Development of Future Electromagnetic Calorimeter Technologies and Applications for the Electron-Ion Collider with GEANT4 Simulations

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Abstract. 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 the physics goals of EIC, a high-resolution electromagnetic calorimeter (EMCAL) is required to measure electrons and photons and to achieve good particle identification. We propose to develop a tungsten/shashlik (W/shashlik) EMCAL with better readout configuration to achieve better energy and position resolution. In this work, we will present the GEANT4 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 resolutions of the EMCAL for ECCE design.

1 Introduction

It is arguably believed that Quantum Chromodynamics (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 polarized 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, GPDs could be accessed in DVCS and DVMP processes [**?**]. According to the EIC Yellow Report [**?**], in order to probe the kinematic regime of $10^{-5} < x < 0.7$, 1 $\text{GeV}^2 < Q^2 < 1000$ GeV^2, and $0 < |t| < 1.6$ GeV^2, the π^0 produced from DVMP should be reconstructed up to at least 50 GeV. Hence, due to the limited installation space, EIC experiments are required to have compact EMCALs with excellent energy resolution, excellent electron-photon separation performance, sufficient radiation hardness, and capabilities of detecting and identifying DVCS single photon and photon pairs from π^0 decays [**?**].

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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 connected by wavelength shifting readout fibers. There are two design options: W and Pb shashlik EMCALs. The Pb shashlik design has the advantages of lower cost and easier to machine. One existing example is the PHENIX EMCAL [**?**]. 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 to the call for the EIC Detector 1 [**?**].

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

3 Detector Simulation Setup

In our design, the EMCAL towers are optically isolated and equipped with wavelength shifting fibers that read out the visible energy. We utilize *TracePro* [**?**], a commercial software that models the optics of light rays, to simulate the light collection efficiency of individual fibers within a tower through position scans with fine steps.

Using the GEANT4 simulation framework, we setup a testbed for the shashlik EMCAL in the EIC hadron going direction to model test team conditions. The EMCAL is a solid circular wall placed about three meters from the beam origin. We use a particle gun to generate the γ and π^0 and simulate photon EM showers in the PHENIX Pb, WCu, and ECCE Pb shashlik EMCALs with different readout granularities. In particular, since the ECCE EMCAL has a 2 × 2 fiber readout for each tower, we define several readout options: individual fiber readout (green), individual tower readout (blue), 2 × 2 towers (red), 3 × 3 towers (orange) and 4 × 4 towers (magenta), and 6 × 6 towers (cyan). The simulation details are documented in reference [**?**].

4 Analysis Results

We performed single photon simulations to study the position and energy resolutions of the WCu and ECCE EMCAL shown below in Figure **??**.

The ECCE EMCAL readout with individual fiber, individual tower, and 2 × 2 towers all have the same position resolution performance. As the granularity decreases to 3 × 3 towers readout, the position resolution is significantly worse due to position bias correction. For 4 × 4 towers readout, the position resolution is only slightly worse than 3 × 3 towers readout. The position resolution continues to drop as the readout size increases to 6 × 6 towers, which is larger than the Moliére radius of the ECCE EMCAL. The position resolution of the WCu EMCAL readout by tower (black) has similar performance to the ECCE tower.

The energy resolution does not depend on granularity. The ECCE EMCAL has a smaller constant term in energy resolution than the WCu EMCAL because its light collection efficiency is more uniform than the WCu one.

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

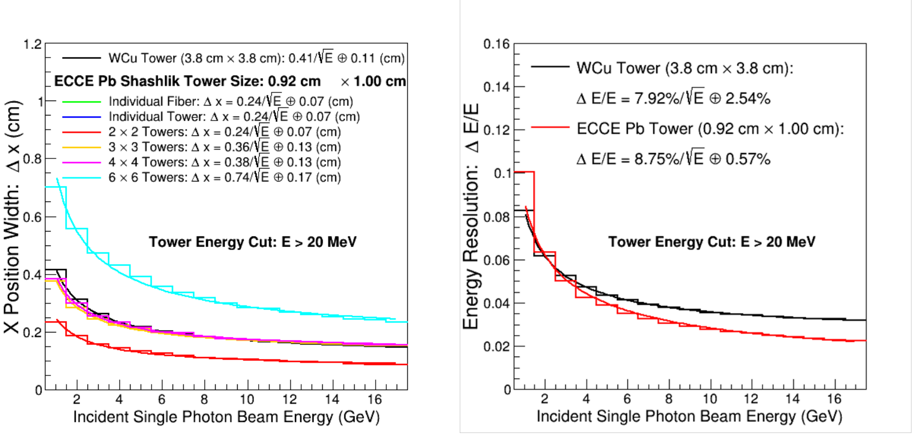

Figure 1. The position resolution of the WCu and ECCE EMCALs with different readout schemes (left) and the energy resolution of the WCu and ECCE EMCALs as well as their fits to the function $y = a/\sqrt{E} \oplus b$ are shown above. Individual fiber (green), individual tower (blue), and 2 × 2 towers (red) are overlapping with each other and only the 2 × 2 towers data points are seen.

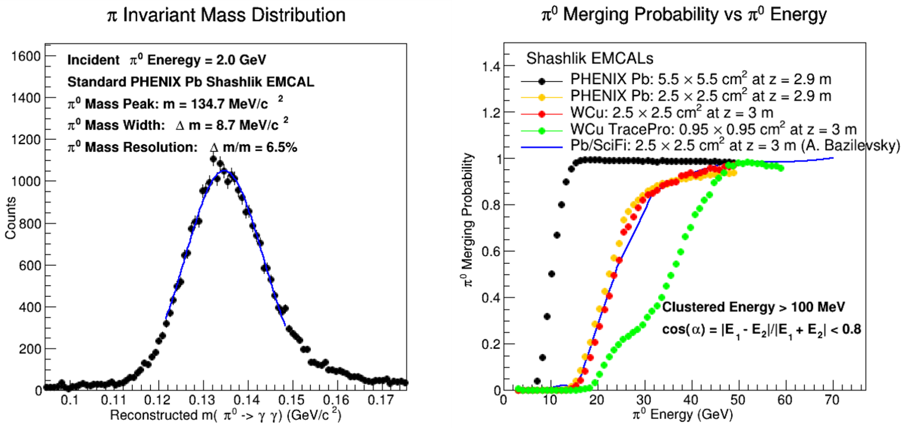

Figure 2. The invariant mass of π^0 reconstructed from the two photon (left) with the EMCAL and π^0 merging probability as a function of π^0 energy with different EMCAL designs (right) are shown above. Only cluster counting information is used to determine the π^0 merging probability. We did not look into the shower profiles of the clusters to distinguish a single photon or two photons.

After the single photon calibration, the shashlik EMCAL is able to reconstruct π^0 with the correct invariant mass (about 135 MeV/c^2) and 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 change 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 to

Pb/SciFi EMCAL (blue) [**?**] with similar granularity and find that they have similar π^0 decay photon separation performance.

5 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 utilized the *TracePro* software to model the optics inside the tower and obtain the light collection efficiency maps.

A strong dependence of the readout granularity on the position resolution and π^0 merging probability is observed and found the significant 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 individual towers readout (3.8×3.8 cm^2) and ECCE Pb shashlik EMCAL with 4×4 towers 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^0 up to 50 GeV with the WCu EMCAL if we read out individual fibers using only cluster counting without utilizing the shower shape information.

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 4, thus saving on cost. In addition, the energy resolution of ECCE EMCAL is better than the WCu EMCAL thanks to the better uniformity of its light efficiency collection map.

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