TMD measurements and requirements at the EIC

EIC science and TMDs
Thoughts on:
• theory requirements
• accelerator requirements
• detector requirements
• computing requirements

Markus Diefenthaler
EIC science program

Study **structure and dynamics of nuclear matter** in **ep and eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.

TMD measurements and requirements at the EIC
EIC science and TMDs

TMD measurements and requirements at the EIC

EIC’s scientific goals: in brief
An electron–ion collider would answer core questions about strongly interacting matter:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from quark and gluon interactions?
- How do colour-charged quarks and gluons, and colourless jets, interact with a nuclear medium? How do confined hadronic states emerge from quarks and gluons? How do quark–gluon interactions create nuclear binding?
- How does a dense nuclear environment affect quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei: does it saturate at high energy, giving rise to gluonic matter with universal properties in all nuclei, even the proton?

TMDs of free nucleons
TMDs of bound nucleons
TMD program in EIC White Paper

Ultimate measurement of TMDs for quarks
- high luminosity
  - high-precision measurement
  - multi-dimensional analysis ($x$, $Q^2$, $\phi_S$, $z$, $P_t$, $\phi_h$)
- broad $x$ coverage $0.01 < x < 0.9$
- broad $Q^2$ range disentangling non-perturbative / perturbative regimes

First (?) measurement of TMDs for sea quarks

First (?) measurement of TMDs for gluons

Systematic factorization studies
INT-18-3: Further developing the TMD program at the EIC

**Week 2: Workshop on Transverse spin and TMDs**
**Conveners** Harut Avakian, Alessandro Bacchetta, Daniel Boer, Zhongbo Kang

The focus will be shifted to the physics of TMDs such as TMD factorization and evolution, phenomenological implementations, relation to jet physics, and lattice results.

**Weeks 5 & 6: eA collisions**
**Conveners** Giovanni Chirilli, Charles Hyde, Anna Stasto, Thomas Ullrich, Bowen Xiao

These two weeks will focus on the physics of electron-ion collisions. Topics such as nuclear PDF/TMD/GPD, (...)
Requirements for TMD measurements

• **Theory** General considerations

• **Accelerator** Building the right probe

• **Detector** Total acceptance detector and particle identification

• **Computing** Towards the next generation research model in nuclear physics, simulations

**Goal**

• What are our goals for the TMD program at the EIC?
• How do we accomplish our goals?
• What can we do now and what do we need to do now?
• **E.g.:** We need to know $R_{\text{SIDIS}}$ and we plan to measure it at Jefferson Lab.
Theory

Developing our science further
Theory requirements

• TMD collaboration covering all topics:
  • TMD factorization
  • TMD evolution
  • TMD global analysis
  • Lattice QCD and TMDs
  • etc.

• Food for thought: Two related questions:
  • Can we explain to the Scientific American reader why TMDs are a key part of the EIC science program?
  • If we have precise measurements of TMD PDFs what do we learn about big questions, e.g., chiral symmetry breaking, confinement, spin of the nucleon etc.?
Understanding the hadronization process

**LUND String Model** for hadronization (1977 – now)
- simple but powerful phenomenological model
- no (promising) new hadronization models in last 40 years
- **ToDo** project at Jefferson Lab
  - review
  - connect with modern QCD, including TMD and spin effects

String breakup

String drawing

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Accelerator design

Designing the right probe
Electron-Proton Scattering

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

$Q^2 = 400 \text{ GeV}^2$
=> $1/Q = 0.01 \text{ fm}$

Ability to change $x$ projects out different configurations where different dynamics dominate

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Where EIC Needs to be in $x$ (nucleon)

- **Saturation Regime**: Needs to be accessed via ions
- **Collective Regime**
- **Many-body Regime**
- **Few-body Regime**

- **QCD Radiation Dominated** (Studied at HERA)
- **Hadron Structure Dominated**

Main interest for EIC Nucleon/Nuclear Program

TMD measurements and requirements at the EIC
Where EIC needs to be in $Q^2$

- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to $Q^2$ of $\sim 1000 \text{ GeV}^2$ ($\sim 0.005 \text{ fm}$)
- Overlap with existing measurements

**Disentangle Pert./Non-pert., Leading Twist/Higher Twist**

TMD measurements and requirements at the EIC
Designing The Right Probe: $\sqrt{s}$

What are the right parameters for the collider for the EIC science program?

We know the $x$ range: down to $\sim 10^{-3-4}$
We know the $Q^2$ range: up to $\sim 1000 \text{ GeV}^2$

$Q^2 = s x y$, $s = 4E_e E_{\text{hadron}}$
$\rightarrow$ energies we need.

$\sqrt{s}$

order 10 GeV electron  order 100 GeV/u ion
JLEIC parameters (nucleon)

Cross section decreases rapidly with higher $X$

This edge determined by $\sqrt{s}$:
$\sqrt{s} = 65 \text{ GeV}$

This edge determined by proton beam energy:
$E_{\text{proton}} < 100 \text{ GeV} \rightarrow E_{\text{electron}} = 10 \text{ GeV}^2$

Measure at $x$ of $10^{-3}$ to 1, exclusive processes
Luminosity: $x$ 10 to 100 that of HERA

Sets some of the basic parameters of the JLEIC design
JLEIC design strategy: High luminosity and polarization

**Figure-8 shaped ring-ring collider**

- zero spin tune (net spin precession)
- energy-independent spin tune

- polarization easily preserved and manipulated:
  - by small solenoids
  - by other compact spin rotators

**High luminosity**

- high-rate collision of short bunches
  - with small emittance
  - with low charge
- ion beam: high-energy electron cooling (R&D)
- electron beam: synchrotron radiation damping

Technology choice determines initial and upgraded energy reach.
What are our luminosity requirements for the updated TMD program? What results would we like to obtain from the first few years of EIC running?
Luminosity requirements

World Data on $F_2^p$

World Data on $g_1^p$

World Data on $h_1^p$

TMD measurements and requirements at the EIC
Detector design

General design considerations
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
Particle Identification

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.**

Gluon TMDs Vertex reconstruction much more important than HERA fixed target.
Final-state particles

The aim is to get \( \sim 100\% \) 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

**For TMD measurements** \( \sim 4\pi \) coverage w.r.t. virtual-photon direction
Interaction region concept

TMD measurements and requirements at the EIC

**Dipoles** analyze the forward particles and create space for detectors in the forward direction.

**Beam crossing angle** creates room for forward dipoles.

NOT TO SCALE!
Interaction region concept

Possible to get ~100% acceptance for the whole event

Total acceptance detector (and IR)
Detector and interaction region

Extended detector: 80m
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer
fully integrated with accelerator lattice

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Computing
Towards the next generation research model in NP Simulations
Computing Challenges in Nuclear Physics (NP)

**NP experiments** driven by beam intensity, polarization, exquisite control of background and systematics

**multi-dimensional challenges**

*example* 3D imaging of quarks and gluons

![3D imaging graph](image)

- high statistics in five or more dimensions and multiple particles

**multiple channel challenges**

*example* discovery search of gluon-based exotic particles (PWA, 1000s of waves)

![Discovery search graph](image)

- strongly iterative analysis for reliable, model-independent analysis

TMD measurements and requirements at the EIC
Donald Geesaman (ANL, former NSAC Chair) “It will be joint progress of theory and experiment that moves us forward, not in one side alone”

Martin Savage (INT) “The next decade will be looked back upon as a truly astonishing period in NP and in our understanding of fundamental aspects of nature. This will be made possible by advances in scientific computing and in how the NP community organizes and collaborates, and how DOE and NSF supports this, to take full advantage of these advances.”
Towards the next generation research model in NP

**NP research model** not changed for over 30 years

**Science & Industry** remarkable advances in computing & microelectronics

**goal** evolve & develop **NP research model** based on these advances

**rethink** how measurements are compared to theory

- examine capabilities of event level analysis taking the multi-dimensional challenges of NP fully into account

What are our requirements? What do theoreticians wish from experiments? What do experimentalists wish from theoreticians? What technical and sociological challenges do we face?
Selected analysis requirements

High-precision analysis tools:

- high-precision MCEG
- radiative correction library
- multi-dimensional analysis

Long-lived data repositories

- COMPASS, HERMES, JLab, RHIC
- document analysis publicly for analysis and theory development (RIVET)
- combined global analysis (e.g., HERA fit), possibly on event level
Lesson from HEP high-precision QCD measurements require high-precision MCEGs
Monte Carlo Event Generator

MCEG

- faithful representation of QCD dynamics
- based on QCD factorization and evolution equations

Algorithm of general-purpose MCEG

1. Generate kinematics according to fixed-order matrix elements and a PDF.
2. QCD Evolution via parton shower model (resummation of soft gluons and parton-parton scatterings).
3. Hadronize all outgoing partons including the remnants according to a model.
4. Decay unstable hadrons.
Pythia8: Simulating DIS results

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Pythia8 with SPIN

Collins

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Collins

Apions in DIS

No transversity PDF

• Linearity in $\mu$ ruined!

Project Jefferson Lab community, LUND, INFN Trieste

First attempt

COMPASS kinematics

u quarks polarized along $y$

d quarks polarized along $-y$

all other quarks unpolarized

no transversity PDF

Albi Kerbizi, Leif Lönnblad

TMD measurements and requirements at the EIC

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Radiative Effects and MCEG

Radiative effects

- change kinematics on an event by event basis:
  - smearing of kinematic distributions
- change of virtual-photon direction:
  - false asymmetries in the azimuthal distribution of hadrons
- correction:
  - unfolding procedure, requires MCEG including radiative corrections / effects

ESC: Radiative effects library

- Elke-Caroline Aschenauer, Andrea Bressan
- essential for high-precision measurements at the EIC
- collaboration with Hubert Spiesberger:
  - start back from HERACLES part of Djangoh
  - work on interface to PYTHIA6/8
Organization

EIC User Group
EIC User Group (http://www.eicug.org)
Currently 822 members from 173 institutions from 30 countries.

Physicists around the world are thinking about and are defining the EIC science program.
EICUG Software Working Group

Charge

The EICUG Software working group’s initial focus will be on simulations of physics processes and detector response to enable quantitative assessment of measurement capabilities and their physics impact. This will be pursued in a manner that is accessible, consistent, and reproducible to the EICUG as a whole. It will embody simulations of all processes that make up the EIC science case as articulated in the White-paper. The Software working group is to engage with new major initiatives that aim to further develop the EIC science case, including for example the upcoming INT program(s), and is anticipated to play key roles also in the preparations for the EIC project(s) and its critical decisions. The working group will build on the considerable progress made within the EIC Software Consortium (ESC) and other efforts. The evaluation or development of experiment-specific technologies, e.g. mass storage, clusters or other, are outside the initial scope of this working group until the actual experiment collaborations are formed. The working group will be open to all members of the EICUG to work on EICUG related software tasks. It will communicate via a new mailing list, eswg@eicug.org, and organize regular online and in-person meetings that enable broad and active participation from within the EICUG as a whole.

Conveners

David Blyth (ANL), Markus Diefenthaler (JLAB)

Engage with theory community and learn about theory tools and requirements.
Discussion

• What are our goals for the TMD program at the EIC?
• How do we accomplish our goals?
• What can we do now and what do we need to do now?

• **Requirements** theory, accelerator, detector, computing