Physics opportunities with an Electron-Ion Collider

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Outline

• Intro: Nucleon and nuclear structure in QCD and the Electron-Ion Collider (EIC) Project

• Basic characteristics and designs of EIC

• The science of an EIC: examples of “golden measurements”

• The EIC project timeline and status
Nucleon and nuclear structure in QCD

- Understanding the internal structure of nucleons and nuclei on the basis of the fundamental theory of strong interactions, Quantum Chromodynamics (QCD), is one of the central problems of modern nuclear physics

  2007 DOE/NSF NSAC
  Long-Range Plan

- The fundamental questions:
  - understanding the dynamical origin of mass in the visible universe
    (99% of mass comes from the gluons)
  - the behavior of matter at astrophysical temperatures and densities
  - understanding of nuclear structure and reactions from first principles
    (from small to astronomical scales)

- While theoretical methods to apply QCD to hadronic and nuclear systems have made dramatic advances in the last two decades but further progress relies crucially on experimental information.
Nucleon and nuclear structure in QCD: open questions

While decades of experiments at SLAC, CERN, Fermilab, DESY, JLab verified many predictions of QCD and explored the internal structure of hadrons, several key questions remain open:

- What is the internal landscape of the nucleon?
- What is the role of gluons and their self-interactions in nucleons and nuclei?
- What governs the transition of quarks and gluons in pions and nucleons?
Nucleon and nuclear structure in QCD: open questions

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These major science questions define the EIC science case which in turn drives the EIC design.
The Electron-Ion Collider Project

Informal recommendation in 2007 DOE/NSF NSAC Long-Range Plan:

"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."
Basic requirements for EIC

• Lepton beam
clean and well-understood probe

• Range of c.m. energies from $s$=few 100 GeV to $s$=few 1000 GeV, variable and upgradable:
  - electrons up to 20 - 30 GeV
  - protons up to 250 – 325 GeV; ions up to 100 - 130 GeV/A (208Pb)

• polarized e and p beams (> 70%), longitudinal and transverse polarization of the proton beam, polarized light nuclei, e.g. $^3$He

• High luminosity $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$ (> 100x HERA)
  required for precision measurements, multidim. binning, rare processes

• Range of nuclei, from D to 208Pb
  light nuclei for flavor separation; heavy nuclei for medium modif. and saturation
Two competing designs of EIC

MEIC/ELIC at Jefferson Lab (ring-ring)

- electrons: Use 11 GeV CEBAF as injector
- protons/ions: build in two stages:
  (i) MEIC (Medium-energy): 1 km ring, 3-11 (e) on 60/96 (p)
  (ii) ELIC (High-energy): 2.5 km ring, 3-11 (e) on 250 GeV (p)

- Luminosity $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Figure-8 for polarization transport
- Up to 4 IP's
Two competing designs of EIC

**eRHIC at Brookhaven National Lab** (linac-ring)

- electrons: build energy recovering linac in tunnel
  - (i) stage-1 eRHIC: $E_e = 5\ \text{GeV}$
  - (ii) stage-2 eRHIC: $E_e = 20-30\ \text{GeV}$

- protons/ions: use RHIC as is
  - $250-325\ \text{GeV}$ (p), $100-130/A\ \text{GeV}$ ($^{208}\text{Pb}$)

- Luminosity $\sim 10^{34}$ (33) cm$^{-2}$ s$^{-1}$ over wide range

- Discussed re-use RHIC detectors
While JLab and BNL designs
• involve “staging”
• converge in main parameters,

they are different in technological challenges and cost (?)
Deep inelastic scattering (DIS) has been the master method to study quark and gluon structure of nucleons and nuclei.

- Momentum transfer $Q$ defines resolution $1/Q$ (e.g., $Q=1$ GeV corresponds to 0.2 fm)
- Energy transfer $x$ defines the momentum fraction of probed parton

\[
Q^2 = -q^2 = -(k - k')^2 \\
Q^2 = 4E_e E'_e \sin^2 \left( \frac{\theta'_e}{2} \right) \\
y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left( \frac{\theta'_e}{2} \right) \\
x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}
\]

\[
\frac{d^2 \sigma_{ep \rightarrow ex}}{dx dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4} \left[ 1 - y + \frac{y^2}{2} \left( F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right) \right]
\]
Accessing sea quarks and gluons at EIC

“Theoretical” kinematic coverage of DIS at EIC

EIC is the machine to study the sea quark and gluon structure of protons/nuclei!

Plot and figure due to C. Weiss
The science of an EIC

Three major science questions for an EIC from NSAC LRP07:

- What is the internal landscape of the nucleon?
- What is the role of gluons and their self-interactions in nucleons and nuclei?
- What governs the transition of quarks and gluon into pions and nucleons?

EIC science goals:

- Map the spin and spatial structure of quarks and gluons in nucleons
- Discover the collective effects of gluons in atomic nuclei
- Understand the emergence of hadronic matter from quarks and gluons
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EIC: gluon polarization $Δg$

Gluon helicity distribution $Δg$:

- indirectly from $Q^2$ dependence of $g_1(x,Q^2)$ from polarized DIS

$$\frac{dg_1}{d\log(Q^2)} \propto -Δg(x,Q^2)$$

- hard processes in polarized pp at RHIC

- $Δg$ poorly constrained
- Low-x behavior is unconstrained
- No reliable estimate of 1\textsuperscript{st} moment

\[ \int_0^1 dx \Delta g(x, Q^2) \]

entering spin sum rule

\[ \frac{1}{2} = \frac{1}{2}ΔΣ + Δg + L_q + L_g \]

DSSV global fit,

de Florian, Sassot, Stratmann, Vogelsang, 2008
EIC: gluon polarization $\Delta g$

- Wider kinematic coverage at EIC will enable to precisely determine $\Delta g$ down to $x \sim 10^{-4}$

- Additional constraints on $\Delta g$ at EIC: charm and jet production in DIS
EIC: sea quark polarization/flavor dependence

To “tag” parton flavor, one uses semi-inclusive DIS (along with inclusive DIS)

- While polarization of valence quarks is known fairly well and will be pinned down by JLab@12, the polarization of sea quarks and their flavor dependence (asymmetry) are poorly know.
- $\Delta s$ is the least known quantity

Example of simulations for mEIC

$EIC \ 5x50 \ GeV$

100 days, $L=10^{33}$

Kinney, Seele 2008
EIC: spatial imaging of sea quarks and gluons

- The impact parameter dependence of parton distributions, i.e., the spatial image of quark and gluon distributions can be accessed in exclusive reactions.
- Transverse distributions (transverse size) derived from t-dependence
- Input for modeling pp collisions at LHC

Sea quark and gluon size from deeply virtual Compton scattering and VM production
Gluon size from J/ψ and φ
Strange and non-strange sea quark size from π and K production
EIC: spatial imaging of sea quarks and gluons

- Exclusive processes are luminosity-hungry
- Require $Q^2 > 10 \text{ GeV}^2$ for factorization (except for DVCS)
- Require differential measurement (binning)

All these conditions met at an EIC

Simulation of cross sections with subsequent extraction of the slope $B$ of the $t$-dependence

$\gamma$ (DVCS) $8 < Q^2 < 15 \text{ GeV}^2$

$J/\psi$ $5 < Q^2 < 10 \text{ GeV}^2$

Sandacz, Hyde, Weiss
EIC: spatial imaging of sea quarks and gluons in nuclei

- Can be accessed in exclusive reactions with nuclei
- Again, important for modeling pA collisions at RHIC and LHC
- Predicted theoretically in the leading twist theory of nuclear shadowing
  
  \[ R^j(x, b, Q^2) = \frac{f_{j/A}(x, Q^2, b)}{A T_A(b) f_{j/N}(x, Q^2)} = \frac{H^j_A(x, \xi = 0, b, Q^2)}{A T_A(b) f_{j/N}(x, Q^2)}. \]

  Frankfurt, Guzey, Strikman, 2010

- Nuclear shadowing is larger at small \( b \) and \( x \)
- Shadowing introduces \( x-b \) correlations

- Average transverse size of the distribution of partons in \( b \)-plane, \( <b^2> \), increases
  --> can be tested experimentally in DVCS and VM production

  gluon PDFs, FGS10_H, \( Q^2=4 \text{ GeV}^2 \)
EIC: spatial imaging of sea quarks and gluons in nuclei

DVCS interferes with Bethe-Heitler (BH) process

\[ B_{DVCS} > B_{BH} \]

\[
A_{LU}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin \phi \frac{H_{A}(\xi, \xi, t) F_{A}(t)}{F_{A}^{2}(t)}
\]
EIC science goals:

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EIC: gluons in nuclei

• Nuclear gluon PDF is poorly constrained by present data (fixed-target nDIS+DY+RHIC)
• Essential input for pQCD predictions for pA at RHIC and LHC at forward rapidities

EIC will accurately determine sea quark and gluon PDFs in nuclei due to:
• wide $x$-$Q^2$ coverage
• direct access to gluons via longitudinal $s_f$ $F_{L,A}$
• measurement of charmed structure functions $F_{2A}$ and $F_{L,A}$
• measurement of light- and heavy-quark jets

\[ R = f_{j/A}(x,Q^2)/[A f_{j/N}(x,Q^2)] \]

\[ R_{V}^{ph}, R_{g}^{ph}, R_{G}^{ph} \]

\[ Q^2 = 1.69 \text{ GeV}^2 \]

\[ Q^2 = 100 \text{ GeV}^2 \]

Eskola, Puukkunen, Salgado, JHEP 04 (2009) 065
EIC: gluon saturation

- At (very) small $x$, the gluon density grows through QCD radiation and one expects an onset of a new high-gluon density (non-linear) regime.
- Realized in Color Glass Condensate formalism, with a new dynamical scale $Q_s(x)$.

- The hope to achieve the saturation regime at (m)EIC rests on $Q_s(x) \sim A^{1/3}$
  (LT shadowing will slow it down).

EIC saturation program: study inclusive/diffractive/exclusive processes
EIC science goals:

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EIC: Parton propagation and fragmentation

- Use coloured probes to study soft nuclear glue
  - a “large-x” probe of small-x gluons
- Use nuclei to study parton propagation and fragmentation
  - parton showers, quark-to-hadron transition
- Ideal program for phase-1 EIC

Advantages of EIC:
- multi-dimensional binning
- large $\nu$-range: $10 < \nu < 1600$ GeV
  - large $\nu$: can experimentally isolate pQCD energy loss
  - small $\nu$: detailed studies of (pre)hadronization
- large $Q^2$: role of virtuality in attenuation
- heavy flavors: B, D mesons; J/psi “normal” absorption
- measurement of jets (first time in e+A)
- ......

A. Accardi,
INT 10-3 workshop and lectures at “QM Italia 2010”
EIC: parton propagation and fragmentation

Simulations for hadron attenuation:

\[ R^h_M (z_h) = \frac{1}{N^A_{DIS}} \frac{dN^h_A (z_h)}{dz_h} / \frac{1}{N^D_{DIS}} \frac{dN^h_D (z_h)}{dz_h} \]

**Energy loss model**

\( \langle \nu \rangle = 14 \text{ GeV} \quad \langle z_h \rangle = 0.4 \)

**Absorption model**

(Simulations by R. Dupré)

(Curves by A. Accardi)

A. Accardi,
INT 10-3 workshop and lectures at “QM Italia 2010”
EIC: other topics

• Map the spin and spatial structure of quarks and gluons in nucleons
  - PDFs at large x
  - TMDs and semi-inclusive processes

• Discover the collective effects of gluons in atomic nuclei
  - gluon EMC effect
  - tagged structure functions and their medium modifications

• Understand the emergence of hadronic matter from quarks and gluons
  - target fragmentation
  - BE correlations
  - ...

Small Electroweak program:
• neutral/charge current structure functions
• parameters of Standard Model
The EIC project timeline and status

- Informal recommendation in 2007 DOE/NSF NSAC Long-Range Plan
  [http://science.energy.gov/np/nsac](http://science.energy.gov/np/nsac)

- EIC Collaboration
  [http://web.mit.edu/eicc](http://web.mit.edu/eicc)
  - formed in 2007, over 100 physicists from > 20 institutions
  - semi-annual collaboration meetings and workshops

- EIC accelerator and physics R&D at Brookhaven and Jefferson Lab
  [http://www.jlab.org/meic](http://www.jlab.org/meic)

- International EIC Advisory Committee, two reviews of physics and accelerator designs in Feb-09 and Nov-09.
The EIC project timeline and status-II

- A series of JLab User Workshops on EIC in 2010
  http://www.physics.rutgers.edu(np)/2010rueic-home.html
  http://michael.tunl.duke.edu/workshop
  http://www.phy.anl.gov/mep/EIC-NUC2010

- EIC science discussed at 2010 Institute for Nuclear Theory INT 10-03 program
  http://www.int.washington.edu/PROGRAMS/10-3

Now the EIC Collaboration and EIC enthusiasts are working towards full recommendation in 2013 NSAC LRP.
EIC realization

Assuming endorsement of EIC at the next 2013 NSAC LRP:

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H. Montgomery, INT 10-03 program, Seattle
EIC is the next generation QCD machine, with many unique opportunities for fundamental physics.