Lecture
Physics at a future
Electron-Ion Collider
(EIC)

Bernd Surrow

Electron-Ion Collider facility concepts

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

DOE NP contract: DE-SC0013405
Bernd Surrow
Introduction

What makes up the world around us?

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Matter</td>
<td>23.3% ± 2.3%</td>
<td></td>
</tr>
<tr>
<td>Visible Matter</td>
<td>4.63% ± 0.24%</td>
<td></td>
</tr>
<tr>
<td>Dark Energy</td>
<td>72.1% ± 2.5%</td>
<td></td>
</tr>
</tbody>
</table>

https://map.gsfc.nasa.gov
### Introduction

- **Force carriers (Fields) and matter constituents within the Standard Model**

<table>
<thead>
<tr>
<th><strong>BOSONS</strong></th>
<th>force carriers spin = 0, 1, 2, ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mass (GeV/c²)</td>
</tr>
<tr>
<td><em>γ</em> photon</td>
<td>0</td>
</tr>
<tr>
<td><em>W</em>⁻</td>
<td>80.39</td>
</tr>
<tr>
<td><em>W</em>⁺</td>
<td>80.39</td>
</tr>
<tr>
<td><em>Z</em>⁰</td>
<td>91.188</td>
</tr>
</tbody>
</table>

**Strong (color) spin = 1**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (GeV/c²)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>g</em> gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Higgs Boson spin = 0**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (GeV/c²)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>H</em> Higgs</td>
<td>126</td>
<td>0</td>
</tr>
</tbody>
</table>

Proton charge: +1  
Proton mass: ~ 1 GeV

- *m_u* ~ 2 MeV
- *m_d* ~ 5 MeV
- *m_g* = 0

Proton mass arises predominantly from interactions / energy in Gluon fields

---

2013: F. Englert and P. Higgs for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles (e.g. quarks), and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider.”
Introduction

Fundamental interactions in nature

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically Charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength at</td>
<td>$10^{-18}$ m</td>
<td>$W^+$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3 \times 10^{-17}$ m</td>
<td>$W^-$</td>
<td>$Z^0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-41}$</td>
<td>$0.8$</td>
<td>$1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-41}$</td>
<td>$10^{-4}$</td>
<td>$1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$25$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$60$</td>
</tr>
</tbody>
</table>


2017: R. Weiss, B. C. Barish and K. S. Thorne: “for decisive contributions to the LIGO detector and the observation of gravitational waves.”

1979: S. L. Glashow, A. Salam and S. Weinberg: “for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current.”


Silent Partners:

Virtual quark-antiquark pairs
(QCD sea) (\(\Delta E \Delta t \sim \hbar\))

Gluons!
Mass in QCD

- Quote from Nobel prize lecture in physics, 2004, given by Frank Wilczek:

Stated as $m=E/c^2$: Possibility of explaining mass in terms of energy.

Einstein’s original paper does not contain the equation $E=mc^2$, but rather $m=E/c^2$:


Modern QCD answers Einstein’s question with a resounding “Yes!”. Indeed, the mass of ordinary matter derives almost entirely from energy - the energy of massless gluons and nearly massless quarks, which are the ingredients from which protons, neutrons, and atomic nuclei are made.
Spin in QCD

Traditional way to introduce spin in QM textbooks:
Stern-Gerlach experiment (1922)

Concept of spin: Long and tedious battle to understand splitting patterns and separations in line spectra

Anomalous magnetic moment of proton by Stern et al. (1933)

Proposal of self-rotating electron by George Uhlenbeck and Samuel Goudsmit (1925)

Paul Ehrenfest: “This is a good idea [self-rotating electron]. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything by making a stupid mistake.”
Spin in everyday life

Proton spins are used to image the structure and function of the human body using the technique of Magnetic Resonance Imaging (MRI).

2003: “for their discoveries concerning Magnetic Resonance Imaging”

Nobel Prize Medicine

Paul C. Lauterbur (1929-2007)
Sir Peter Mansfield (1933-2017)
Outline

- Theoretical foundation
- The EIC Physics Pillars
- The EIC Accelerator Concepts (JLEIC at JLab / eRHIC at BNL): Requirements and Layout
- The EIC Detector Concepts: Requirements & Design
- The US NP Long-Range Plan and EIC Science Assessment by the National Academy of Sciences
- Anticipated next steps and plans
- The EIC Users Group
- Summary
Theoretical foundation

- The Quest to Understand the Fundamental Structure of Matter ("Visible Matter")
EIC - A QCD lab to explore the structure and dynamics of the visible world

\[ \mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j (iD_\mu \gamma^\mu - m_j) \psi_j - \frac{1}{4} \text{Tr} G^{\mu\nu} G_{\mu\nu} \]

- Interactions arise from fundamental symmetry principles: SU(3)_c
- Properties of visible universe such as mass and spin (e.g. proton): Emergent through complex structure of the QCD vacuum

Major goal:
Understanding QCD interactions and emergence of hadronic and nuclear matter in terms of quarks and gluons

Essential elements looking forward:
1) Tomography of hadrons and nuclear matter in terms of quarks and gluons
2) Synergy of experimental progress and theory

D. Leinweber: Quantum fluctuations in gluon fields
Theoretical foundation

- **DIS - Kinematics**

\[
k = \begin{pmatrix}
E_e \\
0 \\
0 \\
-E_e
\end{pmatrix}
\]

\[
p = \begin{pmatrix}
E_p \\
0 \\
0 \\
E_p
\end{pmatrix}
\]

\[
Q^2 = -(k - k')^2 = -q^2
\]

\[
x = \frac{Q^2}{2(p \cdot q)}
\]

\[
y = \frac{p \cdot q}{p \cdot k}
\]

Measure of resolution power

Measure of momentum fraction by struck quark

Measure of inelasticity

\[
k' = \begin{pmatrix}
E'_e \\
E'_e \sin \theta'_e \cos \phi'_e \\
E'_e \sin \theta'_e \sin \phi'_e \\
E'_e \cos \theta'_e
\end{pmatrix}
\]

\[
p' = \begin{pmatrix}
\sum_h E_h \\
\sum_h p_{X,h} \\
\sum_h p_{Y,h} \\
\sum_h p_{Z,h}
\end{pmatrix}
\]
Theoretical foundation

- **Basic ingredients of QCD**
  - **Asymptotic freedom**: $\alpha_s \to 0$ at short distances / Perturbative QCD
  - **Evolution**: Predict $Q^2$ dependence related to level of gluon radiation / Constrain parton structure $f_i(x)$ using measured data
  - **Factorization**: Formulate observables in terms of parton structure

\[
\frac{d\sigma}{dp_T}^{p+p\to h+X} = \sum_{f_1,f_2,f} \int dx_1 dx_2 dz f_1(x_1, \mu^2) f_2(x_2, \mu^2) \times \left( \frac{d\hat{\sigma}}{dp_T} \right)_{x_1p_1, x_1p_1, z, \mu} D_h^f(z, \mu^2)
\]
**Theoretical foundation**

- **DIS - Parton structure: Unpolarized**


**H1 and ZEUS**

- **HERA NC e+p**
  - 0.4 fb⁻¹
  - 0.5 fb⁻¹

- **Fixed Target**
  - HERAPDF2.0 e+p NNLO
  - HERAPDF2.0 e+p NNLO

- **\(\sqrt{s} = 318 \text{ GeV}\)**

- **\(Q^2/\text{GeV}^2\)**

\[
d\sigma_{eP} \propto F_2^P = \sum_i e_i^2 x (q_i + \bar{q}_i)
\]

- **Measure of probability to find parton \(f\) with longitudinal momentum fraction \(x\)**

- **1990: J. I. Friedman, H. W. Kendall and R. E. Taylor:** “for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics.”

- **R. D. Ball et al., arXiv:1207.1303.**

- **NNPDF2.3 (NNLO)**
  - \(xf(x, \mu^2=10 \text{ GeV}^2)\)
  - \(g/10\)
  - \(xf(x, \mu^2=10^4 \text{ GeV}^2)\)

**Quark Matter 2019 International Conference**

Wuhan, China, November 3-9, 2019
Theoretical foundation

**DIS - Parton structure: Polarized**


\[
\frac{1}{2} \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta d + \Delta s + \Delta \bar{s}
\]

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

\[
\Delta f(x) = f^+(x) - f^-(x)
\]

Measure of probability to find parton f with spin aligned to anti-anti-aligned to proton spin at momentum fraction x

\[ g_1^P = \frac{1}{2} \sum_i e_i^2 (\Delta q_i + \Delta \bar{q}_i) \]


\[ \Delta \Sigma = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle \]

\[ \Delta G \]

\[ x \Delta u \]

\[ x \Delta d \]

\[ x \Delta \bar{u} \]

\[ x \Delta \bar{d} \]

\[ x \Delta s \]

\[ x \Delta g \]

\[ x \Delta \tau \]

\[ x \Delta \bar{\tau} \]

\[ x \Delta \rho \]

\[ x \Delta \bar{\rho} \]

\[ x \Delta \nu \]

\[ x \Delta \bar{\nu} \]

\[ x \Delta \mu \]

\[ x \Delta \bar{\mu} \]

\[ x \Delta \tau \]

\[ x \Delta \bar{\tau} \]

\[ x \Delta \rho \]

\[ x \Delta \bar{\rho} \]

\[ x \Delta \nu \]

\[ x \Delta \bar{\nu} \]

\[ x \Delta \mu \]

\[ x \Delta \bar{\mu} \]

\[ x \Delta \tau \]

\[ x \Delta \bar{\tau} \]

\[ x \Delta \rho \]

\[ x \Delta \bar{\rho} \]

\[ x \Delta \nu \]

\[ x \Delta \bar{\nu} \]

\[ x \Delta \mu \]

\[ x \Delta \bar{\mu} \]

\[ x \Delta \tau \]

\[ x \Delta \bar{\tau} \]

\[ x \Delta \rho \]

\[ x \Delta \bar{\rho} \]

\[ x \Delta \nu \]

\[ x \Delta \bar{\nu} \]

\[ x \Delta \mu \]
Theoretical foundation

**Motivation - EIC program**

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?

How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?
EIC: Study
structure and
dynamics of matter
at high luminosity,
wide range of nuclei
high energy with
polarized beams and

Bernd Surrow
LHeC
QCD at Extreme Parton
Densities - Saturation
Parton Distributions
in Nuclei
QCD at Extreme Parton
Densities - Saturation
Spin and Flavor Structure of
the Nucleon and Nuclei
Transverse Momentum
Distribution and Spatial
Imaging
Tomography (p/A)

Luminosity (cm^-2 sec^-1)

10^{32} 10^{33} 10^{34}

1
10
100

\sqrt{s} (GeV)

Integrated Luminosity (fb^-1/yr)

1 LHeC

arXiv:1212.1701

Whitepaper:

Understanding the glue that
binds as all!

17

The EIC Physics Pillars

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

The EIC Physics Pillars

Understanding the glue that
binds as all!

arXiv:1212.1701

Whitepaper:

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!

The EIC Physics Pillars

Understanding the glue that
binds as all!
The EIC Physics Pillars

Requirements

- **Machine:**
  - High luminosity: $10^{33}$ cm$^{-2}$s$^{-1}$ - $10^{34}$ cm$^{-2}$s$^{-1}$
  - Flexible center-of-mass energy $\sqrt{s} = \sqrt{4E_e E_p}$: Wide kinematic range $Q^2 = s x y$
  - Highly polarized electron (0.8) and proton / light ion (0.7) beams: Spin structure studies
  - Wide range of nuclear beams (d to Pb/U): High gluon density

- **Detector:**
  - Wide acceptance detector system including particle ID (e/h separation & π, K, p ID - flavor tagging)
  - Instrumentation for tagging of protons from elastic reactions and neutrons from nuclear breakup: Target / nuclear fragments in addition to low $Q^2$ tagger / polarimetry and luminosity (abs. and rel.) measurement

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

Bernd Surrow
Luminosity / $\sqrt{s}$ / Kinematic coverage

- **JLAB/CEBAF** (6, 12)
- **SLAC**
- **EIC**
- **BCDMS**
- **COMPASS - HIAF-EIC**
- **HERMES**
- **NMC**
- **LHeC/HE-LHC**
- **FCC-he**
- **LHeC/HL-LHC**
- **LHeC/CDR**

**Ep Facilities & Experiments:**
- Past Colliders
- Collider Concepts
- Past Fixed Target
- Ongoing Fixed Target
- EIC Project

**Measurements with $A \geq 56$ (Fe):**
- $eA\mu$A DIS (E-139, E-665, EMC, NMC)
- $\nu A$ DIS (CCFR, CDHSW, CHORUS, NuTeV)
- DY (E772, E866)

**Current polarized DIS data:**
- CERN △ DESY ▲ JLab □ SLAC

**Current polarized BNL-RHIC pp data:**
- PHENIX □ ▲ STAR 1-jet

**EIC Physics Pillars**

- **Luminosity:**
  - $10^{38}$
  - $10^{37}$
  - $10^{36}$
  - $10^{35}$
  - $10^{34}$
  - $10^{33}$
  - $10^{32}$
  - $10^{31}$

- **Kinematic coverage:**
  - $\sqrt{s}$ (GeV)
  - $10^3 - 10^4$
  - Increase in luminosity: HERA to EIC

**Graphs:**
- $Q^2$ vs. $x$
- $x$ vs. $y$
- $\sqrt{s}$ vs. $Q^2$

**Legend:**
- **eA**
- **ep**

---

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019
Explore QCD landscape in various aspects over a wide range in $x$ and $Q^2$.

Heavy nuclei at high energy critical to explore high-density gluon matter!
Inclusive eA scattering measurements

\[ \sigma_{\text{red}} = F_2 - \frac{y^2}{Y_+} F_L \]

\[ \left( \frac{d^2 \sigma}{dx dQ^2} \right) = \frac{2\pi \alpha^2 y_+}{x Q^4} \left( F_2 - \frac{y^2}{Y_+} F_L \right) \]

\[ Y_+ = 1 + (1 - y)^2 \]

The EIC Physics Pillars

- Inclusive eA scattering measurements

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

arXiv:1708.01527

Bernd Surrow
The EIC Physics Pillars

- Charm-associated eA scattering measurements

\[ \sigma^{c\bar{c}}_{\text{red}} = F^c_{2} - \frac{y^2}{Y_+} F^\bar{c}_{L} \]

\[ \left( \frac{d^2\sigma}{dx dQ^2} \right)^{c\bar{c}} = \frac{2\pi\alpha^2 Y_+}{xQ^4} \left( F^c_{2} - \frac{y^2}{Y_+} F^\bar{c}_{L} \right) \]

\[ Y_+ = 1 + (1 - y)^2 \]

\[ \int \text{Ldt} = 10 \text{ fb}^{-1}/A \]

\[ \sqrt{s} = 31.6, 38.7, 44.7 \text{ GeV} \]

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

arXiv:1708.01527

Bernd Surrow
Impact on nuclear gluon behavior in eA scattering

Modifications of nuclear environment:

$R_{g}^{Pb}$

Ratio of gluon distribution in Pb compared to proton

Figure 24: The ratio $R_{g}^{Pb}$, from EPPS16*, of gluon distributions in a lead nucleus relative to the proton, for the low (left) and high (right) $p_{T}$, at $Q^{2} = 1.69$ GeV$^{2}$ and $Q^{2} = 10$ GeV$^{2}$ (upper and lower plots, respectively). The grey band represents the EPPS16* theoretical uncertainty. The orange (blue hatched) band includes the EIC simulated inclusive (charm quark) reduced cross-section data. The lower panel in each plot shows the reduction factor in the uncertainty with respect to the baseline fit.

Impact on Heavy-Ion Physics

Measurements over the last two decades, first at RHIC and later at the LHC, have provided strong evidence for the formation of a strongly coupled plasma of quarks and gluons (sQGP) in high energy collisions of heavy nuclei. This sQGP appears to behave like a nearly perfect liquid and is well described by hydrodynamics at around 1 fm/c after the initial impact of the two nuclei [64–67]. For reviews, see [68–71].

Despite the significant insight accumulated in the past 17 years, little is understood about how the initial non-equilibrium state, whose properties are little known, evolves towards a system in thermal equilibrium. A conjectured picture of the initial phase, based on the CGC framework, suggests that at leading order the collision can be approximated by the collision of “shock waves” of classical gluon fields (Glasma fields), [72–74], resulting in the production of non-equilibrium gluonic matter. Unfortunately, heavy-ion collisions themselves cannot teach us much about the initial state because most of the details are wiped out during the
Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

The EIC Physics Pillars

Spin and Flavor Structure of the Nucleon

- $g_1$ stat. uncertainty projections for 10fb$^{-1}$ for range of CME in comparison to DSSV+ predictions incl. uncertainties
- EIC impact on helicity distributions of anti-u, anti-d and s quarks together with gluons
The EIC Physics Pillars

Impact on proton spin

The EIC Physics Pillars

- Transverse Momentum Distribution and Spatial Imaging
  \[ f(x, k_T) \quad 1+2D \]

- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering

- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

Transverse Momentum Distribution (TMD)

\[ \int d^2b_T W(x, b_T, k_T) \int d^2k_T f(x, b_T) \quad 1+2D \]

Wigner Distribution

Impact Parameter Distribution

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

Bernd Surrow
The EIC Facility Concepts

- EIC accelerator design at JLab and BNL

  Highly polarized electron / Highly polarized proton and lights ions / Unpolarized heavy ion colliding beams

  \[ CME: \sim 20\text{-}100\text{GeV} \]

  \[ \text{Luminosity: } \sim 10^{33-34}\text{cm}^{-2}\text{s}^{-1} \]

- Electron complex with CEBAF as full energy injector and collider ring up to 12GeV
- Ion complex with source and linac, booster and collider ring
- 2 detector IP’s integrated into IR design

JLEIC Collaboration

- Polarized electron source and 400MeV injector linac
- Polarized proton beams and ion beams based on existing RHIC facility
- 2 detector IP’s integrated into IR design

eRHIC Collaboration
Overview of processes and final states

Inclusive

- Unpolarized $f_i(x,Q^2)$ and helicity distribution $\Delta f_i(x,Q^2)$ functions through unpolarized and polarized structure function measurements ($F_2$, $F_L$, $g_1$)

- Define kinematics ($x$, $y$, $Q^2$) through electron (e-ID and energy+angular measurement critical) / hadron final state or combination of both depending on kinematic $x$-$Q^2$ region

Semi-Inclusive DIS (SDIS)

- Flavor tagging through hadron identification studying FF / TMD's (Transverse momentum, $k_T$, dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance
- Heavy flavor (charm / bottom): Excellent secondary vertex reconstruction

Deeply-Virtual Compton Scattering (DVCS)

- Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, $b_T$, dependence) using DVCS and VM production
- $eA$: Impact parameter determination / Neutron tagging using Zero-Degree Calorimeter (ZDC)
The EIC Detector Concepts

- EIC kinematic considerations: $E_e=10\text{ GeV} \times E_p=250\text{ GeV}$ ($\sqrt{s}=100\text{ GeV}$)

![EIC kinematics diagram with kinematic peak location](image)
The EIC Detector Concepts

Overview of general requirements

- **Acceptance**: Close to $4\pi$ coverage with a $\eta$-coverage ($\eta = -\ln(\tan(\theta/2))$) of approximately $\eta < 3.5$ combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage.
- **Low dead material** budget in particular in rear direction (~5% $X/X_0$).
- **Good momentum resolution** $\Delta p/p \sim$ few %.
- **Electron ID** for $e/h$ separation varies with $\theta / \eta$ at the level of $1:10^4 / \sim2-3\%/\sqrt{E}$ for $\eta<-2$ and $\sim7\%/\sqrt{E}$ for $-2<\eta<1$.
- **Particle ID** for $\pi/K/p$ separation over wide momentum range:
  - (Forward $\eta$ up to $\sim50$ GeV/c / Barrel $\eta$ up to $\sim4$ GeV/c / Rear $\eta$ up to $\sim6$ GeV/c).
- **High spatial vertex resolution** $\sim 10-20\mu m$ for vertex reconstruction.
- **Low-angel taggers**:
  - Recoil proton.
  - Low $Q^2$ electron.
  - Neutrons on hadron direction.
- **Luminosity** (Absolute and relative) and local polarization direction measurement.
Generic Detector R&D program for an EIC

In January 2011, BNL, in association with JLab and the DOE Office of NP, announced a generic detector R&D program to address the scientific requirements for measurements at a future EIC facility.

Goals:
- Enable successful design and timely implementation of an EIC experimental program
- Develop instrumentation solutions that meet realistic cost expectations
- Stimulate the formation of user collaborations to design and build experiments

Peer-reviewed program funded by DOE and managed by BNL with $1M/year to $1.5M/year. Initiated and coordinated by Tom Ludlam (BNL) until 2014 / Since 2014 coordinated by Thomas Ullrich (BNL)

Key to success: Standing EIC Detector Advisory Committee
- Current members: Marcel Demarteau (ANL), Carl Haber (LBNL), Peter Krizan (Ljubljana), Ian Shipsey (Oxford), Rick van Berg (UPenn), Jerry Va’vra (SLAC) and Glenn Young (JLab)
- Past members: Robert Klanner (Hamburg) and Howard Wieman (LBL)

Wide range of R&D programs: Calorimetry / Tracking (GEM, MicroMegas, TPC) incl. silicon / Particle ID (TRD, Dual-RICH, Aerogel RICH, DIRC, TOF) / Polarimetry / Background / Simulation Tools /

https://wiki.bnl.gov/conferences/index.php/EIC_R%2520D
The EIC Detector Concepts

- EIC detector design at JLab and BNL

(a) TOPSiDE at JLab:

(b) JLEIC detector design at JLab:

(c) BEAST detector design at BNL:

(d) sPHENIX-EIC detector design at BNL:

---

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

Bernd Surrow
Detector design: JLEIC (2) - JLab

Extended detector: 80m
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer
fully integrated with accelerator lattice
The EIC Detector Concepts

Auxiliary detector systems: Luminosity (Abs. / Rel.) and Polarimetry

- **Luminosity (Absolute / Relative)**
  - Bethe-Heitler process \((e+p \rightarrow e+\gamma+p)\) successfully used at HERA I/II (QED theory precision ~0.2%) / Systematic uncertainty achieved ~1-2%. For polarized beam-mode, polarization dependence. Systematic uncertainty of e/p polarization and theory uncertainty will limit abs./rel. luminosity - Critical for asymmetry measurements in particular at low x.

- **Polarimetry: Lepton**
  - Compton back-scattering / HERA used two setups of measuring trans. (TPOL) and long. (LPOL) polarization and achieved for sys. uncertainties 3.5% (TPOL) and 1.6% (LPOL) at HERA I / 1.9% (TPOL) and 2.0% (LPOL) at HERA II. Prospect to improve precision to ~1%.

- **Polarimetry: Hadron**
  - Extensive experience at RHIC from polarized p program. Two aspects are relevant: Absolute and relative polarization measurement.
    - Absolute: Elastic scattering of polarized p on polarized hydrogen jet target
    - Relative: High statistics bunch-by-bunch polarized proton on carbon fiber target
    - Achieved precision: 3.3% (Run 13 - 255GeV polarized p beam) for single-spin asymmetry
    - Further improvements from stability control of hydrogen jet target / carbon-fiber target and energy calibration of recoil silicon detectors.
Recommendations:

1. Capitalize on investments made to maintain U.S. leadership in nuclear science.

2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.

3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.

4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

The FY 2018 Request supports progress in important aspects of the 2015 LRP Vision.
THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary

The National Academies of Sciences, Engineering, and Medicine (“National Academies”) will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

“U.S.-Based Electron Ion Collider Science Assessment” is now getting underway. The Chair will be Gordon Baym. The rest of the committee, including a co-chair, will be appointed in the next couple of weeks. The first meeting is being planned for January, 2017.
The EIC Science Assessment by the US NAS

NAS Webinar and NAS report release: 07/24/2018

http://www8.nationalacademies.org/onpinews/newsitem.aspx?
RecordID=25171&ga=2.209086742.50427317.1532451645-138591744
4.1532451645

Webinar on Tuesday, July 24, 2018 - Public presentation and report release

Gordon Baym (Co-chair): Webinar presentation

“The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely.”

“Glowing” report on a US-based EIC facility!

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

Bernd Surrow
NAS report main “global” findings

Finding 1: An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Finding 2: These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

Finding 5: Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

Finding 7: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and furthermore, to glean the fundamental insights into QCD that an EIC can reveal.
Current Status and Path forward for the EIC

The “wickets” are substantially aligned for a major step forward on the EIC

- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC has been completed
- DOE is moving forward towards a request for CD-0 (approve “Mission Need”)
- DOE convened a panel to assess options for siting between two proposed concepts.
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment

- The FY 2020 President’s Request includes $1.5 million OPC. The FY 2020 House Mark identifies $10 million OPC and $1 million TEC. Senate Mark identifies $10 million OPC and $1 million TEC.
EIC User Group and R&D activities

EIC User Group:
- EICUG organization established in summer 2016
- In numbers: 945 members (Experimental scientists: 544 / Theory scientists: 221 / Accelerator scientists: 142 / Support: 3 / Other: 39), 192 institutions, 30 countries, 6 world regions
- World map:

R&D activities:
- EIC Detector R&D program operated by BNL with ~$1M / year
- EIC Accelerator R&D with ~$7M / year

Internationalization is critical!

WWW-page: www.eicug.org
EIC Users’ Group: Lab News

- EIC Science Centers at JLab and BNL/Stony Brook University

- Dedicated EIC Science Centers at both JLab and BNL/Stony Brook University

- JLab: EIC2@JLab
  - Co-Directors: Douglas Higinbotham / Amber Boehnlein / Jianwei Qiu
  - WWW-page: https://www.eiccenter.org

- BNL/Stony Brook University: Center for Frontiers in Nuclear Science
  - Director: Abhay Deshpande
  - WWW-page: https://www.stonybrook.edu/cfns/

The Electron-Ion Collider Center at Jefferson Lab (EIC2@JLab) is an organization to advance and promote the science program at a future electron-ion collider (EIC) facility. Particular emphasis is on the close connection of EIC science to the current Jefferson Lab 12 GeV CEBAF science program.

The mission of this Center is to promote and facilitate the realization of the U.S. based EIC by enhancing the science case and collaborations amongst the scientists around the world interested in the EIC.
The EIC Users Group

- EIC community activities / Conferences and Workshops

Poetic 9, LBNL, Sept. 16-21, 2019

Highly Active EIC Community!

Programs related to EIC

The Proton Mass: At the Heart of Most Visible Matter

Joint CTEQ Meeting and POETIC 7 (7th International Conference on Physics Opportunities at an Electron-Ion-Collider)
Temple University, March 28-29, 2016

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

Quark Matter 2019 International Conference
Wuhan, China, November 3-9, 2019

Bernd Surrow
The EIC Users Group

Physics and Detector Conceptual Design - Yellow Report Workshop series

- **Purpose:**
  - Advance state of documented physics studies and detector concepts in preparation for the EIC.
  - Provide basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors.
  - Input towards future Technical Design Reports (TDRs).

- **Approach:**
  - Two WG: Physics requirement and Detector concepts - 4 conveners each.
  - Several sub-groups each, ~2 conveners/sub-group.
  - Time limited effort: ~1 year.

- **Meetings:**
  - December 12-13, 2019, MIT: Kick-off organizational meeting.
  - Workshops:
    - March 19-21, 2020, Temple U., Philadelphia
    - May 22-24, 2020, U. of Pavia, Pavia, Italy
    - September 17-19, 2020, CUA, Washington D.C.
    - November 19-21, 2020, UCB / LBNL, Berkeley, CA
**EIC Physics Pillars:** EIC facility will address fundamental questions on the structure and dynamics of nucleons and nuclei in terms of quarks and gluons using precision measurements including:
- Parton Distributions in Nuclei / QCD at Extreme Parton Densities - Saturation
- Spin and Flavor Structure of the Nucleon and Nuclei
- Tomography (p/A) Transverse Momentum Distribution and Spatial Imaging

**EIC Facility Concepts:**
- **JLEIC:** Added ion complex with source and linac, booster and collider ring to existing CEBAF facility
- **eRHIC:** Added electron storage ring to existing RHIC facility
- Luminosity: $\sim 10^{33-34} \text{cm}^{-2}\text{s}^{-1}$
- Polarized e/p and unpolarized heavy ion beams / CME $\sim 20$-$100 \text{GeV}$

**EIC Status and Plans:**
- NAS review completed - Glowing NAS report / Possible CD0 mission statement $\sim$FY19
- EIC facility construction after FRIB completion realistically in FY22/FY23 timeframe
- EIC facility completion in roughly a decade from now!

*Summary*

An exciting time is ahead of us to realize a future EIC facility!