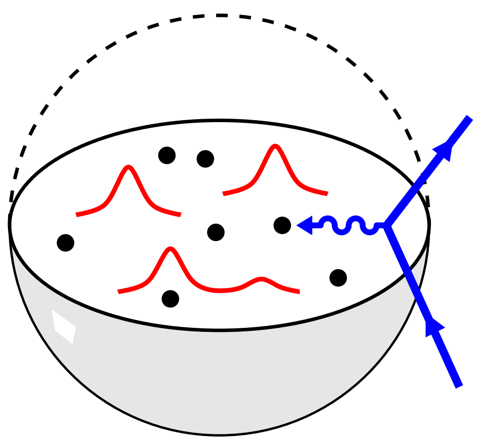
Strong interaction physics with an Electron–Ion Collider

C. Weiss (JLab), UNAM, Mexico City, 03–April–17 [E-mail]



Unique dynamical system
relativistic
quantum-mechanical
strongly coupled

- Internal structure of nucleon
  - Quantum Chromodynamics
  - Concepts and methods for structure
  - Physical characteristics
- High–energy electron scattering
  - Fixed–target vs. colliding beams
  - Facilities JLab 12 GeV, Electron–Ion Collider
- QCD with an Electron–Ion Collider
  - Quark and gluon polarization
  - Spatial distributions and orbital motion
  - Quarks/gluons in nuclei and NN interaction
- Path forward

Context: 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

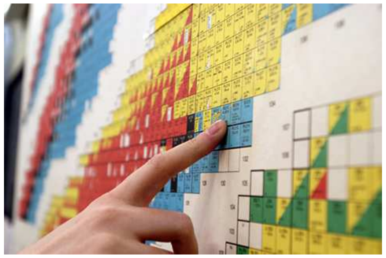
  Conversion of radiation into matter, cosmic ray physics

- Nuclei and nuclear reactions from "first principles"

  Origin of nucleon–nucleon interaction

  Nuclear energy, stellar structure, astrophysical processes

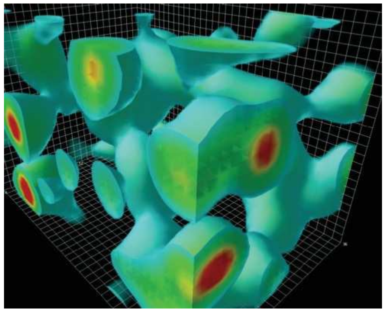
  Neutrino interactions with nuclei



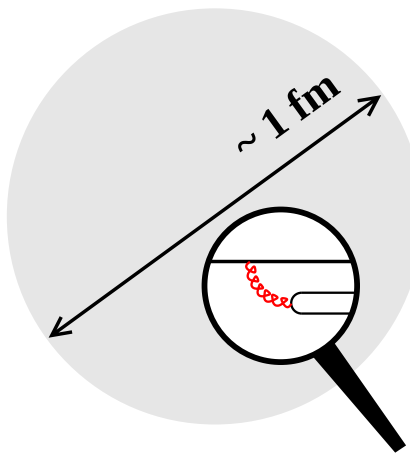
- Concepts and methods

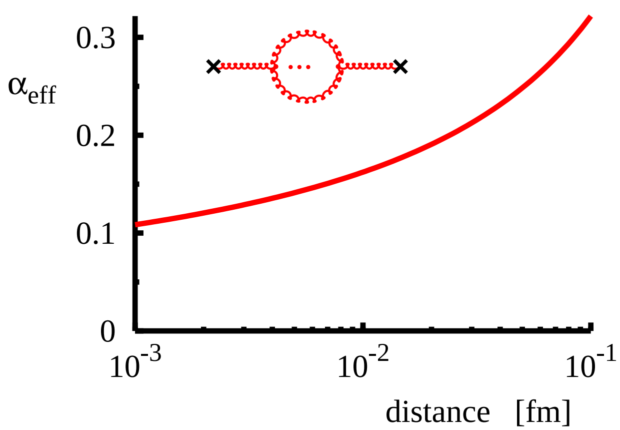
  Quantum field theory: Perturbative methods, renormalization group, topological fields, spontaneous symmetry breaking

  Numerical simulations: Lattice gauge theory



Nucleon structure: Short distances





- Pointlike objects: Quarks

  Almost 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

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

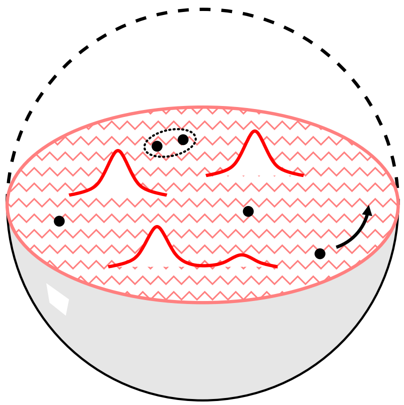
- Larger distances $r \gtrsim 0.3\,\mathrm{fm}$

  Strong gauge fields create condensate
  of quark–antiquark pairs

  Dynamical mass generation

  Dynamics changes with resolution scale!

Nucleon structure: Dynamical system



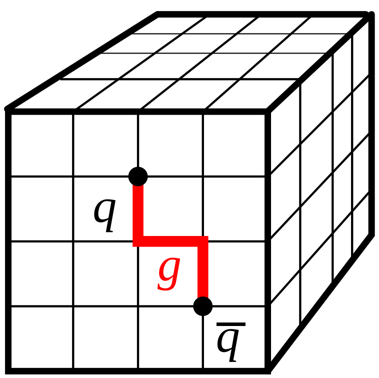
- Understand nucleon structure in QCD!

- Unique dynamical system

  Relativistic

  Quantum-mechanical

  Strongly coupled



- Field–theoretical description

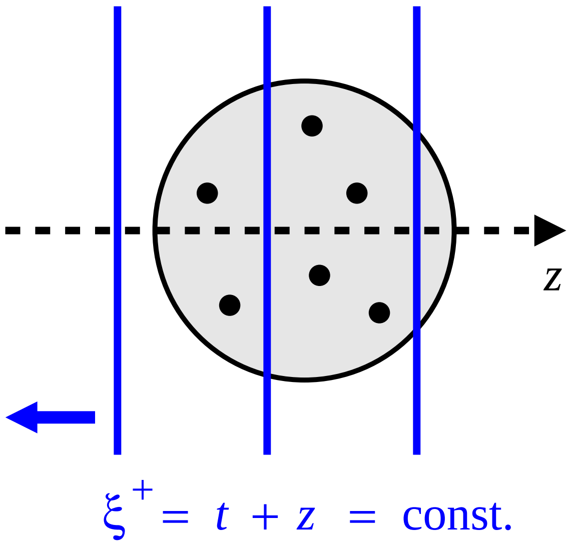
  Imaginary time $t \to i\tau$

  Quantum field theory $\to$ statistical mechanics

  Simulations on space-time lattice:
  Large effort, many groups, much progress

  No concept of particle content,
  composite structure, motion in real time

Nucleon structure: Particle-based description



- Wave function generally frame-dependent

  Relies on notion of "equal time"

- Light-front time $\xi^+ \equiv t + z =$ const.

  Frame-independent time

  Appropriate for relativistic systems

  Natural for high-energy scattering

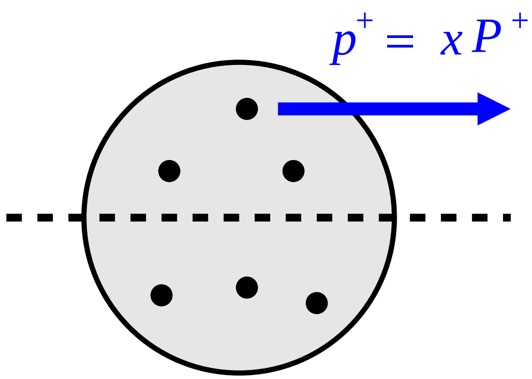
- Composite picture of nucleon

  $|N\rangle = |qqq\rangle + |qqq(q\bar{q})\rangle + |qqqg\rangle + \dots |\text{many}\rangle$ [symbolic!]

  Superposition of configuration with different number of constituents

  Relativistic many-body system!

Nucleon structure: Characteristics



$$\langle N| \underbrace{\bar\psi \ldots \psi}\, |N\rangle$$

QCD operator measuring
momentum-spin density

- Light-front momentum $p^+ = E + p_z$

  Fraction $x = \dfrac{p^+(\text{constituent})}{P^+(\text{nucleon})}, \quad 0 < x < 1$

- Physical characteristics

  Momentum densities of quarks/antiquark/gluons

  Spin distributions in polarized nucleon

  Transverse spatial distributions

  Orbital motion and spin-orbit effects

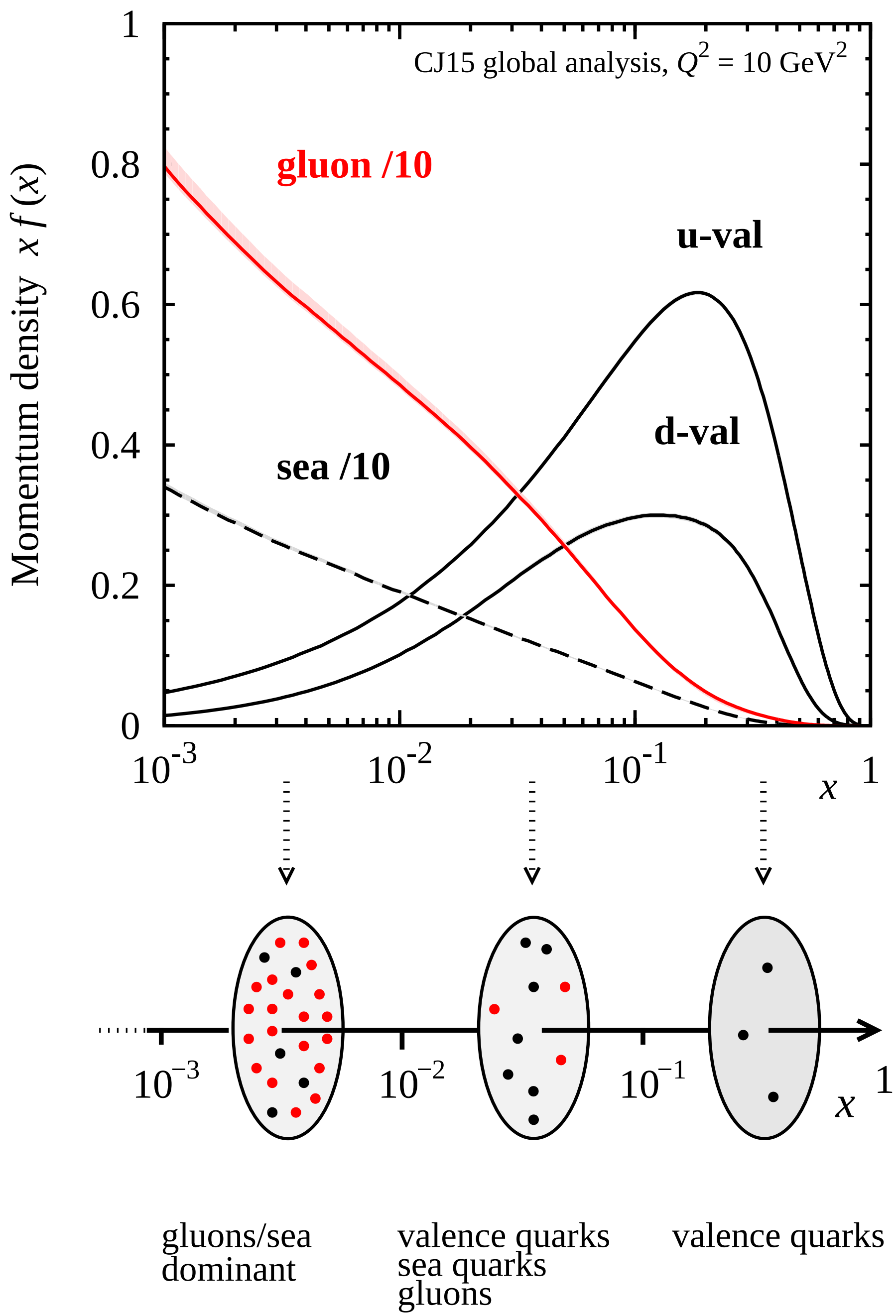
- Quark/gluon distributions

  Matrix elements of 2nd quantized QCD operators:
  Renormalization, scale dependence

  Calculated in Lattice QCD, non-pert. methods

  Measured in high-energy scattering

Nucleon structure: Quark and gluon densities



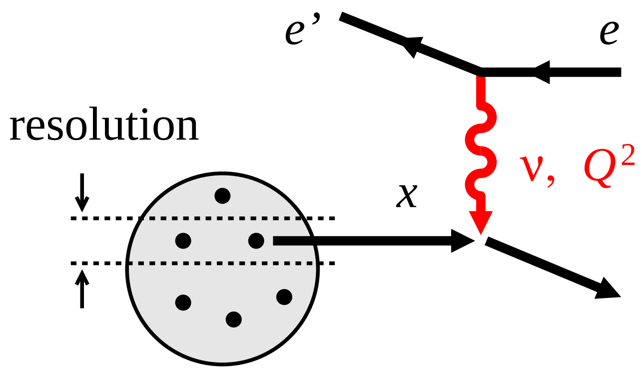
- Momentum densities

$x > 0.3$	valence quarks
$x \sim 10^{-1}$	valence quarks, sea quarks $q\bar{q}$, gluons
$x < 10^{-2}$	gluons/sea dominant

- Basic particle content of nucleon in QCD

- See different components of many-body system!

Electron scattering: Microscope



$$
\begin{aligned}
eN \rightarrow \; & e' + X && \text{inclusive} \\
& e' + h + X && \text{semi-inclusive} \\
& e' + h + N && \text{exclusive}
\end{aligned}
$$

- Electromagnetic interaction well understood

  Couples to EM current of quarks/antiquarks

- Kinematic variables

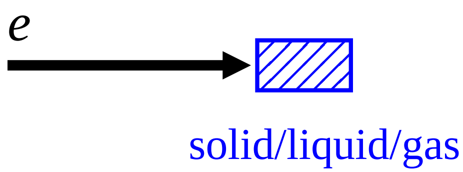
  momentum transfer Q $\rightarrow$ spatial resolution $1/Q$

  energy transfer ν $\rightarrow$ momentum fraction $x = Q^2/(2M_N\nu)$

- Range limited by collision energy $E^2_{\mathrm{cm}}(eN) > Q^2/x$

  Example: $Q^2 = 10\,\mathrm{GeV}^2,\; x = 0.1$ requires $E^2_{\mathrm{cm}}(eN) > 100\,\mathrm{GeV}^2$

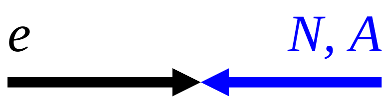
Electron scattering: Technologies



- Beam on fixed target

  High rates from nucleon density in in target

  $E_{\rm cm}^2 = 2 E_e M_N$ linear in beam energy



- Colliding beams

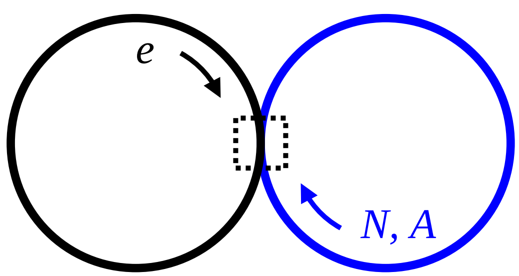
  $E_{\rm cm}^2 = 4 E_e E_N$ product of beam energies

  Energy–efficient: Beams collide multiple times

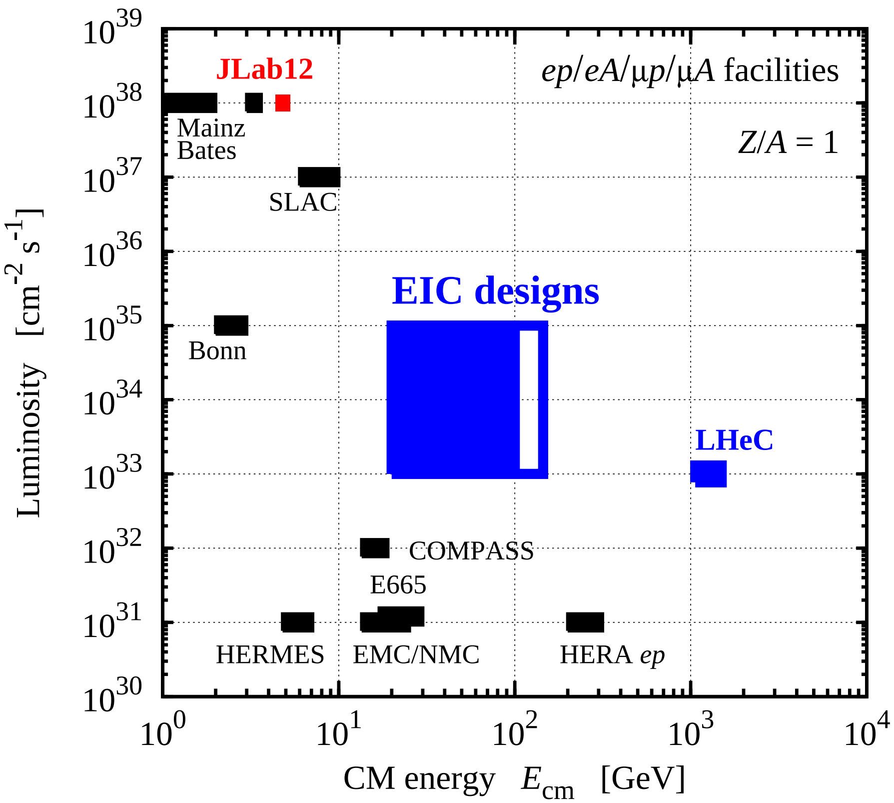
  Experimental advantages: No atomic electrons; detection at large angles; slow hadron products

  Technically demanding: Beam quality — focusing, cooling, time structure; integration of detectors and accelerator

  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, spin asymmetries
  multidimensional binning $[x, Q^2, \ldots]$
  precision measurements

  Limiting factor in most
  nucleon structure experiments!

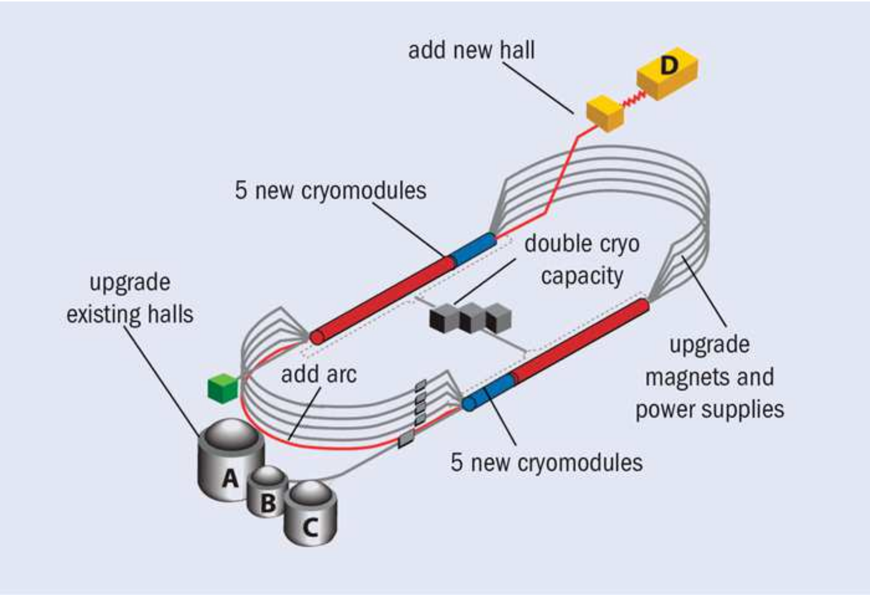
- JLab 12 GeV

  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



- “Race track” accelerator with linacs + arcs, extensible energy

  Uses unique superconducting RF technology and energy recovery

  Continuous beam $\sim 100\,\mu A$

  Operating since 1994

- Experimental halls

A, C	High-res magnetic spectrometers
B	CLAS large-acceptance
D	GlueX large-acceptance γ

- 12 GeV Upgrade

  Doubled beam energy 6 → 12 GeV
  Added Hall D, upgrading other halls

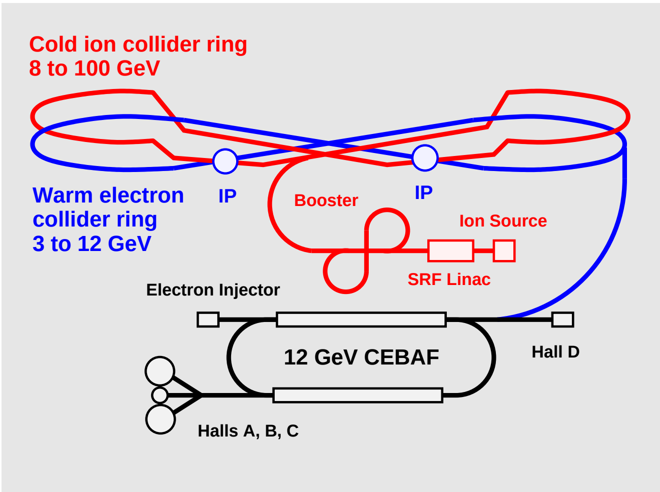
  Physics operations just started!

Physics program

Exotic meson spectroscopy
3D nucleon structure in QCD
Short-range nuclear physics
Electroweak physics

http://www.jlab.org/

Electron scattering: Electron–Ion Collider



- JLab ring–ring design JLEIC

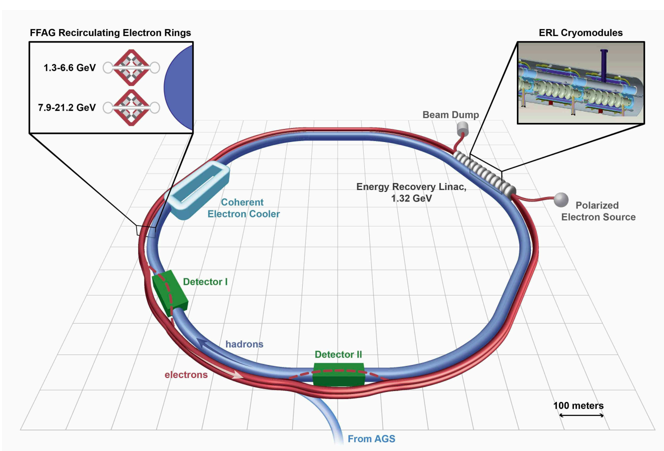
  12 GeV CEBAF as injector continued fixed-target op

  1 km ring with 3-12 GeV e on 8-100 GeV p

  Higher proton energies through magnet upgrades

  Luminosity $\sim 10^{34}$ over wide range

  Figure–8 for polarized deuteron



- BNL linac–ring design eRHIC

  RHIC 250 GeV proton beam, 170 GeV 3He

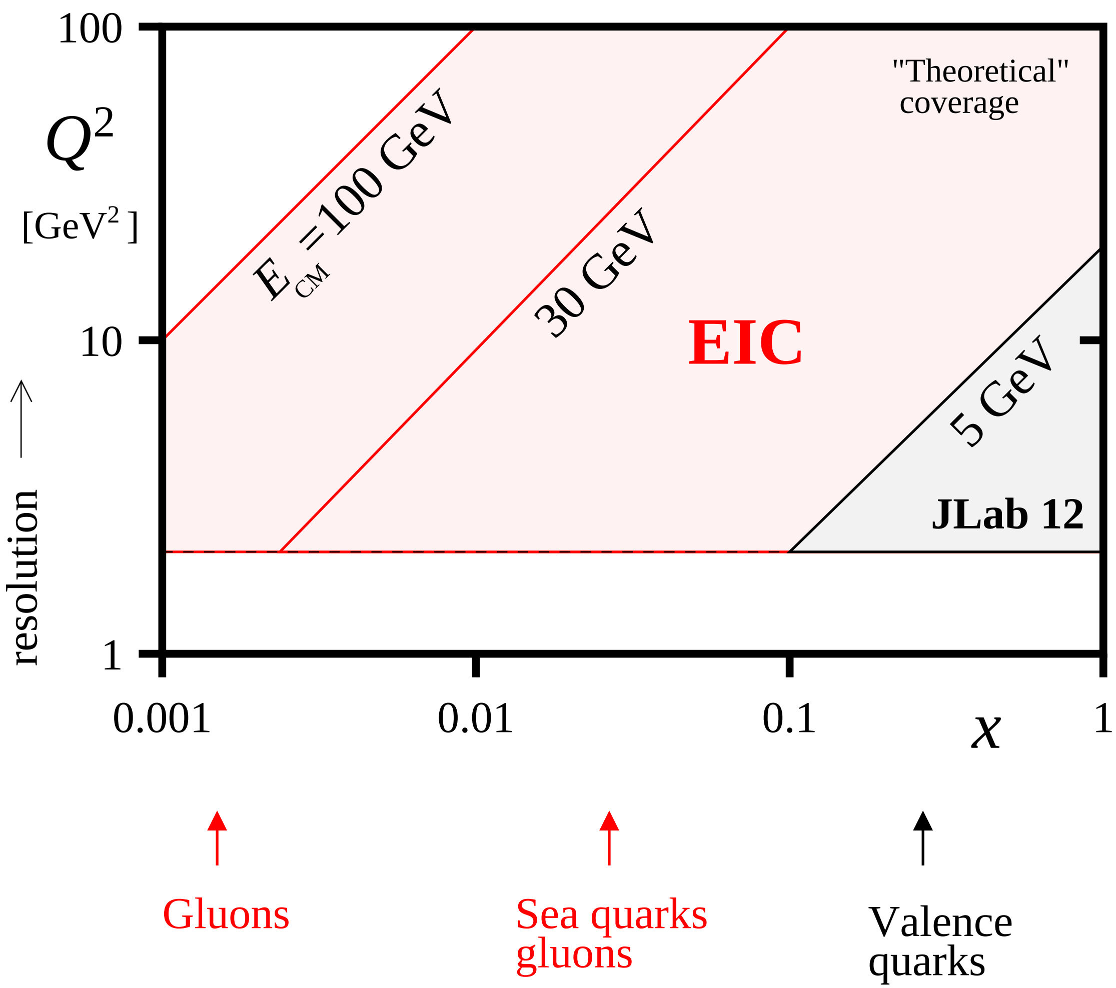
  2–20 GeV pol electron ERL in tunnel

  Luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1} over wide range

  Re-use RHIC detectors? PHENIX, STAR

- Related proposals: CERN LHeC, EIC@China design target similar to JLEIC

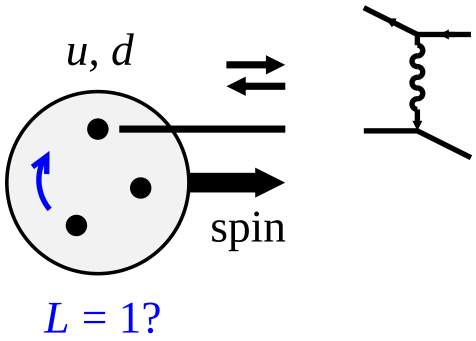
Electron scattering: Kinematic coverage

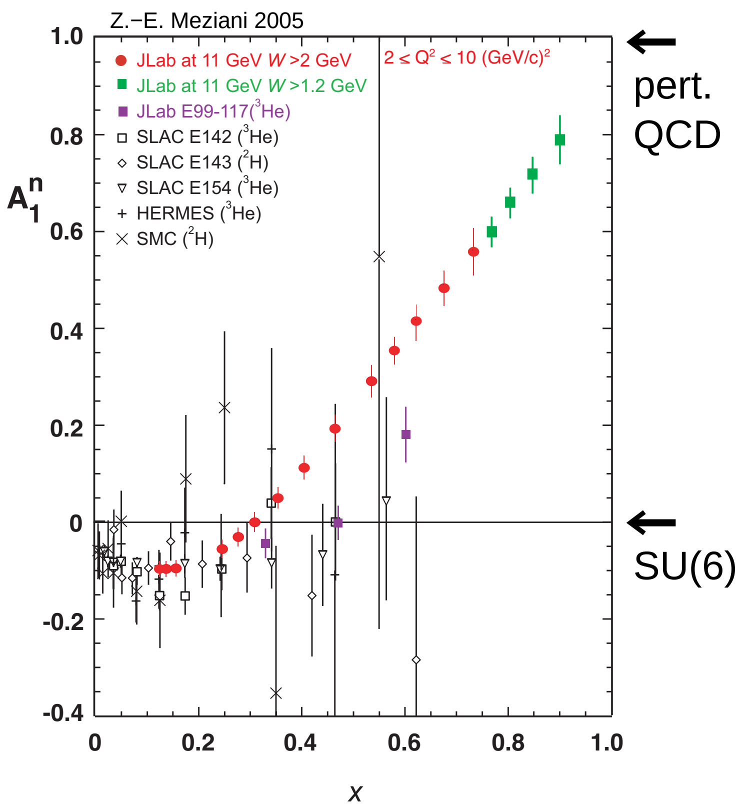


- JLab12: Valence quark region
- EIC: Sea quarks, gluons, Q^2–dependence

} complementary!

JLab12: 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 $\mathrm{L} = 1$?

- d quark polarization from inclusive scattering on neutron

  d in proton $= u$ in neutron, isospin

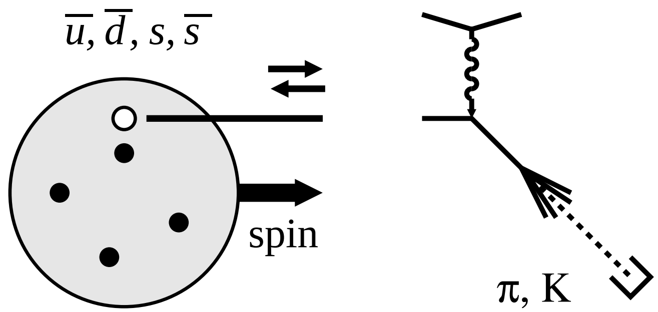
  Poorly constrained by present data

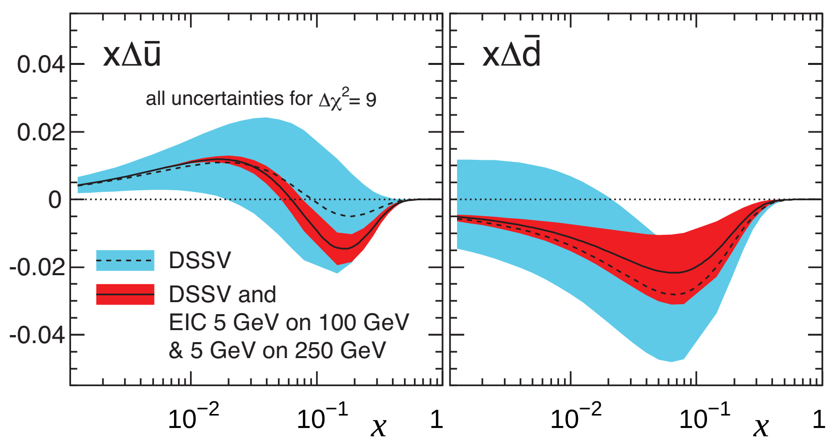
  Precise measurements with JLab12

- Many other applications

  Spatial distributions, orbital motion, nuclei, . . .

EIC: Sea quark polarization





EIC White Paper 2012

- How are sea quarks polarized?

  $q\bar{q}$ pairs from nonperturbative QCD?

  Mesonic degrees of freedom, pion cloud?

- Semi–inclusive scattering identifies hadrons produced from struck quark

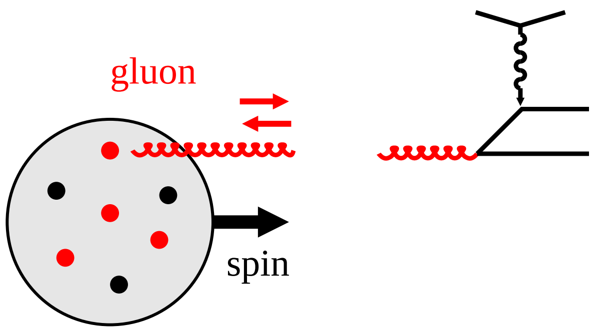
  "Tag" charge and flavor of struck quark

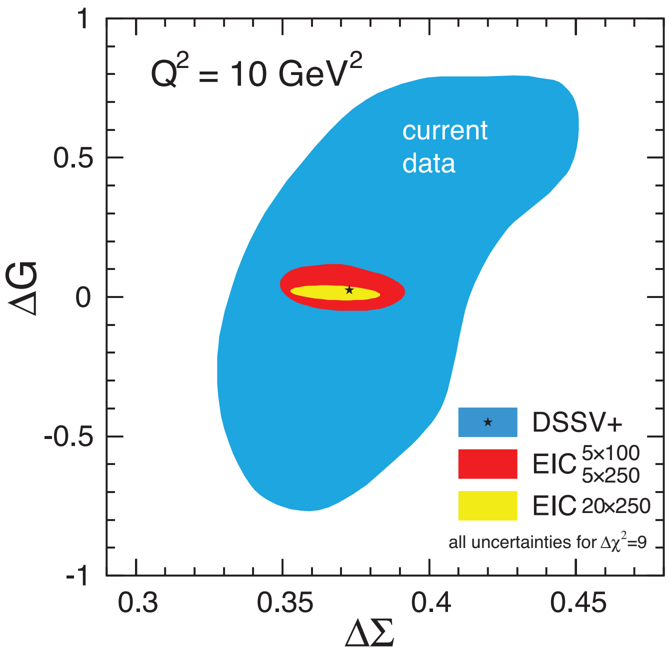
  Flavor decomposition poorly determined
  HERMES, RHIC W±. Analysis DeFlorian et al.

- EIC: Map sea quark distributions and their spin dependence

  High energy ensures independent fragmentation of struck quark

EIC: Gluon polarization





EIC White Paper 2012

- How is the nucleon spin composed of quarks/gluons?

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

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

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

- Polarized gluon density poorly known

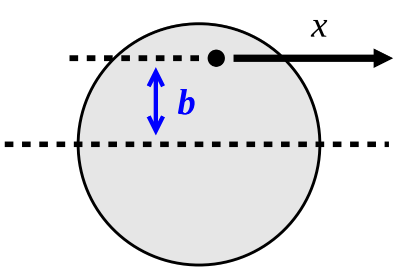
  Q^2 dependence of polarized $\vec{e}\vec{N}$ scattering
  EMC/SMC, SLAC, HERMES, COMPASS, JLab 6/12 GeV

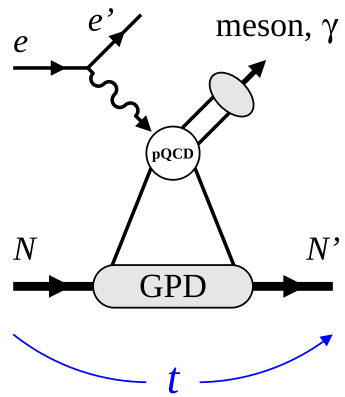
  Hard processes in polarized $\vec{p}\vec{p}$ scattering
  RHIC Spin

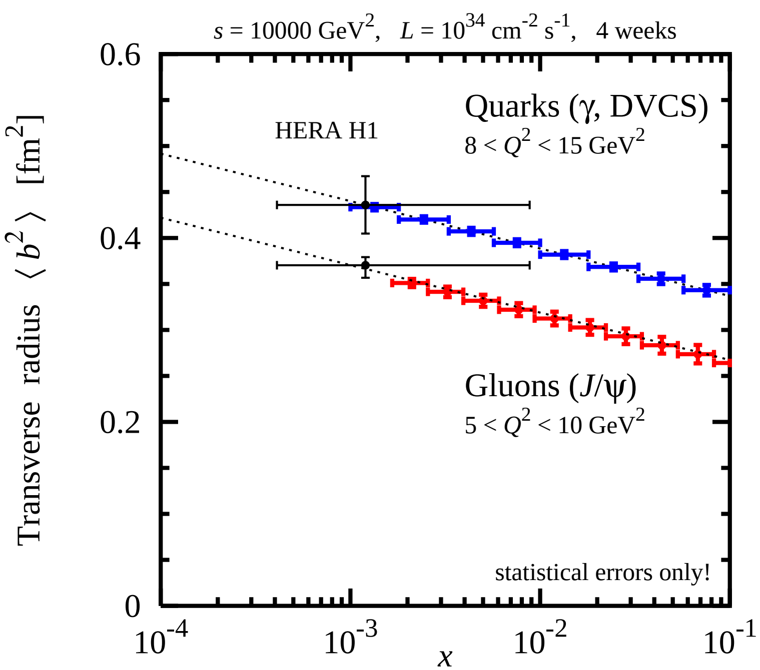
- EIC: Determine polarized gluon density

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

EIC: 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 $eN \to e' + M + N'$

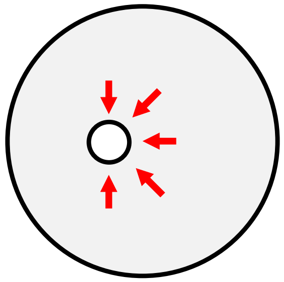
  Quark/gluon form factors of nucleon: Generalized parton distributions

  Theory effort: Reaction, GPD modeling

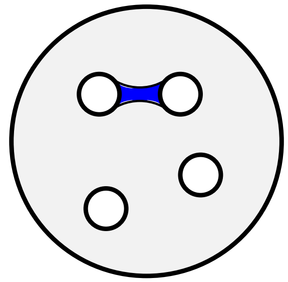
- EIC: Quark/gluon imaging of nucleon

  Luminosity for low rates, differential measurements

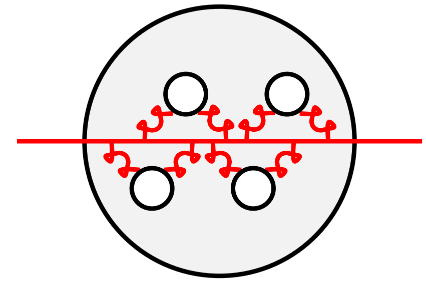
EIC: Nucleon interactions



$x > 0.3$
Modified single-nucleon structure, non-nucleonic DoF



$x \sim 0.1$
Pairwise NN interaction, exchange mechanisms



$x < 0.01$
Collective gluon fields, shadowing, saturation

- How do nucleon interactions emerge from QCD?

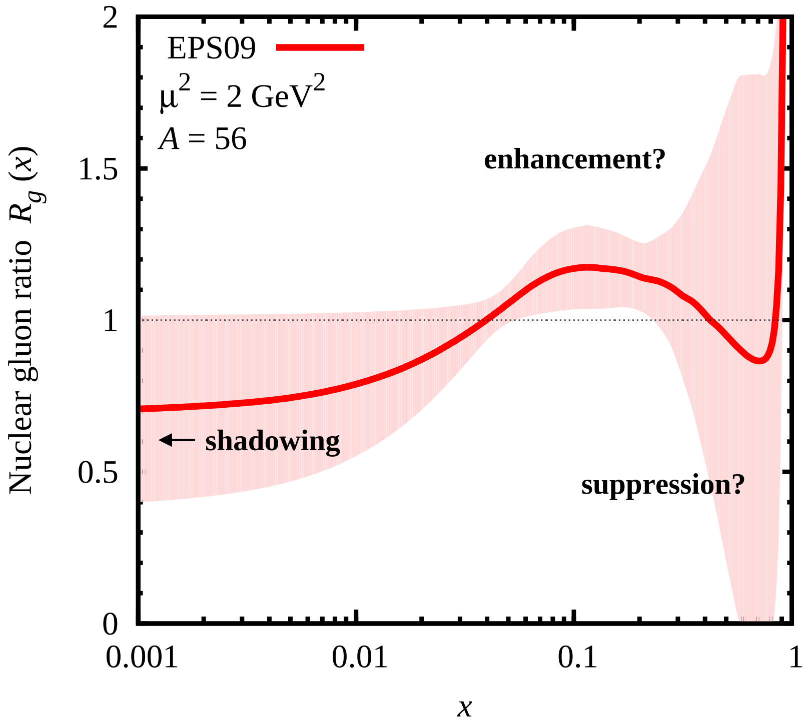
- Quark-gluon structure of nuclei

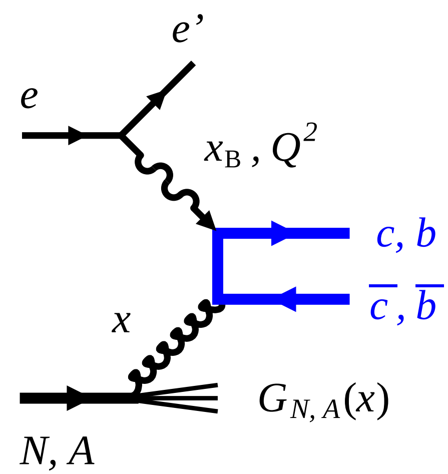
  Modified by nucleon interactions $A \neq \sum N$

  Mechanisms acting at different energies and distances

- Can be explored with EIC!

EIC: Gluons in nuclei





- Nuclear modification of gluons practically unknown at $x > 0.01$
  Shadowing at $x < 0.01$ observed in LHC ALICE 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

EIC: Further topics

- Orbital motion of quarks and gluons

  Quark/gluon transverse momenta, spin-orbit interactions
  Very active field. Much theoretical and experimental progress in last 5 years.

- Quantum fluctuations of gluons

  Diffractive scattering on nucleon and nuclei at small x

- Conversion of energetic color charge into hadrons

  Fragmentation of struck quark/gluon and target remnant, hadron formation

  Hadronization in the nuclear medium, jets
  Many connections with heavy-ion physics.

- Electroweak probes

  Neutral/charged current nucleon structure functions

EIC: Status and prospects

- Long march toward realization

  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: $>$600 physicists, $\sim$100 institutions [webpage]

  Next steps: Critical Decision Process CD0, site selection, timeline tentative

- EIC accelerator, detector, physics, and theory R&D

  U.S. National Labs BNL, JLab, ANL, LBL; university groups [webpage], [webpage]

  Concrete R&D projects, many ways to join/contribute [webpage], [webpage]

- Great interest in nuclear & accelerator physics communities

  Representation at conferences, EIC topical workshops and programs

  Growing international participation

  Mexico contacts: M.-E. Tejeda-Yeomans (DF-USON Sonora), A. Courtoy (CINVESTAV), A. Ayala (ICN-UNAM), M. Hentschinski (UDLAP Puebla)

Summary

- Quantum Chromodynamics as microscopic theory

  Dynamics changes with resolution scale

  Long-distance behavior still poorly understood!

- Nucleon as relativistic many–body system

  High-energy scattering probes different components, varying scales

  Complex characteristics — polarization, spatial size, nucleon interactions

  Major need for visualization, interpretation, communication

- Electron–Ion Collider as next–generation facility

  Energy, luminosity, polarization, detection

  Realistic path forward