Electron-Ion Collider (EIC)

A future high-luminosity polarized $ep, eA$ collider dedicated to the study of the nucleon and nucleus structure.

Center-of-mass energy

Luminosity

$20 \lesssim \sqrt{s} \lesssim 140\,\text{GeV}$

$\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$

2 possible realizations

**Brookhaven**

**Jefferson Lab**
Understand the glue that binds us all

Nucleons and nuclei—the fundamental building blocks of the visible universe. Understand their structure in QCD, namely, in terms of quarks and gluons.

Especially the role of gluons—the least understood particle in the Standard Model. How do they give rise to the nucleon’s mass, spin, etc?
Experiment at EIC: Deep Inelastic Scattering (DIS)

Two most important kinematic variables

\[ Q^2 = -q^2 \]  
(photon virtuality (resolution))

\[ x = \frac{Q^2}{2P \cdot q} \]  
(Bjorken variable (inverse energy))

Roughly,

\[ x \approx \frac{E_{\text{parton}}}{E_{\text{proton}}} \]
(Momentum fraction carried by the participating parton)

Electron, proton and light nuclei can be polarized.

proton, deuteron, helium, gold… any nucleus of your choice!

Electron, proton and light nuclei can be polarized.

(5-18GeV)

(41-275GeV)
EIC Kinematical coverage

Polarized DIS

Unprecedented coverage in kinematics. Tremendous physics opportunities!

Nuclear DIS

High resolution

High energy
Scientific goals of EIC

- Origin of nucleon mass
- Origin of nucleon spin
- Gluon saturation
- Nucleon tomography

White paper arXiv:1212.1701

NAS report July 2018
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Parton distribution function

\[ u(x) = \int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle P | \bar{u}(-z^-/2) \gamma^+ u(z^-/2) | P \rangle \]

Number distribution of up quarks with momentum fraction \( x \) inside the proton

QCD factorization \( \sigma = \sigma_0 \otimes g(x_1) \otimes g(x_2) \)

Universality of PDF—the same function can be used for different processes. Fundamental to the predictive power of pQCD
Multi-dimensional tomography

The nucleon is much more complicated! Partons also have transverse momentum $\vec{k}_\perp$ and are spread in impact parameter space $\vec{b}_\perp$.

$u(x, \vec{k}_\perp)$ Transverse momentum dependent distribution (TMD)

$u(x, \vec{b}_\perp)$ Generalized parton distribution (GPD)

$u(x, \vec{b}_\perp, \vec{k}_\perp)$ Wigner distribution

3D tomography

5D tomography
Measuring TMD: Semi-inclusive DIS

Measure particular hadron species with fixed transverse momentum $P_\perp$ plus anything else.

When $P_\perp$ is small, TMD factorization

$$\frac{d\sigma}{dP_\perp} = H(\mu) \int d^2q_\perp d^2k_\perp f(x, k_\perp, \mu, \zeta) D(z, q_\perp, \mu, Q^2/\zeta)\delta^{(2)}(zk_\perp + q_\perp - P_\perp) + \cdots$$

TMD PDF TMD frag. func.

Open up a new class of observables where perturbative QCD is applicable!
TMD evolution

Define Fourier transform

\[ \int d^2 k_\perp e^{i k_\perp r_\perp} f(k_\perp...) = f(r_\perp...) \]

RG equation

\[ \frac{\partial}{\partial \ln \mu} f(x, r_\perp, \mu, \zeta) = \gamma_F f(x, r_\perp, \mu, \zeta) \]

Collins-Soper equation

\[ \frac{\partial}{\partial \ln \zeta} f(x, r_\perp, \mu, \zeta) = -\mathcal{D}(r_\perp) f(x, r_\perp, \mu, \zeta) \]

- Known to three loops

- Recently computed to three loops!
  - Li, Zhu (2017); Vladimirov (2017)
TMD global analysis

Global analysis of TMD based on ~8000 data points from SIDIS, Drell-Yan.

Bacchetta, Delcarro, Pisano, Radici, Signori (2017)

arTeMiDe state-of-the-art (NNLO+NNLL) implementation

Scimemi, Vladimirov (2017)

TMDlib public library  Hautmann, Jung, Mulders,...

Still in its infancy. Fully blossoms in the EIC era!
Universality up to a sign

Sivers function for the transversely polarized nucleon

\[ \sim \vec{S}_\perp \times \vec{k}_\perp f_{1T}^T(x, k_\perp) \]

→ Single spin asymmetry

The same function, but with opposite signs in DIS and Drell-Yan. (Collins, 2002)

Experimental test at Compass and RHIC. Continue at EIC. EIC can also probe gluon Sivers function from open charm SSA.
Generalized parton distributions (GPD)

\[ P^+ \int \frac{dy^-}{2\pi} e^{ix^+y^-} \langle P' S' | \bar{\psi}(0) \gamma^\mu \psi(y^-) | P S \rangle \]

\[ = H_q(x, \Delta) \bar{u}(P' S') \gamma^\mu u(P S) + E_q(x, \Delta) \bar{u}(P' S') \frac{i\sigma^{\mu\nu} \Delta^\nu}{2m} u(P S) \quad \Delta = P' - P \]

Distribution of partons in **impact parameter** space \( b_\perp \)

Measurable in
Deeply Virtual Compton Scattering (DVCS)

Dupre, Guidal, Vanderhaeghen (2017)
Towards measuring GPD $E$ at the EIC

Ji sum rule for proton spin

$$\frac{1}{2} = J_q + J_g$$

$$J_q = \frac{1}{2} \int dx (H_q(x) + E_q(x))$$

$$J_g = \frac{1}{4} \int dx (H_g(x) + E_g(x))$$

Currently very little is known about $E_q$, nothing about $E_g$ from experiments.

At EIC, we can get a handle on $E_q$.

Aschenauer, Fazio, Kumericki, Muller (2013)

$E_g$ is still challenging, but EIC is the only hope.
D-term: the last global unknown

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

\(D(t = 0)\) is a conserved charge of the nucleon, just like mass and spin!

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Neutron</th>
</tr>
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<tbody>
<tr>
<td>Mass</td>
<td>938.3MeV</td>
<td>939.6MeV</td>
</tr>
<tr>
<td>Spin</td>
<td>½</td>
<td>½</td>
</tr>
<tr>
<td>Charge</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>D-term</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Pressure and stability of the nucleon

D-term related to the radial pressure distribution inside a nucleon  Polyakov, Schweitzer,...

\[ \langle P' | T^{ij} | P \rangle \sim (\Delta^i \Delta^k - \delta^{ik} \Delta^2) D(t) \]

\[ T^{ij}(r) = \left( \frac{r^i r^j}{r^2} - \frac{1}{3} \delta^{ij} \right) s(r) + \delta^{ij} p(r) \]

Enters DVCS as the subtraction constant in the dispersion relation between the real and imaginary parts of amplitude.  Teryaev (2005)
First extraction from Jlab.

Large model dependence so far.
Need significant lever arm in \( Q^2 \) to disentangle different moments of GPDs
Also measure the gluon D-term.  \( \Leftarrow \) talk by Detmold
Scientific goals of EIC

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QCD at small-\(x\)

Probability to emit a soft gluon diverges

\[
\sum_n \frac{1}{n!} (\alpha_s \ln 1/x)^n \sim \left(\frac{1}{x}\right)^{\alpha_s}
\]

A myriad of small-\(x\) gluons in a high energy hadron/nucleus!

BFKL (Balitsky-Fadin-Kuraev-Lipatov) resummation
Gluon saturation

The gluon number eventually saturates, forming the universal QCD matter at high energy called the Color Glass Condensate.

Gribov, Levin, Ryskin (1980); Mueller, Qiu (1986); McLerran, Venugopalan (1993)

Gluons overlap when

$$\frac{\alpha_s}{Q^2} x G(x, Q^2) = \pi R_p^2$$

The saturation momentum

$$Q = Q_s(x) \gg \Lambda_{QCD}$$

High density, but weakly coupled many-body problem
Has saturation been observed at HERA, RHIC, LHC?
eA collision at EIC: ideal place to study saturation

No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)

\[ Q_s^2 \propto A^{1/3} \]
BK-JIMWLK equation

Photon-nucleus scattering at high energy

Photon-nucleus scattering at high energy

Balitsky
Kovchegov
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

Leading Logarithmic (LL) evolution of the scattering amplitude with energy

\[
\frac{\partial}{\partial \ln 1/x} S(r_\perp) = \frac{N_c \alpha_s}{2\pi} \int d^2 r_\perp \frac{r_\perp^2}{z_\perp^2 (r_\perp - z_\perp)^2} (S(z_\perp)S(z_\perp - r_\perp) - S(r_\perp))
\]

Extension to NLL  Balitsky, Chirilli (2008)
Even to NNLL?  Caron-Huot (2016)
Need collinear improvement  Iancu, Mueller, Soyez, Triantafyllopoulos (2015); YH, Iancu (2016)
Golden channel for saturation: Diffraction

Cross sections proportional to the square of the gluon distribution

More sensitive to saturation!

`Day 1 prediction’  \[ \frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}} \bigg|_{eA} \approx 20\% > \frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}} \bigg|_{ep} \]  
Nucleus stays intact in every 1 out of 5 events!

State-of-the-art: NLL + NLO
Complete NLO calculation for exclusive diffraction (vector meson, dijet production)

Boussarie, Grabovsky, Szymanowski, Wallon (2016)
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The proton spin problem

The proton has spin $\frac{1}{2}$.
The proton is not an elementary particle.

Jaffe-Manohar sum rule

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L^q + L^g$$

In the quark model,

$$|P, +\rangle = \frac{1}{3\sqrt{2}} \left\{ |uud\rangle (2|+++\rangle - |++-\rangle - |+-+\rangle - |-++\rangle) + \text{perm} \right\}$$

$$\Delta \Sigma = 1$$
In 1987, EMC (European Muon Collaboration) announced a very small value of the quark helicity contribution

$$\Delta \Sigma = 0.12 \pm 0.09 \pm 0.14$$

Recent value from NLO global analysis

$$\Delta \Sigma = 0.25 \sim 0.3$$
Gluon polarization $\Delta G$

$$\Delta G = \int_0^1 dx \Delta G(x)$$

Result from the NLO global analysis after the RHIC 200 GeV pp data

$$\int_{0.05}^1 dx \Delta G(x, Q^2) \approx 0.2 \pm 0.06_{0.07}$$

($Q^2 = 10 \text{GeV}^2$)

HUGE uncertainty from the small-x region

Small-x evolution revisited.
Kovchegov, Pitonyak, Sievert (2016~)

DeFlorian, Sassot, Stratmann, Vogelsang (2014)
Helicity measurements at EIC

After one-year of data taking at EIC...

Wider coverage in $x$ and $Q^2$ ... finally solve the spin puzzle? No!
Don’t forget orbital angular momentum. It’s there!

Understanding of the nucleon spin structure cannot be complete without OAM. EIC should seriously address it.

You can not learn about OAM from TMD or GPD.
OAM and the Wigner distribution

What exactly is $L^{q,g}$ in the Jaffe-Manohar sum rule? Controversial issue for a long time, but not anymore!

The Wigner distribution naturally defines OAM

$$L^{q,g} = \int dx \int d^2b_\perp d^2k_\perp (\vec{b}_\perp \times \vec{k}_\perp) W^{q,g}(x, \vec{b}_\perp, \vec{k}_\perp)$$

One can also define the ‘PDF’ of OAM

$$L^{q,g}(x) = \int d^2b_\perp d^2k_\perp (\vec{b}_\perp \times \vec{k}_\perp) W^{q,g}(x, \vec{b}_\perp, \vec{k}_\perp)$$

Warning: this is not a twist-2 PDF. It has twist-three components. YH, Yoshida (2012)
Accessing OAM at EIC

Measuring OAM = Measuring Wigner
Unprecedented challenge, but there is some hope.  YH, Xiao, Yuan (2016)

Longitudinal single spin asymmetry in diffractive dijet production

\[ d\Delta\sigma \sim \sin(\phi_P - \phi_\Delta) d\tilde{\sigma} \]

Look for the azimuthal angular dependence

Need more work, more new ideas!
**Scientific goals of EIC**

**Finding 1:** An EIC can uniquely address three profound questions about nucleons—protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?
Lattice QCD can reproduce the hadron masses with great precision.
Proton mass crisis

u,d quark masses add up to ~10MeV, only 1 % of the proton mass!

Higgs mechanism explains quark masses, but not hadron masses!

In relativity, mass and energy are equivalent. The ‘missing mass’ comes from the kinetic energy of quarks and gluons?
Mass from trace anomaly

QCD Lagrangian approximately scale (conformal) invariant. Why is the proton mass nonvanishing in the first place?

→ Conformal symmetry is explicitly broken by the trace anomaly.

QCD energy-momentum tensor

\[ T^{\mu\nu} = -F^{\mu\lambda} F^{\nu}_\lambda + \frac{\eta^{\mu\nu}}{4} F^2 + i\bar{q}\gamma^{(\mu} D^{\nu)} q \]

Trace anomaly

\[ T^\mu_\mu = \frac{\beta(g)}{2g} F^2 + m(1 + \gamma_m(g))\bar{q}q \]

Mass generation

\[ \langle P|T^\mu_\mu|P\rangle = 2M^2 \]
Can we measure the trace anomaly $\langle P| F^{\mu\nu} F_{\mu\nu} | P \rangle$?

The operator $F^{\mu\nu} F_{\mu\nu}$ is twist-four, highly suppressed in high energy scattering.

Instead, we should look at low-energy scattering.

Purely gluonic operator. Use quarkonium as a probe.


$\rightarrow J/\psi$ production near threshold.

Kharzeev, Satz, Syamtomov, Zinovjev (1998)
Photo-production of $J/\psi$ and $\Upsilon$ near threshold

$e \rightarrow \gamma^{(*)} \rightarrow J/\psi, \Upsilon$

$P \rightarrow t \rightarrow P'$

$$\sigma^{\gamma p}_{tot} = \int_{t_{min}}^{t_{max}} dt \frac{d\sigma}{dt}$$

QCD factorization difficult to establish.
Need nonperturbative methods.
Holographic approach

Scattering of hadrons in QCD(-like theories)

\[ \approx \text{scattering of closed strings in asymptotically } \text{AdS}_5 \]

\[
\langle P|\epsilon \cdot J(0)|P'k\rangle \approx -\frac{2\kappa^2}{f_\psi R^3} \int_0^{z_m} dz \frac{\delta S_{D7}(q, k, z)}{\delta g_{\mu\nu}} \frac{z^2 R^2}{4} \langle P|T_{\mu\nu}^{TT}|P'\rangle \leftarrow \text{graviton exch.}
\]

\[ + \frac{2\kappa^2}{f_\psi R^3} \frac{3}{8} \int_0^{z_m} dz \frac{\delta S_{D7}(q, k, z)}{\delta \phi} \frac{z^4}{4} \langle P|\frac{1}{4} F^{a\mu\nu} F_{a\mu\nu}\rangle \mid P'\rangle \leftarrow \text{dilaton} \]
Gluon condensate enhances the cross section. The closer to threshold, the larger the effect is.

\[ M = \frac{1}{2M} \langle P | \frac{\beta}{2g} F^2 + m(1 + \gamma_m) \bar{q}q | P \rangle \]

\[ x \quad 1 - x \]

At EIC, use \( \gamma \) instead.

\[ W = \sqrt{s_{\gamma p}} = 4.3 \text{ GeV} \]

\[ W_{th} = 10.4 \text{ GeV} \]

\[ t_{min} \approx -8.1 \text{GeV}^2 \]
Conclusion

- EIC will significantly advance our knowledge of the nucleons/nuclei, the fundamental building blocks of the universe.

- Many challenges ahead—The deepest questions can only be answered by going to higher twists.

  Tomography  twist-2
  Saturation  all twists
  Spin  twist-2 (helicity) & twist-3 (OAM)
  Mass  twist-4

EIC = higher twist machine