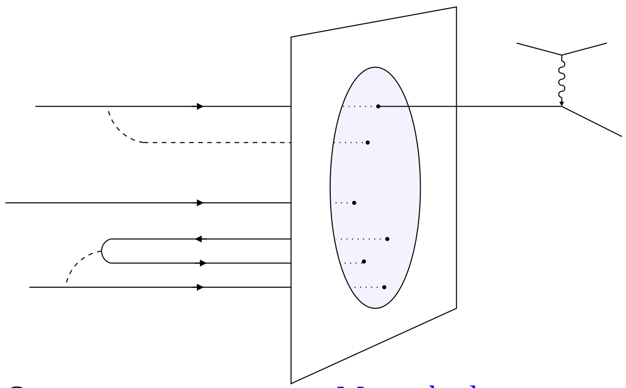
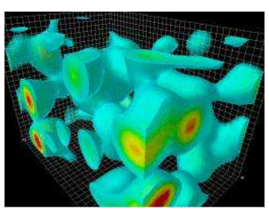
Quantum Chromodynamics in action: Nuclear physics with an Electron–Ion Collider

C. Weiss (JLab), FIU Physics Colloquium, Miami, 11–Mar–11



Quantum Chromodynamics

Many−body system



Theoretical methods, simulations

- Internal structure of proton/neutron

  Quantum Chromodynamics

  Many–body system: Relativity, quantum mechanics, strong interactions

- High–energy electron scattering

  Fixed–target JLab 12 GeV

  Colliding beams Electron–Ion Collider EIC

- QCD with an Electron–Ion Collider

  Sea quark and gluon polarization

  Spatial imaging of quarks/gluons

  Gluons in nuclei and coherent effects

  High gluon densities, saturation

- The road ahead

Why Quantum Chromodynamics

- Fundamental structure of matter

  Origin of mass: $> 99\%$ from energy in strong fields

  Phases of matter at high density/temperature: Early universe

  Conversion of energy/radiation into matter

- Nuclear structure and reactions from "first principles"

  Nuclear energy

  Astrophysics: Stellar structure

  Fundamental symmetries: Neutrino interactions with nuclei

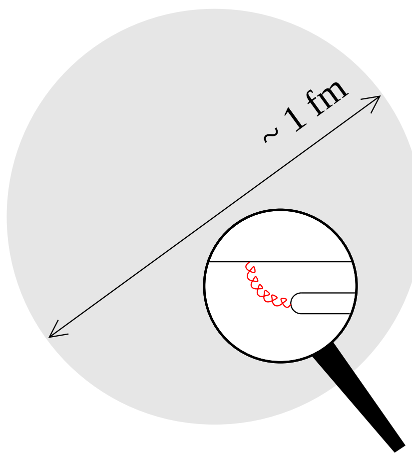
- Concepts and methods

  Gauge theories in non-perturbative regime: Strong fields, topology

  Geometic methods: Gauge $\leftrightarrow$ string correspondence

  Numerical simulations: Lattice gauge theory

Nucleon structure: Short distances



- Pointlike objects: Quarks

  Practically massless $M_{u,d} < 0.01\, M_p$

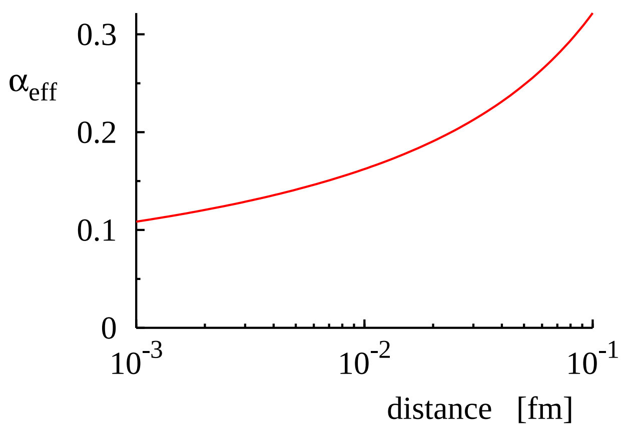
  Fermions with spin 1/2

  Electromagnetic and weak charge:
  Coupling to external probes!

- Quantum Chromodynamics

  Gauge theory with $SU(3)$ group charge: "Color"
  cf. Electrodynamics

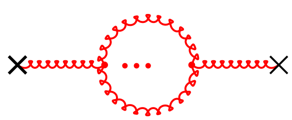
  Effective coupling decreases with distance:
  "Asymptotic freedom" Gross, Politzer, Wilczek 73



- Larger distances $r \sim 0.3\,\mathrm{fm}$

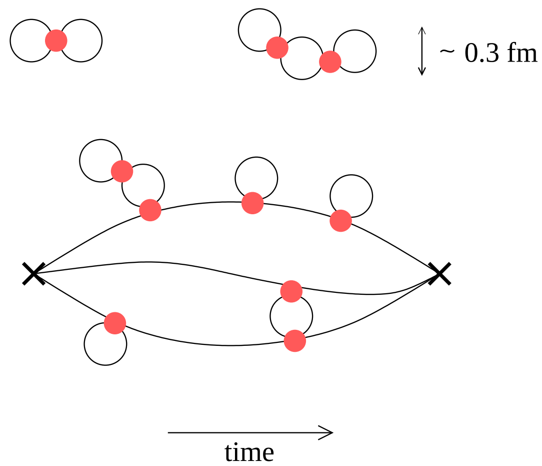
  Strong non-perturbative fields create
  "condensate" of quark–antiquark pairs

  Dynamical mass generation



Dynamics changes with resolution scale!

Nucleon structure: From fields to particles



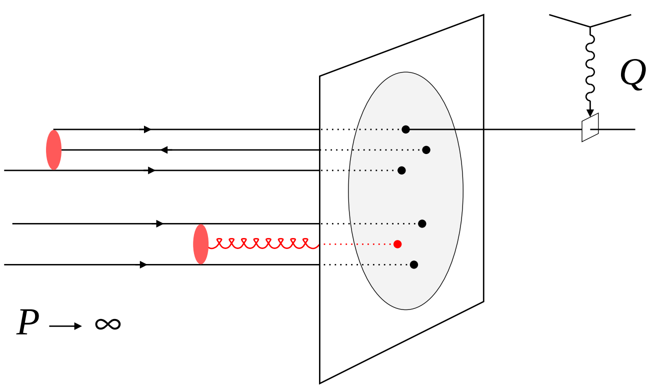
- Understand/describe nucleon structure in terms of QCD degrees of freedom!

  Uniquely challenging problem:
  Relativity + QM + Strong coupling

- Nucleon at rest: Interacting fields

  Imaginary time $t \to i\tau$:
  Statistical mechanics, lattice simulations

  No concept of particle content:
  Cannot separate "constituents" from vacuum fluctuations!



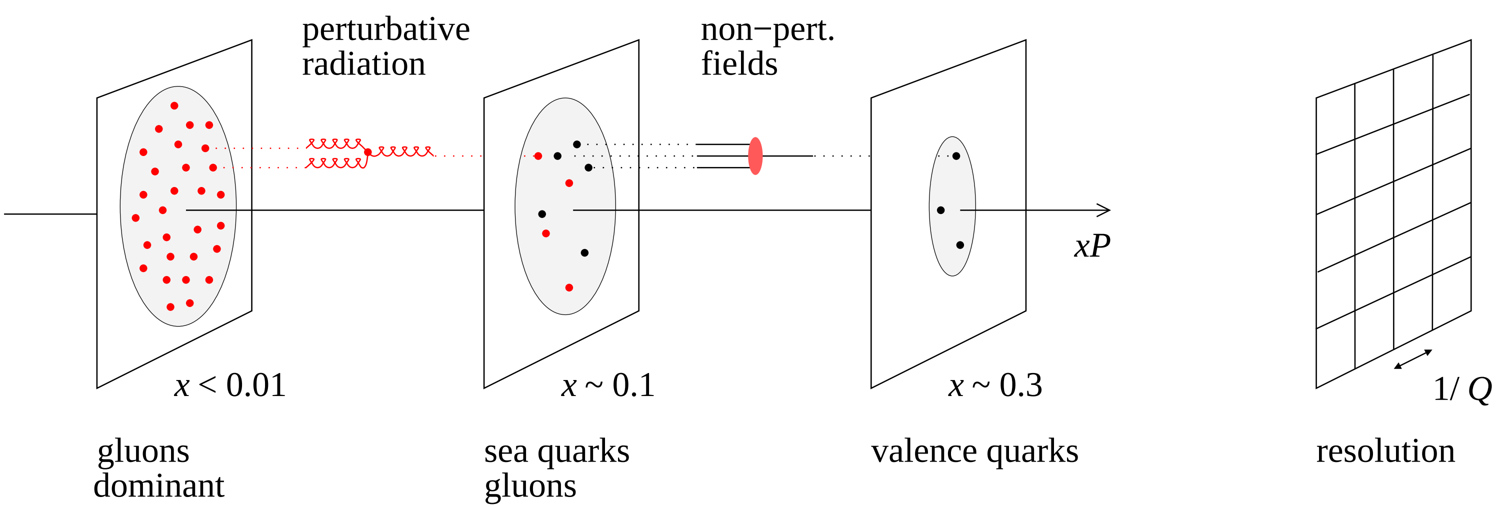
- Nucleon fast: Particle content

  Closed system: Wave function description
  Gribov, Feynman

  Components with different particle number:
  $|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + |qqqg\rangle + \ldots$

  High–energy scattering process: "Snapshot" with resolution $1/Q$

Nucleon structure: Many–body system



- Different components of wave function

Few particles	with	large $x \equiv$ fractional momentum
Many particles	with	small x

- Measurable properties

Particle densities, including spin/flavor dependence

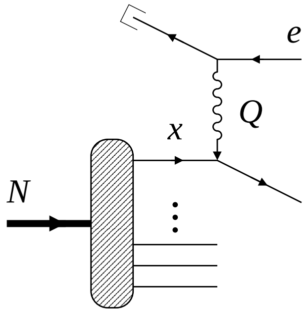
Transverse spatial distributions

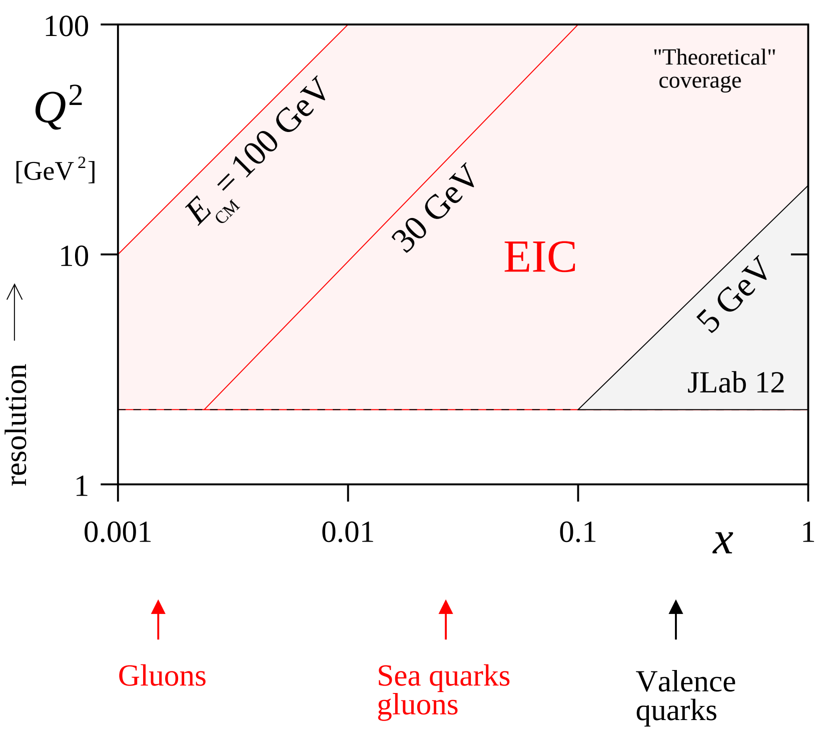
Orbital motion: Transverse momenta, polarization

Particle–particle correlations

} change with resolution scale $1/Q$!

Electron scattering: Probing short distances





- Electron–nucleon scattering
  Also: positron, muon

  EM interaction well–known

  Momentum transfer → Resolution $1/Q$
  Energy transfer Configuration x

  Variety of final states: Inclusive, semi–inclusive, exclusive

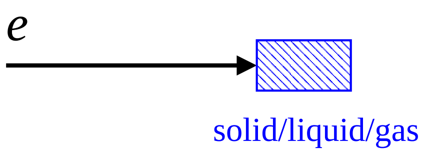
- Accessible region

  Want spatial resolution $1/Q \ll 0.2\,\mathrm{fm}$, or $Q \gg 1\,\mathrm{GeV}$

  $Q^2 < x\,E^2_{\mathrm{CM}}$ from kinematics
  Small x reqiure high center–of–mass energies

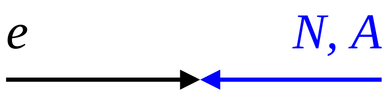
- Alt: Nucleon–nucleon scattering with high–momentum transfer processes
  Sensitive to antiquarks, gluons. LHC, Tevatron, RHIC

Electron scattering: Technologies



- Beam on fixed target

  High rates: Density of particles



- Colliding beams

  Higher energies: $E^2_{\mathrm{CM}} = 4 E_e E_p$ vs. $2 E_e M_p$

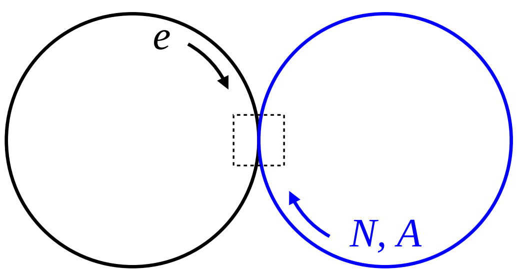
  Energy–efficient: Beams collide multiple times

  Clean: No scattering from atomic electrons

  Detection: Recoil proton/nucleus, variable angles

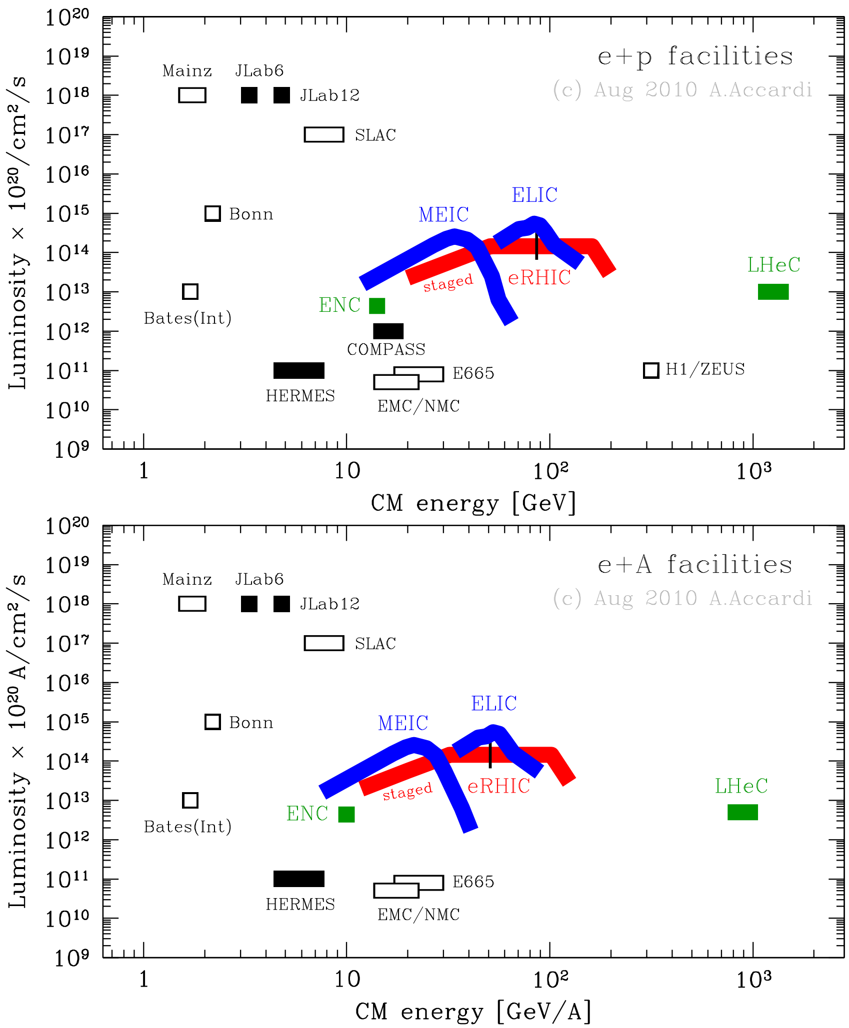
  Much more demanding of beam quality:
  Optics, cooling, time structure

  Integration of detectors and accelerator
  elements at interaction point



Experience with storage rings: e^+e^- (LEP, PEPII, KEK, DAΦNE), $pp/p\bar{p}$ (RHIC, Tevatron, LHC), AA (RHIC, LHC), ep (HERA)

Electron scattering: Facilities



- Luminosity

  Rate = Luminosity × Cross section

  High luminosity required for
  rare processes exclusive channels, high p_T
  multidimensional binning spatial imaging
  precision measurements Q^2 dependence

  Limiting factor in most
  nucleon structure experiments!

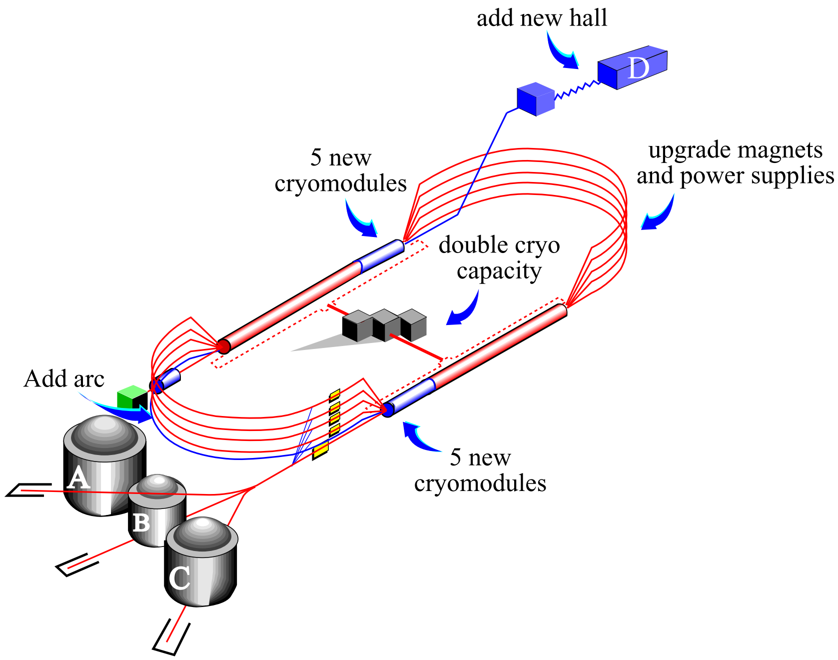
- JLab 12 GeV

  Energy × luminosity frontier
  in fixed–target scattering

- Electron–Ion Collider EIC

  A high–luminosity, polarized ep/eA
  collider for QCD and nuclear physics!

Electron scattering: JLab 12 GeV



CW beam $\sim 100\,\mu A$
Present beam energy 6 GeV
Operating since 1994

- "Race track" accelerator with linacs + arcs, extensible to 24 GeV

  Uses unique superconducting
  RF technology and energy recovery

- Experimental halls

A, C	Magnetic spectrometers
B	Large acceptance CLAS

- 12 GeV Upgrade

  Double beam energy 6 $\rightarrow$ 12 GeV

  Add Hall D (γ beam, GlueX detector)

  Upgrade existing halls

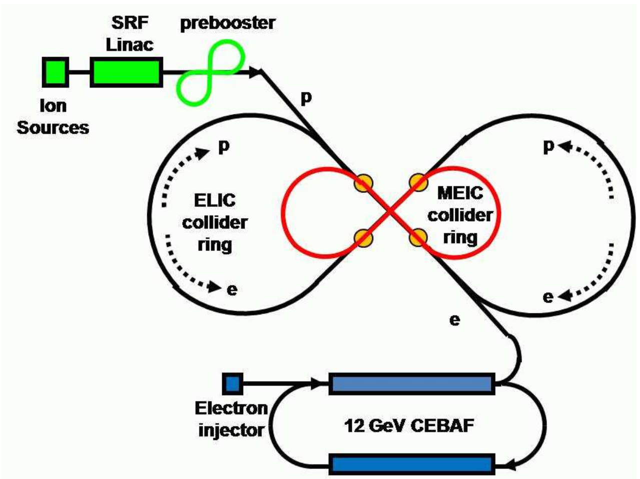
  DOE project (CD0 2004, CD3 2008)

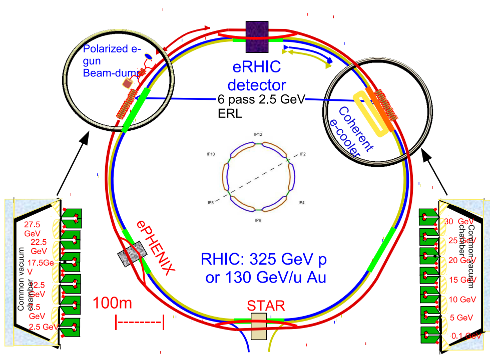
  Construction on–going, beam exp. 2013

  Total cost $\sim$ 300M$

  http://www.jlab.org/12GeV/

Electron scattering: Electron–Ion Collider





Convergence in parameters, “staging”

Differences in technological challenges, cost (?)

- JLab ring–ring design MEIC/ELIC

  11 GeV CEBAF as injector continued fixed-target op
  Medium–energy: 1 km ring, 3–11 on 60/96 GeV
  High–energy: 2.5 km ring, 3–11 on 250 GeV
  Luminosity $\sim 10^{34}$ cm^{-2}s^{-1} over wide energy range
  Figure–8 for polarization transport, up to four IP’s

- BNL linac–ring design eRHIC

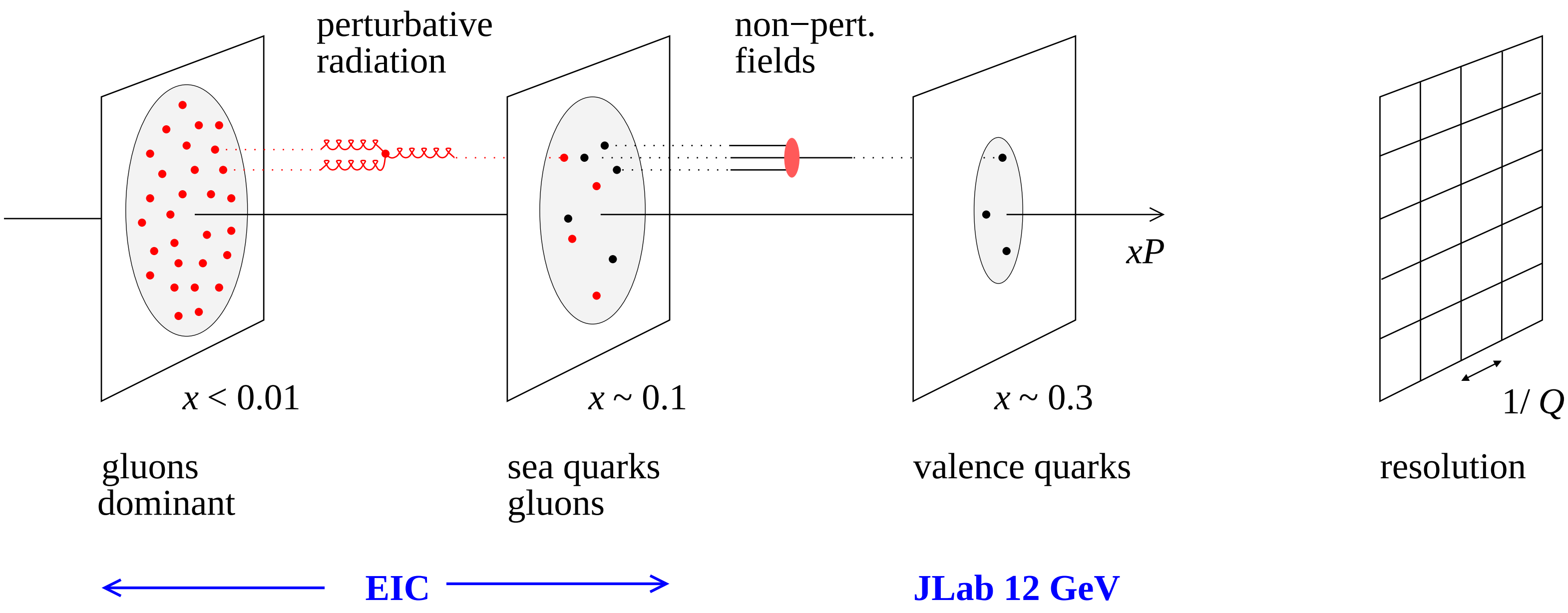
  RHIC proton/ion beam up to 325 GeV
  5–20 (30) GeV electrons from linac in tunnel staged
  Luminosity $\sim 10^{34} (10^{33})$ over wide range
  Re-use RHIC detectors? ePHENIX

- Related proposals

  CERN LHeC: 20–150 GeV on 7 TeV ep
  Ring–ring and linac–ring discussed, $L \sim 10^{33}$
  Mainly particle physics after LHC, but also high–energy QCD

  GSI ENC: 3.3 GeV on 15 GeV $\vec{e}\vec{p}$
  Ring–ring using FAIR HESR, $L \sim 10^{32}$ PANDA detector

Nucleon structure: Many–body system



- Different components of wave function

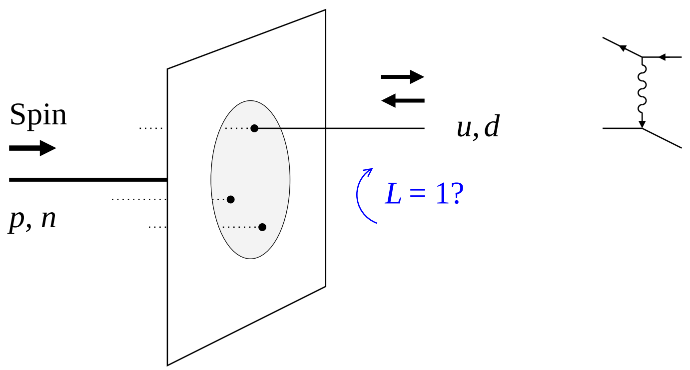
Few particles	with	large $x \equiv$ fractional momentum
Many particles	with	small x

- Measurable properties

Particle densities, including spin/flavor dependence
Transverse spatial distributions
Orbital motion: Transverse momenta, polarization
Particle–particle correlations

} change with resolution scale $1/Q$!

JLab 12 GeV: Valence quark polarization

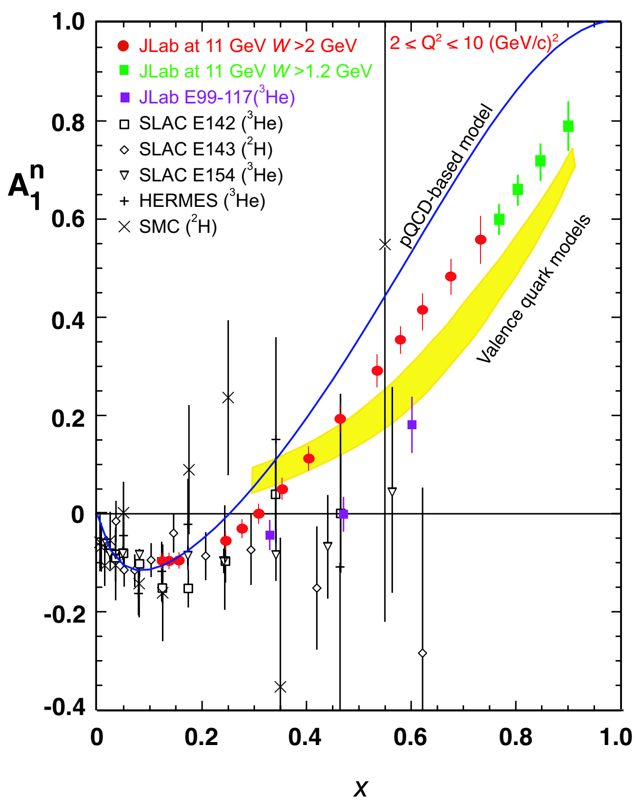


- How are valence quarks in nucleon polarized at $x \to 1$?

  Basic $3q$ component of nucleon wave fn

  Non–perturbative QCD interactions?

  Orbital angular momentum L $= 1$?



- d quark polarization from inclusive scattering on neutron

  d in proton $= u$ in neutron   isospin symmetry

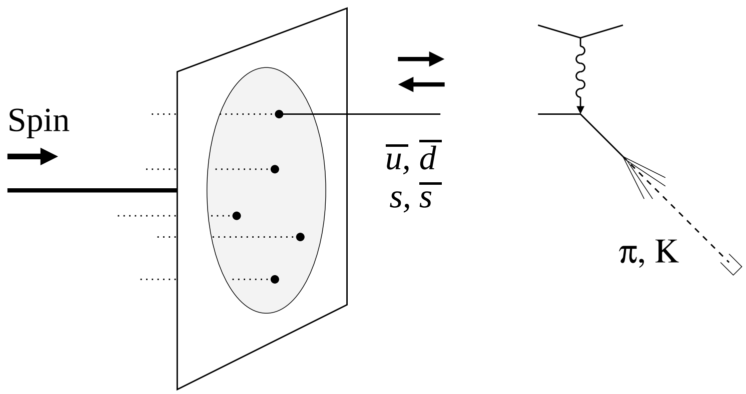
  Poorly constrained by present data
  SLAC, HERMES

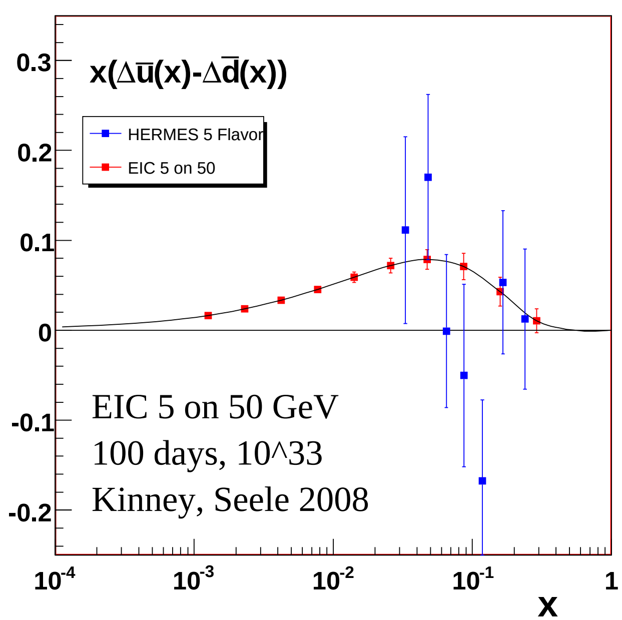
- JLab12: Map d quark polarization precisely up to $x \sim 0.8$

  Combination of energy and luminosity!

  Many more applications: Spatial imaging, orbital motion, nuclei, . . .

EIC: Sea quark polarization





- How are sea quarks polarized in nucleon?

  Non-perturbative interactions connecting valence ↔ sea quarks?

  Flavor asymmetry related to mesonic degrees of freedom? "Pion cloud"

- Semi–inclusive scattering

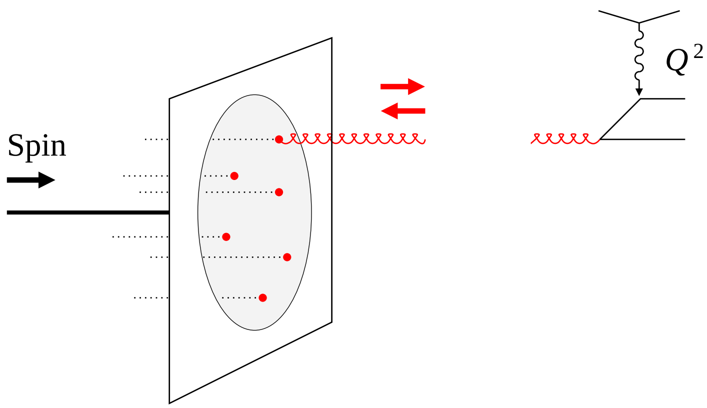
  "Tag" charge and flavor of struck quark by detecting hadrons in jet

  Flavor asymmetries poorly determined from present data HERMES

- EIC: Map sea quark distributions and their spin dependence

  High energy ensures independent fragmentation of struck quark

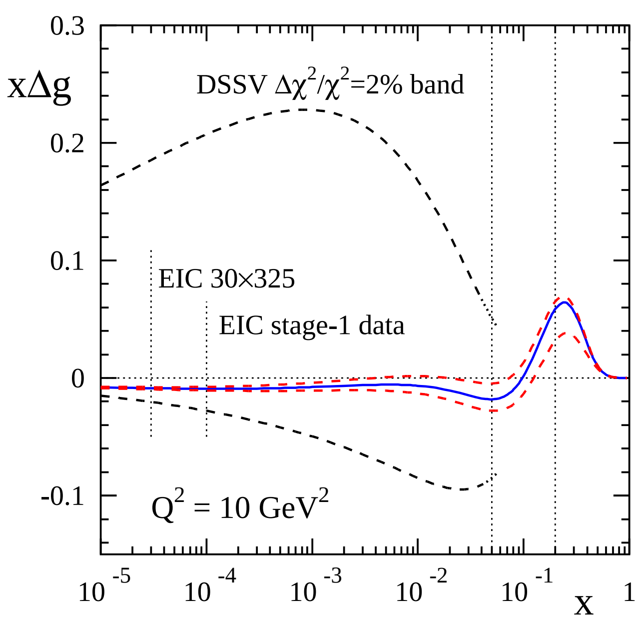
EIC: Gluon polarization



- How does gluon spin respond to nucleon polarization?

  Non-perturbative gluon fields?

  Orbital angular momentum in nucleon wave function? "Spin puzzle"



M. Stratmann, INT Workshop 2010

- $\Delta G(x)$ presently poorly constrained

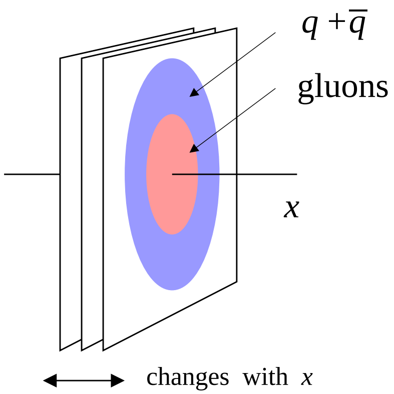
  Q^2 dependence of polarized nucleon structure function $g_1(x, Q^2)$
  EMC/SMC, SLAC, HERMES, COMPASS, JLab 6/12 GeV

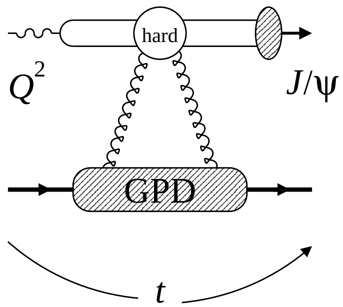
  Hard processes in $\vec{p}\vec{p}$ RHIC Spin

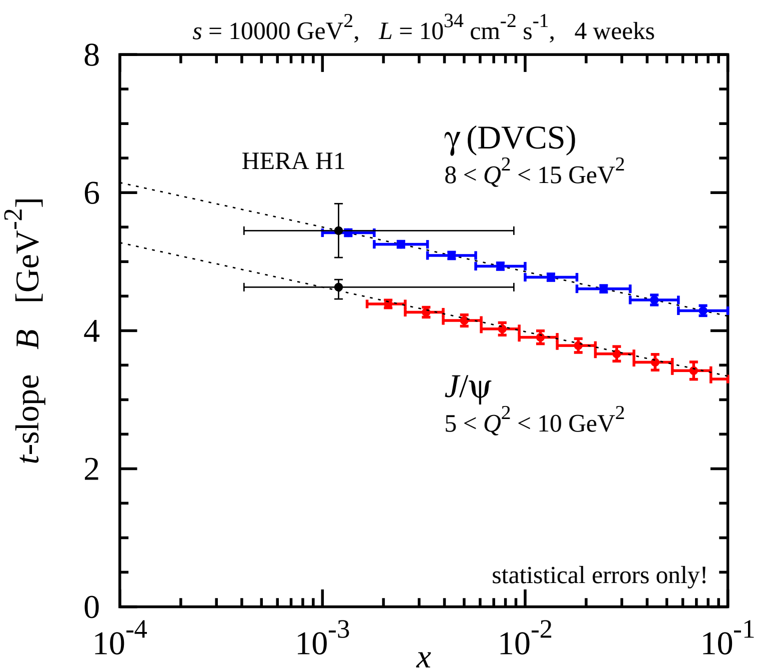
- EIC: Fully quantitative determination of gluon polarization

  Wide kinematic coverage enables study of Q^2 evolution

EIC: Spatial distributions







- How are quarks/gluons distributed in transverse space?

  Fundamental size and "shape" of nucleon in QCD

  Distributions change with x: Diffusion, chiral dynamics

  Input for modeling pp collisions at LHC

- Exclusive processes $\gamma^* + N \to J/\psi + N$

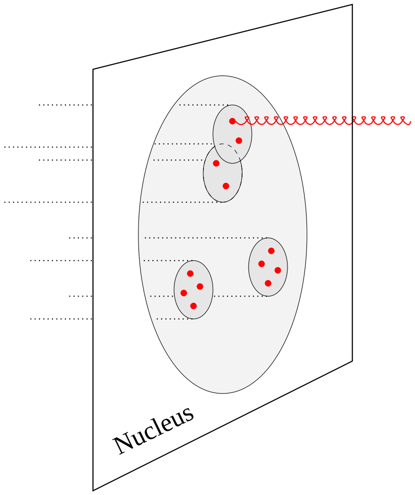
  Gluonic form factor of nucleon: Generalized parton distribution

  Other channels γ, ρ^0, π, K sensitive to quarks

- EIC: "Gluon imaging" of nucleon

  Luminosity for low rates, differential measurements

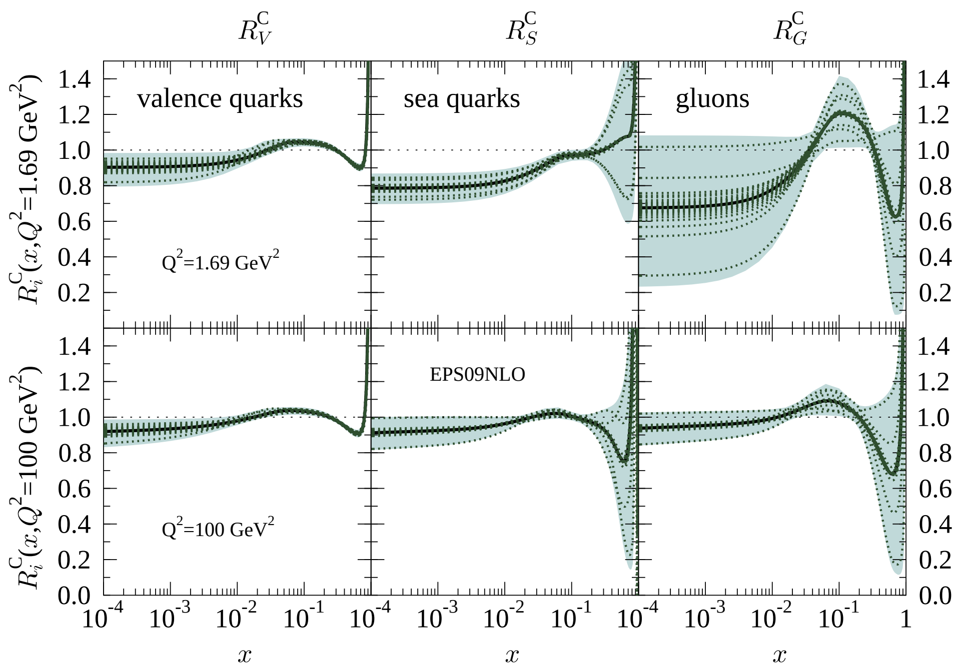
EIC: Gluons in nuclei



- How are the fundamental quark/gluon densities affected by nuclear binding?

  $x > 0.1$ Modification of free nucleon structure: Quark–gluon basis of NN interaction?

  $x \ll 0.1$ QM interference of gluon fields of different nucleons: "Shadowing"



Ratio nuclear/($A\times$ nucleon) densities. Eskola, Paukkunen, Salgado 09

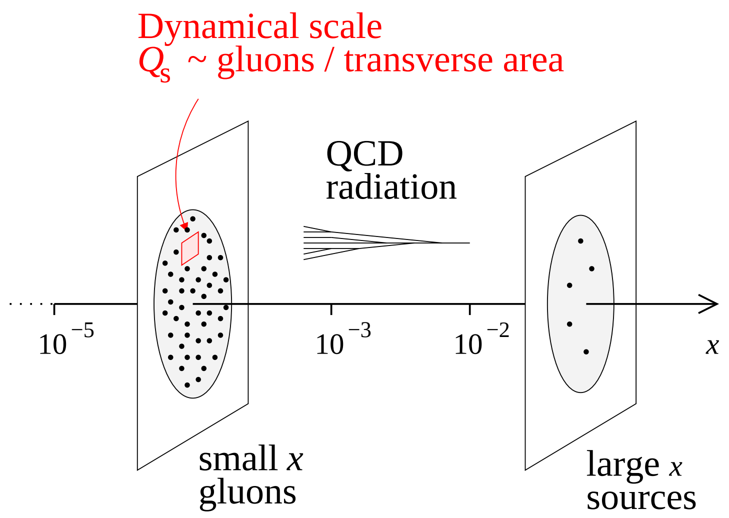
- Nuclear gluon density poorly constrained by present data

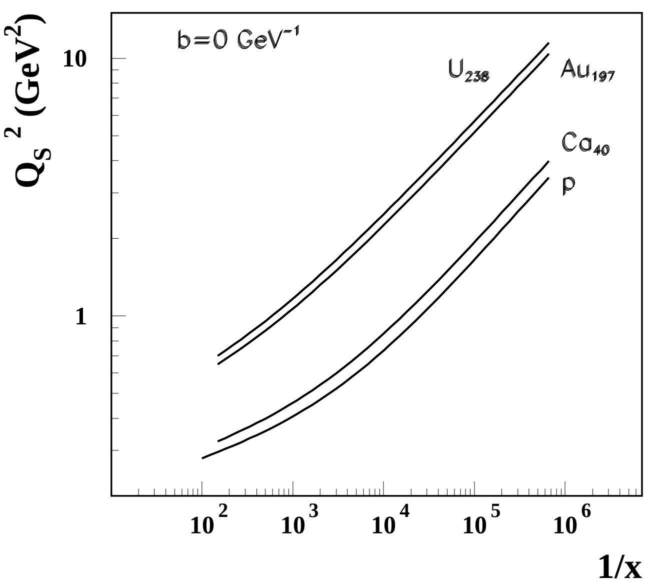
  Q^2 dependence of nuclear structure function $F_{2A}(x, Q^2)$

- EIC: Accurate determination of quark/gluon densities of nuclei!

  Wide coverage in x, Q^2

EIC: Gluon saturation





Kowalski, Teaney 03

- New dynamical scale in wave function at small x: $Q_s(x)$

  Gluon density grows through QCD radiation

  Theory: Non–linear QCD evolution,
  Classical fields "Color Glass Condensate"
  McLerran, Venugopalan; Balitsky, Kovchegov, JIMWLK

- New phenomena

  Breakdown of Bjorken scaling in F_L, F_2

  High p_T in forward particle production

  Multiple hard processes, correlations

- Expected to be enhanced in nuclei

  $Q_s(x) \sim A^{1/3}$ without shadowing,
  depends on nuclear gluon density

- EIC: Study saturation through inclusive/diffractive/exclusive processes

EIC: Other topics

- Orbital motion of quarks and gluons

  Transverse momenta and polarization effects in semi–inclusive hadron production

  Quark/gluon orbital angular momentum, QCD spin–orbit interactions

- Color transparency: Interaction of small–size $q\bar{q}$ configurations with color fields

  High–Q^2 meson production on nuclei

- Hadronization: Conversion of color charge to hadrons

  Quark fragmentation, target break–up, correlations
  Hadronization in the nuclear medium

- Electroweak physics

  Neutral/charged current nucleon structure functions
  Standard model parameters

EIC: Project status and next steps

- Informal recommendation in 2007 DOE/NSF NSAC Long–Range Plan
  http://www.er.doe.gov/np/nsac/ Also in DOE 20–year facility plan

- EIC accelerator and physics R&D at Brookhaven and Jefferson Lab
  http://www.jlab.org/meic/

  International EIC Advisory Committee, two reviews
  of physics and accelerator designs Feb–09 and Nov–09

  Increasingly supported by lab users JLab User Workshops 2010

- EIC Collaboration http://web.mit.edu/eicc/

  Formed 2007, over 100 physicists from > 20 institutions, advancing EIC physics and accelerator R&D. Semi–annual collaboration meetings/workshops

- EIC science discussed at 2011 Institute of Nuclear Theory INT Program

  Very strong participation. Talks on-line; written summaries in preparation
  http://www.int.washington.edu/PROGRAMS/10-3/

- Working toward full recommendation in 2013 NSAC LRP
  Further timeline tentative. Site selection? CD0? Budget realities

Needs support of the nuclear physics and broader scientific community!

Summary

- Quantum Chromodynamics remains a uniquely challenging problem

  Mature field with 40+ years of experience

  Full of surprises! Revolutions sure to come

- Nucleon as a many–body system — a unifying perspective

  Relativity + quantum mechanics + strong interactions

  Connections with nuclear/condensed matter physics

- High–luminosity Electron–Ion Collider as the next–generation machine for QCD and nucleon structure

  Complements/extends JLab 12 GeV, RHIC Spin,
  HERA small–x, and LHC/RHIC Heavy–Ion programs