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

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The Electron-Ion Collider (EIC) is a future collider planned to be built at BNL in about a decade. It will provide physicists with high luminosity and highly polarized beams with a wide range of nuclei species at different energies, covering an extensive kinematic range. The EIC physics goals include measuring the Generalized Parton Distribution (GPD) from Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) experiments, performing precision 3D imaging of the nuclei structure, studying color confinement and hadronization mechanisms, and understanding the spin structure of the proton. In order to meet EIC physics goals, a high-resolution electromagnetic calorimeter (EMCAL) is required to measure electrons and photons and to achieve good particle identification. We propose two design options for EIC EMCALs. The first technique is to improve the resolution of tungsten/scintillating fiber (W/SciFi) EMCAL being built for sPHENIX with new technologies. The other possibility is to develop tungsten/shashlik (W/shashlik) EMCAL with better readout configuration to achieve better energy and position resolution. In this work, we will present the GEANT 4 detector simulation results of W and Pb shashlik EMCAL to study π^0 merging probability as a function of π^0 energy and the performance of position and energy resolution of ECCE EMCAL design.

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1. Introduction

It is believed that QCD is the last frontier of the Standard Model. So far, there is still no first principle calculations yet available to precisely describe the basic properties of proton such as mass, spin, and charge radius. Therefore, the EIC, providing high luminosity and highly beams with a variety of nuclei species, will be built to perform 3D tomography of the nucleons and nuclei by probing the transverse momentum distribution and generalized parton distribution function (GPD). Experimentally, GPD could be accessed in DVCS and DVMP processes [1]. According to the EIC Yellow Report [2], in order to probe the kinematic region of $10^{-5} < x < 0.7$, 1 $\mathrm{GeV}^2 < Q^2 < 1000$ GeV^2, $0 < |t| < 1.6$ GeV^2, the π^0 produced from DVMP should be constructed to at least 50 GeV. Hence, EIC experiments are required to have compact EMCALs with excellent energy resolution, excellent electron-photon separation, sufficient radiation hardness, and capabilities of detecting and identifying DVCS single photon and photon pairs from π^0 decays [2].

2. Shashlik EMCAL Design

We proposed to apply novel technologies in the development of the next generation shashlik sampling EMCAL for the EIC experiments. In the shashlik design, EMCAL plates with absorber material and scintillators are pierced by wavelength shifting readout fibers. There are two types of design options: W and Pb shashlik EMCALs. The Pb shashlik design has the advantages of lower cost and easier to machine. One existing example of the Pb shashlik EMCAL is the PHENIX EMCAL [3]. We can refurbish and reuse it by adding more silicon photomultiplier (SiPM) readout to increase its segmentation. Moreover, the ECCE Collaboration proposed a Pb shashlik EMCAL design with very fine granularity in its proposal submitted to the call for EIC Detector 1 [4].

On the other hand, W absorber material offers smaller radiation length and Moliére radius, allowing for compact EMCAL design, which is a prime factor of EIC experiments. However, W is generally more expensive and hard to machine. Thus, a softer alloy made of 80% W and 20% as the absorber material of the EMCAL prototype is employed by the UTFSM group in Chile [5] and will be studied in this paper. The WCu EMCAL design with high granularity and individual fiber readout is a novel calorimeter technology.

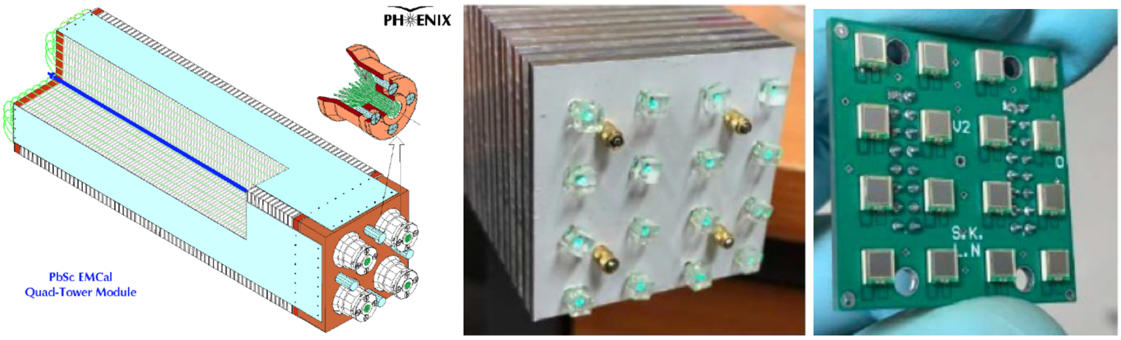

Figure 1: The schematic plot of PHENIX EMCAL (left), the front shashlik tower (middle), and 4 × 4 SiPM matrix readout electronics at the back (right) of WCu EMCAL prototype are shown above.

The general parameters of the PHENIX, ECCE, and WCu shashlik EMCALs are summarized on table below:

Table 1: Summary of the PHENIX, WCu, and ECCE shashlik EMCAL configurations

Shashlik EMCALs	PHENIX	WCu	ECCE Forward
Absorber Materials	Pb	W(80%) + Cu (20%)	Pb
Absorber Thickness	0.15 cm	1.025 cm	0.16 cm
Scintillator Thickness	0.40 cm	0.16 cm	0.40 cm
Number of Plates	66	72	66
Total Radiation Length (X/X_0)	18.2	18.0	18.5
Moliére Radius (R_M)	4.5 cm	2.5 cm	5.2 cm
Tower Dimension	5.535 cm × 5.535 cm	3.8 cm × 3.8 cm	0.92 cm × 1.00 cm
Readout Matrix	1 × 1	4 × 4	2 × 2

3. Light Collection Efficiency Map from *TracePro* Simulations

In shashlik EMCALs, the wavelength shifting fibers collect the light produced from the EM shower and transfer it to the electronic readout. For a tower with multiple fibers, the light produced inside the tower will be redistributed among all the fibers. In this work, EMCAL towers are assumed to be optically isolated. The light will undergo reflection and refraction and eventually be collected by the fibers within the tower. Thus, there will a light collection efficiency for each fiber dependent on the position of the light produced. Generally speaking, it has a strong dependence on the distance between position the light is produced and the fiber. We use *TracePro*, a commercial software modeling the optics of light rays, to perform a fine position scan simulation over the towers and obtain the light collection map of WCu and ECCE EMCAL towers.

Figure 2 shows the tower model implemented in *TracePro* and light efficiency collection maps of WCu EMCAL

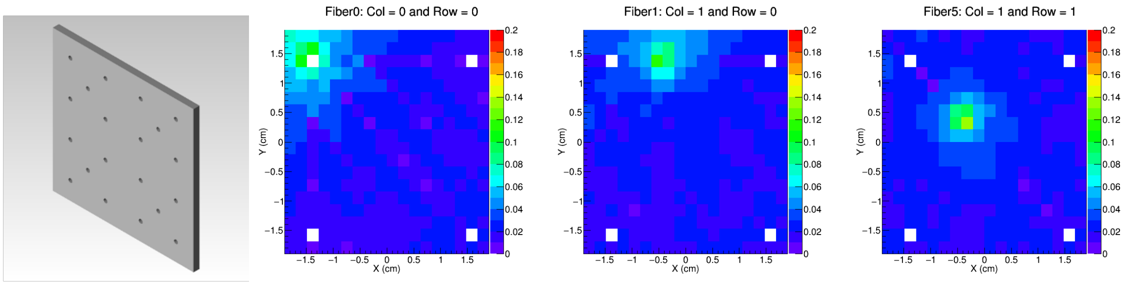

Figure 2: The schematic model of WCu EMCAL in *TracePro* simulation (left) and three light collection maps for fibers located at row and column (0,0), (1,0), and (1,1) are shown above. We should note that zero response happens when the light is produced right on four edges fixing the EMCAL plates.

Figure 3 shows the schematic design of ECCE forward EMCAL tower and the light efficiency collection map

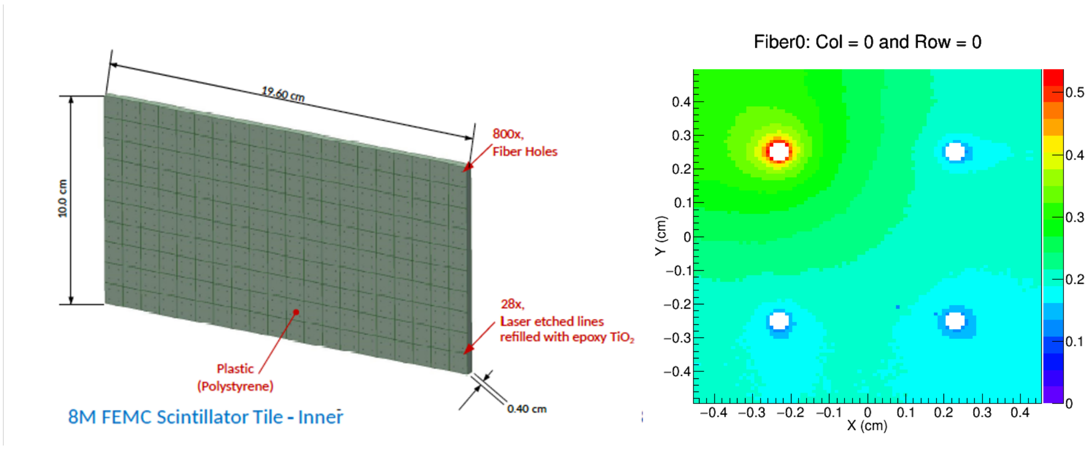

Figure 3: The schematic design of ECCE EMCAL towers (left) and the light collection maps for fibers located at (0,0) are shown above. The diameter of the the readout fiber is 500 μm.

It should be noted that we do not need to perform position scan on all fibers. The light collection maps of all other fibers within the WCu and ECCE towers can be generated by exploiting the reflection and rotational symmetry from the ones obtained in *TracePro* simulation.

4. GEANT 4 Simulation

Because we do not have the resources to conduct test beam on the shashlik EMCAL prototypes, we decide to carry out our studies using GEANT 4 simulations. We setup a testbed based on the geometry of the shashlik EMCAL and place the EMCAL in the forward direction shown below in Figure 4

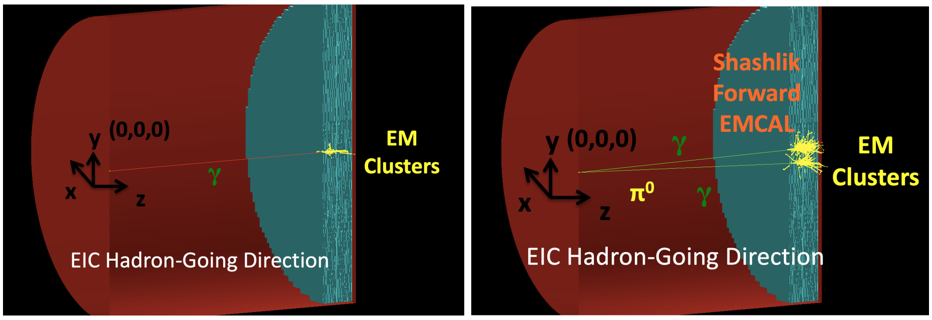

Figure 4: The event displays of a single photon (left) and $\pi^0 \to \gamma\gamma$ (right) producing EM showers in the EMCAL along the EIC hadron-going forward direction in GEANT 4 simulation are shown above.

In the simulations, photons and π^0 are generated from the particle gun. The EMCAL is placed about 3 m away from the particle gun. The EMCAL is setup as a wall without any hole just to emulate the test beam conditions. The radii of the PHENIX and WCu EMCAL are 183.5 cm, corresponding to the rapidity of $|\eta| > 1.27$. The radius of the ECCE EMCAL is 40 cm (significantly smaller due to memory issues in the simulation), corresponding to the rapidity of $|\eta| > 2.71$. We perform the studies on different readout schemes of the PHENIX, WCu, and ECCE EMCALs and study their performance. Figure 5 defines the readout variation of the ECCE EMCAL

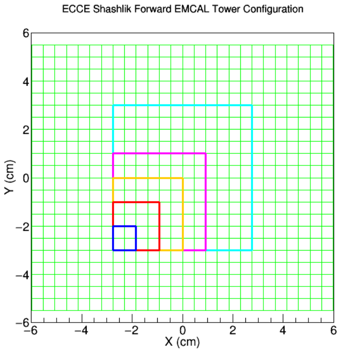

Figure 5: In our simulations of the ECCE EMCAL, we define the fiber (green, tower × 1/2), optically isolated tower (blue), tower × 2 (red), tower × 3 (orange), tower × 4 (magenta), and tower × 6 (cyan) shown as above. We save the fiber readout and then regroup the energy and position to model other readout scenarios.

5. Analysis Results

We perform the single photon with an energy scan from 1 – 17 GeV over a square range of -30 cm $< x <$ 30 cm and -30 cm $< y <$ 30 cm to study the position and energy resolution WCu and ECCE EMCAL shown below in Figure 6

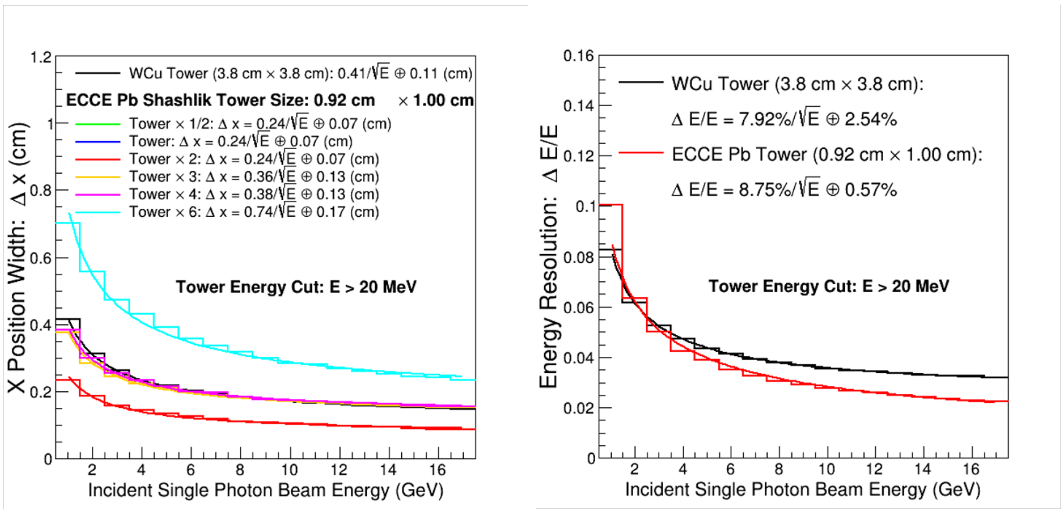

Figure 6: The position resolution of WCu and ECCE EMCALs with different readout schemes (left) and the energy resolution of WCu and ECCE EMCALs as well as their fits to the function $y = a/\sqrt{E} \oplus b$ are shown above.

For the position resolution, ECCE readout with fiber, tower, and tower × 2 have the same performance. As the granularity of ECCE EMCAL decreases to tower × 3, the position resolution is worsen significantly due to the effects of position bias correction. For tower × 4, the position resolution is only slight worse than tower × 3. There is yet another drastic drop in position resolution as the tower size increase to tower × 6, larger than the Moliére radius of the ECCE EMCAL. The position resolution of WCu EMCAL readout by tower (black) has similar performance to ECCE tower × 3 and tower × 4.

The energy resolution does not depend on granularity. The ECCE EMCAL has a better constant term in energy resolution than the WCu EMCAL because of the better energy uniformity of its light collection map.

In addition, we study π^0 reconstruction and merging probability of the PHENIX and WCu EMCALs shown in Figure 7.

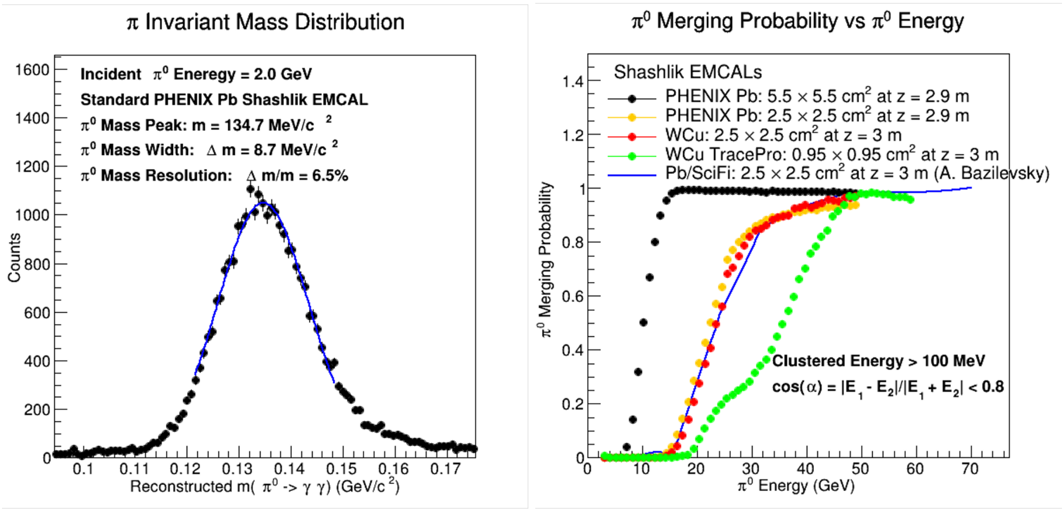

Figure 7: The invariant mass of π^0 reconstructed from the two photon (left) with the EMCAL and π^0 merging probability as a function of π^0 energy with different EMCAL designs are shown above. It should be noted that we only use cluster counting information to determine π^0 merging probability. We do not look into the shower profiles of the clusters in each event to distinguish whether they come from a single photon or two photons.

After single photon calibration, the shashlik EMCAL is able to reconstruct π^0 with correct invariant mass (about 135 MeV/c^2) with good resolution. However, the PHENIX EMCAL (black) can only reconstruct π^0 up to about 10 GeV. When we increase the PHENIX EMCAL segmentation by a factor of 2 (orange), the EMCAL pushes the π^0 energy up to about 40 GeV. However, if we switch the absorber material from Pb (orange) to WCu (red), which has a smaller Moliére radius, but keep the same granularity, the WCu EMCAL is only slightly better than the PHENIX Pb EMCAL. For reference, we compare our shashlik EMCALs with Pb/SciFi EMCAL (blue) [6] at similar granularity and find that they have similar π^0 decay photon separation performance. Finally, the WCu EMCAL with light efficiency collection map and individual fiber readout (green) is capable of reconstructing π^0 up to 50 GeV, which satisfies the requirements for EIC physics.

6. Summary

In summary, we have explored different Pb and WCu shashlik sampling EMCAL designs and studied their performance including the case that tower size is smaller than the Moliére radius. We also apply the *TracePro* software to simulate the optics inside the tower and obtain the light collection efficiency maps.

A strong dependence of the tower granularity on the position resolution and π^0 merging probability is observed from the drastic improvement of the position resolution and the π^0 merging probability as the granularity increases. However, the dependence of Moliére radius of the EMCAL is weak because the position resolution of WCu EMCAL with tower readout (3.8×3.8 cm^2) and ECCE Pb shashlik EMCAL with tower × 4 readout (3.68×4.0 cm^2) and the π^0 merging probability of WCu and PHENIX EMCALs at 2.5×2.5 cm^2 tower granularity are both similar. We are able to reconstruct π^0s up to 50 GeV with the WCu EMCAL if we readout individual fibers.

We also find that due to the lack of sensitivity to the Moliére radius in the ECCE EMCAL design, the tower readout size could be increased by a factor of 2, which would reduce the readout channels by a factor of 16, thus saving on cost. In addition, the energy resolution of ECCE EMCAL is better than the WCu EMCAL due to the better uniformity of its light efficiency collection map.

7. Outlook

We plan to finish the π^0 merging probability study of ECCE EMCAL with different readout options and compare them with the alternative design of WCu EMCAL for ECCE. However, the clustering algorithm we are currently using is optimized for the heavy-ion experiments PHENIX and sPHENIX at RHIC where the tower size is greater than the Moliére radius but not for EIC experiments where the tower size will be smaller than the Moliére radius. Multiple clusters are observed in a single photon event, which makes it impossible to study the π^0 merging probability using a simple cluster counting method. Therefore, the clustering algorithm will be a critical factor to decide the EIC EMCAL design. Hence, we need to develop a new clustering algorithm dedicated for EIC EMCALs. Machine learning techniques may be applied to develop the clustering algorithm.

In the future, we should also study the π^0 merging probability by investigating the shower profile to push up the energy of π^0 decay photons separation. The study of electron-hadron separation performance should also be carried out as part of the requirements of EIC EMCALs.

8. Acknowledgement

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