SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Development of Future Electromagnetic Calorimeter Technologies and Applications for the Electron-Ion Collider with GEANT 4 Simulations

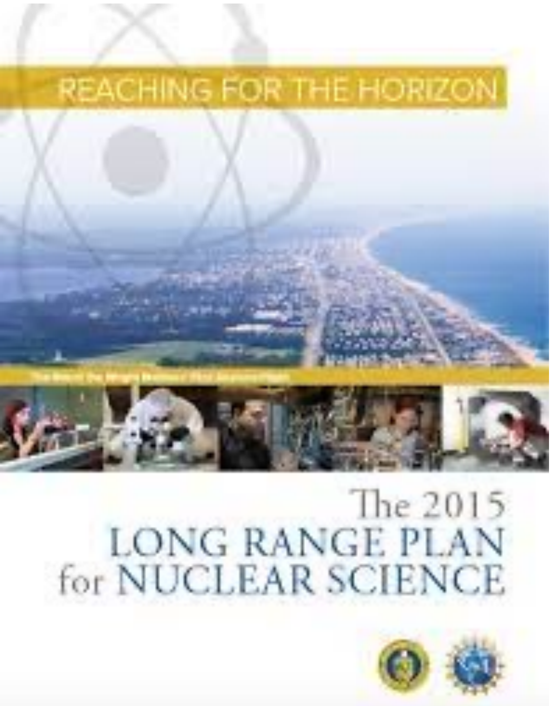
Zhaozhong Shi

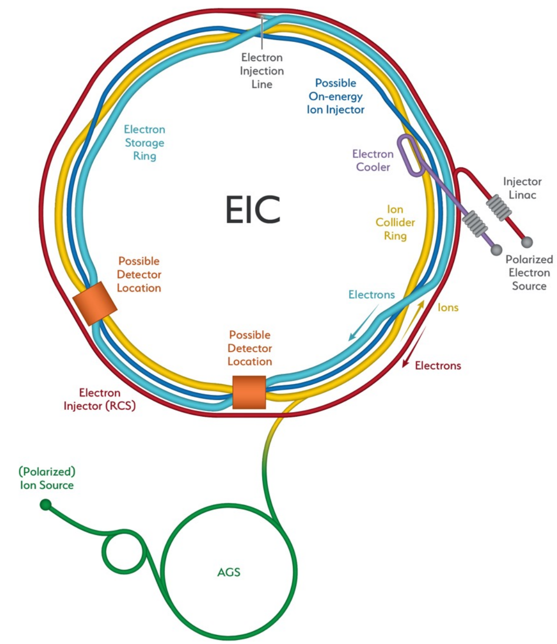
Los Alamos National Laboratory
Email: zhaozhongshi@lanl.gov

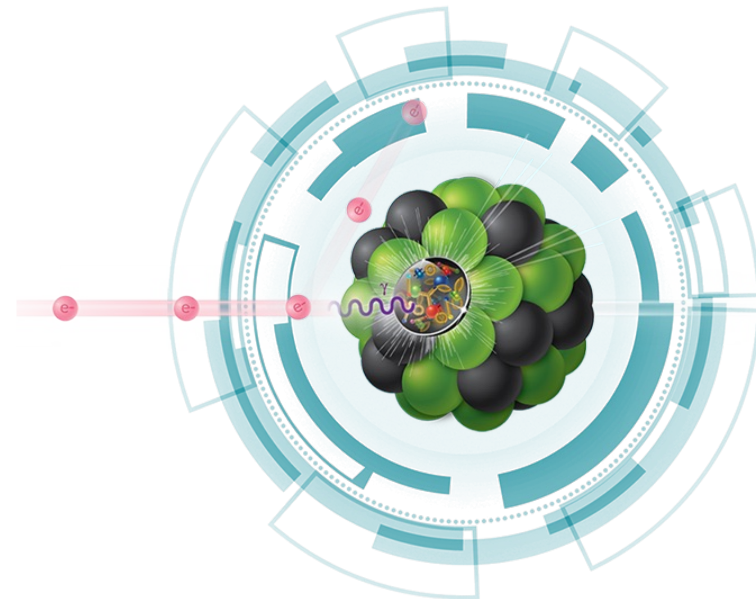
06/14/2022

The Electron-Ion Collider

NSAC Long Range Plan for Nuclear Science – The Electron Ion Collider (EIC)





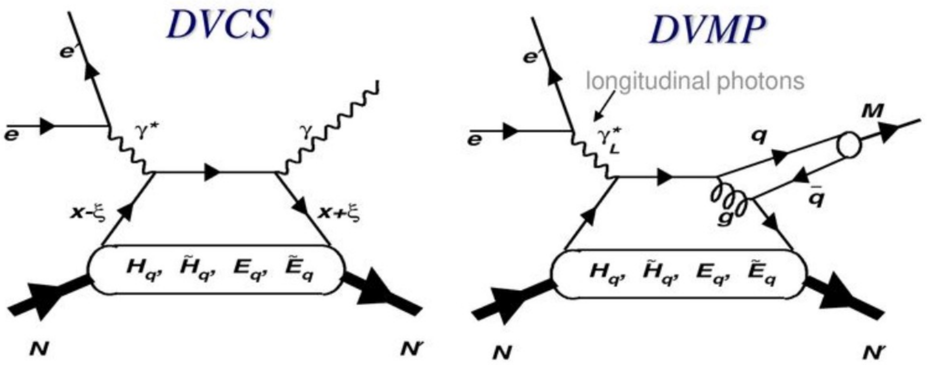


- EIC: moving toward CD-2 stage this year according to Detector Proposal Advisory Panel (DPAP)
- Provide versatile beams to cover a broad kinematic range
- Expected to have two interaction regions to potentially host two large scale detectors, named **detector 1 (priority)** and **detector 2 (coming next)**

Electromagnetic Calorimeters for EIC

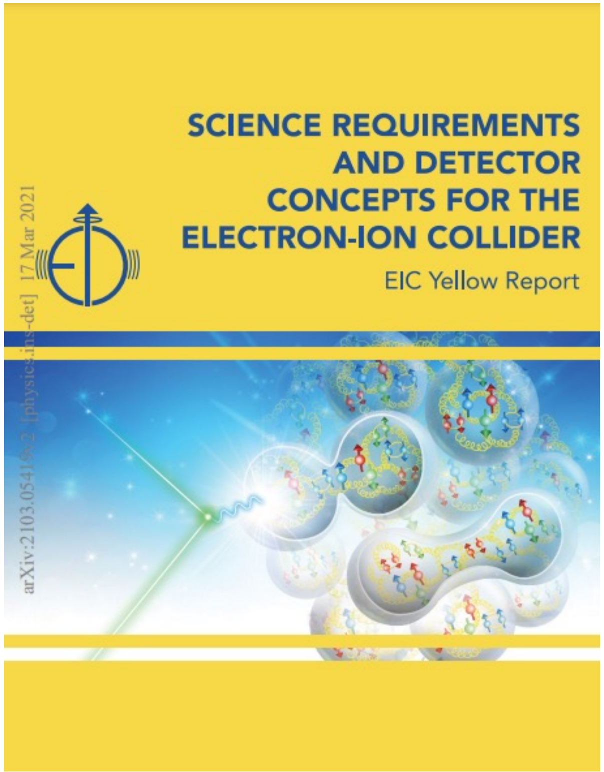
EIC Physics Goals

- Precision 3D imaging of nucleons and nuclei
- Extract GPD from DVCS and DVMP processes



EIC EMCAL Requirements

- Excellent energy resolution
- Excellent electron identification capabilities
- High energy $\pi^0 \rightarrow \gamma\gamma$ reconstruction from DVMP (up to about 50 GeV)
- Separation of electrons from DVCS photon

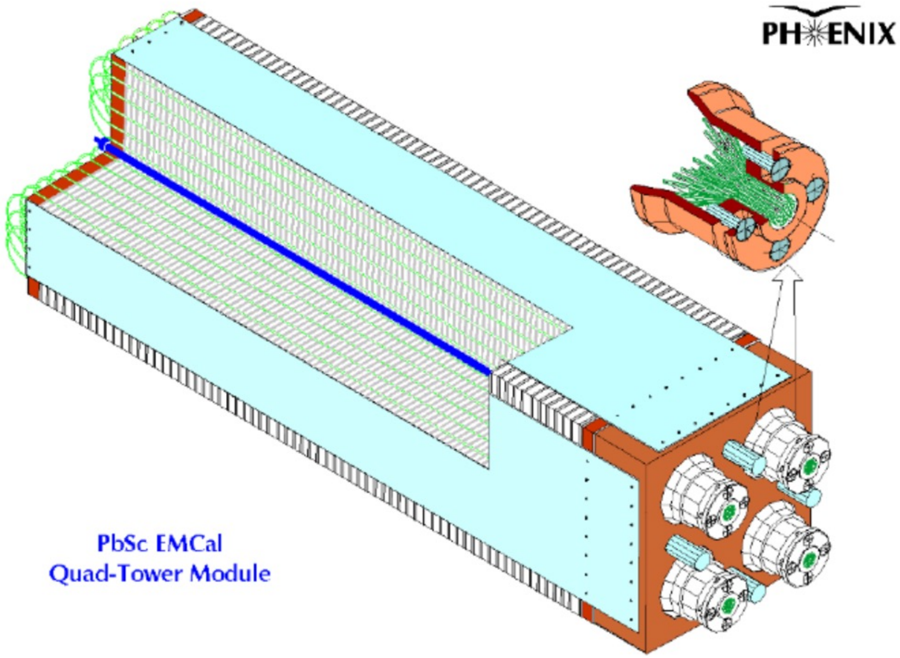


Technical Challenges

- Limited space → compact EMCAL design
- High granularity EMCAL
- Radiation damage on SiPMs by neutrons

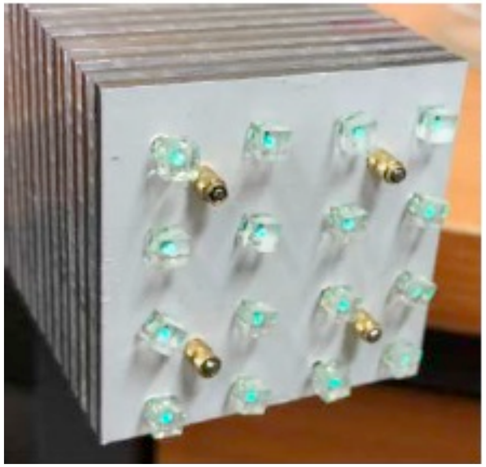
Shashlik EMCAL Design Options

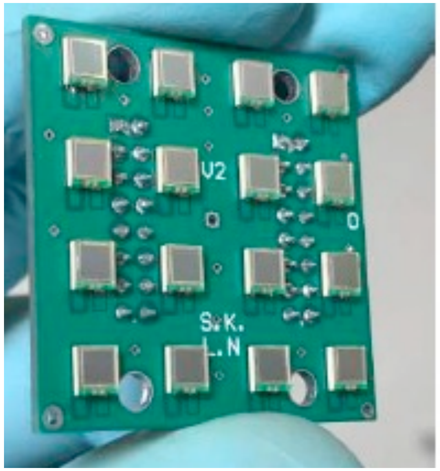
PHENIX Pb EMCAL



X_0 = 2.02 cm and R_M = 5.2 cm

W/Shashlik tower design with high granularity and individual readout





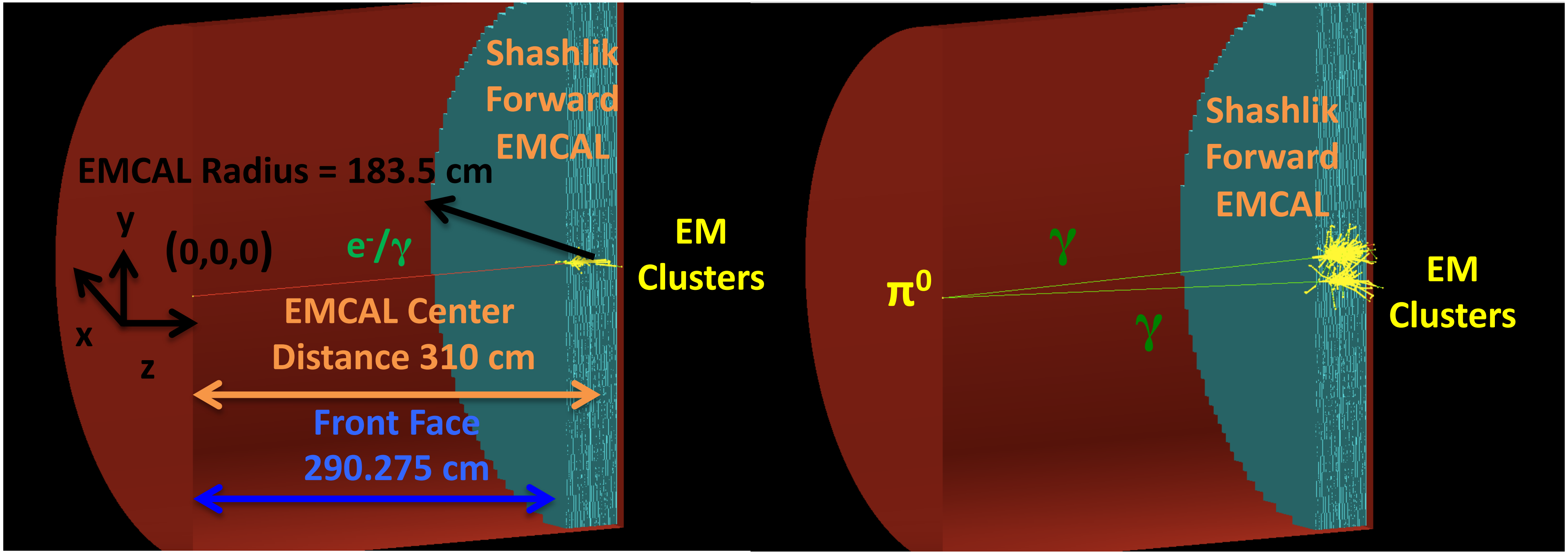
X_0 = 0.41 cm and R_M = 4.25 cm

✓ Existing PHENIX EMCAL for reuse and refurbishing
✓ Easy to build
✓ Lower cost

✓ Smaller radiation length and Moliere radius
✓ Allow more compact design

- Hard for machining
- More expensive

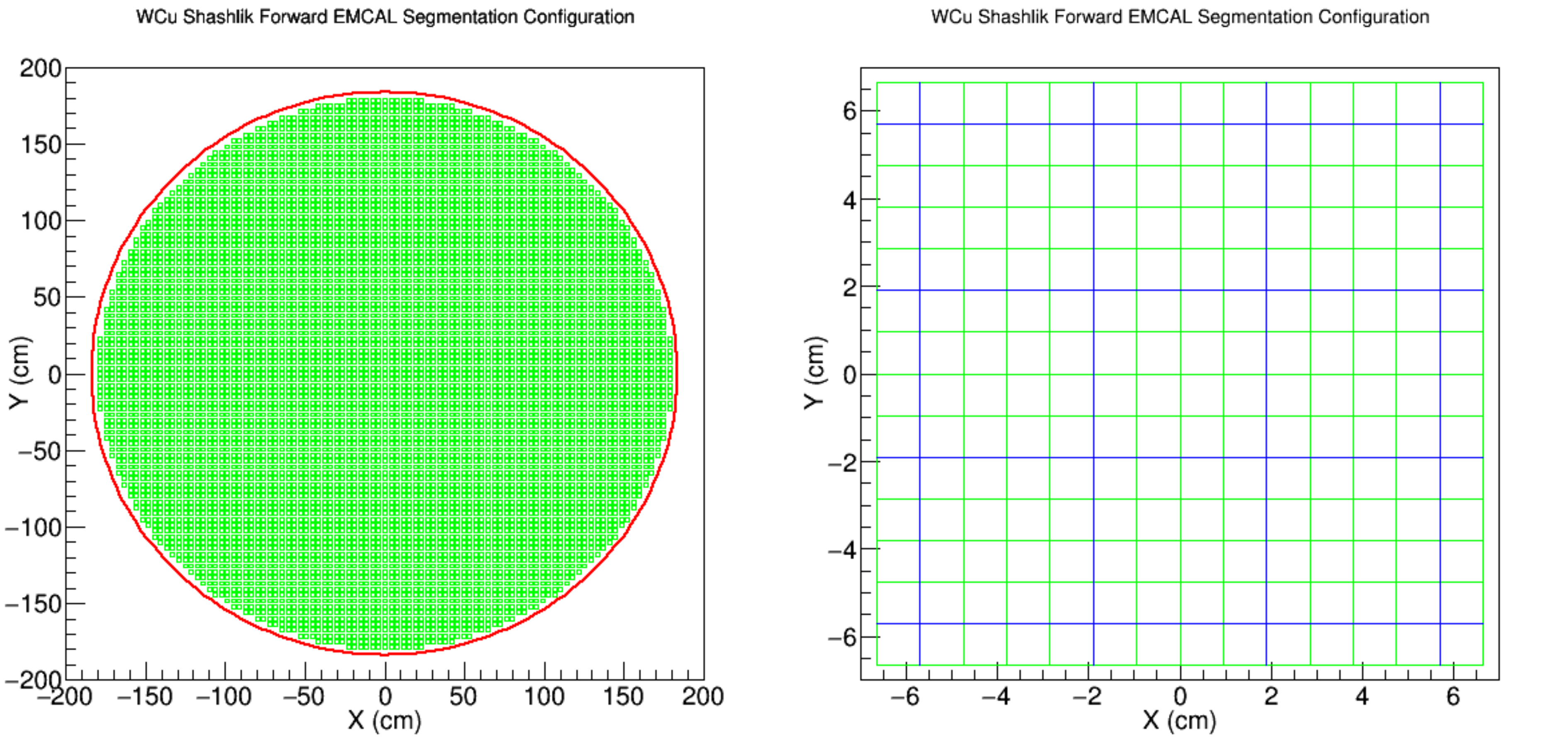
Event Displays of GEANT Simulation



Testbed GEANT Simulation for EIC Forward EMCAL

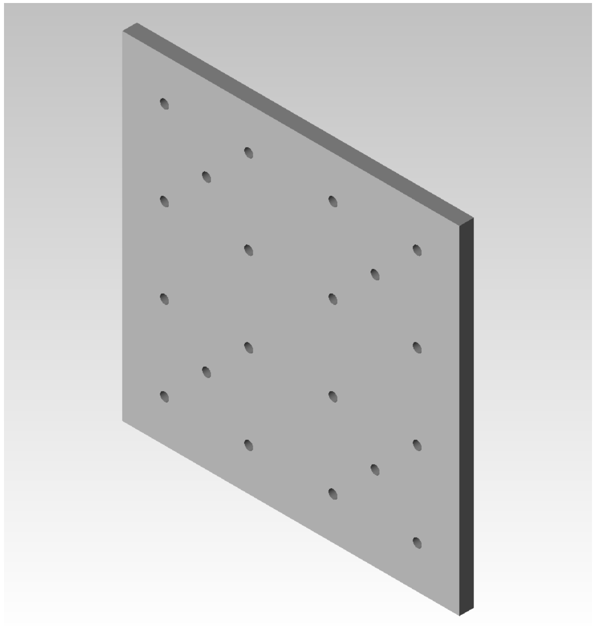
- Forward EMCAL: EIC hadron beam going direction
- Shashlik EMCAL only: no other detector components
- Left setup: electron or photon beam at normal incidence
- Right setup: $\pi^0 \rightarrow \gamma\gamma$ beam at normal incidence

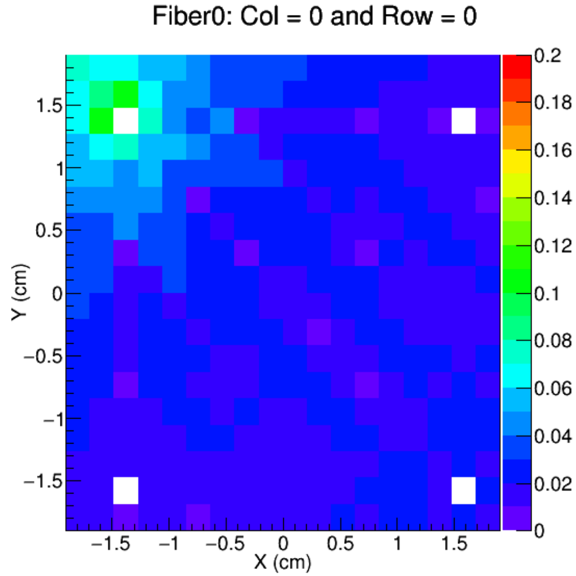
WCu Shashlik EMCAL Tower in Simulation

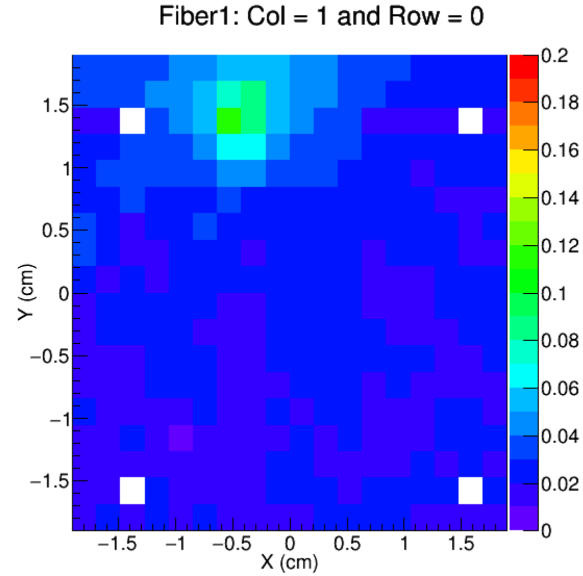


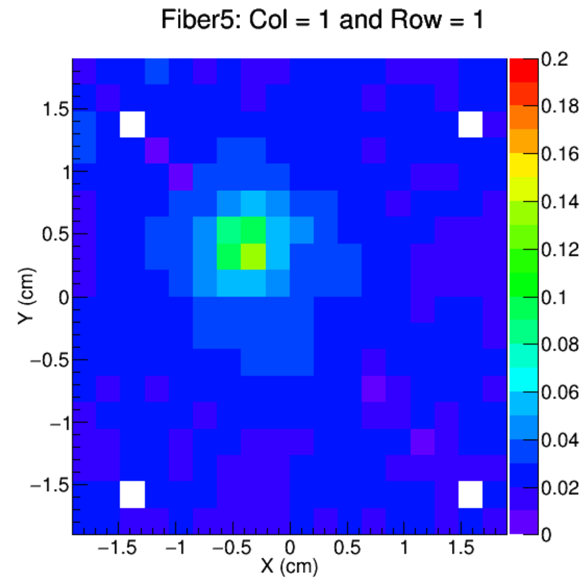
- Simulation setup: **individual readout scintillator in green** and **EMCAL tower in blue**
- Tower size 3.8 cm × 3.8 cm with 4 × 4 fiber readout (0.95 × 0.95 cm)

Light Efficiency Collection Map with *TracePro*



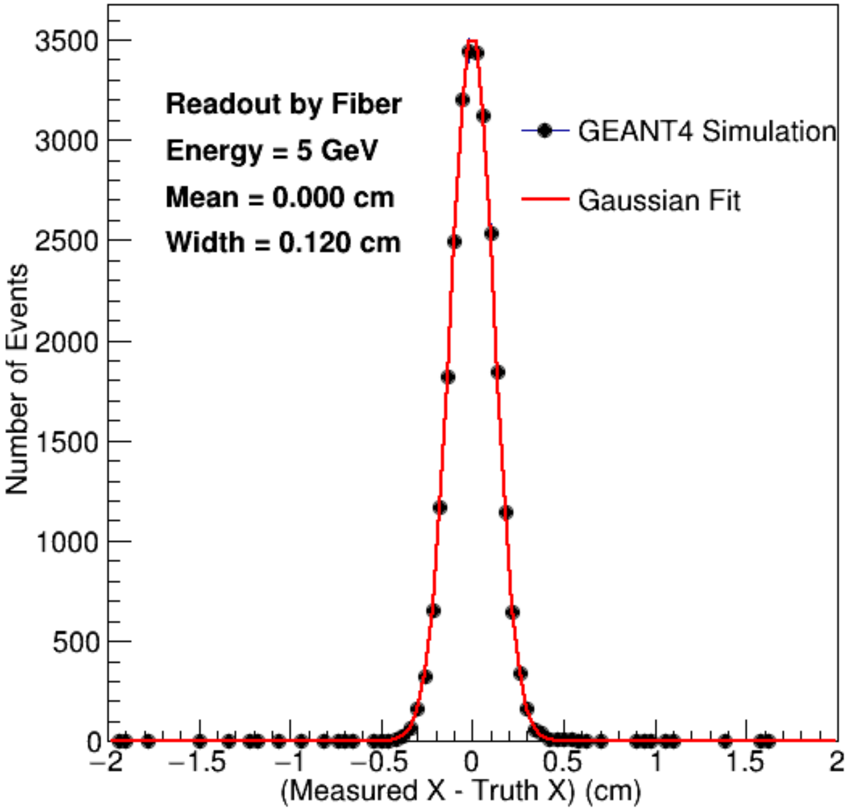


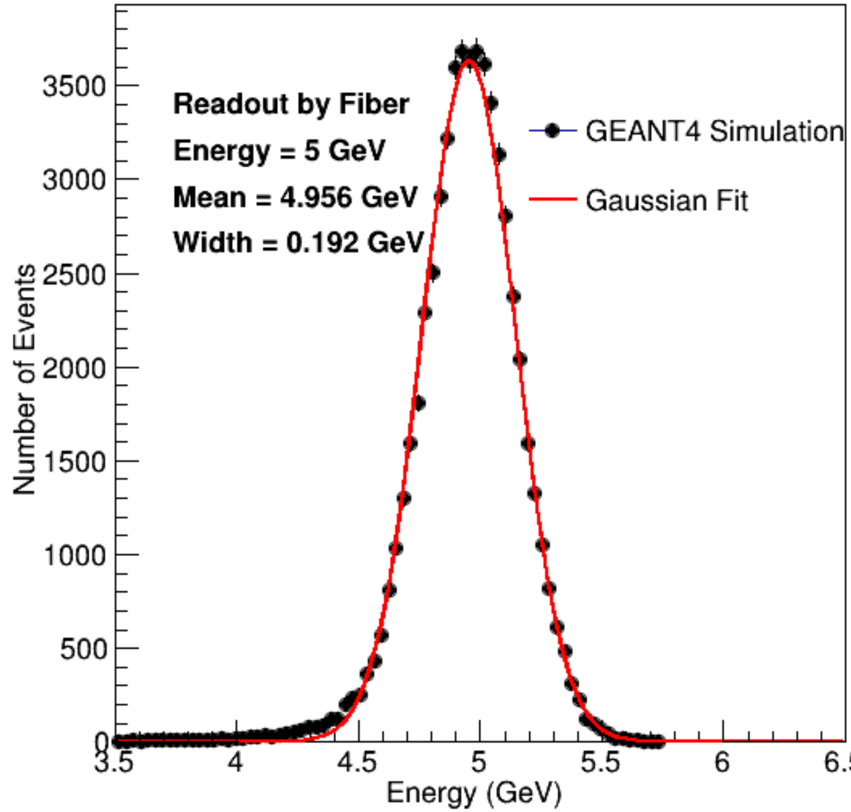




- ***TracePro*** software to simulate the optics
- Optically isolated towers
- Light yield redistribution within tower based on light efficiency collection maps
- Others fibers generated from rotational and reflection symmetry

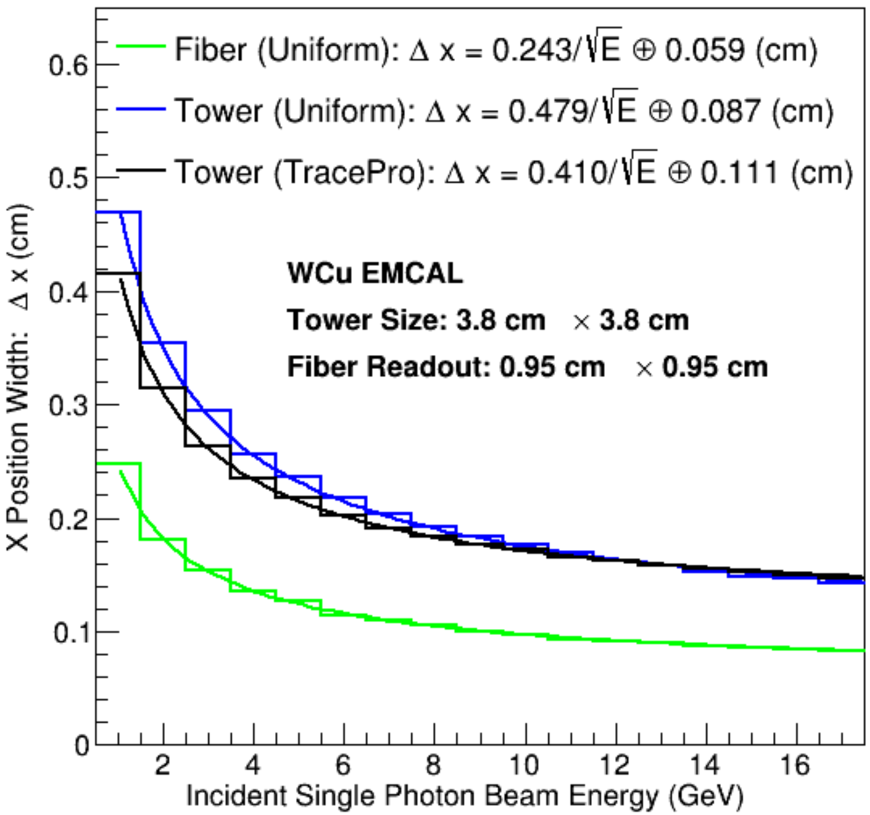
Tower Measured Position and Energy

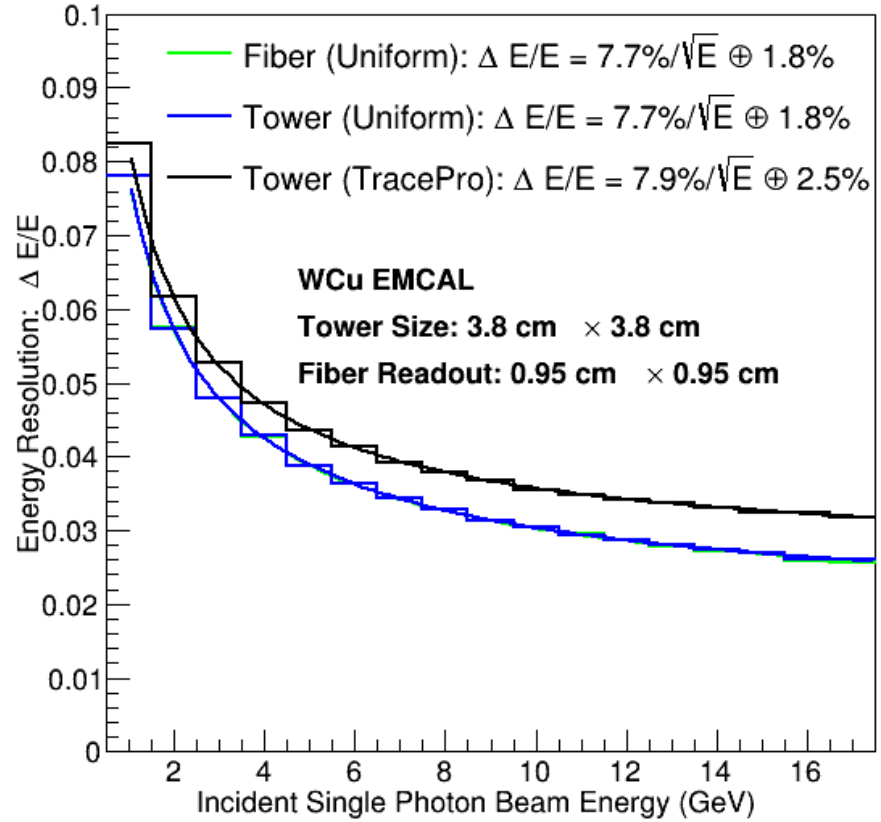




- Position measurement: weighted average over all readout energy with the center of the readout position
- Energy measurement: sum over all readout energy
- Resolution: extracted from Gaussian fits

Position and Energy Resolution vs Photon Energy

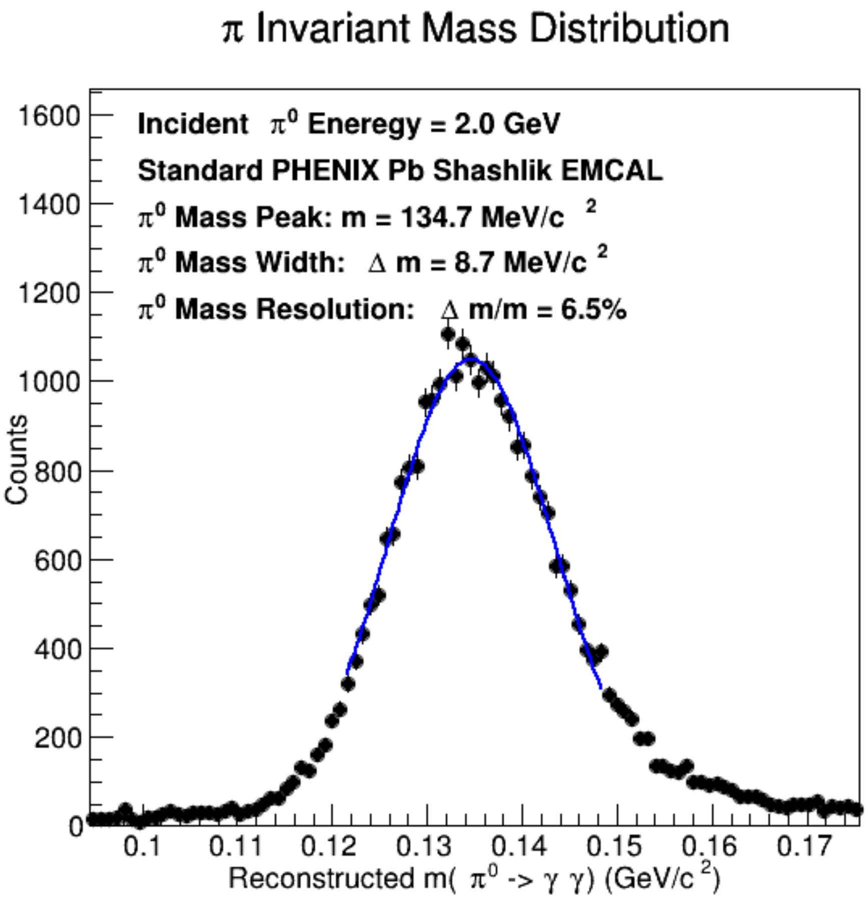


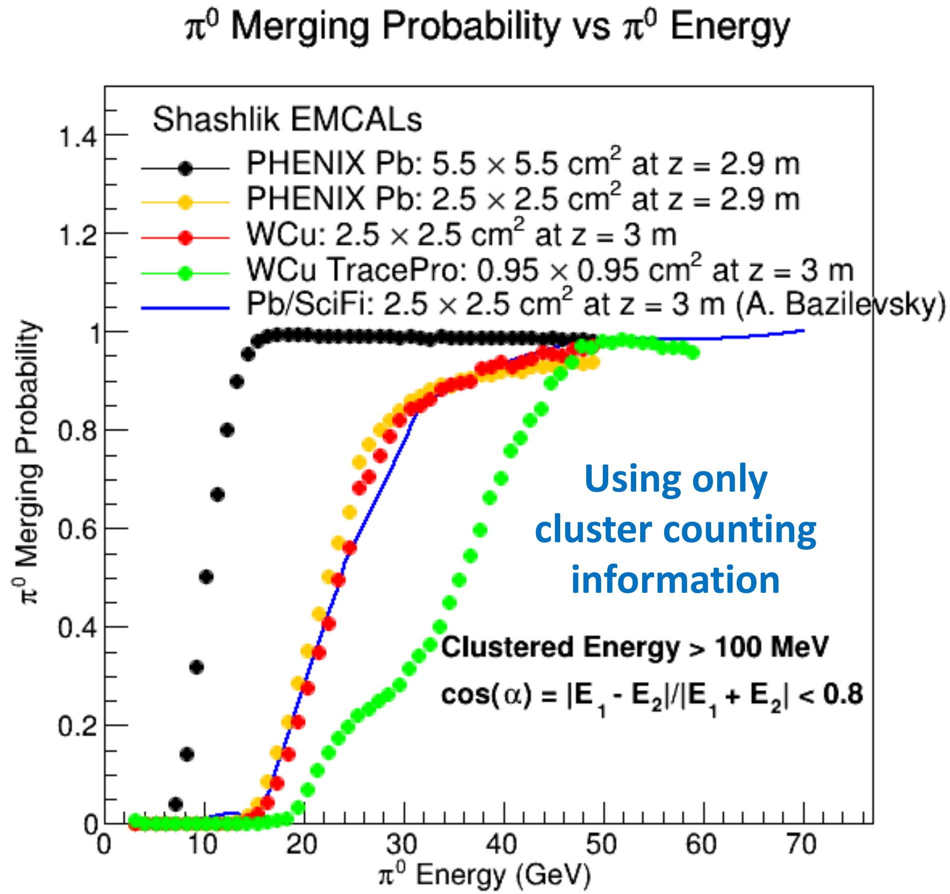


<u>Non-uniformity of light collection efficiency map</u>

- Improves the position measurement
- Worsens the energy resolution

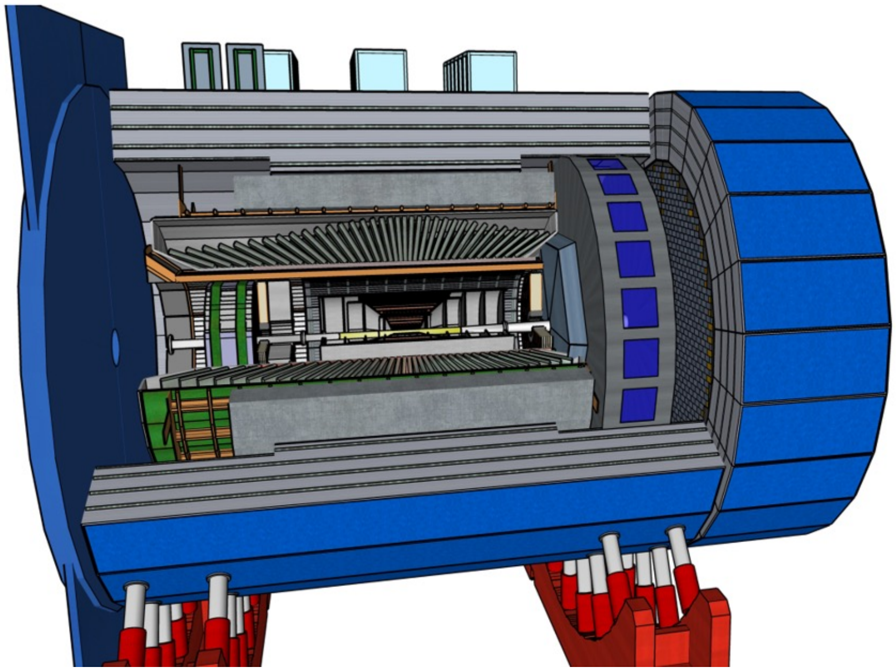
π^0 Reconstruction and Merging Probabilities Studies

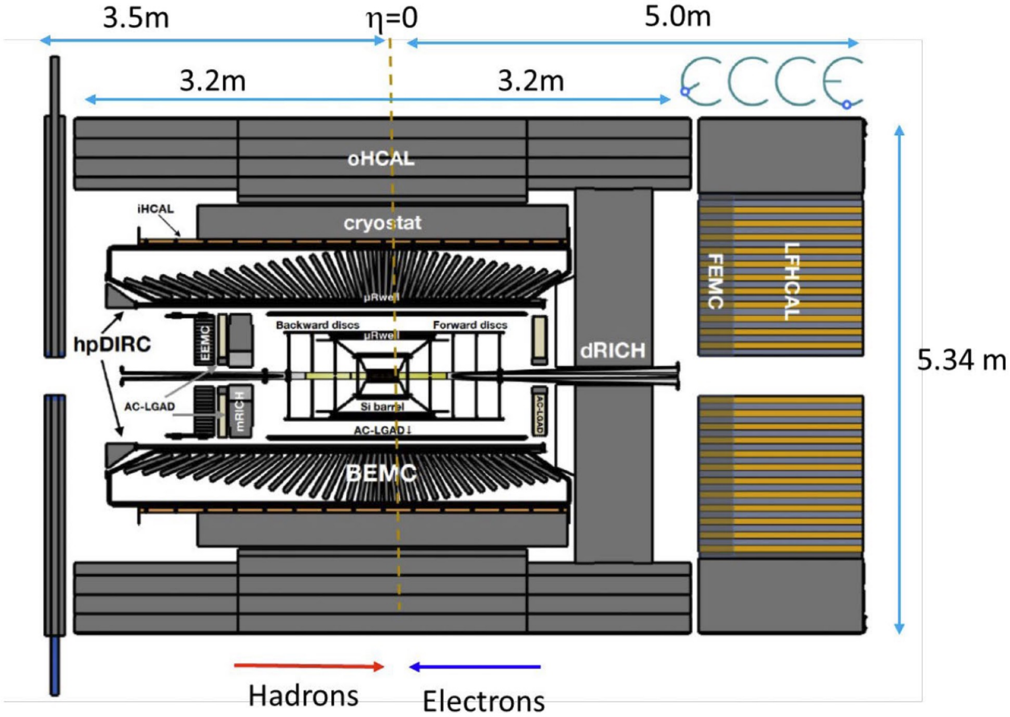




- Correct π^0 invariant mass and good resolution
- π^0 merging probability decreases with finer tower granularity
  $\rightarrow$ reconstruct π^0 up to higher energy
- Strong dependence on EMCAL granularity
- Weak dependence on Moliere radius

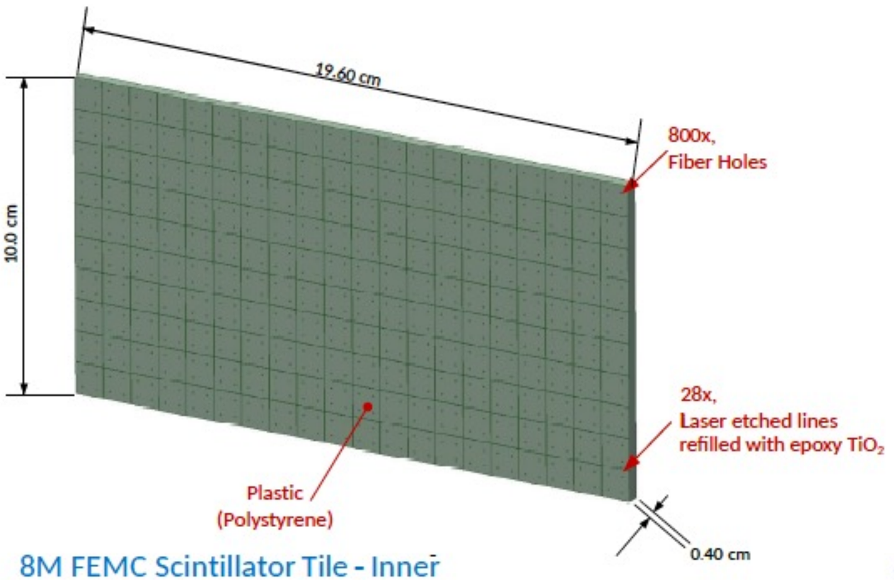
ECCE Detector at the EIC

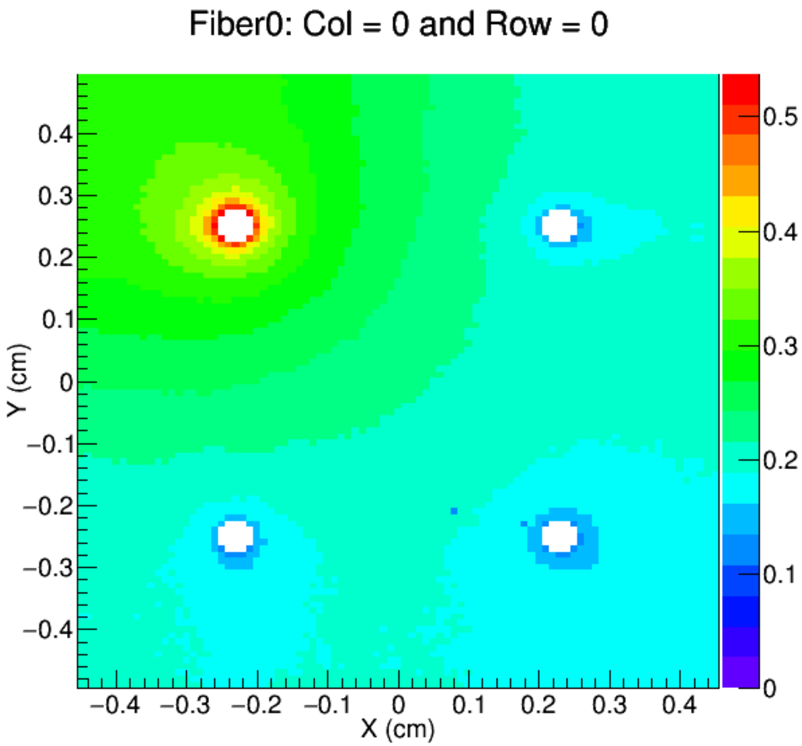




- ECCE Experiment: recommended unanimously by DPAP as the detector 1 at the EIC in March 2022
- International contributions to design and build the subdetectors
- EMCAL with fine granularity and efficient readout
- Still ongoing discussion about forward EMCAL design

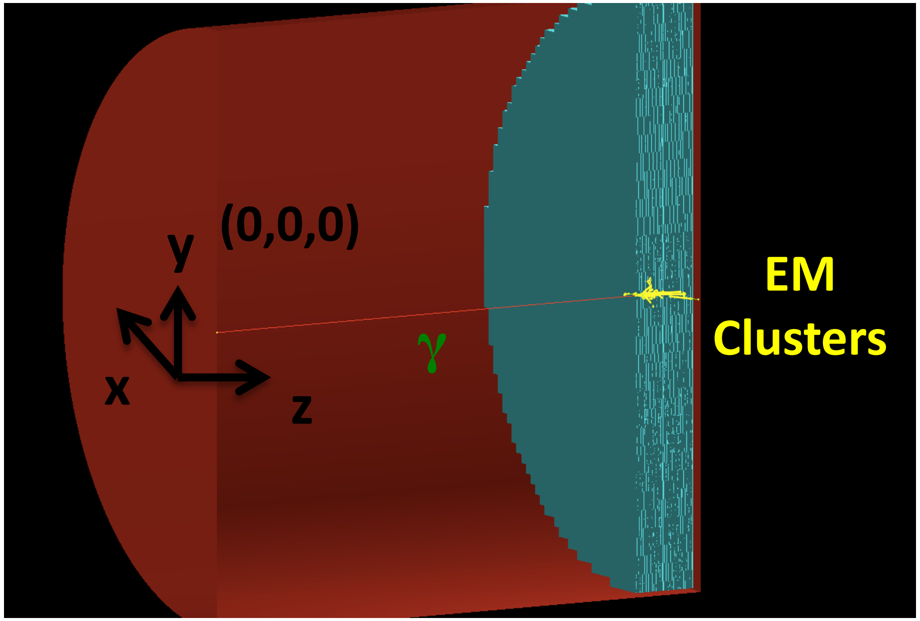
Proposed ECCE Forward EMCAL Design

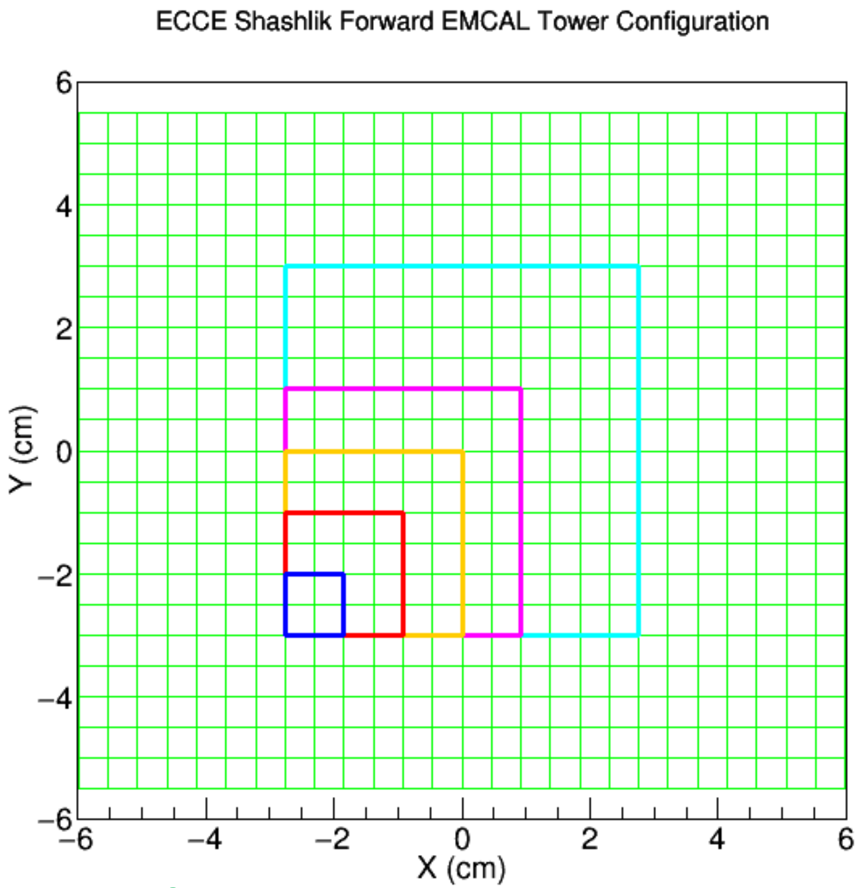




- Proposal submitted in December 2021
- Pb shashlik EMCAL design
- Acceptance: $1.5 < |\eta| < 3.5$
- Tower Geometry: 0.92 cm × 1.00 cm, 2 × 2 readout fibers with a thickness 500 µm
- Light Collection Map: modeled by *TracePro.* Other fibers generated by the reflection symmetry

ECCE EMCAL GEANT 4 Simulation Setup

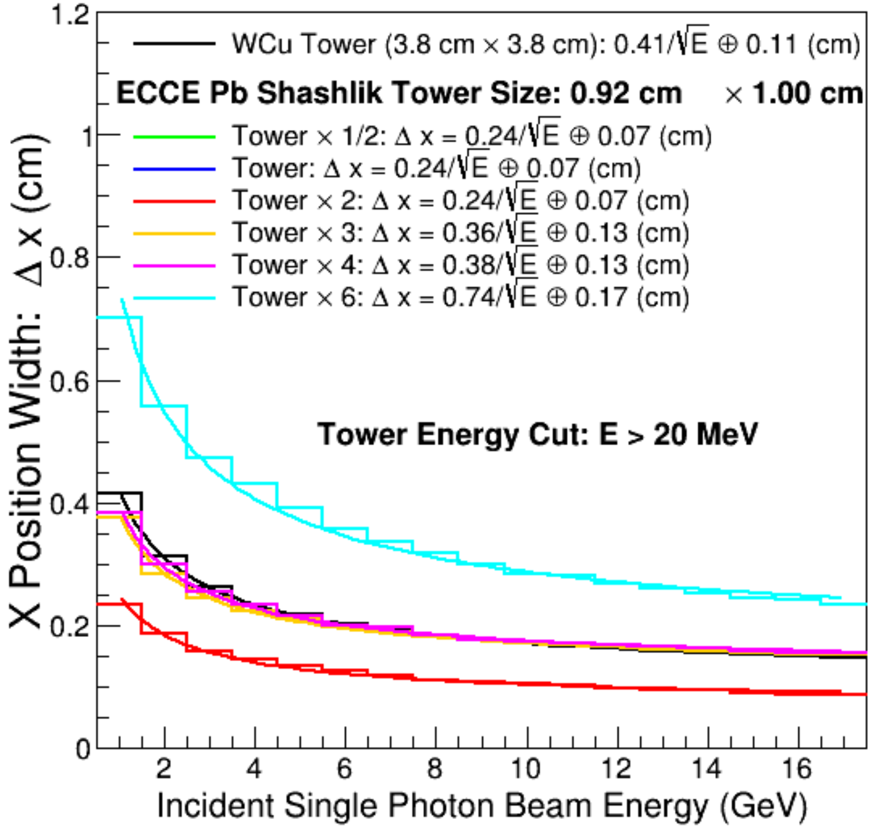


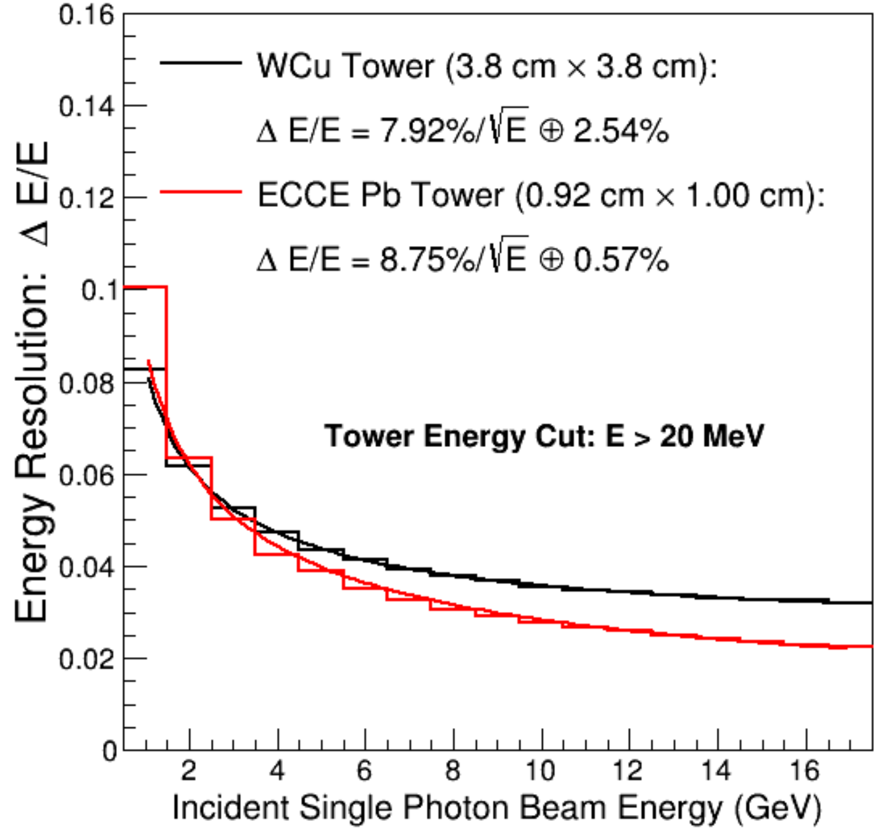


Definition of Readout

- Each **green box** is a readout fiber **Tower × 1/2**
- Each **blue box** is an optically isolated EMCAL **tower**
- The **red**, **orange**, **magenta**, and **cyan** boxes define **Tower × 2**, **Tower × 3**, **Tower × 4**, and **Tower × 6**

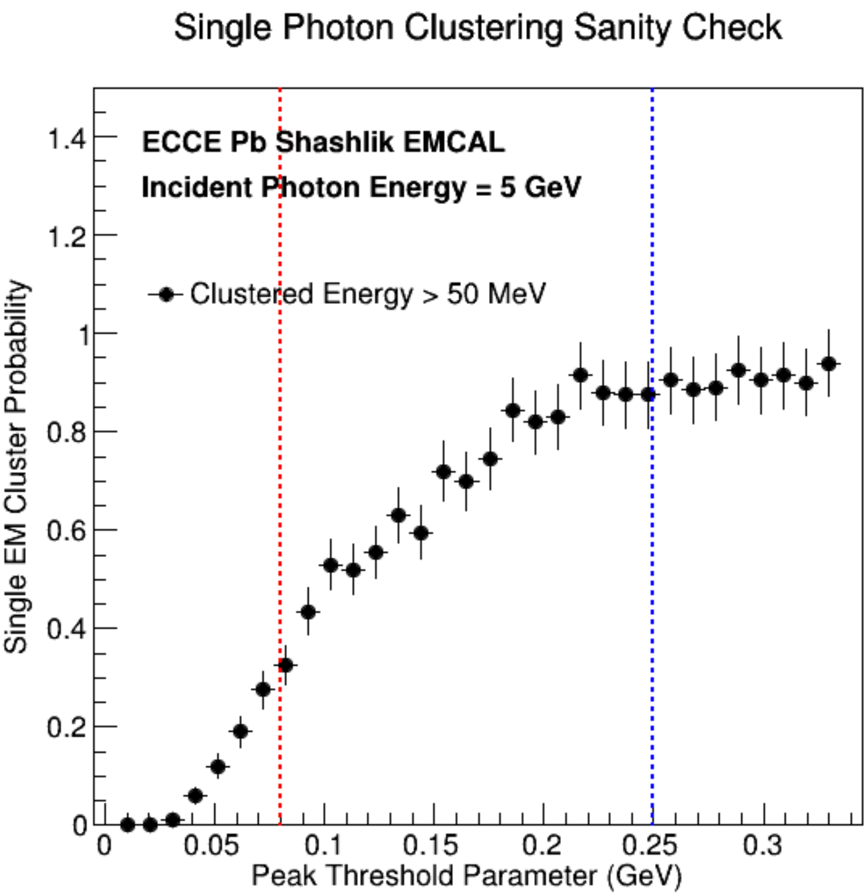
Position and Energy Resolution vs Photon Energy

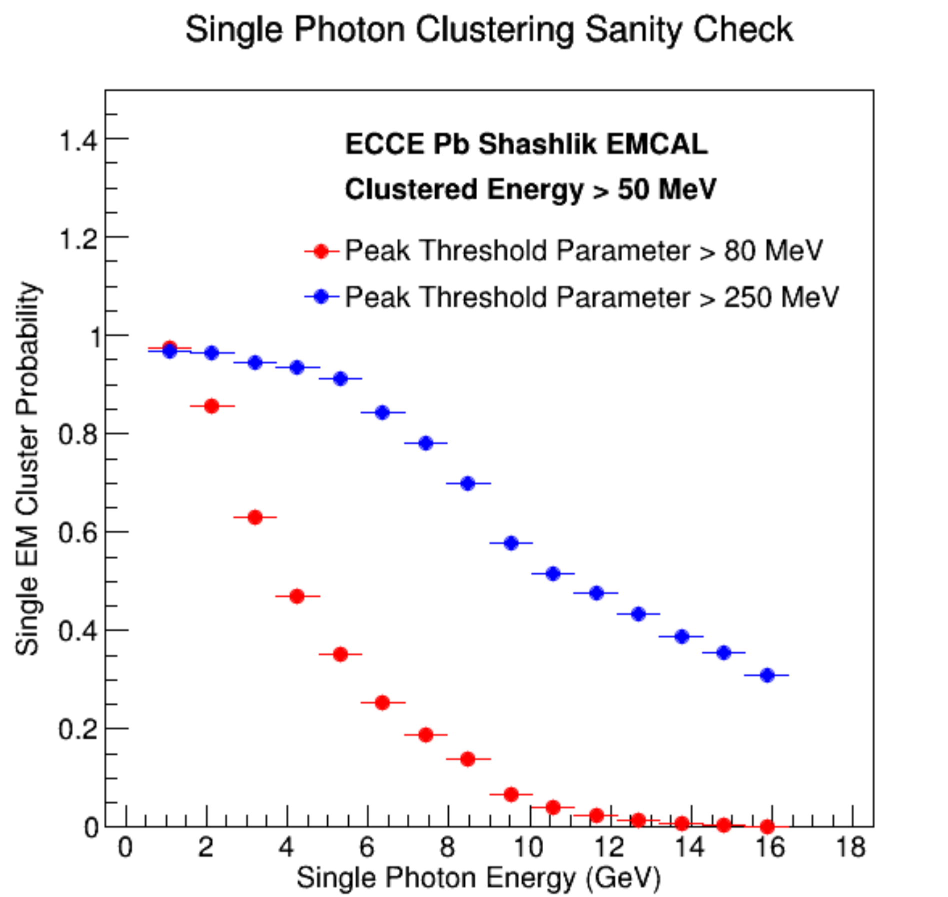




- The same position resolution for **Tower × 1/2**, **Tower**, and **Tower × 2** → no need to go with every single fiber readout
- Position resolution: **ECCE EMCAL** better than **WCu EMCAL** (black curve from slide 9)
- Energy resolution: **ECCE EMCAL** better than **WCu EMCAL**

Cluster Algorithm Parameter Tuning for EIC EMCAL

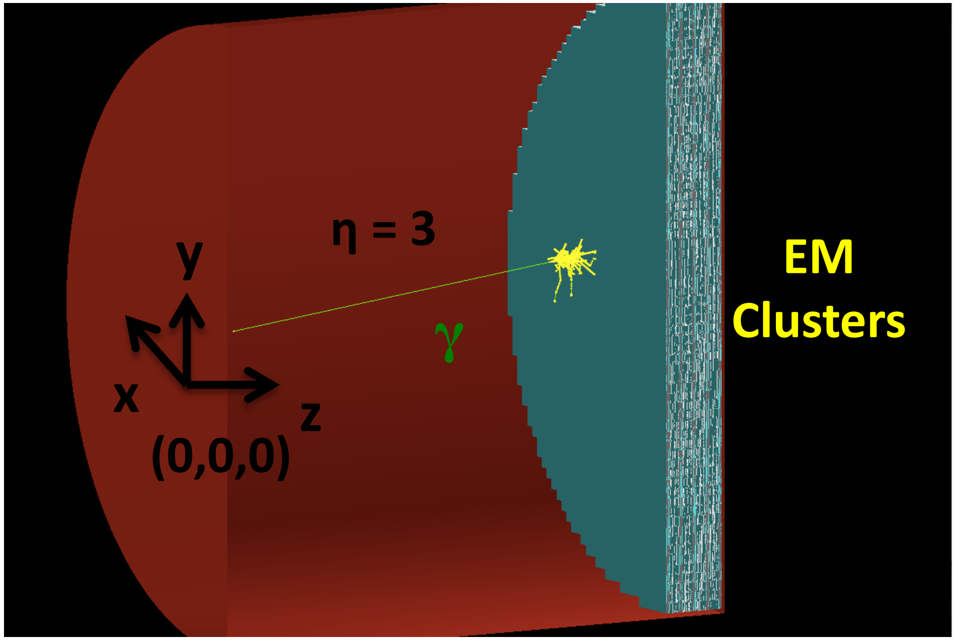


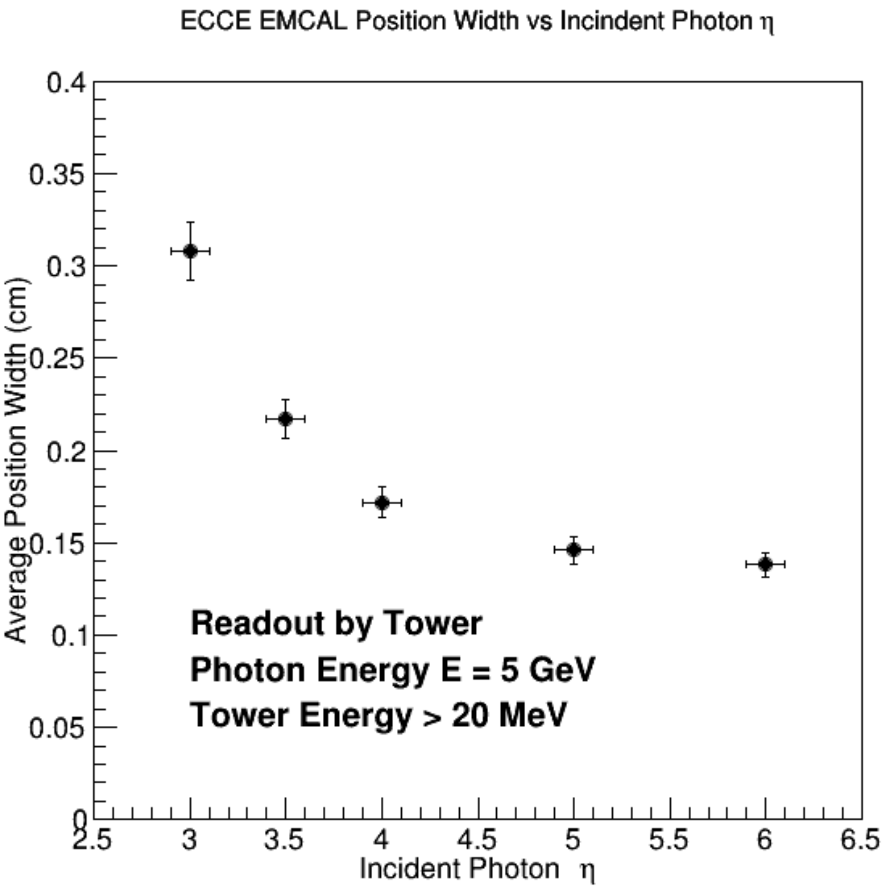


- **Peak Threshold Parameter:** the energy threshold of local maxima to spilt clusters
- Current value: **0.08 GeV**, optimal for PHENIX and sPHENIX at RHIC, but not EIC
- Parameter tuning for better performance, for example, **0.25 GeV**
- Possible improvement of the clustering algorithm with **machine learning technique**

Incident Single Photon η Studies

Single Photon Event Display

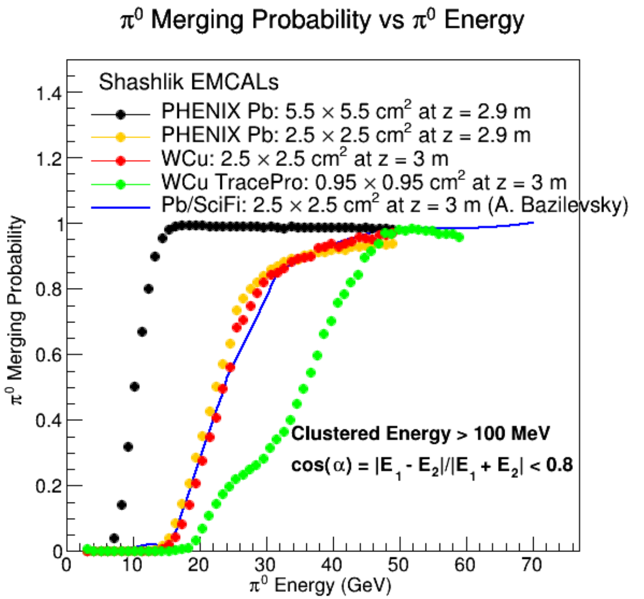


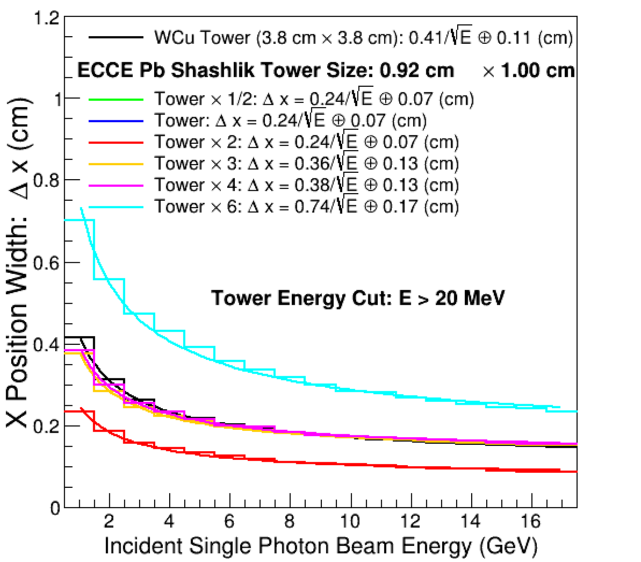


- Photon entering the EMCAL at a finite angle rather than normal incidence
- Contribution of longitudinal shower to the position resolution in addition to transverse shower profile
- Consider **projective design** or **use WCu absorber** with smaller radiation length?

Summary and To Do List

- π^0 reconstruction with WCu shashlik EMCAL can go up to 50 GeV readout individual fiber by cluster counting
- Strong dependence on tower granularity while weak Moliere radius for π^0 reconstruction
- Better position and energy resolution of the ECCE proposed Pb than WCu shashlik EMCAL design
- Compatible cluster algorithm for tower size much smaller than Moliere radius, a critical factor to decide EIC EMCAL design
- Study π^0 merging probability by looking into the shower profile to push up energy of the π^0 decay photon separation
- A lot more interesting studies to do in the future!





Acknowledgement

- This work is supported by the United States Department of Energy Office of Science Graduate Student Research (SCGSR) Award and Los Alamos National Laboratory Laboratory Directed Research & Development (LDRD)
- Special thanks to my mentor Dr. Craig Woody and collaborators Dr. Jin Huang, Dr. Alexander Brazilevsky, Dr. John Haggerty, Professor John Lajoie, and Ian Delk
- **Thank you very much for your attention!**

U.S. DEPARTMENT OF ENERGY | Office of Science

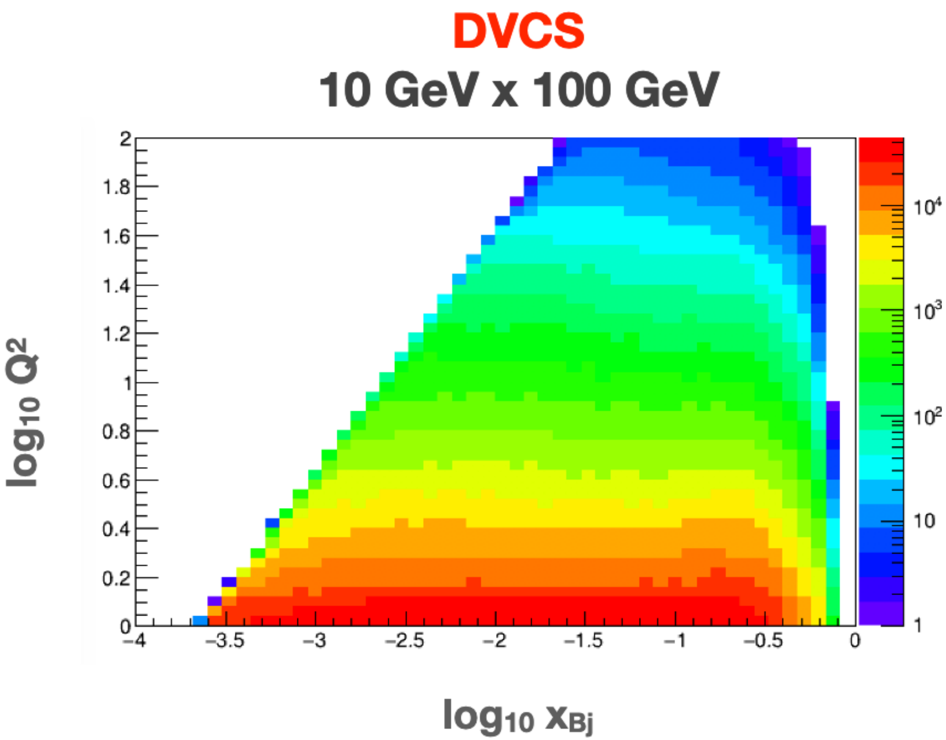
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

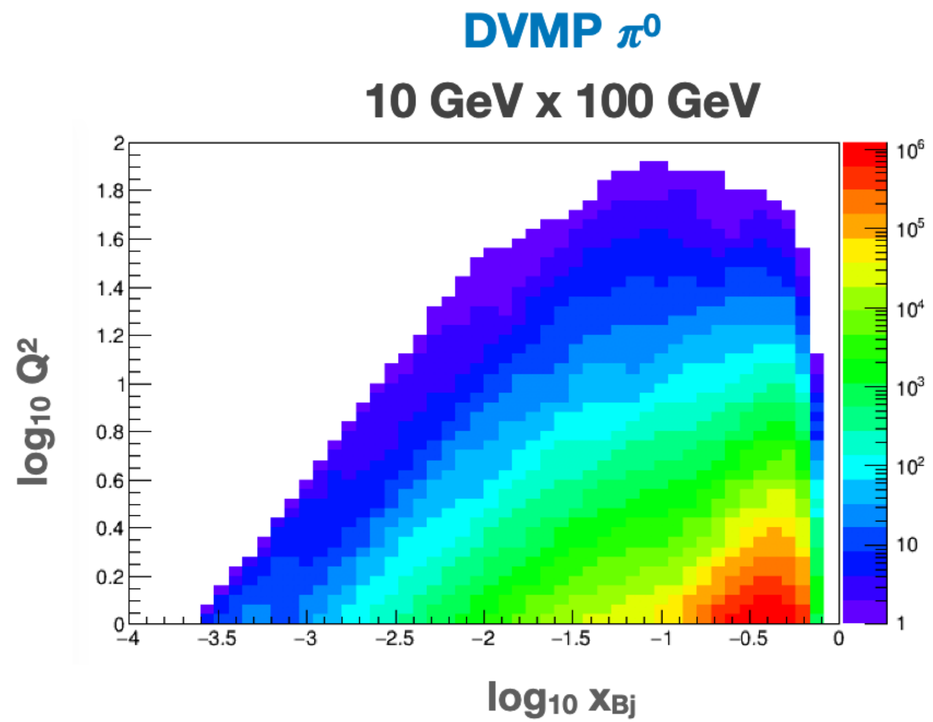
ECCE

Los Alamos NATIONAL LABORATORY

Back Up

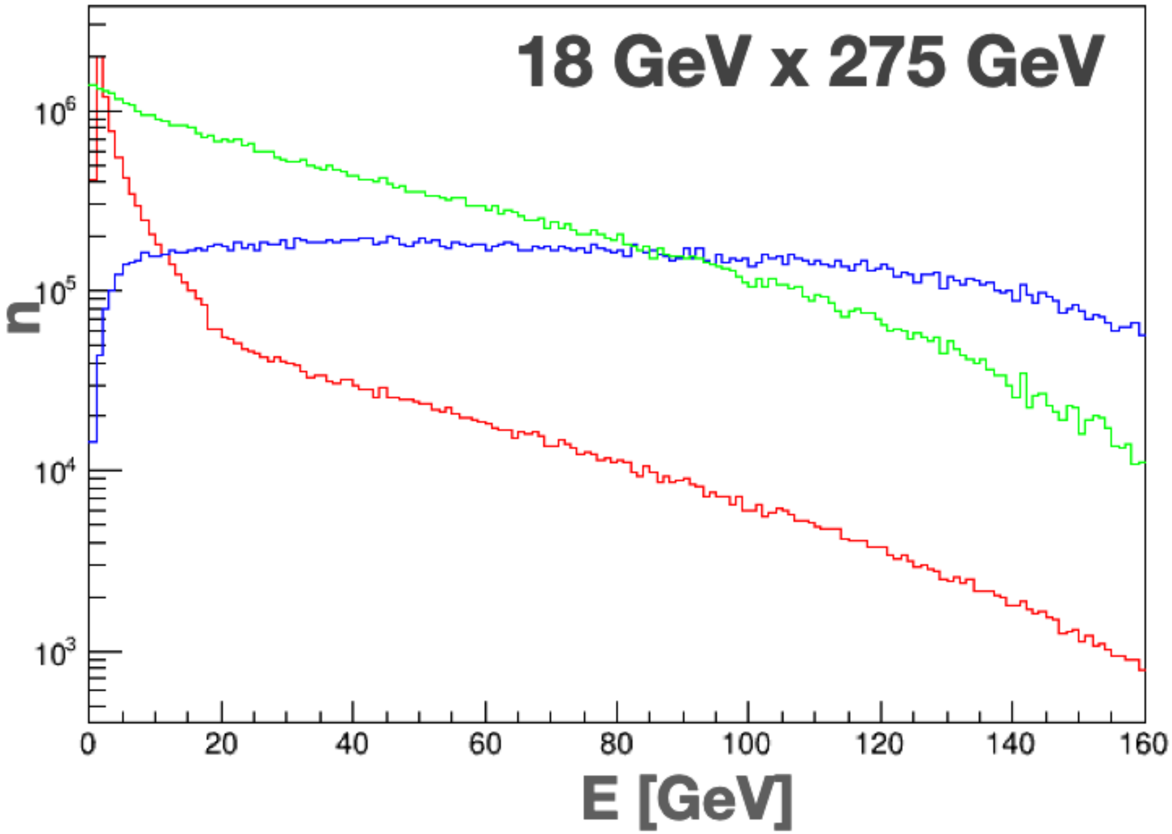
DVCS and DVMP for GPD





- DVCD and DVMP probing different (x, Q^2) kinematic regions for the GPD

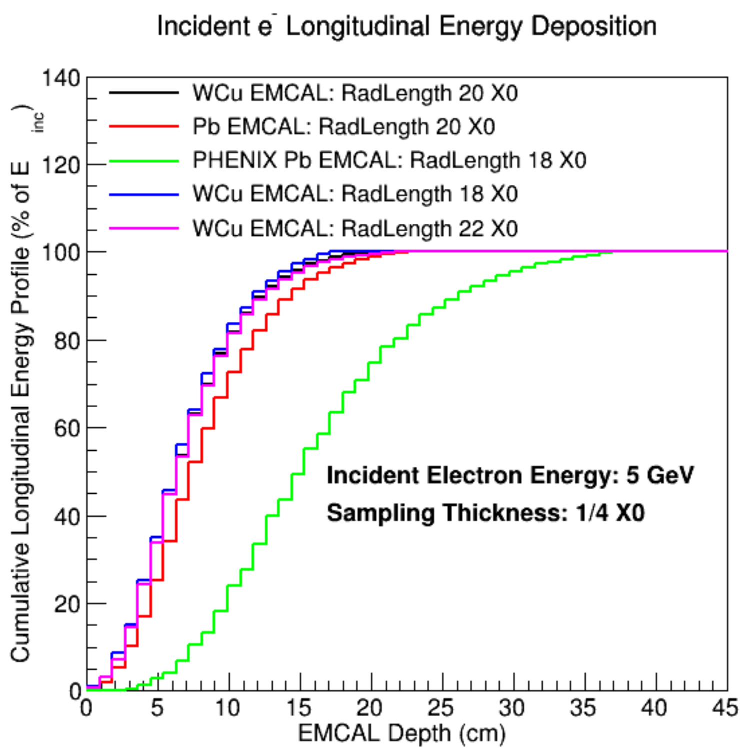
DVCS and DVMP Kinematics

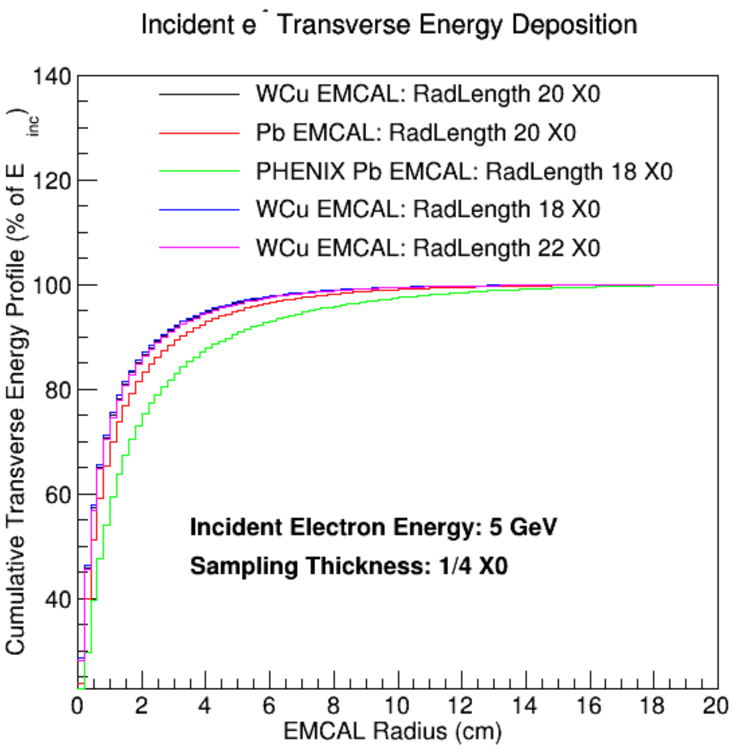


DVCS γ
DVMP π^0
DVMP γ from $\pi^0 \rightarrow \gamma\gamma$

- π^0 energy can go above 150 GeV for the beam energy of E_e = 18 GeV and E_p = 275 GeV
- Need to correctly cluster and separate merging photons for EIC EMCAL up to high energy, at least E > 50 GeV

Forward Shashlik EMCAL Shower Profile

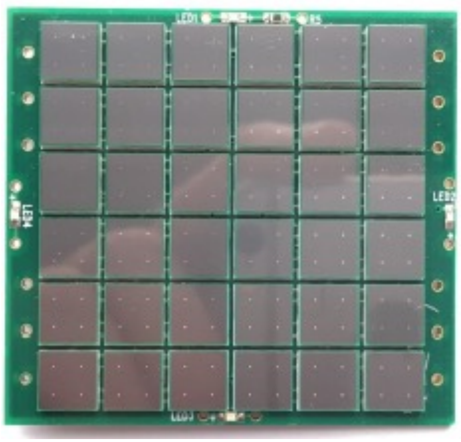


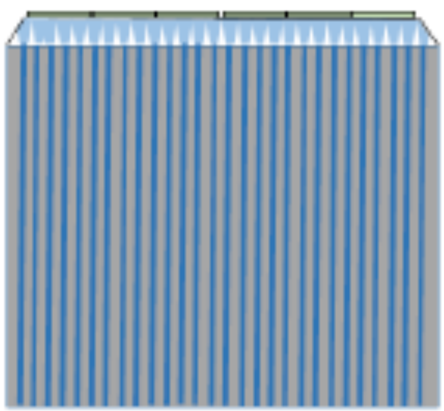


- **PHENIX EMCAL as reference:** Pb Shashlik EMCAL with total radiation length of 18 X0, scintillator thickness of 1.5 mm, and tower granularity about 5.5 × 5.5 cm^2
- **WCu**: an alloy of 80% W and 20% Cu absorber material for EIC shashlik EMCALs
- **WCu and Pb:** scintillator thickness of 1.0 mm
- **Longitudinal shower profile – effective radiation length:** PHENIX > Pb > WCu
- **Simulated Moliere radius:** WCu = 2.65 cm, Pb = 3.15 cm, PHENIX = 4.15 cm, reasonably consistent with the expected results WCu = 2.5 cm, Pb = 3.3 cm, and PHENIX = 4.5 cm

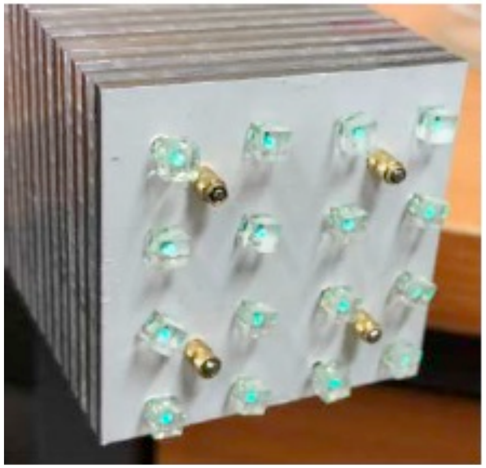
EIC EMCAL Design Options

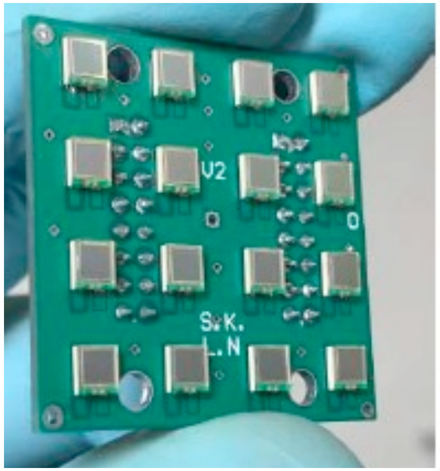
W/SciFi SPECAL design with more SiPMs and shorter light guides to have larger photocathode coverage





W/Shashlik tower design with high granularity and efficient readout



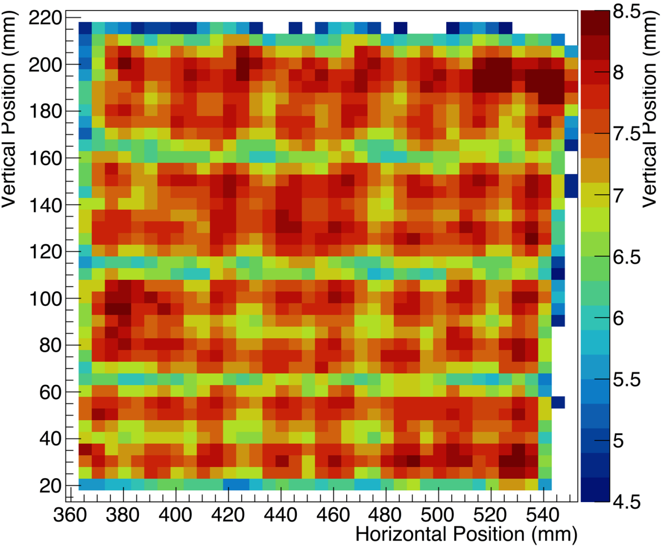


Proposed Novel Technologies

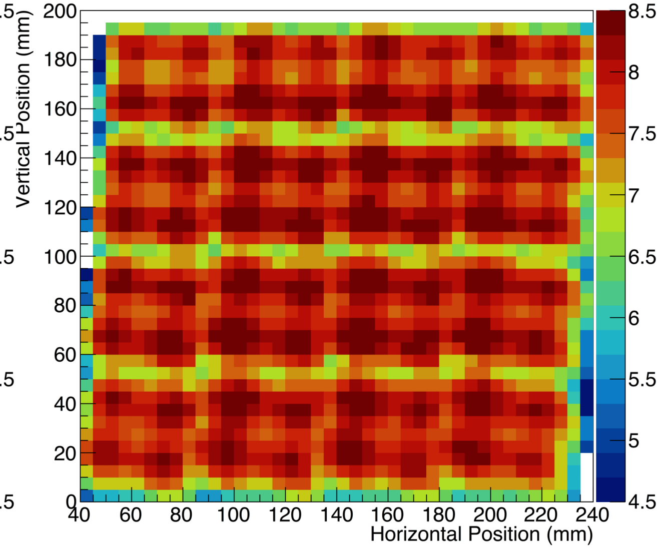
- W absorber for EMCAL to allow compact design to save space, crucial for EIC experiments
- Novel SiPMs to improve light collection efficiency and uniformity
- High granularity shashlik calorimeter with SiPM readout on every fiber

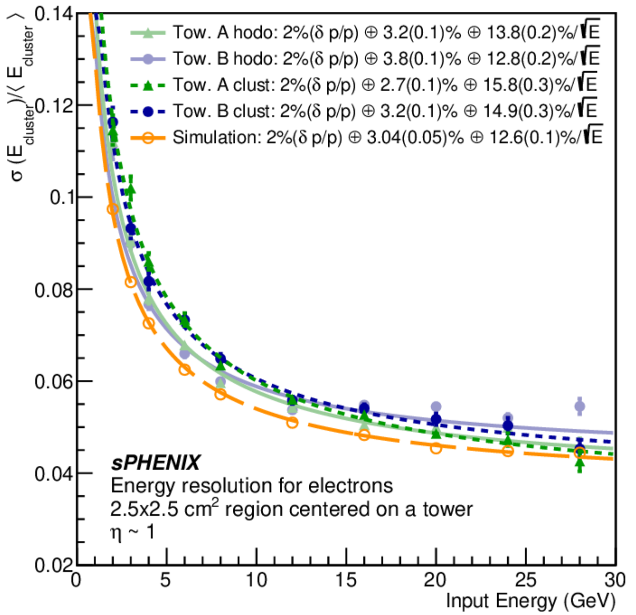
sPHENIX W/SciFi EMCAL Uniformity and Energy Resolution

Data



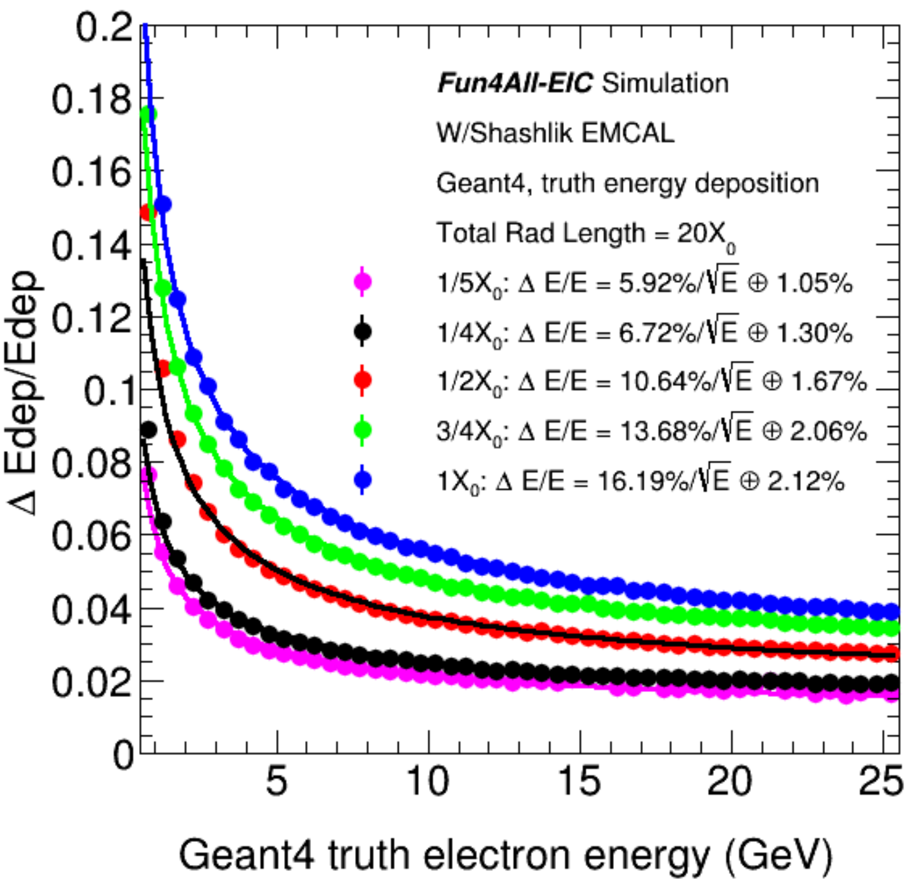
Simulation

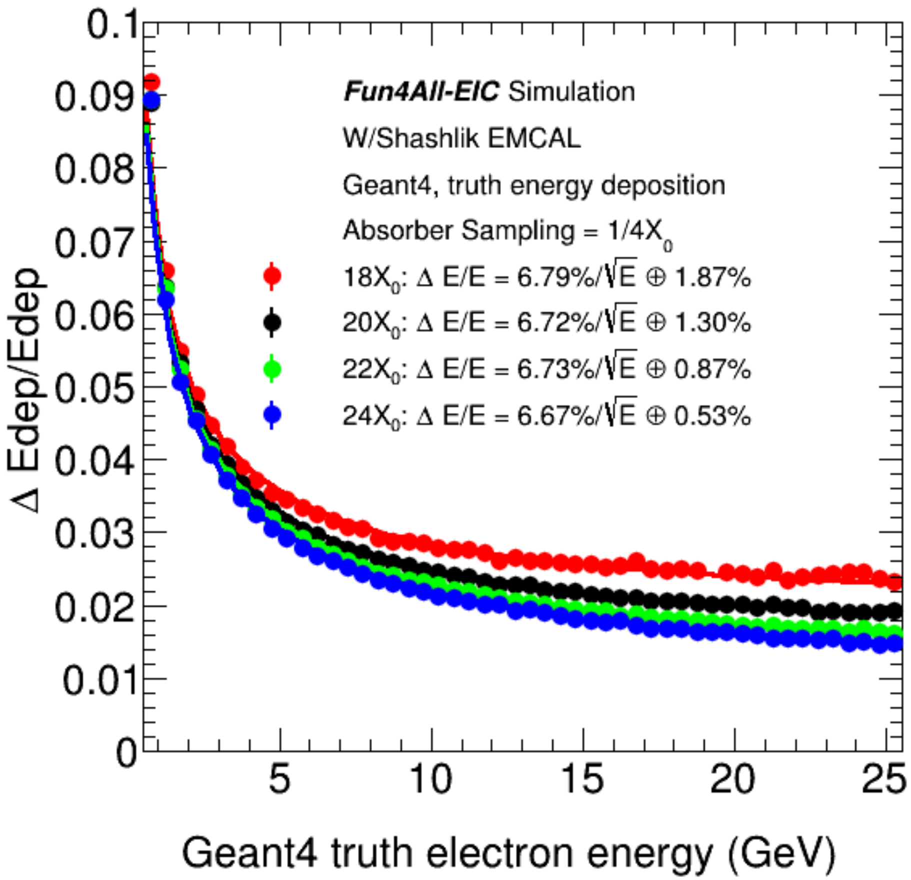




- Reasonably good agreement between the data and the simulation
- Significant non-uniformity, particularly between the block boundaries and the center of four blocks → position dependent correction with the simulations
- The uniformity and energy resolution both meet the requirements to achieve sPHENIX physics goals

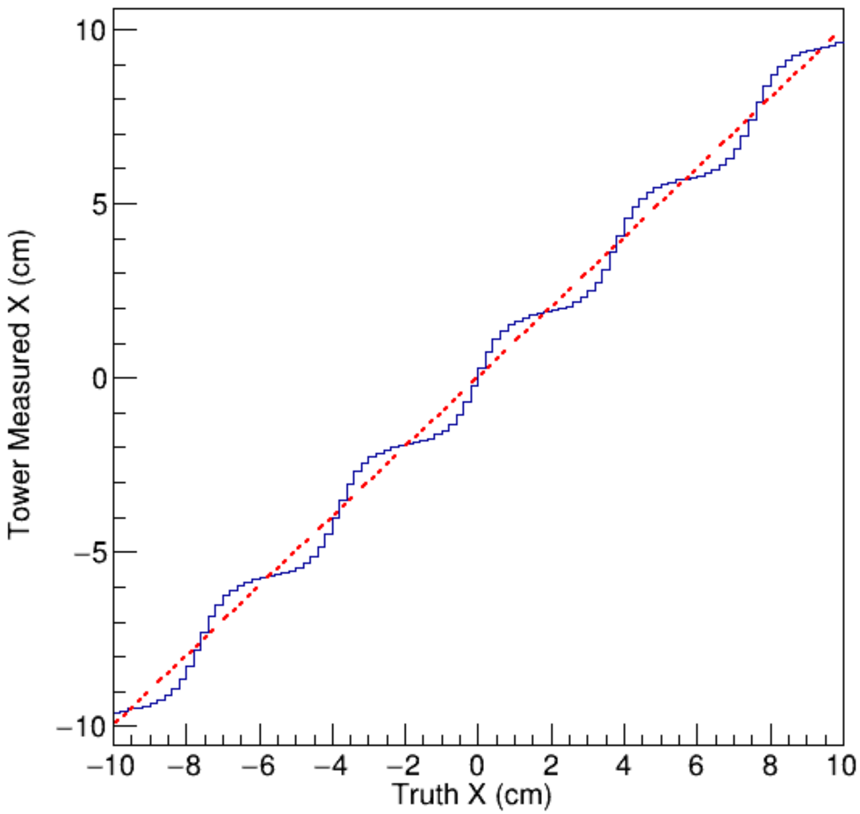
W/Shashlik EMCAL Energy Resolution

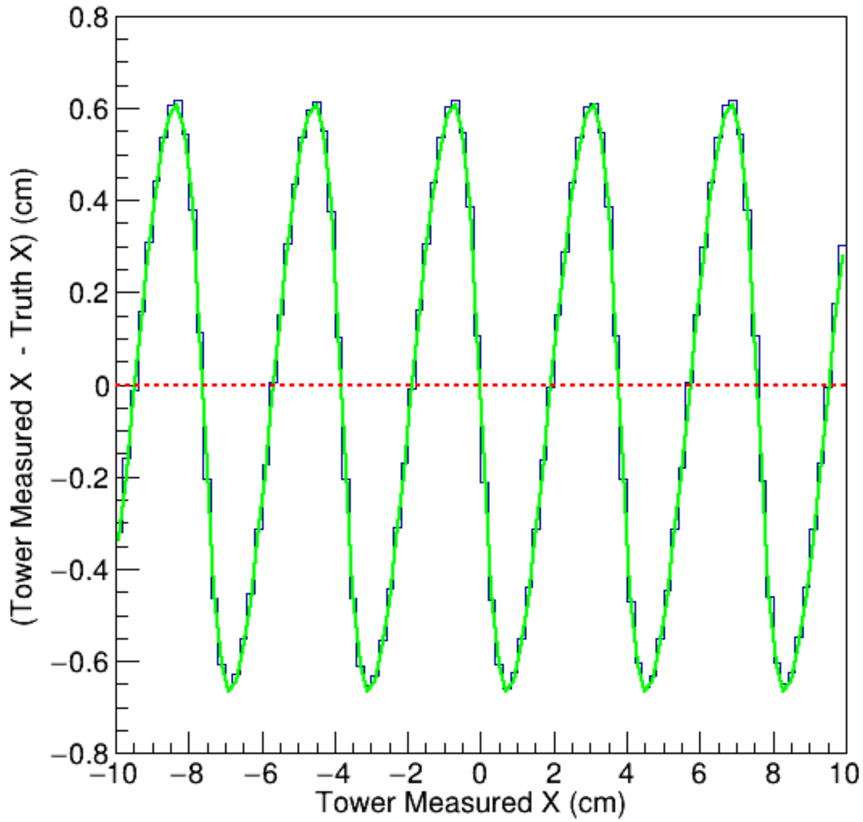




- The statistical term of the shashlik EMCAL improves as the sampling frequency increases
- The constant term of the shashlik EMCAL improves as the total radiation length increases
- This work is included in the EIC Yellow Report and ECCE and EIC Calorimetry workshops

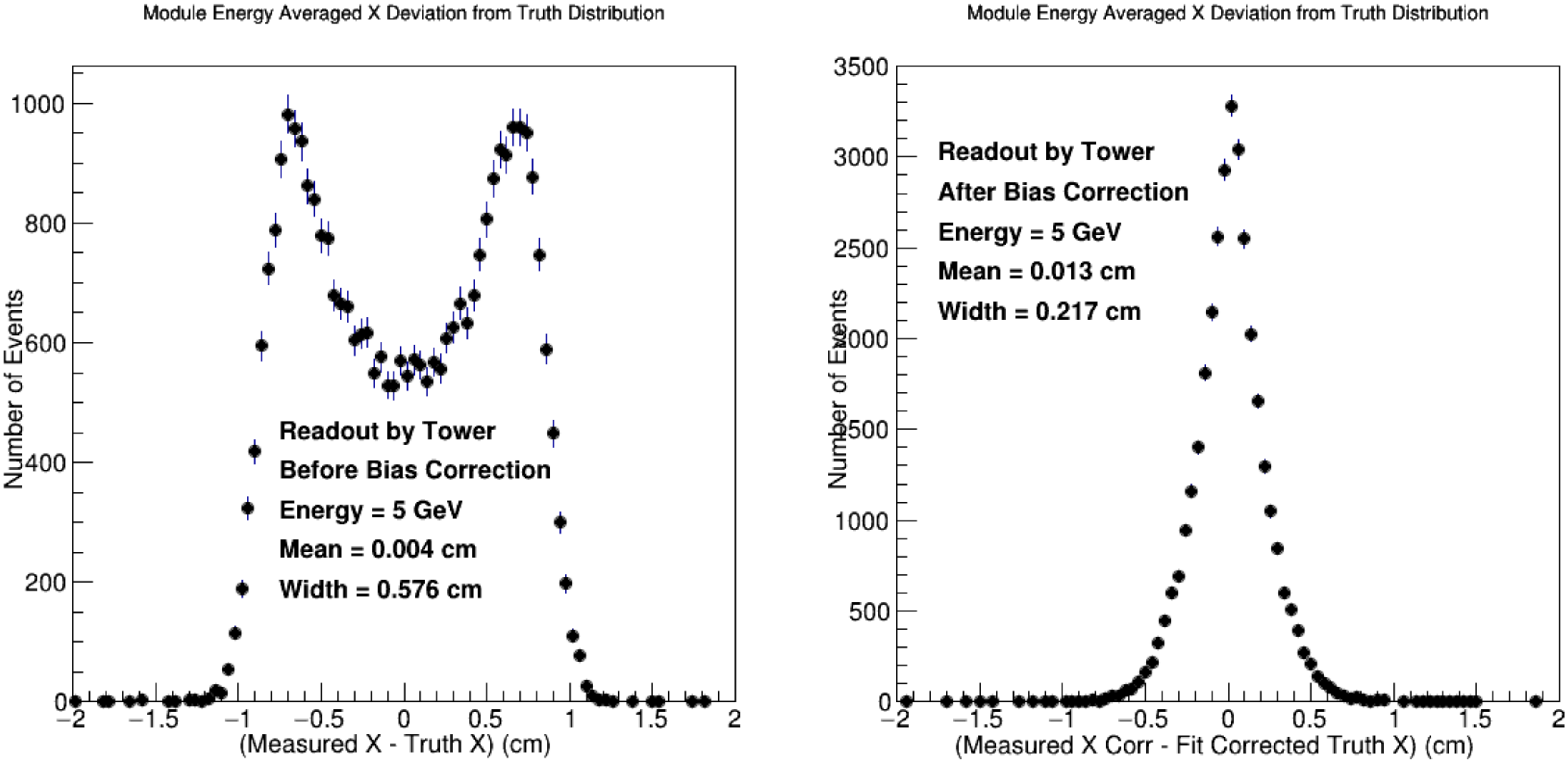
Position Bias Correction from Fits





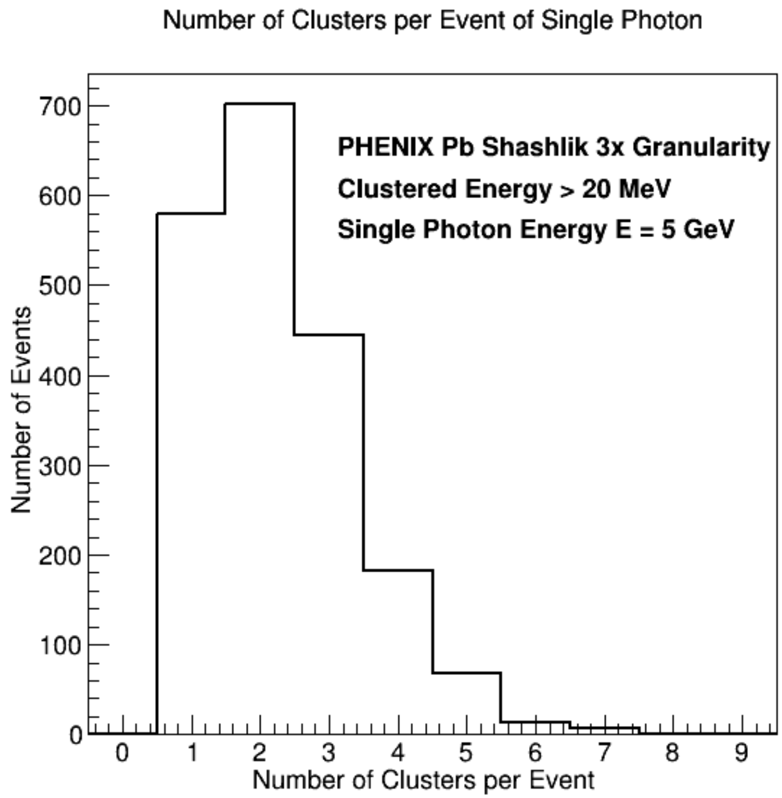
- Due to the large tower size and Moliere radius of the EM shower, there is potential bias of the measured (readout energy averaged) position
- Plot the measured position to 10th order Fourier function to correct the bias

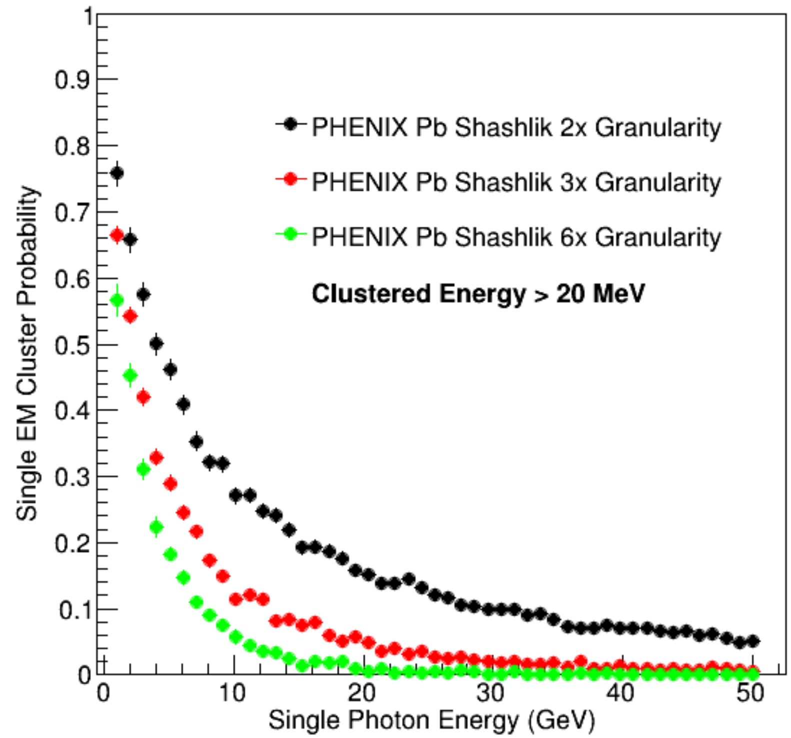
Correction for Position Resolution Studies



- Apply the fit functions to correct the position bias
- Deviation distribution changed from non-Gaussian to Gaussian centered at 0 after applying the bias correction function

Modification of Cluster Algorithm at High Segmentation





- More than 1 clusters for single photon events
- Current cluster algorithm parameter optimized for PHENIX and sPHENIX at RHIC
- Generally applied to EMCAL tower > Moliere radius R_M
- Optimize the parameter for EIC EMCAL: EMCAL tower size << Moliere radius R_M
- Potentially apply machine learning techniques in the clustering algorithm to improve the performance for EIC physics

Next Steps

- Develop the clustering algorithm dedicated for EIC EMCAL
- Finish π^0 merging probability studies for ECCE Pb EMCAL design with different tower sizes
- Compare the performance of alternative ECCE Pb EMCAL design with WCu absorber (smaller R_M)
- Study the π^0 merging probability with the analysis of EMCAL shower profile
- Investigate the feasibility of projective tower design in the forward EMCAL
- Present these studies at ECCE calorimeter meeting and provide recommendations for forward EMCAL design
- Possible test beam studies of shashlik EMCAL prototypes in the future