EIC: AN OVERVIEW

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A NEW ACCELERATOR FOR FUNDAMENTAL QUESTIONS

What are we made of?

How did hadrons form after Big Bang?

We have discovered the SM fundamental particles, but still many question on how they act.
How can the hadrons mass & spin emerge from a quark/gluon “paella” dish?
Spin and Flavor Structure of the Nucleon and Nuclei

EIC PHYSICS

LHeC

Tomography (p/A)
Transverse Momentum Distribution and Spatial Imaging

Spin and Flavor Structure of the Nucleon and Nuclei

Parton Distributions in Nuclei
QCD at Extreme Parton Densities - Saturation

Luminosity (cm$^{-2}$ sec$^{-1}$)

$\sqrt{S}$ (GeV)

Integrated Luminosity (fb$^{-1}$/yr)

Understanding the glue that binds as all!

arXiv:1212.1701

arXiv:1507.05267
EIC: TYPE OF EVENTS

Inclusive events: $e + N \rightarrow e' + X$
(a modern Rutherford experiment)

Semi-Inclusive events: $e + N \rightarrow e' + (\pi, K, p, jet) + X$
(cleaner than hh collision: initial hadron is broken)

Exclusive events: $e + N \rightarrow e' + N + (\pi, K, p, jet) + X$
(almost impossible for other colliders: initial hadron is not broken)

$Q^2$ fixes the resolution scale
$y$ fixes the inelasticity scale
$x, z$ momentum fraction of the quarks/gluons

$Q^2 = s \times y$
# EIC Physics and Goals

<table>
<thead>
<tr>
<th></th>
<th>HERA@DESY</th>
<th>LHeC@CERN</th>
<th>eRHIC@BNL</th>
<th>JLEIC@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 → 65</td>
<td>14</td>
</tr>
<tr>
<td>Proton $x_{min}$</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>$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$</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>$10^{33-34}$</td>
<td>$10^{32-33} \rightarrow 10^{35}$</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 → 2030</td>
<td>upgrade to FAIR</td>
</tr>
</tbody>
</table>

The past

Possible future
THE PROTON MASS

Mass – intrinsic to a particle:

= Energy of the particle when it is at the rest

✧ QCD energy-momentum tensor in terms of quarks and gluons

\[ T^{\mu \nu} = \frac{1}{2} \bar{\psi} i \gamma^\nu D^{(\mu} \gamma^{\nu)} \psi + \frac{1}{4} g^{\mu \nu} F^2 - F^{\mu \alpha} F^{\nu \alpha} \]

✧ Proton mass:

\[ m = \frac{\langle p | \int d^3 x \ T^{00} | p \rangle}{\langle p | p \rangle} \sim \text{GeV} \]
THE SPIN PUZZLE

- The sum rule: \[ S(\mu) = \sum_f \langle P, S| \hat{J}_f^z(\mu)|P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) \]
  - Infinite possibilities of decompositions – connection to observables?
  - Intrinsic properties + dynamical motion and interactions

- An incomplete story:
  \[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g) \]
  - Jaffe-Manohar, 90
  - Ji, 96, ...

- Proton Spin

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

- Gluon helicity
  - Start to know
  \[ \Delta G = \int dx \Delta g(x) \sim 40\% \text{(with RHIC data)} \]

- Orbital Angular Momentum of quarks and gluons
  - Little known

Net effect of partons’ transverse motion?
THE SPIN PUZZLE

- The power & precision of EIC:

- Reach out the glue:

\[
\frac{d g_1(x,Q^2)}{d \ln Q^2} = \frac{\alpha_s}{2\pi} P_{q0} \otimes \Delta g(x,Q^2) + \ldots
\]

- One-year of running at EIC:

Wider $Q^2$ and $x$ range including low $x$ at EIC!

- Ultimate solution to the proton spin puzzle:

- Precision measurement of $\Delta g(x)$ – extend to smaller $x$ regime
- Orbital angular momentum contribution – measurement of TMDs & GPDs!
EIC PHYSICS AND GOALS: WIGNER DISTRIBUTIONS

\[ W(x, k_{\perp}, b_{\perp}) \]

- Momentum space: \( q(x, k_{\perp}) \to \int db_{\perp} \)
- Coordinate space: \( q(x, b_{\perp}) \to \int dk_{\perp} \)

3Dim images in mom. space
Transverse-Momentum Depend distribution functions
TMD's
SIDIS: factor. th. if \( k_{\perp} \ll Q \)

2 + 1 Dim images
\( \perp \) coord. space + x long. mom.
Fourier Transformed \( (b_{\perp} \leftrightarrow q) \) of
Generalized Parton Distributions
GPD's
exclusive processes: factor. th. if \(-q^2 \ll Q^2\)
TMD ZOO AND EVOLUTION

SIDIS: \[ e + N \rightarrow e' + \text{jet(s)} + X \]
\[ e + N \rightarrow e' + h + X \]

the “TMD zoo” at leading twist

\[ \int dk_{\perp}^2 \frac{k_{\perp}^2}{2M^2} f_{1T} u \bar{u} \]

u(x, k_{\perp})

Sivers function

distortion of q distribution

because of N↑ polarization

Sivers, P.R. D 41 (90) 83
WHAT DO WE NEED? THEORY VS EXPERIMENT

Classification of processes/experiment according to their value:

**Testing Factorization Theorems in Ideal Conditions**

EIC/LHC/Tevatron/RHIC?

**Testing Factorization Theorems in Less Ideal Conditions**

EIC/Compass/Jlab/LHC/Tevatron/RHIC

**Testing Un-Factorizable Processes**

Hermes/Jlab/EIC
**SMALL-X AND CGC**

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

- **Color entanglement enhanced at small-x:**
  - $\sigma_{\text{DIS}}^{\text{tot}} = \sum_f \hat{C}_f \otimes \Phi_f + O\left(\frac{Q_s^2}{Q^2}\right) + O\left(\frac{Q_s^4}{Q^4}\right) + ...$

- **Saturation:**
  - is a part of QCD!
  - Where to find it?
    - Expectation: $x=10^{-5}$ in a proton at $Q^2=5$ GeV$^2$
  - Color entangled or correlated between two active partons
WHAT DO WE NEED? THEORY VS EXPERIMENT

What can we learn from HEP high precision QCD measurements?
Can we encode all our information in a MC event generator?
WHAT DO WE NEED? THEORY VS EXPERIMENT

What can we learn from HEP high precision QCD measurements?

A dedicated work is necessary!!

How to include Evolution?!

MCEG

Experiment

- Comparing to theory
- Analysis Prototyping
- EIC Detector Design

Theory

- Investigate theory advances
- Validate against theory advances
- Simulate EIC data

CURRENT IDEAS OR STARTING POINTS?

TMD MCEG

- gmc_trans
  - single-hadron inclusive DIS
- TMDGen
  - two-hadron inclusive DIS

CASCADE

- CCFM evolution, parton branching unintegrated PDFs
- Pythia
- General purpose MCEG
WHAT DO WE NEED? ANALYSIS/EXTRACTION/CODING

Artemide (TMD analysis)

Partons (GPD)

TMDlib

Up-coming ideas

Lattice

MCEG
Donald Geesaman (ANL, former NSAC Chair) “It will be joint progress of theory and experiment that moves us forward, not in one side alone”

Martin Savage (INT) “The next decade will be looked back upon as a truly astonishing period in NP and in our understanding of fundamental aspects of nature. This will be made possible by advances in scientific computing and in how the NP community organizes and collaborates, and how DOE and NSF supports this, to take full advantage of these advances.”
EIC GENERAL REQUIREMENTS

**Machine**

- **Ion beam:** protons, deuterons heavier ions
- **Polarization:** ~80% for electrons, ~70% for protons, light nuclei
- **c.m. energy** 20-100 GeV up to 140 GeV
- **High luminosity:** $10^{33-34}$ cm$^{-2}$ sec$^{-1}$
- **Wide range of nucleon beams (d to Pb/U):** High gluon density

**Detector**

- **Wide acceptance including particle ID** (pions, kaons, proton, ID-flavor tagging) including **protons from elastic reactions and neutrons from nuclear breakup**

![Graph showing Q^2 (GeV^2) vs. Luminosity]

**Legend:**
- Non-perturbative
- Perturbative

**Instruments:** HERMES, COMPASS, JLab6, JLAB12

**HERA**

**EIC**

**Q^2 (GeV^2)**

$10^{-1} \quad 1 \quad 10 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5$
Figure 1.2 shows the reduction in the range of parton momentum fraction in different center-of-mass energies, compared to existing data.

Current polarized DIS data:
- CERN
- DESY
- JLab
- SLAC

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

The Spin and Flavor Structure of the Nucleon

The EIC would offer the most powerful tool to precisely quantify how the spin of gluons contributes to the proton's spin, with an orbital motion contributing to nucleon spin.

An intensive and worldwide experimental program, such as the 12 GeV upgrade of CEBAF at JLab and the COMPASS at CERN, will initiate such studies in predominantly valence quark regions. However, these programs will be dramatically extended at the EIC to explore the role of the gluons and sea quarks in determining the hadron structure and properties. This will resolve crucial questions such as whether a substantial "missing" portion of nucleon spin resides in the gluons.
The EIC Facility Concepts

- **eRHIC layout and parameters**
  - **eRHIC design concept:**
    - Added electron storage ring (5-18GeV) (~80% pol.) with up to 2.1A e-current and 10MW max RF power
    - Proton beams up to 275GeV (~70% pol.) and ion beams up to 100GeV/n - existing RHIC facility
    - $^3$He and possibly d / A up to U
    - Repetition rate: 112.6MHz (With cooling)
    - Flat proton beam formed by cooling
    - Polarized electron source and 400MeV injector linac
    - On-energy polarized electron injector
    - Alternative approach of e-ERL accelerator considered in past / Technology risks addressed by R&D

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*23rd International Spin Physics Symposium - SPIN 2018*
Ferrara, Italy, September 10-14, 2018
The EIC Facility Concepts

- **JLEIC layout and parameters**
  - **JLEIC design concept:**
    - Polarized electrons 3 to 12GeV and polarized protons 40 to 100-400GeV and ions 40 to 160GeV/u - Polarization > 70%
    - Polarized light ions d, $^3$He and possibly Li / A above 200 (Au,Pb)
    - Electron complex with CEBAF as full energy injector and collider ring up to 12GeV
    - Ion complex with source and linac, booster and collider ring
    - Polarization - Figure-8 topology for ions rings / Spin precessions in left/right section of Figure arrangement cancel
    - Repetition rate: 476MHz - High lumi. concept!
**EIC User Group and R&D activities**

- **EIC User Group:**
  - EICUG organization established in summer 2016
  - In numbers...: **817 members** (470: Experimentalists / 163: Theorists / Accelerator Scientists: 142 / Support: 3 / Other: 39), 173 institutions, 30 countries, 7 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!
The 2015 Long Range Plan for Nuclear Science

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 (“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 charge and status**
  - Charge: Focus on **scientific justification** besides impact to other fields in science and society
  - Status: NAS report released 07/24/2018!

[Link to NAS report](https://www8.nationalacademies.org/pa/projectview.aspx?key=49811)
NAS Webinar and NAS report release: 07/24/2018


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!
The EIC Science Assessment by the US NAS

- NAS report main findings: Webinar on July 24, 2018 (1)

TheNationalAcademiesof
SCIENCES•ENGINEERING•MEDICINE

BOARDONPHYSICSANDASTRONOMY(BPA)

AnAssessmentof
U.S.-BasedElectron-Ion
ColliderScience

A study under the auspices of the
U.S. National Academies of Sciences, Engineering, and Medicine
GordonBaymandAniAprahamian,Co-Chairs
The study is supported by funding from the DOE Office of Science.
(Further information can be found at: https://www.nap.edu/25171)

CommitteeStatementofTask--fromDOEtotheBPA

CommitteeMembership

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider?
- What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?
The EIC Science Assessment by the US NAS

NAS report main findings: Webinar on July 24, 2018 (2)

Bottom Line

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

The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be a unique facility in the world that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.

The project is strongly supported by the nuclear physics community.

The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.
**The EIC Science Assessment by the US NAS**

- **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.
Anticipated next steps and plans

- **Towards a future EIC facility**
  - **NAS review following NSAC / LRP 2015 recommendation**
    - NAS study started in February 2017 with a series of meetings in 2017 / Report submitted by committee for review
    - Report released on July 24, 2018! - Very positive!
    - CD-0 (US Mission Need Statement) could be awarded after the completion of the NAS study ~2018/2019
  - Various (critical) accelerator R&D questions will not be answered until ~2019
  - Site selection may occur around 2019/2020
  - EIC facility construction has to start after FRIB (Facility for Rare Isotope Beams) completion, with anticipated FRIB construction to ramp down around 2020
  - Most optimistic scenario would have EIC funds start in FY20, more realistically begin of construction funds in FY22/FY23 time frame
  - Best guess for completion of EIC facility construction would be after 2025, around 2025-2030 - in roughly a decade from now!
Using simple logic: application presupposes discovery, and discovery requires research, and research implies exploring the unknown, with, by definition, the inability to predict how useful or profitable whatever will be found could turn out to be.

Christian de Duve, Nobel prize in Physiology/Medicine 1974

Nature volume 467, page S5 (14 October 2010)
How can the public be convinced of the importance of fundamental research with no applications in sight?

"Using simple logic: application presupposes discovery, and discovery requires research, and research implies exploring the unknown, with, by definition, the inability to predict how useful or profitable whatever will be found could turn out to be.

[...]

As an aside, before trying to convince the public of these basic truths, one should perhaps start with the administrators who too frequently tend to ignore them.

Christian de Duve, Nobel prize in Physiology/Medicine 1974

Nature volume 467, page S5 (14 October 2010): The joy of discovery
THANKS!