HERA - Electron Proton Collider

460-920 GeV protons
27.5 GeV electrons

HERA-I 1992-2000
HERA-II 2003-2007
Vast body of *precision* measurements over a wide kinematic range,
Best possible insight in high-energy proton structure to date.
Proton structure at high-energy is:
- far from elementary,
- gluon-dominated for $x < 0.1$,

Gluon content increases with decreasing $x$,

Gluons pose a number of questions

HERAPDF2.0:
15 parameters,
$\sim$1400 combined data points,
Factorization, the separation of short distance and long distance physics, combined with PDFs are ‘universally invaluable’ in hard scattering processes.
QCD radiation and saturation

QCD splitting:

\[ dP \propto \alpha_s \frac{d^2 k_\perp}{k_\perp^2} \frac{dx}{x} \]

is calculable; it is soft and collinear divergent - these divergencies must be resummed,

Density of gluons per unit of transverse area:

\[ \rho \propto x \, g(x, Q^2) / \pi R^2 \]

Cross section for gluon recombination:

\[ \sigma \propto \alpha_s / Q^2 \]

Saturation:

\[ 1 < \rho \sigma \rightarrow Q^2 < Q_s^2(x) \sim \left( \frac{A}{x} \right)^{\frac{1}{3}} \]

Gribov, Levin, Ryskin 1983

Dense system, non-linear evolution - onset is largely an experimental question, effective theory/theories.
Saturation at HERA? - Think outside the PDF!

- No evidence from DGLAP fits in sub-ranges, comparison with $F_L, \ldots$

- HERA c.s. data exhibit geometrical scaling with respect to

$$\tau = \frac{Q^2}{Q_s^2(x)} = \frac{Q^2}{Q_0^2} \frac{x}{x_0}^\lambda \text{ for } x < 0.01$$

_not_ seen in prior fixed-target experiments - Stasto et al.

However, DLL LO solution to DGLAP _also_ scales - Caolo et al.

- $\sim 15\%$ of events is diffractive (!).
HERA’s Legacy

Exquisite insight in proton structure in terms of quark and gluon degrees of freedom, … and also some quite remarkable voids;

Precision $F_L$ - insufficient time,

Test isospin, u-d, - no deuterons,

d/u at large $x$ - luminosity,

Strange quark distributions - luminosity,

Spin puzzle - no hadron beam polarization,

Quark-gluon dynamics in nuclei - no nuclei,

Saturation - insufficient $\sqrt{s}$ / no nuclei, …
### Electron Ion Collider Initiatives

#### Past & Possible Future

<table>
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<tr>
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#### High-Energy Physics

#### Nuclear Physics

#### World Wide Interest
Electron Ion Collider Initiatives

Past

Strategy: optimally use existing investments, pursue luminosity; 10x - 100x HERA nuclei and polarization (eRHIC, MEIC), nuclei and energy (LHeC), optimized instrumentation.

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+ popular press, most recently “Les gluons nous posent encore des colles”, Ent, Ullrich, Venugopalan, Pour La Science 455, Sept. ‘15
U.S.-based EIC - Two Facility Concepts

eRHIC:
- upgrade to RHIC hadron beam,

MEIC:
- upgrade to CEBAF 12 GeV electron beam,
U.S.-based EIC - Two Facility Concepts

**eRHIC:**
- upgrade to RHIC hadron beam,
- add ERL and FFAG Recirculating electron ring,
- 6.3 - 15.9 and 21.2 GeV e energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$ up to 93 GeV
- $L \sim 10^{33}$ cm$^{-2}$s$^{-1}$/A base design.

**MEIC:**
- upgrade to CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3-12 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy,
- $L \sim 10^{34}$ cm$^{-2}$s$^{-1}$/A
Electron Ion Collider: The Next QCD Frontier
Understanding the glue that binds us all
SECOND EDITION

coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as “embod-
ing the vision for reaching the next QCD frontier” [1]. It would extend the QCD sci-
ence programs in the U.S. established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally impor-
tant ways. The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental under-
standing of QCD in this frontier environment are:
• 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?
• 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?
• 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?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:
• A collider is needed to provide kinematic reach well into the gluon-dominated regime;
• Electron beams are needed to bring to bear the unmatched precision of the electro-
magnetic interaction as a probe;
• Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;
• Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facili-
ties around the world by being at the intensity frontier with a versatile range of kine-
matics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In partic-
ular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-
ion beams; c) two to three orders of magnitude increase in luminosity to facilitate to-
mographic imaging; and d) wide energy vari-
ability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-
The Next QCD Frontier
Understanding the glue that binds us all
Key questions:

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

- Where does the saturation of gluon densities set in?

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Key measurements:

- Inclusive Deep-Inelastic Scattering,
- Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,
- Exclusive deep-inelastic scattering,
- Diffraction.

ArXiv:1212.17010
Key requirements:

- **Electron identification - scattered lepton**
- **Momentum and angular resolution - x, Q^2**
- **\(\pi^+, \pi^-, K^+, K^-, p^+, p^-, \ldots\) identification, acceptance**
- **Rapidity coverage, t-resolution**

Key measurements:

- **Inclusive Deep-Inelastic Scattering**
- **Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state**
- **Exclusive deep-inelastic scattering**
- **Diffraction**
U.S.-based EIC - Detector Concepts

**Key requirements:**

- **Electron identification - scattered lepton**
- **Momentum and angular resolution -** $x, Q^2$
- $\pi^+, \pi^-, K^+, K^-, p^+, p^-, ...$ identification, acceptance
- **Rapidity coverage, t-resolution**

**Key measurements:**

- **Inclusive Deep-Inelastic Scattering,**
- **Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,**
- **Exclusive deep-inelastic scattering,**
- **Diffraction.**
Existing eA landscape - eRHIC kinematic range

LHeC, if realized, will obviously provide unprecedented kinematic reach, complementarity in polarization, A capabilities.
eRHIC - selected baseline measurements

\[
\frac{d^2 \sigma^{eA \rightarrow eX}}{dx dq^2} = \frac{4 \pi \alpha^2}{x Q^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]
\]
eRHIC - selected baseline measurements

\[
\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]
\]
eRHIC - impact on nuclear modification

- $R_{\text{valence}}^{(C)} (x, Q^2=5 \text{ GeV}^2)$
- $R_{\text{sea}}^{(C)} (x, Q^2=5 \text{ GeV}^2)$
- $R_{\text{gluon}}^{(C)} (x, Q^2=5 \text{ GeV}^2)$

$R_i^{(C)}(x, Q^2=5 \text{ GeV}^2)$

- Current EPS09
- with eRHIC (no charm)
- with eRHIC (with charm)
eRHIC - *baseline* semi-inclusive measurements

Combined sensitivity to hadronization, energy loss
eRHIC - dihadron probes of saturation

Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,
Sizable fraction of events is diffractive in saturation models;

Enhancement not seen in Leading Twist Shadowing pQCD model.
eRHIC - exclusive vector meson production

\[ t = (p_A - p_{A'})^2 = (p_{VM} + p_{e'} - p_e)^2 \]

Nucleus escapes down the beampipe (In)coherence tagged with ZDC

Dipole Cross-Section:

- Non-sat dipole model
- \( Q_s^2 \sim \frac{1}{r^2} \)
- Dilute linear-regime

\( J/\psi \)
eRHIC - exclusive vector meson production

Towards Imaging!
Key questions:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Identified measurements and quantified uncertainties

- Inclusive Deep-Inelastic Scattering,
- Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,
- Exclusive deep-inelastic scattering,
- Diffraction.

Look forward to a strong recommendation in the soon-to-be-finalized/released U.S. Long-Range-Plan.

Thank you!