Calorimetry for the Electron Ion Collider

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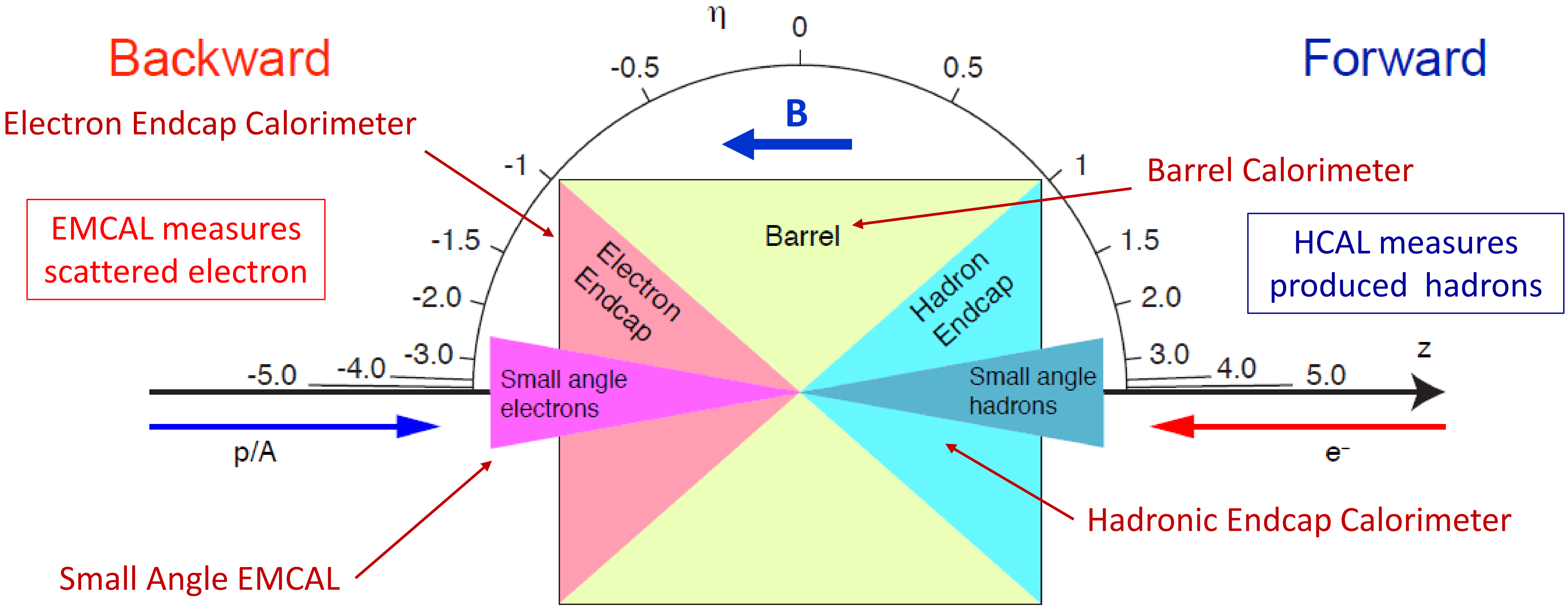
CPAD Instrumentation Frontier Workshop 2021

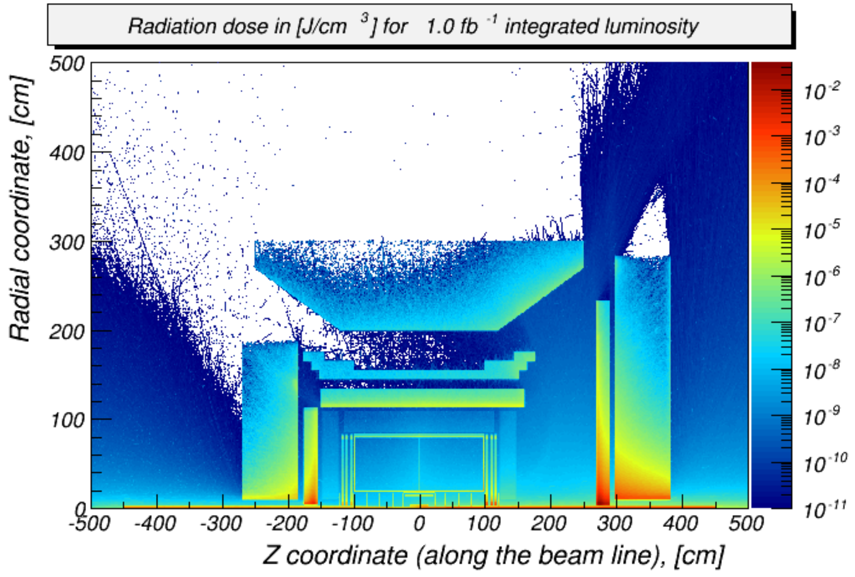
March 19, 2021

EIC Detector (Conceptual)

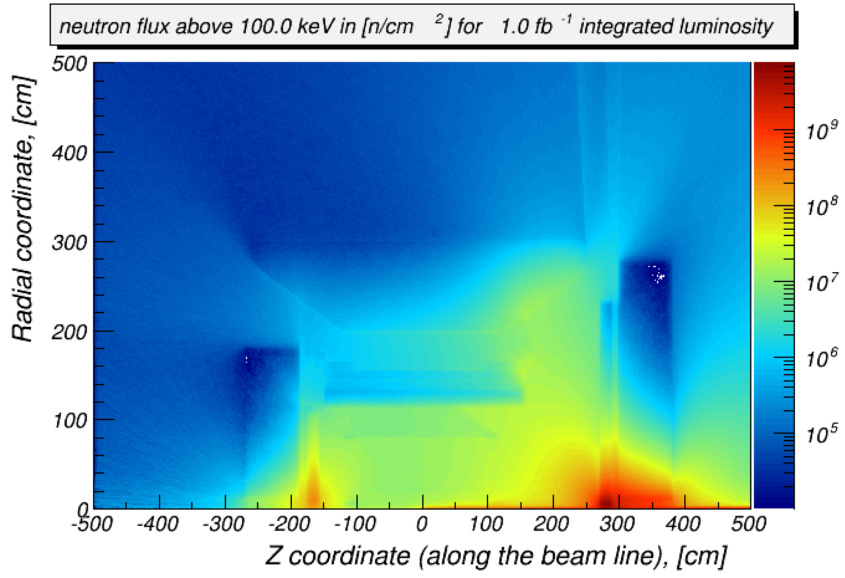


EIC Environment

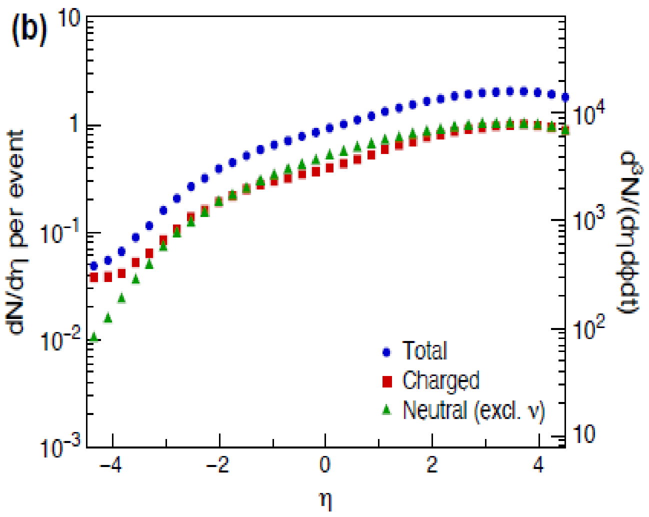
- High luminosity but relatively low event rates and low multiplicity (no pileup)
- Much lower radiation environment than LHC
- Space limited along beam direction due to accelerator IR design and existing experimental halls ($\Delta z = \pm$ 4.5 m)



Ionizing Radiation Dose ~ 250 rad/yr at L ~ 10^{33} cm^2/sec



Neutron Dose: ~ 10^9 n/cm^2 per fb^{-1} (1-100 fb^{-1} expected)



$dN_{ch}/d\eta$ ~ few

Event rate < 500 KHz

Detector Matrix (Calorimetry) – EIC Yellow Report

http://www.eicug.org/web/sites/default/files/Yellow_Report_v1.0.pdf

EIC Calorimeter Workshop
March 15-16, 2021

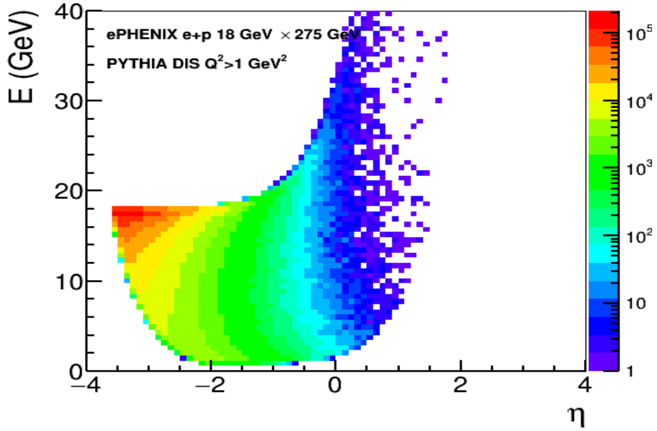
https://indico.phy.ornl.gov/event/38/overview

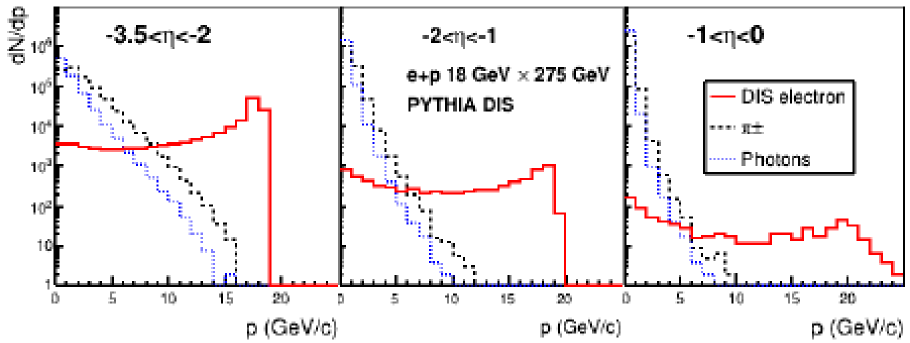
EIC Detector R&D Program
(since 2011)
eRD1 Calorimeter Consortium

η	Nomenclature			Electrons and Photons			π/K/p		HCAL	
				Resolution σ_E/E	PID	min E	p-Range (GeV/c)	Separati	Resolution σ_E/E	Energy
-4.5 to -4.0	↓ p/A	Auxiliary Detectors	Instrumentation to separate charged particles from photons	2%/√E(+1-3%)		50 MeV				
-4.0 to -3.5						50 MeV			~50%/√E + 6%	
-3.5 to -3.0						50 MeV				
-3.0 to -2.5			Backward Detector			50 MeV	≤ 7 GeV/c		~45%/√E+6%	
-2.5 to -2.0				2%/√E(+1-3%)		50 MeV				
-2.0 to -1.5				7%/√E(+1-3%)	π suppression up to 1:1E-4	50 MeV				
-1.5 to -1.0				7%/√E(+1-3%)		50 MeV				
-1.0 to -0.5						50 MeV	≤ 10 GeV/c		~85%/√E+7%	
-0.5 to 0.0		Central Detector	Barrel			50 MeV		≥ 3 σ	~85%/√E+7%	~500 MeV
0.0 to 0.5						50 MeV			~85%/√E+7%	
0.5 to 1.0						50 MeV	≤ 15 GeV/c		~85%/√E+7%	
1.0 to 1.5						50 MeV	≤ 30 GeV/c			
1.5 to 2.0						50 MeV	≤ 50 GeV/c			
2.0 to 2.5						50 MeV				
2.5 to 3.0			Forward Detectors	(10-12)%/√E(+1-3%)	3σ e/π	50 MeV	≤ 30 GeV/c		35%/√E	
3.0 to 3.5						50 MeV	≤ 45 GeV/c			
3.5 to 4.0	↑ e	Auxiliary Detectors	Instrumentation to separate charged particles from photons			50 MeV				
4.0 to 4.5						50 MeV				
4.5 to 5.0			Neutron Detection	4.5%/√E for photon energy > 20 GeV	<= 3 cm granularity	50 MeV			35%/√E (goal), <50%/√E (acceptable)*, 3mrad/√E (goal)	

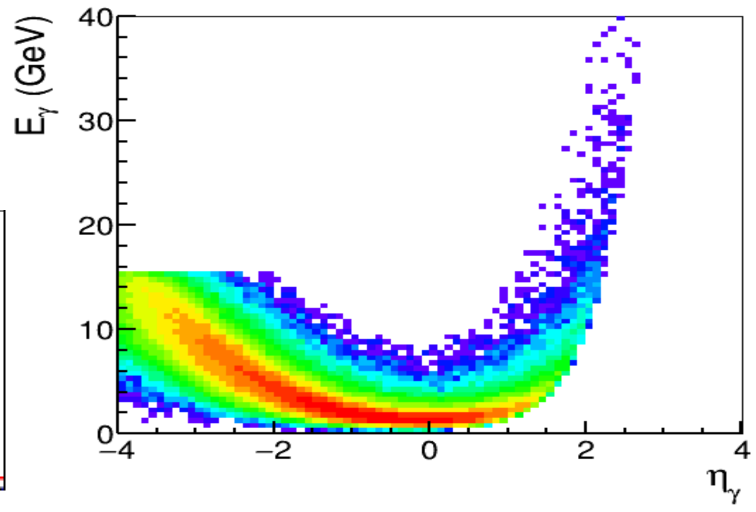
EMCAL

DIS e

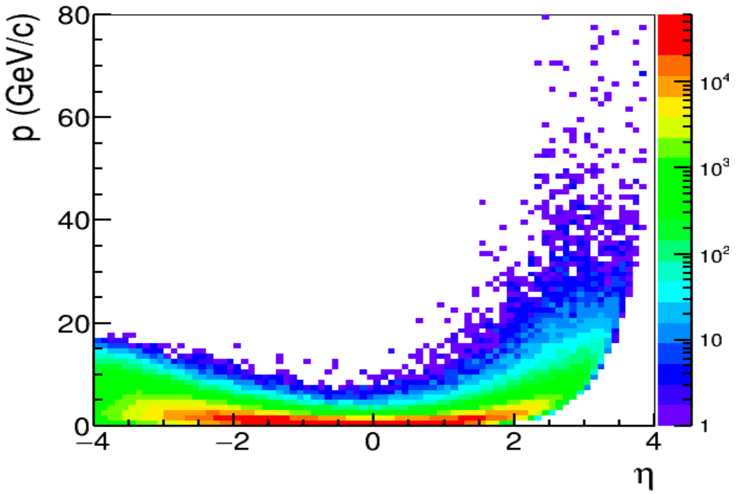




DVCS γ



SIDIS π^0s



	Backward -4 < η < -2	Backward -2 < η < -1	Barrel -1 < η < -1	Forwward 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 (GeV)	0.02	0.05	0.1	0.1	Require low E_{min} to measure decays
Granularity (Δθ)	< 0.02	< 0.02	< 0.025	< 0.01	γ/π^0, e/h discrimination (~ $10^{-2} – 10^{-3}$)
Space	ΔZ = 60 cm	ΔZ = 60 cm	ΔZ = 30 cm	ΔZ = 40 cm	Including all services

Promising EMCAL Technologies for EIC

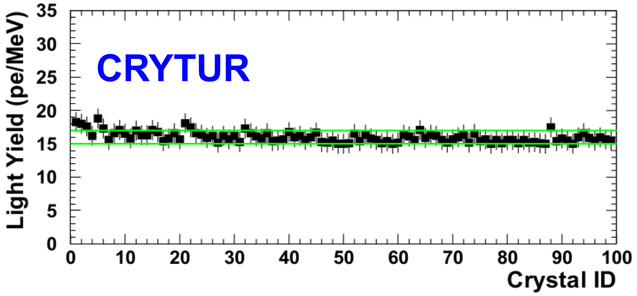
$\sigma_E/E = \alpha \oplus \beta/\sqrt{E}$

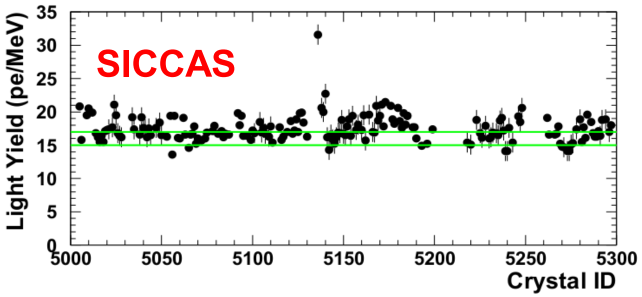
#	Type	sampling, mm	f_{samp}	X_0 mm	R_M mm	λ_I mm	cell mm^2	$\frac{X}{X_0}$	ΔZ cm	σ_E/E, % α	σ_E/E, % β
1	W/ScFi** sPHENIX	∅0.47 ScFi W powd.	2%	7.0	19	200	25^2	20	30	2.5	13
2	$PbWO_4$***	-	-	8.9	19.6	203	20^2	22.5	35	1.0	2.5
3	Shashlyk*** eRD1	0.75 W/Cu[a] 1.5 Sc	16%	12.4	26	250	25^2	20	40	1.6	6.3
4	W/ScFi** with PMT	0.59^2 ScFi W powd.	12%	13	28	280	25^2	20	43	1.7	7.1
5	Shashlyk***	0.8 Pb 1.55 Sc	20%	16.4	35	520	40^2	20	48	1.5	6
6	TF1 Pb glass***	-	-	28	37	380	40^2	20	71	1.0	5-6
7	Sc. glass*[b]	-	-	26	35	400	40^2	20	67	1.0	3-4

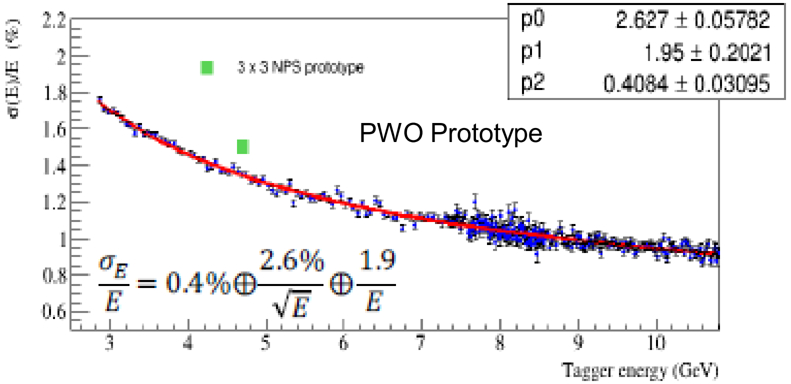
Crystals and Scintillating Glass

Inner Region (-4<η<-2) - Lead Tungstate Crystals

Neutral Particle Spectrometer
at JLAB (1080 PWO crystals)

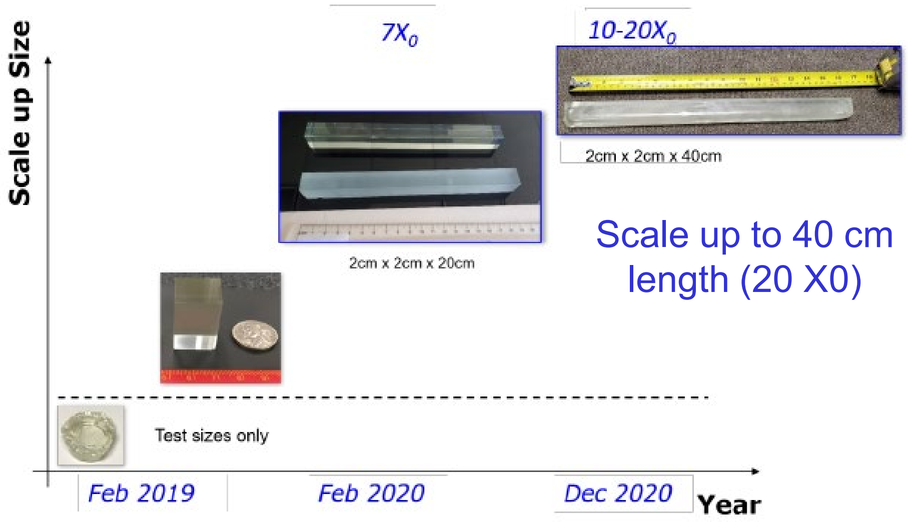




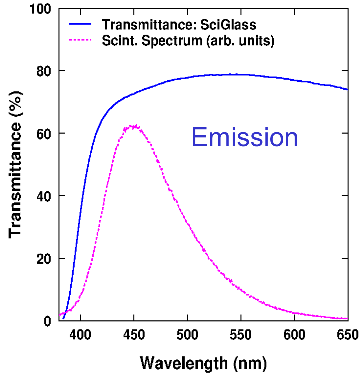


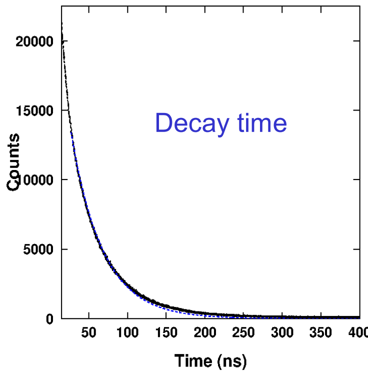
Outer Region (-2<η<-1) - Scintillating Glass

Being developed at Catholic University
at its Vitreous State Laboratory

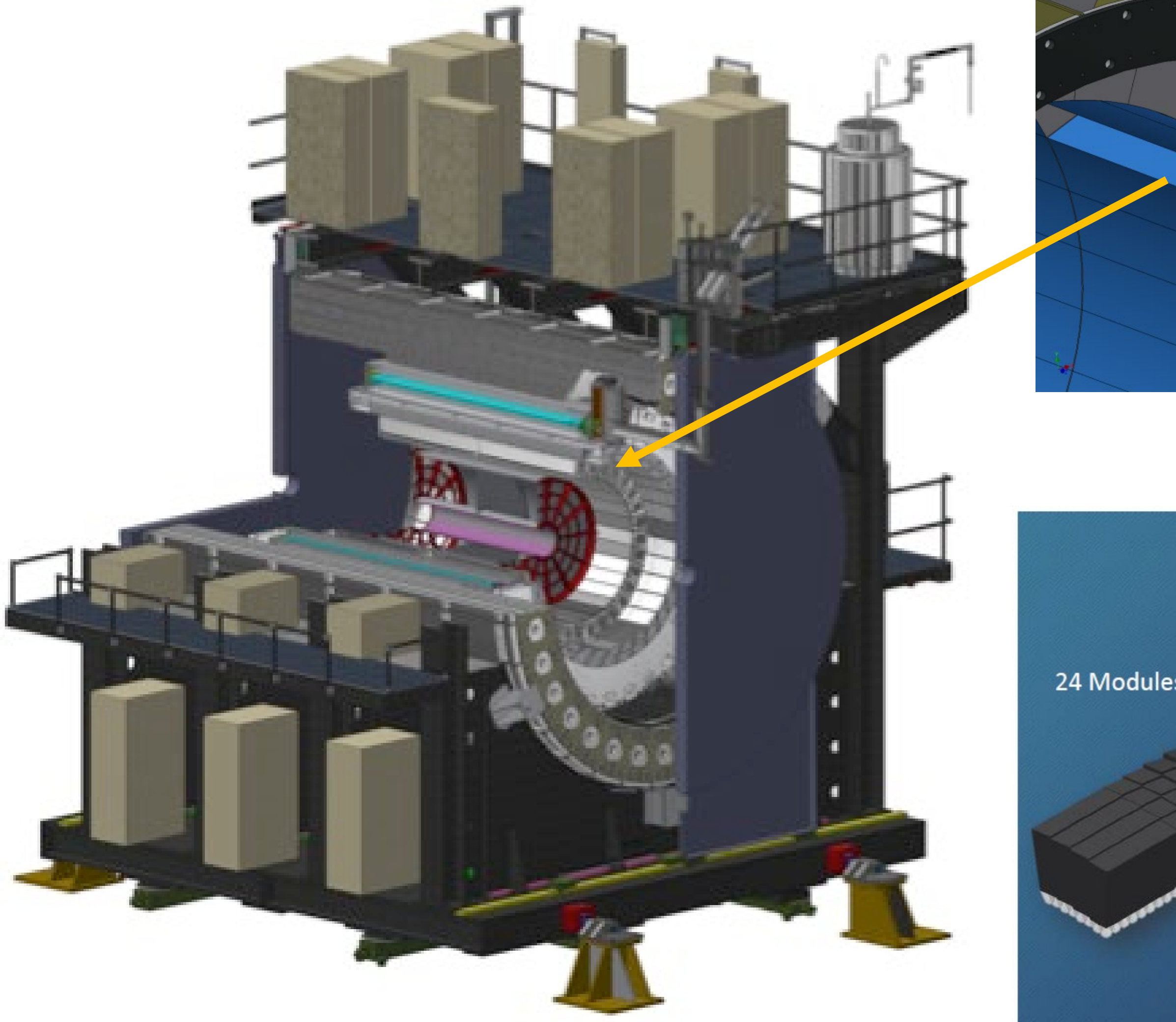


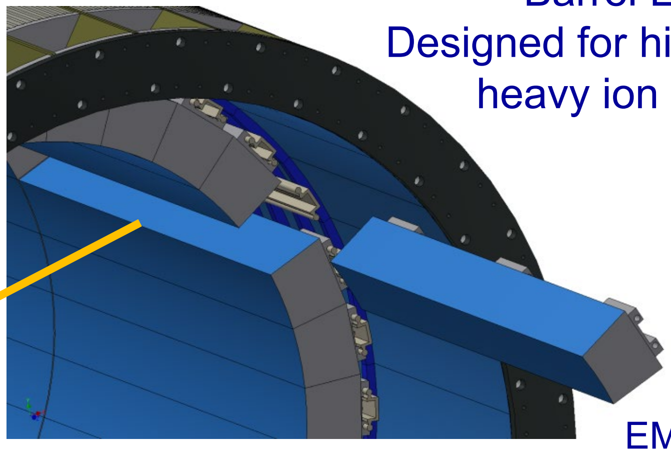
Scale up to 40 cm
length (20 X0)



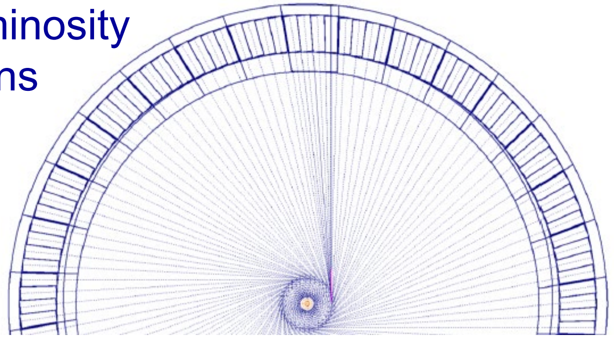


sPHENIX W/SciFi EMCAL



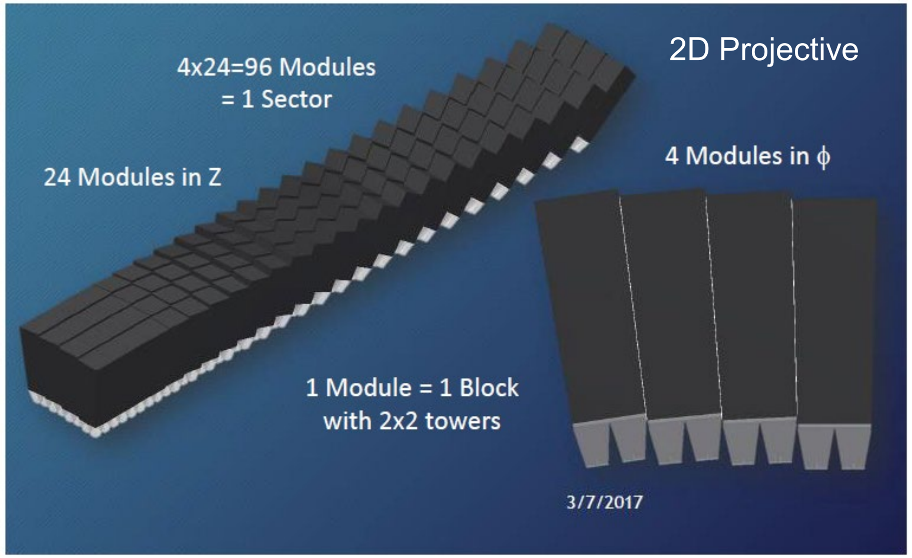


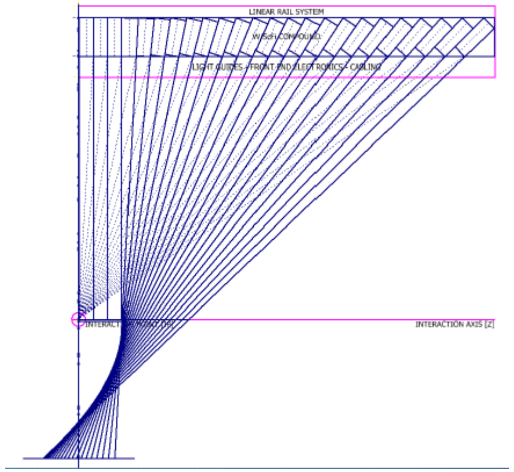
Barrel EMCAL
Designed for high Luminosity
heavy ion collisions



EMCAL Sector

$2(\pm\eta) \times 32\ (\phi) = 64$ Sectors

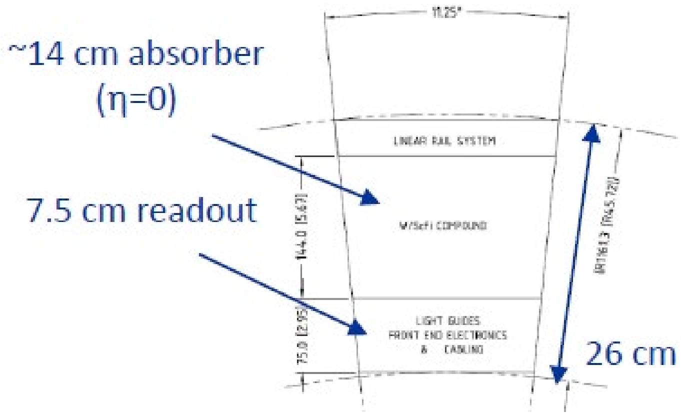




Sectors and blocks are approximately projective and tilted in η and ϕ

sPHENIX W/SciFi EMCAL

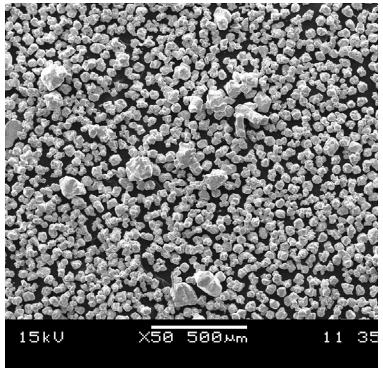
- The sPHENIX EMCAL is a W/SciFi SPACAL consisting of a matrix of tungsten powder and epoxy with embedded scintillating fibers
  - 0.47 mm dia. fibers, spacing 1 mm, SF ~ 2%
  - Density ~ 9.0 g/cm^3, X0 = ~ 7 mm, ~ 20 X0 total, R_M ~ 2.3 cm



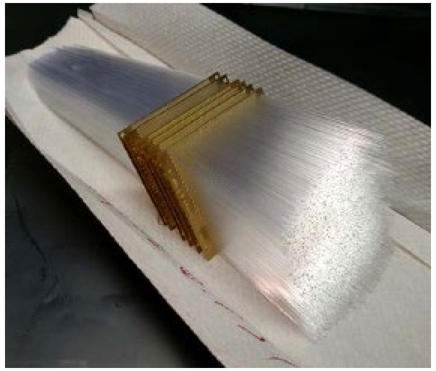
- W/SciFi modules consist of 4 towers, each with its own light guide that is read out on the front with a 2x2 array of 3x3 mm^2 SiPMs.

6144 Modules (24,576 towers)

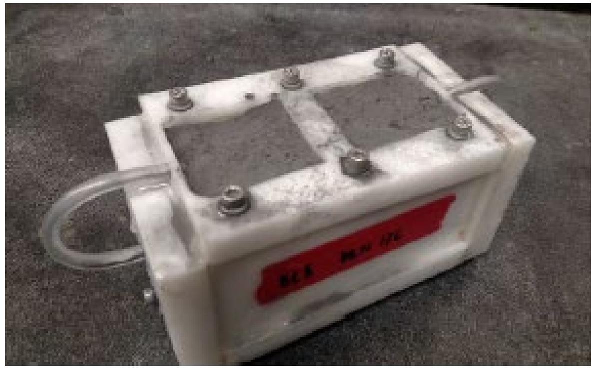
W Powder ~ 50 μm

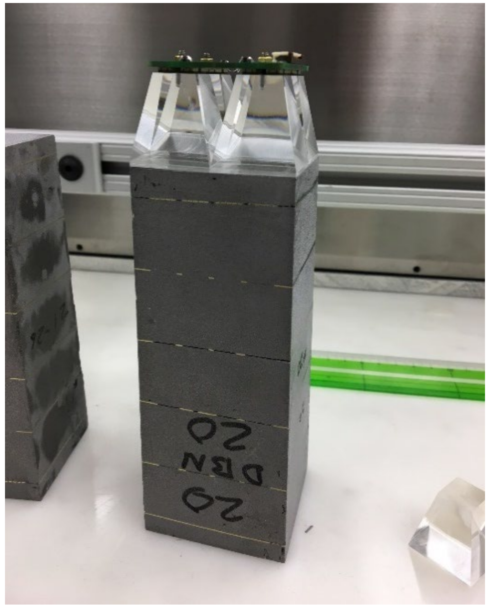


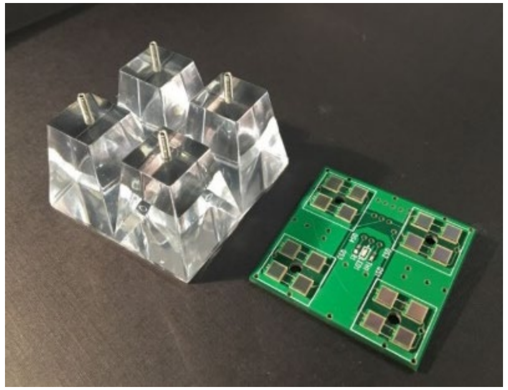
Fiber Assembly



Mold with W powder, fibers + epoxy







Readout with light guides (1”) and SiPMs

~ 100K SiPMs

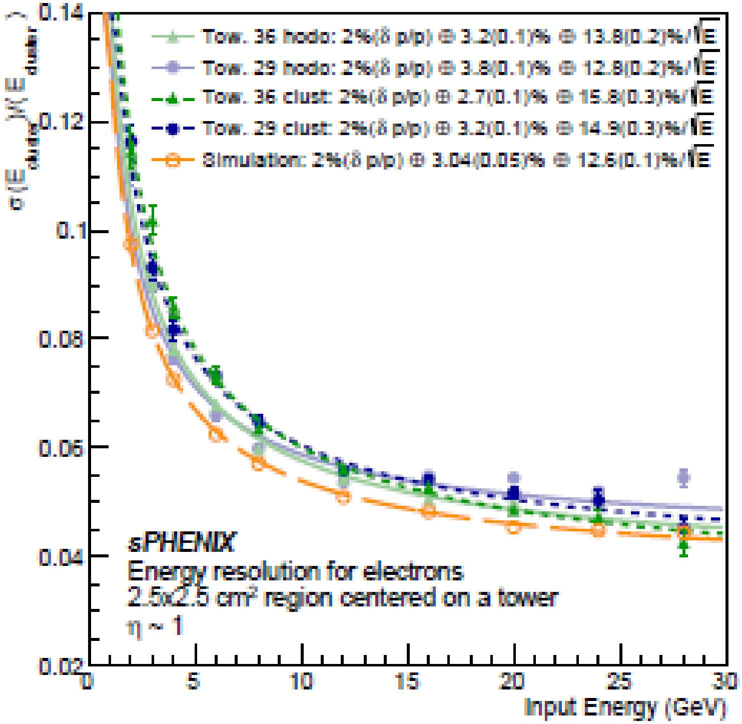
Hamamatsu S12572-015P

Energy Resolution

Energy resolution after position dependent correction

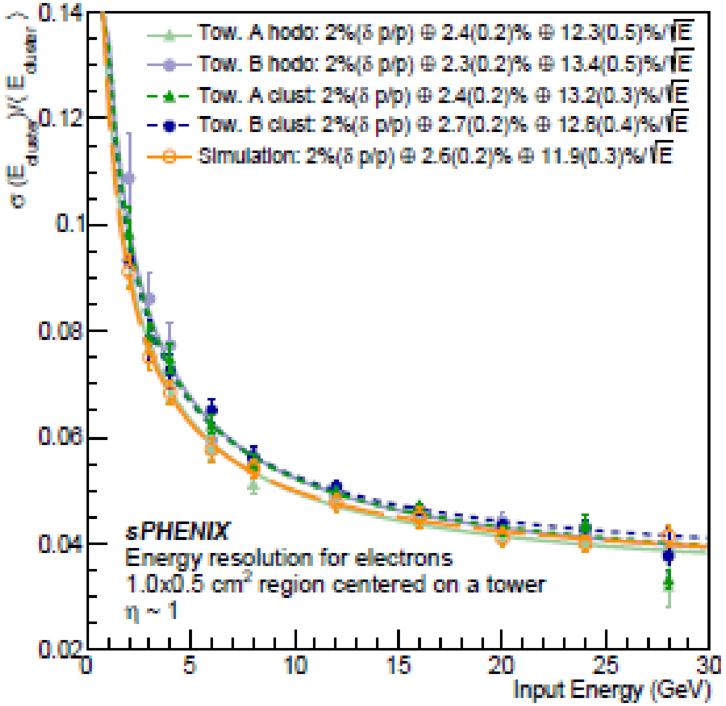
Beam Test 2018

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



Resolution ~ (13-15)%/√E ⊕ 3%

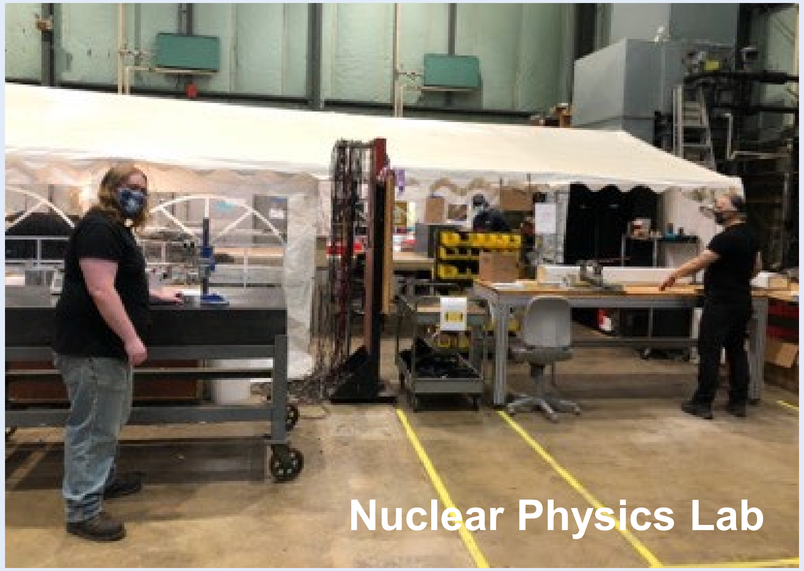
Beam covering a 1.0 x 0.5 cm^2 area centered on a tower

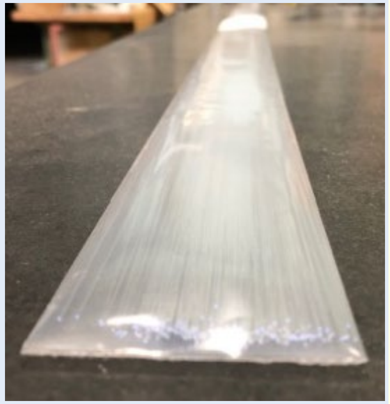


Resolution ~ (12-13)%/√E ⊕ 2.5%

sPHENIX EMCAL Currently Under Construction (Completion Jan 2022)

Block Production at UIUC (also Fudan U – Shanghai)



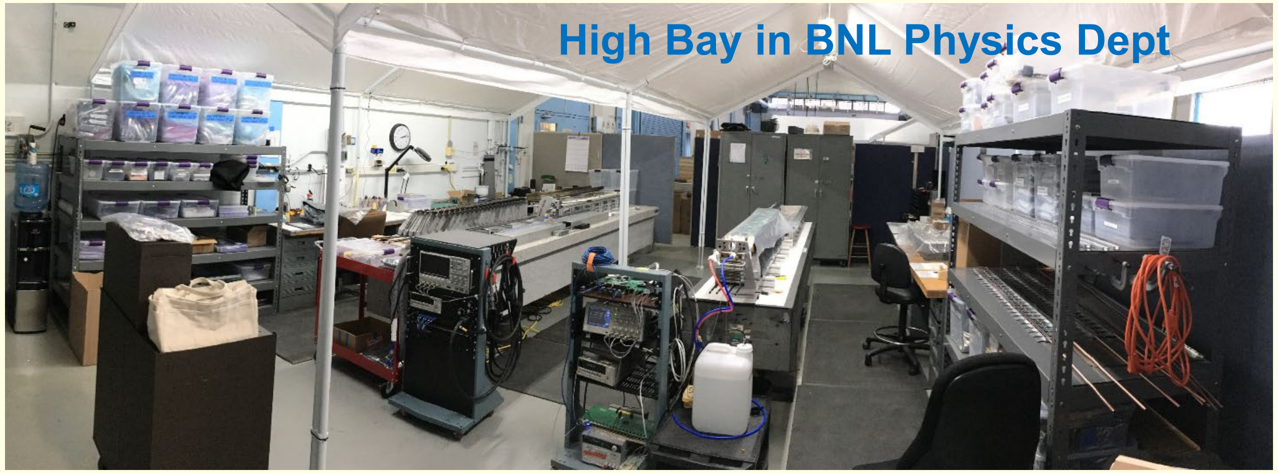


2600 km of fiber
665 kg of epoxy
88 m^2 of screens

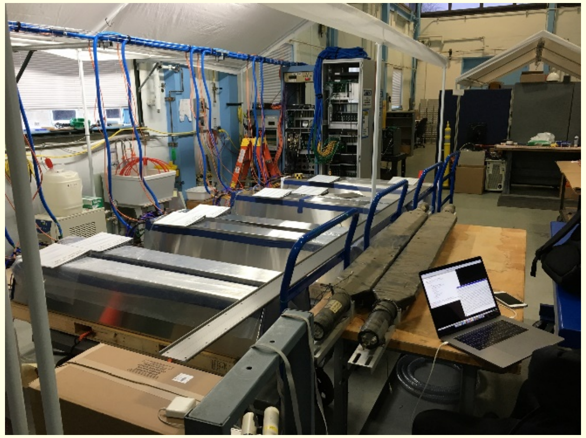
20 Tons of W powder

Blocks awaiting removal from molds

Module and Sector Production at BNL



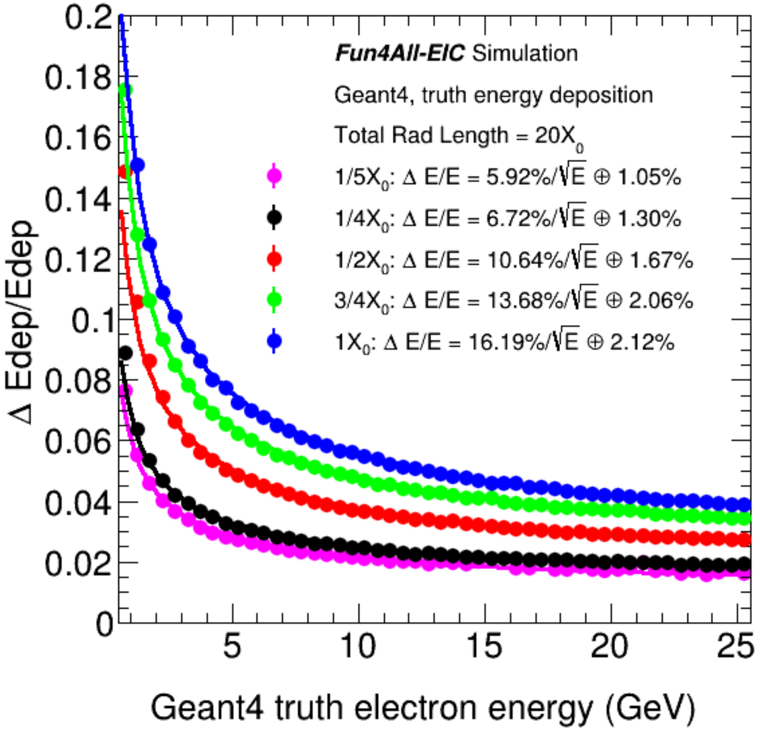
Modules being
glued into sectors



Sector Burn-in and Testing

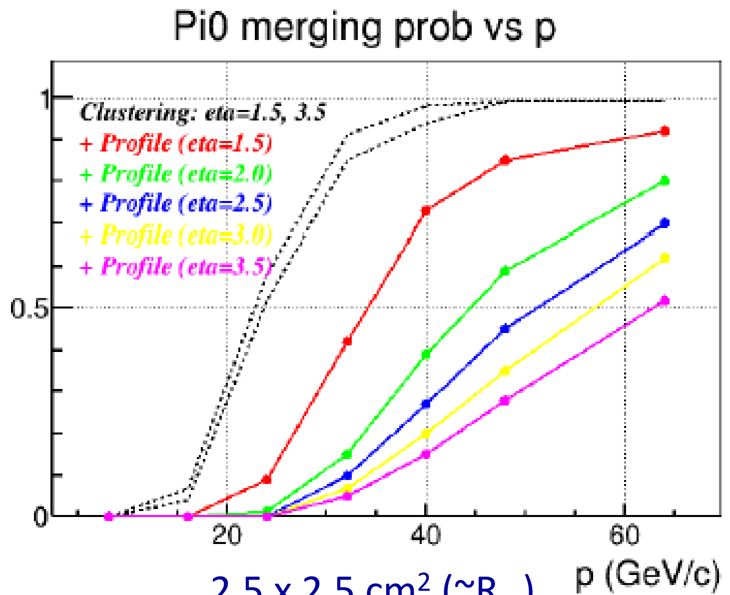
EMCAL Shashlik Calorimetry – Pb vs W

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

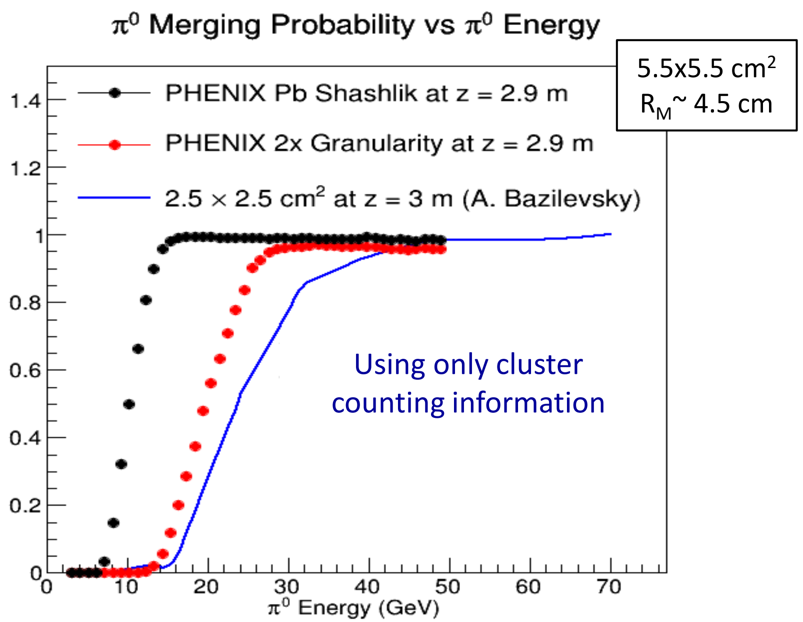


Require fine segmentation and small R_M to resolve γ/π^0 at high momentum

Non projective geometry



2.5 x 2.5 cm² (~R_M)



Note:

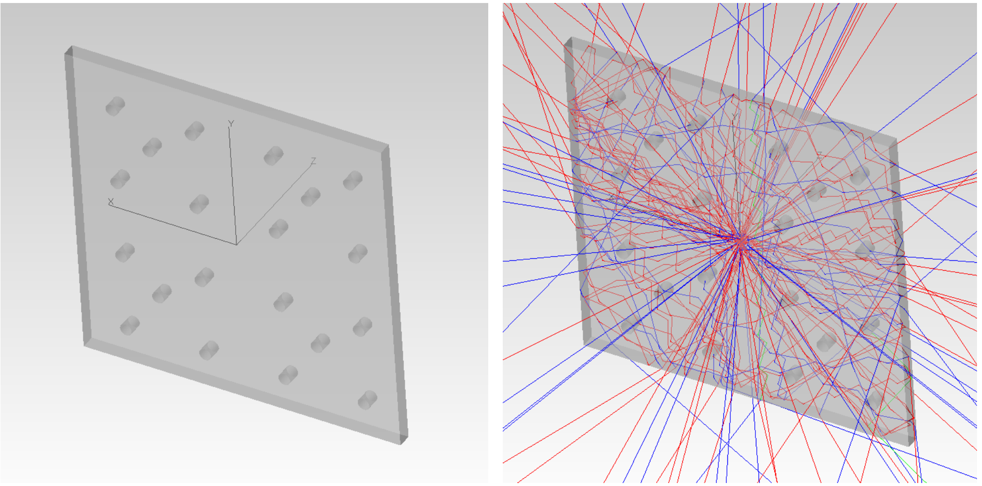
- Projective geometry will improve separation, particularly in the η ~ 1-3 region
- Can also achieve γ/π^0 separation using a preshower detector

Improving Shashlik Spatial Resolution

- The availability of low cost SiPMs allows the possibility of reading out *each fiber individually.* This allows determining the shower position even within a tower (< 1 R_M).

- Non-uniformities of light collection within a tile causes position dependence but can in principle be corrected for.

- A compact shashlik may also offer the possibility of improving the position dependence due to the short light path to the WLS fibers.



Ray tracing withing a scintillation tile

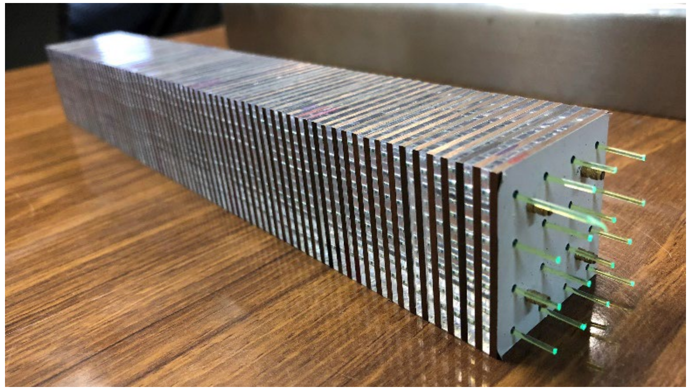
Ray tracing and lab measurements can produce a light collection map for each fiber

A Prototype W/Shashlik EMCAL (eRD1)

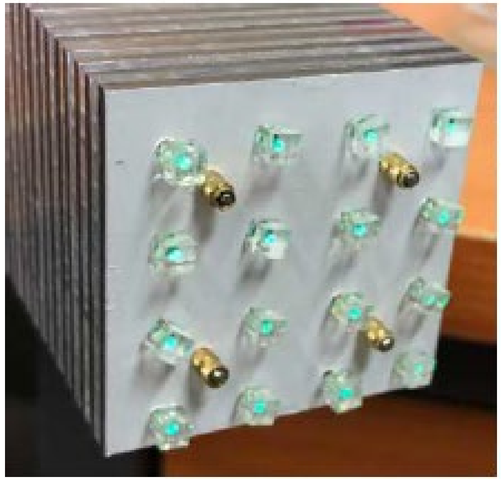
Originally designed for the NA64 Experiment at CERN

Andres Bello University
Santiago, Chile

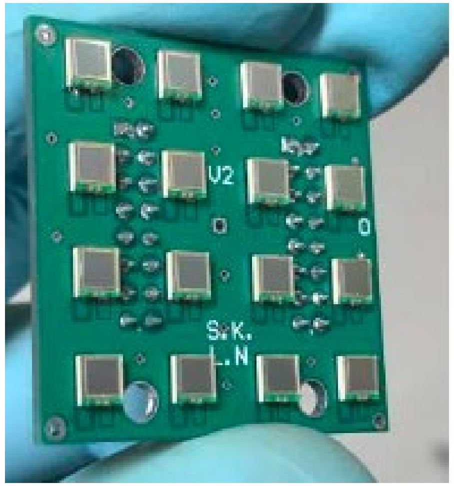
- Absorber plates are a W(80%)/Cu(20%) alloy that is easily machinable
  ρ = 17.2 g/cm^3, X0 = 4.2 mm, 38 x 38 x 1.58 mm^3
- Scintillating tiles: 38 x 38 x 1.63 mm^3 injection molded polystyrene (Uniplast, Russia).
- 1 mm dia WLS fibers (Saint-Gobain BCF-91A)
- 80 sampling layers, 31 X0 (27 cm)
- Each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



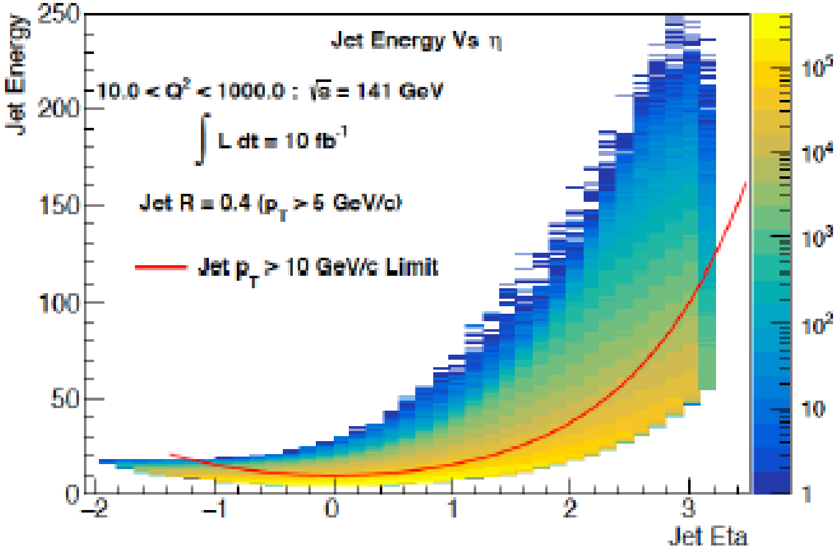
Each fiber coupled to small lucite light mixer

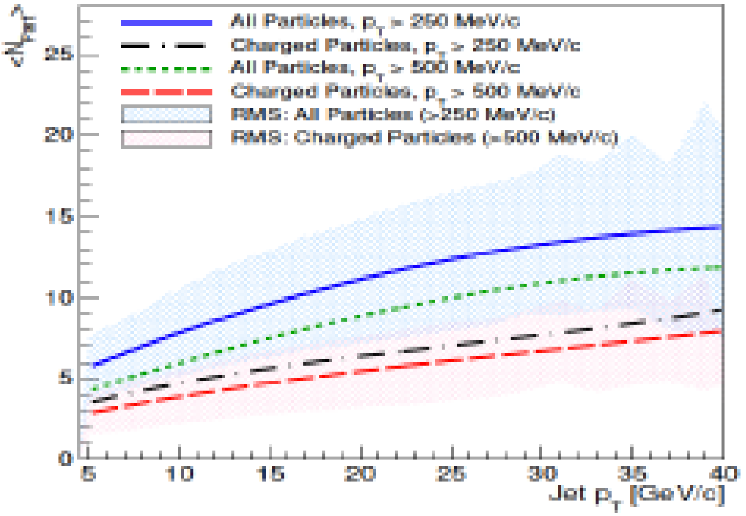


Hamamatsu S14160-3015P

3x3 module prototype

HCAL





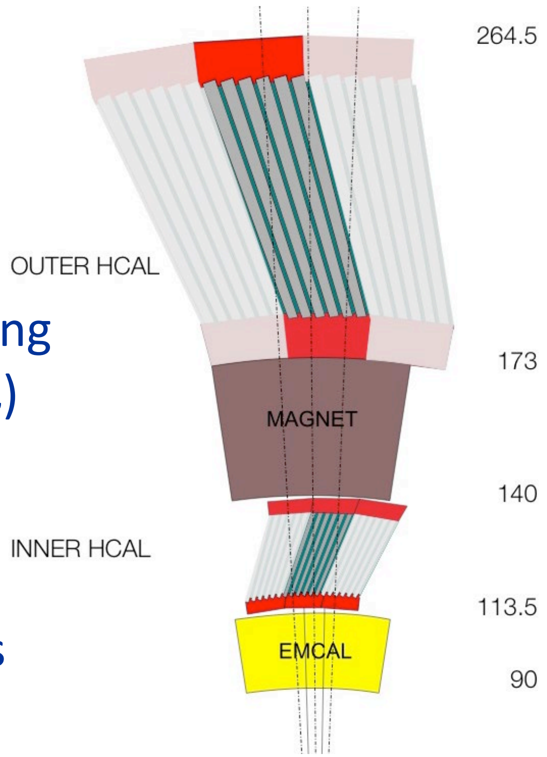
- Jet energies typically < 50 GeV
- Particle multiplicity within a jet is typically ~ 10

	Backward Endcap -4 < η < -1	Barrel -1 < η < -1	Forwward Endcap 1 < η < 2.5	Forwward Endcap 2.5 < η < 4	
Resolution σ_E/E	50%/√E ⊕ 6%	85%/√E ⊕ 7%	50%/√E ⊕ 6%	35%/√E ⊕ 5%	Would benefit from better calorimeter resolution for η > 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

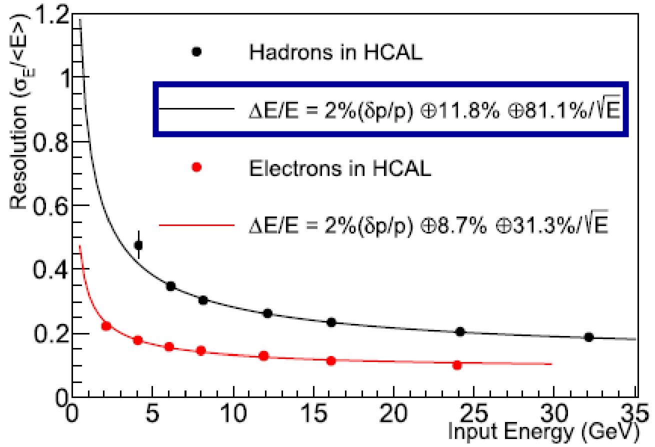
Barrel HCAL

Concept based on the sPHENIX Barrel Calorimeter

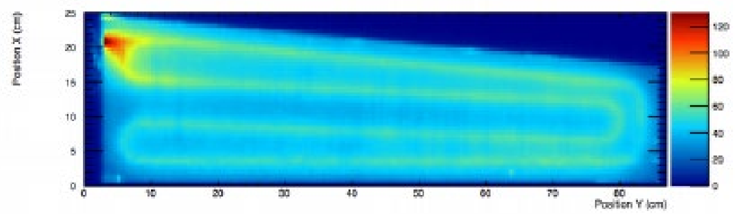
- Steel plates + scintillating tiles with WLS fiber readout
- **Plates oriented parallel to beam**
- **Iron serves as flux return**
- Plates are tilted to avoid channeling
- Two longitudinal sections (~ 4.5 λ)
  - Inner HCAL inside magnet
  - Outer HCAL outside magnet
- $\Delta\eta \times \Delta\phi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



Test Beam 2016

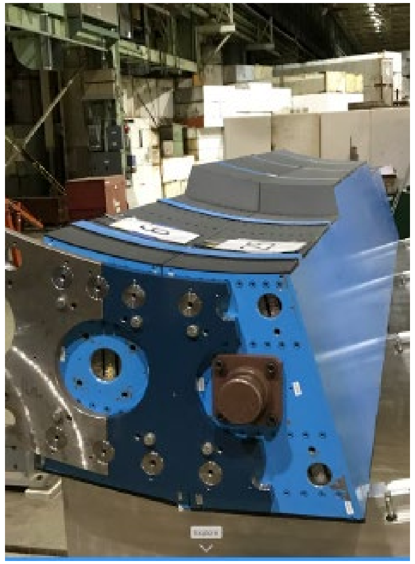


Hadronic resolution ~81%/√E ⊕ 12%



Scintillating tile with WLS fiber

sPHENIX HCAL under construction at BNL

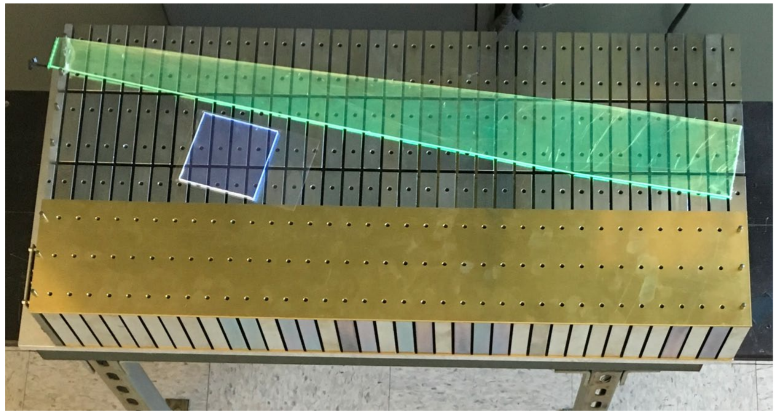


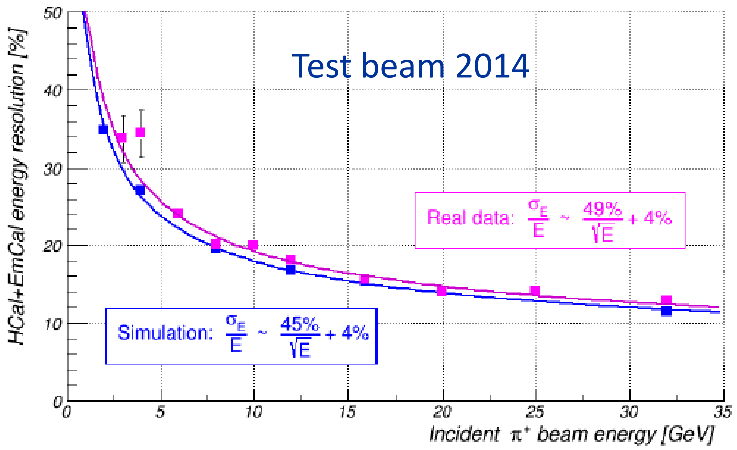
Forward HCAL

Concept based on the STAR Forward Calorimeter System

Originally proposed

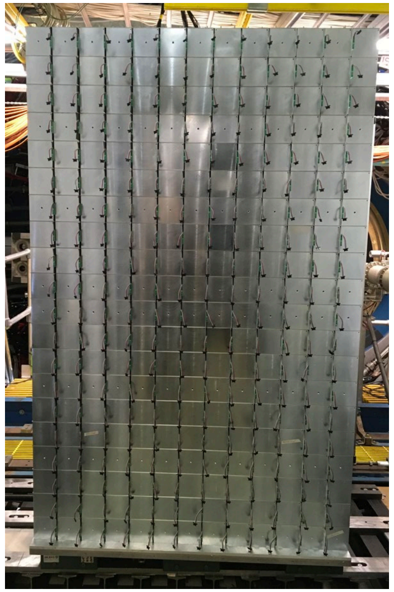
W/SciFi EMCAL followed by a Pb/Scint (10/2.5 mm) HCAL

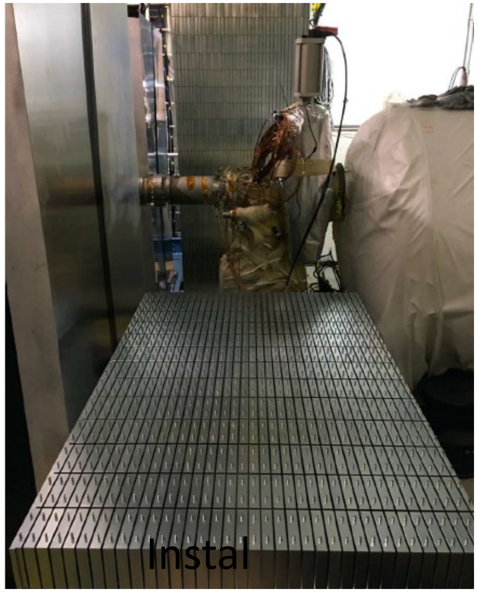


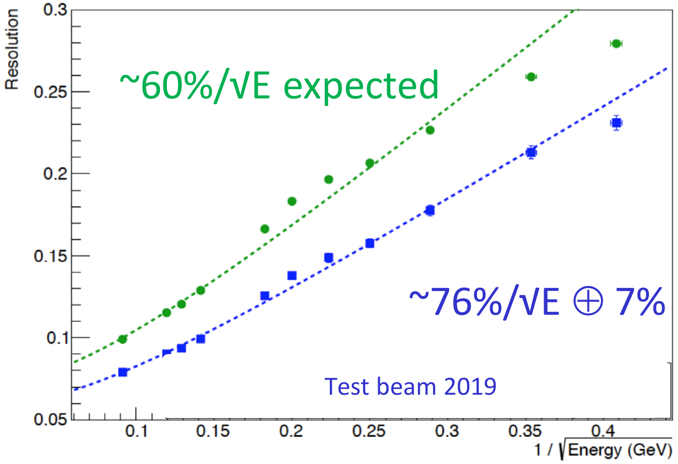


Finally implemented
(to save cost)

Pb Shashlik EMCAL followed by a Fe/Scint (20/3 mm) HCAL





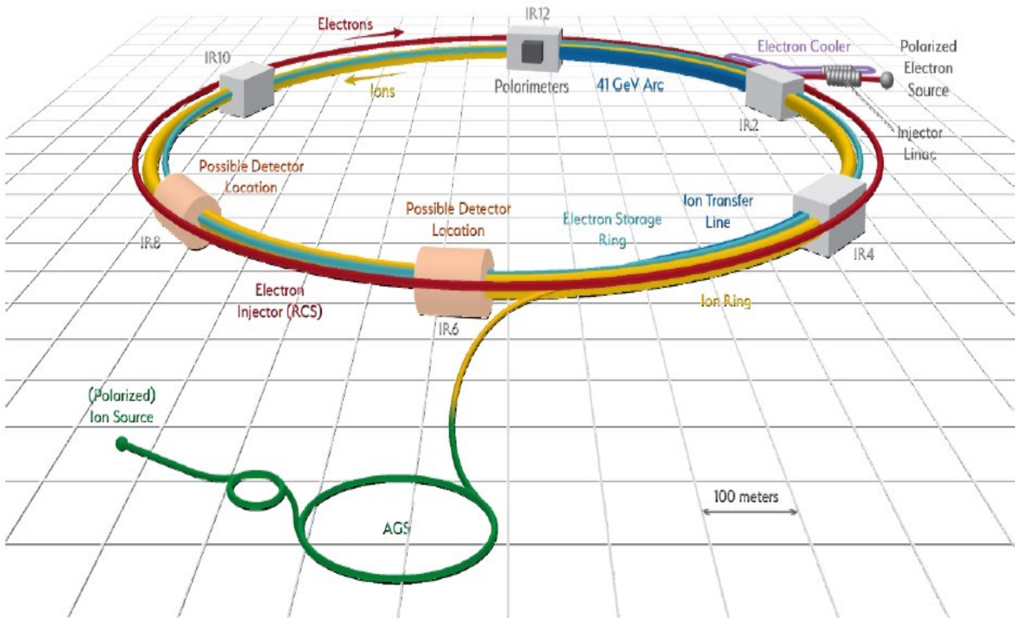


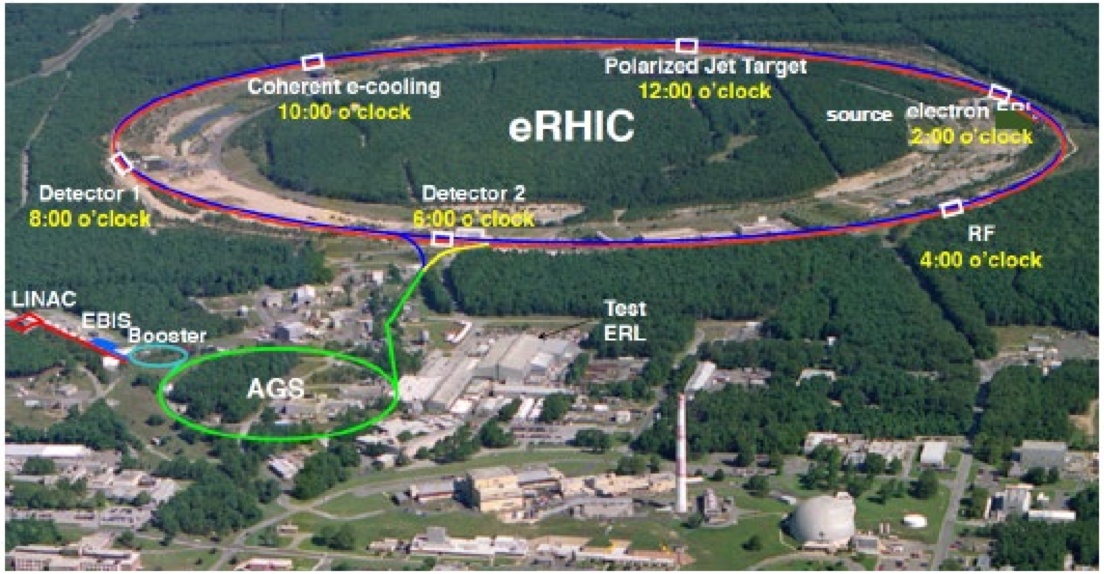
Summary & Conclusions

- EIC requires nearly 4π calorimeter coverage with regions requiring high resolution EMCAL and HCAL performance. However, there are 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 and W/Shashlik EMCAL technologies and tilted plate configurations for the HCAL).
- Given that the project is seeking CD2 approval in less than 2 years the schedule is very tight to come up with a detailed detector design.

Backup

The Electron Ion Collider





Relativistic Heavy Ion Collider (RHIC) Complex at BNL

- Add an electron storage ring 2.5-18 GeV (80% polarization) to the existing RHIC Collider
- Proton beams ~ 40 - 275 GeV/c (70% polarization)
- Ion beams (A up to U, E up to 100 GeV/A, E_{cm} ~ 10-140 GeV))
- Polarized light ions: d, He^3 (pol > 80%)
- Luminosity ~ 10^{33} - 10^{34} cm^{-2}/s^{-1} (10 – 100 fb^{-1}/yr)
- 2 Intersection Regions (1 IR and detector funded by DOE)

Detailed description given in the EIC Yellow Report
http://www.eicug.org/web/sites/default/files/Yellow_Report_v1.0.pdf

Early Completion Date – July 2031

The Physics of EIC

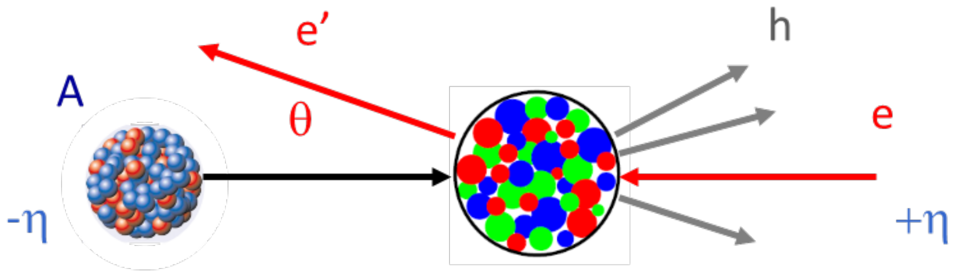
The physics goals of EIC are to address three fundamental questions about nucleons:

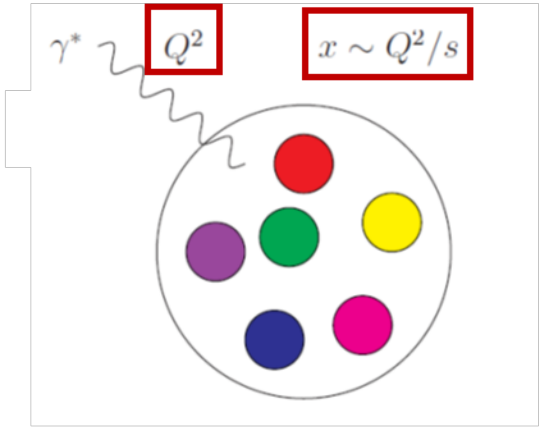
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the properties of dense systems of gluons?

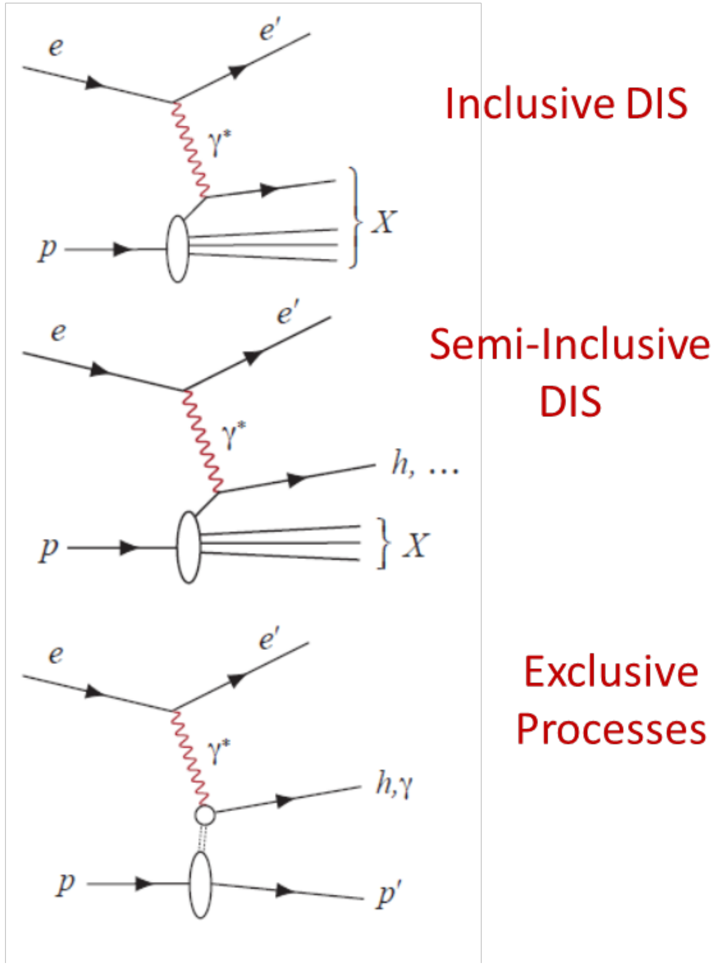
Primary tool is Deep Inelastic Scattering (DIS) of electrons off partons

Kinematics is determined by measuring the energy/momentum and angle of the scattered electron

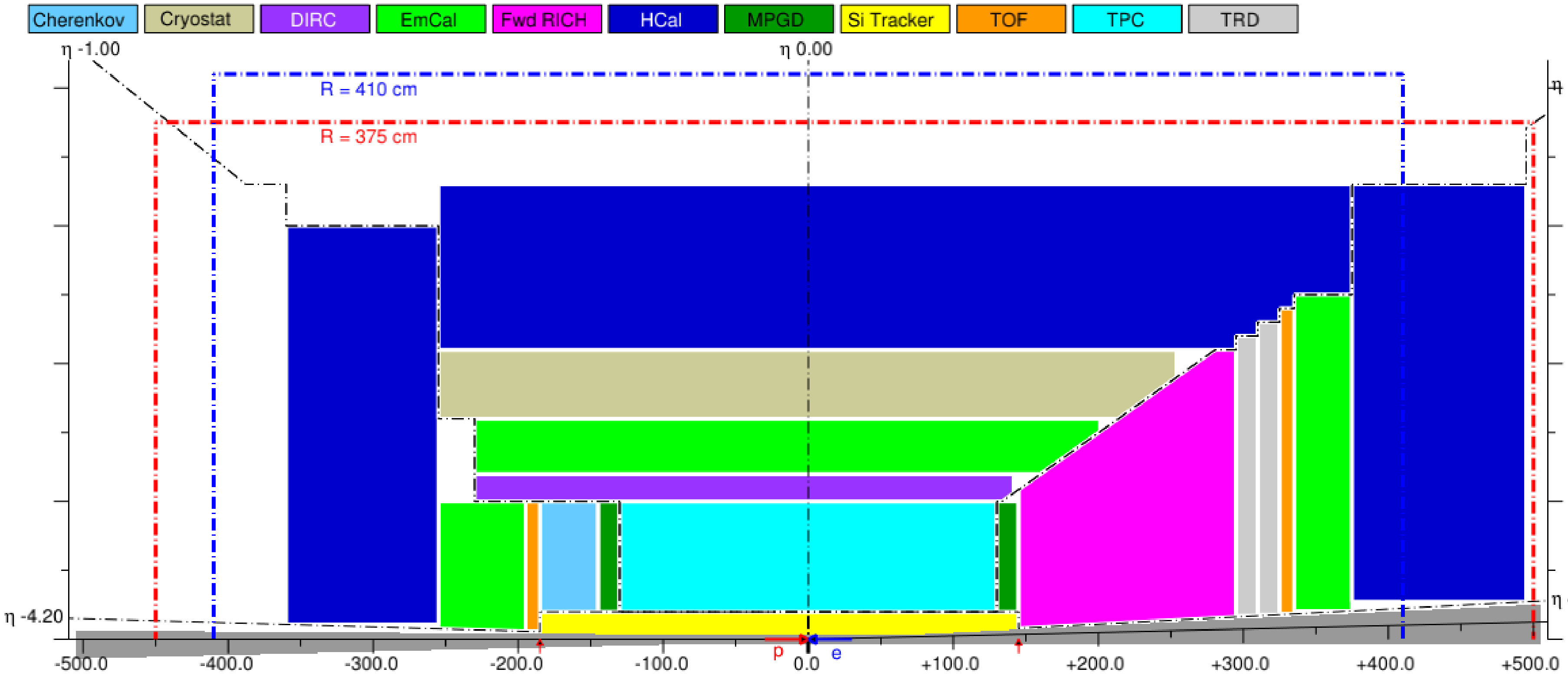
$$Q_e^2 = 2E_eE_e'(1+\cos\theta_e') = 4E_eE_e'\cos^2\left(\frac{\theta_e'}{2}\right)$$







EIC Reference Detector

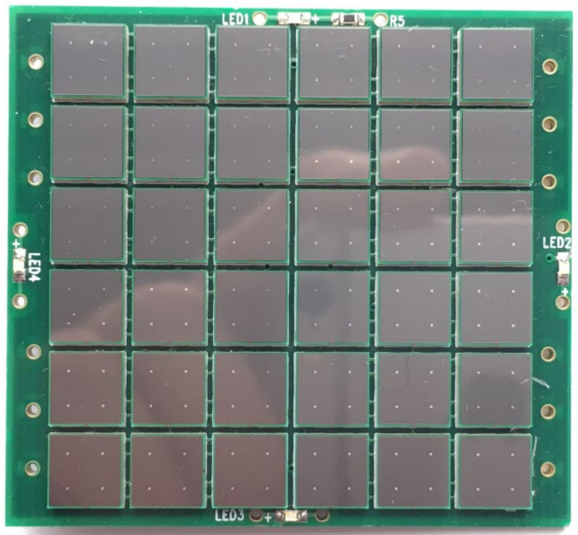


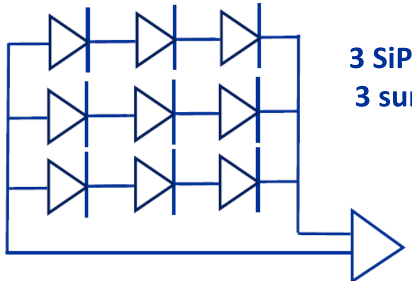
Hadrons → ← Electrons

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

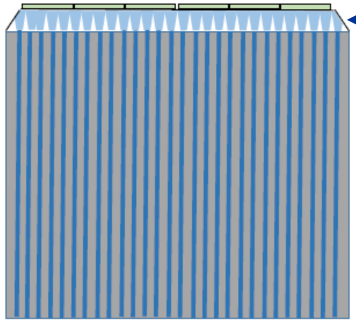
Maximum photocathode coverage using the sPHENIX blocks





3 SiPMs in series then 3 summed in parallel

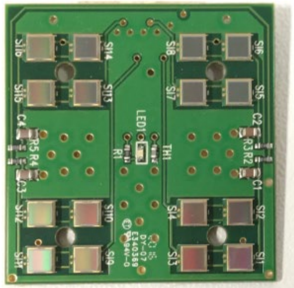
(C/3 x 3 = C)

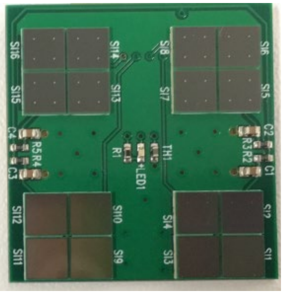


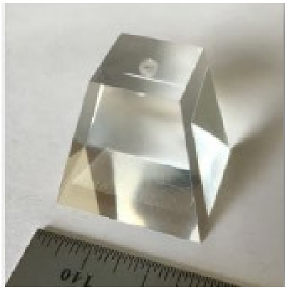
Short light guide covering entire block

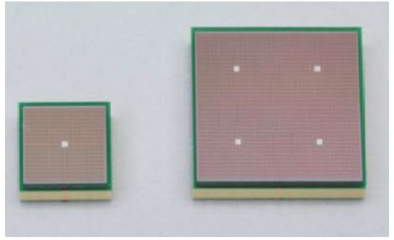
Hamamatsu S13360
6x6 mm^2 SiPM with TSVs
(50 μm pixels)

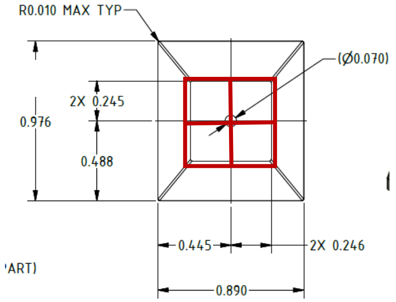
Increased coverage using existing sPHENIX light guides









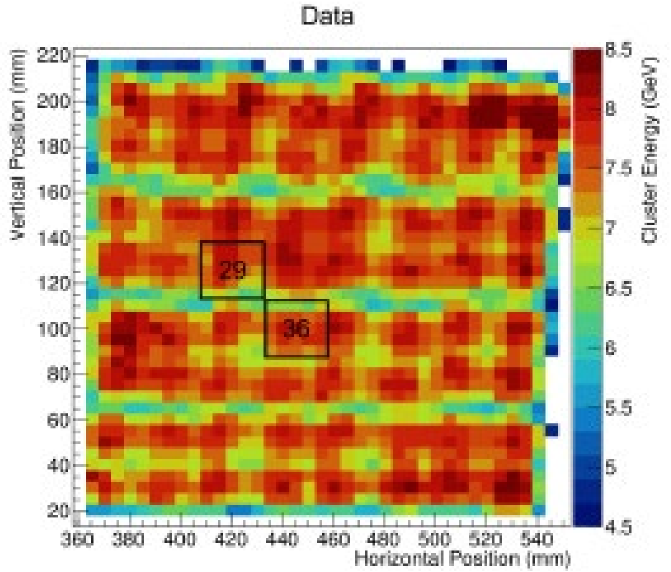


2x2 array of 6x6 mm^2 SiPMs

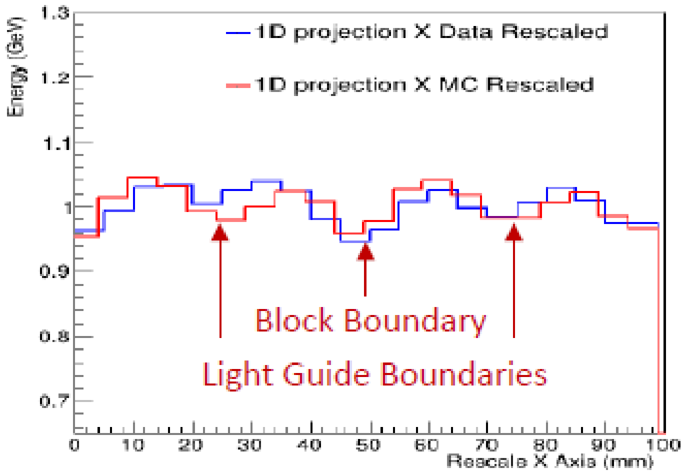
Uniformity of W/SciFi - Effect on Energy Response

Non-uniformities are inherent in the design and contribute to the energy resolution

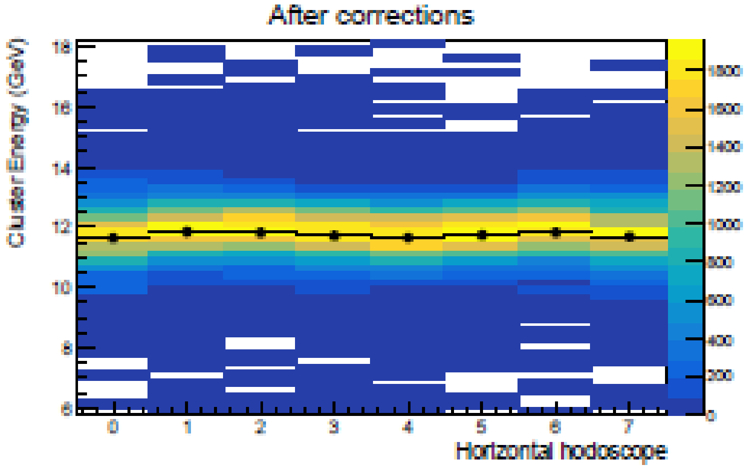
Uniformity of response over 8x8 towers with 8 GeV electrons (Test Beam Data)



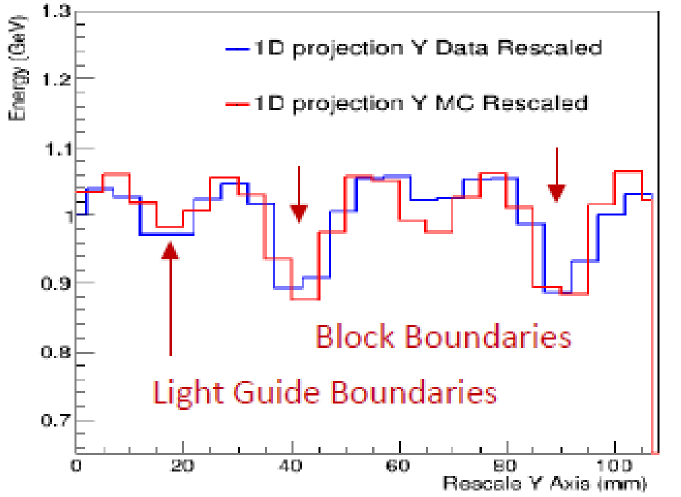
X axis projection



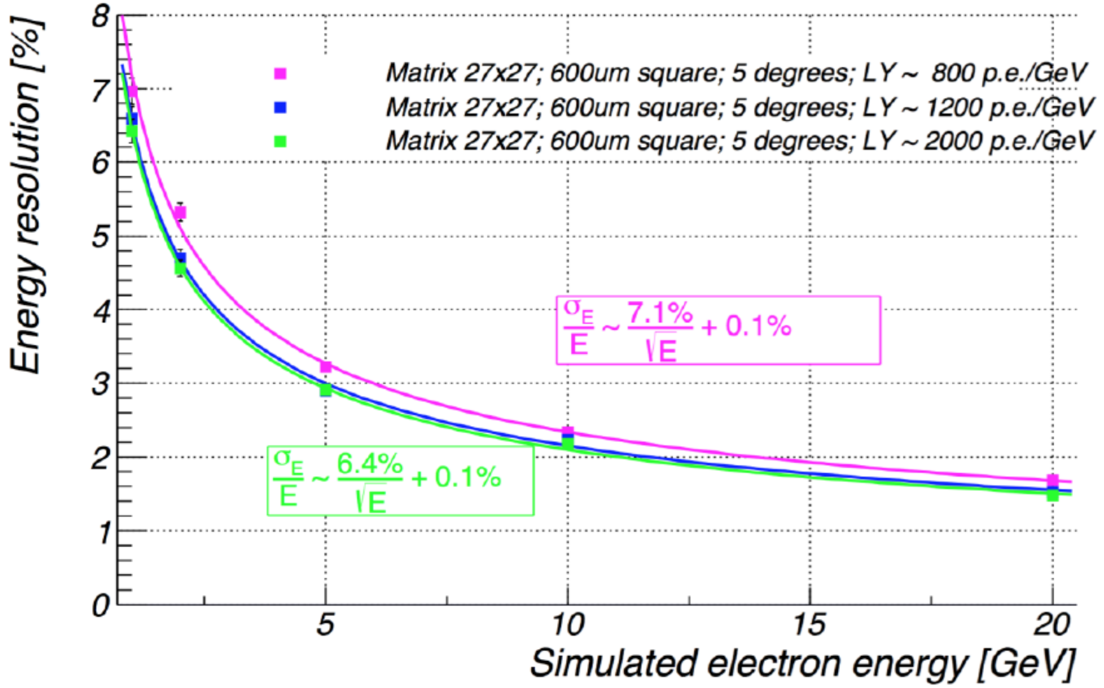
Uniformity after position dependent correction

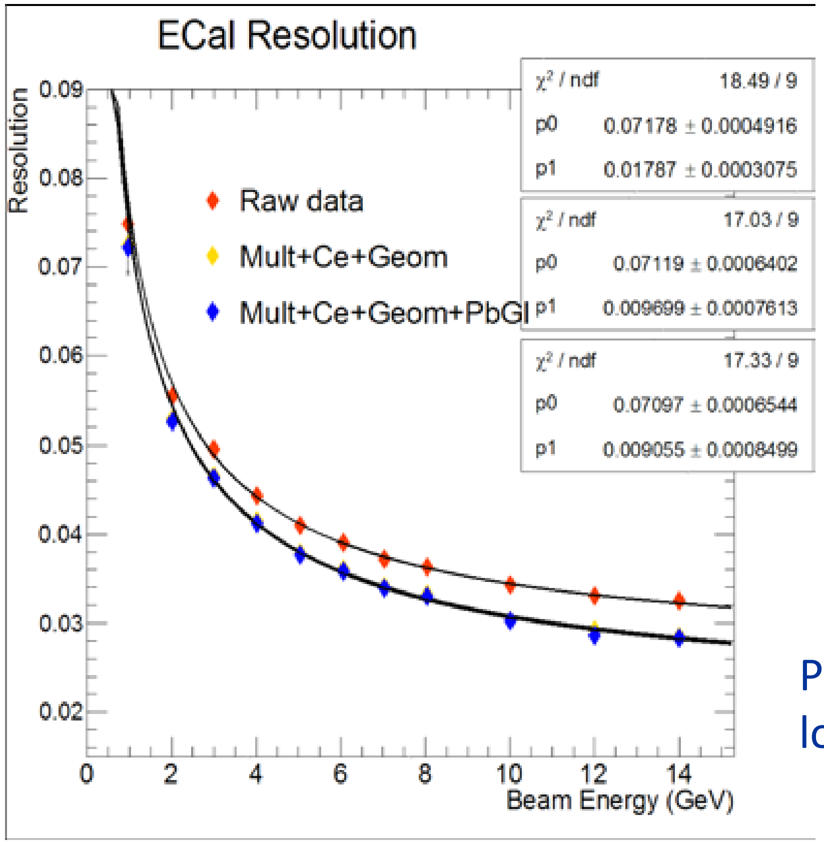


Y axis projection



HiRes W/SciFi





PMT readout with long light guides

eRD1 Report Jan 2016

eRD1 Report July 2016

O.Tsai UCLA

PHENIX Shashlik

Fine segmentation for high multiplicity heavy ion collisions

$\Delta\eta$ =0.01, $\Delta\phi$ = 0.01 $\Rightarrow$ 5.535 x 5.535 cm^2 towers at R = 5 m

3888 modules $\Rightarrow$ 15,552 towers total

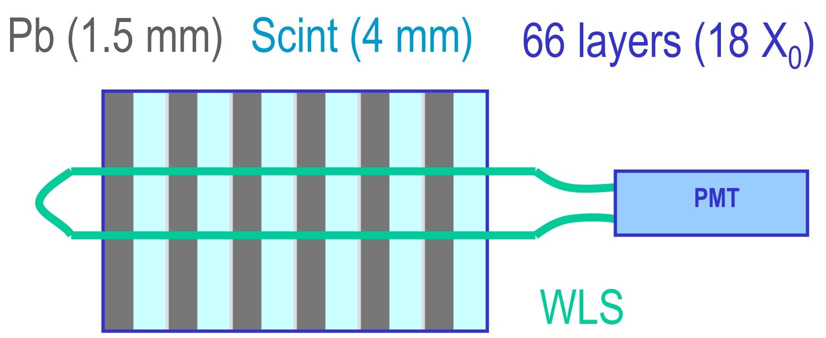
X0 = 2.0 cm, R_M ~ 4.5 cm,

Total length = 18 X0, 0.85 λ_{int}

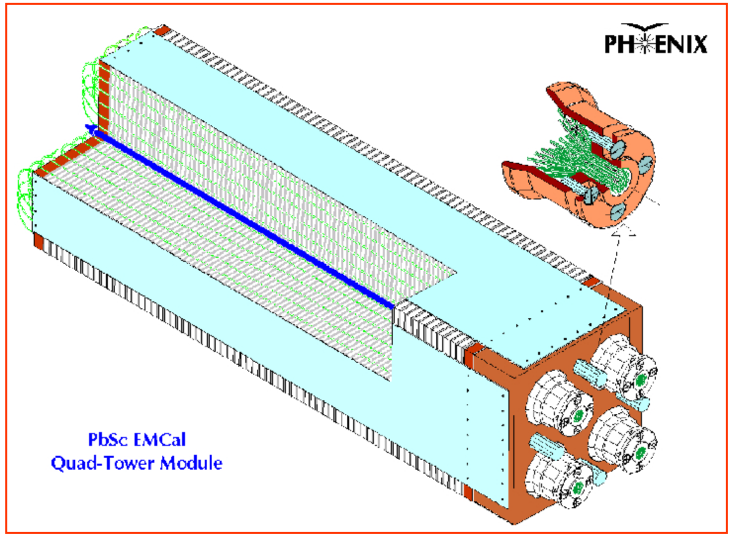
Resolutions

$$\frac{\sigma_E}{E} = \frac{8.1\%}{\sqrt{E}} \oplus 2.1\% \qquad \sigma_x = \frac{5.7\ (mm)}{\sqrt{E}} \oplus 1.55\ (mm)$$

$$\sigma_t \sim 200ps$$



Light Yield ~ 1.5 p.e./MeV



1500 modules now deployed in STAR FCS w/ SiPM readout