ATHENA @ EIC

A Totally Hermetic Electron Nucleus Apparatus proposed for the Electron-Ion Collider

Silvia Dalla Torre * INFN Trieste * Bernd Surrow

on behalf of the ATHENA Collaboration
The Context
The EIC, WHY?

- Ultimate understanding of QCD

  - By answering to the open questions
    - N spin structure and overall N tomography
    - Origin of the N mass
    - Evolution of the gluons in high density nuclear matter and gluon saturation
    - ...

  - By conjugating High Energy and High Luminosity enriched with Beam Polarization
    - Several e-h colliders proposed by the community
    - The EIC is an approved project!
The EIC, an approved project


The next milestones in front of the project (present projection):

- **CD2/3A** ~ Jan. 2024 (pre-TDR needed)
- **CD-3** ~ Apr. 2025 (TDR)
- **CD4A** ~ 2031 (start of operation)
- **CD4** ~ 2033 (project completion)
The EIC project in a nutshell

“SPECIFICATIONS”:

- spanning a wide kinematical range
  - ECM: 20 – 141 GeV

- High luminosity
  - up to $10^{34}$ cm$^{-2}$ s$^{-1}$

- highly polarized e (~70%) beams
- highly polarized light A (~70%) beams

- wide variety of ions: from H to U

- Number of interaction regions: up to 2

- True $4\pi$-coverage
  - Fully integrated detector-IR

- Detector

h-sources, acceleration, polarization, storage ring
empowering the existing complex

e-sources, acceleration, polarization, storage ring

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The EIC Detector

(general considerations)
Detector requirements dictated by the Physics Scope

Measurements by categories (from WP & NAS Report)

- **Parton Distributions in nucleons and nuclei**
- **QCD at Extreme Parton Densities - Saturation**
- **Spin and Flavor structure of nucleons and nuclei**
- **Tomography Transverse Momentum Dist.**
- **QCD at Extreme Parton Densities - Saturation**
- **Tomography Spatial Imaging**

**Detector Requirements, Including Jet Reconstruction**

### Inclusive DIS
- Detect, measure and identify the scattered lepton
- Hermeticity and h reconstruction
- Jet reconstruction
- Acceptance & resolution for multi-dimensional binning: x, Q^2

### Semi-inclusive DIS
- Measure scattered lepton and hadrons in coincidence
- Identify hadrons
- Jet reconstruction
- Vertex resolution to reconstruct heavy hadron decays
- Acceptance & resolution for multi-dimensional binning: x, Q^2, z, p_T, θ

### Exclusive processes (small cross-sections)
- Measure all particles in event
- Tagging nuclear fragments for background suppression
- e/π separation for background suppression
- Identify hadron for background suppression
- Acceptance & resolution multi-dimensional binning: x, Q^2, t, θ

**∫Ldt:**

- **1 fb⁻¹**
- **10 fb⁻¹**
- **10 - 100 fb⁻¹**

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The evolution of the detector concept

- **White paper** (2012, 2014)
- followed by the initial concepts

- **The Call for Detector proposals** (2021)
  - **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
  - **CORE**
    - COmpact detector for the Eic
    - Concept: Nearly hermetic, general purpose compact detector, 2T baseline
  - **ECCE**
    - EIC Comprehensive Chromodynamics Experiment
    - Concept: General purpose detector based on 1.5T BaBar magnet

- **The Yellow Report** reference detector (2020)
  - A global effort of the EIC-User Group

- 2022: Merging of ECCE and ATHENA proposal strengths forming a new collaboration for **DETECTOR 1**
  - Ongoing process!
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**2022**: Merging of ECCE and ATHENA proposal strengths forming a new collaboration for DETECTOR 1

- Ongoing process!
Central detector 9.5 m long
The ATHENA Detector

(by highlights)
Central Detector Overview

- Highlights of the ATHENA design

- Large-bore 3T solenoid, material budget in nuclear interaction length \(~1.3 \lambda/\lambda_1\)
- Hybrid tracking: Silicon pixel sensors by MAPS 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 and innovative approach for single photon detection
ATHENA – Central Detector acceptance

Tracking
Complete coverage
-3.8 < η < +3.75

Calorimetry (E & H)
Complete coverage
-4 < η < +4

PID
Complete coverage
-3.8 < η < +3.7
Material budget in front of ECals

- **Backward endcap**
  - Material scan to front of the nECAL
  - $\eta = -2.5, \phi = 0$

- **Barrel**
  - Material scan to front of the bECAL
  - $\eta = 0.0, \phi = 0$

- **Forward endcap**
  - Material scan to front of the pECAL
  - $\eta = 2.5, \phi = 0$
ATHENA VERTEX & TRACKING, a description

**Si Trackers** *(from eRD16/eRD18/eRD25→eRD111)*
- 1 single technology
- 65-nm technology MAPS (10 µm pitch, < 20 mW cm\(^{-2}\))
- Developed for ALICE ITS3
- EIC Si consortium (leadership within ATHENA)

- **Silicon Vertex**, 3 layers
  - first layer @ R = 33 mm
  - material: 0.05 X/X\(_0\) / layer
- **Silicon barrel**, 2 layers
  - material: 0.55 X/X\(_0\) / layer
- **F & B Silicon disks**
  - material: 0.24 X/X\(_0\) / layer

**MPGDs** *(from eRD3/eRD6→eRD108)*
- material < 1% X/X\(_0\) / layer
- R&D needed for 2-D read-out

- **barrel**, cylindrical, 2 x 2 layers, Micromegas
- **rings**, GEM
- behind dRICH, µRWell

**Additional space-point information (not included in present tracking studies)**
- bTOF layer in front of Micromegas
- Imaging bECal, coordinate-measurement behind DIRC
- nECal high-granularity in the central region, behind pfRICH
ATHENA VERTEX & TRACKING, performances

Momentum resolution vs $p$ in 3 $\eta$-bins

Transfer distance of closest approach to the primary vertex vs $p$ in 3 $\eta$-bins

**KEY INGREDIENTS for these PERFORMANCES**

- High magnetic field / Maximized lever-arm / Minimized material / Sensor pitch
ATHENA Calorimetry, overview

- **Global characteristics of ATHENA Calorimetry:**
  - high granularity  
  - high resolution  
  - Si PM sensors → fine time information

- **nECAL**
  - Finest resolution needed → PbWO4 crystals in the central part  
  - eRD1→eRD105, eRD110 & EEEMCAL consortium

- **pECal & pHCAL**, compensated calorimeters
  - A global development, eRD1 → eRD107, eRD110  
  - W/SciFi, Fe/Scint  
  - Measurements of longitudinal shower development

- **bHCal and nHCal**
  - Both Fe/Scint sandwich  
  - Well established technology, no R&D needed  
  - bHCal as tail catcher following bECal (~ 1 $\lambda_I$) and solenoid (~1.3 $\lambda_I$): 95 % of hadrons contained
bECal (ECal in the barrel and part of backward endcap)

- Hybrid concept:
  - 6 imaging layer: AstroPix and Pb/SciFi
    - AstroPix, monolithic Si sensor, developed (from ATLASPix)
    - Pb/SciFi following KLOE, GlueX
  - Reconstruct scattered and secondary electrons
  - Separate e/\pi
  - Identify and reconstruct \( \gamma \) (also radiated from e)
  - Identify \( \pi^0 \) also at high momenta

- Also >1 \( \lambda \) contributing to bHCal

- "Separate e/\pi at low p"

- "\( \gamma \)'s from 15 GeV/c \( \pi^0 \) decay"

- "FullSim"

- "Expected performance"

- "Energy Resolution 5.5%/\( \sqrt{E} \) @ 1%\( E \)
- e/\pi separation > 99.8% pion rejection with 95% electron efficiency at \( p \geq 0.1 \) GeV/c
- \( E^\gamma_{\text{min}} \) < 100 MeV
- Spatial Resolution Cluster position resolution for 5 GeV photons at normal incident angle is below \( \sigma = 2 \) mm (at the surface of the stave \( r = 103 \) cm) or 0.12\(^\circ\). For comparison, the minimal opening angle of photons from \( \pi^0 \rightarrow \gamma\gamma \) at 15 GeV is ~ 1.05\(^\circ\) (about 19 mm - 37 pixels - of separation at \( r = 103 \) cm)."
PID in ATHENA detector

barrel

hpDIRC (barrel) (a)

Prism & lenses allow focusing (not in BABAR DIRC)

Fused Silica Bar

Re-usage of BABAR bars, disassembled

Photon Sensor

Commercial MCP-PMTs, fine pixel (3.3mm x 3.3mm)

AC-LGAD: adding fine pixelization to LGAD (synergies with FF sensors)

AC-LGAD ToF layer (barrel)

dRICH (forward)

Mirror

Aerogel

Size: 3 mm x 3 mm

SiPM array

Gas (C$_2$F$_6$), ~135 cm

dRICH & pfRICH, large overlap of technologies

- SiPMs
- Aerogel
- Radiator gas

pfRICH (backward)

Aerogel

Size: 3 cm, n=1.014

SiPM array

Gas (C$_2$F$_6$), 40 cm
With positive identification of the higher mass particle in the couple

Using also the Cherenkov threshold information

EXAMPLE:

pfRICH, FullSim

Aerogel only
**FAR FORWARD instrumentation**

### ZDC

- **Extracted Energy Resolution:**
  - EMCal: $\Delta E/E = 0.11999\pm0.0002956$ (photons)
  - Full ZDC (7 $\lambda$ HCAL): $\Delta E/E = 0.3604\pm0.0230$ (neutrons)
  - Pb/Sci ZDC (8 $\lambda$): $\Delta E/E = 0.442\pm0.042$ (neutrons)

### FF trackers

- **Detector Resolution Only:**
  - B0 Detector, $p = 100$ GeV/c
  - B0 Detector, $p = 41$ GeV/c
  - Roman Pots, $p = 275$ GeV/c
  - Roman Pots, $p = 100$ GeV/c
  - OMD, $x_0 = 0.5$

### Detectors and Technology

<table>
<thead>
<tr>
<th>Detector</th>
<th>$\theta$ accep. [mrad]</th>
<th>Rigidity accep.</th>
<th>Particles</th>
<th>Technology</th>
</tr>
</thead>
<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>
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<tr>
<td>Off-Momentum</td>
<td>0.0–5.0</td>
<td>45%–55%</td>
<td>Charged particles</td>
<td>AC-LGAD</td>
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<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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<td></td>
<td></td>
<td></td>
<td>Light nuclei</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>
</tr>
</tbody>
</table>

- **B0 Silicon Tracker and Preshower**
  - 2 m

- **Off-Momentum Detectors**
  - 2 m

- **Focusing Quadrupoles**

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- **ATHENA @ EIC**

- **S. Dalla Torre**
• measure IP6 luminosity with an absolute precision better than 1% absolute and a relative precision better than 0.01% using the electron-ion bremsstrahlung by three largely independent and complementary measurements

• electron detectors will also be used to tag low-$Q^2$ Events (photoproduction) in ATHENA

Technologies for the calorimetry:

• Spaghetti W-calorimeter with radiation-hard scintillating fiber, read out with fast PMTs

• Cherenkov-radiating quartz fibers read out by SiPMs

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ATHENA PERFORMANCE for PHYSICS

(selected items)
DI S resolution in the \((x, Q^2)\) plane

- reconstruction via \(e\) only for NC, \(y\) not too small – **key**: ECAL performance

- Reconstruction with support of hadrons (small \(y\)) - **key**: good reconstruction of the whole \(h\) final state

- For large QED radiation correction regions and CC, \(h\) detection only – **key**: good reconstruction of the whole \(h\) final state

Resolution in \(y\) (reminder: \(Q^2 \approx sxy\))
DIS reach in \((x, Q^2)\) plane

**ep SCATTERING**, \(100 \text{ fb}^{-1}\) (=1 year of data taking)

\([Q^2 > 1, \ 0.01 < y < 0.95]\)

- grid of points: simulated unpolarized measurements
- negligible statistical error
- 1.5-2.5% systematic error point to point

inclusive NC cross section: the fundamental ingredient for measurement of:
- collinear **parton densities**
- semi-inclusive, exclusive and hadronic final state **cross section**
Sample purity respect to main background source, i.e. pions

Included in this study:
- NC DIS events from PYTHIA6
- ECAL performance
- Kinematic cuts:
  - Isolation of the scattered electron
  - $e - \Sigma$ check

Not included:
- Contribution to $e/\pi$ separation from PID devices

Final $\pi^-/e$ ratio

FastSim

10% contamination
Resolution demonstrated in the plot

- only a small low-mass shoulder from bremsstrahlung is observed
- possibility for correction with more advanced analysis (key is bECal)

**Key for excellent resolution:** low-mass tracking (including beam pipe)
Jet reconstruction

Jets reconstructed with anti-\( k_T \) algorithm, \( R = 1.0 \), with energy-flow reconstruction

- Jet energy resolution better than 10% for \( E_{\text{jet}} > 40 \) GeV
- Jet azimuthal angle resolution better than 1 degree for \( E_{\text{jet}} > 25 \) GeV
- Low \( E_{\text{jet}} \) affected by threshold
- Very high \( E_{\text{jet}} \) affected by acceptance

**KEY** - tracking and calorimetry resolution
**Charm reconstruction, secondary vertices**

**for secondary decays, for example, D⁰ reconstruction**

**Key - resolution and low mass vertexing layers**

- displaced-track resolutions →
- Secondary decay reconstruction (D⁰, ...)
- good charm-jet tagging based on a displaced track counting
- charm efficiency 10% - 30% for 5-30 GeV/c, excellent purity (misidentification < 1%)
SUMMARY and PERSPECTIVES

- We have reported about the ATHENA effort
  - As underlined, more efforts in parallel

- Review of EIC detector proposals concluded in March 2022

- Merging of ATHENA and ECCE proposal strengths forming a new collaboration for DETECTOR 1
  - Ongoing process!

- 2nd experiment (DETECTOR 2) planned on a different timescale
  - CORE proposal a starting point

- Preparation of pre-TDR / TDR in front of us
  - 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!

- Great opportunities for physics and frontier detectors ➔ Join us!

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