Nuclear physics with a medium–energy EIC

C. Weiss (JLab), POETIC Workshop, Indiana University, Bloomington, 20–Aug–12

I) 3D structure of nucleon in QCD

Sea quark and gluon polarization

Spatial distributions, orbital motion

Multiparton correlations

II) Fundamental color fields in nuclei

Nuclear quark/gluon densities

Shadowing, coherent processes

Color transparency

III) Emergence of hadrons from color charge

Color neutralization, hadron formation

Interaction of color charge with matter

- Overview of ep/eA physics with "generic" medium–energy EIC

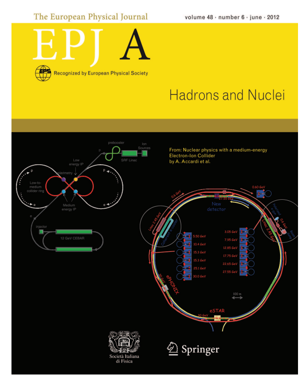
  $$\sqrt{s} = 20\text{–}70 \text{ GeV}, L \sim 10^{34}\text{cm}^{-2}s^{-1}$$

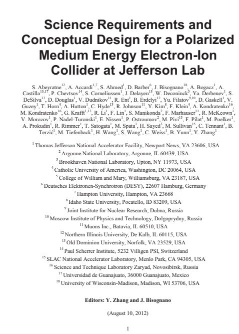
  Based on review article A. Accardi et al., EPJA48 (2012) 92.
  Input to JLab MEIC Concpetual Design Report (2012)

- Guiding principles

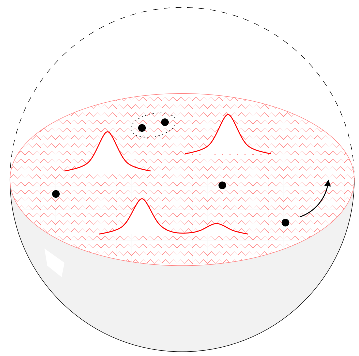
  Focus on physical system, not formal descriptors:
  "What do we learn about dynamics?"

  Unifying perspective low $\leftrightarrow$ high energies




Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

3D nucleon structure: Fields and particles

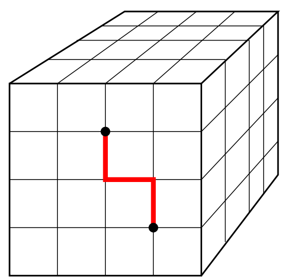


- Hadrons in QCD

  Relativity: Particle creation/annihilation, space–time picture frame dependent

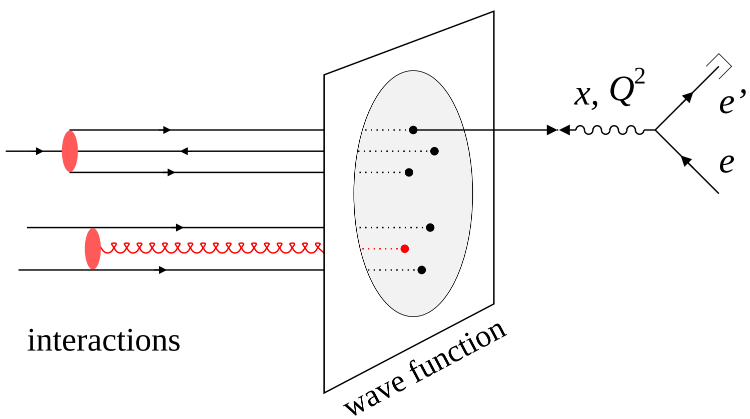
  Strong interactions: Vacuum structure, non–perturbative effects

  Quantum mechanics: Fluctuations
  Uniquely challenging dynamical system!



- Field–theoretical description

  Imaginary time $t \rightarrow i\tau$, statistical mechanics
  Lattice QCD; analytic methods



- Particle–based description

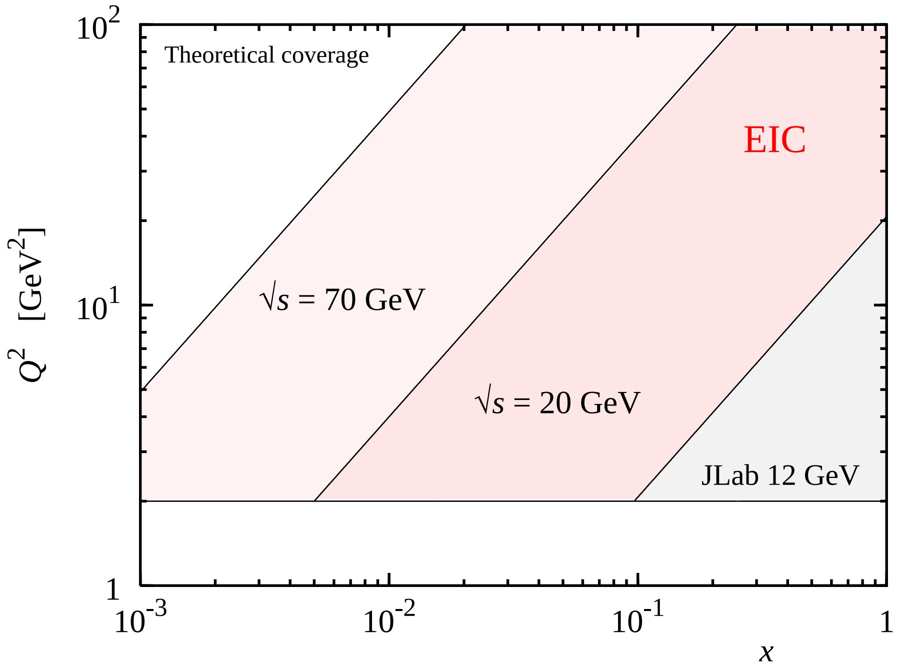
  Parton picture $P \rightarrow \infty$: Wave function
  Feynman, Gribov: Closed system. Alt: Light–front quantization

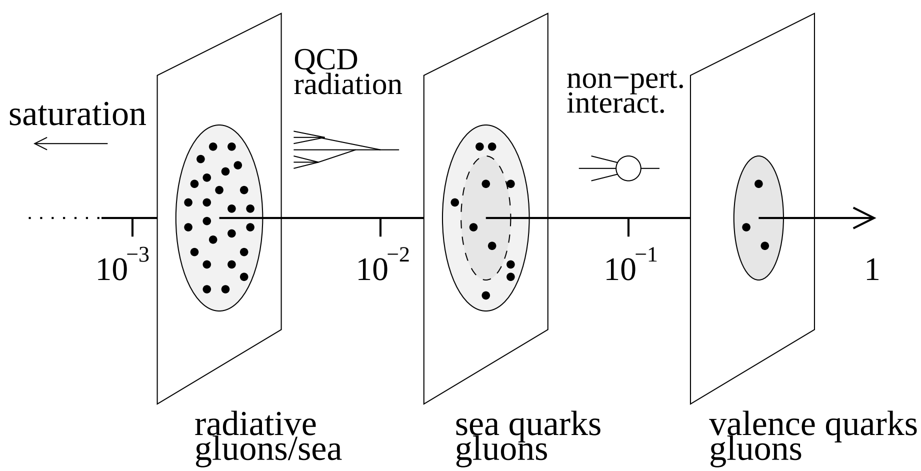
  Components with different particle number

  Many–body system: Constituents, interactions, spatial structure, orbital motion, . . .

  High–energy process takes snapshot
  Short–distance interactions: Factorization

3D nucleon structure: Landscape





- Components probed predominantly

$x > 0.1$	Valence quarks: Source, quantum numbers Also gluons at large x! Intrinsic sea $s\bar{s}$, $c\bar{c}$?
$x \sim 10^{-1}$ -10^{-2}	Sea quarks, gluons: Quantum numbers Generated by non–perturbative QCD interactions!
$x < 10^{-2}$	Gluons, singlet sea: Radiatively generated Saturation at small x: New dyn. scale

Learn about interactions!

- Quantities measured

Particle number densities, incl. spin/flavor dependence — PDFs

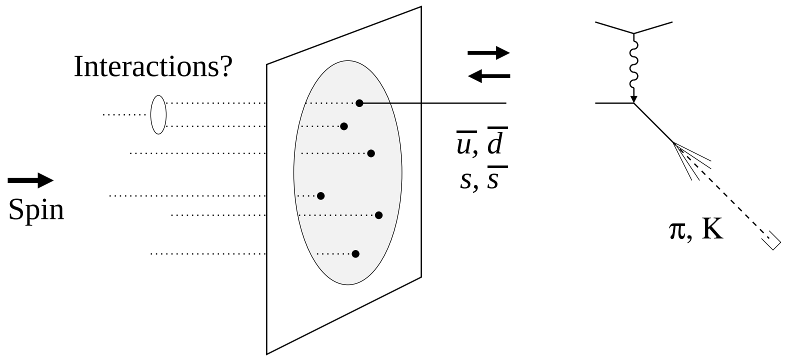
Transverse spatial distributions — GPDs

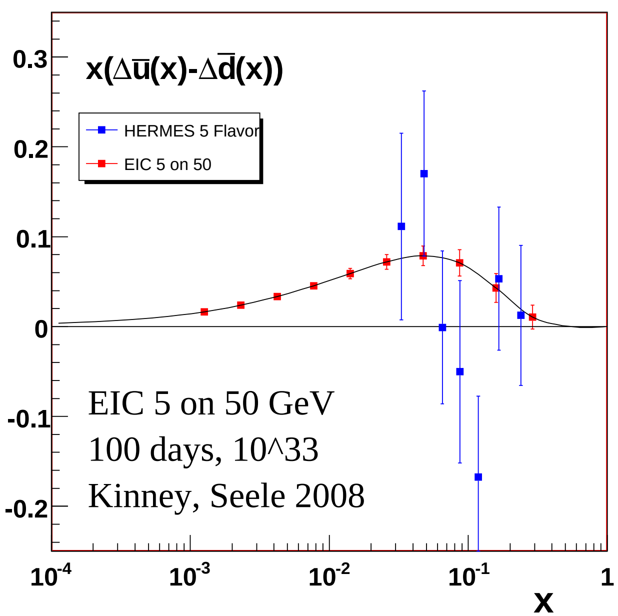
Orbital motion, angul. momentum — TMDs

Particle correlations — MP distributions, GPDs

Densities with operator definition $\langle N | \, \mathrm{QCD{-}Op} \, | N \rangle$
Calculable with non–perturbative methods
Scale dependence from RNG equation.

3D nucleon structure: Sea quark polarization





- How are sea quarks polarized in nucleon?

  Non-perturbative QCD interactions connecting valence $\leftrightarrow$ sea quarks

  Role of mesonic degrees of freedom?

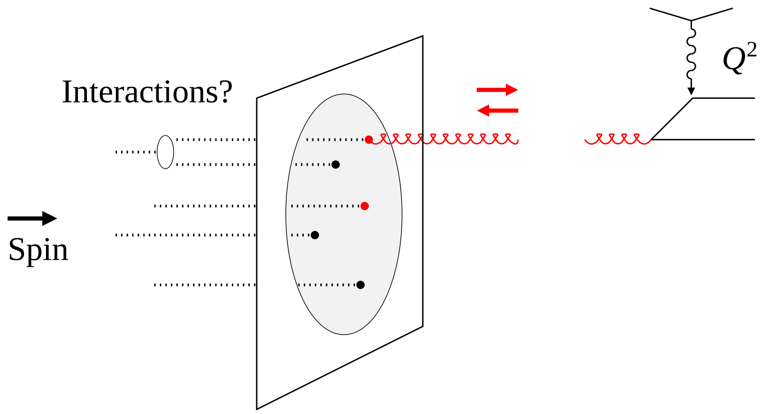
- Semi–inclusive scattering: Identify particles produced from struck quark

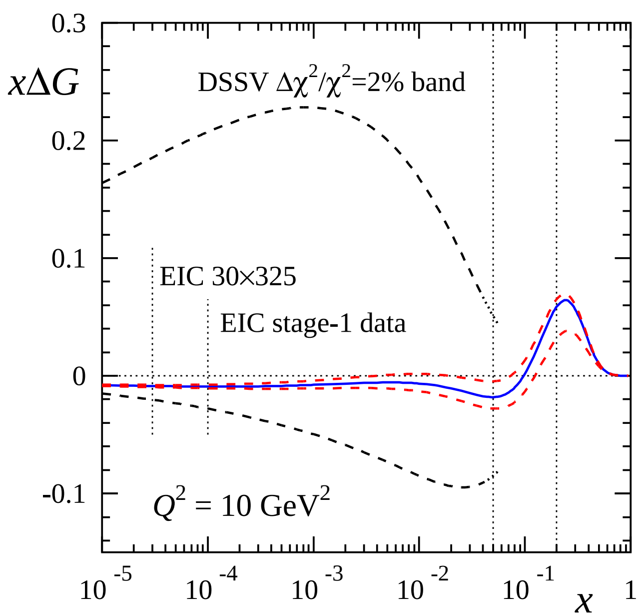
  Flavor asymmetries poorly constrained by present data
  HERMES SIDIS
  First constraints from RHIC W data

- EIC: Map sea quark distributions and their spin dependence

  High energy ensures independent fragmentation of struck quark

3D nucleon structure: Gluon polarization





M. Stratmann, INT Workshop 2010

- What is the polarized gluon distribution?

  Origin of non-perturbative gluon fields?
  "Constituent quark" structure, quark correlations?

  Gluon contribution to nucleon spin?
  Orbital angular momentum in wave function?

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

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

  Hard processes in $\vec{p}\vec{p}$ RHIC: Recent data

- EIC: Fully quantitative determination
  Good results already with medium energy $\rightarrow$ Talk Stratmann

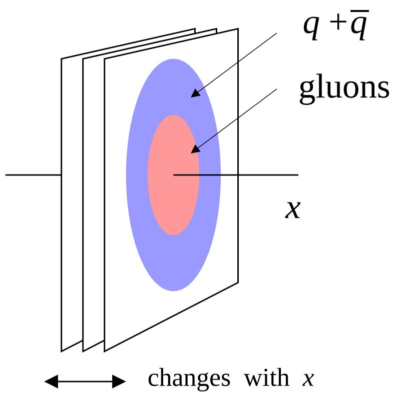
- Quark/gluon orbital angular momentum

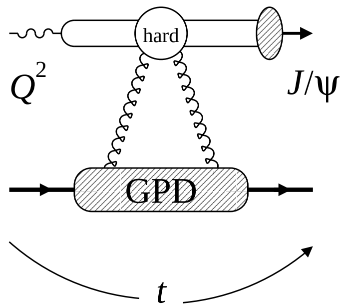
  Much progress in theoretical understanding
  INT Workshop Feb–12; many recent papers

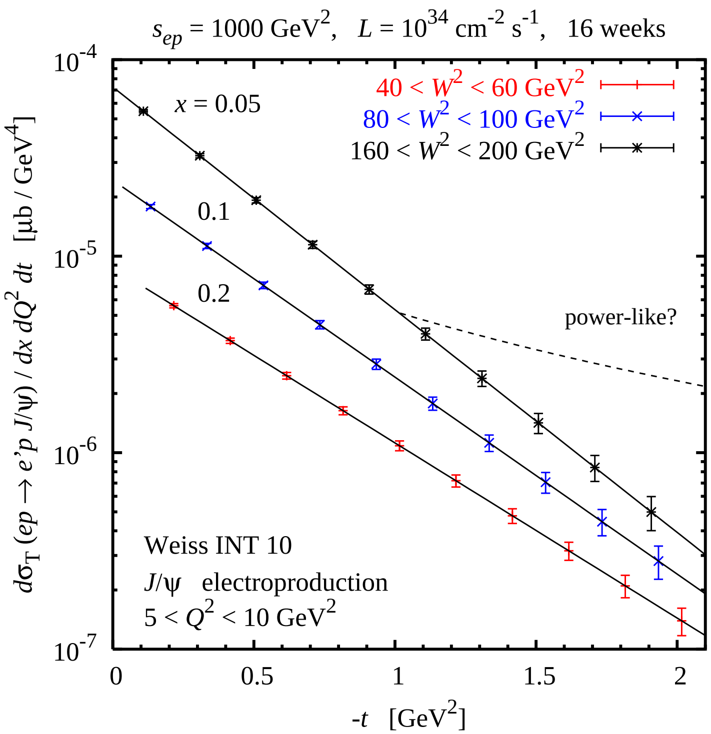
  Manifest in semi–inclusive spin asymmetries
  e.g. Sivers effect $\rightarrow$ Talk Prokudin

  Challenge to separate OAM in wave function from QCD final–state interactions
  $\rightarrow$ Talk Burkardt

3D nucleon structure: 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 saturation models, multiparton interactions in pp@LHC

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

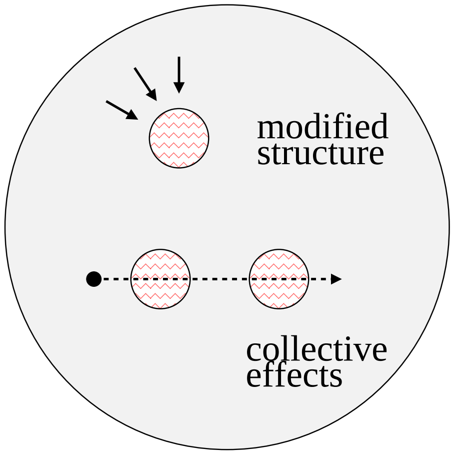
  Gluonic form factor of nucleon: Generalized parton distribution

  Other channels γ, ρ^0, π, K sensitive to quarks $\to$ Talks Hasch, Liuti, Fazio

- EIC: "Gluon imaging" of nucleon

  Luminosity for low rates, differential measurements

Color fields in nuclei: Physics



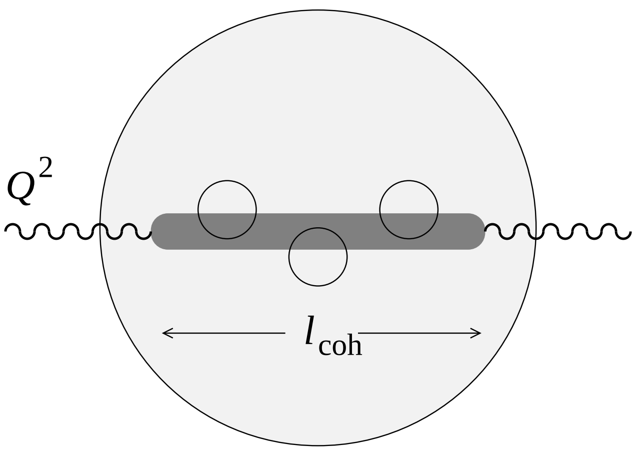
- What are the fundamental color fields in nuclei?

  Modification of nucleon structure

  Collective effects $A \neq \sum N$

  Non–nucleonic degrees of freedom

  $\rightarrow$ QCD origin of NN interaction at different energies
  $\rightarrow$ Approach to black–disk/saturation regime



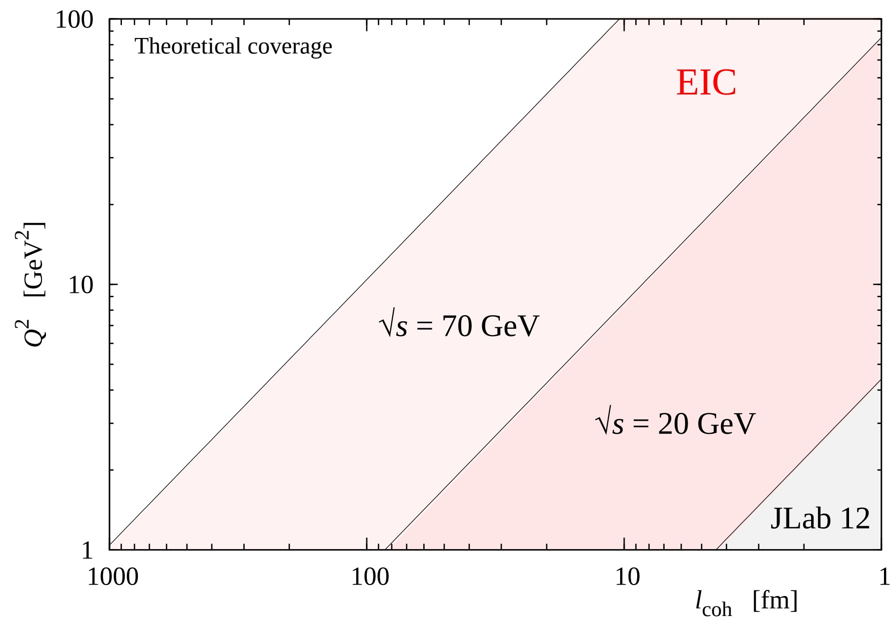
- Interaction with high–energy probe

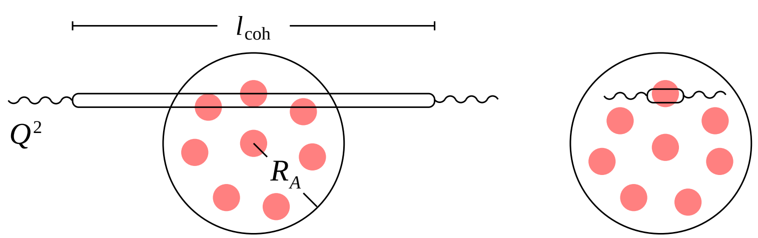
  Transverse resolution $r \sim 1/Q$

  Coherence length $l_{\mathrm{coh}} \sim \nu/Q^2 \times \mathrm{factor}$

  Final states: Inclusive, identified spectators, exclusive, . . .

Color fields in nuclei: Landscape





- Fields probed in eA

  $l_{\rm coh} \ll R_A$: Modified nucleon structure, short–range correlations
  JLab 12 GeV: EMC effect for valence quarks
  EMC effect for gluons, antiquarks?

  $l_{\rm coh} \gtrsim R_A$: Collective effects
  New regime accessible with medium–energy EIC!

- QCD phenomena

  Shadowing: QM interference in scattering from multiple nucleons
  Is it different for gluon and quark fields?

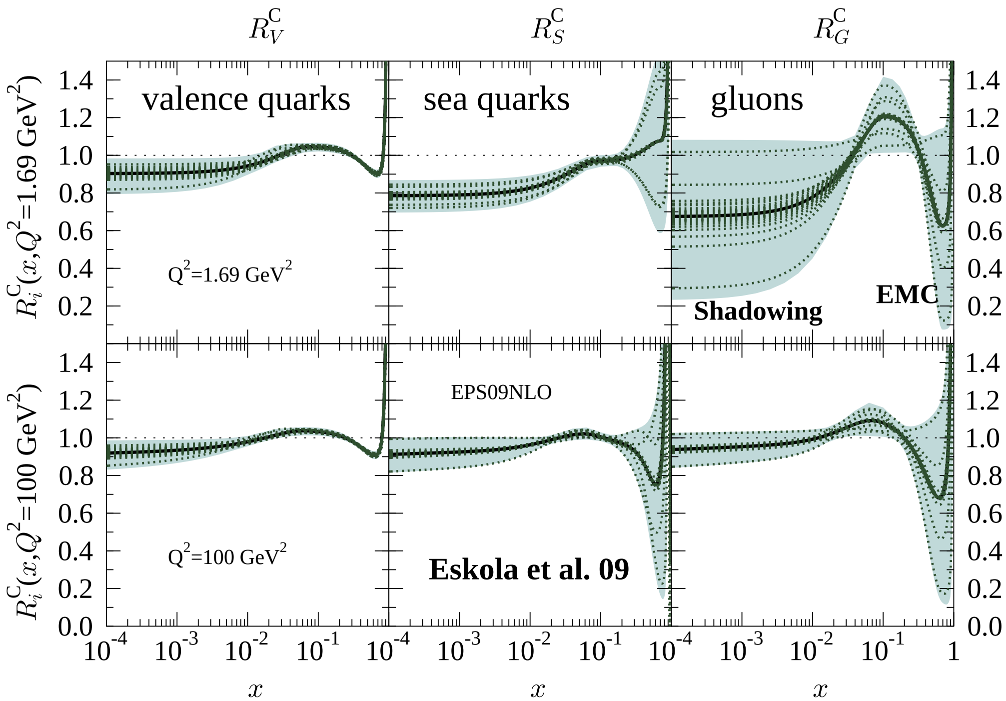
  Color transparency: Disappearance of interaction for small probes $\sigma \propto r^2$
  Fundamental prediction of QCD as gauge theory

  Coherent scattering: Quark/gluon fields of entire nucleus Nuclear GPDs, quark/gluon size

  Quantum fluctuations: Diffraction

  Saturation: Strong gluon fields, black disk regime in hard interactions
  New dynamical scale Q_s

Color fields in nuclei: Gluon density



- Nuclear quark/gluon densities

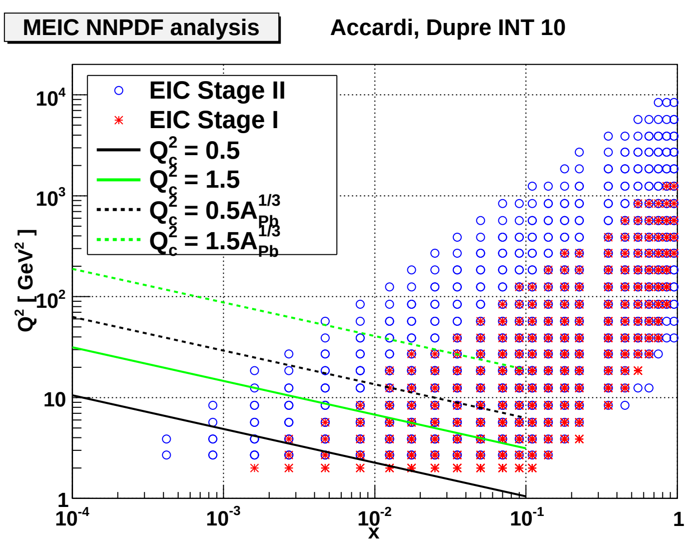
  $x > 0.1$ "EMC effect:" Modification of free nucleon structure:

  $x \sim 0.1$ Antishadowing: Poorly understood

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

- Gluon poorly constrained

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



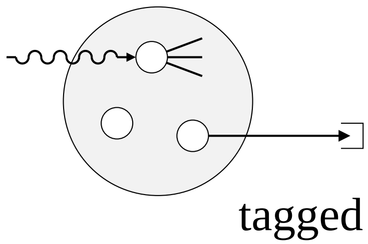
- Medium–energy EIC: Precise determination of nuclear quark/gluon densities

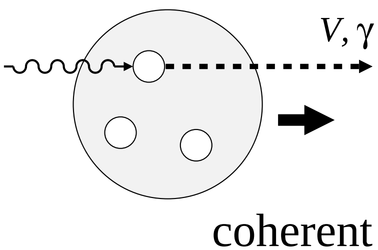
  Wide coverage in x, Q^2

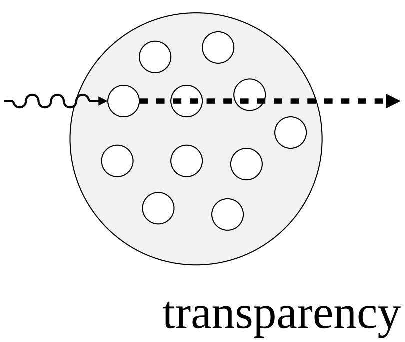
- Inportant for understanding approach to saturation at small x

  Shadowing affects nuclear enhancement of Q_S

Color fields in nuclei: New probes with EIC







- Spectator tagging

  Bound nucleon structure: EMC effect

  Neutron structure from $D(e, e'p)X$
  JLab BONUS experiment

  Requires forward p/n detection

- Coherent nuclear processes $A(e, e'M)A$

  Fundamental quark/gluon radii of light nuclei
  Kowalski, Caldwell 09: Heavy nuclei, very challeging

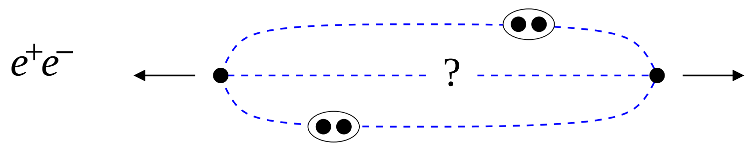
  Impact parameter dependent shadowing

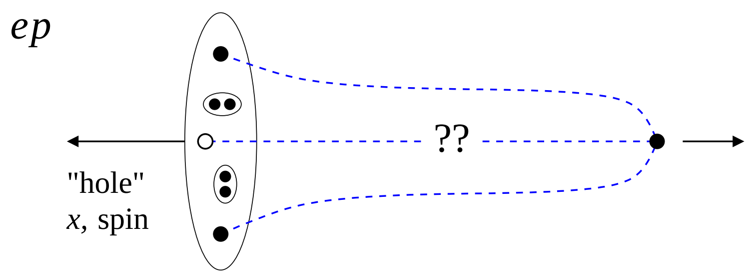
- Color transparency in meson production

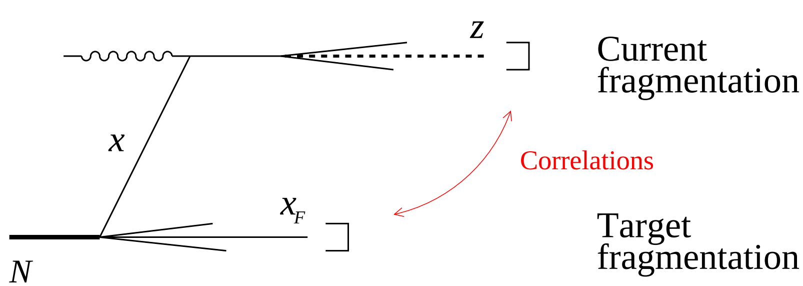
  Fundamental prediction of QCD

  Complement to saturation experiments:
  "Disappearance" at high Q^2

Hadrons from color charge: Fragmentation







- How do hadrons emerge from QCD color charge?

  Conversion energy $\longrightarrow$ 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

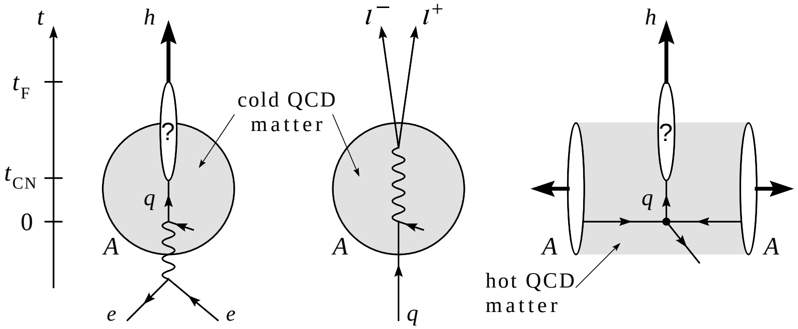
  Fragmentation functions from ep:
  Favored $\leftrightarrow$ unfavored, test universality

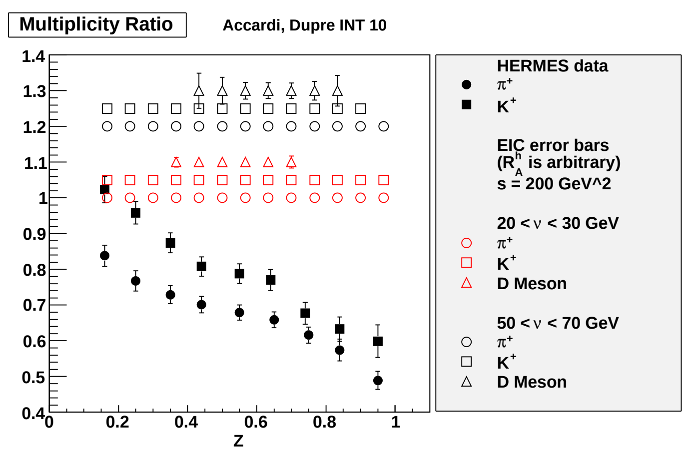
  Target fragmentation: How does nucleon with "color hole" materialize?
  x, spin dependence

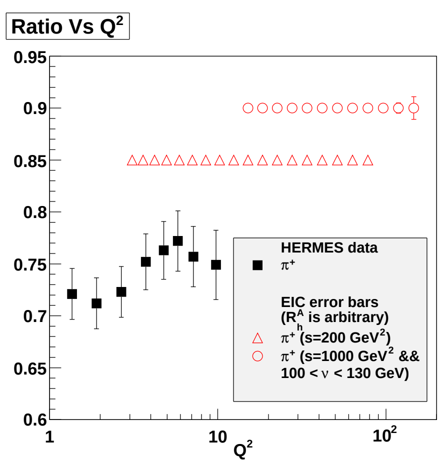
  Correlations current–target regions:
  Multiparton correlations
  New field of study: pp at LHC
  New possibilities for nucleon structure

  Qualtiatively new! Many applications! Unique for EIC

Hadrons from color charge: 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
  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

Summary

- Unique nuclear physics program with medium-energy EIC $\sqrt{s} =$ 20-70 GeV

  Three–dimensional structure of nucleon in QCD
  Fundamental color fields in nuclei
  Emergence of hadrons from color charge

  Natural organization . . . could be sharpened further!

- Focus on what we learn about the dynamical system

  Many questions addressed by more than one measurement:
  Orbital angular momentum — inclusive ΔG, semi–inclusive asymmetries;
  Quark correlations — exclusive and semi–inclusive processes

- Qualitatively new probes available in eA

  Spectator tagging, coherent processes: Should be developed further!

  ep better formalized, but eA completely new