Physics at Electron-Ion Collider (EIC)

2024.6.20 at RIKEN

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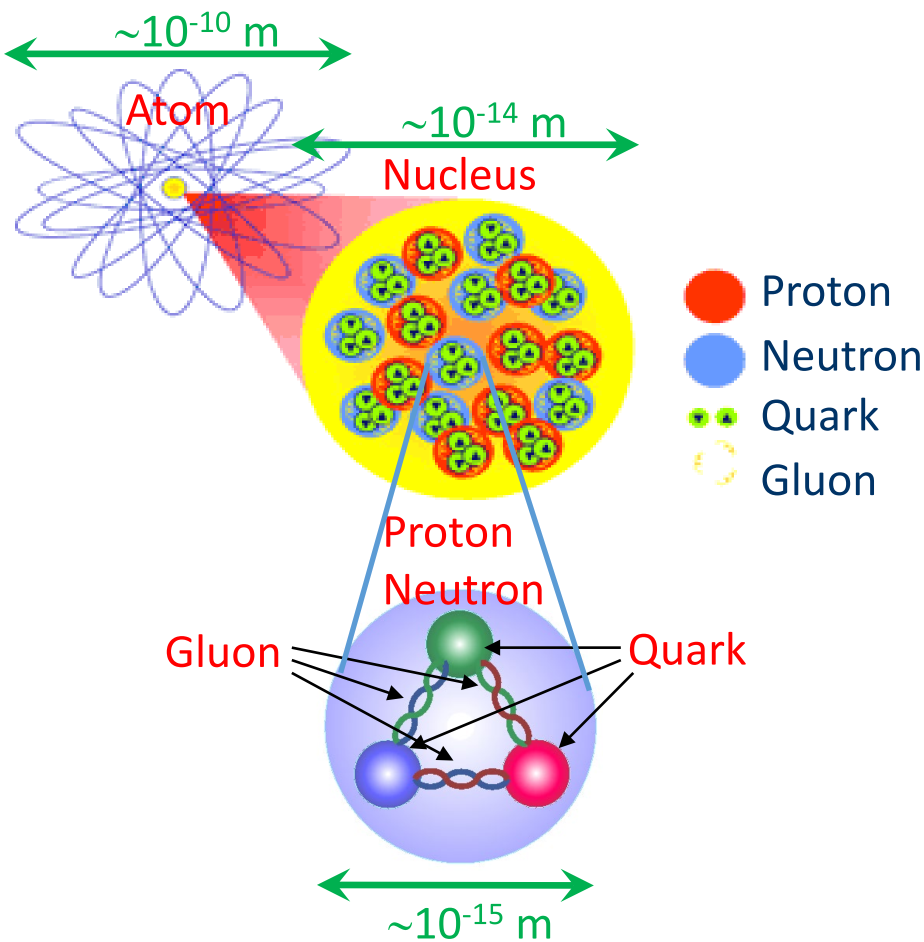
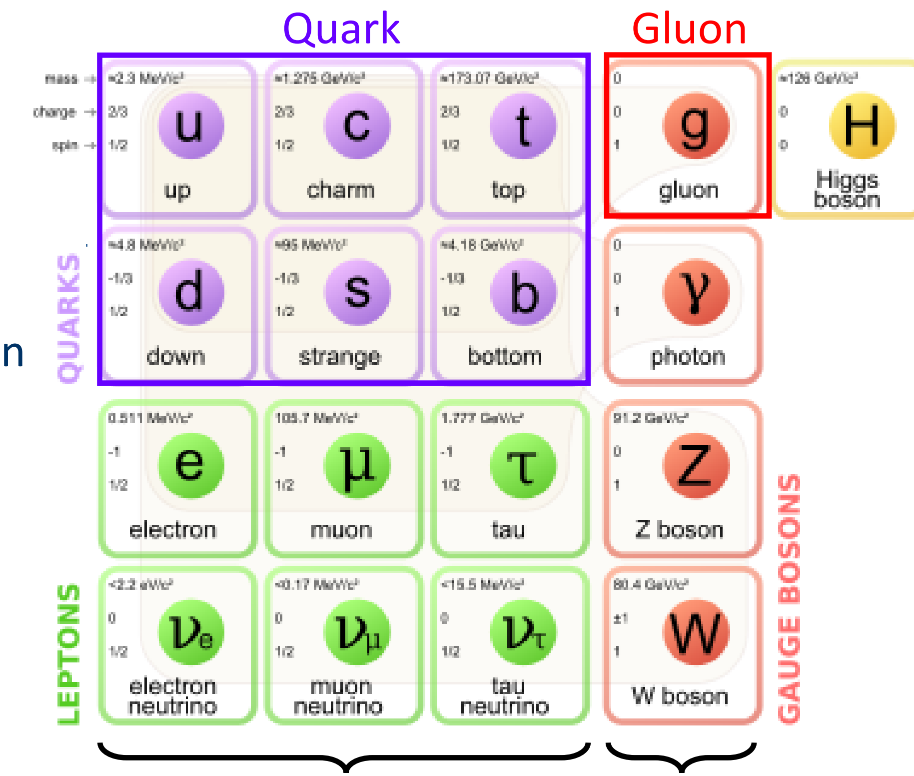
Outline of this talk

- Basics and history
  - Quark-gluon structure
- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation
  - Hadronization

Physics of Quarks and Gluons



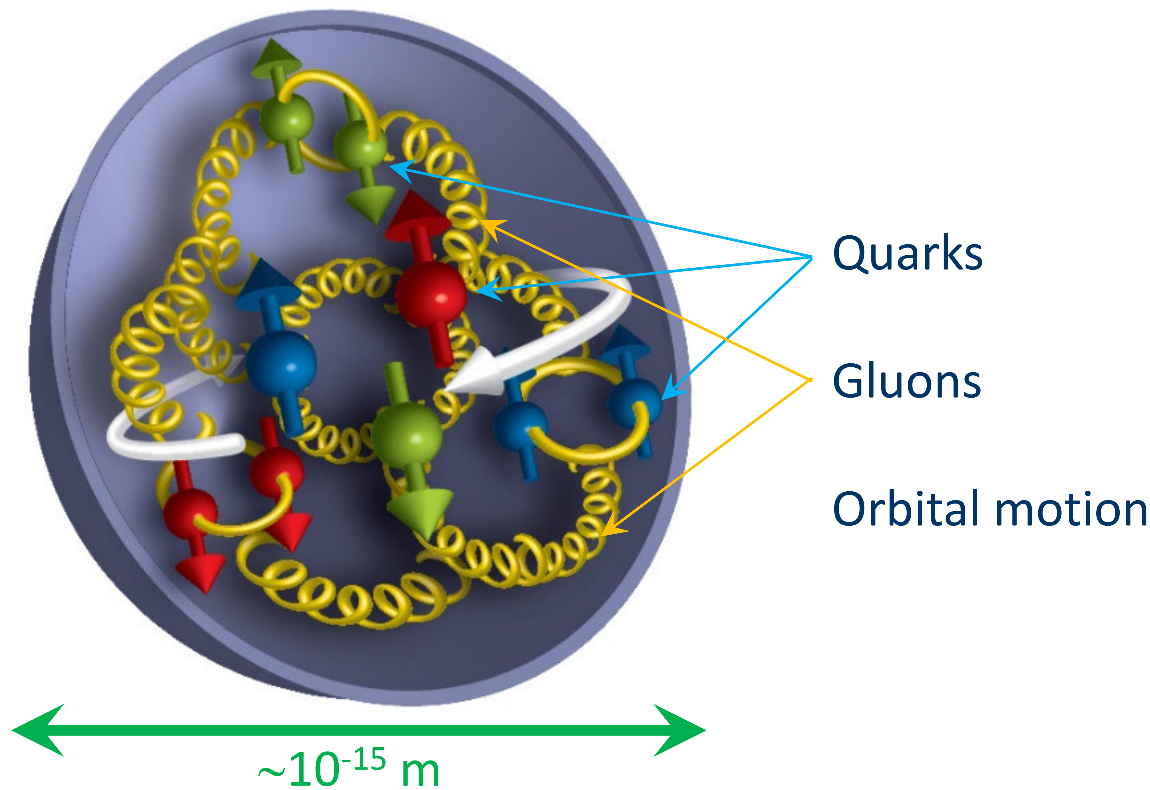


- Experimental study of quantum chromodynamics (QCD)
  - Study of quark-gluon plasma (QGP)
  - Study of the spin structure of protons, solving the spin puzzle

Physics of Quarks and Gluons

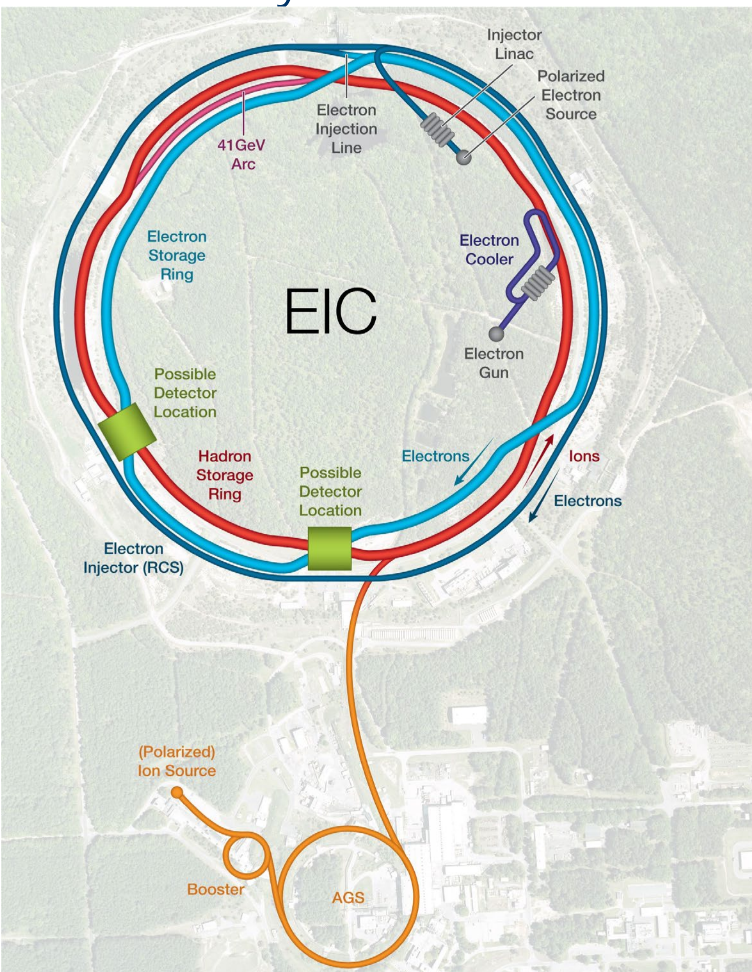
- We need much higher resolution than that of the electron microscope

→ Electron Ion Collider



Electron-Ion Collider (EIC)

- 2020.1.9: U.S. Department of Energy selected Brookhaven National Laboratory to host major new nuclear physics facility, the Electron-Ion Collider
- World's first polarized electron + proton / light-ion / heavy-ion collider



Project Design Goals

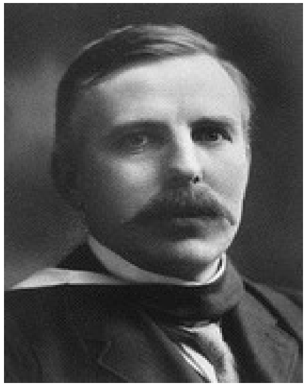
- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

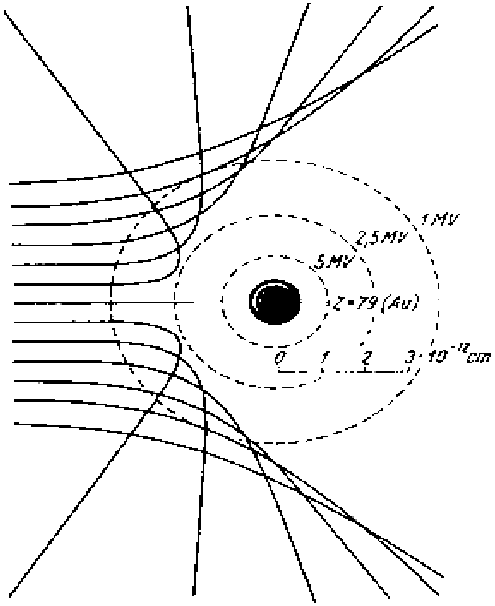
Polarized beam: e, p, d, ^{3}He

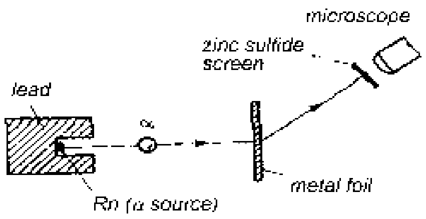
Atomic structure

- Scattering experiment of α-rays
  - α-ray irradiation to gold foil
  - Only small angle scattering if charge is uniformly distributed in atoms (Thomson model)
  - Observation of large angle scattering, discovery of point nuclei, concentration of charge in a narrow region
- Rutherford scattering (1911)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Rutherford}} = \frac{Z^2\alpha^2}{4E^2\sin^4\theta/2}$$

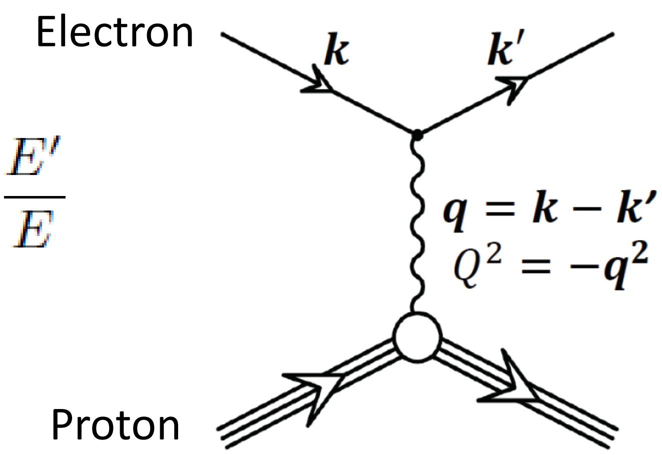






Structure of nucleus and nucleon

- Electron Beam Scattering Experiment
  - Mott scattering
  - Electron spin 1/2, target recoil



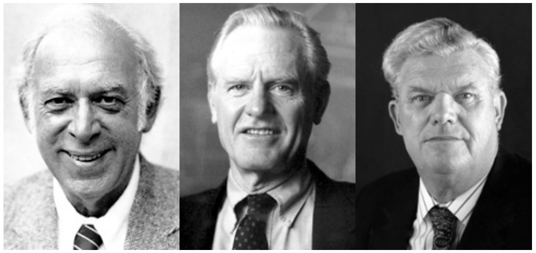
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Rutherford}} \cdot \cos^2\frac{\theta}{2} \cdot \frac{E'}{E}$$

- Electron-proton elastic scattering
  - Electron beam at SLAC (1950s-60s)
  - Form factor measurement
    - Momentum transfer dependence of angular distribution
  - Rosenbluth formula

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

    - G_E : Electric form factor
    - G_M : Magnetic form factor
  - Measurement of proton size: 0.8 fm
    - Internal structure of nucleons shown as a mean distribution

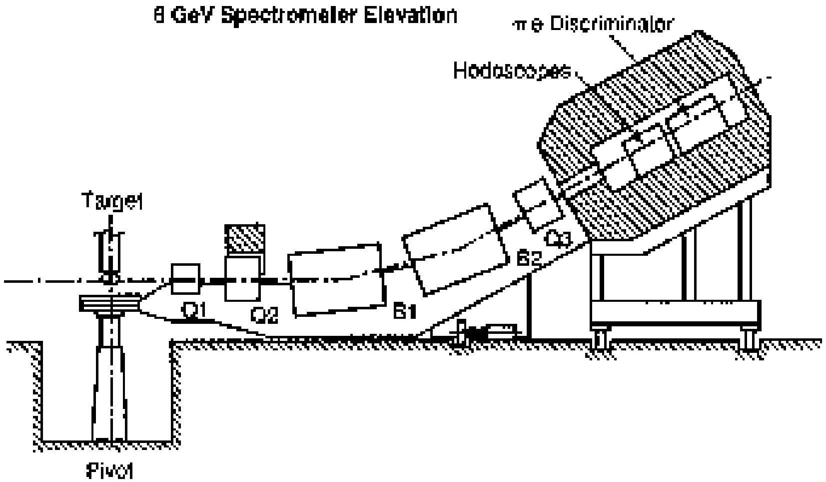
Nucleon structure

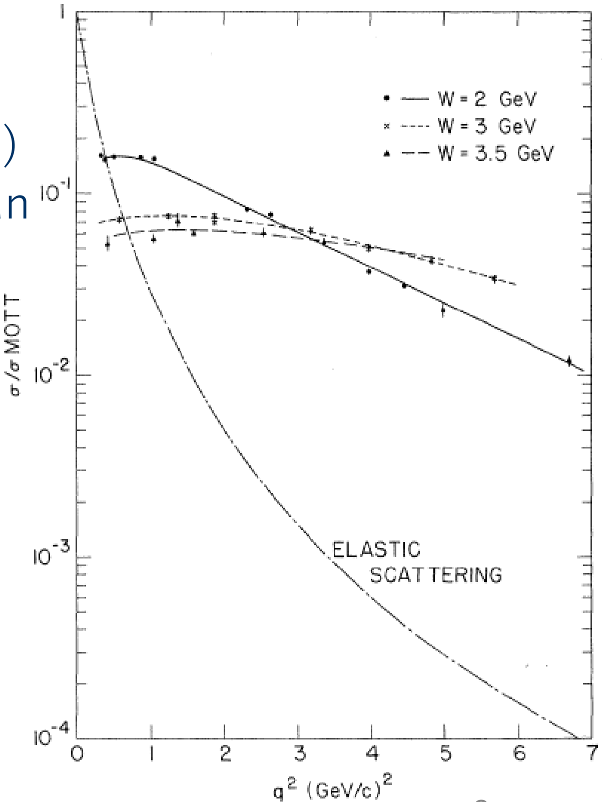


- Deep Inelastic Scatterin (DIS) Experiment

$$\frac{d^2\sigma}{dQ^2 d\nu} = \sigma_{\text{Mott}} \left[W_2(Q^2,\nu) + 2W_1(Q^2,\nu) \tan^2\frac{\theta}{2} \right]$$

  - MIT-SLAC experiment (1969, Friedman, Kendall, Taylor)
    - Scattering cross section does not decrease as Q^2 increases
      - Large angle scattering
      - Point-like components in the proton (parton)
    - Scattering with point-like components rather than scattering by the nucleon as a whole





Quark-Parton Model (QPM)

- Bjorken scaling rule

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\frac{E'}{E}\frac{1}{x}\left[F_2(Q^2,x)\cos^2\frac{\theta}{2} + \frac{Q^2}{2x^2M^2}2xF_1(Q^2,x)\sin^2\frac{\theta}{2}\right]$$

  - F_2 and F_1 are functions of x only, independent of Q^2
- Dirac scattering: spin 1/2 target like muon

$$\left(\frac{d\sigma}{dQ^2}\right)_{\mathrm{Dirac}} = \frac{4\pi Z^2\alpha^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\theta}{2} + \frac{Q^2}{2M^2}\sin^2\frac{\theta}{2}\right]$$

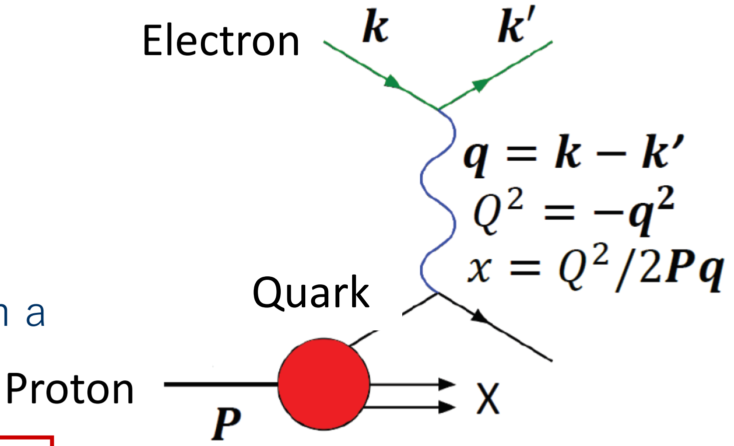
- Callan-Gross relation

$$F_2 = 2xF_1$$

  - Parton spin 1/2 as muon

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{xQ^4}\{1+(1-y)^2\}F_2(Q^2,x)$$

  - DIS is the superposition of elastic scattering with a point-like component (parton) in the proton



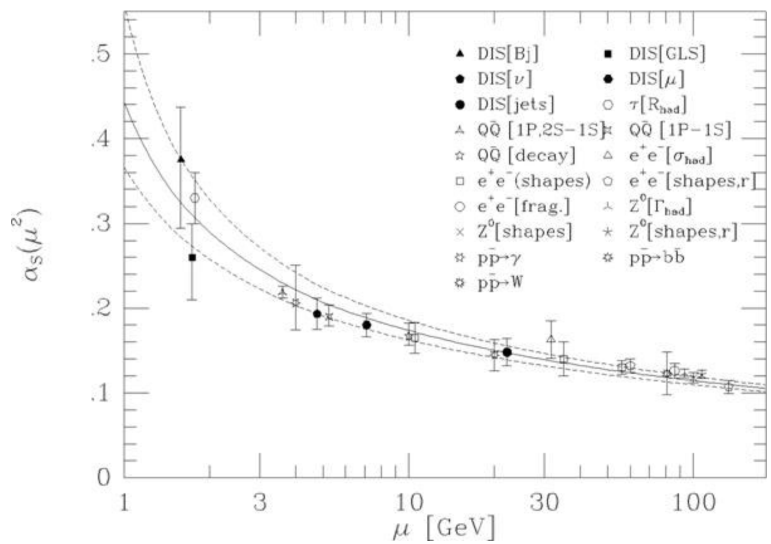
- Parton Distribution Function (PDF)

$$F_2 = x\sum_q e_q^2 q(x)$$

  - Internal structure of nucleon shown as parton distribution
  - $q(x)$: parton distribution function of quark q

From QPM to QCD

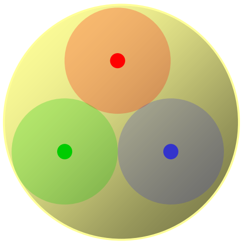
- Breaking of the scaling rule
  - When measured precisely, the Callan-Gross relation is broken
    - F_2 depends on Q^2
  - Gluon presence
- QCD
  - Asymptotic freedom and confinement



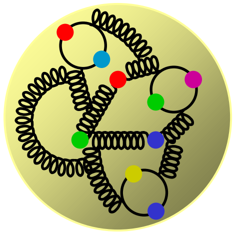
Gross Politzer Wilczek

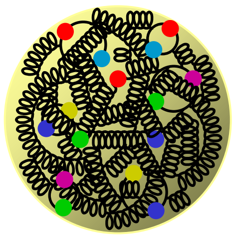
Nucleon structure

- Constituent-quark model
  - Quarks with the effective mass (caused by the gluon)
  - Explains the magnetic moment of the nucleons
  - But, the quark spin cannot explain the nucleon spin (“spin puzzle”)



- Quark-gluon model
  - Current quarks and gluon interaction
  - Initial state of high-energy hadron colliders

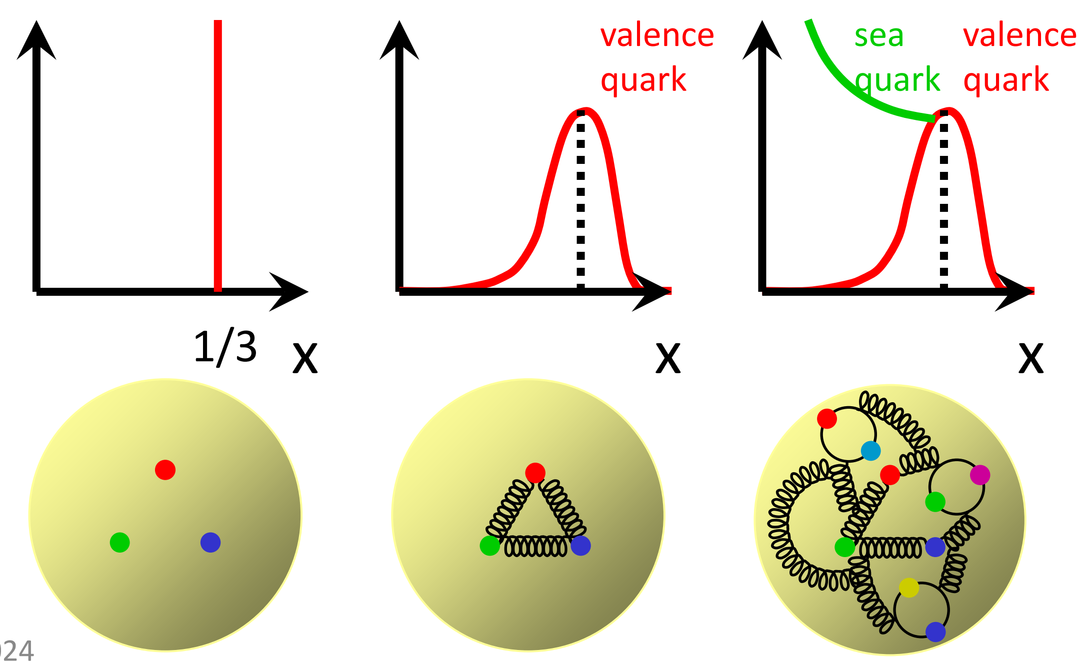




- Understanding the differences (or gap) of these models
  - Chiral symmetry (breaking)
  - Confinement

Nucleon structure

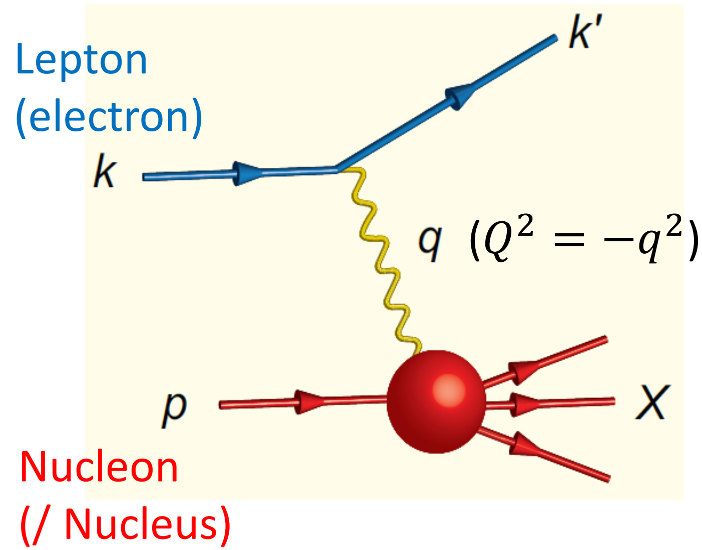
- Nucleon: the simplest multi-body system for studying dynamics of confined quarks and gluons
- Simple parton picture
  - 1-dimensional picture: in “longitudinal” direction
  - The nucleon consists of incoherent quarks and gluons
  - Described by the parton distribution functions (PDF)



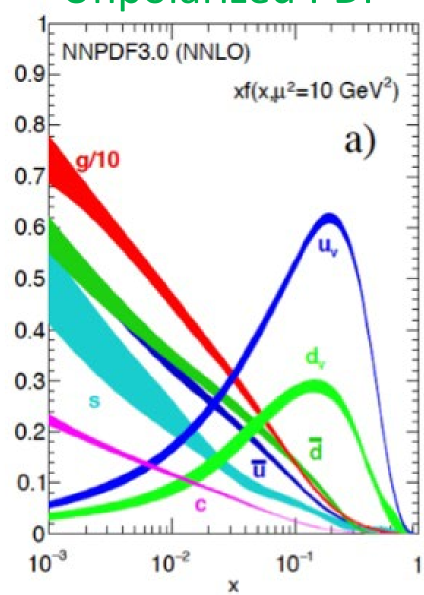
x: Bjorken’s x
“longitudinal” momentum fraction
(1-dimensional picture)

Quark-gluon structure

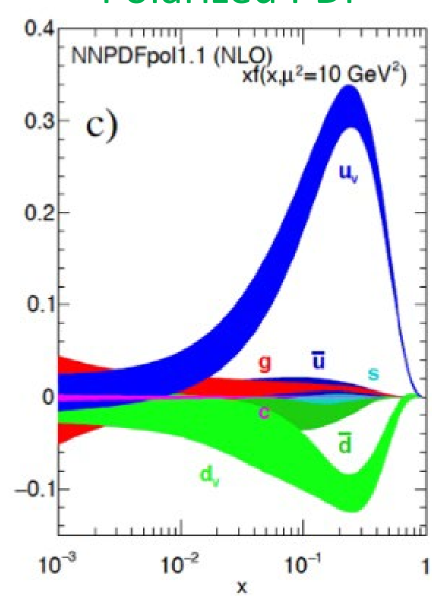
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant improvement of precision of the polarized PDF at EIC



Unpolarized PDF

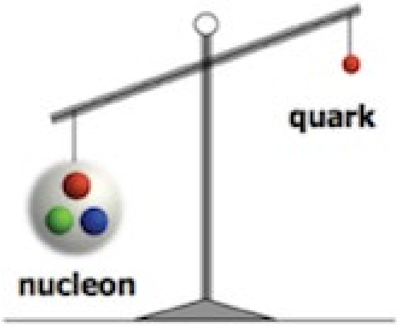


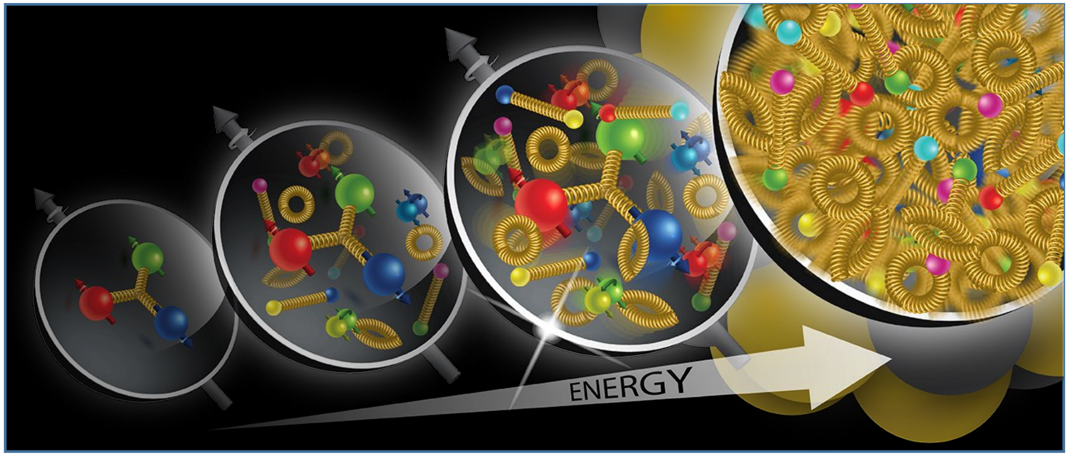
Polarized PDF



Physics at EIC

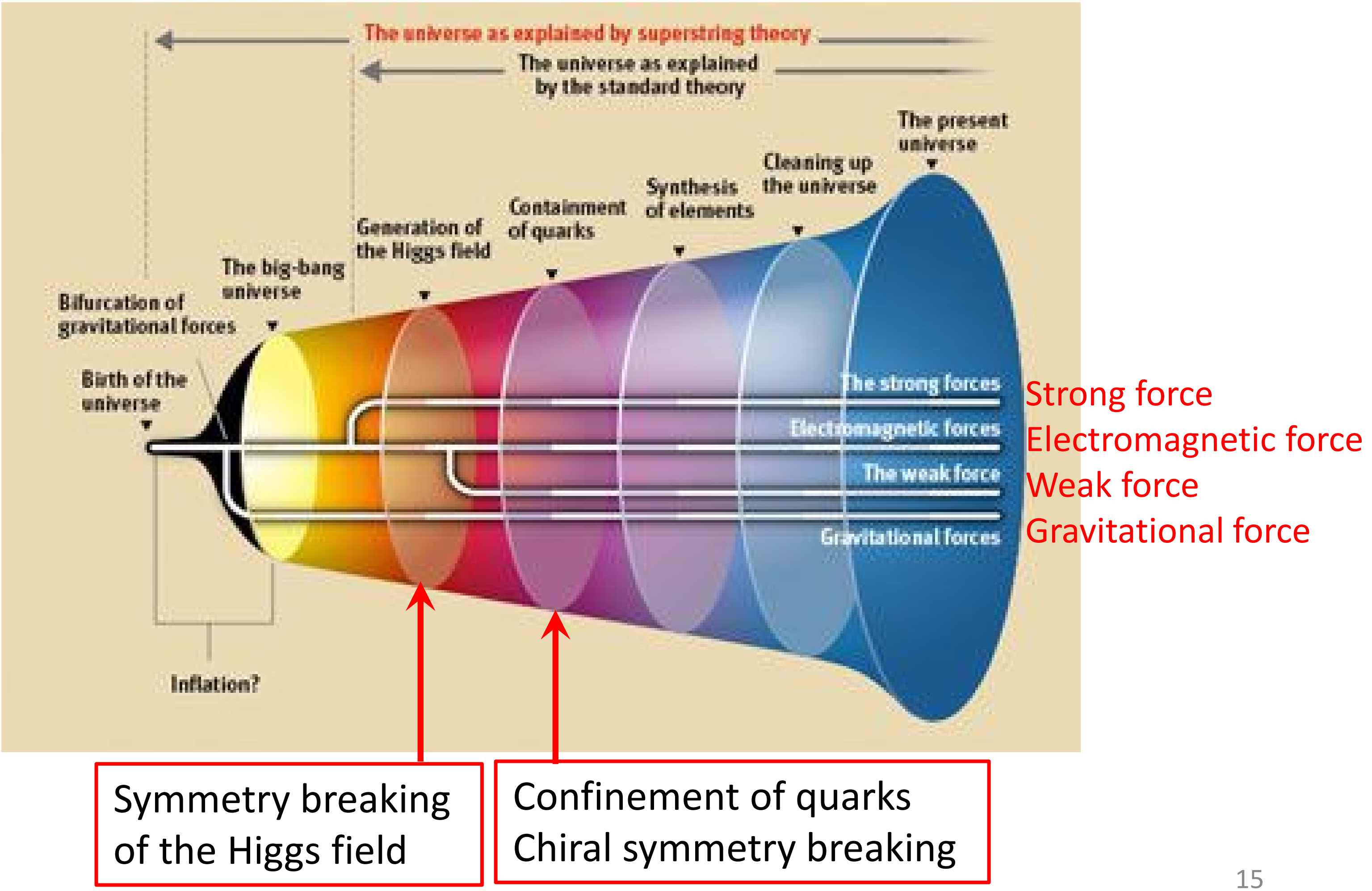
- How does the mass of the nucleon arise?
  - The Higgs mechanism accounts for only ~1% of the mass of the proton.
- How does the spin of the nucleon arise?
  - The spin of the quarks accounts for only one-third of the spin of the proton.
- What are the emergent properties of dense system of gluons?
  - The gluon saturation describes a new state of matter at extreme high density.





Mass

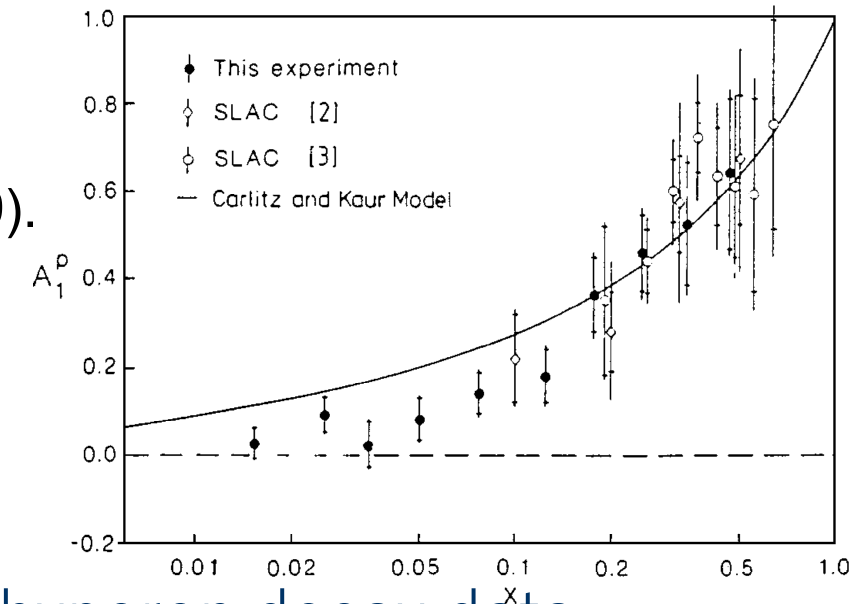
- The Higgs mechanism accounts for only ~1% of the mass of proton.
- The symmetry breaking emerges the mass.



Origin of the nucleon spin 1/2

- EMC experiment at CERN

  J. Ashman et al., NPB 328, 1 (1989).



$$\int_0^1 dx g_1^p(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= 0.123 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$$

  - combining with neutron and hyperon decay data

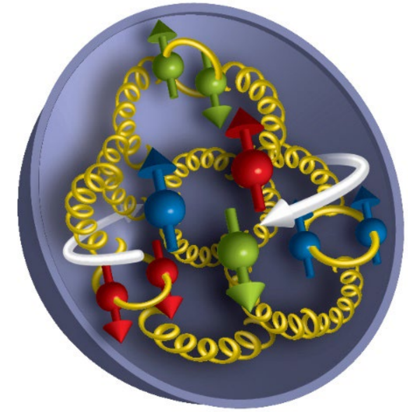
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin puzzle"
"proton spin crisis"

    - total quark spin constitutes a small fraction of the nucleon spin
  - integration in x = 0 ~ 1 makes uncertainty
    - more data to cover wider x region with more precise data necessary

➔ SLAC/CERN/DESY/JLAB experiments

Spin



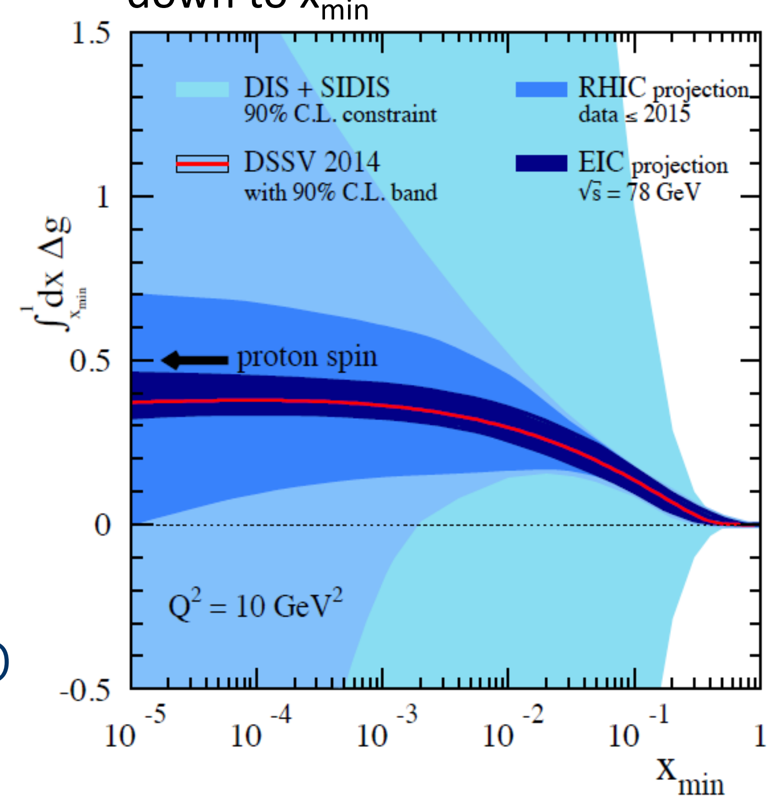
- Spin puzzle
  - Origin of the nucleon spin in the quark-gluon structure

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

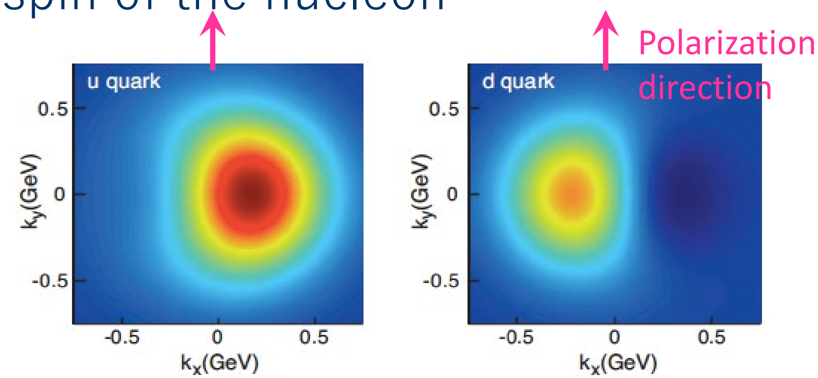
  - Quark-spin contribution is only 20%-30% of the nucleon spin
- Gluon polarization measurement with polarized DIS at EIC
  - Small Bjorken-x region with QCD evolution (DGLAP equation)

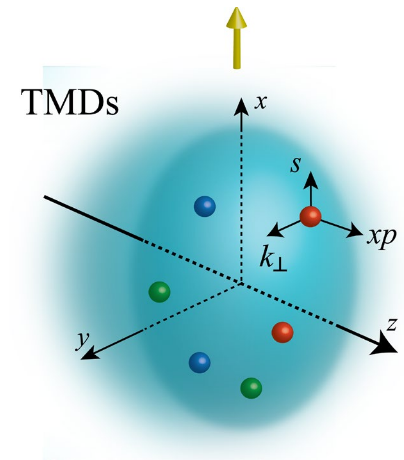
Integrated gluon polarization down to x_{min}



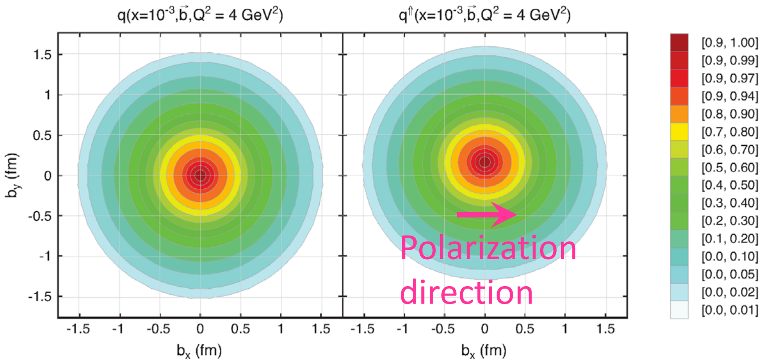
3D structure of the nucleon

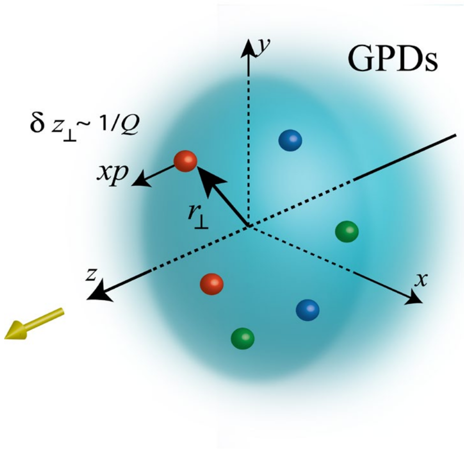
- Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between the (orbital) motion, spin of partons, and spin of the nucleon





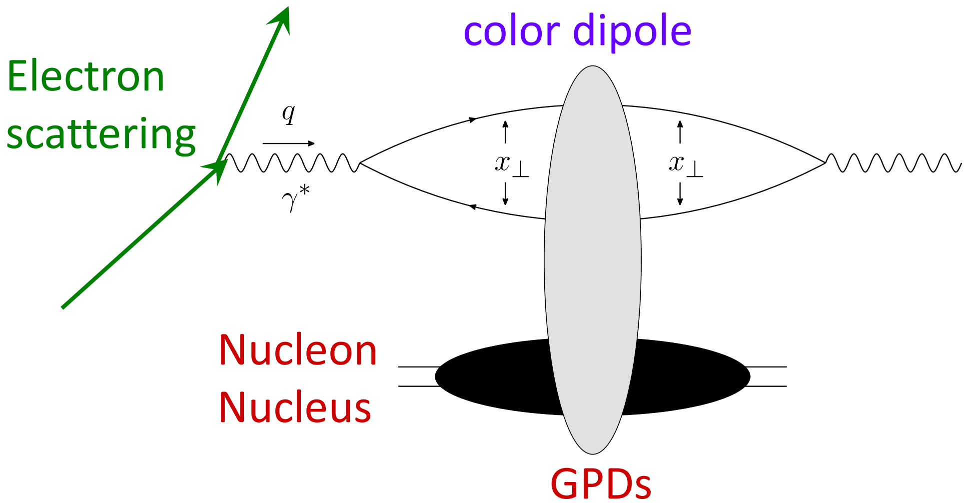
- GPD (Generalized Parton Distribution)
  - Spatial distribution or tomography



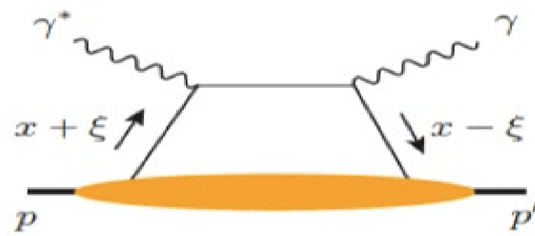


Tomography of the nucleon / nucleus

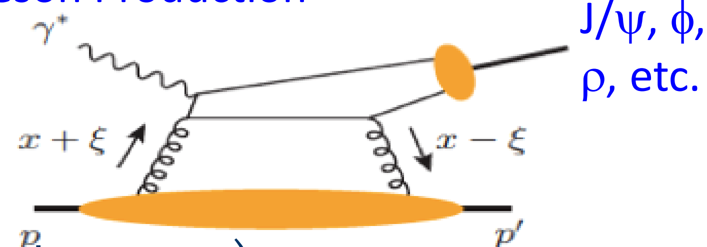
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production

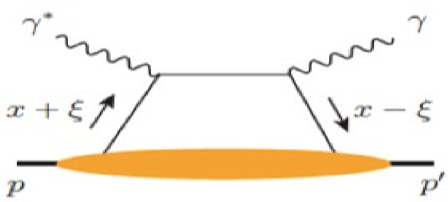


- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

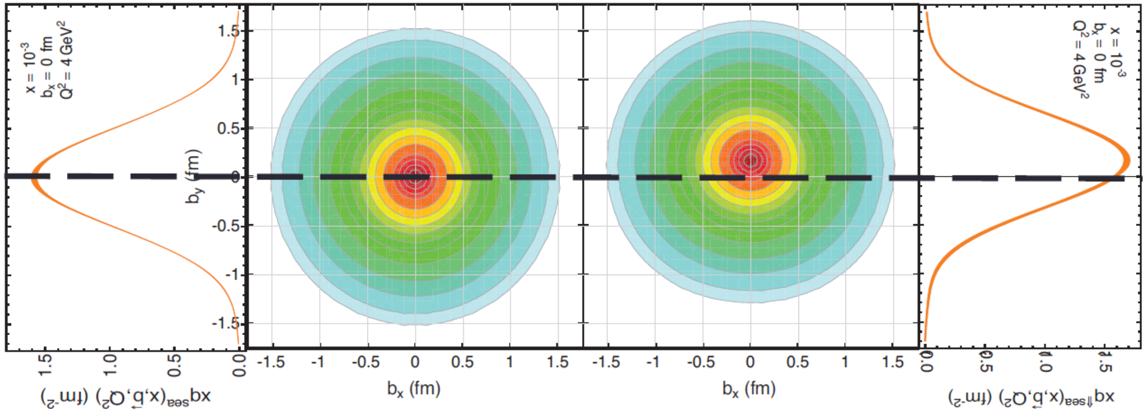
$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q = \frac{1}{2}\left(\int_{-1}^{1} x dx (H^q + E^q)\right)_{t\to 0}$$

Tomography of the nucleon / nucleus

- DVCS
  - Deeply virtual Compton scattering

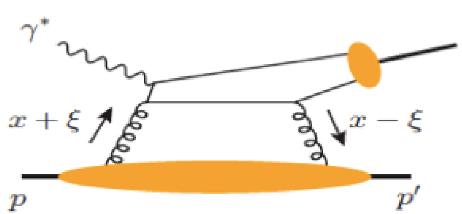


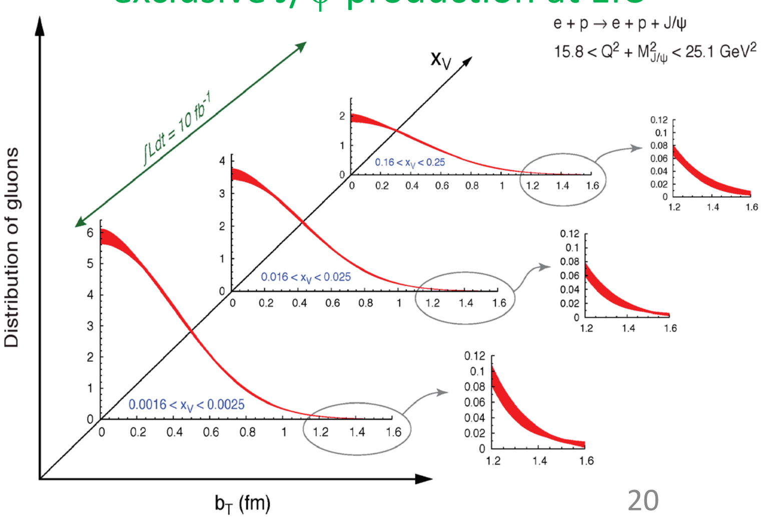
Spatial distribution of sea quarks at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane



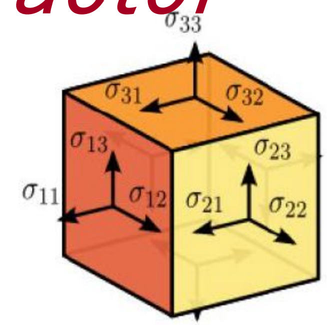
- Meson production
  - Gluon tomography by measuring J/ψ, ϕ, ρ, etc.
  - Precision measurement at large radius with high luminosity

x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC

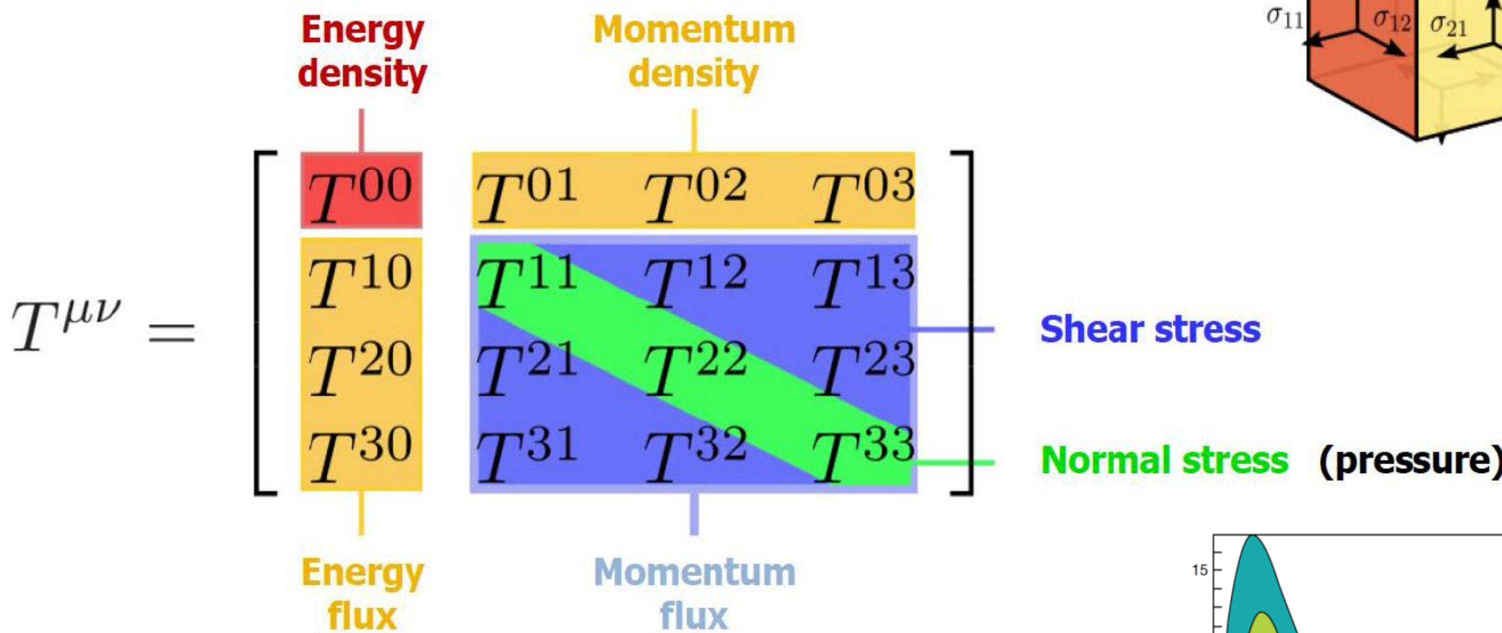




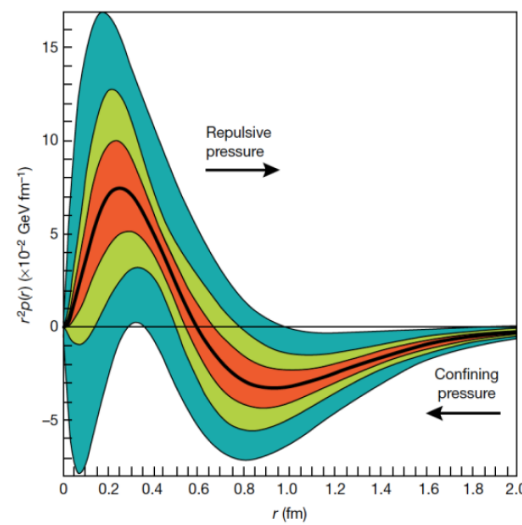
Generalization of the form factor



- Energy Momentum Tensor (EMT)



- GPD measurement → 3D distribution of mass, spin, pressure, etc. in the proton
  - 1st measurement of pressure in the proton using DVCS data from JLab



Nature, **557**, May 17, 2018

Mass of the nucleon

- Sum rule for the nucleon mass

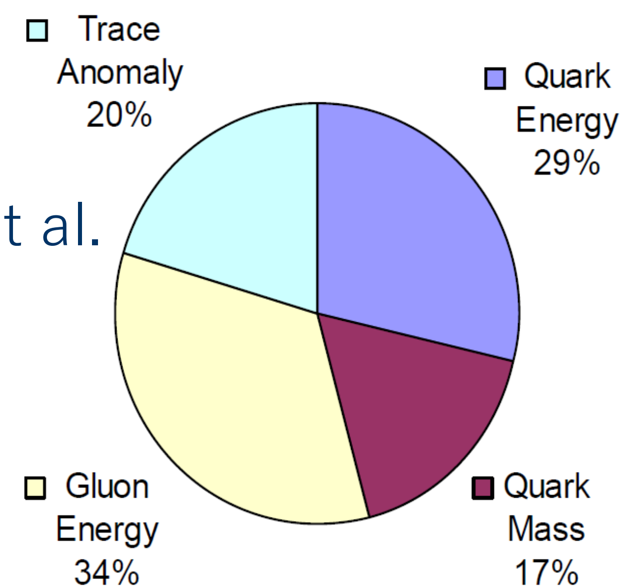
Relativistic Motion | **Chiral Symmetry Breaking** | **Quantum Fluctuations**

$$M = E_q + E_g + \chi m_q + T_g$$

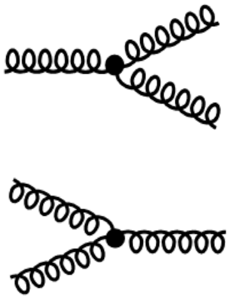
X. Ji, PRL 74 1071 (1995)

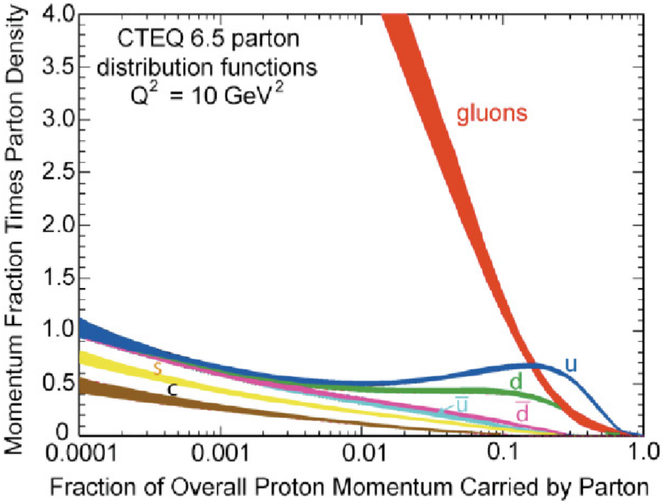
Quark Energy | **Gluon Energy** | **Quark Mass** | **Trace Anomaly**

  - How to determine the different contribution not yet reached
- Lattice QCD calculation
  - arXiv:1710.09011, update by K.-F. Liu et al.
- Precision comparison of experiment and theory in the future
  - Mass, spin, pressure, radius,…

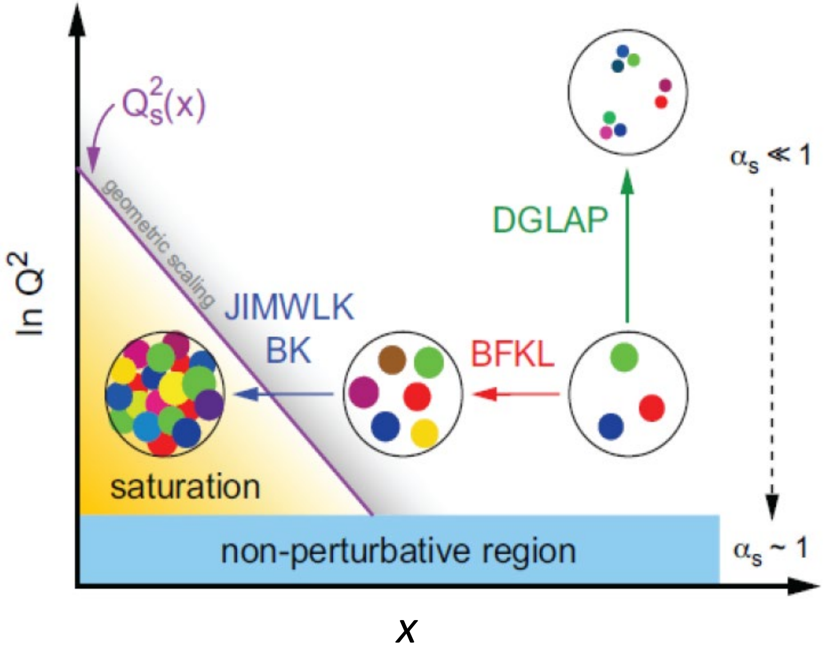


Gluon saturation



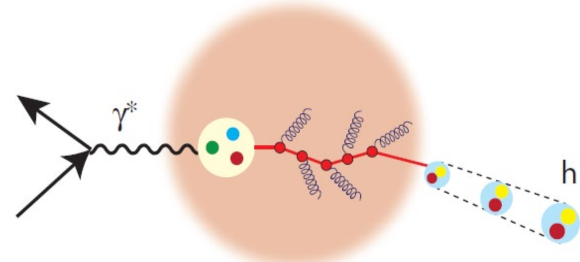


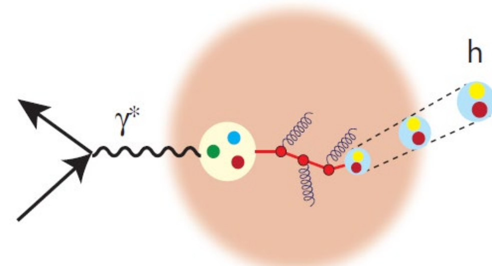
- Gluon emission
  - Divergence at small *x*
- Gluon recombination
  - Restriction of divergence
- Gluon saturation in balanced
  - Based on classical idea of the saturation
- Discovery of quantum collective gluon
  - Saturated gluon model, the color glass condensate (CGC) model, allows precision comparison with experiments
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism

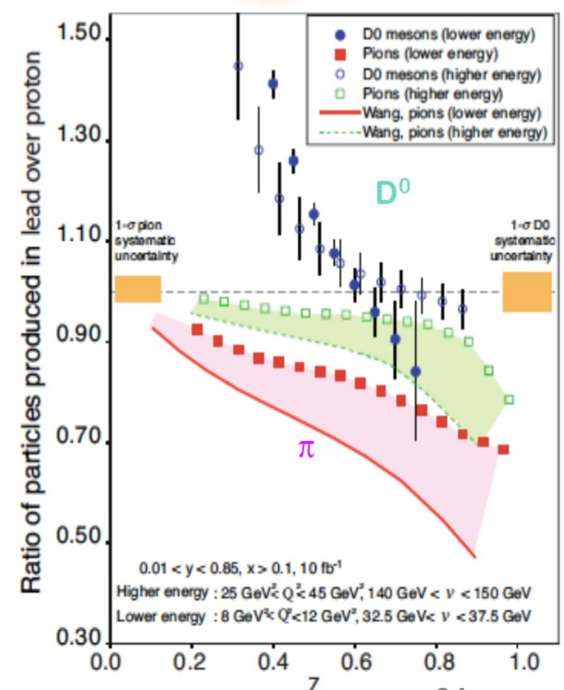


Hadronization in the nucleus

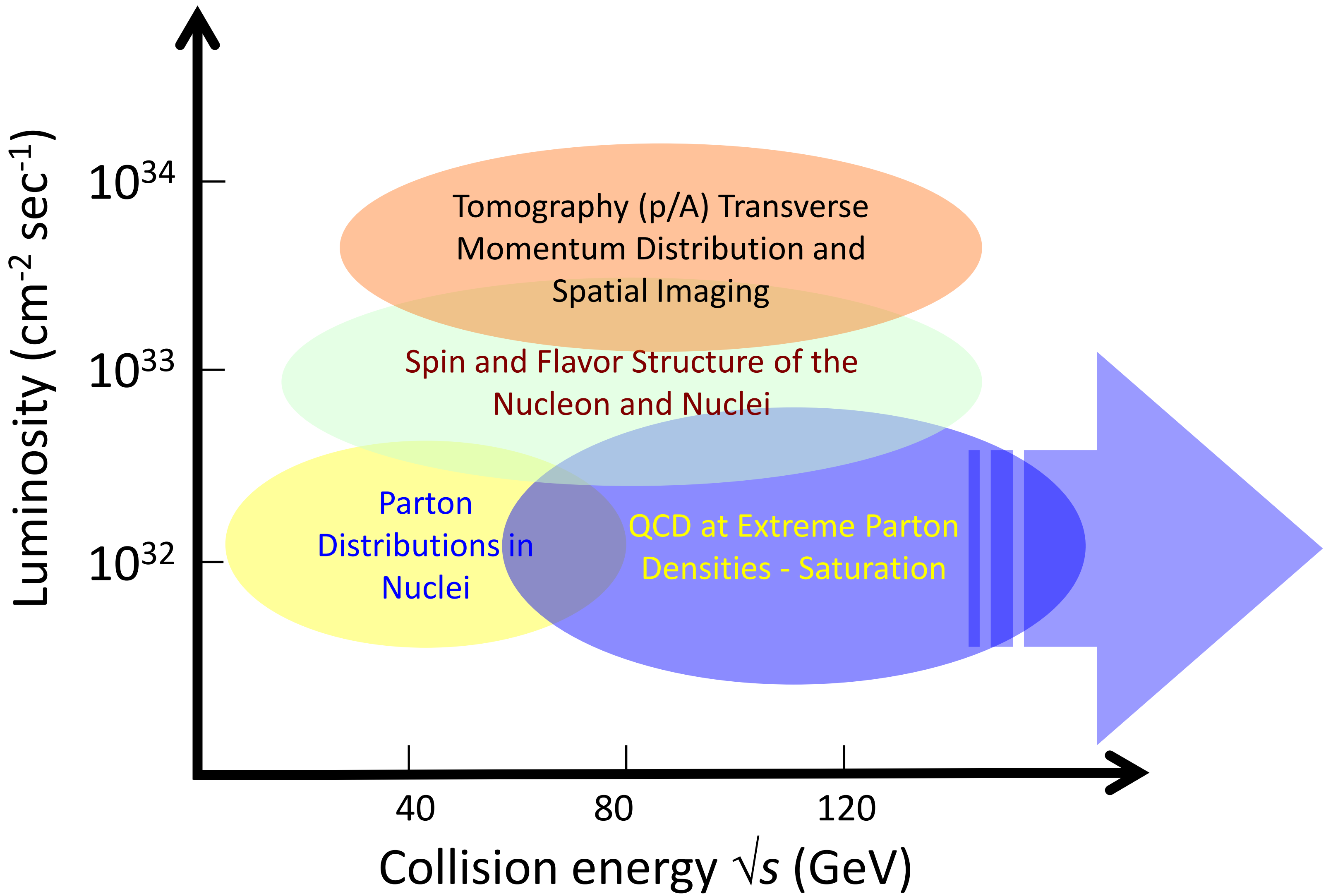
- Hadron and jet production from quarks and gluons in the nucleus (cold nuclear matter)
  - Response of nuclear matter to fast moving color charge passing through it?
  - Structure of jet?
- Mass dependence of hadronization
  - Energy loss by light vs. heavy quarks
- Comparison with hot nuclear matter (QGP)







EIC physics vs luminosity & energy



Development of lattice QCD

- Lattice QCD over the next decade will match or exceed experimental accuracy
  - Advances in computational technology
  - Need for computational projects
- Quark and gluon physics advances toward EIC as lattice QCD advances
- Study QCD by comparing precise theoretical calculations with precise experimental measurements to establish an understanding of nucleons, nuclei, and QGP

Supercomputer Fugaku

Summary of this talk

- Basics and history
  - Quark-gluon structure
- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation
  - Hadronization
  - Ultra-precise electron microscope, revealing the origin of mass and spin in three dimensions
  - Discovery of emergent high-density gluon state (gluon condensation)