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ECCE forward physics and detector design at the future Electron-Ion Collider

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The proposed ECCE detector at the future Electron-Ion-Collider (EIC) at Brookhaven National Laboratory is a physics-driven design concept, meeting and exceeding the EIC physics program requirements. To gain further insights on the partonic structure of the nucleon, jets in the hadron-going (forward) direction provide an excellent probe. They provide a strong handle on parton kinematics in e-p and e-A collisions and their internal structure can further advance our understanding of the complex hadronization process as well as basic principles of QCD. Thus, ECCE features highly granular electromagnetic and hadronic calorimetry, as well as high resolution tracking and excellent PID detectors to enable detailed studies of jets and their components. For this, the appropriate mix of novel and established detector technologies have been selected and their performance have been studied in detail. The performance of the forward detectors and the resulting physics capabilities are presented.

International Converence on High Energy Physics (ICHEP 2022)
6–13 July 2022
Bologna, Italy

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PoS(ICHEP2022)315

1. The Electron-Ion Collider at BNL

In the long standing history of nuclear physics, multiple large and small scale experiments have aimed at studying the stages of matter as it existed in the early universe. With the help of these experiments it has become possible to shine a light on a special form of matter where quarks and gluons form a "perfect liquid" and can move freely without being confined into bound states. In addition, the main building block of the universe, the proton, stands at the center of such experiments as its inner structure and the properties inherited by its constituents remain a critical component in our understanding of a large fraction of nuclear physics.

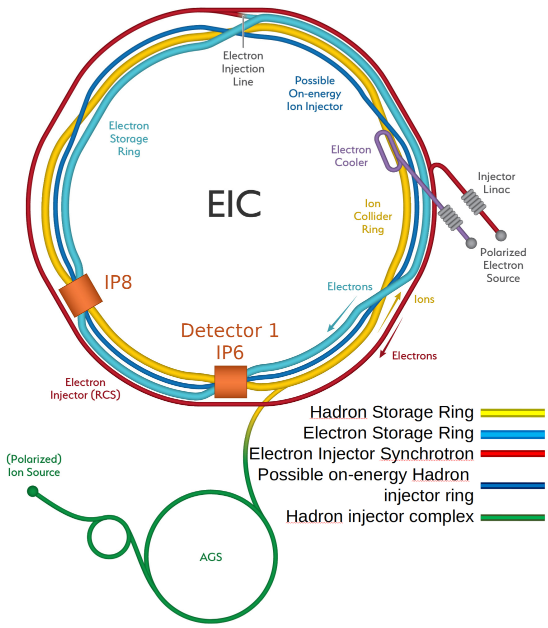

Figure 1: The future Electron-Ion Collider accelerator complex at Brookhaven National Laboratory including both interaction points. The hadron and electron accelerator and storage rings are shown in yellow and blue, respectively.

The new facility of the Electron-Ion Collider at the Brookhaven National Laboratory is part of a large project that builds on top of the existing infrastructure of the RHIC accelerator complex [1]. The addition of new electron accelerator and storage rings as well as a new electron source will allow for collisions of electrons and hadrons (e+p and e+A). The full accelerator complex is visualized in Figure 1. Similar to RHIC, a vast range of center-of-mass energies ($\sqrt{s} = 20 - 140$ GeV) can be sampled in order to possibly determine thresholds for certain physics processes. With the upgrades to the accelerator it will also be possible to run at a high polarization ($\sim 70\%$) for both the electron and the hadron beam. Located along the accelerator ring are two interaction points (IP6 and IP8), where the STAR and PHENIX experiments were placed at RHIC. The first interaction point to be instrumented is IP6, while the instrumentation of IP8 is considered as a future upgrade.

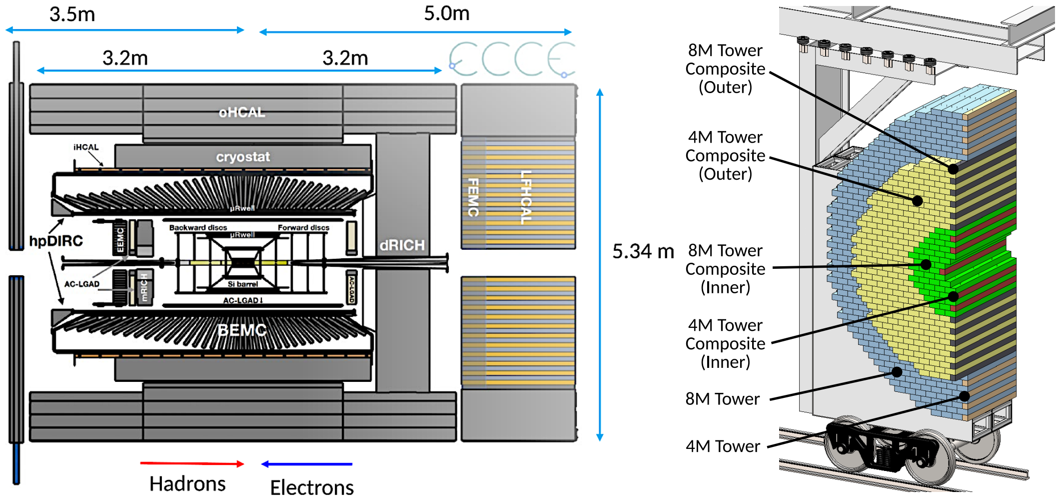

Figure 2: Left: Profile sketch of the ECCE detector indicating the beam directions and different subdetectors [2]. Right: Mechanical drawing of the combined FEMC and LFHCAL assembly and the various module sizes required to build the full detector geometry.

2. The EIC Comprehensive Chromodynamics Experiment - ECCE

Chosen as the reference design for the EIC project detector 1, the ECCE detector [2] originated from the efforts of hundreds of scientists around the globe to fulfill the detector requirements outlined in the EIC yellow report [3]. The detector is largely based around a reuse of existing components like the 1.5T BaBar solenoid or the sPHENIX outer hadronic calorimeter as well as large parts of already available infrastructure [4]. This approach was chosen to minimize costs and risks associated with detector technologies. Based on the dimensions of the BaBar solenoid, the detector itself is compact with 8.5m length and an approximate diameter of 5.4 meters while fulfilling the requirements to be installed at IP6 where a beam crossing angle of 25mrad is expected. A profile view of the detector is shown in Figure 2 (left) indicating the different subsystems as well as the beam directions.

The detector is composed of a multitude of subsystems based on different technologies. In general, a separation into the backward (electron-going), barrel and forward (hadron-going) direction can be made where the focus is put on the reconstruction of the expected particles in those regions. The backward region requires an excellent reconstruction and identification of the scattered beam electron. For this, the combined information from high resolution MAPS-based tracking [5], Cerenkov and time-of-flight (TOF) based PID as well as $PbWO_4$ crystal calorimetry for a precise energy measurement are employed. In the barrel region, the focus is shifted to lower momentum particle measurements with multiple MAPS silicon and μRWell tracking layers for a precise track reconstruction that is supported by additional Cherenkov and TOF-based PID. Furthermore, energy measurements of electromagnetic particles can be made with a semi-projective SciGlass calorimeter and with a hadronic calorimeter for hadronic particles.

Similar to the other detector regions, the forward region is also covered by MAPS-based tracking layers (5 disks at different positions along the beam axis with 10μm pixel size) and

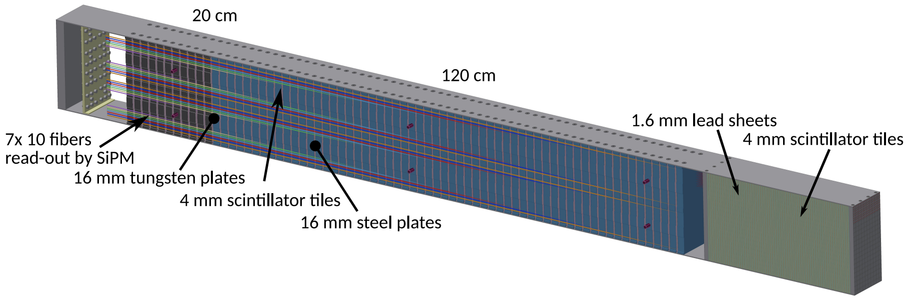

Figure 3: Combined FEMC and LFHCAL 8M module assembly indicating the individual components and their properties.

supported by a combined forward tracking and timing layer (FTTL) using AC-LGAD sensors. The resulting tracking performance of the ECCE detector fulfills the EIC Yellow Report requirements in all detector regions [3]. The design of the FTTL disk is derived from the CMS ETL [6] and aims to provide PID in the low momentum ($p < 2$ GeV) region whereas higher momenta are covered by a Dual-Radiator Ring Imaging Cerenkov Detector (dRICH). Significant efforts were put into the optimization of the dRICH geometry using AI-tools for the integration into the limited space available in the BaBar solenoid.

The ECCE forward calorimeter system consists out of an electromagnetic and a hadronic calorimeter and is shown in Figure 2 (right) in the full mechanical assembly. The forward electromagnetic calorimeter (FEMC) is envisioned to be a lead-scintillator shashlik calorimeter similar to previous calorimeters installed in ALICE, STAR or PHENIX. It consists out of 66 alternating layers of 1.6mm lead and 4mm scintillator plates that result in a total of 18.5 X/X_0 radiation lengths in order to maximize the shower containment. A modern approach with this calorimeter is the additional sub-Molière radius tower segmentation of 1.65×1.65 cm^2 front faces compared to $R_\mathrm{M} = 2.9$cm. This will enable a better particle identification based on a more differential shower shape analysis. The FEMC layers are meant to installed in the same module assembly as the hadronic calorimeter as shown in Figure 3 and thus, a 8M module assembly will contain 72 FEMC towers.

The longitudinally separated forward hadronic calorimeter (LFHCAL) consists out of 70 alternating absorber and scintillator plates of 16mm and 4mm, respectively. For the first 60 layers the absorber material is iron, while the last ten layers are designed as a tail catcher and are made out of tungsten. The main feature of this calorimeter is the longitudinal separation of the readout, where 7 segments (10 layers each) can be read out individually using silicon photo-multipliers (SiPMs).

Both calorimeter systems fulfill the energy resolution requirements laid out in the EIC Yellow Report as shown in Figure 4, where the requirement is indicated as a shaded area and the performance estimated using full Geant4 detector simulations is shown as points.

3. Physics prospects in the forward region

Based on the tracking, PID and calorimeter systems in ECCE a vast range of physics processes can be observed [2]. A few select examples will be discussed in the following. With its excellent track reconstruction and vertex finding capabilities, the ECCE detector is expected to provide precise

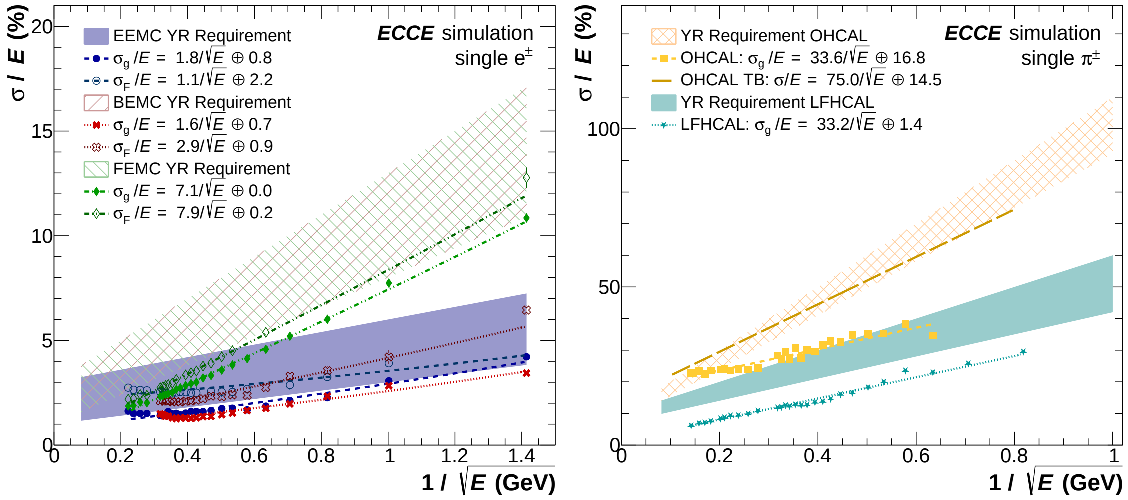

Figure 4: Left: Single electron energy resolution for the different electromagnetic calorimeter systems in ECCE. Right: Single charged pion energy resolution for the different hadronic calorimeter systems in ECCE. The EIC Yellow Report requirements [3] are shown as shaded bands, while full detector Geant4-based simulation data is indicated as points. Fits to the data are provided to give an estimate of the energy resolution performance.

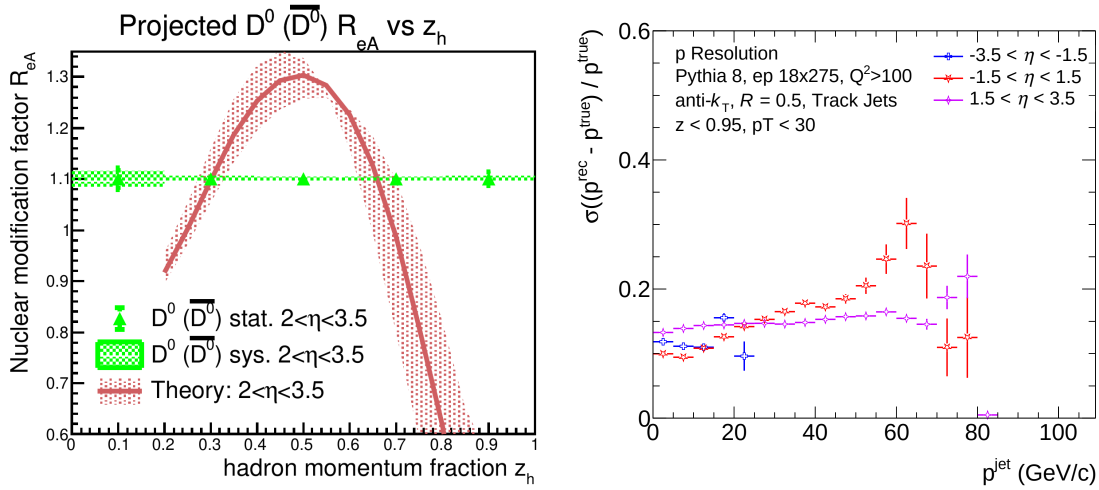

Figure 5: Left: Projected nuclear modification factor and uncertainties of the D^0 measurement as a function of the momentum fraction z_h in the forward region. Right: Charged jet energy resolution in the backward, central and forward region based on the tracking information provided by the ECCE detector.

measurements of the D^0 nuclear modification factor (R_{eA}) in order to further constrain theoretical models, as seen in Figure 5 (left). One of the main tasks of the forward detector systems is the reconstruction of particle jets with a high energy resolution and with varying radii. Jets at the EIC are expected to only have a small number of constituents (4–8 charged hadrons, 2–6 photons and approximately 1 neutral hadron) and thus their reconstructions requires high efficiency and resolution on each of their constituents. As can be seen in Figure 5 (right), the pure tracking based charged-jet energy resolution is about 10–25% depending on the detector region and momentum.

This resolution can be further improved with a full particle flow approach that incorporates also the performance of the calorimeter systems.

Using these jets in different collision systems at the EIC, the jet nuclear modification factor can probe anti-shadowing and the EMC regions of nuclear PDFS at large x as well as provide crucial inputs for final state effect studies via jet $\mathrm{R_{eA}}$ double ratio measurements of varying radii. Based on the projected detector performance and collected statistics of about 10 fb^{-1}, the latter measurement will only be sensitive to effects larger than 10% within uncertainties.

4. Conclusion

The ECCE detector is designed to explore the rich physics program at the EIC and has been selected as the reference design for the EIC project detector 1. It is based on low risk detector reuse of existing components, while employing modern approaches for the detector design. Its performance has been studied using full detector Geant4 simulations and further performance evaluations using testbeam data are expected in the following years. Based on this reference detector, further studies and final selection of the detector technologies are planned in order to be able to take data when the Electron-Ion Collider provides its first particle beams.

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