ATHENA
A new detector proposed at the Electron-Ion Collider

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On behalf of the ATHENA Collaboration
Outline

- Introduction
- ATHENA
  - Physics Highlights
  - Detector Layout
- EIC Project status
- Summary

ATHENA Detector Proposal
A Totally Hermetic Electron Nucleus Apparatus proposed for IP6 at the Electron-Ion Collider

The ATHENA Collaboration
December 1, 2021
EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei.

Whitepaper: arXiv:1212.1701
**Introduction**

- **Requirements**
  - **Machine:**
    - High luminosity: $10^{33} \text{cm}^{-2}\text{s}^{-1} - 10^{34} \text{cm}^{-2}\text{s}^{-1}$
    - Flexible center-of-mass energy $\sqrt{s} = \sqrt{4 E_e E_p}$: Wide kinematic range $Q^2 = s x y$
    - Highly polarized electron (0.7) and proton / light ion (0.7) beams: Spin structure studies
    - Wide range of nuclear beams (d to Pb/U): High gluon density
  - **Detector:**
    - Wide acceptance detector system including particle ID (e/h separation & π, K, p ID - flavor tagging)
    - Instrumentation for tagging of protons from elastic reactions and neutrons from nuclear breakup: Target / nuclear fragments in addition to low $Q^2$ tagger / polarimetry and luminosity (abs. and rel.) measurement

- **Graph:**
  - HERMES, COMPASS, JLab6, JLAB12
  - HERA
  - EIC
  - $Q^2(\text{GeV}^2)$
  - $10^{-1}$ to $10^5$
Introduction

Critical steps over the last couple of years - 1

- INT Workshop series / Documentation of Physics Case - Whitepaper: “Understanding the glue that binds us all!”
- INT Workshop: 2010
- WP: 2012, updated in 2014 for LRP
- 2015 Long-range plan (LRP): T. Hallman

The 2015 Long Range Plan for Nuclear Science

Recommendations:
1. Capitalize on investments made to maintain U.S. leadership in nuclear science.
2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.
4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

The FY 2018 Request supports progress in important aspects of the 2015 LRP Vision

- Request to review EIC Science Case by National Academy of Sciences, Engineering, and Medicine (NAS)
Introduction

- NAS Webinar and NAS report release: 07/24/2018

  - Webinar on Tuesday, July 24, 2018 - Public presentation and report release
  - Gordon Baym (Co-chair): Webinar presentation
    “The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely.”
  - Glowing” report on a US-based EIC facility!

  Download pdf-file of final report!
**EIC accelerator design**

- **Center of Mass Energies:** 29GeV - 140GeV
- **Luminosity:** $10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1} / 10-100\text{fb}^{-1} / \text{year}$
- **Highly Polarized Beams:** 70%
- **Large Ion Species Range:** p to U
- **Number of Interaction Regions:** Up to 2!
WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility. The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the “strong force” that binds the atomic nucleus together.


Introduction

Press release by JLab and BNL

JEFFERSON LAB TO BE MAJOR PARTNER IN ELECTRON ION COLLIDER PROJECT

The Department of Energy announced that Jefferson Lab will collaborate on plans to build a future Electron Ion Collider in New York.

NEWPORT NEWS, VA – The Department of Energy announced that it has taken the next step toward construction of an Electron Ion Collider (EIC) in the United States. DOE announced on Thursday that the collider will be sited at DOE's Brookhaven National Laboratory in Upton, N.Y. In addition, DOE's Thomas Jefferson National Accelerator Facility will be a major partner in realizing the EIC, providing key support to build this next new collider, which will be the most advanced particle collider of its type ever built.

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

January 9, 2020

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will provide crucial infrastructure for the new Electron Ion Collider.

WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

https://www.jlab.org/news/releases/jefferson-lab-be-major-partner-electron-ion-collider-project

Yellow Report Activity - Critical EIC Community activity for CD-1

- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!
- Review: Community review within EICUG and external readers (~30) worldwide covering physics and detector expert fields!
Introduction

Overview of processes and final states

**Inclusive DIS**

\[ e + p/A \rightarrow e' + X \]

**Semi-Inclusive DIS (SDIS)**

\[ e + p/A \rightarrow e' + h + X \]

**Deeply-Virtual Compton Scattering (DVCS)**

\[ e + p/A \rightarrow e' + A'/\gamma + \gamma/m \]

**Inclusive**

- Unpolarized \( f_i(x,Q^2) \) and helicity distribution \( \Delta f_i(x,Q^2) \) functions through unpolarized and polarized structure function measurements (\( F_2, F_L, g_1 \))

- Define kinematics (\( x, y, Q^2 \)) through electron (e-ID and energy+angular measurement critical) / hadron final state or combination of both depending on kinematic \( x-Q^2 \) region

**SDIS**

- Flavor tagging through hadron identification studying FF / TMD's (Transverse momentum, \( k_T \), dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance

**Heavy flavor** (charm / bottom): Excellent secondary vertex reconstruction

**Exclusive**

- Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, \( b_T \), dependence) using DVCS and VM production

- \( eA \): Impact parameter determination / Neutron tagging using Zero-Degree Calorimeter (ZDC)
Overview of general requirements

- **Acceptance**: Close to $4\pi$ coverage with a $\eta$-coverage ($\eta = -\ln(\tan(\theta/2))$) of approximately $\eta < |3.5|$ combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage.

- **Low dead material** budget in particular in rear direction ($\sim 5\% \times X_0$).

- **Good momentum resolution** $\Delta p/p \sim$ few %.

- **Electron ID** for $e/h$ separation varies with $\theta / \eta$ at the level of $1:10^4 / \sim 2-3\%/\sqrt{E}$ for $\eta < -2$ and $\sim 7\%/\sqrt{E}$ for $-2 < \eta < 1$.

- **Particle ID** for $\pi/K/p$ separation over wide momentum range.
  
  (Forward $\eta$ up to $\sim 50\text{GeV/c}$ / Barrel $\eta$ up to $\sim 4\text{GeV/c}$ / Rear $\eta$ up to $\sim 6\text{GeV/c}$).

- **High spatial vertex resolution** $\sim 10-20\mu m$ for vertex reconstruction.

- **Low-angel taggers**:
  - Forward proton / A fragment spectrometer (Roman pots).
  - Low $Q^2$ tagger.
  - Neutrons on hadron direction.

- **Luminosity** (Absolute and relative) and local polarization direction measurement.
Open Call for Detector Proposals

Call for Collaboration Proposals for Detectors at the Electron-Ion Collider

Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerator Facility (JLab) are pleased to announce the Call for Collaboration Proposals for Detectors to be located at the Electron-Ion Collider (EIC). The EIC will have the capacity to host two interaction regions, each with a corresponding detector. It is expected that each of these two detectors would be represented by a Collaboration.

ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

Concept: General purpose detector inspired by the YR studies based on a new central magnet of up to 3T
WWW-page: https://www.athena-eic.org

CORE: COmpact detector for the Eic

Concept: Nearly hermetic, general-purpose compact detector, 2T baseline
WWW-page: https://userweb.jlab.org/~hyde/EIC-CORE/

ECCE: EIC Comprehensive Chromodynamics Experiment

Concept: General purpose detector based on 1.5T BaBar magnet
WWW-page: https://www.ecce-eic.org
ATHENA - Overview

- Highlights of ATHENA design
  - Large-bore 3T solenoid
  - Hybrid tracking: Silicon pixel sensors and state-of-the-art MPGDs
  - Calorimetry: Backward high-resolution crystal calorimeter / Barrel novel hybrid imaging / sampling EM calorimeter / Forward high-energy jet reconstruction
  - PID: Large bore allows for layered, complementary, state-of-the-art PID technologies
  - Dedicated FarBackward (Luminosity and low-$Q^2$ tagger) and FarForward detector systems
Kinematic Acceptance

- Kinematic coverage and $y$-resolution studies
- Optimized reconstruction methods

Simulated measurements shown for $Q^2 > 1\text{GeV}^2$ and $0.01 < y < 0.95$
Helicty measurements: Singlet quark distribution and Gluon helicity distribution

GPD measurements through elastic electroproduction of J/Psi measurements
Reduced charm cross-section and $F_2$ - Gluon density probe for $e+p$ (Shown!) vs. $eA$
Probing nuclear pdf’s

Gluons

Sea u-quarks

Valence u-quarks
ATHENA Tracking

- Complimentary silicon and MPGD technologies: Cost-effective with high momentum, angular, and vertex resolution / Large acceptance
- Backward tracker: 5 Si disks / 2 micro RWell rings
- Barrel tracker: 3 Si vertex layers / 2 Si barrel layers / 2 X 2 MicroMegas layers
- Forward Tracker: 6 Si disks / 2 micro RWell rings / 1 Large micro RWell tracker behind dRICH

XXIX International Workshop on DIS and Related Subjects - DIS2022
Santiago de Compostela, Chile, May 2-6, 2022
Bernd Surrow
ATHENA Calorimetry

- **Backward calorimetry:**
  
  EMCAL Hybrid PbWO₄ inner crystals / SciGlass outer blocks - Readout via SiPMs and HCAL (Fe/Sci)

- **Barrel calorimetry:** EMCAL
  
  Hybrid design of Pb/ScFi layers and imaging silicon sensors and HCAL (Fe/Sci)

- **Forward calorimetry:**

  EMCAL W powder embedded with ScFi and HCAL (STAR forward HCAL)
**Athena PID**

- **Forward PID**: Dual-radiator RICH (dRICH) utilizing aerogel and gas radiators focused by mirrors onto a focal plane instrumented with SiPMs.

- **Backward PID**: Proximity-focusing aerogel RICH (pfRICH) featuring minimal material budget, easy pattern recognition, large acceptance.
ATHENA - Detector Layout

ATHENA PID

Barrel PID: 100-cm radius high-performance DIRC (hpDIRC)

with re-use of Babar bars, complemented by a

Barrel PID: AC-LGAD Tof detector at 52.5cm radius
High precision luminosity measurement at 1% level for absolute luminosity and 0.01% for relative luminosity measurement using several methods based on the Bremsstrahlung process:

1. Counting photons converted in thin exit window using dipole field and measuring $e^+e^-$ pairs
2. Energy measurement of unconverted photons
3. Counting of unconverted photons

2. Two low Q2 taggers
ATHENA FarForward system

- FarForward detector system to measure very forward neutral and charged particle production: 4 detector systems:
  - B0 tracker with $\theta$ accep. 5.5–20.0 mrad and N/A rigidity accep.
  - Off-Momentum Detector with 0.0–5.0 mrad and 45%–65% rigidity accep.
  - Roman Pots with 0.0–5.0 mrad and 60%–95% rigidity accep. for protons and light nuclei.
  - Zero-Degree Calorimeter with 0.0–4.0 mrad and N/A rigidity accep.

### Table 2.4: Summary of the geometric acceptance for far-forward protons and neutrons in polar angle and magnetic rigidity percentage provided by the baseline EIC far-forward detector design [3].

<table>
<thead>
<tr>
<th>Detector</th>
<th>$\theta$ accep. [mrad]</th>
<th>Rigidity accep.</th>
<th>Particles</th>
<th>Technology</th>
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<tbody>
<tr>
<td>B0 tracker</td>
<td>5.5–20.0</td>
<td>N/A</td>
<td>Charged particles</td>
<td>MAPS</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Tagged photons</td>
<td>AC-LGAD</td>
</tr>
<tr>
<td>Off-Momentum Detector</td>
<td>0.0–5.0</td>
<td>45%–65%</td>
<td>Charged particles</td>
<td>AC-LGAD</td>
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<tr>
<td>Roman Pots</td>
<td>0.0–5.0</td>
<td>60%–95%*</td>
<td>Protons</td>
<td>AC-LGAD</td>
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<tr>
<td></td>
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<td>Light nuclei</td>
<td></td>
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<tr>
<td>Zero-Degree Calorimeter</td>
<td>0.0–4.0</td>
<td>N/A</td>
<td>Neutrons</td>
<td>W/SciFi (ECal)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Photons</td>
<td>Pb/Sci (HCal)</td>
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Figure 2.12: 3-D rendering of the far-forward region of IP6 with the proposed ATHENA detector instrumentation from the DD4HEP geometry implementation.

2.6.1 Technology choices

The B0 spectrometer requires approximately $20 - 30$–m position resolution to provide the required $p_T$ resolution for high-momentum hadrons near the beam line and good timing resolution to aid in background rejection, and to correct for effective vertex smearing from the crab cavity rotation. Our design consists of three silicon MAPS disks serving as the first, second, and fourth layers of the detector, complemented by a single AC-LGAD layer with 500–300 μm pixel pitch and 20–30 ps timing resolution. Each tracking layer is separated by 30 cm.

The silicon preshower following the tracker has two radiation lengths of lead as a photon converter, and a layer of silicon to tag the produced lepton pair. We envision use of AC-LGAD sensors for the preshower. These sensors enable the required spatial resolution to measure lepton pairs while providing excellent timing resolution.
## EIC Project Status

### Schedule

<table>
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<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
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**Critical Decisions**

- **CD-0(A)** Dec 2019
- **CD-1(A)** Jun 2021
- **CD-2/3A** Apr 2023
- **CD-3** Jul 2024
- **CD-4A** Approval date of operation Jul 2031
- **CD-4** Completion Jul 2031

**Infrastructure**

- Conceptual Design
- Design
- Construction & Installation

**Accelerator Systems**

- Conceptual Design
- Research & Development
- Design
- Construction & Installation
- Commissioning & Pre-Ops
- Full RF Power Buildout

**Project Detector**

- Conceptual Design
- Research & Development
- Design
- Construction & Installation
- Commission & Pre-Ops

**Detector #2**

- Research & Development and Design
- Construction & Installation
- Commission & Pre-Ops

### Key

- (A) Actual
- Green: Completed
- Yellow: Planned
- Pink: Data Date
- Orange: Critical Path
- Red: Schedule Contingency
Review of EIC detector proposals concluded in March 2022

Merging of ATHENA and ECCE proposal efforts forming a new collaboration (DETECTOR 1) - Ongoing process!

2nd experiment (DETECTOR 2) planned on a different timescale, e.g. CORE proposal!

Preparation of CD-2/3A:
- Review (expected) requires pre-TDR: ~October 2023*
- Award: ~January 2024*

CD-3 (expectation): ~April 2025*

A very exciting time is ahead of us to explore the structure and dynamics of matter at a new ep/eA collider facility, following years of preparation!

Join us!

* Taking into account constraints from Continuing Resolution of US budget discussions!