Performance characteristics of the SiD detector for deep inelastic events at the electron-ion collider (Proposal)

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Abstract

We propose to perform a comprehensive characterization of the SiD detector in terms of its response to scattered electrons in deep-inelastic scattering (DIS) events. To achieve this, we will simulate and reconstruct ep (eA) collision events using the SiD detector. The reconstructed events will be processed and analyzed to produce the description of this detector in terms of the main characteristics of DIS - negative four-momentum transfer squared, Q^2, and Bjorken x_{BJ} variable. Such a mapping of the SiD detector response will set the stage for possible adoption of the SiD detector design for the EIC.

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1. Physics motivation

The Standard Model describes ep neutral-current deep-inelastic events (DIS) in terms of the space-like exchange of a virtual photon and a virtual Z-boson. The DIS events, which play a key role in the physics program of the electron-ion collider (EIC) [1], are characterized by the presence of scattered electrons. A future detector for the EIC should be well optimized for the reconstruction of the energy of electrons and their positions in order to enable the physics program at the EIC.

Let us remind the conventional DIS kinematic variables: Q^2, the negative of the squared four–momentum transfer carried by the virtual photon, $Q^2 = -q^2 = -(k-k')^2$, where k and k' are the four–momentum vectors of the initial and final-state electron respectively; y, the energy transfer to the hadronic final state $y = \frac{q \cdot P}{k \cdot P}$, where P is the four–momentum vector of the incoming proton; $x_{\rm BJ}$, the Bjorken variable $x_{\rm BJ} \equiv \frac{Q^2}{2q \cdot P} = \frac{Q^2}{ys}$, where s is the center-of-mass energy squared of the ep system; and W, the energy of the $\gamma^* p$ system, $\frac{Q^2(1-x_{\rm BJ})}{x_{\rm BJ}} + {M_p}^2$, where M_p is the mass of the proton. For the electron method, Q^2 and $x_{\rm BJ}$ can be calculated from the measured energy, E'_e, and scattering angle, θ_e of the electron,

$$Q^2_e = 4E_e E'_e \cos^2(\theta_e/2), \qquad x_{\rm BJ} = \frac{E_e E'_e \cos^2(\theta_e/2)}{E_p(E_e - E'_e \sin^2(\theta_e/2))},$$

where E_e and E_p are the electron and proton beam energies and the scattered electron angle is measured with respect to the positive Z direction.

Detector resolutions of the Q^2 and $x_{\rm BJ}$ variables determine the precision with which physics observables are reconstructed in bins of these variables. In the electron method, these resolutions are determined by the energy and position resolutions of scattered electrons. Another characteristics of DIS measurements is the electron-reconstruction efficiency. It affects many factors required for an accurate measurements in DIS, including the size of detector correction factors and systematic uncertainties. Electron misidentification rate is another crucial characteristics which should be well understood for DIS measurements, as well as for other measurements based on identification of final-state electrons. These reconstruction characteristics will be the central focus of the detector-simulation effort described in this proposal.

2. Proposal

In order to achieve the physics goals at the EIC, a detector should be well optimized for measurements of scattered electrons in a wide kinematic range of Q^2 and $x_{\rm BJ}$. We propose to perform a comprehensive characterization of the Silicon Detector (SiD) detector [2] in terms of identification of electrons over a wide range of energies and pseudorapidity (or electron angle measured with respect to the beam direction). Such studies will be used for the calculation of resolution and efficiency of reconstructed Q^2 and $x_{\rm BJ}$ using the original SiD detector. In addition, we will reconstruct the purity of the reconstructed Q^2 and $x_{\rm BJ}$ in bins of these variables using fully simulated ep and eA collisions. Such studies will require good knowledge of electron misidentification rates, which will also be measured.

We believe that such studies will have a broad impact on design characteristics of a future detector for the EIC. The obtained characteristics can be used to tune the SiD detector to ep (eA) collisions, and for comparisons with other detector designs in order to identify the best possible technology for the EIC.

3. Approach

The Silicon Detector (SiD) [2] developed for the International Linear Collider (ILC) [3] has several attractive technical characteristics that can be vital for the success of the EIC project. The abbreviation "SiD" stands for "silicon detector" – a compact general-multipurpose detector designed for high-precision measurements of e^+e^- annihilation. Some key characteristics of the SiD detector are:

1. 4π solid angle coverage for reconstructed particles;
2. Full 5-layer silicon tracking system with 50 μm readout pitch size;
3. Silicon-pixel detector with 20 μm readout pitch size;
4. Superconducting solenoid with a 5 Tesla (T) field;
5. Highly segmented silicon-tungsten electromagnetic calorimeter (ECAL) with the transverse cell size of 0.35 cm;
6. Highly segmented hadronic calorimeter (HCAL) with a transverse cell size of 1×1 cm. The depth of the HCAL in the barrel region is about 4.5 interaction length.

This detector is illustrated in Fig. 1. Both ECAL and HCAL calorimeters are finely segmented for "imaging" capabilities: Together with the efficient tracking [2], the fine segmentation of the calorimeter is well suited for particle-flow algorithms (PFA) via the Pandora program [4, 5].

We will use the standard method for particle identification used by the SiD detector. In this method, high-energy electrons are identified using a combination of information from the silicon tracker and the calorimeters after applying the Pandora algorithm.

The SiD detector, designed by the ILC community, should be significantly modified for ep (eA) collisions. For example, there is a little motivation in using the 5 T solenoid for an EIC detector. We also remind that the SiD calorimeter was designed for jets up to 500 GeV in transverse energy, assuming e^+e^- collisions with the centre-of-mass collision energy of 1 TeV. Such transverse jet energies are significantly higher than those expected at the EIC experiment. Therefore, the hadronic calorimeter can be simplified. From the other hand, the SiD detector can be improved, keeping in mind the proton/ion beam in the initial state of the collisions.

Much of the information about the angular coverage and the energy resolution of electrons can be borrowed from the original SiD design report [2]. But this information is not sufficient when it comes to the reconstruction of fundamental DIS kinematic variables. In order to make the necessary modifications of the SiD detector for the EIC, it is important to understand the response of the unmodified SiD detector to ep (eA) collisions, and to evaluate the performance of this detector in terms of the fundamental kinematic variables, Q^2 and $x_{\rm BJ}$, used for DIS processes.

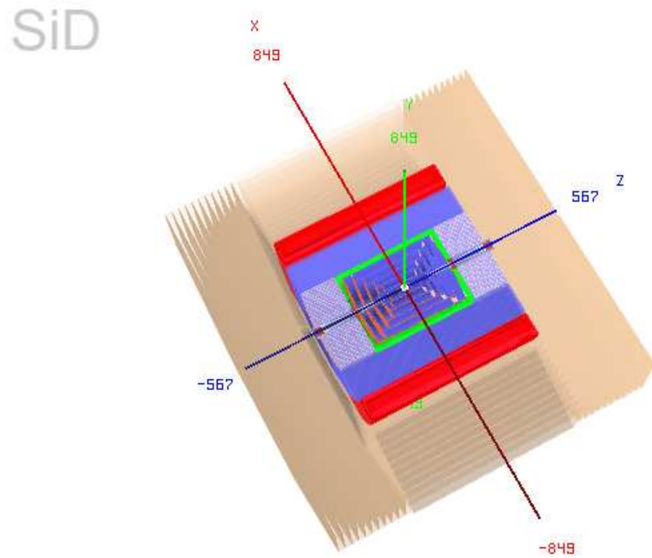

Figure 1: The SiD detector [2]. The red color indicates the superconducting solenoid, the light green volume indicates Si/W electromagnetic calorimeter (ECAL) which will be used for the electron identification. The outer and inner tracker is located inside the ECAL. The blue color shows the hadronic calorimeter, while the brown color shows the muon detector. The size of the detector is indicated in mm. The image was taken from the HepSim repository [6].

The simulation and reconstruction of ep (eA) Monte Carlo events will be performed using the SLIC software package ("Simulator for the Linear Collider") [7] on the Open-Science Grid (OSG) [8]. Initially, DIS ep collision events will be generated using the LEPTO Monte Carlo generator [9], which is a part of the HepSim repository [6]. Later we will consider other generators. Monte Carlo events before and after the simulation of the detector response will be registered in the HepSim Monte Carlo repository [6]. Initially, we will use particle gun data samples where single electrons are distributed randomly in energy and pseudorapidity. Then we will reconstruct a complete map of this detector in terms of Q^2 and x_{BJ}. By comparing these reconstructed values with the generated Q^2 and x_{BJ} at the "truth" (or generated) level, we will calculate the efficiencies and resolutions for these variables.

Electron misidentification rates as a function of the DIS kinematic variables must be known for many measurements at the EIC. Such studies are crucial for eA collisions characterized by a larger number of final-state particles compared to the ep collisions. To perform this study, we will need to generate, simulate and reconstruct a large number of non-DIS events. The precision with which such information can be extracted depends on the available CPU time to create background events using the Open-Science Grid (OSG).

This proposal will be focused on the "electron" method for the reconstruction of the DIS kinematics, in which identified electrons will be exclusively used for the calculation of Q^2 and x_{BJ} variables. Alternative methods for the reconstruction of Q^2 and x_{BJ} will also be considered, but such methods will not be the main focus of this proposal.

4. Available resources

Currently the ANL/HEP group maintains several software tools required for this project. The HepSim Monte Carlo repository [6] already includes several data samples useful for this project. They need to be processed with the full SiD detector simulation and reconstruction programs. The response of the SiD detector for physics processes is simulated using the SLIC software developed for the ILC project. This package is also supported by the ANL group.

The Monte Carlo simulations will be performed using the resources provided by the OSG grid [8], a project supported by the National Science Foundation and the U.S. Department of Energy's Office of Science. We expect to use one million CPU*hours for this proposal. Note that the needed CPU time does not require additional funds beyond those requested by the proponent of this proposal.

5. Expected deliverables

The main result of this proposal is a comprehensive mapping of the SiD detector in terms of resolution, efficiency, purity and misidentification rates of the kinematic variables Q^2 and $x_{\rm BJ}$, in bins of these variables. Such a characterization will set the stage for possible adoption of the SiD detector design for ep (eA) collisions at the EIC. The performance results of the original SiD detector will guide the design of a new detector which will be better optimized for ep (eA) collisions and, at the same time, can be less expensive compared to the original SiD detector developed for the International Linear Collider.

The results of this proposal can lead a broad impact on the design of future IEC detectors. For example, the obtained benchmark characteristics will be used for comparisons with other detector designs considered at BNL and JLab. This will help to identify the most promising detector geometry and readout technology.

The proponents of this proposal are expected to participate in planning a future EIC detector based on the knowledge obtained by running the realistic SiD detector simulation for ep (eA) collision environment.

In addition to the reconstruction quality of electrons for the fundamental DIS variables, the resolutions and misidentification rates of electrons can be used for various physics channels that involve detection of electrons in the final state.

6. Timeline

Year 1. During the first half of the Year 1, we plan to simulate and reconstruct electrons generated by a single-particle gun using the SiD detector. By the end of the first year of this proposal, we expect to obtain all needed results for the efficiency and resolutions of scattered electrons for different angles with respect of the beam direction. This information will be transformed to the corresponding plots expressed in terms of Q^2 and Bjorken $x_{\rm BJ}$.

In addition, we will explore different options to identify scattered electrons, such as those based on neutral networks and adopted in the past by the ZEUS experiment [10].

Year 2. By the end of the second year, we plan to reconstruct electron misidentification rates. This work will require a full simulation of ep photoproduction and electron-ion events. During the first half of the Year 2, we plan to simulate and reconstruct realistic *ep* (*eA*) background events (i.e. without scattered electrons) using the OSG grid. We expect to generate at least 100k events to calculate the misreconstruction rate with the precision below 0.1%. The rest of the Year 2 will be dedicated to the physics analysis of the simulated and reconstructed events.

7. Requested resources and budget

This proposal is expected to last for 2 years. We would like to request one post-doc working for 2 years on this project and hosted at the HEP/ANL. The cost for the post-doc stationed at the ANL laboratory is $110k/year. In addition, this project requires $10k/year for the travel support and $30k/year for M&S (computer servers for data analysis and for data storage). Other resources for the large-scale simulations and event reconstruction will be provided by the OSG grid.

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