Electron-Ion Collider (EIC) Project

Workshop on Progress on Hadron Structure Functions

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KEK, Tsukuba, Japan

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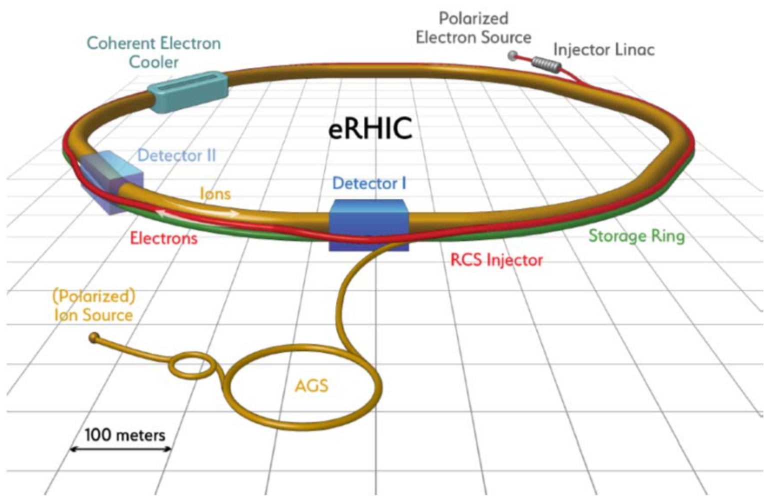
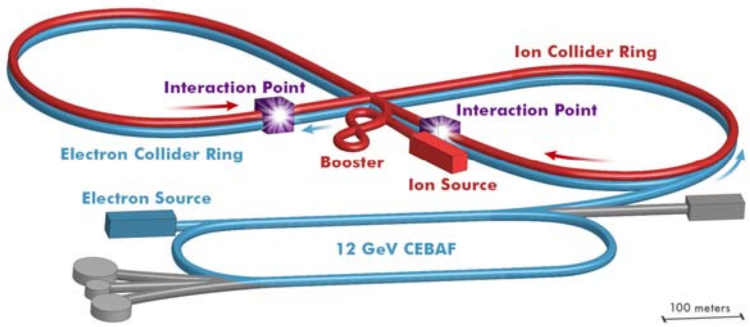
EIC (Electron Ion Collider) project

- 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

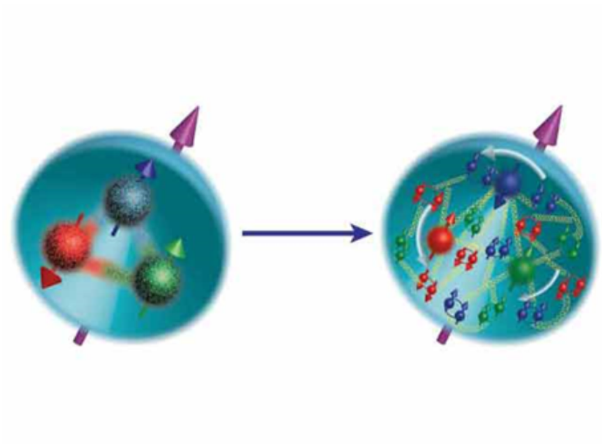


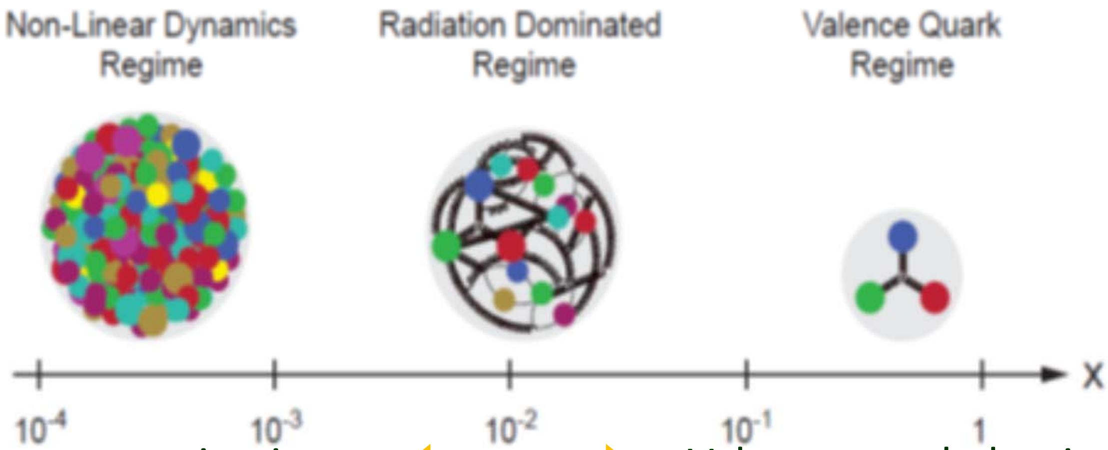
JLEIC at Jefferson Lab



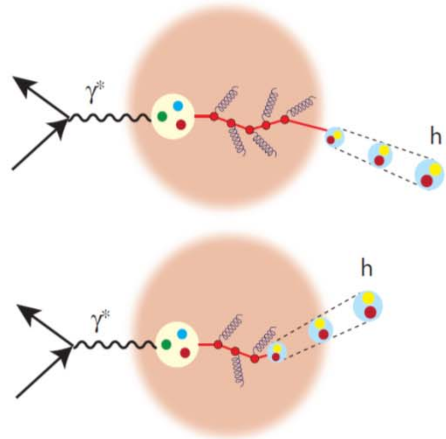
Physics at EIC

- Understanding emergent properties of the nucleon and the nucleus from quarks and gluons
  - Precision measurement of PDFs
  - Tomography of the nucleon / nucleus
  - Mass, spin, and more puzzles
- Gluon saturation
- Hadronization





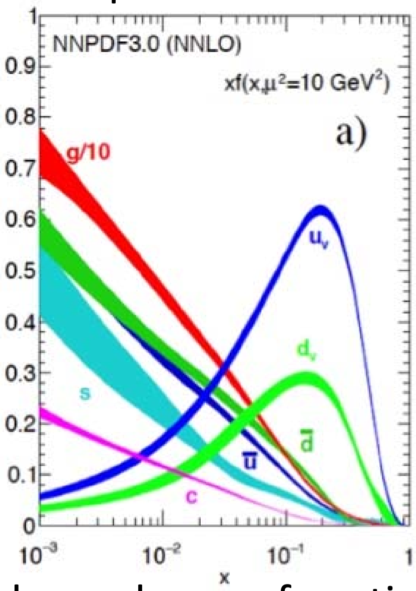
Gluon saturation in small Bjorken-x region ⟷ Valence quark dominant in large Bjorken-x region



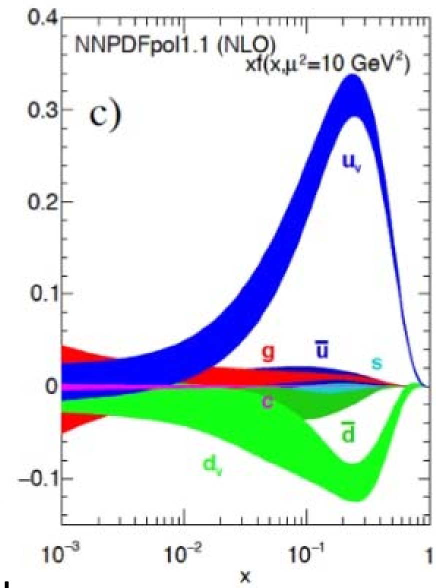
Quark-gluon structure

- 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
  - and their radius (R)
  - orbital motion / orbital angular momentum

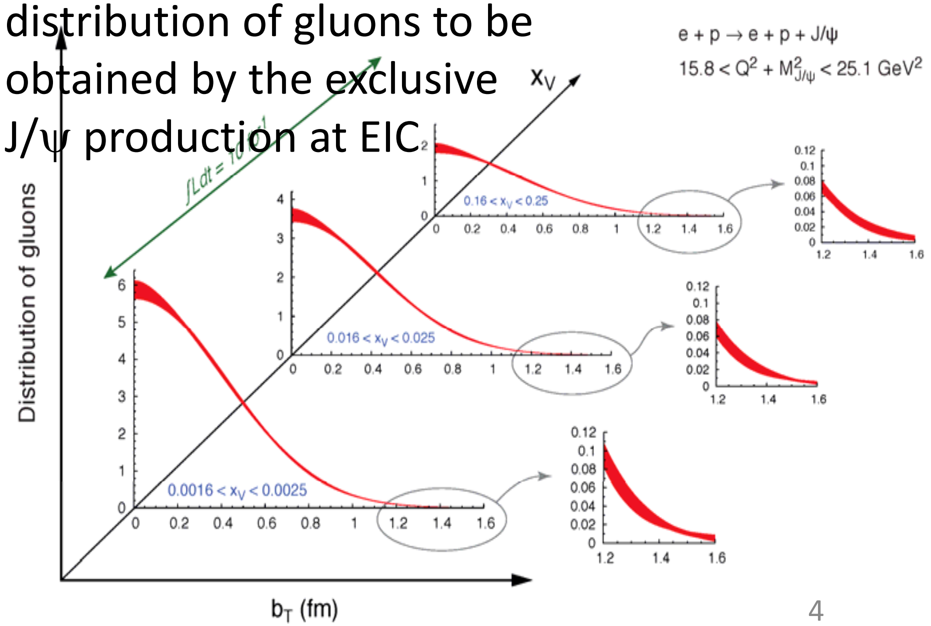
Unpolarized PDF



Polarized PDF

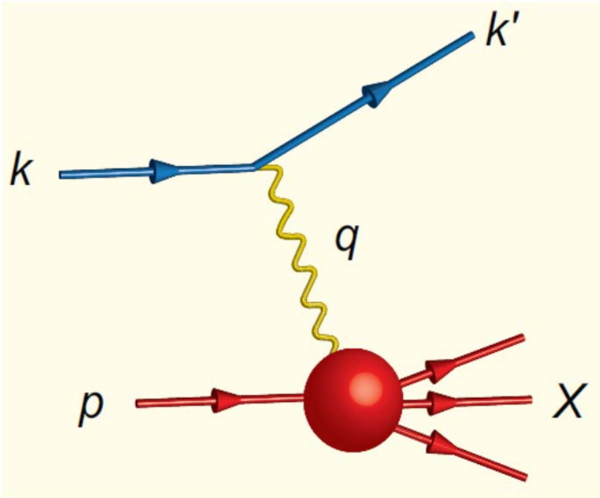


x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC



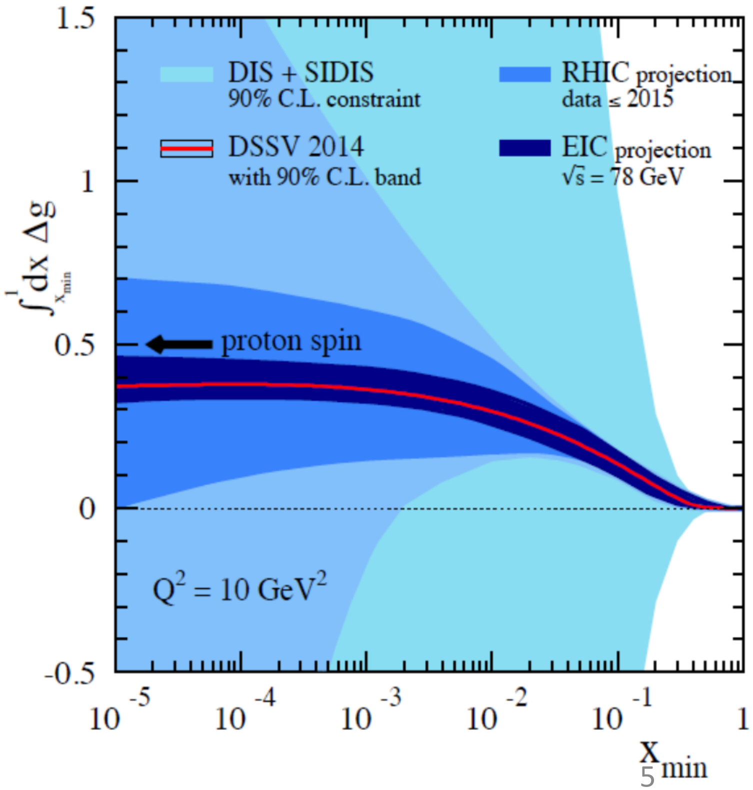
Precision measurement of PDFs

- 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)



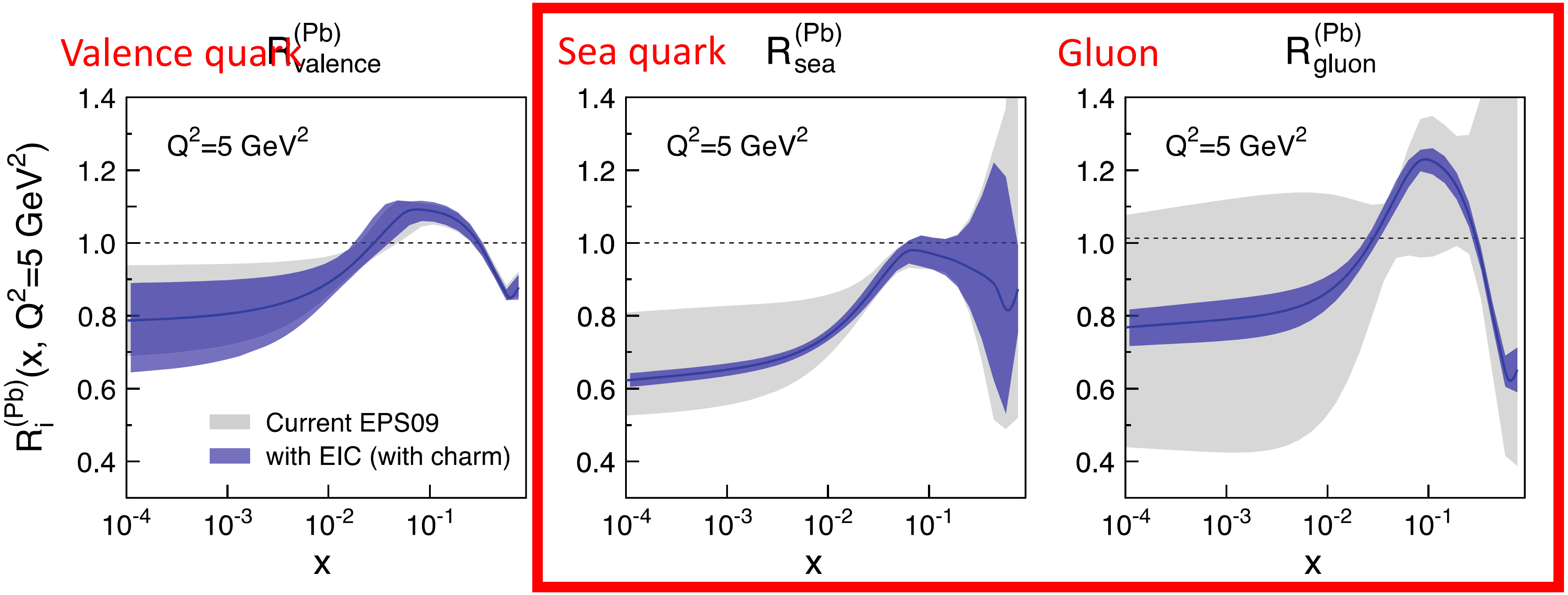
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

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



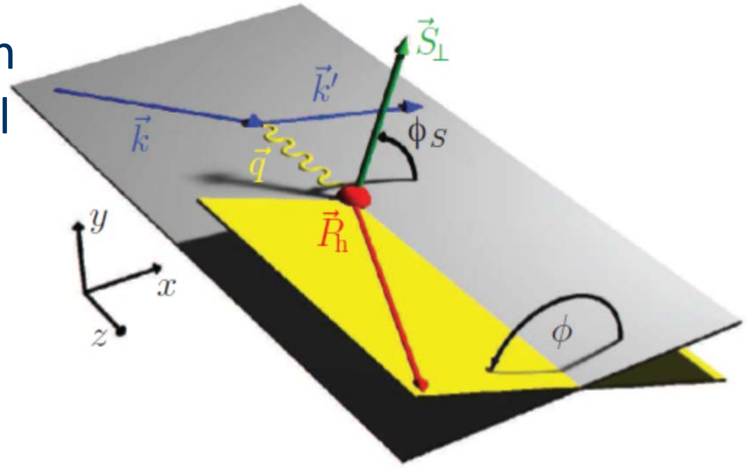
Precision measurement of PDFs

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



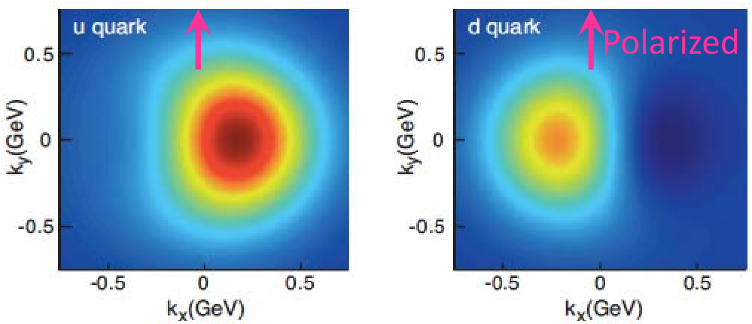
Precision measurement of PDFs

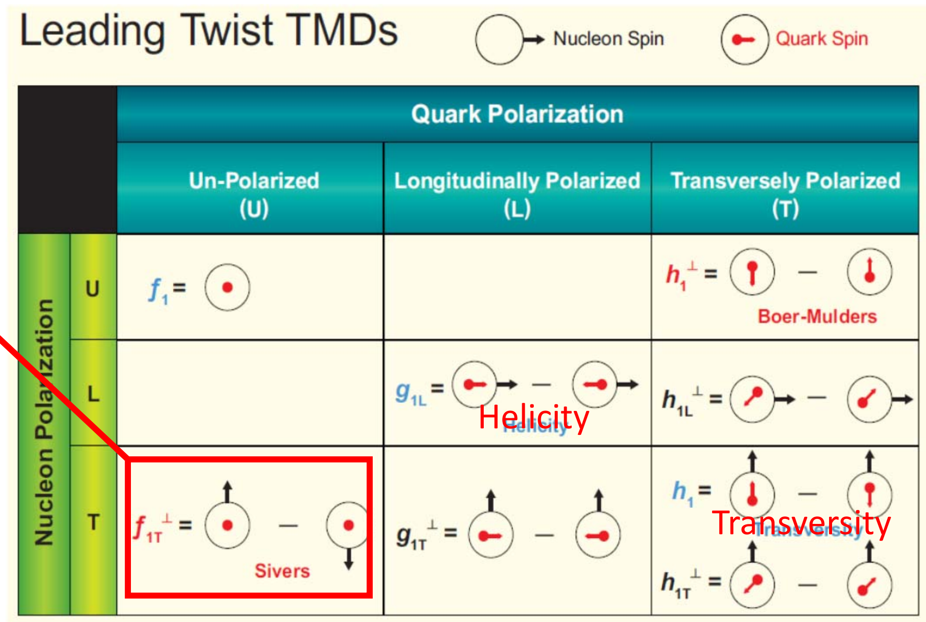
- Semi-Inclusive DIS (SIDIS)
  - Flavor dependence of the quark polarization
  - Transverse-momentum dependence (orbital motion)
- TMD distribution function
  - TMD = Transverse Momentum Dependent
  - Quark, anti-quark, gluon
  - 3D distribution incl. transverse momentum
  - Correlation of spin and parton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



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

Sivers function at x = 0.1

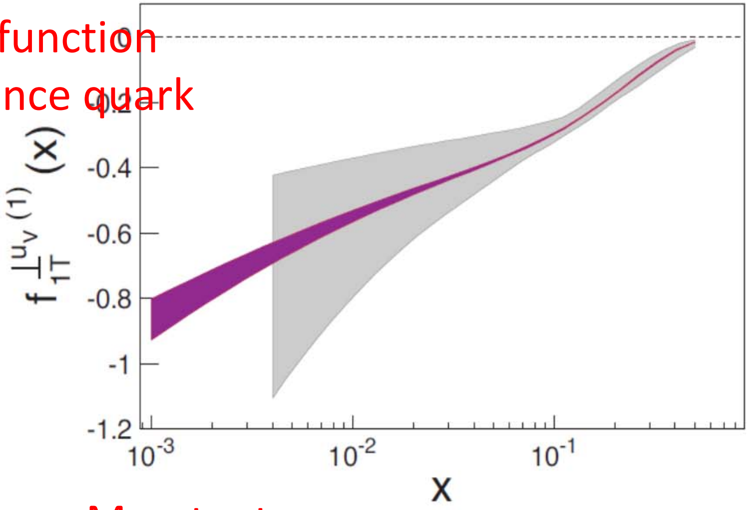




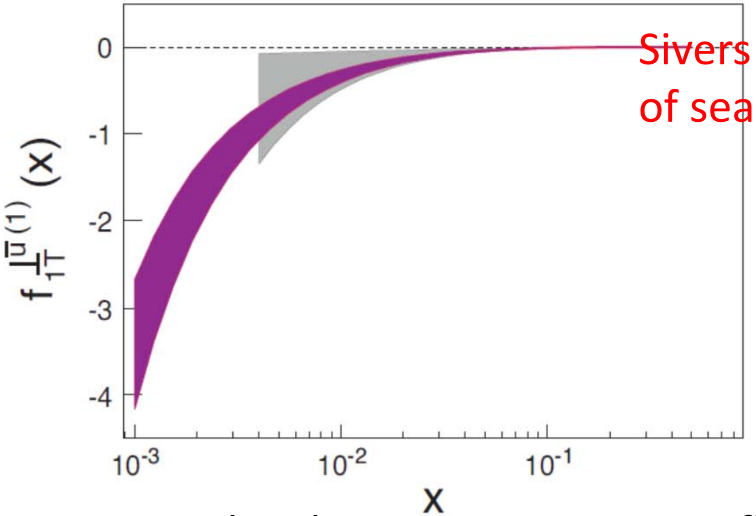
TMDs at EIC

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

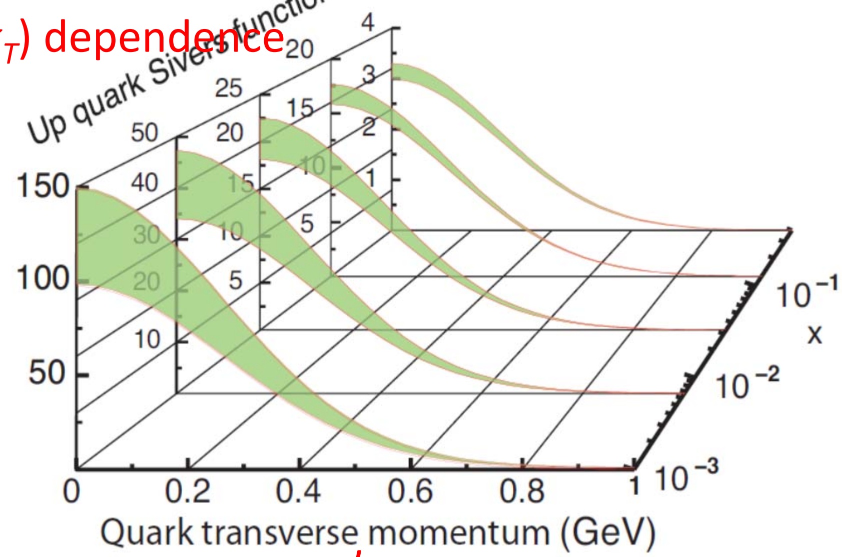
Sivers function of valence quark



Sivers function of sea quark

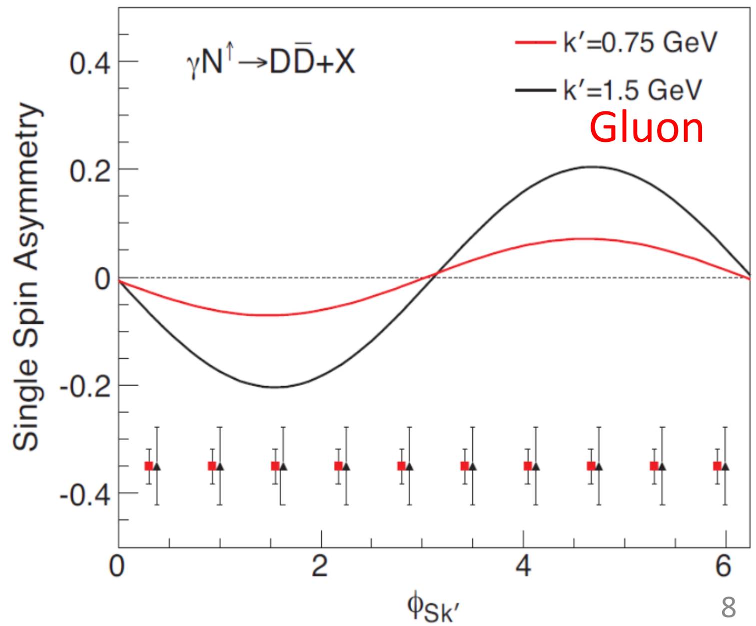


Transverse Momtentum (k_T) dependence



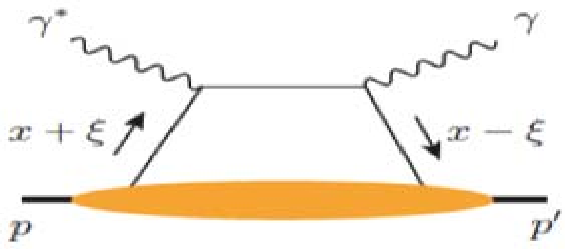
k_T

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



Tomography of the nucleon / nucleus

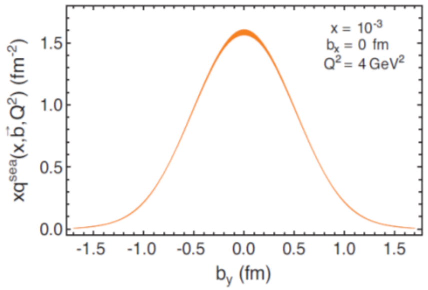
DVCS (Deeply Virtual Compton Scattering)



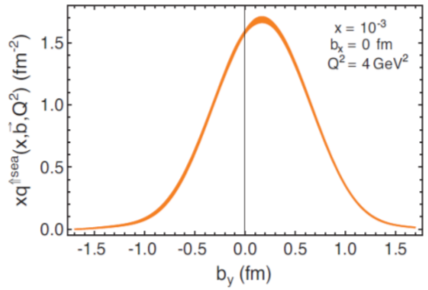
- DVCS
  - Deeply virtual Compton scattering
  - Exclusive process
- GPD
  - Generalized Parton Distribution
  - Spatial distribution in the transverse direction = tomography

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

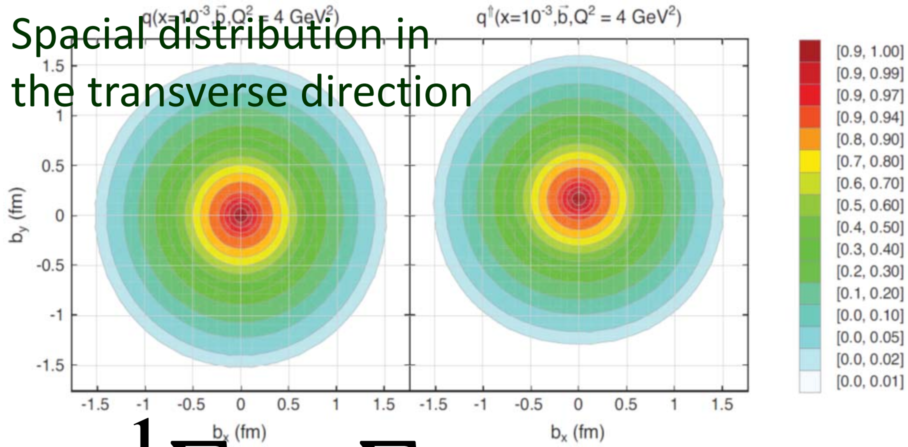
Unpolarized



Polarized



Spacial distribution in the transverse direction



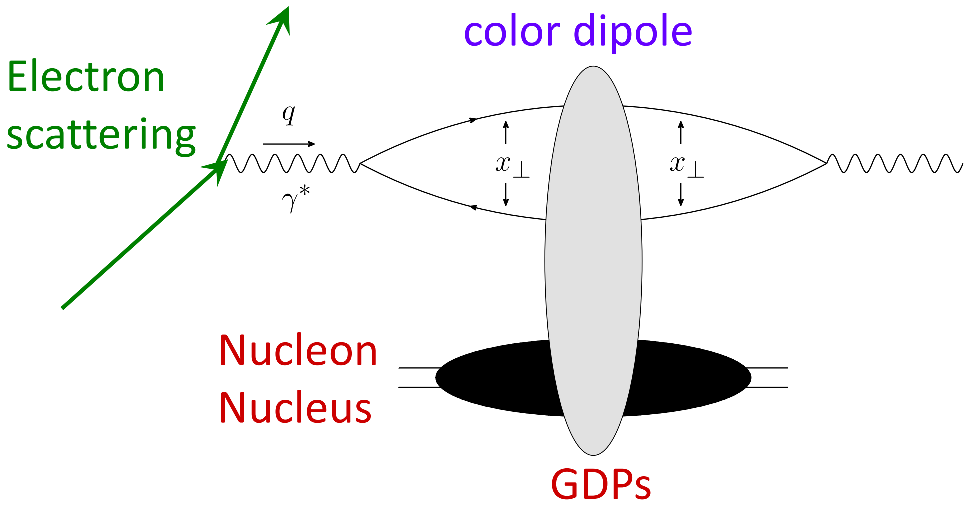
- Orbital angular momentum
  - Ji's sum rule

$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q^z$$

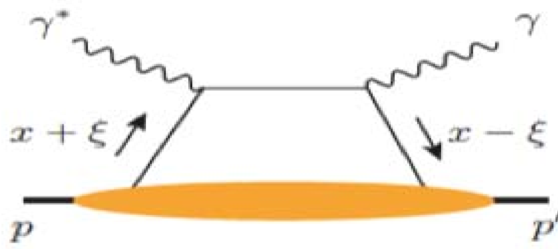
$$J_q^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^q + E^q\right)\right)_{t\to 0}$$

Tomography of the nucleon / nucleus

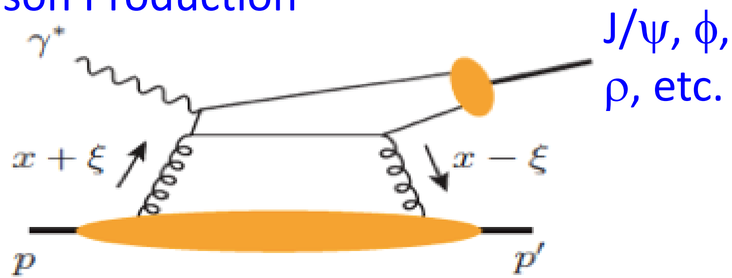
- EIC = color dipole microscope



DVCS (Deeply Virtual Compton Scattering)



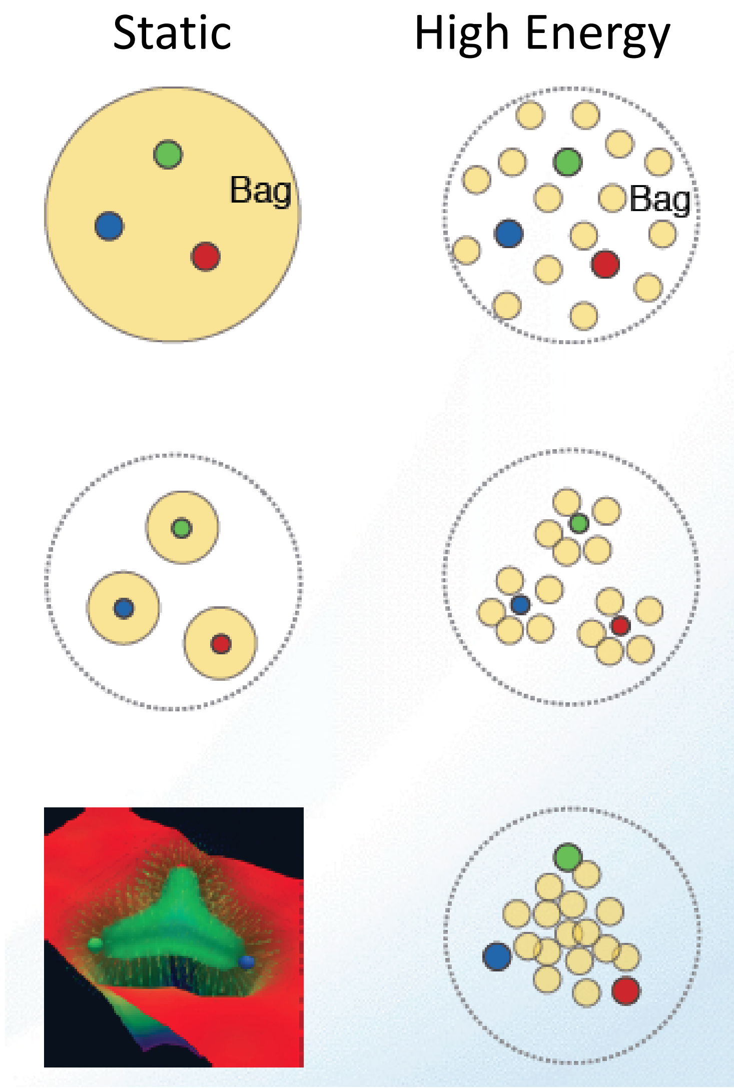
Meson Production



- 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

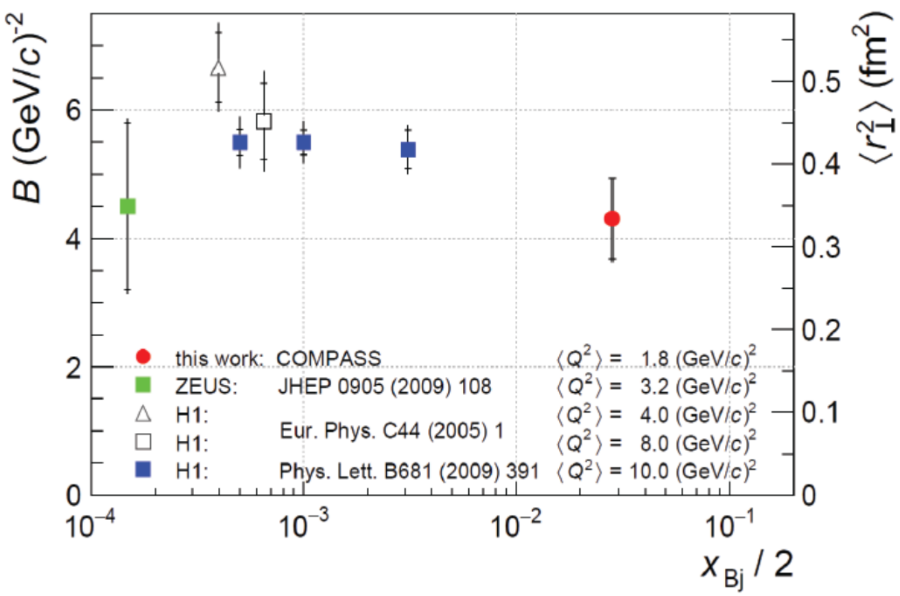
3D structure of the nucleon

- 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?



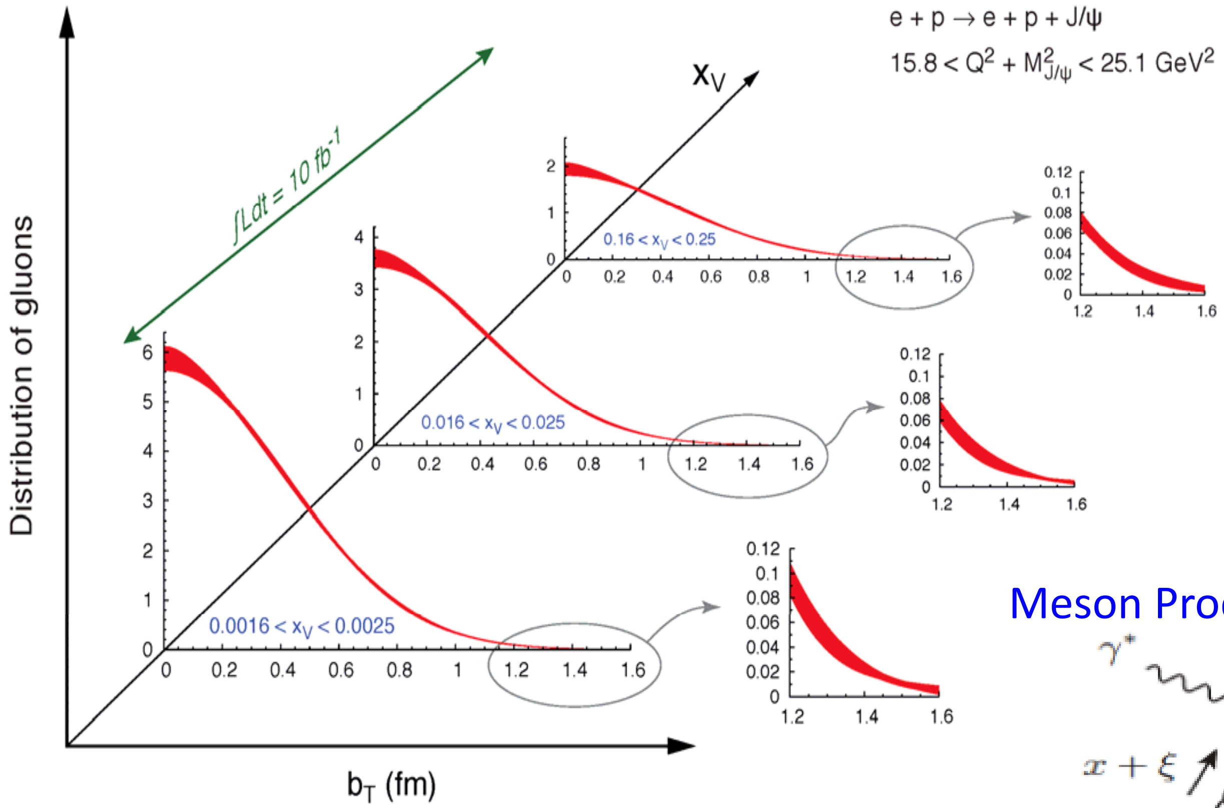
Proton radius

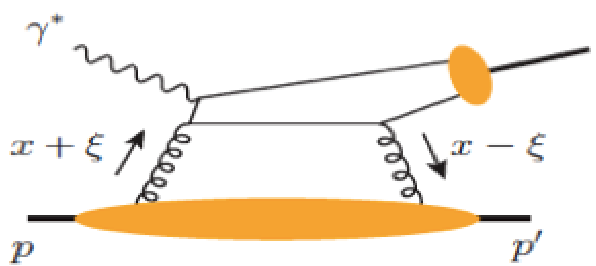
- Proton tomography with DVCS measurement
  - R = 0.6 – 0.7 fm for gluon (HERA) and sea quark (COMPASS)
  - Smaller than 0.84 – 0.9 fm with EM interaction



Tomography of the nucleon / nucleus

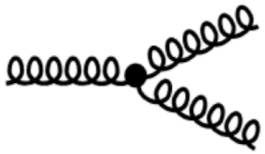
- Meson production
  - Gluon tomography by measuring J/ψ, ϕ, ρ, etc.
  - Precision measurement at large radius with high luminosity



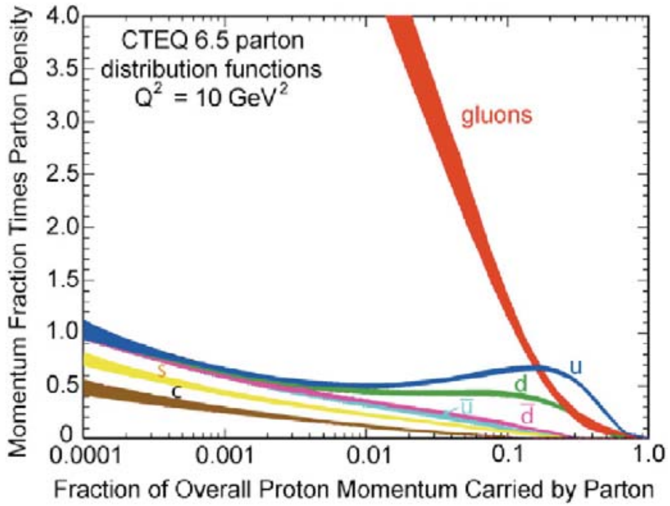


Gluon saturation

- Gluon emission
  - Divergence at small x



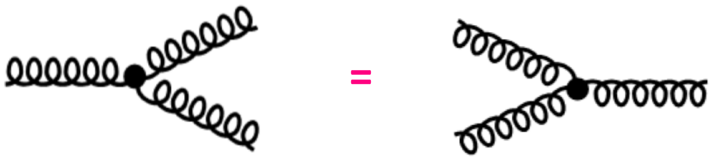
- Gluon recombination
  - Restriction of divergence



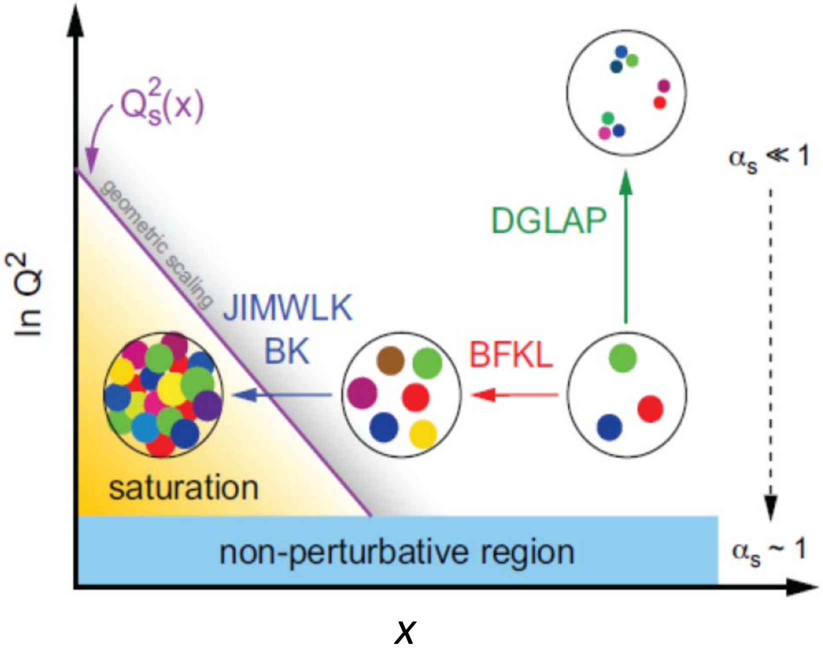
- Gluon saturation in balanced

gluon emission

gluon recombination

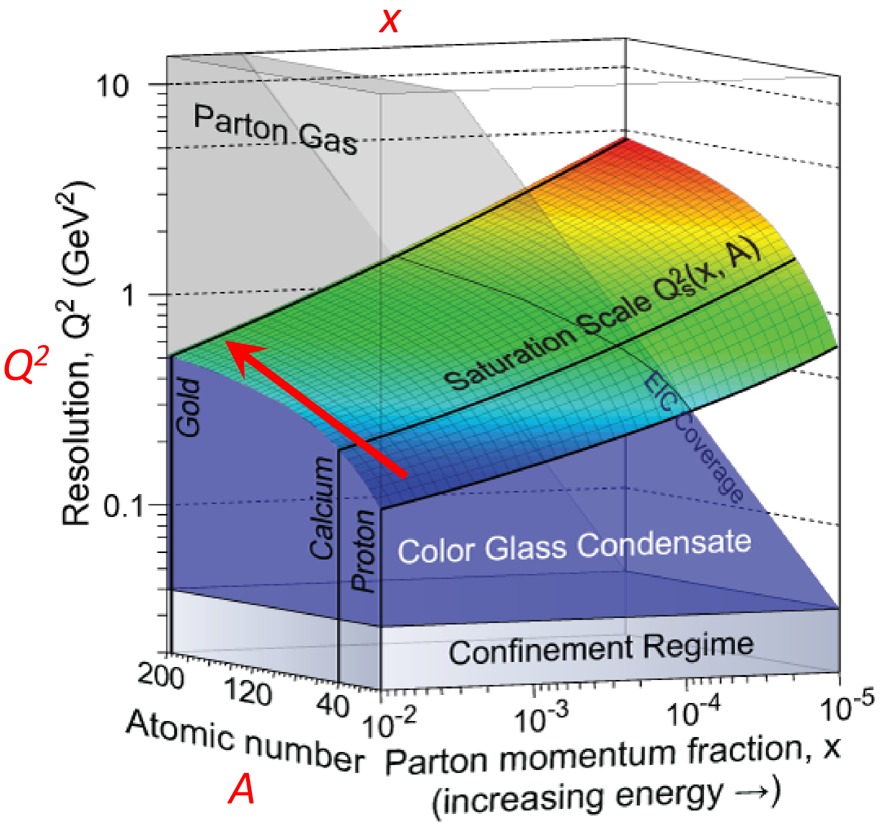


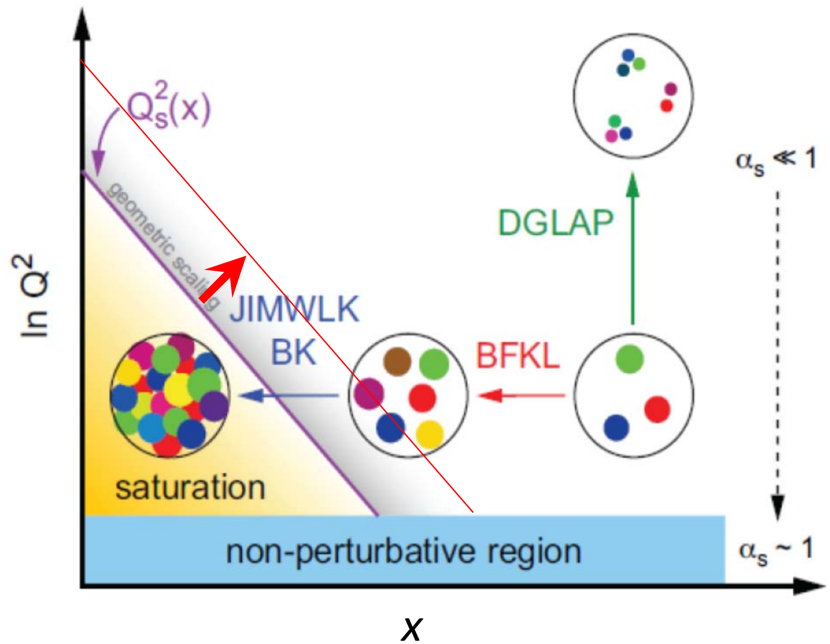
- First observation of a quantum collective gluonic system
  - Based on classical idea of the saturation



Gluon saturation

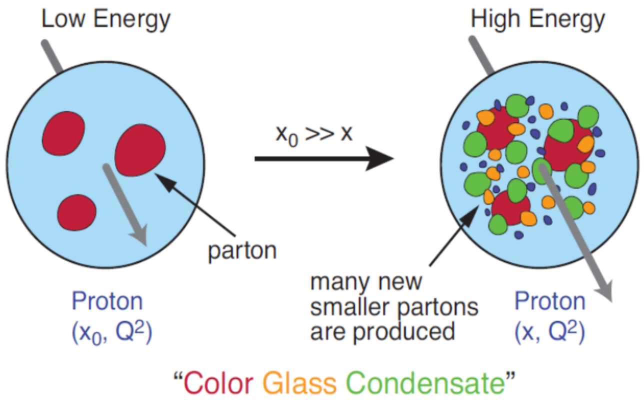
- Enhancement of the Q_S^2 scale with nucleus
  - Electron + ion collision



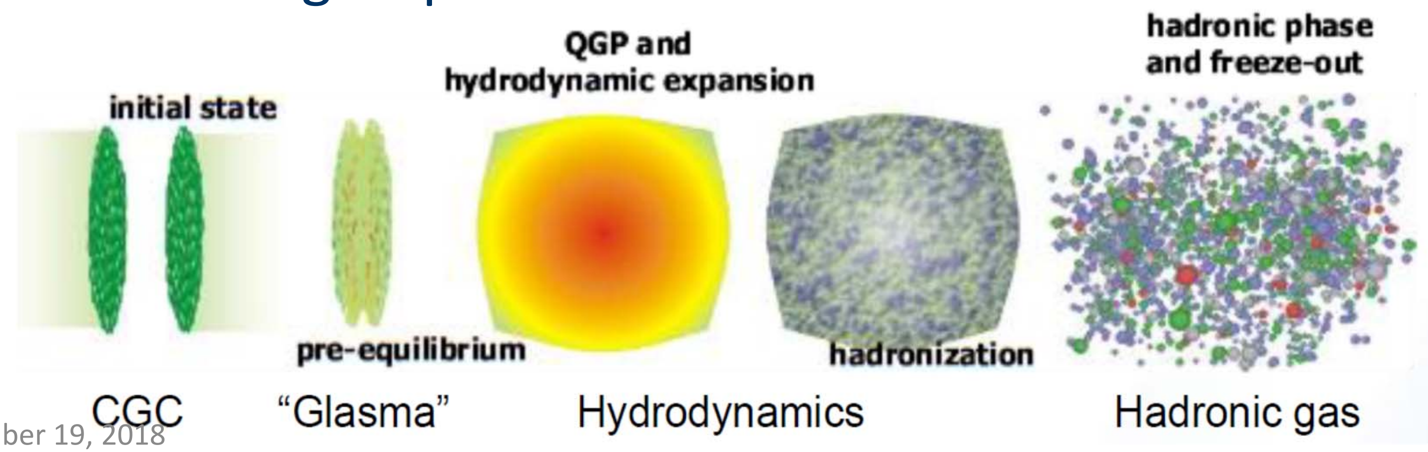


Gluon saturation

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

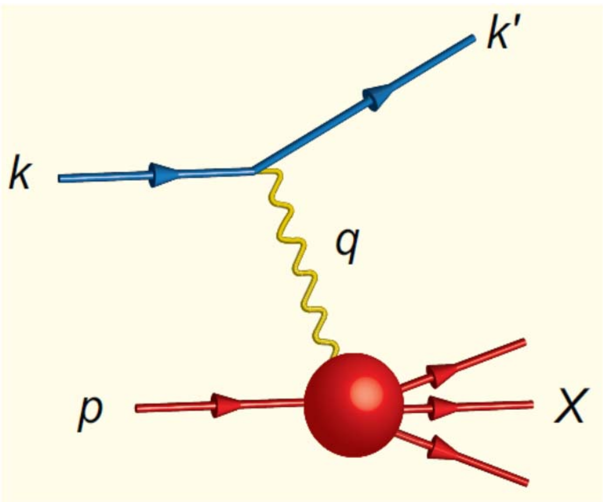


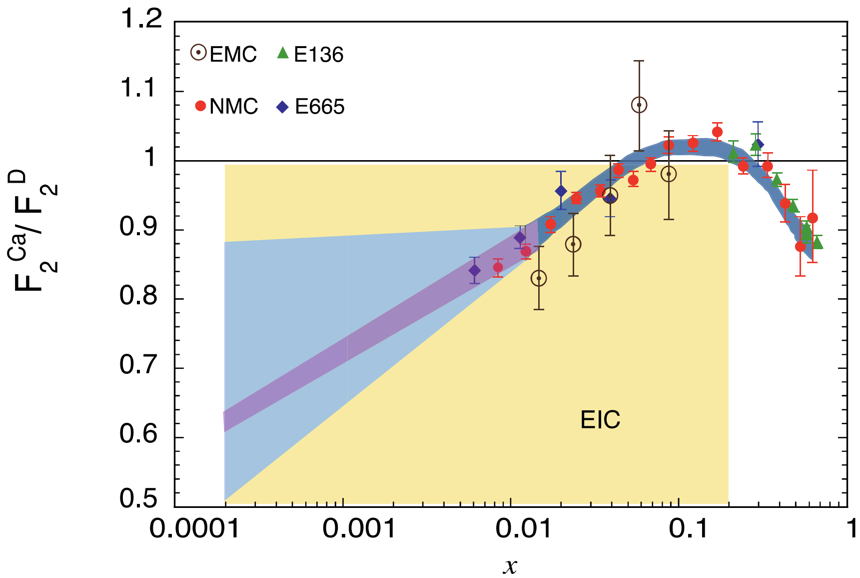
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism



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



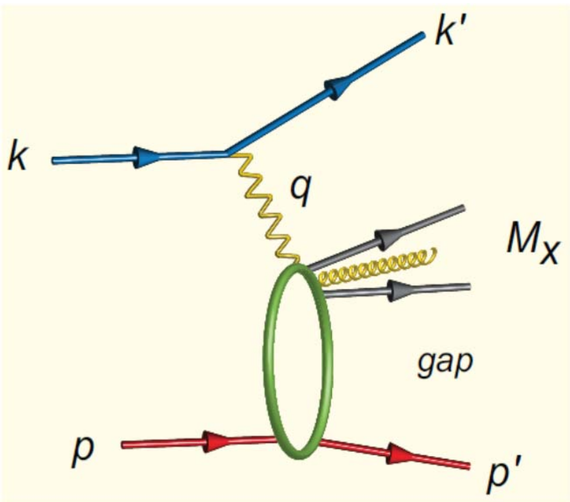


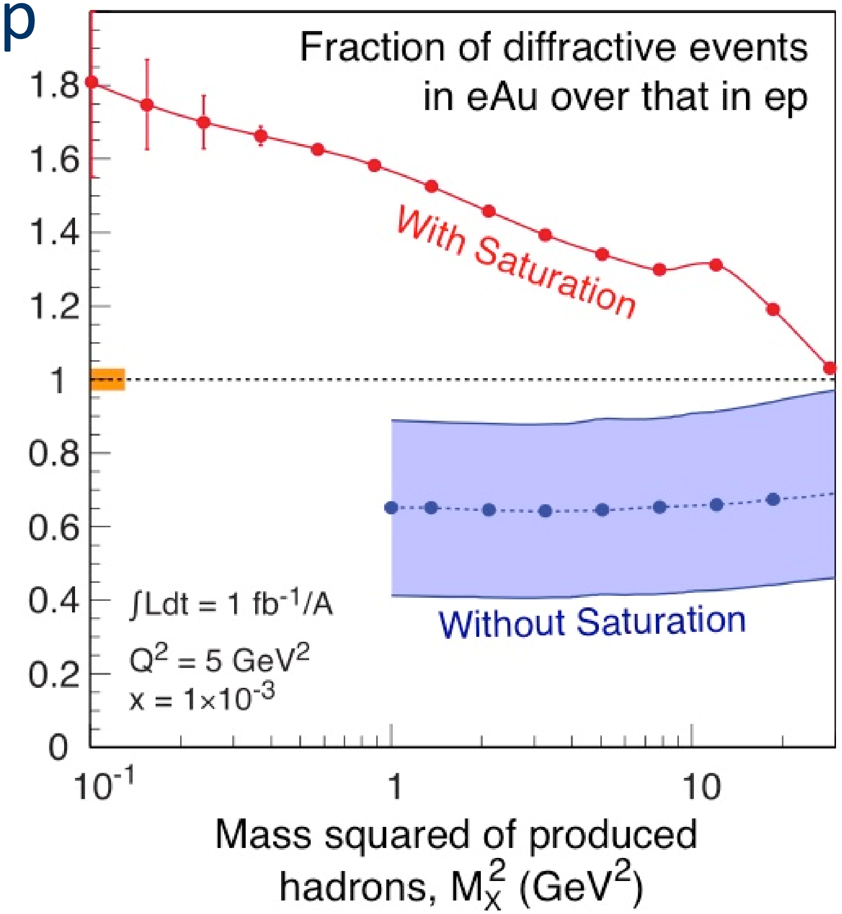
Gluon saturation

- Diffractive cross section
  - Most sensitive way to study the gluon saturation

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

- 10-15% diffractive at HERA e+p
- 25-30% diffractive predicted by CGC at EIC e+A

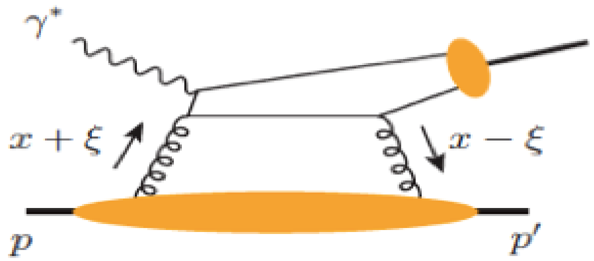




3D structure of the nucleus

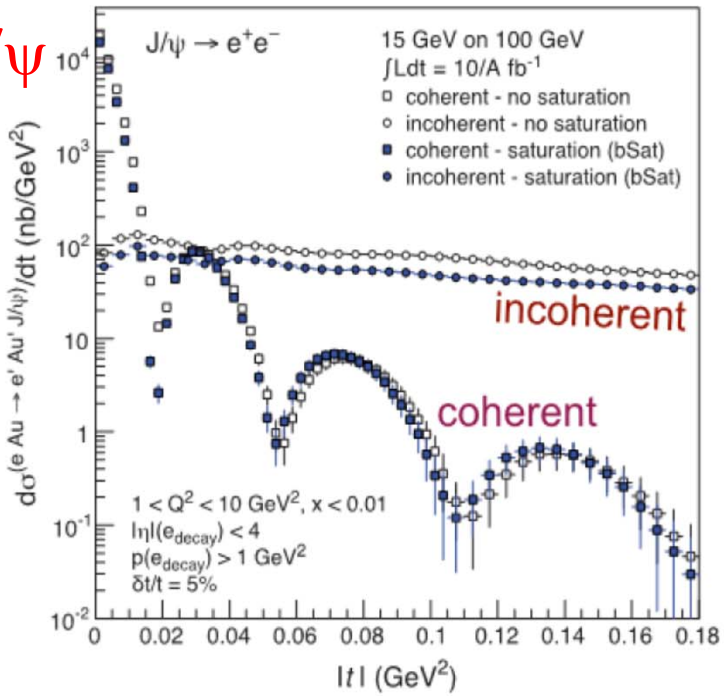
- Diffractive vector meson production
  - ϕ meson sensitive to the gluon saturation

Meson Production

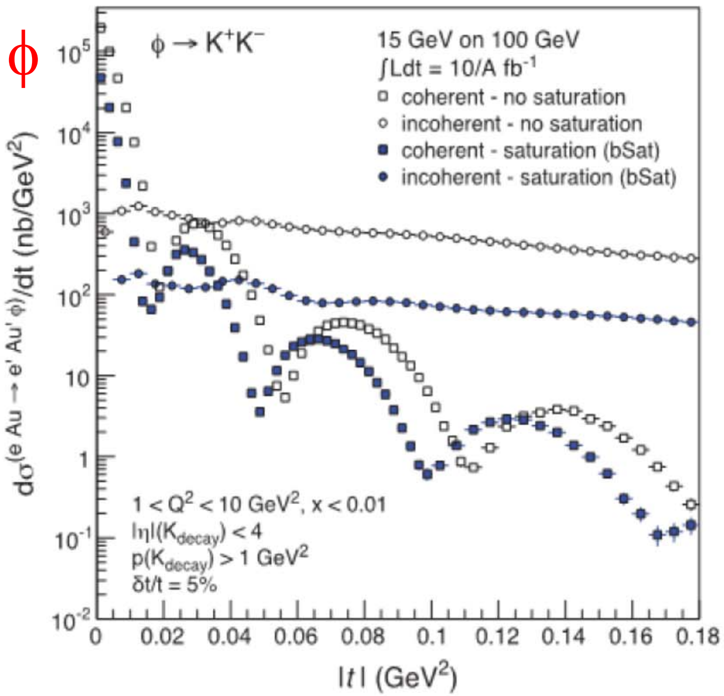


J/ψ, φ, ρ, etc.

J/ψ

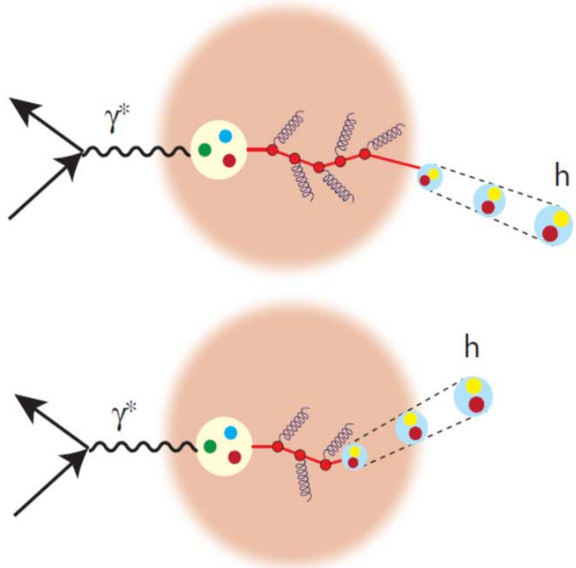


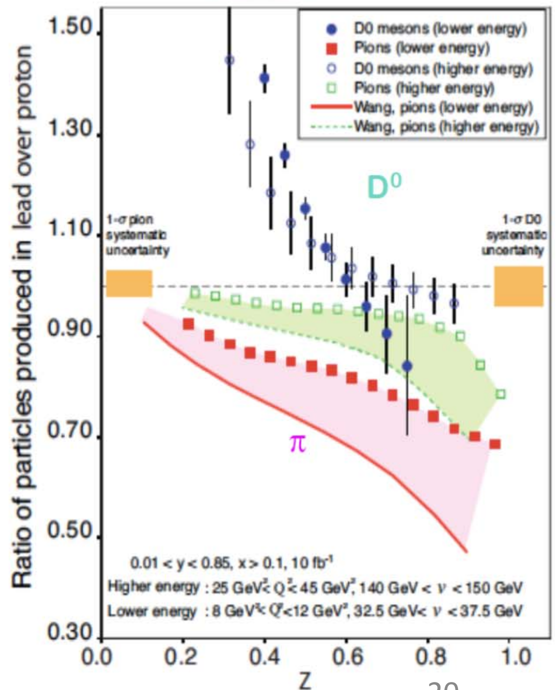
φ



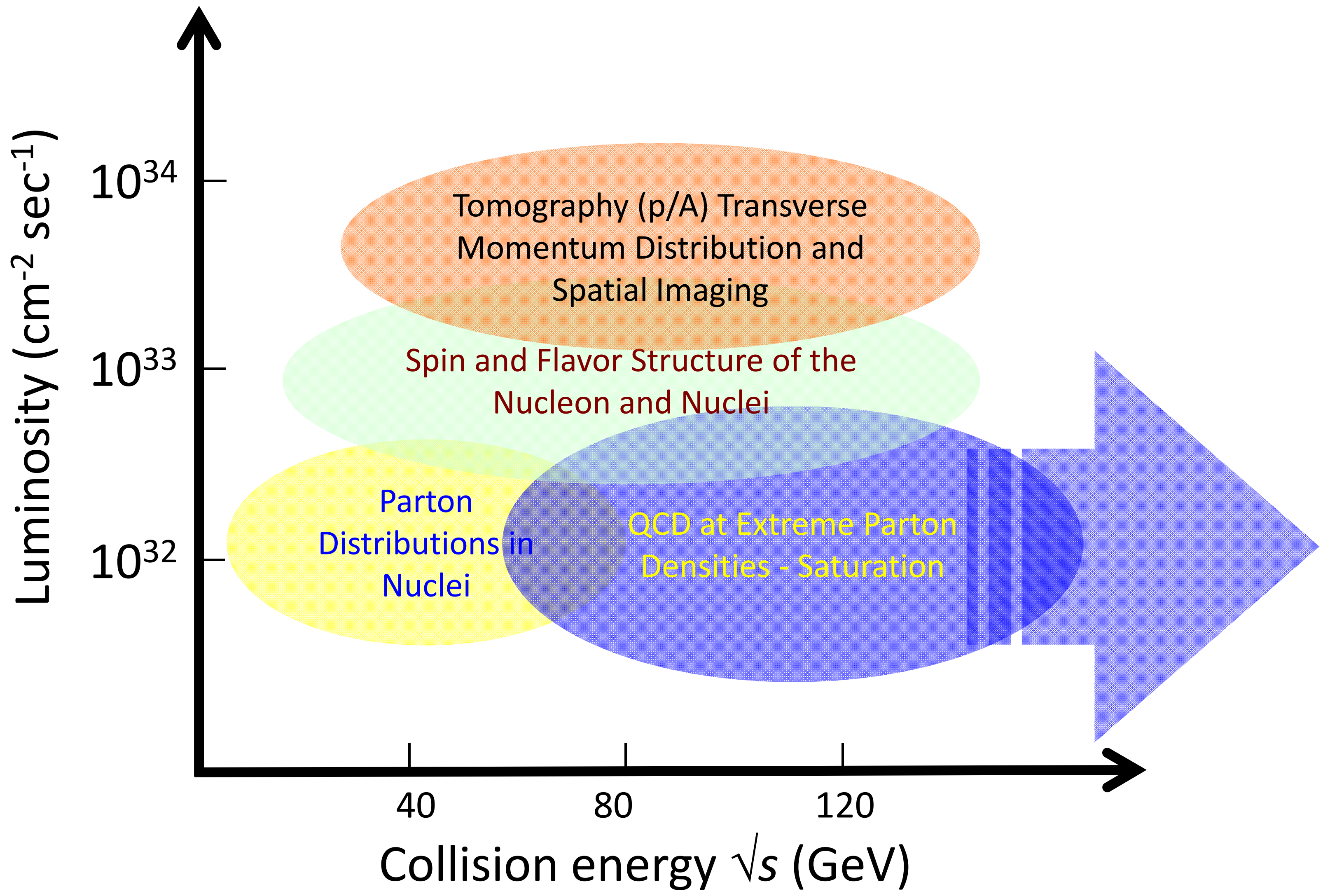
Hadronization in the nucleus

- 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)



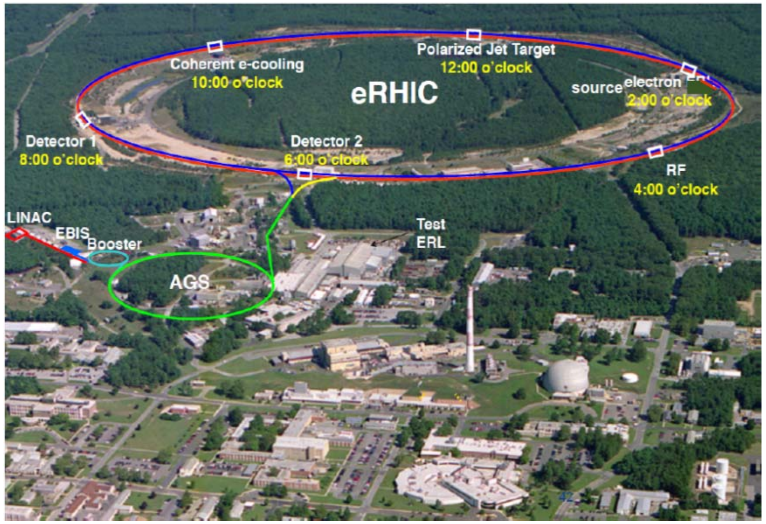


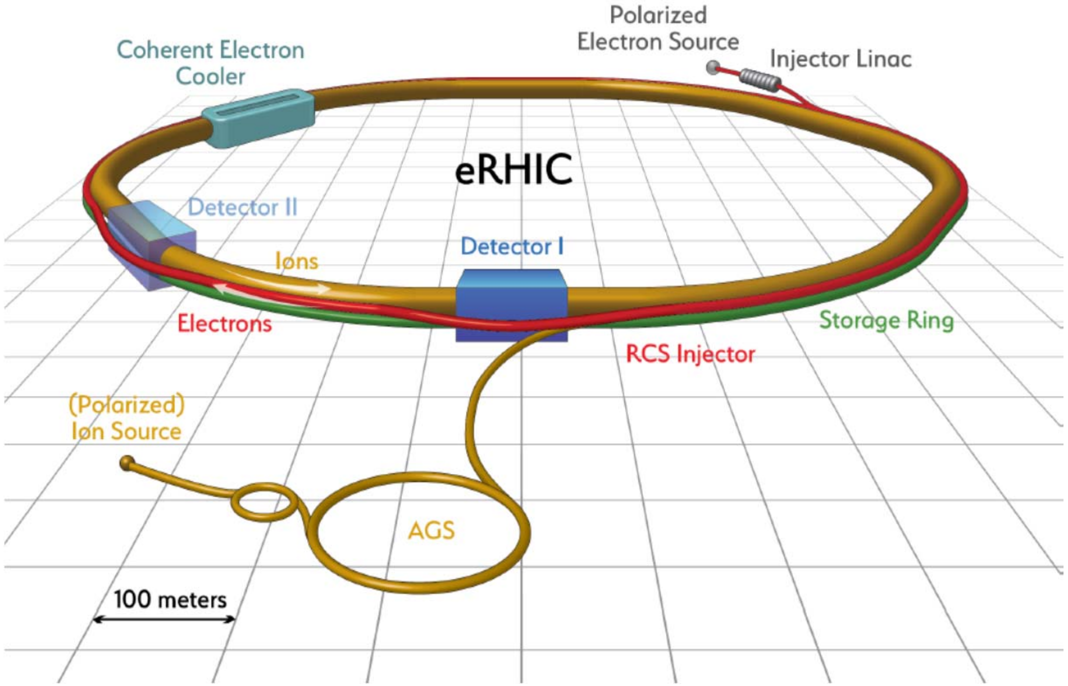
EIC physics vs luminosity & energy

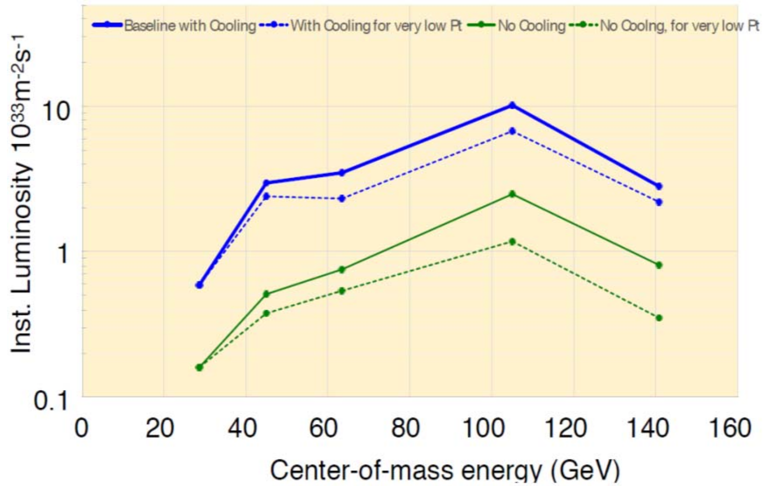


eRHIC @ BNL

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

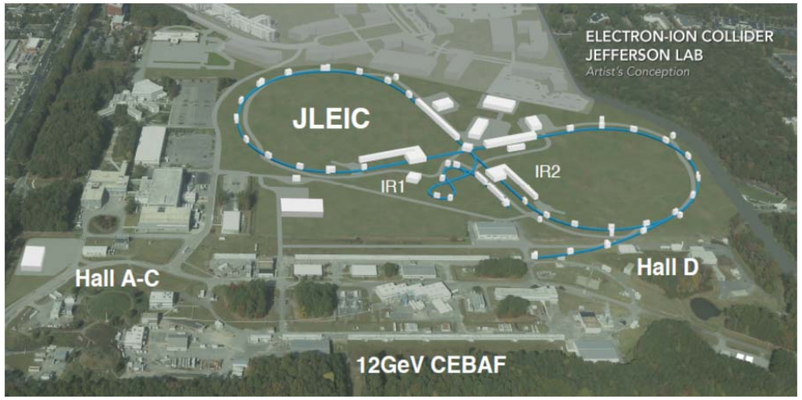


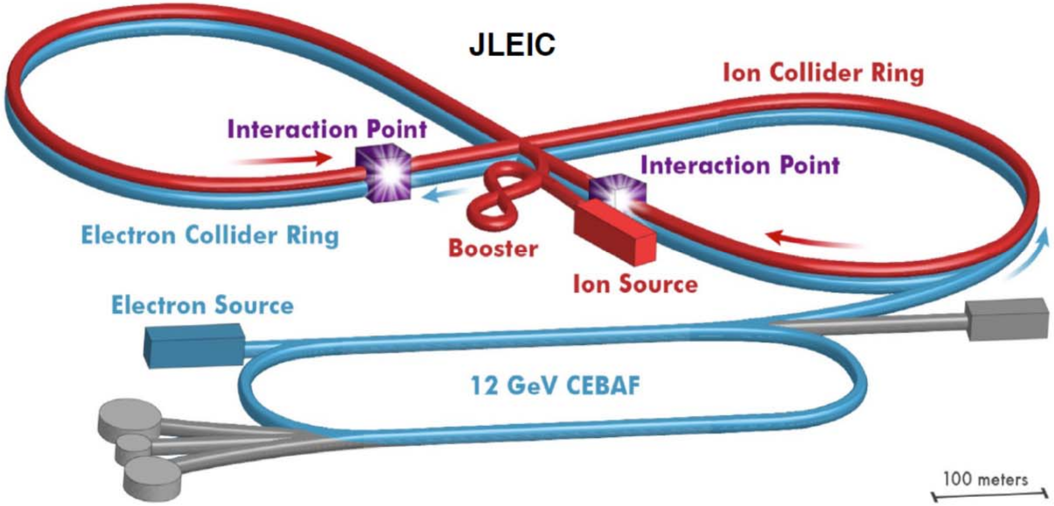


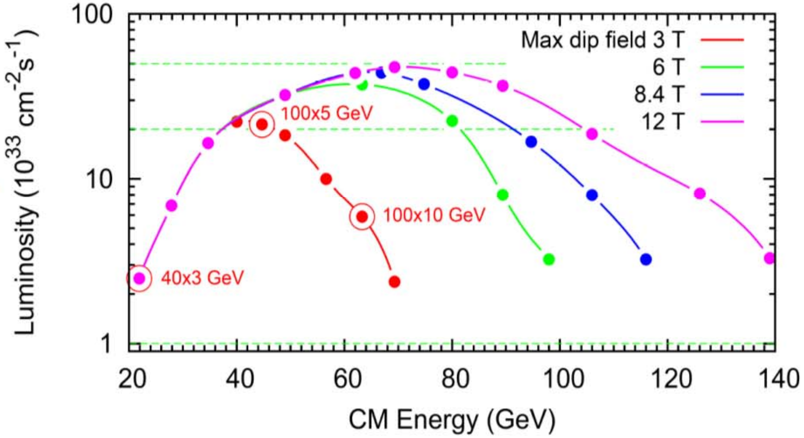


JLEIC @ JLab

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

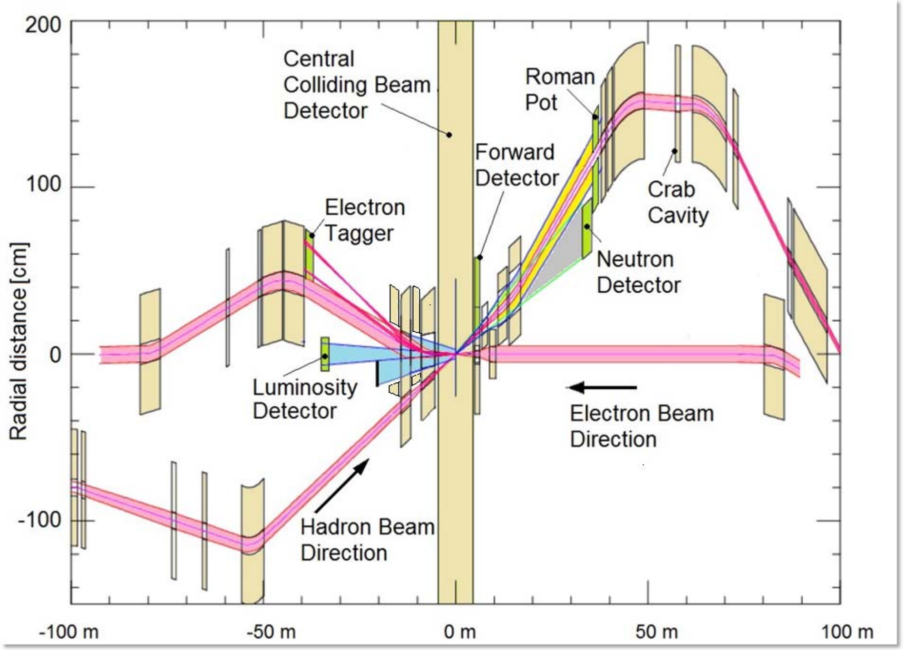




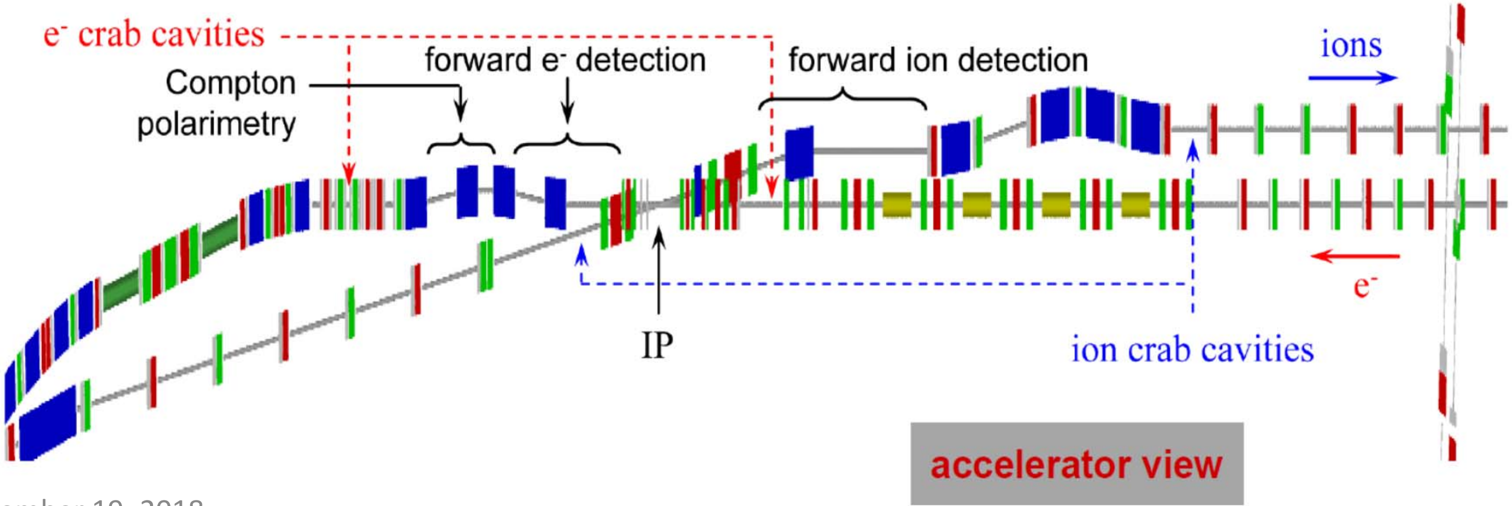


Interaction region design

- BNL

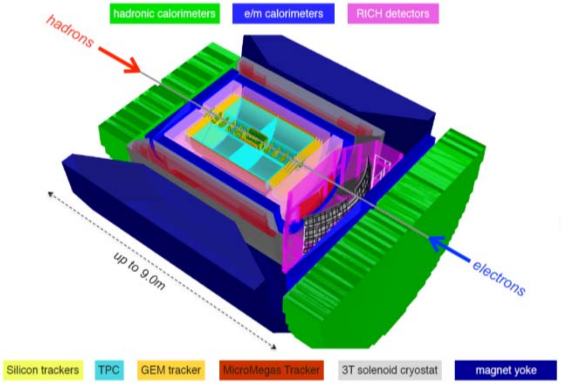


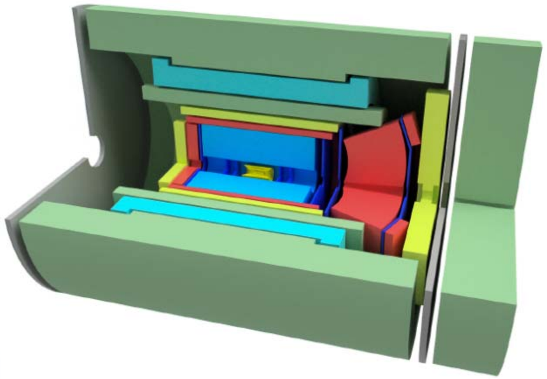
- JLab



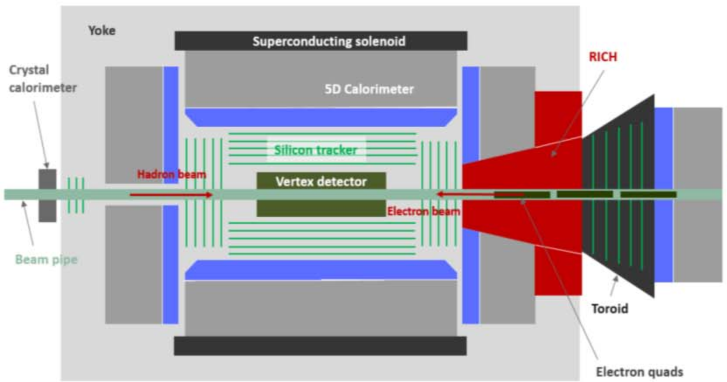
EIC detector

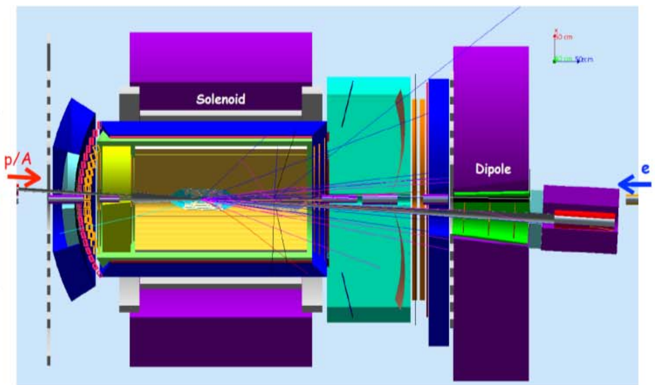
- BNL
  - BEAST
  - EIC-sPHENIX





- JLab
  - TOPSiDE
  - JLEIC



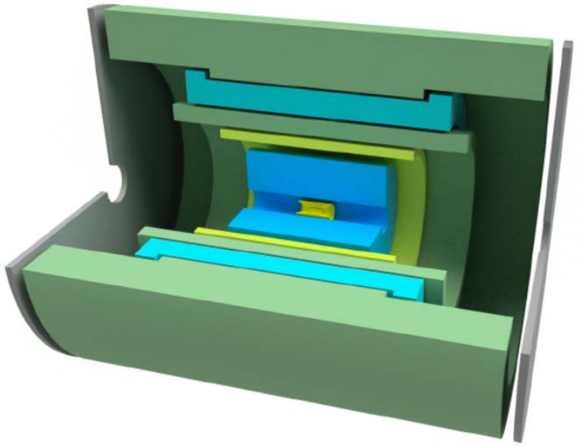


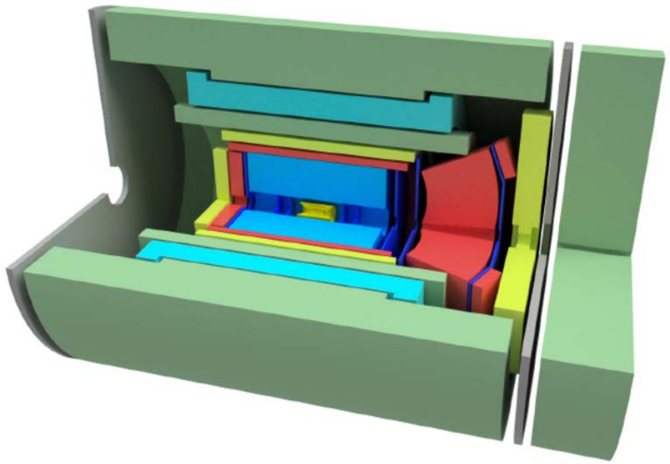
EIC detector

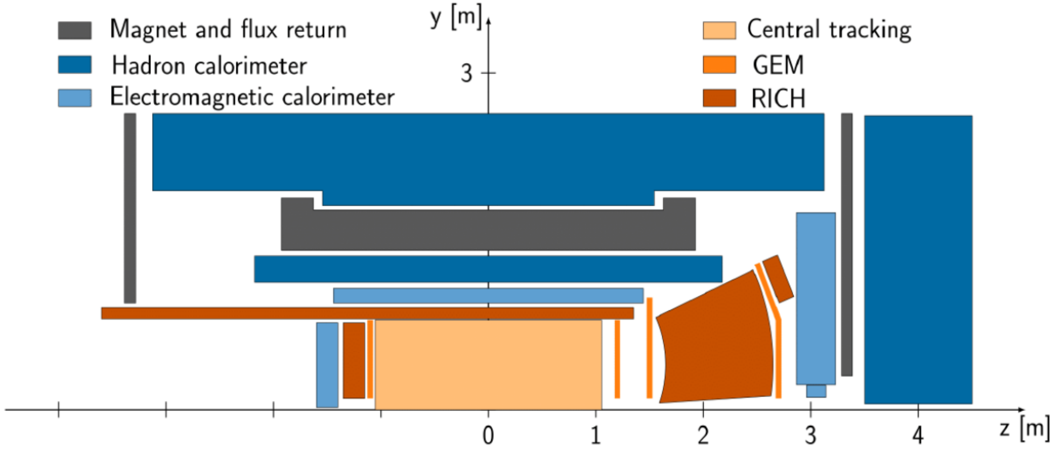
- Mid and forward rapidity detectors
  - 4π coverage, $|\eta| < 3.5$
  - EM & hadron calorimeters
  - Tracking detectors, $\Delta p/p \sim$ few%
  - Particle-ID, π/K/p separation in wide kinematical region
  - Vertex detector, 10-20 μm
- Scattered electron detector, backward and mid rapidity
  - Low material, $\sim$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

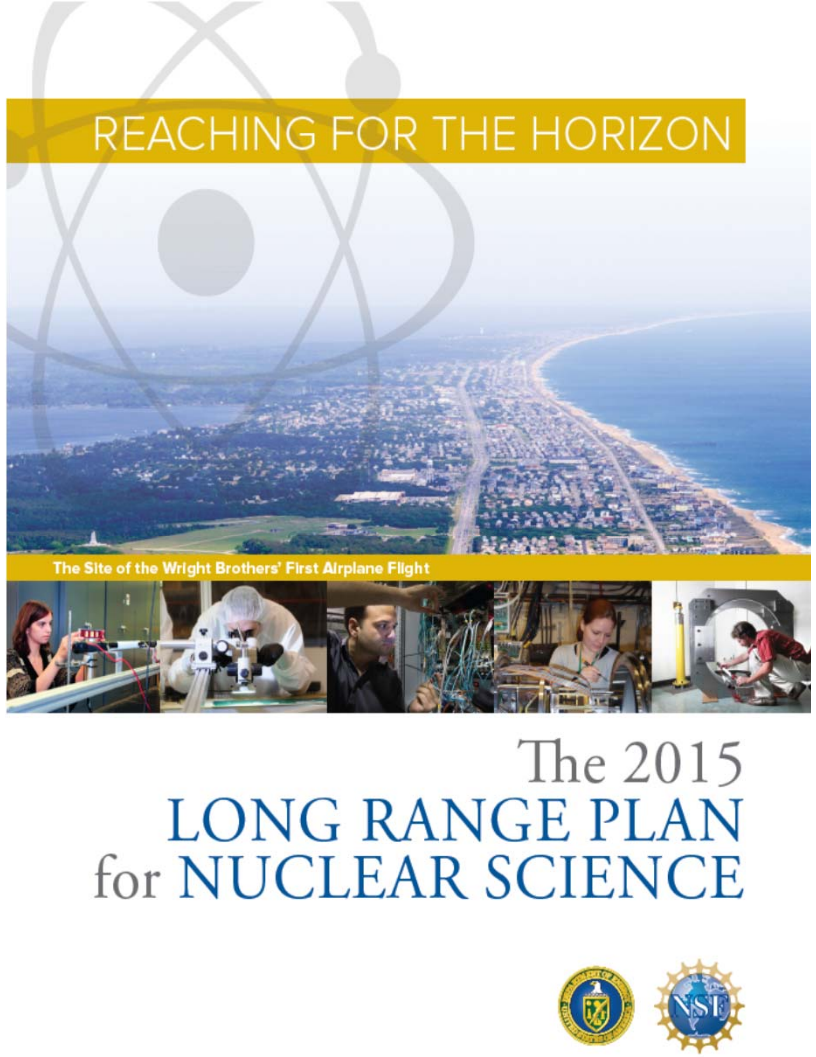






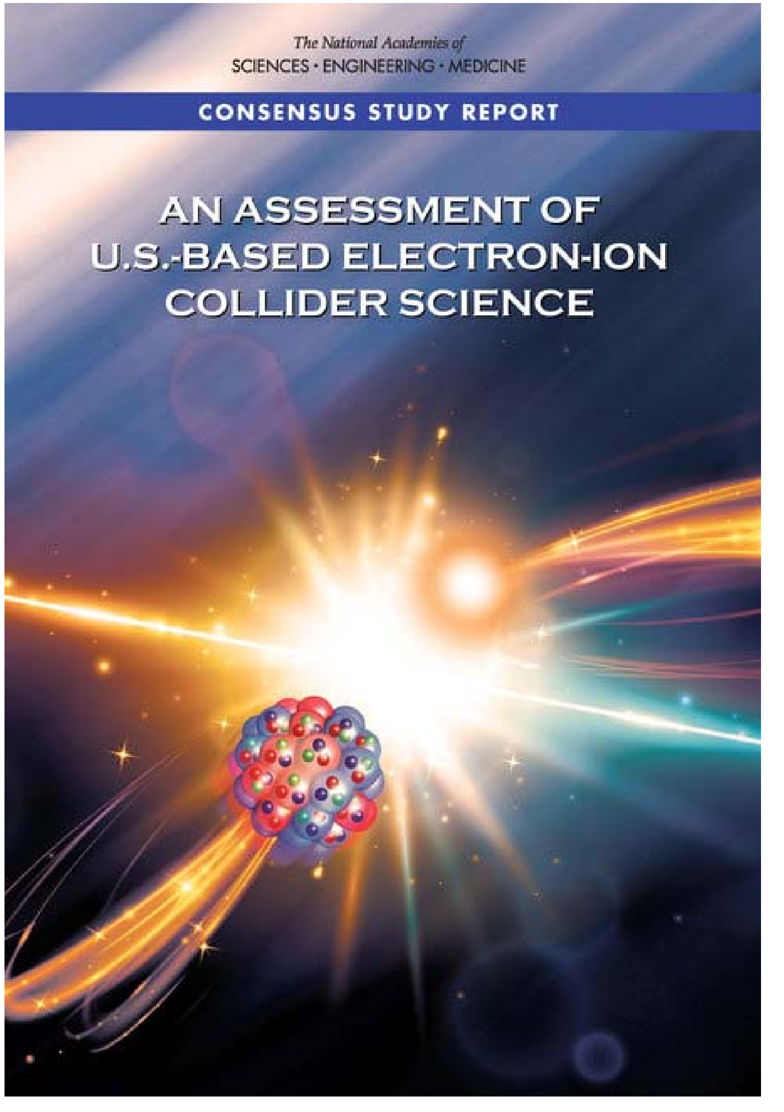
Status of the EIC project

- NSAC 2015 Long Range Plan
  - We recommend a high-energy high luminosity polarized Electron Ion Collider as the 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



Status of the EIC project

- NAS webinar and NAS report release 7/24/2018
  - Webinar presentation by Gordon Baym (Co-chair)
    - The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely.
  - Very positive report
- CD-0 (US mission need statement) could be awarded after the completion of the NAS study ~2018/2019



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

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

Summary

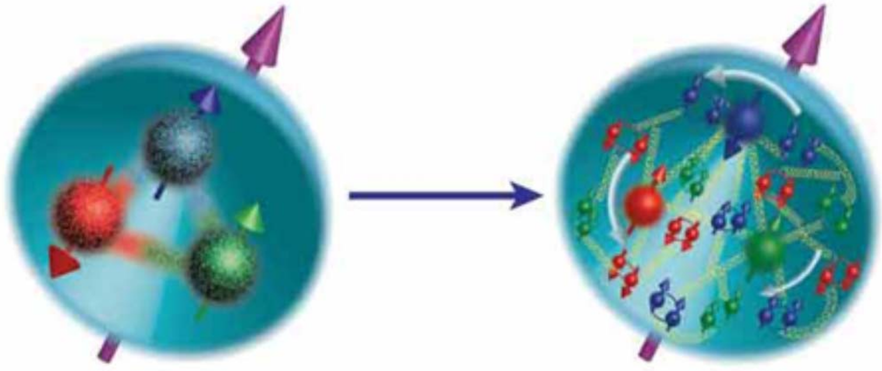
- Physics at EIC
  - High-energy QCD frontier to study nucleon (hadron) and nucleus (cold nuclear matter) emerging from quarks and gluons
    - Precision measurement of PDFs
    - Tomography of the nucleon and nucleus
    - Mass, spin, and more puzzles
  - First observation of a quantum collective gluonic system
    - Gluon saturation
  - Hadronization
- EIC accelerator and detectors
  - BEAST and EIC-sPHENIX at BNL
  - TOPSiDE and JLEIC detector at JLab
- 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
- EIC Users Group and R&D activities
  - Welcome for your participation

Backup Slides

Nucleon puzzles

- Two pictures

static picture
low energy
low resolution



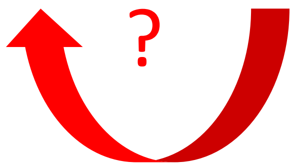
dynamic picture
high energy
high resolution

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



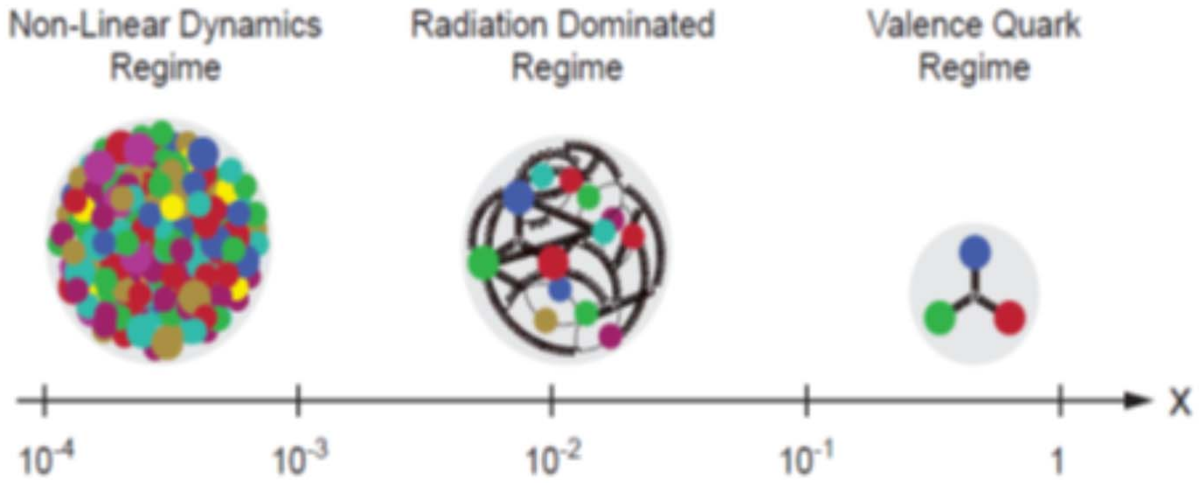
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Quark spin ($\Delta\Sigma$), Gluon spin (Δg), Orbital angular momentum (L)

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) → 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