How EIC can help us to understand heavy-ion collisions

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Outline

• TMD
• GPD
• Spin
• Saturation
• Initial geometry
• Jets
• Proton mass
Since the discovery of quarks, DIS has been instrumental to our understanding of the smallest building blocks of our universe.

But we have not yet fully explored the structure of nucleon/nuclei. There are still lots of things to be learned.

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?
Future DIS experiments worldwide

Planned DIS Colliders around the world

<table>
<thead>
<tr>
<th>Facility</th>
<th>Years</th>
<th>$E_{cm}$ (GeV)</th>
<th>Luminosity ($10^{33}$cm$^{-2}$s$^{-1}$)</th>
<th>Ions</th>
<th>Polarization</th>
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<tr>
<td>EIC in US</td>
<td>&gt; 2028</td>
<td>20 - 100 → 140</td>
<td>2 - 30</td>
<td>p → U</td>
<td>e, p, d, $^3$He, Li</td>
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<td>LHeC (HE-LHeC)</td>
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<td>200 - 1300 (1800)</td>
<td>10</td>
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<td>e possible</td>
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<td>PEPIC</td>
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<td>FCC-eh</td>
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<td>15</td>
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<td>e possible</td>
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R. Yoshida, talk at DIS2019
The era of precision EW, pQCD, and precision study of nucleon and nuclear structures in the next 20-30 years!
Exploring *terra incognita*

Unprecedented coverage in kinematics.

Tremendous physics opportunities.

EIC, polarized DIS

EIC, nuclear DIS

FCC-eh, LHeC, VHEeP

Unprecedented coverage in kinematics.

Tremendous physics opportunities.
Tomography
(TMD, GPD)
Multi-dimensional tomography

\[ u(x) = \int \frac{d z^-}{4\pi} \langle P| \bar{u}(0) \gamma^+ u(z^-) |P \rangle \quad x = \frac{E_{\text{parton}}}{E_{\text{proton}}} \]

Ordinary PDF \( \rightarrow \) 1D tomographic image of the nucleon

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

Transverse momentum dependent distribution (TMD) 3D tomography
Generalized parton distribution (GPD) 3D tomography
Wigner distribution 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

Collins, Soper, Sterman; Ji, Ma, Yuan,...

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

TMD PDF TMD frag. function

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

Still in its infancy. Fully blossoms in the EIC era!

<table>
<thead>
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<th>Framework</th>
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<th>COMPASS</th>
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<th>Z</th>
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<td>W</td>
<td>x</td>
<td>x</td>
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\[
\begin{align*}
\langle Q^2 \rangle &= 2 \text{ GeV}^2 \\
\langle x \rangle &= 0.022 \\
\langle Q^2 \rangle &= 2 \text{ GeV}^2 \\
\langle x \rangle &= 0.033 \\
\langle Q^2 \rangle &= 2 \text{ GeV}^2 \\
\langle x \rangle &= 0.055
\end{align*}
\]

\[
\begin{align*}
\text{Norm. multiplicity} & \\
P_{\text{HT}} [\text{GeV}] & \\
0.3 & 0.6 & 0.9 & \\
0.3 & 0.6 & 0.9 & \\
0.3 & 0.6 & 0.9 & \\
\end{align*}
\]
TMD in heavy-ions: Unintegrated gluon distribution at small- $x$

\[
\frac{1}{P^+} \int \frac{d^3k}{(2\pi)^3} e^{i k_{\perp} \cdot z_\perp} \langle P | F^{+i}(z) W F^{+j}(0) | P \rangle = \frac{\delta^{ij}}{2} x G(x, k_\perp) - \frac{1}{2} \left( \delta^{ij} - 2 \frac{k_i^\perp k_j^\perp}{k_\perp^2} \right) x h_\perp(x, k_\perp)
\]

unpolarized gluon

linearly polarized gluon

Can be constrained at EIC

\[\cos 2\phi \text{ correlation in dijet angular distribution} \quad \text{Metz, Zhou (2011) + many others}\]

\[\frac{d\sigma}{dP.S.} \propto x G(x, k_\perp) + \cos(2\phi) x h_\perp(x, k_\perp)\]

Applications in heavy-ions

- Angular correlation in UPC \(\gamma\gamma \rightarrow e^+e^-\) talk by Brandenburg on Monday
- Initial axial charge fluctuations in heavy-ion Lappi, Schlichting (2017)

\[\langle \hat{\nu}(x) \hat{\nu}(y) \rangle = \frac{3g^4 N_c^2 (N_c^2 - 1)}{32} \left[ \left( G_{(U)}^{(1)}(x, y) \right)^2 - \left( h_{(U)}^{(1)}(x, y) \right)^2 \right] \]
Generalized parton distributions (GPD)

Non-forward matrix element of the collinear operator

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

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

\[
\Delta = P' - P
\]

Distribution of partons in impact parameter space

Fourier transform

\[
\Delta_\perp \rightarrow b_\perp
\]

Measurable in Deeply Virtual Compton Scattering (DVCS)

Dupre, Guidal, Vanderhaeghen (2017)
Nucleon gravitational form factors

\[ \langle P' | T_{q,g}^{\mu\nu} | P \rangle = \bar{u}(P') \left[ A_{q,g} \gamma^{(\mu} \tilde{P}^{\nu)} + B_{q,g} \frac{\tilde{P}^{(\mu} i \sigma^{\nu)}_{\alpha} \Delta_\alpha}{2M} + D_{q,g} \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{4M} + \bar{C}_{q,g} M g^{\mu\nu} \right] u(P) \]

All the form factors are interesting and measurable!

- **A\(_{q,g}\)\:** Momentum fraction
- **B\(_{q,g}\)\:** Ji sum rule
- **D\(_{q,g}\)\:** `Pressure’ and `shear’ inside proton
- **\(\bar{C}_{q,g}\)\:** Mass, pressure

Berkert, Elouadrhiri, Girod (2018)
Proton spin
The proton has spin $\frac{1}{2}$. The proton is not an elementary particle.

Jaffe-Manohar sum rule

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

$\Delta \Sigma = 1$ in the quark model

$\Delta \Sigma = 0.25 \sim 0.3$

Experiments revealed that less than 30% of the proton spin comes from quark spin.
Evidence of nonzero $\Delta G$

$\int dx \Delta g(x, Q^2 = 10\text{GeV}^2) = 0.20^{+0.06}_{-0.07}$  \hspace{1cm} \text{DSSV++}

$\int dx \Delta g(x, Q^2 = 10\text{GeV}^2) = 0.17 \pm 0.06$  \hspace{1cm} \text{NNPDFpol1.1}

$\int dx \Delta g(x, Q^2 = 1\text{GeV}^2) = 0.5 \pm 0.4$  \hspace{1cm} \text{JAM15}

- RHIC spin program elucidated that the gluon spin contribution is significant!

- Beware, there is huge uncertainty from the small-$x$ region

- EIC will finally pin down the value of $\Delta G$

  - How does spin behave at small-$x$? Is saturation important for spin? \hspace{1cm} Kovchegov, Pitonyak, Sievert; Boussarie, YH, Yuan

  - What is the role of the orbital angular momentum? Can we measure OAM?
Orbital angular momentum of partons

QCD Wigner distribution  Belitsky, Ji, Yuan (2003)

\[ W(x, \vec{k}_\perp, \vec{b}_\perp) = \int \frac{d^2 \Delta_{\perp}}{(2\pi)^2} \frac{d^3 z}{16\pi^3} e^{ix P^+ z^- - i\vec{k}_\perp \cdot \vec{z}_\perp} \langle P - \frac{\Delta}{2} | \bar{\psi}(b - \frac{z}{2}) \gamma^+ W \psi(b + \frac{z}{2}) | P + \frac{\Delta}{2} \rangle \]

Define \[ L^q = \int dx \int d^2 b_\perp d^2 k_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z W^q(x, \vec{b}_\perp, \vec{k}_\perp) \]  Lorce, Pasquini (2011); YH (2011); Xiong, Ji, Yuan (2012)

Similar discussions in heavy-ion community in the context of global polarization.

\[ \frac{d\Pi^\alpha(p)}{d^3 p} \approx \frac{\hbar}{2mE_p} \int d^3 x \sum_p \lambda^\alpha_\sigma p_\sigma f_{FD}(x, p)(1 - f_{FD}(x, p)) \]

vorticity

Becattini, Chandra, Del Zanna, Grossi (2013)
Becattini, talk on Wednesday
Saturation

\[ Y = \ln \frac{1}{x} \]

\[ \ln Q_s^2(Y) = \lambda Y \]

**Saturation**

**Dilute system**

BFKL

DGLAP
Has saturation been observed at HERA, RHIC, LHC?
EIC: Dream machine for saturation

No initial state interactions (advantage over LHC, RHIC)
Nuclear enhancement of the saturation momentum (advantage over HERA)

\[ R_A \sim A^{1/3} \]

At EIC, for heavy nuclei, \( Q^2_s \) becomes perturbative!
(It wasn’t the case at HERA actually...)
Can saturation become precision physics?

No all-order proof of factorization.  
`Leading order’ already contains infinitely many diagrams with infinitely many twists.

\[ \text{NLL Balitsky-Kovchegov (BK)} \quad \text{Balitsky, Chirilli (2008)} \]
\[ \text{NNLL BK} \quad \text{Caron-Huot, Herranen (2016)} \]

Factorization should be checked order by order. Currently NLO for a few processes.

\[ \text{Chirilli, Xiao, Yuan; Beuf; Mulian, Iancu; Roy, Venugopalan…} \]

\[ \text{e.g., NLO exclusive diffractive dijet, vector meson production at EIC} \]

\[ \text{Boussarie, Grabovsky, Szymanowski, Wallon (2016)} \]

Need also `collinear improvement’ \text{Iancu, talk on Wednesday}

\[ \text{NLO global analysis of the dipole S-matrix at EIC? cf. Albacete, Armesto, Milhano, Salgado (2009)} \]
Initial geometry
Initial geometry and fluctuations

Proton/nucleus wavefunction at small-\(x\) full of fluctuations and correlations

**DIPSY**
Monte Carlo event generator based on Mueller’s dipole model. Includes BFKL cascade and saturation.  
Avsar, Flensburg, Gustafson, Lonnblad

Dipole evolution implemented in PYTHIA8, can simulate large nucleus and virtual photon

\(\rightarrow\) Full simulation of \(\gamma^* A\) including final states!  
Bierlich, Rasmussen (2019)

\[ \text{Eccentricity in pp 7 TeV at LHC} \]

Avsar, Flensburg, YH, Ollitrault, Ueda (2011)
Incoherent diffraction

Probe of fluctuations inside the target (Good-Walker picture)

\[ \frac{d\sigma^{\text{diff}}}{dt}_{\text{incoherent}} = \langle T^2 \rangle - \langle T \rangle^2 \]

Bumpy initial condition + b-dependent JIMWLK Mantysaari, Schenke (2016,2019)

Good description of the HERA data at large- \( t \). Extension to light nuclei \( \rightarrow \) EIC
Jets
Jets at EIC

Compared to jets at LHC,

Smaller $p_T$, smaller multiplicity

Less underlying events and pileups

Stronger power corrections.

New opportunities for jet physics

Perturbation theory stabilizes at NNLO!

NNLO single inclusive jet in ep collisions at EIC
Abelof, Boughezal, Liu, Petriello (2016)
Jet quenching at EIC

Clean environment to study jet quenching
The effects will be small compared to AA, precision required.
→ useful to discriminate different approaches to jet quenching.

Insights into hadronization  Vitev, talk at POETIC2019
Vitev, Sievert (2018)

Heavy-flavor $R_{eA}$
→ sensitive to different scenarios of hadronization

hadronization inside

hadronization outside the medium
Proton mass

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?
Proton mass crisis

u,d quark masses add up to \( \sim 10\text{MeV} \), only 1% of the proton mass!

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

\[ \langle P|T_\mu|P\rangle = 2M^2 \]

Nonperturbative gluon condensate \( \langle P|F^{\mu\nu}F_{\mu\nu}|P\rangle \) responsible for hadron masses.
Photo-production of $J/\psi$ near threshold

Sensitive to the gluon condensate

$$\langle P' | F^{\mu\nu} F_{\mu\nu} | P \rangle$$

Ongoing experiments at JLab
Can be an interesting physics case at EIC, especially in China

Holographic calculation fitted to the latest JLab data.
YH, Yang (2018)
YH, Rajan, Yang (2019)

Red: with gluon condensate
Blue: without gluon condensate
Threshold production at high energy colliders?

- **EIC photo-production limit**
- **eSTARlight Monte Carlo**
  - Lomnitz, Klein (2018), Klein, talk at POETIC 2019

- **RHIC, Ultra-peripheral pA collisions**
  - YH, Rajan, Yang (2019)

Challenging to measure, need forward detectors. Heavy-ion can help us to understand EIC physics!
Conclusion

• In 10-15 years from now, DIS experiments will be running in the US, China and Europe.

• Tremendous physics opportunities for theory, experiments, and lattice QCD

• Many feedbacks to heavy-ion physics, especially gluon saturation and initial geometry

• Conversely, heavy-ion can help us to understand EIC physics
  → Ultra-peripheral collision (UPC)