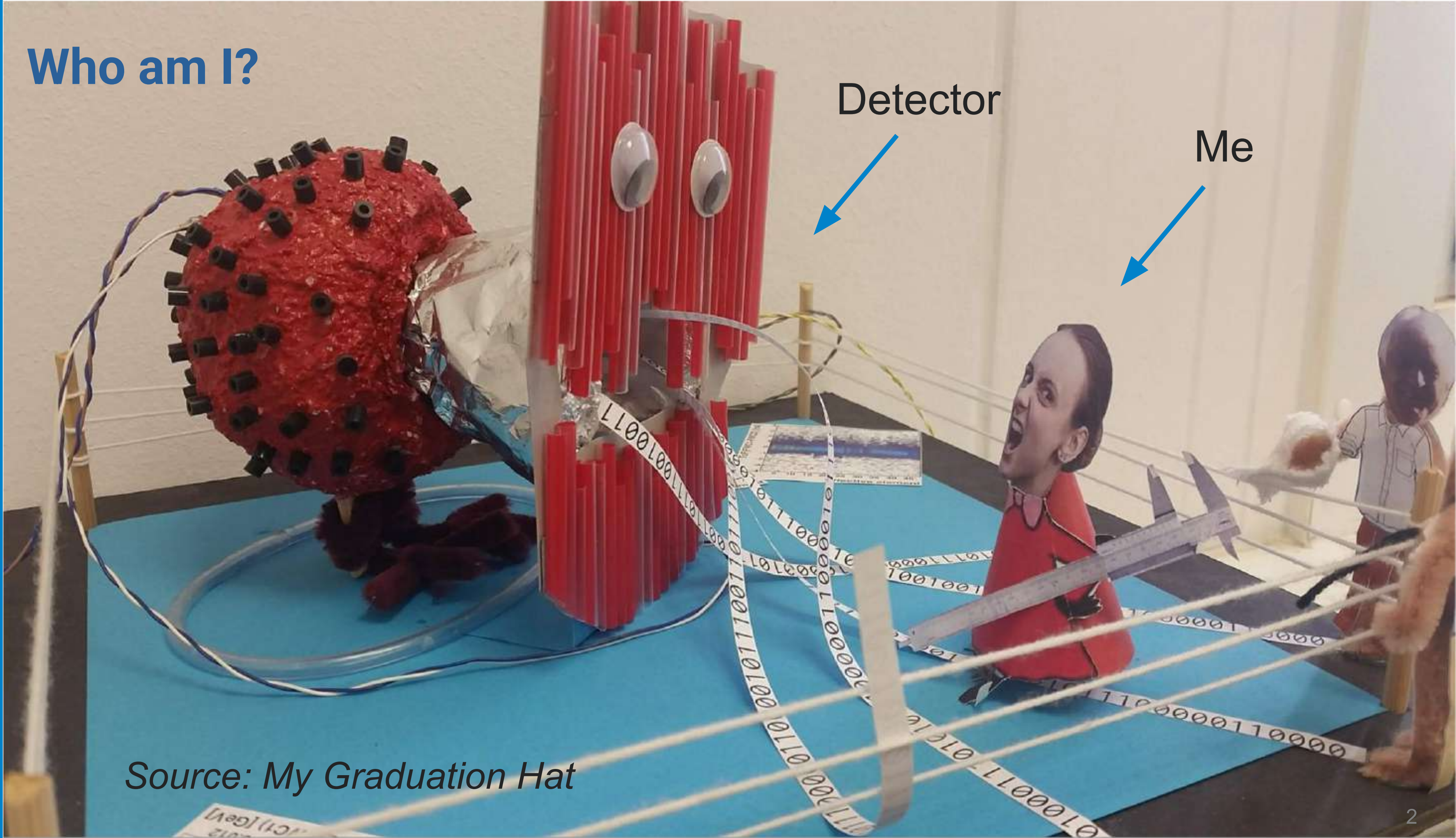
Stony Brook University, USA, June 2-13, 2024
The 2025 CFNS-SURGE Summer Workshop on the Physics of the Electron-Ion Collider

Experimental Introduction to Electron-Ion Collider Physics

Lecture 1: Probing the Structure of Matter — From Rutherford to the EIC

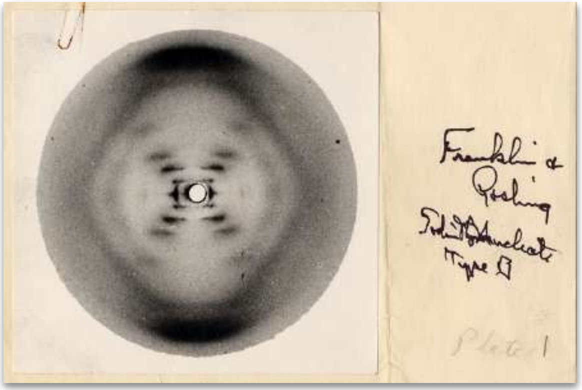
Maria ŻUREK, Argonne National Laboratory

Who am I?

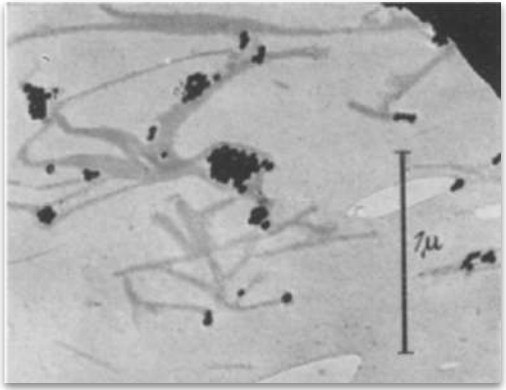


Source: My Graduation Hat

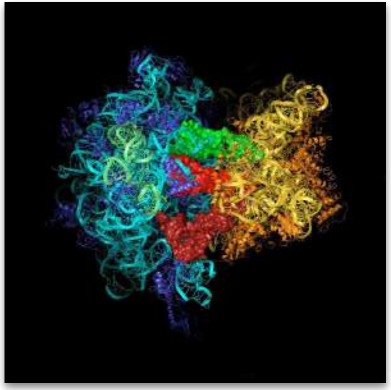
Are you an Experimentalist or Theorist?



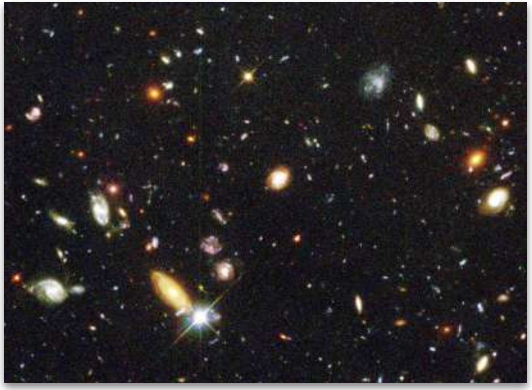
Rosalind Franklin's "Photo 51" (1952) – DNA Double Helix



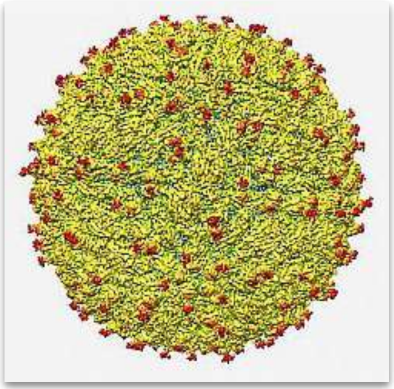
First Electron Microscope Image of a Virus (1939)



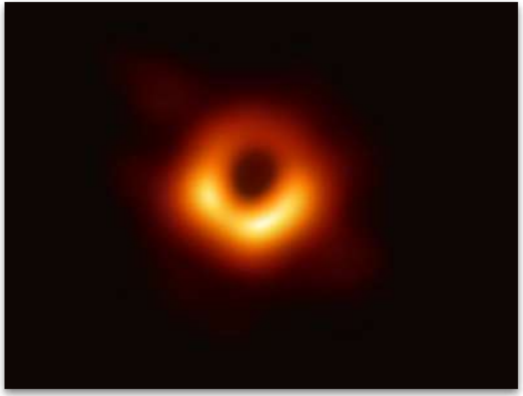
High-resolution Ribosome Structure (2000)



Hubble Deep Field Picture (1995)

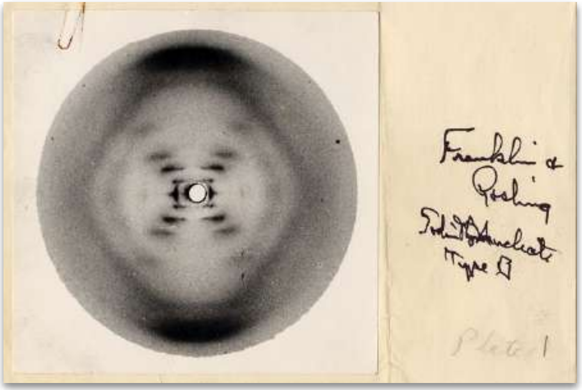


Cryo-EM Image of Zika Virus (2016)



First Image of a Black Hole (2019)

Pictures: See Bibliography in the backup



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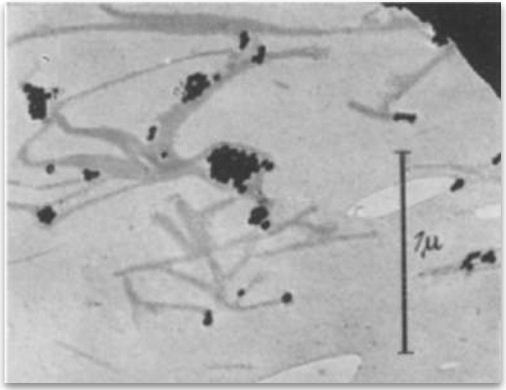

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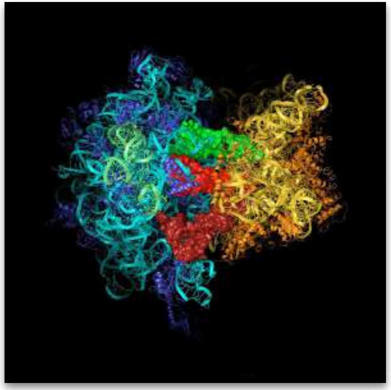
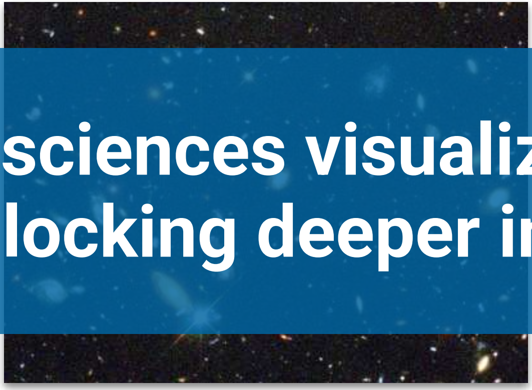


High-resolution Ribosome Structure (2000)

In sciences visualizing complex objects is key to unlocking deeper insights and advancing knowledge



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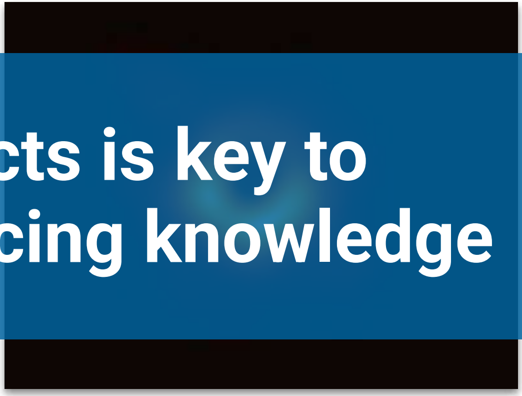


First Image of a Black Hole (2019)

Pictures: See Bibliography in the backup

Why scattering?

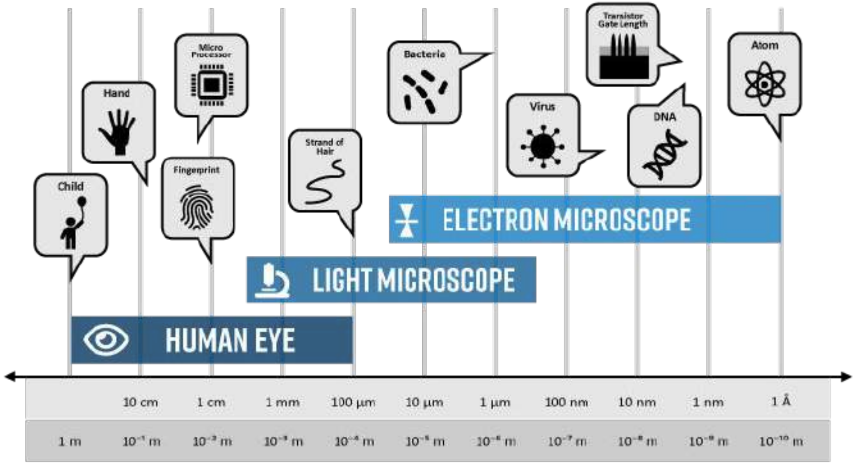
We can't use visible light to "see" inside atoms or protons: resolution is limited by wavelength

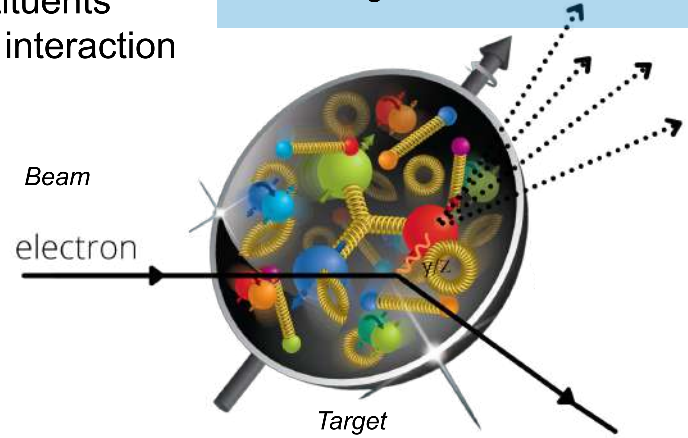
Scattering high-energy particles gives us a **quantum microscope**

The pattern and probability of deflections reveal:

- The **size and shape** of the target
- Whether it's made of **point-like or composite** constituents
- How its **internal charges and spins** respond to the interaction

Fixed Target and Accelerator Experiments





larger scattering angle → larger momentum transfer → finer resolution

Wave length: 0.01 fm (20 GeV) Resolution: ~ 0.1 fm

Plan

Today:

- How did we get to where we are? A historical journey through proton structure experiments
- What open questions remain, and how the EIC will address them

Tomorrow:

- How do we experimentally access EIC physics? (Overview + case study)
- What are the experimental requirements to make it happen?

Decades of Discovery: The Proton Revealed

But Not Yet Fully Understood

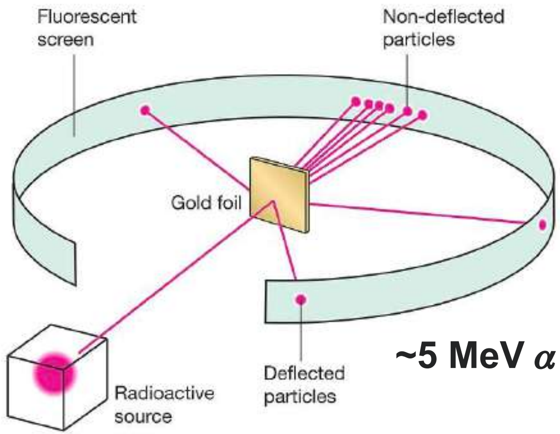
Imagine it's 1950. You're a physicist studying the proton.
What do we know about it? What is still unknown?

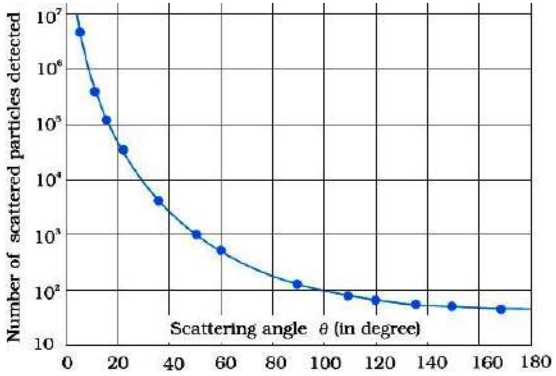
Rutherford Scattering

- Strong angular dependence → rare but significant large-angle scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{16\pi\epsilon_0 E}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

- Inconsistent with a diffuse charge distribution (e.g., Thomson model)
- Implies scattering off a **compact, point-like Coulomb center**





Main takeaway:
- The observed cross section matches a Coulomb potential from a target with radius $\lesssim 10^{-14}$ m while the atom's size is $\sim 10^{-10}$ m
  - The nucleus occupies less than 1 part in 10,000 of the atomic volume, **but carries nearly all the mass and positive charge**

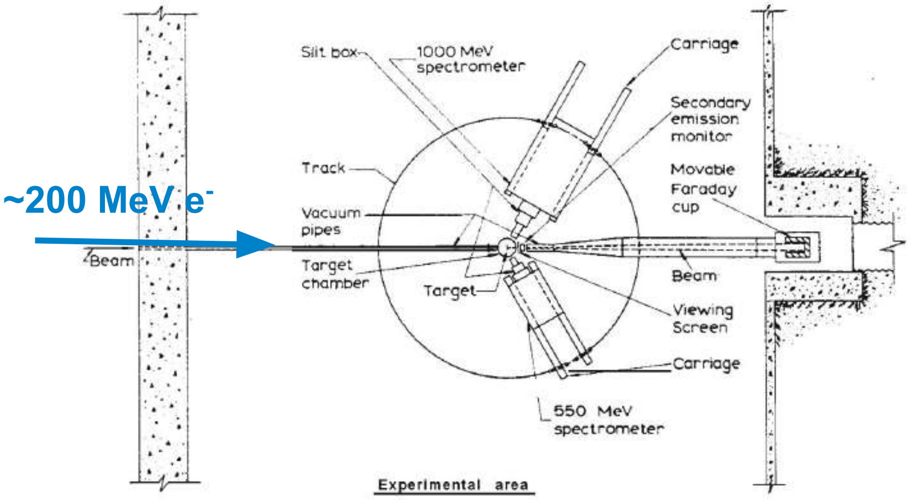
Pictures: adapted from physicsopenlab.org and Science Photo Library

M. Żurek

Electron Elastic Scattering

Why Use Electrons?

- Clean probe: electrons are **point-like**, experience only **electromagnetic interaction**



Hofstadter-era experiments used a ~200 MeV electron beam, thin targets, magnetic spectrometers, scintillators, and Cherenkov detectors to measure the angle, energy, and identity of elastically scattered electrons.

Scattering experiments 1955-1961

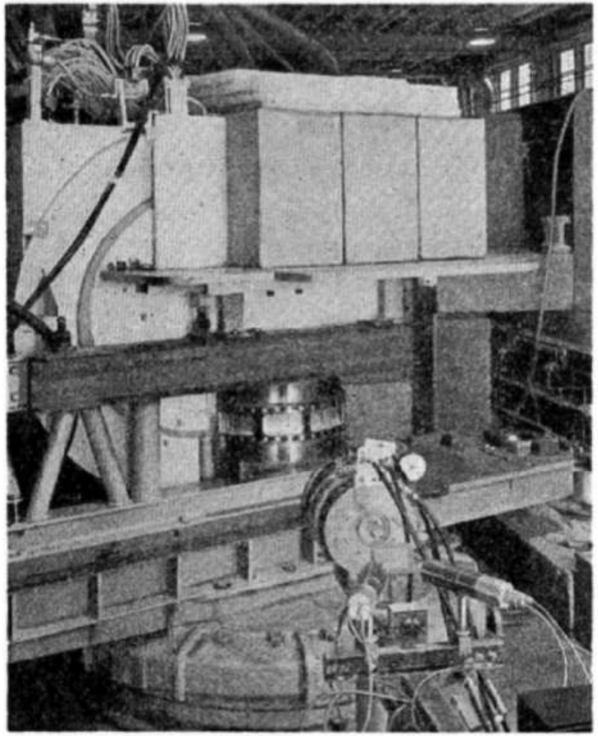
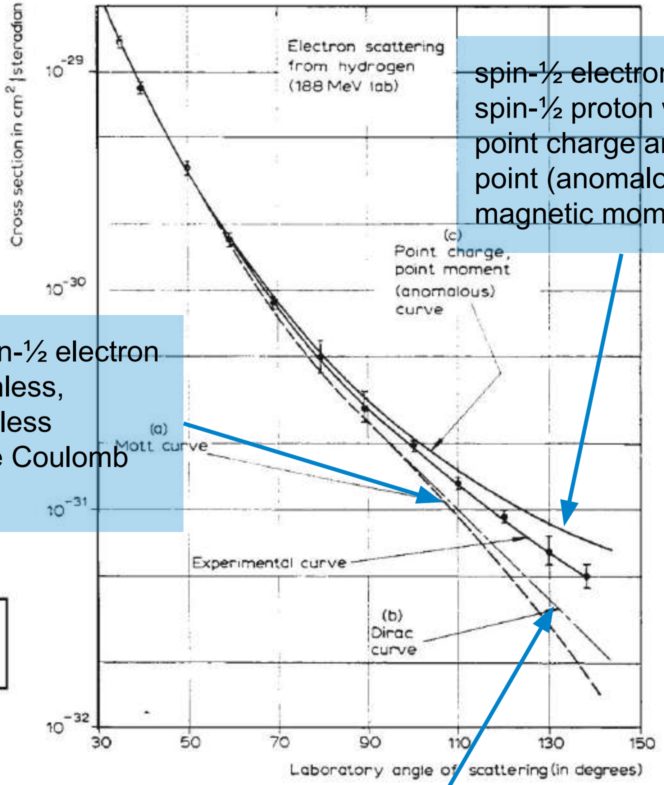


FIG. 15. The semicircular 190-Mev spectrometer, to the left, is shown on the gun mount. The upper platform carries the lead and paraffin shielding that encloses the Čerenkov counter. The brass scattring chamber is shown below with the thin window encircling it. Ion chamber monitors appear in the foreground.

Electron Elastic Scattering

Robert Hofstadter - Nobel Prize 1961

Picture: Robert Hofstadter - Nobel Lecture



spin-½ electron off spin-½ proton with point charge and point (anomalous) magnetic moment

Mott: spin-½ electron off a spinless, structureless point-like Coulomb potential

Dirac: spin-½ electron off spin-½ proton point charge with Dirac magnetic moment

Why Use Electrons?

- Clean probe: electrons are **point-like**, experience only **electromagnetic interaction**

What We Learn:

- Nucleons are **not point-like**: charge and magnetization are spread over a few fm
- The spatial structure is revealed via the **Fourier transform** of form factors
- Confirms the proton's **anomalous magnetic moment** is due to internal structure: $\mu_p \approx 2.79\,\mu_N$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\left(\frac{\theta}{2}\right)\right]$$

electric form factor   magnetic form factor

At $Q^2 = 0$: $G_E(0) = 1$, $G_M(0) = \mu_p$ (in nuclear magnetons, μ_N)
Deviations from point-like scattering in the **Q² dependence** of G_E and G_M

Why Does the Q^2 Dependence of G_E and G_M Indicate Internal Structure?

- If the proton were **point-like**, its form factors would be **constant**:
  - $G_E(Q^2)=1$
  - $G_M(Q^2)=\mu_p$
- But experimentally, both **fall with increasing Q^2**
- This means that as we probe the proton at **shorter distances (higher Q^2)**, we **see less response**: like its internal charge and magnetization are **spread out**, not concentrated at a point
- So the **fall-off in GE and GM** directly tells us that the proton has **finite size and internal structure**

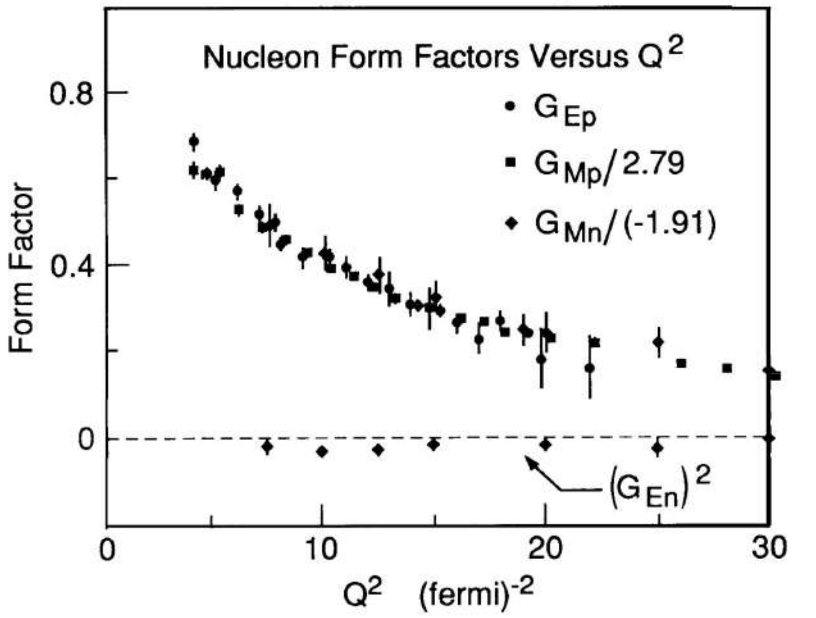
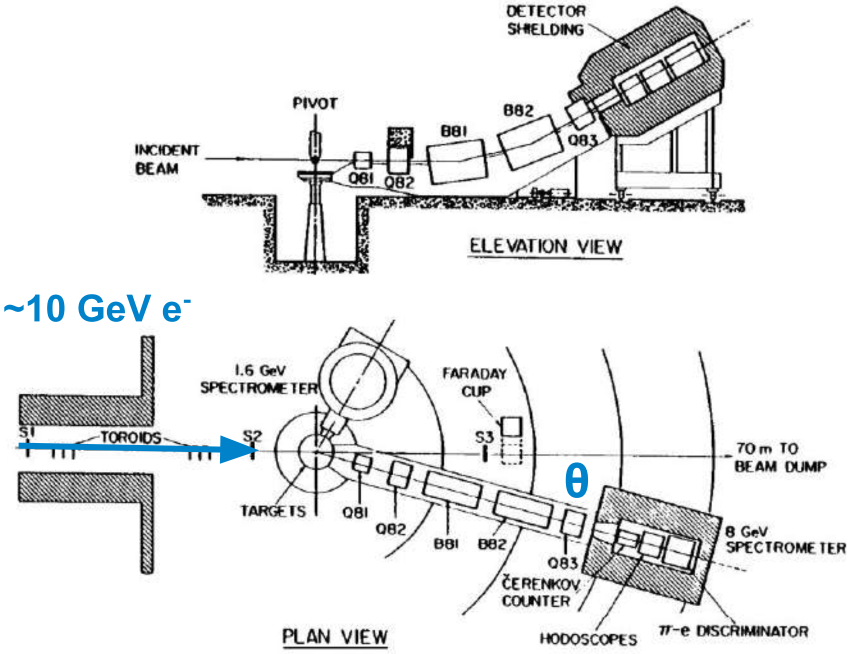


Fig. 23. Summary of results on nuclear form factors presented by the Stanford group at the 1965 "International Symposium on Electron and Photon Interactions at High Energies". (A momentum transfer of 1 GeV^2 is equivalent to 26 $Fermis^2$.)

Deep Inelastic Scattering (SLAC, 1960s)

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor - Nobel Prize 1990



SLAC DIS experiments upgraded this setup with multi-GeV beams, large magnetic spectrometers, tracking chambers, Cherenkov detectors, and calorimeters to precisely measure high-energy inelastic scattering and identify scattered electrons among backgrounds.

Pictures: Henry W. Kendall - Nobel Lecture and SLAC National Laboratory

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor - Nobel Prize 1990

Deep Inelastic Scattering (SLAC, 1960s)

- Measured cross sections at large Q^2, wide angular range

$$\frac{d^2\sigma}{dx\,dQ^2} \propto \left[F_2(x,Q^2) + 2xF_1(x,Q^2)\cdot\tan^2\left(\frac{\theta}{2}\right)\right]$$

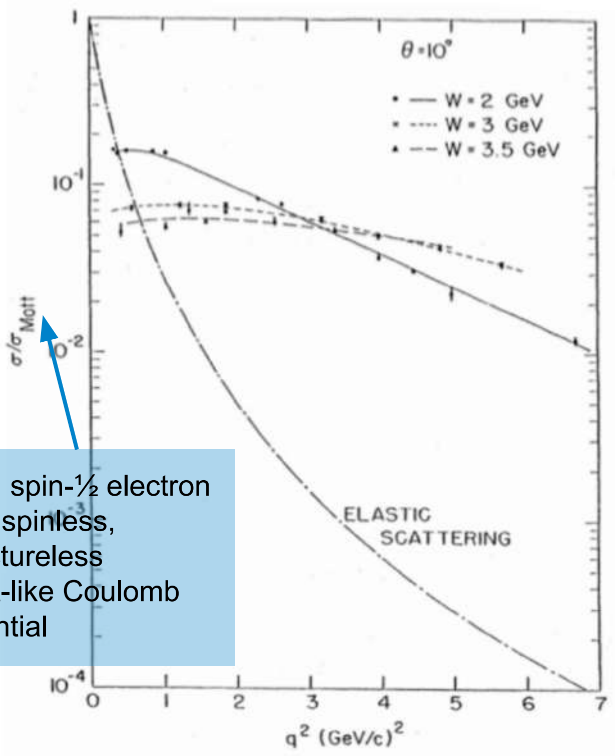
- Structure functions showed **scaling** → scattering off **point-like constituents**

- Identified as **quarks** → experimental foundation for the **quark-parton model**

Structure functions:

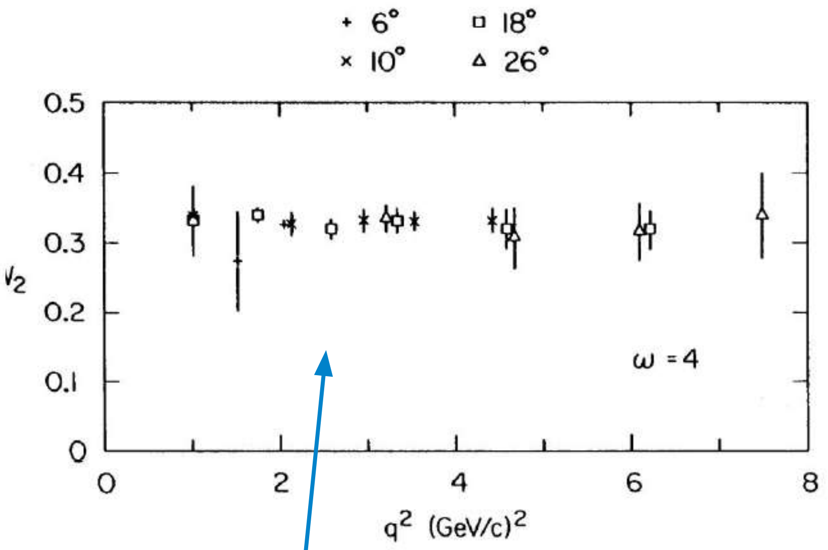
- **$F_2(x, Q^2)$:** Measures momentum distribution of quarks (both quarks and antiquarks), weighted by their charge squared
- **$F_1(x, Q^2)$:** Related to the transverse response to the virtual photon

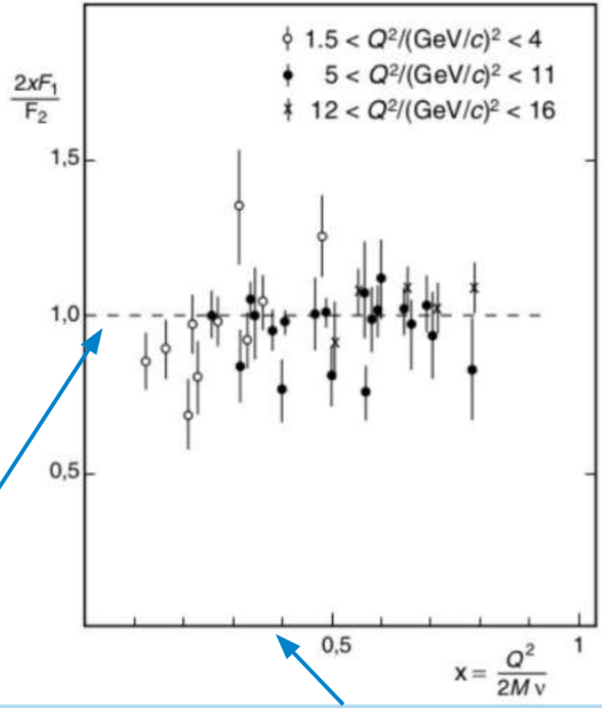
Early data on DIS from the SLAC-MIT experiment PRL23(1969)935



Mott: spin-½ electron off a spinless, structureless point-like Coulomb potential

Quarks and the Emergence of Scaling





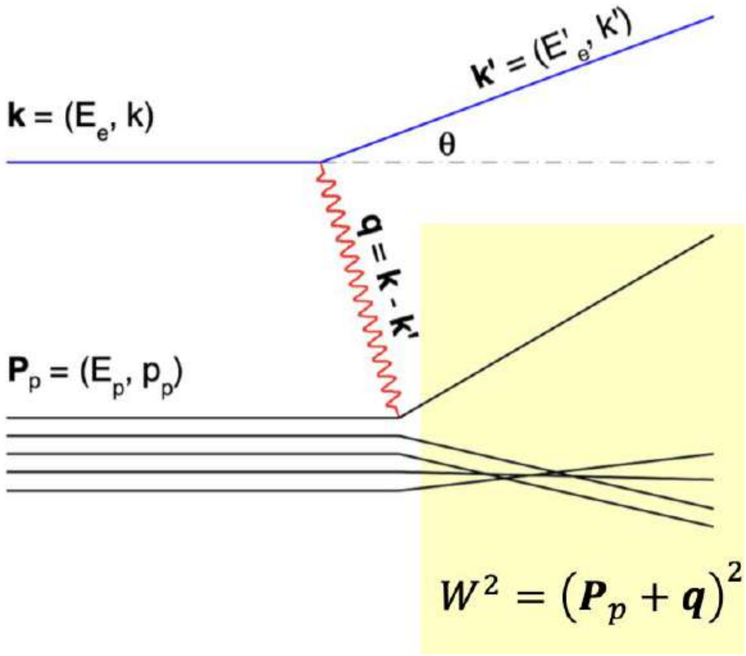
Experimental result:

- At large Q^2, F_2 depends mostly on x:
  $\mathbf{F_2(x, Q^2) \approx F_2(x)}$, this behavior is called **scaling**
- Callan–Gross relation (for spin-½ quarks):
  $\mathbf{F_2(x) = 2x\, F_1(x)}$

Bjorken variable: $x = Q^2 / (2M\nu)$
Interpreted as the fraction of the proton's momentum carried by the struck quark
ν = energy transferred to the proton in the lab frame

Pictures: Henry W. Kendall - Nobel Lecture

Kinematics Refresher



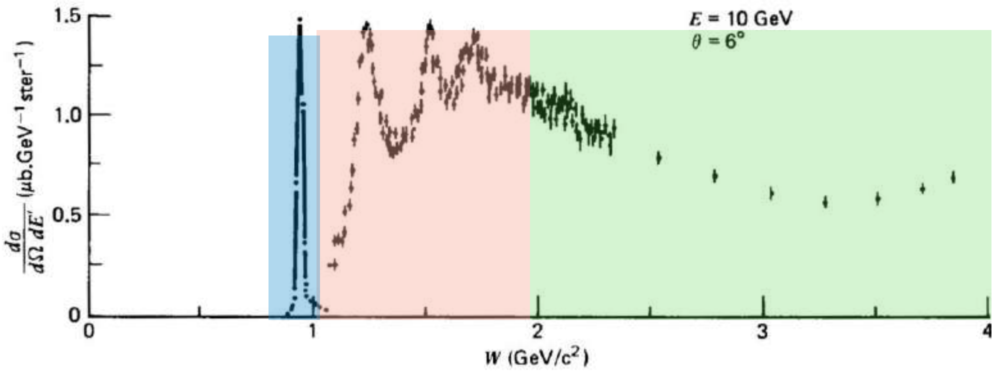
Key variables:

- **Momentum transfer:** $q = k - k'$
  So $\mathbf{Q^2 = -q^2}$ = momentum transfer squared (resolution scale)
- $\mathbf{\nu = E_e - E_e'}$ = energy transferred to the proton
- $\mathbf{x = Q^2 / (2M\nu)}$ = Bjorken-x → momentum fraction of the struck quark
- $\mathbf{y = \nu / E_e}$ = inelasticity (how much energy is transferred)
- $\mathbf{W^2 = M^2 + 2M\nu - Q^2}$ = invariant mass of the hadronic system

Full kinematics can be determined from either:

- Measured values of: E' and θ: *Experimentally easy to understand*
- Any two of: x, y, Q^2: *Lorentz invariant*   Related by: $\mathbf{Q^2 = xys}$

Kinematics Refresher



Results from SLAC (elastic peak /8.5)

Elastic peak: **W=M**, **x=1** (proton doesn't break up: **ep→ep**)

Resonances: **$W=M_R$**, **$1/x=1+(M_R^2-M^2)/Q^2$**

There is also some non-resonant background in the resonance region

Continuum' or 'inelastic region': **W>~1.8 GeV** complicated multiparticle final states resulting in a smooth distribution in **W**

Charmonium and bottonium resonances at W~3 and 9 GeV

Gluons and Scaling Violations

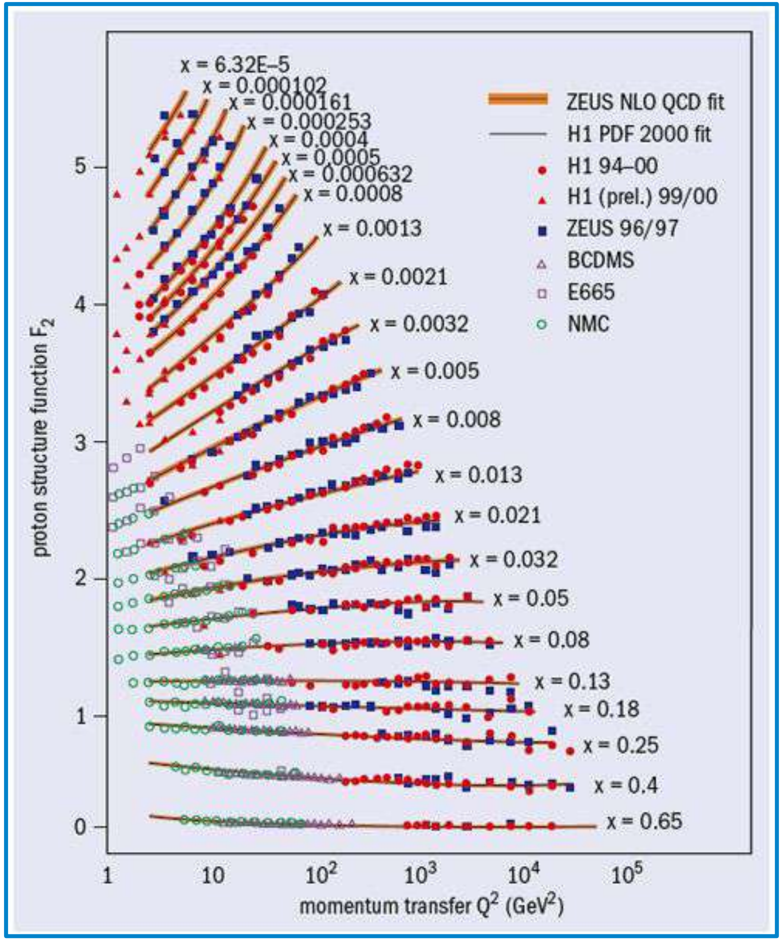
What we observe:

- Small but clear **Q^2-dependence** of F_2
  → **Scaling is violated**
  → A sign of **QCD dynamics** at play

Why it happens:

- Quarks **radiate gluons** as Q^2 increases
- This changes the **probability distributions** of quarks → i.e., PDFs evolve with Q^2

Interpretation: Scaling violations give us indirect access to **gluon distributions** through QCD evolution (DGLAP)



Example PDF fit: CTEQ14NNLO

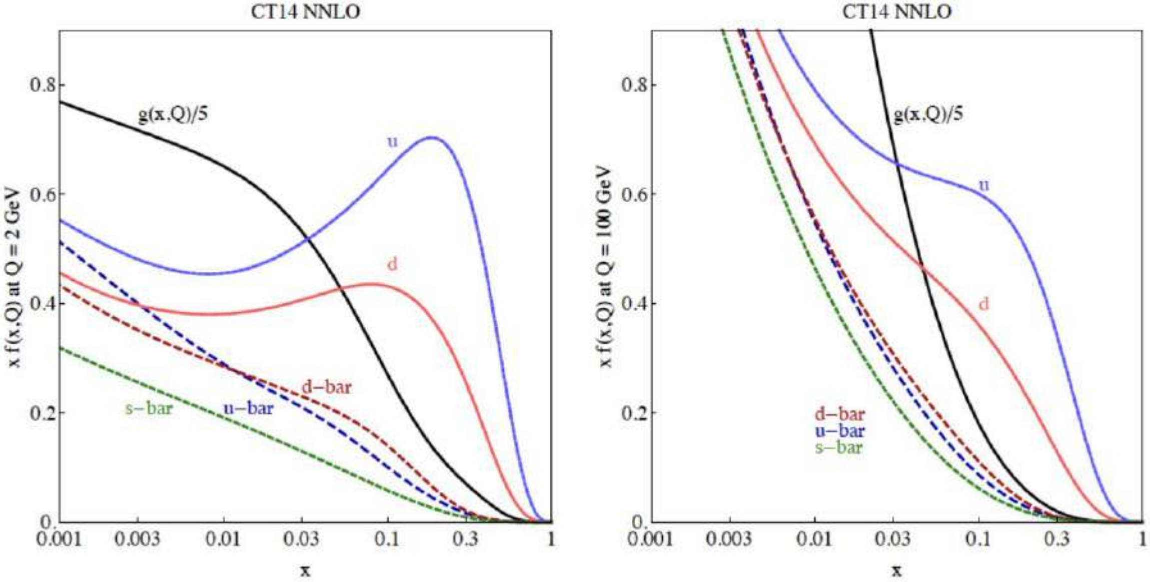


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \overline{u}, d, \overline{d}, s = \overline{s}$, and g.

Q = 2 GeV

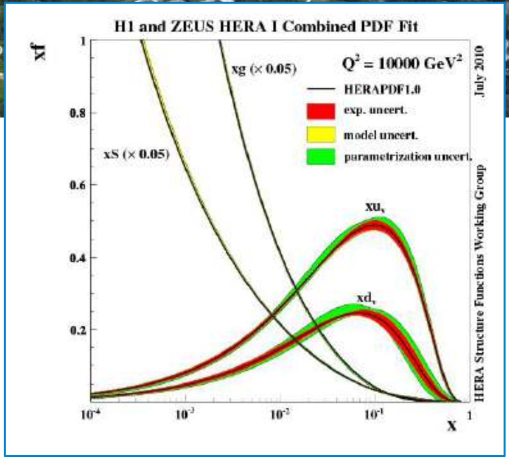
Q = 100 GeV

HERA Legacy

HERA (DESY, 1992–2007) collided electrons with protons at $\sqrt{s} \approx 300$ GeV

Extended the measured range of **x** and **Q²** by orders of magnitude

- Revealed the **sharp rise of F_2** at low **x**, especially as Q^2 increased
- Scaling violations at low x driven by **gluon dynamics**
- **Confirmed DGLAP evolution** and gluon-dominated behavior at small x
- Provided global fits used to extract modern **PDFs**
- And much, much more: heavy flavor PDFs, diffraction, jets, low-x physics…
- Laid the groundwork for future precision studies at the **EIC**

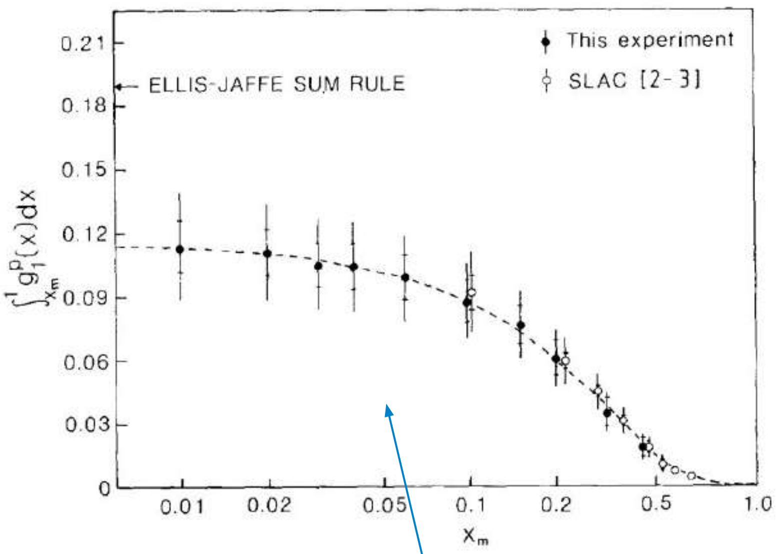


Picture: https://www.desy.de/h1zeus/combined_results/

The Proton Spin Crisis → Puzzle

- In the naive quark model, proton spin = sum of quark spins
- But the 1988 EMC experiment found that **quarks carry only ~30%** of the proton's spin
- This result shocked the community → became known as the **"proton spin crisis"**
- Measuring each term requires different experimental probes: **still an open puzzle**
- **EIC will play a central role** in resolving it

J. Ashman et al, Nucl. Phys. B328 (1989) 1



$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\, \Delta q(x)$$

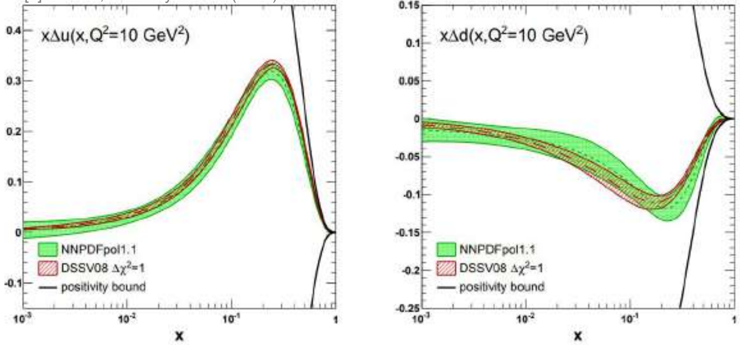
In (LO QCD) Quark Parton Model

Quark helicity distribution

Longitudinal Spin Structure - Where Are We?

u and d quark helicities

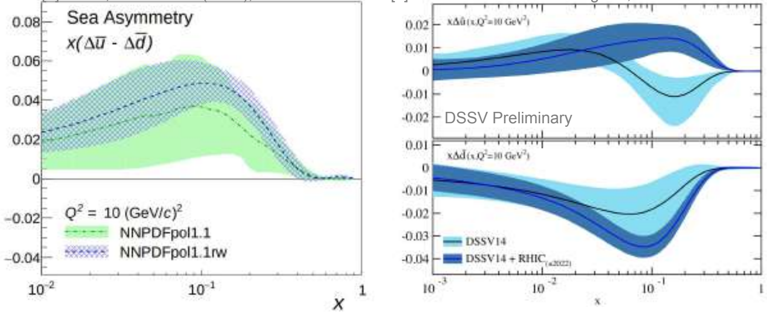
[1] NNPDF, Nucl.Phys.B 887 (2014) 276-308



Sea-quark polarization asymmetry

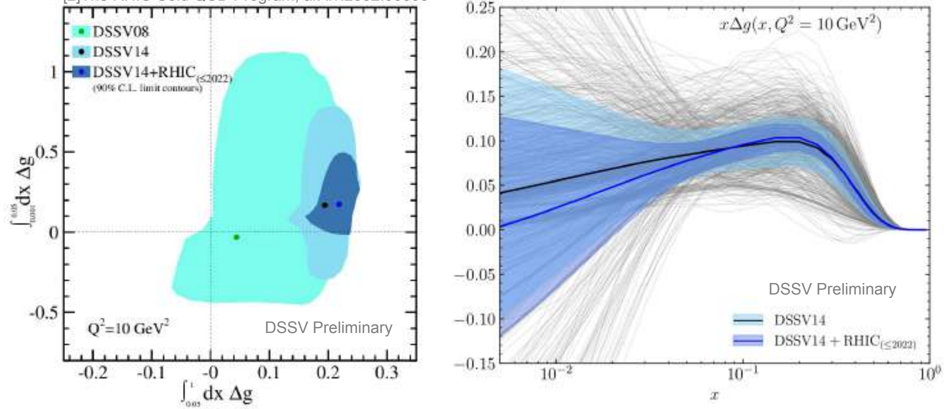
[3] STAR, PRD RC 99 (2019), 051102

[2] The RHIC Cold QCD Program, arXiv:2302.00605



Gluon Helicity

[2]The RHIC Cold QCD Program, arXiv:2302.00605



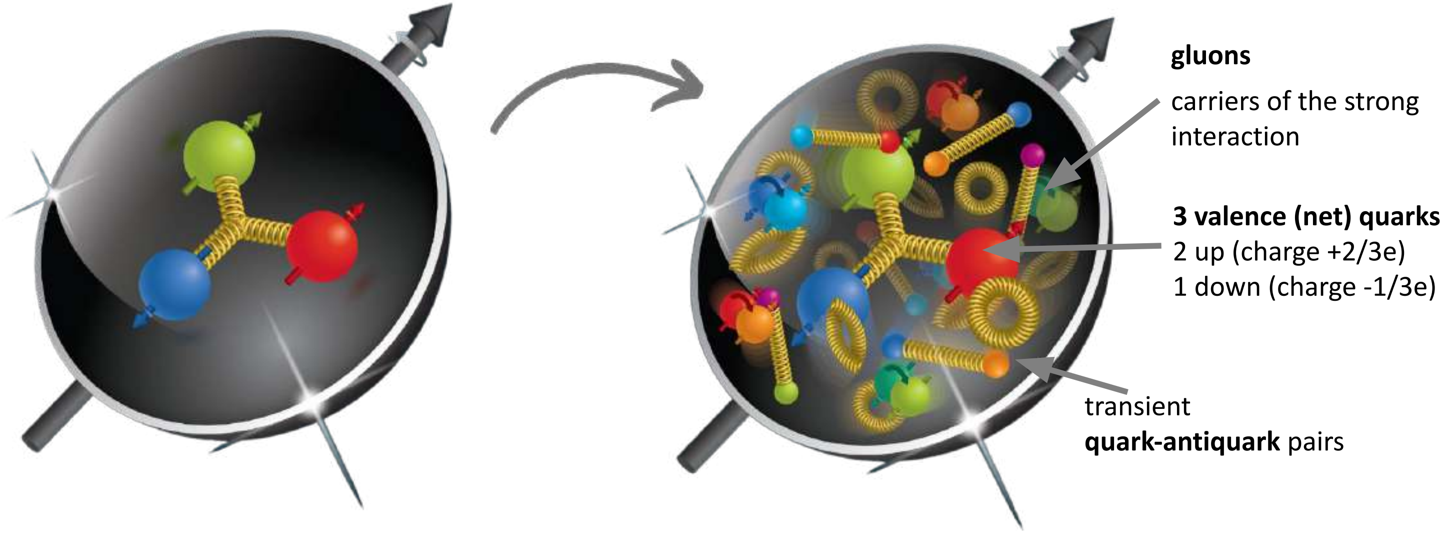
	NNPDF1.1[1]	DSSV08[1]
x	(0.001, 1)	
$\Delta\Sigma$	$+0.25 \pm 0.10$	$+0.366^{+0.042}_{-0.062}\ (+0.124)$

	DSSV14 + RHIC(2022)[2]	
x	(0.001, 0.05)	(0.05, 1)
ΔG	0.173 ± 0.156	0.218 ± 0.027

What We've Learned About the Proton (Pre-EIC)

- **Rutherford scattering** revealed the atomic nucleus
- **Elastic electron scattering** showed the proton is not point-like
  → charge and magnetization are spatially distributed
- **Deep Inelastic Scattering** revealed point-like **quarks** inside the proton
  → confirmed by **scaling** and **Callan–Gross relation**
- **Quarks carry fractional electric charges** (e.g. $+\frac{2}{3}$, $-\frac{1}{3}$): inferred from DIS and confirmed by neutrino scattering
- **Scaling violations**: presence of **gluons**, described by **QCD**
- **Structure functions** like F_2 led to the development of **Parton Distribution Functions (PDFs)**
- **EMC effect** showed that quark distributions are **modified in nuclei** — still not fully understood
- **HERA** mapped PDFs across a wide x–Q^2 range and exposed low-x gluon dominance
- **Proton spin puzzle**: quarks carry only ~30% of the total spin
  → Spin decomposition remains an open challenge

The Evolving Understanding of the Structure of the Proton



Protons and nuclei **gain their fundamental properties**, like mass and spin, from the **intricate interactions between quarks and gluons** within this complex system

What We’ve Learned About the Proton (Pre-EIC)

- **Rutherford scattering** revealed the atomic nucleus
- **Elastic electron scattering** showed the proton is not point-like
  → charge and magnetization are spatially distributed

📌 This is not a complete list, but it highlights how scattering has revealed the proton’s inner landscape

📌 3D pictures of gluons remain largely uncharted territory as well as an understanding of emergent properties of the proton and nucleus like spin and mass

- **HERA** mapped PDFs across a wide x–Q^2 range and exposed low-x gluon dominance
- **Proton spin puzzle**: quarks carry only ~30% of the total spin
  → Spin decomposition remains an open challenge

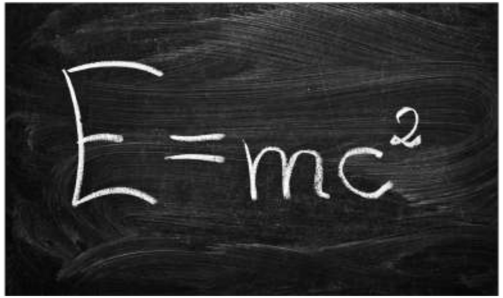
What do you think is still unknown about the proton, or what mystery should the EIC help solve?

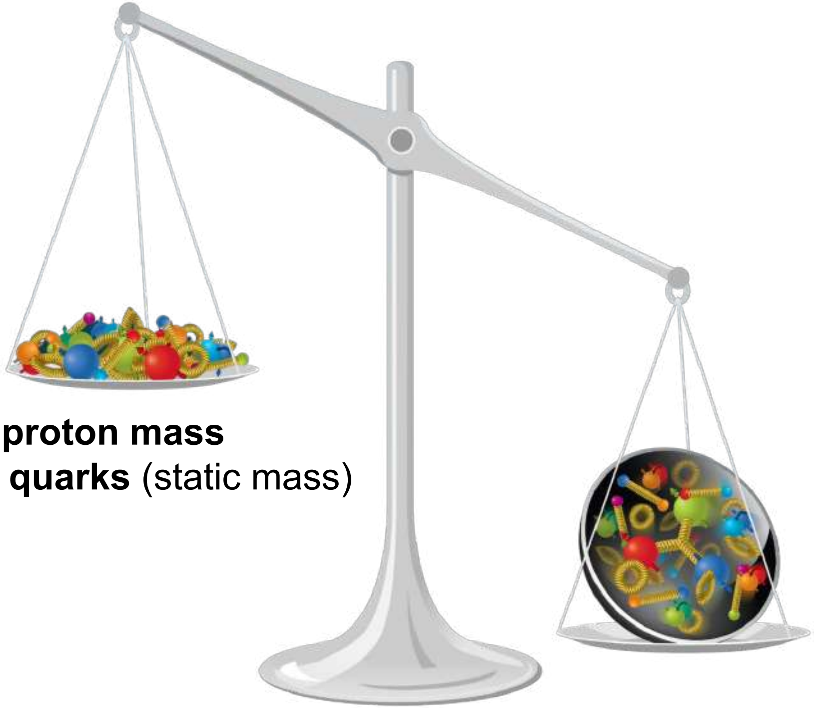
(Selected) Open Questions that EIC will address

How do Protons and Neutrons Acquire Mass?

Gluons have no mass and **quarks are nearly massless**, but protons and nuclei are heavy, making up most of the visible mass of the Universe

Where does the mass of the visible world come from?





<1% proton mass from quarks (static mass)

99% from interactions

Our mass arises from the energy of the strong force between quarks and gluons!

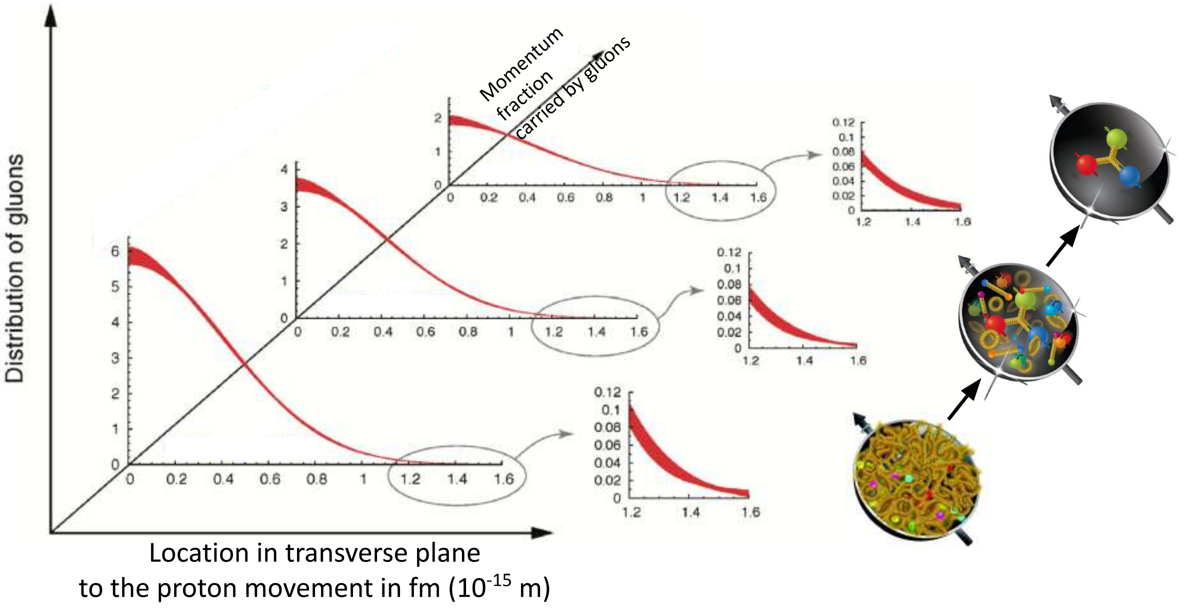
Pictures: adapted from Brookhaven National Laboratory

3D Mapping of Gluons Inside Matter

EIC will provide the **first ever 3D images of gluons inside protons:**

- How do gluon interactions contribute to the **proton's mass**?
- How do they mediate the forces that **bind quarks together**?

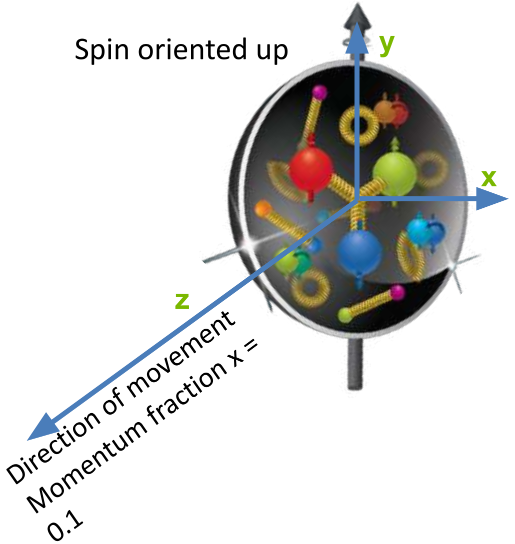
- Analogous to how the discovery of DNA's double helix unveiled the structure and organization of genetic information

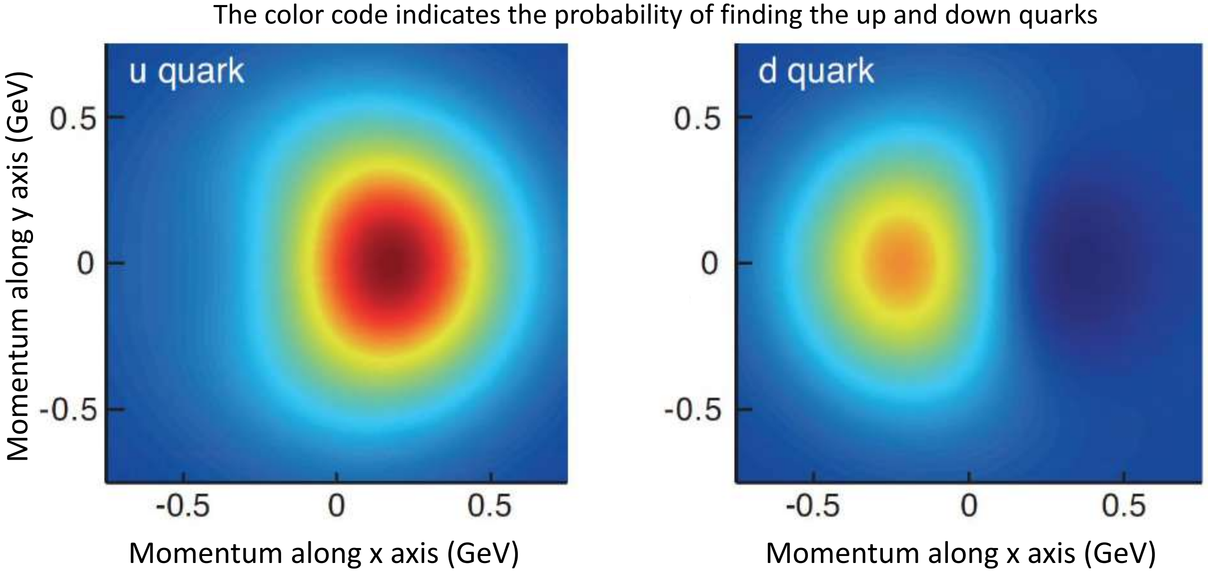


EIC will **3D map gluons inside protons** using special reactions that keep the proton intact and produce a quark-antiquark bound state

Motion of Gluons and Quarks Inside the Proton

The EIC will create the first 3D map of gluon and sea quark motion inside the proton, revealing their correlation with the proton's spin.

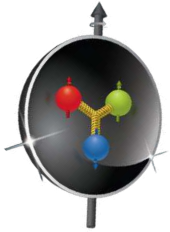




Current Understanding: Existing 3D maps only illustrate the motion of quarks, leaving the dynamics of gluons and sea quarks completely unexplored

Pictures: adapted from Brookhaven National Laboratory and EIC White Paper

Unraveling the Mystery of the Origin of the Proton Spin



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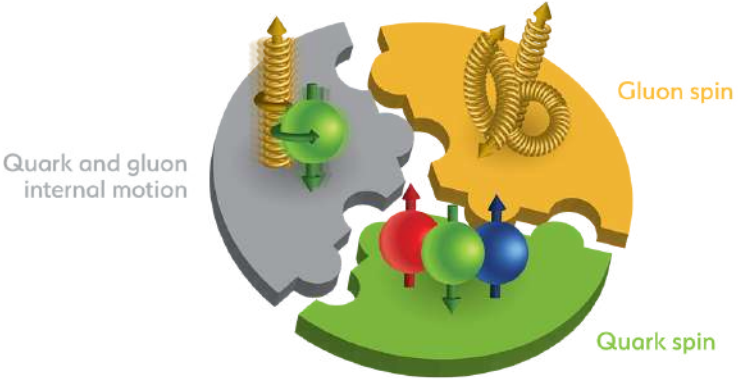
Proton Spin Puzzle



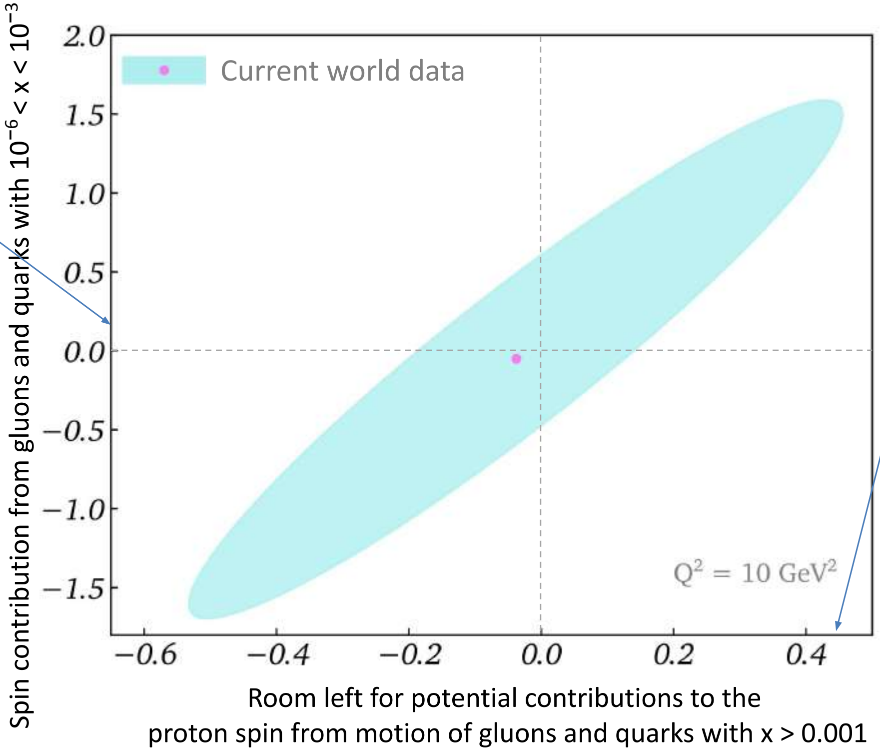
After decades of experiments: **quark spins account for only about 30%** of the proton's spin

We now know that **quarks, gluons**, and **their motion** all contribute, but the full picture remains elusive

Origin of the Proton Spin - Unknown Components

How much do the **spins of quarks and gluons very "deep" inside the proton** contribute to its spin?

Massive uncertainty range from -300% to +300% of the total proton spin!



How much does **the motion of quarks and gluons** contribute to the proton's spin?

Close to zero—but with a huge uncertainty ranging from -100% to +80% of the total proton spin!

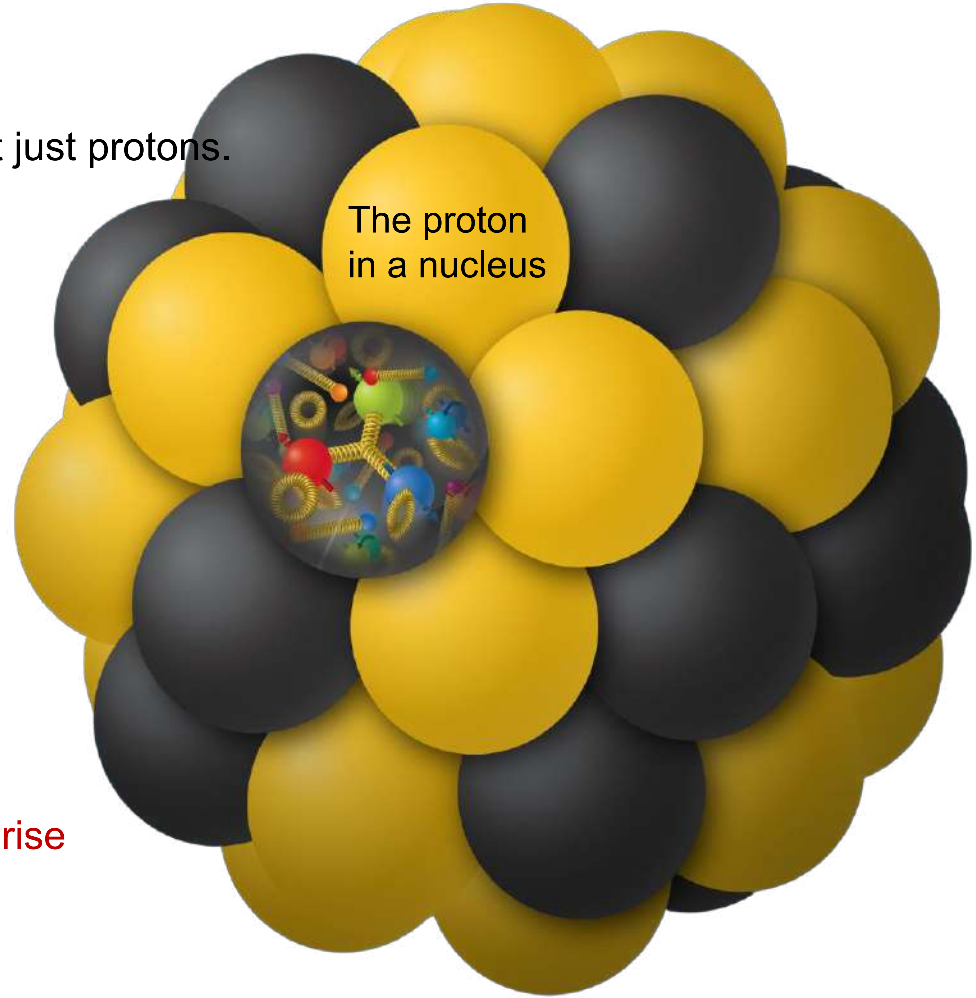
Pictures: adapted from arXiv:2007.08300

Heart of Nuclear Matter

We are made of atoms, with heavier nuclei, not just protons.

The proton (1980s)

The proton (2020s)



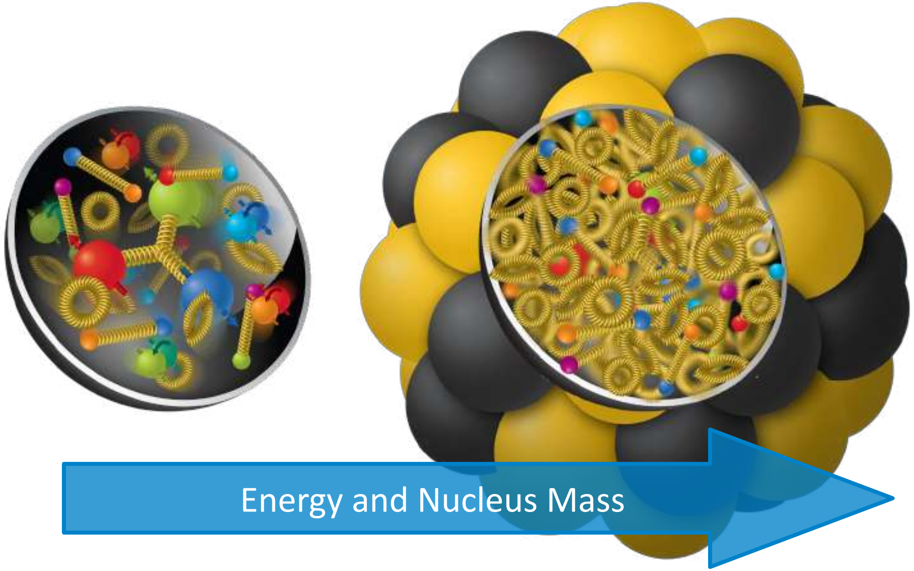
How does a high-density nuclear environment affect the behaviors of quarks and gluons?

The EIC will provide a complete view of the nucleus with insights into interactions that give rise to the forces binding protons and neutrons together in nuclei

Pictures: adapted from Brookhaven National Laboratory

New State of Gluonic Matter

- High-energy protons are packed with **increasing numbers of gluons**
- At extreme densities, gluon multiplication halts, **giving rise to a new state of matter**—this is gluon saturation
- **Heavy ion beams** at the EIC are key to creating the extreme conditions needed to study and **magnify this effect**



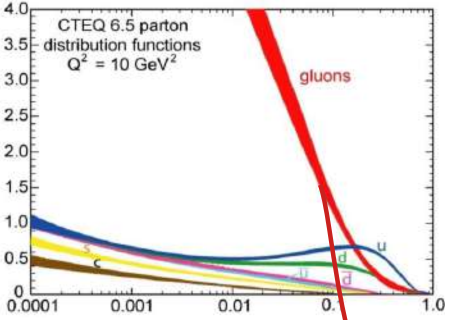
The EIC will probe the unexplored dense gluon environments, potentially unveiling new states of matter and deepening our understanding of the fundamental forces that bind everything in the visible Universe

Pictures: adapted from Brookhaven National Laboratory

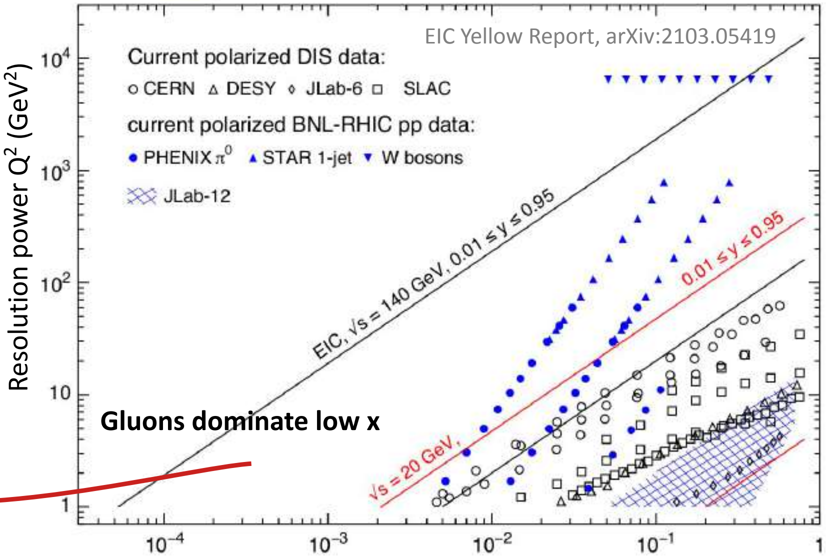
Probing Uncharted Territory

Unprecedented Access to Nucleon and Nucleus Structure

Quarks and gluons momentum fraction times their density inside the proton



Parton momentum fraction x



Parton momentum fraction x

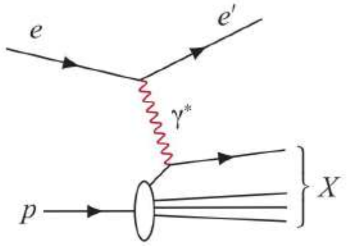
Larger center of mass energy

Larger center of mass energy and luminosity

Pictures: adapted from Brookhaven National Laboratory

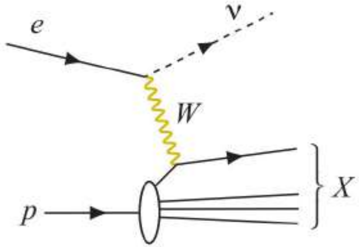
To be continued…

Experimental Access EIC Physics: how and what do we need?



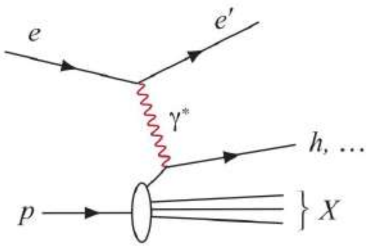
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



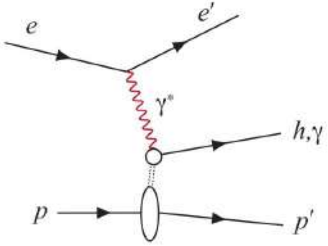
Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)



Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron



Deep Exclusive Processes

- Detection of all particles in event

Parton Distributions in nucleons and nuclei

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

Audience Q&A

Backup

Callan–Gross Relation

What it is:

- In the naive parton model with spin-½, massless, non-interacting quarks:

$$F_2(x) = 2xF_1(x)$$

Why it holds:

- Only **transverse virtual photons** interact at leading order
- **Longitudinal photons (helicity 0)** can't be absorbed without quark spin flip
- **Massless quarks can't flip helicity** → No longitudinal contribution

Implication:

- Longitudinal structure function: $F_L = F_2 - 2xF_1 = 0$

Key Takeaway:

The Callan–Gross relation is a signature of **spin-½ quarks** behaving as free particles at high energies. Deviations from it probe QCD effects and quark-gluon dynamics.

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Pictures on Slide 2

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