Long Term Future: EIC

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Outline:

- Introduction
- EIC at JLab
- Physics examples
- Conclusion
“An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.”
Some of the NSAC LRP Overarching QCD questions (December 2007)

- What is the internal spin and flavor landscape of hadrons?
- What is the role of gluons and gluons self interactions in nucleon and nuclei?
- What governs the transition of quarks and gluons into pions and nucleons?
EIC: a natural extension of studies planned for JLab but to probe the glue and the sea

- Generalized Parton Distributions
- Inclusive Sum rules and polarizabilities
- Transverse Momentum Distributions
- Semi-Inclusive DIS
- Distributions and Fragmentation functions
- Beyond the standard model

- Elastic form factors
- Deep Virtual Compton Scattering
- Deep Virtual Meson Production

- Since 1998
- Since 2000

- GPDs and TMDs in Nuclei
- Exclusive
- Semi-inclusive
- Initial and final medium effects
Why ELIC/mEIC?

- A natural extension of the 12 GeV physics program of hadron structure/QCD

However, the emphasis is not the valence quarks but

Gluons and Sea Quarks in the valence region and beyond

- This requires high luminosity and good center of mass energy
  - Luminosity is key for probing rare processes
  - Energy reach key for clean interpretation
JLab beyond the 12 GeV upgrade

- Jlab community hopes to articulate a comprehensive physics program using an electron ion collider that will complement, extend, and complete (?) our current physics program and our plans for 12 GeV.

- The community, together with the Lab had a series of workshops to assess the physics potential of such a facility (all are welcome to participate in this endeavor).

- An important part of this effort will be a clarification of the machine and detector specifications that are optimal for completing this program.
Physics Areas Under Investigation and Workshops

- **Study group on Hadronic Physics**
  - Nucleon spin and quark-gluon correlations: Transverse spin, quark and gluon orbital motion, semi-inclusive processes
    - *(Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark Gluons Interactions: workshop at Duke U., March 12-13, 2010)*
    - H. Gao et al.
    - [http://michael.tunl.duke.edu/workshop](http://michael.tunl.duke.edu/workshop)
  - 3D mapping of the glue and sea quarks in the nucleon
    - R. Gilman et al.

- **Study group on Nuclear Physics**
  - 3D tomography of nuclei, quark/gluon propagation and the gluon/sea quark EMC effect
    - *(EIC Nuclear Chromodynamics: workshop at Argonne National Lab, April 7-9, 2010)*
    - K. Hafidi, et al.

- **Study group on Electroweak Physics**
  - Electroweak structure of the nucleon and tests of the Standard Model
    - *(workshop at the College of W&M, May 17-18, 2010)*
    - K. Kumar, D. Armstrong et al.

- **Study group on interaction region and detectors**
  - EIC Detectors/Instrumentation
    - *(workshop at JLab, June 03-04, 2010)*
    - C. Hyde et al.
    - [http://conferences.jlab.org/eic2010/program.html](http://conferences.jlab.org/eic2010/program.html)
ELIC presented at the LRP

Luminosity $\sim 10^{35} \text{ cm}^{-1}\text{s}^{-1}$

30-150 GeV light ions

Electron Cooling

Snake

IR

D

3-7 GeV electrons

3-7 GeV positrons

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More Recently

Medium Energy Electron Ion Collider

Map the spin and 3D quark-gluon structure of protons
Discover the role of gluons in atomic nuclei
Understand the creation of the quark-gluon matter around us

Luminosity $\sim$ few $10^{34}$ cm$^{-1}$s$^{-1}$

MEIC = EIC@JLab
1 low-energy IR $(s \sim 200)$
3 medium-energy IRs $(s < 2600)$

ELIC = high-energy EIC@JLab $(s = 11000)$ (limited by JLab site)
EIC Kinematic Coverage

ep mEIC: 11+60

eA mEIC: 3+30/11+30 (0.04<\(y<0.6\))
eA eLIC: 11+120 (\(y=0.6\))

EIC connects JLab and HERA kinematic region
Generalized Parton Distributions

Matrix elements of non-local operators with quarks and gluon field

\[ \langle p | O | p \rangle \]

Depend on two longitudinal momentum fractions

\[ x, \xi \text{ and } t = (p - p')^2 \]

For unpolarized quarks we have two distributions:

\[ H_q \text{ conserves proton helicity} \]

\[ E_q \text{ flips proton helicity} \]

\[ p = p' \quad \implies \quad H_q(x, 0, 0) = \begin{cases} q(x) & \text{for } x > 0 \\ -\bar{q}(x) & \text{for } x < 0 \end{cases} \]
The handbag dominance:

Deeply Virtual Compton Scattering is the simplest hard exclusive process involving GPDs

Factorization Theorem

Model by Goeke, Polyakov, Vanderhaeghen
empirical quark
transverse densities
in neutron

\[ \rho_0^n, \rho_T^n \ [1/fm^2] \]

induced EDM : \( d_y = F_{2n}(0) \cdot e / (2 M_N) \)

data: Bradford, Bodek, Budd, Arrington (2006)
densities: Miller (2007); Carlson, Vdh (2007)
Angular Momentum Sum Rule

\[ \frac{1}{2} = J^q(\mu) + J^g(\mu) \]

Ji Sum rule

\[ J^q(\mu) = \frac{1}{2} \Delta \Sigma + L^q(\mu) \]

\[ J^q = \int dxx [H^q + E^q] \]

\[ J^g = \int dx [H^g + E^g] \]

- A goal is to determine the glue GPDs \( H^g \) and \( E^g \)
- The momentum sum rule put constraints on GPD \( H^g \). Data come mainly from HERA exclusive measurements of J/Psi production
- However nothing is known about GPD \( E^g \)
- If the quark angular momentum is small like some Lattice QCD is suggesting than \( J^g \) is large.
$^{0}$ electroproduction

VGG GPD model
GK GPD Model
JML Regge Model
Deeply Virtual $\rho^0$, $\rho^+$ production and GPDs

Exploration of GPD application in meson sector.


$\rho^+$: In preparation

GPDs model agrees fairly with the data at low $x_B$ (high $W$)

Hint of GPD E dominance at low $x_B$ (high $W$)

Differences of GPD prediction and measurements shrink with increasing $Q^2$ at fixed $x_B$. 

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exclusive $\rho^0$ production on transverse target

$$A_{UT} = -\frac{2\Im(AB^*)/\Box}{|A|^2(1-\xi^2) - |B|^2(\xi^2 + t/4m^2) - \Re(AB^*)2\xi^2}$$

Projected results

$A \sim 2H^u + H^d$
$B \sim 2E^u + E^d$

$A \sim H^u - H^d$
$B \sim E^u - E^d$

$E^u, E^d$ needed for angular momentum sum rule.

Goeke, Polyakov, Vanderhaegen (2001)
100% acceptance & integrated over all variables but $(x_B, Q^2)$

M. Guidal

11 GeV e
60 GeV p

Counting rate for 1000 hours at $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Limitation comes from luminosity.
SIDIS electroproduction of pions

- Separate Sivers and Collins effects

- **Sivers** angle, effect in distribution function:
  \((\phi_h - \phi_s)\) = angle of hadron relative to *initial* quark spin

- **Collins** angle, effect in fragmentation function:
  \((\phi_h + \phi_s) = \pi + (\phi_h - \phi_{s'})\) = angle of hadron relative to *final* quark spin
# Leading Twist Transverse Momentum Distributions

<table>
<thead>
<tr>
<th>Quark/Nucleon</th>
<th>Un-Polarized</th>
<th>Longitudinelly Polarized</th>
<th>Transversely Polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_1 = \bullet$</td>
<td></td>
<td>$h_{1T} = \bullet$ - $\bullet$</td>
</tr>
<tr>
<td>U</td>
<td></td>
<td></td>
<td>Boer-Mulder</td>
</tr>
<tr>
<td>L</td>
<td>$g_1 = \text{Helicity}$</td>
<td></td>
<td>$h_{1L} = \bullet$ - $\bullet$</td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T} = \text{Sivers}$</td>
<td>$g_{1T} = \text{Transversity}$</td>
<td>$h_{1T} = \bullet$ - $\bullet$</td>
</tr>
</tbody>
</table>

Nucleon Spin

Quark Spin
Simulations of Transverse SSA from SIDIS @ EIC

Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions

Min Huang    Xin Qian
Duke University / TUNL
Advisor: Haiyan Gao
Projection with Proton

• 11 + 60 GeV
  36 days
  $L = 3 \times 10^{34} \text{/cm}^2\text{/s}$
  $2 \times 10^{-3}$ $Q^2 < 10 \text{ GeV}^2$
  $4 \times 10^{-3}$ $Q^2 > 10 \text{ GeV}^2$

• 3 + 20 GeV
  36 days
  $L = 1 \times 10^{34} \text{/cm}^2\text{/s}$
  $3 \times 10^{-3}$ $Q^2 < 10 \text{ GeV}^2$
  $7 \times 10^{-3}$ $Q^2 > 10 \text{ GeV}^2$

Polarization 80%
Overall efficiency 70%

$z$: 12 bins 0.2 - 0.8
$P_T$: 5 bins 0-1 GeV

$\phi_h$ angular coverage considered
Show the average of Collins/Sivers/Pretzlosity projections

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Projection with $^3$He (neutron)

- 11 + 60 GeV
  72 days
- 3 + 20 GeV
  72 days
- 12 GeV SolId

$^3$He: 86.5% effective polarization
Dilution factor: 3

D: 88% effective polarization
Effective dilution $\sqrt{8}$

Equal stat. for proton and neutron (combine $^3$He and D)

<table>
<thead>
<tr>
<th></th>
<th>11 + 60 GeV</th>
<th>3 + 20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>36 d ($3 \times 10^{34}$/cm$^2$/s)</td>
<td>36 d ($1 \times 10^{34}$/cm$^2$/s)</td>
</tr>
<tr>
<td>D</td>
<td>72 d</td>
<td>72 d</td>
</tr>
<tr>
<td>$^3$He</td>
<td>72 d</td>
<td>72 d</td>
</tr>
</tbody>
</table>
Superfast quarks – Short range correlations @ larger $Q^2$

- EIC is limited by cross section
- For $s=1000$, $L \approx 10^{34}$, statistics running out for $x \approx 0.85$
- Might be possible to reach interesting $x$ range
  - Need factor of 10, 100, 1000 to reach $x \approx 1.0, 1.15, 1.30$
  - Need to evaluate statistics for lower $s$
  - Not clear just how high in $x$ required to isolate short-range structure that we’re interested in
JLab users group annual meeting

June 8th, 2010

Kawtar Hafidi
Parton propagation and fragmentation

- **Nuclei as space-time analyzers**
- **Non perturbative aspects**
  - Color confinement dynamics
  - Probe nuclear gluons
  - New look at TMDs in “bound” nucleons
  - Novel access to gluon GPDs

Partons created in the medium could be used as a color probe of the gluon density in a nucleus when parton lifetime and energy loss mechanisms are under theoretical control.

- **Connection to other fields**
  - Quark-Gluon Plasma at RHIC: medium unknown and rapidly expanding
  - Neutrino experiments: nucleus increases cross section

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Hadronization in cold nuclear matter

- Observables to measure are multiplicity ratios and transverse momentum broadening
- For the EIC @ $s = 1000 \text{ GeV}^2$, one can isolate parton energy loss in cold nuclear medium when fragmentation starts outside the nucleus
- For lower energies when hadronization is expected to occur inside the nucleus, one would be able to study pre-hadron absorption
- Compare $\pi^0$ and $\eta$ for energy loss versus pre-hadron absorption
Heavy flavors

- EIC offers a unique opportunity to study heavy quark propagation and fragmentation in a medium with known properties.
- Large mass of charm and bottom allow in principle to calculate fragmentation in perturbative QCD.
- Heavy quarks are expected to have reduced energy loss compared to light quark not observed in RHIC.
- Heavy quark detection requires a vertex determination of at least 100 μm and high luminosity especially bottom quarks of at least few $10^{34}$.

11 + 30 GeV/A
L = 0.4 $10^{33}$ cm$^{-2}$ s$^{-1}$
1 month 100% running
Summary

- A high polarized luminosity EIC with variable energy will be important for the future of Hadron Physics and QCD.
- More than one interaction region is important for complementarity of explored physics (exclusive vs semi-inclusive) and confirmation of discoveries.
- The JLab community started to explore further the physics of this new generation of machine in preparation for the next Long Range Plan.
- We welcome you to join this physics effort help with new physics ideas and experimental simulations.

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