The Science Case for An Electron-Ion Collider: The Next QCD Frontier

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for both BNL and JLab EIC efforts, ...

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White Paper for the Electron-Ion Collider

Electron Ion Collider: The Next QCD Frontier

Understanding the glue that binds us all

arXiv:1212.1701
Community effort and commitment

- 2007 Nuclear Physics Long Range Plan
  Designated Electron-Ion Collider (EIC) as “embodying the vision for reaching the next QCD frontier”

- Many workshops on EIC physics:
  Ten-week program (9/13–11/19, 2010) at Institute for Nuclear Theory

- Commitment from BNL and JLab:
  - BNL EIC Task force
  - EIC@JLab
    (https://eic.jlab.org/wiki/index.php/Main_Page)
  - EICAC – jointly by BNL and JLab
Outline

- Why do we need an Electron-Ion Collider (EIC)?
  In the big picture of Nuclear Science and QCD
- What is the impact and discovery potential of the EIC?
  In terms of the most intellectually pressing questions in QCD
- What are the goals and deliverables of the EIC?
  In the context of key measurements
- Realization: the staged approach
  the stage-I deliverables, and the stage-II opportunities
- International context, a path to the full potential of an EIC
  ENC@GSI, HIAF@CAS, LHeC@CERN, ...
- Summary and outlook
Nuclear Science and QCD

- **Nuclear Science:**
  to discover, explore, and understand all forms of nuclear matter and its benefits to our society

- **Nuclear matter:**
  - the nucleus
  - the nucleons
  - the quarks and gluons

  Accounting for essentially all of the mass of the visible universe

- **Quantum Chromodynamics (QCD):**
  - A fundamental theory for the dynamics of quarks and gluons
  - It describes the formation of all forms of nuclear matter

*Understanding QCD is a fundamental and compelling goal of Nuclear Science!*
Successes of QCD

@low energy:

- Hadron mass spectrum from lattice QCD

@high energy:

- Asymptotic freedom + perturbative QCD

Measure e-p at 0.3 TeV (HERA)
Predict p-p and p-p at 0.2, 1.96, and 7 TeV
Puzzles and challenges

- **Proton mass “puzzles”:**
  - Quarks carry $\sim 1\%$ of proton’s mass
  
  How does glue dynamics generate the energy for nucleon mass?

- **Proton spin “puzzles”:**
  - Quarks carry $\sim 30\%$ of proton’s spin
  
  Why does quark spin contribute so little to proton’s spin?

- **3D structure of nucleon:**
  - Color Confinement
  - Asymptotic freedom
  
  Probing momentum

  How does glue bind quarks and itself into a proton and nuclei?

  Can we scan the nucleon to reveal its 3D structure?
Puzzles and challenges

QCD at high densities and temperatures:

- Heavy ions
- Initial conditions
- Glasma
- sQGP - perfect fluid
- Hadron gas

Puzzles:

How can we measure such initial-state of gluons independently?

Initial condition - Fluctuation
Flow and viscosity
New regime of gluonic matter

- HERA’s discovery: proliferation of soft gluons:
  How does the unitarity bound of the hadronic cross section survive if soft gluons in a proton or nucleus continue to grow in numbers?
  QCD: Dynamical balance between radiation and recombination
  Saturation of gluons?

- Gluon saturation has to be there!
  A new regime of QCD matter
  – Color Glass Condensate (CGC)
  Hints from HERA, RHIC and LHC

Can we find this regime for sure and study/understand its properties?
Fundamental QCD question - I

How do quarks and gluons confine themselves into a proton?

The color confinement

“Hints” from knowing hadron structure

- Hadron structure:
  - How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?

- Proton spin:
  - If we do not understand proton spin from QCD, we do not understand QCD!
    - It is more than the number \( \frac{1}{2} \)! It is the interplay between the intrinsic properties and interactions of quarks and gluons
  - Need a polarized proton beam!
How do gluons saturate themselves into a new form of matter?
Color Glass Condensate

- Gluon ≠ photon:
  - Radiate:
    - Dynamical scale $Q_s$ from the balance
  - Recombine:
    - New mathematical framework
    - Universal properties (CGC)

From the EIC White Paper

- Where does the saturation of gluon densities set in? Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

*Need a heavy ion beam!*
Fundamental QCD question - III

How do hadrons emerge from a created quark or gluon?
Neutralization of color - hadronization

- Femtometer detector/scope:
  Nucleus, a laboratory for QCD

- Quark/gluon properties:
  Initial-condition for hadronization
  Semi-inclusive DIS

From the EIC White Paper:

How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Need an EM probe to precisely control the initial-condition for hadronization!
Electron-Ion Collider

- **An ultimate machine to provide answers to these fundamental QCD questions:**
  - A collider to provide kinematic reach well into the gluon-dominated regime
  - An electron beam to bring to bear the unmatched precision of the EM interaction as a probe
  - Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin
  - Heavy ion beams to provide precocious access to the regime of saturated gluon densities, and to offer a precise dial in the study of propagation-length for color charges in nuclear matter

- **A machine at the frontier of polarized luminosity, combined with versatile kinematics and beam species**

  *Allow all these important QCD questions to be tackled at this facility*
Kinematics and machine properties

For e-N collisions at the EIC:
- First polarized e-p collider
- Polarized beams: e, p, d/\(^3\)He
- Variable center of mass energy
- Luminosity \(L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}\)
- HERA luminosity \(\sim 5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}\)

For e-A collisions at the EIC:
- First e-A collider
- Wide range in nuclei
- Variable center of mass energy
- Luminosity per nucleon same as e-p
EIC: A bright sub-femtometer scope

- New DIS “Rutherford” experiment:

\[ Q^2 = 4EE' \sin^2(\theta/2), \quad x_B = \frac{Q^2}{2m_N \nu}, \quad \nu = E - E' \]

- A sub-femtometer scope:

Sub-femtometer probe

Cross section

Asymptotic freedom

Parton in a hadron

Factorization (theoretical advances in recent years!)
EIC: Goals and deliverables

The key measurements

Why existing facilities, even with upgrades, cannot do the same?
Proton spin and hadron structure?

- **Proton – composite particle of quarks and gluons:**
  Spin = intrinsic (parton spin) + motion (orbital angular momentum)

- **Proton spin:**
  \[
  S(\mu) = \frac{1}{2} \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} J_q(\mu) + J_g(\mu) = \frac{1}{2} \Delta \Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + L_g(\mu)
  \]

- **Over 20 years effort (following EMC discovery):**
  - Quark (valence + sea) helicity: \( \sim 30\% \) of proton spin
  - Gluon helicity (latest RHIC data): \( \sim 20\% \) from limited \( x \) range

  How to explore the “full” gluon and sea quark contribution?
  How to quantify the role of orbital motion?
Proton spin and hadron structure?

- The EIC – the decisive measurement (1st year of running):
  (Low x and wide x range at EIC)

- Solution to the proton spin puzzle:
  - Precision measurement of $\Delta g$ – extend to smaller x regime
  - Orbital angular momentum – motion transverse to proton’s momentum

No other machine in the world can achieve this!
Unified view of nucleon structure

- **Wigner distributions:**
  - Wigner Distributions: $W(x, b_T, k_T)$
  - 5D
  - 3D
  - 1D
  - HERMES
  - JLab12
  - COMPASS
  - FOR
  - Valence

- **EIC – 3D imaging of sea and gluons:**
  - TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - GPDs – Spatial imaging of quarks and gluons (exclusive DIS)
EIC is the best for probing TMDs

- **TMDs - rich quantum correlations:**
  
<table>
<thead>
<tr>
<th>Quark Polarization</th>
<th>Un-Polarized (U)</th>
<th>Longitudinally Polarized (L)</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nucleon Polarization</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>U</strong></td>
<td>$f_1$</td>
<td></td>
<td>$h_1$</td>
</tr>
<tr>
<td><strong>L</strong></td>
<td>$g_{1L}$</td>
<td>Helicity</td>
<td>$h_{1L}$</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>$f_{1T}^\perp$</td>
<td>Sivers</td>
<td>$g_{1T}^\perp$</td>
</tr>
</tbody>
</table>

  Leading twist TMDs

  ![Nucleon Spin](image1.png)

  ![Quark Spin](image2.png)

  Similar for gluons

- **Naturally, two scales and two planes:**
  
  - **Two scales:**
    - high $Q$ - localized probe
    - Low $p_T$ - sensitive to confining scale
  
  - **Two planes:**
    - angular modulation to separate TMDs

  Hard to separate TMDs in hadronic collisions
Confined motion in a polarized nucleon

- **Single-spin asymmetry:**
  \[ A(\ell, s) = \frac{\Delta \sigma(\ell, s)}{\sigma(\ell)} = \frac{\sigma(\ell, s) - \sigma(\ell, -s)}{\sigma(\ell, s) + \sigma(\ell, -s)} \]
  More sensitive to the role of quantum correlation!

- **Quantum correlation between hadron spin and parton motion:**
  
  Sivers effect – Sivers function
  
  Hadron spin influences parton’s transverse motion

- **Quantum correlation between parton spin and hadronization:**
  
  Collins effect – Collins function
  
  Parton’s transverse spin influence its hadronization

*JLab12 and COMPASS for valence, EIC covers the sea and gluon!*
What can EIC do for Sivers function?

- Coverage and simulation:
  - No other machine in world can do this!

- Unpolarized quark inside a transversely polarized proton:
  - For Large-\(x\)

No other machine in world can do this!
How is color distributed inside the proton?

- The “big” question:
  How color is distributed inside a hadron? (clue for color confinement?)

- Electric charge distribution:
  Elastic electric form factor \( \rightarrow \) Charge distributions

- But, NO color elastic nucleon form factor!
  Hadron is colorless and gluon carries color
Spatial imaging of quarks and gluons

- Need Form Factor of density operator:
  - Exchange of a colorless “object”
  - “Localized” probe
  - Control of exchanging momentum

- Exclusive processes - DVCS:
  \[
  \frac{d\sigma}{dx_B dQ^2 dt} = H_q(x, \xi, t, Q), E_q(x, \xi, t, Q), ...
  \]
  F.T. of t-dep
  Spatial distributions

- Quark GPDs and its orbital contribution to proton’s spin:
  \[
  J_q = \frac{1}{2} \lim_{t \to 0} \int dx x [H_q(x, \xi, t) + E_q(x, \xi, t)] = \frac{1}{2} \Delta q + L_q
  \]
  The first meaningful constraint on quark orbital contribution to proton spin
  by combining the sea from the EIC and valence region from JLab 12

  This could be checked by Lattice QCD?
Spatial imaging of gluon density

- Exclusive vector meson production:
  \[ \frac{d\sigma}{dx_B dQ^2 dt} \]

- Fourier transform of the t-dep
- Spatial imaging of glue density
- Resolution \( \sim 1/Q \) or \( 1/M_Q \)

- Gluon imaging from simulation:

*Images of gluons from exclusive J/\( \psi \) production*

*Only possible at the EIC*
Nucleus, a QCD Laboratory

- **EMC discovery:**
  - Nuclear landscape ≠ superposition of nucleon landscape

How would/does a nucleus look if we only saw its quarks and gluons?  

- “Snapshot” does not have a “sharp” depth at small $x_B$

- Hard probe is very “sharp” in space:
  - Transverse size - $\frac{1}{Q} \ll 1 \text{ fm}$, longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1 \text{ fm}$

- Longitudinal size $>\text{Lorentz contracted nucleon:}$
  
  $$\frac{1}{xp} > 2R_A \frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

**Hard probe can “see” gluons from all nucleons at the same impact parameter!**
Reaching the saturation with eA

- Many more soft gluons in nucleus at the same impact parameter: $Q_s^2(eA) \propto Q_s^2(ep) A^{1/3}$

With a gold ion beam: EIC can reach the saturation regime at the stage-I
Saturation/CGC: What to measure?

- **Inclusive events – structure functions, \( F_2 \) and \( F_L \):**
  - High energy – smaller \( x \), and larger range of \( Q^2 \)
  - Search for deviation from DGLAP and BFKL

- **Diffractive cross section:**
  \[
  \sigma_{\text{diff}} \propto [g(x, Q^2)]^2
  \]
  At HERA: ep observed 10-15% / total

- If CGC/Saturation – multiple coherent gluons
  - Diffraction eA expect ~25-30%/total

  **Nucleus with 8 MeV/N binding can stay intact at 1 of 4 times when hit by a “TeV” beam!**

- **Diffractive vector meson production:**
  - Cross section ratio for eA/ep: J/\( \psi \) and \( f \)
  - Imaging of gluons in nuclei
The best signature for gluon saturation

- Hard scattering with a rapidity gap:

$$k' \quad q \quad M_x \quad \text{gap}$$

Double ratios:
Diffractive over total cross section
eA over ep

- Strong non-linear effect, color singlet exchange
- Factorization works in DIS, not in pp, pA, AA

The factor of 2 enhancement is only for eA
(no equivalent in pA!)

This is a clean and unambiguous signal of saturation physics
already at EIC stage-1
Another clean signature for gluon saturation

- Strong suppression of dihadron correlation in eA:
  - Never be measured!
  - Directly probe Weizsacker-Williams (saturated) gluon distribution in a large nucleus
  - A factor of 2 suppression of away-side hadron-correlation!
  - No-sat: Pythia + nPDF (EPS09)
Spatial imaging of the glue in a nucleus

- Diffractive vector meson ($\Phi, J/\psi, ..$) production:

$$\frac{d\sigma}{dx_BdQ^2dt}$$

- Coherent: Nucleus stays intact
- Incoherent: Nucleus breaks up

- $\Phi$-production – clean probe for spatial distributions:

Fourier transform of the t-dependence

Need EIC’s energy to do this!
Range of color correlation inside a nucleus?

- **Ratio of DIS $F_2$ structure functions:**

  - Color range ~ size of nucleon
  - Systematic error
  - Color range ~ size of nucleus

**A clean stage-I measurement at EIC (statistical error < systematic error)**
Hadronization – energy loss

- Unprecedented $\nu$ range at EIC:
  $$\nu = \frac{Q^2}{2m_x}$$
  semi-inclusive DIS

- Heavy quark energy loss:
  - Mass dependence of fragmentation

Need the collider energy of EIC and its control on parton kinematics
Electroweak physics at EIC

Running of weak interaction – high luminosity:

- Fills in the region that has never been measured
- Has a real impact on testing the running of weak interaction
Physics deliverables of the stage-I EIC

- **EIC at the stage-I:**
  - Collision energy: $\sqrt{s} \sim 20 - 100$ GeV
  - Luminosity: $10^{33-34}$ cm$^{-2}$ s$^{-1}$ (HERA luminosity $\sim 5 \times 10^{31}$ cm$^{-2}$ s$^{-1}$)
  - Polarized proton and various nuclei

- **Deliverables at the stage-I:**

<table>
<thead>
<tr>
<th>Processes</th>
<th>What we learn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive polarized e-p</td>
<td>Sea and gluon helicity contribution to proton spin</td>
</tr>
<tr>
<td>Inclusive e-A</td>
<td>Nuclear PDFs: $x_B$, $Q^2$, A-dep</td>
</tr>
<tr>
<td></td>
<td>Range of color correlation</td>
</tr>
<tr>
<td>Semi-inclusive e-p</td>
<td>TMDs, Quark-gluon correlation functions</td>
</tr>
<tr>
<td></td>
<td>Fragmentation functions</td>
</tr>
<tr>
<td>Semi-inclusive e-A</td>
<td>Hadronization and color neutralization</td>
</tr>
<tr>
<td></td>
<td>TMDs of nuclei, Energy loss mechanism</td>
</tr>
<tr>
<td>Diffractive e-p</td>
<td>Quark GPDs, and its evolution</td>
</tr>
<tr>
<td></td>
<td>Spatial imaging of quarks</td>
</tr>
<tr>
<td>Diffractive e-A</td>
<td>Unambiguous signal of gluon saturation</td>
</tr>
</tbody>
</table>
Physics opportunities at the stage-II EIC

- The stage-II machine – as a upgrade:
  - Collision energy: \( \sqrt{s} \sim 90 - 170 \text{ GeV} \)
  - Luminosity: \( 10^{33-34} \text{ cm}^{-2} \text{ s}^{-1} \) (HERA luminosity \( \sim 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \))
  - Polarized proton and various nuclei

- Key measurements:

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Observables</th>
<th>What we learn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea/gluon at ( x \sim 10^{-4} ) EW spin S.F.</td>
<td>Inclusive DIS at low-( x ) at high ( Q^2 )</td>
<td>Sea/gluon to proton spin flavor separation</td>
</tr>
<tr>
<td>Polarized and unpolarized TMDs</td>
<td>Dihadron and heavy flavors</td>
<td>3D momentum images of quarks and gluons</td>
</tr>
<tr>
<td>Sea quarks and gluon GPDs</td>
<td>DVCS, Exclusive J/( \Psi ), ( \rho ), ( \phi ) production</td>
<td>Spatial images of sea and gluon, angular mom. ( J_q ), ( J_g )</td>
</tr>
<tr>
<td>Nuclear gluon density in 3D momentum</td>
<td>Dihadron correlation, diffractive x-section</td>
<td>Non-linear QCD evolution Gluon saturation</td>
</tr>
<tr>
<td>Color transport coefficient in medium</td>
<td>Semi-inclusive DIS for light/heavy flavors</td>
<td>Color propagation, energy loss, hadronization, color fluctuation</td>
</tr>
<tr>
<td>Weak mixing angle</td>
<td>PV asymmetries in DIS</td>
<td>EW symmetry breaking, BSM</td>
</tr>
</tbody>
</table>
Electron-Ion Colliders in the world:

<table>
<thead>
<tr>
<th></th>
<th>HERA@DESY</th>
<th>LHeC@CERN</th>
<th>eRHIC@BNL</th>
<th>MEIC@JLab</th>
<th>HIAF@CAS</th>
<th>ENC@GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{CM}$ (GeV)</td>
<td>320</td>
<td>800-1300</td>
<td>45-175</td>
<td>12-140</td>
<td>12 $\to$ 65</td>
<td>14</td>
</tr>
<tr>
<td>proton $x_{\text{min}}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$5 \times 10^{-5}$</td>
<td>$7 \times 10^{-3}$ $\to 3 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>ion</td>
<td>p</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to $^{40}$Ca</td>
</tr>
<tr>
<td>polarization</td>
<td>-</td>
<td>-</td>
<td>$p, ^3$He</td>
<td>$p, d, ^3$He ($^6$Li)</td>
<td>$p, d, ^3$He</td>
<td>p,d</td>
</tr>
<tr>
<td>$L$ [cm$^{-2}$ s$^{-1}$]</td>
<td>$2 \times 10^{31}$</td>
<td>$10^{33}$</td>
<td>$10^{33-34}$</td>
<td>$10^{34-35}$</td>
<td>$10^{32-33} \to 10^{35}$</td>
<td>$10^{32}$</td>
</tr>
<tr>
<td>IP</td>
<td>2</td>
<td>1</td>
<td>2+</td>
<td>2+</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Year</td>
<td>1992-2007</td>
<td>2022 (?)</td>
<td>2022</td>
<td>Post-12 GeV</td>
<td>2019 $\to$ 2030</td>
<td>upgrade to FAIR</td>
</tr>
</tbody>
</table>

Possible future

High energy polarized proton beam
Sits near the “sweet spot” for the transition into the saturation regime

EIC@US [arXiv:1212:1701]:
EIC is a machine to understand the glue that bind us all

Is THE brightest sub-femtometer scope to ANSWER fundamental questions in QCD in ways that no other facilities in the world can

Extends the QCD programs developed at BNL and Jlab in dramatic and fundamentally important ways

EIC@US would extend (and maintain) US leadership in nuclear science and accelerator/detector technology

Facilities and experiments:

- Rutherford exp’t
  - 1911
  - Revolutionized our view of atomic structure

- SLAC “Rutherford”
  - 1968
  - Open the gateway to nucleon structure

- EIC - future “Rutherford”
  - 2020?
  - Revolutionize our view of nucleon structure and the glue!
Thanks!

Acknowledgment

Received inputs from both BNL and JLab communities
Backup slices
EICAC

- **Members (Latest):**
  
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- **Last meeting:**
  
  April 9, 2011 at JLab
What needs to be covered BY THE DETECTOR

Inclusive Reactions in ep/eA:
- Physics: Structure Fcts.: $F_2$, $F_L$
- Very good electron id $\rightarrow$ find scattered lepton
- Momentum/energy and angular resolution of $e'$ critical
- scattered lepton $\rightarrow$ kinematics

Semi-inclusive Reactions in ep/eA:
- Physics: TMDs, Helicity PDFs $\rightarrow$ flavor separation, dihadron-corr.,...
  $\rightarrow$ Kaon asymmetries, cross sections
- Excellent particle ID: $p^\pm, K^\pm, p^\pm$ separation over a wide range in $h$
- full F-coverage around $g^*$
- Excellent vertex resolution $\rightarrow$ Charm, Bottom identification

Exclusive Reactions in ep/eA:
- Physics: GPDs, proton/nucleus imaging, DVCS, excl. VM/PS prod.
- Exclusivity $\rightarrow$ large rapidity coverage $\rightarrow$ rapidity gap events
- $\rightarrow$ reconstruction of all particles in event
- high resolution in $t$ $\rightarrow$ Roman pots
Formation of nuclear matter

QCD influenced how the universe evolve
- the dynamics of early universe
- the emergence of nucleons, and nuclei

Accelerator technology allows us to:
- recreate the condition of early universe
- repeat the formation of nuclear matter

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>1.5 – 4.5 MeV</td>
</tr>
<tr>
<td>$d$</td>
<td>5.0 – 8.5 MeV</td>
</tr>
<tr>
<td>$s$</td>
<td>80 – 155 MeV</td>
</tr>
<tr>
<td>$c$</td>
<td>1.0 – 1.4 GeV</td>
</tr>
<tr>
<td>$b$</td>
<td>4.0 – 4.5 GeV</td>
</tr>
<tr>
<td>$t$</td>
<td>174.3 ± 5.1 GeV</td>
</tr>
</tbody>
</table>
Hadron mass:
Higgs mechanism generates too little quark mass to be relevant!

QCD and the “dark” gluons:

- “Quark” Mass function:
  \[ S_F(p) = \frac{\mathcal{F}(p)}{\not{p} - \mathcal{M}(p)} \]

- Mystery:
  “Mass without mass!”

- Hadron mass spectrum:
  Lattice QCD calculation
  With limited input, predicted the rest!

Success of lattice QCD!

Bhagwat & Tandy/Roberts et al
Dyson-Schwinger Equations

\[ m_q \sim 10 \text{ MeV} \]
\[ m_N \sim 1000 \text{ MeV} \]
We tested QCD - high energy

- From inclusive DIS to Drell-Yan (EM probe):
  - Probe size < 1/10 fm

- From RHIC to LHC (dominated by gluon fusion):
  - Probe as small as ~ $10^{-3}$ fm

Success of perturbative QCD!
Generalized parton distributions (GPDs)

- **Quark:**

\[
F_q(x, \xi, t, \mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{q}(\lambda/2) \frac{\gamma \cdot n}{2P \cdot n} q(-\lambda/2) | P \rangle \\
= H_q(x, \xi, t, \mu^2) \left[ \bar{U}(P') \gamma^\mu U(P) \right] \frac{n_\mu}{2P \cdot n} + E_q(x, \xi, t, \mu^2) \left[ \bar{U}(P') \frac{i\sigma^{\mu\nu}(P' - P)_\nu}{2M} U(P) \right] \frac{n_\mu}{2P \cdot n}
\]

with \( \xi = (P' - P) \cdot n/2 \) and \( t = (P' - P)^2 \Rightarrow -\Delta^2 \) if \( \xi \to 0 \)

\( \tilde{H}_q(x, \xi, t, Q), \quad \tilde{E}_q(x, \xi, t, Q) \) Different quark spin projection

- **Total quark’s orbital contribution to proton’s spin:**

\[
J_q = \frac{1}{2} \lim_{t \to 0} \int dx \, x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right]
\]

\[
= \frac{1}{2} \Delta q + L_q
\]

- **Connection to normal quark distribution:**

\[
H_q(x, 0, 0, \mu^2) = q(x, \mu^2)
\]

The limit when \( \xi \to 0 \)

Ji, PRL78, 1997
Lattice calculation on parton orbital motion

- Moments of GPDs on lattice:

\[ \langle J_q^i \rangle = S^i \int dx [H_q(x, 0, 0) + E_q(x, 0, 0)] x \]

- Ji’s relation:

\[ L^z_q = J^z_q - \frac{1}{2} \Delta q \]

- Both \( L_u \) and \( L_d \) large:

  But, \( L_u + L_d \sim 0 \)

- Spin from the gluon?

  EIC is an ideal place to measure gluon GPDs
  From QCD evolution and diffractive \( J/\psi \)
Transition from low $p_T$ to high $p_T$

- TMD factorization to collinear factorization:

$$A_N(Q^2, p_T)$$

- Quantum interference – high $p_T$ region (integrate over all $k_T$):

Single quark state

```
\[ \begin{array}{c}
\text{Single quark state} \\
\text{\(p\)} \\
\text{\(\frac{1}{2}\)}
\end{array} \]
```

- quark-gluon composite state

```
\[ \begin{array}{c}
\text{quark-gluon composite state} \\
\text{\(p\)} \\
\text{\(-\frac{1}{2}\)}
\end{array} \]
```

Non-probabilistic quark-gluon quantum correlation – color Lorentz force:

$$T^{(3)}(x, x) \propto$$

Complication with hadronic machine!
What and why EIC can do and do better?

- **Higher energy + collider:**
  - Semi-inclusive scattering - probing the confined motion of quarks and gluons – 3D momentum distributions/images

- **Higher luminosity:**
  - Diffractive scattering - CAT scan the proton/nucleus – 1+2D spatial imaging

- **Polarization:**
  - \[
      \frac{\sigma(s) - \sigma(-s)}{\sigma(s) + \sigma(-s)}
  \]
  - Suppress probability – enhance quantum interference

- **Nucleus, a QCD Laboratory:**
  - More soft gluons – Lab for exploring non-linear gluon dynamics
  - Condensed color matter – Lab for QCD tomography
  - Nuclear landscape – color confinement and quantum fluctuation

How would/does a nucleus look if we only saw its quarks and gluons?
Nucleus in terms of quarks and gluons?

- Ratio of $F_2$ structure functions – large momentum transfer:

![Graph showing the ratio of $F_2$ structure functions with data from Rochester-SLAC-MIT (E49B), SLAC, and EMC experiments.](image)

Shadowing and antishadowing!

Nucleus ≠ a simple sum of nucleons with Fermi motion?

How would/does a nucleus look if we only saw its quarks and gluons?

(Crystal(s) of nuclei and electrons)
Color fluctuation and QGP properties?

- **Initial-state color fluctuation:**
  - Gluon fields before collision at the LHC

- **“Plus” viscous relativistic hydro:**
  - Energy density - CGC

How can we measure such initial-condition independently?
Jet quenching – QGP property:

Leading particle

Why do heavy quarks lose as much energy as the light quarks?

Independent test of energy loss mechanism, formation of hadrons?
Azimuthal asymmetry - fluctuation

- Preliminary low energy data: Hicks, KEK-JPAC2013

  - Classical expectation:
    Any distribution seen in Carbon should be washed out in heavier nuclei

  - Surprise:
    Quantum effect in transverse momentum broadening – fluctuation!
Competitions?

- **EIC@China** [http://qcd2013.csp.escience.cn/dct/page/65560]:
  - Energy: 3 GeV electron + 12 GeV proton
  - Luminosity: $10^{32-33}$ cm$^{-2}$ s$^{-1}$
  - Sit between JLab12 and COMPASS
  - Physics goals are complementary to US-EIC

- **LHeC@CERN** [arXiv:1211:4831]:
  - Proton structure & QCD
  - Small x physics
  - eP & eA
  - Electron-Quark Systems BSM: at 1 TeV scale
  - Search for new EW physics: RH-W’s, Contact Interactions

Did not make the recent European’s priority list