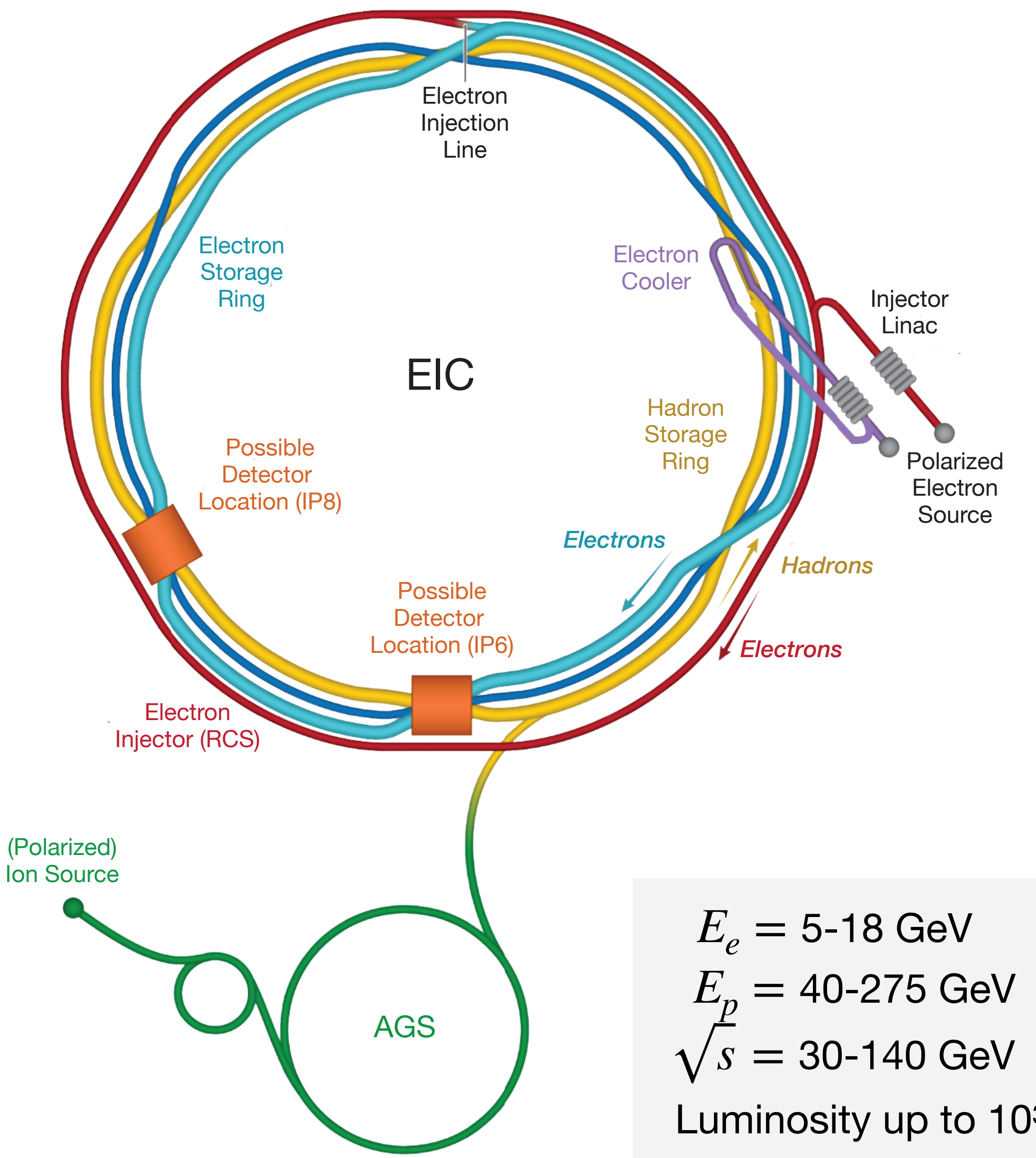
Exploring QCD at the Electron-Ion Collider

C. Weiss (JLab), HUGS 2024 Lectures, JLab, 30-31 May 2024

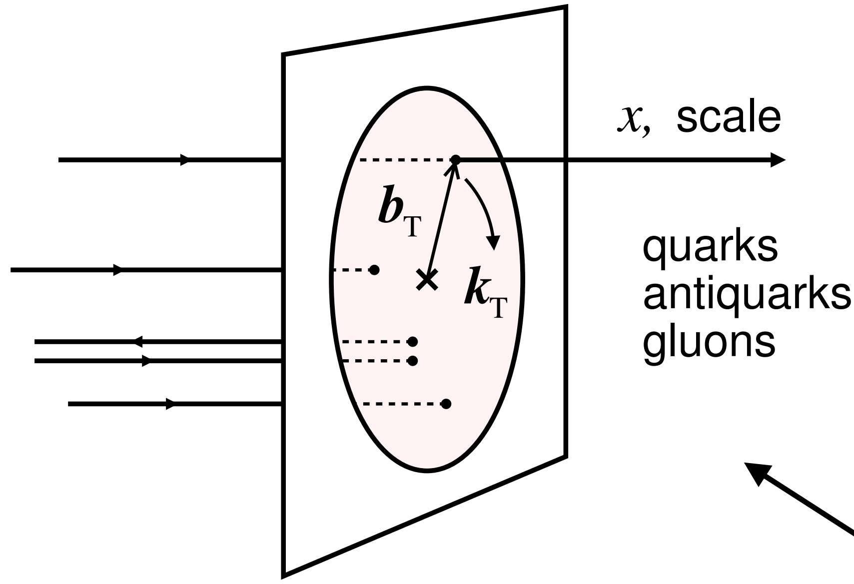
Jefferson Lab



E_e = 5-18 GeV
E_p = 40-275 GeV
$\sqrt{s}$ = 30-140 GeV
Luminosity up to 10^{34} cm^{-2} s^{-1}

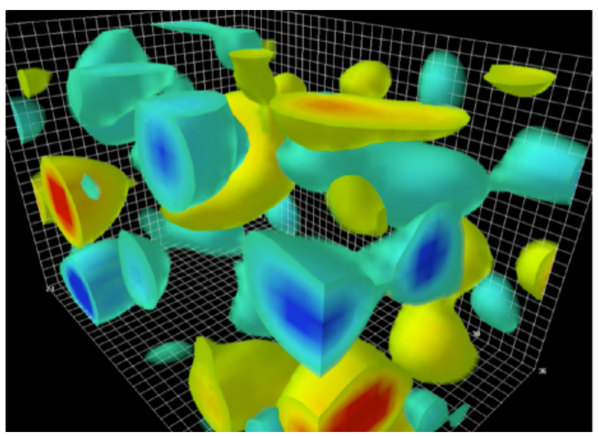
- Concepts ←
- Measurements ←
- Accelerator and detector
- Organization

This lecture

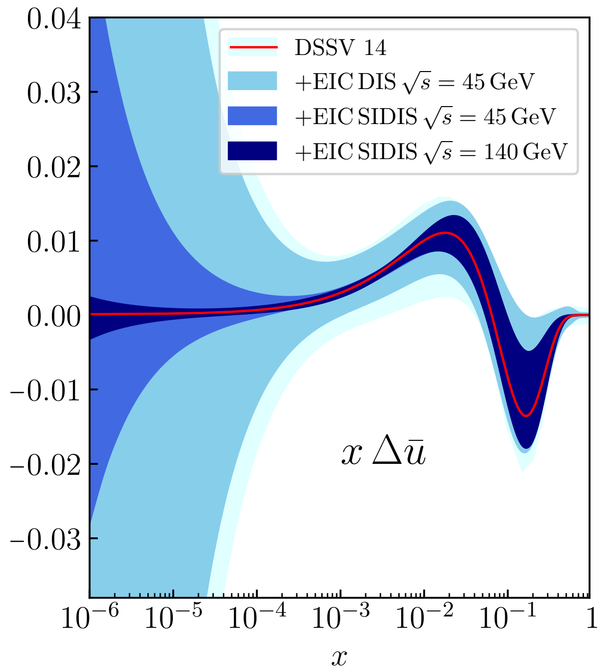


Many-body system

Dynamics



Measurements



Focus on understanding/explaining hadrons and nuclei as emergent phenomena of QCD

Use parton picture to view hadron as many-body system — particle content, measurable properties

Develop physical picture — formal derivations can be provided

Plan

Concepts I

QCD as dynamical system

Parton picture of hadron structure

Factorization and parton densities

High-energy electron scattering

Kinematics and cross sections

Energy and luminosity

Fixed-target vs. colliding-beam

EIC physics I: Nucleon structure

Sea quark and gluon polarization

Orbital angular momentum

Transverse spatial distributions

Neutron structure from D/3He

Concepts II

Nuclear interactions and partonic structure

EIC physics II: Nuclei and hadronization

Nuclear gluon density

Shadowing and saturation

Hadronization in vacuum and in nuclei

[Accelerator and detector]

Organization

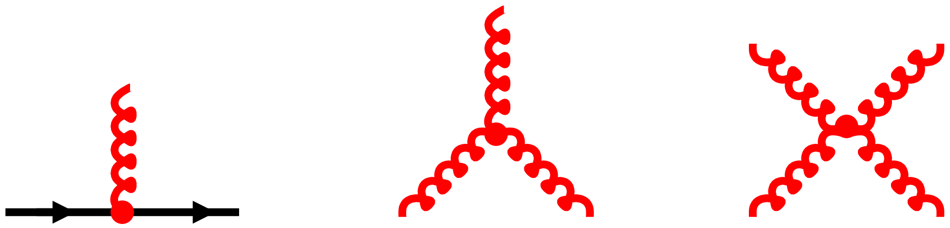
EIC User Group, ePIC Collaboration, Project

Getting involved

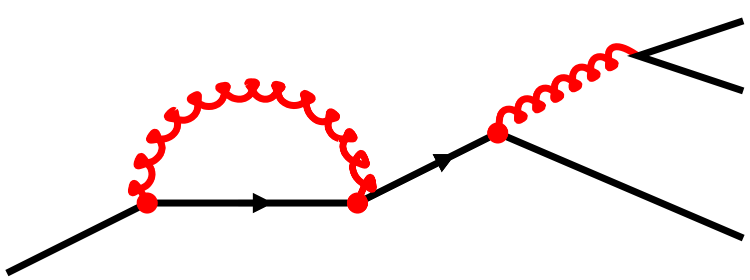
QCD: Dynamical system

$A_\mu(x), \quad \psi, \bar{\psi}(x)$ gauge and matter fields

modes e^{-ikx} particles — gluons, quarks/antiquarks



modes coupled by gauge interaction

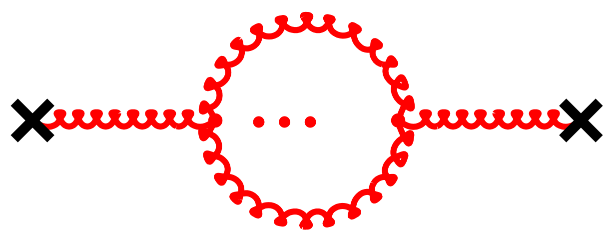


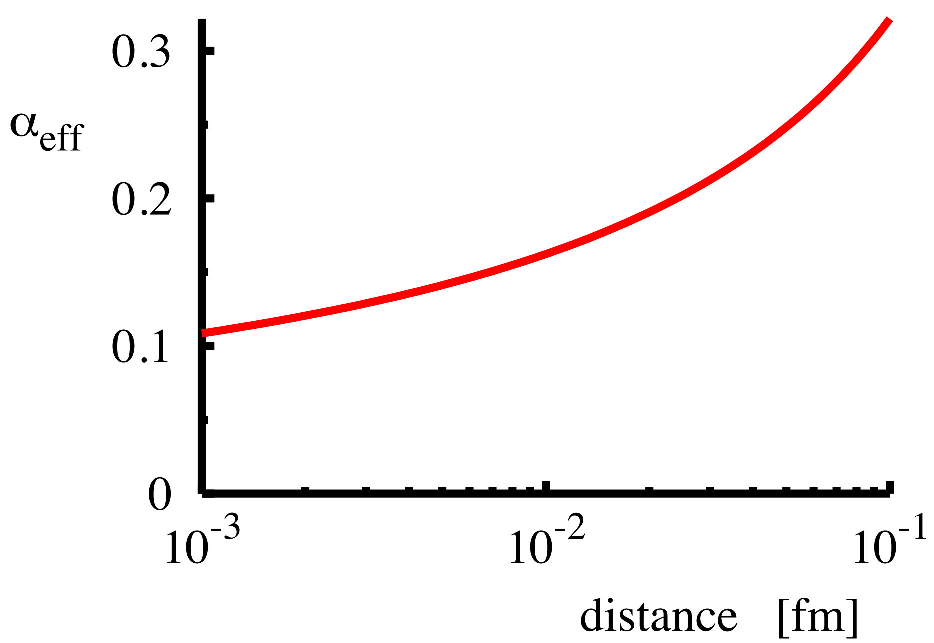
quantum motion involves radiation, particle creation/annihilation

essentially relativistic: momenta $k \sim$ few 100 MeV $\gg$ quark masses $\sim$ few MeV

"particles" and "radiation" cannot be separated

QCD: Scale dependence





Here: 1-loop accuracy

Modes depend on resolution scale, “how much radiation is included”

Effective coupling scale-dependent

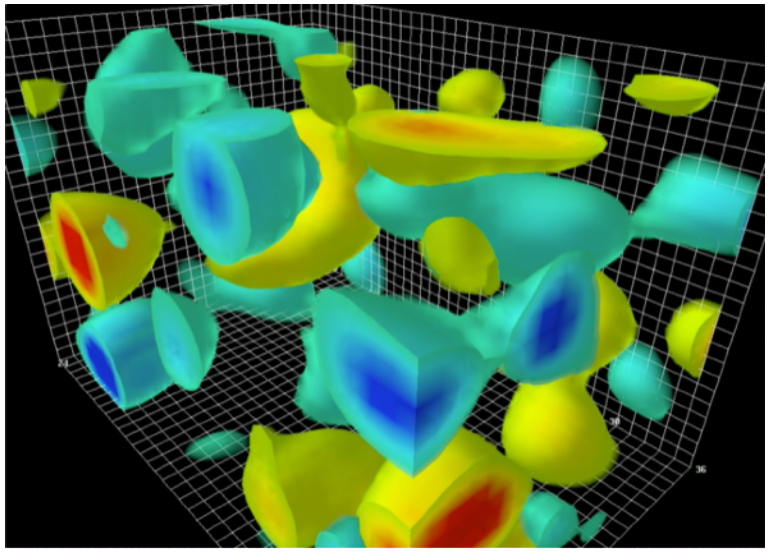
Example: Interaction of static sources

$$V_{Q\bar{Q}}(r) = \frac{4\pi\alpha_{\rm eff}(r)}{r} \quad \text{+ gauge-dep.}$$

Asymptotic freedom: Effective coupling decreases at short distances

Perturbative calculations generally applicable at short distances (typically $\lesssim$ 0.2 fm)

QCD: Larger distances



↔
~ 0.3 fm

Leinweber 2003: “Cooled” lattice QCD configurations

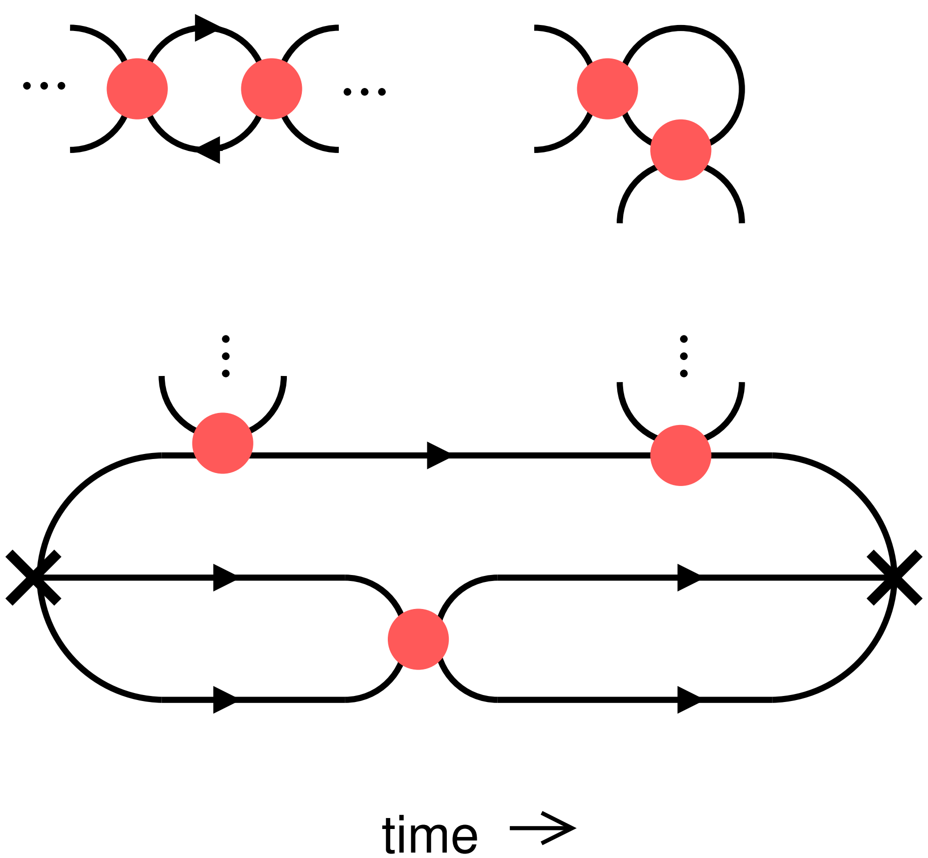
Nonperturbative vacuum fluctuations of gauge fields - tunneling, topology

Condensate of quark-antiquark pairs - chiral symmetry breaking

Dynamical mass generation:
Effective degrees of freedom
↔ e.g. constituent quark picture

Hadron formation at distances ~ 1 fm

Rich spectrum of meson and baryon excitations



Correlation functions of color-singlet operators with meson/baryon quantum numbers

$\langle 0 \,|\, T\, J(x)\, J(0) \,|\, 0 \rangle$ in vacuum state

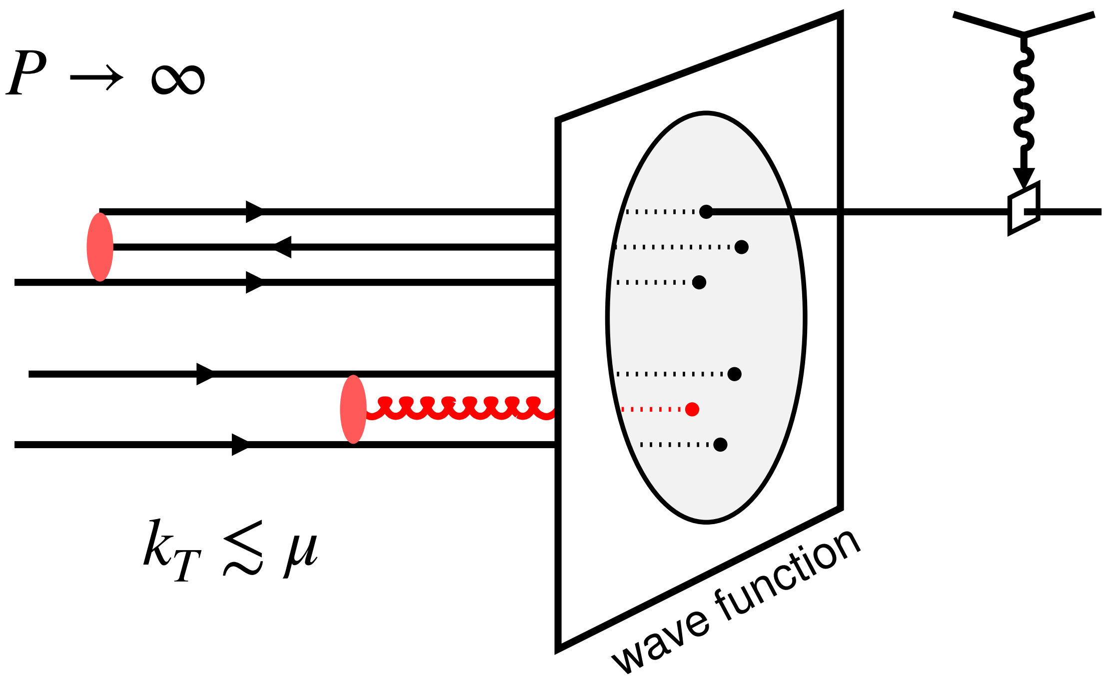
Imaginary time $t \to i\tau$: Statistical mechanics
Lattice simulations, analytic methods

Hadron spectrum m_h, structure $\langle h \,|\, \mathcal{O} \,|\, h \rangle$
→ Lecture Huey-Wen Lin

No concept of particle content:
Cannot separate modes "belonging to hadron" from vacuum fluctuations

No notion of hadron wave function:
Not a closed system

Hadron structure: Parton picture



Momentum $P \to \infty$ $(\gg \mu_{\text{vac}})$

Separate modes:

$k_{\parallel} = xP, \;\; x > 0$ "hadron"

$k_{\parallel} \lesssim \mu_{\text{vac}}$ "vacuum"

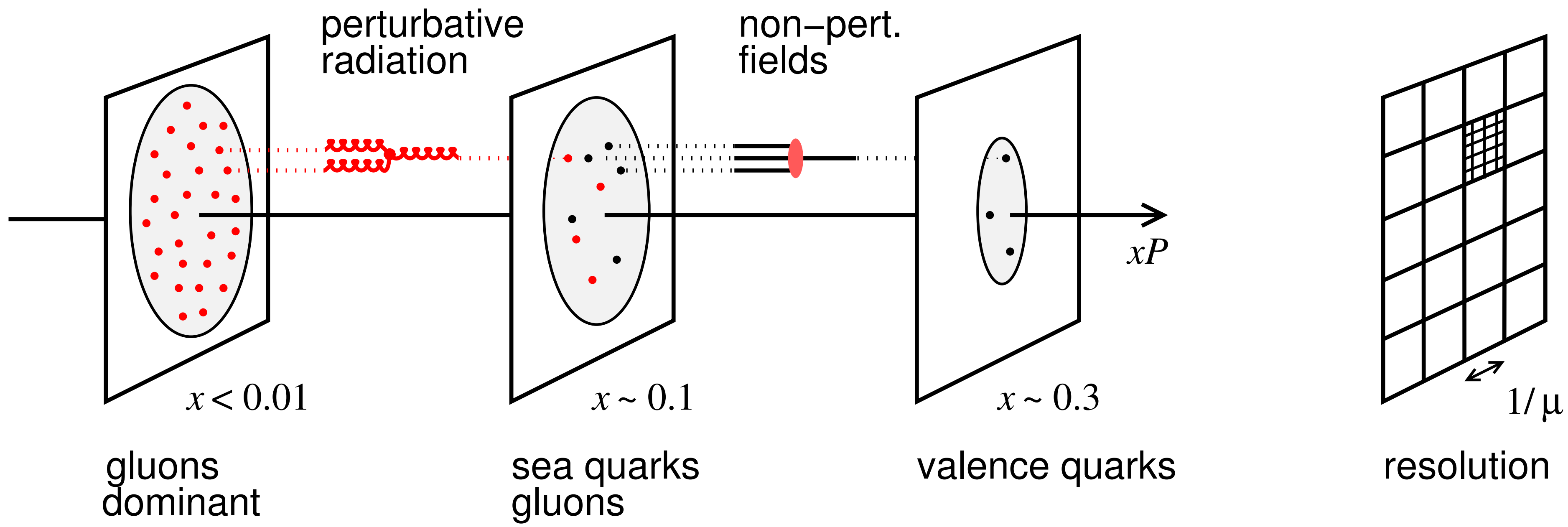
Hadron becomes closed system:
Described by wave function

Wave function has components with different particle number:
$|N\rangle = |qqq\rangle \; + \; |qqq\bar{q}q\rangle \; + \; |qqqg\rangle \; + \; \dots$ (schematically)

Many-body system in particle degrees of freedom

In QCD this picture emerges after factorization and renormalization:
Transverse momentum cutoff $k_T \lesssim \mu$, scale dependence → later

Hadron structure: Many-body system



Components of wave function

Few particles with large $x = O(1)$ fractional momentum

Many particles with small $x \ll 1$

} connected by QCD interactions

Measurable properties

Particle number densities, incl. spin/flavor dependence

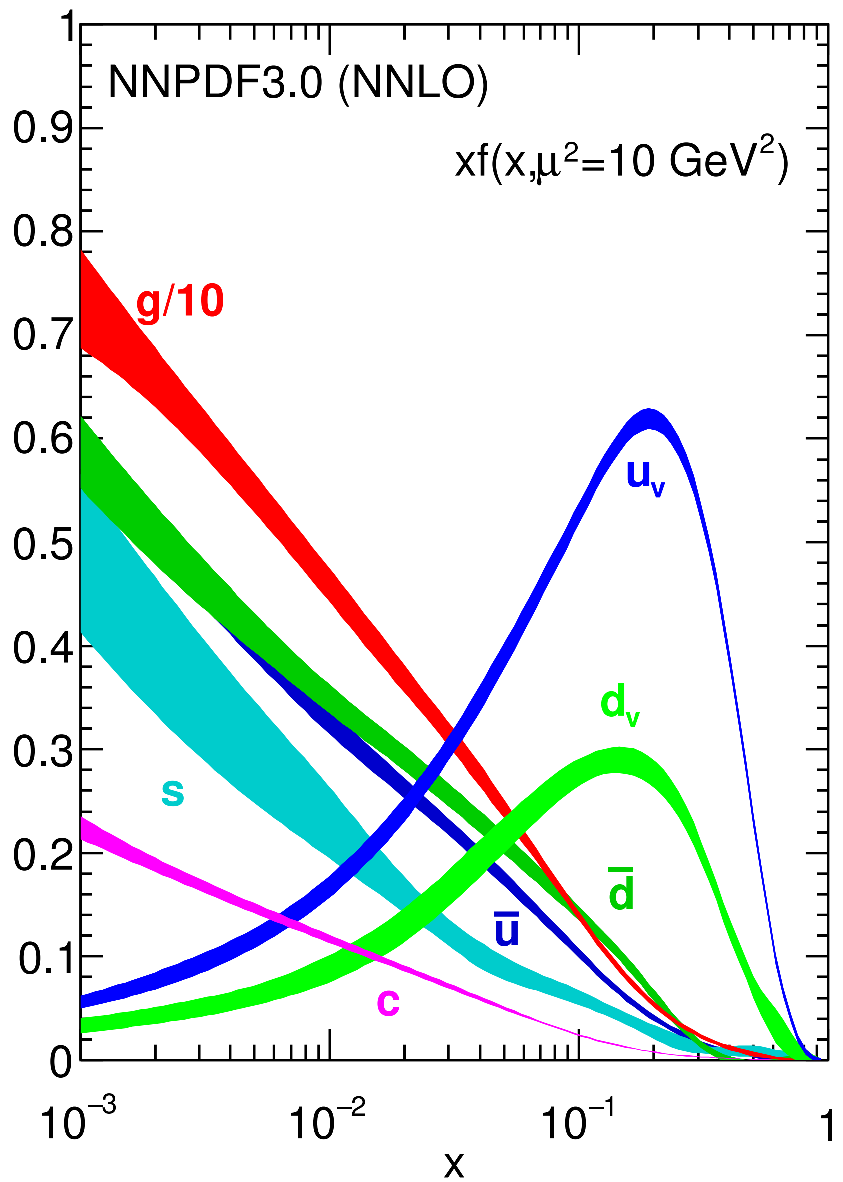
Transverse spatial distributions

Transverse orbital motion, spin-orbit correlations

Particle correlations

} change with resolution scale μ

Hadron structure: Quark/gluon number densities



$u_v \equiv u - \bar{u}$ etc.

Number densities $f(x, \mu)$

x — longitudinal momentum fraction

μ — resolution scale $\int d^2 k_T < \mu$

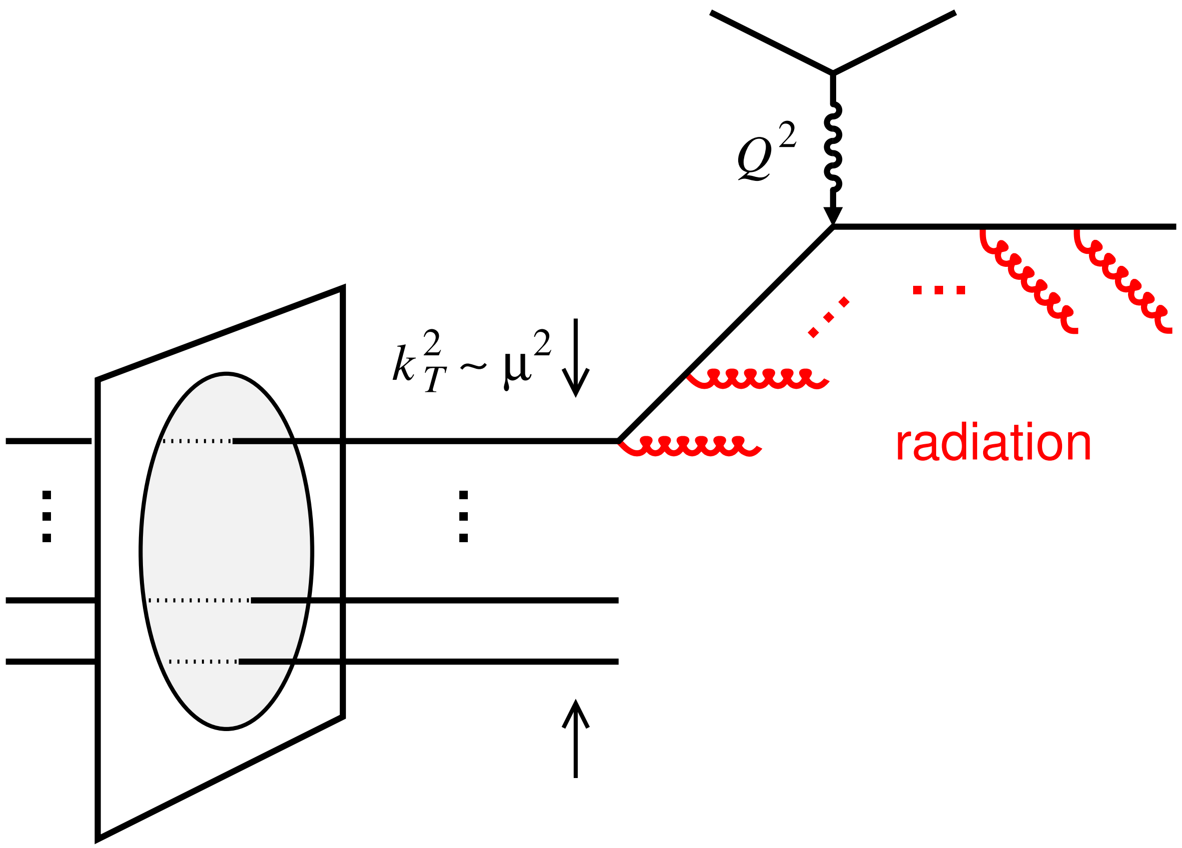
Extracted from global analysis of various scattering processes → Lecture Nobuo Sato

Types of particles

$x \gtrsim 0.3$	Valence quarks
$x \sim 10^{-1}$	Sea quarks, gluons
$x \lesssim 10^{-2}$	Gluons dominant

Basic particle content of nucleon in QCD!

Factorization: Separation of scales



Scattering process at momentum transfer $Q^2 \gg$ hadronic scale

Separate scales:

$k_T^2 \sim Q^2$	hard scattering process
	↕ radiation
$k_T^2 \sim \mu^2$	hadron structure

Types of final states

inclusive	$e + N \rightarrow e' + X$	Σ all radiation
semi-inclusive	$e + N \rightarrow e' + h + X'$	radiation restricted
exclusive	$e + N \rightarrow e' + M + N'$	radiation only internal, emitted + absorbed

Hadron structure described by particle densities = reduction of “wave functions”

$$f(x,\mu) \;=\; \langle N(P)\,|\,a^\dagger a\,(k_\| = xP, k_T < \mu)\,|\,N(P)\rangle_{P\to\infty}$$

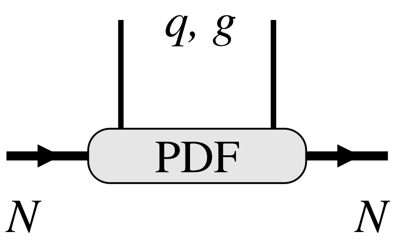
Number density of quarks
in fast-moving nucleon state

$$\to \int \frac{d\lambda}{2\pi}\, e^{i\lambda x(Pn)}\, \langle N(P)\,|\,\bar\psi(\lambda n)\ldots\psi(0)_\mu\,|\,N(P)\rangle_{\text{any } P}$$

Correlation function of quark fields
at light-like separation $\lambda n^\mu, n^\mu n_\mu = 0$

→ Lecture Nobuo Sato

Properties



Rigorously defined: Matrix elements of 2nd quantized QCD operator,
renormalized at scale μ, scale dependence described by evolution eqs

Process-independent, universal: Same distribution can appear in multiple processes
as directed by factorization

Sum rules: $\int dx\,[f - \bar f](x,\mu) =$ global charges

Computable: Distributions can be computed using lattice QCD, other non-perturbative methods

Extensions: Spin-dependent distributions, transverse-momentum dependent distributions TMD,
generalized parton distributions GPD with $P \neq P'$

Principal tools for characterizing hadron structure in QCD

Summary

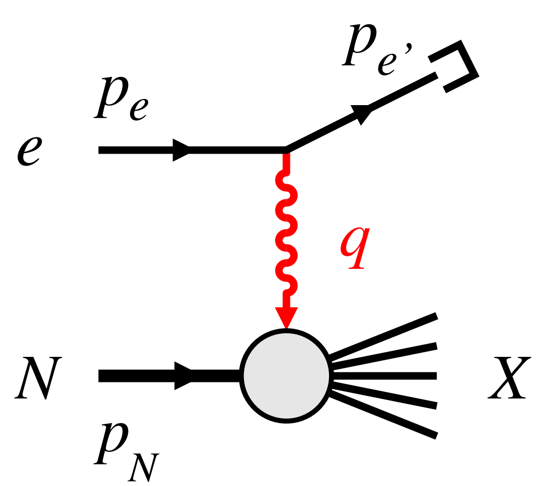
Fast-moving hadron state ($P \gg \mu_{\text{vac}}$) decouples from vacuum fluctuations, becomes "closed system" described by wave function

Hadron state has components with variable particle number, connected by QCD interactions

Rigorous definition of parton densities can be provided in the context of factorization of high-momentum transfer processes: Second-quantized QCD operator, renormalization

Think of hadron as many-body system with physical characteristics: Particle content, spatial size, orbital motion, correlations…

Electron scattering: Kinematic variables



Particles described by 4-momenta $p_e = (E_e, \mathbf{p_e})$ etc.

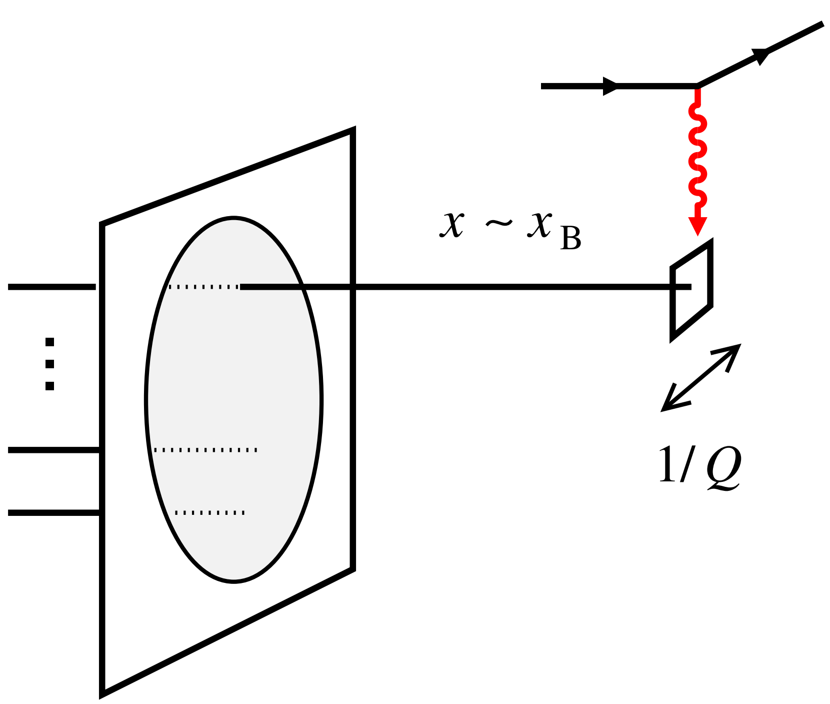
$q \equiv p_e - p_{e'} = (q^0, \mathbf{q})$ 4-momentum transfer

Inelastic scattering: Energy and momentum transfer independent

Relativistically invariant variables

$Q^2 \equiv -q^2$ invariant momentum transfer

$$x_B \equiv \frac{Q^2}{2(p_N q)}$$ Bjorken scaling variable



Probing nucleon structure

$x \sim x_B$ selects momentum fraction

$1/Q$ sets resolution scale

Direct connection of external kinematic variables with internal variables of parton picture

Electron scattering: Cross section

Inclusive scattering $e + N \to e' + X$

$$\frac{d\sigma}{dx_B dQ^2} = \text{[Flux]} \times \left[F_1(x_B, Q^2) + \ldots \right]$$

Differential cross section (1-photon exchange) parametrized by invariant structure functions

$$F_1(x_B, Q^2) = \sum_{q=u,d,s} e_q^2 \int dx\, C_q(x_B, x; Q^2/\mu^2) \, \left[q(x,\mu^2) + \bar{q}(x,\mu^2) \right]$$

$$+ e_q^2 \int dx\, C_g(x_B, x; Q^2/\mu^2)\; g(x,\mu^2)$$

Factorization: Structure function expressed through parton densities

Coefficients contains hard scattering and radiation effects (evolution)

Predict cross section from parton densities model
Extract parton densities from measured cross section

Similar workflow in semi-inclusive scattering $e + N \to e' + h + X$,
exclusive scattering $e + N \to e' + M + N'$

Electron scattering: Polarization

Inclusive scattering $\vec{e} + \vec{N} \rightarrow e' + X$, beam and target polarized

$$\frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\downarrow\uparrow}}{dx_B dQ^2} = \text{[Flux']} \times \left[g_1(x_B, Q^2) + \ldots \right]$$

Spin difference of differential cross sections parametrized by spin structure functions

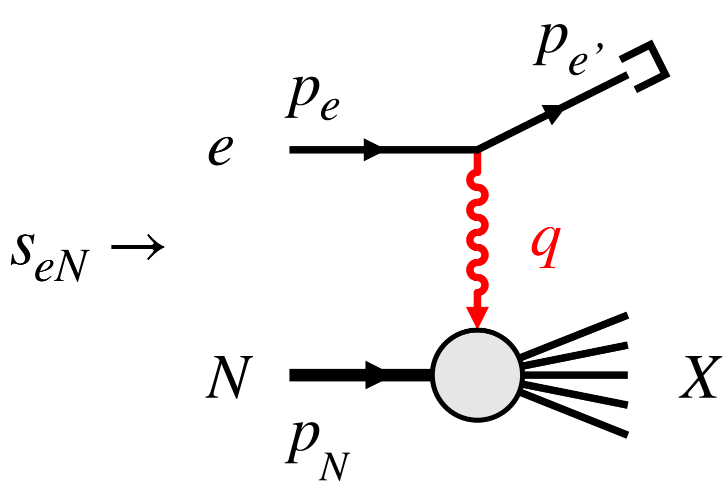
$$g_1(x_B, Q^2) = \sum_{q=u,d,s} e_q^2 \int dx\, C_q'(x_B, x; Q^2/\mu^2) \left[\Delta q(x, \mu^2) + \Delta \bar{q}(x, \mu^2) \right]$$
$$+ e_q^2 \int dx\, C_g'(x_B, x; Q^2/\mu^2)\, \Delta g(x, \mu^2)$$

Factorization: Structure function expressed through polarized parton densities

$$\frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\downarrow\uparrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\downarrow\uparrow}} = \frac{\text{Flux'}}{\text{Flux}} \times \frac{g_1(x_B, Q^2)}{F_1(x_B, Q^2) + \ldots}$$

Alt. observable: Spin asymmetry of cross section, experimentally simpler than absolute cross section

Similar workflow in polarized semi-inclusive and exclusive scattering

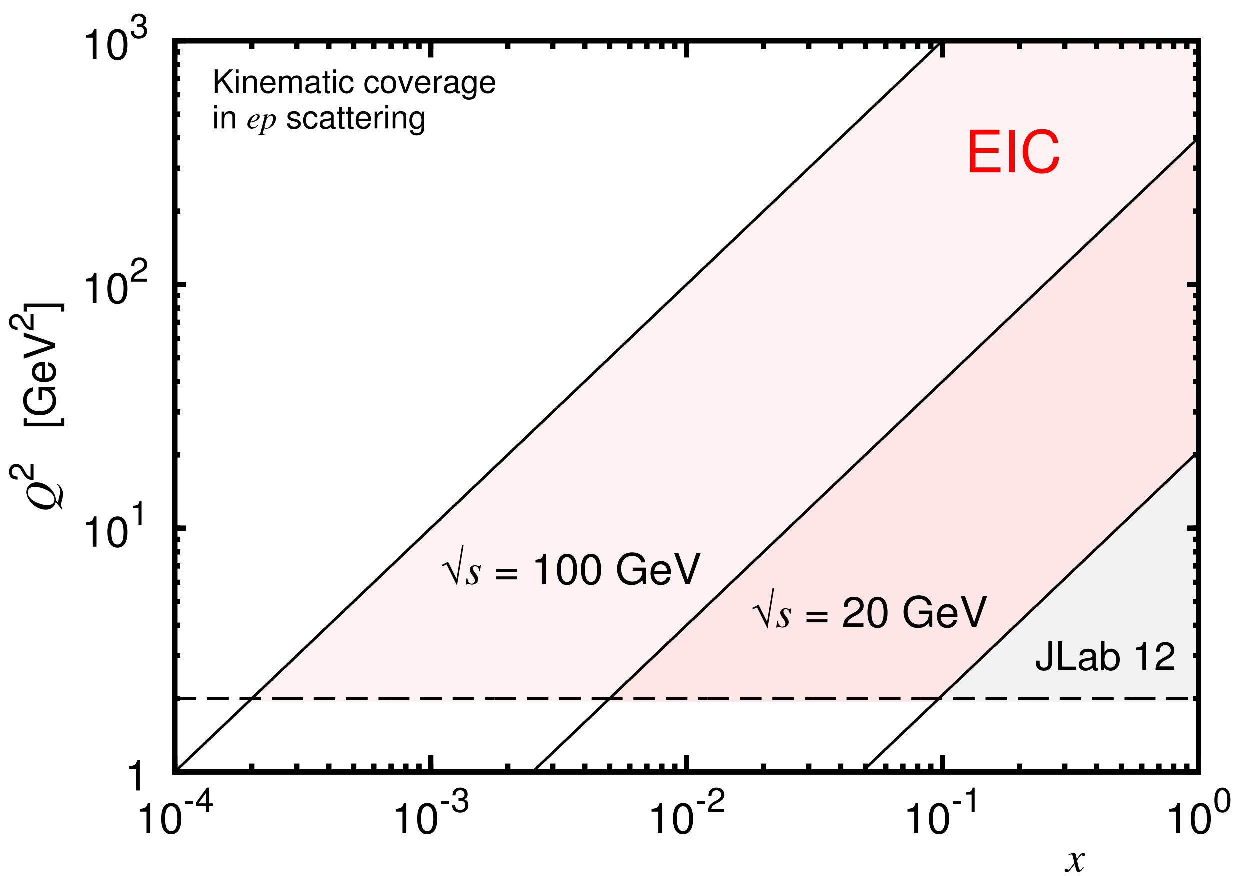


$$s = (p_e + p_N)^2 \quad \text{electron-nucleon invariant}$$

$$= (E_e + E_p)^2_{\text{CM}} \quad \text{energies of particles in CM frame}$$

Kinematic range

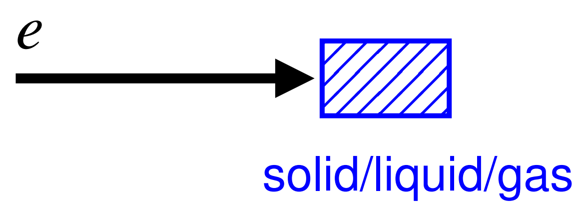
$$Q^2 < x_B(s - m^2) \quad \text{kinematic limit}$$



Experimental limitations at low Q^2 and large x_B — resolution

Large s needed to access small x_B, high Q^2

Electron scattering: Setups

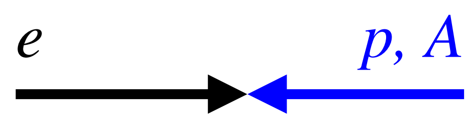


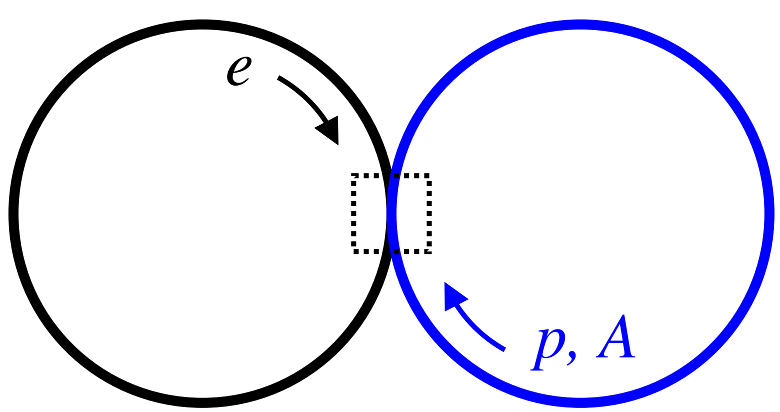
Beam on fixed target

High luminosity from density of protons/nuclei in target

Polarized target technology

CM energy grows as $s = 2E_e m_p + m_p^2$





Colliding beams

CM energy grows as product $s \sim 4E_e E_p$

Energy-efficient: Beams in storage rings can collide multiple times

Clean: No target material, no scattering from atomic electrons, no dilution by other nuclei

Detection: Final-state particles can have large angles depending on energies; far-forward detection

Achieving high luminosity much more challenging: Beam quality (cooling), focusing, collision geometry

Integrated design needed: Interaction region, detector

Electron scattering: Luminosity

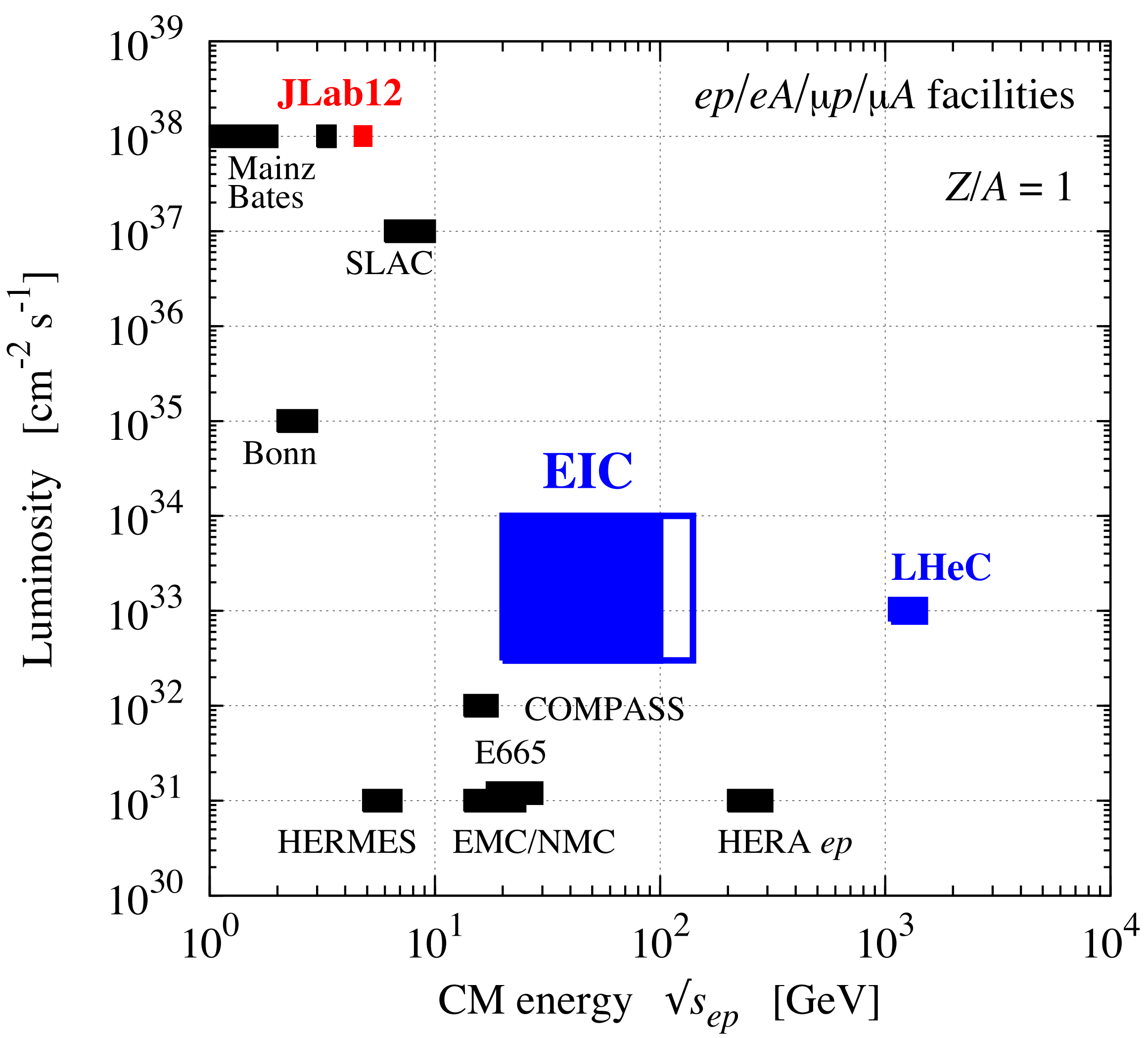
$$\frac{N_{\text{event}}}{T} = L \times \sigma$$

rate | luminosity | cross section

Luminosity determines event rate for given cross section

High luminosity required for

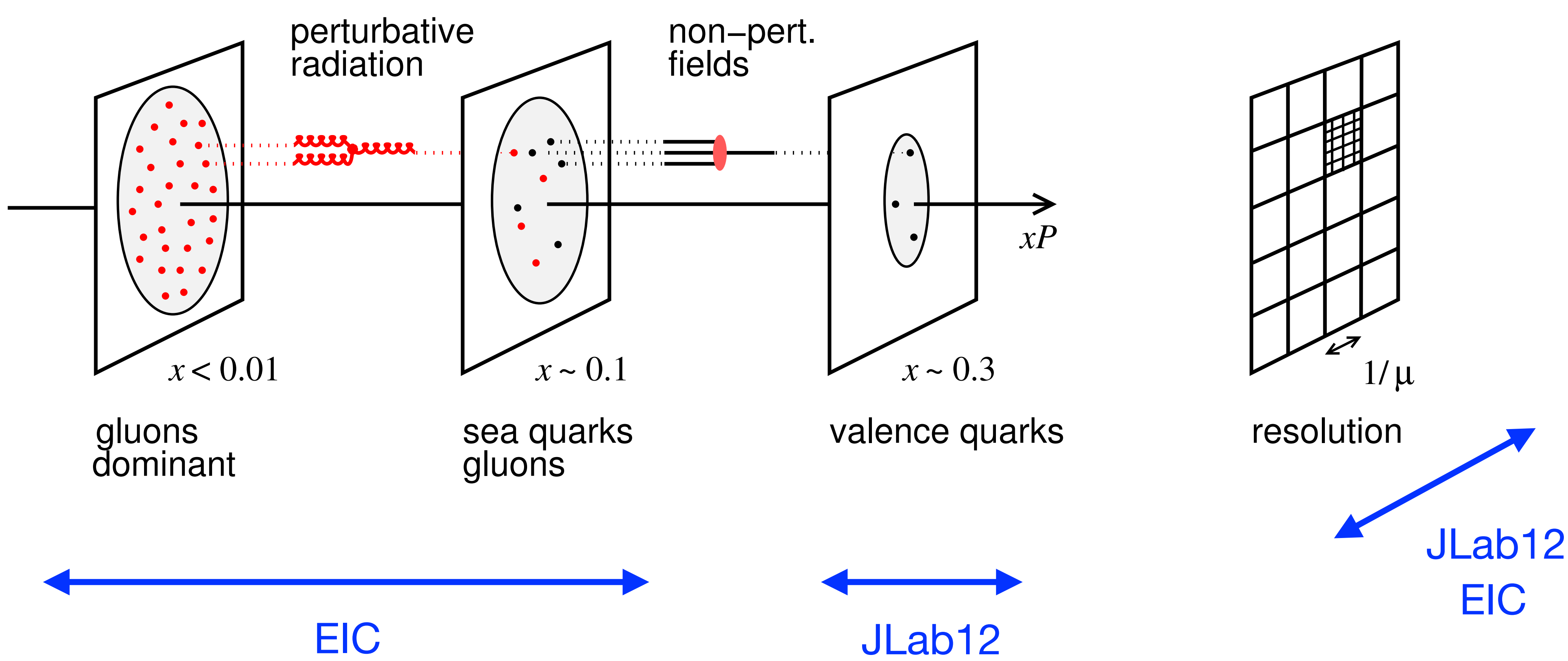
- rare processes — exclusive processes, high p_T hadrons, rare nuclear configurations
- multidimensional binning — transverse imaging, TMD evolution, jets
- spin asymmetries — polarized partons



JLab 12 GeV: Energy x luminosity frontier in fixed-target scattering

EIC: First high-luminosity polarized ep/eA collider

Hadron structure: Many-body system



Measurable properties

Particle number densities, incl. spin/flavor dependence

Transverse spatial distributions

Transverse orbital motion, spin-orbit correlations

Particle correlations

} change with resolution scale μ

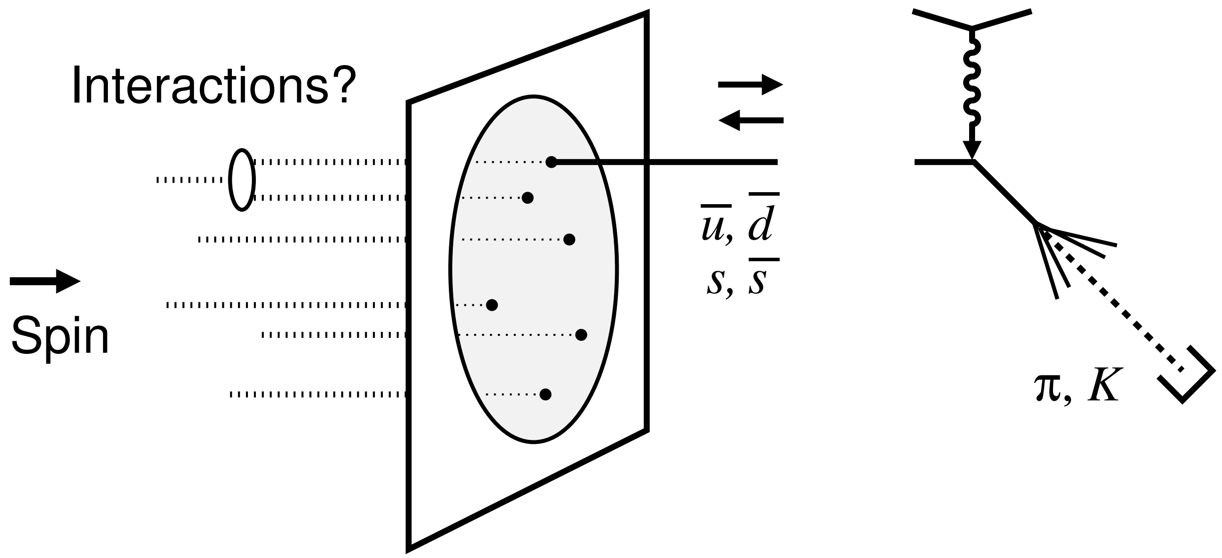
Summary

Electron scattering probes partonic structure differentially in $x \sim x_B$ (momentum fraction) and $\mu^2 \sim Q^2$ (resolution scale)

JLab 12 GeV and EIC are complementary:
JLab 12 GeV: $x \gtrsim 0.1$, valence quarks, highest luminosity
EIC: $x \lesssim 0.1$, sea quarks and gluons, scale dependence

Luminosity critical for many applications

EIC: Sea quark polarization



How are sea quarks polarized?

Nonperturbative interactions connecting valence and sea quarks?

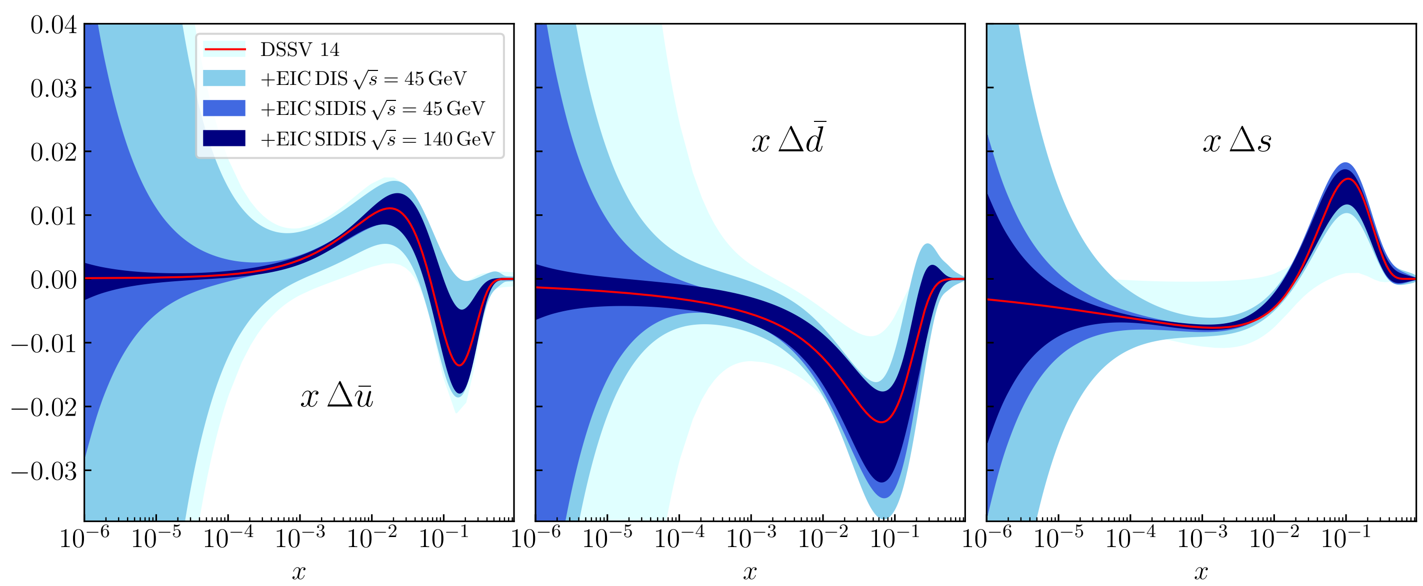
Mesonic degrees of freedom?

Semi-inclusive scattering

Detect π, K from fragmentation

Determine charge/flavor of active quark

Fixed-target: HERMES, COMPASS, JLab12 GeV



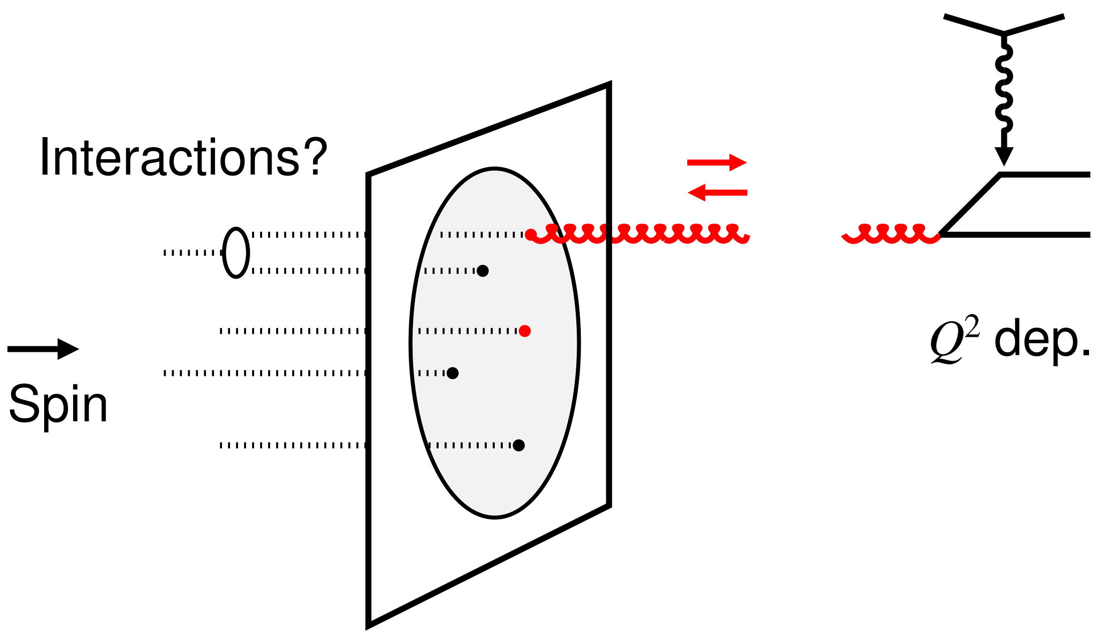
EIC Yellow Report 2022

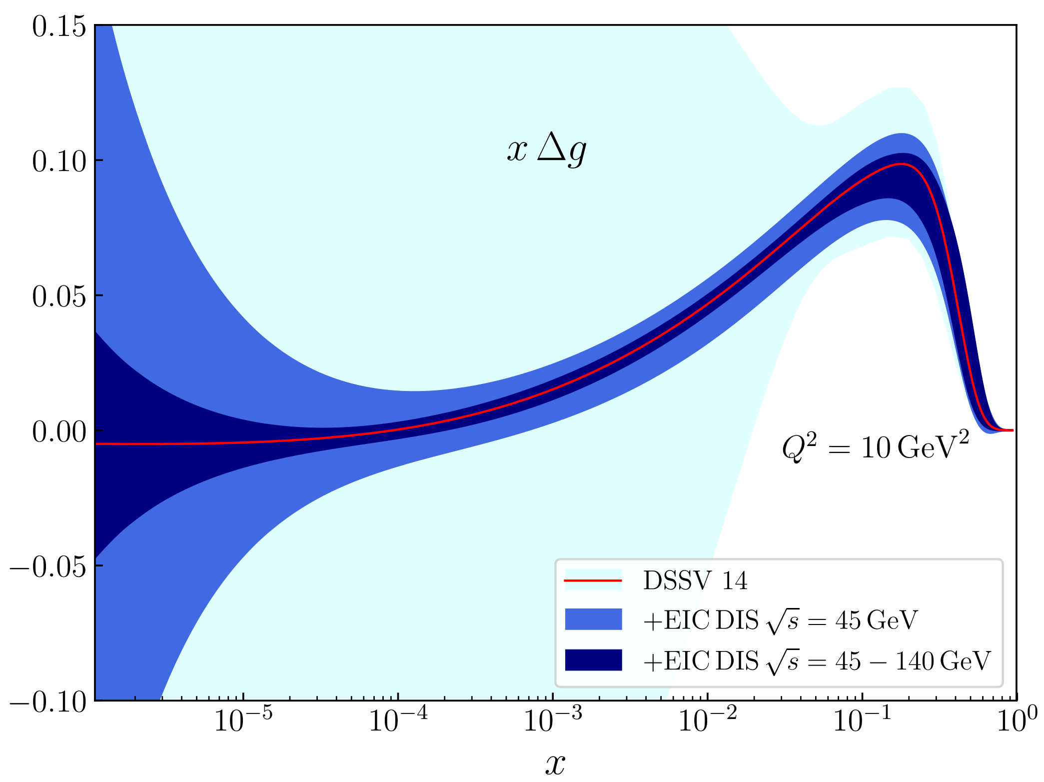
EIC measurements

High energy ensures independent fragmentation of active quark

Accurate extraction of sea quark polarization

EIC: Gluon polarization





How are gluons polarized?

Nonperturbative interactions creating “physical” gluon modes?

Gluon spin contribution to nucleon spin?
Orbital angular momentum in nucleon?

Gluon polarization from ep scattering

Q^2 dependence of spin structure function $g_1(x, Q^2)$ from QCD evolution

Heavy quark pair production $c\bar{c}$

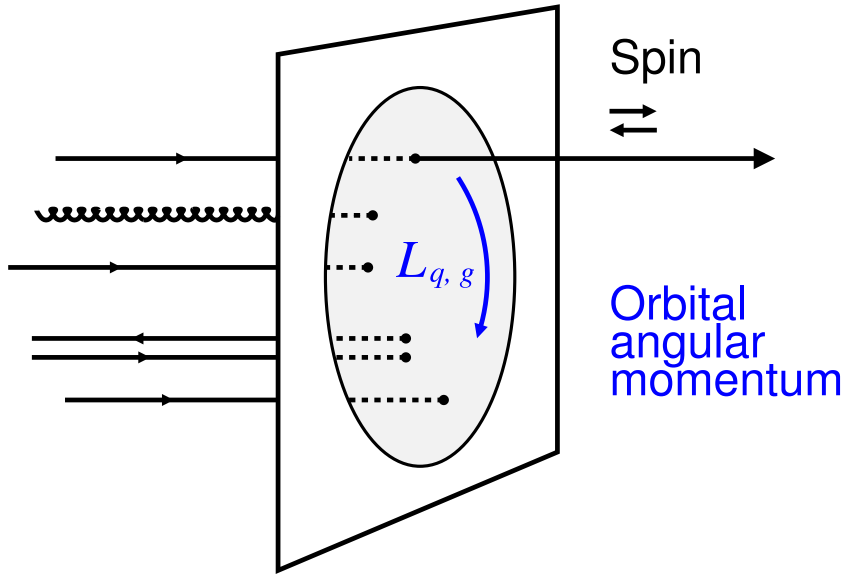
Alt: Polarized pp scattering at RHIC

EIC measurements

Wide range of x, Q^2 enables effective extraction from evolution

Accurate determination of Δg

EIC: Spin sum rule and orbital angular momentum



Nucleon spin sum rule

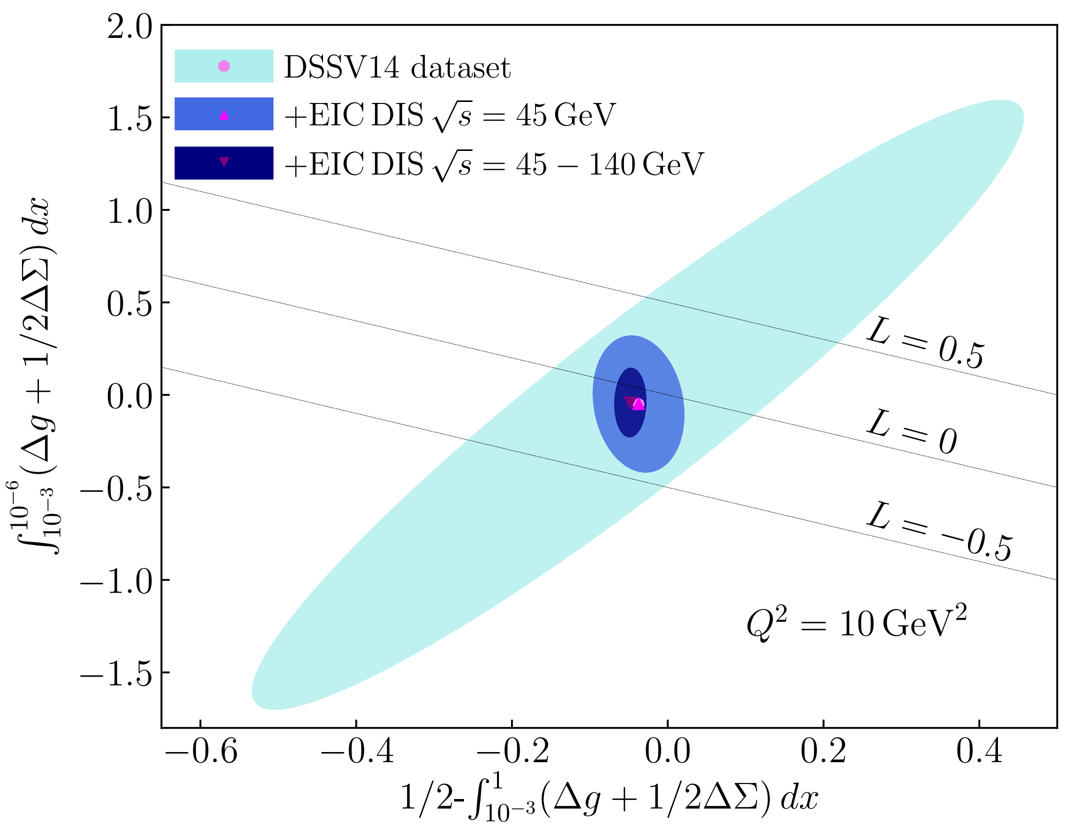
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_q + L_g$$

$$\Delta\Sigma(\mu) = \sum_{q=u,d,s} \int_0^1 dx\, [\Delta q + \Delta\bar{q}](x,\mu)$$

$$\Delta G(\mu) = \int_0^1 dx\, \Delta g(x,\mu)$$

Nucleon spin composed of quark + gluon spins and orbital angular momentum

Determination of gluon spin by EIC measurements provide constraint on orbital angular momentum



Direct demonstration of orbital AM?

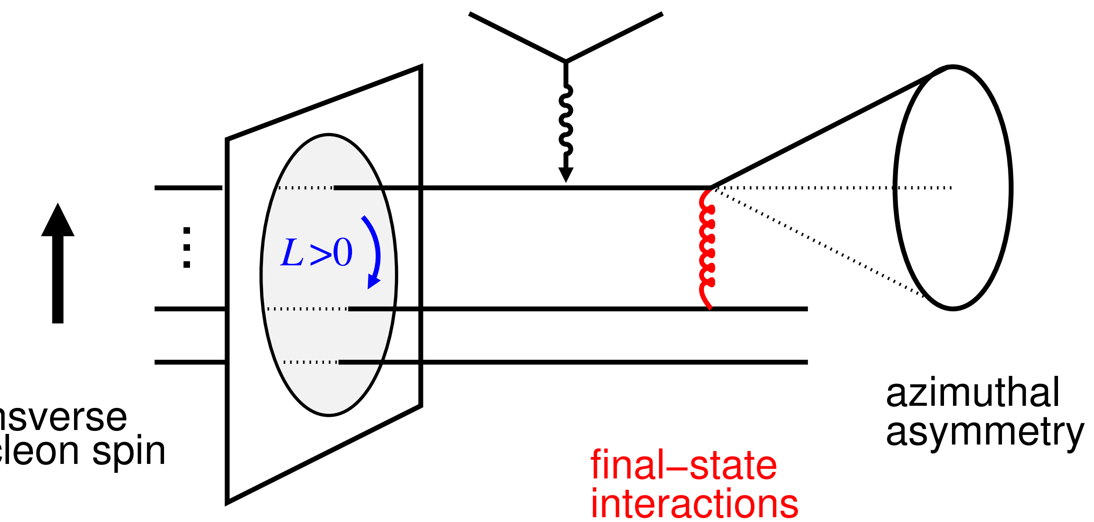
Semi-inclusive transverse single-spin asymmetries

Exclusive processes probing GPDs

Nucleon structure at $x \to 1$: PDFs, form factors

JLab12 GeV + beyond

EIC: Spin-orbit interactions

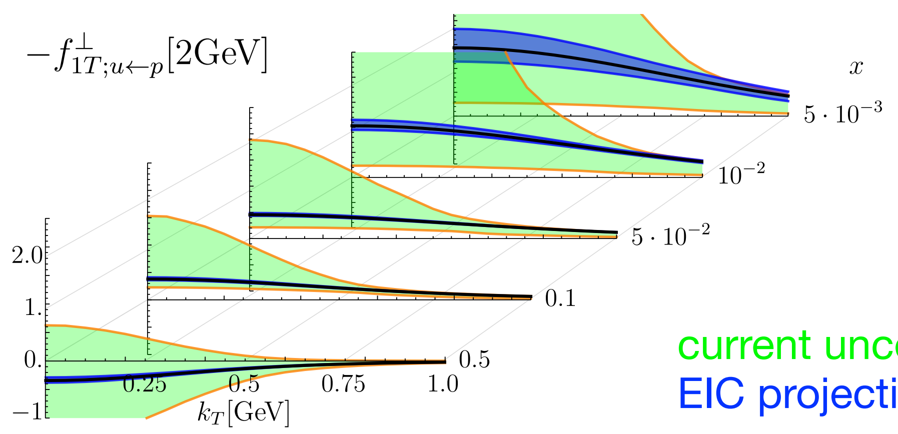


Spin-orbit interactions in QCD

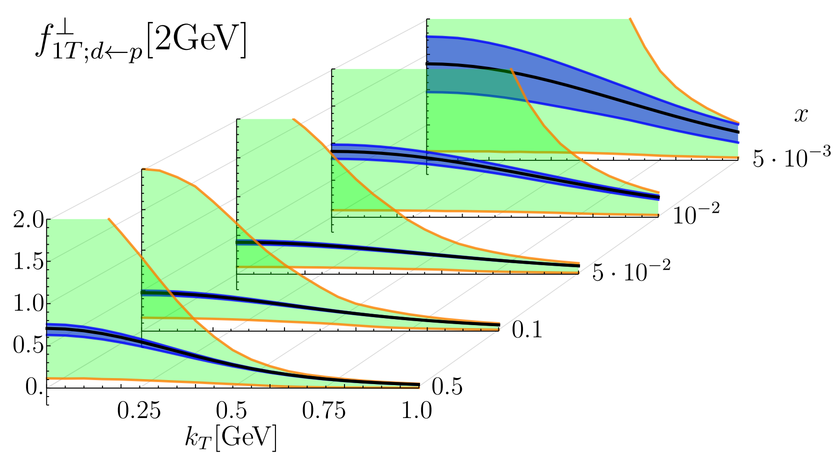
Azimuthal asymmetry $\propto \mathbf{e}_L \cdot (\mathbf{S_T} \times \mathbf{p_{hT}})$ in semi-inclusive hadron production on transversely polarized proton

Requires orbital angular momentum $L > 0$ and QCD final-state interaction

What nonperturbative dynamics is at work?



current uncertainty
EIC projections

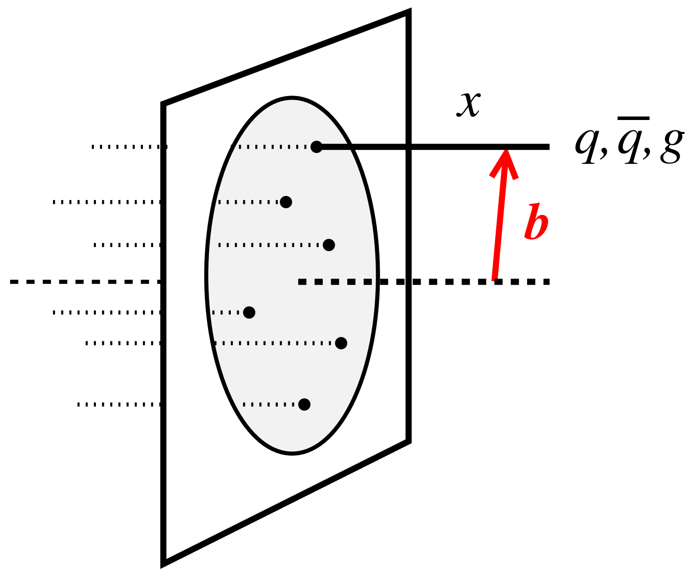


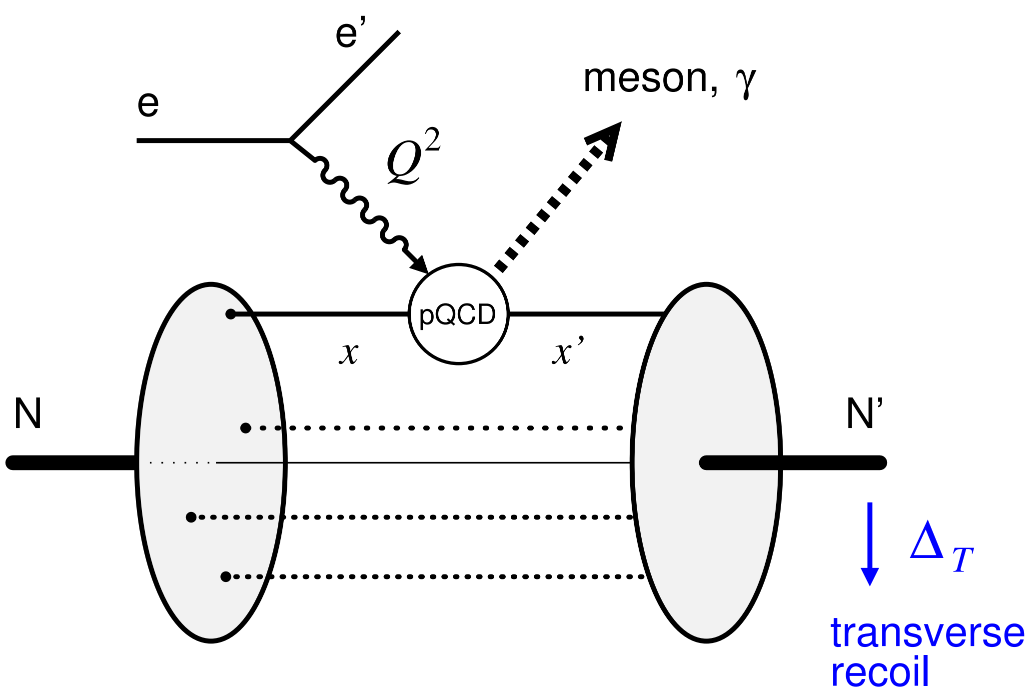
EIC measurements

Extraction of azimuthally dependent quark distribution from semi-inclusive scattering

Wide x, Q^2 coverage allows for test of reaction mechanism, QCD evolution studies

EIC: Transverse spatial distributions





How are partons distributed in transverse space?

Defines “size” and “shape” of nucleon in QCD

Transverse spatial distributions change with x, nucleon polarization, quark/gluon spin

Exclusive process e + N → e’ + (meson, γ) + N

High Q^2 production process takes place in interaction with single quark/gluon

Nucleon form factor for quarks/gluons with longitudinal momentum fraction x — generalized parton distribution

Transverse spatial distribution of quarks/gluons as Fourier transform $\Delta_T \rightarrow \mathbf{b}_T$

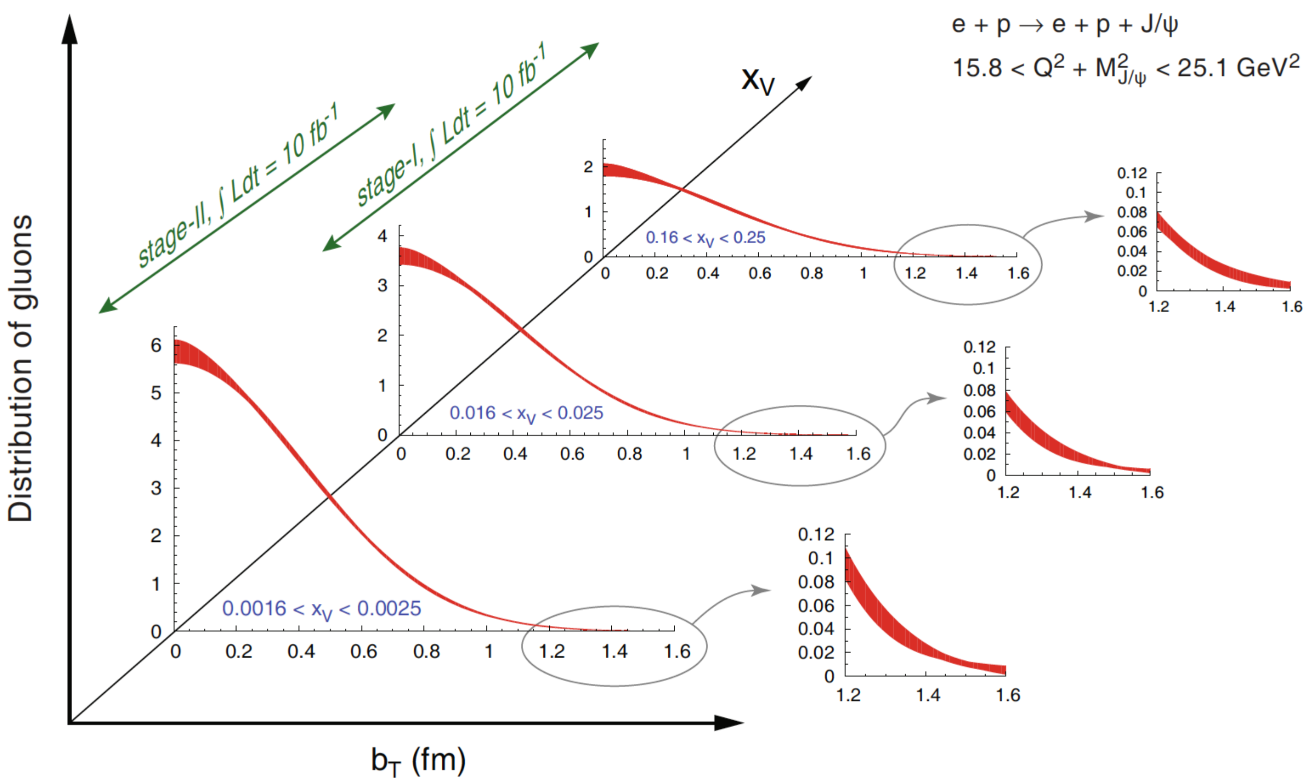
Channels sensitive to quarks and gluons:

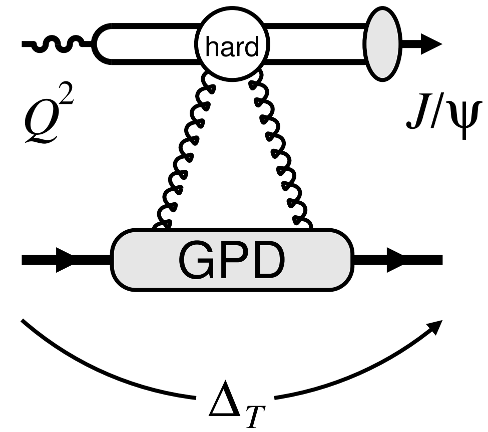
$J/\psi, \Upsilon$: Gluons

ρ^0, ϕ: Gluons + singlet quarks

γ (DVCS): Quarks, gluons at NLO

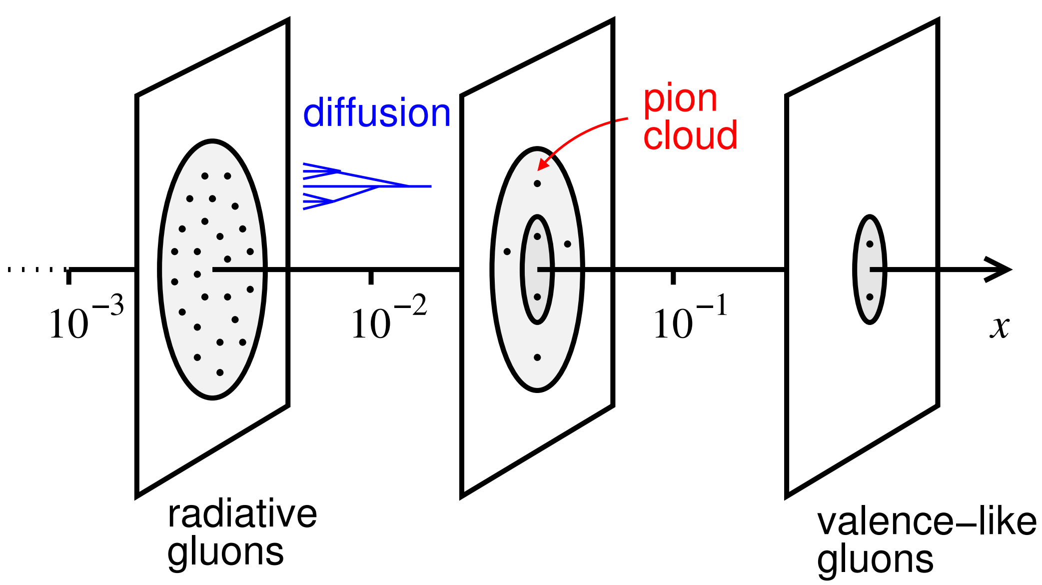
EIC: Transverse spatial distribution of gluons





Exclusive J/ψ photo/electroproduction as clean probe of gluon GPD

Differential measurements in $x_B, Q^2, \Delta_T^2 \sim -t$

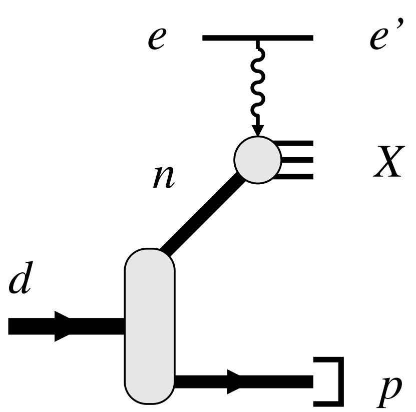


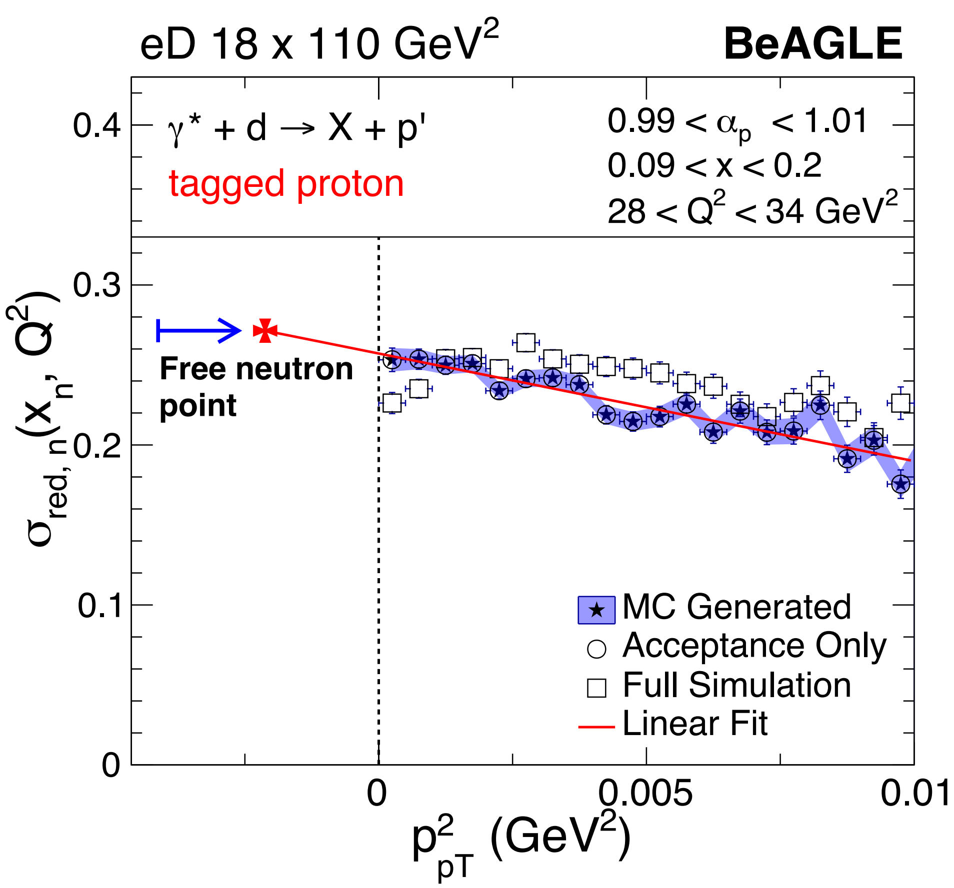
Spatial distribution broadens with decreasing x

$x > 0.2$	valence-like gluons
$x \lesssim 0.1$	gluons in pion cloud
$x < 10^{-2}$	partonic diffusion

Test ideas about dynamics!

EIC: Neutron structure with spectator tagging





Measurements on neutron essential for
$u - d$ flavor separation of quark distributions

Neutron available only in scattering on nuclei:
Corrections from motion, binding, polarization

Cleanest method: Scattering on deuteron with
detection of spectator proton

identifies events with active neutron

controls nuclear configuration during
high-energy process

Free neutron structure from "on-shell extrapolation"
in spectator momentum

Uses EIC far-forward detectors

EIC: Other hadron structure measurements

TMD evolution: Validating/testing theory of QCD radiation in TMD observables, transition from low to high p_T

Parton structure studies using QCD jets

Diffractive scattering on proton: Diffractive parton densities, quantum fluctuations of gluon density

Pion/kaon structure from peripheral scattering on nucleon

Electroweak charged-current scattering for charge/flavor separation of quarks

Many more “creative” applications…

Detailed information: EIC Yellow Report 2021 [INSPIRE]

Summary

EIC will answer basic questions nucleon/hadron partonic structure in region of sea quarks and gluons

Partonic structure probed in high-Q2 scattering processes directly connected with QCD effects/phenomena in perturbative and nonperturbative domains

Need for CM energy and luminosity evident in applications discussed here