THE PHYSICS OF THE ELECTRON ION COLLIDER

2023 RHIC/AGS ANNUAL USERS’ MEETING
CELEBRATING NEW BEGINNINGS AT RHIC and EIC
Brookhaven National Laboratory
08/04/2023

Many thanks to Yoshitaka Hatta, Swagato Mukherjee, Thomas Ullrich, and Raju Venugopalan
PILLARS OF EIC SCIENCE

- Origin of Nucleon Mass
- Origin of Nucleon Spin
- Gluon Saturation
- Nucleon Tomography
- Nuclear PDFS
- Confinement Physics
The Higgs is responsible for quark masses that make up ~ 2% of the nucleon mass.

How do the interactions of massless gluons and almost massless quarks generate the proton mass?

What does the energy momentum tensor of a proton look like?
How can we understand the spin of the proton within QCD?

What we know:

- Quarks (valence and sea): ~30% of spin in limited x-range
- Gluons (latest RHIC data): ~40% of spin in limited x-range
- Where is the rest?
GLUON SATURATION

Number of gluons grows with decreasing $x$

BUT: Recombination will balance gluon splittings
Non-linear evolution at low $x$ and low to moderate $Q^2$
Saturation of gluon density characterized by scale $Q_s(x)$
Can we find evidence for gluon saturation in the data?
EIC will also help understand Short Range Correlations in nuclei: Scatter electron from one nucleon in a correlated pair and detect its spectator correlated partner.
Mother of all functions describing the structure of the proton:

5D Wigner Function: \( W(x, b_T, k_T) \)

- **longitudinal momentum fraction**
- **transverse momentum**
- **transverse position**

The Wigner distribution was considered not measurable

Recent efforts indicate opportunities via diffractive dijet measurements

Y. Hatta, B.-W. Xiao, F. Yuan, Phys. Rev. Lett. 116, 202301 (2016) for gluon Wigner function at small \( x \)
Spin-dependent transverse momentum dependent PDF

Transverse Momentum Distributions (TMDs)
3D imaging

\[ \int d^2b_T \]
\[ \int d^2k_T \]
\[ f(x, k_T) \]
\[ f(x) \]
\[ f(x, b_T) \]

\[ W(x, b_T, k_T) \]

Momentum space

Coordinate space

Parton densities
∫d²bₜ \quad W(x, b_T, k_T) \quad ∫d²k_T

\begin{align*}
\int d^2b_T & \quad f(x, k_T) \\
\int d^2k_T & \quad f(x) \\
\int d^2b_T & \quad H(x, 0, t) \\
\int dx & \quad F(t)
\end{align*}

Coordinate space

Momentum space

Form factor

Fourier
3D IMAGING

\[ f(x, k_T) \xrightarrow{\int d^2k_T} W(x, b_T, k_T) \xrightarrow{\int d^2b_T} H(x,0,t) \xrightarrow{\text{Fourier}} H(x, \xi, t) \]

\[ f(x) \xrightarrow{\int d^2k_T} \]


Momentum space

Coordinate space

Generalized Parton Distribution (GPD)

\[ H(x,0,t) \]

\[ f(x, k_T) \]

\[ f(x, b_T) \]
These $M_i$ can be computed using forward matrix elements of $T_{i00}^0$ (e.g. lattice results from ETMC and $\chi$QCD)

Experimentally, only off-forward matrix elements $\langle P'| T^{\mu\nu} | P \rangle$ can be measured:

$$
\langle P'| T^{\mu\nu} | P \rangle = \bar{u}(P') \left[ A(t)\gamma^{(\mu}(P')\gamma^{\nu)} + B(t)\frac{\bar{P}^{(\mu}(i\sigma^\nu)\alpha}_\alpha}{2M} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} \right] u(P)
$$

where $\bar{P}^\mu = (P^\mu + P'^\mu)/2$ and $\Delta^\mu = P'^\mu - P^\mu$

$A(0)$ and $B(0)$ are constrained by theoretical considerations

$D$-term $D = D(0)$ must be determined experimentally; related to stress tensor and internal forces
**MEASURING GRAVITATIONAL FORM FACTORS**

Measure $T_{\mu\nu}$ form factors:

\[
\int_{-1}^{+1} dx \, x^{(2-1)} H(x, \xi, t) = A(t) + \xi^2 D(t)
\]

Graviton spin=2

\[
\int_{-1}^{+1} dx \, x^2 E(x, \xi, t) = B(t) - \xi^2 D(t)
\]

\(D = D_q + D_g\)

Quark $D_q$ can be extracted from GPDs measured in Deeply Virtual Compton Scattering (DVCS)

I. V. Anikin and O. V. Teryaev

Threshold vector meson production also provides access to D-terms, especially $D_g$ and $D_s$

Connection to gluon GFF better for heavier vector mesons and higher $Q^2$: EIC has advantage!

PRESSURE DISTRIBUTION IN THE PROTON FROM D(t)


LATTICE QCD

Extraction from LQCD using two different methods

Gluon GFFs: B. Duran et al., Nature 615 (2023) 7954, 813-816
GPDs can also teach us about quark and gluon contributions to the proton spin:

\[ J_{q,g} = \frac{1}{2} \int_0^1 dx \ x (H_{q,g}(x) + E_{q,g}(x)) \]

with \[ \frac{1}{2} = J_q + J_g = \frac{1}{2} \Delta \Sigma + L_{q,\text{kin}} + J_g \]


Alternative spin sum rule:

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]


Missing spin could come from \( \Delta G \) at small \( x \) and orbital angular momentum (OAM)

At small \( x \) OAM has been computed:
It can have opposite sign to the helicities


OAM from Wigner function, from diffractive dijets

Get quark and gluon helicities by measuring the **proton’s spin structure function** $g_1(x, Q^2)$ in the inclusive process $e + p \rightarrow e' + X$ with longitudinally polarized $e$ and $p$ beams

$$g_1(x, Q^2) \simeq \frac{1}{2} \sum q^2 (\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2)) \quad \frac{dg_1(x, Q^2)}{d \log Q^2} \propto \Delta g(x, Q^2) \quad \frac{1}{2} \left[ \frac{d^2 \sigma^{=}}{dx^2 Q^2} - \frac{d^2 \sigma^{\Rightarrow}}{dx^2 Q^2} \right] \simeq \frac{4\pi\alpha^2}{Q^4} y(2 - y) g_1(x, Q^2)$$

The structure function $g_1(x, Q^2)$ presently is terra incognita for $x < 0.004$ and $Q^2 > 1 \text{ GeV}^2$

Theory also needs better control at small $x$: **Helicity evolution equations**

Y. V. Kovchegov, D. Pitonyak, M. D. Sievert, JHEP 01 (2016) 072

Computations including the **chiral anomaly** of QCD indicate that $g_1$ is governed by QCD **topological sphaleron transitions** at small $x \rightarrow$ strong quenching of $g_1$ with decreasing $x$

A. Tarasov, R. Venugopalan, Phys.Rev.D 105 (2022) 1, 014020

If observed at EIC: **First evidence for a topological phenomenon** conjectured to play a key role in the generation of matter-antimatter asymmetry in the early universe
CONSTRaining quark and gluon helicity distributions

Decreasing $x$

See talk by Y. Hatta, Tue, 9AM, for more on spin @ EIC
GLUON SATURATION

Observables that are sensitive to saturation:

- Inclusive: Structure functions
- Semi-inclusive: dihadron, dijet correlations
- Diffractive processes: e.g. ratio of diffractive and total cross-section, vector meson production, diffractive dijet production, …

for a recent review: A. Morreale, F. Salazar, Universe 7 (2021) 8, 312 • e-Print: 2108.08254

For nuclei at the EIC, saturation effects on structure functions should become more prominent

J. Bartels, K. Golec-Biernat, and L. Motyka
Back-to-back peak suppressed more in larger nuclei as momentum imbalance $\sim Q_s$

Broadening is also affected by soft gluon radiation (Sudakov effect)
NEXT TO LEADING ORDER CALCULATIONS

Calculations of saturation effects are advancing to NLO

Example: Inclusive dijet production and modification of the back-to-back peak in the CGC


Ratio showing the modification in a large nucleus over expectation from scaled proton target

Modification as a function of nuclear mass number
Diffractive processes

Diffractive events are characterized by rapidity gap

Neutral color exchange requires at least two-gluons → enhanced sensitivity to gluon saturation

Ratio of diffractive and total cross-section in e+p and e+Au collisions →

Clear difference between saturation models and leading twist shadowing (LTS)


SEE TALKS BY YURI KOVCHEGOV AND MINJUNG KIM ON TUESDAY MORNING FOR MORE ON DIFFRACTION @ EIC
Sartre event generator (bSat & bNonSat = linearized bSat)

- Big difference for $\phi$; less so for $J/\psi$ (larger mass reduces sensitivity to saturation)
Incoherent diffractive vector meson production is sensitive to fluctuations in the target.

The transverse momentum transfer sets the length scale we probe.
FLOW IN $\gamma^* + A$ COLLISIONS

ATLAS has measured $v_2$ in ultra-peripheral collisions (UPC) $\rightarrow$ photon-nucleus collisions


Compared to CGC calculation

Compared to hydrodynamics

Models predict opposite $Q^2$-dependence. This can be studied at the EIC
MORE PHYSICS POTENTIAL AT THE EIC

- Study fragmentation and learn about confinement
  - For example using flavor tagging in jets
- Photon PDF
  - Dijet measurements at EIC provide high precision to constrain unpolarized photon PDFs and first measurements of polarized photon PDFs
- Beyond the standard model physics
  - Charged Lepton Flavor Violation
  - Complementarity of the EIC with the LHC in exploring the SMEFT
  - Nucleon electric dipole moment (CP-violation)
  - Probes of anomalous dipole moments at the EIC
- ...

SEE TALKS BY KEVIN ADKINS AND JUAN LI, TUE, 11:30 AM, 11:50AM FOR MORE ON JETS (AND HEAVY FLAVOR) @ EIC
The EIC will address fundamental questions on the structure and dynamics of nucleons and nuclei in terms of quarks and gluons using precision measurements. Among other topics it will have great impact on our understanding of:

- 3D structure of protons and nuclei
- Gluon saturation
- Origins of proton mass and spin
- Quark and gluon confinement
DIFRACTIVE DIJET PRODUCTION

F. Salazar, B. Schenke, Phys.Rev. D100 (2019) 034007

Slow-down of growth of the cross section for heavy nuclei

Saturation leads to diffractive dip even for a Gaussian proton \( \rightarrow \) shape is modified

also sensitive to the Wigner distribution