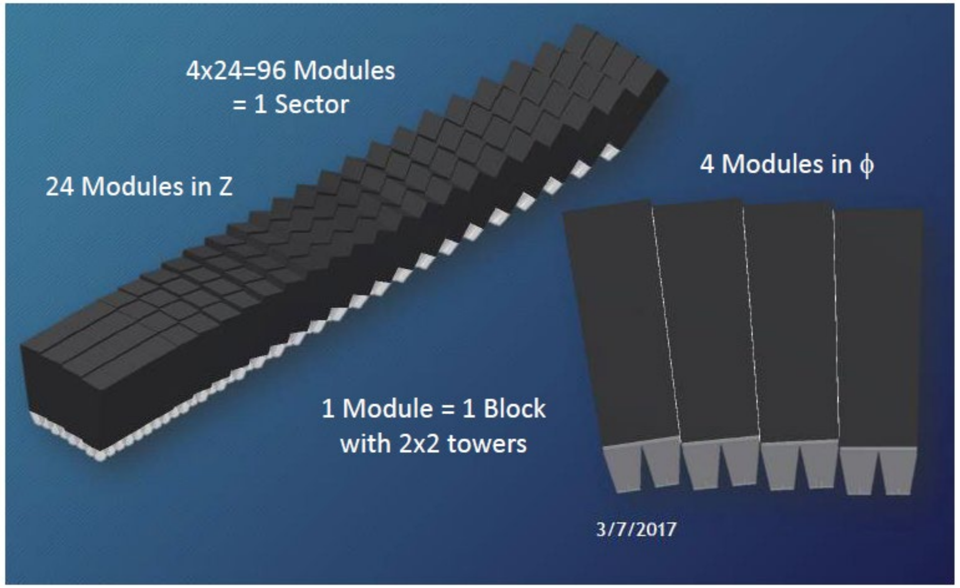
sPHENIX W/SciFi EMCAL

Designed for high luminosity heavy ion collisions



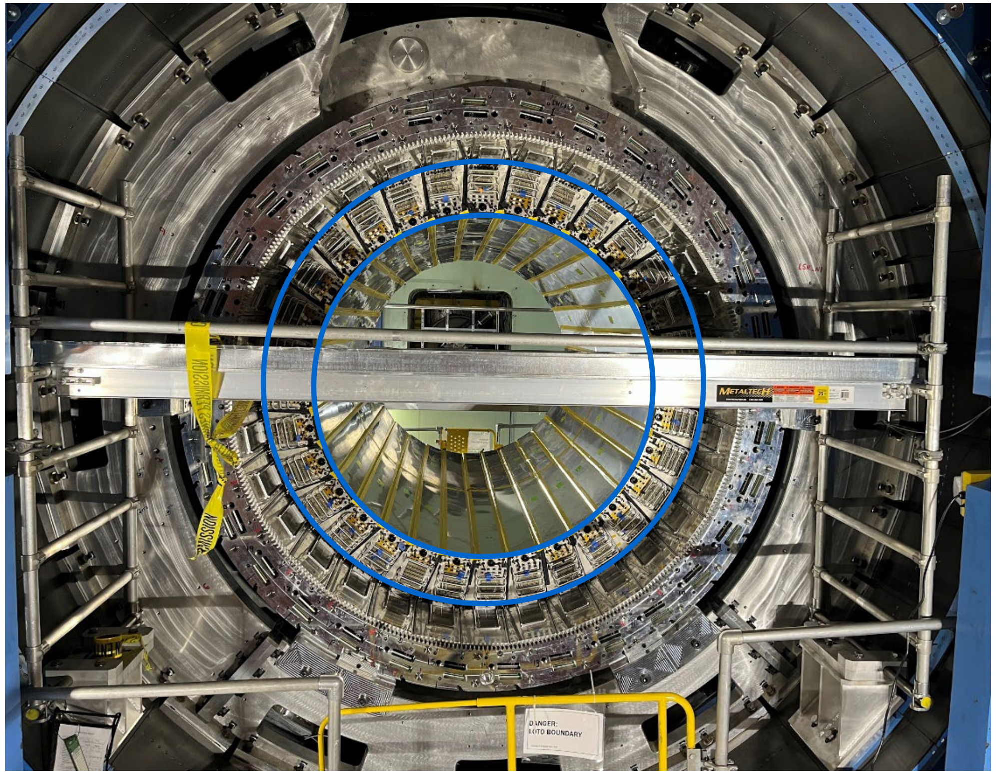
Divided into 64 Sectors
2(±η) x 32 (ϕ)

Sector consists of 96 modules (384 towers)



Blocks and Sectors are approximately projective and tilted in both η and ϕ

EMCAL sectors installed on the Inner HCAL of sPHENIX



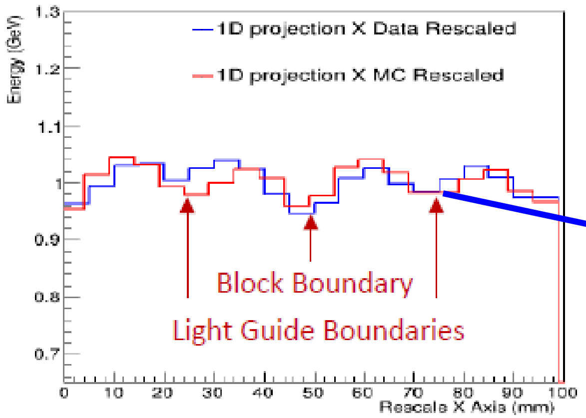
Assembly completed in April 2022
Installation completed 11/23/2022

Improvements of W/SciFi Calorimetry for EIC

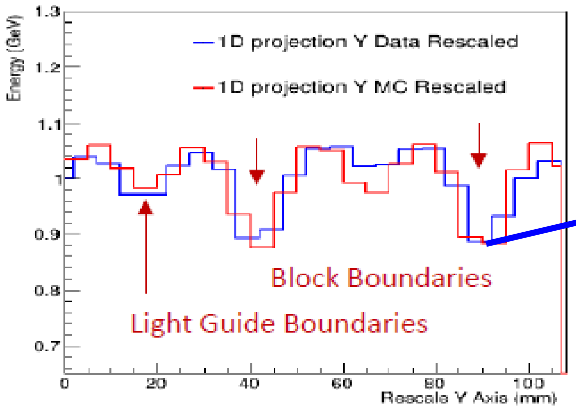
Uniformity of the sPHENIX EMCAL measured in the test beam

- Improve uniformity of light collection with a compact SiPM readout (→ reduce constant term)
- Improve the light collection efficiency (→ improve energy response at low energy)

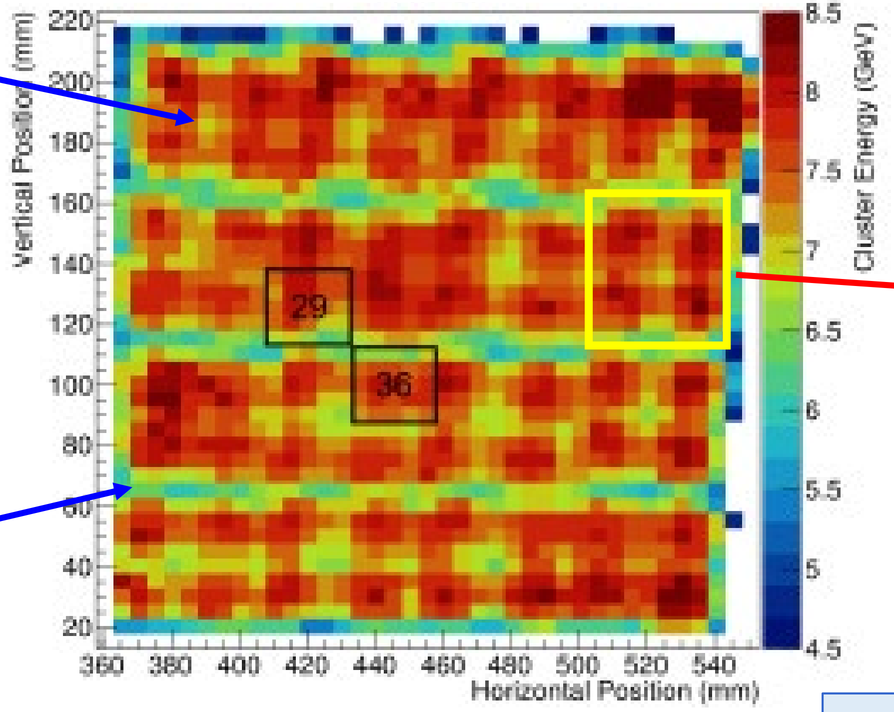
X axis projection



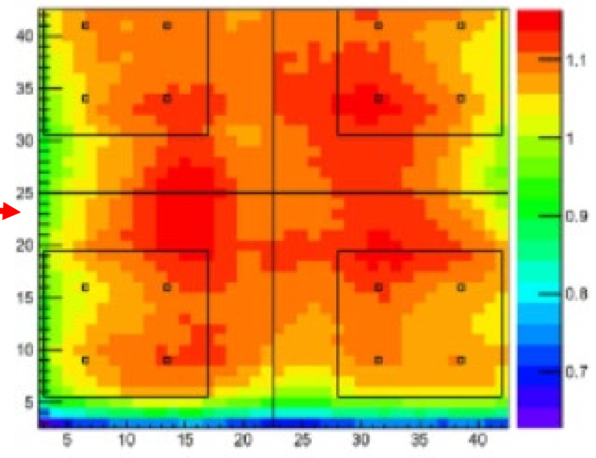
Y axis projection



8x8 Tower Prototype



Improved fiber arrangement and better optical coupling



O.Tsai UCLA

New BEMC, Lumisil 591, 3x3 mm^2 SiPMs

Will also use 6x6 mm^2 SiPMs

Following talk in this session by Z.Ji

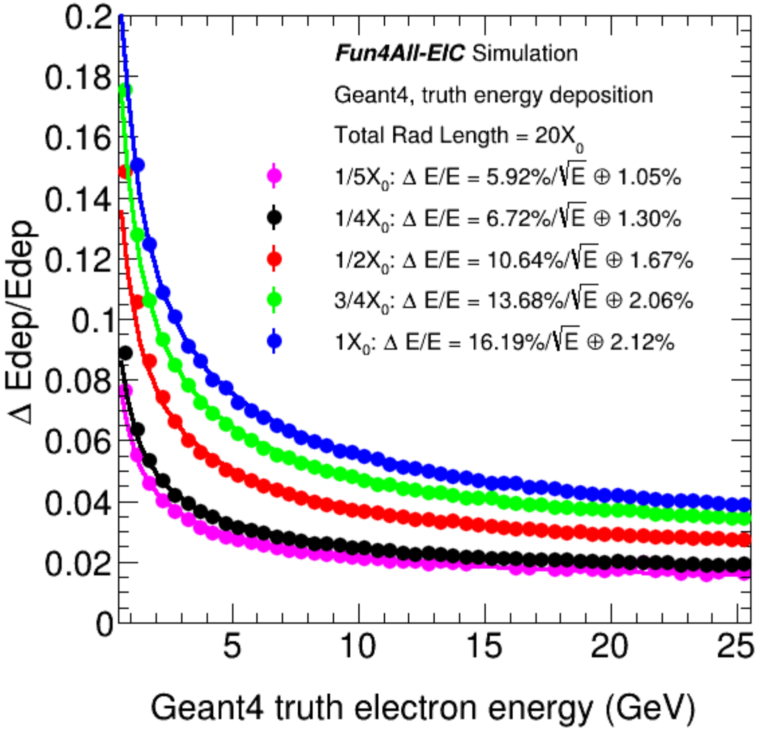
Shashlik Calorimetry

- Mature technology
  - The energy resolution can be tuned by changing the sampling fraction and/or the sampling frequency.
  - The absorber can be chosen to optimize the desired properties of the calorimeter (e.g., cost, compactness, degree of compensation w/HCAL,...).
  - Readout can be done on either end which allows for a variety of different geometrical configurations.
  - The availability of low cost SiPMs now allows the possibility of reading out *each fiber individually* and determining the shower position < 1 R_M.
- Most shashlik calorimeters that have been built so far have use Pb as the absorber. However, using W as an absorber has several advantages:
  - For the same total X0, a W shashlik calorimeter will occupy less space.
  - The R_M of W is much smaller than for Pb (9.3 mm vs 16.0 mm). The showers are therefore much smaller and have less overlap with neighboring showers which improves the γ/π^0 separation and e/h separation.

  Using W as an absorber also has some disadvantages:
  - W is more expensive and harder to machine.
  - It is more difficult and costly to make a shashlik calorimeter projective.

EMCAL Shashlik Calorimetry – Pb vs W

Energy resolution vs sampling fraction
20 X0 total length (L ~ 30 cm w/readout)

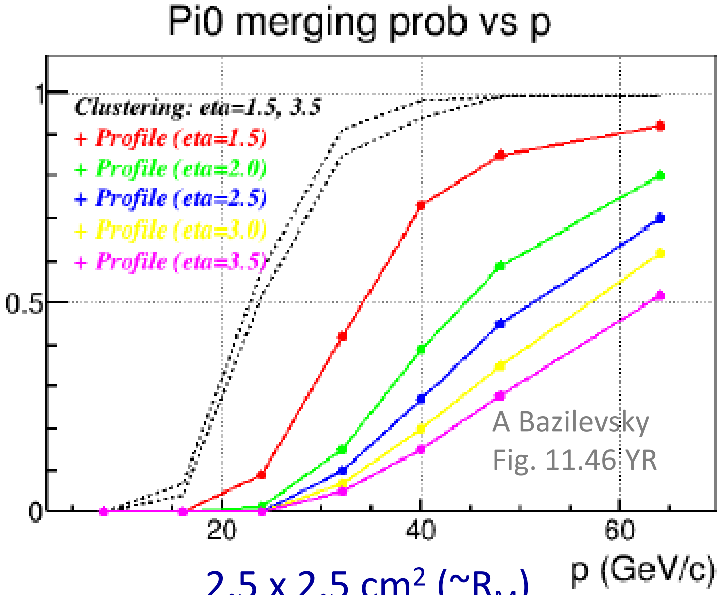


W Shashlik

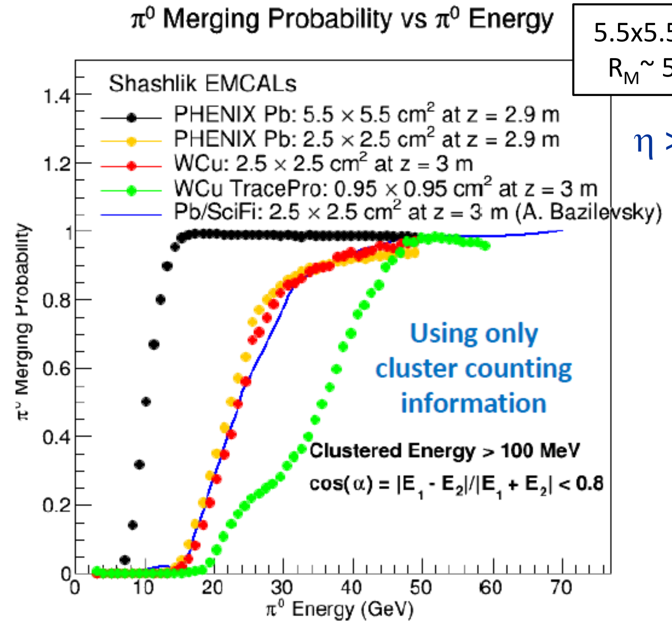
(Z.Shi Fig. 11.55 YR)

In order to resolve γ/π^0 at high momentum fine segmentation and a small R_M is required

Non projective geometry



2.5 x 2.5 cm² (~R_M)



5.5x5.5 cm²
R_M~ 5 cm

η > 1.27

Note:

- Projective geometry will improve separation, particularly in the η ~ 1-3 region
- Can also use a preshower detector to improve γ/π^0 separation

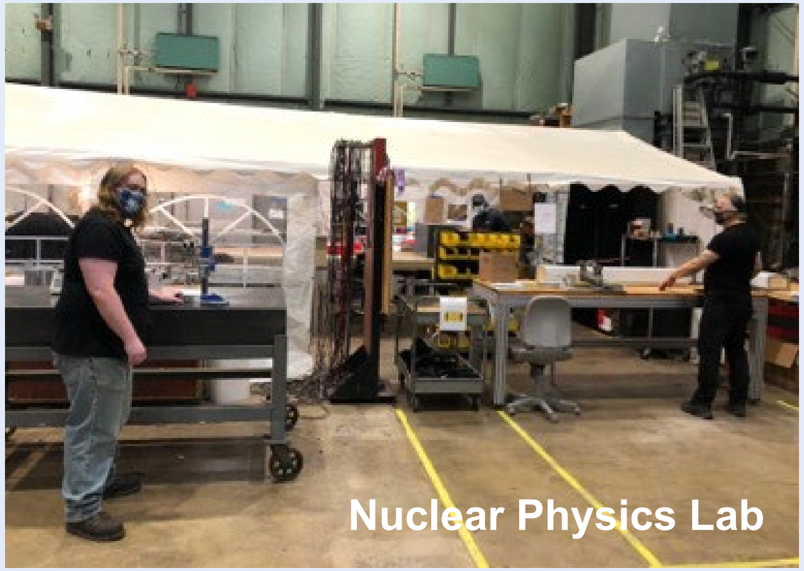
Summary & Conclusions

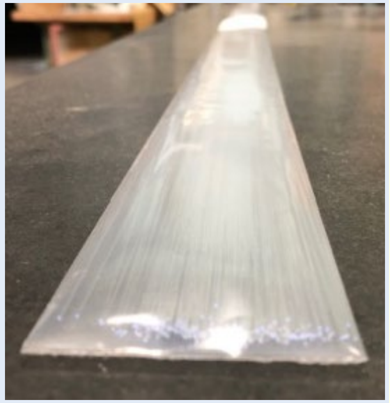
- EIC requires nearly 4π calorimeter coverage with regions requiring high resolution EMCAL and HCAL performance. However, there are also severe space limitations, particularly along the beam direction.
- The most demanding requirements for the EMCAL are in the backward direction to measure the scattered electron.
- The most demanding requirements for the HCAL are in the forward direction where one would like to measure all hadrons and the tracking resolution deteriorates due to the axial magnetic field.
- There are a number of promising new technologies to meet these requirements (e.g., new scintillating glasses, W/SciFi, W/Shashlik and Imaging EMCAL technologies, and longitudinally segmented and tilted plate configurations for the HCAL).

Backup

sPHENIX EMCAL Under Construction (Completed April 2022)

Block Production at UIUC (also Fudan U – Shanghai)



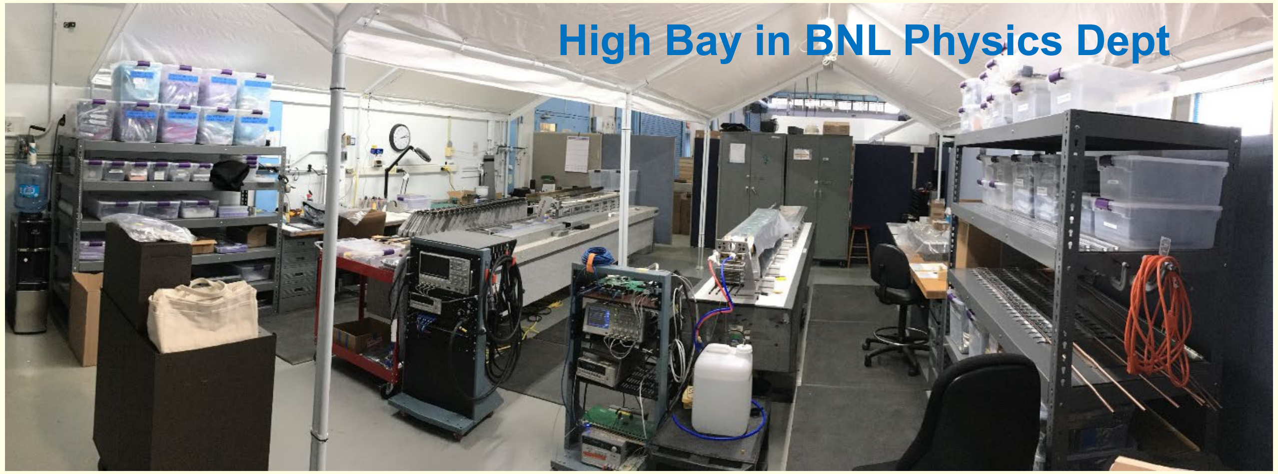


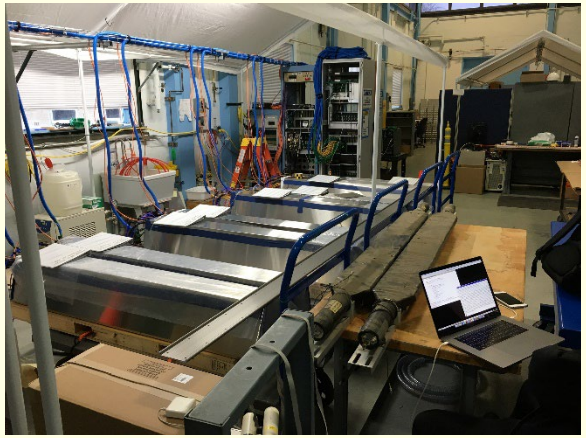
2600 km of fiber
665 kg of epoxy
88 m^2 of screens

20 Tons of W powder

Blocks awaiting removal from molds

Module and Sector Production at BNL





Sector Burn-in and Testing

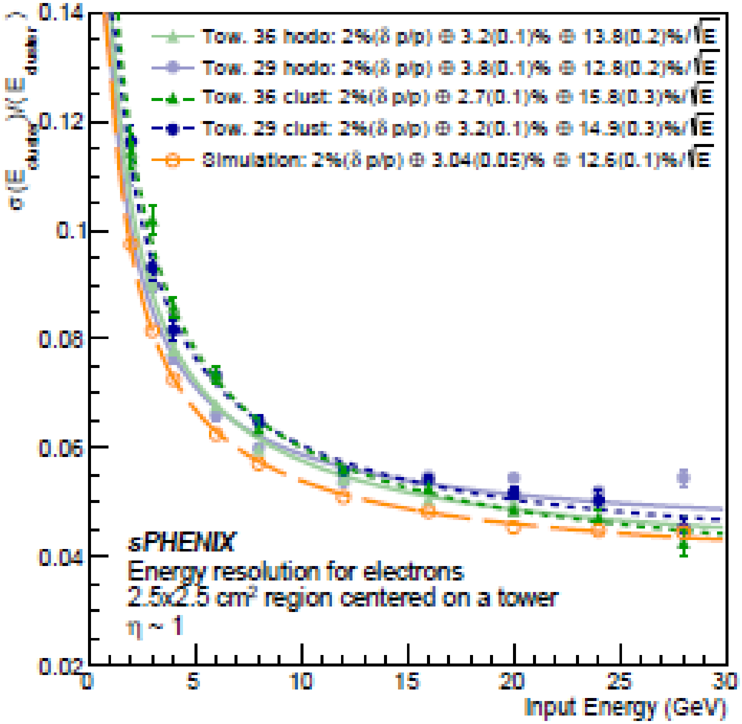
Modules being
glued into sectors

Energy Resolution

Energy resolution after position dependent correction

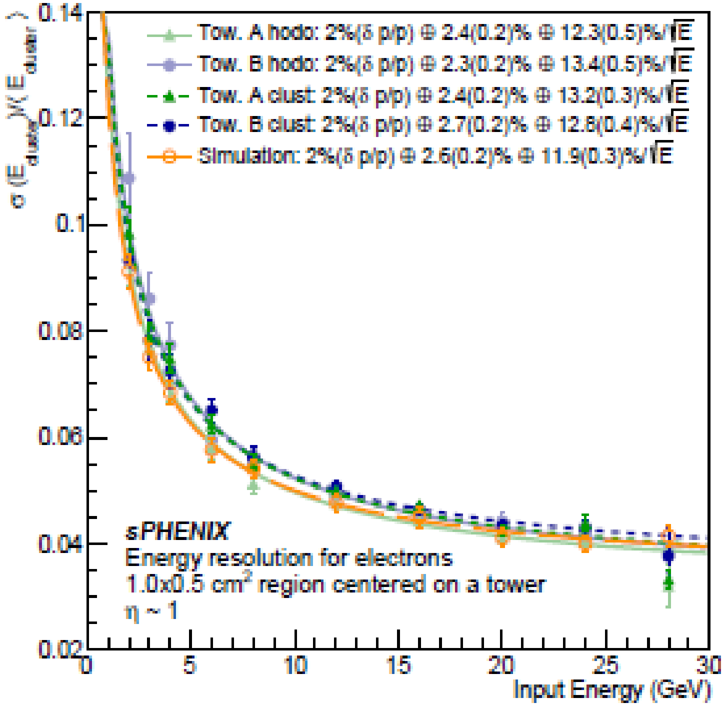
Beam Test 2018

Beam covering a 2.5 x 2.5 cm^2 area centered on a tower



Resolution ~ (13-15)%/√E ⊕ 3%

Beam covering a 1.0 x 0.5 cm^2 area centered on a tower

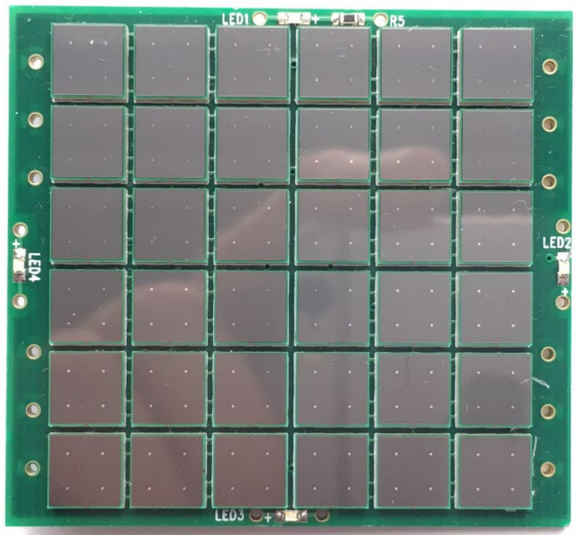


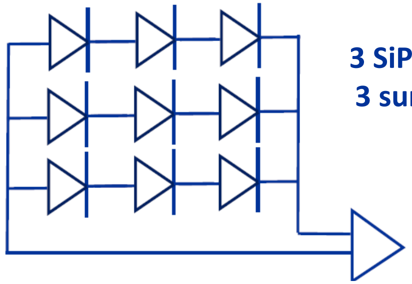
Resolution ~ (12-13)%/√E ⊕ 2.5%

Increasing Photocathode Coverage of W/SciFi Blocks

- The uniformity of the light exiting the fibers is very good but the light guide provides poor mixing and the SiPMs cover only 23% of the readout area of the light guide (6.4% of the total readout area of the block).
- The light collection efficiency and uniformity can be greatly improved by increasing the photocathode area coverage on the readout end of the block

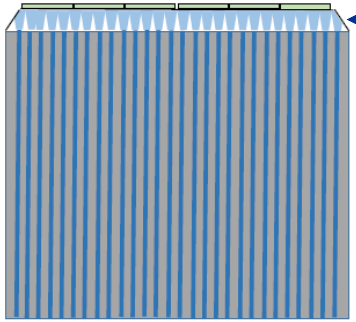
Maximum photocathode coverage using the sPHENIX blocks





3 SiPMs in series then 3 summed in parallel

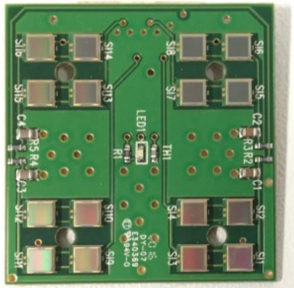
(C/3 x 3 = C)

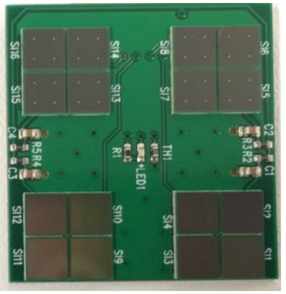


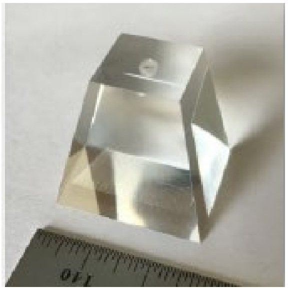
Short light guide covering entire block

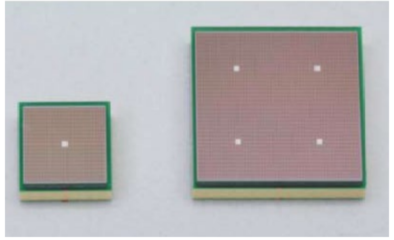
Hamamatsu S13360 6x6 mm² SiPM with TSVs (50 μm pixels)

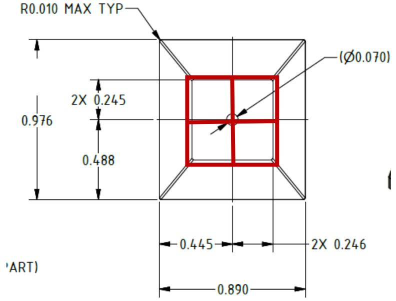
Increased coverage using existing sPHENIX light guides









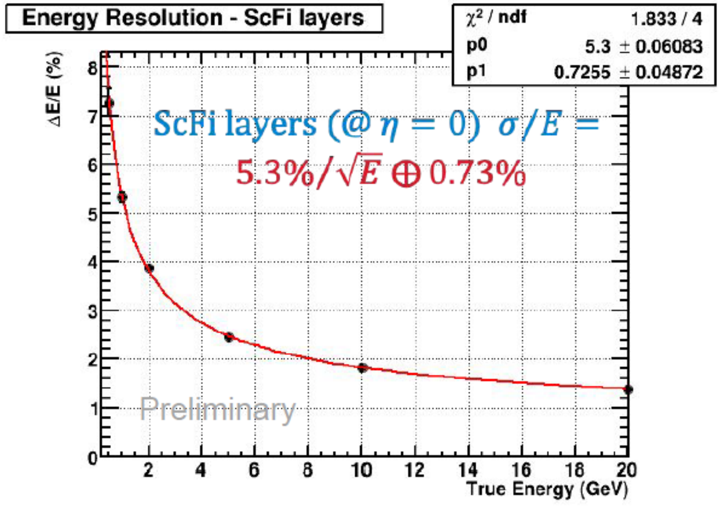


2x2 array of 6x6 mm² SiPMs

Imaging Calorimetry

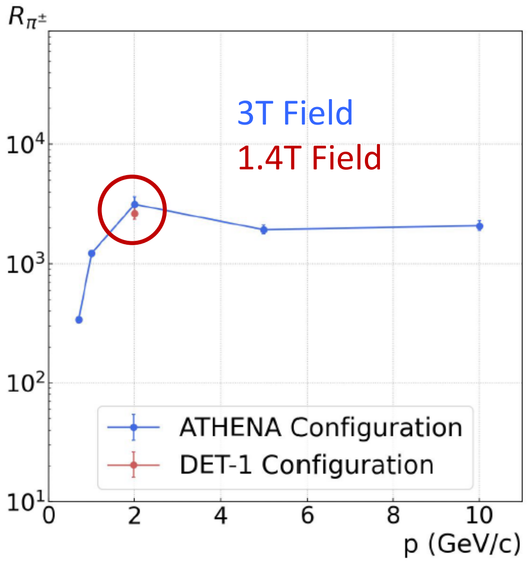
Pb/SciFi Barrel EMCAL similar to GlueX design with embedded Si sensor layer

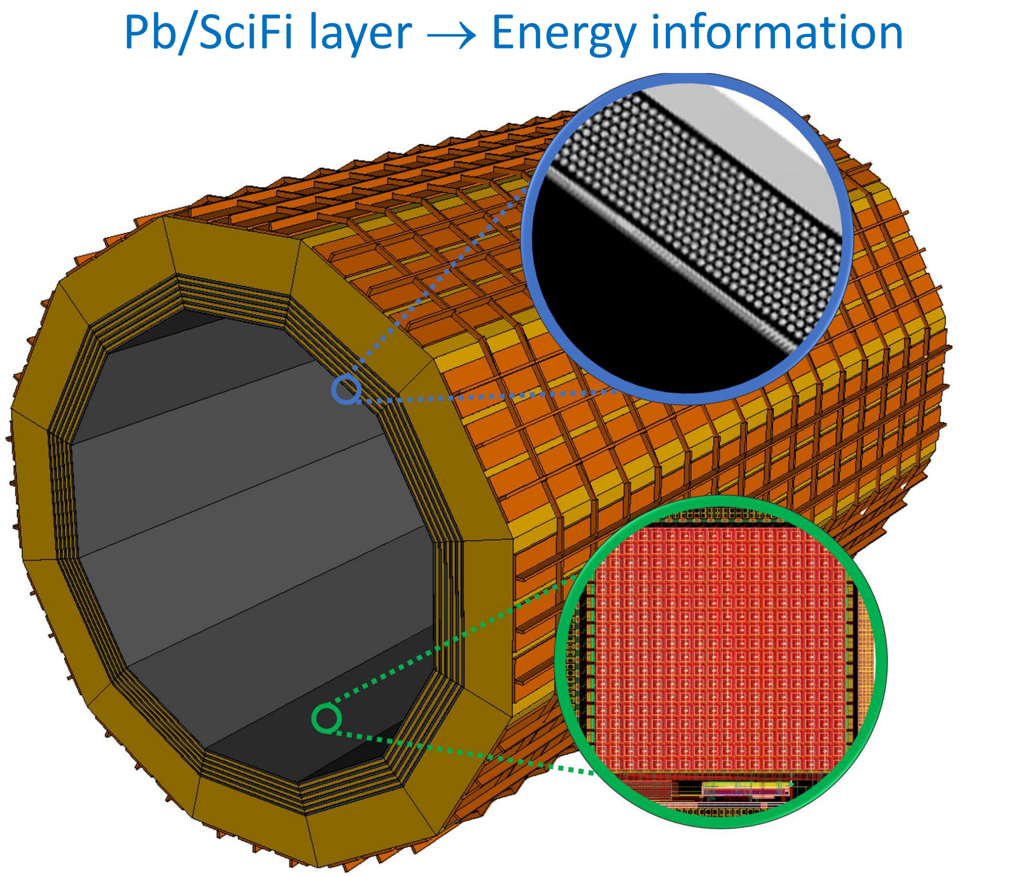
- 6 layers of imaging Si sensors using AstroPix chip interleaved with 5 Pb/SciFi layers followed by additional Pb/SciFi layers
- ~ 0.5 mm spatial resolution (~ pixel size)
- Coverage -1.5 < η < 1.2



(GlueX ScFi ECal $\sigma/E = 5.2\%/\sqrt{E} \oplus 3.6\%$)

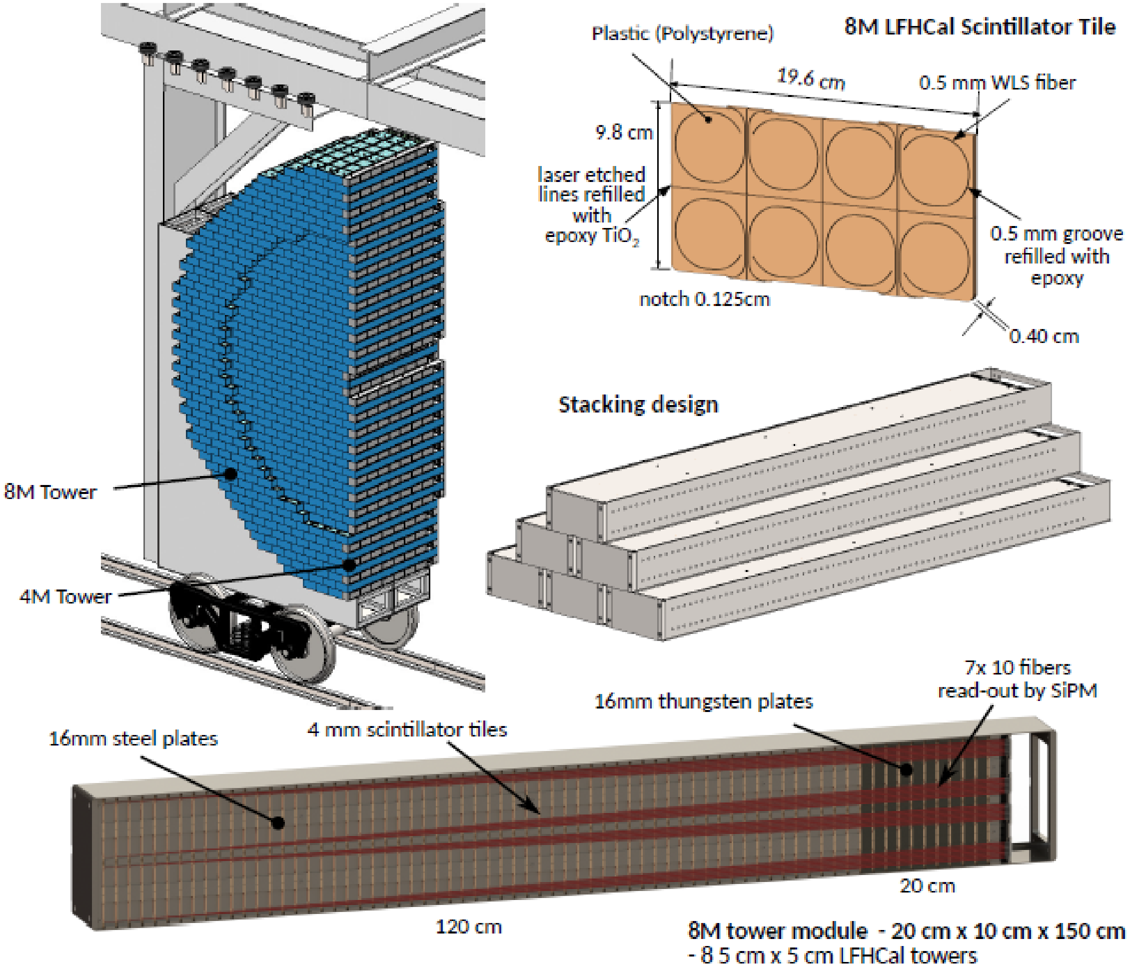
e/h separation





Following talk in this session by J.Kim

Forward HCAL



Longitudinally segmented Forward HCAL

- 60 layers of steel and 10 layers of W absorbers (160 mm plates) $\rightarrow$ ~ 7 λ_h
- Scintillating tiles (4 mm) read out with WLS fibers
- Divided longitudinally into 7 segments
- SiPM readout (10 fibers/SiPM, 7/tower)
- Modules of different sizes arranged radially from beam pipe to maximize efficiency and ease of assembly.

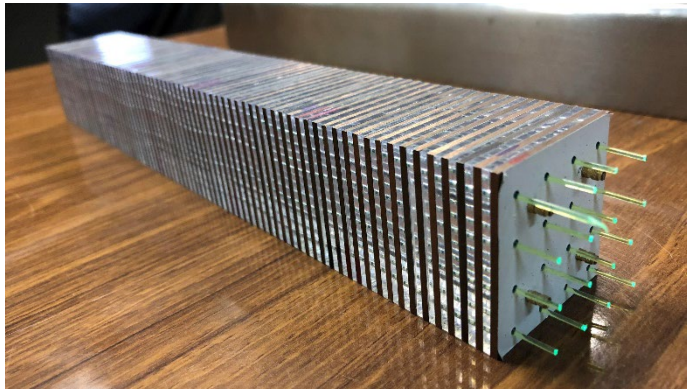
Following talk in this session by N.Novitzky

A Prototype W/Shashlik EMCAL (eRD1)

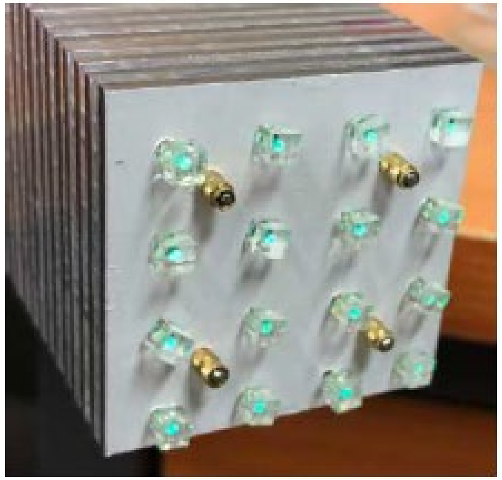
Originally designed for the NA64 Experiment at CERN

Andres Bello University
Santiago, Chile

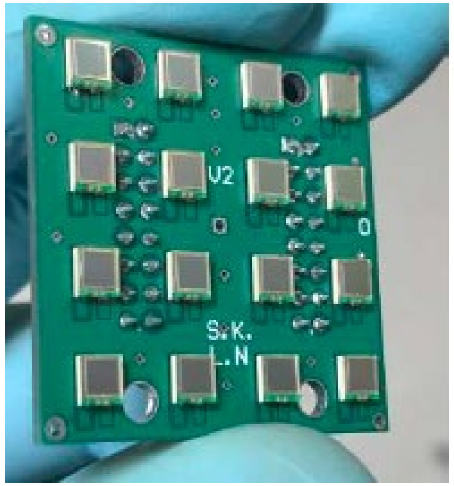
- Absorber plates are a W(80%)/Cu(20%) alloy that is easily machinable
  ρ = 17.2 g/cm^3, X0 = 4.2 mm, 38 x 38 x 1.58 mm^3
- Scintillating tiles: 38 x 38 x 1.63 mm^3 injection molded polystyrene (Uniplast, Russia).
- 1 mm dia WLS fibers (Saint-Gobain BCF-91A)
- 80 sampling layers, 31 X0 (27 cm)
- Each fiber read out with 3x3 mm^2 SiPMs



WLS fibers pass through stack in a slight spiral pattern to improve light collection uniformity and reduce dead areas



Each fiber coupled to small lucite light mixer

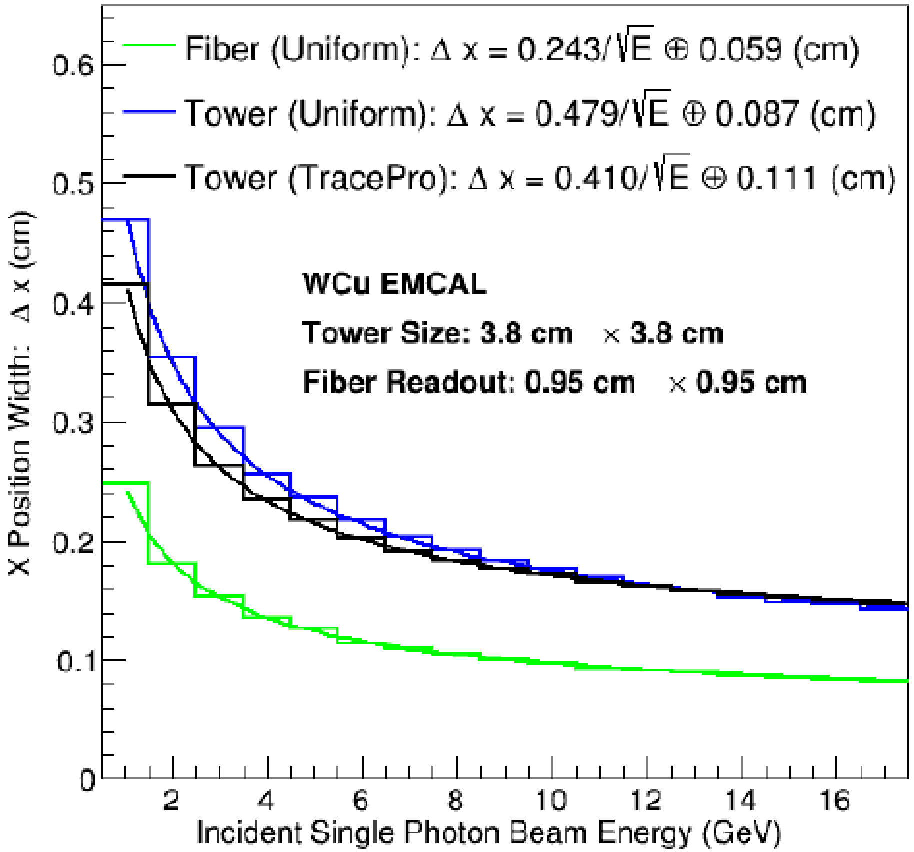


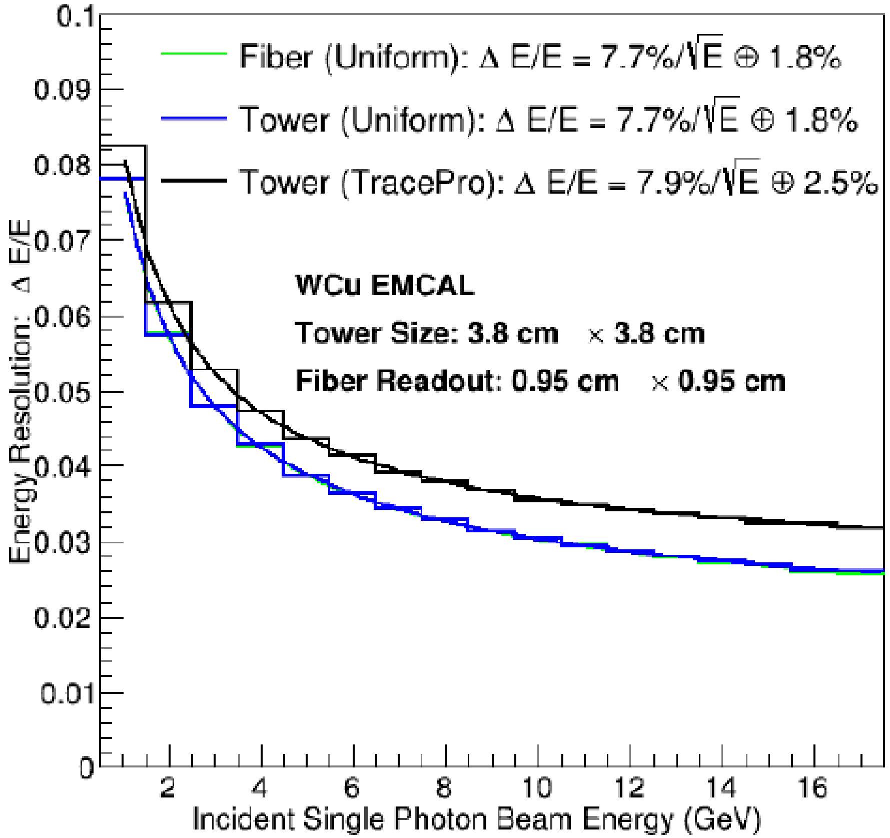
Hamamatsu S14160-3015P

3x3 module prototype

W/Cu Shashlik – Position and Energy Resolution

Effect of light collection map





Non-uniformity of light collection efficiency map

- Improves the position measurement
- Slightly worsens the energy resolution

Z. Shi (LANL/MIT)