PROCEEDINGS OF SCIENCE

The Backward Hadronic Calorimeter (nHCal) of the ePIC Experiment at EIC

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The planned Electron-Ion Collider (EIC) at Brookhaven National Laboratory will be a unique, high-luminosity accelerator which will explore the parton and spin structure of protons and nuclei by colliding polarized electrons with polarized protons and ions. The ePIC (electron-Proton/Ion Collider) detector will be the first general-purpose detector designed for the EIC, covering a wide area in the $x_{Bj} - Q^2$ across a range of center-of-mass energies. The backward hadronic calorimeter (nHCal) will be crucial for low-x_{Bj} measurements, which are essential to the EIC's physics program. This detector will enhance hermeticity and improve scattered electron tagging by serving as a hadronic veto. This proceeding presents the design, physics motivation, and expected performance of the nHCal.

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1. Introduction

The Electron-Ion Collider (EIC) is a next-generation accelerator facility to be constructed at the current site of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The EIC will yield electron-proton and electron-ion collisions with variable center-of-mass energies ranging from 20 to 140 GeV for electron-proton collisions, with ion beams spanning from deuterons to heavy nuclei such as gold, lead, and uranium [1]. The facility is designed to achieve high electron-nucleon luminosities of 10^{33} to 10^{34} cm^{-2}s^{-1}.

The EIC science program addresses fundamental questions about the structure of visible matter. How are sea quarks, gluons distributed inside the nucleon? How do nucleon properties such as mass and spin emerge from quark and gluon interactions? What happens to gluon density in nuclei at high energy, corresponding to low Bjorken-x, and does it saturate, potentially giving rise to a universal gluonic matter with similar properties across all nuclei and perhaps even within individual nucleons [2]?

The ePIC detector will be the first general-purpose detector of EIC to be installed at interaction point IP6. It features a 1.7 T solenoidal superconducting magnet and comprehensive detector systems covering both forward (positive pseudorapidity, hadron-going direction) and backward (negative pseudorapidity, electron-going direction) regions. As shown in Figure 1, ePIC is designed to provide extensive tracking, particle identification, and calorimetry.

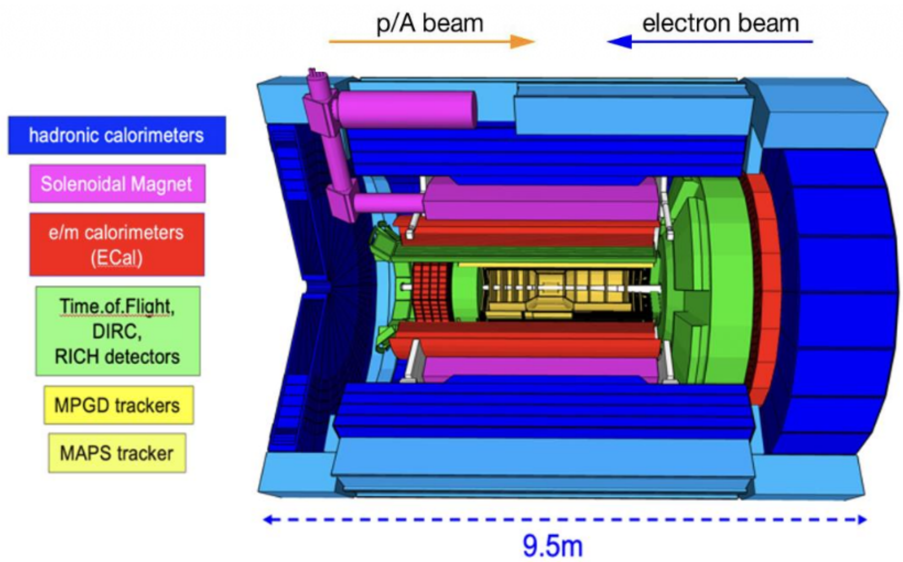

Figure 1: The ePIC detector layout showing the sub-systems. The nHCal is located in the backward (electron going) region.

2. The Backward Hadronic Calorimeter Design

The negative hadronic calorimeter (nHCal) is a tail-catcher sampling calorimeter in the backward region of the ePIC detector at $z = -3.95$ m from the interaction point. It provides pseudorapidity coverage of $-4.14 < \eta < -1.18$, corresponding to the electron-going direction.

2.1 Technical Specifications

One possible design of nHCal consists of ten alternating layers of steel absorber and plastic scintillator tiles, with a total depth of approximately 45 cm, corresponding to about 2.4 nuclear interaction lengths (λ_0). Each layer comprises 4 cm thick non-magnetic steel absorber plates and 4 mm plastic scintillator tiles. Silicon photomultipliers (SiPMs) will be mounted on tiles for light collection.

The calorimeter will be surrounded by an outer collar and backed by a flux return plate, with an oculus ring placed in front [3] as illustrated in Figure 2. The backward region experiences relatively low radiation doses compared to the forward region, which makes the use of SiPMs safe as those are expected to maintain stable performance throughout the planned operational lifetime of the experiment without requiring replacement or significant recalibration.

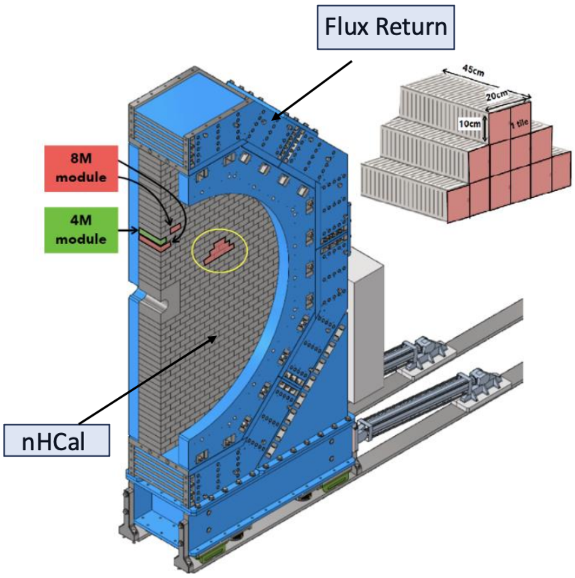

Figure 2: Schematic of the nHCal detector, showing its placement within the backward flux return plate. The inset illustrates the modular, stepped structure of the calorimeter modules.

The nHCal project is a collaborative effort involving several institutions, including The Ohio State University (OSU), University of Illinois Urbana-Champaign (UIUC), Czech Technical University in Prague (CTU), University of New Hampshire (UNH), and Brookhaven National Laboratory (BNL). Tile testing using cosmic ray muons is currently in progress at OSU to characterize light yield, minimum ionizing particle (MIP) response, and detection efficiency.

3. Physics Motivation

3.1 Lessons from HERA

The importance of backward hadronic calorimetry in electron-hadron collisions was demonstrated by the H1 detector at HERA, particularly following the SpaCal calorimeter upgrade [5, 6]. The difference in energy depositions between electromagnetic and hadronic sections enabled improved electron-pion separation at low-x_{Bj}. At low energies, fake electron signatures from photoproduction events, where the scattered electron escapes through the beampipe, could be effectively mitigated. The improved hermeticity proved crucial for reconstructing events requiring accurate hadronic energy measurements, such as photoproduction and charged-current interactions.

3.2 Diffractive Processes

Diffractive deep inelastic scattering (DDIS) processes constitute a significant fraction of the total electron-proton cross-section. Exclusive vector meson production, where a specific vector meson such as J/ψ or ϕ is produced and the target remains intact, provides a powerful tool for exploring hadron structure and will be a key measurement at the EIC. As shown in Figure 3, Sartre simulations [4] of these processes at EIC kinematics indicate that the produced J/ψ mesons often fall within the acceptance of the nHCal. The nHCal is essential for the reconstruction of these final states, especially to achieve significant geometric acceptance for accessing the low-x_{Bj} region ($x_{Bj} < 10^{-3}$), as demonstrated in studies of exclusive ϕ production (Figure 4) [7].

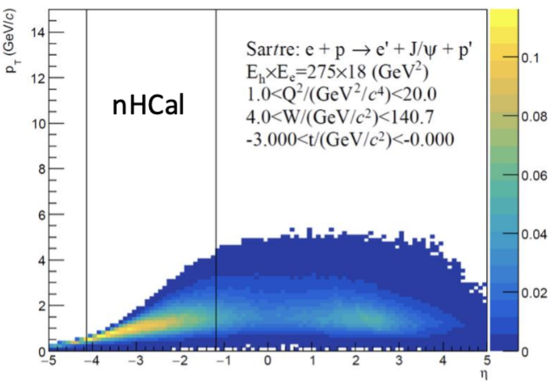

Figure 3: Simulated kinematics (p_T vs. η) for exclusive J/ψ production. The nHCal acceptance region is indicated.

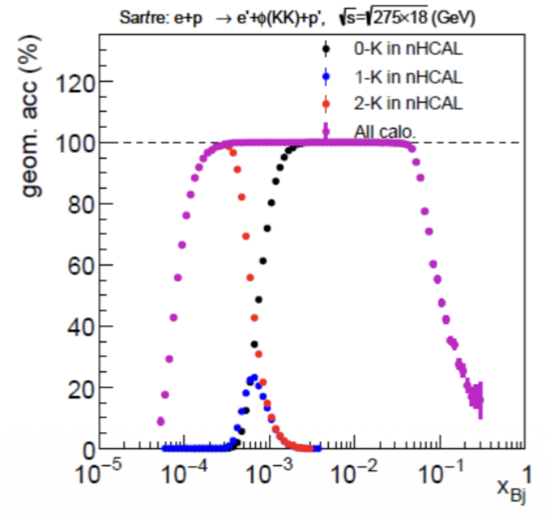

Figure 4: Geometric acceptance for exclusive $\phi \to K^+K^-$ production as a function of x_{Bj}, showing the different number of K in nHCal [7].

3.3 Neutral Hadron Veto and Jet Measurements

Accurate jet energy measurement is crucial for many physics analyses at the EIC. The resolution of jets is affected by the presence of neutral hadrons (neutrons, K_L^0, etc.), which do not leave a track and deposit energy differently than charged hadrons. Events at low x_{Bj} and high inelasticity (y) often produce hadronic activity in both the forward and backward directions. The nHCal provides the capability to veto jets containing neutral hadrons in the backward region. As shown in the EIC Yellow Report studies [1], this veto capability can substantially improve both the jet energy scale and resolution. This functionality depends critically on the ability to isolate individual particle showers within the calorimeter.

4. Performance Studies

4.1 Charged Hadron Correction and Neutral Energy Reconstruction

A key challenge in hadronic calorimetry is separating the energy deposits of neutral hadrons from nearby charged hadrons. When a charged hadron and a neutral hadron hit the calorimeter in close proximity, their showers can overlap, leading to the merging of reconstructed clusters. To address this, a "charged hadron correction" algorithm was implemented. The algorithm uses information from the tracking system to identify clusters associated with charged particles. If the energy of a charged-matched cluster ($E^{\mathrm{Reco}}_{\mathrm{charged}}$) is significantly larger than the momentum (p) measured by the tracker, it suggests that a neutral hadron's energy has been merged into the cluster. A condition, such as $|\left(E^{\mathrm{Reco}}_{\mathrm{charged}} - p\right)/\sigma_E| > 3.0$, can be used to flag such cases. The excess energy can then be attributed to a neutral hadron. Figure 5 indicate that good neutral energy separation is achievable for clusters separated by approximately 30 cm or more in the nHCal plane. This spatial separation requirement guides optimization of the detector segmentation and clustering algorithms.

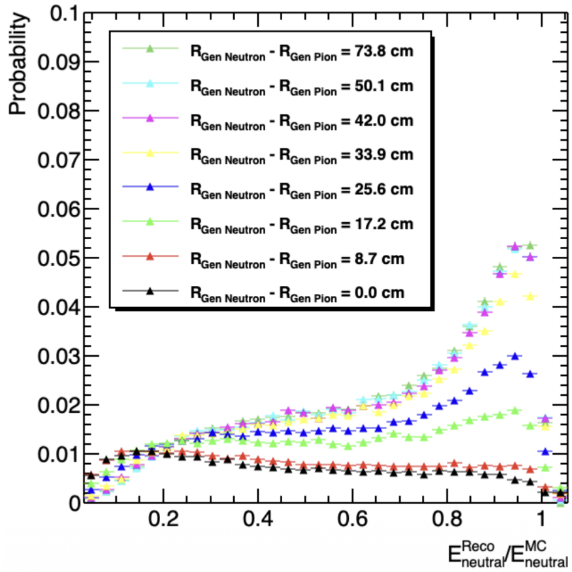

Figure 5: Performance of the neutral energy reconstruction as a function of the reconstructed-to-MC energy ratio. The different curves correspond to varying separations between the generated neutron and pion impact points in the nHCal plain. Good separation is achieved for distances greater than $\sim$ 30 cm.

4.2 Position Resolution

Single-particle neutron simulations have been performed to optimize detector geometry and study position resolution. Studies demonstrate that tile size has negligible impact on transverse position resolution, as hadronic showers are significantly wider than the tile dimensions in consideration (5cm $\times$ 5cm, 10cm $\times$ 10cm, and 15cm $\times$ 15cm). This gives flexibility in the choice of segmentation for the final design. Approximately 68% of neutrons interact in the upstream electron endcap electromagnetic calorimeter (EEEMCal) before reaching the nHCal, which can affect position resolution due to scattering. This scattering may also cause some neutron energy to fall outside jet reconstruction cones, potentially affecting jet energy measurements.

5. Summary and Outlook

The backward hadronic calorimeter (nHCal) is a crucial component of the ePIC detector for studying the low-x_{Bj} physics program at the EIC. Its role includes facilitating studies of diffractive events and vector meson production at low-x_{Bj}, acting as a neutral hadron veto to improve charged jet identification and energy measurement, and providing hermetic coverage for complete event reconstruction in the backward region.

The nHCal collaboration continues to grow, with ongoing activities in simulation, hardware testing, and reconstruction algorithm development. One possible design features a sampling calorimeter with steel absorbers and scintillator tiles read out by SiPMs, providing approximately 2.4 nuclear interaction lengths of material. Performance studies demonstrate the feasibility of separating neutral and charged hadron contributions through tracking-calorimeter matching and shower position analysis.

Opportunities exist for additional contributions in all areas including simulation studies, tile testing and characterization, hardware development, and reconstruction algorithm optimization. The successful implementation of the nHCal will be essential for realizing the full physics potential of the EIC in exploring the fundamental structure of visible matter.

References

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