RHIC and the Electron-Ion Collider: Our Quest to Understand the Structure of Visible Matter in our Universe

Alex Jentsch, Brookhaven National Lab
ajentsch@bnl.gov

NuSTEAM/NuPUMAS @ BNL
July 5th, 2023
Visible Matter

• All of the visible matter in the universe is comprised of atoms, which contain nuclei.

• Nuclei are held together by the strong nuclear force, which governs interactions between the “quarks” and “gluons” found inside the proton.
  • Quarks and gluons collectively called “partons”.
Visible Matter

• Some fundamental questions we can ask:
  • What are the properties of the proton?  
    → Spin, mass, charge.
  • How do these properties manifest?

• Quantum Chromodynamics (QCD) describes the interactions between the quarks and gluons (the strong force), and introduces the concept of “color”, the strong force charge.
The proton gets even more complicated

- As you ramp up the energy, the proton becomes awash with more partons (quarks and gluons)!

Three “valence” quarks inside proton.
The Proton Spin Puzzle

Spin structure – the three “valence” quarks do not account for the total spin of the proton!

Proton spin: \( \frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta G + L_{g,q} \)

Only 20-30% comes from the quarks!
The Proton Mass

• The proton mass composition is also rather complicated to pin-down!

PROTON MASS BUDGET

• Mass does not arise as simple sum of quark masses!
  • ~99% of the mass is driven by quark and gluon dynamics!
Some QCD Peculiarities

Another peculiar thing about QCD: confinement.

3-quarks: baryon
Quark + anti-quark: mesons
Collectively: hadrons

\[
\begin{align*}
\text{u} & \quad \text{d} \\
\text{u} & \quad \text{d} & \quad \text{u}
\end{align*}
\]

\(\pi^+\) meson

\(\pi^0\) meson

\(\pi^+\) meson
Some QCD Peculiarities

An additional wrinkle in QCD → **gluons can interact with themselves.**

- Opposite of the EM force and gravity, which decrease as a function of $\frac{1}{(\text{distance})^2}$.

**Consequences:**
- QCD calculations become non-perturbative (exceedingly hard) when the coupling constant is large (i.e. at low energy).

**QCD requires experimental data to make progress!**
Okay, so the structure of matter and QCD seem complicated...how can we study them?
Different kinds of interactions (just a few)

**Deep-Inelastic Scattering:**
electron + proton (or nucleus) collisions

**Electron + positron annihilation:**
electron + positron collisions

**Hadronic interactions:**
Proton + proton collisions

Led to discovery of the quark! (SLAC)
Led to discovery of the gluon! (PETRA)
Discovery of the Higgs! (LHC)
Building our microscope!

SLAC 1969: $e + p$ (fixed)

LEP @ CERN: 1989-2001: $e^+e^-$

JLAB/CEBAF: 1984 – present: $e + p$ (fixed)


LHC: 2008 – present: $p+p$, $p+A$, $A+A$
Building our microscope!

~ 8-10 meters
“Illuminating” the Structure of Matter

• **Use Deep-Inelastic Scattering (DIS)**
  - Collide electrons with protons or nuclei – the photon that is exchanged literally **illuminates** the target, allowing you to build a microscope of sorts to study the structure of matter!

![Diagram of electron and proton interactions](image.png)
“Illuminating” the Structure of Matter

Kinematics:

$$Q^2 = 2E_e E'_e (1 - \cos \theta'_e) = -q^2$$

Measure of resolution power

Low $Q^2$ = low resolution

High $Q^2$ = high resolution
"Illuminating" the Structure of Matter

Kinematics:

\[ Q^2 = 2E_e E_e' (1 - \cos \theta_e') = -q^2 \]

Measure of resolution power

\[ x = \frac{Q^2}{2pq} \]

Measure of momentum fraction of struck parton

"Bjorken-x"

\[ x \sim \frac{1}{3} \text{ for just the "valence" quarks.} \]
“Illuminating” the Structure of Matter

Kinematics:

\[ Q^2 = 2E_e E'_e (1 - \cos \theta'_e) = -q^2 \]

\[ x = \frac{Q^2}{2pq} \]

Measure of momentum fraction of struck parton

Measure of resolution power

“Bjorken-x”
Saturation – gluon density increases drastically at low-x! At some point, does the density saturate? **New state of matter?**

**Q**

**S**

Matter of Definition and Frame (II)

Infinite Momentum Frame:
- **BFKL** (linear QCD): splitting functions → gluon density grows
- **BK** (non-linear): recombination of gluons → gluon density tamed

**BFKL:**

**BK** adds:

\[ \alpha_s \ll 1 \]
\[ \alpha_s \sim 1 / \Lambda_{QCD} \]

know how to do physics here?

max. density

\[ Q_s \]

\[ k_T \]

~ \[ 1/k_T \]

\[ k_T \phi(x, k_T^2) \]

- At \( Q_s \): gluon emission balanced by recombination

Unintegrated gluon distribution depends on \( k_T \) and \( x \): the majority of gluons have transverse momentum \( k_T \sim Q_s \) (common definition)

Parton Distribution Function (PDF)
What is needed experimentally?

EIC Yellow Report, Fig. 2.1

Existing Measurements with $A \geq 56$ (Fe):

Current measurements

Unexplored Territory

EIC, $\sqrt{s} = 20 - 89$ GeV, $0.01 \leq y \leq 0.95$
Lots of microscopes...and still unanswered questions?

Is there a machine that can help?
The Electron-Ion Collider (EIC)

• Deep-Inelastic Scattering machine → electron + proton (or nucleus) collisions.
• Built on the infrastructure of the existing Relativistic Heavy-Ion Collider (RHIC) facility at Brookhaven Lab, in partnership with Jefferson Lab.
  • This machine combines the functionality of HERA and RHIC.
The Electron-Ion Collider (EIC)

What is the EIC:
A machine for colliding polarized electrons with polarized protons/light-nuclei, or unpolarized heavy-nuclei.

What is new/different:
• A factor of 100 - 1000 higher luminosity than HERA \(\rightarrow\) more statistics, higher precision!
• Both electrons and protons / light nuclei polarized \(\rightarrow\) spin-dependent observables!
• Nuclear beams: d to U \(\rightarrow\) heavy-nuclei provide access to novel studies in QCD!

Data taking to start after 2030!
Intermission: Cute Animals

Julep

They (mostly) get along.

Lilu

She’s in a death metal band.
More about QCD

Universality

• QCD interactions arising from different collision systems should be universal.

Measurements from one collision system can inform studies on other systems!
More about QCD

QCD Interactions ~ PDF ⊗ high-energy parton interaction ⊗ Hadronization

high-energy parton interaction: calculable in QCD

PDFs and Hadronization: need to be determined experimentally

- Initial state: nuclear structure and parton distributions
  - How does the initial distribution of partons (PDF) affect the interaction?
    - Protons vs. nuclei?
  - How does polarization (spin) modify these distributions? → Proton spin puzzle!

- Final state: Fragmentation & Hadronization
  - How do the produced partons fragment and hadronize into the particles we measure?
  - Hadronization can aid in our understanding of confinement in QCD.
Focusing on the Initial State: Proton and Nuclear Structure
Quantifying proton structure – structure functions

Gluons manifest themselves through

- the behavior of the cross section as function of $x$ and $Q^2$
- without gluons the cross section depends only on $x$, no dependence on $Q^2 \rightarrow F_2(x)$

\[ \text{cross section} \sim \alpha F_2(x, Q^2) + \beta F_L(x, Q^2) \]

quark+anti-quark momentum distributions

Bjorken scaling

\[ F_2 \text{ and } F_L \text{ - ”structure functions”} \]

“cross section” – essentially a probability for an event.

\[ \text{DIS cross section} \times \text{luminosity} = \text{DIS event rate} \]

BUT: (e.g. number of collisions per second)

Observe strong rise of cross section with both $x$ and $Q^2$

Because of gluon-initiated processes

EIC:
- How are the structure functions modified in nuclei?
- Spin dependence?
- Protons vs. neutrons?
Neutron Structure Functions

EIC enables use of deuteron beams → the next best thing to a beam of neutrons!

- Measurements on unpolarized deuterons\(^1\) (or polarized He-3\(^2\)) at the EIC.
- Spectator proton momentum → enables selection of nuclear (p/n) configurations.
  - Extract free neutron structure function\(^3\) → Not possible elsewhere!
  - Study nuclear modifications of both nucleons in the deuteron (study in progress).

---

What about nuclei?
Nuclear Parton Distribution Functions

More data from EIC = Better constraints on nPDFs

E. C. Aschenauer, S. Fazio, M. A. C. Lamont, H. Paukkunen, and P. Zurita
So, how do we take pictures of the collisions at the EIC? What is our *microscope*?
Defining the Requirements: Yellow Report Initiative

Physics Topics → Processes → Detector Requirements

Physics Working Group:
- Inclusive Reactions
- Semi-Inclusive Reactions
- Jets, Heavy Quarks
- Exclusive Reactions
- Diffractive Reactions & Tagging

Detector Working Group:
- Tracking + Vertexing
- Particle ID
- Calorimetry
- DAQ/Electronics
- Polarimetry/Ancillary Detectors
- Central Detector: Integration & Magnet
- Far-Forward Detector & IR Integration

The EIC Users Group: EICUG.ORG
3 Years Later: The ePIC Collaboration
3 Years Later: The ePIC Collaboration

hadronic calorimeters  solenoid coils  e/m calorimeters

MAPS tracker  MPG trackers  ToF, DIRC, RICH detectors

Scattered (detected) electron

Scattered (detected) particles

Electron beam

Proton/nucleus beam

8.5 m
Overall detector requirements:

- Large rapidity (-4 < \( \eta < 4 \)) coverage; and far beyond in far-forward/far-backward detector regions

Rapidity is related to the polar angle \( \theta \) as follows:

\[ \eta = -\ln(\tan(\theta/2)) \]

This equates to \( 2.1^\circ < \theta < 90^\circ \).
Overall detector requirements:
- Large rapidity (-4 < \( \eta \) < 4) coverage; and far beyond in far-forward/far-backward detector regions

Rapidity is related to the polar angle \( \rightarrow 0 < \eta < 4 \) equates to \( 2.1^\circ < \theta < 90^\circ \) \( \eta = -\ln(\tan(\theta/2)) \)

Far-forward here means \( \theta < 2.1^\circ \) (~37 mrad)

\[ \eta = -\ln(\tan(\theta/2)) \]

3 Years Later: The ePIC Collaboration
3 Years Later: The ePIC Collaboration

Overall detector requirements:
• Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions

Rapidity is related to the polar angle → 0 < η < 4 equates to 2.1° < θ < 90° \[ η = -ln(tan(θ/2)) \]

pseudorapidity

Need detectors here!!
The Interaction Region (IR6)
Intermission: fun animal facts

- Live primarily in desert regions in North Africa and Arabian peninsula.
- Their bat-like ears radiate body heat and help keep the foxes cool.
- They have been known to jump in the air 2 feet (.6 meters) high from a standing position, and they are able to leap a distance of 4 feet (1.2 meters).
- Live in adorable colonies of around 10 foxes.
- They are omnivorous, but they prefer Tex-Mex and craft beer.
  - Okay, maybe not, but if they tried it, they’d like it.
So, the EIC seems far away...what else can we do NOW? (we are impatient, after all)
The STAR Detector

Solenoidal Tracker at RHIC
- Multi-purpose collider detector with tracking, calorimetry, and particle identification detector subsystems.

Located at Brookhaven National Laboratory in Upton, NY (Long Island). Various energies and species such as Au, Cu, U, He, deuteron, etc. Primarily Au+Au, p+p, p+Au collisions. 2.38 miles in circumference! Only polarized proton collider on earth!
Physics of RHIC – Hot and Cold QCD

Hot vs. Cold QCD – refers to temperature. All of the physics we have been talking about has been “cold”.

“Hot” QCD

• Studies of hot, dense environment formed in heavy-ion (e.g. Au+Au) collisions!
• Extreme form of QCD matter → the Quark-Gluon Plasma → a “soup” of deconfined quarks and gluons.
Physics of RHIC – Hot and Cold QCD

“Cold” QCD

RHIC Cold QCD ⇔ EIC physics

Universality!! – We are impatient, but we also need the RHIC data to fully utilize the EIC data!

Lots of un-analyzed RHIC Cold QCD data (e.g. 2017 data), and more datasets being collected NOW!

Polarized proton + proton collisions

- Proton spin (gluon contribution).

Proton + nucleus collisions

- Hints of saturation?
- Nuclear PDFs.

Ultra-Peripheral Au + Au (or p+p, p+A) collisions

- Proton spin (orbital angular momentum contribution).

Physics of RHIC – Hot and Cold QCD
Looking Forward: The STAR Forward Upgrade

- Addition of silicon tracking system and EM and hadronic calorimetry → forward rapidity coverage.
  - More coverage in x!

First data-taking run with these new components happened in 2022 – data being produced now!
Looking Forward: The STAR Forward Upgrade

- Addition of silicon tracking system and EM and hadronic calorimetry → forward rapidity coverage.
  - More coverage in x!

- **STAR Forward Upgrade**
  
  Collecting Data Now + next 3 years

  Proton spin: \( \frac{1}{2} = \frac{1}{2} \sum q \Delta q + \Delta G + L_{g,q} \)

  Lots of overlap with EIC topics!
• Leverage STAR Cold QCD program and perform studies relevant to EIC physics.

• EIC detector and physics impact studies.

2022-2025
Our understanding of the structure of visible matter in the universe!

Thank you!