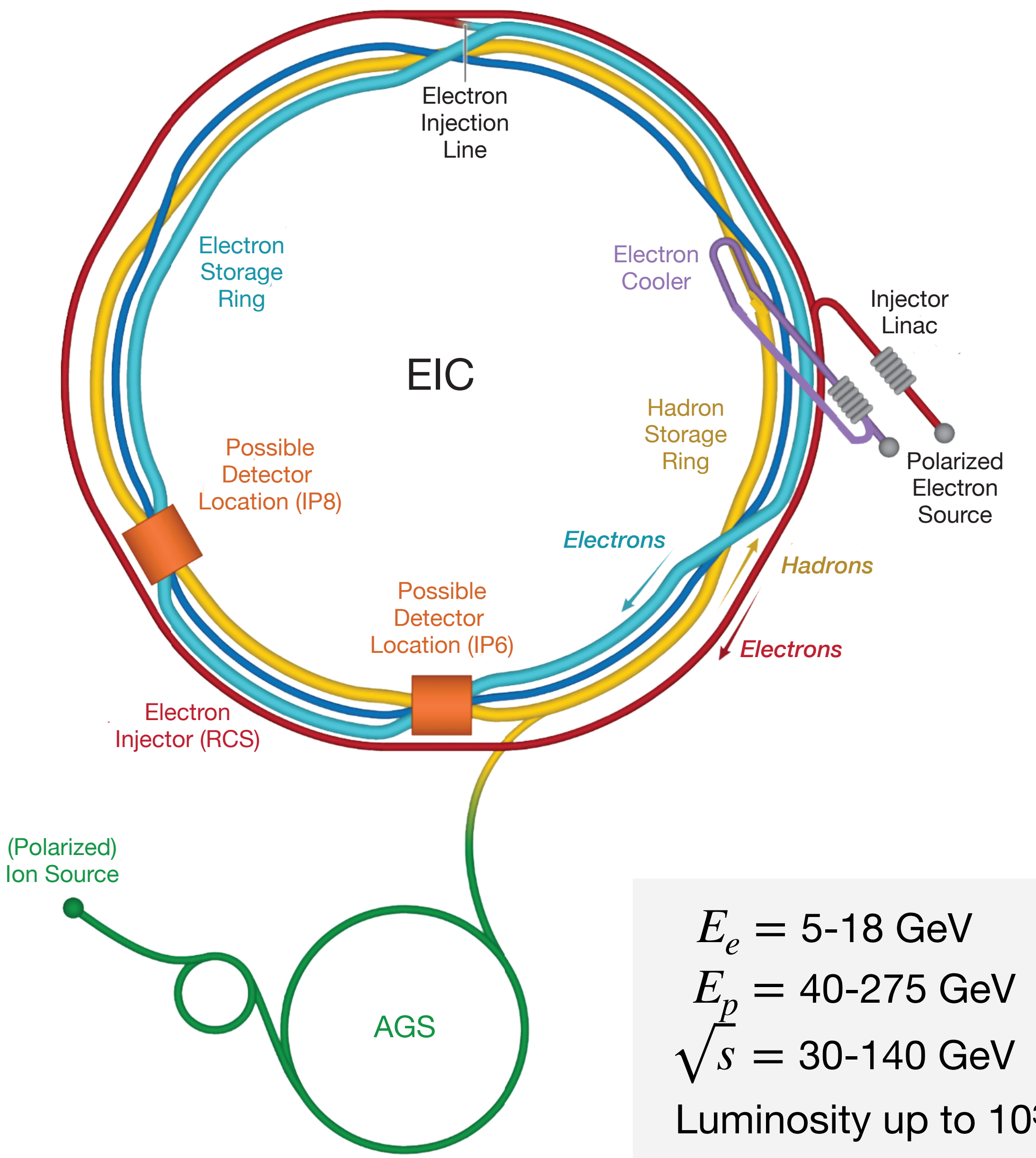
Exploring QCD at the Electron-Ion Collider

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}

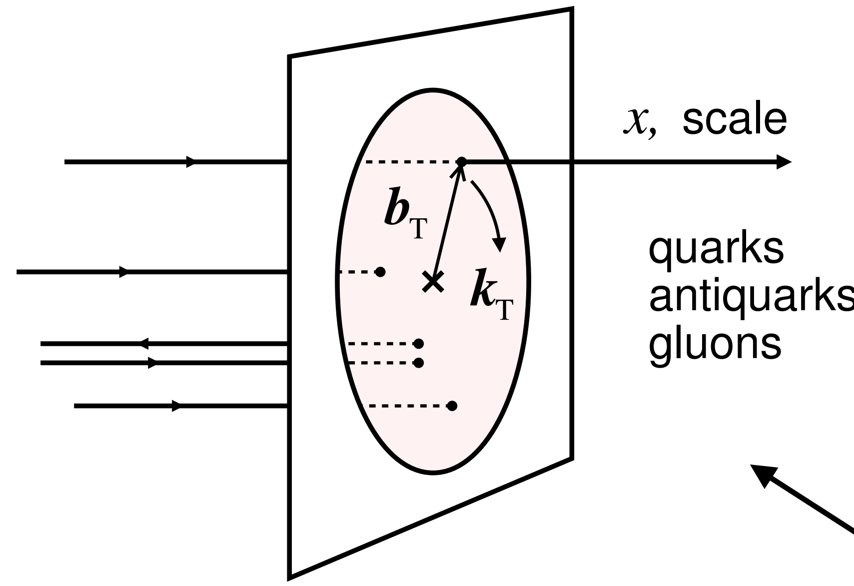
Concepts ←

Measurements ←

Accelerator and detector

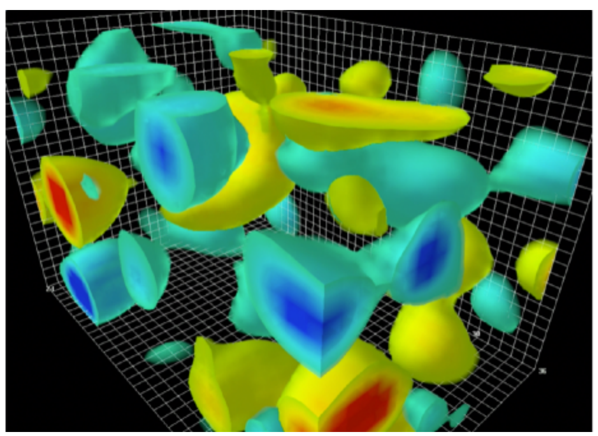
Organization

This lecture

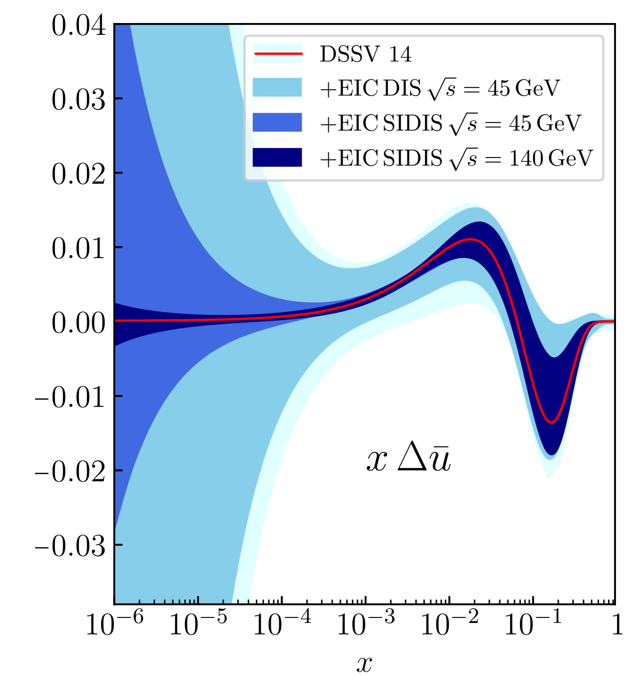


Many-body system

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

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

EIC physics II: QCD in nuclei

Nuclear interactions and partonic structure

Nuclear gluon density

Gluon shadowing at small x

Gluon saturation

EIC physics III: Hadronization

Fragmentation functions

Hadronization in nuclear medium

[Accelerator and detector]

Organization

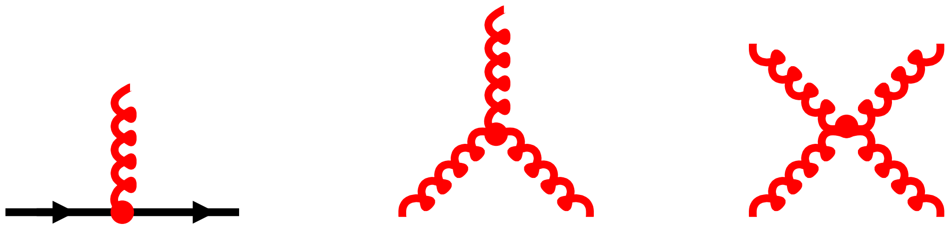
EIC User Group, ePIC Collaboration, Project

Timeline

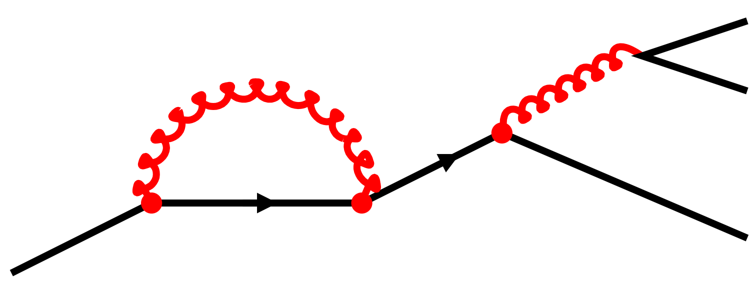
QCD: Dynamical system

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

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



modes coupled by gauge interaction



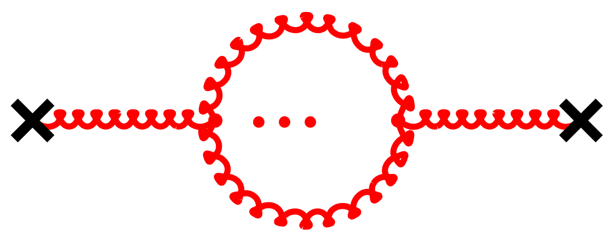
quantum motion involves radiation, particle creation/annihilation

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

"particles" and "radiation" cannot be separated

QCD: Scale dependence

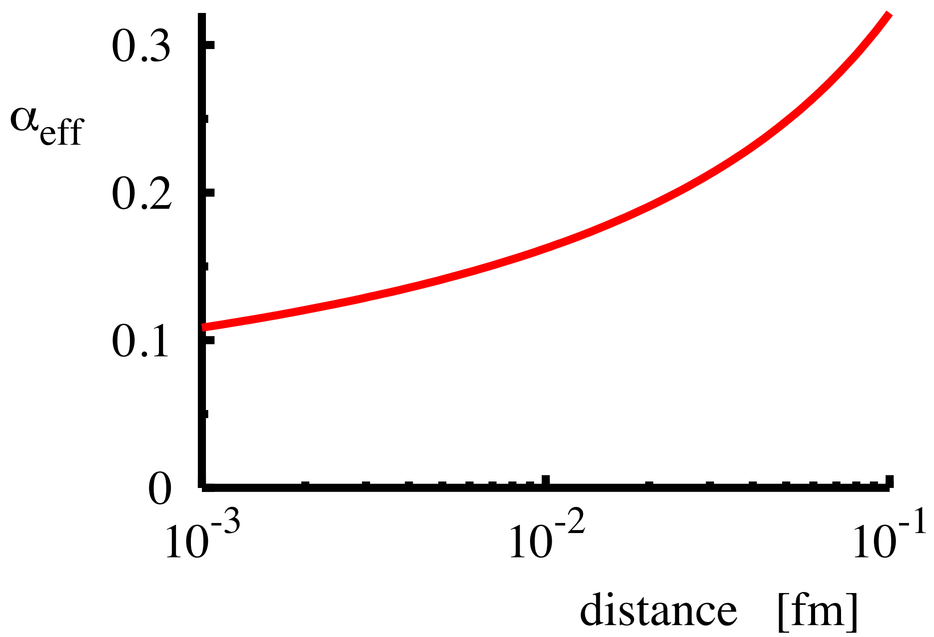
Modes depend on resolution scale,
"how much radiation is included"



Effective coupling scale-dependent

Example: Interaction of static sources

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

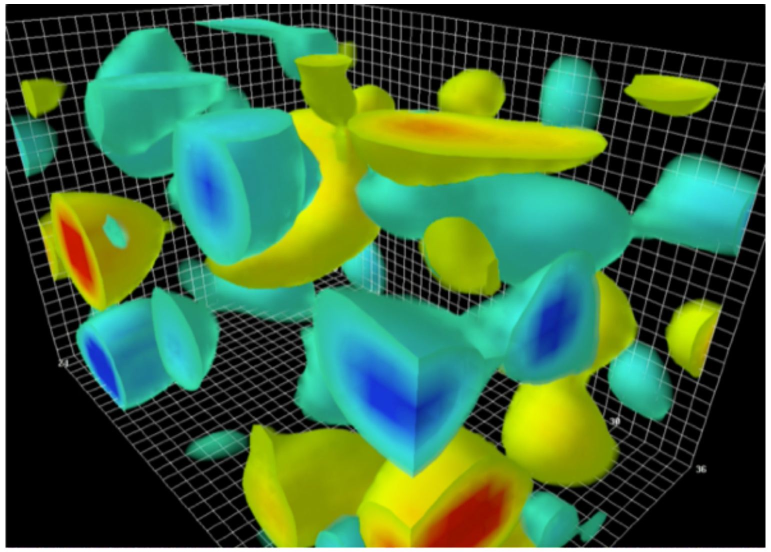


Asymptotic freedom: Effective coupling decreases at short distances

Here: 1-loop accuracy

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

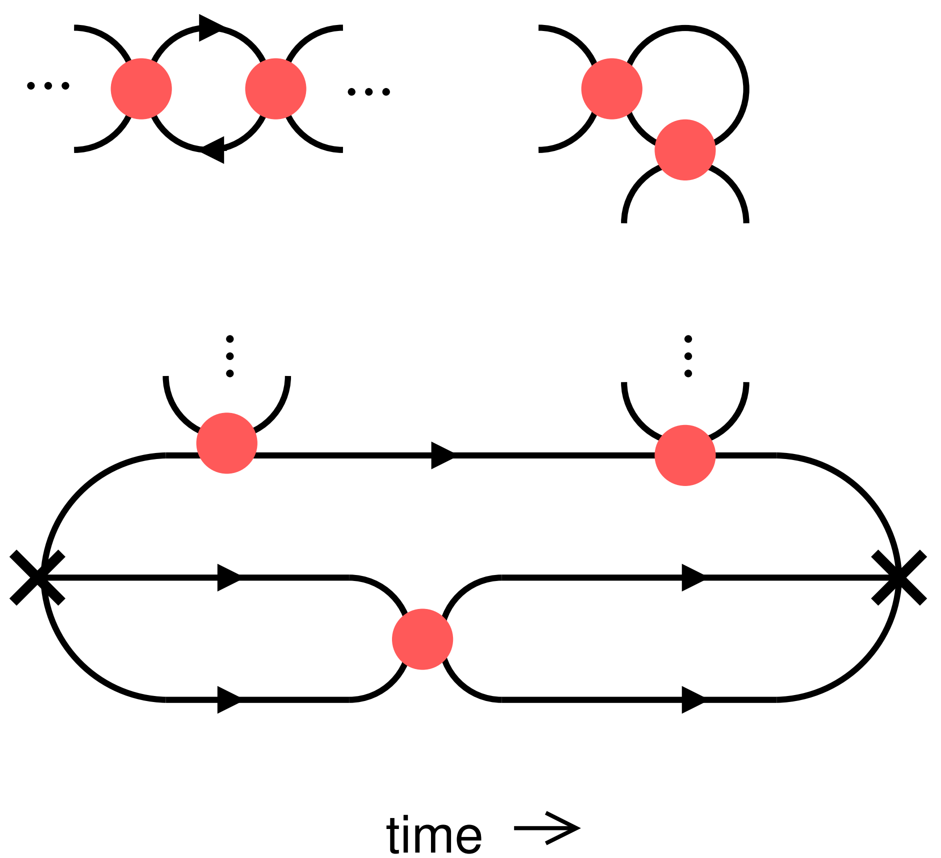
Condensate of quark-antiquark pairs - chiral symmetry breaking

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

Hadron structure: Correlation functions



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

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

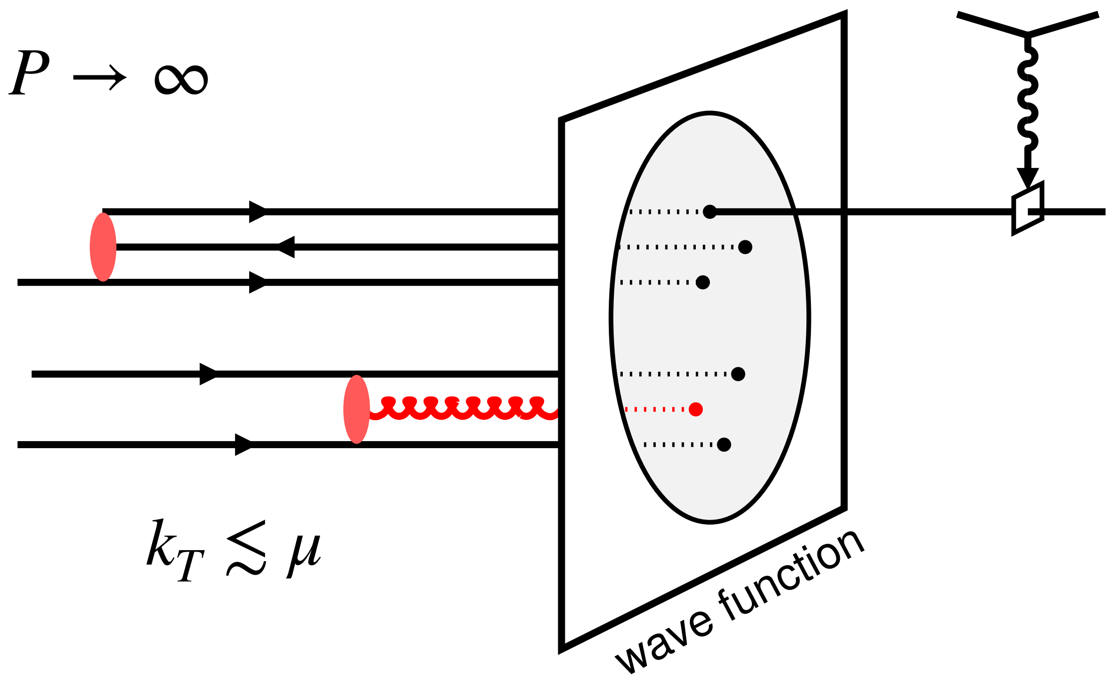
Imaginary time $t \to i\tau$: Statistical mechanics
Lattice simulations, analytic methods

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

Separate modes:

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

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

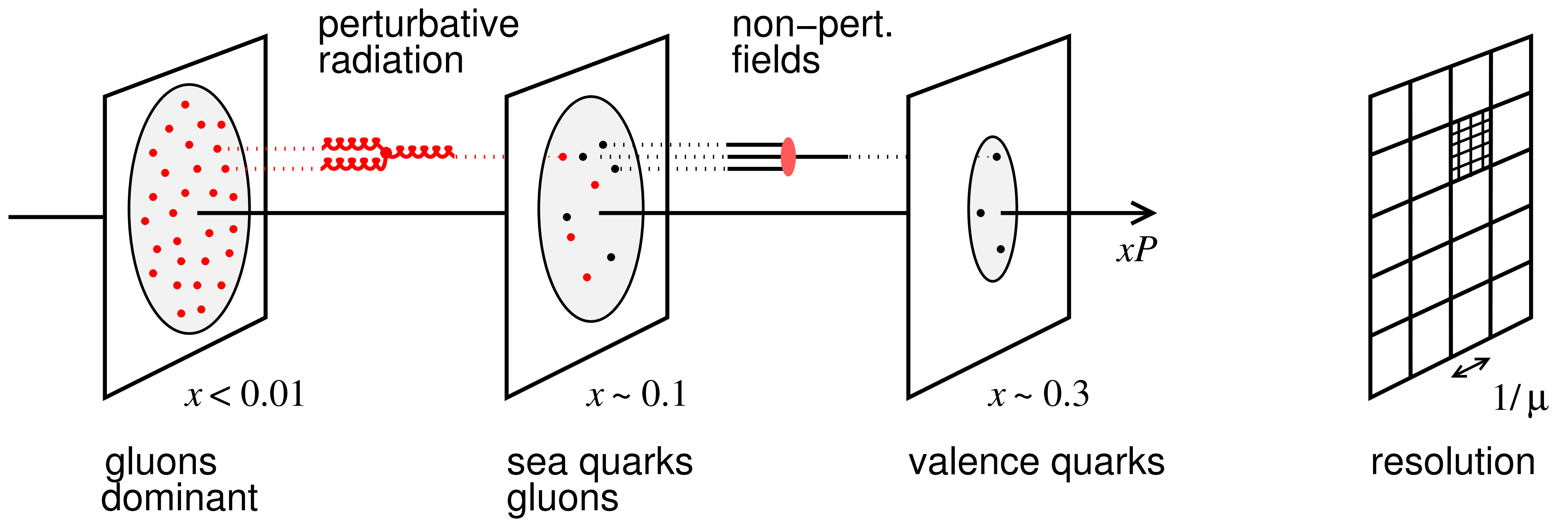
Hadron becomes closed system:
Described by wave function

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

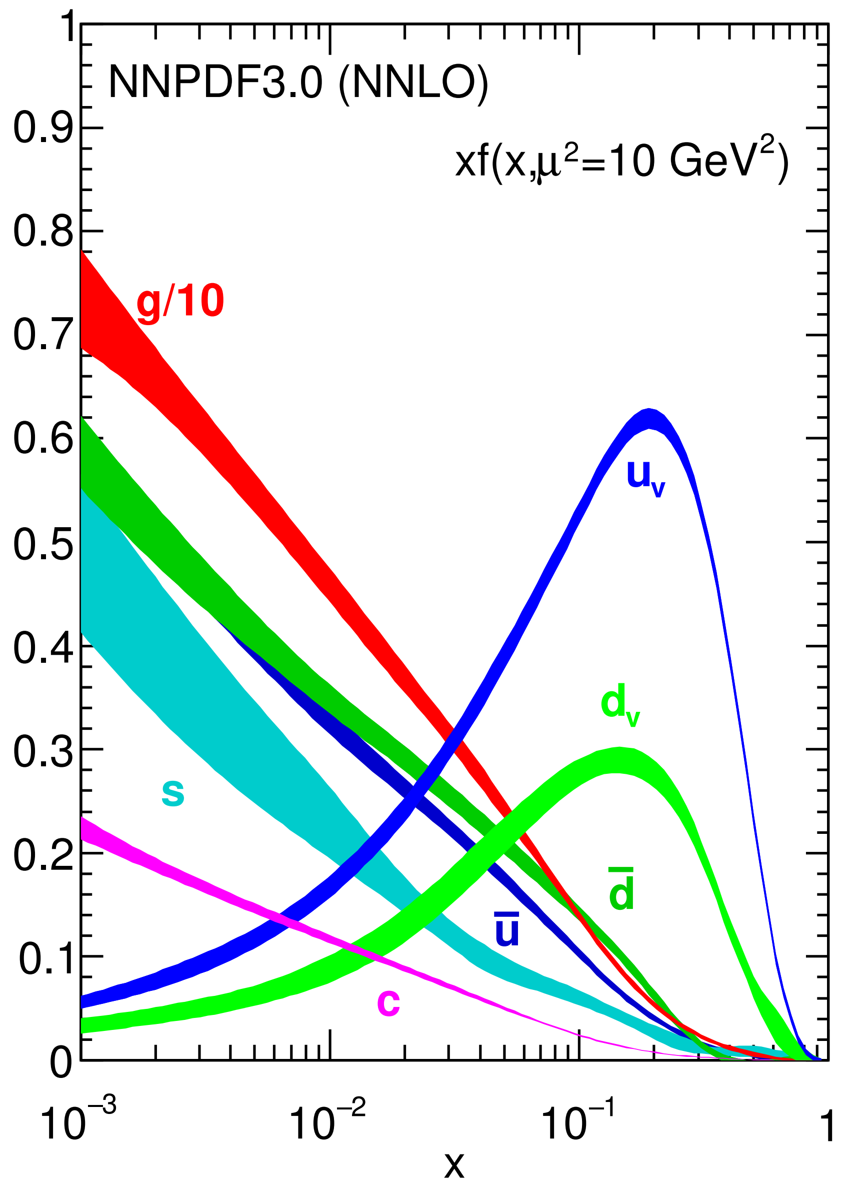
Transverse spatial distributions

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 $\int d^2 k_T < \mu$

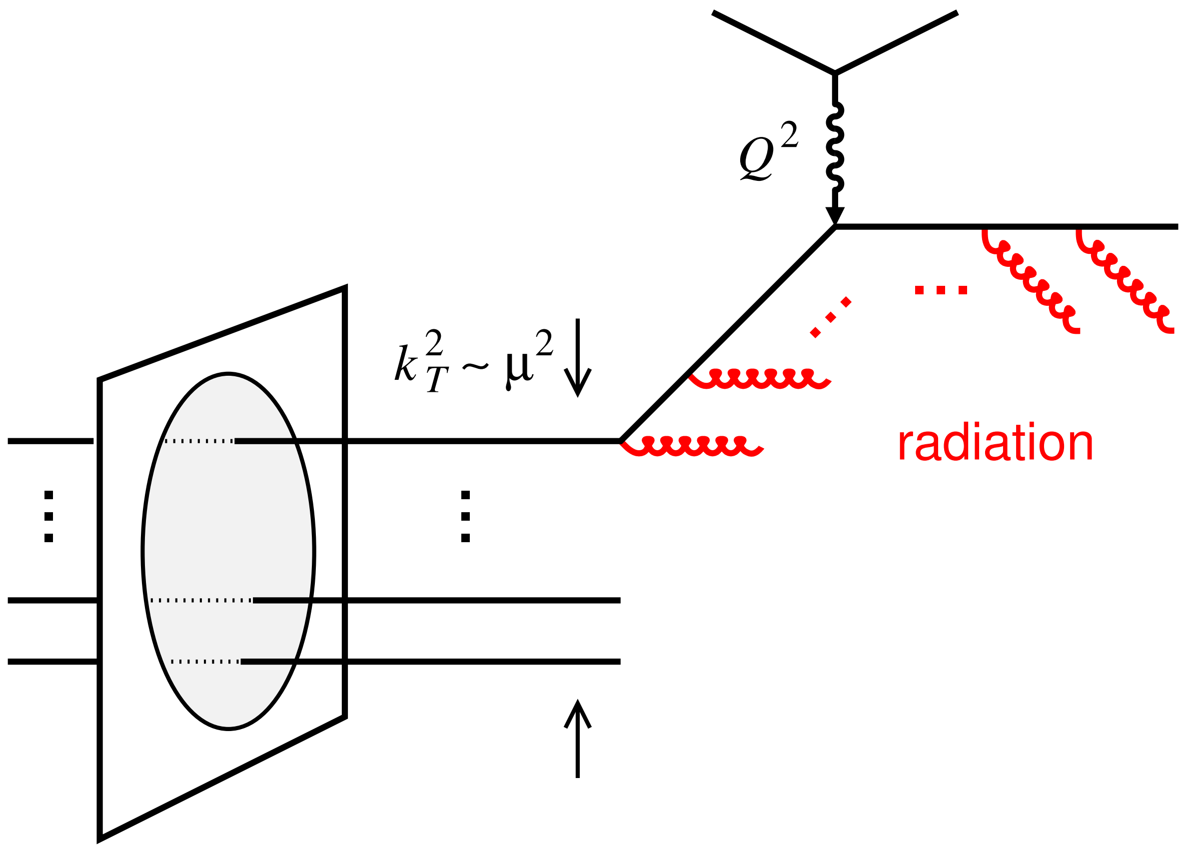
Extracted from global analysis of various scattering processes → Lecture Nobuo Sato

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

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

Factorization: Parton distributions

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

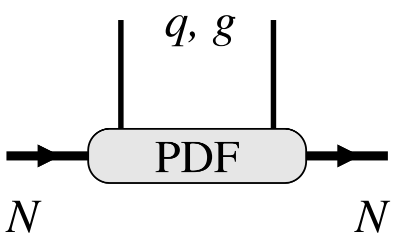
Number density of quarks in fast-moving nucleon state

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

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

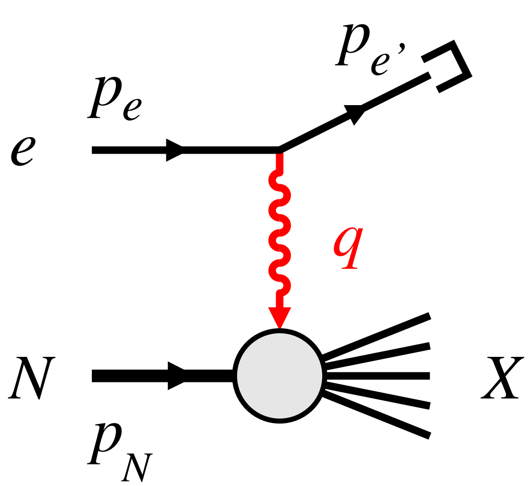
Fast-moving hadron state ($P \gg \mu_{\text{vac}}$) decouples from vacuum fluctuations, becomes "closed system" described by wave function

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.

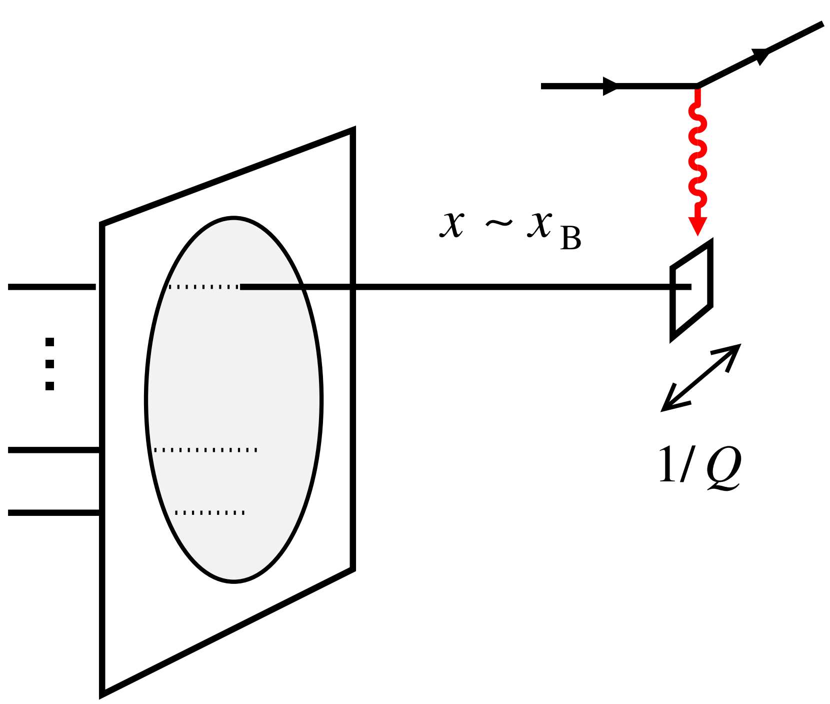
$q \equiv p_e - p_{e'} = (q^0, \mathbf{q})$ 4-momentum transfer

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 $e + N \to e' + M + N'$

Inclusive scattering $\overrightarrow{e} + \overrightarrow{N} \rightarrow e' + X$, 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

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

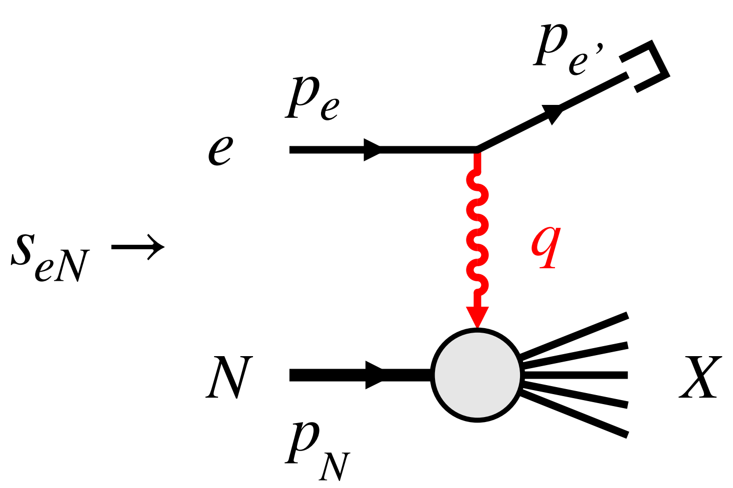
Factorization: Structure function expressed through polarized parton densities

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

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

Similar workflow in polarized semi-inclusive and exclusive scattering

Electron scattering: Kinematic range

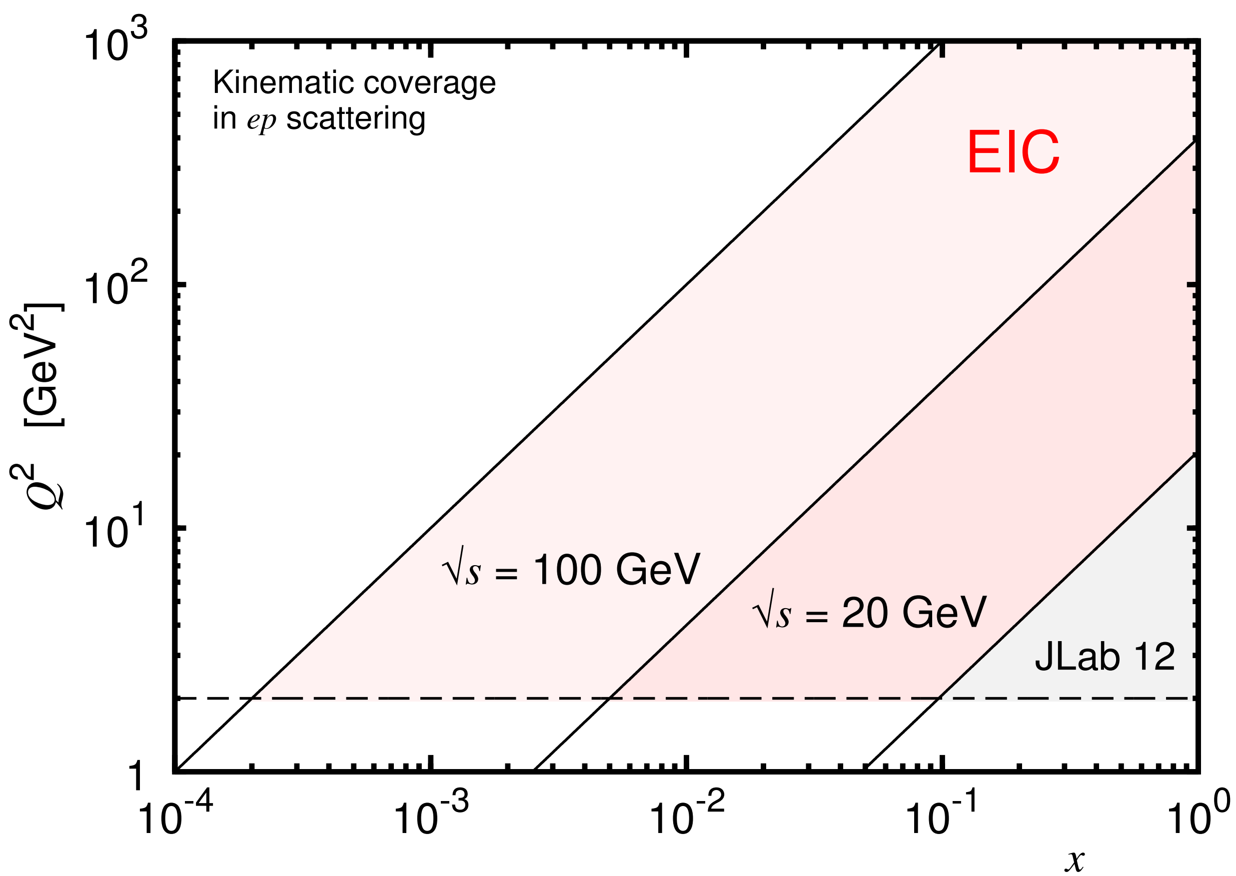


$$s = (p_e + p_N)^2 \qquad \text{electron-nucleon invariant}$$

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

Kinematic range

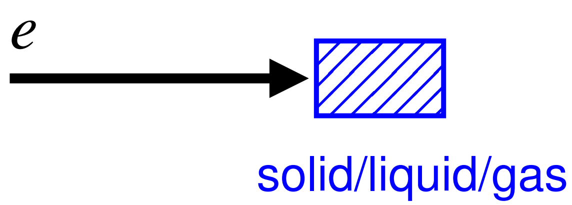
$$Q^2 < x_B(s - m^2) \qquad \text{kinematic limit}$$



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

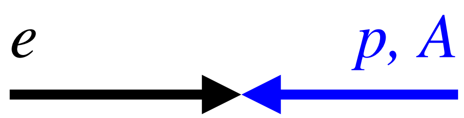


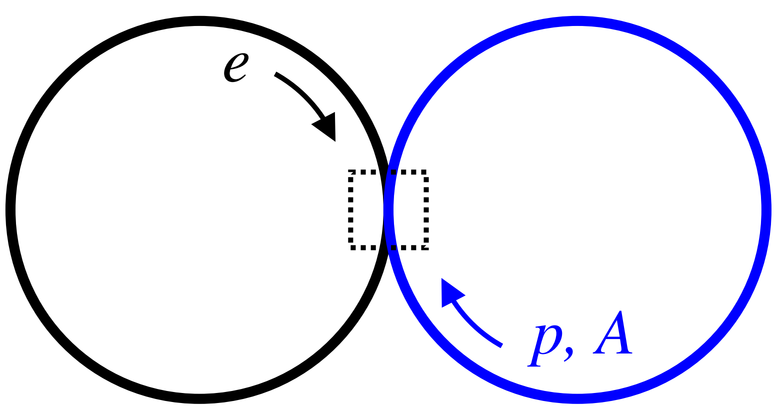
Beam on fixed target

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

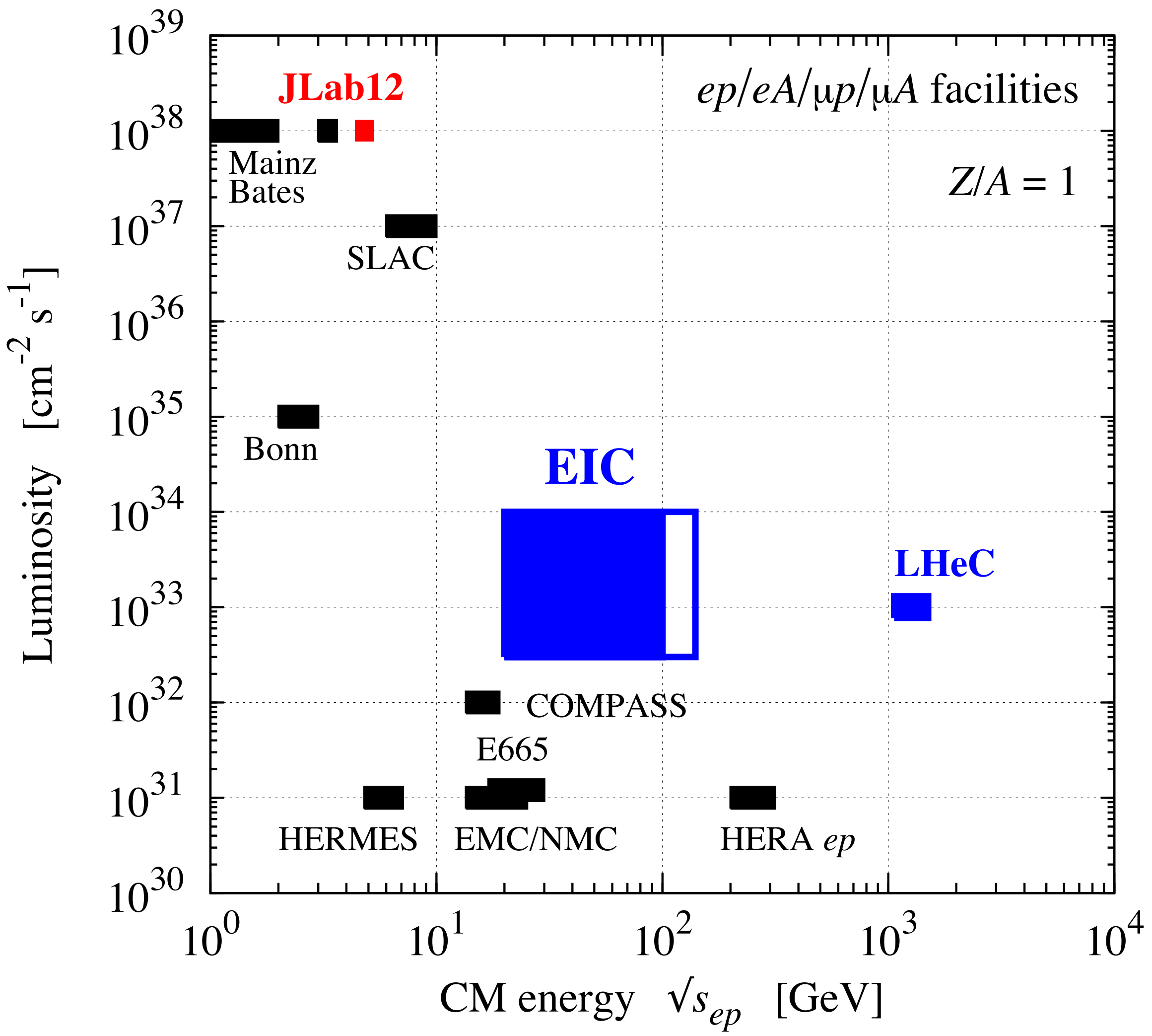
$$\frac{N_{\text{event}}}{T} = L \times \sigma$$

rate luminosity cross section

Luminosity determines event rate for given cross section

High luminosity required for

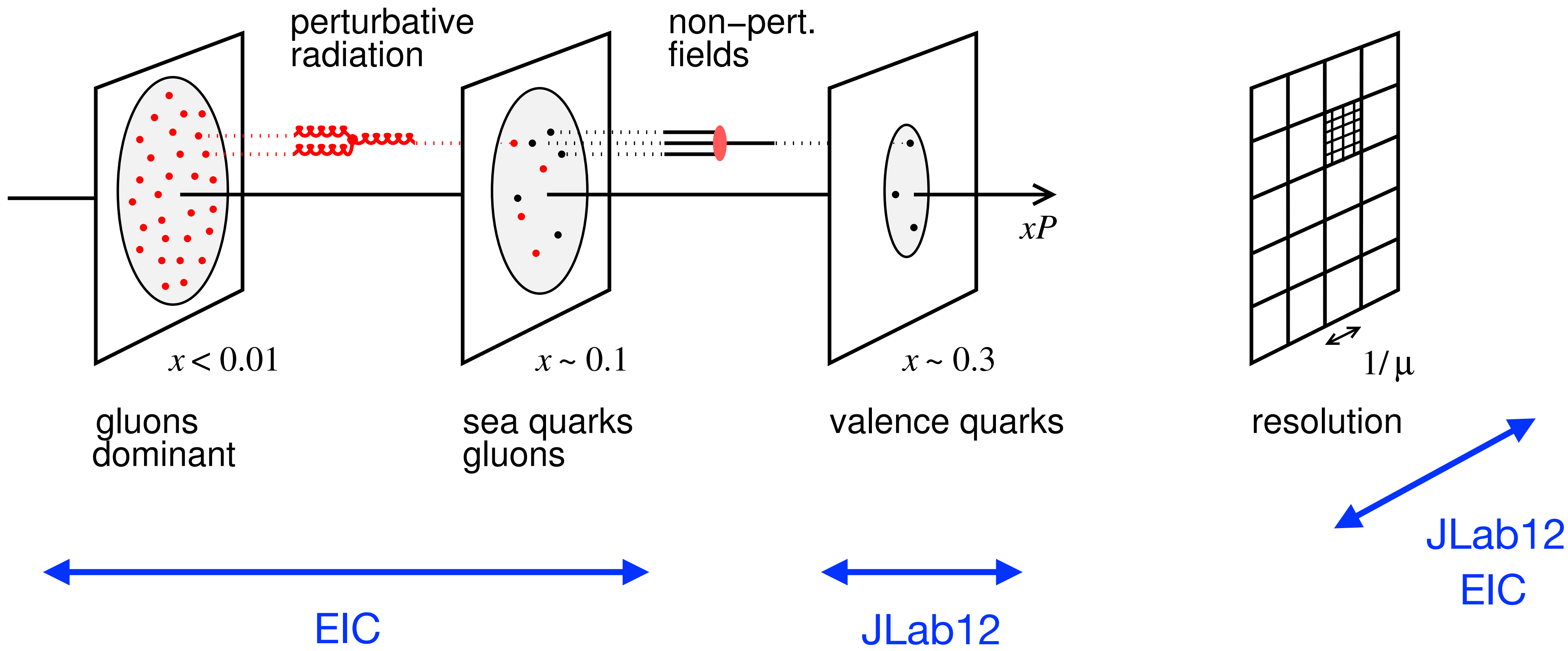
rare processes	exclusive processes, high p_T hadrons rare nuclear configurations
multidimensional binning	transverse imaging, TMD evolution, jets
spin asymmetries	polarized partons



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

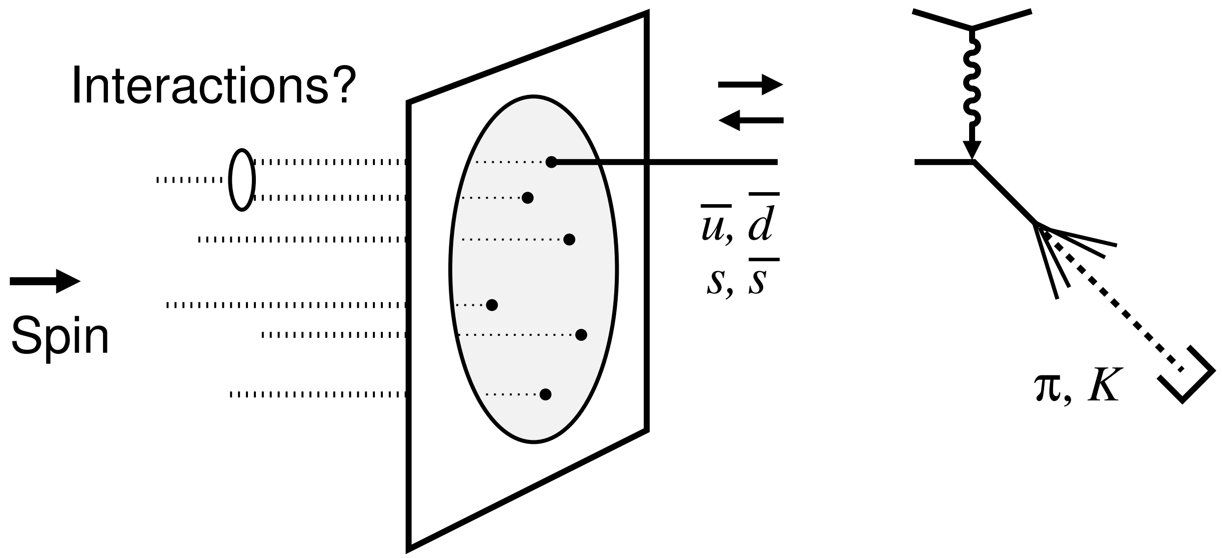
Summary

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?

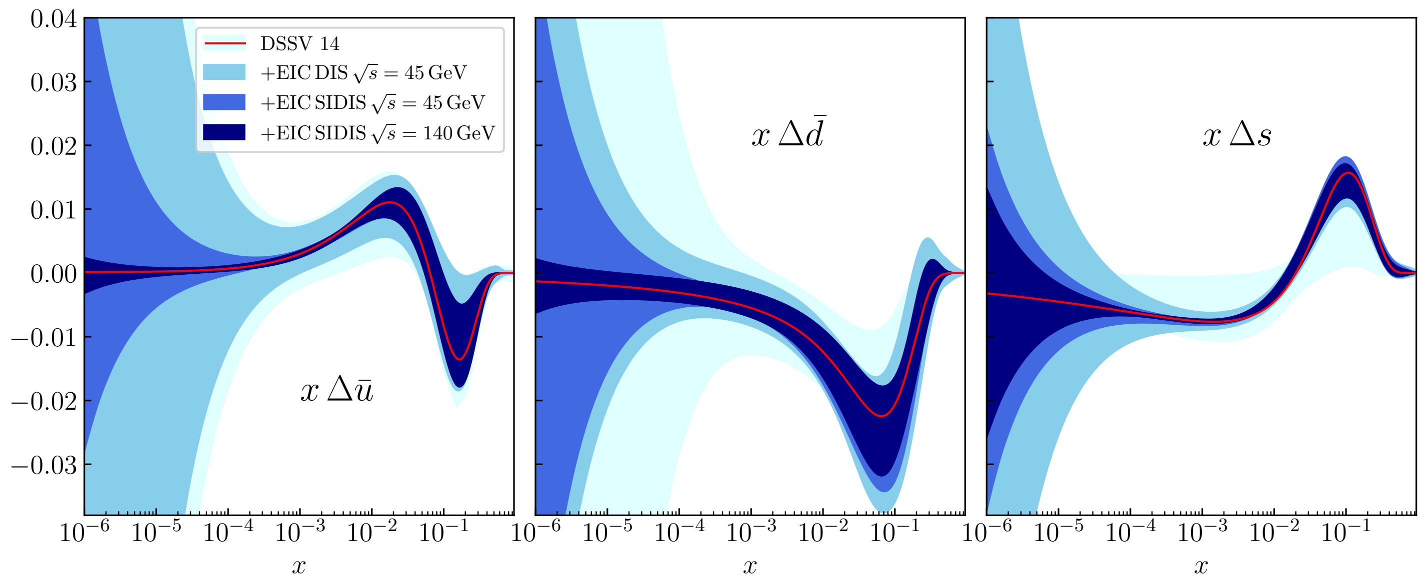
Mesonic degrees of freedom?

Semi-inclusive scattering

Detect π, K from fragmentation

Determine charge/flavor of active quark

Fixed-target: HERMES, COMPASS, JLab12 GeV



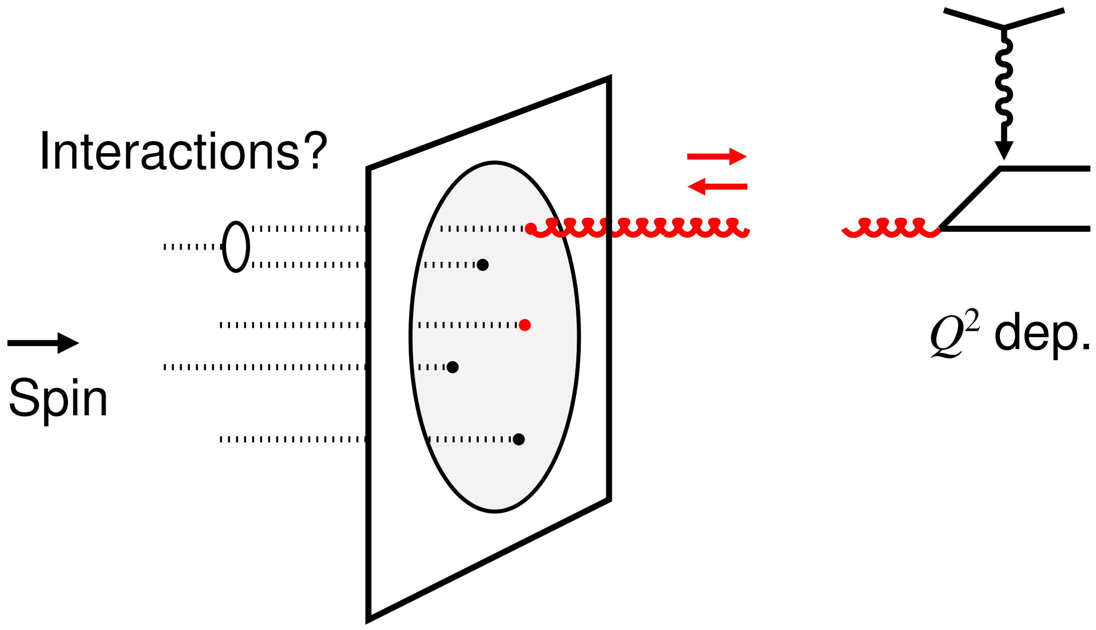
EIC Yellow Report 2022

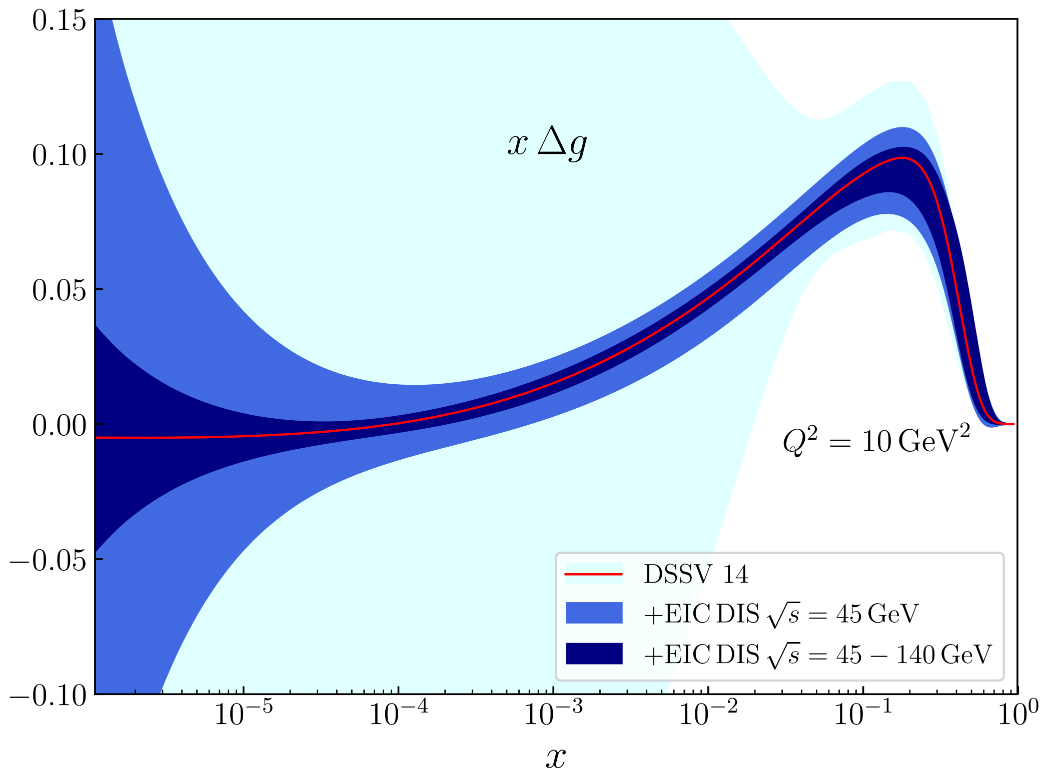
EIC measurements

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 $c\bar{c}$

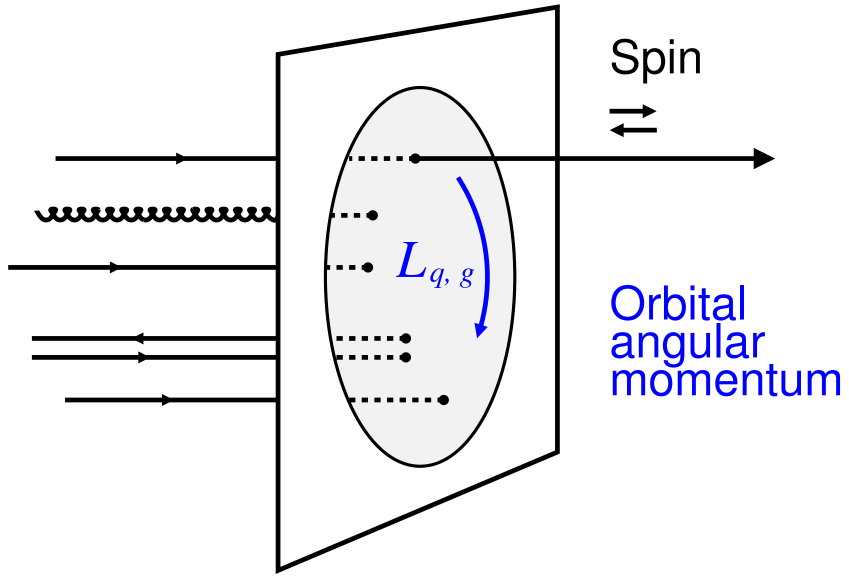
Alt: Polarized pp scattering at RHIC

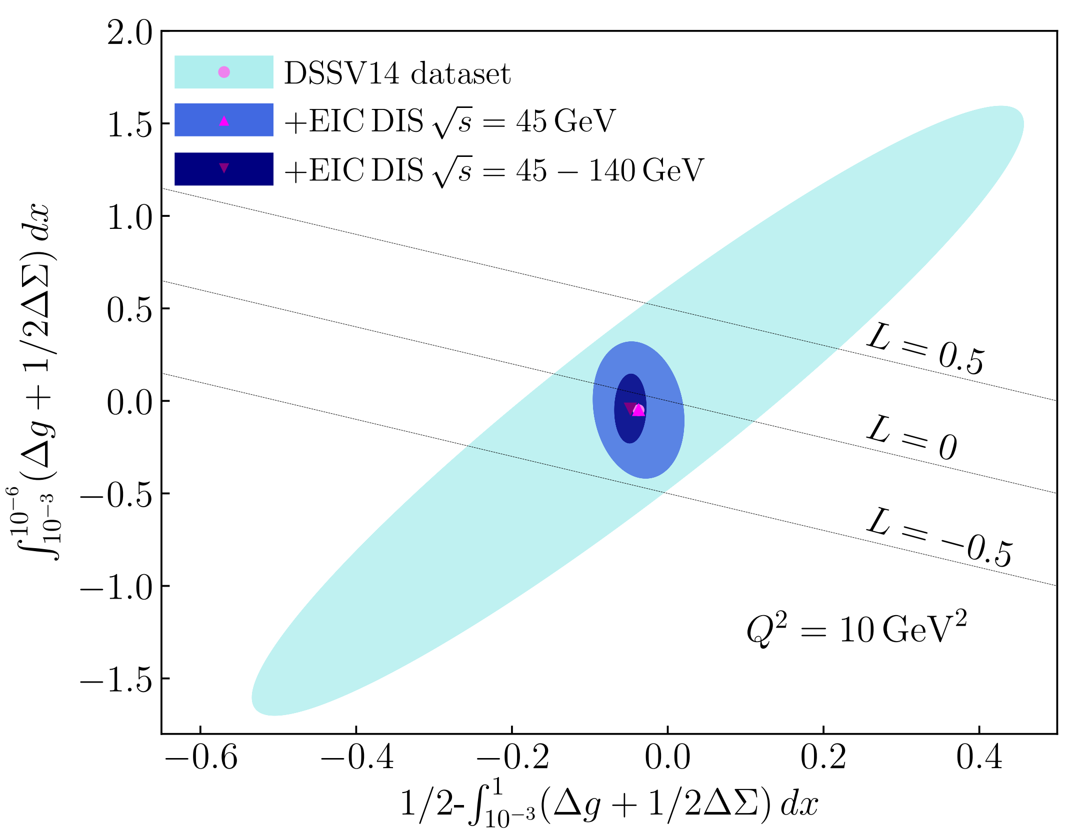
EIC measurements

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

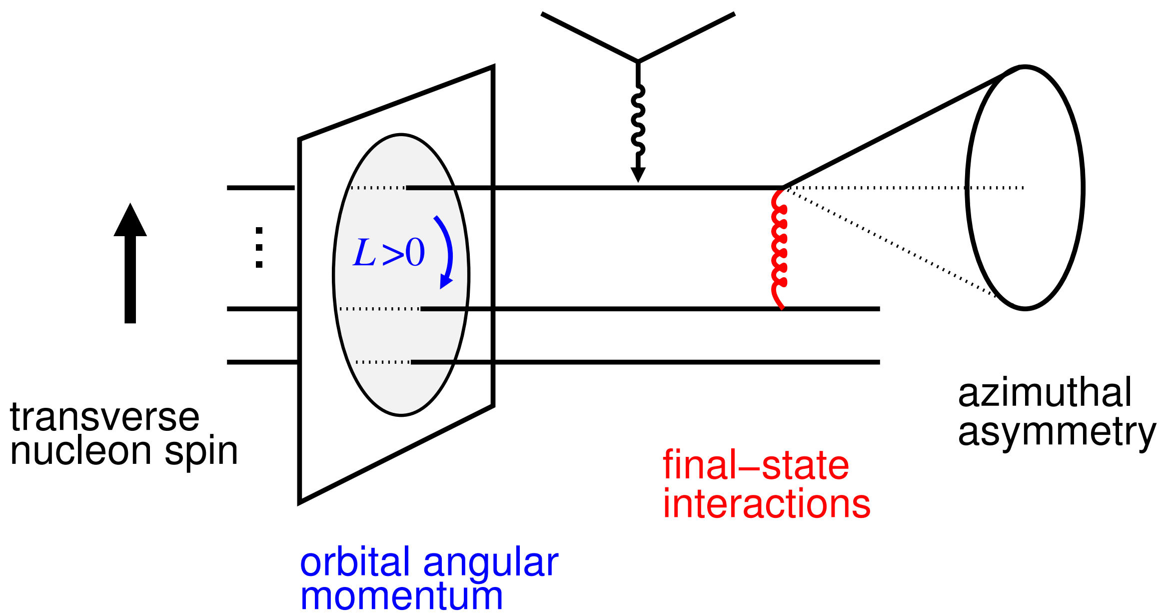
Direct demonstration of orbital AM?

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

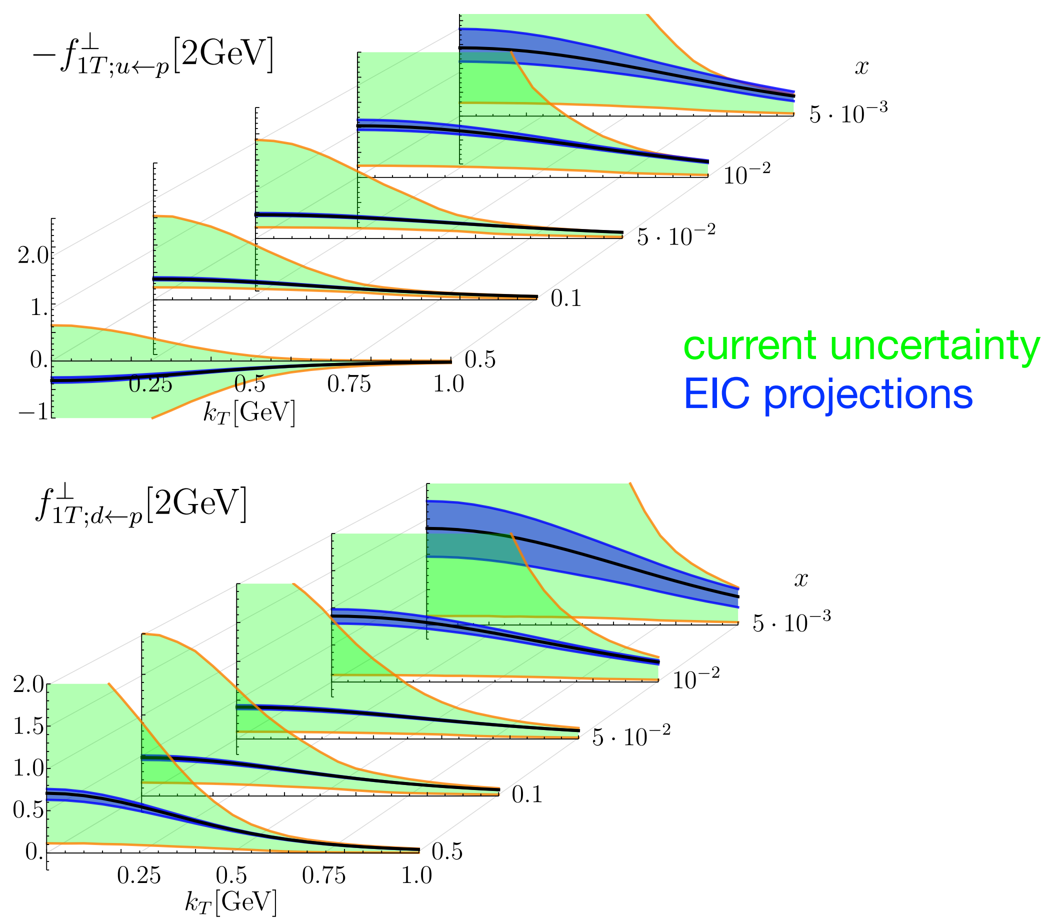


Spin-orbit interactions in QCD

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?

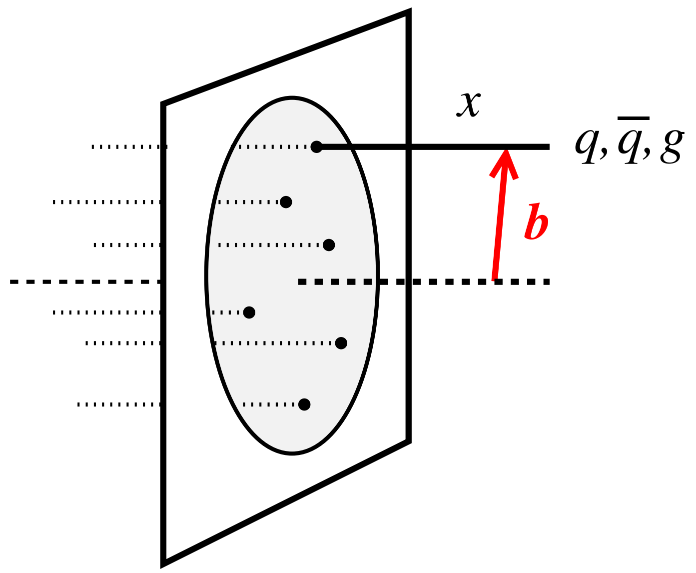


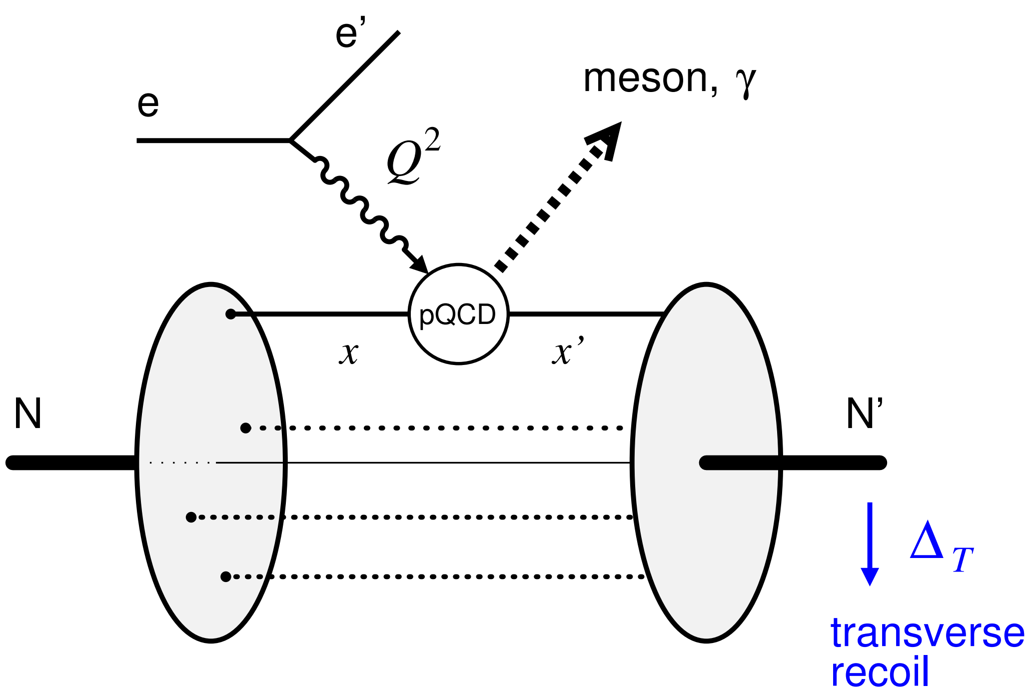
EIC measurements

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 $\Delta_T \to \mathbf{b}_T$

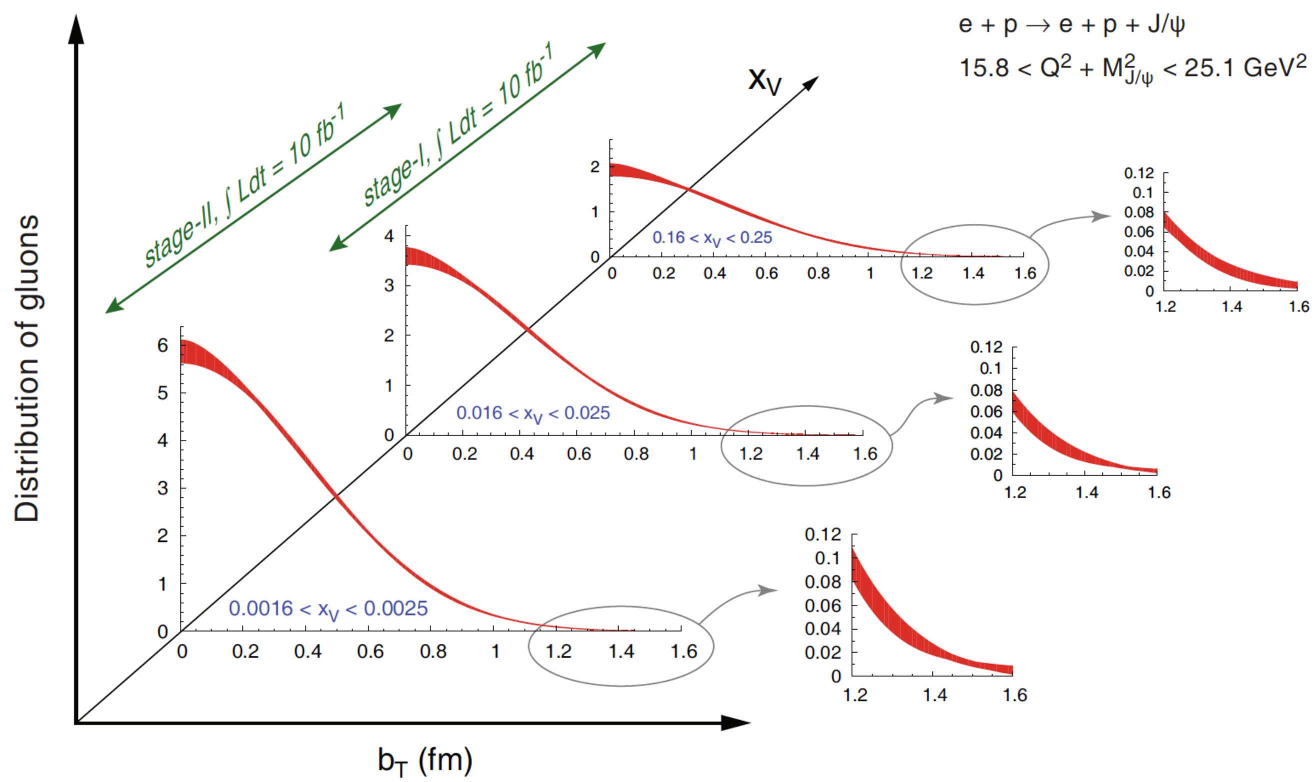
Channels sensitive to quarks and gluons:

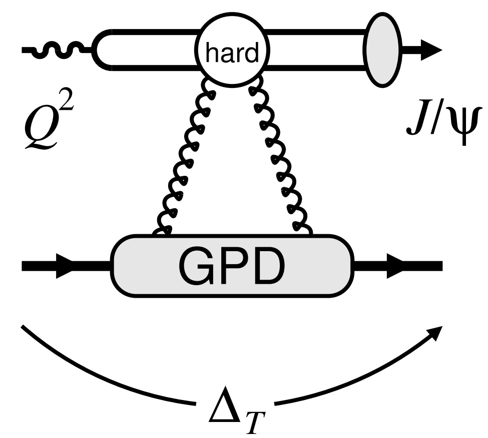
$J/\psi, \Upsilon$: Gluons

ρ^0, ϕ: Gluons + singlet quarks

γ (DVCS): Quarks, gluons at NLO

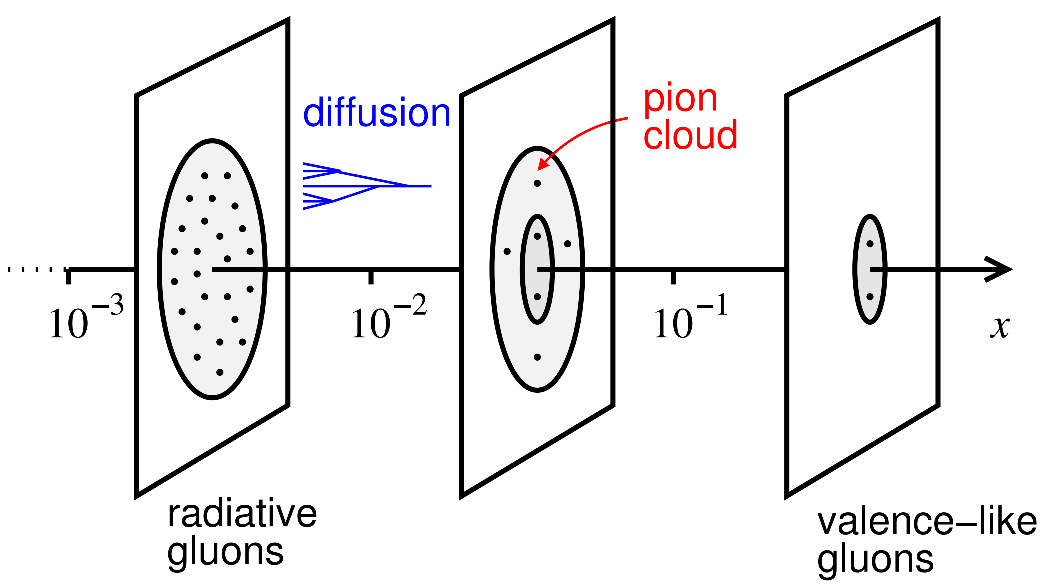
EIC: Transverse spatial distribution of gluons





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

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

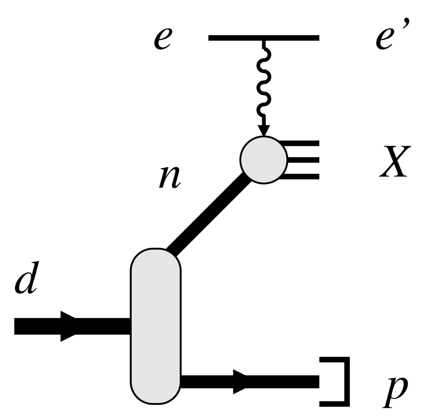


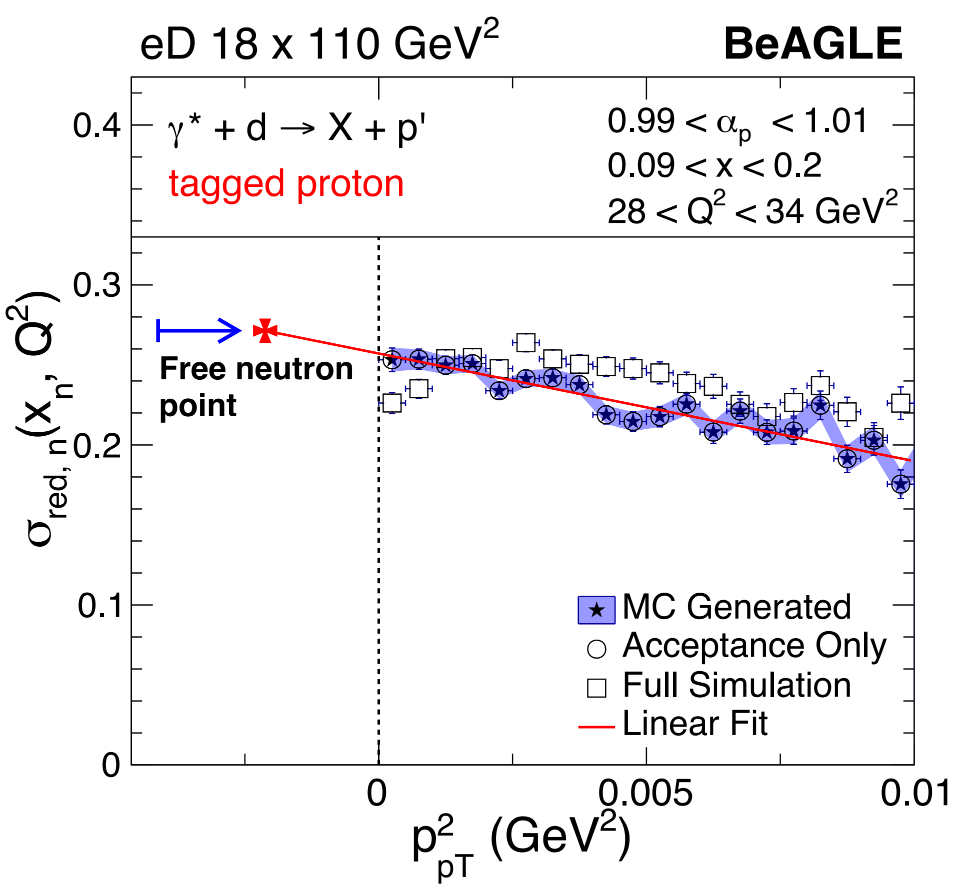
Spatial distribution broadens with decreasing x

$x > 0.2$	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

Plan

Concepts

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

EIC physics II: QCD in nuclei ←

Nuclear interactions and partonic structure

Nuclear gluon density

Gluon shadowing at small x

Gluon saturation

EIC physics III: Hadronization ←

Fragmentation functions

Hadronization in nuclear medium

[Accelerator and detector]

Organization ←

EIC User Group, ePIC Collaboration, Project

Timeline

Nuclei: Nucleon interactions and partonic structure

How do nucleon interactions and nuclear binding emerge from QCD?
“Next step” after exploring nucleon structure

Concepts of partonic structure, factorization, etc. for nuclei defined in same way as for nucleon

Compare partonic structure of nuclei and free nucleons

$$f_A(x, \mu^2) \neq \sum_N f_N(x, \mu^2) \quad (N = p, n)$$

nuclear modifications from motion + binding

x defined as fraction of P_A/A = nominal nucleon momentum

Nucleon interactions expressed in nuclear modifications of partonic structure

What type of nucleon interactions causes modification at given x?

What distances are involved at given x?

Longitudinal distances involved in parton density

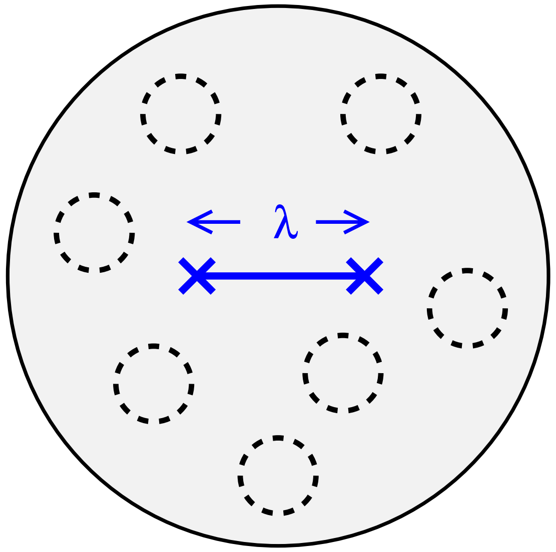
$$f_A(x, \mu^2) = \int \frac{d\lambda}{2\pi} \, e^{i\lambda m_N x} \, \langle A \, | \, \bar{\psi}(\lambda n) \ldots \psi(0)_\mu \, | \, A \rangle$$

parton density as correlation function in nucleus rest frame, $P_A^0 \approx A m_N$

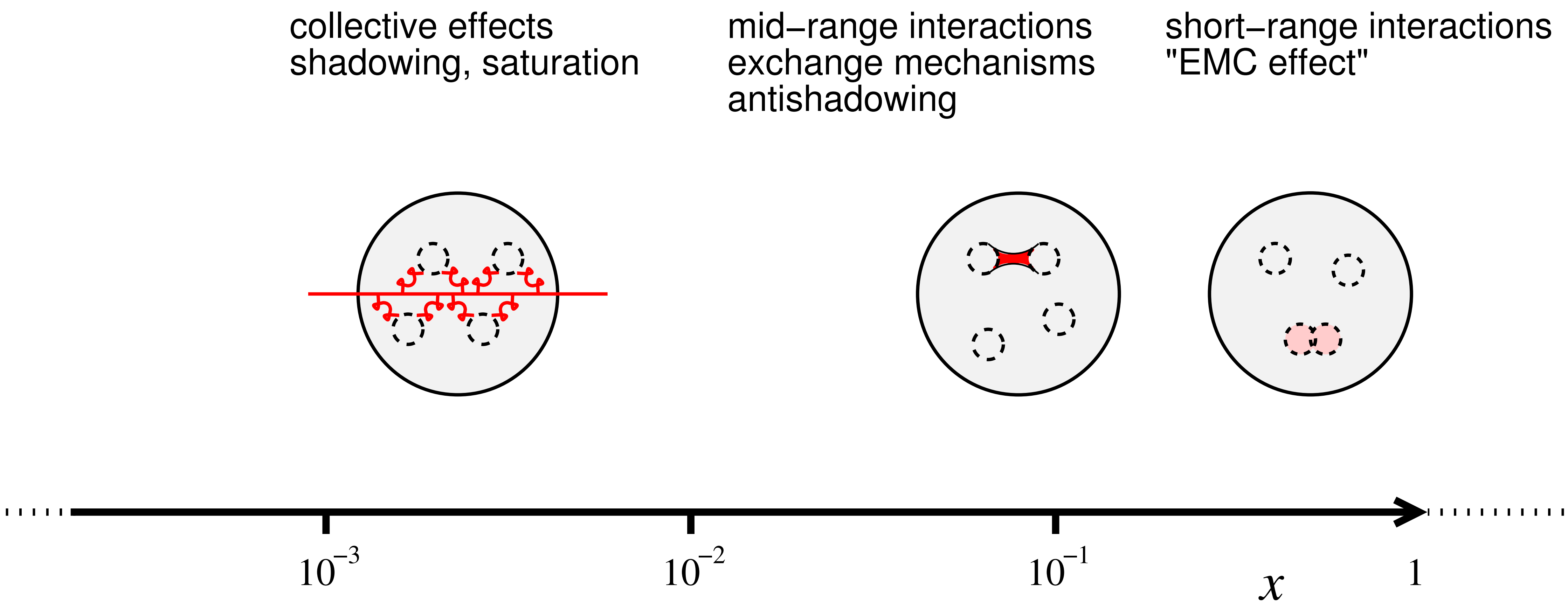
$$\lambda \sim \frac{1}{x m_N}$$

typical distances in correlation function at given x

$x = 0.5$	$\lambda = 0.4$ fm	< nucleon size
$x = 0.1$	$\lambda = 2$ fm	~ typical NN distance
$x = 10^{-2}$	$\lambda = 20$ fm	$\gg$ diameter of nucleus

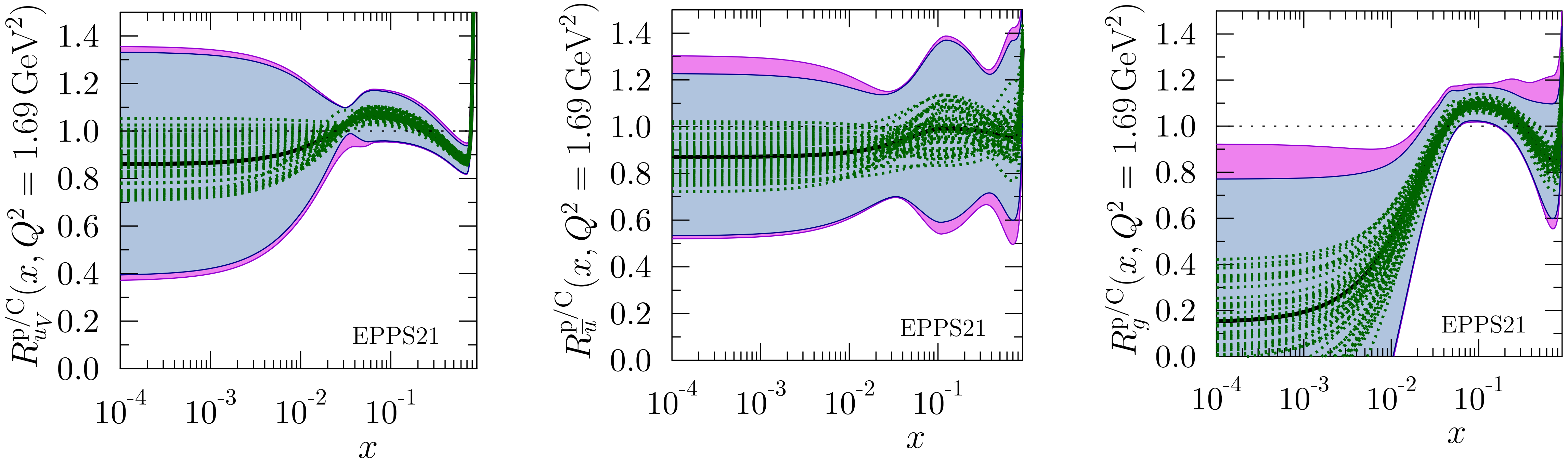


Nuclei: Nucleon interactions and partonic structure



Different types of nucleon interactions are expressed in the nuclear modifications of the parton densities in different ranges of x

Nuclei: Nuclear parton densities



Nuclear parton densities from global analysis

$$R_A(x,\mu^2) \equiv \frac{f_A(x,\mu^2)}{[N_p f_p + N_n f_n](x,\mu^2)}$$

$x > 0.3$

Suppression of valence u-quark densities observed
Further information coming/expected from JLab12: Flavor and spin dependence
Sea quarks? Gluons?

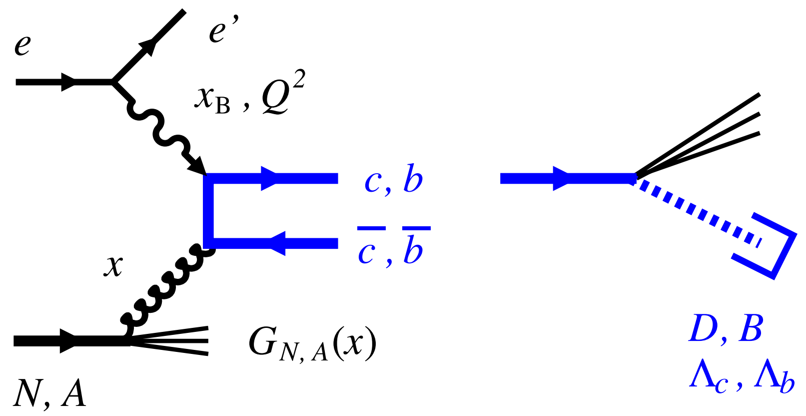
$x \sim 0.1$

Some indications of gluon antishadowing
Valence and sea quarks? Flavor dependence?

$x \lesssim 0.1$

Gluon shadowing observed
Quarks?

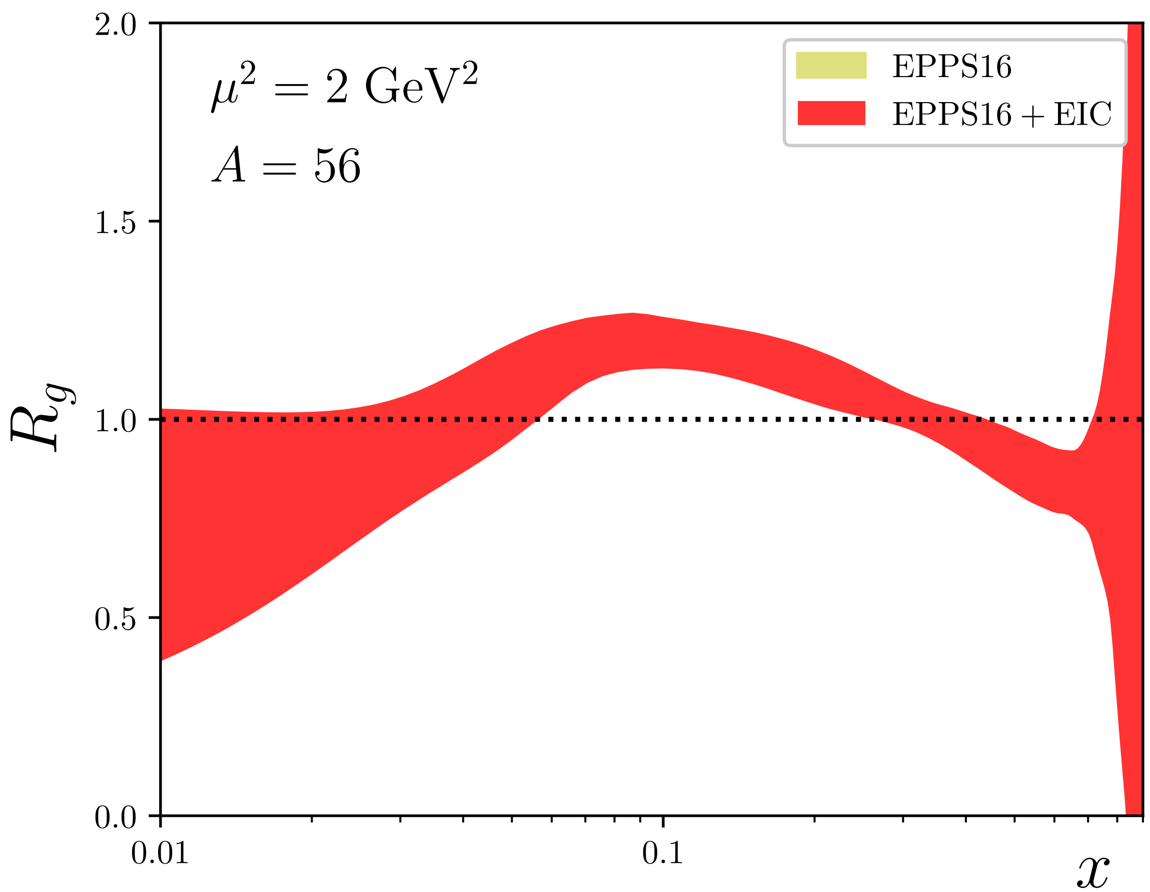
EIC: Nuclear gluon densities



Nuclear gluon density can be determined from

Q^2 dependence of inclusive eA cross section
F_2 and F_L structure functions

Open heavy flavor production c, b:
Direct probe, good theoretical control



c, b quarks identified through D, B mesons
High charm production rates and reconstruction efficiency at EIC

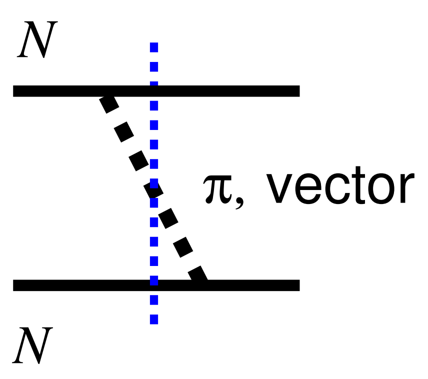
Impact on nuclear gluons at $x \gtrsim 0.1$

→ Gluon EMC effect?

→ Gluon antishadowing?

[Furletova, Sato, Weiss; 2020 INT Report, arXiv:2002.12333; Aschenauer et al. PRD 96 114005 (2017)]

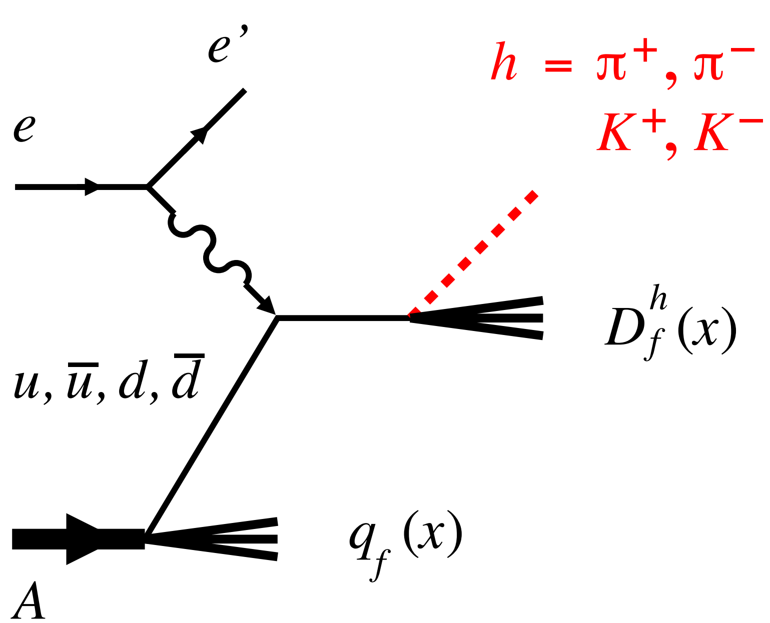
EIC: Nuclear quark charge/flavor densities



How are the quark/antiquark and flavor densities in nucleus modified at $x \sim 0.1$?

Meson exchange in NN interaction:
Enhancement of antiquarks?

Inclusive DIS cannot separate $q \leftrightarrow \bar{q}$



EIC: Semi-inclusive DIS on nuclei

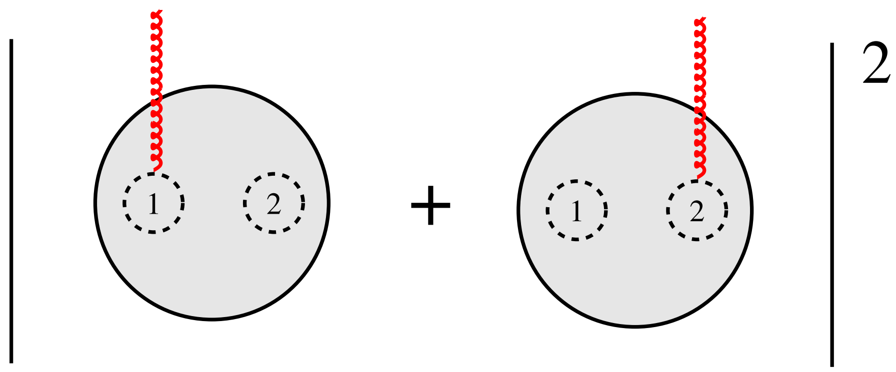
Can separate $q \leftrightarrow \bar{q}$, constrain nuclear sea

High energy ensures independent fragmentation of active quark

Strategies for separating parton structure modifications from nuclear final-state interactions

Detector simulations planned

EIC: Gluon shadowing at small x



Distance in correlator ≫ size of nucleus

Gluons are “pulled” from different nucleons coherently at amplitude level

$$f_A(x) = f_1(x) + f_2(x) + f_{1-2\,\text{interference}}(x)$$

Interference term in gluon density*
Nuclear density ≠ sum of nucleon densities

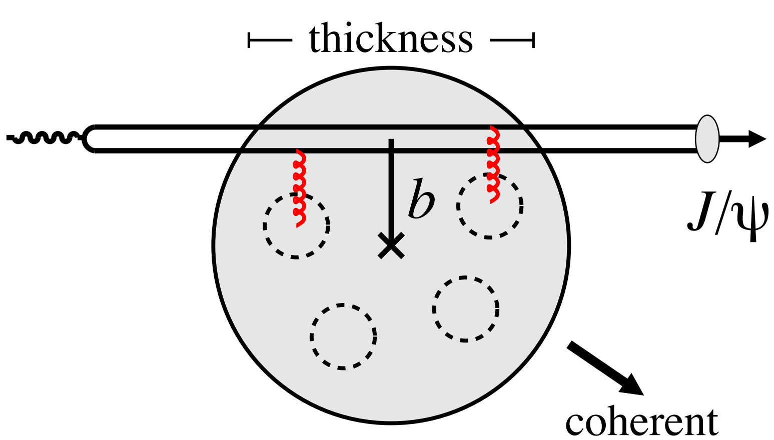
Interference term reduces nuclear gluon density compared to sum of nucleon densities

QM effect. Analog of classical “shadowing” — nucleon 2 hidden behind nucleon 1

Observed in heavy quarkonium production in γA collisions at LHC
Can be tested and explored at EIC

*Interference made possible by diffractive amplitudes $N \to g + X' + N$.
Shadowing effect closely connected to diffractive scattering.

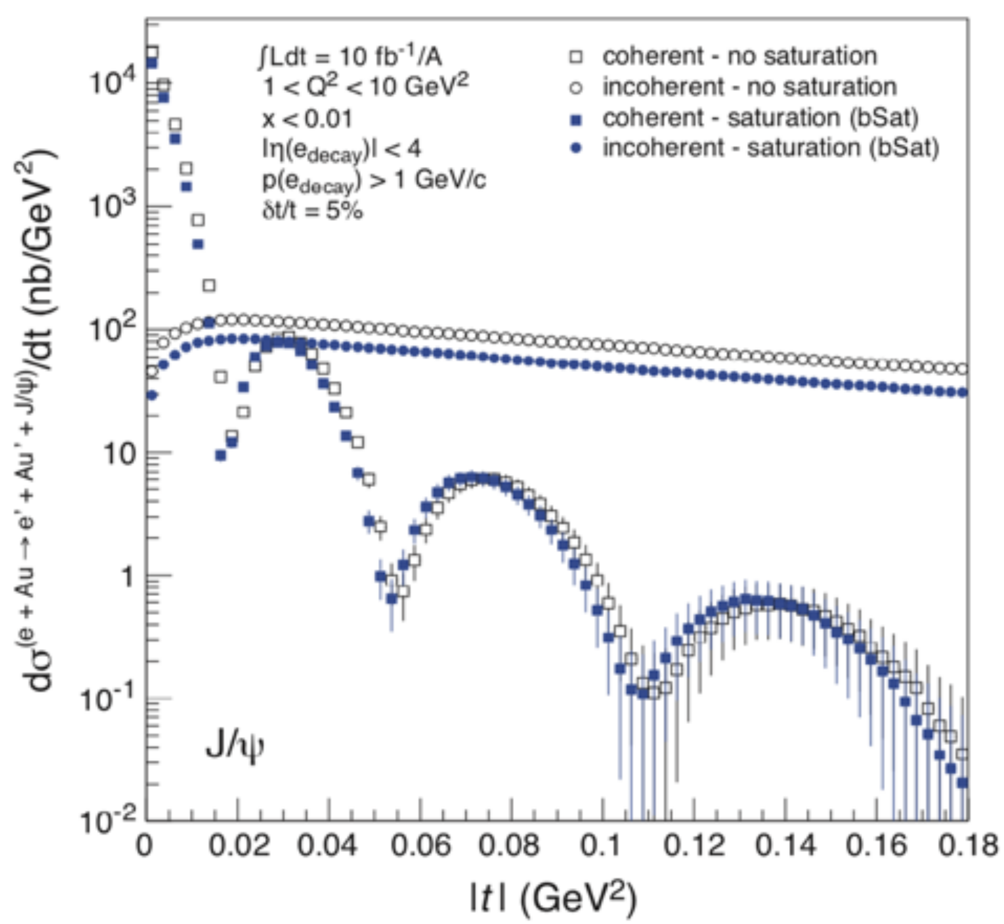
EIC: Gluon shadowing in coherent processes



Coherent quarkonium production on heavy nuclei

Amplitude probes gluon density in nucleus at fixed impact parameter b

Differential cross section exhibits “diffraction pattern” determined by Fourier transform of amplitude squared



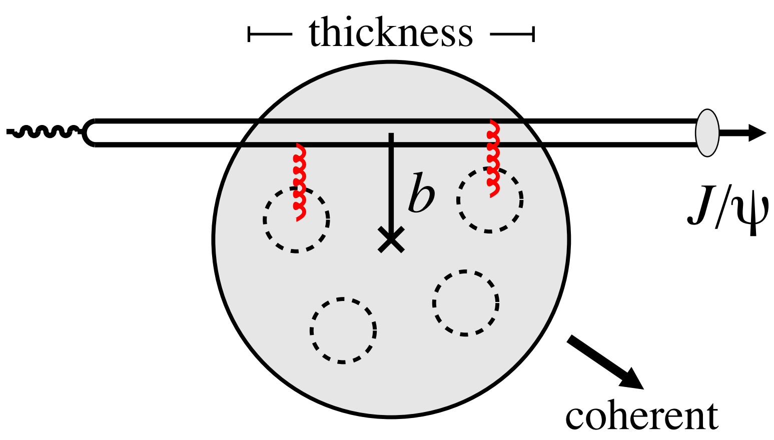
EIC Yellow Report

Shadowing effect in gluon density proportional to nuclear thickness correlated with impact parameter → expressed in diffraction pattern

Detection

Difficult measurement: Coherent events identified by vetoing nuclear breakup events (neutron emission)

Uses far-forward detection system: Zero-degree calorimeter for neutrons

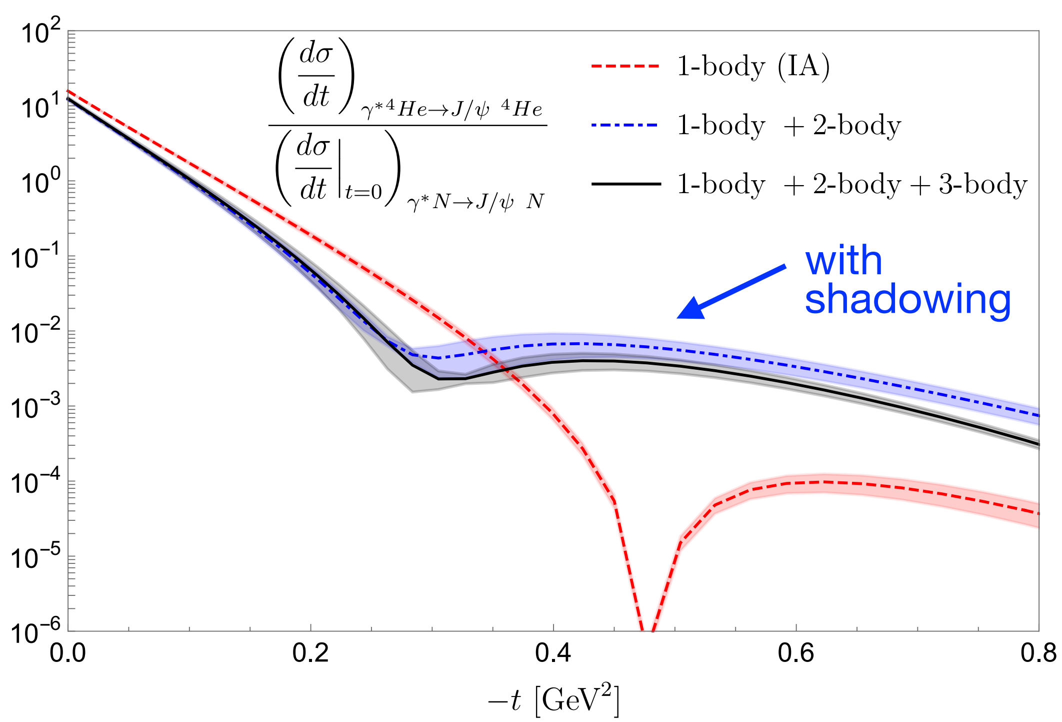


Alt. approach: Coherent quarkonium production on light nuclei (D, 3He, 4He)

Shadowing effect smaller, but expression in diffraction pattern better understood

Cross section without shadowing has well-established diffractive minimum

Shadowing will “fill” the minimum - large effect!



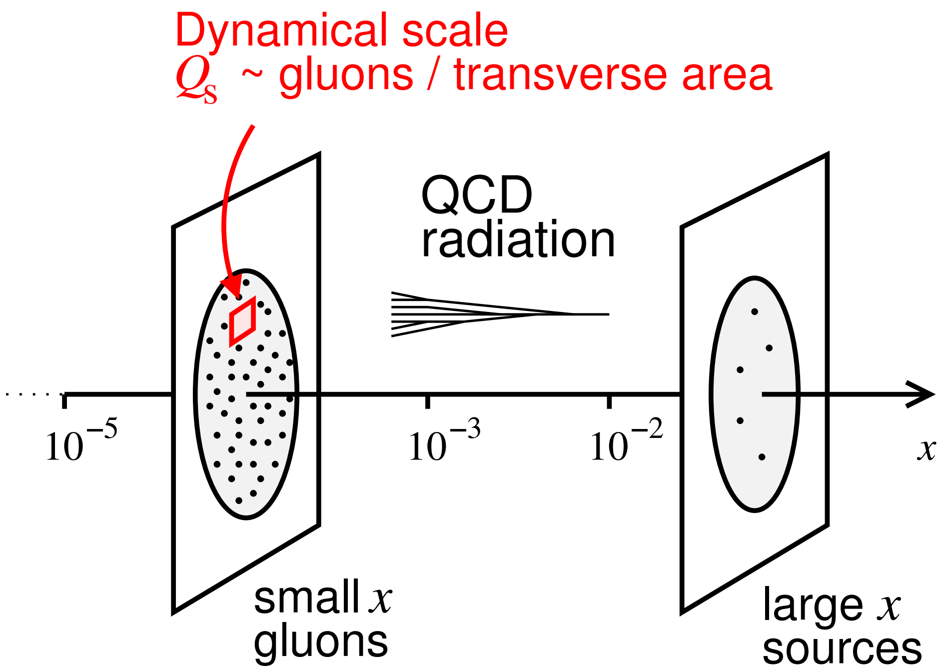
Guzey, Rinaldi, Scopetta, Strikman, Viviani 2022

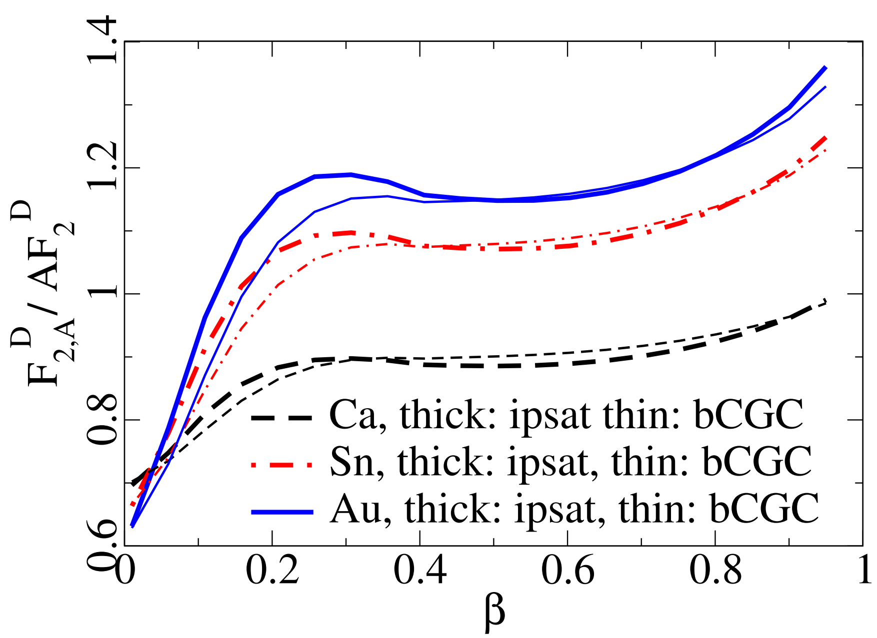
Detection

Active detection of recoiling nucleus using far-forward detectors

Recoiling nucleus is charged particle, detected with Roman Pot detectors

EIC: Gluon saturation at small x





Example: Nucleus/proton ratio of diffractive structure functions predicted by CGC. EIC Yellow Report

New dynamical scale in wave function at small x

Gluon number grows through QCD radiation

Gluon density per transverse area becomes scale: $Q_S(x)$

Theory: Nonlinear QCD evolution BK, JIMWLK; classical fields "color-glass condensate"

Effect enhanced in nuclei, naively $Q_S \propto A^{1/3}$, but diminished by shadowing

New phenomena

Breakdown in Bjorken scaling of F_2, F_L

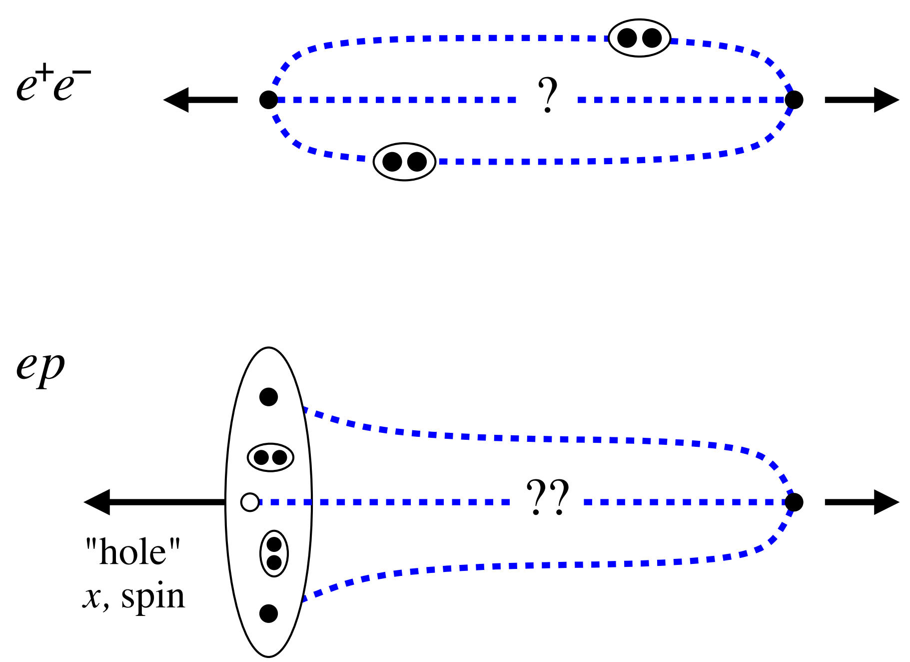
High $p_T \sim Q_S$ in forward particle production

Parton correlations, multiparton processes

EIC measurements

Saturation studies using exclusive, diffractive and inclusive processes

Hadronization



How do hadrons emerge from energetic QCD modes?

Basic process of “conversion of energy to matter"

What is role of QCD radiation, nonperturbative fields, chiral symmetry breaking?

As fundamental as hadron structure, but much less understood…

Fragmentation functions

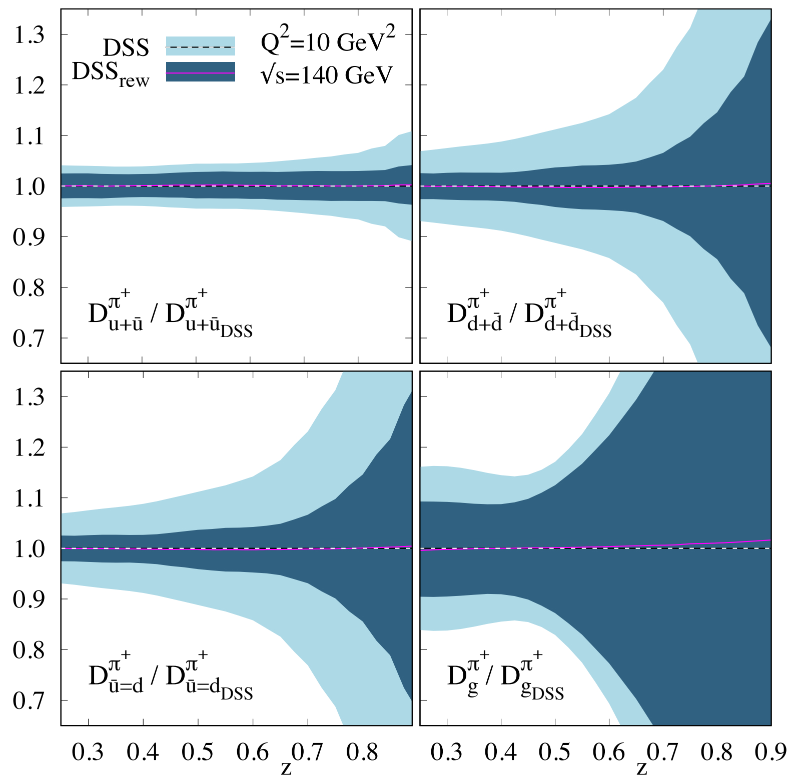
Describe probability for energetic quark/antiquark/gluon to decay into certain hadron with energy fraction z plus unidentified colored remnant

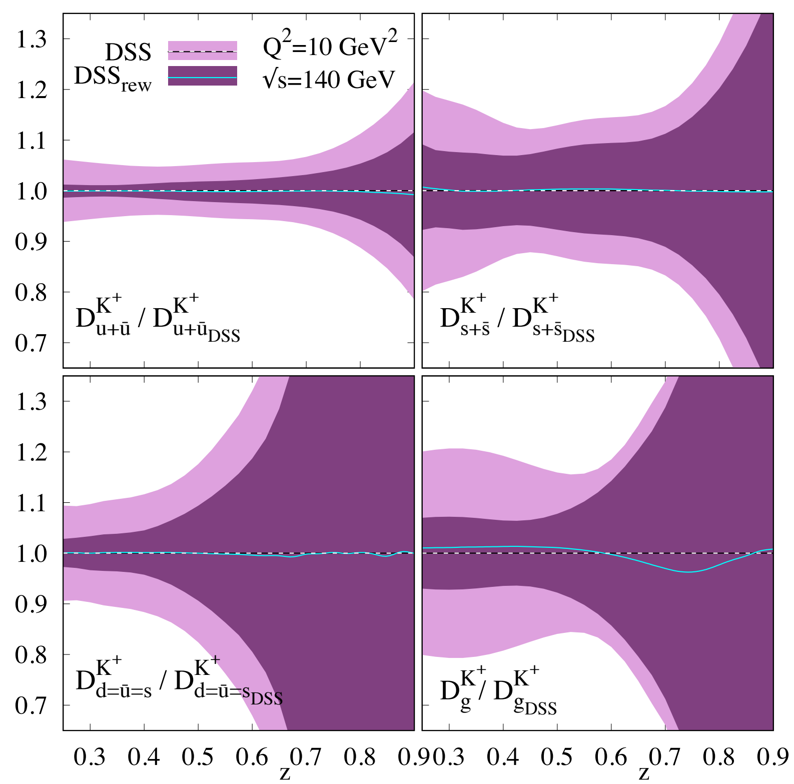
Analogies with parton distributions in hadrons: Appear in factorization, universal

$e^+e^- \to h + X$: Accurate measurements, but only $q + \bar{q}$, cannot separate q and $\bar{q}$

$ep \to e' + h + X$ (semiinclusive DIS): Separate information on q and $\bar{q}$, test universality

EIC: Fragmentation functions





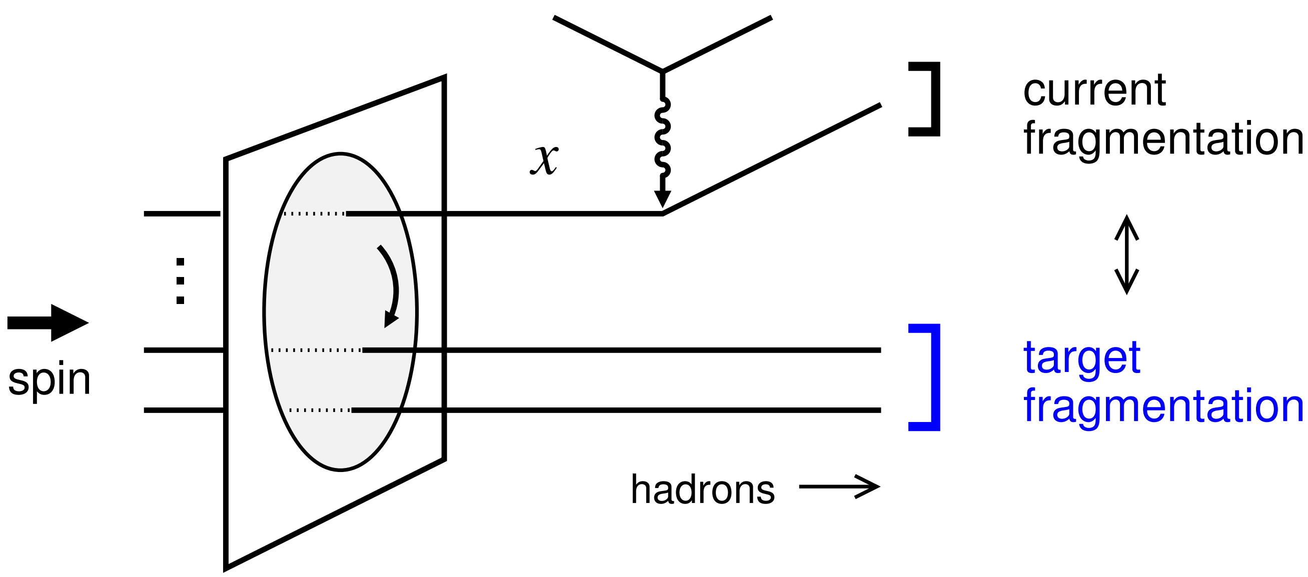
Quark/antiquark fragmentation functions from global analysis

EIC: Semi-inclusive pion and kaon production

Major improvement in flavor separation, “unfavored” fragmentation

EIC Yellow Report

EIC: Target fragmentation of nucleon



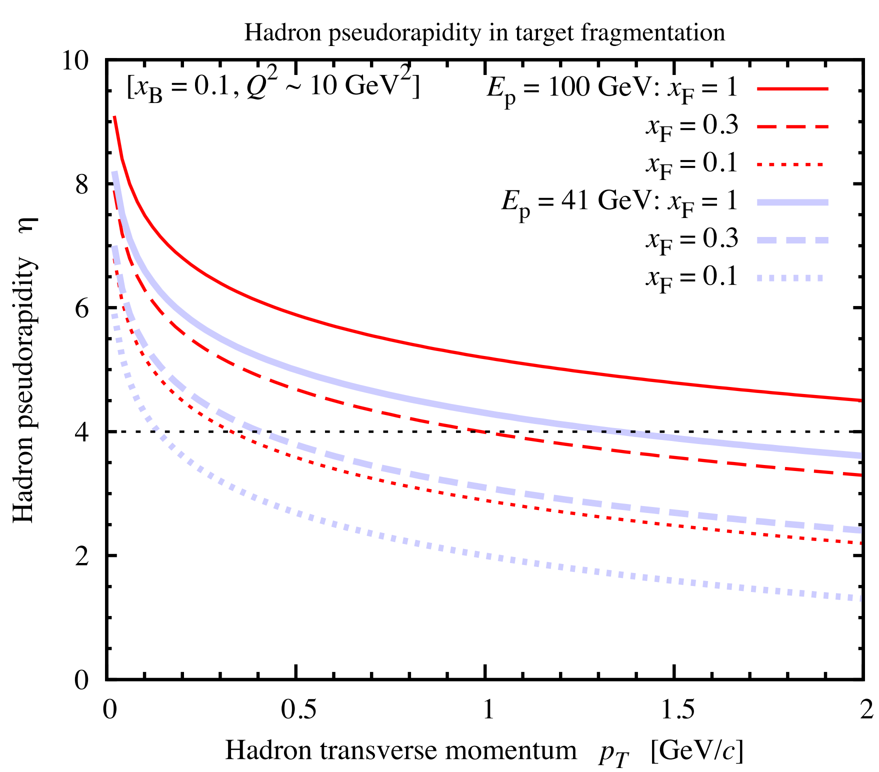
Target fragmentation: Hadronization of nucleon remnant when removing quark with given x

Provides information on configurations in nucleon partonic wave function: particle content, motion

New observables in fragmentation of polarized nucleon

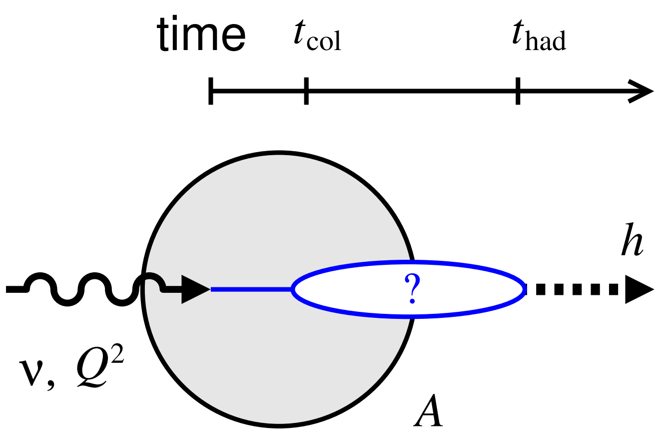
New information from measurements of correlations between current and target fragmentation

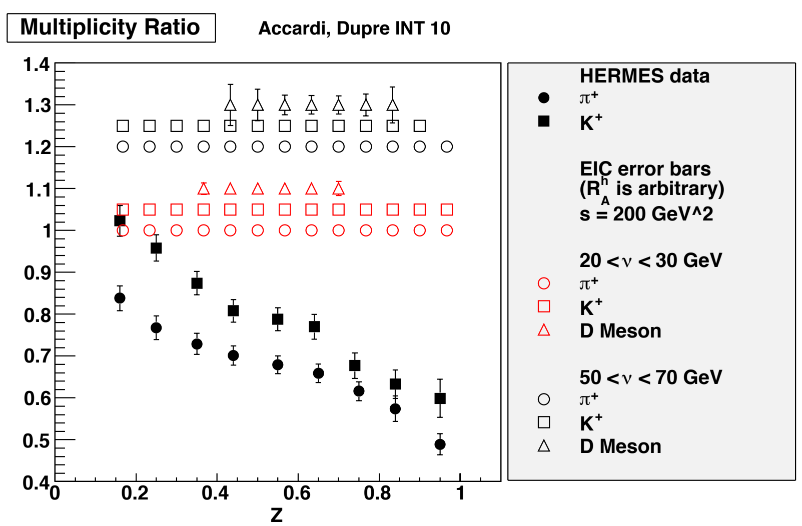
Feasibility with EIC detectors being explored

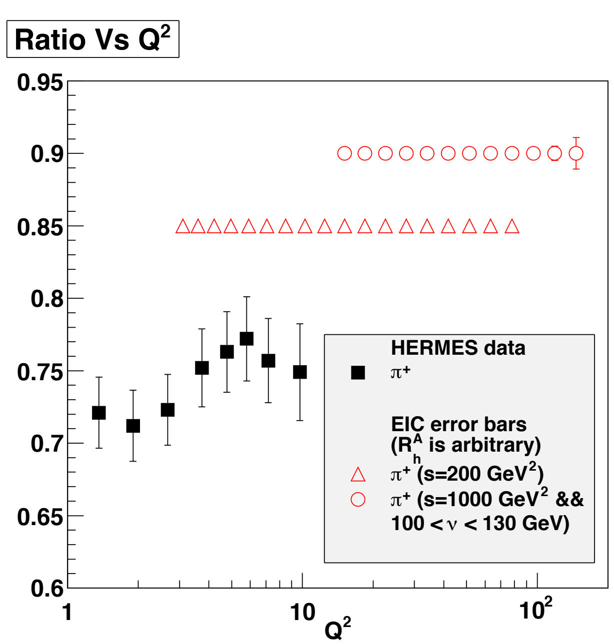


EIC Yellow Report

EIC: Hadronization in nuclear medium







How does energetic color charge interact with hadronic matter?

Energy loss, transverse momentum broadening

Induced radiation, modified fragmentation

Timescales for color neutralization, hadronization?

Cold matter results as input to hot matter in heavy-ion

EIC measurements

Wide range of energies ν = 10-100 GeV:
Move hadronization in and out of nucleus

Wide range of momentum transfers Q^2:
Scale dependence of medium effects

Hadronization of heavy quarks:
Clean probe, QCD predictions

High luminosity for multidimensional binning

EIC: Organization

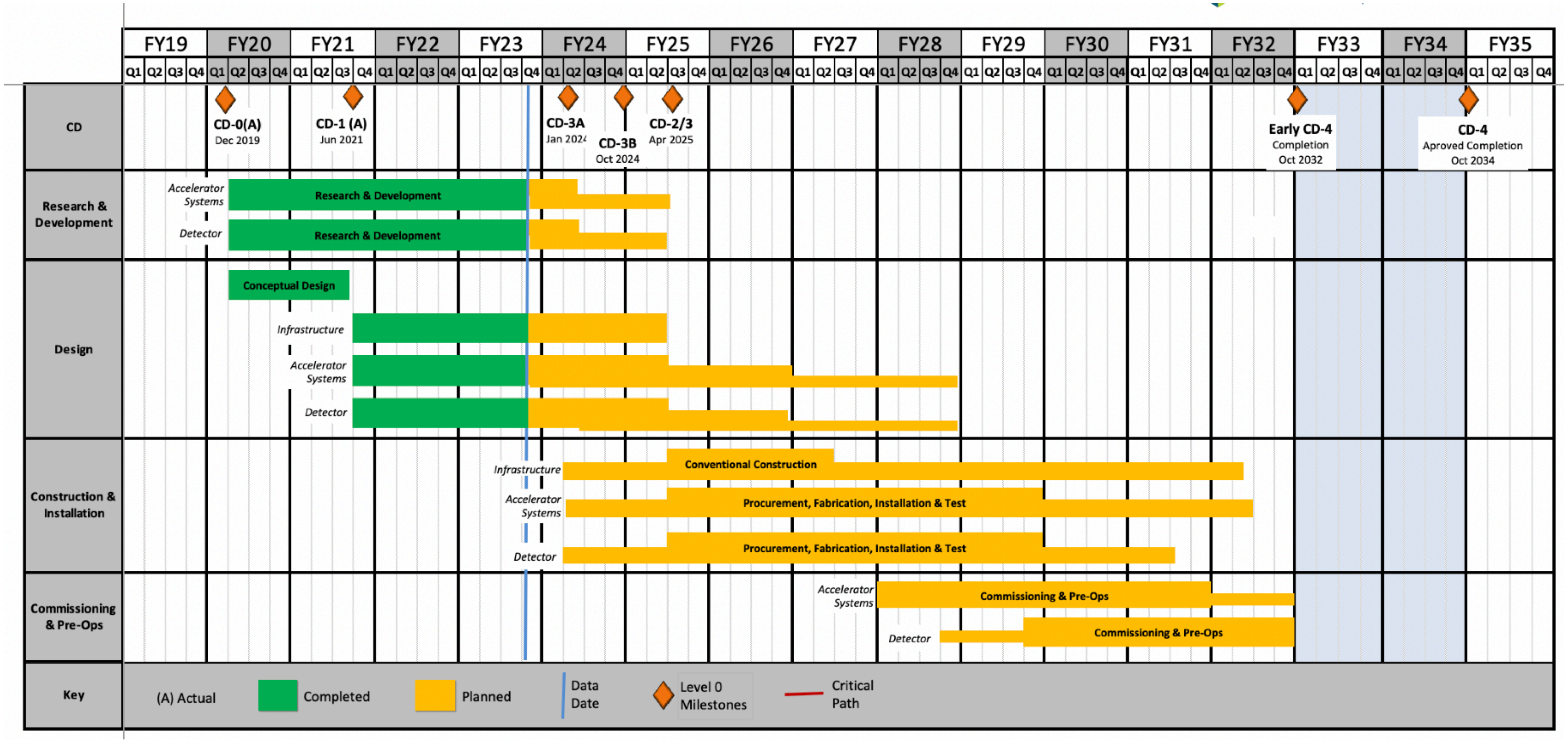
DOE Project: Standard structure/process for construction of new facilities. Integrated project, managed/executed according to project management best practices (scope, cost, schedule, risk, critical decisions, reviews, etc.). Also integrates international contributions to EIC detector.

BNL and JLab: Host facility (BNL) and supporting efforts such as detector assembly, testing. Lab staff extensively involved in DOE project, and engaged in scientific and technical development. Labs also engage and connect with user community.

ePIC Collaboration: International collaboration designing/building EIC detector. Formed in 2022. 171 institutions, 25 countries, >500 members. [Webpage]

EIC User Group: International association of scientists promoting EIC in scientific, technical, and educational matters. >1400 members, 290 institutions, 38 countries. Includes theorists. Working groups, e.g. for EIC Theory and second detector. Holds meetings, provides online resources. [Webpage]

EIC: Project timeline



CD0: Approve mission need, site selection. December 2019 ✓

CD1: Approve scope, analyze alternatives. June 2021 ✓

CD3A: Approve start of long-lead procurements. March 2024 ✓

CD2: Approve preliminary design (maturity >60%), requires pre-TDR

CD3: Approve final design (maturity >90%), requires TDR

CD4: Project completion, expected ~2034

Progress depends on budget allocations, timeline may be revised

Measurements and analysis will be done by “next generation!”