Electron-Ion Collider: Quark-Gluon Imagining in the Era of Streaming Readout and AI/ML

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Seminar Subject: The Electron-Ion Collider (EIC)

- World’s first collider of:
  - Polarized electrons and polarized protons,
  - Polarized electrons and light ions (d, \(^3\)He),
  - Electrons and heavy ions (up to Uranium).

- The EIC will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that is relevant.

- BNL and Jefferson Lab will be host laboratories for the EIC Experimental Program. Leadership roles in the EIC project are shared.

What will you hopefully get out of the seminar:

- What is the EIC? Why are we working on the EIC? What is the status of the EIC project and the detector collaboration?
- What is streaming readout? How do we advance EIC science with streaming readout and AI/ML?
Nuclear Physics

Journey into the heart of matter
Nuclear Physics

Further exploration of the Standard Model

Dark matter searches

Gravitational Interactions

Electroweak Interactions

Deeper understanding of QCD

Strong Interactions

Mission of Nuclear Physics Quest to understand the origin, evolution, and structure of the matter of the universe.

Frontiers in Nuclear Physics

• **Nature of matter**: What are its basic constituents and how do they interact to form the properties we observe?
  • The largest contribution by far to visible mass in the universe comes from protons and heavier nuclei.
• **Quark-gluon structure of nuclear matter**: How do quark and gluons interact and combine to form the different types of matter observed in the universe today and during its evolution remains largely unknown.
Nuclear matter is unique

Molecular and atomic matter: Most known matter has localized mass and charge centers – vast open space.

Not so in nuclear matter: Interactions and structures are inextricably mixed up in protons and other forms of nuclear matter.
The dynamical nature of nuclear matter

**Nuclear Matter** Interactions and structures are inextricably mixed up.

**Observed properties** such as mass and spin emerge out of the complex system.

**Ultimate goal** Understand how matter at its most fundamental level is made.

**To reach goal** precisely image quarks and gluons and their interactions.

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**QCD's Dyson-Schwinger Equations**

The equations of motion of QCD

\[ \text{QCD's Dyson-Schwinger equations} \]

are an infinite tower of coupled integral equations.

The most important DSE is QCD's gap equation

\[ \text{gap equation} \]

where

\[ S(p) = Z(p^2) i/p + M(p^2) \]

has correct perturbative limit

\[ \text{quark propagator} \]

\[ S(p) \]

mass function,

\[ M(p^2) \]

exhibits dynamical mass generation

\[ \text{complex conjugate poles} \]

no real mass shell

\[ \text{confinement} \]

\[ \text{effect of gluon cloud} \]

\[ \text{Rapid acquisition of mass is effect of gluon cloud} \]

\[ \text{DOI 10.1103/PhysRevC.68.015203} \]

\[ \text{M}_p = 1000 \text{ MeV} \]

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Pioneering measurements
The first Electron-Ion Collider
HERA: The first Electron-Ion Collider

HERA beam facility

proton beam (920 GeV)
electron beam (27.6 GeV)

(1) LINAC II  (2) LINAC III  (3) DESY II / III

$\sqrt{s_{ep}} = 320$ GeV
Deep-inelastic scattering (DIS) of electrons off protons

Ability to change $Q^2$ changes the resolution scale

$Q^2 = 400 \text{ GeV}^2 \Rightarrow \frac{1}{Q} = 0.01 \text{ fm}$

Ability to change $x$ projects out different configurations where different dynamics dominate
Parton distribution functions (PDF)

Observable cross section → structure functions

QCD Factorization and Evolution PDFs

process-dependent

universal

QCD at extremes: Parton saturation

- Dramatic rise of gluon PDF

  - $Q^2 = 10 \text{ GeV}^2$

  - $x_g(0.05)$, $x_u(x)$, $x_d(x)$

- Parton splitting and recombination

  - Rise of gluon PDF cannot go on forever as $x$ becomes smaller and smaller
  - **Parton saturation**: parton recombination must balance parton splitting
  - Unobserved at HERA for a proton and expected at extreme low $x$

In nuclei, the interaction probability enhanced by $A^{1/3}$

Will nuclei saturate faster as color leaks out of nucleons?
Polarized DIS measurements

Polarization

Novel QCD phenomena

3D imaging in space and momentum
- longitudinal structure (PDF)
- transverse position information (GPDs)
- transverse momentum information (TMDs)
3D imaging in momentum space: TMDs

A. BACCHETTA, M. CONTALBRIGO: THE PROTON IN 3D

The transverse-momentum distribution may be different for quarks of different flavors. There are some indications that the up-quarks are closer to the center than the down-quarks. The above pictures are compatible with existing data.

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Fig. 6  The transverse-momentum distribution may be different for quarks of different flavors. There are some indications that the up-quarks are closer to the center than the down-quarks. The above pictures are compatible with existing data.

Fig. 7  Polarization-averaged distributions, as in figs. 4 and 5, are cylindrically symmetric. But when the spin of the nucleon is taken into account (indicated by the white arrow in the plots), the distribution can be distorted. These images are elaborated starting from real data and show that the distortion for up- and down-quarks is opposite (see, e.g., [19, 20]). Large uncertainties are still affecting these pictures.

3D DISTRIBUTIONS EXTRACTED FROM DATA

Figure 8. The down quark TMD PDF in b-space(left) and kT-space(right) presented at different values of x. The colors show the size of the uncertainty relative to the value of distribution.

Conclusions

We have extracted the unpolarized transverse momentum dependent parton distribution function (TMDPDF) and rapidity anomalous dimension (also known as Collins-Soper kernel) from Drell-Yan data. The analysis has been performed in the \(-\) prescription with NNLO perturbative inputs. We have also provided an estimation of the errors on the extracted functions with the replica method. The values of TMDPDF and rapidity anomalous dimension, together with the code that evaluates the cross-section, are available at [45], as a part of the artemide package. We plan to release grids for TMDPDFs extracted in this work also through the TMDlib [69].

Theoretical predictions are based on the newly developed concepts of \(-\) prescription and optimal TMD proposed in ref. [27]. This combination provides a clear separation between the non-perturbative effects in the evolution factor and the intrinsic transverse momentum dependence. Additionally, the \(-\) prescription permits the usage of different perturbative orders in the collinear matching and TMD evolution. For that reasons, the precise values of the rapidity anomalous dimension (\(\pm 1\% (4\%, 6\%)\) accuracy at \(b = 1 (3, 5) \text{GeV}^2\)) are relevant for any observable to be obey TMD evolution.

In our analysis, we have included a large set of data points, which spans a wide range of energies (\(4 < Q < 150 \text{GeV}\)) and \(x (x > 10^{-4})\), see fig. 1. The data set can be roughly split into the low-energy data, which includes experiments E288, E605, E772 and PHENIX at RHIC, and the high-energy data from Tevatron (CDF and D0) and LHC (ATLAS, CMS, LHCb) in similar proportion. To exclude the influence of power corrections to TMD factorization we consider only the low-\(q_T\) part of the data set, as described in sec. 3. A good portion of data is included in the fit of TMD distributions for the first time, that is the data from E772, PHENIX, some parts of ATLAS and D0 data. For the first time, the data from LHC have been included without restrictions (the only previous attempt to include LHC data in a TMDPDF fit is [13], where systematic uncertainties and normalization has been treated in a simplified manner). We have shown that the inclusion of LHC data greatly restricts the non-perturbative models at smaller \(b (b > 2 \text{GeV})\) and smaller \(x (x < 0.05)\), and therefore they are highly relevant for studies of the intrinsic structure of hadrons.

A detailed comparison of fits with and without LHC data has been discussed in sec. 5.
New Frontier in Nuclear Physics
The Electron-Ion Collider
Advances in Nuclear Physics

Steady advances in all of these areas mean that →
## EIC: A new frontier in science

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2012: White paper on EIC

Theme: The glue that binds us all.

“The quantitative study of matter in this new regime [where sea quarks and gluons dominate] requires a new experimental facility an Electron-Ion Collider...”

Focus areas of research:
• Spin and three-dimensional structure of the nucleon
• The nucleus: A laboratory for QCD

Nobel Prizes in Physics related to role of gluons in Nuclear Physics

Hideki Yukawa (1949) “for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces”
But the quark-gluon origin of the nuclear binding force remains unknown.

Robert Hofstadter (1961) “for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons”
But the 3D quark-gluon structure of nucleons remains unknown.

Jerome Friedman, Henry Kendall, Richard Taylor (1990) “for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics”
But the role of gluons in protons and bound neutrons remains unknown.

But the confinement aspect of the theory remains unknown.

But how dynamical chiral symmetry breaking shapes the mass and structure of quark-gluon systems remains unknown.
1. The highest priority in this 2015 Plan is to capitalize on the investments made.
   • 12 GeV – unfold quark & gluon structure of hadrons and nuclei
   • FRIB – understanding of nuclei and their role in the cosmos
   • Fundamental Symmetries Initiative – physics beyond the SM
   • RHIC – properties and phases of quark and gluon matter

2. We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

3. We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

4. We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.
2016: Formation of the **EIC User Group** (EICUG)

### EICUG in 2023
- **1382 members** from
- **269 institutions** from
- **36 countries**.
“In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.

In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics.”

Reference
NAS Report defines EIC science parameters

Versatile range of
- Beam energies: vs_{ep} range ~20 to ~100 GeV upgradable to ~140 GeV
- Beam polarizations of at least 70% for e, p, and light ions (longitudinal, transverse, tensor)
- Ion beam species: D to heaviest stable nuclei

High luminosity
- 100 to 1000 times HERA luminosity

Two Competing EIC Designs

eRHIC

JLEIC

Brookhaven National Laboratory and Jefferson Lab will be host laboratories for the EIC Experimental Program. Leadership roles in the EIC project are shared.
Mapping position and motion of quarks and gluons

Study nuclear matter **beyond longitudinal description** makes the **requirements for IR and detector design different** from all previous colliders including HERA.

**3D imaging in space and momentum**

- longitudinal structure (PDF)
- + transverse position Information (GPDs)
- + transverse momentum information (TMDs)

order of a few hundred MeV **measurement**
Transverse and flavor structure measurement of the nucleon and nuclei:
The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA colliders.**
Final-state particles in the central rapidity

Asymmetric collision energies will boost the final state particles in the ion beam direction: Detector requirements change as a function of rapidity.
The aim is to get ~100% acceptance for all final state particles, and measure them with good resolution.

Experimental challenges:
- beam elements limit forward acceptance
- central Solenoid not effective for forward
Possible to get ~100% acceptance for the whole event:
- Beam crossing angle of 25mrad creates room for forward dipoles.
- Dipoles create space for detectors in the forward ion and electron direction and analyze the forward particles.
• The EIC Yellow Report describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the EIC.
  • Detector concepts further developed in detector collaboration proposals (ATHENA, CORE, ECCE).

• The studies leading to the EIC Yellow Report were commissioned and organized by the EIC User Group.

• The EIC Yellow Report has been important input to the successful DOE CD-1 review and decision.

Ref.: *Nucl.Phys.A 1026 (2022) 122447*
EIC General Purpose Detector

Integrated interaction and detector region (+/- 40 m) to get ~100% acceptance for all final state particles, and measure them with good resolution.

Overall detector requirements:
• Large rapidity (-4 < h < 4) coverage; and far beyond in far-forward detector regions.
• Large acceptance solenoid of 1.7 T (up-to 2 T).
• High control of systematics: luminosity monitor, electron and hadron polarimetry.

2022–2023: Formation of ePIC Collaboration

In a Decade: Start of EIC Operations

The thinner bars indicate that R&D and design can continue at a small level beyond CD-2 and CD-3.

for LLP construction starts at CD-3A
After a presentation on “Breakthroughs in Detector Technology”, Ian Shipsey (Oxford) was asked about the role of software.

"Software is the soul of the detector,” Ian Shipsey replied in a poetic way and emphasized the importance of great software for great science. He added that we need to work together, on a global scale and with other fields, to achieve this goal.
Compute-Detector Integration to Maximize Science

- **Problem** Data for physics analyses and the resulting publications available after $O(1\text{year})$ due to complexity of NP experiments (and their organization).
  - Alignment and calibration of detector as well as reconstruction and validation of events time-consuming.
- **Goal** Rapid turnaround of data for physics analyses.
- **Solution** Compute-detector integration using:
  - AI/ML for autonomous alignment and calibration as well as reconstruction in near real time,
  - Streaming readout for continuous data flow and heterogeneous computing for acceleration.

![Data Flow Diagram]

Data Flow: 100 Tbps $\rightarrow$ 10 Tbps $\rightarrow$ 0.1 Tbps
CODA: Trigger-based readout system

Based upon assumptions in traditional DAQ design

- The data rate from a detector is impossible to capture with an affordable data acquisition system without a trigger to reduce event rates.
- Even if the untriggered data rate could be captured, it would be impossible to store.
- Even if it could be stored the full dataset would represent a data volume that would require impractically large computing resources to process.

With computing advances Assumptions no longer valid

Limitation in trigger-based readout systems

- Bias to low-energy particles.
- Do not deal well with event-pileup.
- Not an ideal for complex, general-purpose detectors.
Alternative readout mode: Streaming

Traditional trigger-based readout
- data is digitized into buffers
- trigger starts readout
- parts of events are transported to an event builder where they are assembled into events
- at each stage the flow of data is controlled by *back pressure*
- data is organized sequentially by events

Streaming readout
- data is read continuously from all channels
- validation checks at source reject noise and suppress empty channels
- data then flows unimpeded in parallel channels to storage or a local compute resource
- data flow is controlled at source
- data is organized in multiple dimensions by channel and time
Streaming Readout: Trigger-Less Data Acquisition

Definition of Streaming Readout

• Data is digitized at a fixed rate with thresholds and zero suppression applied locally.
• Data is read out in continuous parallel streams that are encoded with information about when and where the data was taken.
• Event building, filtering, monitoring, and other processing is deferred until the data is at rest in tiered storage.

Advantages of Streaming Readout

• Simplification of readout (no custom trigger hardware and firmware).
• Continuous data flow provides detailed knowledge of background.
• Streamline workflows and take advantage of other emerging technologies:
  • AI/ML for autonomous experimentation and control,
  • Heterogeneous computing.
On-Beam Validation of Streaming Readout at Jefferson Lab

Tests included AI-supported real-time tagging and selection algorithms (Eur.Phys.J. Plus 137 (2022) 8, 958)

- Standard operation of Hall-B CLAS12 with high-intensity electron-beam
- Streaming readout of forward tagger calorimeter and hodoscope
- Measurement of inclusive $\pi^0$ hadron production

- Prototype of EIC PbWO4 crystal EMCAL in Hall-D Pair Spectrometer
- Calorimeter energy resolution of SRQ compatible with triggered DAQ.
Tremendous interest and activity in AI/ML in NP:

- NP researchers already have the talent and many of the tools required for the AI/ML revolution.
- NP addresses challenges that are not addressed in current technologies.
- NP presents data sets that expose limitations of cutting edge methods.
- **Cross collaboration:** To solve the many complex programs in the field and facilitate discoveries strong collaborations between NP, data science, and industry would be beneficial for all parties.
- **Education** is key to increase the level of AI-literacy – research programs and curricula in data science can help to attract students.

NP is a highly distributed scientific field, utilizing various data types across different scales, making it **ideal for AI/ML applications** (Colloquium Article).
AI/ML for Streaming Readout at the EIC

Automated Data Quality Monitoring

Online Monitoring Tasks: Hydra

- Take off-the-shelf ML technologies and deploy in near real-time monitoring tasks for GlueX in Hall D.
- Use ML for a) online change detection and b) online data-quality monitoring.
- Hydra was created to tackle these challenges. Hydra is an AI system that leverages Google’s Inception v3 for image classification.
- Developed Multi Scale Method:
  - Represent data in multiscale basis: Increase of base coefficients → Change.
  - Transform to coefficient space: Outliers in the distribution → Change.
  - Detect Changes → Detect outliers using IQR.

- Large network, ~75% of processing time spent on inference. Techniques are being tested to make Hydra models interpretable (e.g., Layerwise Relevance Propagation). Plans to deploy Hydra in other experimental halls.

Event Reconstruction

AI-based Tracking

- Different networks were evaluated for classification and segmentation. MLP is chosen to be the best fit, due to implementation simplicity, accuracy and inference speed.
- Autoencoders are typically used for de-noising, but can be used for fixing glitches.
- AI track classification and segment recovery network was implemented as a CLARA service, providing dramatic speedup for track finding.
- The implementation of AI-assisted tracking into the CLAS12 reconstruction workflow provided a 6 times code speedup.

Reconstruction of DIS Events

AI ML for Streaming Readout at the EIC

Critical Path for Compute-Detector Model for the EIC

Automated Alignment and Calibrations

Approach

- Identify different data-taking periods. Use ML for all online changes. Different data-taking periods to a baseline.

Development Multi Scale Method:

- Adjusted data in multiscale basis. Increase of base coefficients → Change.
- Transform to coefficient space: Outliers in the distribution → Change.
- Detect Changes → Detect outliers using IQR.

- Automatically adapt changes to the underlying probability distribution.
- Reduce to use of changes.
- Monitor performance and calculate.

Reconstruction of DIS Events

Deeply Learning Deep Inelastic Scattering

- Use of DNN to reconstruct the kinematic observables $Q^2$ and $x$ in the study of neutral current DIS events at the ZEUS experiment at HERA.
- The performance of DNN-based reconstruction of DIS kinematics is compared to the performance of the electron method, the Jacquet-Blondel method, and the double-angle methods using data-sets independent from those used for the training.
- Compared to the classical reconstruction methods, the DNN-based approach enables significant improvements in the resolution of $Q^2$ and $x$.
- DIS measurements at upcoming EIC.
Summary

Electron-Ion Collider: Quark-Gluon Imagining in the Era of Streaming Readout and AI/ML
Jefferson Lab’s Science and Technology Vision

**Nuclear Physics at CEBAF**
- Vibrant 12 GeV research program, operating >30 weeks/yr, supporting 1,700 annual users
- MOLLER Project & SoLID proposal
- Future opportunities in fixed-target, high-luminosity complementary to EIC
- Theory and computation supporting NP goals

**Electron-Ion Collider**
- Partnering with BNL in the management, design, and construction of the Electron-Ion Collider Project
- Leadership in EIC scientific program

**Computational Science & Technology**
- Vision for world-leading computational program
- Developing concept of a High Performance Data Facility focused on the unique challenges and opportunities for data-intensive applications and near real-time computing needs
- Computational Nuclear Physics

**Accelerator Science & Technology**
- Accelerator component production for DOE/SC projects, including LCLS-II and LCLS-II-HE at SLAC, and SNS-PPU at ORNL
- R&D in accelerators, detectors, isotopes

The EIC will enable us to embark on a precision study of the nucleon and the nucleus at the scale of sea quarks and gluons.

Software & Computing will be an integral part of EIC science. "Software is the soul of the detector".

In synergy with the computing for the 12 GeV CEBAF science program, we are working to accelerate science:

- AI/ML and heterogenous computing for next-generation simulations.
- Seamless data processing from DAQ to analysis using streaming readout and AI/ML.
- Rapid turnaround of data to start work on publications.
A podcast about exploring a new frontier in nuclear physics at the upcoming Electron Ion Collider, by Maria Żurek and Markus Diefenthaler.

Stories straight from the heart of matter.

https://www.stronginteractions.org