Shashlik EMCAL Options for EIC

Craig Woody

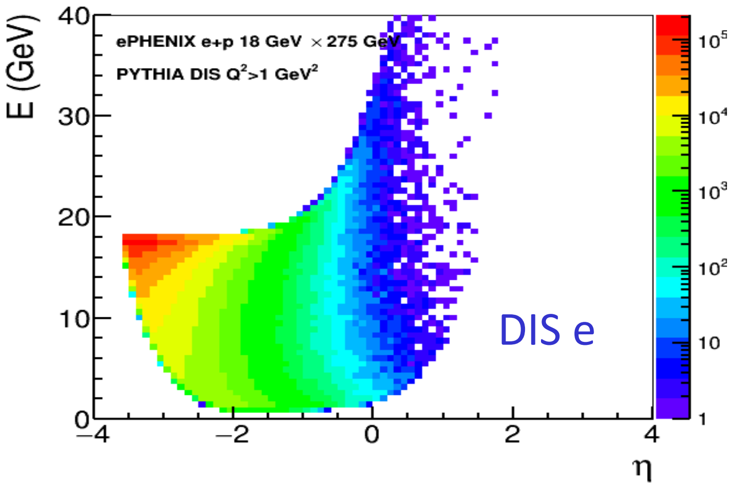
Brookhaven National Lab

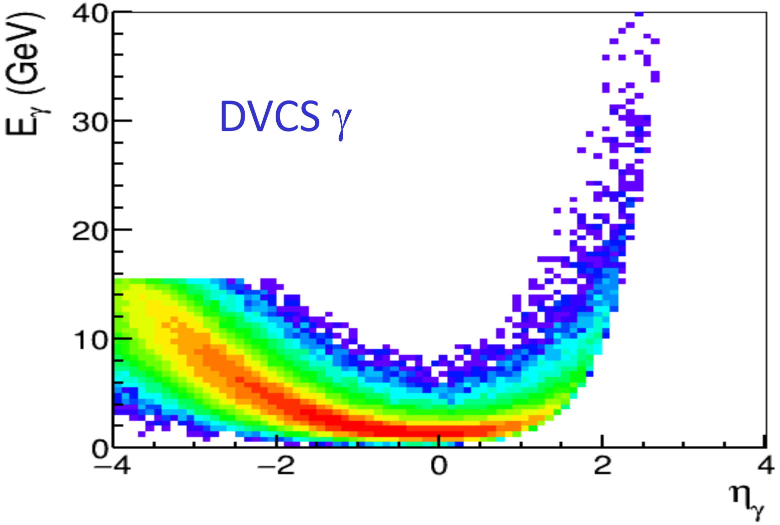
CORE Meeting

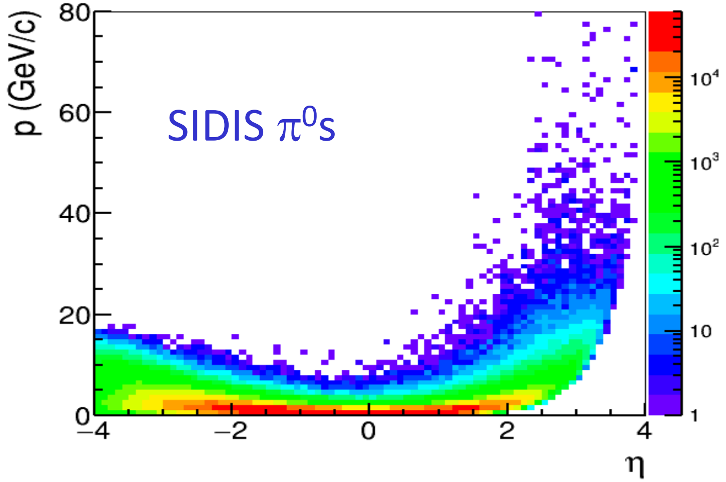
July 12, 2022

Introduction

The calorimetry requirements for EIC have not changed since the Yellow Report.







	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

Detector Technologies

The three initial proposals each selected different technologies for their central and forward calorimetry.

Forward Calorimeter Technology Choices

	EMCAL	HCAL
ATHENA	W/SciFi (similar to sPHENIX)	Fe/Scint (similar to STAR FCS)
ECCE	Pb/Shashlik	Fe/W/Scint Longitudinally Segmented (LFHCAL)
CORE	W/Shashlik	Fe/Scint (similar to STAR FCS)
Detector 1 (Recommended)	W/SciFi (ATHENA design)	Fe/W/Scint LFHCAL (ECCE Design)

Barrel EMCAL for Detector 1 is still currently SciGlass (ECCE).
Alternative is Pb/SciFi imaging design (ATHENA).

SciFi and Shashlik Technologies

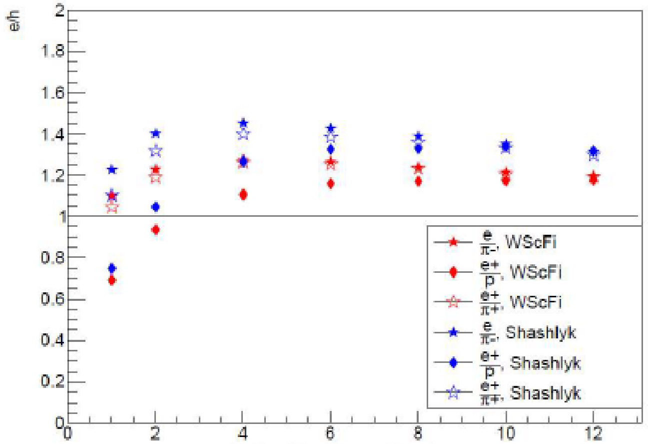
- Both technologies are very mature and have been used by a number of experiments.
- The energy resolution can be tuned by changing the sampling fraction and/or the sampling frequency.
- The absorber (e.g., W, Pb) can be selected to optimize the desired properties of the calorimeter (e.g., cost, compactness, degree of compensation w/HCAL,...). *Note: For EM calorimetry, the ability to use W absorbers in various forms allows for compact designs which utilize less space which is a prime consideration for EIC.*
- The readout in both cases can be done on the ends of the calorimeter (either the front or the back or both) which allows a variety of different geometrical configurations.

(a) ATHENA related work, Introductory detector -1 meeting

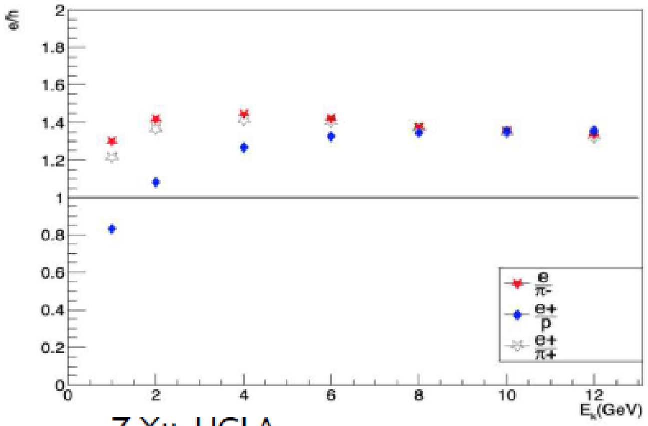
- $e/h \neq 1$
- $e/h\_ecal \neq e/h\_hcal$
- $e/h = f(E)$
- $e/p \neq e/\pi$
- $f_{em} = 0.11 \ln[E(GeV)]$

Jet energy resolution is always poorer than for a single hadron. Despite ~ 20% of jet energy (em) measured very accurately by Ecal.

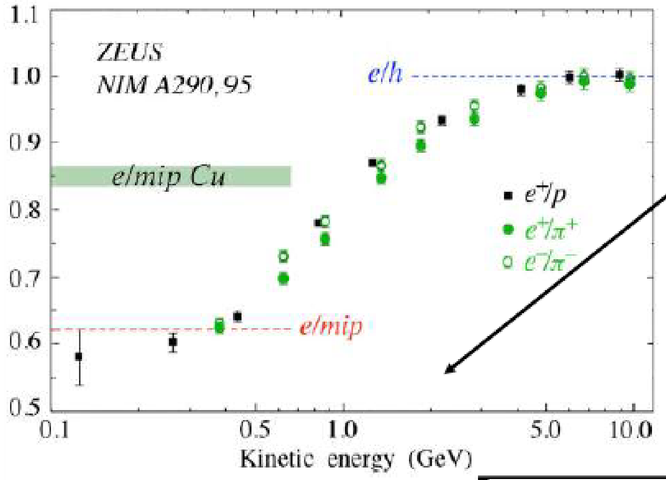
e/h for WScFi vs Shashlyk at 20 degree



e/h for Fe/Sc at 20 degree

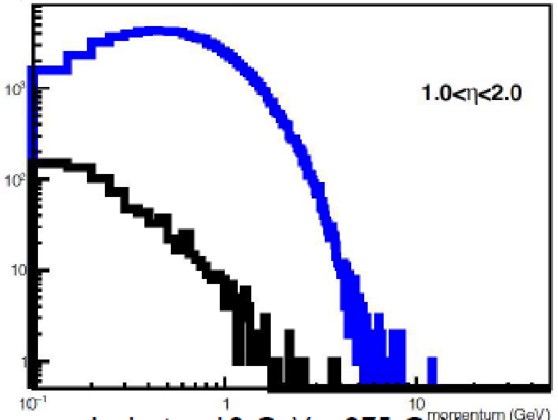


Z.Xu UCLA



EIC Calorimetry need measurements In this energy range.

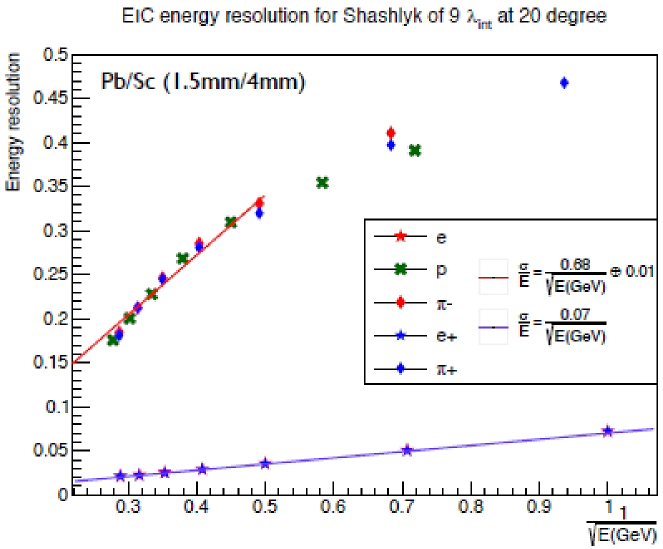
- ZEUS are experimental results
- eRD1 – GEANT4 with physics list validated for LHC (FTFP_BERT_HP).
- Validation of MC can be done only using experimental data form detector with correct chemical composition.

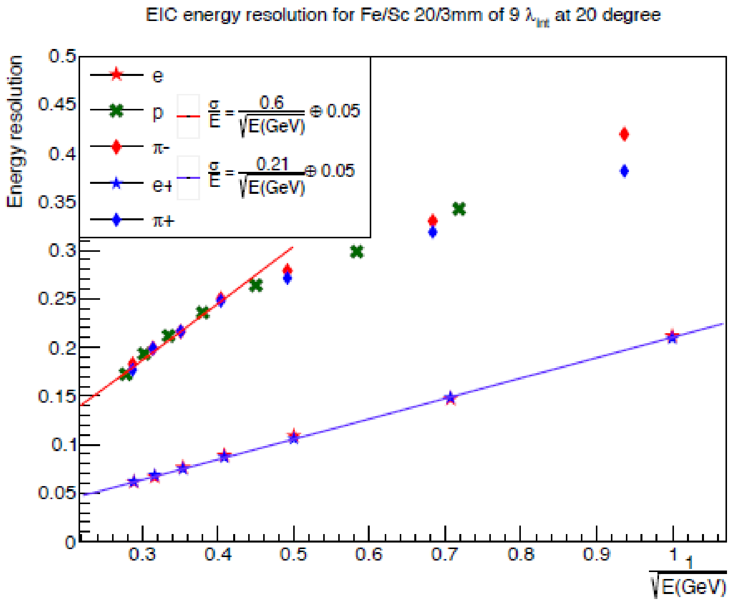


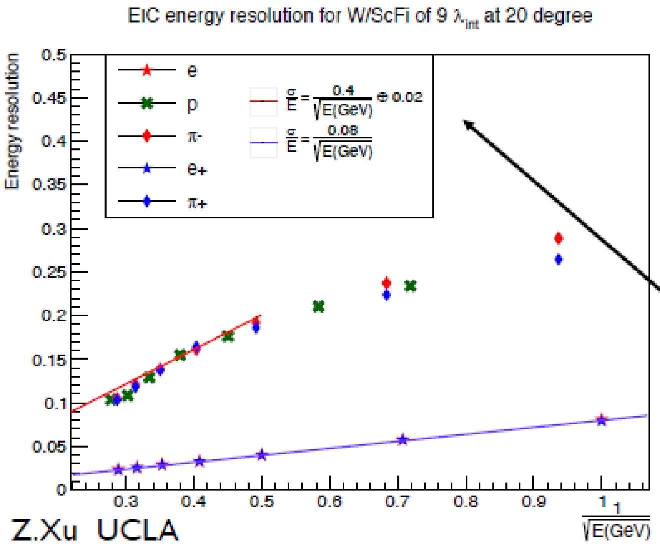
Inclusive, 18 GeV x 275 GeV

Oleg Tsai

(a) Introductory detector-1meeting, pECal, e/h







Z.Xu UCLA

Hypothetical variant, 9 interaction lengths long calorimeters. Same structure for Ecal and Hcal sections. Three different technologies:

- SHASHLYK (Phenix, STAR Forward)
- WScFi (STAR Forward 2014) – compensated
- Fe/Sc (STAR Forward 2020)

Proper detector composition required for good hadronic resolution. I.e. desired to keep e/h as close as practically possible to 1.

N.B. these are MC not an experimental results.

Shashlik Calorimetry for EIC

- Shashlik calorimetry was listed in the YR as one of the possible technologies for EIC over a wide range of rapidities ($-2.0 < \eta < 4.0$)
- Shashlik calorimetry is a mature technology but most shashlik calorimeters that have been built so far have used 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, either longitudinally along the beam direction or radially in the central barrel.
  - The R_M of W is much smaller than for Pb and the showers will be much smaller and therefore have less overlap with neighboring showers.
    (Improves 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.

PHENIX Pb/Shashlik

Designed for heavy ion collisions
5.535 x 5.535 cm^2 towers $\Rightarrow$ $\Delta\eta$ =0.01, $\Delta\phi$ = 0.01 at R = 5 m
X0 = 2.1 cm, R_M ~ 5 cm
Total absorber depth = 37.5 cm (18 X0, 0.85 λ_{int})

3888 modules $\Rightarrow$ 15,552 towers total

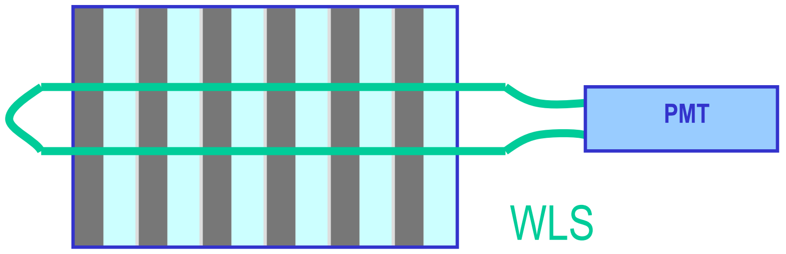
Resolutions

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

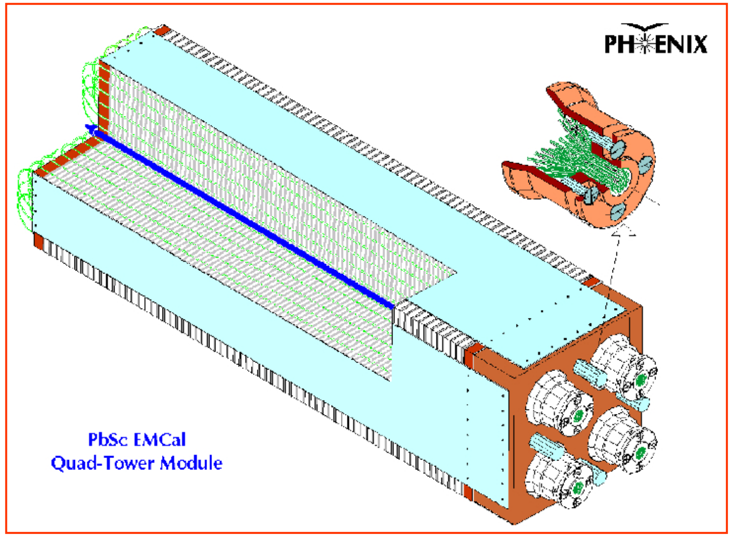
$$\sigma_t \sim 200ps$$

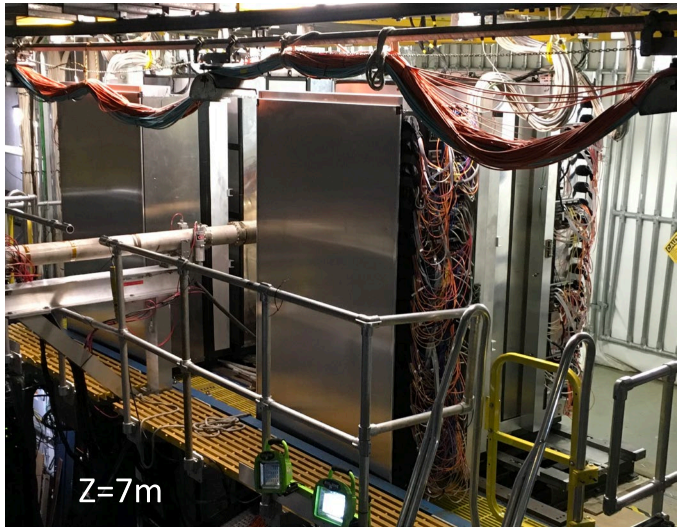
1500 modules now deployed in STAR FCS w/ SiPM readout

Pb (1.5 mm) Scint (4 mm) 66 layers (18 X_0)



Light Yield ~ 1.5 p.e./MeV





KOPIO Pb/Shashlik Prototype

Development of Shashlyk calorimeter for KOPIO

G.S. Atoian[a,b], V.V. Issakov[a,b], O.V. Karavichev[a], T.L. Karavicheva[a],
A.A. Poblaguev[a,b,*], M.E. Zeller[b]

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[b] Physics Department, Yale University, New Haven, CT 06511, USA

Nuclear Instruments and Methods in Physics Research A 531 (2004) 467–480

Can achieve very good energy resolution !

$$\frac{\sigma_E}{E} = (0.1 \pm 0.8)\% \oplus \frac{(3.8 \pm 0.1)\%}{\sqrt{E}} \oplus \frac{(0.8 \pm 0.6)\%}{E},$$

$$0.5 < E < 2.0,$$

Table 1
Parameters of the prototype Shashlyk module for KOPIO

Transverse size	110×110 mm^2
Number of the layers	240
Polystyrene scintillator thickness	1.5 mm
Lead absorber thickness	0.35 mm
Reflective paper (TYVEK) thickness	2×0.06 mm
Number of holes per layer	12×12
Holes spacing	9.5 mm
Holes diameter in scintillator/lead	1.4/1.5 mm
WLS fibers per module	72×1.3 m ≈ 92 m
Diameter of WLS fiber	1.0 mm, (1.2 mm)
Diameter of fiber bundle	14 mm, (17 mm)
Effective radiation length X_0	31.5 mm
Effective Molière radius R_M	54.9 mm
Effective density	2.75 g/cm^3
Active length	473 mm ($15.9 X_0$)
Total length (without photo-detector)	610 mm
Total weight	18.0 kg

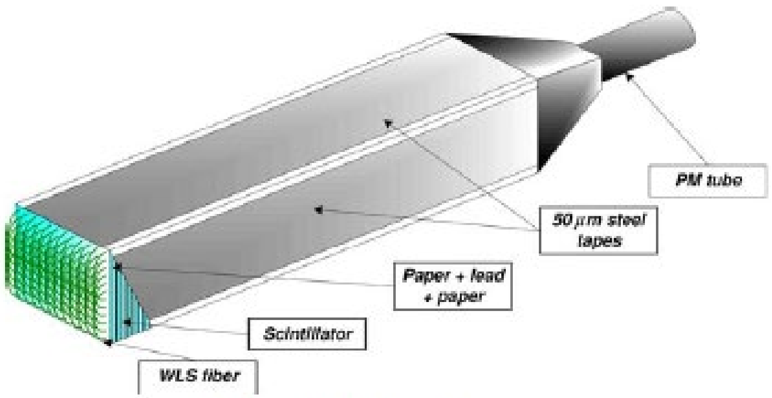
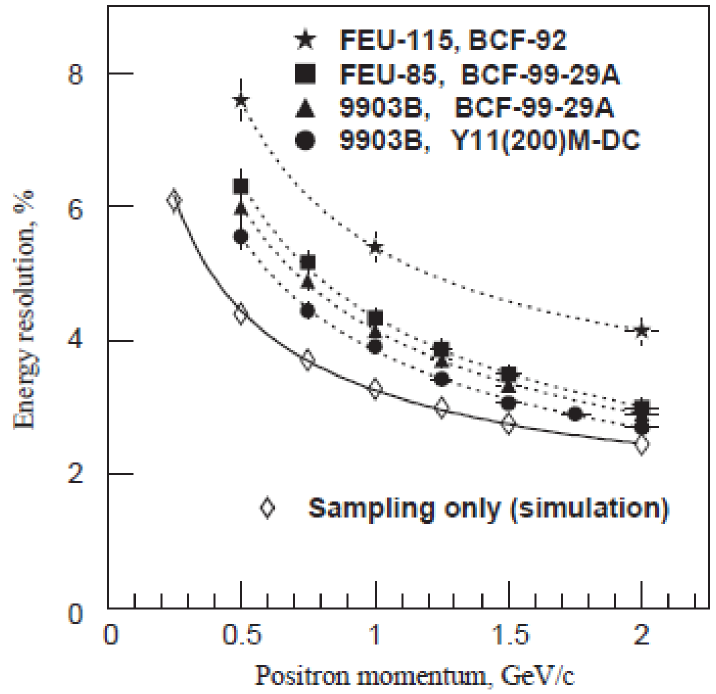
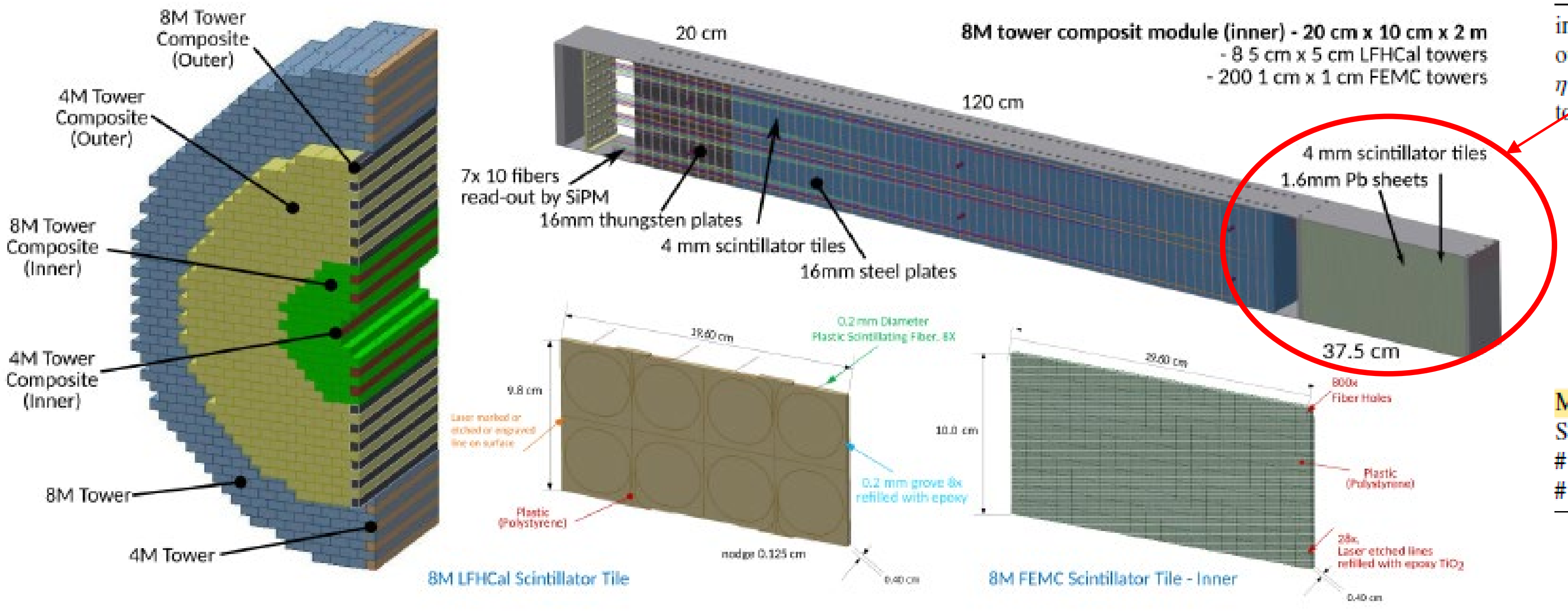


Fig. 1. Shashlyk module design.



ECCE FEMC & LFHCAL

Note: Tower size << R_M



parameter	FEMC	LFHCAL
inner radius (envelope)	17 cm	17 cm
outer radius (envelope)	170 cm	270 cm
η acceptance	$1.3 < \eta < 3.5$	$1.2 < \eta < 3.5$
tower information		
x, y (R </> 0.8 m)	1 cm/ 1.65 cm	5 cm
z (active depth)	37.5 cm	140 cm
z read-out	5 cm	20 cm
# scintillor plates	66 (0.4 cm each)	70 (0.4 cm each)
# aborber sheets	66 (0.16 cm Pb)	60 (1.6 cm steel)
	Similar to PHENIX	10 (1.6 cm tungsten)
weight	~ 6.4 kg	~ 30.6 kg
radiation lengths	18.5 X/X_0	? X/X_0
interaction lengths	? λ/λ_0	6.9 λ/λ_0
Molière radius R_M	5.2 cm ($e^{\pm}$ shower)	21.1 cm ($\pi^{\pm}$ shower)
Sampling fraction f	0.220	0.040
# towers (inner/outer)	19,200/ 34,416	9040
# read-out channels	53,616	7 x 9,040 = 63,280

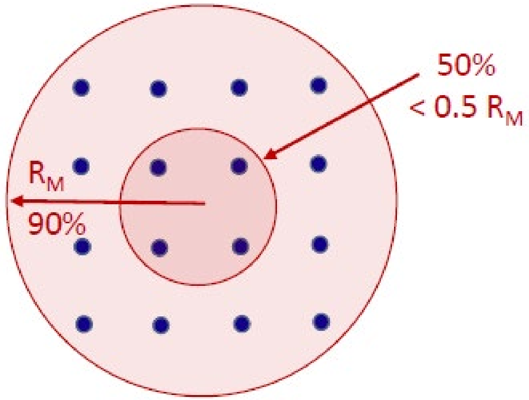
Reasons for Det-1 Choosing W/SciFi over Pb/Shashlik

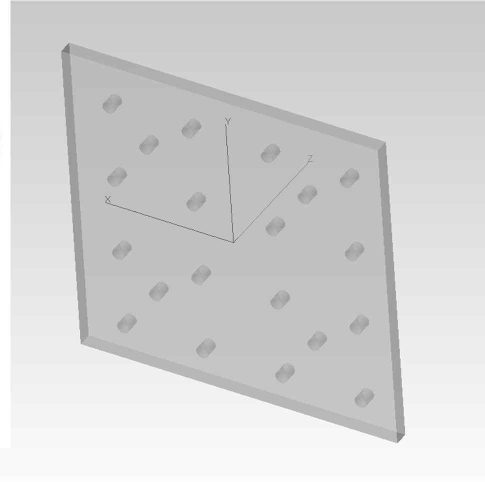
- Ease of construction
- Less space needed for W/SciFi and better shower containment
- Costs comparable given unavailability of scintillator tiles from Uniplast and smaller calorimeter dimensions

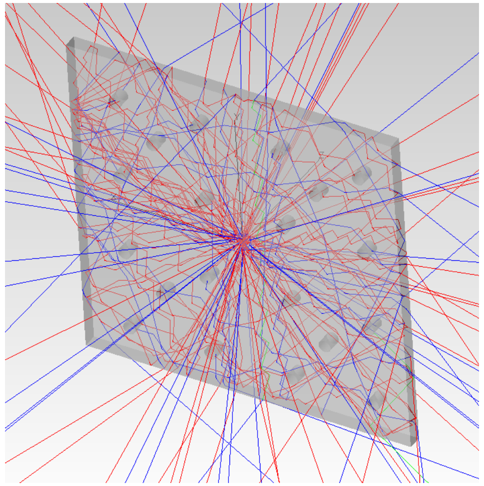
Improving Shashlik Spatial Resolution

- The availability of low cost SiPMs allows the possibility of reading out *each fiber individually.* This allows determining the shower position even within a Moliere radius.

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

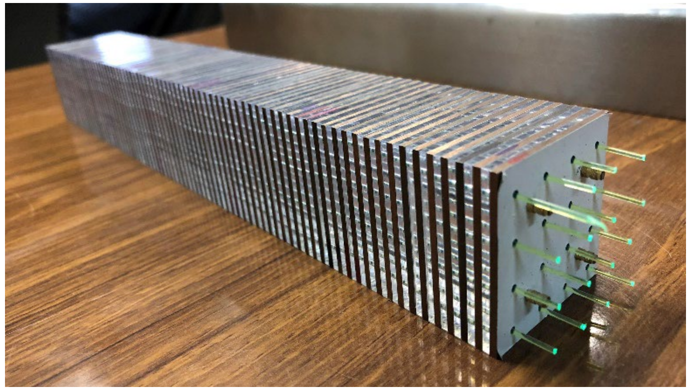
- Non-uniformities of light collection within a tile will cause a position dependence. However, this can in principle be corrected for using lab measurements and ray tracing can produce a light collection map for each fiber.

Prototype W/Shashlik EMCAL

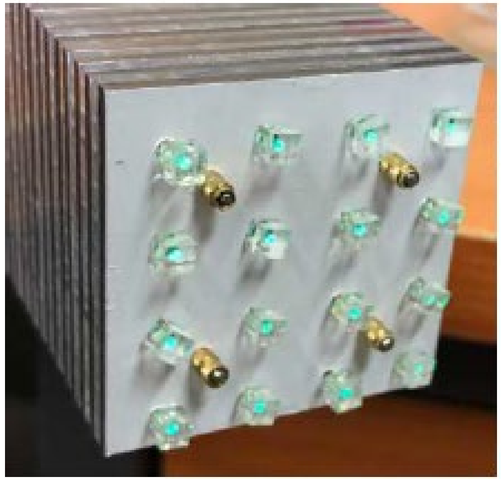
Originally designed for the NA64 Experiment at CERN (not optimized for EIC)

Andres Bello University
Santiago, Chile
S. Kuleshov

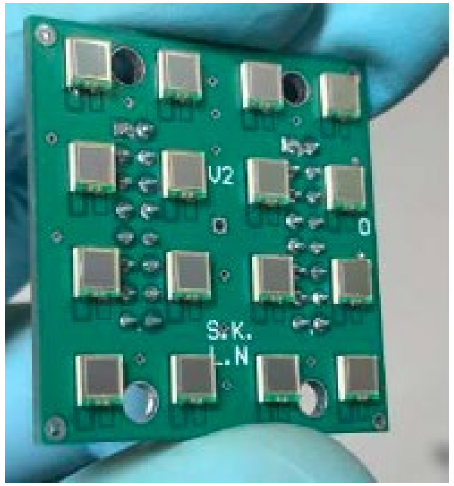
- Absorber plates are a W(80%)/Cu(20%) alloy that is easily machinable
  ρ = 17.2 g/cm^3, X0 = 4.1 mm, 38 x 38 x 1.58 mm^3
- Scintillating tiles: 38 x 38 x 1.63 mm^3 injection molded polystyrene (Uniplast, Russia).
- 1 mm dia WLS fibers spaced on a 9.5 x 9.5 mm^2 grid
- 80 sampling layers, X0 = 8.5 mm, Total ~ 31 X0 (27 cm), R_M ~ 2.5 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

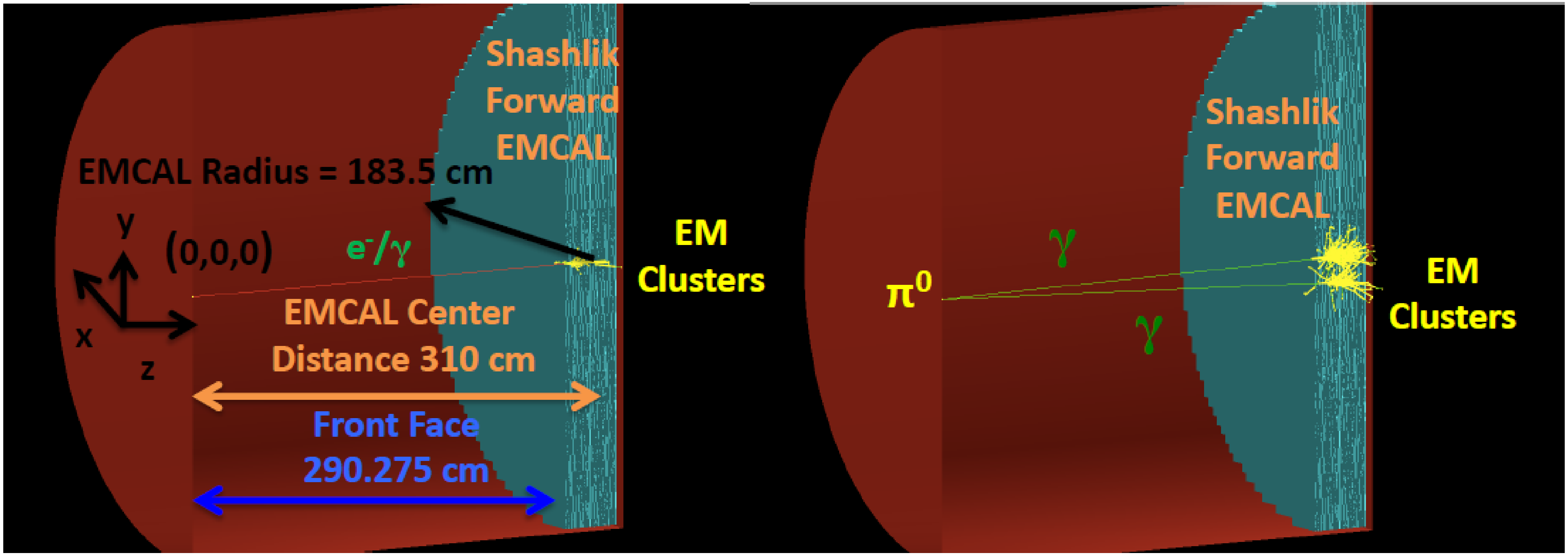


Hamamatsu S14160-3015P

3x3 module prototype

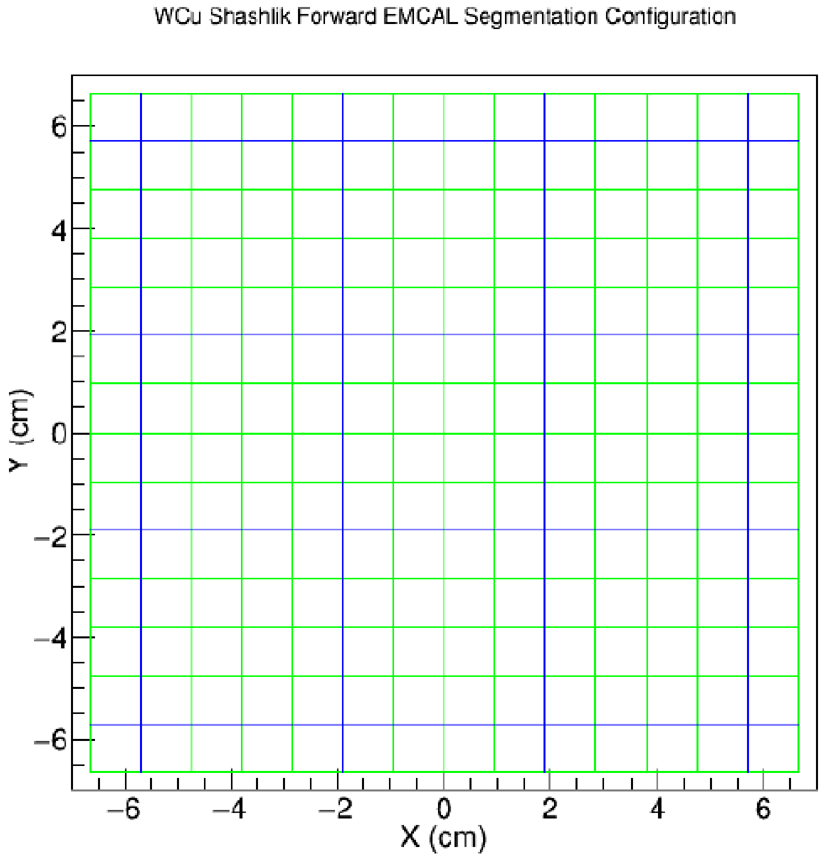
Shashlik GEANT Simulations

Z. Shi (LANL/MIT)
I. Delk (ISU)

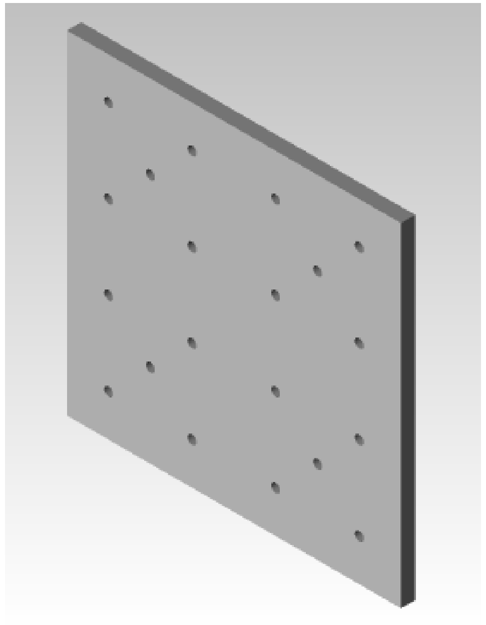


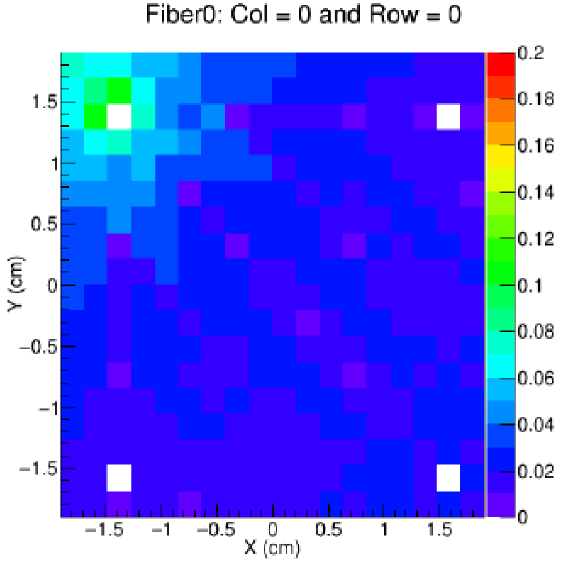
W/Cu Shashlik

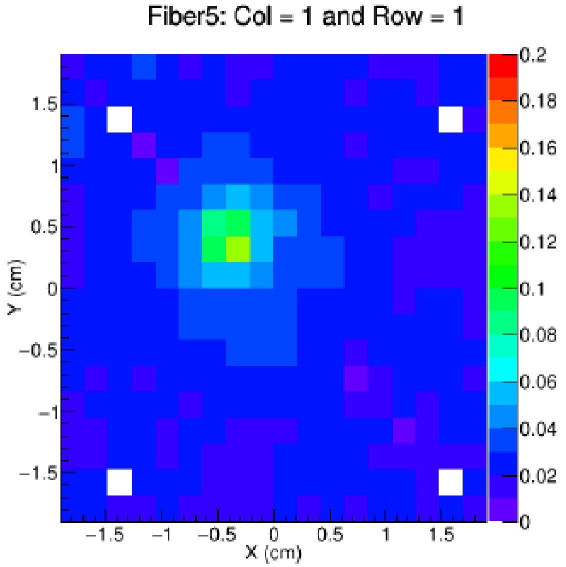
TracePro Ray Tracing
Light Collection Simulation



Z. Shi (LANL/MIT)
I. Delk (ISU)



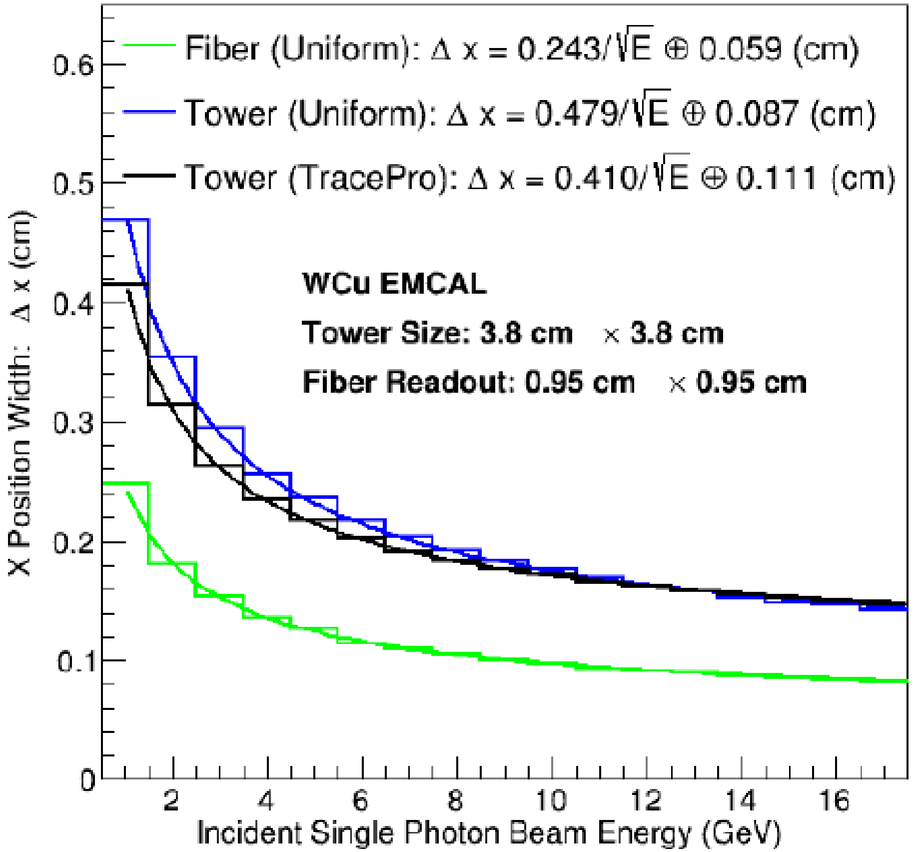


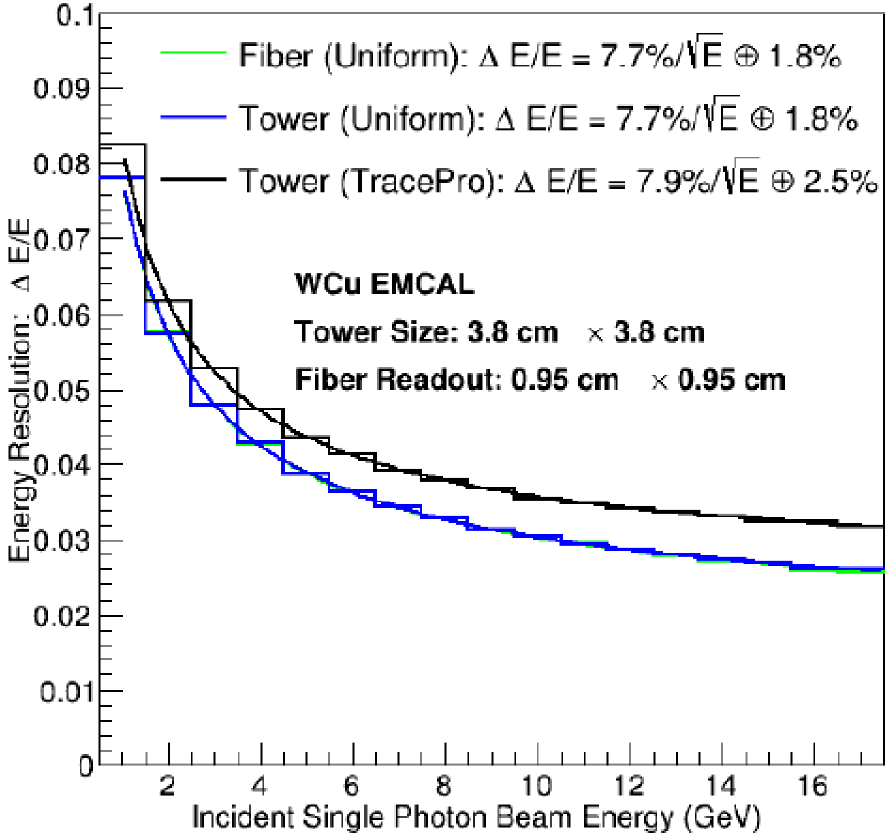


- Individual fiber readout in green and EMCAL tower (16 fibers) in blue
- Tower size 3.8 cm × 3.8 cm with 4 × 4 fiber readout (0.95 × 0.95 cm)

W/Cu Shashlik – Position and Energy Resolution

Effect of light collection map





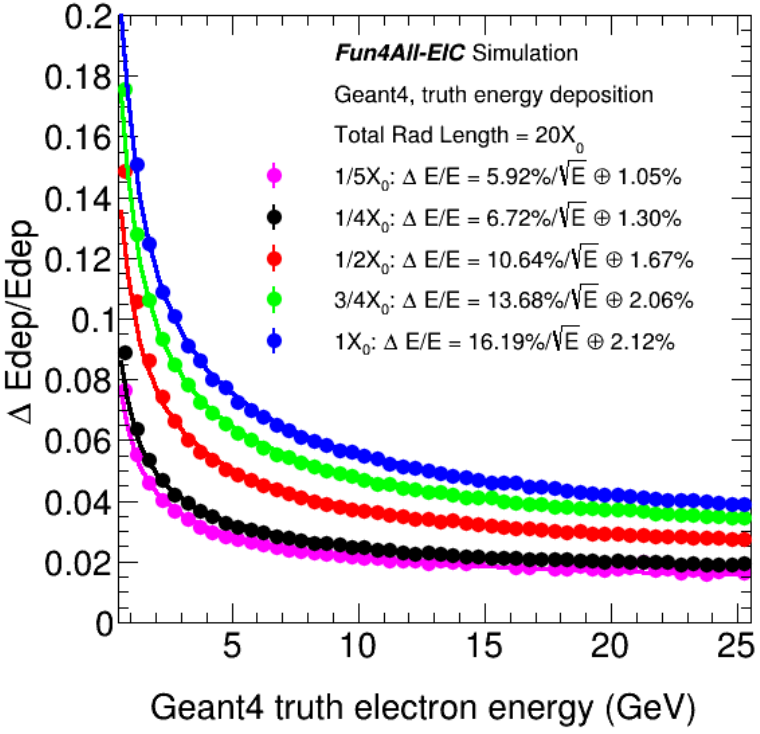
Non-uniformity of light collection efficiency map

- Improves the position measurement
- Slightly worsens the energy resolution

Z. Shi (LANL/MIT)

EMCAL Shashlik Calorimetry – Pb vs W

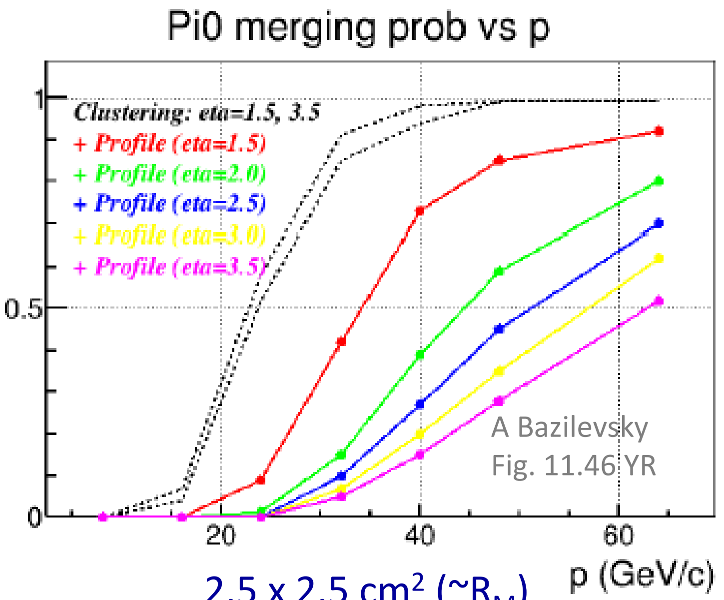
Energy resolution vs sampling fraction
20 X0 total length (L ~ 30 cm w/readout)



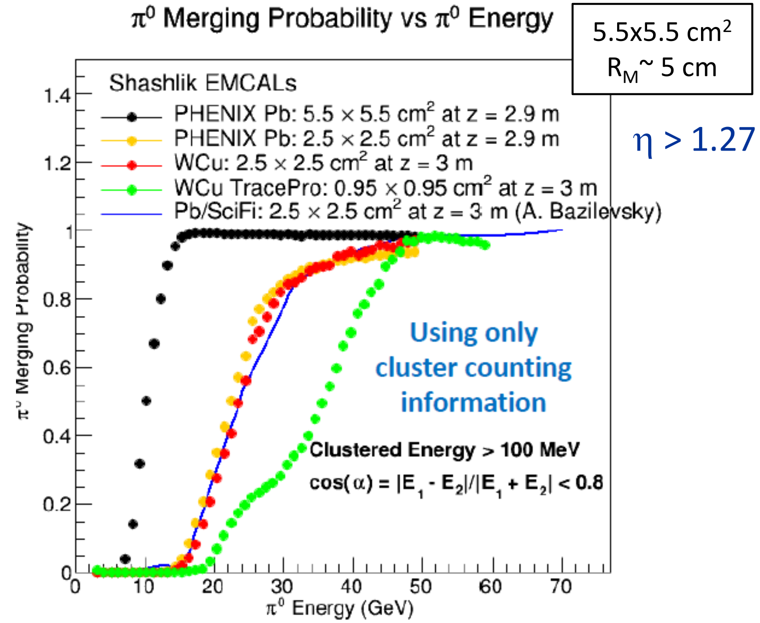
W Shashlik
(Z.Shi Fig. 11.55 YR)

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

Non projective geometry



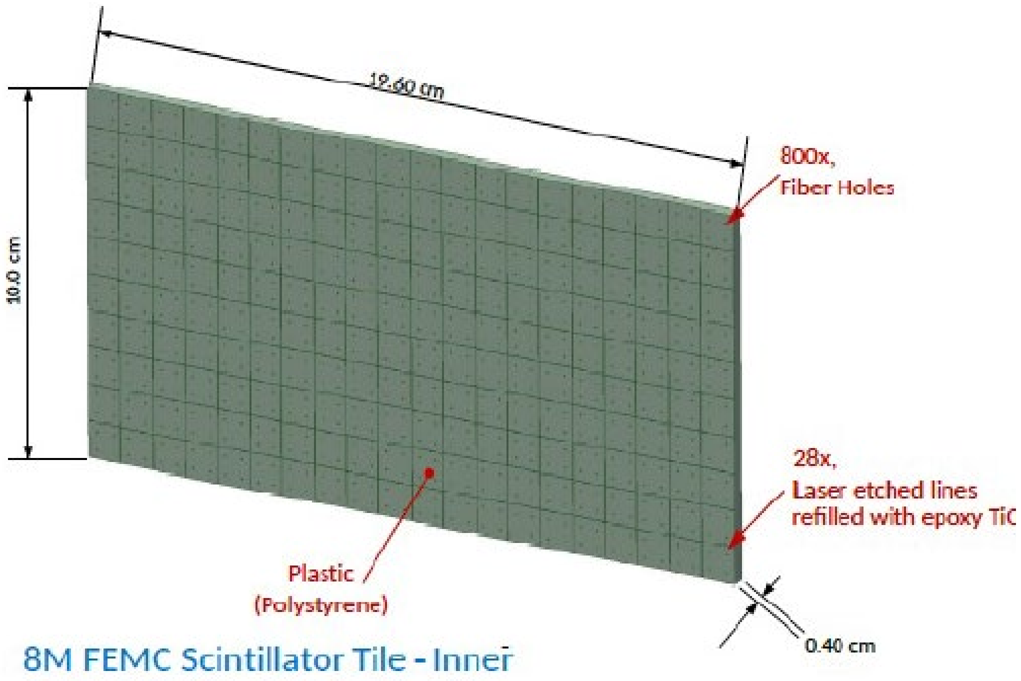
$2.5 \times 2.5\ cm^2$ (~R_M)

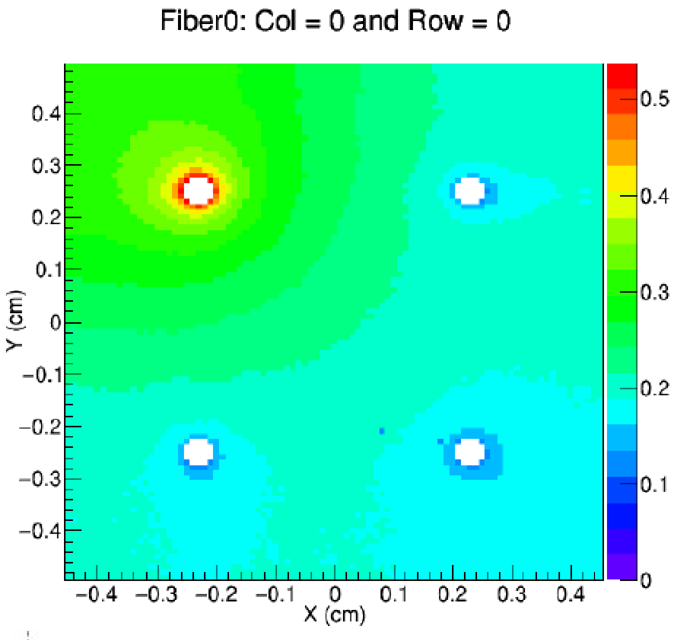


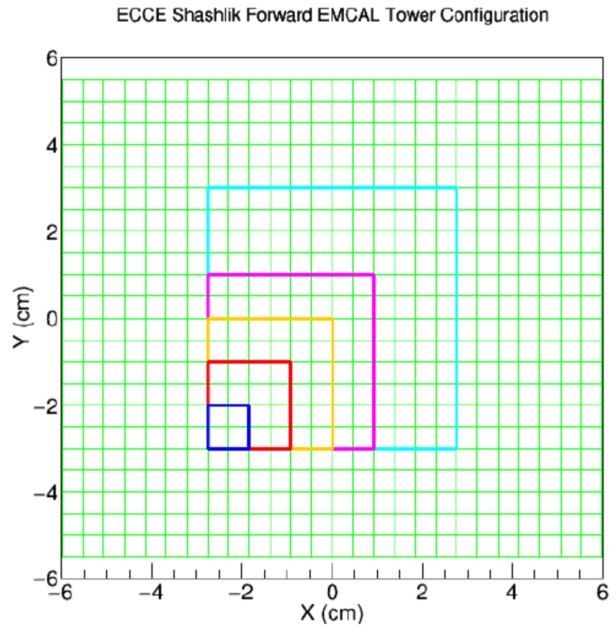
Note:

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

ECCE Pb/Shashlik Simulations







Study effect of changing the readout segmentation

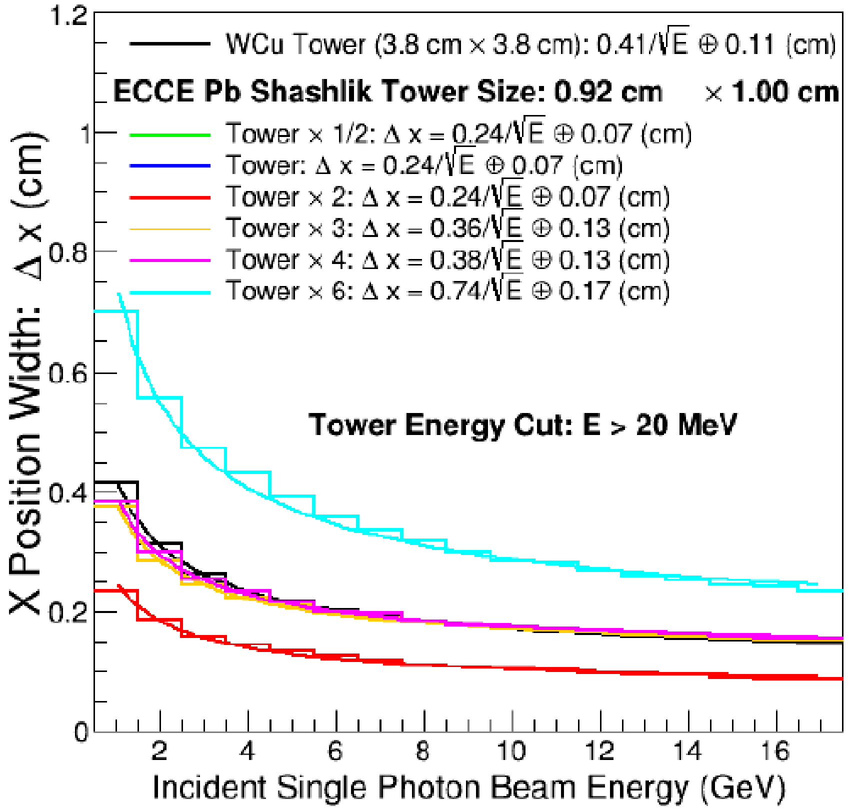
Each green box is a single fiber readout (Tower × ½) (0.49 x 0.50 cm)
Each blue box is an optically isolated EMCAL tower containing 4 fibers (0.98 x 1.00 cm)
The red, orange, magenta, and cyan boxes define Tower × 2, Tower × 3, Tower × 4, and Tower × 6

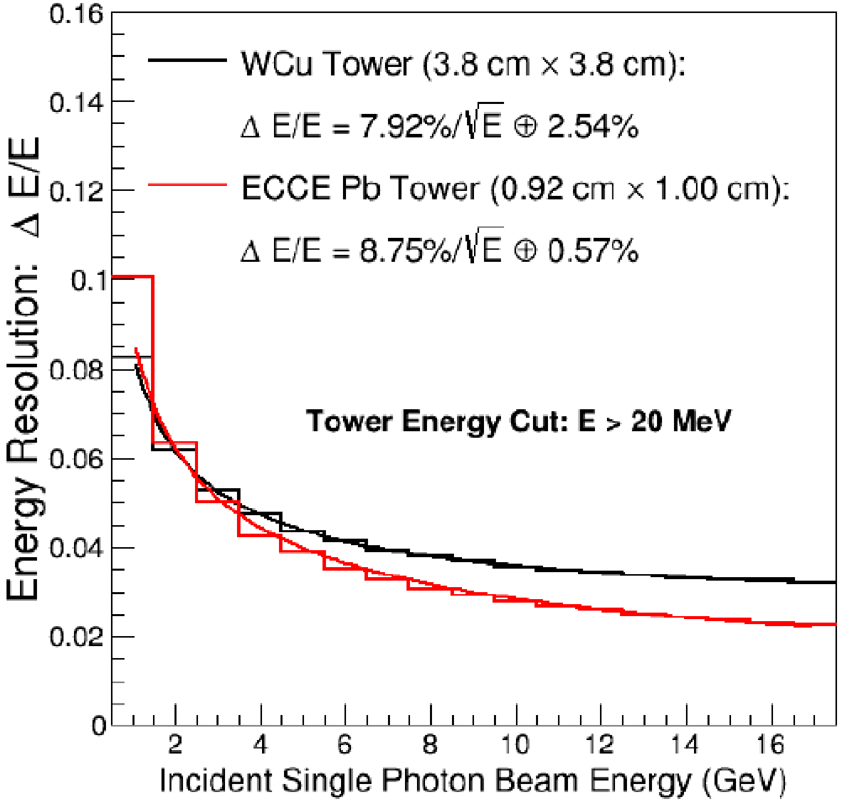
Note difference in definition of “tower” for ECCE vs W/Cu prototype

Z. Shi (LANL/MIT)

ECCE Pb/Shashlik EMCAL

Effect of Changing Readout Segmentation





Z. Shi (LANL/MIT)
(to appear in DIS 2022 Proceedings)

- No change in position resolution up to Tower x 2 (~ 2x2 cm^2)
- Same as W/Cu shashlik at ~ 4x4 cm^2 segmentation
- Constant term in energy resolution for WCu is slightly worse due to non-uniformity of light collection

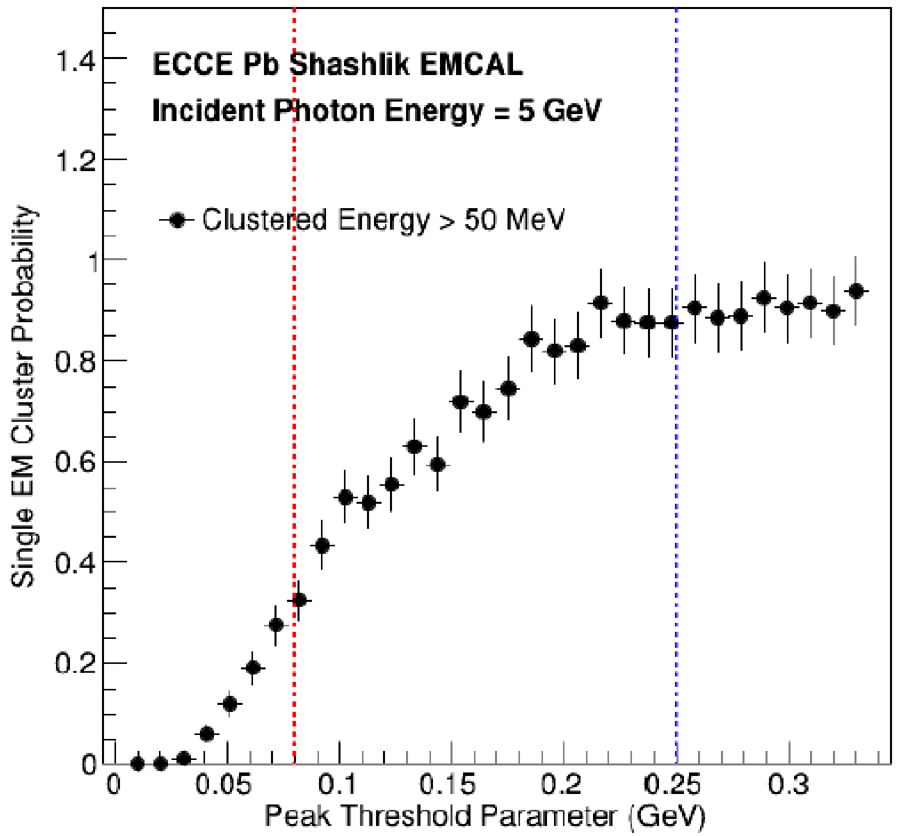
Summary & Conclusions

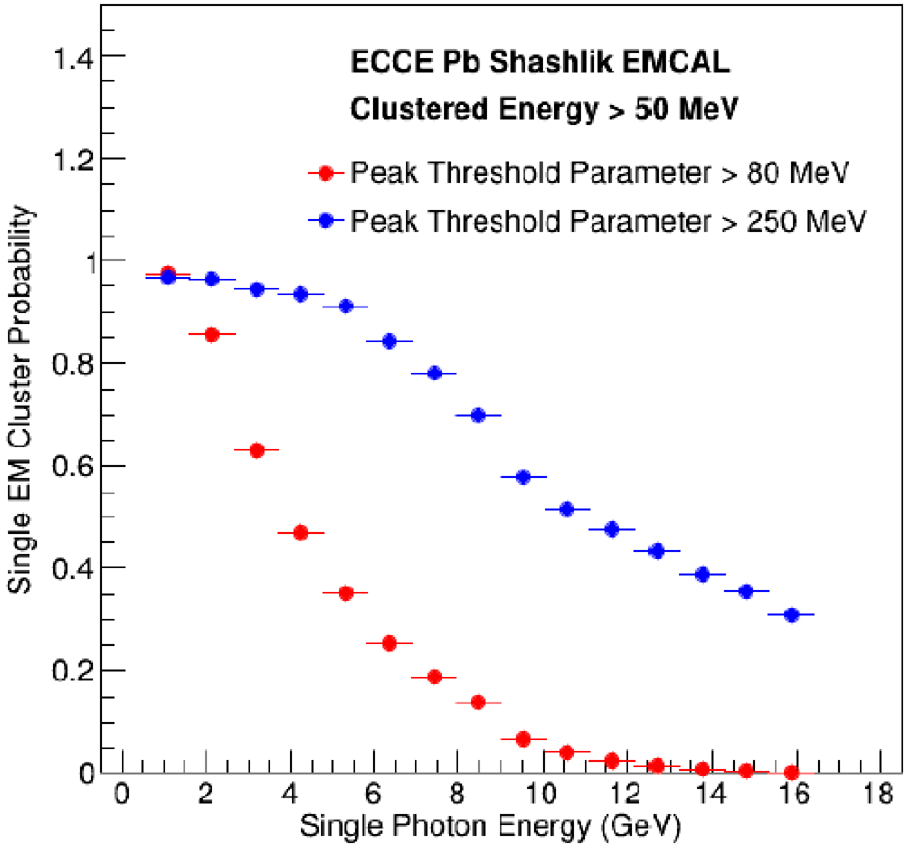
- A shashlik EMCAL can be designed to meet the physics requirements at EIC, both in the forward region and in the barrel. This can be achieved with both Pb and W absorbers.
- The use of a W absorber will make the calorimeter more compact, thus saving space and producing smaller shower sizes, but W is more expensive and difficult to work with. However, a W absorber may provide the best ultimate performance in terms of γ/π^0 and e/h separation at high p_T.
- The potential cost savings of obtaining scintillating tiles as final detector components from Uniplast is no longer a viable option. Therefore, the cost advantages of a shashlik over a SciFi design are greatly diminished.
- Designing and constructing a projective shashlik calorimeter is going to be more difficult and more costly than a SciFi design.

Backup

Cluster Algorithm

As a first step, apply the cluster finding algorithm developed for PHENIX (HI collisions) to forward EMCAL
Apply cuts on total cluster energy and peak threshold for finding separate clusters

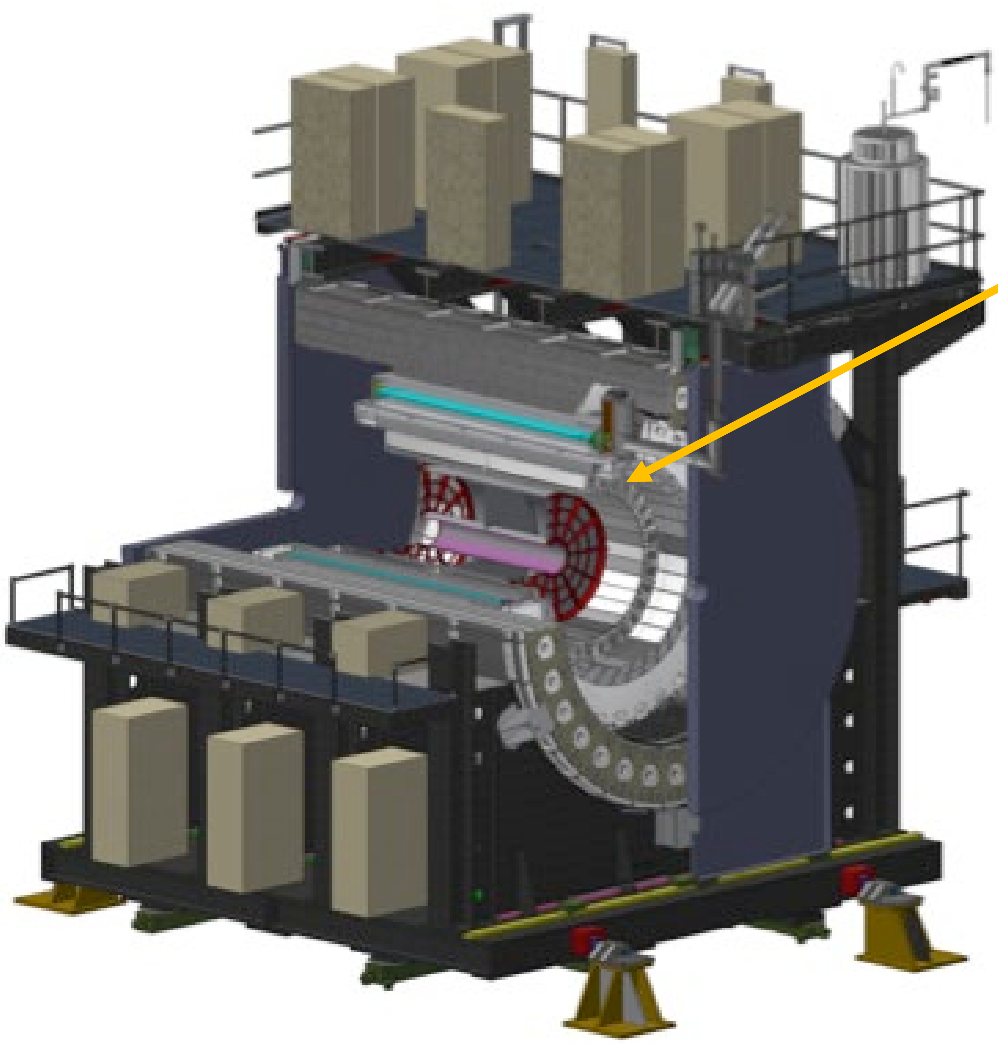


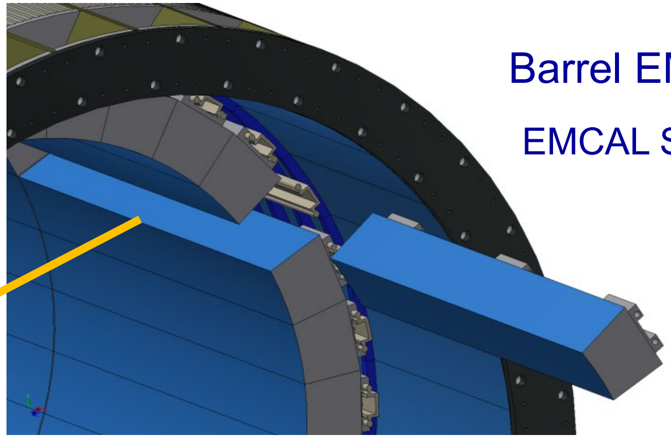


Obviously needs work in order to adapt algorithm for Forward EMCAL

Z. Shi (LANL/MIT)

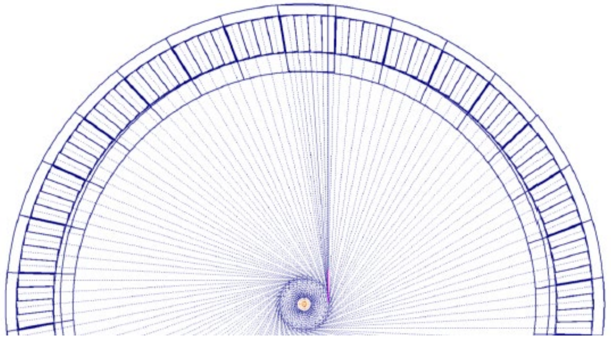
sPHENIX W/SciFi EMCAL



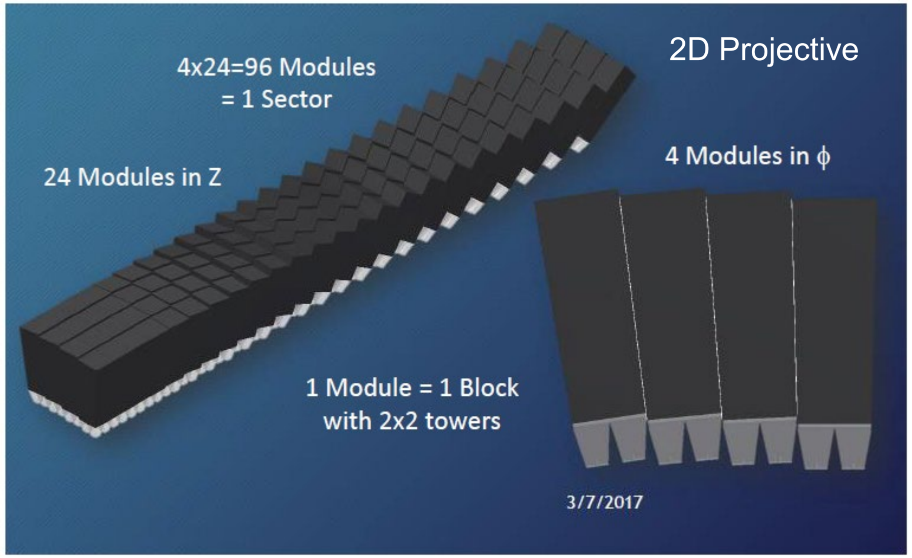


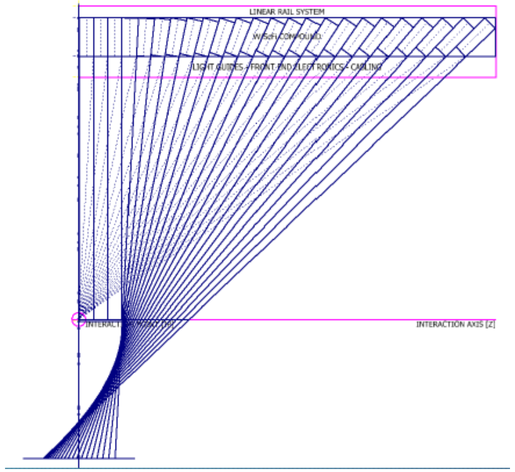
Barrel EMCAL

EMCAL Sector



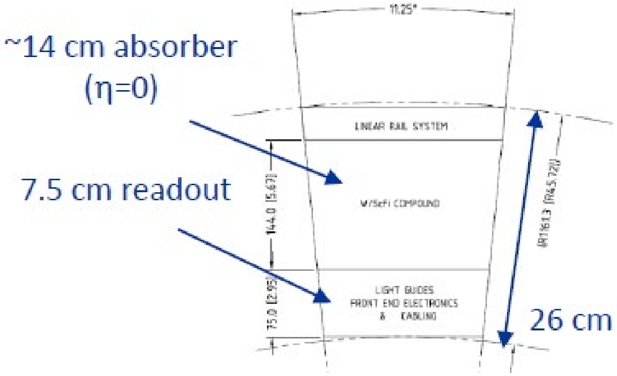
$2(\pm\eta) \times 32\ (\phi) = 64$ Sectors





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

sPHENIX W/SciFi EMCAL



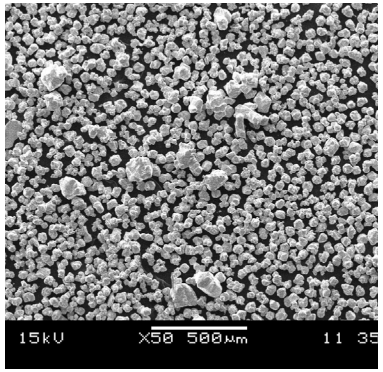
- The sPHENIX EMCAL is a W/SciFi SPACAL consisting of a matrix of tungsten powder and epoxy with embedded scintillating fibers
  - 0.47 mm dia. fibers, spacing 1 mm, SF ~ 2%
  - Density ~ 9.0 g/cm^3, X0 = ~ 7 mm, ~ 20 X0 total, R_M ~ 2.3 cm
- W/SciFi modules consist of 4 towers, each with its own light guide that is read out on the front with a 2x2 array of 3x3 mm^2 SiPMs (Hamamatsu S12572-015P)

SiPMs are susceptible to radiation and will receive a dose ~ 10^{11} n/cm^2 over the currently 3 yr lifetime of sPHENIX

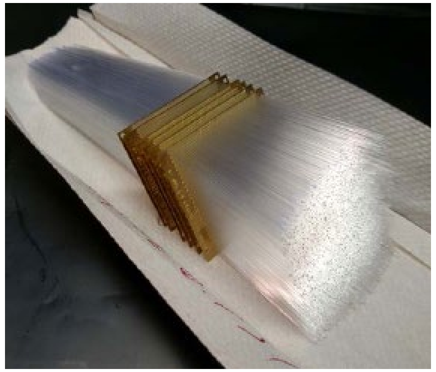
Modules will be re-instrumented with new SiPMs for EIC

6144 Modules (24,576 towers)

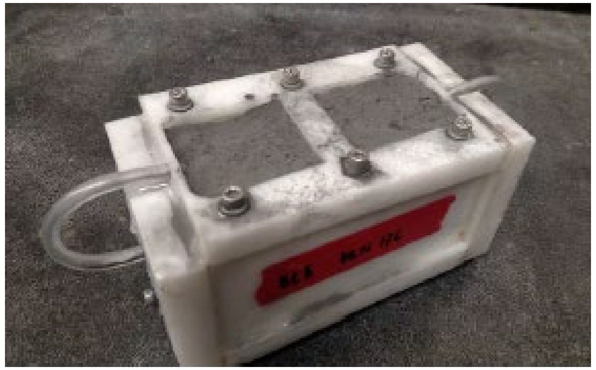
W Powder ~ 50 μm

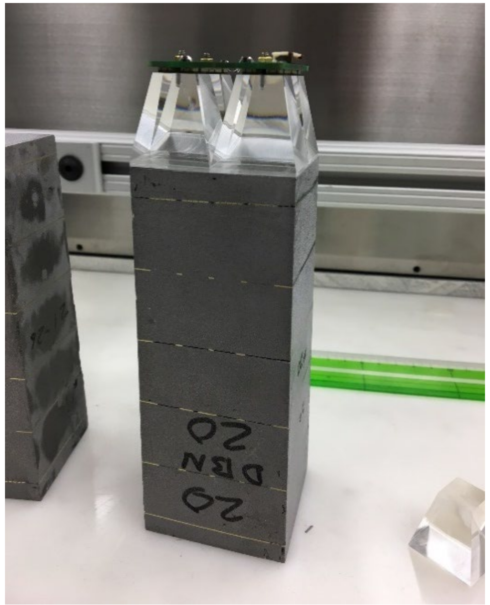


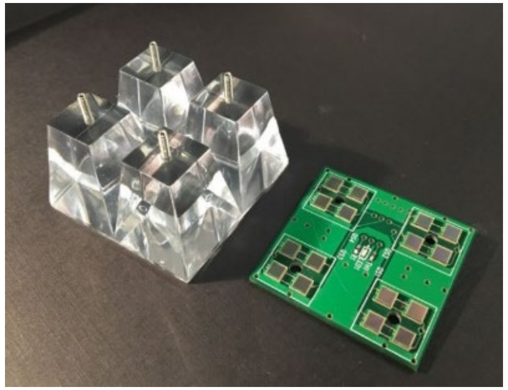
Fiber Assembly



Mold with W powder, fibers + epoxy







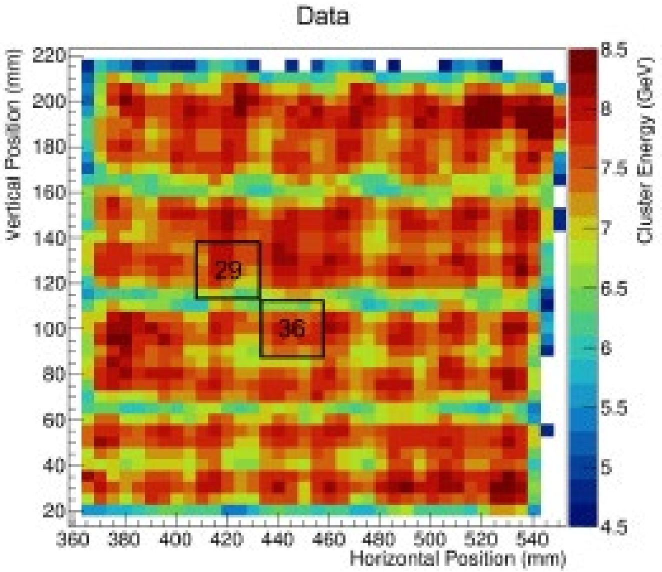
Readout with light guides and SiPMs

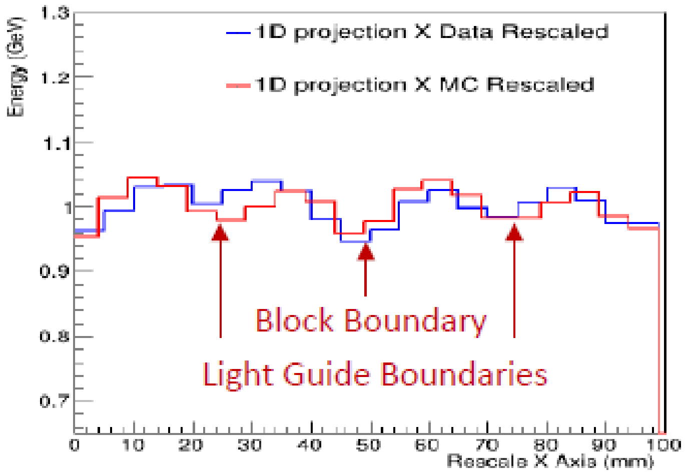
(~ 100K SiPMs)

Uniformity of W/SciFi - Effect on Energy Response

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

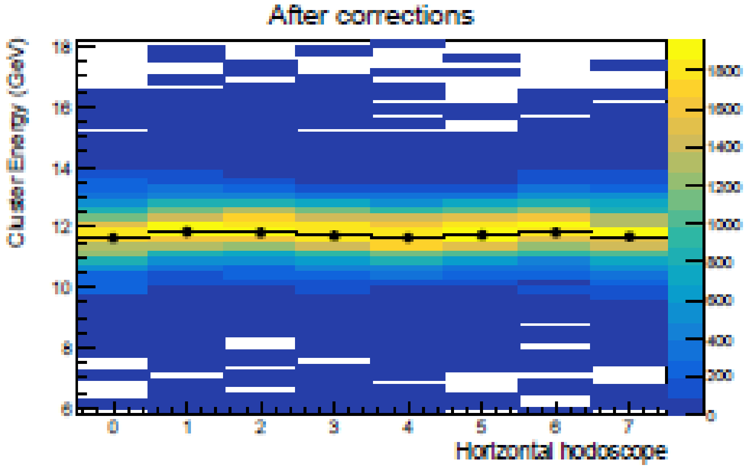
Uniformity of response over 8x8 towers with 8 GeV electrons (Test Beam Data)

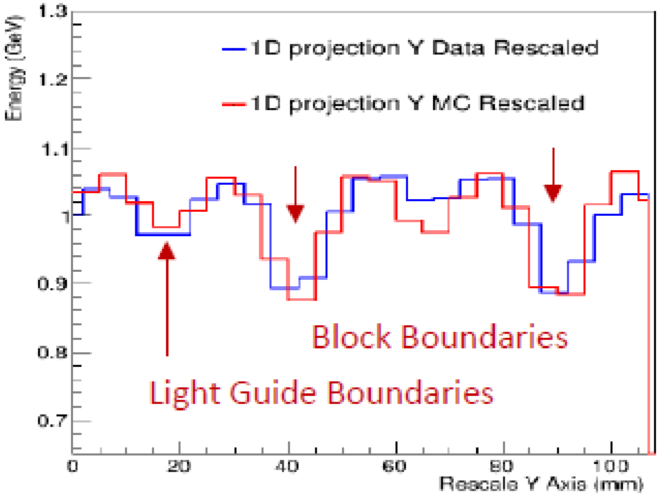




X axis projection

Uniformity after position dependent correction



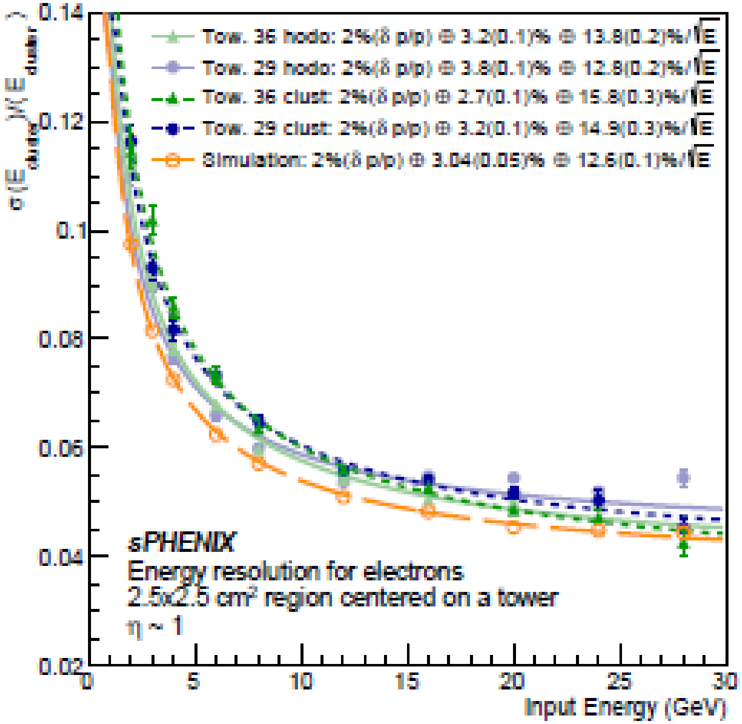


Y axis projection

Energy Resolution

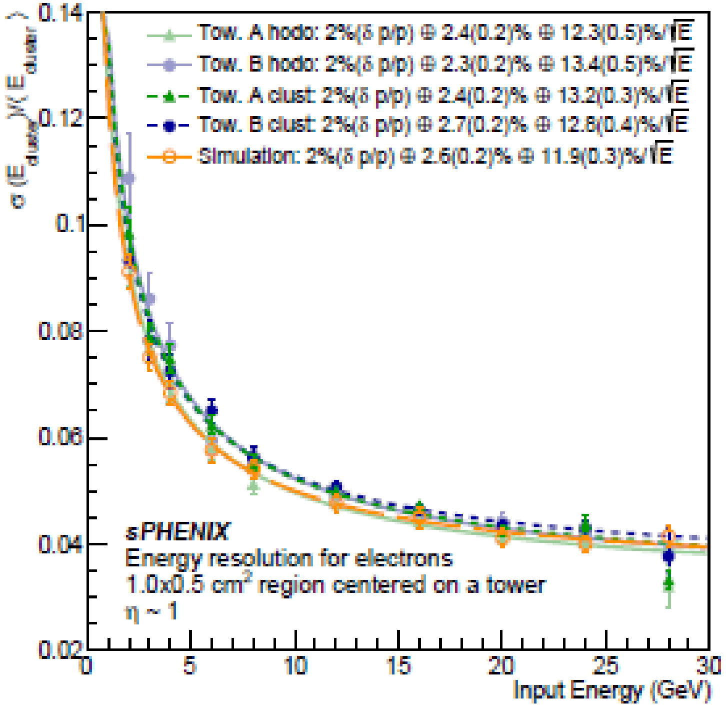
Energy resolution after position dependent correction

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



Resolution ~ (13-15)%/√E ⊕ 3%

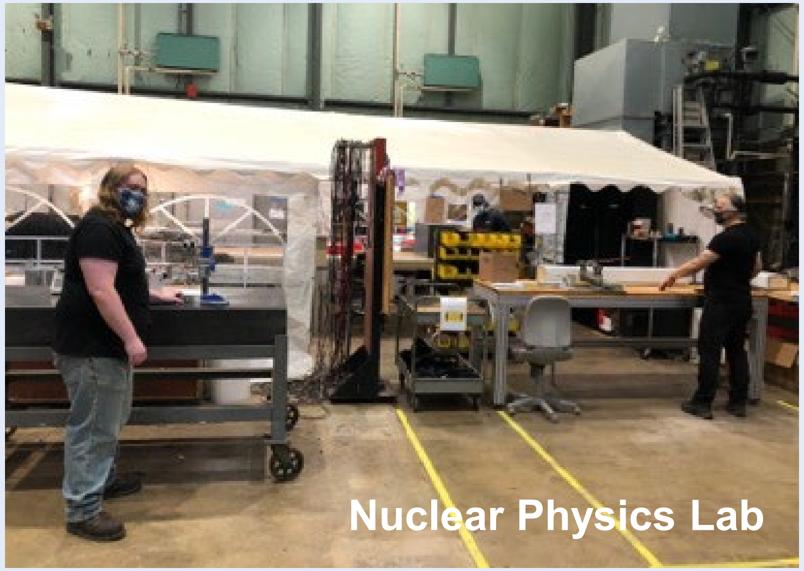
Beam covering a 1.0 x 0.5 cm^2 area centered on a tower

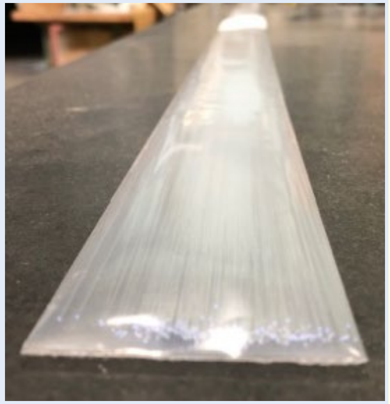


Resolution ~ (12-13)%/√E ⊕ 2.5%

sPHENIX EMCAL – Completed June 2022 – Installation Begins July 2022

Block Production at UIUC (also at Fudan U, PKU & CIAE)



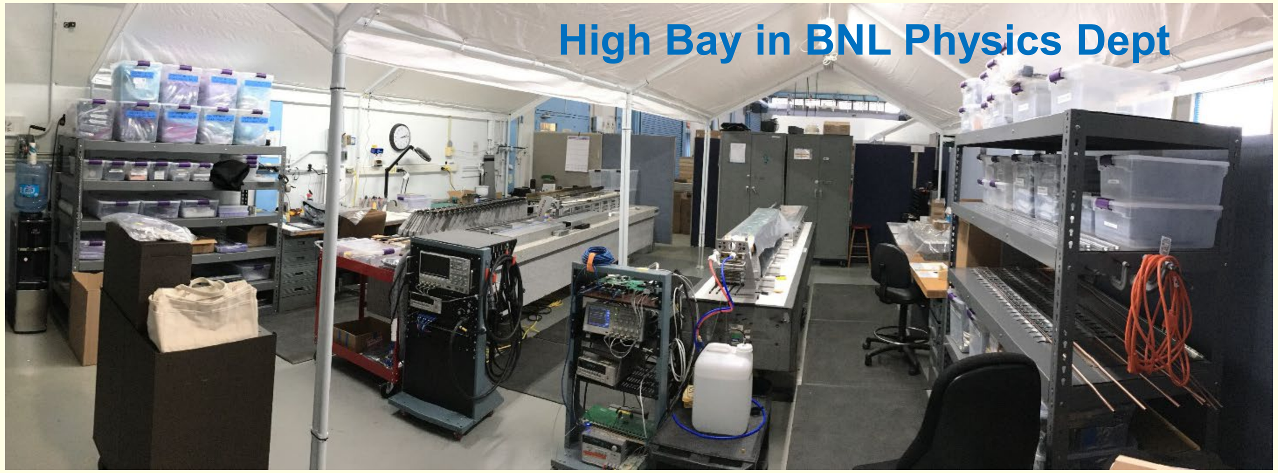


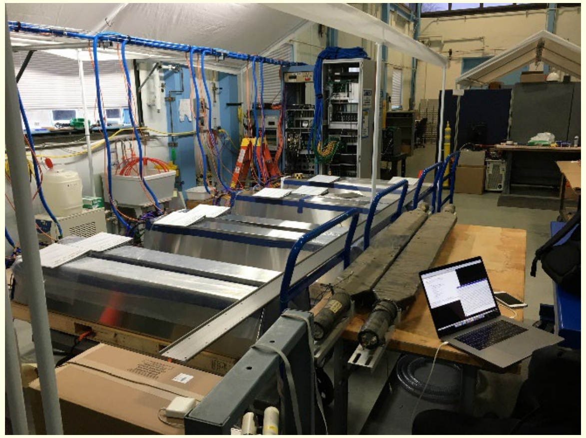
2600 km of fiber
665 kg of epoxy
88 m^2 of screens

20 Tons of W powder

Blocks awaiting removal from molds

Module and Sector Production at BNL





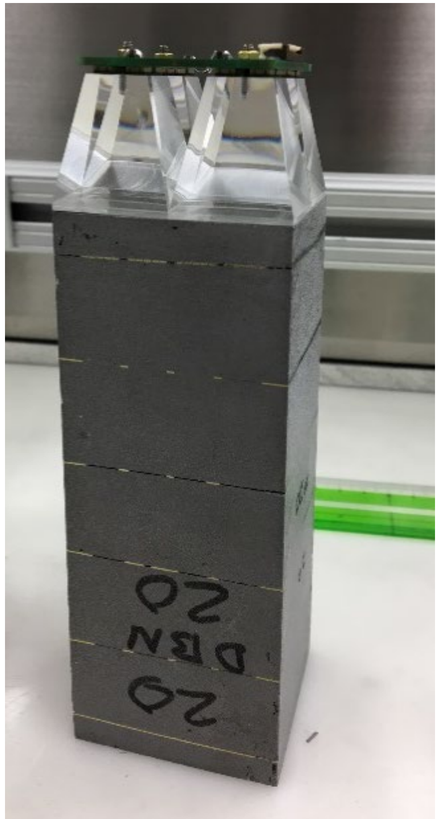
Sector Burn-in and Testing

Modules being
glued into sectors

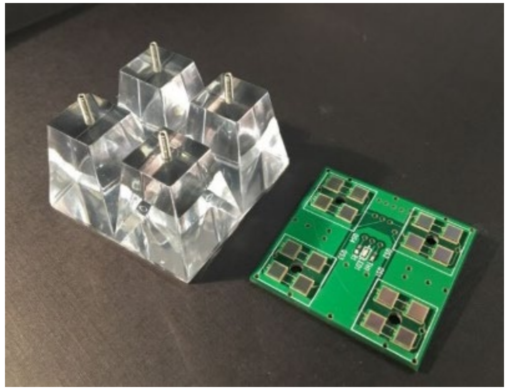
Future Developments for W/SciFi Calorimetry

We believe we can improve the light output, energy resolution and uniformity of response of the sPHENIX calorimeter by increasing the photocathode coverage for the readout of the absorber blocks.

Light output from fibers is very uniform but light collection efficiency is low (~ 6 %)



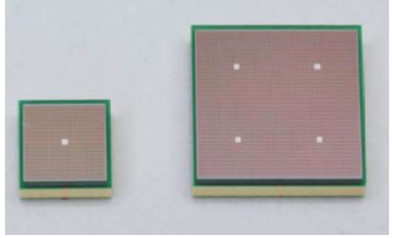
Readout end of block

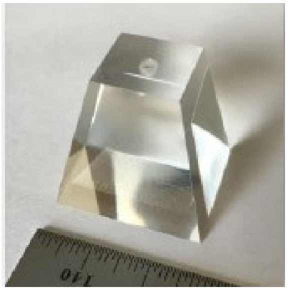


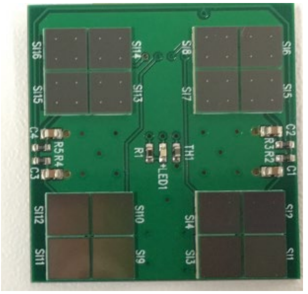
Two possible ways to increase photocathode coverage:

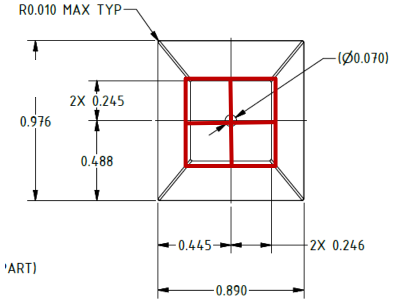
- Keep existing light guides and replace 2x2 array of 3x3 mm^2 SiPMs with four 6x6 mm^2
- Remove or cut down existing light guides and cover entire readout end of block with a 6x6 array of 6x6 mm^2 SiPMs.

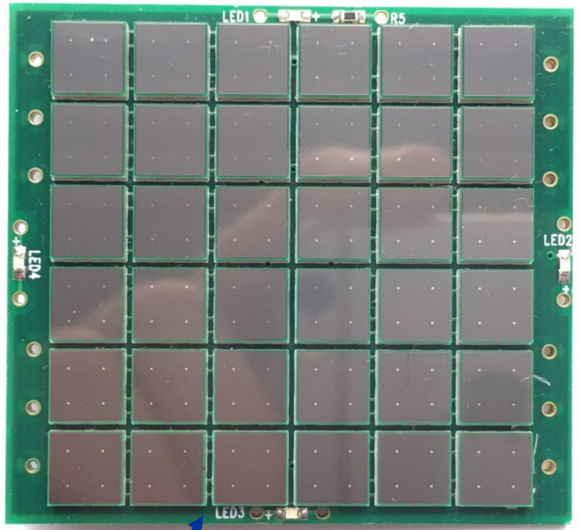
Hamamatsu S13360 6x6 mm^2 SiPM with TSVs (50 μm pixels)





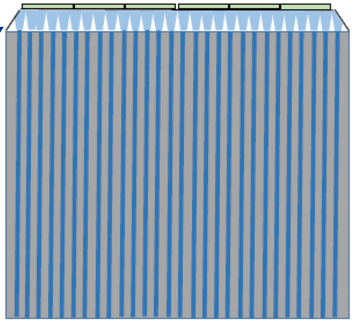






Note small gaps

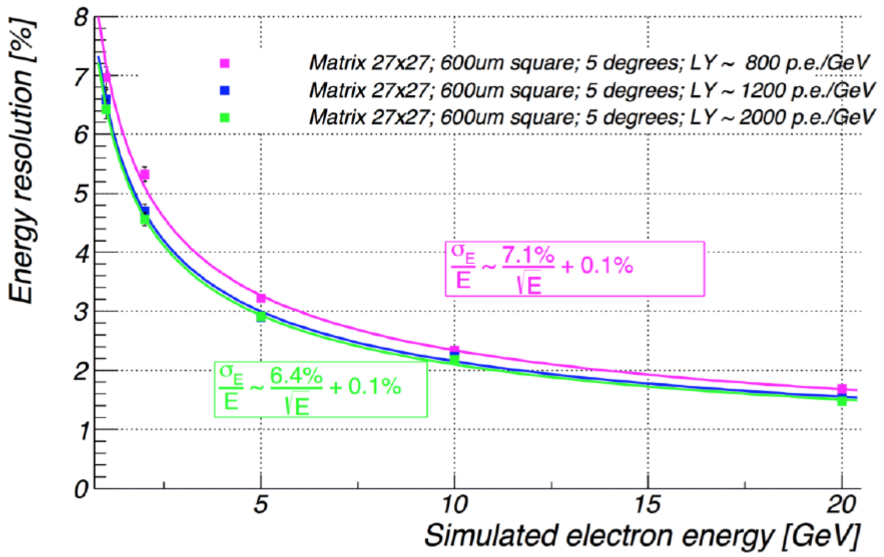
Short light guide covering entire block

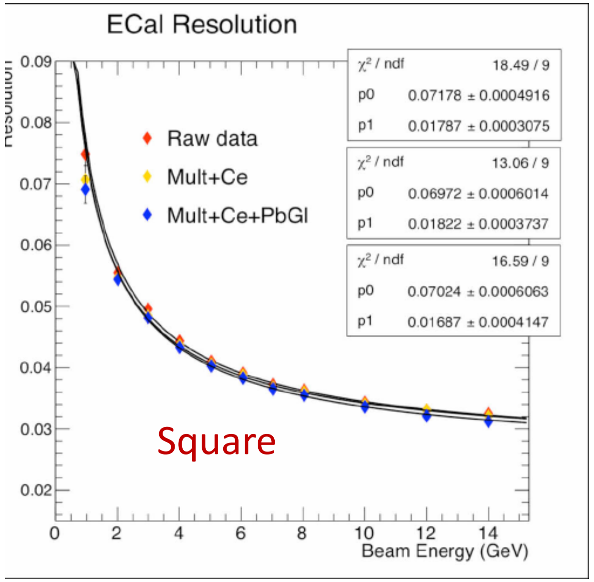


HiRes W/SciFi

eRD1 Report Jan 2016

PMT Readout with long light guides

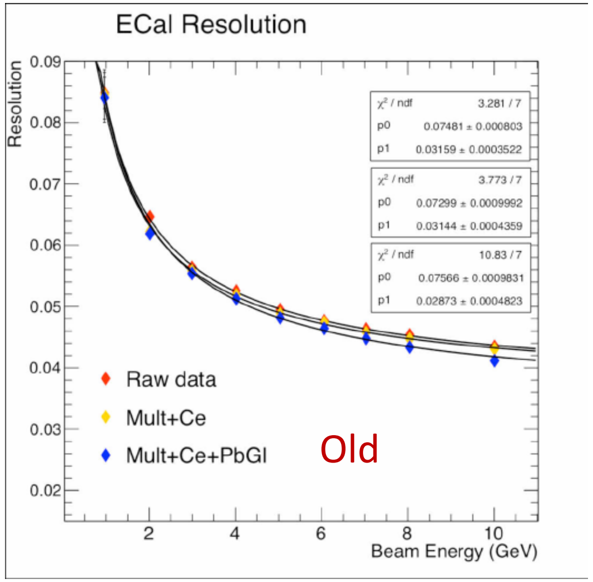




Detector	Fibers SCSF 78	Absorber	Sampling Frequency	Composition by weight	Number of fibers in superblock
"Old" High sampling frequency	Round, 0.4mm	75% W 25% Sn	0.671 mm Staggered Pattern	W -0.665 Sn – 0.222 Sc – 0.057 Epoxy- 0.056	25112 Damaged 3
"Square" High sampling fraction	Square, 0.59 x 0.59 mm^2	100% W	0.904 mm Square Pattern	W – 0.858 Sc- 0.075 Epoxy- 0.067	11664 Damaged 0

O.Tsai (UCLA)

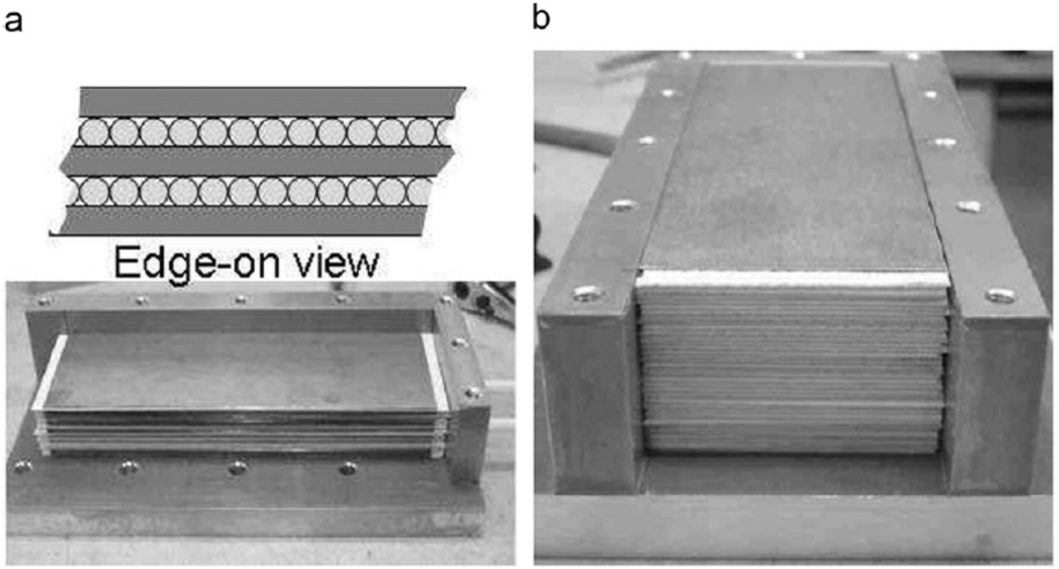
eRD1 Report July 2016



g-2 W/SciFi

Overall: $\frac{\sigma_E}{E} = \frac{11.8\%}{\sqrt{E}} \oplus 3.7\%$

Fiber ribbons embedded between 0.5 mm W plates



Also tried this in an "accordion" configuration in eRD1

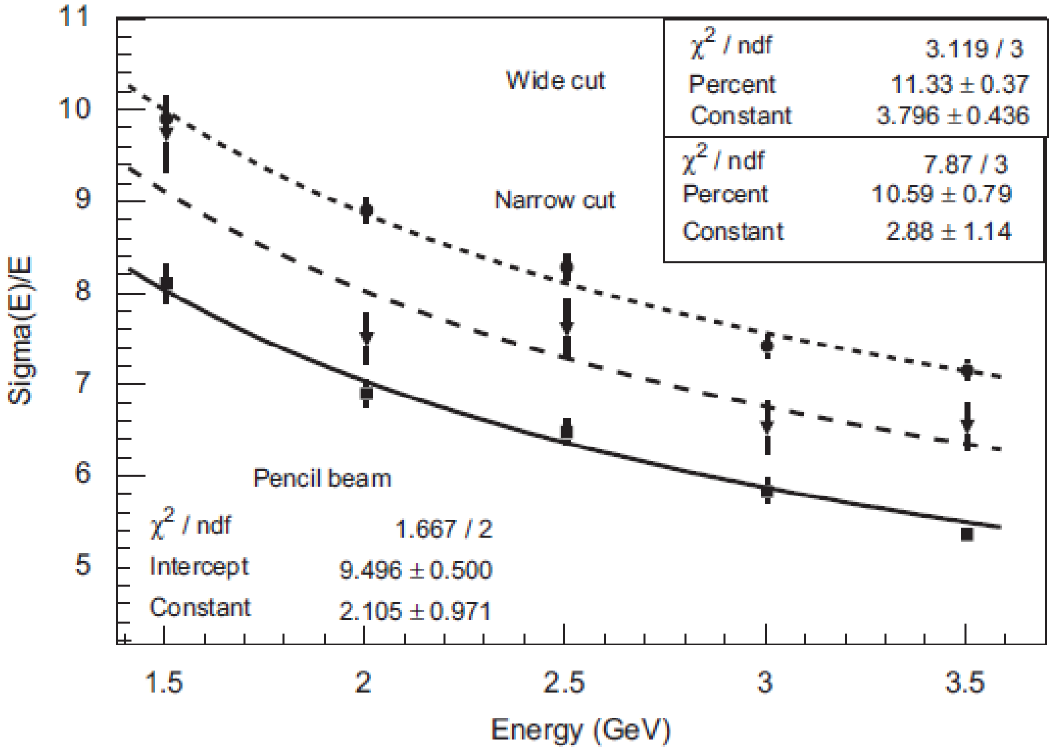


Fig. 7. Fits to resolution versus energy in the central module of an array of W/SciFi modules. Three entrance width cuts are imposed: 25 (dotted); 5 (dashed); and 1 mm "pencil" (solid).

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