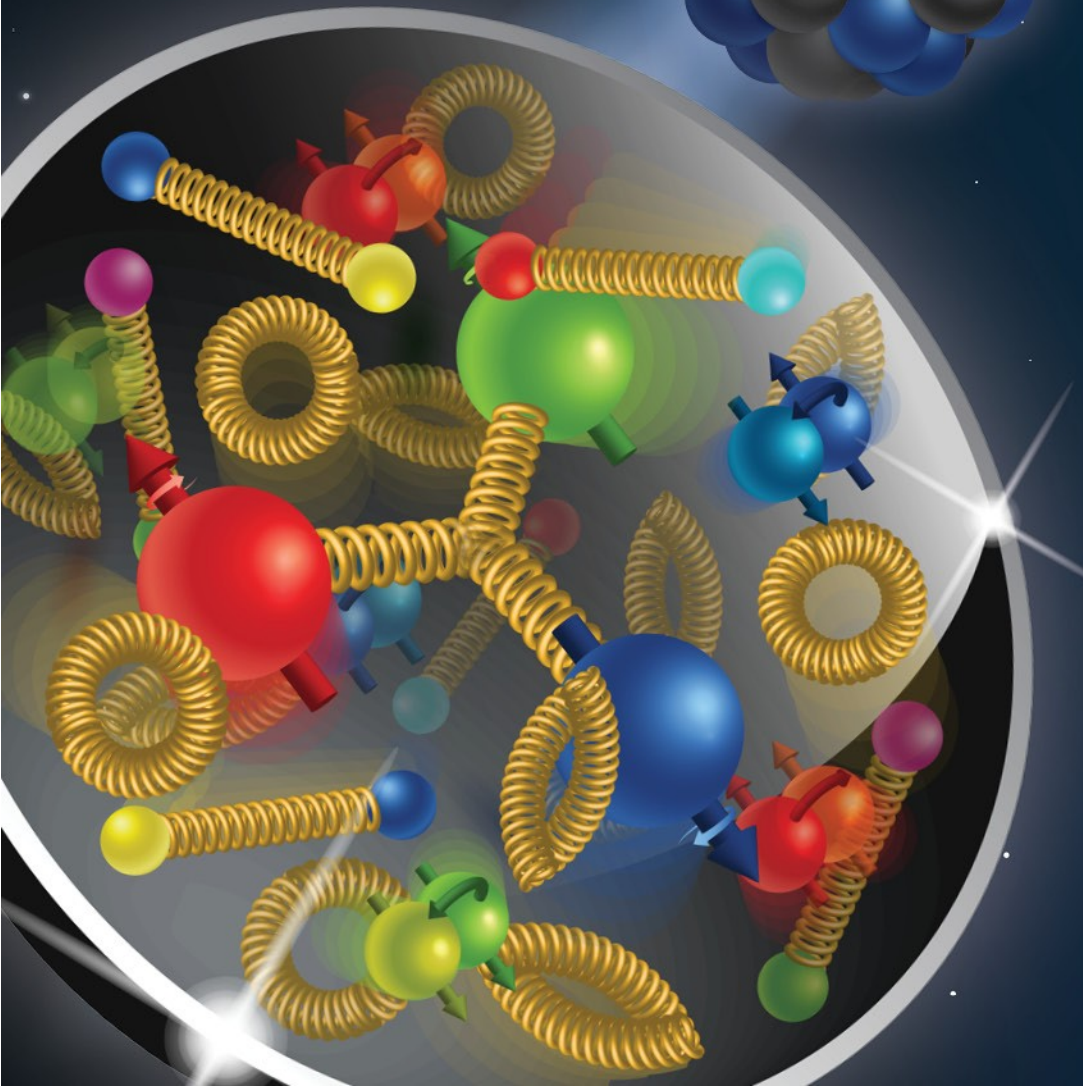
EIC Resource Review Board Meeting, Stony Brook
April 3-4, 2023



Shedding Light on Visible Matter: An Overview of the EIC Science

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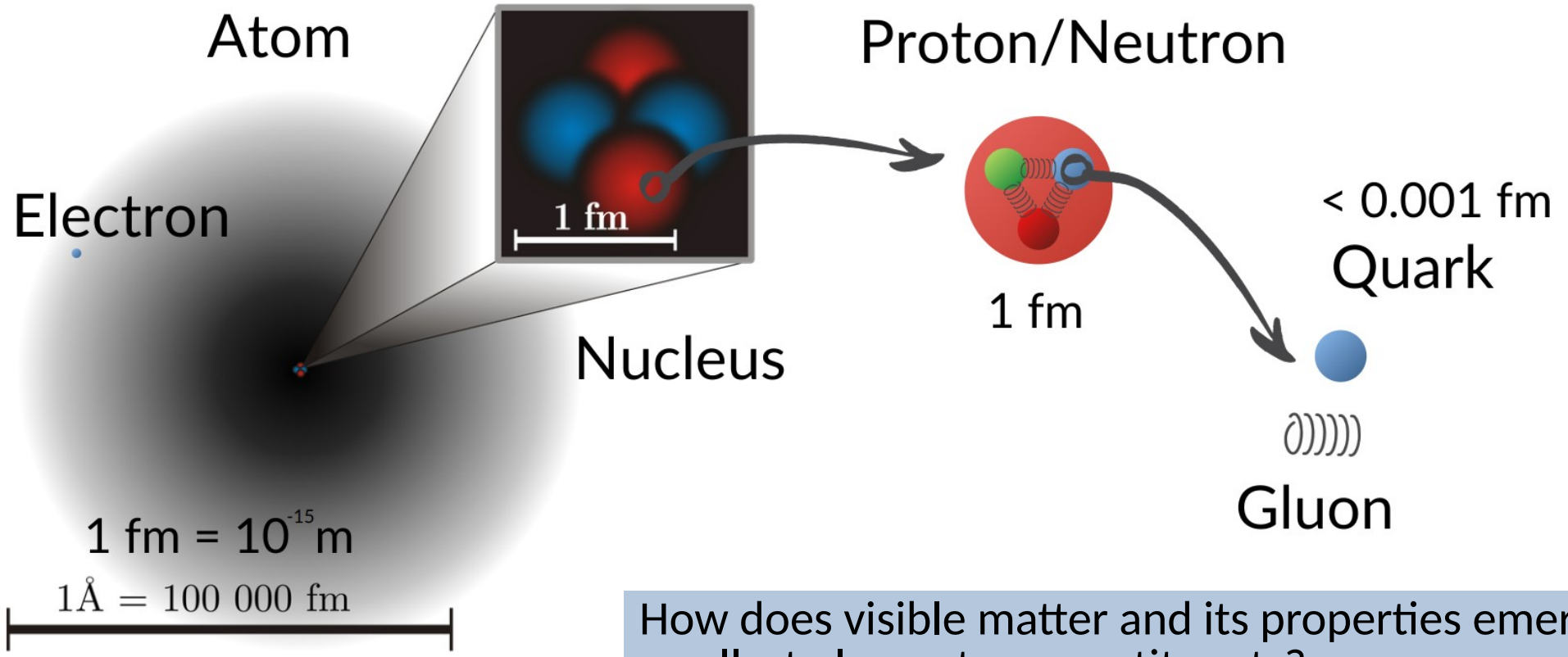
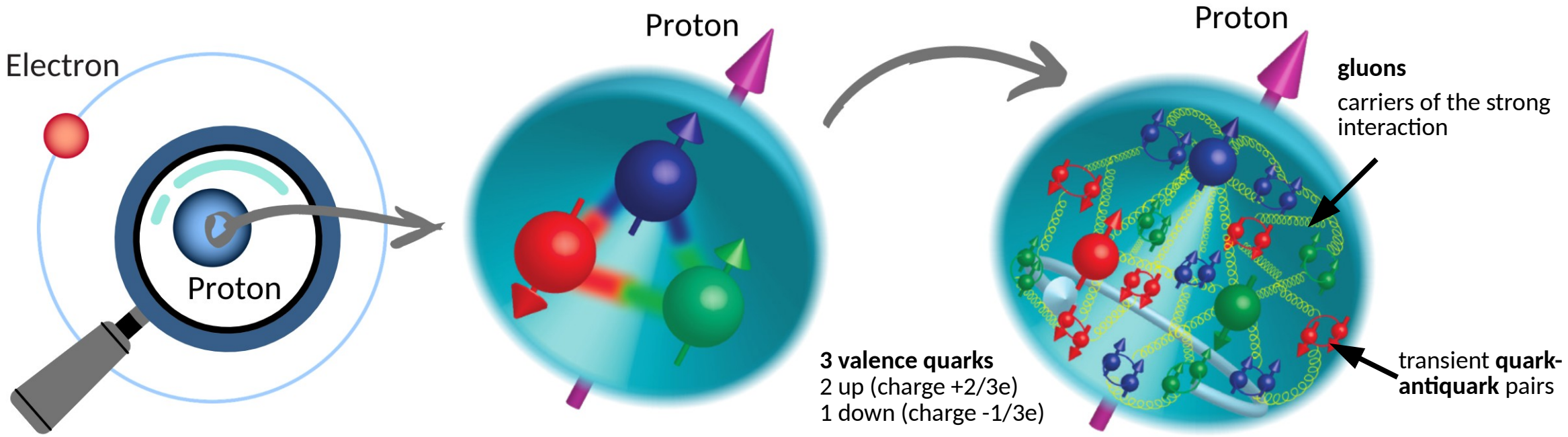
Exploring the Structure of Visible Matter: Nuclear Femtoscopy



How does visible matter and its properties emerge from the smallest elementary constituents?

EIC: *Understanding the Glue that Binds Us All*

The Evolving Understanding of the Structure of the Nucleon



The theory that describes interactions between quarks and gluons (partons): **Quantum Chromodynamics**

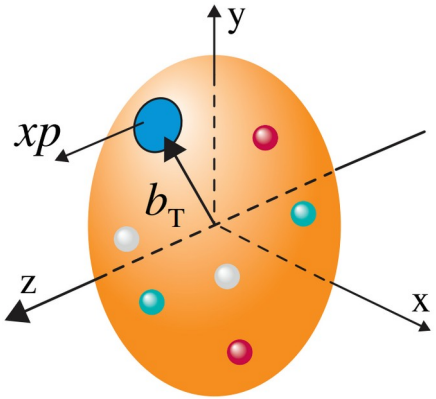
- The *color* force gets stronger at large distances → quarks and gluons can not be found in isolation
- At very small distances (large energies) quarks interact weakly and are nearly free

The observed **properties of nucleons and nuclei**, such as mass and spin, **emerge** out of this complex system of interacting quarks and gluons

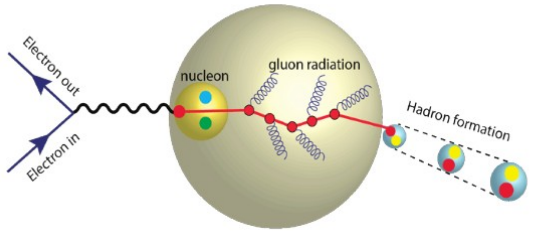
The EIC aims to reveal the internal structure of the proton and nuclei, comparable to our understanding of the electronic structure of atoms that drives modern technologies

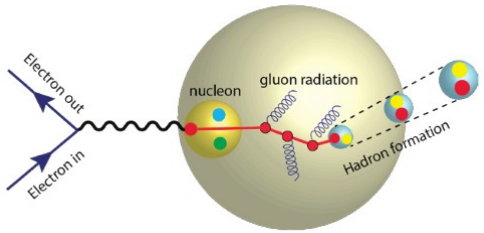
Peering into the Heart of Matter

The Physics Quest of the EIC

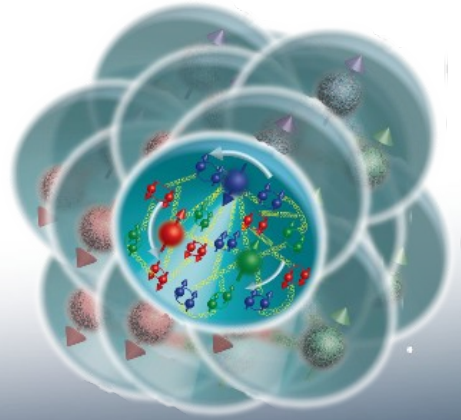


- How do the **nucleon properties like mass and spin emerge** from them and their interactions?
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?





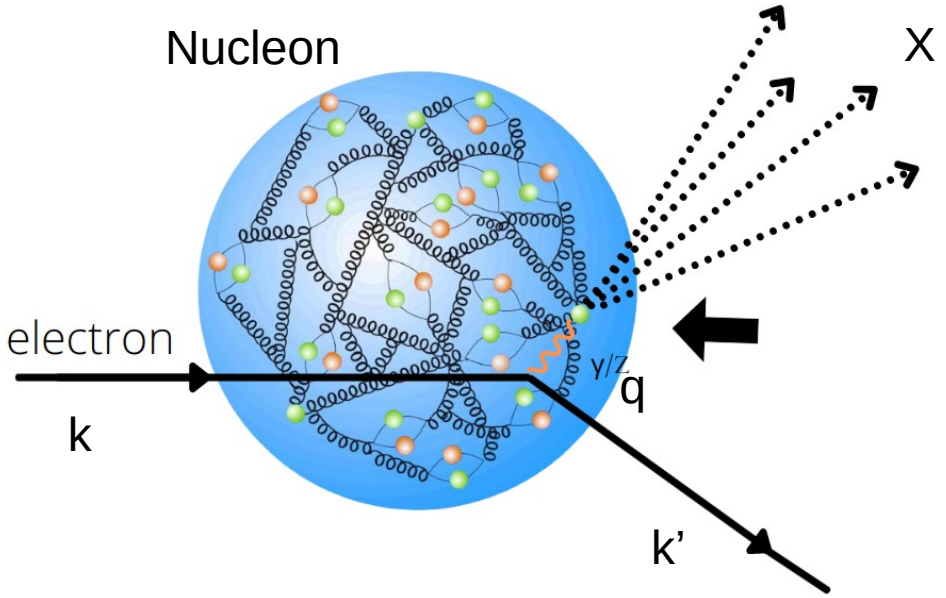
- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium? And how do the confined hadronic states emerge from these quarks and gluons?
- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?



- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?
- Is there a **saturation point** for the density of gluons in nuclei at high energies, and does this lead to the **formation of gluonic matter** with universal properties across all nuclei, including the proton?

Electron-Ion Collider

How will the EIC Study the Structure of Visible Matter

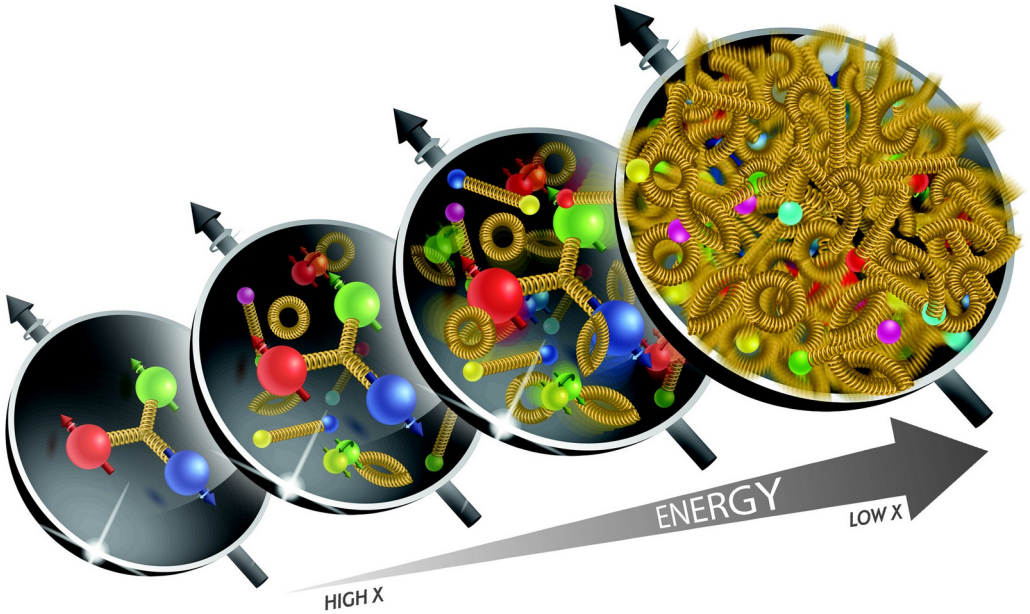


$Q^2 = s \cdot x \cdot y$

Q^2 – resolution power (virtuality of the photon)
s – center-of-mass energy squared
x - the fraction of the nucleon's momentum that the struck quark caries
y - inelasticity

Deep Inelastic Scattering: e + p → e' + X

- **Golden process to probe nucleons and nuclei** with electron beams providing the unmatched precision of electromagnetic interactions



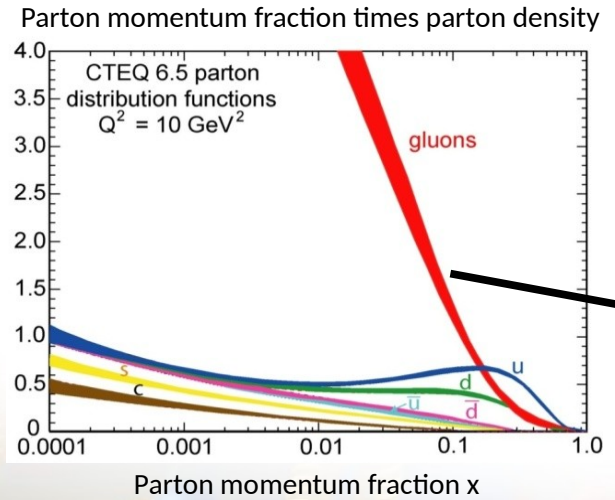
Center-of-mass energy √s: 20 – 140 GeV

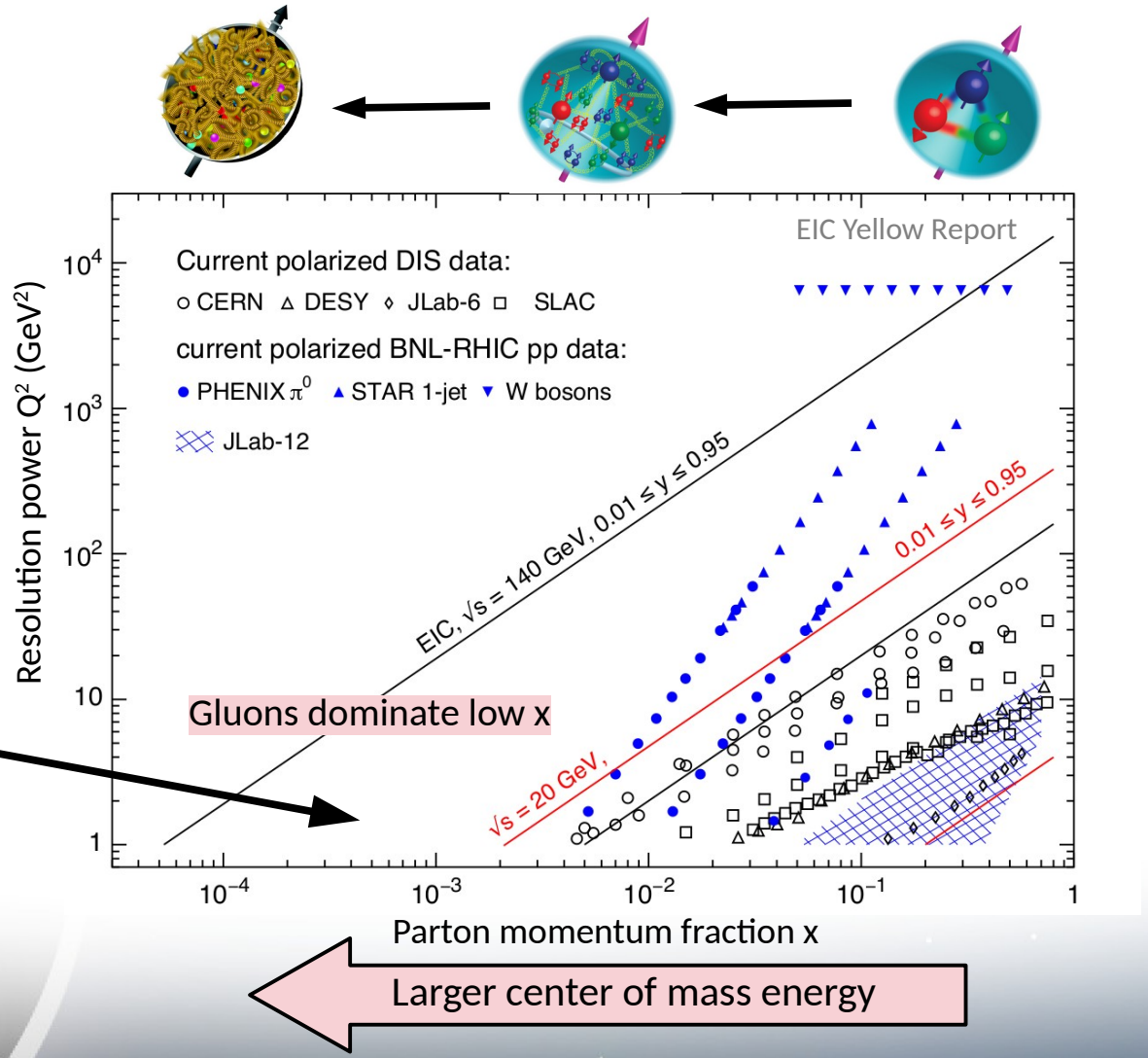
- Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

Probing Uncharted Territory

Unprecedented Access to Nucleon and Nucleus Structure

- Access to x and Q^2 over a wide range
- Bridge between measurements in different regimes
- Heavy nuclei critical to explore high-density gluon matter



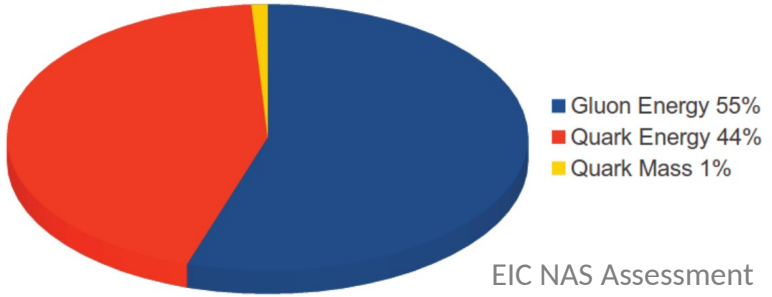


How do Nucleons Acquire Mass?

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

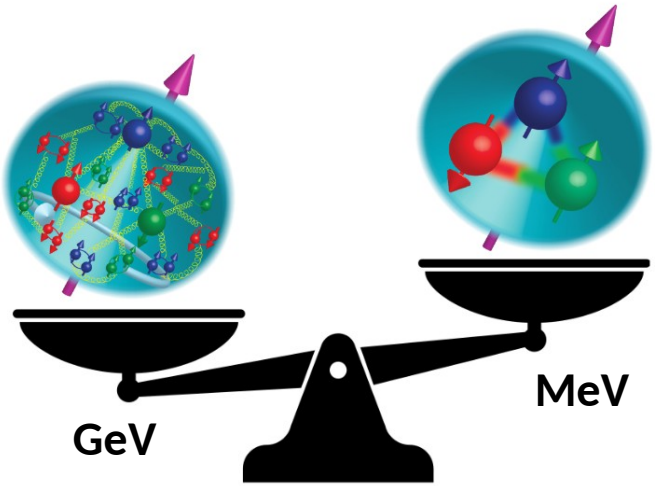
- Visible world mostly made out of light quarks: **masses emerge form quark-gluon interactions**

Contributions to the total mass of the nucleon



EIC NAS Assessment

Proton (valence content *uud*) - mass ~940 MeV
- The mass is dominated by the energy of the highly relativistic gluonic fields
- EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly" → accessible in exclusive reactions



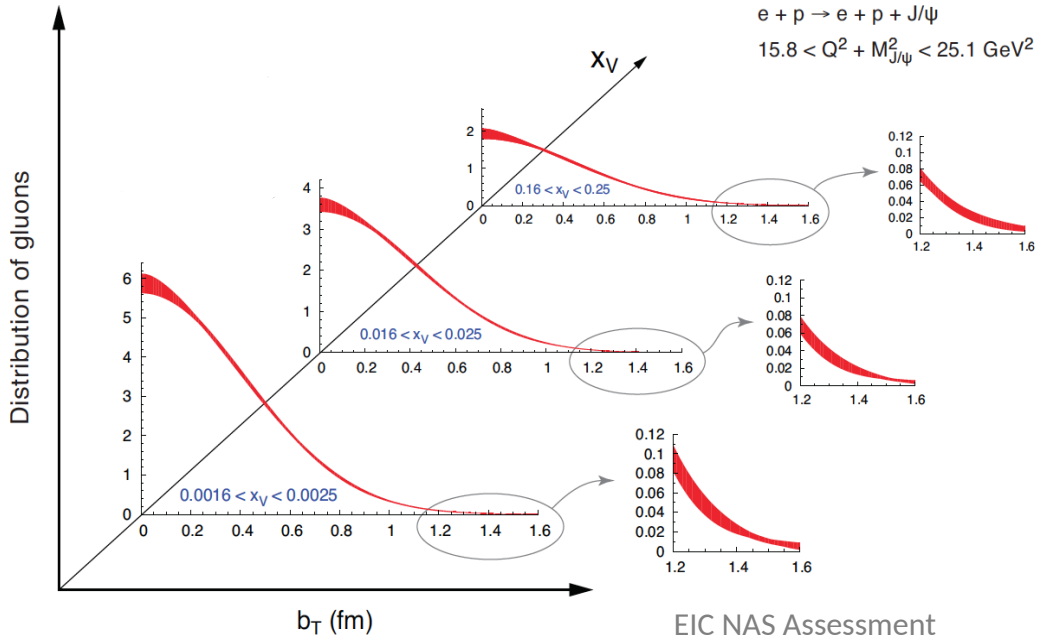
What about the mass of light mesons?

Pions (valence content *ud*) mass ~140 MeV
- Cleanest expression of the emergent mechanism
- Empty or full of gluons?

Kaons (valence content *us* – strange content!) mass ~ 490 MeV
- Probing boundary between emergent and Higgs-mass mechanisms
- More or less gluons than in pion?

Tomographic Image of Quarks and Gluons within Matter

- **Spatial imaging of Quarks and Gluons** via so-called exclusive reactions where the nucleon is left intact in the final state
  - Deeply Virtual Photon scattering – real photon is produced
  - Deeply Virtual Meson production – quark-antiquark bound state is produced



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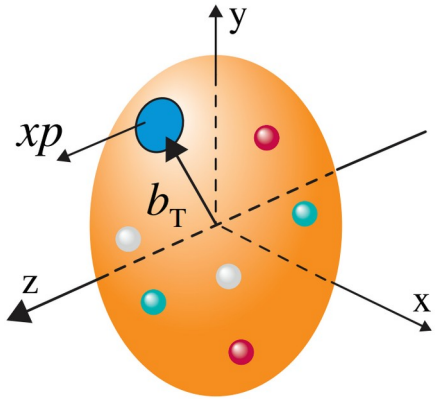
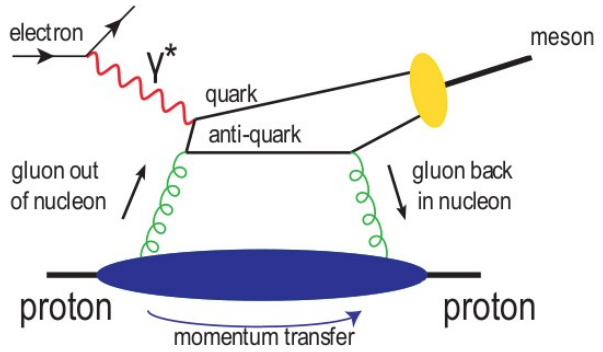


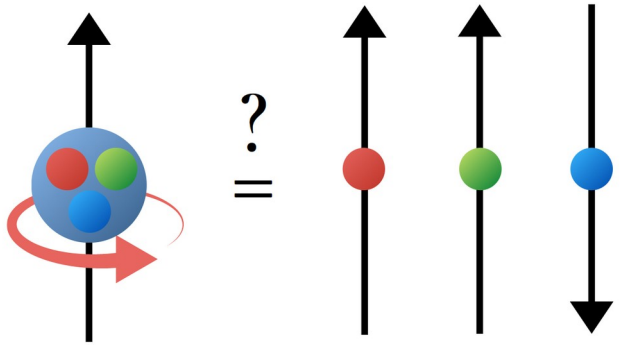


How are gluons spatially distributed in a proton or a nucleus?
First ever tomographic images of ocean of gluons within matter

Unraveling the Mystery of the Origin of the Nucleon Spin

Spin – one of the fundamental properties of particles

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?



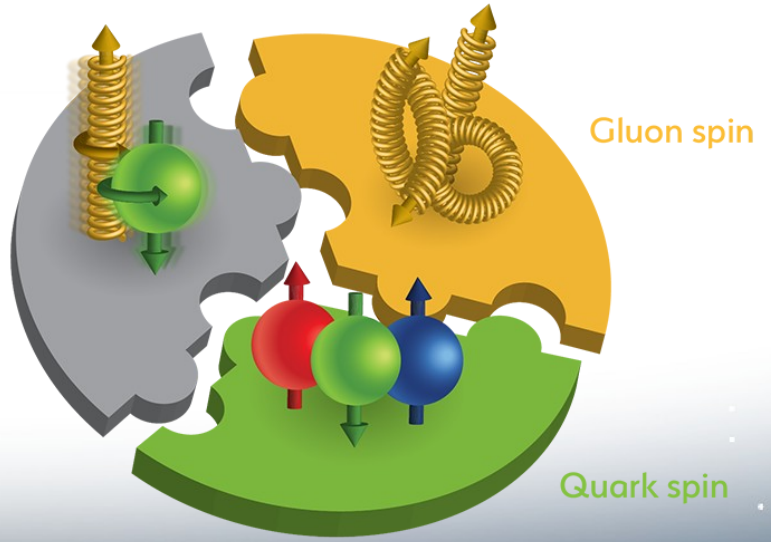
Proton Spin Puzzle
EMC Experiment (1987)

- Proton spin doesn't originate only from its 3 valence-quark spins
- After decades of experiments: quark spins contribute ~30% to the proton spin

$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

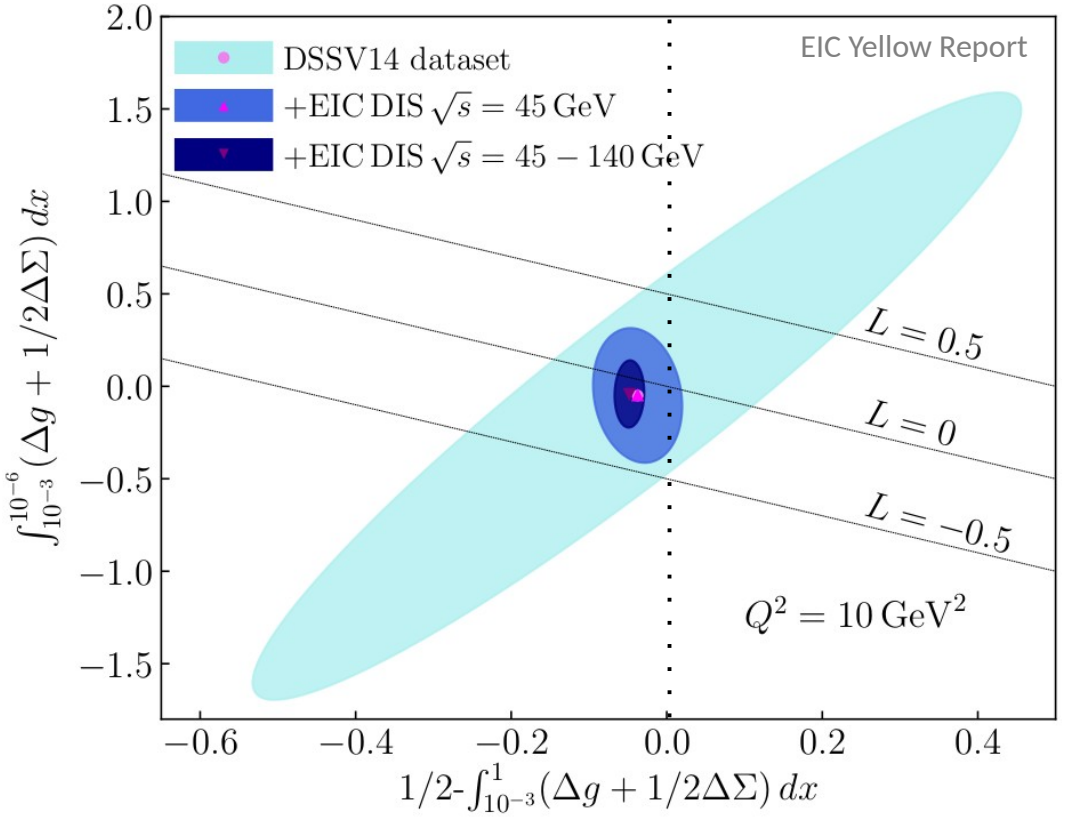
Quark spins | Gluon spins | Quark orbital angular momentum | Gluon orbital angular momentum

Quark and gluon internal motion



Electron-Ion Collider

Unraveling the Mystery of the Origin of the Nucleon Spin

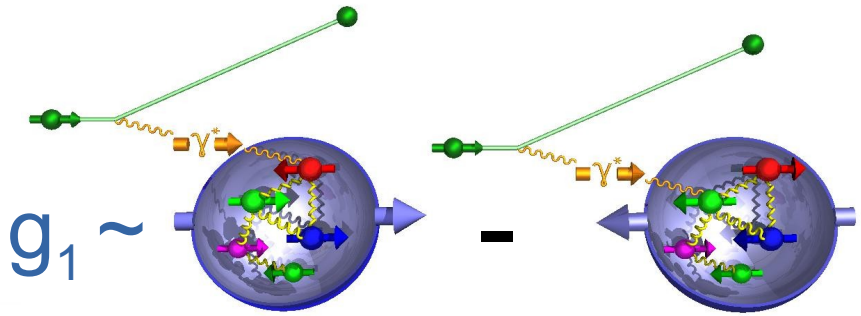


Spin contribution from partons with x = (10^{-6}–10^{-3})

Room left for potential OAM contributions to the proton spin from partons with x > 0.001

Access to gluon spin with the measurement of the g_1 structure function

- Through difference of cross-sections with different longitudinal spin orientation of electron and proton



Access to quark contribution of OAM – through exclusive processes

Spatial and Momentum Structure of Nucleons and Nuclei in 3D

Wigner functions
$W(x,b_T,k_T)$

$\int d^2b_T$

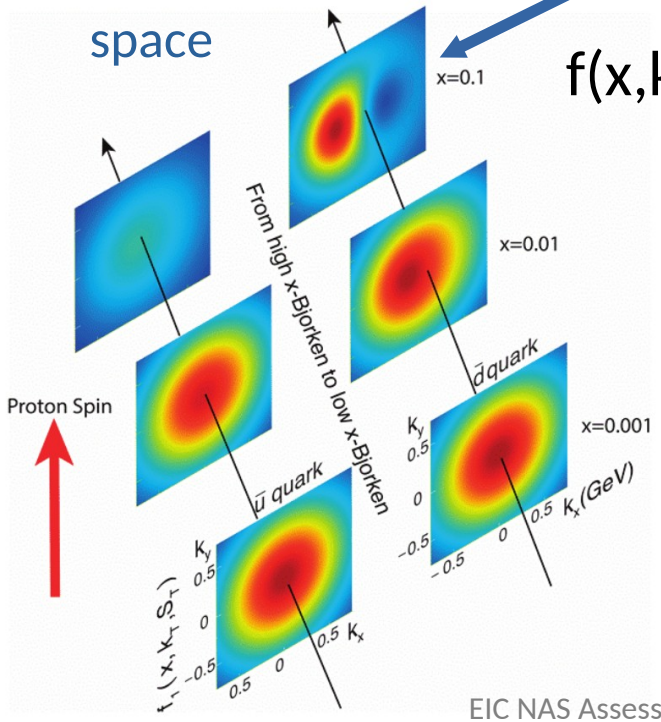
$\int d^2k_T$

$f(x,k_T)$

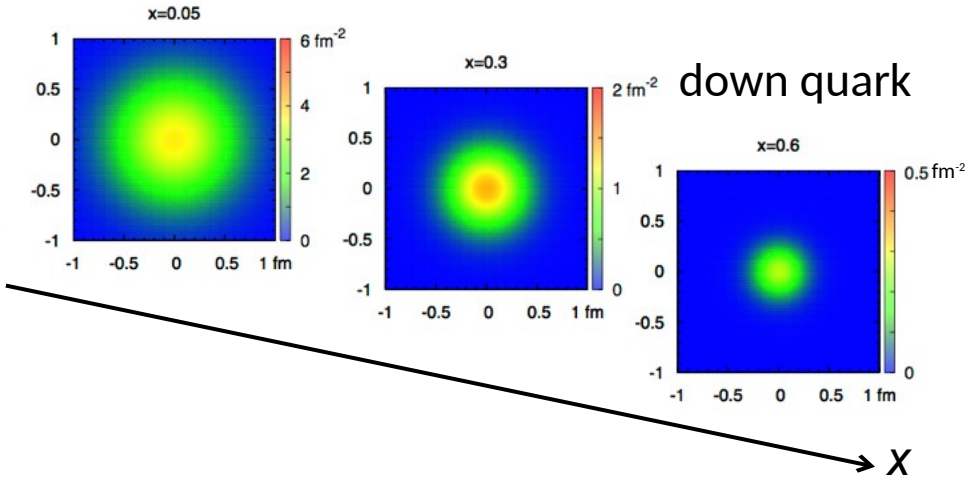
$f(x,b_T)$

Momentum space

Coordinate space



EIC NAS Assessment



down quark

→ Access to e.g., spin-orbit correlations
Spin-dependent 3D momentum space images from semi-inclusive scattering

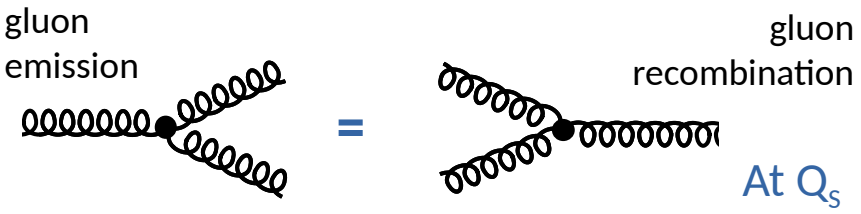
Spin-dependent 2+1D coordinate space images from exclusive scattering

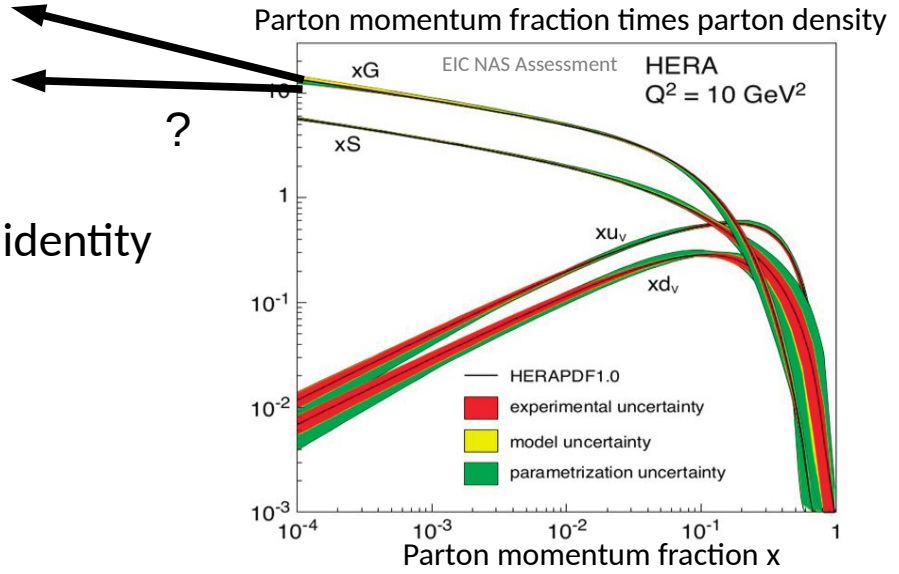
Electron-Ion Collider

Can the EIC Give Us Access to New State of Gluonic Matter?

What happens to the gluon density in nuclei?

- Number of gluon **grows in the low-x limit**
- At some point the **density becomes so large** that gluons lose their individual identity and are **strongly overlapping**

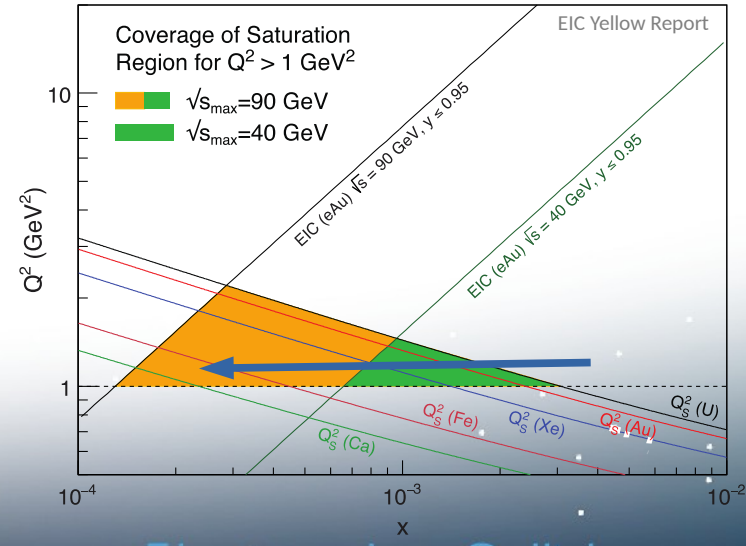




Q_s - resolution scale at which the number density so large that gluons are no longer independent → **saturated gluon matter**

EIC provides a unique opportunity to have very high gluon densities
electron – heavy nuclei (e.g., Pb) collisions
Combined with an unambiguous observables, e.g., **di-jets in ep and eA, diffractive processes**

EIC will allow to unambiguously map the transition from a non-saturated to saturated regime



Electron-Ion Collider

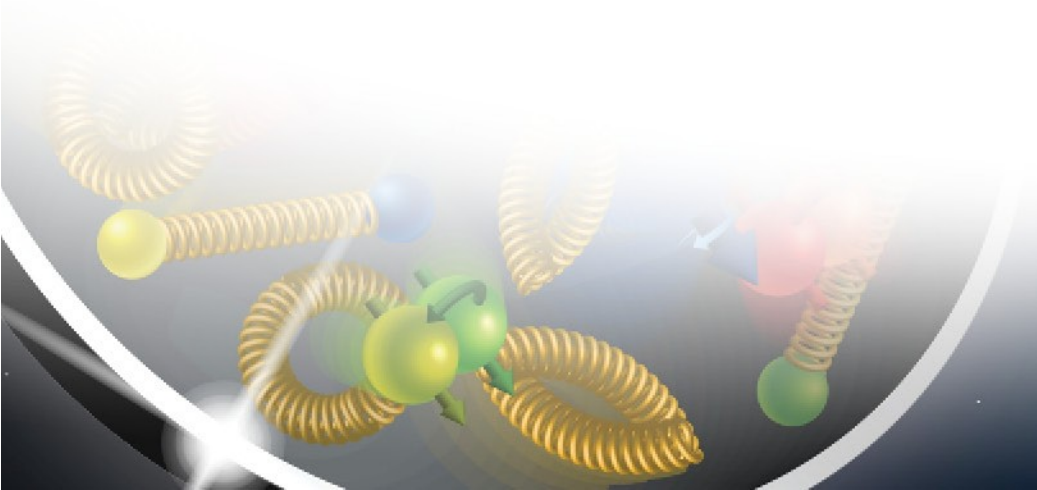
Summary

- **EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all**

- Our current knowledge about the structure of matter is a **mysterious dark room** even after decades of studies
  - We can see shadows and shapes with some important bright spots with existing tools
  - With the EIC, we can turn on the light and reveal the hidden details inside

- **Access to EIC Physics** through
  - Large kinematic coverage
  - Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
  - Detector setup fulfilling specific requirements of the polarized e-p/A collider

Backup

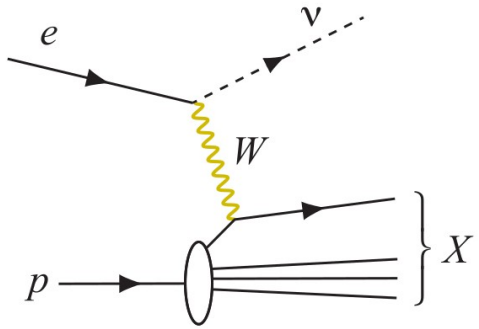


Experimental Processes to Access EIC Physics

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)

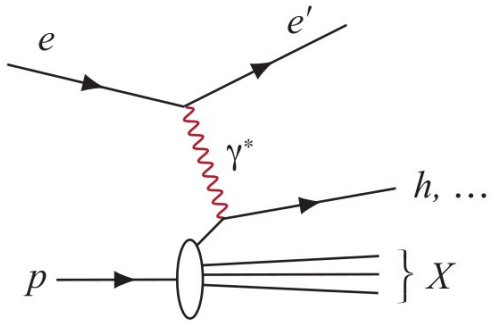
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



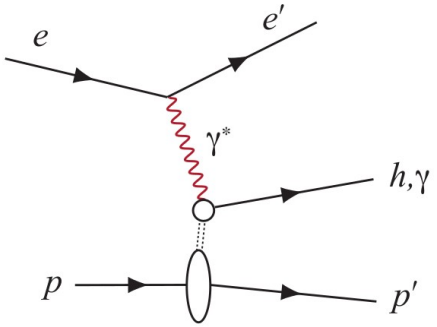
Charged Current DIS

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



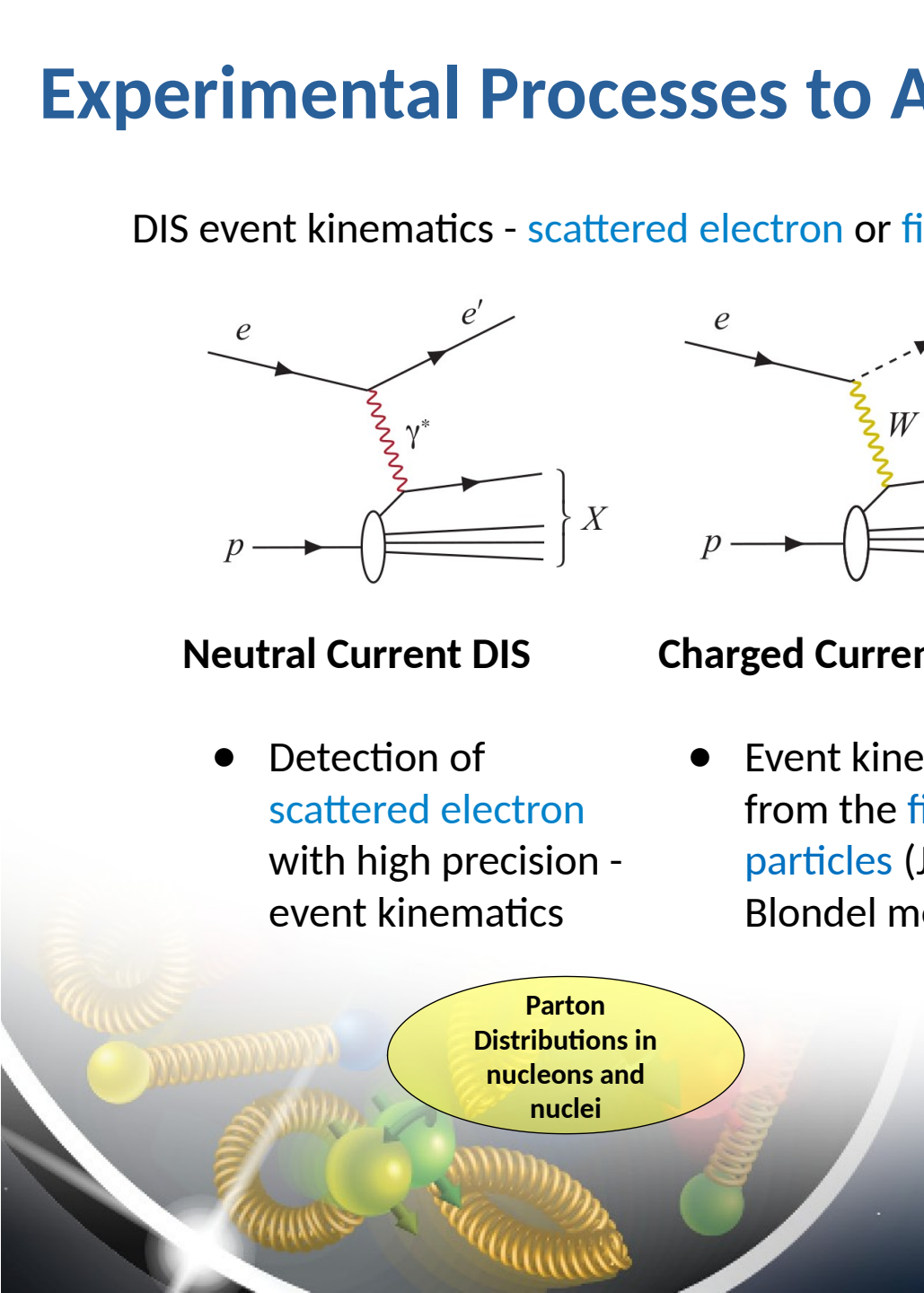
Semi-Inclusive DIS

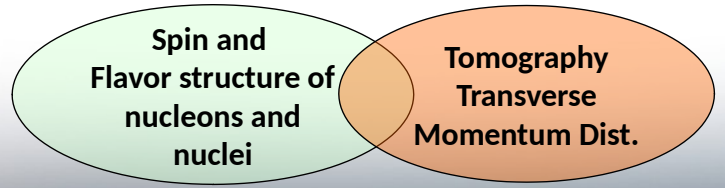
- Precise detection of scattered electron in coincidence with at least 1 hadron

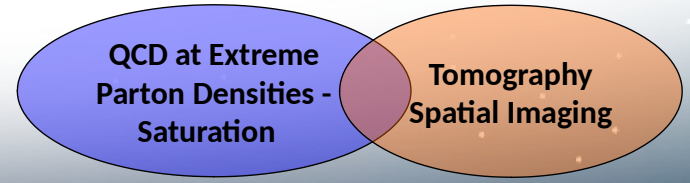


Deep Exclusive Processes

- Detection of all particles in event







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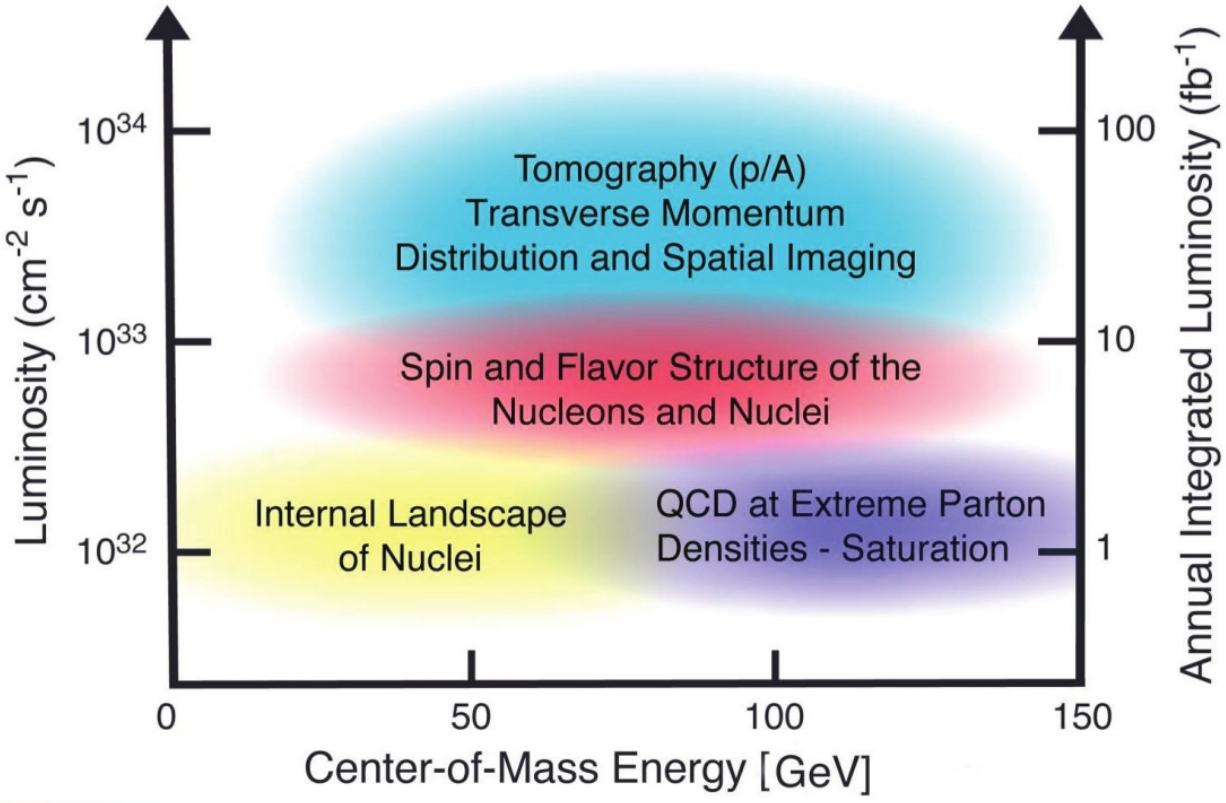
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