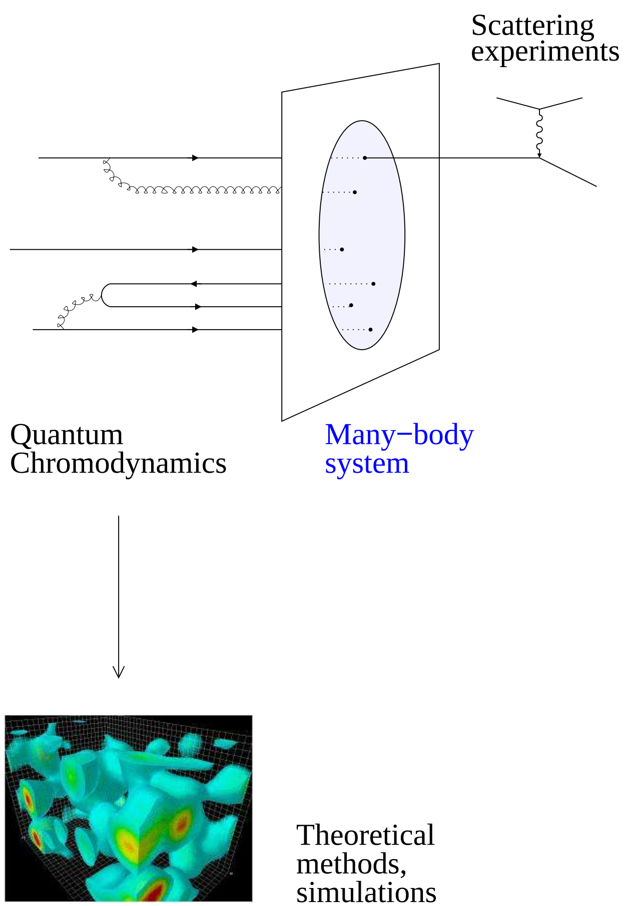
Strong interaction physics with an Electron–Ion Collider

C. Weiss (JLab), HUGS 2014 Lectures, 06–Jun–14

Jefferson Lab



- Internal structure of nucleon

  Quantum Chromodynamics

  Many–body system: Relativistic, quantum–mechanical, strongly coupled
  Uniquely challenging! Cf. condensed matter, atomic physics

- High–energy electron scattering

  Fixed–target JLab 12 GeV

  Colliding beams Electron–Ion Collider EIC

- EIC physics I: Nucleon structure

  Sea quark and gluon polarization

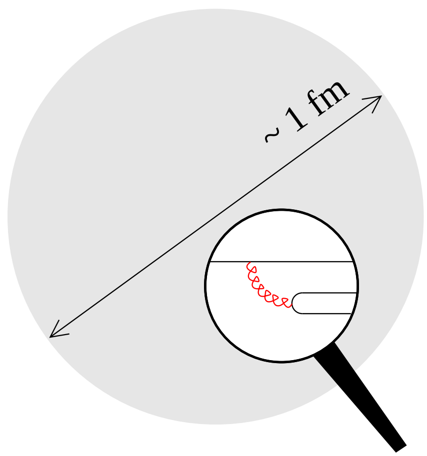
  Spatial distributions

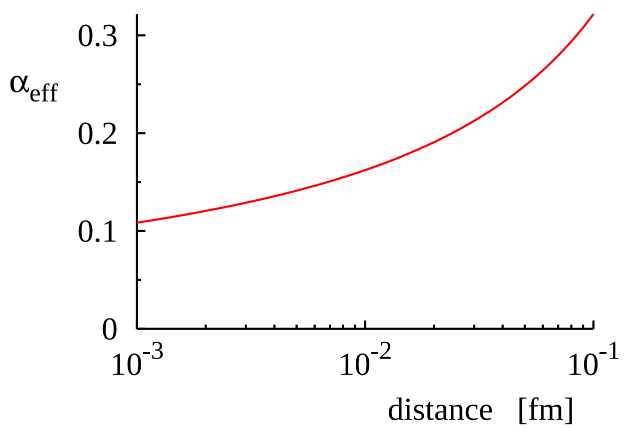
  Orbital motion

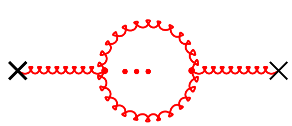
  Correlations

- EIC physics II: Nuclei, hadronization
  Quarks/gluons in nuclei, coherence, saturation, . . .

Nucleon structure: Short distances







Dynamics changes with resolution scale!

- 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:
  cf. Electrodynamics

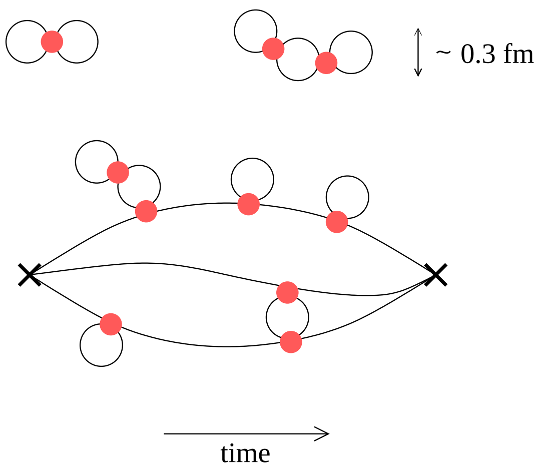
  Effective coupling decreases with distance:
  Asymptotic freedom Gross, Politzer, Wilczek 73

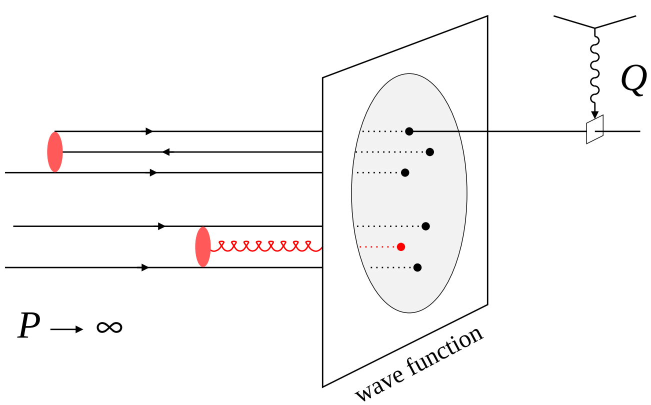
- Larger distances $r \gtrsim 0.3\,\mathrm{fm}$

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

  Dynamical mass generation,
  effective degrees of freedom
  cf. Constituent quark model → Lecture Capstick

Nucleon structure: Fields vs. particles





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

  Uniquely challenging problem:
  relativistic + QM + strongly coupled

- 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!

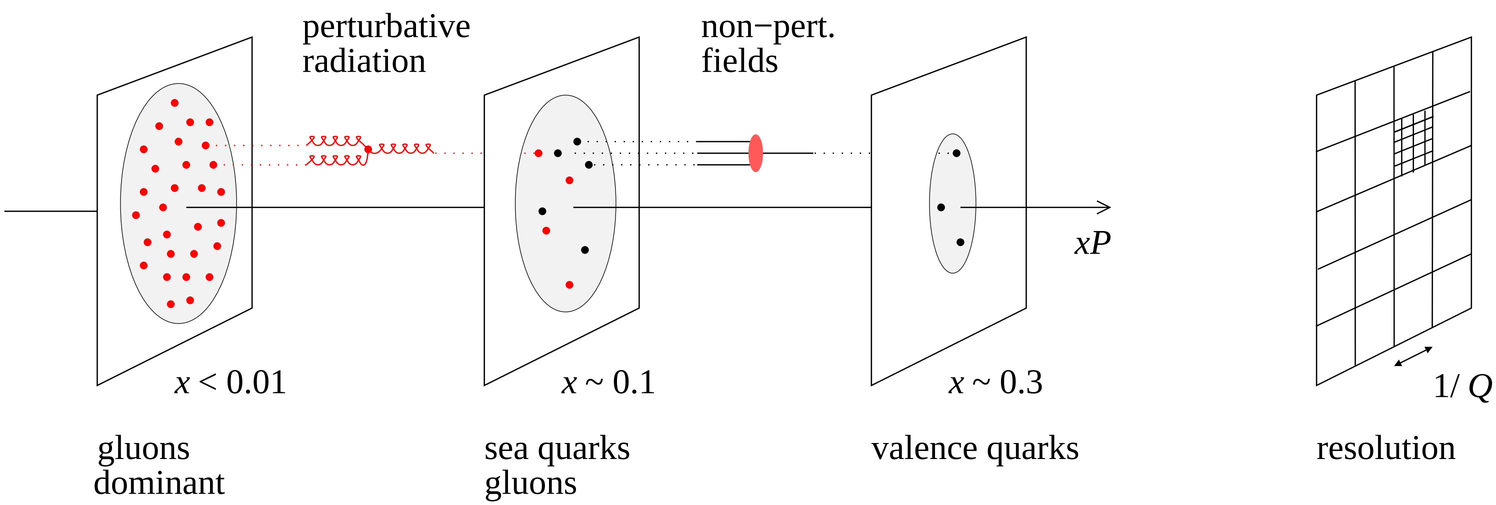
- Nucleon fast: Particle content

  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



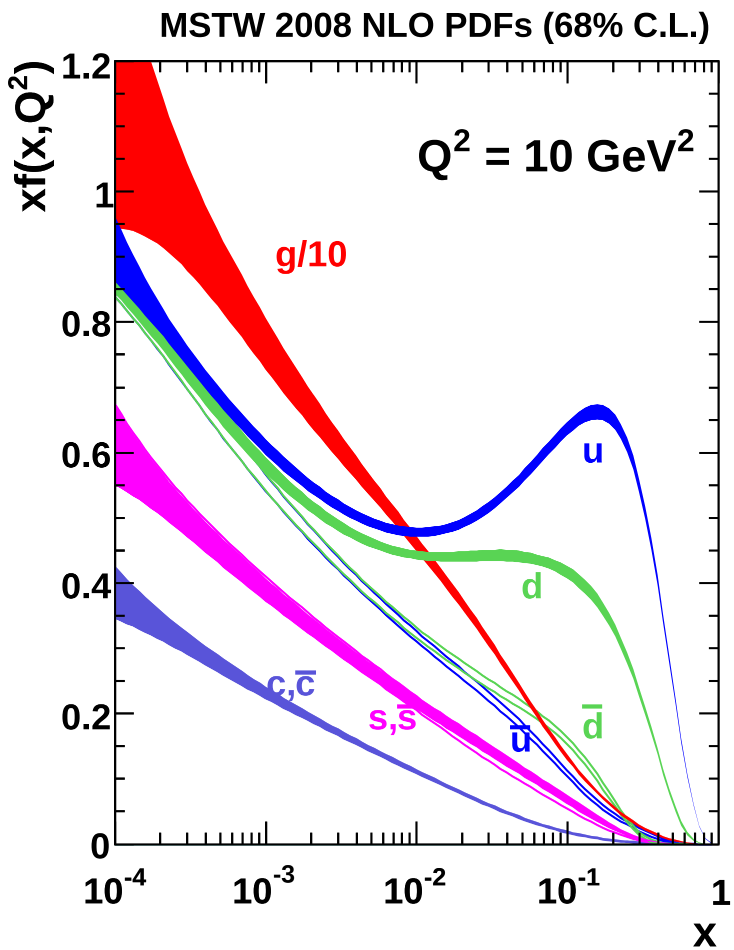
- Different components of wave function

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

- Measurable properties

$$\left.\begin{array}{l}\text{Particle number densities, incl. spin/flavor dependence}\\ \text{Transverse spatial distributions}\\ \text{Orbital motion: Transverse momenta, polarization}\\ \text{Particle–particle correlations}\end{array}\right\}\ \begin{array}{l}\text{change with}\\ \text{resolution scale}\\ 1/Q!\end{array}$$

Nucleon structure: Particle number densities



$f(x)$ probability to find $q, \bar{q}, g$ with momentum fraction x

Extracted from data. Here Martin et al. 2008

- Particle number densities

$x \sim 0.3$	valence quarks
$x \sim 0.1$	sea quarks, gluons
$x < 0.01$	gluons dominant

- Basic "particle content" of nucleon in QCD!

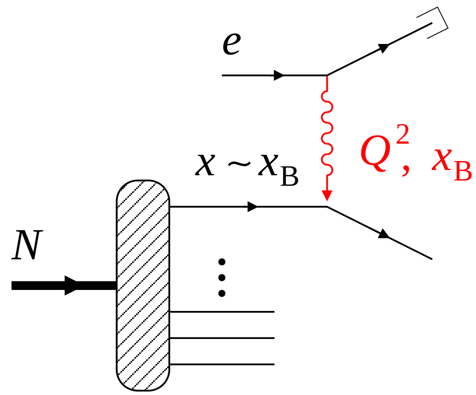
- Depends on resolution scale Q^2

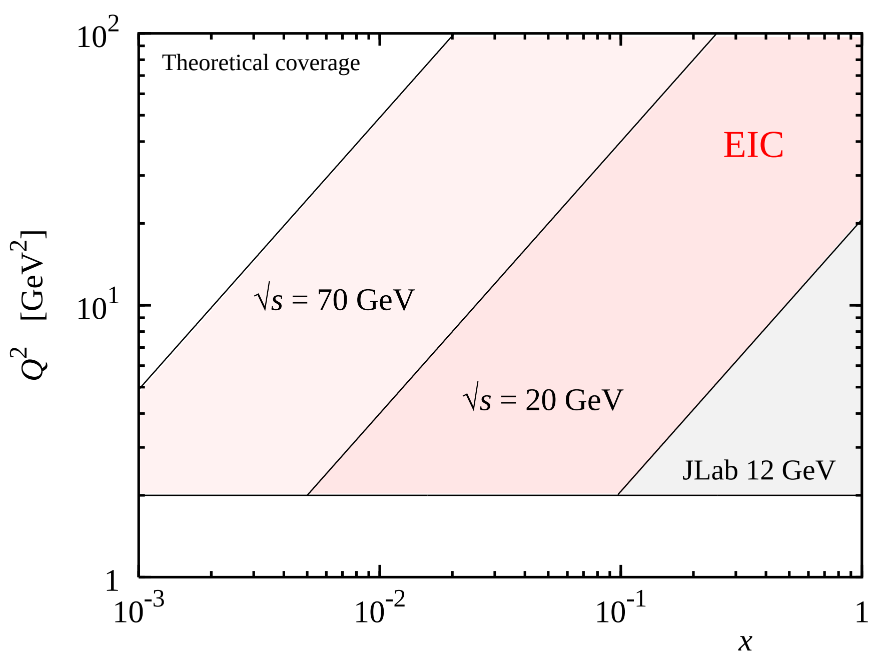
Q^2 limits phase space for particle creation through elementary processes

$$k_T^2 < Q^2$$

Q^2 dependence calculable perturbatively for $Q^2 \gg 1\,\mathrm{fm}^{-2}$: "Evolution"

Electron scattering: Probing short distances





- Electron–nucleon scattering
  Also: positron, muon

  Energy and momentum transfer:
  Use Lorentz–invariant variables

  $$Q^2 = -q^2 \qquad \rightarrow \qquad \text{resolution } 1/Q$$

  $$x_B = \frac{Q^2}{2(p_N q)} \qquad \rightarrow \qquad \text{constituent } x$$

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

- Kinematic range

  $$s = (p_e + p_N)^2 \qquad eN \text{ invariant}$$

  $$= E^2_{\text{CM}} \qquad \text{in center-of-mass}$$

  $$Q^2 < x_B s \qquad \text{kinematic limit}$$

  High Q^2/small x_B reqiure high energies!

Electron scattering: Inclusive scattering

- Inclusive scattering (Deep-inelastic scattering, DIS)

$$\frac{d\sigma(eN \to e'X)}{dx_B dQ^2} = \text{Flux factor} \times \Big[F_2(x_B, Q^2) + \ldots\Big]$$ diff. cross section

$$F_2(x_B, Q^2) = \sum_q e_q^2\, x \Big[f_q(x, Q^2) + f_{\bar{q}}(x, Q^2)\Big]_{x=x_B}$$ structure function

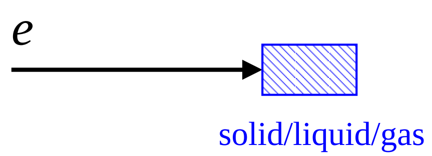
Scattering process selects quarks/antiquarks with $x = x_B$!

Used to extract quark/antiquark densities.

Approximation valid at $Q^2 \gtrsim 1\,\mathrm{GeV}^2$, spatial resolution $\ll 0.3\,\mathrm{fm}$

- Similar expressions/techniques for polarized scattering, non-inclusive final states

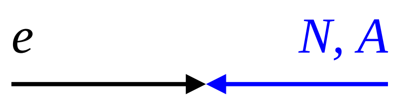
Electron scattering: Technologies



- Beam on fixed target

  High rates from density of particles in target

  Center–of–mass energy grows as $s = 2 E_e M_p$



- Colliding beams

  Higher energies: $s = 4 E_e E_p$ Product of beam energies!

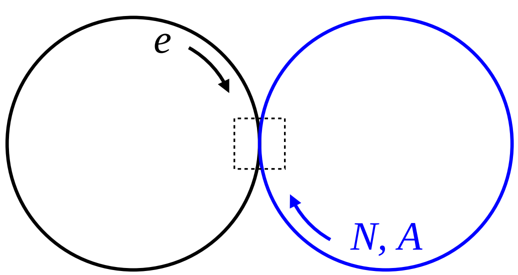
  Energy–efficient: Beams collide multiple times

  Clean: No scattering from atomic electrons

  Detection: Recoil proton/nucleus, variable angles

  Demands much higher beam quality:
  Focusing, cooling, time structure

  Integration of detectors and accelerator
  elements at interaction point

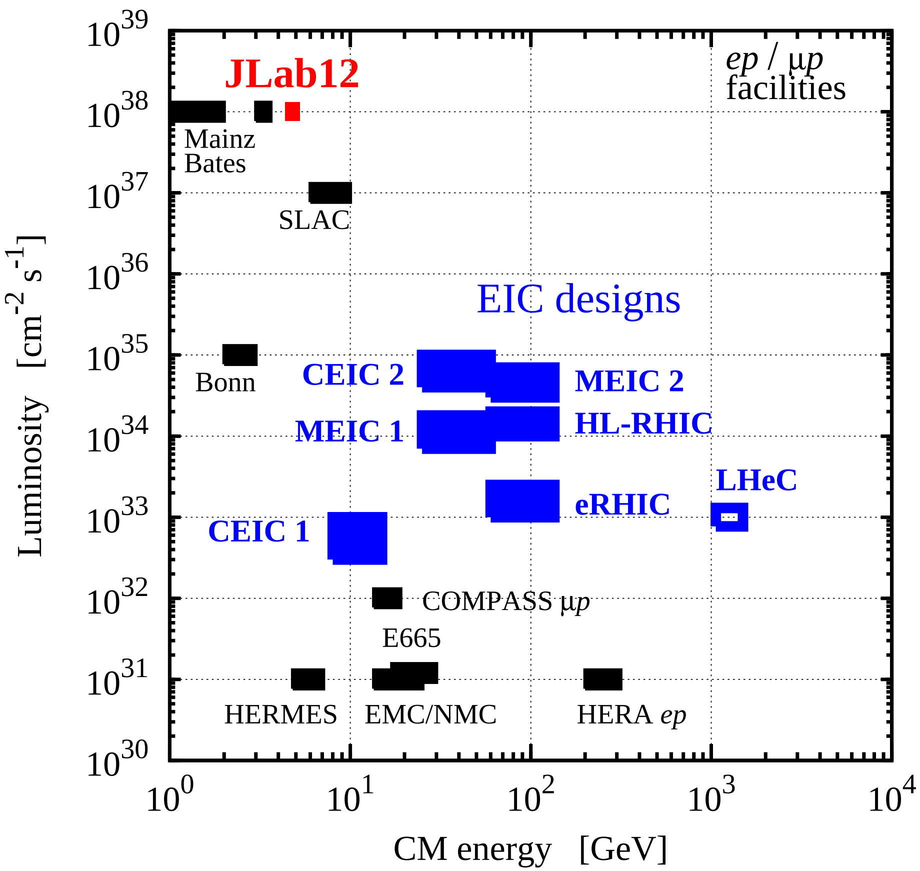


Experience with storage rings: e^+e^- (LEP, PEPII, KEK, DAΦNE), $pp/p\bar{p}$ (RHIC, Tevatron, LHC), AA (RHIC, LHC), ep (HERA)

Electron scattering: Luminosity

$$\frac{N_{\text{event}}}{T} = L \times \sigma$$

Rate Luminosity Cross section



- Luminosity

  Determines event rate for given scattering 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!

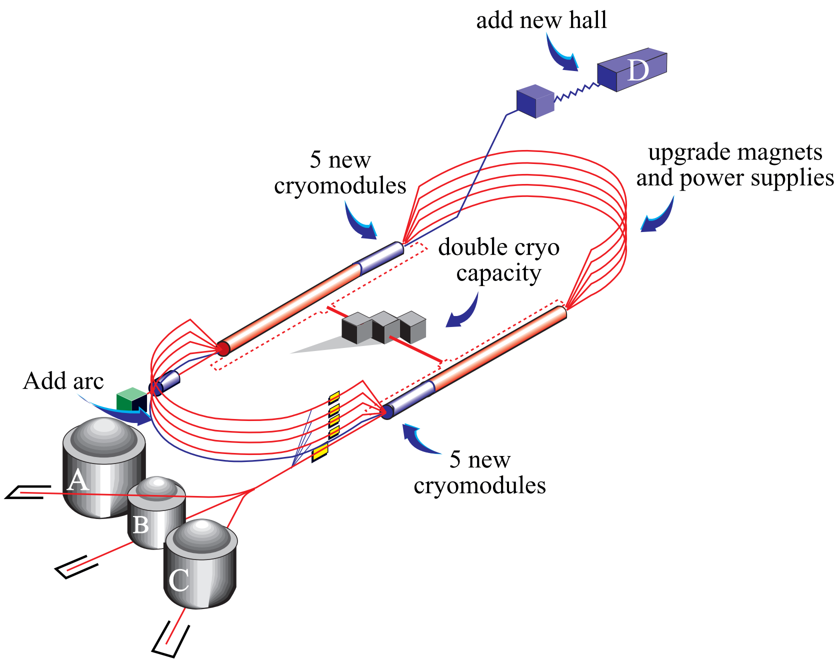
- JLab 12 GeV

  Energy $\times$ 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

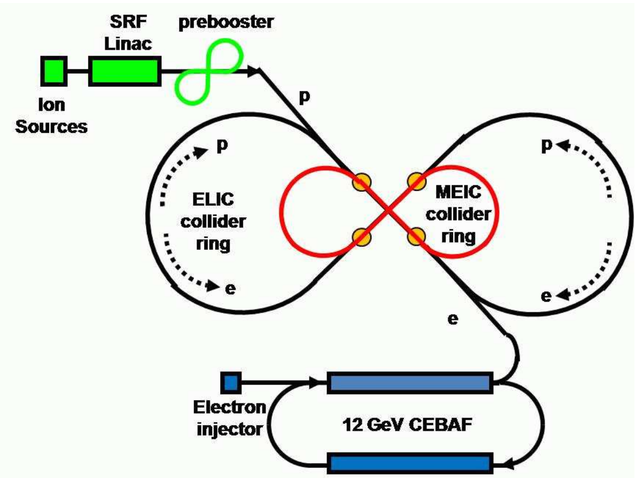
  DOE project (CD0 2004, CD3 2008)

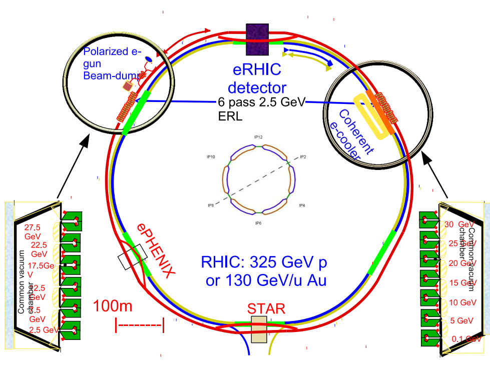
  Construction on–going, beam exp. 2013

  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

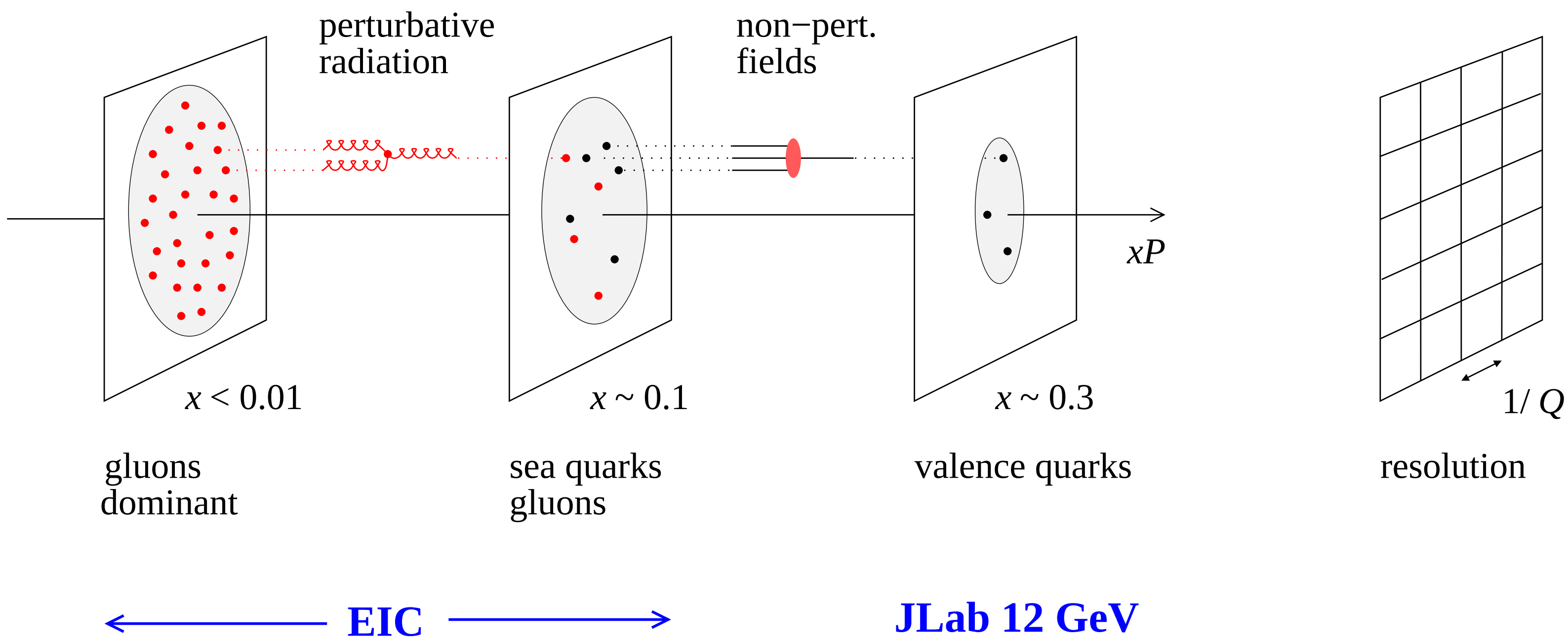
  RHIC proton/ion beam up to 325 GeV
  5–20 (30) GeV electrons from linac in tunnel staged
  Luminosity $\sim 10^{34} (10^{33})$ over wide range
  Re-use RHIC detectors? ePHENIX

- 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

  EIC@China project in Lanzhou
  Design targets similar to JLab MEIC

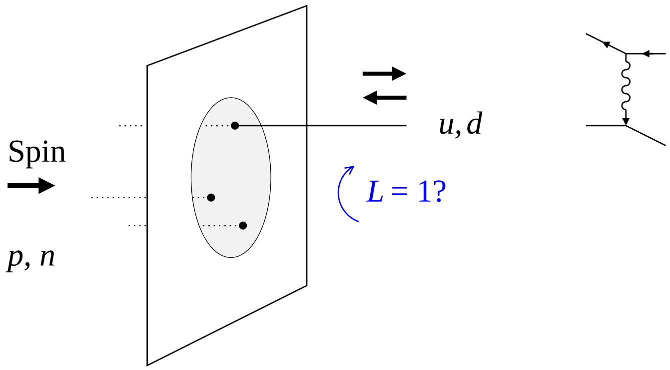
Nucleon structure: Many–body system

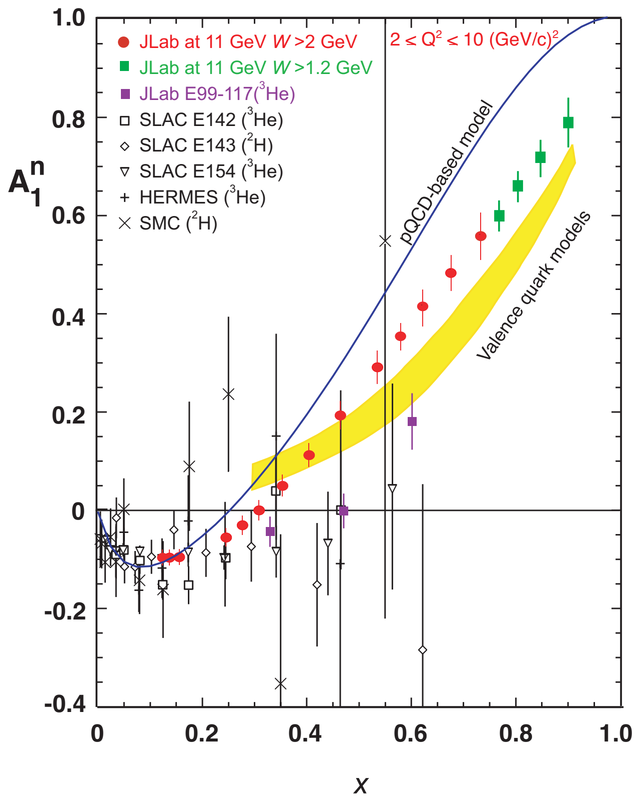


- Measurable properties

$$\left.\begin{array}{l}\text{Particle densities, including spin/flavor dependence}\\ \text{Transverse spatial distributions}\\ \text{Orbital motion: Transverse momenta, polarization}\\ \text{Particle–particle correlations}\end{array}\right\}\ \begin{array}{l}\text{change with}\\ \text{resolution scale}\\ 1/Q!\end{array}$$

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

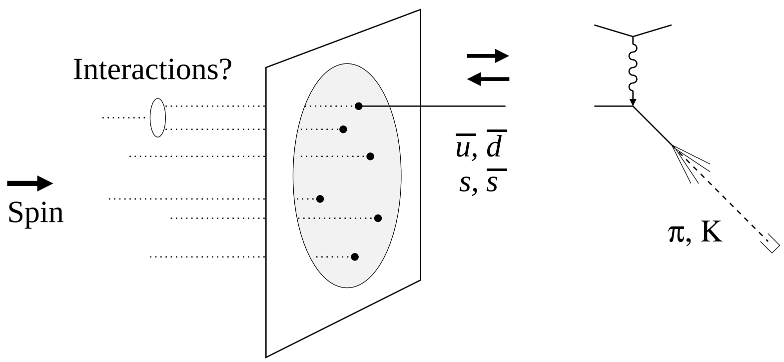
  Poorly constrained by present data
  SLAC, HERMES

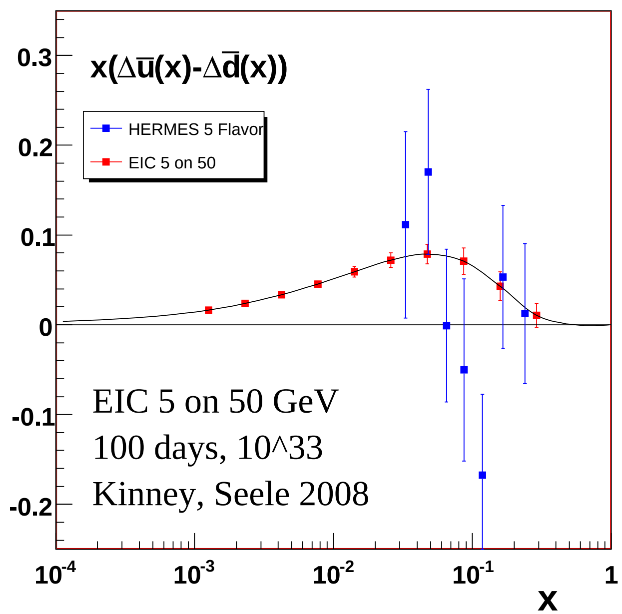
- JLab12: Map d quark polarization precisely up to $x \sim 0.8$

  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 QCD interactions connecting valence ↔ sea quarks?

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

- Semi–inclusive scattering: Identify particles produced from struck quark

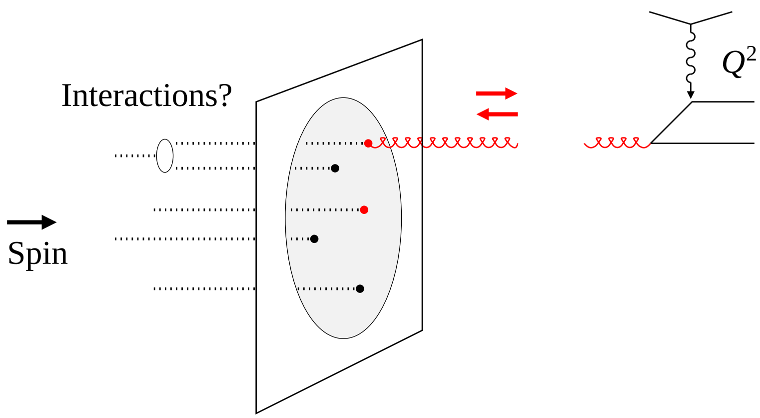
  "Tag" charge and flavor of struck quark

  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

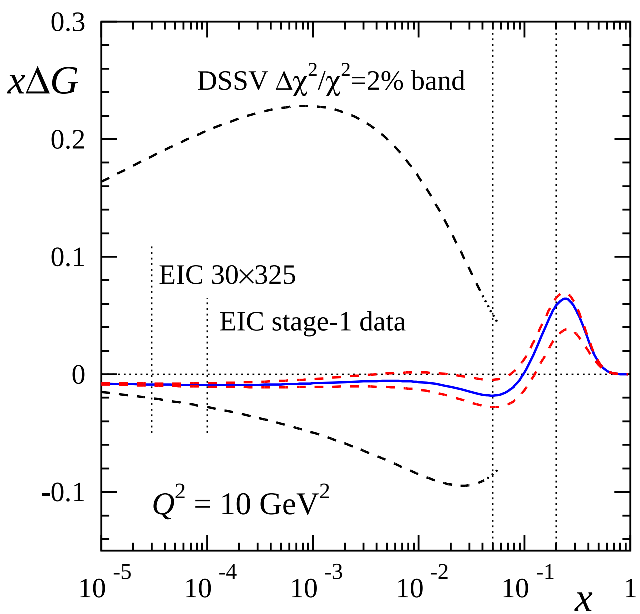


- How do gluons respond to nucleon spin?

  Origin of non-perturbative gluon fields?

  Gluon contribution to nucleon spin?
  "Spin puzzle"

  Orbital angular momentum in nucleon wave function?



M. Stratmann, INT Workshop 2010

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

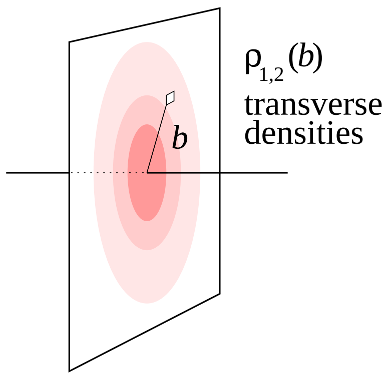
  Q^2 dependence of polarized nucleon structure function $g_1(x, Q^2)$
  EMC/SMC, SLAC, HERMES, COMPASS, JLab 6/12 GeV

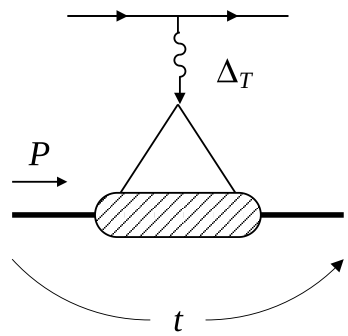
  Hard processes in $\vec{p}\vec{p}$ RHIC Spin

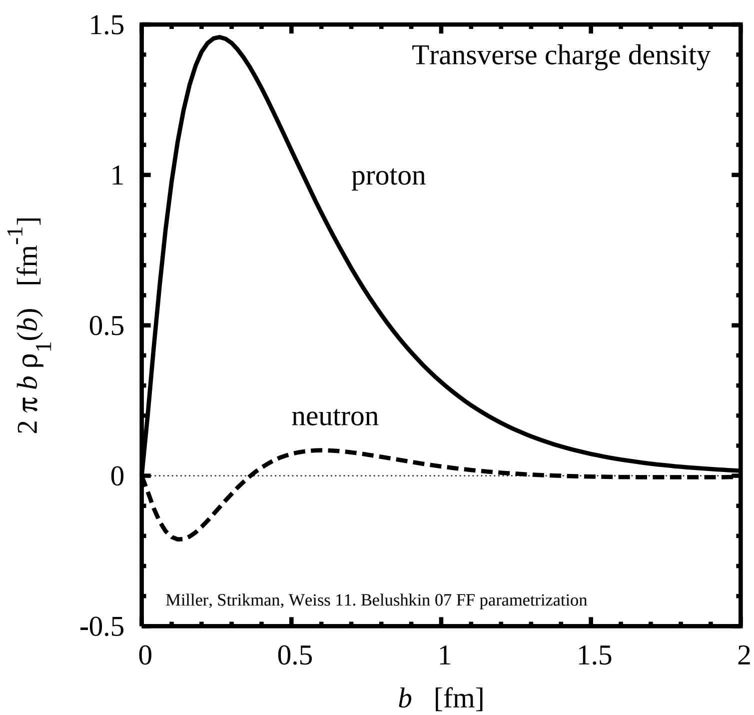
- EIC: Fully quantitative determination of gluon polarization

  Wide kinematic coverage enables study of Q^2 evolution

Nucleon structure: Transverse densities







- How are quarks distributed in transverse space?

  Spatial size of nucleon?

  Dynamics: Valence quarks, pion cloud

- Transverse densities
  Soper 76, Burkardt 00, Miller 07

  Elastic scattering at low $t = -\boldsymbol{\Delta}_T^2$

  $\langle N' | J_\mu | N \rangle \;\; \rightarrow \;\; F_1(t), F_2(t)$ Dirac, Pauli

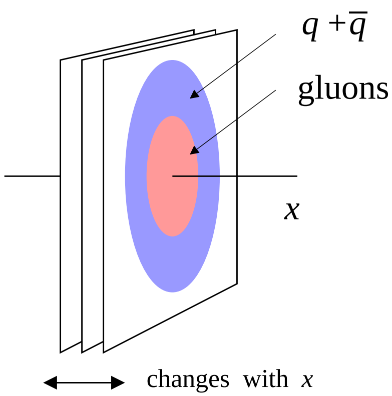
  $$F_{1,2}(t) \;=\; \int d^2 b \; e^{i \boldsymbol{\Delta}_T \boldsymbol{b}} \; \rho_{1,2}(b)$$

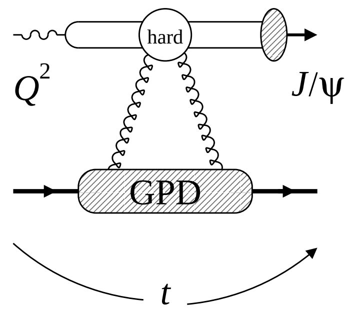
  Transverse charge/magnetization density

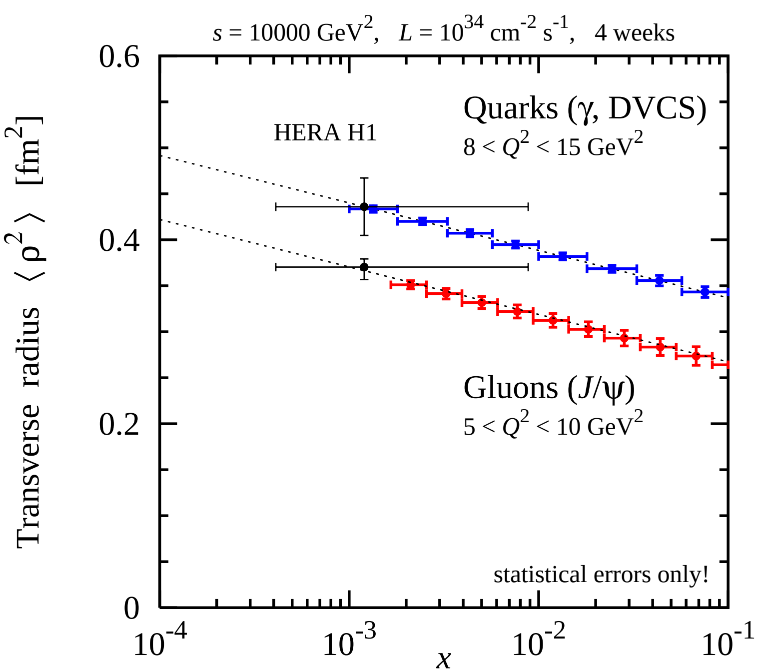
- Projection of quark distributions

  $$\rho_1(b) = \sum_q e_q \int dx \; f_{q-\bar{q}}(x, \boldsymbol{b})$$

EIC: Transverse distribution of quarks/gluons







- 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

Nucleon structure: 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

- Quark/gluon correlations

  Multiparton distributions, perturbative and non-perturbative correlations

  Higher–twist effect (power corrections)

- Electroweak probes

  Neutral/charged current nucleon structure functions

Summary

- Nucleon in parton picture — a many–body system

  Unifying perspective

  Relativity + quantum mechanics + strong interactions

  Natural connection with high-energy scattering processes

- Partonic structure beyond number desities

  Polarized distributions, flavor decomposition

  Transverse spatial distributions

  Transverse momentum, correlations

  Enabled by luminosity, polarization, detection capabilities!

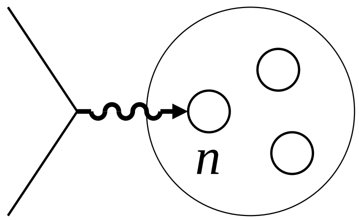
- JLab 12 GeV and EIC complementary

  Both extend energy–luminosity frontier in electron scattering

  JLab 12 GeV: Valence quark structure

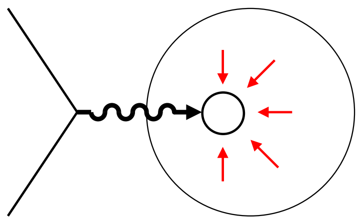
  EIC: Sea quarks, gluons, Q^2 dependence

Nuclei: Physics questions



- Neutron structure

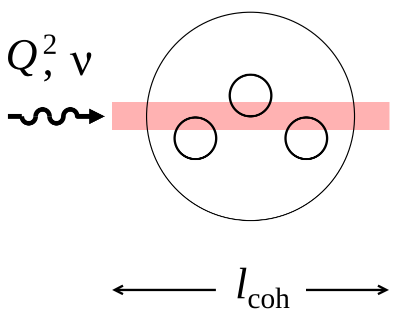
  Needed for flavor decomposition of quark spin, sea quarks $\Delta\bar{u}$, $\Delta\bar{d}$, gluon polarization Δg



- Bound nucleon in QCD

  Modification of basic quark/gluon structure by nuclear medium

  QCD origin of nuclear forces?
  Short-range NN correlations
  Non-nucleonic degrees of freedom?



Here: Nucleus rest frame view

- Coherent phenomena

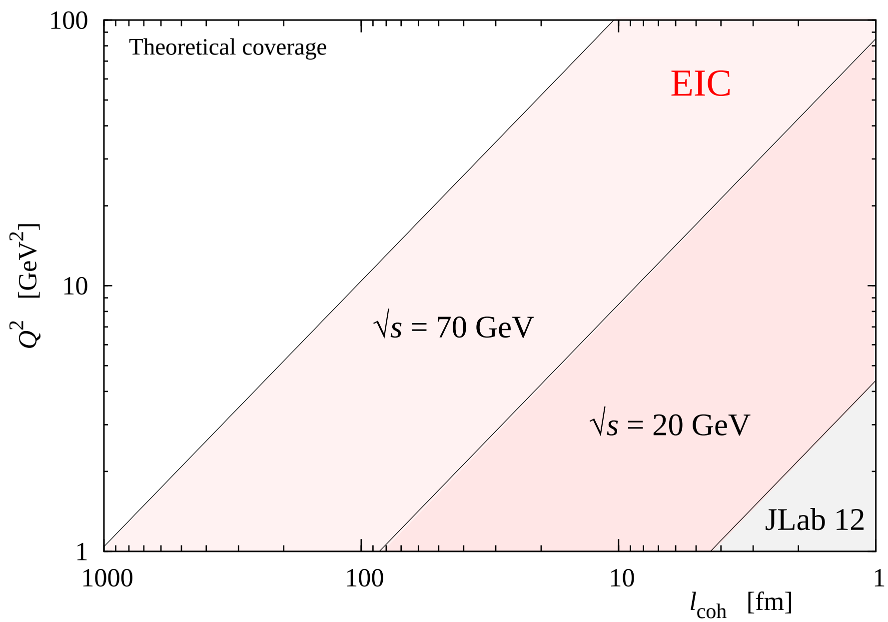
  $$l_{\mathrm{coh}} \sim \frac{2\nu}{Q^2} = \frac{1}{x_B M_N} \qquad \text{coherence length}$$

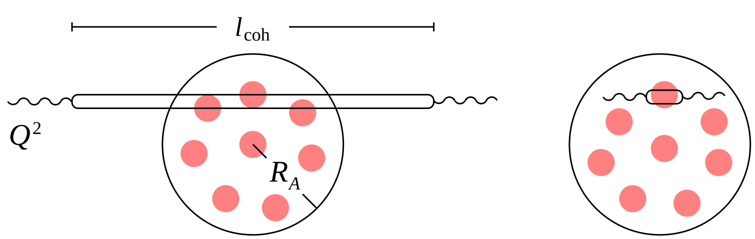
  $l_{\mathrm{coh}} \gg$ nucleon distance: High–energy probe interacts coherently with quarks/gluons in multiple nucleons

  QCD phenomena: Shadowing, saturation, diffraction

  Other uses of nuclei: Transparency, hadronization

Nuclei: Kinematic range





- JLab 12 GeV

  Neutron valence quarks $x \sim 0.3$

  Bound nucleon valence structure: EMC effect, short–range correlations

- EIC

  Neutron sea quarks $x < 0.1$

  Nuclear modification of sea and gluons, Q^2 dependence

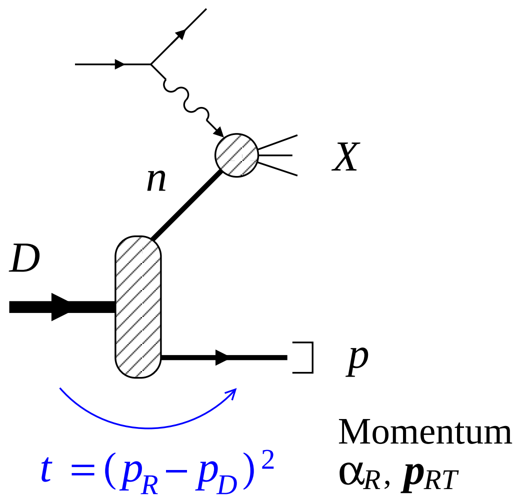
  Color transparency: Disappearance of interaction for small probes $\sigma \propto r^2$
  Fundamental prediction of QCD as gauge theory

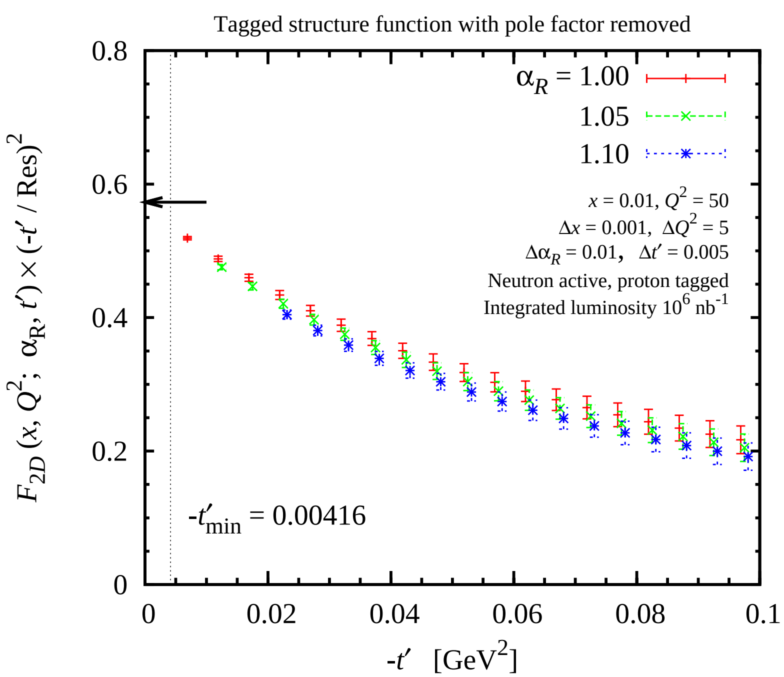
  Shadowing: QM interference in scattering from multiple nucleons

  Saturation: High gluon densities, unitarity limit in hard interactions
  New dynamical scale Q_S

  Quantum fluctuations: Diffraction

JLab, EIC: Neutron structure





- What are the quark/antiquark densities in the polarized neutron?

  Flavor decomposition of quark spin

  Nuclear targets: dilution from protons, Fermi motion, binding, final-state interaction

- Spectator tagging $\vec{e}\vec{D} \to e' + p + X$

  Identifies active nucleon

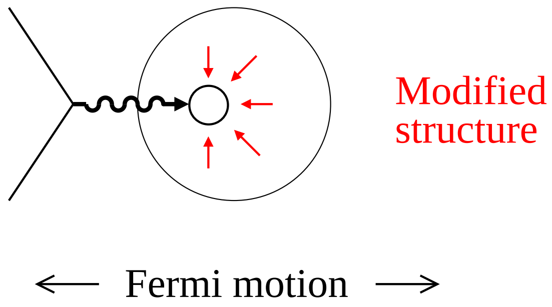
  On-shell extrapolation $t \to M_N^2$ eliminates Fermi motion, binding, FSI
  Sargsian, Strikman 05. Model–independent method

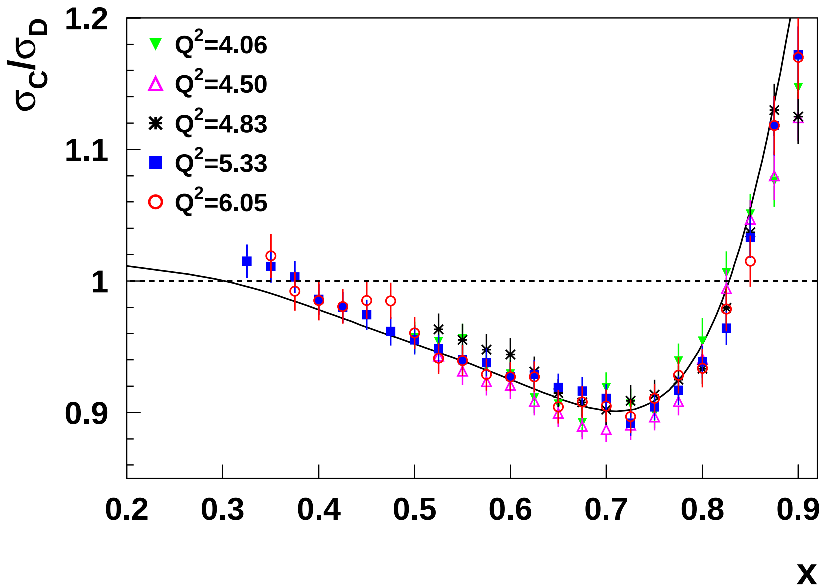
  JLab 6/12 BONUS: Unpolarized D, $x > 0.3$

  EIC: Polarized D, $x < 0.1$, forward proton detection, precision measurements!
  JLab 2014 LDRD project

  EIC: Forward neutron detection, bound proton structure function
  Compare with free proton: Binding effects!

JLab: Bound nucleon





JLab 6 GeV: Seely et al. 2009.
Extended measurements with 12 GeV

- How are the nucleon's quark/antiquark distributions modified in the nucleus?

  Modification caused by "mean field" or short–range NN correlations?

  QCD origin of NN interaction?

- JLab 6/12 GeV: Inclusive $eA \rightarrow e' + X$

  σ_A/σ_D ratio shows modification

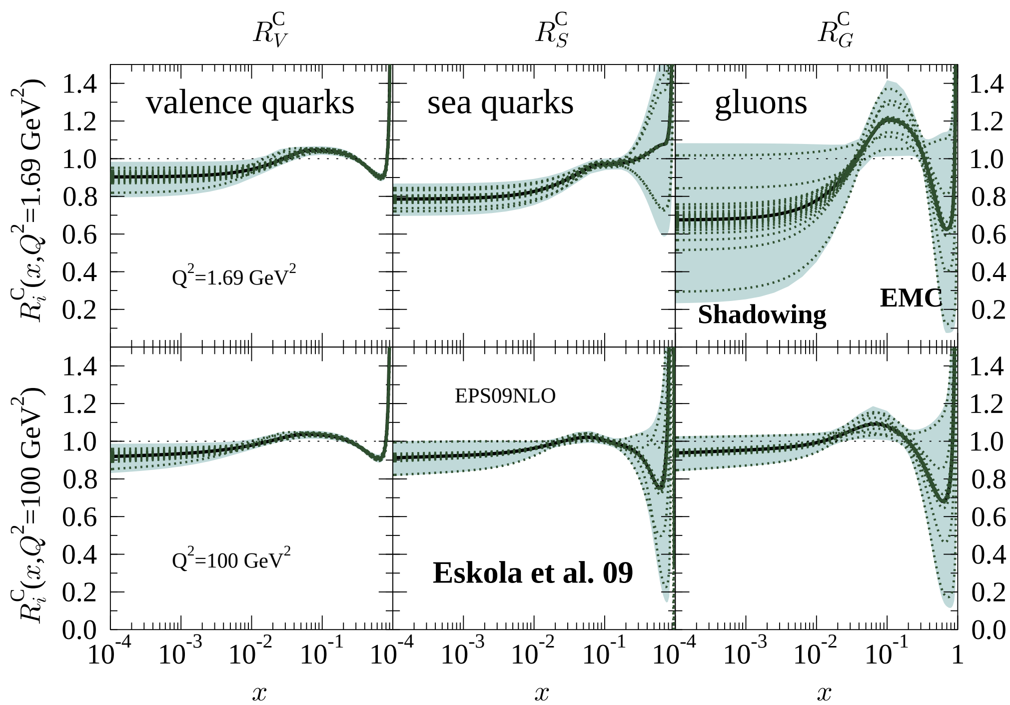
  Spectator tagging $eA \rightarrow e' + N + X$: Short-range correlations?

- Spectator tagging $eA \rightarrow e' + N + X$

  Modification $\leftrightarrow$ short-range correlations?

- EIC: Q^2 dependence and $x < 0.1$

EIC: Gluons and sea quarks in nuclei



- Nuclear quark/gluon densities

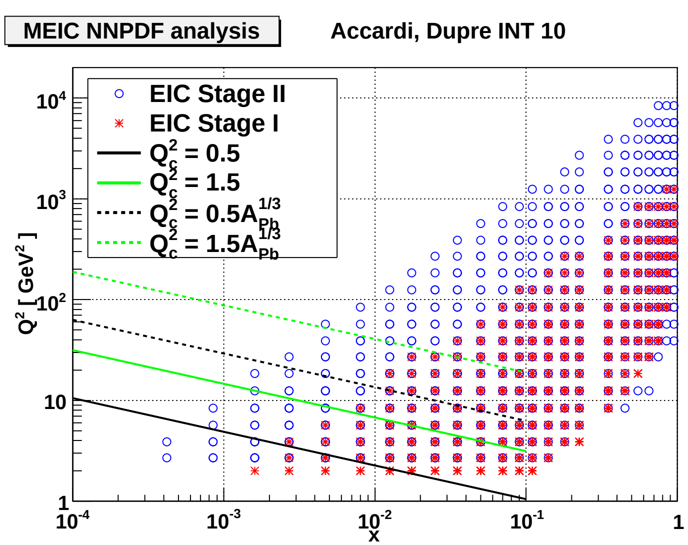
  $x > 0.1$ "EMC effect:" Modification of free nucleon structure:

  $x \sim 0.1$ Antishadowing: Poorly understood

  $x \ll 0.1$ "Shadowing:" QM interference

- Gluon poorly constrained

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



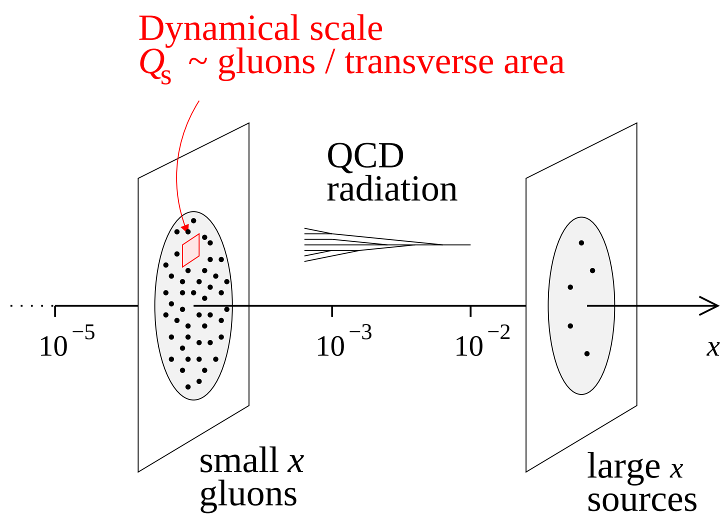
- Medium–energy EIC: Precise determination of nuclear quark/gluon densities

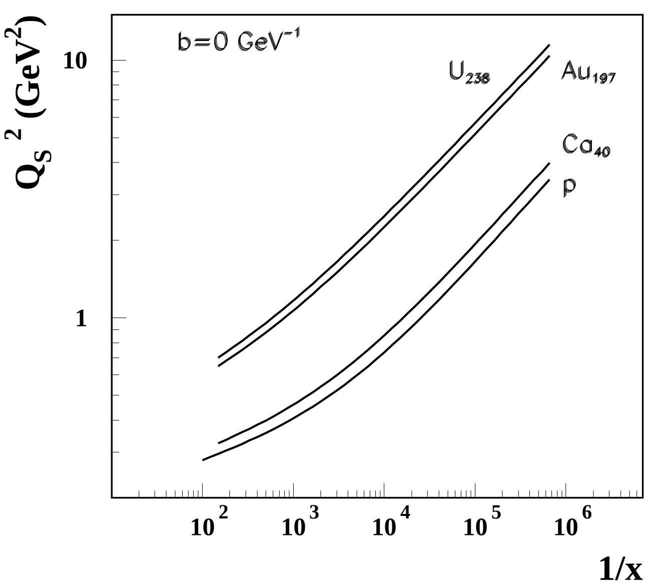
  Wide coverage in x, Q^2

- Inportant for understanding approach to saturation at small x

  Shadowing affects nuclear enhancement of Q_S

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

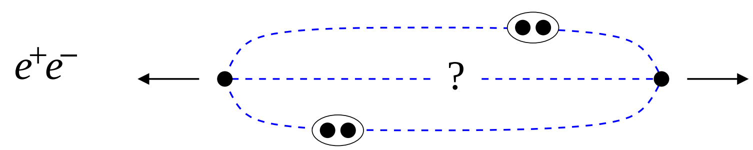
  Multiple hard processes, correlations

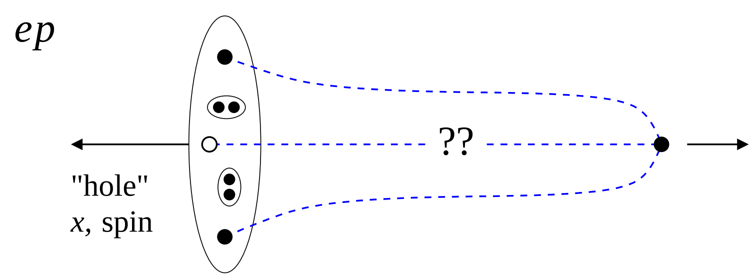
- Expected to be enhanced in nuclei

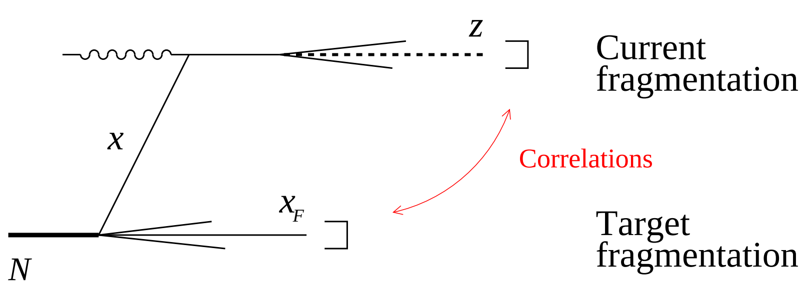
  $Q_s(x) \sim A^{1/3}$ without shadowing, depends on nuclear gluon density

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

Hadronization: Quark 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
  Vacuum structure, $q\bar{q}$ condensate

- Fragmentation functions from e^+e^-

  Many puzzles: $s\bar{s}$, kaons, baryons
  Essential input to SIDIS

- EIC: New possibilities

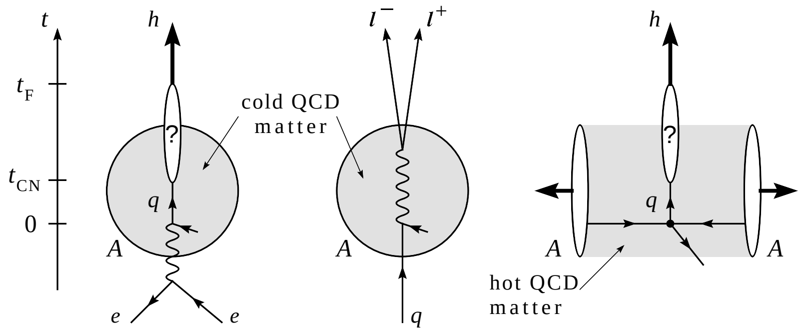
  Fragmentation functions from ep:
  Favored $\leftrightarrow$ unfavored, test universality

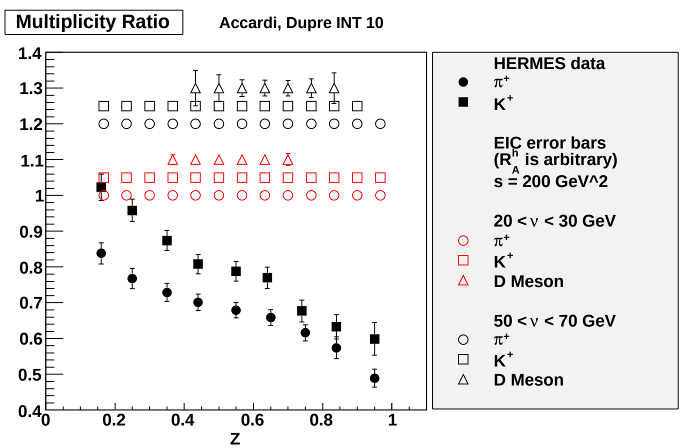
  Target fragmentation: How does nucleon with "color hole" materialize?
  x, spin dependence

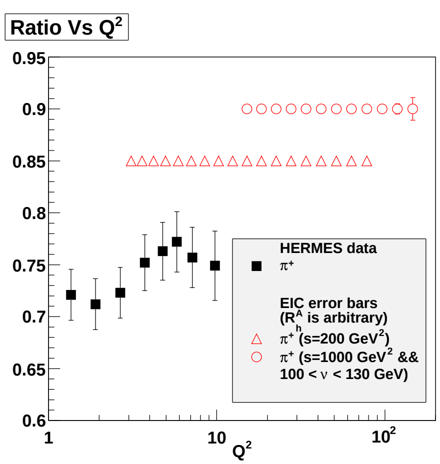
  Correlations current–target regions:
  Multiparton correlations
  New field of study: pp at LHC
  New possibilities for nucleon structure

  Qualtiatively new! Many applications! Unique for EIC

Hadronization: In medium







- 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
  Fixed–target: Correlations ν–Q^2

  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

EIC: Project status, 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 BNL and JLab
  http://www.jlab.org/meic/

  International EIC Advisory Committee, several reviews of physics and accelerator designs

  Increasingly supported by lab users JLab User Workshops 2010

- Topical conferences/workshops dedicated to EIC science & technology

  2011 Institute of Nuclear Theory Program (INT): Very strong participation. Talks on-line at http://www.int.washington.edu/PROGRAMS/10-3/

  EIC14 Accelerator Science & Technology Workshop, JLab, March 17-21, 2014
  http://www.jlab.org/conferences/eic2014/

- Working toward full recommendation in 2014 NSAC LRP
  Further timeline tentative. Site selection? CD0? Budget realities

Needs support of the nuclear physics and broader scientific community!

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`http://arxiv.org/abs/arXiv:1212.1701`

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`http://arxiv.org/abs/arXiv:1110.1031`

3. Detailed summary report of 2010 INT Program: "Gluons and the quark sea at high energies: Distributions, polarization, tomography," D. Boer et al.
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4. Web resources at:
`http://eic.jlab.org/` (JLab)
`https://wiki.bnl.gov/eic/` (BNL)

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