Next-generation hadronic physics with EIC

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Jefferson Lab

- High-energy electron scattering

  Energy, luminosity, polarization, detection

- Nucleon structure with EIC

  Parton picture

  Spin, spatial distributions, orbital motion, correlations

  Connection with dynamics, χ-symmetry breaking

- Nuclear QCD with EIC

  Quarks/gluons in nuclei

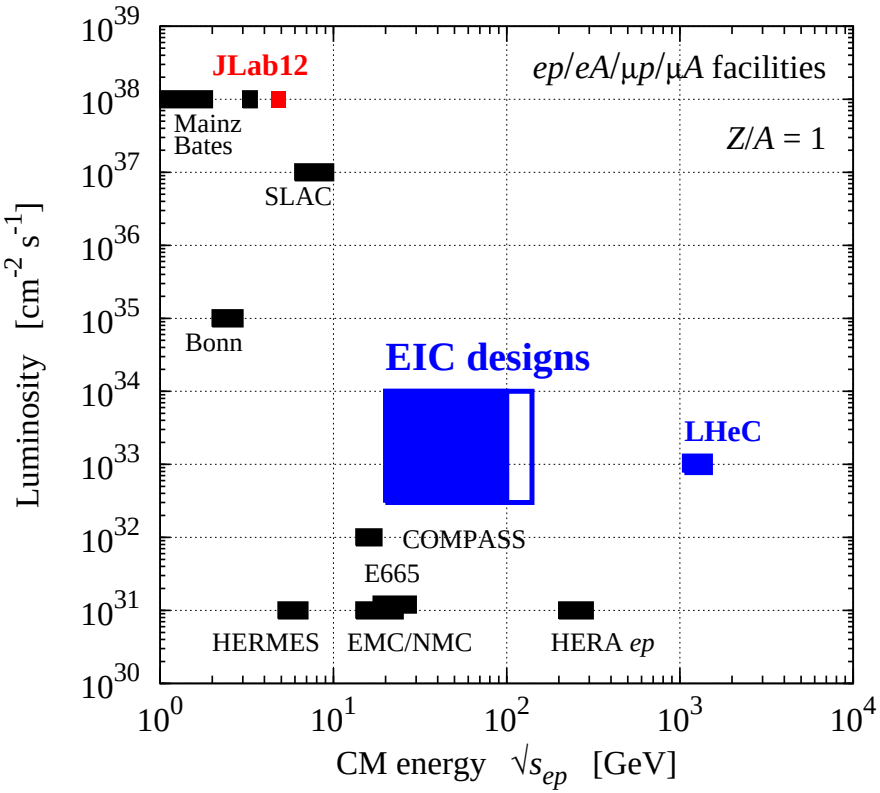
  Connection with NN interactions

  Novel probes: Nuclear breakup, heavy quarks

- Path forward

This overview:
– Physics of MENU interest
– Connection with dynamics

EIC: High-energy electron scattering



- CM energy $\sqrt{s_{ep}} \sim$ 20-100 (140) GeV

  DIS in wide range $x \sim 10^{-1}$–10^{-4}

- Luminosity $\sim 10^{33}$–10^{34} cm^{-2} s^{-1}

  $10^3 \times$ HERA luminosity

  Low-rate processes, multivariable analysis

- Polarized proton and light-ion beams

  Spin observables proton/neutron/nuclei

- Heavy-ion beams

[Parameters from EIC White Paper, NAS Study]

- Next-generation detectors

  Central: DIS final states, including vertex detection and PID

  Forward ion: Exclusive p, nuclear breakup, coherent processes

  Forward electron: Low-Q^2 tagger for quasireal photoproduction

EIC: Physics topics

- **3D nucleon structure and spin**

  Sea quark and gluon polarization, nucleon spin decomposition
  Spatial distributions of quarks/gluons
  Orbital motion and spin-orbit effects
  Quark-gluon correlations and fluctuations

- **QCD in nuclei**

  Nuclear quark/gluon densities
  Coherent effects, nuclear shadowing
  Gluon saturation at small x

[• **Further physics topics**

  Final states: Quark/gluon fragmentation, hadronization, jets

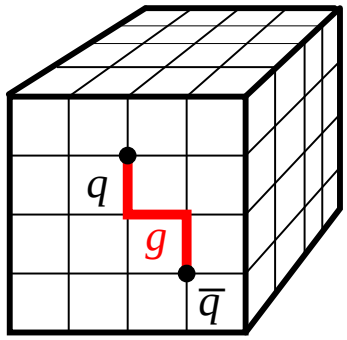
  Hadron spectroscopy: Heavy flavors, hard production processes

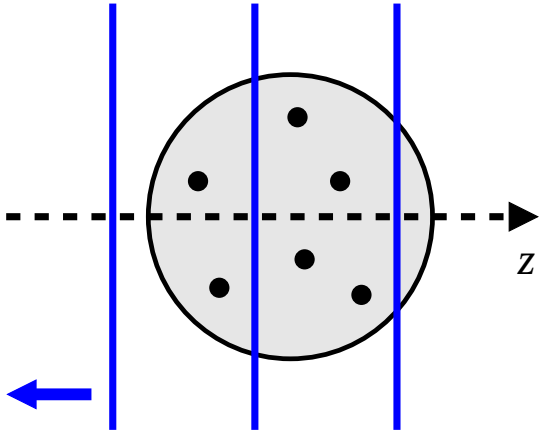
  Pion and kaon structure

  Electroweak physics: Charged and neutral-current processes

  ....

Nucleon structure: Dynamical system





$t + z = \text{const.}$

- Emergent phenomena of QCD

  Relativistic: Particle creation/annihilation
  Quantum-mechanical: Coherent superposition
  Strongly coupled: Chiral SB, mass generation

  Unique dynamical system!

- Field-theoretical description

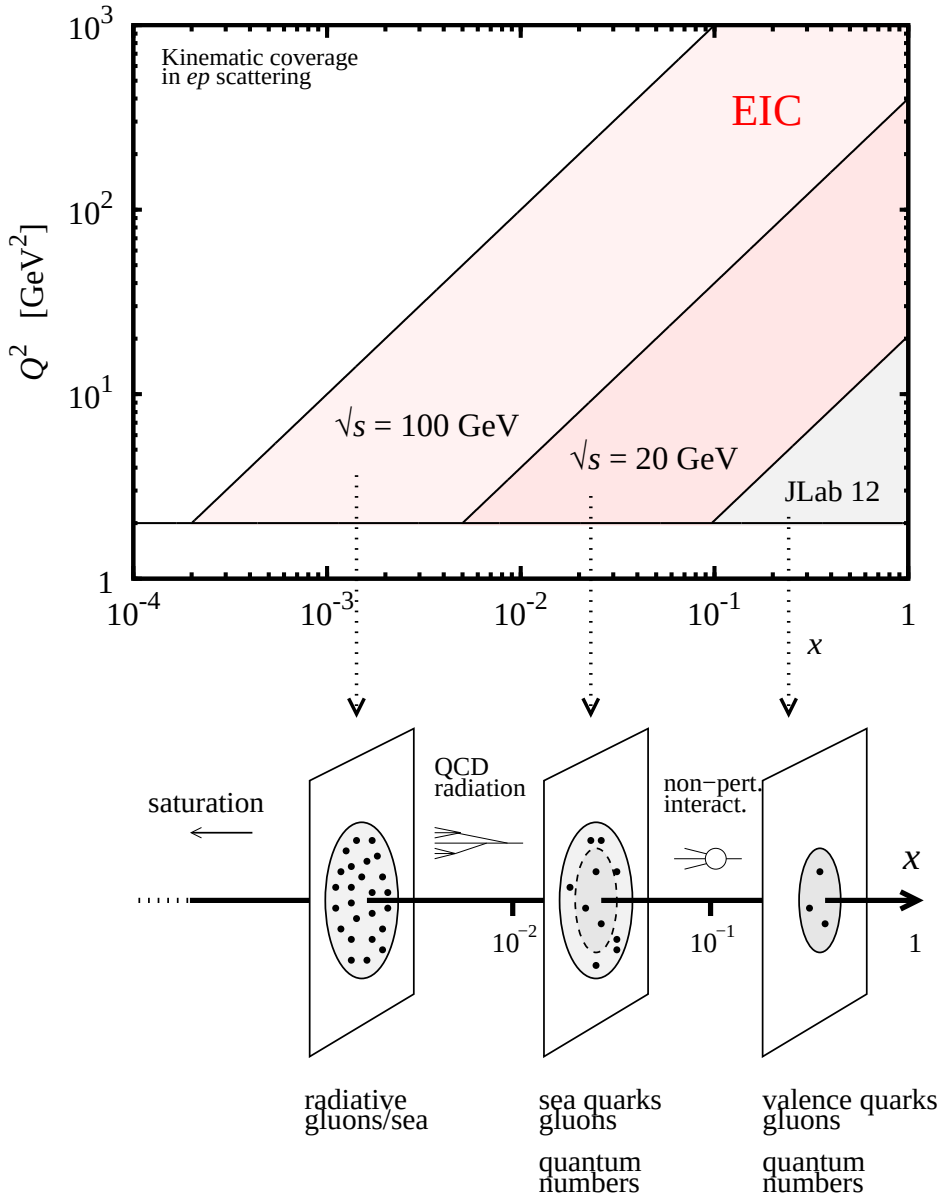
  Imaginary time $t \to i\tau$: Statistical mechanics, correlation functions, lattice methods

- Particle-based description

  High-energy process probes system at fixed light-front time $t + z = \text{const}$

  Many-body system: Constituents, interactions, motion, spatial structure

Nucleon structure: Landscape



- Components probed

  $x > 0.1$: Valence quarks and gluons, spin/flavor, few-body dynamics

  $x \sim 10^{-1}...10^{-2}$: Sea quarks, gluons, spin/flavor, non-perturbative dynamics

  $x \ll 10^{-2}$: Gluons and singlet sea, radiative dynamics

- Measurable quantities

  Quark/gluon number densities, spin/flavor dependence: PDFs

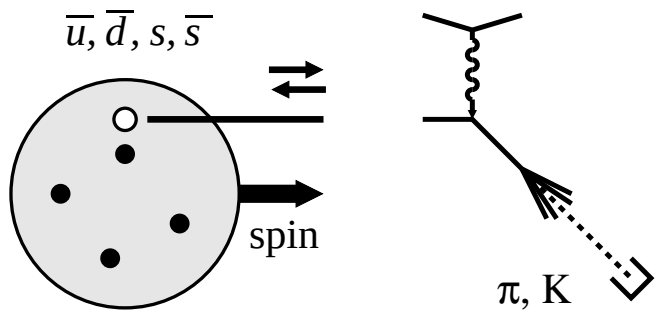
  Spatial distributions: GPDs

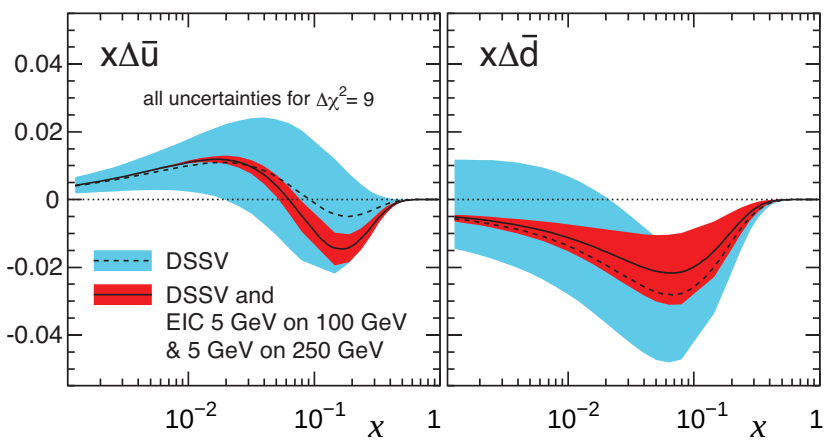
  Intrinsic motion, spin-orbit: TMDs

  Universal quantities: Matrix elements of QCD operators, renormalization, scale dependence, LQCD

  → Talk Contalbrigo

Nucleon structure: Sea quark polarization





EIC White Paper 2012

- How are sea quarks polarized?

  $q\bar{q}$ pairs from chiral SB?
  Large $\Delta\bar{u} - \Delta\bar{d}$ predicted
  Diakonov et al. 96, see also Soffer et al.

  Mesonic components?

- RHIC W$\pm$: New information → Talk Seidl

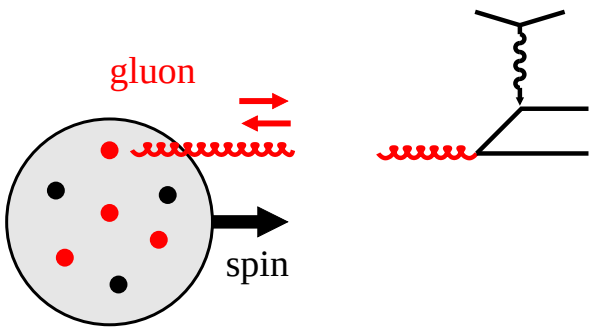
- EIC: Map sea quark distributions

  Semi-inclusive DIS
  $eN \to e' + \pi/K + X$

  Tags charge and flavor of active quark

  High collision energy ensures separation of photon and nucleon fragments

Nucleon structure: Gluon polarization

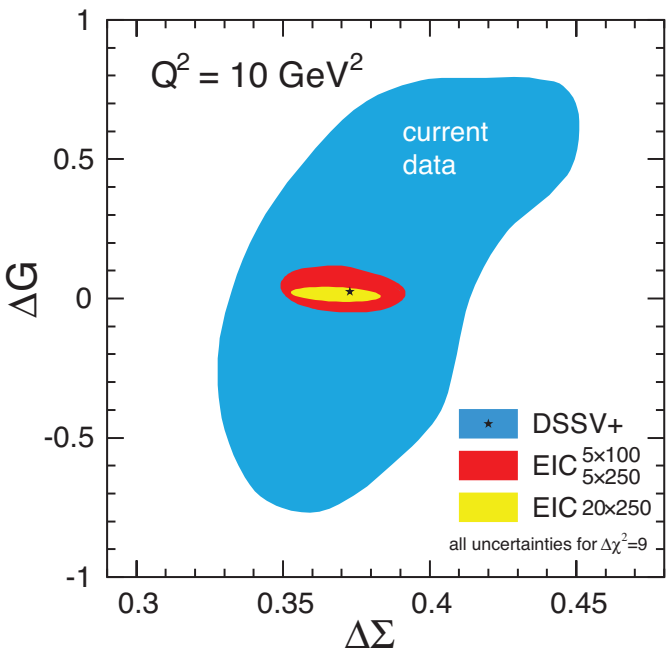


- How is the nucleon spin composed of quark/gluon spin and orbital ang mom?

$$\Delta\Sigma = \int_0^1 dx\ [\Delta q + \Delta\bar{q}](x, Q^2) \quad \text{quark spin}$$

$$\Delta G = \int_0^1 dx\ \Delta G(x, Q^2) \quad \text{gluon spin}$$

$$\tfrac{1}{2}\Delta\Sigma + \tfrac{1}{2}\Delta G + \text{orbital} = \tfrac{1}{2} \quad \text{sum rule}$$



EIC White Paper 2012

- Polarized gluon density

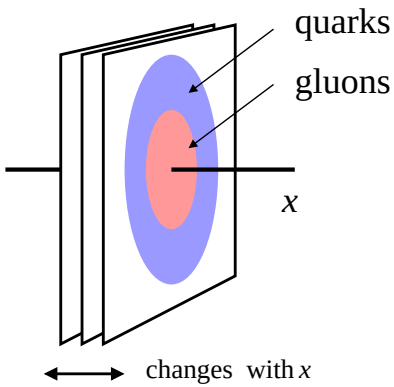
  Q^2 dependence of polarized $\vec{e}\vec{N}$ scattering
  EMC/SMC, SLAC, HERMES, COMPASS, JLab 6/12 GeV

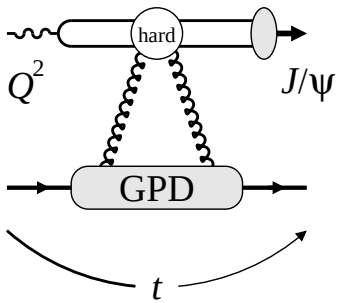
  Hard processes in polarized $\vec{p}\vec{p}$ scattering
  RHIC Spin

- EIC: Determine gluon spin

  Wide kinematic coverage enables measurement of Q^2 evolution, x integral

Nucleon structure: Spatial distributions



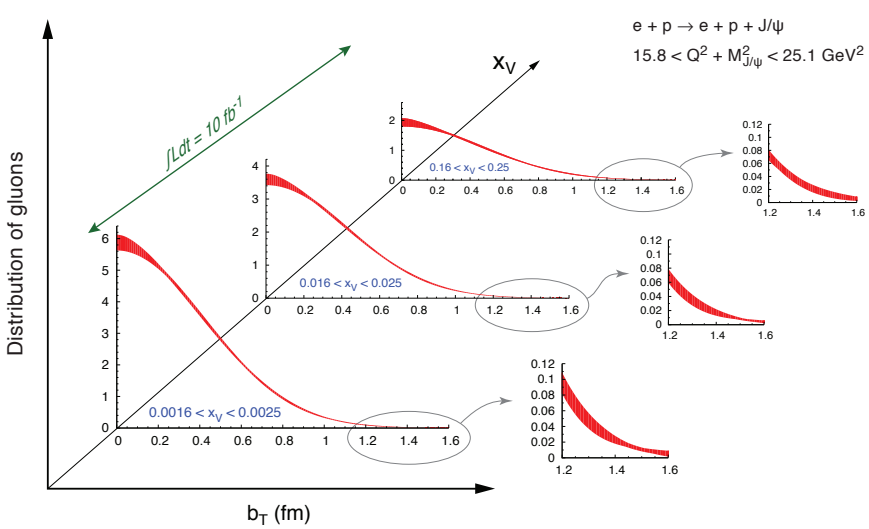


- How are quarks/gluons distributed in transverse space?

  Size and "shape" of nucleon in QCD

  Distributions change with x, spin

  Input for modeling pp collisions at LHC



- Exclusive processes $eN \to e' + M/\gamma + N'$

  Quark/gluon form factors of nucleon: Generalized parton distributions

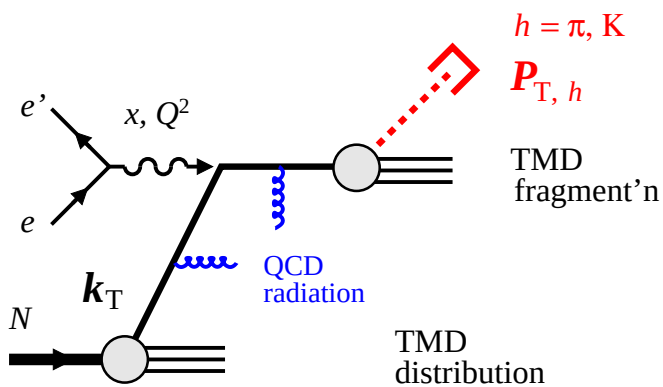
- EIC: Quark/gluon imaging of nucleon

  Luminosity for low rates, differential measurements

  Forward proton detection

Other channels: ϕ, ρ, γ, π/K, ...

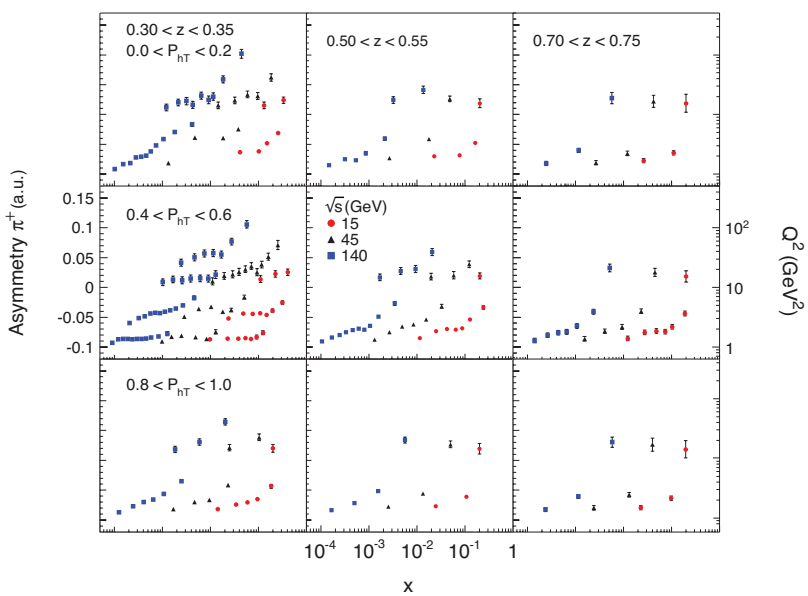
Nucleon structure: Transverse momentum



- Transverse motion of quarks/gluons

  Observed hadron P_T compounded:
  Nucleon structure $\leftrightarrow$ parton fragmentation
  Pert. radiation $\leftrightarrow$ nonpert. dynamics

  TMD factorization: Very active field,
  much progress Collins, Rogers, Ji, Yuan, Qiu, Kang, ...



EIC White Paper 2012

- EIC: P_T dependent hadron production

  High energy for separating rapidity regions

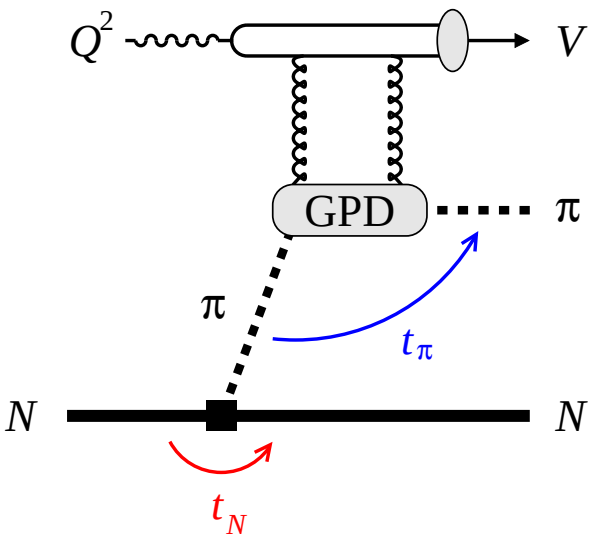
  Wide Q^2 range for separating perturbative radiation and nonperturbative dynamics

  High luminosity for multidimensional binning

Further topics: Hadron spectroscopy

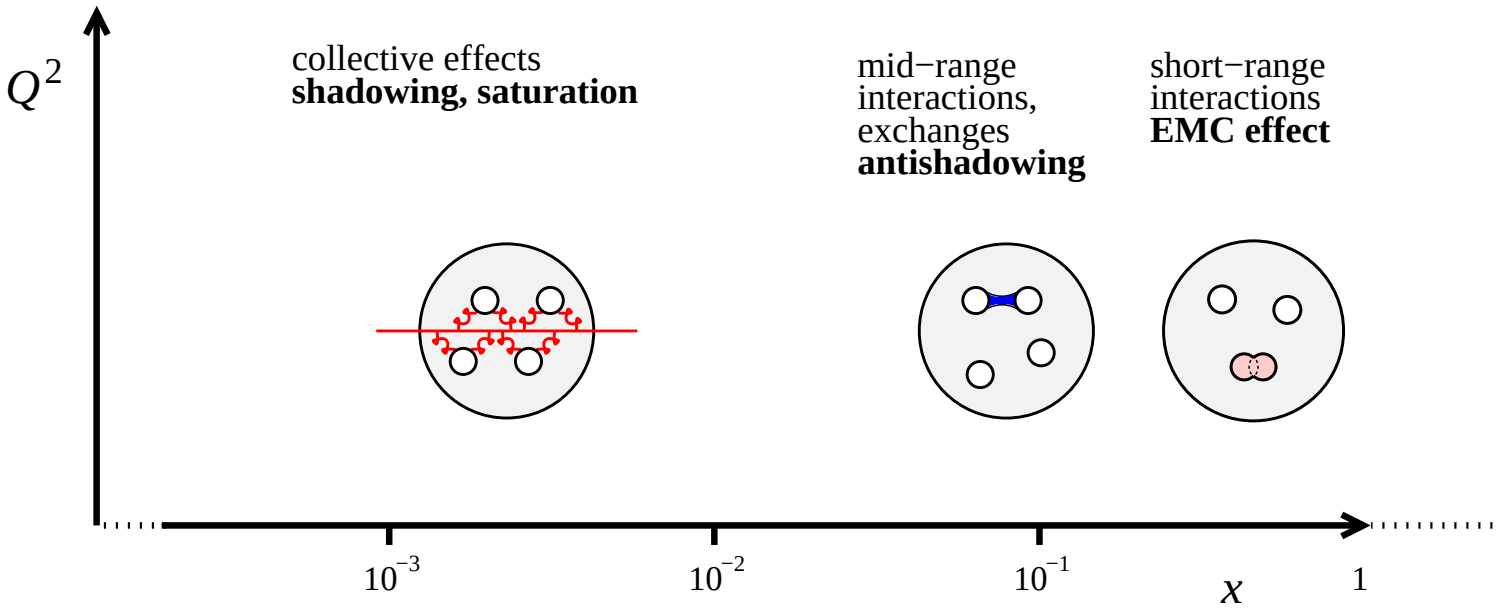
- Photo/electroproduction of heavy-light or heavy-heavy systems
- $N \to N^*$ excitation using high-Q^2 exclusive processes
  Workshop "The spectroscopy program at EIC and future accelerators", ECT* Trento, Dec 19-21, 2018 [Webpage]

Pion structure



- Pion GPDs and quark/gluon size $\leftrightarrow$ chiral SB
- Peripheral eN scattering with pion knockout:
  Kinematics $t_N = O(M_\pi^2)$ and $|t_\pi| \gg |t_N|$
  selects production on peripheral pion Strikman, CW 04
- Uses central and forward detection

Nuclei: Nucleon interactions



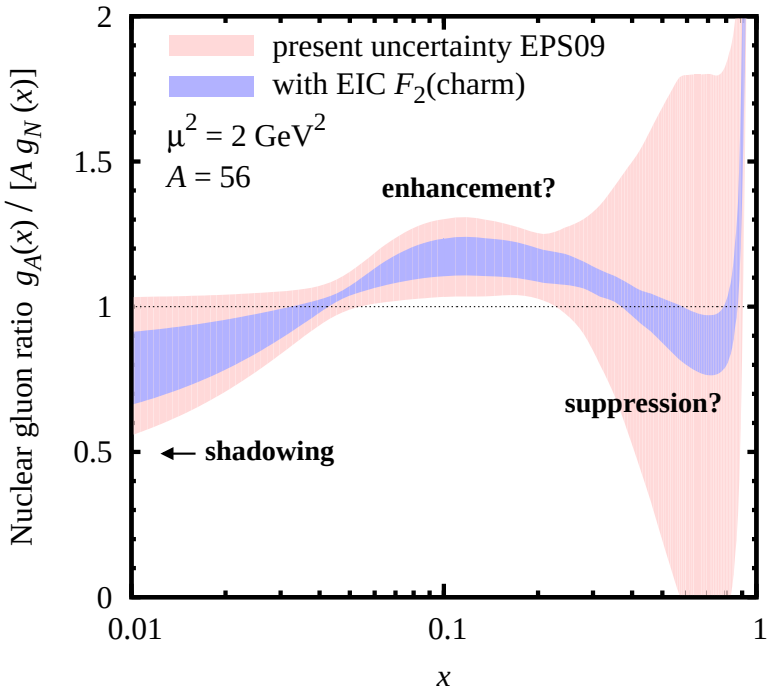
- How do nucleon interactions emerge from QCD?
  "Next step" after exploring nucleon structure

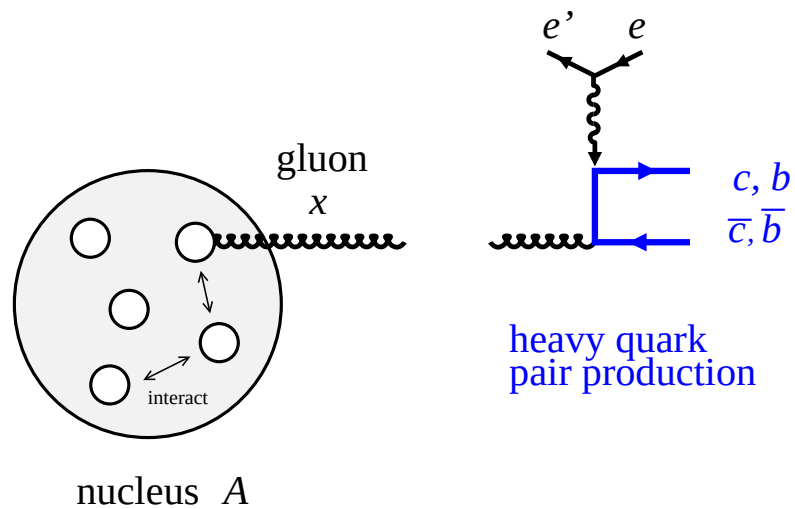
- Expressed in quark-gluon structure of nuclei:
  Nuclear modifications $A \neq \sum N$, mechanisms depend on x

  JLab 12 GeV: Valence quark EMC effect, short-range correlations

  EIC: Nuclear gluons, sea quarks, EMC effect, antishadowing, shadowing, approach to saturation

Nuclei: Nuclear gluons





- Nuclear modification of gluons practically unknown at $x > 0.01$

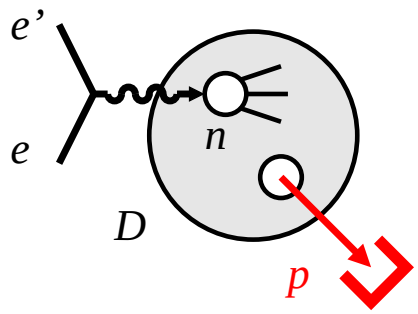
  Indications of gluon shadowing at $x < 0.01$ in LHC ultraperipheral J/ψ data

- EIC: Measure nuclear gluons

  Q^2 dependence of inclusive eA cross section, F_{2A} and F_{LA}

  Heavy flavor production (c, b) as direct probe of gluons
  Aschenauer et al. PRD 96 114005 (2017). JLab LDRD [webpage]

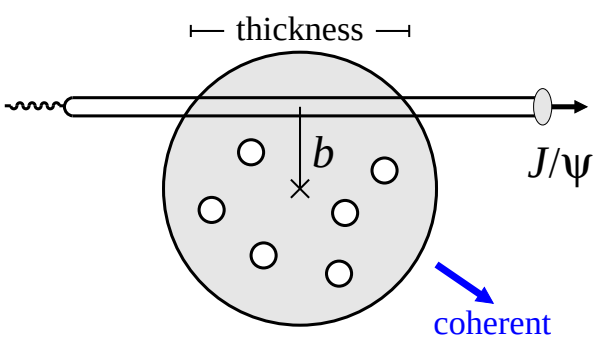
Nuclei: Breakup and coherent processes



- Deuteron DIS with spectator tagging

  Controls nuclear configuration in DIS process:
  Free neutron structure, EMC effect

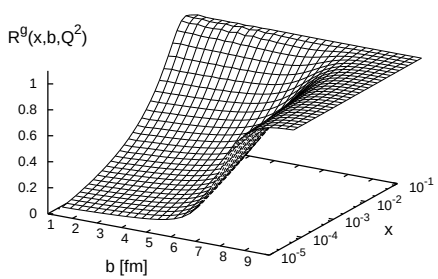
  EIC: Forward proton detection
  JLab LDRD 2014/15 [webpage]



- Coherent nuclear processes

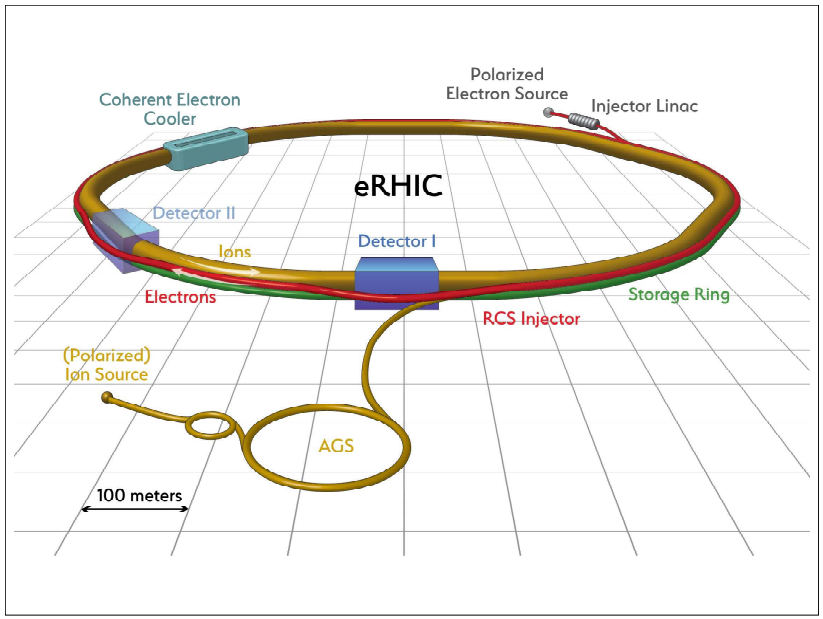
  Nuclear GPDs $\langle A|\,\mathrm{Twist\text{-}2}\,|A\rangle$:
  Quark/gluon imaging of nucleus

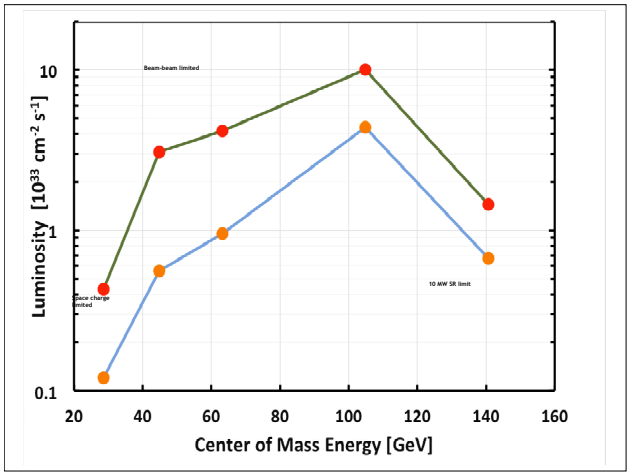
  New approach to nuclear gluon shadowing:
  Thickness $\leftrightarrow$ impact parameter b
  Theoretical predictions: Goeke, Guzey, Siddikov 09



  Forward ion detection
  Light ions $A \lesssim 12$: Positive detection
  Heavy ions: Veto nuclear breakup
  Caldwell, Kowalski 09

EIC: BNL eRHIC Design





eRHIC pre-conceptual Design Report (July 2018)
Current information at [BNL C-AD Webpage]

- Hadron beam

  Reuses injection chain and one of RHIC rings; partially reuses components of other ring

  Hadron cooling required for 10^{34} cm^{-2} s^{-1} luminosity; lower lumi achievable without cooling

- Electron accelerator

  Added inside existing RHIC tunnel

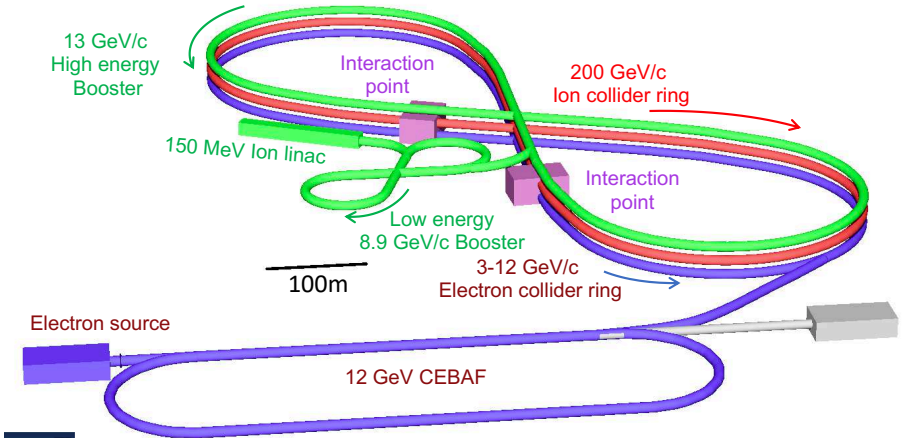
  5-18 GeV storage ring

  On-energy injector: 18 GeV Rapid Cycling Synchrotron

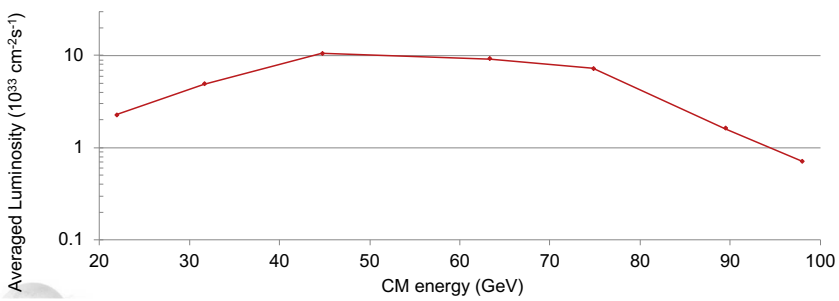
  Polarized electron source and 400 MeV injector linac: 10 nC, 1 Hz

- Two detectors planned

EIC: JLab JLEIC Design



- Electron complex: CEBAF as injector, Electron ring 3-12 GeV
- Ion complex: Ion source, SRF linac 150 MeV for protons, Low-energy booster 8.9 GeV, High-energy booster 13 GeV, Ion collider ring 200 GeV
- Up to two detectors at minimum-background locations



Average luminosity, includes beam storage, formation, duty factor

S. Abeyratne et al. [arXiv:1209.0757] [arXiv:1504.07961]
Current information at [JLab EIC Webpages]

Design concept

- High luminosity: High collision rate, short bunches, small beam size
- High polarization: Figure-8 ring compensates spin precession, enables deuteron polarization
- Full-acceptance primary detector, including far-forward ion acceptance

EIC: Toward realization

- Timeline of main events

  Planning & designing started in late 1990's

  EIC recommended for future construction in U.S. DoE 2015 Long-Range Plan [webpage]

  EIC User Group formed 2016: >800 physicists, >170 institutions [webpage]

  National Academies of Sciences 2018 study endorses EIC physics program [webpage]

  DoE Critical Decision CD0 expected 2019

  Further steps: Site selection, timeline tentative

- EIC accelerator, detector, physics, and theory R&D:
  U.S. National Labs BNL, JLab, ANL, LBNL; university groups [webpage], [webpage]

- Great interest in nuclear & accelerator physics communities

- Growing international participation

Summary

- Understand hadrons and nuclei as emergent phenomena of QCD

  Nonperturbative dynamics encoded in partonic structure

- Compelling physics program in nucleon structure and QCD in nuclei

  Enabled by energy, luminosity, polarization, next-generation detection

- Opportunities for hadron structure physics beyond defined program

  Meson and baryon spectroscopy, structure of excited states

  Pion and kaon structure

  High-energy scattering on light nuclei with tagging/breakup

  Final states, jets, hadronization

- On path to realization