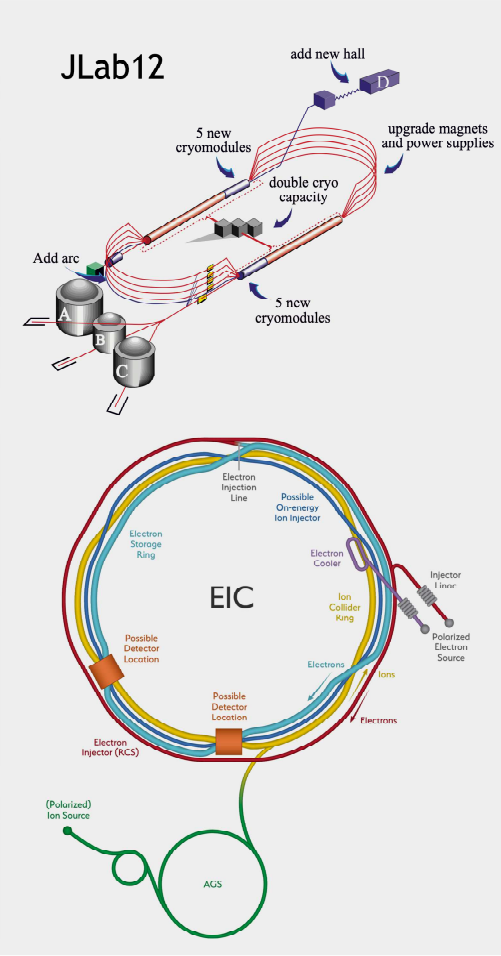
Next-generation nuclear physics with EIC

C. Weiss (JLab) [E-mail], Hall A Collaboration Meeting, JLab, 31-Jan-2020 Jefferson Lab



This overview:
Continuity of physics JLab12 → EIC
Program evolving, many new ideas

- EIC capabilities → Talk Higinbotham

  Energy, luminosity, polarization, detection

- EIC physics

  Nucleon structure in QCD: Sea quarks, gluons
  Spin/spatial/momentum distributions, correlations
  Connection with dynamics, χ-symmetry breaking

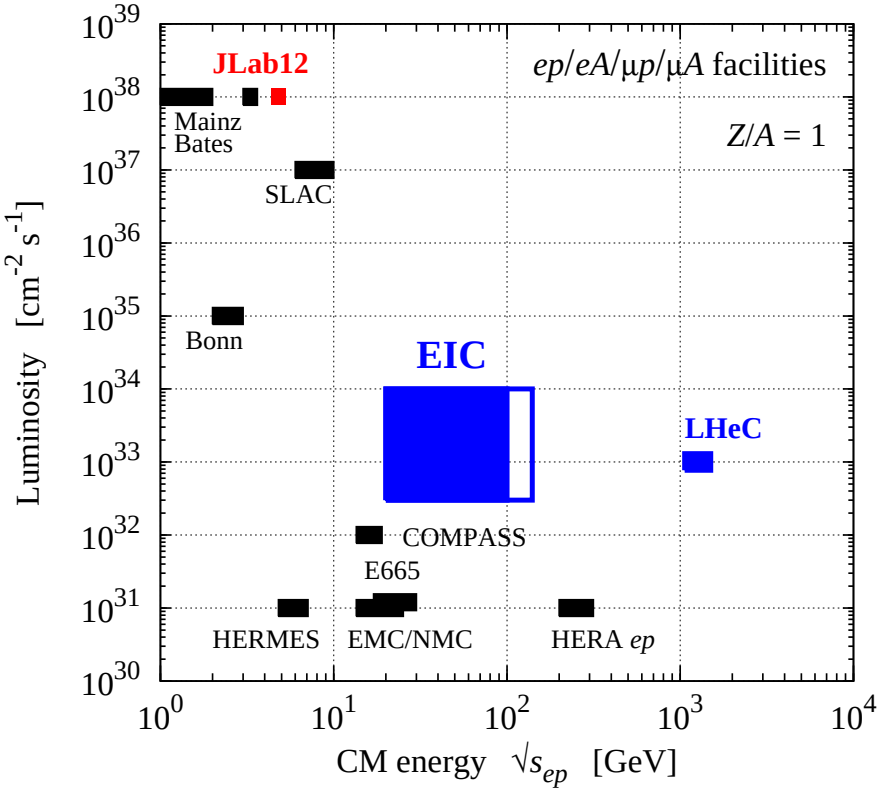
  Nuclear interactions in QCD: Nuclear quarks, gluons
  Novel probes: Nuclear breakup, heavy quarks
  Connection with NN forces, SRCs

  Hadronization: Current and target fragmentation
  Jets, color propagation and hadronization in nuclei

  Further topics: Meson structure, spectroscopy

- Path forward

EIC: Capabilities



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

  DIS in wide range x $\sim 10^{-1}$–10^{-3}

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

  $10^{2-3}\times$ HERA luminosity

  Low-rate processes, multivariable analysis

- Polarized proton and light-ion beams

  Polarized D(?), 3He, possibly higher

  Spin observables proton/neutron/nuclei

- Heavy-ion beams

- Next-generation detectors

  Central: DIS final states, including PID and vertex detection

  Forward ion: Exclusive p, nuclear breakup, coherent processes

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

EIC: Physics topics

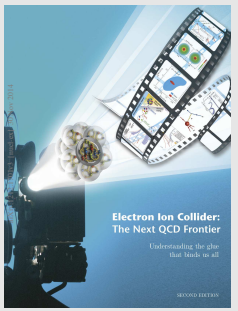
- **3D nucleon structure and spin**
  Sea quark and gluon PDFs, nucleon spin decomposition
  Spatial distributions GPDs, transverse motion TMDs, spin-orbit effects
  chiral symmetry breaking "origin of mass", correlations and fluctuations

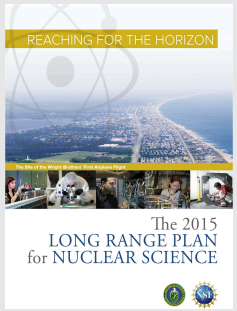
- **QCD in nuclei**
  Nuclear modification of quark/gluon densities
  Short-range correlations, emergence of NN interactions from QCD
  Shadowing, non-linear effects, gluon saturation at small x

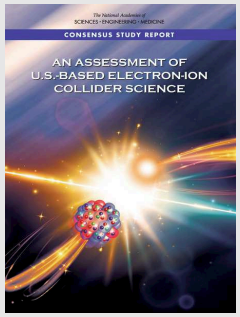
- **Color propagation and hadronization**
  Current and target fragmentation, jet evolution and properties
  Interaction of color charge with matter

[• **Further physics topics**
  Hadron spectroscopy: Heavy flavors, hard production processes
  Pion and kaon structure
  Electroweak physics: Charged and neutral-current processes...]

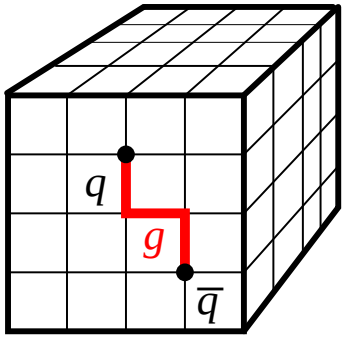
Physics program still evolving!
New concepts and measurements proposed in last 5 years
EIC User Group Physics-Detector Yellow Reports

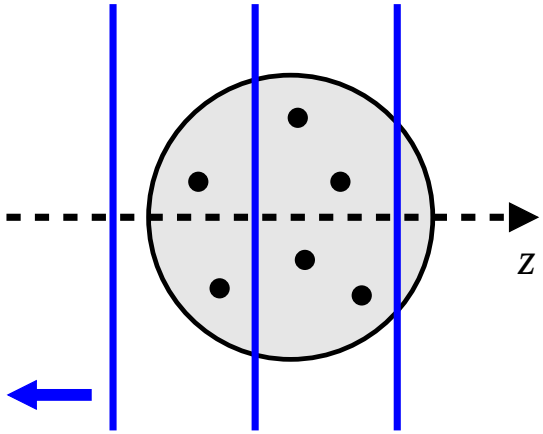






Nucleon structure: Dynamical system





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

- Emergent phenomena of QCD

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

  Unique dynamical system!

- Field-theoretical description

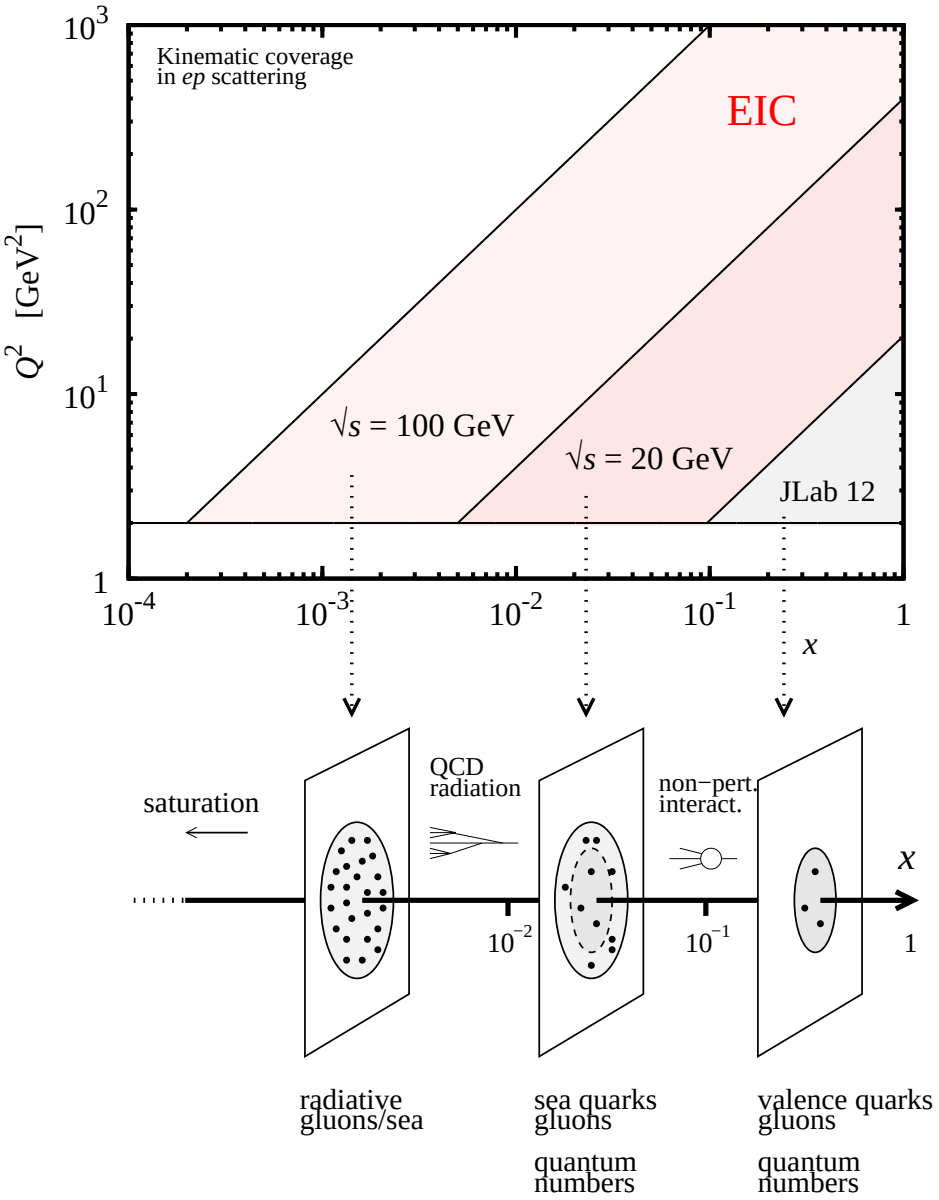
  Imaginary time $t \to i\tau$: Statistical mechanics, correlation functions, lattice methods

- Particle-based description

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

  Many-body system: Constituents, motion, size; interactions "expressed" in 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

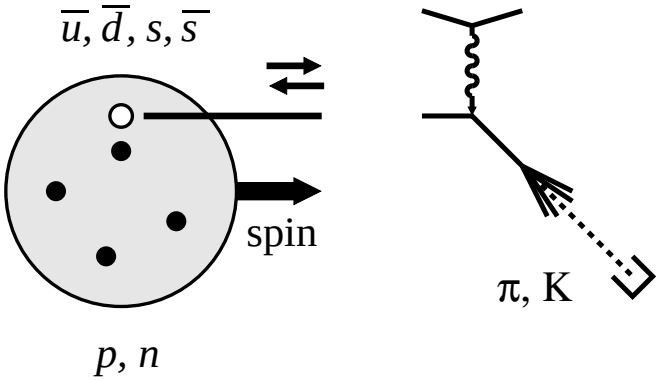
  Quark/gluon number densities, spin/flavor dependence: PDFs

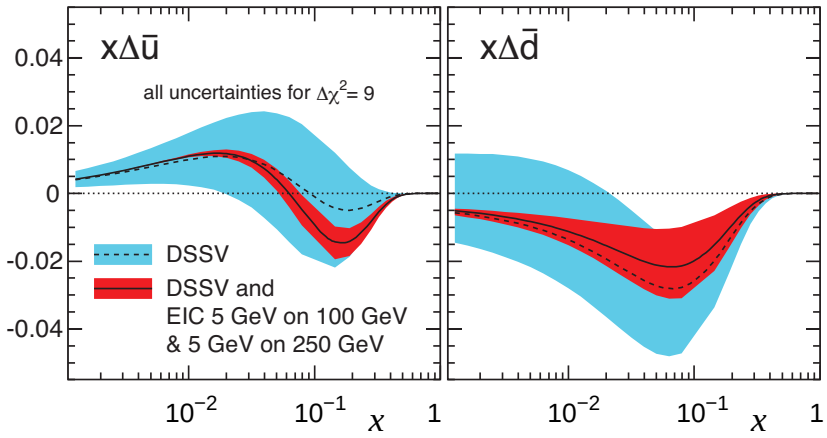
  Spatial distributions: GPDs

  Intrinsic motion, spin-orbit: TMDs

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

Nucleon structure: Sea quark polarization





EIC White Paper 2012

- How are sea quarks polarized?

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

  Mesonic components? Other mechanisms?
  Thomas et al; Soffer et al.

- RHIC W±: Recent results

- JLab12: Valence quark spin
  Polarized DIS: Hall A 3He; CLAS12 H/D
  SIDIS: CLAS12, SoLID

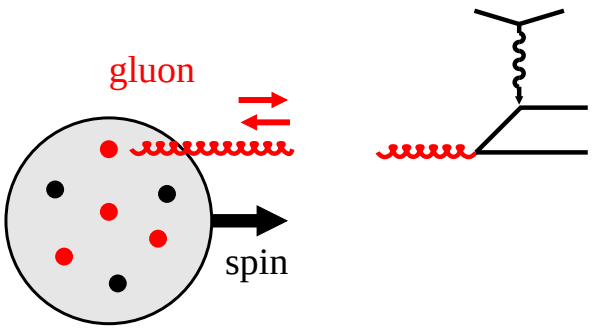
- EIC: Sea quark spin/flavor with SIDIS

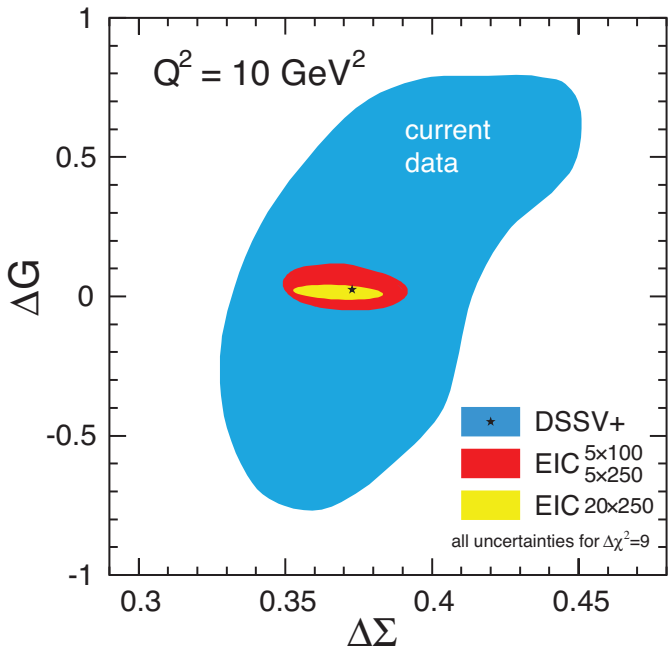
  $W \sim$ few 10 GeV ensures indep fragmentation

  PID for π–K separation

  Extensions to be explored:
  Neutron SIDIS with deuteron + proton tagging
  Correlations current–target fragmentation K–Λ

Nucleon structure: Polarized gluon and spin





EIC White Paper 2012

- How is nucleon spin composed of quark/gluon spin and orbital AM?

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

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

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

- Polarized gluon density

  Q^2 dependence of polarized DIS
  EMC/SMC, SLAC, HERMES, COMPASS, JLab 6/12 GeV

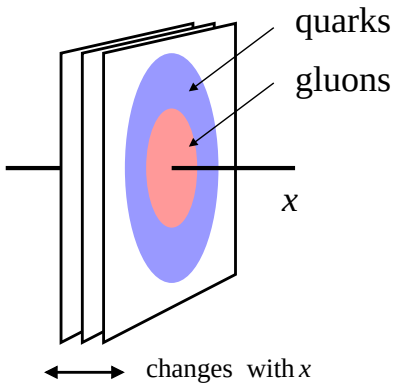
  Hard processes in polarized pp at RHIC

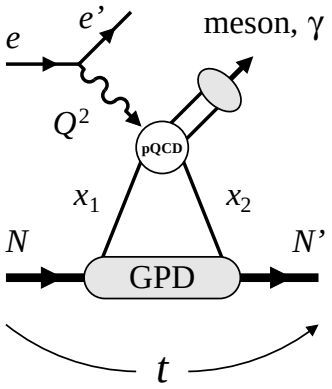
- EIC: Polarized gluon density from DIS

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

- JLab12: Quark orbital AM in FFs/GPDs/TMDs
  Develop concepts and measurements!

Nucleon structure: Spatial distributions



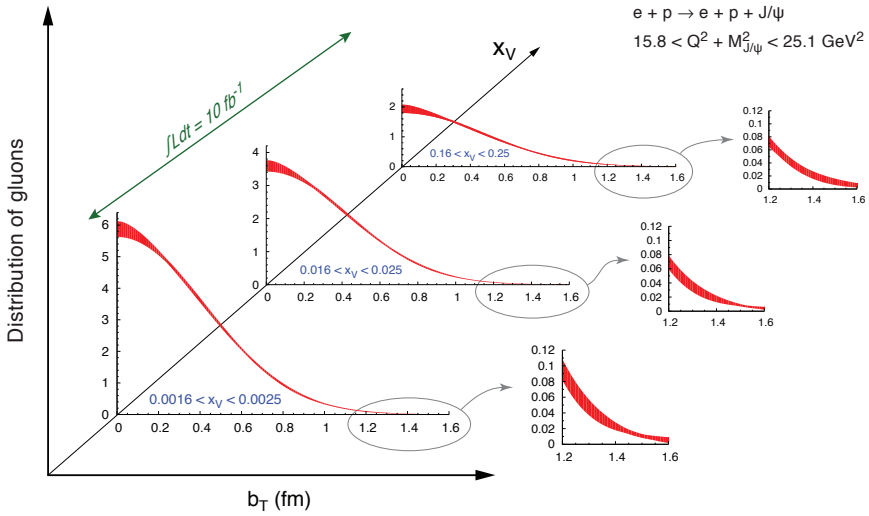


- How are quarks/gluons distributed in transverse space?

  Size and "shape" of nucleon in QCD
  Distributions change with x, spin – dynamics
  Input for modeling pp collisions at LHC

- GPDs: Unify densities and form factors

  Exclusive processes $eN \to e' + M + N'$



EIC example: Transverse gluon distribution from exclusive J/ψ
Other channels: ϕ, ρ, DVCS γ

- JLab12: Valence quark GPDs
  DVCS γ: Hall A, CLAS12. π^0, η: CLAS12
  Gluons ϕ, J/ψ: CLAS12, GlueX, Hall C, SoLID

- EIC: Quark/gluon imaging of nucleon

  Luminosity for low rates, multidim binning
  $Q^2 \sim$ few 10 GeV^2 for QCD mechanism
  Multiple channels for universality
  Forward proton detection

Nucleon structure: GPDs with EIC

- QCD energy momentum tensor form factors
  D-term: Quark pressure in nucleon. Extracted from dispersion relation for DVCS amplitude
  Interpretation: Polyakov 03; Review Polyakov, Schweitzer 19; JLab6 analysis: Burkert, Elouadrhiri, Girod 18

- Quark transversity in GPDs and exclusive processes
  Pseudoscalars π^0, η: Helicity flip in meson wave function from χSB, twist-3 mechanism
  JLab6: Hall A, CLAS; JLab12: CLAS12 experiments
  Goldstein, Liuti 08+; Goloskokov, Kroll 11+; CLAS6: Kubarovsky et al 14+

  Exclusive high-mass pair production $\rho\rho, \gamma\rho$
  Ivanov, Pire, Szymanowski, Teryaev 02+; Enberg et al. 06

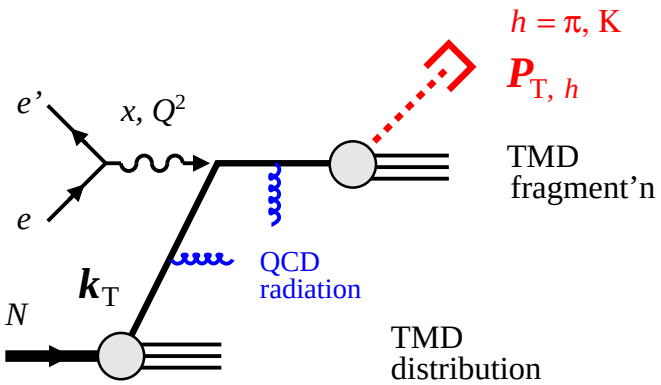
- Gluonic form factors in heavy quarkonium production near threshold
  High-t gluon form factor. Suggested connection with EM tensor, trace anomaly
  JLab12 J/ψ: GlueX results; approved expts CLAS12, Hall A/C, SoLID
  Brodsky et al 01; Frankfurt, Strikman 02. Kharzeev et al. 99; Hatta, Yang 18
  EIC simulations: Joosten, Meziani 18

- Quantum fluctuations of gluon density in diffractive vector meson production
  Frankfurt, Strikman, Treleani, CW 08; Schenke, Schlichting 14+

Many new ideas! Feasibility of measurements with EIC should be explored!
EIC User Group Physics-Detector Yellow Reports

Updates: INT-18-3 "Probing Nucleons and Nuclei in High Energy Collisions", Week 1, presentations+proceedings [Webpage]

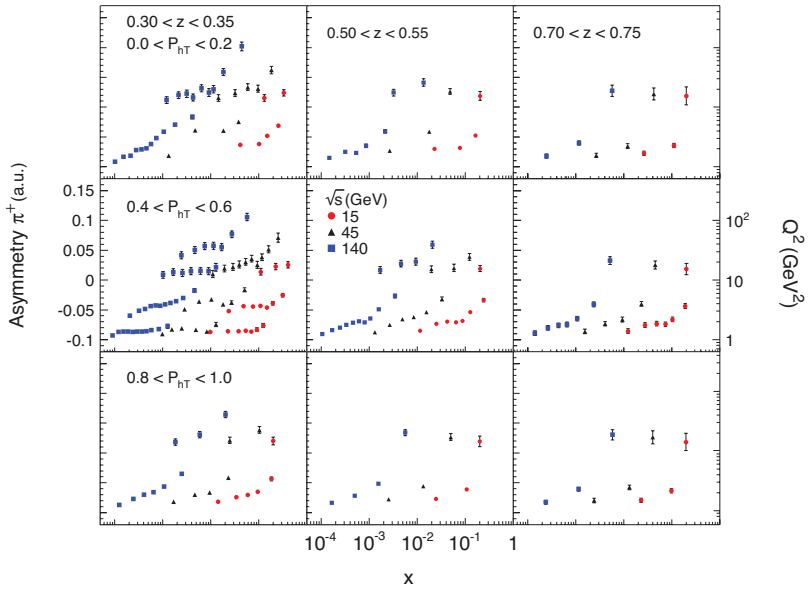
Nucleon structure: Transverse motion



- Transverse motion of quarks/gluons

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

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



EIC White Paper 2012

- JLab12: Hadron production at large x
  P_T distributions, spin-orbit effects in azimuthal dep

- EIC: TMD mechanism and structures

  High W for separating rapidity regions

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

  High luminosity for multidimensional binning

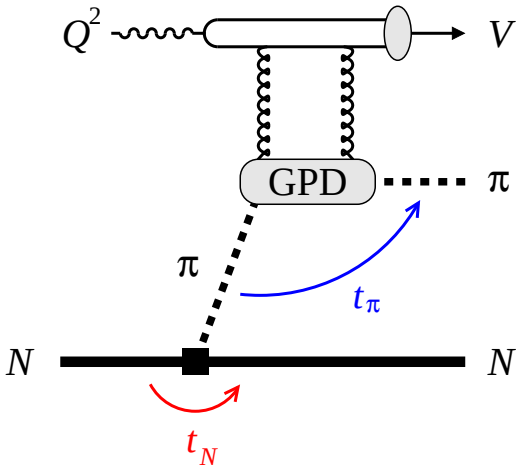
Updates: INT-18-3 "Probing Nucleons and Nuclei in High Energy Collisions" [Webpage]

Related topics: Hadron spectroscopy

- Photo/electroproduction of heavy-light or heavy-heavy systems
- $N \to N^*$ excitation using high-Q^2 exclusive processes

  Workshop "Spectroscopy program at EIC and future accelerators," ECT* Trento, 2018 [Webpage]

Pion structure



- Pion PDFs/GPDs $\leftrightarrow$ chiral SB in QCD

  LQCD quasi/pseudo-PDFs, effective models

- JLab12: Hall A TDIS

- EIC: Peripheral pion knockout

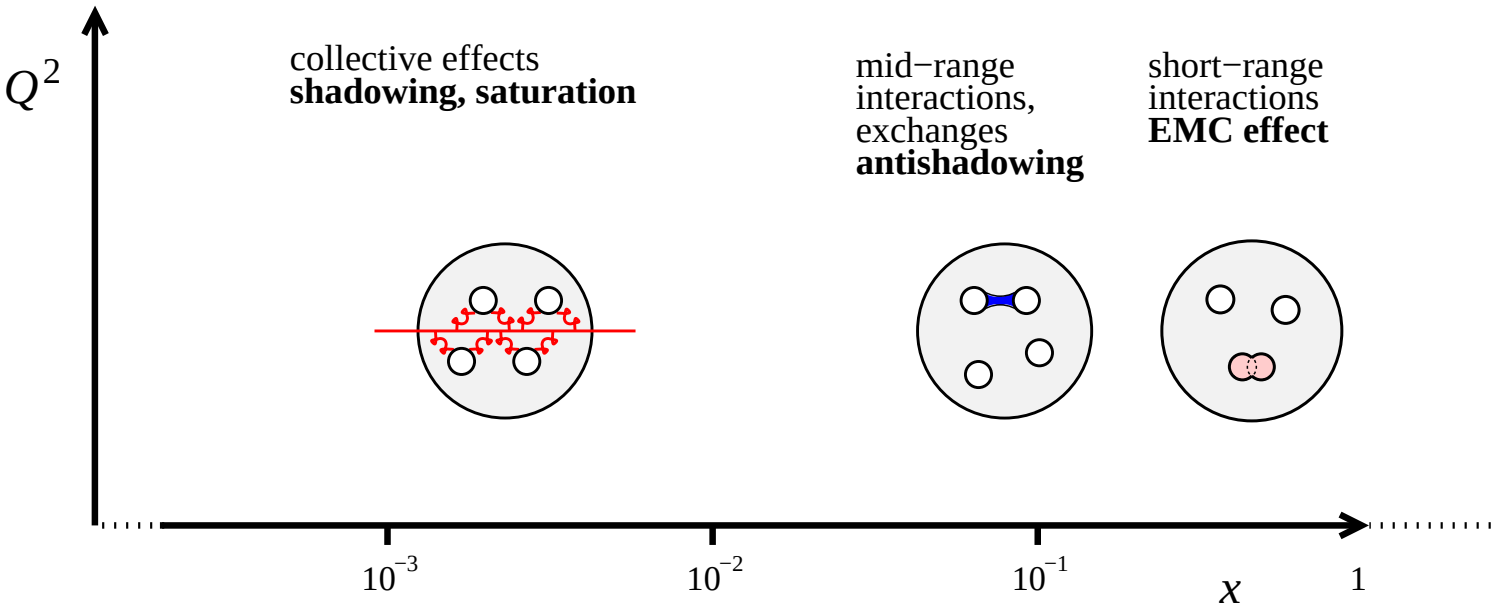
  Kinematics $t_N = O(M_\pi^2)$ and $|t_\pi| \gg |t_N|$ isolates production on peripheral pion
  Strikman, CW 04

  Example: Pion's gluon GPD with exclusive J/ψ

  Uses central and forward detection
  Options: $n \to \pi^- p$ or $p \to \pi^+ n$

  Other EIC pion measurements: Aguilar et al, EPJA 55, 190 (2019)

Nuclei: Nucleon interactions



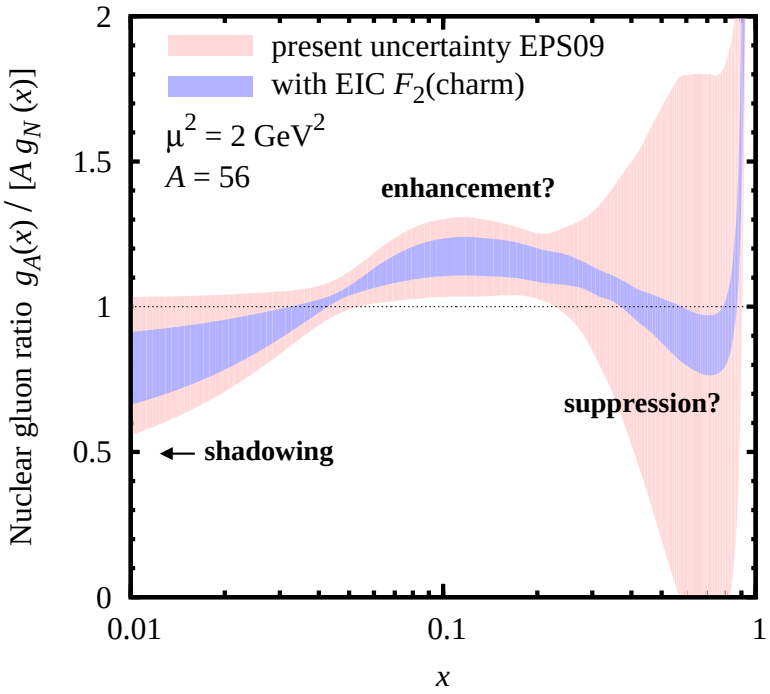
- How do nucleon interactions emerge from QCD?
  "Next step" after exploring nucleon structure

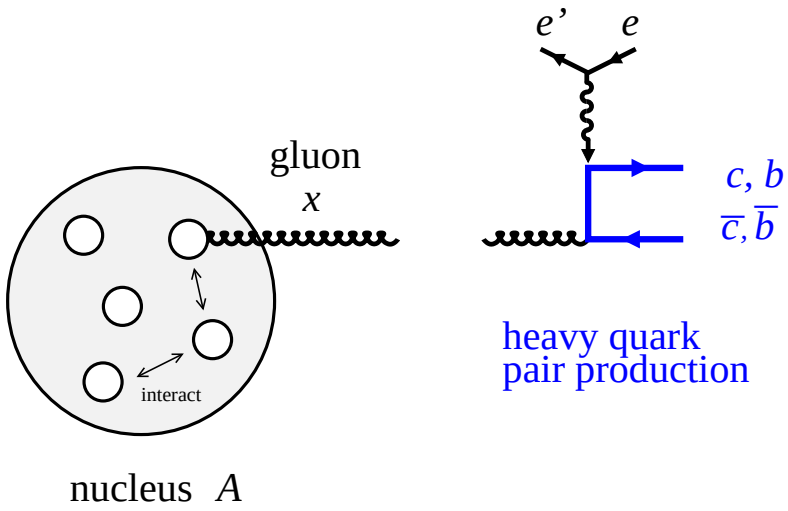
- Expressed in quark-gluon structure of nuclei:
  Nuclear modifications $A \neq \sum N$, mechanisms depend on x

  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 $x > 0.01$

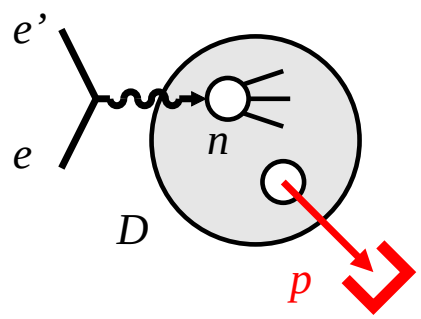
  Indications of gluon shadowing at $x < 0.01$ in LHC ultraperipheral J/ψ data

- 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]

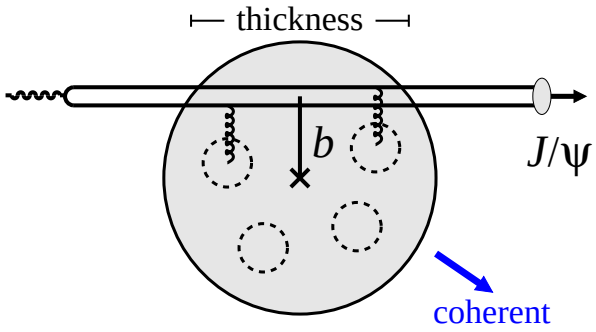
Nuclei: Breakup and coherent processes



- Deuteron DIS with spectator tagging

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

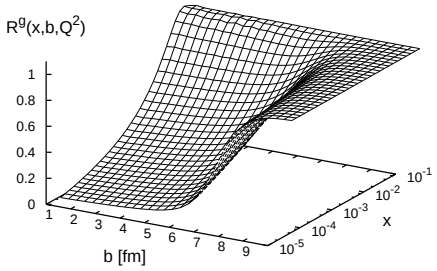
  EIC: Forward proton/neutron detection
  JLab LDRD 2014/15 [webpage]



- Coherent nuclear processes

  Nuclear GPDs $\langle A|\,\text{Twist-2}\,|A\rangle$:
  Quark/gluon imaging of nucleus
  Theory/models: Guzey et al., Scopetta et al., Liuti et al.

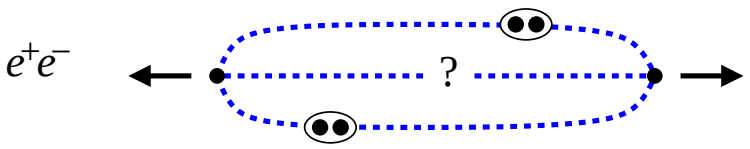
  New approach to nuclear gluon shadowing:
  Thickness $\leftrightarrow$ impact parameter b
  Guzey et al 09

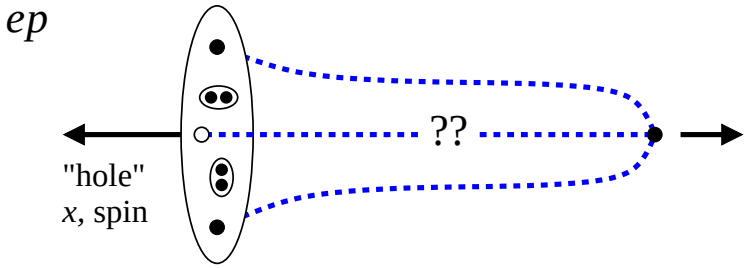


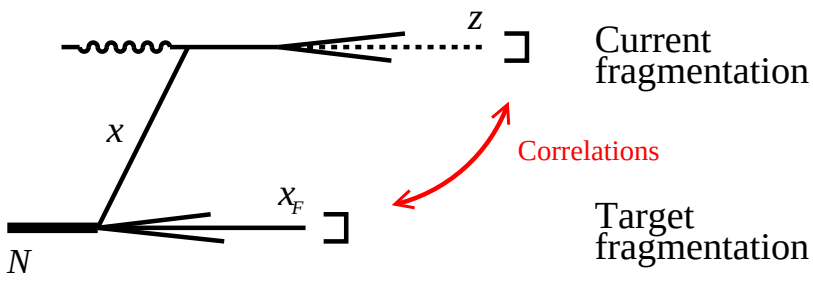
  EIC: Forward detection of light ions $A \lesssim 12$,
  veto detection of heavy ions
  Caldwell, Kowalski 09

  Updates: Workshop "Exploring QCD with light nuclei at EIC,"
  CFNS Stony Brook, 2020 [Webpage]

Hadronization: Fragmentation







- How do hadrons emerge from QCD color charge?

  Conversion energy $\rightarrow$ matter:
  Cosmic ray physics, early universe

  Dynamical mechanisms: QCD radiation, pair creation by soft fields, χSB

- Fragmentation functions from e^+e^-

  Many puzzles: $s\bar{s}$, kaons, baryons

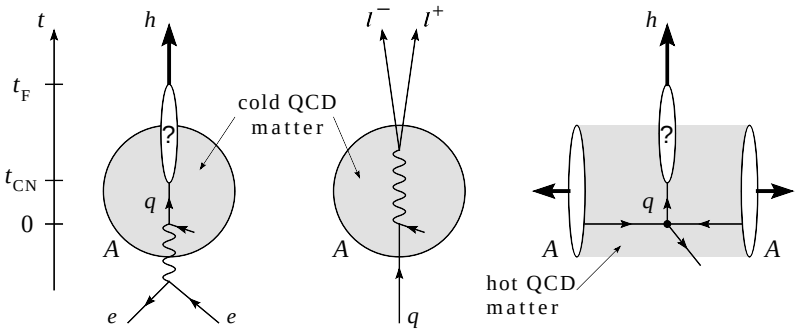
- EIC: New possibilities

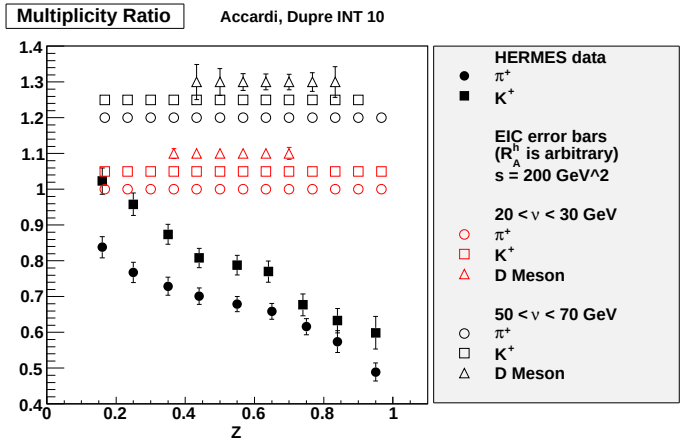
  Fragmentation functions from ep:
  Favored $\leftrightarrow$ unfavored, test universality

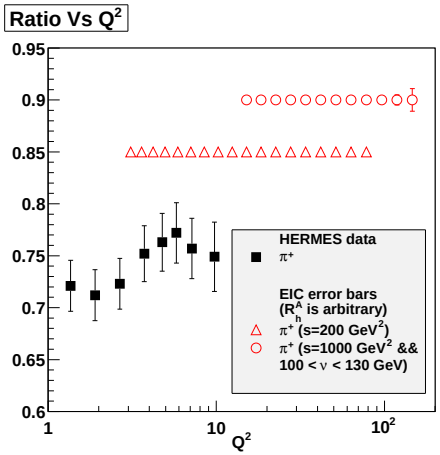
  Target fragmentation: How does nucleon with "color hole" materialize? x, spin dep?

  Correlations current–target regions:
  Multiparton structure
  New field: QCD theory, MPI in pp at LHC

Hadronization: In matter







- How does fast color charge interact with hadronic matter?

  Energy loss, attenutation

  Time scales for color neutralization t_N, hadron formation t_F

  Cold vs. hot matter? $eA/\gamma A \leftrightarrow$ jets in AA

- EIC: Comprehensive studies

  Wide range of energy $\nu = 10 - 100$ GeV: Move hadronization inside/outside nucleus, distinguish energy loss and attenuation

  Wide range of Q^2: QCD evolution of fragmentation functions and medium effects

  Hadronization of charm, bottom: Clean probes, QCD predictions

  High luminosity: Multidimensional binning

  $\sqrt{s} > 30\,\mathrm{GeV}$: Study jets and their substructure in eA

Summary

- Understand hadrons and nuclei as emergent phenomena of QCD

  Simple microscopic dynamics generates complex structure at multiple scales

- Continuity between EIC and JLab12 physics programs

  Much of expertise and tools are "dual use"

  Programs provide mutual context and strengthen each other

- EIC physics program still evolving

  New ideas/concepts/measurements proposed in last < 5 years [→ see References]

  Physics "beyond the White Paper" welcome and appreciated!

- Now is the time to get involved in physics and detector studies through

  Personal initiative and collaboration / JLab EIC group / EIC User Group Yellow Reports