Overview of the future programs at JLAB and EIC

Jianwei Qiu
Theory Center, Jefferson Lab
The 12 GeV Upgrade greatly expands the research capabilities of Jefferson Lab, adding a fourth experimental hall – D, upgrading existing halls and doubling the power of the lab's accelerator.

Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6, ...

**Project Scope**
- Doubling the accelerator beam energy – **DONE**
- New experimental Hall D and beam line – **DONE**
- Civil construction including utilities – **DONE**
- Upgrades to Experimental Halls B & C – ~99%
  - Halls B & C Detectors – **DONE**

**TPC = $338M**
99% complete!
JLab 12 GeV Scientific Capabilities

*Hall D* – exploring origin of **confinement** by studying **exotic mesons**

*Hall B* – understanding **nucleon structure** via generalized parton distributions

*Hall C* – precision determination of **valence quark** properties in nucleons and nuclei

*Hall A* – form factors, **future new experiments** (e.g., SoLID and MOLLER)
The next QCD frontier – the “big” questions, ...

JLAB12 and the Electron-Ion Collider (EIC)

How JLAB12/EIC could answer the “big” questions?

Path forward to the EIC era – unique role of JLAB12

Summary
The next QCD frontier

- What is the role of QCD in the evolution of the universe?

- How are hadrons emerged from quarks and gluons?

- How does QCD make up the properties of hadrons?
  - Their mass, spin, magnetic moment, ...

- What is the QCD landscape of nucleon and nuclei?
  - Color Confinement 200 MeV (1 fm)
  - Asymptotic freedom 2 GeV (1/10 fm)

- How do the nuclear force arise from QCD?

... Have to understand the role of glue!
The next QCD frontier

Understanding the glue – the Next QCD Frontier!

Gluons are weird particles!

- Massless, yet, responsible for nearly all visible mass

“Mass without mass!”

Higgs mechanism

Dynamics of gluons

Quarks

Mass \( \approx 1.78 \times 10^{-26} \) g

\(~1\% of proton mass\)

Proton

Mass \( \approx 1.68 \times 10^{-26} \) g

\(~99\% of proton mass\)

Bhagwat & Tandy/Roberts et al
The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!

- Gluons are weird particles!
  - Massless, yet, responsible for nearly all visible mass
  - Carry color charge, responsible for color confinement and strong force

![Diagram of quarks and gluons](image)

Force between a heavy quark pair

![Graph showing force between quarks](image)

Heavy quarks experience a force of ~16 tons at ~1 Fermi (10^{-15} m) distance
The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!

- Gluons are weird particles!
  - Massless, yet, responsible for nearly all visible mass
  - Carry color charge, responsible for color confinement and strong force
  - but, also for asymptotic freedom

Nobel Prize, 2004

QCD perturbation theory
The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!

- Gluons are weird particles!
  - Massless, yet, responsible for nearly all visible mass
  - Carry color charge, responsible for color confinement and strong force
  - but, also for asymptotic freedom, as well as the abundance of glue
Gluons are weird particles!

- Massless, yet, responsible for nearly all visible mass
- Carry color charge, responsible for color confinement and strong force
- but, also for asymptotic freedom, as well as the abundance of glue

Without gluons, there would be
NO nucleons, NO atomic nuclei...
NO visible world!
Unprecedented Intellectual Challenge!

- **Facts:**
  - We measure/detect leptons and hadrons
  - No modern detector has been able to see quarks and gluons in isolation!

- **The challenge:**

  How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?

- **Answer to the challenge:**

  **Theory advances:**
  - QCD factorization – matching the quarks/gluons to hadrons with controllable approximations!

  **Experimental breakthroughs:**
  - Energy, luminosity and measurement – Unprecedented resolution, event rates, and precision probes, especially EM probes, …
    - **Quarks** – Need the probe to “see” their existence, …
    - **Gluons** – Varying the probe’s resolution to “see” their effect, …
    - **Jets** – Footprints of energetic quarks and gluons
QCD factorization is an approximation

- Cross section with identified hadron(s) is NON-Perturbative!

\[
\sigma_{\text{DIS}}(x, Q^2) = 2 = \text{Leading power/twist factorization!}
\]

\[
= c_q \otimes q(x, Q^2) + c_g \otimes g(x, Q^2) + c_{qg} \otimes T_{qg}(\{x\}, Q^2) + c_{gg} \otimes T_{gg}(\{x\}, Q^2)
+ \mathcal{O}\left(\langle k_T^2 \rangle / Q^n, \langle F^{2n} \rangle / Q^n\right) + \ldots
\]

Approximation – Leading power/twist factorization!

- Power corrections
  - Non-Lineral contribution
  - Non-linear correlations

- Leading power
  - Linear contribution
  - DGLAP regime

- Non-perturbative physics neglected or in input PDFs!
How to “see” and quantify the hadron structure?

- **EM probe:** Not a camera!
  - Collision by photon exchange with a large momentum transfer: \( Q \)
  - e.g. Photon momentum: \( q^2 = -Q^2 \) in DIS

- **Resolution:**
  - \( 1/Q \sim 1/10 \) fermi = \( 10^{-14} \) cm = 2 GeV\(^{-1} \)
  - Breit frame (Brick-Wall frame) in DIS:
    - \( q = (q_0, q_\perp, q_z) = (0, 0_\perp, -Q) \)
    - \( p = (Q/2, 0_\perp, Q/2) \)
    - \( x_B = x = Q/(2P_z) \propto 1/P_z \)
  - **Resolution in Breit frame:**

- **High energy:** boosted partonic structure
  - Could be the same as this!
  - Time dilation!
JLAB12 & the Electron-Ion Collider (EIC)

- **A giant “Microscope”:**
  - “see” quarks/gluons and their dynamics by breaking the hadron

- **A sharpest “CT”:**
  - “imagine” the quark/gluon structure without breaking the hadron
  - “cat-scan” the nucleon and nuclei with better than $1/10$ fm resolution
  - “see” the proton “radius” of quark/gluon density
  - “explore” the range of color force

“see” the non-linear dynamics of the glue!
Many complementary probes at one facility

- High energy and luminosity Lepton-hadron facility:

\[ Q^2 \rightarrow \text{Measure of resolution} \]
\[ y \rightarrow \text{Measure of inelasticity} \]
\[ x \rightarrow \text{Measure of momentum fraction of the struck quark in a proton} \]
\[ Q^2 = S \times y \]

**Inclusive events:** \( e+p/A \rightarrow e^'+X \)
Detect only the scattered lepton in the detector

**Semi-Inclusive events:** \( e+p/A \rightarrow e^'+h(\pi,K,p,\text{jet})+X \)
Detect the scattered lepton in coincidence with identified hadrons/jets

**Exclusive events:** \( e+p/A \rightarrow e^'+p'/A'+h(\pi,K,p,\text{jet}) \)
Detect every things including scattered proton/nucleus (or its fragments)
How to answer the “big” questions?

How does QCD generate the nucleon mass?

“... The vast majority of the nucleon’s mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. ...”  

The 2015 Long Range Plan for Nuclear Science

Hadron mass from Lattice QCD calculation:

How does QCD generate this? The role of quarks vs that of gluons?

If we do not understand proton mass, we do not understand QCD
How to answer the “big” questions?

- Three-pronged approach to explore the origin of hadron mass
  - Lattice QCD
  - Mass decomposition – roles of the constituents
  - Model calculation – approximated analytical approach

The Proton Mass
At the heart of most visible matter.
Temple University, March 28-29, 2016

https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/
Three-pronged approach to explore the origin of hadron mass

- Lattice QCD
- Mass decomposition – roles of the constituents
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The 2015 Long Range Plan for Nuclear Science

Role of quarks and gluons?

QCD energy-momentum tensor:

\[ T^{\mu\nu} = \frac{1}{2} \bar{\psi} i \not{D}^{(\mu \gamma^{\nu})} \psi + \frac{1}{4} g^{\mu\nu} F^{2} - F^{\mu\alpha} F^{\nu}_{\alpha} \]

Trace of the QCD energy-momentum tensor:

\[ T^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_{q}(1 + \gamma_{m}) \bar{\psi}_{q} \psi_{q} \]

QCD trace anomaly

\[ \beta(g) = -(11 - 2n_{f}/3) g^{3}/(4\pi)^{2} + \ldots \]

Mass, trace anomaly, chiral symmetry break, and ...

\[ \langle p | T^{\mu\nu} | p \rangle \propto p^{\mu} p^{\nu} \quad \Rightarrow \quad \langle p | T^{\mu\nu} | p \rangle (g_{\mu\nu}) \propto p^{\mu} p^{\nu} (g_{\mu\nu}) = m^{2} \gamma^{*} \]

\[ m^{2} \propto \langle p | T^{\alpha}_{\alpha} | p \rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g} \langle p | F^{2} | p \rangle \]

Heavy quarkonium production near the threshold, from JLab12 to EIC
How to answer the “big” questions?

How does QCD generate the nucleon’s spin?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g) = \sum \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle \]

Proton Spin

Quark helicity
Best known

\[ \frac{1}{2} \int dx \left( \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right) \sim 30\% \]

Spin “puzzle”

Gluon helicity
Start to know

\[ \Delta G = \int dx \Delta g(x) \sim 20\% \text{(with RHIC data)} \]

Orbital Angular Momentum of quarks and gluons
Little known

If we do not understand proton spin, we do not understand QCD
How to answer the “big” questions?

- How does QCD generate the nucleon’s spin?

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

- What can JLab12 and EIC do?

Plus many more JLab12 experiments – flavor
New role of the lattice calculations

Lattice QCD

- New ideas – from quasi-PDFs (lattice calculable) to PDFs:
  - High $P_z$ effective field theory approach:
    \[
    \tilde{q}(x, \mu^2, P_z) = \int_x^1 \frac{dy}{y} Z \left( \frac{x}{y}, \frac{\mu}{P_z} \right) q(y, \mu^2) + O \left( \frac{\Lambda^2}{P_z^2}, \frac{M^2}{P_z^2} \right)
    \]
  - QCD collinear factorization approach:
    \[
    \tilde{q}(x, \mu^2, P_z) = \sum_f \int_0^1 \frac{dy}{y} C_f \left( \frac{x}{y}, \frac{\mu^2}{\bar{\mu}^2}, P_z \right) f(y, \bar{\mu}^2) + O \left( \frac{1}{\mu^2} \right)
    \]

Non-perturbative lattice UV renormalization:
  Effective mass renormalization, Gradient flow, …

- The TMD Collaboration + on-going effort around the world!
  Plus the intense JLab and world-wide theory effort!
New role of the lattice calculations

- New ideas – from quasi-PDFs (lattice calculable) to PDFs:
  - High $P_z$ effective field theory approach:
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    \tilde{q}(x, \mu^2, P_z) = \int_x^1 \frac{dy}{y} Z \left( \frac{x}{y}, \frac{\mu}{P_z} \right) q(y, \mu^2) + \mathcal{O} \left( \frac{\Lambda^2}{P_z^2}, \frac{M^2}{P_z^2} \right)
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  - QCD collinear factorization approach:
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    \tilde{q}(x, \mu^2, P_z) = \sum_f \int_0^1 \frac{dy}{y} C_f \left( \frac{x}{y}, \frac{\mu^2}{\bar{\mu}^2}, P_z \right) f(y, \bar{\mu}^2) + \mathcal{O} \left( \frac{1}{\mu^2} \right)
    \]

Non-perturbative lattice UV renormalization:
- Effective mass renormalization, Gradient flow, …

- Tremendous potentials!
  - PDFs of proton, neutron, pion, …; TMDs, GPDs, …; JLab12 expts
How to answer the “big” questions?

- How does QCD generate the nucleon’s spin?

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

To understand the proton spin, fully, we need to understand the confined motion of quarks and gluons in QCD.

TMDs, GTMDs, …

Need “probes” for two-scale observables!
Two-momentum-scale observables

Cross sections with two-momentum scales observed:

\[ Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{QCD} \]

- **Hard scale**: \( Q_1 \) localizes the probe to see the quark or gluon d.o.f.
- **“Soft” scale**: \( Q_2 \) could be more sensitive to hadron structure, e.g., confined motion

Two-scale observables with the hadron broken:

- **SIDIS**: \( Q \gg P_T \)
- **DY**: \( Q \gg P_T \)
- Two-jet momentum imbalance in SIDIS, ...

Natural observables with TWO very different scales

- TMD factorization: partons’ confined motion is encoded into TMDs
Cross sections with two-momentum scales observed:

\[ Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{QCD} \]

- **Hard scale**: \( Q_1 \) localizes the probe to see the quark or gluon d.o.f.

- **“Soft” scale**: \( Q_2 \) could be more sensitive to hadron structure, e.g., confined motion

Two-scale observables with the hadron unbroken:

- Natural observables with TWO very different scales
- GPDs: Fourier Transform of t-dependence gives spatial \( b_T \)-dependence

\[ t = (p_1 - p_2)^2 \]

DVCS: \( Q^2 \gg |t| \)

DVEM: \( Q^2 \gg |t| \)

EHMP: \( Q^2 \gg |t| \)

J/\( \Psi \), \( \Phi \), ...

+ ...
How to answer the “big” questions?

- 3D boosted partonic structure:

  ![Diagram of partonic structure](image)

  - **Momentum Space**
  - **Coordinate Space**

  - **TMDs**
  - **GPDs**
  - **Confined motion**
  - **Spatial distribution**

  Two-scales observables

  - \( f(x,k_T) \)
  - \( f(x,b_T) \)

  3D momentum space images

  - \( Q \gg P_T \sim k_T \)

  2+1D coordinate space images

  - Exclusive DIS
  - Semi-inclusive DIS

  - \( Q \gg |t| \sim 1/b_T \)

JLab12 – valence quarks, EIC – sea quarks and gluons
TMDs: confined motion, its spin correlation

- Power of spin – many more correlations:
  - Un-Polarized (U): $f_1 = \bullet$
  - Longitudinally Polarized (L): $g_{1L} = \bullet$
  - Transversely Polarized (T): $h_{1T} = \bullet$

- Physical scales: Require two

- More than one TMD contribute to the same observable!

- Similar for gluons

- $A_N$ – single hadron production:
  - Di-jet, photon-jet not exactly back to back
  - No asymmetry for the jet axis
  - Transversity
  - Collins-type
  - Sivers-type

Photons have asymmetry
Jet vs. Photon sign flip predicted
SIDIS is the best for probing TMDs

- Naturally, two scales & two planes:

\[ A_{UT}(\varphi_h, \varphi_S) = \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \]

\[ = A_{UT}^{\text{Collins}} \sin(\phi_h + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi_h - \phi_S) \]

\[ + A_{UT}^{\text{Pretzelosity}} \sin(3\phi_h - \phi_S) \]

- Separation of TMDs:

\[ A_{UT}^{\text{Collins}} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp \]

\[ A_{UT}^{\text{Sivers}} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1 \]

\[ A_{UT}^{\text{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp \]

Hard, if not impossible, to separate TMDs in hadronic collisions

Using a combination of different observables (not the same observable): jet, identified hadron, photon, ...
TMD Topical Theory Collaboration

Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD Collaboration)

Co-spokespersons: W. Detmold, J.W. Qiu

One of three DOE supported Topical Theory Collaborations
Has 4 National Labs + 9 Universities
Objectives/Deliverables – 3D Confined Motion:

Unique three pronged scientific effort:
(1) theory, (2) phenomenology and
(3) lattice QCD, to explore 3D hadron structure – 3D confined motion!

- Matching x-section to parton motion
  - QCD factorization

- Parton motion vs. probing scale
  - QCD quantum evolution
  - RHIC Run17 – W program

- Lattice QCD calculation of TMDs
  - QCD 1st principle prediction?

- Fast software to extract TMDs
  - Service to community

- JLab12 data, …

Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction
Why 3D nucleon structure?

Rutherford’s experiment – atomic structure (100 years ago):

Atom:

J.J. Thomson’s plum-pudding model → Rutherford’s planetary model → Modern model Quantum orbitals

Discovery of nucleus
A localized charge/force center
A vast “open” space

1911

Completely changed our “view” of the visible world:

- Mass by “tiny” nuclei – less than 1 trillionth in volume of an atom
- Motion by quantum probability – the quantum world!

3D nucleon/nuclear structure:

- Distribution and motion of quarks and gluons – confining mechanism?
Why 3D nucleon structure?

Spatial distributions of quarks and gluons:

- **Bag Model**: Gluon field distribution is wider than the fast moving quarks.
  - Gluon radius > Charge Radius

- **Constituent Quark Model**: Gluons and sea quarks hide inside massive quarks.
  - Gluon radius \sim Charge Radius

- **Lattice Gauge theory (with slow moving quarks)**: Gluons more concentrated inside the quarks.
  - Gluon radius < Charge Radius

3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

Relation between charge radius, quark radius (x), and gluon radius (x)?
How to answer the “big” questions?

- **Run away gluon density at small x?**
  - What causes the low-x rise?
    - gluon radiation
      - non-linear gluon interaction
  - What tames the low-x rise?
    - gluon recombination
      - non-linear gluon interaction

- **QCD vs. QED:**
  - **QCD – gluon in a proton:**
    \[
    Q^2 \frac{d}{dQ^2} x G(x, Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' G(x', Q^2)
    \]
  - **QED – photon in a positron:**
    \[
    Q^2 \frac{d}{dQ^2} x \phi\gamma(x, Q^2) \approx \frac{\alpha_{em}}{\pi} \left[ -\frac{2}{3} x \phi\gamma(x, Q^2) + \int_x^1 \frac{dx'}{x'} x' \left[ \phi_{e+}(x', Q^2) + \phi_{e-}(x', Q^2) \right] \right]
    \]
  - ✧ At very small-x, proton is “black”, positronium is still transparent!
  - ✧ Recombination of large numbers of glue could lead to saturation phenomena
How to answer the “big” questions?

Run away gluon density at small x?

- What causes the low-x rise?
  - gluon radiation
    - non-linear gluon interaction

- What tames the low-x rise?
  - gluon recombination
    - non-linear gluon interaction

Particle vs. wave feature:

Gluon saturation – Color Glass Condensate

Radiation = Recombination

Leading to a collective gluonic system?

with a universal property of QCD?

new effective theory QCD – CGC?

Expectation: x=10^-5 in a proton at Q^2=5 GeV^2
If color is localized inside the nucleon, using a large nucleus does not change gluon dynamics inside nucleon:
- no advantage for seeing the gluon saturation,
- but, provides an opportunity to study QCD multiple scattering.

If color leaks outside of the nucleon inside a large nucleus, color interaction between nucleons modifies the nuclear landscape:
- large nucleus could have an advantage for discovering the universal properties of the gluon saturation “earlier”.
If the color is localized inside nucleon, ... Qiu, Vitev, PRL2004

\[ \xi^2 = 0.09 - 0.12 \text{ GeV}^2 \]

One number for all \( x_B, Q, \) and \( A \) dependence!
Saturation in $F^A_2$

No saturation in $F^A_2$

Collision effects

A simple question:

Will the suppression/shadowing continue to fall as $x$ decreases?
A simple question:

Will the suppression/shadowing continue to fall as $x$ decreases?

Ratio of $F_2$: Shadowing vs. Saturation

Saturation in $F_2^N$
No saturation in $F_2^A$

Saturation in nucleon

Collison effects

Color localized inside nucleons

Color leaks outside nucleons
Soft gluon radius is larger

Saturation in RF
No saturation in $F_2^A$

Collision effects

Fermi motion

EMC finding
The EIC Users Group: EICUG.ORG

(no students included as of yet)

670 collaborators, 28 countries, 150 institutions... (December, 2016)

Map of institution’s locations

The EIC Users Meeting at Stony Brook, June 2014:
→ http://skipper.physics.sunysb.edu/~eicug/meeting1/SBU.html

The EIC UG Meeting at University of Berkeley, January 6-9, 2016
http://skipper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html

Recent EICUG Argonne National Laboratory July 7-10, 2016
http://eic2016.phy.anl.gov

Remote/Internet: meeting: March 16th: For NAS Review preparation

Next meeting:
July 18-22, 2017 Trieste, Italy
• Registration opening by April 30

EICUG MEETING – July 18-22
TRIESTE

eicug2017.ts.infn.it
EIC is a ultimate QCD machine:
1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
2) to search for hints and clues of color confinement, and
3) to measure the color fluctuation and color neutralization

JLAB/EIC are tomographic machines for nucleons and nuclei with a resolution better than 1/10 fm

EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

JLAB12 is a prerequisite of the full EIC program, in addition to its own rich physics program

EIC@US is sitting at a sweet spot for rich QCD dynamics – capable of taking us to the next QCD frontier

Thanks!
US EIC – Kinematic reach & properties

For e-N collisions at the EIC:
- Polarized beams: e, p, d/\(^3\)He
- Variable center of mass energy
- Wide \(Q^2\) range → evolution
- Wide x range → spanning from valence to low-x physics
- 100-1K times of HERA Luminosity

For e-A collisions at the EIC:
- Wide range in nuclei
- Variable center of mass energy
- Wide \(Q^2\) range (evolution)
- Wide x region (high gluon densities)

EIC explores the “sea” and the “glue”, the “valence” with a huge level arm