The Electron-Ion Collider: A New Tool for Studying QCD

Christine A. Aidala
University of Michigan

Student Day, Quark Matter 2017
Chicago
February 5, 2017

arXiv:1212.1701
Areas of study in QCD

• Structure/properties of QCD matter

• Formation of states of QCD matter

• Interactions within QCD
Structure/Properties of QCD matter

• Bound states: Mesons and baryons

• Bound states of bound states: Nuclei, neutron stars

• Deconfined states: Quark-gluon plasma
Formation of states of QCD matter

- Hadronization mechanisms
- Formation of bound states of bound states
- Jet structure
- Equilibration of QGP
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments
Interactions within QCD

- Parton energy loss in cold and hot QCD matter
- Flow of partons within QGP
- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One parton $\rightarrow$ multiple hadrons
    - Multiple partons $\rightarrow$ one hadron
- Color flow effects
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of partons across colliding hadrons
Complexity and richness of QCD: Confinement

- QCD theory: Quarks and gluons
- QCD experiment: QCD bound states

- Always an interplay between partonic/hadronic descriptions, reductionist/emergent pictures
High-energy collisions: 
Tools to study QCD

• Need high (enough) energies to
  – Access subnuclear distance scales
  – Form new states of QCD matter

• High energies can also
  – Allow use of perturbative theoretical tools
  – Provide access to new probes, e.g. heavy flavor, Z/W bosons
High-energy collisions: 
Tools to study QCD

Can study QCD via

- **Hadron-hadron collisions**: p+p, p+A, A+A, pbar+p/A, π+A

- **Lepton-hadron collisions**: e/μ+p, e/μ+A, ν+A

- **Lepton-lepton collisions**: e⁺e⁻ (hadronization)
High-energy collisions: Control

The more aspects of the collisions we can control/manipulate, the more powerful our tools

- Collision species $\rightarrow$ state of matter to be studied, geometry, path length, flavor/isospin, electroweak vs. strong interactions
- Energy $\rightarrow$ distance/time scales, probes accessible, states of matter
- Polarization $\rightarrow$ spin-spin and spin-momentum correlations in QCD systems or in hadronization, sensitivity to system properties (e.g. gluon saturation)

Some aspects we select rather than control

- Centrality, final-state produced particles and their kinematics

Multidifferential measurements even more powerful

- $p_T$, rapidity, centrality, angular distribution/correlation, PID, . . .
Why an Electron-Ion Collider?

• Electroweak probe
  – “Clean” processes to interpret (QED)
  – Measurement of scattered electron \( \rightarrow \) full kinematic information on partonic scattering

• Collider mode \( \rightarrow \) Higher energies
  – Quarks and gluons relevant d.o.f.
  – Perturbative QCD applicable
  – Heavier probes accessible (e.g. charm, bottom, W boson exchange)
EIC facility concepts

- Beams of light $\rightarrow$ heavy ions
  - Previously only fixed-target $e^{+}A$ experiments
- Polarized beams of $p$, $d/He^3$
  - Previously only fixed-target polarized experiments
EIC facility concepts

- Beams of light $\rightarrow$ heavy ions
  - Previously only fixed-target e+A experiments
- Polarized beams of p, d/He$^3$
  - Previously only fixed-target polarized experiments
- Luminosity 100-1000x that of HERA e+p collider
- Two concepts: Add electron facility to RHIC at BNL or ion facility to CEBAF at JLab
Partonic momentum structure of nuclei: Not just superposed protons and neutrons

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction $x$
- Regions of both enhancement and depletion—only Fermi motion reasonably understood

$R_A \equiv \frac{1}{A} \frac{F_{2A}}{F_{2N}} \neq 1$

SLAC: Gomez et al. PRD49, 4348 (1994)
Partonic momentum structure of nuclei: Nuclear parton distribution functions

(Traditional collinear, unpolarized) Nuclear PDFs

EPPS16 – arXiv:1612.05741
Partonic momentum structure of nuclei: EMC effect and local density

- Fit slope of ratios for $0.3 < x < 0.7$; compare across nuclei
- EMC slope doesn’t scale with A or with avg nuclear density...
Partonic momentum structure of nuclei: EMC effect and local density

Density determined from *ab initio* few-body calculation
*S.C. Pieper and R.B. Wiringa,*

But appears to scale with local density!
Local density in nuclei is important!

Partonic spatial structure of nuclei: Diffraction

• X-ray diffraction used to probe spatial structure of atomic crystal lattices
  – Measure in momentum space, Fourier transform to position space

• Nuclear distance scales → Need gamma ray diffraction!
  – Again measure diffractive cross section in momentum space (Mandelstam $t$), Fourier transform to position space

---

Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius

From E. Aschenauer
Partonic spatial structure of nuclei: Diffraction

Expected diffraction pattern from gamma ray incident on ~spherical nucleus

Diffractive $\rho$ production in Au+Au ultraperipheral collisions

e+A, p+A, or A+A. Probed nucleus in one beam. Gamma emitted by electron or Coulomb-excited proton/nucleus passing nearby in second beam.
Partonic spatial structure of nuclei: Diffraction

Goal: Cover wide range in t. Fourier transform \( \Rightarrow \) impact-parameter-space profiles. Obtain \( b \) profile from slope vs. t.

Note: Can use Bose-Einstein correlations (HBT) in e+A to probe spatial extent of particle production region, as in hadron-hadron collisions.
Diffraction to study universal state of gluonic matter: Gluon saturation

• In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei
Gluon saturation

At small $x$ linear evolution gives strongly rising $g(x)$ — but must be bounded!

BK/JIMWLK non-linear evolution includes recombination effects $\rightarrow$ saturation

- Dynamically generated scale
  - Saturation Scale: $Q_s^2(x)$
    - Increases with energy or decreasing $x$
  - Scale with $Q^2/Q_s^2(x)$ instead of $x$ and $Q^2$ separately

$$\sigma_{tot} = \frac{\pi}{m_\pi^2} (\ln s)^2$$

Bremsstrahlung $\sim \alpha_s \ln(1/x)$

Recombination $\sim \alpha_s \rho$

$x = \frac{P_{\text{parton}}}{P_{\text{nucleon}}}$
**Diffraction in e+A as a probe of gluon saturation**

- Fewer potential competing effects in e+p/A than hadron-hadron collisions
- Easier to reach predicted saturation regime with e+A than e+p
- e+Au at higher c.m. energies for EIC will provide window of overlap where both Color-Glass Condensate effective field theory calculations and perturbative QCD calculations can be done and compared
**Diffraction in e+A as a probe of gluon saturation**

- **Top panel:** EIC projections for ratio of diffraction cross section to total, along with predictions based on saturation and shadowing models.
- **Bottom panel:** Projections and predictions for double ratio: \( \frac{\text{diffractive/total}}{\text{total}} |_{e+A} / \frac{\text{diffractive/total}}{\text{total}} |_{e+p} \)
  - Very strong handle to distinguish saturation from shadowing!

- **Note:** Saturation can also be probed via 2-particle correlations in e+A, as in p/d+A.
**Parton dynamics in QCD systems**

- Angular correlations in particle production: one way to probe parton dynamics
- Can look at Fourier amplitudes

Large cos $2\phi$ modulation in d+Au at 200 GeV, p+Pb at 5.02 TeV

Significant cos $2\phi$ modulation also in p+p at 13 TeV

PHENIX: PRL 114, 192301 (2015)

arXiv:1609.06213
Parton dynamics in QCD systems: How many ways can a $\cos 2\phi$ modulation be generated in hadronic collisions??

- Large modulation in direct photon production in 200 GeV Au+Au collisions
- Huge modulation in pion-induced Drell-Yan
  - Understood as due to spin-momentum correlations of partons inside unpolarized hadrons
  - These correlations will be studied in detail at EIC

C. Aidala, QM Student Day, 2/5/17

E615, PRD39, 92 (1989)
NA10, ZPC31, 513 (1986)
Formation of QCD bound states: Hadronization at EIC

- Use nuclei as femtometer-scale detectors of the hadronization process!
- Wide range of scattered parton energy; small to large nuclei
  - Move hadronization inside/outside nucleus
  - Distinguish energy loss and attenuation

Comprehensive studies of hadronization as well as of propagation of color charges through nuclei possible at EIC
As in A+A and p+A, fragmentation functions are modified in e+A, e.g. suppression of pion production.
Formation of QCD bound states: Hadronization in higher-density partonic environments

Baryon enhancement observed in central A+A but also peripheral A+A and in p/d+A.

p/π ratio for central d+Au and peripheral Au+Au—shape and magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$\langle N_{\text{coll}} \rangle$</th>
<th>$\langle N_{\text{part}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60-92%</td>
<td>14.8 ± 3.0</td>
<td>14.7 ± 2.9</td>
</tr>
<tr>
<td>d+Au</td>
<td>15.1 ± 1.0</td>
<td>15.3 ± 0.8</td>
</tr>
</tbody>
</table>

PRC88, 024906 (2013)
Formation of QCD bound states: Hadronization in higher-density partonic environments

- Evidence for baryon enhancement also in e+A!
- Baryon enhancement in A+A, p+A, e+A suggests mechanism(s) other than “vacuum fragmentation”
- Binding of nearby partons in phase space?

HERMES, NPB780, 1 (2007)
Links to collective behavior in high-multiplicity $p+p$, and in $p+A$?

Lots of interesting behavior when extra partons come into play, whether it’s “hot” or “cold” QCD
Formation of bound states of bound states: Creating nuclei

Will it be possible to create e.g. d, dbar in e+A??
Formation of QCD bound states: Hadronization at EIC

Fragmentation from QCD vacuum

Virtual photon

Incoming lepton

String Breaking

Scattered lepton

Current fragmentation

Target fragmentation

\[ +\eta \sim 4 \]

\[ -\eta \sim -4 \]
Formation of QCD bound states: “Target fragmentation” region

- Related to color neutralization of remnant—soft particle production

- Electron-Ion Collider will map out target fragmentation region well
  - Collider geometry – easier than in fixed-target to separate “current” from “target” fragmentation

- Connections to
  - “Underlying event” in hadron-hadron collisions
  - Forward hadron production in hadron-hadron collisions
  - Cosmic ray physics

- “Fracture functions” – theoretical tools to describe target fragmentation
Conclusions

• These are exciting times in QCD!
• Complementary facilities, as well as theoretical advances, are allowing us to probe QCD’s rich complexities in ever-greater detail, with ever-increasing sophistication
  – Part of new era of QCD as a more mature field

Electron-Ion Collider → next major facility in the ongoing quest to address the fundamental questions of QCD
  • How do we describe different QCD systems in terms of their quark and gluon degrees of freedom?
  • In what ways can colored quarks and gluons form colorless QCD bound states?
  • What are unique properties of QCD interactions?
Extra
Bose-Einstein correlations for nuclear semi-inclusive DIS

- Sensitive to spatial separation of production of the two particles
- No nuclear dependence found within uncertainties

HERMES, EPJ C75, 361 (2015)
Hadronization: Parton propagation in matter

• Interaction of fast color charges with matter?
• Conversion of color charge to hadrons through fragmentation and breakup?

Existing data $\Rightarrow$ hadron production modified on nuclei compared to the nucleon!
EIC will provide ample statistics and much greater kinematic coverage!
- Study time scales for color neutralization and hadron formation
- $e+A$ complementary to jets in $A+A$: cold vs. hot matter
Accessing quarks and gluons through DIS

Kinematics:

Quark splits into gluon
Gluon splits into quarks

\[ Q^2 = -q^2 = -(k_{\mu} - k'_{\mu})^2 \]
\[ Q^2 = 2E_e E'_e (1 - \cos \Theta_{e'}) \]
\[ y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left( \frac{\Theta'_{e}}{2} \right) \]
\[ x = \frac{Q^2}{2pq} = \frac{Q^2}{sy} \]

Measure of resolution power
Measure of inelasticity
Measure of momentum fraction of struck quark

Quark density
Valence quark
Sea quark

Momentum fraction x
10^{-16}m
10^{-19}m

10^{-19}m
higher \sqrt{s}
increases resolution
Accessing gluons with an electroweak probe

\[
\text{DIS: } \frac{d^2 \sigma^{ep \rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]
\]

Access the gluons in DIS via scaling violations:
\[dF_2/d\ln Q^2\] and linear DGLAP evolution in \[Q^2 \rightarrow G(x, Q^2)\]

OR

Via \(F_L\) structure function

OR

Via dihadron production

OR

Via diffractive scattering
Accessing gluons with an electroweak probe

\[ \frac{d^2 \sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right] \]

Access the gluons in DIS via scaling violations:

- \(dF_2/d\ln Q^2\) and linear DGLAP evolution in \(Q^2\)

Or

- Via FL structure function

Or

- Via dihadron production

Or

- Via diffractive scattering

C. Aidala, QM Student Day, 2/5/17

Gluons dominate low-x wave function

\[ xG \sim \frac{1}{20} \]

\[ xd \sim \frac{1}{20} \]
Accessing gluons with an electroweak probe

\[ \frac{d^2 \sigma^{ep \rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2) \right] \]

Access the gluons in DIS via scaling violations:

Via FL structure function
Via dihadron production
Via diffractive scattering

Gluons in fact dominate (not-so-)low-x wave function!
Hyperon polarization from unpolarized collisions

- 1976 lambda polarization discovery: p+Be, 300 GeV beam
- Polarization transverse to production plane up to ~20% for forward-angle lambda production; Polarizing TMD FF?
- Confirmed 1977 at CERN, p+Pt, 24 GeV beam (and by various proton-nucleus and proton-proton experiments afterwards . . .)
\( \Sigma^+ \) polarized with opposite sign

- 1981: \( p+\text{Be} \), 400 GeV beam
$\Xi^0$ polarization similar to $\Lambda^0$

- 1983: p+Be, 400 GeV beam
- Similar results for p+Cu and p+Pb
$x_F$ dependence of lambda polarization in hadronic collisions

- Same sign and general $x_F$ dependence for neutron beams
- But for K- and $\Sigma$-beams, positive polarization at positive $x_F$
- And for $\pi$-beam, positive polarization but at negative $x_F$!
- Consistent with zero for $\pi^+$ and K+ beams
Lambda polarization observed in semi-inclusive DIS

- Nonzero in both forward and backward directions

HERMES, PRD90, 072007 (2014)
Formation of QCD bound states: Heavy flavor

• Open heavy flavor—vacuum fragmentation picture

• Heavy quarkonium states—different thinking
  – Handles on production via $p_T$ dependence, polarization, in-medium modification
  – For very high $p_T$ production in hadronic collisions, return to vacuum fragmentation picture? How to handle multiple hard scales in calculations?
Transverse-momentum-dependent (TMD) factorization breaking and color entanglement

- 2010: Rogers and Mulders predict color entanglement in processes involving p+p production of hadrons if parton transverse momentum taken into account
- Due to gluon exchange between scattering parton and proton remnant in both initial and final state
- Partons become correlated across the two colliding protons
  - Can no longer factorize the nonperturbative functions into independent pdfs and fragmentation functions
  - Will need new (unknown) nonperturbative functions describing quantum-correlated partons across bound states
- Consequence of QCD specifically as a non-Abelian gauge theory!

\[ p + p \to h_1 + h_2 + X \]

Color flow can't be described as flow in the two gluons separately. Requires simultaneous presence of both.
Searching for evidence of predicted TMD-factorization breaking at RHIC

- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial-state hadrons
  - Color exchange between a scattering parton and remnant of other proton
- And at least 1 final-state hadron
  - Exchange between scattered parton and either remnant

→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production
**Out-of-plane momentum component distributions**

- Clear two-component distribution
  - Gaussian near zero—nonperturbative transverse momentum
  - Power-law at large $p_{\text{out}}$—kicks from hard (perturbative) gluon radiation

- Different colors $\rightarrow$ different bins of trigger particle $p_T$, proxy for hard interaction scale

Curves are fits to Gaussian and Kaplan functions, not calculations!
Look at evolution of nonperturbative transverse momentum widths with hard scale \((Q^2)\)

- Theoretical proof of factorization within transverse-momentum-dependent framework directly predicts that nonperturbative transverse momentum widths increase as a function of the hard scattering energy scale (Collins-Soper-Sterman evolution)
  - Increased phase space for gluon radiation
- Confirmed experimentally in semi-inclusive deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)

Nonperturbative momentum widths observed to decrease in processes where factorization breaking predicted

- Suggestive of TMD-factorization breaking effects?
- Have not yet completely ruled out a “trivial” nonperturbative correlation between partonic longitudinal momentum fraction $x$ and partonic transverse momentum $k_T$
- Steeper negative slope for photon-hadron than dihadron correlations—counterintuitive?
  - Photon can’t exchange gluon with remnant—might expect weaker effects than dihadron case
Nonperturbative momentum widths observed to decrease in processes where factorization breaking predicted

- Slope of decrease for both photon-hadron and dihadron correlations reproduced ~exactly in PYTHIA p+p event generator—could this effect be in PYTHIA??
- Effectively yes! Unlike analytic pQCD calculations, PYTHIA forces entire event including remnants to color neutralize, implemented via something they call “color reconnection”