EIC Master Plan

Radiation-Lab PHENIX/RHICf Meeting

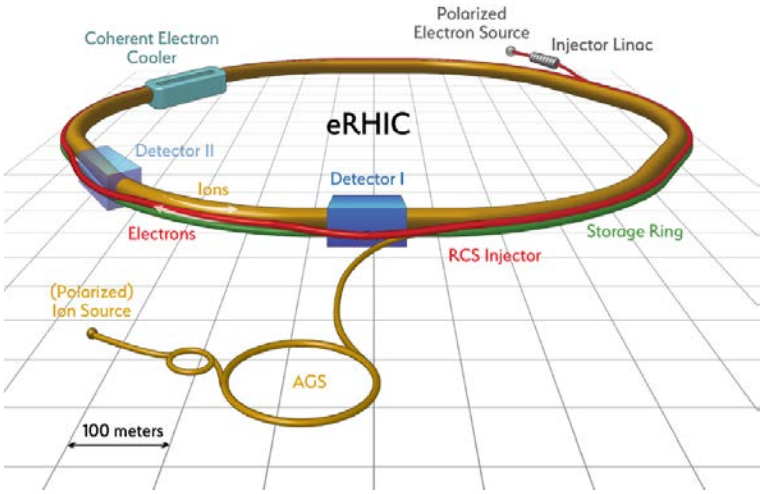
February 15th, 2019

Yuji Goto

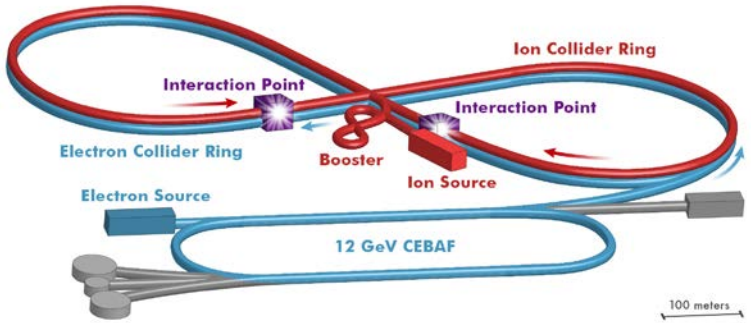
EIC (Electron Ion Collider) project

- High-energy QCD frontier to study nucleon (hadron) and nucleus (cold nuclear matter) from quarks and gluons
- World's first polarized electron + proton / light-ion / heavy-ion collider
  - Wide (Q^2, x) region
- Electron + proton / light-ion collision
  - Polarized beam
    - e, p, d/^{3}He
  - High luminosity
    - $L_{ep} \sim 10^{33\text{-}34}\ cm^{-2}s^{-1}$
    - 100-1000 times HERA
  - Collision energy
    - $\sqrt{s}$ = 20 – 100 (140) GeV
- Electron + heavy-ion collision
  - Wide range in nuclei

eRHIC at BNL

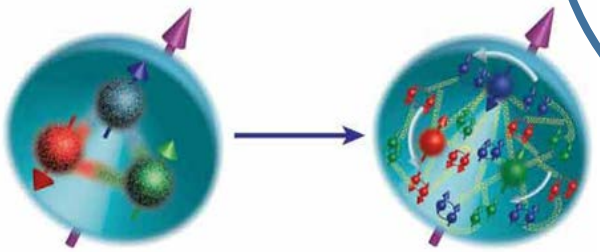


JLEIC at Jefferson Lab



Physics at EIC

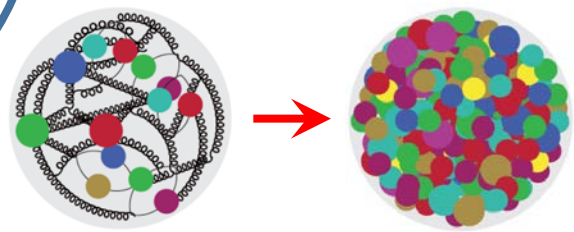
How does the nucleon with its structure and properties (mass, spin, …) emerge from quarks and gluons of QCD?



3D Picture of the Nucleons and Nuclei

- *Transverse -Momentum Distribution and Spatial Imaging*
- *Orbital Motion of Quarks and Gluons Inside*
- *Mass of the Nucleon*

How is the internal structure of the nucleons and nuclei systematically understood over a wide kinematical range?



New Picture

Precision Measurement

Discovery

Luminosity

Collision Energy

Spin and Flavor Structure of the Nucleons and Nuclei

- *Gluon Polarization*
- *Quarks and Gluons Inside the Nuclei*
- *Hadronization*

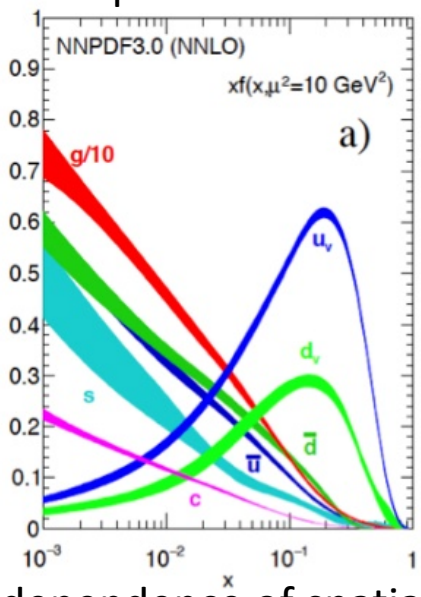
Gluon Saturation at Extreme Density

- *Emergent Properties of Dense System of Gluons*
- *Initial State of the QGP (Quark-Gluon Plasma)*

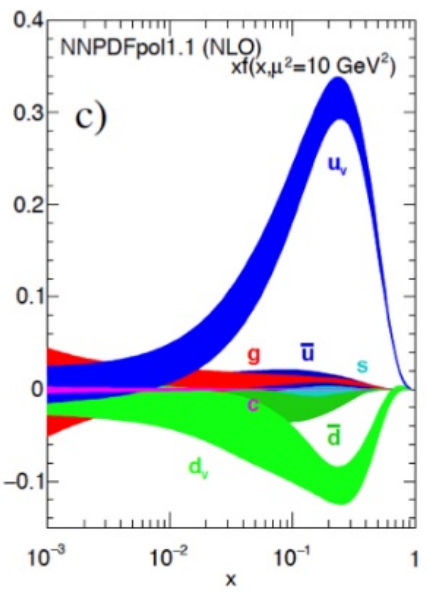
Quark-gluon structure

- 1-D picture
  - Parton distribution function (PDF) of quarks and gluons
  - *x*: momentum fraction of quarks and gluons
- 3-D picture
  - Generalized parton distribution (GPD) function
    - charge distribution
    - magnetic-moment distribution
    - mass distribution
  - Comparison of radii (R)
  - Orbital motion / orbital angular momentum
    - Ji's sum rule

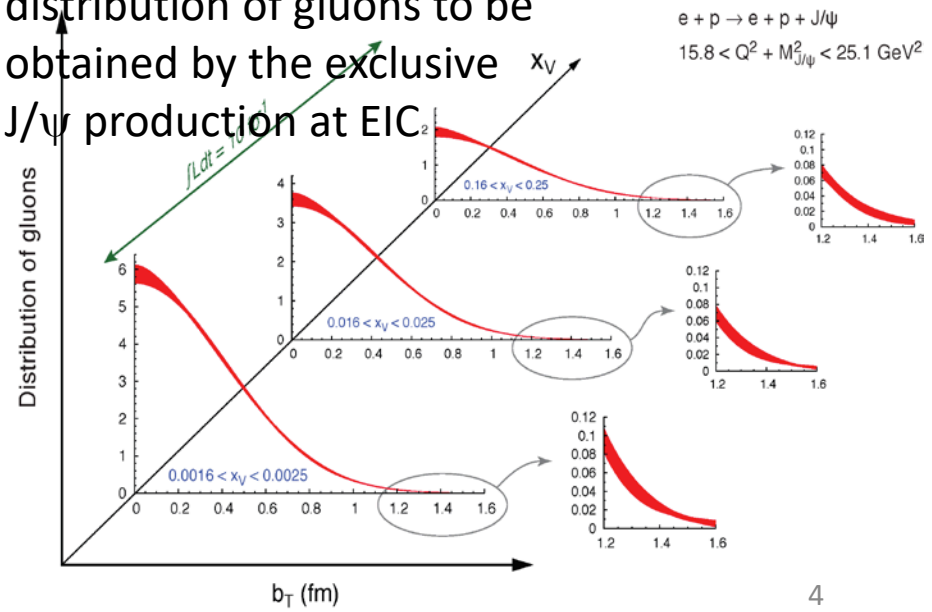
Unpolarized PDF



Polarized PDF

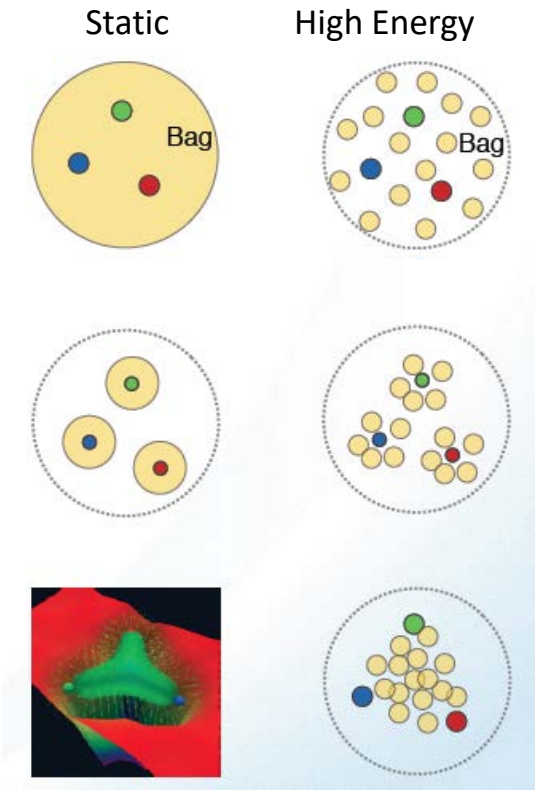


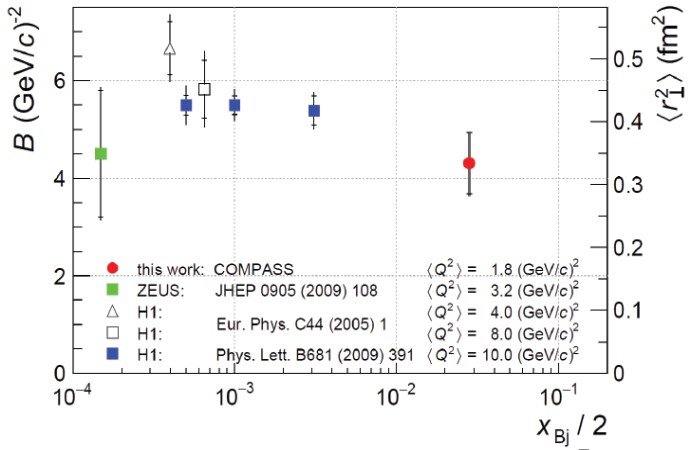
x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC



3D structure of the nucleon

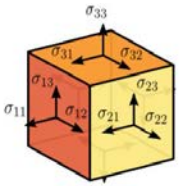
- How are quarks and gluons confined inside the nucleon?
  - Bag model
    - gluon radius > charged radius
  - Constituent quark model
    - gluon radius ~ charged radius
  - Lattice gauge theory (with slow moving quarks)
    - gluon radius < charged radius
- Proton tomography with DVCS measurement
  - R = 0.6 – 0.7 fm for gluon (HERA) and sea quark (COMPASS)
  - Smaller than 0.85 fm with EM interaction





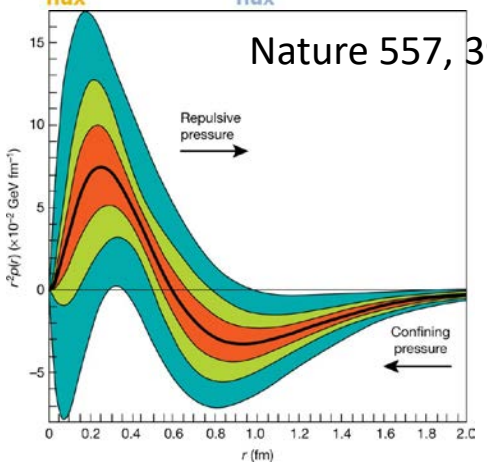
Generalization of the form factor

- Energy Momentum Tensor (EMT)
  - 3D distribution of mass, spin, pressure, etc. in the proton
  - 1st measurement of pressure in the proton using DVCS data from Jefferson Lab
- Sum rule for the nucleon mass
  - How to determine the different contribution not yet reached
  - Lattice QCD calculation
- Precision comparison of experiment and theory in the future
  - Mass, spin, pressure, radius,…

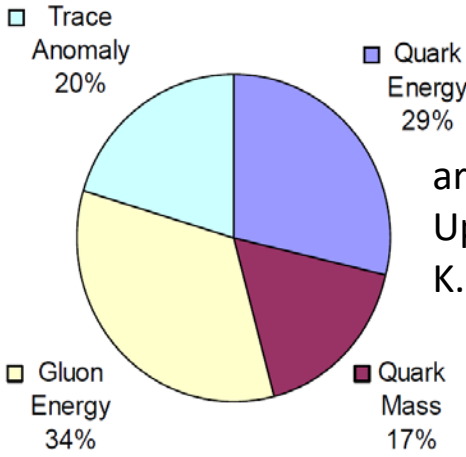


$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

Energy density; Momentum density; Shear stress; Normal stress (pressure); Energy flux; Momentum flux



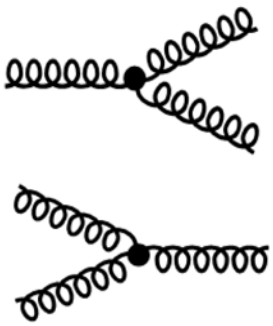
Nature 557, 396–399 (2018)

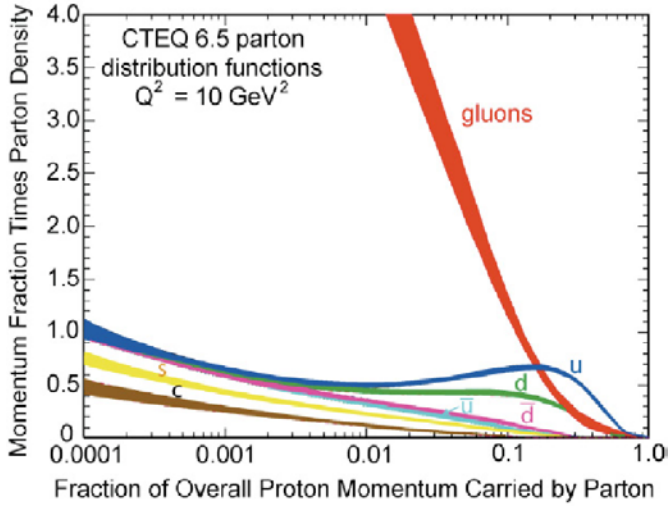


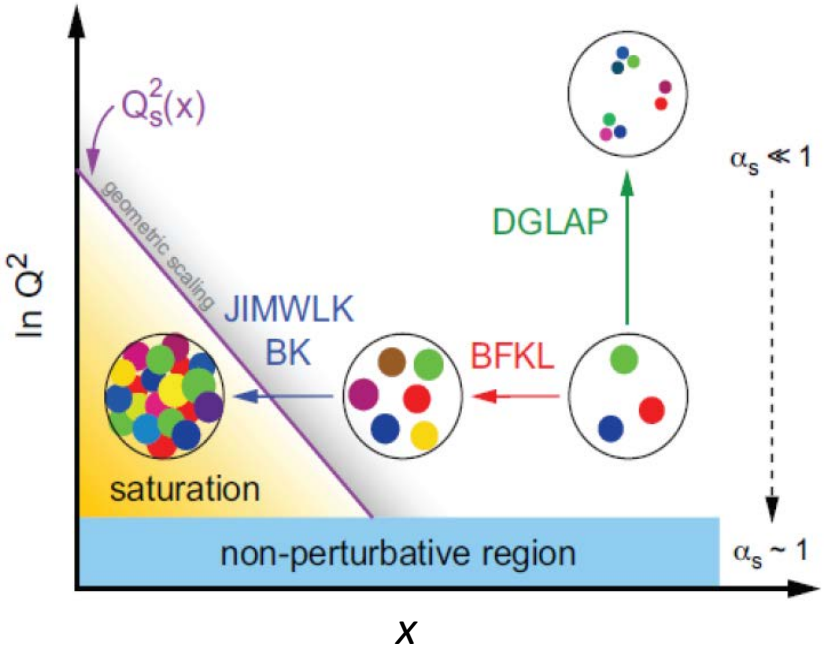
arXiv:1710.09011
Updated by
K.-F Liu et al.

Gluon saturation

- Gluon emission
  - Divergence at small x
- Gluon recombination
  - Restriction of divergence
- Gluon saturation in balanced
- First observation of a quantum collective gluonic system
  - Based on classical idea of the saturation
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism





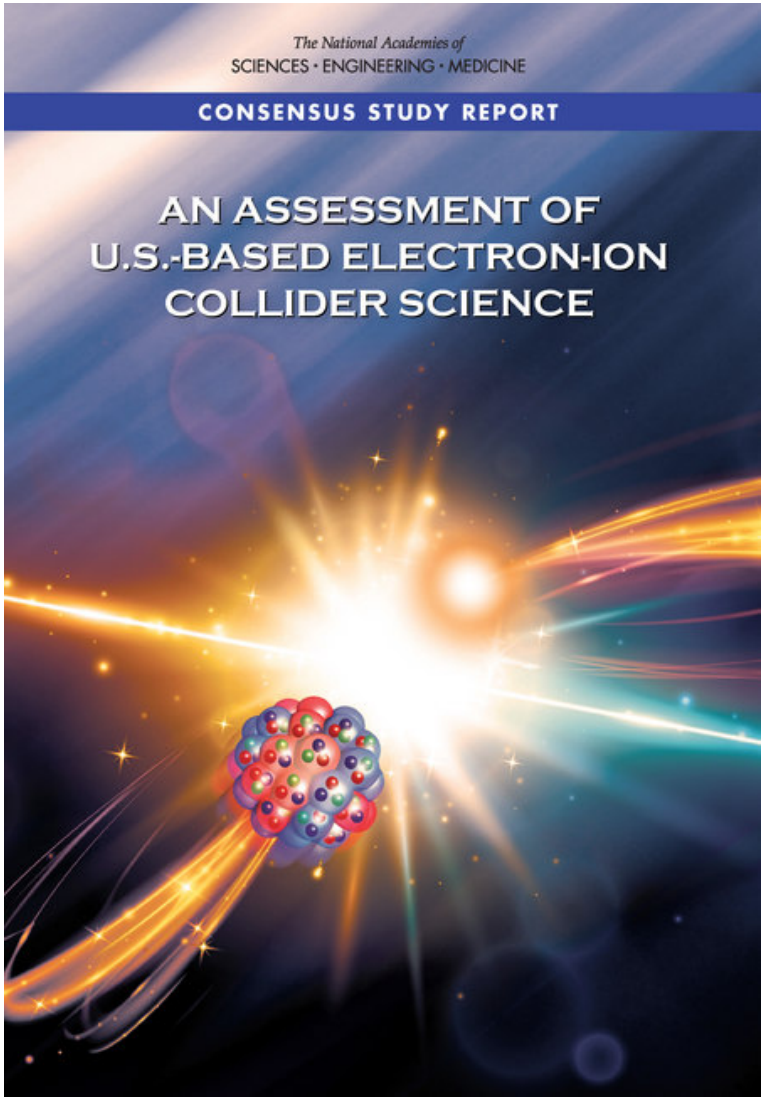


Other physics at EIC

- Hadronization
  - Cold nuclear matter (CNM) effects
  - Exotics
- Fundamental symmetries
  - LFV, weak F.F., etc.
- Polarized deuteron
  - Polarized neutron structure
  - Tensor polarization
- Short range correlations
  - EMC effect
- High-energy neutrino reaction

Status of the EIC project

- NSAC 2015 Long Range Plan
  - Highest priority for new facility construction after the completion of FRIB
- NAS (National Academies of Sciences, Engineering, and Medicine) review request by DOE
  - US-based EIC Science Assessment
- NAS webinar and NAS report release 7/24/2018
  - Science that can be addressed by an EIC is compelling, fundamental and timely
- CD-0 (US mission need statement) could be awarded in 2019



Status of the EIC project

- Site selection may occur around 2019/2020
- EIC facility construction has to start after FRIB completion, with anticipated FRIB construction to ramp down around 2020
- Optimistic scenario would have EIC funds start in FY20, more realistically begin of construction funds in FY22/FY23 time frame
- Completion of EIC facility construction would be around 2025-2030 timeframe

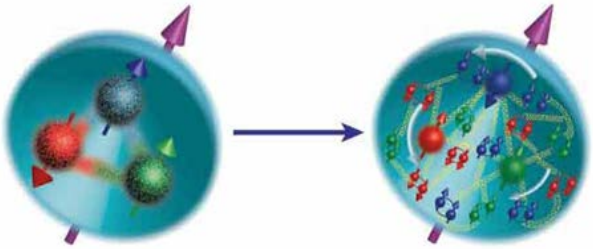
Master Plan 2020

- EIC-Japan Collaboration
- Leading Univ / Inst
  - Yamagata Univ / RIKEN
- Collaboration Univ/Inst
  - Tokyo Tech / Kobe Univ / Nihon Univ / KEK / Kyorin Univ / Niigata Univ / …
- Contributing to construct a Day-1 Detector for the EIC
  - Forward / backward calorimeter systems
  - R&D: 2019 – 2024
  - Construction: 2025 – 2030
  - Estimated cost: $35M
- EIC R&D
  - Generic Detector R&D for an Electron Ion Collider
    - Operated by BNL with ~$1M / year
  - Very forward measurement
    - Radiation tolerance
    - Position-sensitive calorimeter R&D

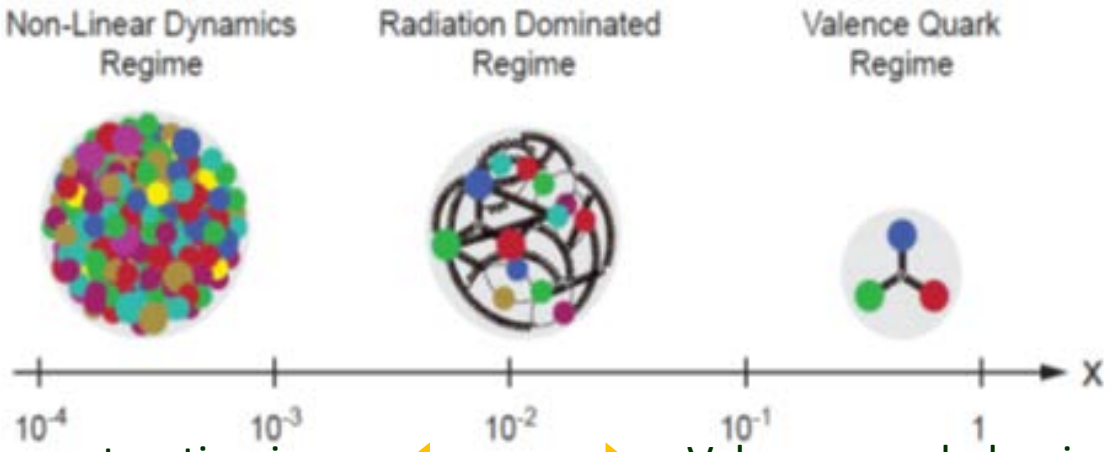
Backup Slides

Physics at EIC

- How does the nucleon with its structure and properties (mass, spin,…) emerge from quarks and gluons of QCD?
  - Precision measurement of PDFs
  - Tomography of the nucleon / nucleus

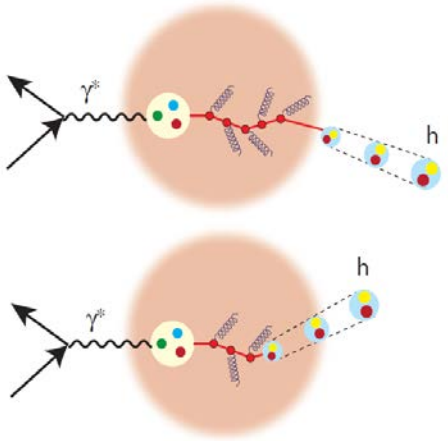


- Gluon saturation
  - Emergent properties of dense systems of gluons
- Hadronization



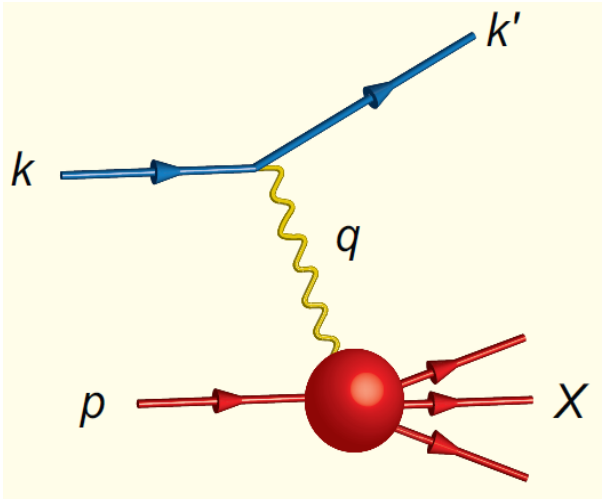
Gluon saturation in small Bjorken-x region

Valence quark dominant in large Bjorken-x region



Precision measurement of PDFs

- Inclusive DIS
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
  - 1D longitudinal motion of partons
- Spin puzzle
  - Gluon polarization measurement with polarized DIS
    - Small Bjorken-x region with QCD evolution (DGLAP equation)



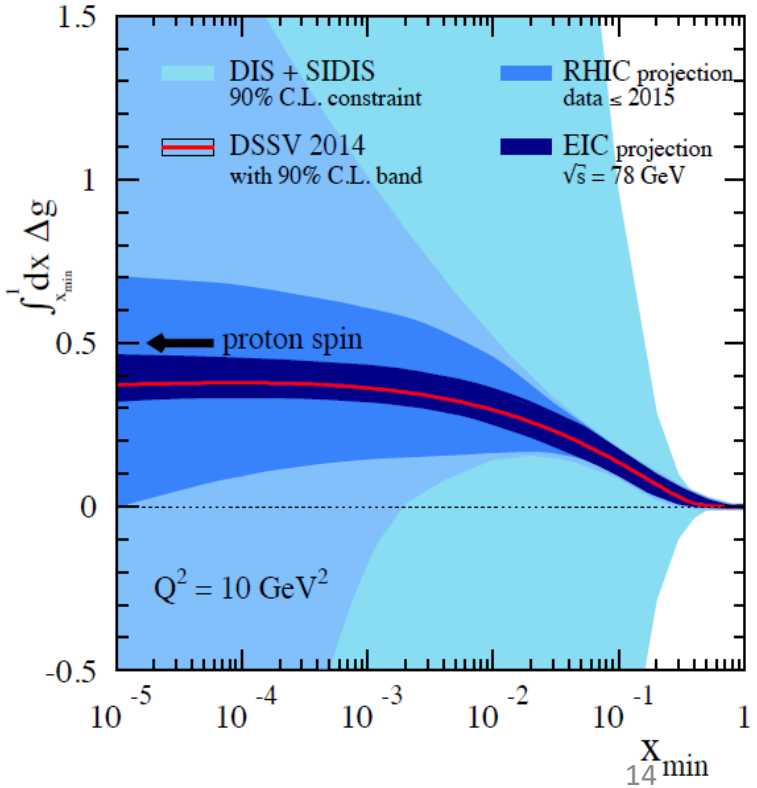
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin

L_Q = Quark Orbital Ang. Mom

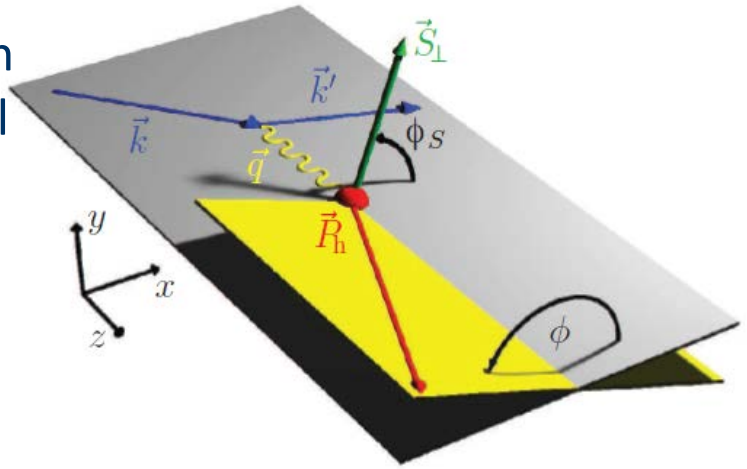
Δg = Gluon contribution to Proton Spin

L_G = Gluon Orbital Ang. Mom



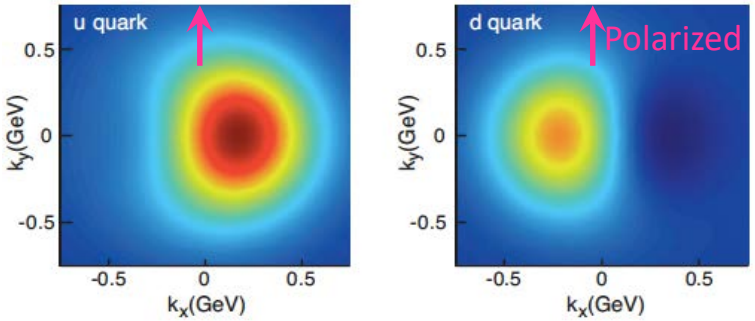
Precision measurement of PDFs

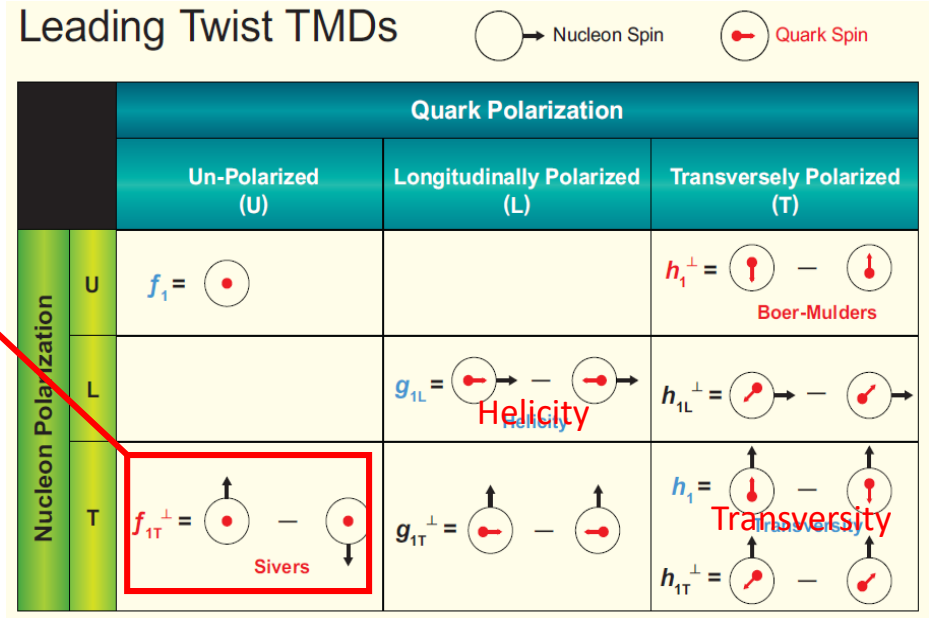
- Semi-Inclusive DIS (SIDIS)
  - Flavor dependence of the quark polarization
  - Transverse-momentum dependence (orbital motion)
- TMD distribution function
  - TMD = Transverse Momentum Dependent
  - Quark, anti-quark, gluon
  - 3D distribution incl. transverse momentum
  - Correlation of spin and parton orbital motion



Sivers function:
Correlation of the nucleon spin and the parton transverse momentum

Sivers function at x = 0.1

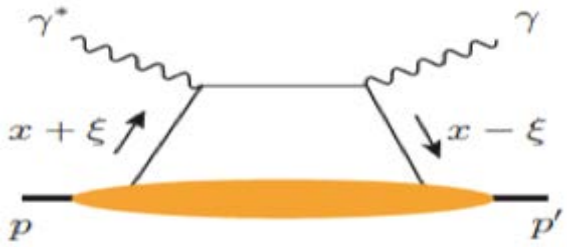




Tomography of the nucleon / nucleus

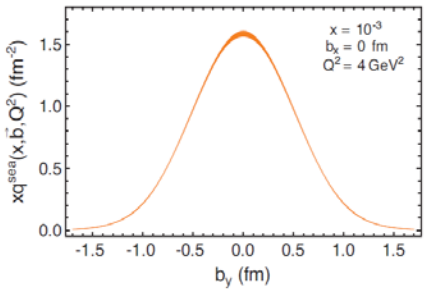
- DVCS
  - Deeply virtual Compton scattering
  - Exclusive process
- GPD
  - Generalized Parton Distribution
  - Spatial distribution in the transverse direction = tomography

DVCS (Deeply Virtual Compton Scattering)

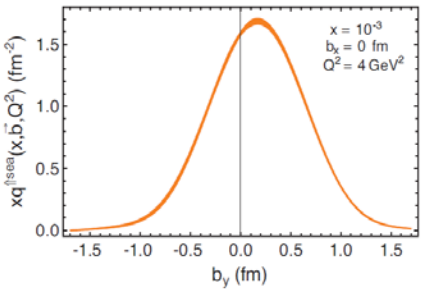


Spatial distribution of sea quarks in unpolarized proton (left) and polarized proton (right) at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane

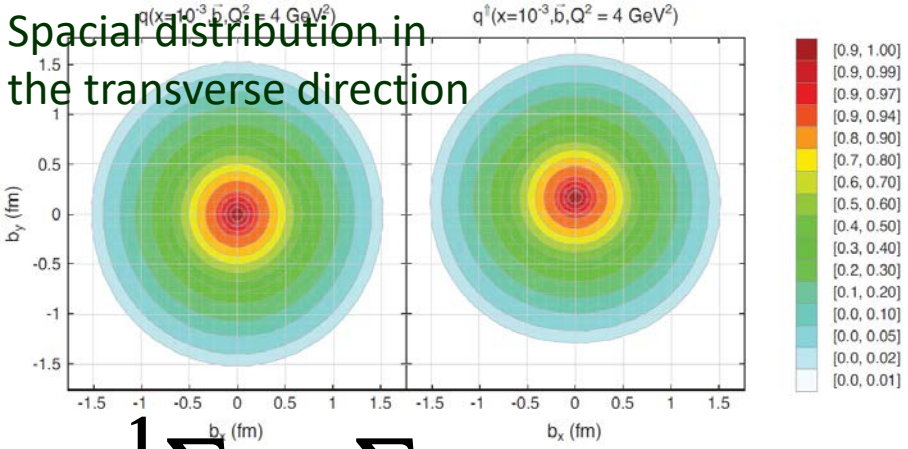
Unpolarized



Polarized



Spacial distribution in the transverse direction



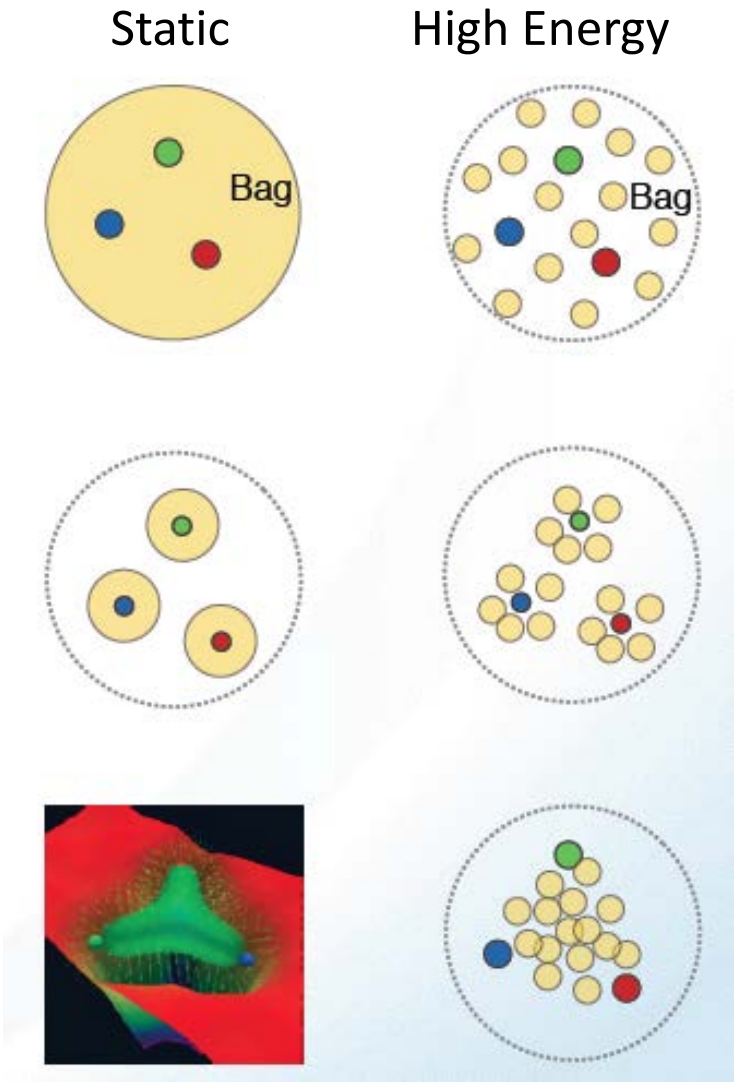
- Orbital angular momentum
  - Ji's sum rule

$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q \mathcal{L}_q^z$$

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

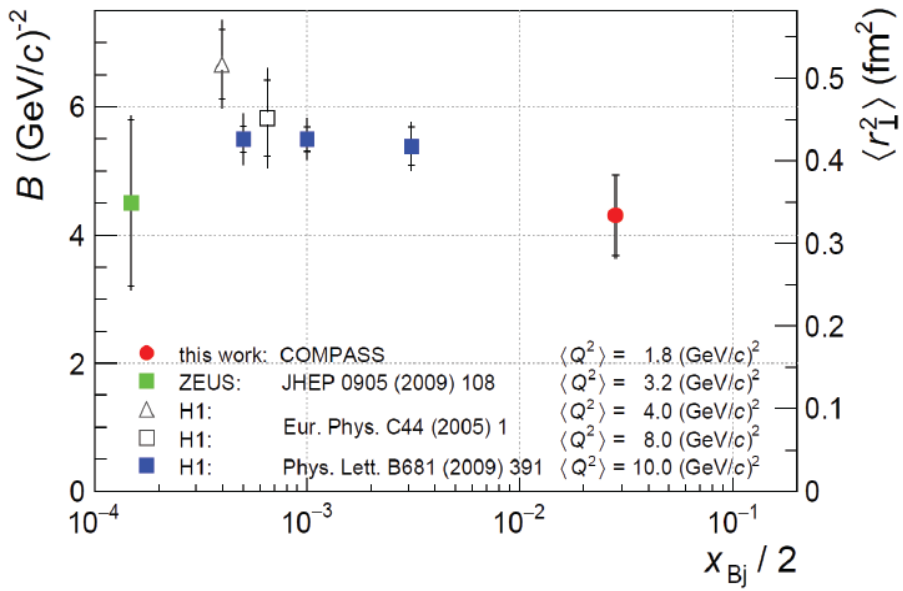
3D structure of the nucleon

- How are quarks and gluons confined inside the nucleon?
  - Bag model
    - Gluon field distribution is wider than the fast moving quarks
    - gluon radius > charged radius
  - Constituent quark model
    - Gluons and sea quarks hide inside massive quarks
    - gluon radius ~ charged radius
  - Lattice gauge theory (with slow moving quarks)
    - Gluons more concentrated inside the quarks
    - gluon radius < charged radius
- Need measurement of transverse images of the quarks and gluons in the nucleon
  - How can the properties of nucleon (hadron) at low energy and at high energy combine?



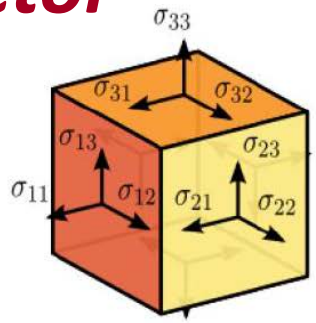
Proton radius

- Proton tomography with DVCS measurement
  - R = 0.6 – 0.7 fm for gluon (HERA) and sea quark (COMPASS)
  - Smaller than 0.85 fm with EM interaction



Generalization of the form factor

- Energy Momentum Tensor (EMT)



Energy density

Momentum density

$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

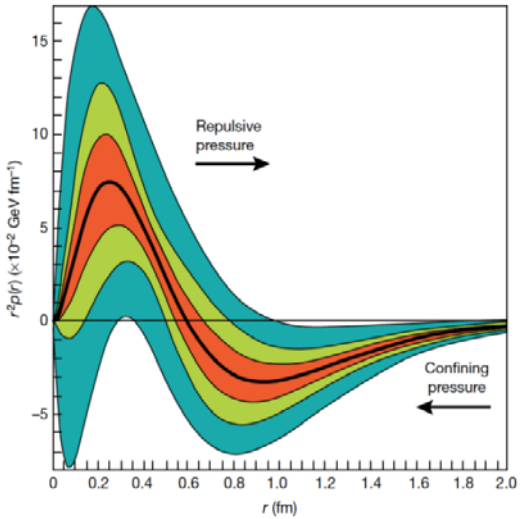
Shear stress

Normal stress (pressure)

Energy flux

Momentum flux

- 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

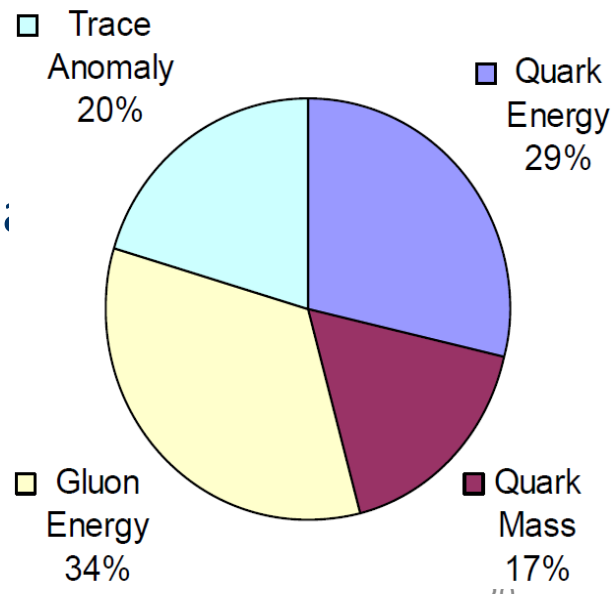
Quantum Fluctuations

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

X. Ji, PRL 74 1071 (1995)

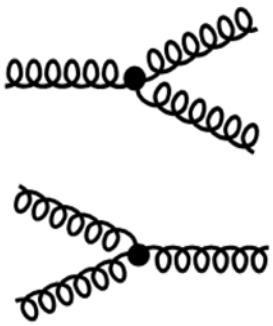
Quark Energy **Gluon Energy** **Quark Mass** **Trace Anomaly**

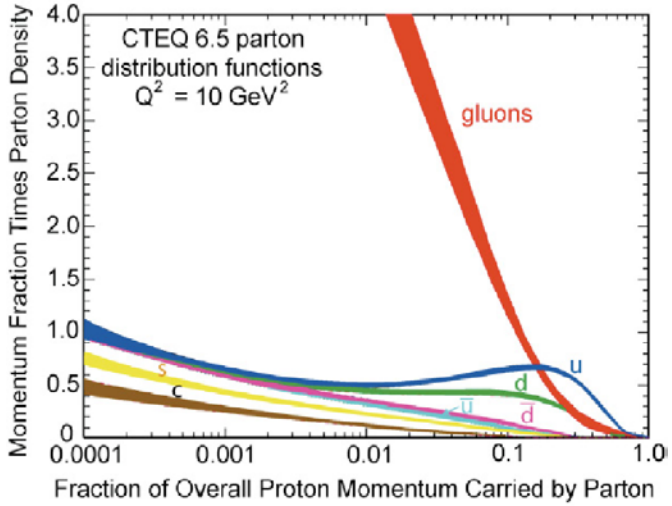
  - How to determine the different contribution not yet reached
- Lattice QCD calculation
  - arXiv:1710.09011, update by K.-F. Liu et a
- Precision comparison of experiment and theory in the future
  - Mass, spin, pressure, radius,…



Gluon saturation

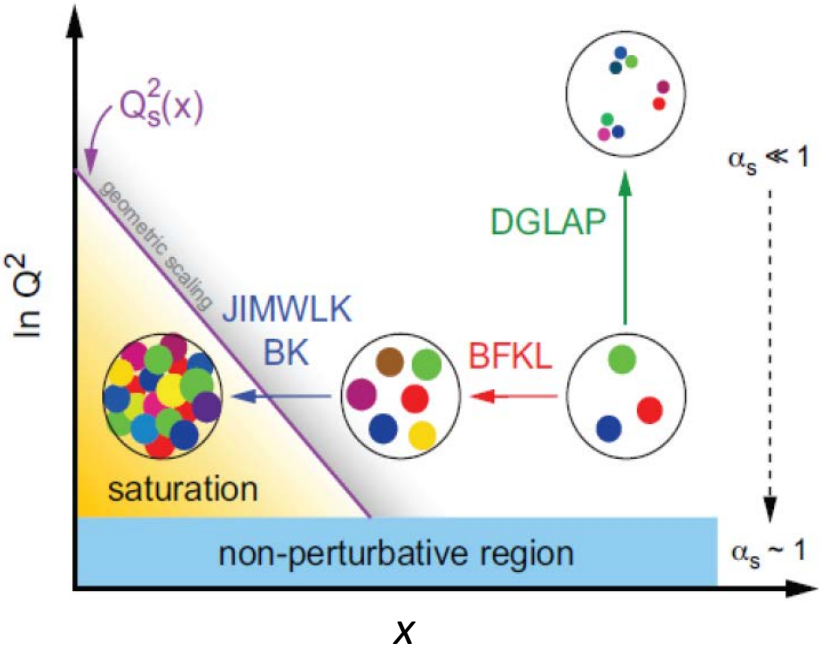
- Gluon emission
  - Divergence at small x
- Gluon recombination
  - Restriction of divergence
- Gluon saturation in balanced





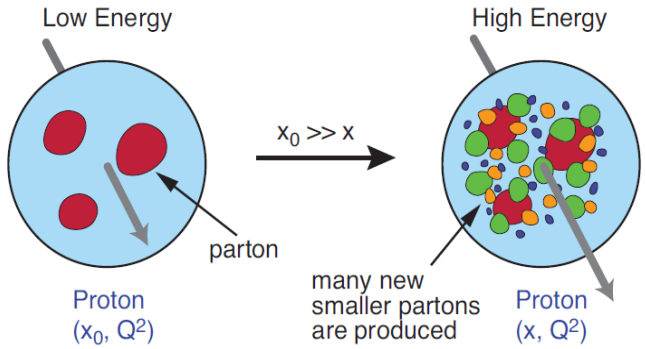
gluon emission = gluon recombination at Q_S

- First observation of a quantum collective gluonic system
  - Based on classical idea of the saturation



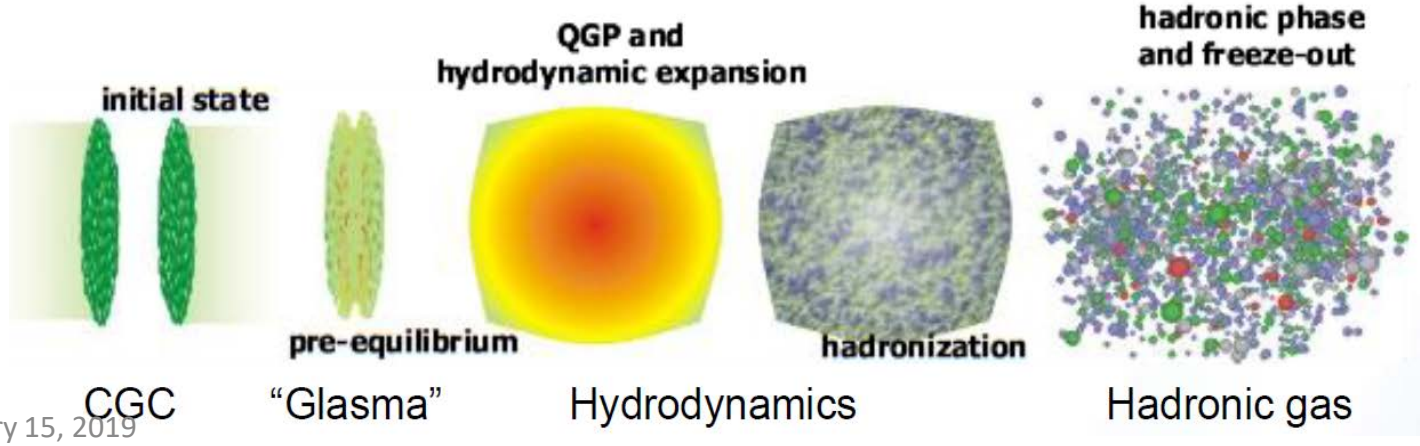
Gluon saturation

- Precision comparison of experiment and Chiral Glass Condensate (CGC) as a theoretical model of the gluon saturation
  - Not understandable classically if not discovered?



"Color Glass Condensate"

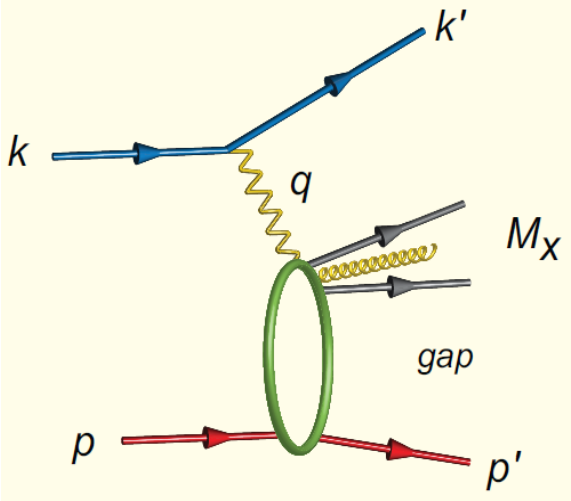
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism

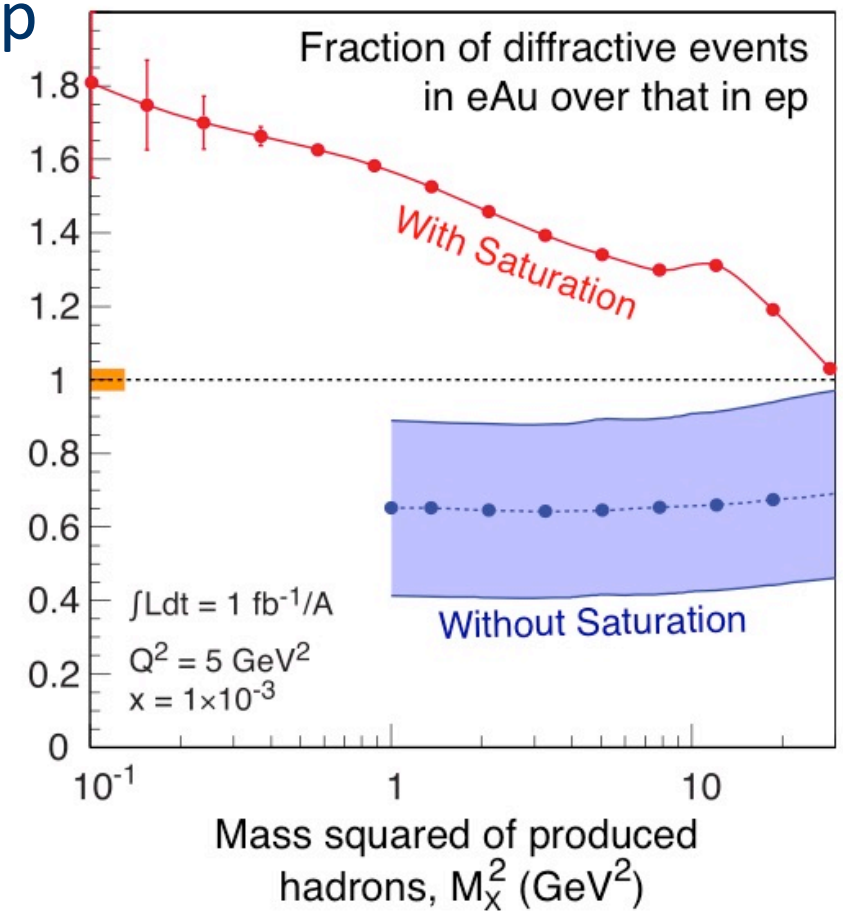


Gluon saturation

- Diffractive cross section
  - Most sensitive way to study the gluon saturation
- 10-15% diffractive at HERA e+p
- 25-30% diffractive predicted by CGC at EIC e+A

$$\sigma_{\mathrm{diff}} \propto [g(x, Q^2)]^2$$



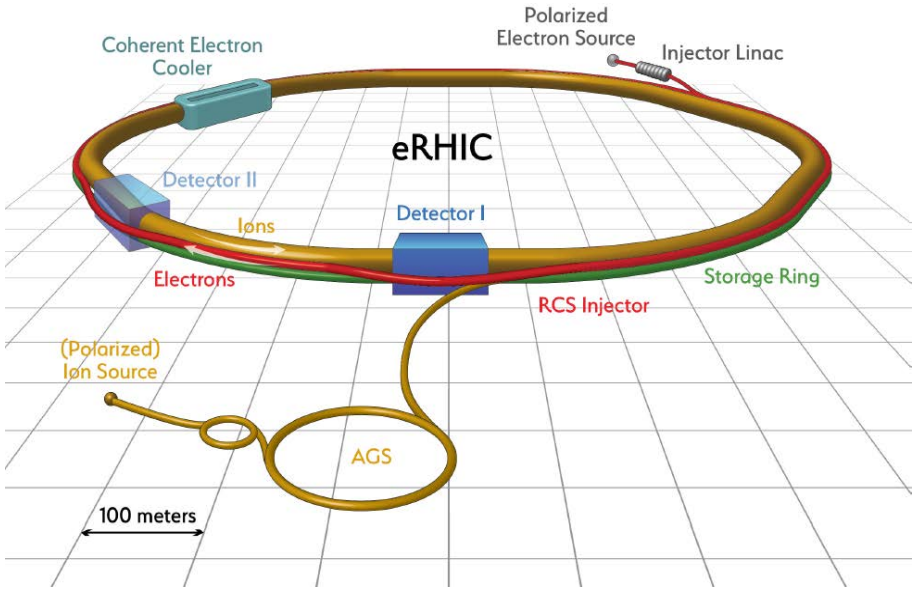


Summary

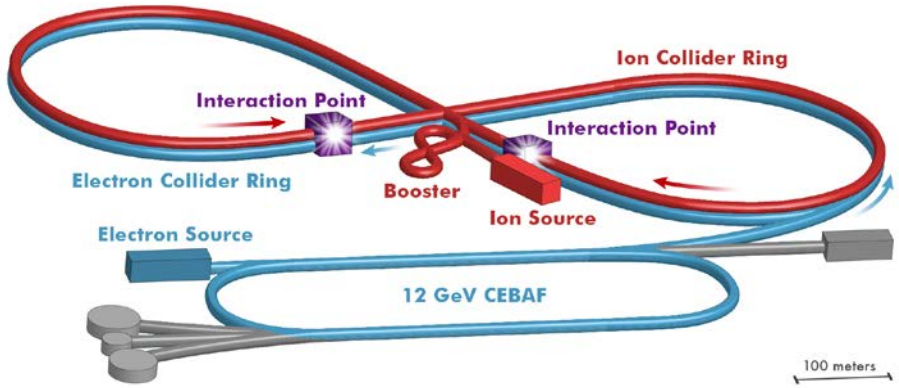
- Physics at EIC
  - High-energy QCD frontier to study nucleon (hadron) and nucleus (cold nuclear matter) emerging from quarks and gluons
    - Precision measurement of PDFs
    - Tomography of the nucleon and nucleus
  - First observation of a quantum collective gluonic system
    - Gluon saturation
  - Hadronization, many other topics
- Status of the EIC project
  - NAS webinar & report release 7/24/2018
  - CD-0 ~2018/2019, site selection ~2019/2020
  - Construction start in 2020-23, completion in 2025-30
- Large international collaboration
  - EIC Users Group and R&D activities ongoing
  - Resources of successful RIKEN-BNL collaborations
  - Good experiences for young students & postdocs

Electron Ion Collider (EIC) Project

eRHIC at Brookhaven Natl Lab



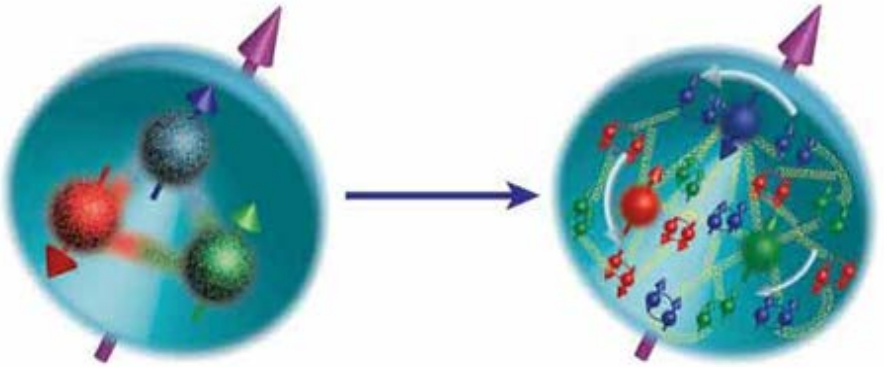
JLEIC at Jefferson Lab



- World's first polarized electron + proton / light-ion / heavy-ion collider
  - High-energy QCD frontier to study the nucleons and nuclei from quarks and gluons
- EIC-Japan Collaboration
  - Leading Univ / Inst
    - Yamagata Univ / RIKEN
  - Collaboration Univ/Inst
    - Tokyo Tech / Kobe Univ / Nihon Univ / KEK / Kyorin Univ / Niigata Univ / …
  - Contributing to construct a Day-1 Detector for the EIC
    - Forward / backward calorimeter systems
    - R&D: 2019 – 2024
    - Construction: 2025 – 2030
    - Estimated cost: $35M

Nucleon puzzles

- Two pictures



static picture
low energy
low resolution

dynamic picture
high energy
high resolution

Constituent quark picture

explaining magnetic moment
of nucleon/hadron

Quark-gluon picture

Nucleon spin puzzle:
only 30% of the nucleon spin
is contributed by the quark spin

?

Orbital angular momentum

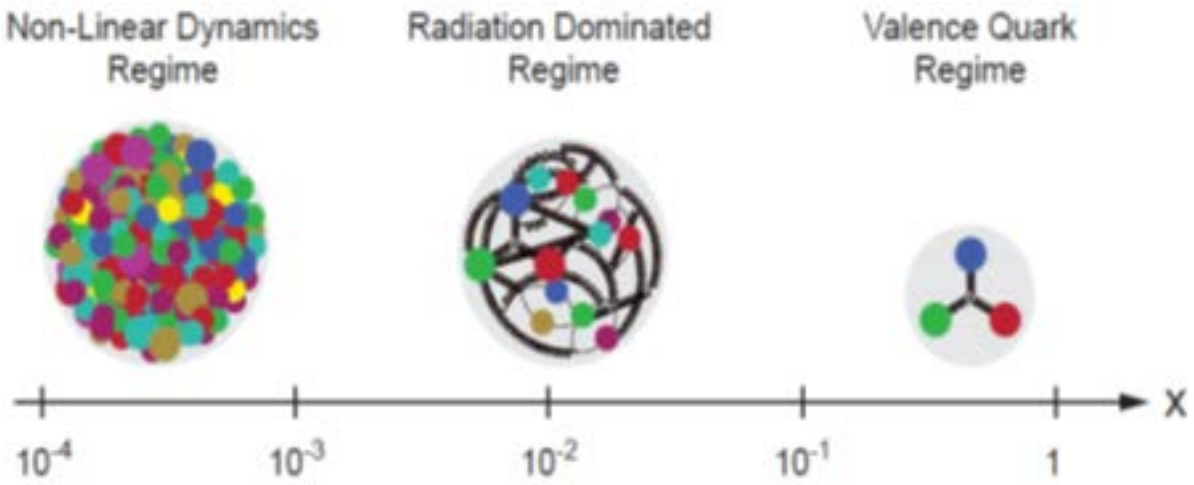
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Quark spin — Gluon spin

How can the constituent quark be explained by the quark+gluon?
Impossible? No correspondence?

Quark-gluon structure

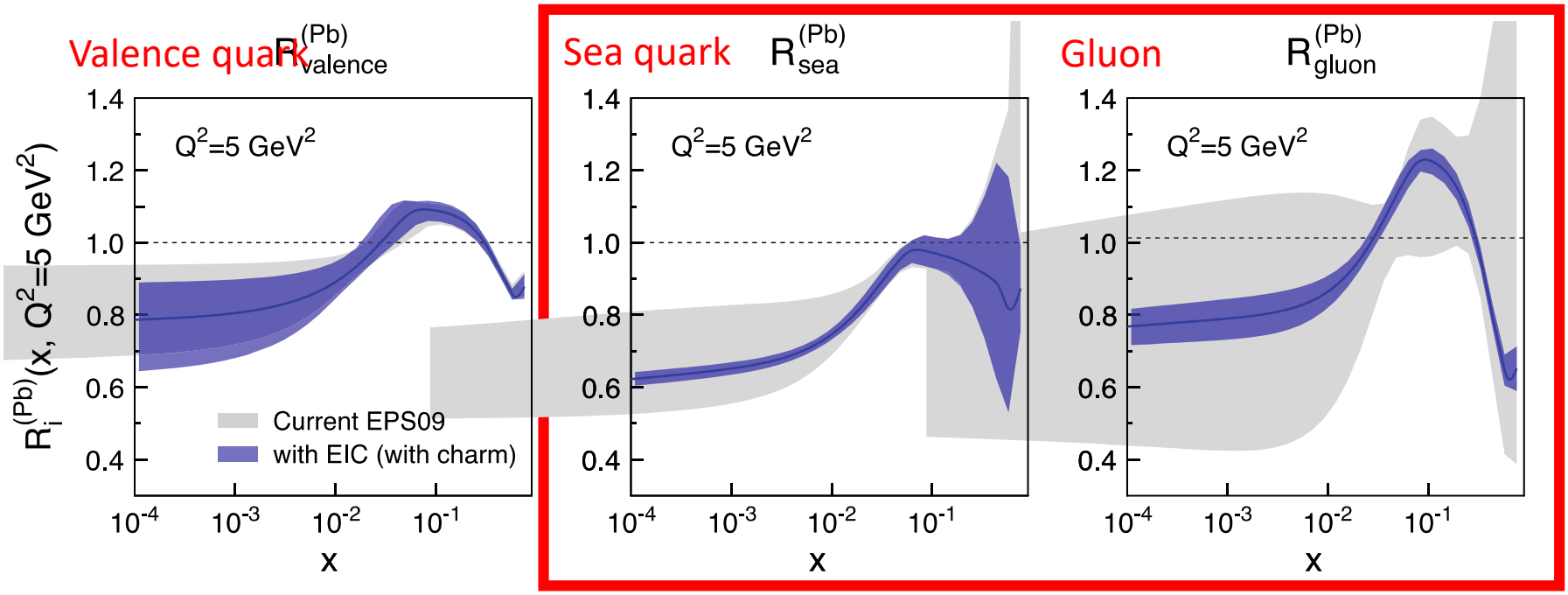
- Establishing new 3-D picture of the nucleon



  - Gluon saturation at small-x
    - Color Glass Condensate (CGC) $\rightarrow$ Quark Gluon Plasma (QGP)
- Nucleon puzzles
  - Spin, radius, mass, pressure…
  - and more for standard model & beyond, stability of universe…
    - Neutron EDM, Neutron lifetime, Proton lifetime…
  - Importance of precise comparison with Lattice QCD

Precision measurement of PDFs

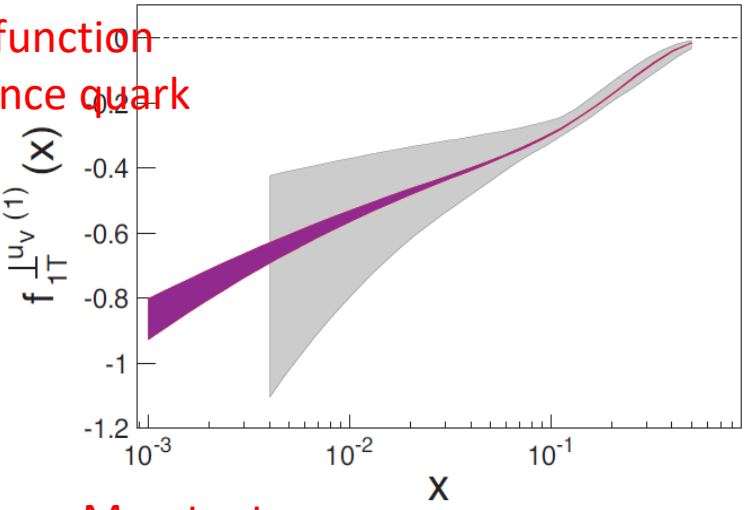
- Nuclear PDF (nPDF)
  - For sea quark and gluon
  - Unreachable at present (and future) LHC and RHIC
  - Gluon saturation at small Bjorken's *x*

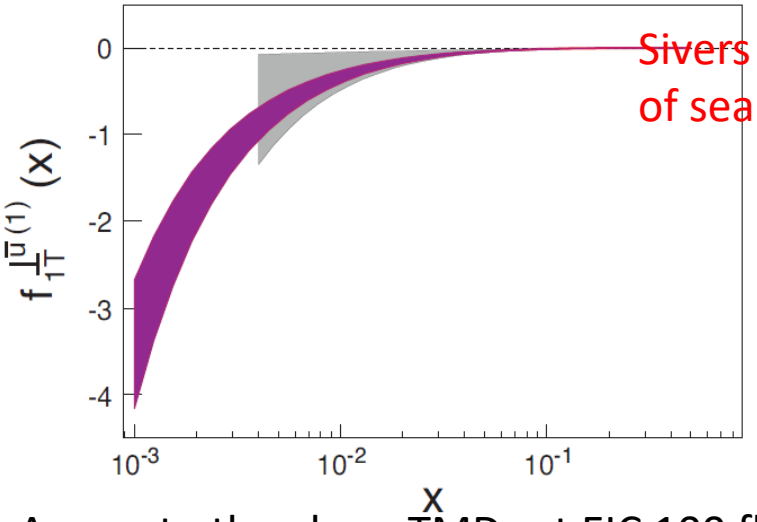


TMDs at EIC

Sivers function extracted for valence (left) and sea (right) up quarks from (grey) currently available data and (purple) projection at EIC $\sqrt{s}$ = 45 GeV, 10 fb^{-1}

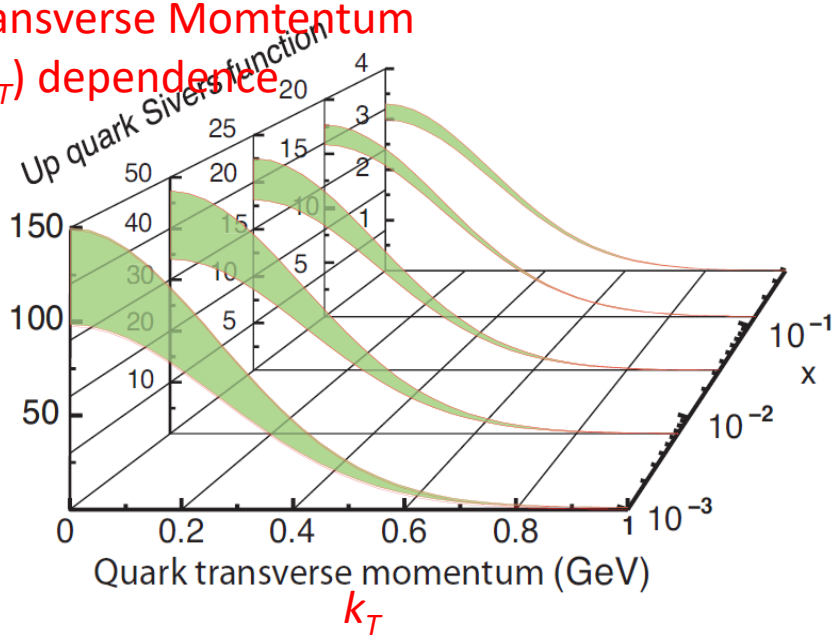
Sivers function of valence quark



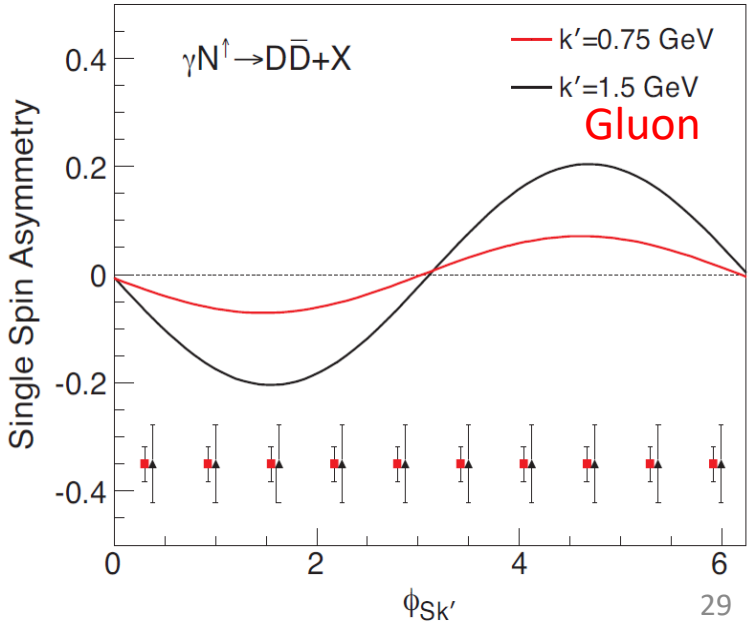


Sivers function of sea quark

Transverse Momtentum (k_T) dependence

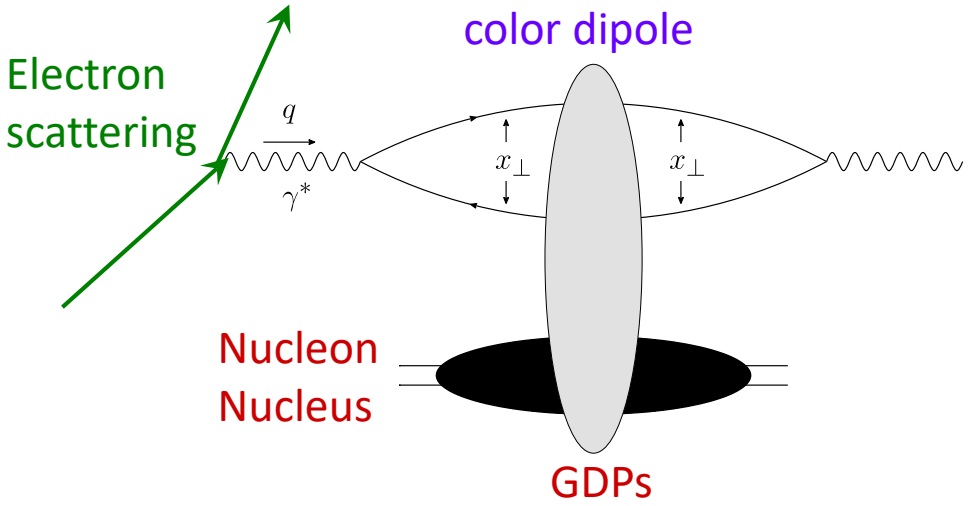


Access to the gluon TMDs at EIC 100 fb^{-1}

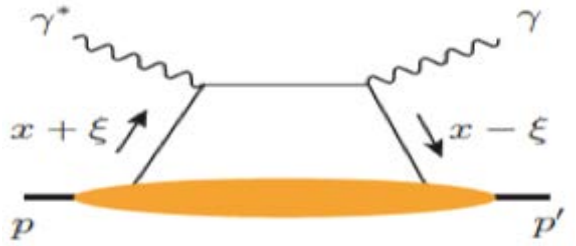


Tomography of the nucleon / nucleus

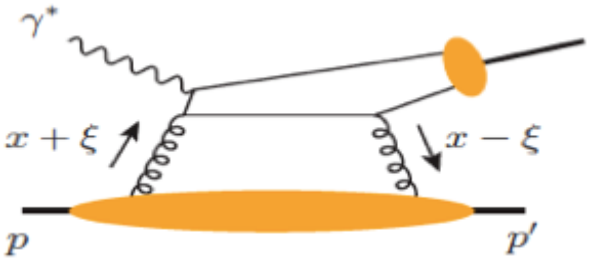
- EIC = color dipole microscope



DVCS (Deeply Virtual Compton Scattering)



Meson Production

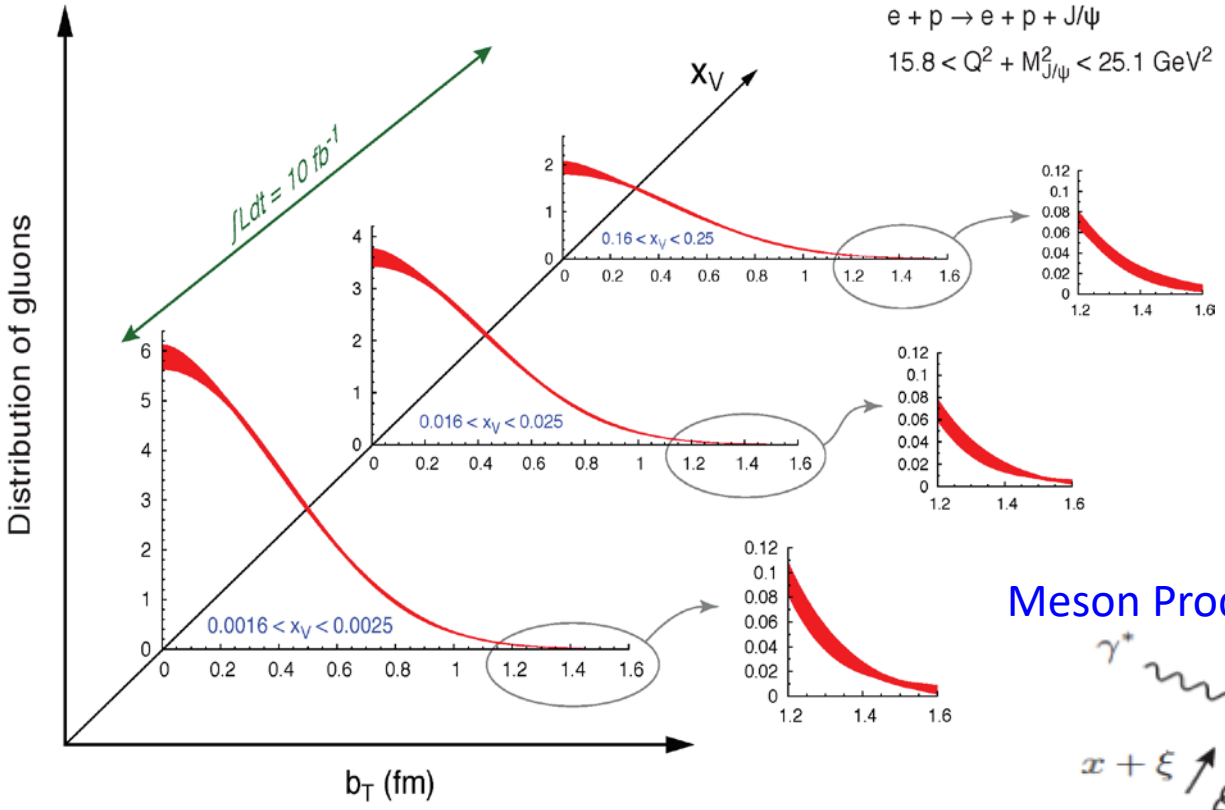


J/ψ, ϕ, ρ, etc.

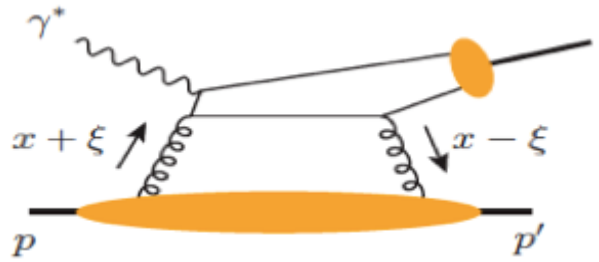
- Spatial imaging of gluons and quarks with exclusive process and diffractive process
  - HERA: 1st generation
  - EIC: 2nd generation (high luminosity, heavy ion, polarization)
- Gluon saturation study with gluon tomography

Tomography of the nucleon / nucleus

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



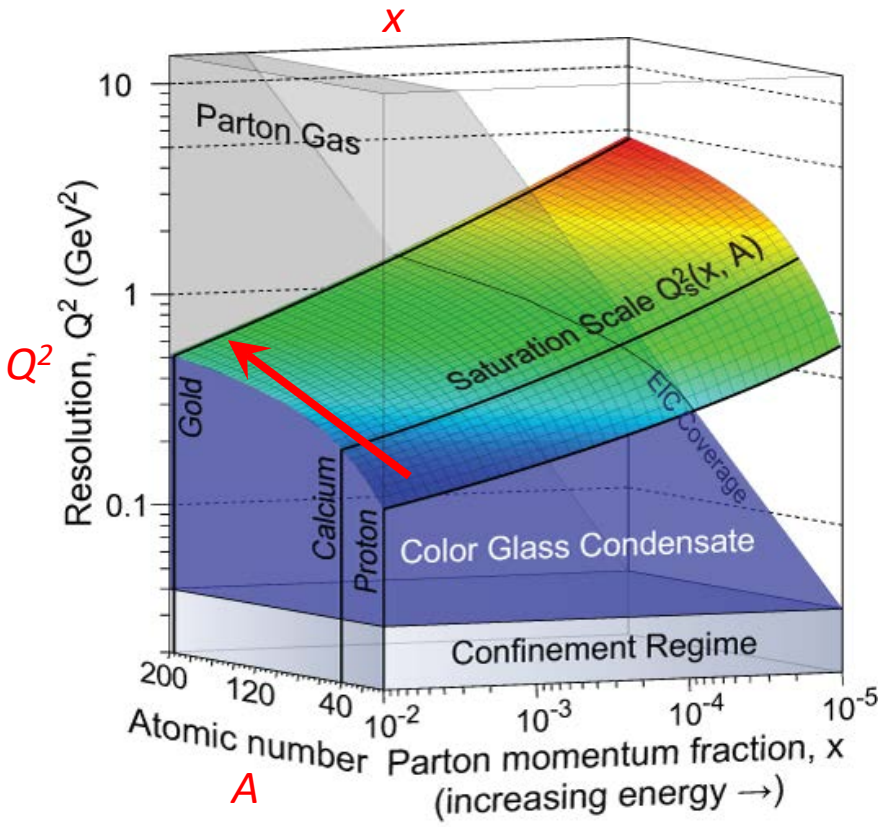
Meson Production

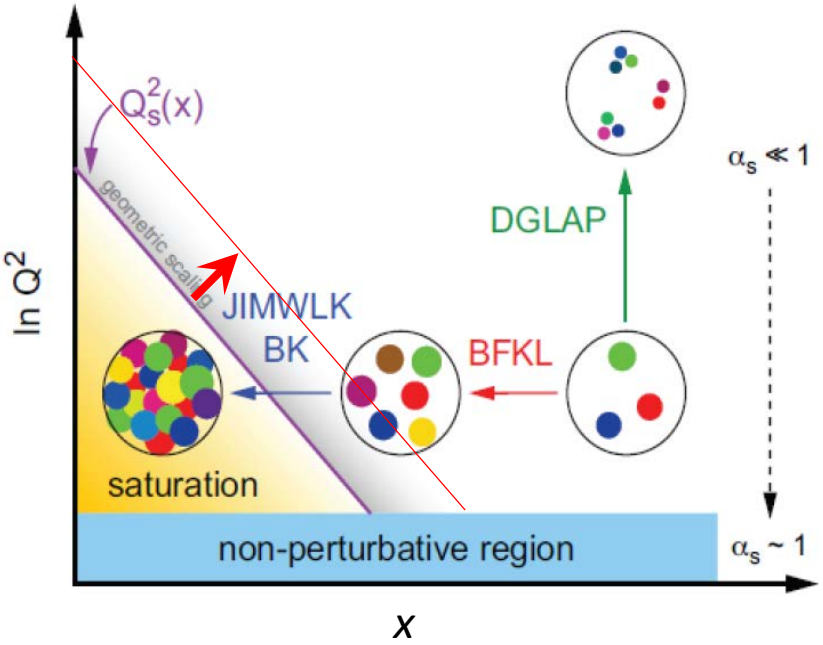


J/ψ, ϕ, ρ, etc.

Gluon saturation

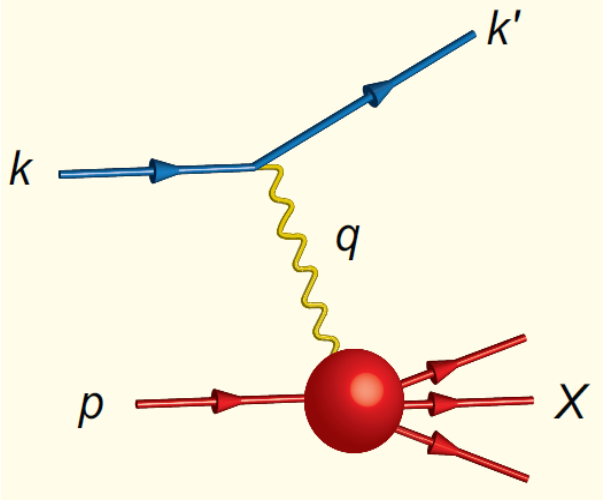
- Enhancement of the Q_s^2 scale with nucleus
  - Electron + ion collision

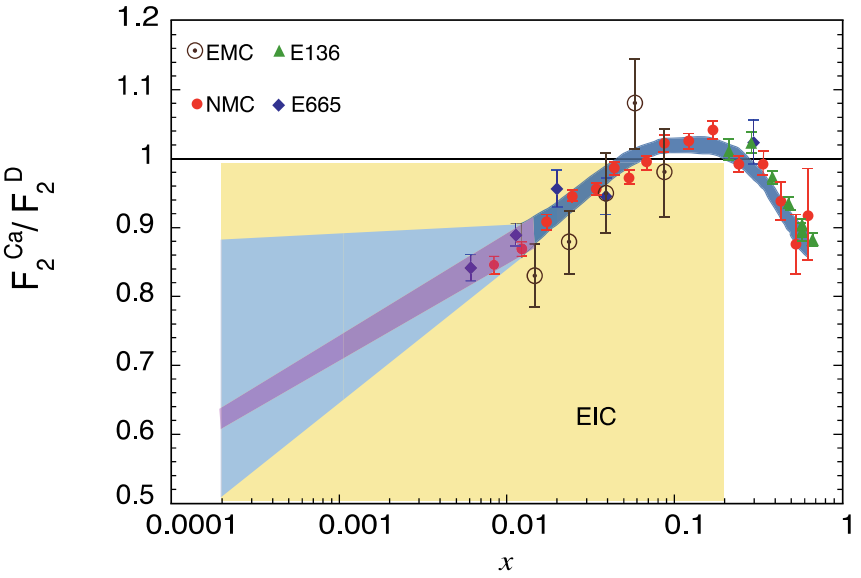




Gluon saturation

- Inclusive DIS
- Probed by the change of the nuclear structure functions
- Ratio of the structure function F2
  - How quark / gluon distribution and interaction affected in the nucleus?
  - Fermi motion, EMC effect, shadowing, saturation

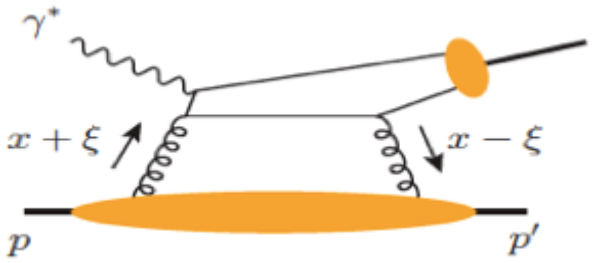




3D structure of the nucleus

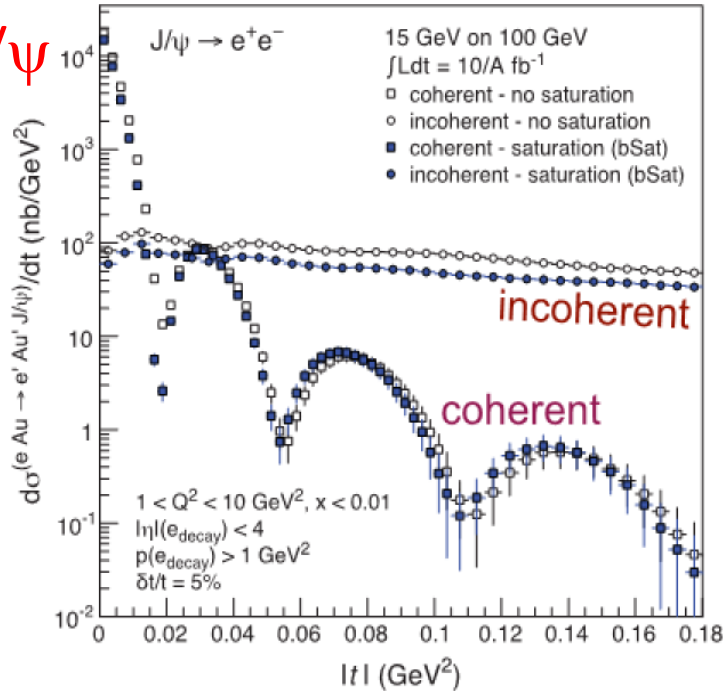
- Diffractive vector meson production
  - ϕ meson sensitive to the gluon saturation

Meson Production

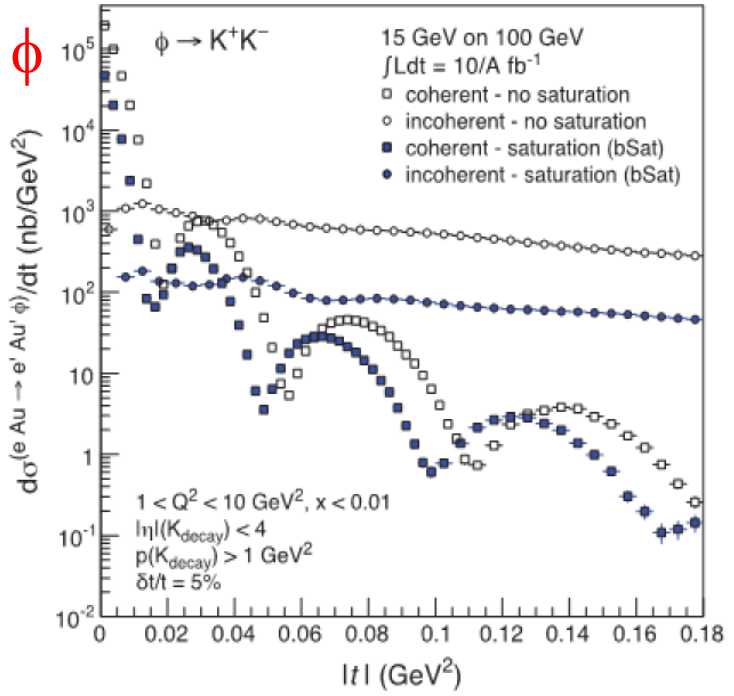


J/ψ, ϕ, ρ, etc.

J/ψ

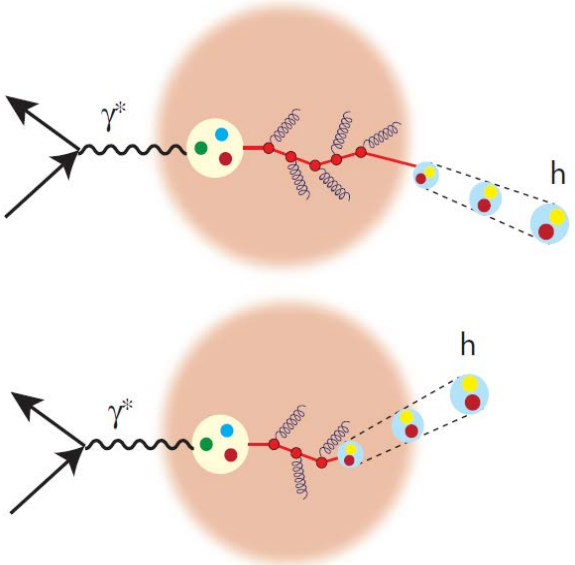


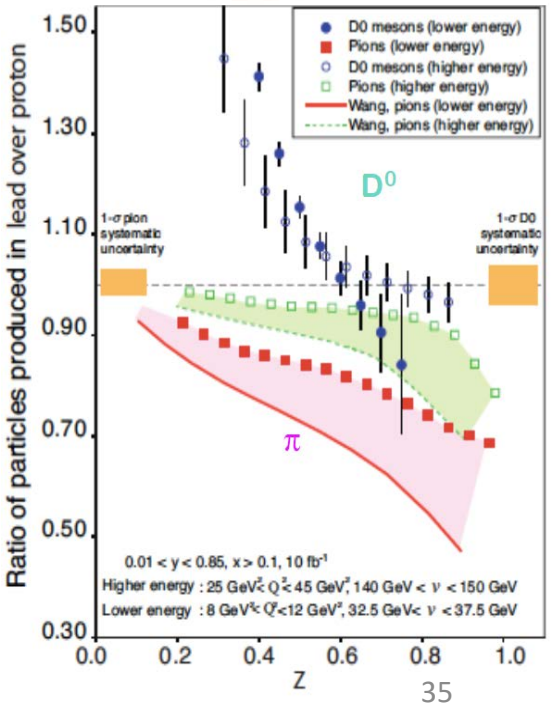
ϕ



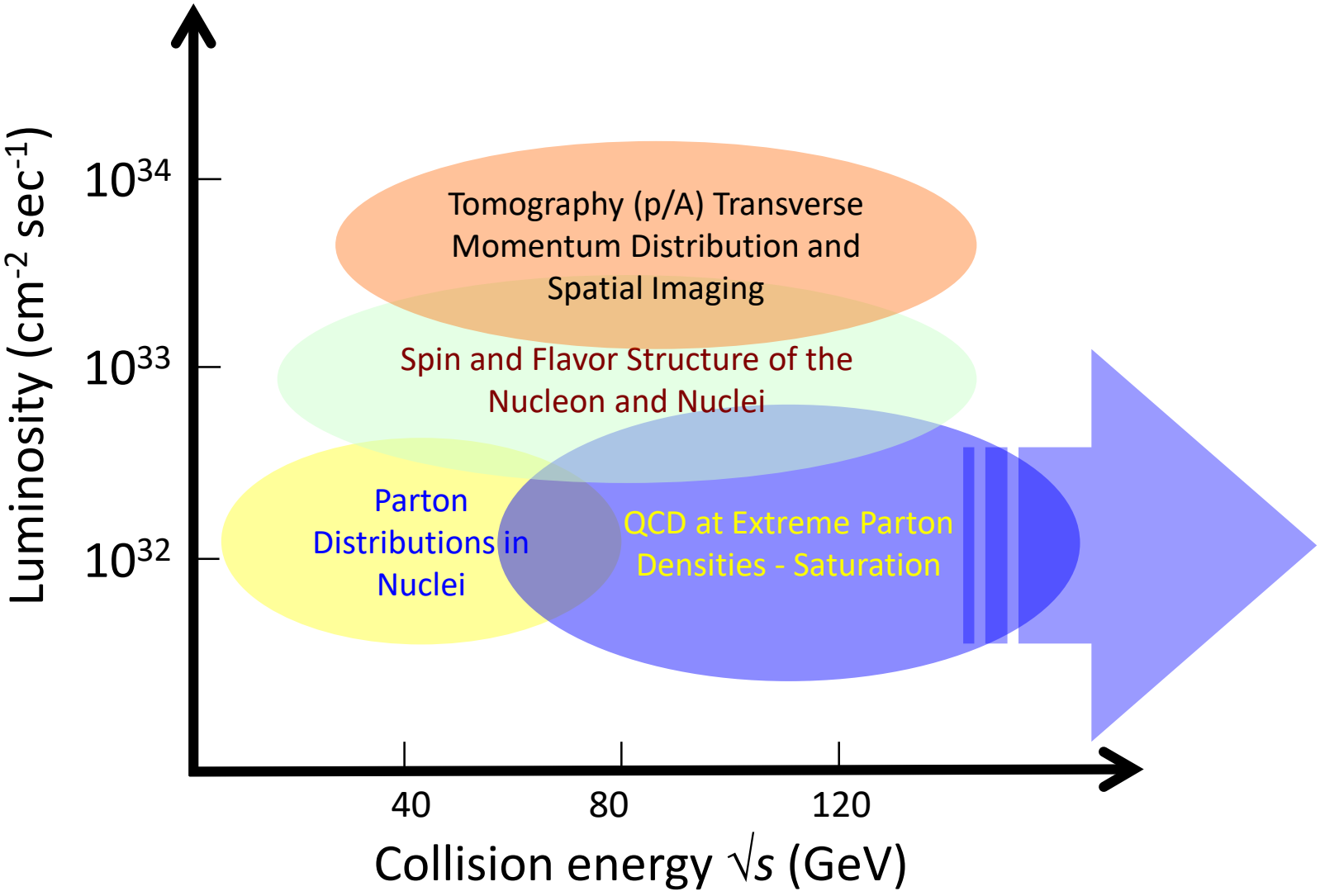
Hadronization in the nucleus

- 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 of heavy quarks
- Comparison with hot nuclear matter (QGP)



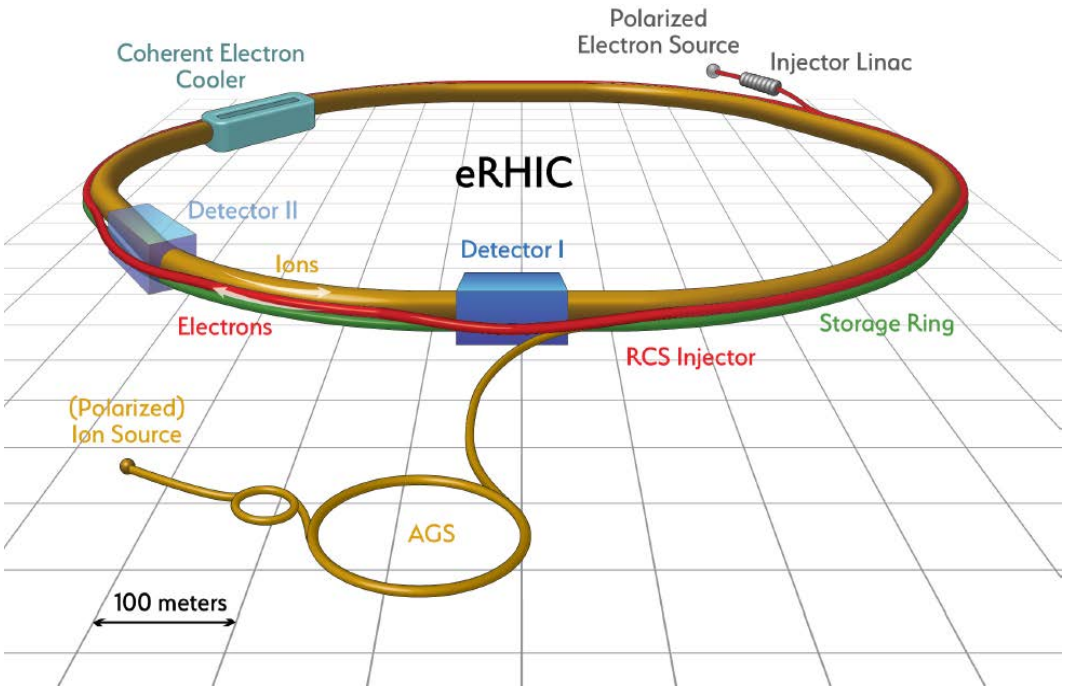


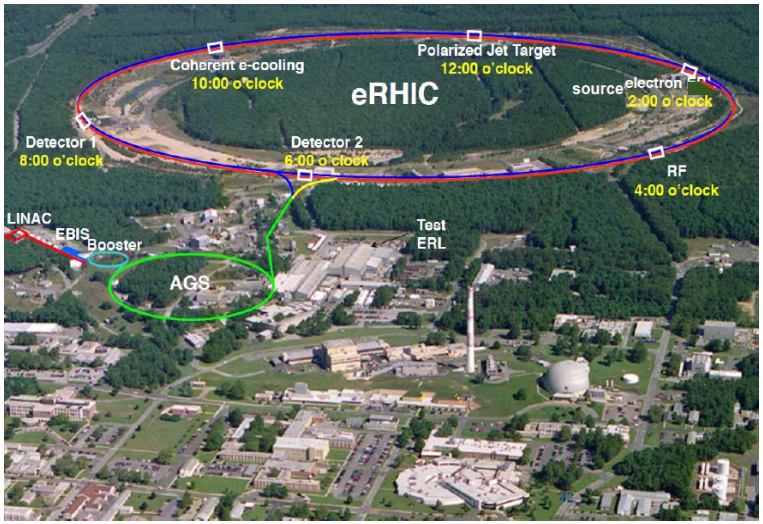
EIC physics vs luminosity & energy

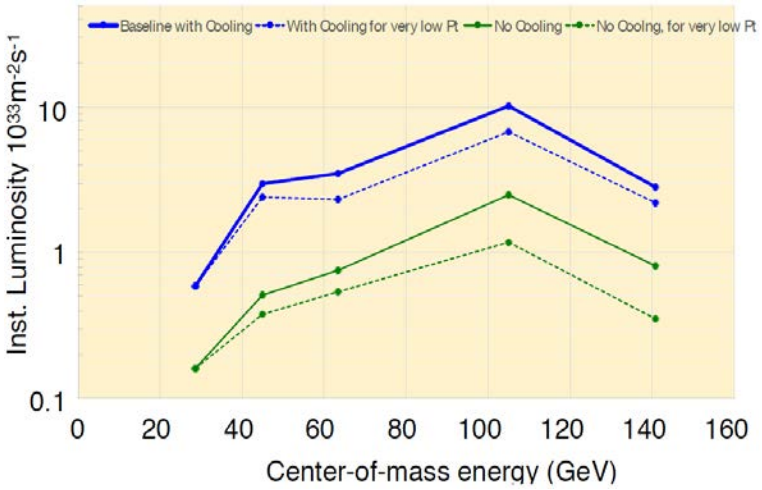


eRHIC @ BNL

- Electron storage ring 5 – 18 GeV
  - ~80% polarization
- Proton beams up to 275 GeV
  - ~70% polarization
- Ion beams up to 100 GeV/u

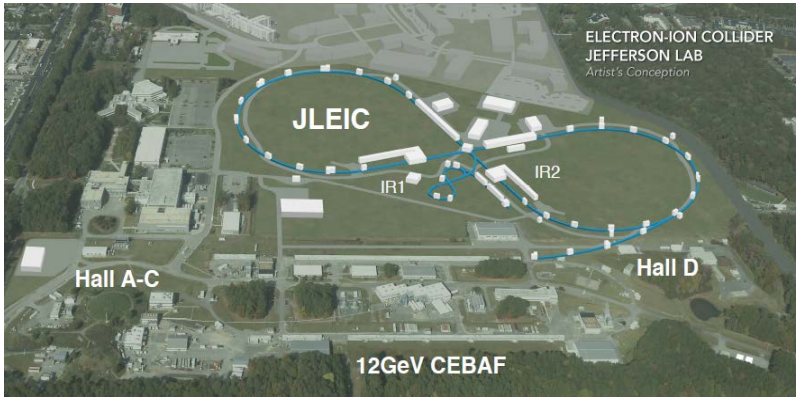


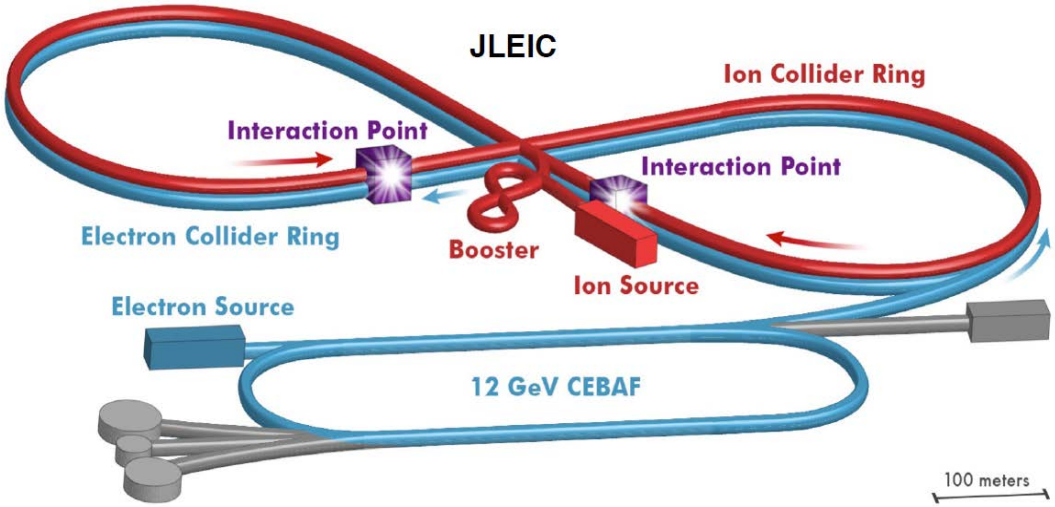


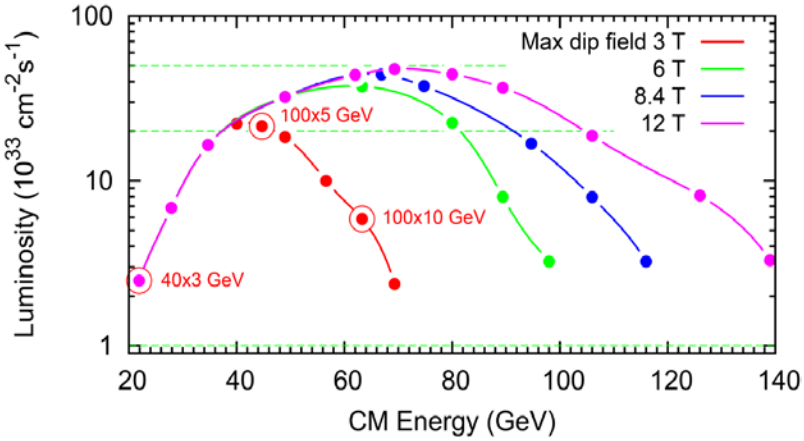


JLEIC @ JLab

- Polarized electrons 3 – 12 GeV
  - 75-80% polarization
- Polarized protons 40 – 100 GeV
  - 80% polarization
- Ions 16 – 40 GeV/u

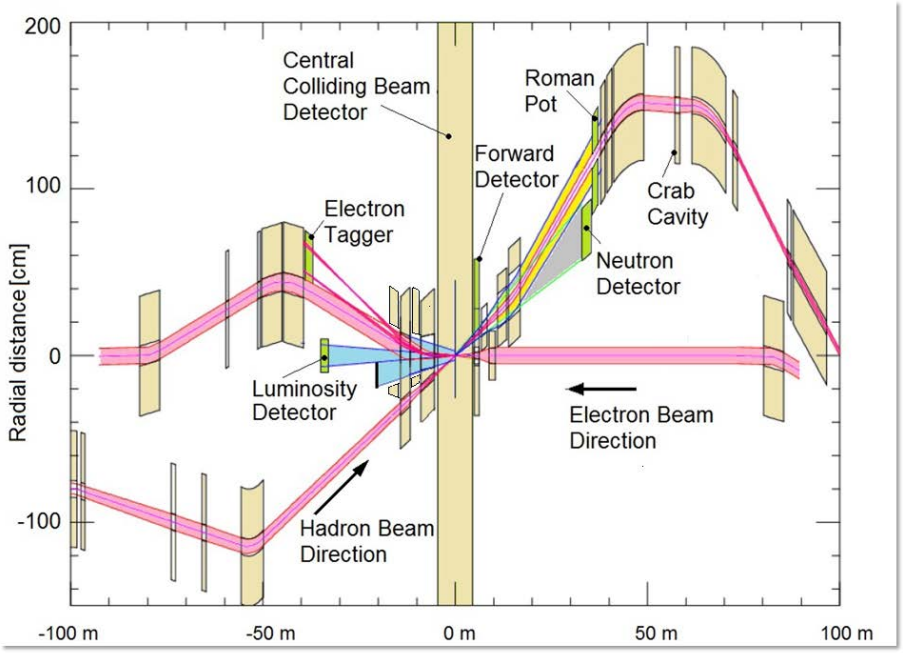




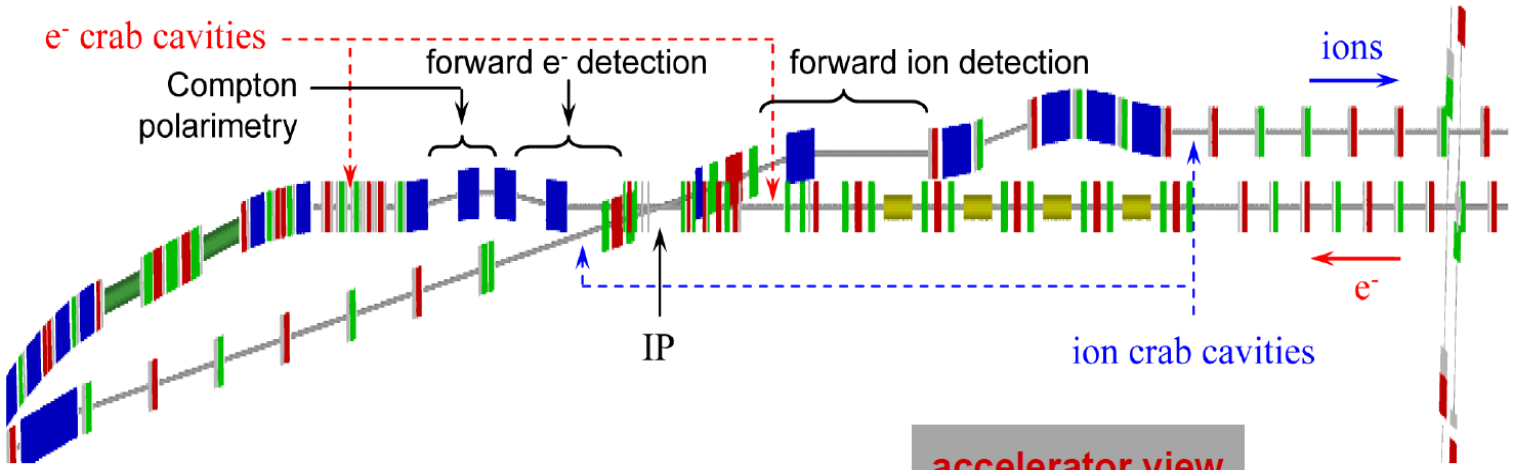


Interaction region design

- BNL

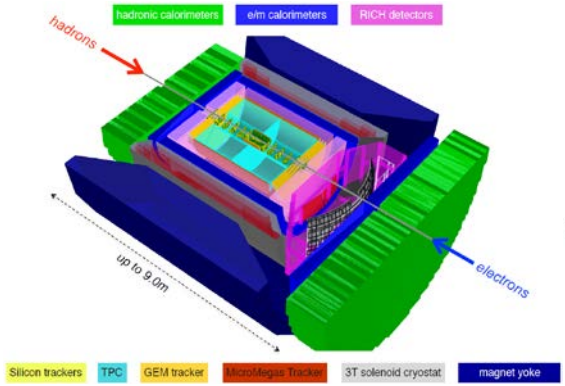


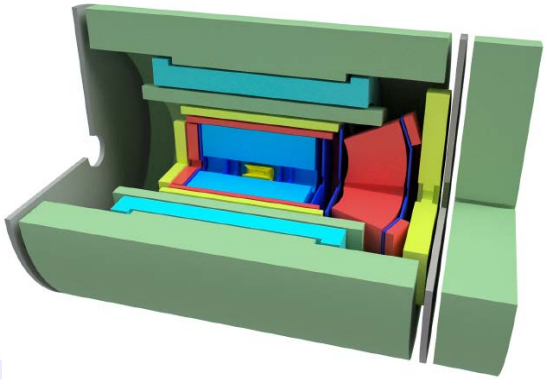
- JLab



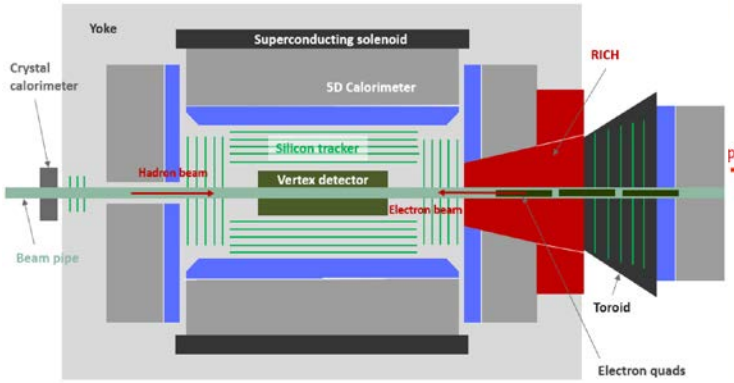
EIC detector

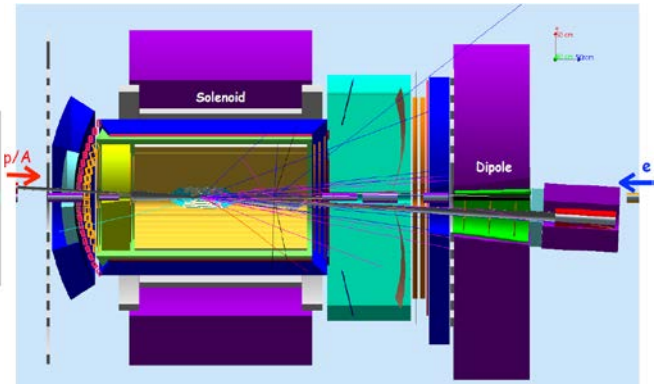
- BNL
  - BEAST
  - EIC-sPHENIX





- JLab
  - TOPSiDE
  - JLEIC



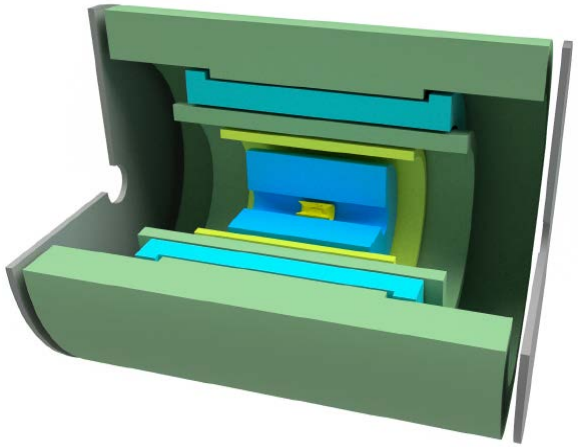


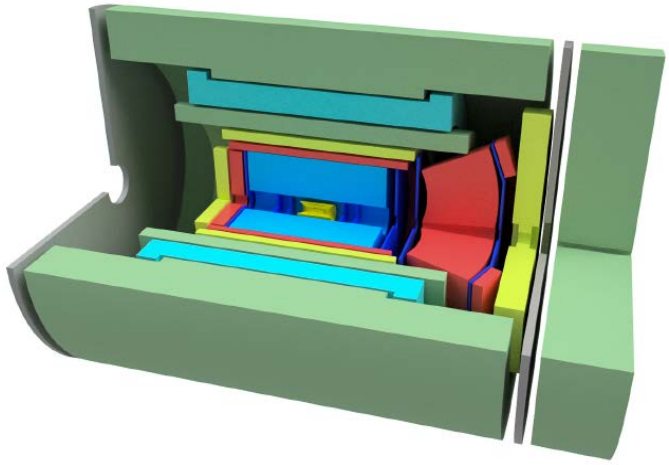
EIC detector

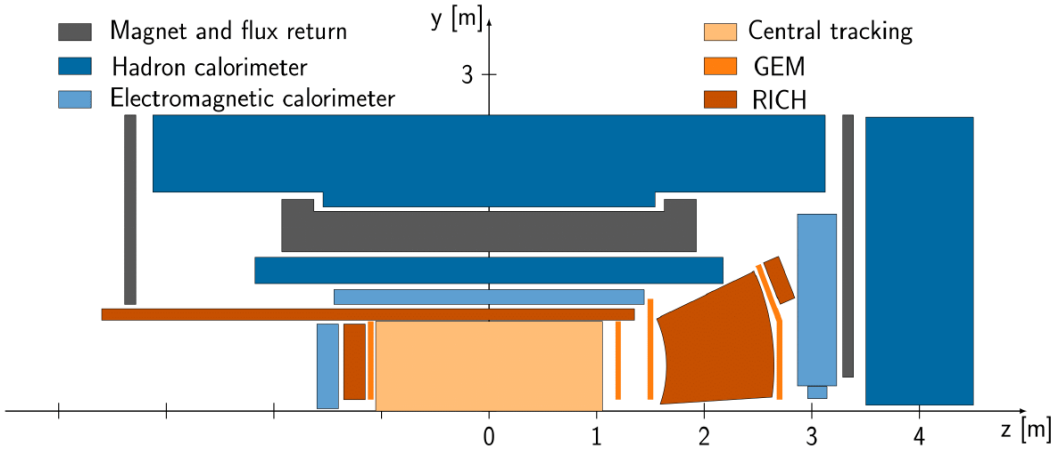
- Mid and forward rapidity detectors
  - 4π coverage, $|\eta| < 3.5$
  - EM & hadron calorimeters
  - Tracking detectors, $\Delta p/p \sim$ few%
  - Particle-ID, π/K/p separation in wide kinematical region
  - Vertex detector, 10-20 μm
- Scattered electron detector, backward and mid rapidity
  - Low material, ~5% X/X_0
  - Electron-ID, e/h separation
- Low angle trigger
  - Recoil proton, low Q^2 scattered electron, forward neutron
- Absolute and relative luminosity measurement
  - Bethe-Heitler process
- Polarization measurement
  - Electron and proton, light ion

EIC-sPHENIX detector

- sPHENIX detector
  - 4π detector with BaBar superconducting solenoidal magnet
  - $|\eta| < 1.1$ and $0 < \phi < 2\pi$
    - EM and hadron calorimeters
    - TPC
    - Silicon detector
  - Under construction to operate from 2022-2023
- EIC-sPHENIX detector
  - Design study ongoing







EIC Users Group (EICUG)

- EIC Users Group
  - Established in summer 2016
  - > 800 collaborators
    - Experimentalists
    - Theorists
    - Accelerator scientists
    - Support and others
  - > 170 institutes
  - 30 countries
- R&D activities
  - EIC detector R&D program operated by BNL with ~$1M / year
  - EIC accelerator R&D with ~$7M / year