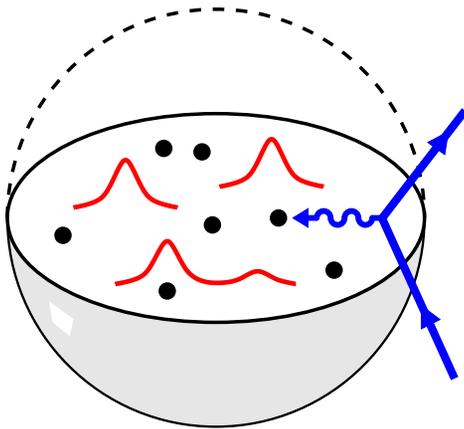


Strong interaction physics with an Electron-Ion Collider

C. Weiss (JLab) [E-mail], VCU Physics Colloquium, 15-Sep-2017

Jefferson Lab



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

2

- Fundamental structure of matter

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

Phases of matter at high density/temperature, early universe

Conversion of radiation into matter, cosmic ray physics

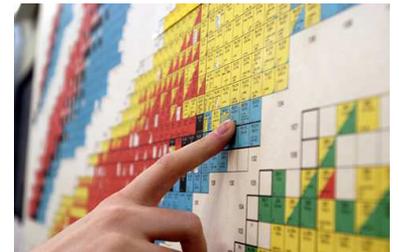


- Nuclei and nuclear reactions from “first principles”

Origin of nucleon–nucleon interaction

Nuclear energy, stellar structure, astrophysical processes

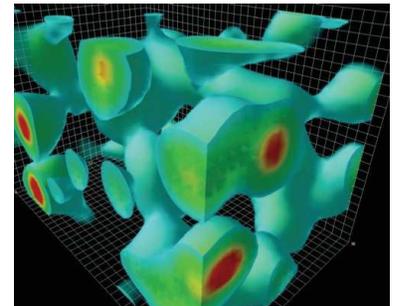
Neutrino interactions with nuclei

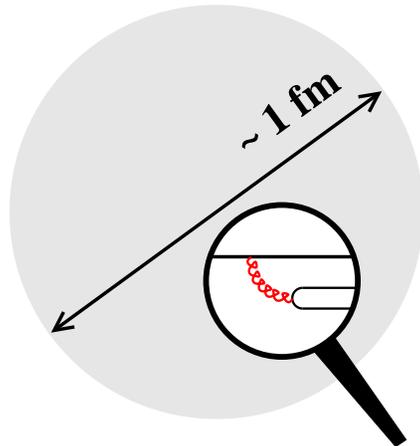


- Concepts and methods

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

Numerical simulations: Lattice gauge theory





- 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 field theory with $SU(3)$ group charge

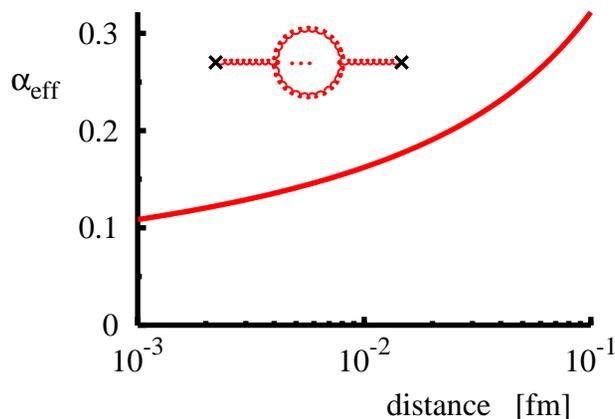
Effective coupling decreases with distance
Asymptotic freedom: Gross, Politzer, Wilczek 73

- Larger distances $r \gtrsim 0.3 \text{ fm}$

Strong gauge fields create condensate
of quark–antiquark pairs

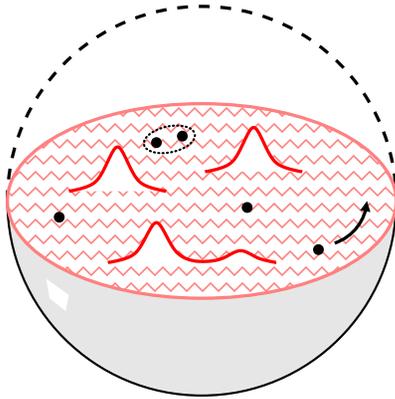
Dynamical mass generation

Dynamics changes with resolution scale!



Nucleon structure: Dynamical system

4



- Understand nucleon structure in QCD!

- Unique dynamical system

Relativistic

Quantum-mechanical

Strongly coupled

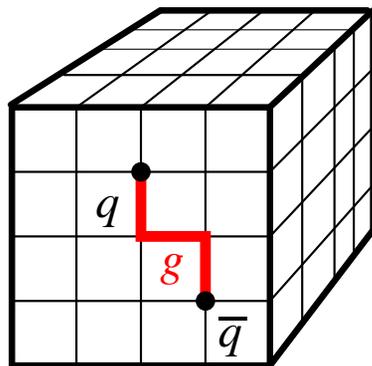
- Field-theoretical description

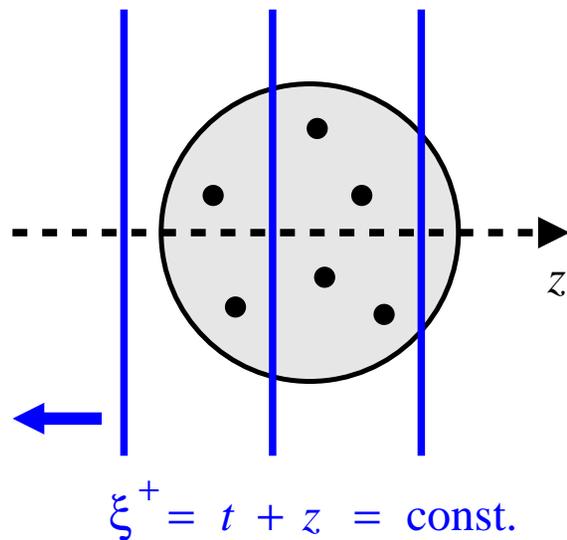
Imaginary time $t \rightarrow i\tau$

Quantum field theory \rightarrow statistical mechanics

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

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





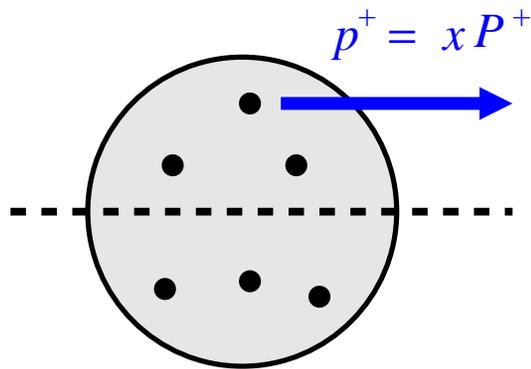
- Wave function generally frame-dependent
 - Relies on notion of “equal time”
- Light-front time $\xi^+ \equiv t + z = \text{const.}$
 - Frame-independent time
 - Appropriate for relativistic systems
 - Natural for high-energy scattering

- Composite picture of nucleon

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

Superposition of configuration with different number of constituents

Relativistic many-body system!



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

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

- Physical characteristics

Momentum densities of quarks/antiquark/gluons

Spin distributions in polarized nucleon

Transverse spatial distributions

Orbital motion and spin-orbit effects

$$\langle N | \underbrace{\bar{\psi} \dots \psi}_{\text{QCD operator}} | N \rangle$$

QCD operator measuring momentum-spin density

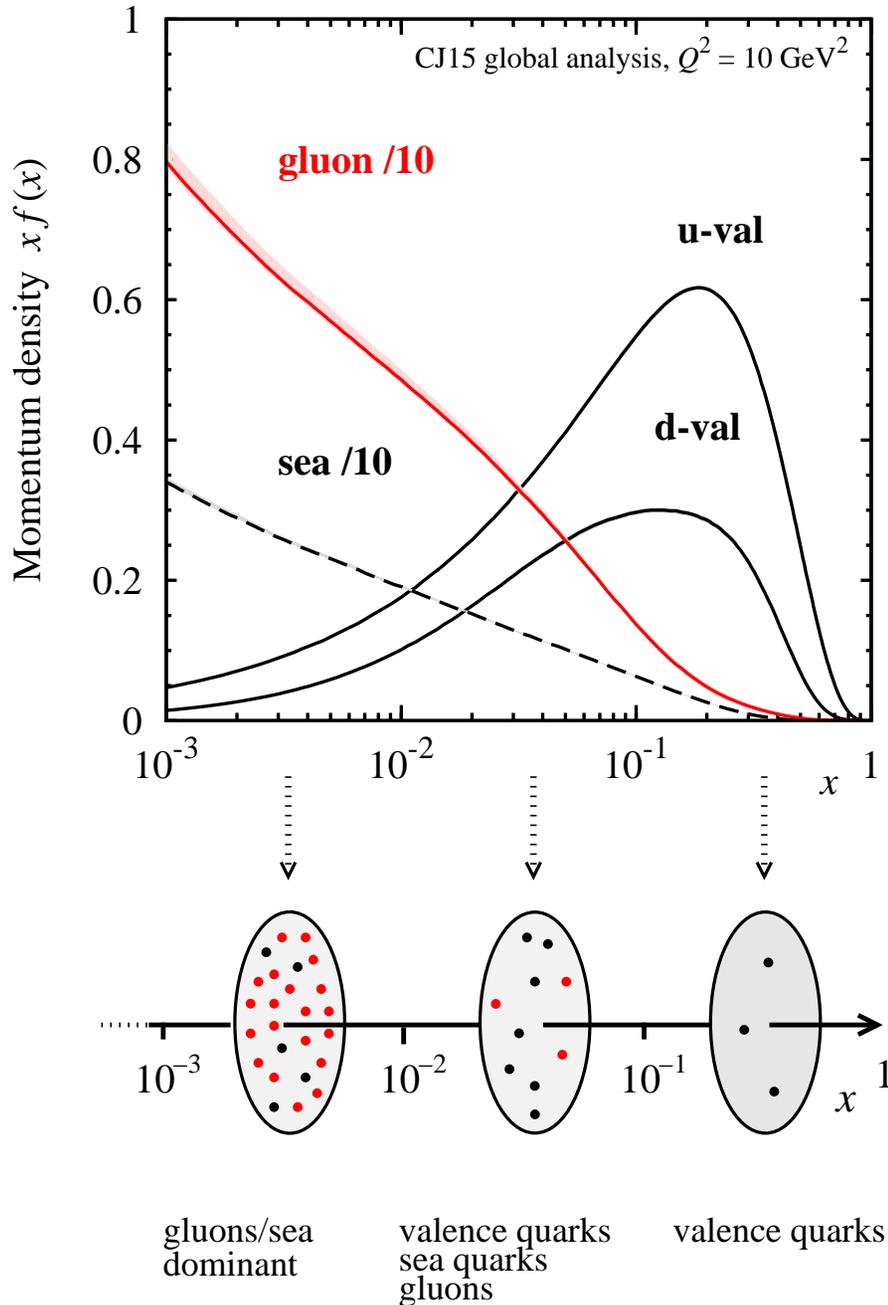
- Quark/gluon distributions

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

Calculated in Lattice QCD, non-pert. methods

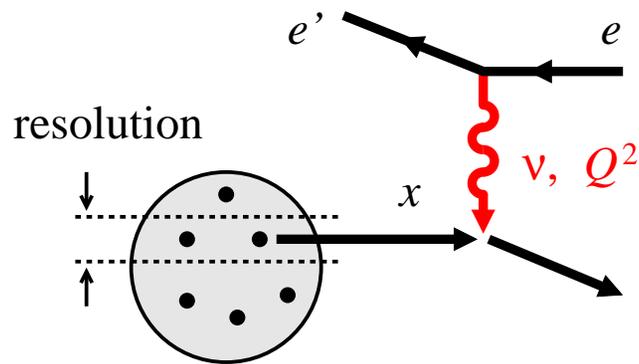
Measured in high-energy scattering

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



$eN \rightarrow e' + X$	inclusive
$e' + h + X$	semi-inclusive
$e' + h + N$	exclusive

- Electromagnetic interaction well understood

Couples to EM current of quarks/antiquarks

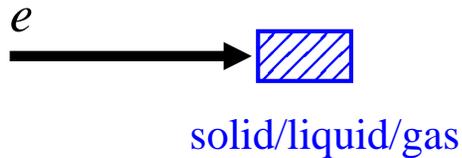
- Kinematic variables

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

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

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

Example: $Q^2 = 10 \text{ GeV}^2, x = 0.1$ requires $E_{\text{cm}}^2(eN) > 100 \text{ GeV}^2$



- Beam on fixed target

High rates from nucleon density in target

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

- Colliding beams

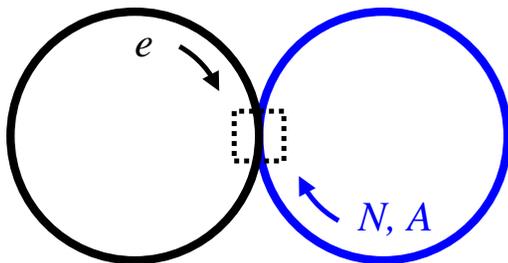


$$E_{\text{cm}}^2 = 4E_e E_N \quad \text{product of beam energies}$$

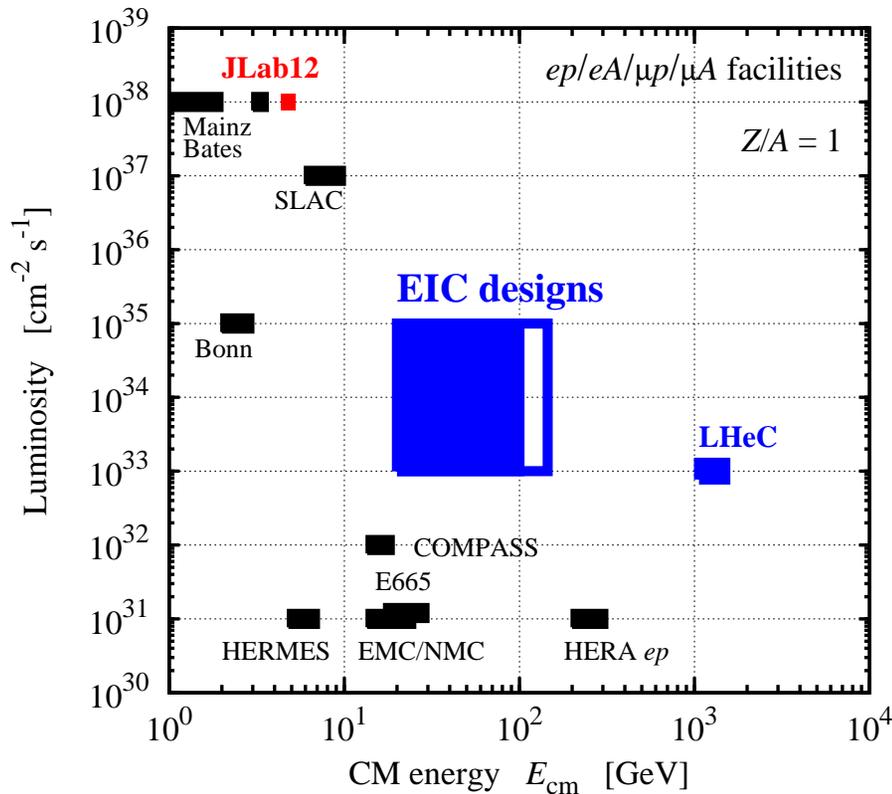
Energy-efficient: Beams collide multiple times

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, PEP-II, KEK, DAΦNE), $pp/p\bar{p}$ (RHIC, Tevatron, LHC), AA (RHIC, LHC), ep (HERA)



- Luminosity

$$\text{Rate} = \text{Luminosity} \times \text{Cross section}$$

High luminosity required for rare processes, spin asymmetries, multidimensional binning $[x, Q^2, \dots]$, precision measurements

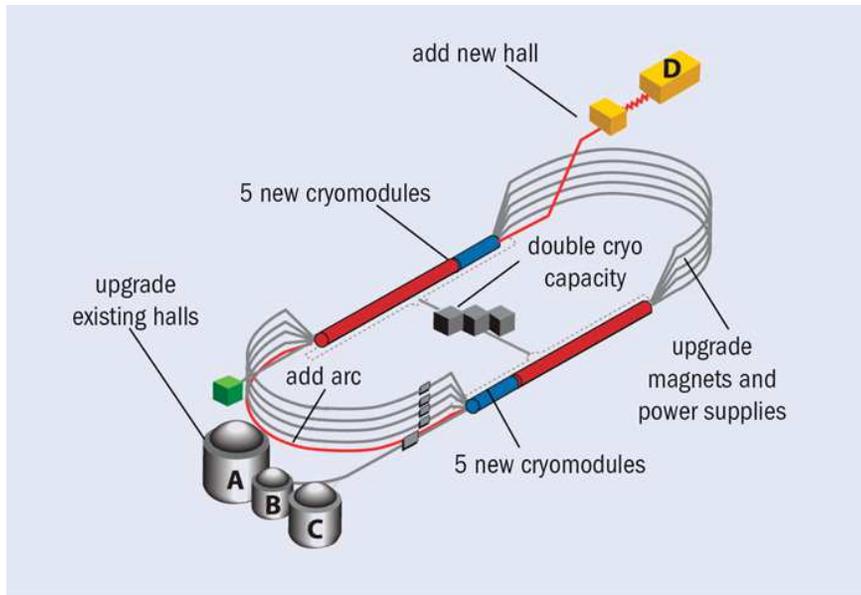
Limiting factor in most nucleon structure experiments!

- JLab 12 GeV

Energy \times luminosity frontier in fixed-target scattering

- Electron-Ion Collider EIC

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



- “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

Physics program

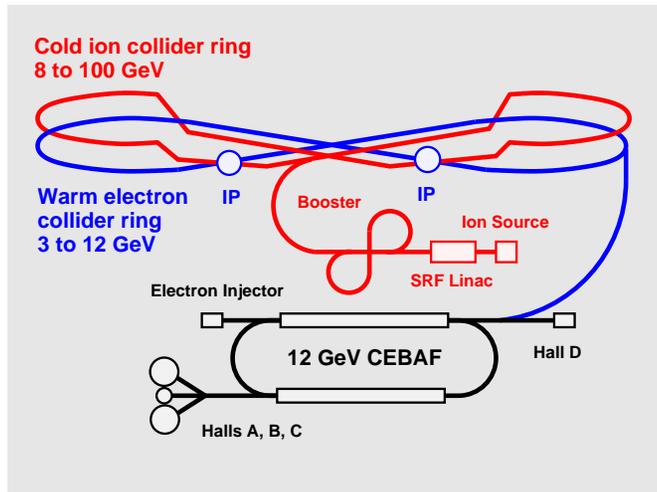
Exotic meson spectroscopy
3D nucleon structure in QCD
Short-range nuclear physics
Electroweak physics

<http://www.jlab.org/>

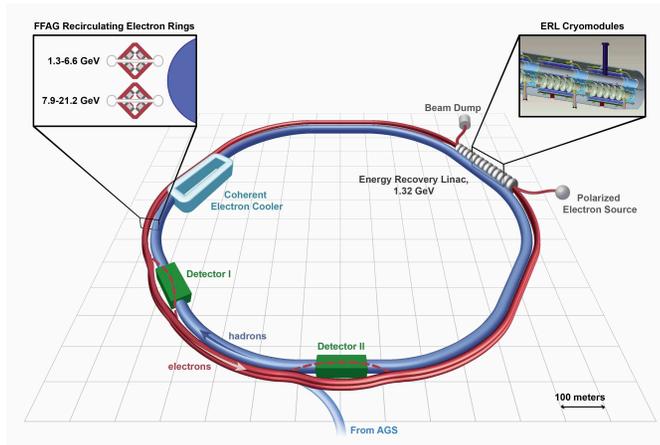
- 12 GeV Upgrade

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

Physics operations just started!

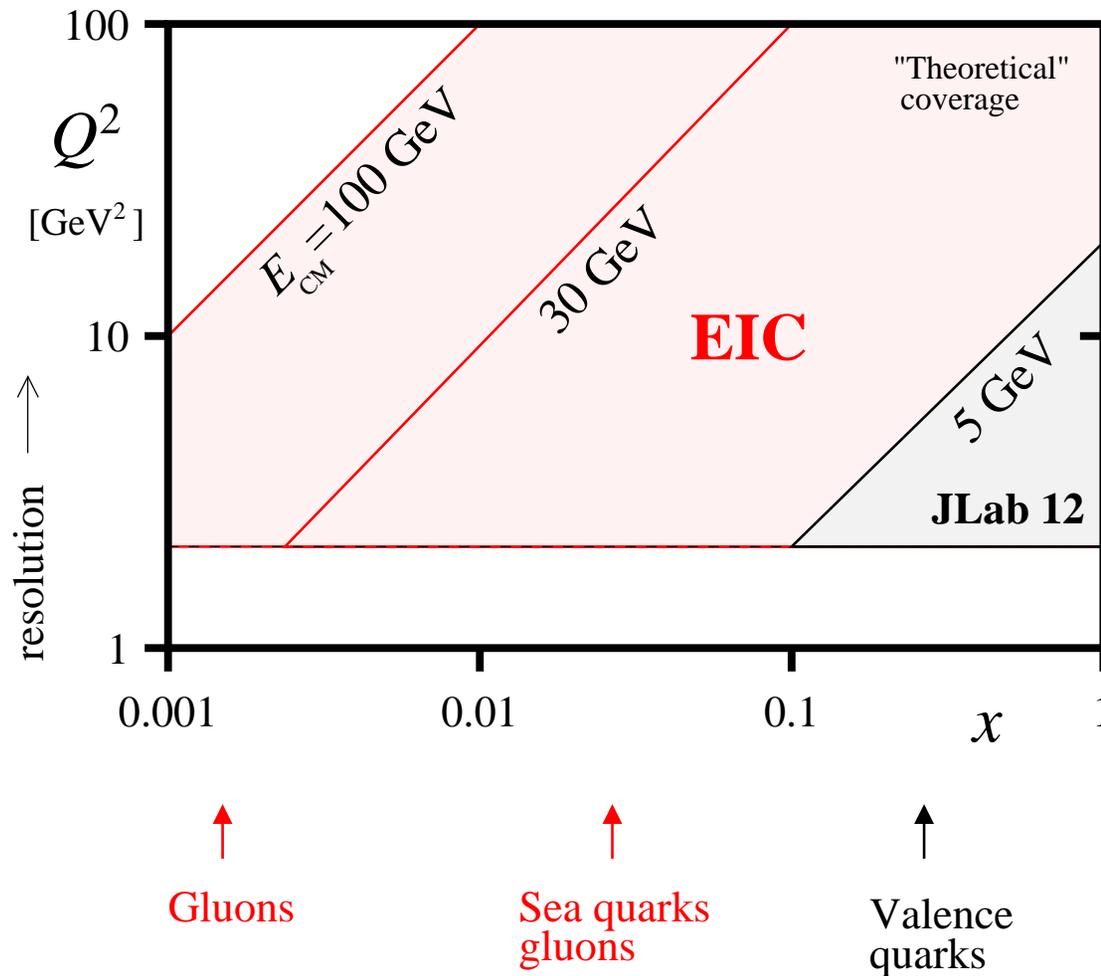


- Jefferson Lab ring-ring design JLEIC
 - 12 GeV CEBAF as injector *continued fixed-target op*
 - 1 km ring with 3-12 GeV e on 8-100 GeV p
 - Higher proton energies through magnet upgrades
 - Luminosity $\sim 10^{34}$ over wide range
 - Figure-8 for polarized deuteron



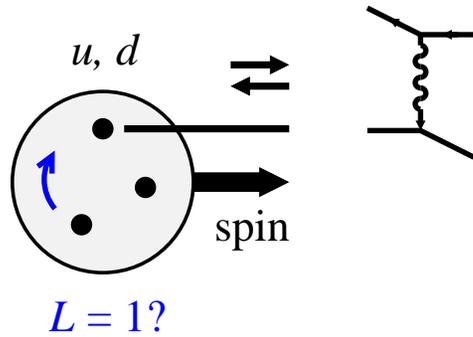
- Brookhaven NL linac-ring design eRHIC
 - RHIC 250 GeV proton beam, 170 GeV ^3He
 - 2-20 GeV pol electron ERL in tunnel
 - Luminosity $\sim 10^{33-34} \text{ cm}^{-2} \text{ s}^{-1}$ over wide range
 - Re-use RHIC detectors? *PHENIX, STAR*
- Related proposals: CERN LHeC, EIC@China design target similar to JLEIC

Electron scattering: Kinematic coverage



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

} complementary!

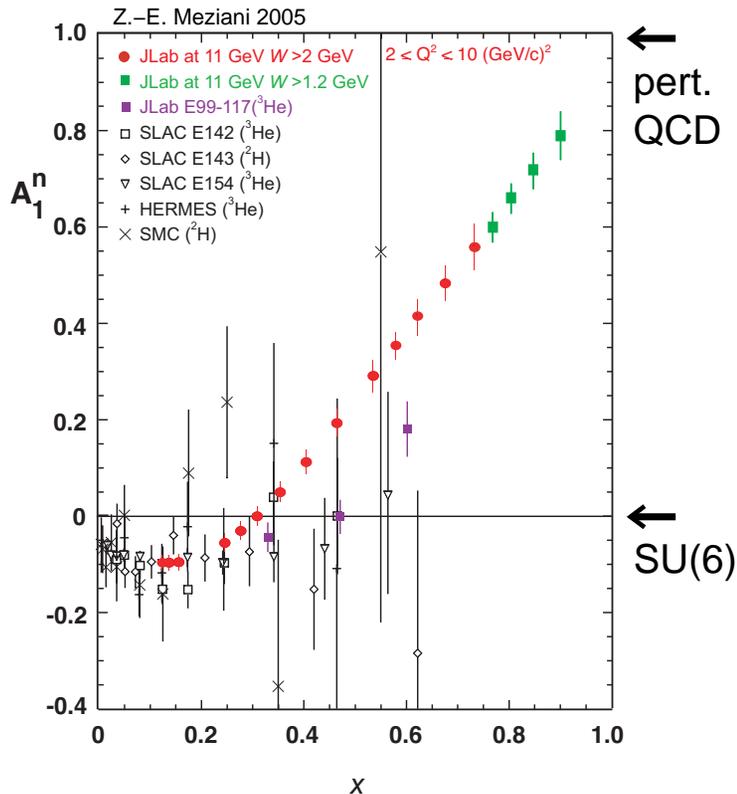


- How are valence quarks in nucleon polarized at $x \rightarrow 1$?

Basic $3q$ component of nucleon wave fn

Non-perturbative QCD interactions?

Orbital angular momentum $L = 1?$



- d quark polarization from inclusive scattering on neutron

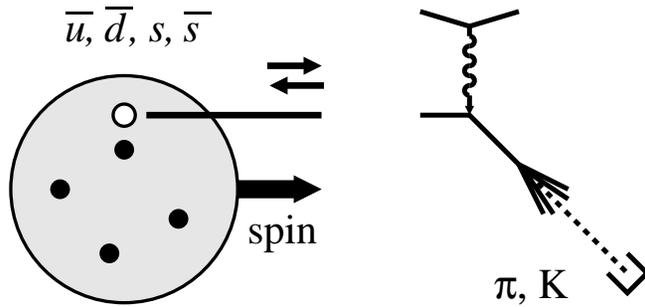
d in proton = u in neutron, isospin

Poorly constrained by present data

Precise measurements with JLab12

- Many other applications

Spatial distributions, orbital motion, nuclei, . . .



- How are sea quarks polarized?
 - $q\bar{q}$ pairs from nonperturbative QCD?
 - Mesonic degrees of freedom, pion cloud?

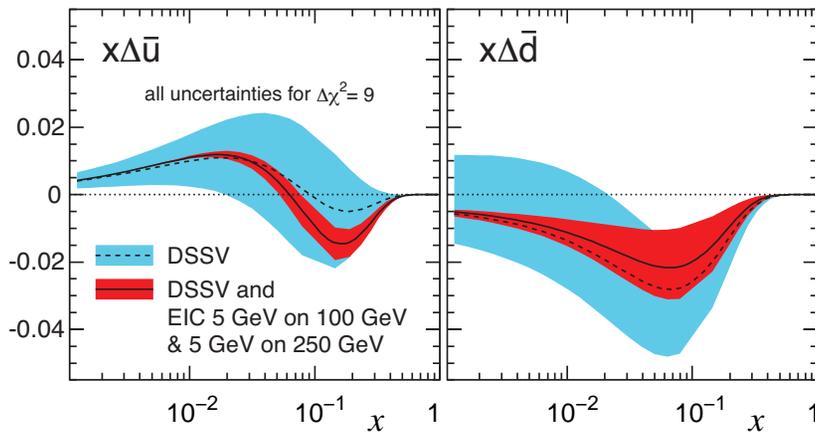
- Semi-inclusive scattering identifies hadrons produced from struck quark

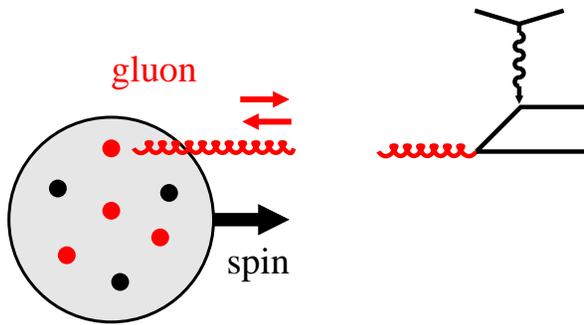
“Tag” charge and flavor of struck quark

Flavor decomposition poorly determined
 HERMES, RHIC W^\pm . Analysis DeFlorian et al.

- EIC: Map sea quark distributions and their spin dependence

High energy ensures independent fragmentation of struck quark



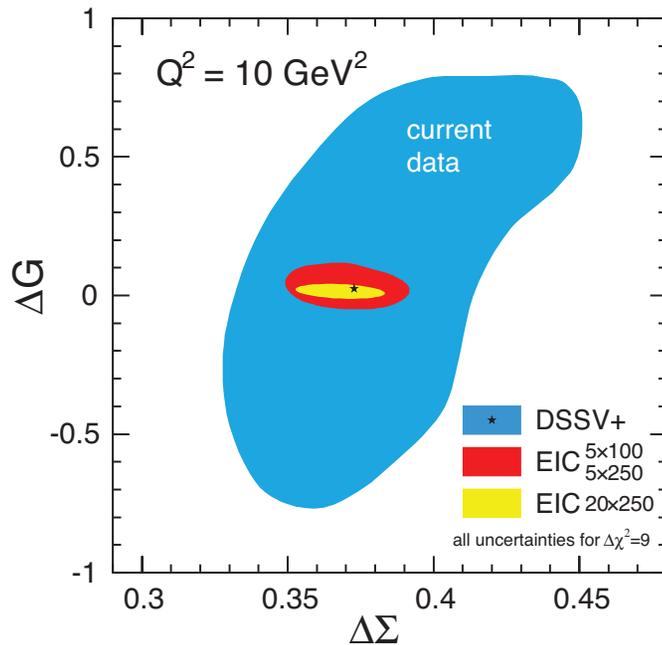


- How is the nucleon spin composed of quarks/gluons?

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

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

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



EIC White Paper 2012

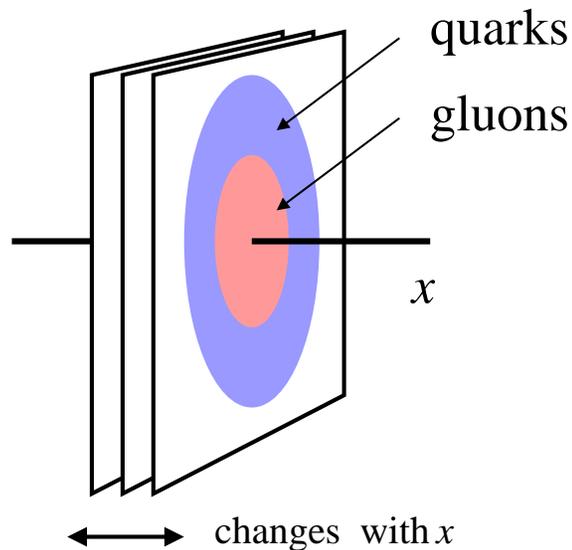
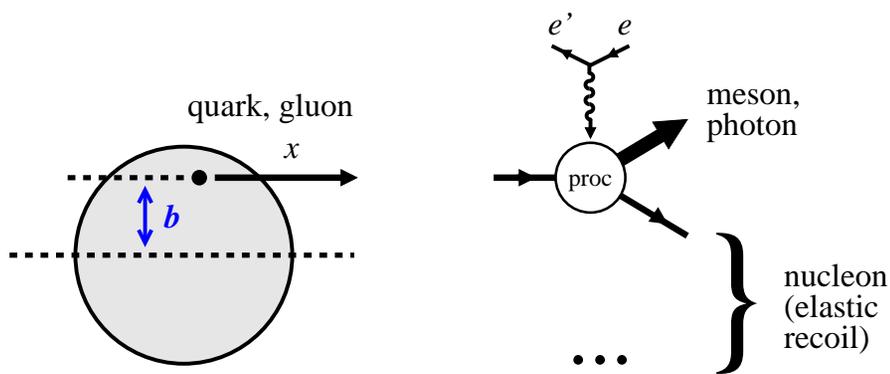
- Polarized gluon density poorly known

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

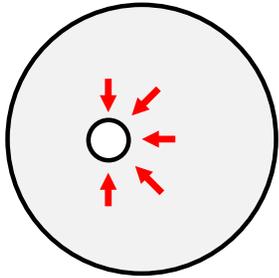
Hard processes in polarized $\vec{p}\vec{p}$ scattering
 RHIC Spin

- EIC: Determine polarized gluon density

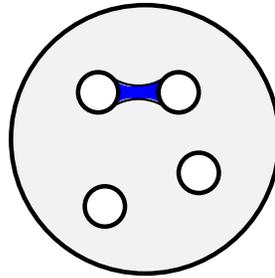
Wide kinematic coverage enables measurement of Q^2 evolution, x integral



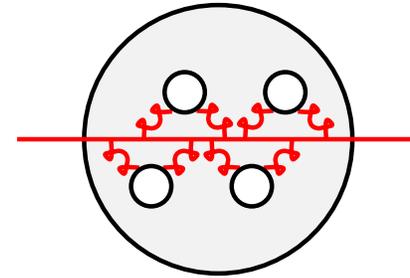
- How are quarks/gluons distributed in transverse space?
 - Size and "shape" of nucleon in QCD
 - Distributions change with x , spin
 - Input for modeling pp collisions at LHC
- Exclusive processes $eN \rightarrow e' + M + N'$
 - Quark/gluon form factors of nucleon: Generalized parton distributions
- EIC: Quark/gluon imaging of nucleon
 - Luminosity for low rates, differential measurements
 - Tomographic images of nucleon



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

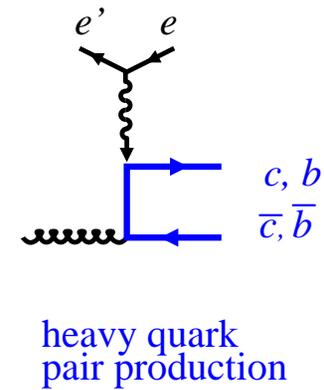
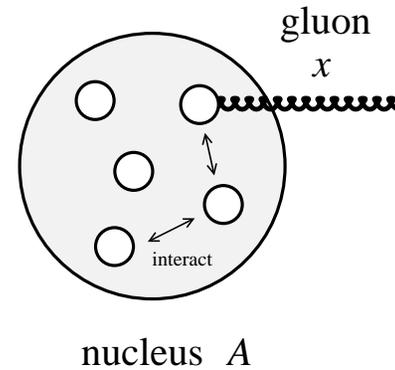
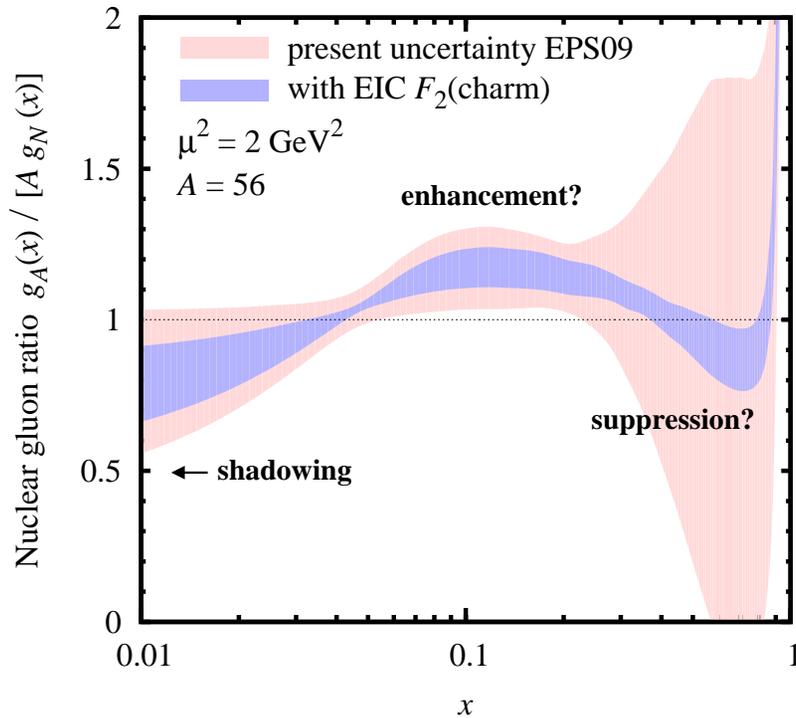


$x \sim 0.1$
Pairwise NN interaction,
exchange mechanisms



$x < 0.01$
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!



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

Gluon 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

2016/17 R&D project at JLab [webpage]

- 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

Diffraction 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

- 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, ~100 institutions [\[webpage\]](#)

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

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

U.S. National Labs: Brookhaven, Jefferson Lab, Argonne, Berkeley; 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

- 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