Multidimensional imaging of the partonic structure of hadrons with an Electron-Ion Collider

Salvatore Fazio
Brookhaven National Lab

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Plan of the talk

- Introduction to the Electron-Ion collider project
- Imaging with an EIC (the impact!)
  - GPDs
- Nuclei (imaging, saturation)
- Summary
To investigate the nucleon’s partonic structure, the previous and only e+p collider, HERA, was built.

*The x (of Bjorken) variable*: fraction of the nucleon’s momentum carried by the interacting parton

**HERA’s discovery**: Gluon density dominates at $x<0.1$

**Proton**:
- Quark-Masses: $\sim 1\% M_p$
- Mass of the “visible matter” is completely dominated by gluons, QCD dynamics
Most Compelling Physics Goals

How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties emerge from them and their interactions?

What happens to the gluon density in nuclei?
Does it saturate at high energy?
Does this saturation give rise to a gluonic matter with universal properties in all nuclei, even proton?

How does a dense nuclear environment affect the quarks and gluons, and their correlations and their interactions?
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?
Ingredients for a High Resolution “Femtoscope”

Large center-of-mass coverage:
Access to wide kinematic range in $x$ and $Q^2$

Polarized electron and hadron beams:
- access to spin structure of nucleons and nuclei
- Spin vehicle to access the 3D spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe $q$-$g$ structure of NN and NNN interaction in light nuclei

Nuclear beams:
- Accessing the highest gluon densities → amplification of saturation phenomena

High luminosity:
- Detailed mapping the 3D spatial and momentum structure of nucleons and nuclei
- Access to rare probes

All these requirement must be addressed by a future Electron-Ion Collider
The Electron Ion Collider

Two proposals for realization of the Science Case

For e-N collisions at the EIC:
✓ Polarized beams: e, p, d/³He
✓ Luminosity $L_{ep} \sim 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$
  100-1000 times HERA
✓ $\sqrt{s} = 20-100 (140) \text{ GeV}$ Variable CoM

For e-A collisions at the EIC:
✓ Wide range in nuclei
✓ Luminosity per nucleon same as e+p
✓ Variable center of mass energy

World’s first
Polarized electron-proton/light ion and electron-Nucleus collider

Both designs use DOE’s significant investments in infrastructure
“General-porpose” detector general requirements

Overall detector requirements:
- **Large acceptance in pseudorapidity**: \(-4.5 \leq \eta \leq 4.5\)
- Equal coverage of tracking and EM-calorimetry
- High performance PID to separate p, K, π on track level
- High precision low mass tracking
- **Forward instrumentation** for protons and neutrons
- High control on systematic effects

A full silicon detector concept also proposed by Argonne
EIC Detector and R&D program

→ https://wiki.bnl.gov/conferences/index.php/EIC_R%2520A

A model detector concept: BeAST
(Brookhaven eA Solenoidal Tracker)
Partonic tomography of the nucleons

2D+1 picture in momentum space
transverse momentum dependent PDFs
→ SIDIS, Drell-Yan, weak bosons
\[ x f_1(x, k_T, S_T) \]

2D+1 picture in coordinate space
generalized parton distributions
→ exclusive reaction

TMDs
\[ d^2 r_T \]

GPDs
\[ d^2 k_T \]

Wigner distribution
\[ W(x, k_T, r_T) \]

R. Yoshida
H. Avagyan

Quarks
unpolarized
polarized

S. Fazio (BNL)
The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized versions). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of**

\[
F^q = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ix\vec{P}z^-} \langle p'| \bar{q}(\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle_{z^+=0, z=0} \\
= \frac{1}{2P^+} \left[ H^q(x, \xi, t, \mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x, \xi, t, \mu^2)\bar{u}(p') \frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N} u(p) \right]
\]
Exclusive Vector Meson and real photon production

**DVCS (γ)**

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by $Q^2$
- Sensitive to both quarks and gluons [via $Q^2$ dependence of xsec (scaling violation)]

**Scale:** $Q^2$

**DVCS on a real neutron target** → polarized Deuterium or He$^3$

**VM (ρ, ω, φ, J/ψ, Υ)**

- Uncertainty of wave function
- $J/Ψ$ → direct access to gluons, c+bar-c pair produced via quark(gluon)-gluon fusion
- Light VMs → quark-flavor separation

**VMP:**

- Alternative/complementary way to quark-flavor separation

Square 4-momentum at the $p$ vertex:

$$t = (p' - p)^2$$
Accessing the GPDs in exclusive processes

\[
\frac{d\sigma}{dt} \sim A_0 \left[ |H|^2(x,t,Q^2) - \frac{t}{4M_p^2} |E|^2(x,t,Q^2) \right]
\]

\( \varphi = \phi_h - \phi_l \) 
Angle btw the production and scattering planes

\( \varphi_s = \Phi_T - \phi_h \) 
Angle btw the scattering plane and the transverse pol. vector

\[
A_C = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto Re(A)
\]

Requires a positron beam
done @ HERA

\[
A_{UT} \propto \sqrt{-\frac{t}{4M^2}} \left[ F_2(t)H(\xi,\bar{\xi},t,Q^2) - F_1(t)E(\xi,\bar{\xi},t,Q^2) + ... \right]
\]

\( \sin(\Phi_T-\phi_N) \) 
governed by E and H
Requires a polarized proton-target

Spin-Sum-Rule in PRF:
\[
\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2} \Delta \Sigma + \sum_q \mathcal{L}_q^z + J_g^z
\]
from \( g_1 \)

\[
J_q^z = \frac{1}{2} \left( \int_{-1}^1 x \, dx \left( H_q^z + E^q_\perp \right) \right)_{t \to 0}
\]

Dominated by \( H \) 
slightly dependent on \( E \)

S. Fazio (BNL)
The HERA Collider and experiments

- 27.5 GeV electrons/positrons on 920 GeV protons $\rightarrow \sqrt{s}=318$ GeV
- 2 collider experiments: H1 and ZEUS
- HERA I: 16 pb$^{-1}$ e-p, 120 pb$^{-1}$ e+p
  HERA II (after lumi upgrade): 500 pb$^{-1}$, polarisation of e+,e-

Closed July 2007, still lot of excellent data to analyse...

Detectors not originally designed for forward physics, but diffraction at HERA is great success story!

ZEUS forward instrumentation no longer available in HERA II

- Fixed target experiment
- Intense program on DVCS!
two electromagnetic candidates (ordered in energy) and up to one track

BH must be removed [uncertainty on BH xsec ~ 3%]

$\gamma$ sample: no tracks matching to the second candidate

Signal sample

(DVCS+BH)

e sample: a track match to the second candidate

Control sample

(BH+ dilepton + J/$\psi$)

Wrong-sign sample: a negative track match to the second candidate

Control sample

(dilepton + J/$\psi$)

Kinematic region:

$1.5 < Q^2 < 100 \text{ GeV}^2$

$40 < W < 170 \text{ GeV}$

Details on the event selection in the back up slides
The ZEUS result still statistically compatible with H1, but hints for a flatter trend
DVCS at an EIC

E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093

Comprehensive EIC studies
- Signal extraction “a la HERA”
- xSec meas.: Specific requirements to suppress BH (*see backup*)
  \[ \rightarrow \text{keep BH/sample below 60\% at high energies} \]
- Radiative Corrections evaluated (*bkup*)
- detector acceptance & smearing
- $|t|$-binning is (3*resolution)
- 5\% systematic uncertainties

HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries
- EIC will provide sufficient luminosity to bin in multi-dimensions
- Wide $x$ and $Q^2$ range needed to extract GPDs

13 Sep. 2018
S. Fazio (BNL)
DVCS & J/ψ differential cross section

Luminosity: 10 fb⁻¹

- Measurement dominated by systematics
- Fourier transf. of dσ/dt → partonic profiles

DVCS

\[ \gamma^* + p \rightarrow \gamma + p \]

Distribution of gluons

Transverse distance from center, \( b_T \) (fm)
Transverse target-spin asymmetry

EIC pseudo data
20 GeV on 250 GeV
∫Ldt = 100 fb⁻¹

Q² = 4.4 GeV²
x_B = 8.2 × 10⁻⁴
t = -0.25 GeV²

Different assumptions for E

\[ A_{UT} \propto \sqrt{\frac{-t}{4M^2}} \left[ F_2(t)H(\xi,\xi,t,Q^2) - F_1(t)E(\xi,\xi,t,Q^2) + \ldots \right] \]

Spin-Sum-Rule in PRF:
\[ \frac{1}{2} = J_q^z + J_g^z = \frac{1}{2} \Delta \Sigma + \sum_q \mathcal{A}_q^z + J_g^z \]
\[ J_q^z = \frac{1}{2} \left( \int_{-1}^{1} x \, dx \left( H_q^{q,g} + E_q^{q,g} \right) \right)_{t \to 0} \]

\[ \sin(\Phi_T - \phi_N) \]
governed by E and H

Gives access to GPD E

E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093
DVCS-based imaging

- A global fit over all mock data was done, based on: [Nuclear Physics B 794 (2008) 244–323]
- Known values $q(x)$, $g(x)$ are assumed for $H^q$, $H^g$ (at $t=0$ forward limits $E^q$, $E^g$ are unknown)

\[
q(x, \tilde{b}, \mu^2) = \frac{1}{4\pi} \int_0^\infty dt J_0(|\tilde{b}|\sqrt{|t|}) H(x, \eta = 0, t, \mu^2)
\]

E.C. Aschenauer, S. F., K. Kumerički, D. Müller, JHEP09(2013)093
Spatial Imaging – as in the EIC White Paper

Impact of EIC (based on DVCS only):

- Excellent reconstruction of $H^{\text{sea}}$, and $H^g$ (from $d\sigma/dt$)
- Reconstruction of sea-quarks GPD E

Other capabilities still to be evaluated?

- GPD H-Gluon is nice but can be much better by including $J/\psi$
- Access to GPD E-gluon $\rightarrow$ orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)
Topical Workshop, CFNS, Stony Brook U., 4-6 June 2018  
Organizers: Marie Boer, S. F., Lech Szymanowski, Christian Weiss  
35 participants, 3 days of presentations and discussions  
INDICO page: https://indico.bnl.gov/event/4346/  

Objective: Assess potential of hard exclusive meson production and related processes for GPD studies and plan EIC simulations  

• Concepts and interpretation: Quark/gluon imaging, energy-momentum tensor  
• Reaction theory: QCD factorization, finite-size effects  
• Experimental results: HERA, JLab 6 & 12 GeV, COMPASS; LHC UPC pA, future RHIC UPC plans  
• EIC machine and detector requirements  
• Simulation tools: Physics models, PARTONS framework, detector models
Scattered Proton measurement

**Note:**

- high energy colliders (HERA, Tevatron, LHC, RHIC) use Roman Pots to detect these protons
- RPs are high resolution movable small tracking detectors (Si strips, Si pixels...), a crucial component
- $\theta < 10$ mrad
  - impact on large $p_T$-acceptance
- small $p_T$-acceptance limited by beam divergence and immittance
- rule of thumb keep 10s between RP and beam

Remember:

- Detector -4 to 4 in $h$
  - $35$ mrad from beam line
  - so not seen in main detector
  - need different detection technology

$p_T$ of proton critical for physics

\[ p_T = p' \sin(\theta) \]

\[ p'_{L} > 97\% \text{ of } p_{\text{Beam}} \]

**Note:**

- ZEUS Coll, JHEP 06 (2009) 074

**Graph:**

- X-axis: proton momentum [GeV/c]
- Y-axis: proton scattering angle [mrad]
- Legend: ZEUS LPS, SATRAP
- $X_L = p'_{L}/p_{\text{Beam}}$

Events

- Non-diffractive events

- ZEUS LPS

- SATRAP
Impact of proton acceptance

We need large acceptance Proton spectrometers!

Requirement:
\[ \int L_{\text{int}} = 10 \text{fb}^{-1} \]
\[ 0.18 < p_T (\text{GeV}) < 1.3 \]
\[ 0.03 < |t| (\text{GeV}^2) < 1.6 \]

\[ \int L_{\text{int}} = 10 \text{fb}^{-1} \]
\[ 0.44 < p_T (\text{GeV}) < 1.3 \]

\[ \int L_{\text{int}} = 10 \text{fb}^{-1} \]
\[ 0.18 < p_T (\text{GeV}) < 0.8 \]
Proton acceptance with eRHIC

- Plots: HD (high divergence) mode
- Acceptance gap between RP and B0 will be further optimized

Accept $0.3 < p_T < 1.3$ GeV and higher
→ Low $p_T$-part can be filled in with HA (high acceptance, smaller beam divergence) running mode
Proton acceptance with JLEIC

R. Yoshida
Polarized Light Ions at EIC 2018

Two forward charged hadron detector regions:
- Region 1: Small dipole covering scattering angles from 0.5 up to a few degrees (before quads)
- Region 2: Far forward, up to one degree, for particles passing through (large aperture) accelerator quads. Use second dipole for precision measurement. (Hi Res)
And What about nuclei?
Imaging the gluons in nuclei

Diffractive physics in eA
→ Measure spatial gluon distribution in nuclei
→ Reaction: e + Au \rightarrow e' + Au' + J/\psi, \varphi, \rho
→ Momentum transfer \( t = |p_{Au} - p_{Au'}|^2 \)

Hot topic:
- Lumpiness of source?
- Just Wood-Saxon+nucleon \( g(b_T) \)
- coherent part probes “shape of black disc”
- incoherent part (large \( t \)) sensitive to “lumpiness” of the source \[= proton\] (fluctuations, hot spots, ...)

Possible Source distribution with \( b_T g = 2\text{ GeV}^2 \)

Physics requires forward scattered nucleus needs to stay intact
→ Veto breakup through neutron detection

Sensitive to saturation effects!
The National Academy of Science (& Engineering & Arts) in July 2018 unanimously concluded that an EIC will be: “... a unique facility in the world that would answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics”.

Following these recommendation we would expect DOE to launch its Critical Decision (CD) process...

- CD0 (possibly soon)
- CD1: site selection (possibly ~> a couple of years after CD0)
- CD3: start of construction (possibly within ~three years after CD1)

**EIC is an International enterprise!**
Currently ~807 members from 171 institutions, 30 countries, 7 world regions
USA: 47% Europe: 28% Asia: 19% → continuously growing! (B. Sorrow’s talk for details)
Summary

We studied and quantified the capability of an EIC to provide high precision and fine binned DVCS and VMP measurements of both cross sections and asymmetries over a large phase-space. This opens an unprecedented possibility for

- Accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons, and their correlations
- Investigate the proton-spin decomposition puzzle (orbital angular momentum)
- Study of GPDs in nuclei (and possible gluon saturation effects)

EIC science program will profoundly impact our understanding of nucleon structure and the glue
Back up
...and what we don’t know!

- gluons distribution cannot rise forever
  - non-linear pQCD effects provide a natural way to tame this growth
  - characterized by the saturation scale $Q^2_s(x)$

QCD: Dynamical balance between splitting and recombination

A new regime of QCD matter
- Color Glass Condensate (CGC)

Hints from HERA, RHIC and LHC need to test it unambiguously!

- Which correlations constitute the dynamics of the multi body system at low $x$

- How does quark and gluon dynamics generate the proton spin?
  - It is more than the number $1/2 \hbar$!
  - crucial interplay between the intrinsic properties and interactions of quarks and gluons

- How do hadrons emerge from a created quark or gluon?
  - Neutralization of color - hadronization

- 2+1D Structure of nucleons and nuclei
  - How does the glue bind quarks and itself into nucleons and nuclei?

Enhancement of $Q_s^A$ with $A$
- $Q_s^A \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3}$
- saturation regime reached at significantly lower $\sqrt{s}$ in nuclei
- $Au$: ~200 times smaller effective $x$!

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Structure functions

What we Know:
- Extensive program carried at HERA
- $F_2$ precisely measured in a large $x$ range
- At low-$x$ gluons dominate

Differential cross section:

$$ \frac{d\sigma^{ep}}{dx dQ^2} = \frac{2\pi\alpha^2 Y}{xQ^4} \sigma_r(x,Q^2) $$

Reduced cross section:

$$ \sigma_r(x,Q^2) = F_2(x,Q^2) - \frac{Y^2}{Y^*} F_L(x,Q^2) $$
Summary of Detector Requirements

Detector requirements coming directly from the physics case!

Inclusive Reactions in ep/eA:
- Physics: Structure Functions: $g_1, F_2, F_L$
- → Very good scattered electron ID
- → High energy and angular resolution of $e'$ (defines kinematics $\{x,Q^2\}$)

Semi-inclusive Reactions in ep/eA:
- Physics: TMDs, Helicity PDFs, FFs (with flavor separation); di-hadron correlations; Kaon asymmetries, cross sections; etc
- → Excellent hadron ID: $p^\pm, K^\pm, \pi^\pm$ separation over a wide $\{p, \eta\}$ range
- → Full $\Phi$-coverage around $\gamma^*$, wide $p_T$ coverage (TMDs)
- → Excellent vertex resolution (Charm, Bottom separation)

Exclusive Reactions in ep/eA:
- Physics: DVCS, exclusive VM production (GPDs; parton imaging in $b_T$)
- → Exclusivity (large rapidity coverage; reconstruction of all particles in a given event)
- → High resolution, $\sim 100\%$ acceptance, wide coverage in $t$ → Roman pots
- → (eA): veto nucleus breakup, determine impact parameter of collision
  → Sufficient acceptance for neutrons in ZDC
Detector Requirements for Exclusive Reactions in ep/eA

- **Exclusivity criteria:**
  - **eA:** large rapidity coverage \(\rightarrow\) rapidity gap events
    - HCal for \(1<\eta<4.5\) (ballpark \(~50%/\sqrt{E}\))
  - **ep:** reconstruction of all particles in event
    - wide coverage in \(t (=p_T^2)\) \(\rightarrow\) Roman pots

- **eA:** large acceptance for neutrons from nucleus break-up
  - Zero Degree Calorimeter
    - veto nucleus breakup
    - determine impact parameter of collision
BH suppression

**BH electron has very low energy (often below 1 GeV)**

**Important:** em Cal must discriminate clusters above noise down to 1 GeV

DVCS: most of the $\gamma$ are less “rear” than $e$ ($\theta_{el} - \theta_{\gamma} > 0$) → rejects most of the BH cuts keep BH below 60% of the sample even at large $\gamma > 0.5$ – at high energies
DVCS – clusters separation in rapidity

Very important: **hermetic tracker**

\[
\begin{array}{c}
\begin{align*}
\theta_\gamma (\text{rad}) & \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \\
\theta' (\text{rad}) & \quad 2 \quad 2.2 \quad 2.4 \quad 2.6 \quad 2.8 \quad 3 \quad 3.2
\end{align*}
\end{array}
\]

- **N.B.** - Need for a emCAL with a very fine granularity, to distinguish clusters down to \(\Delta \theta = 1\) deg

This is also important for \(\Delta \phi\) calculation in asymmetries measurement and for BH rejection in the xsec measurement

- **N.B.** – when electron lies at a very small angle its track can be missing

A pre-shower calorimeter needed to control background from \(\pi^0 \to \gamma \gamma\)

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BH subtraction will be not an issue for $y < 0.6$

20 x 250 GeV$^2$

BH subtraction will be relevant at lower energies and large $y$, in some of the $x$-$Q^2$ bin

**BUT...**

higher-lower $\sqrt{s}$ kin. overlapping:

x-sec. measurements at a higher $\sqrt{s}$ at low-$y$ can cross-check the BH subtraction made at lower $\sqrt{s}$
Rosenbluth separation

\[ d\sigma = d\sigma_{DVCS} + d\sigma_{BH} + d\sigma_{INT} \]

To separate DVCS from BH even at lower energies, we need a Rosenbluth separation of the electroproduction cross section into its parts.

- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential \(|t|\)-dependence assumed
Requirements:

- Need at +/- 4 mrad beam element free cone before the zero degree calorimeter to detect the breakup neutrons
- Neutrons are also critical to reconstruct collisions geometry
  → precision neutron energy reconstruction → transverse size of ZDC

E.C. Aschenauer