

Nuclear physics with a medium-energy EIC

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

- Overview of ep/eA physics with “generic” medium-energy EIC

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

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

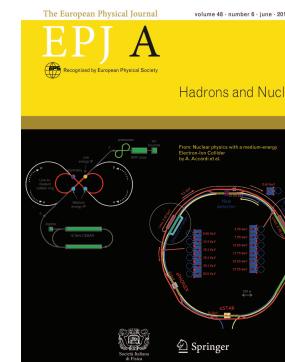
Color neutralization, hadron formation
Interaction of color charge with matter

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

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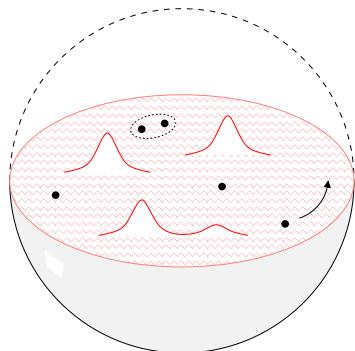
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3D nucleon structure: Fields and particles

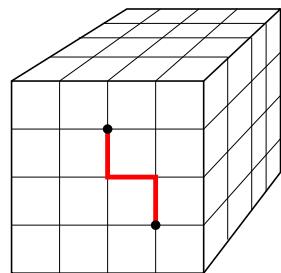


- Hadrons in QCD

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

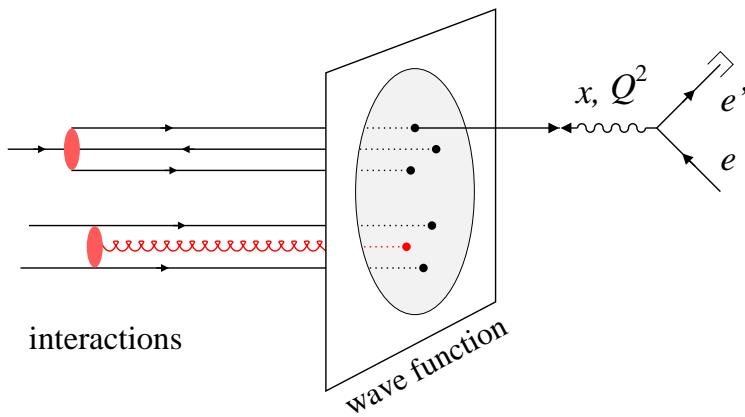
- Particle–based description

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

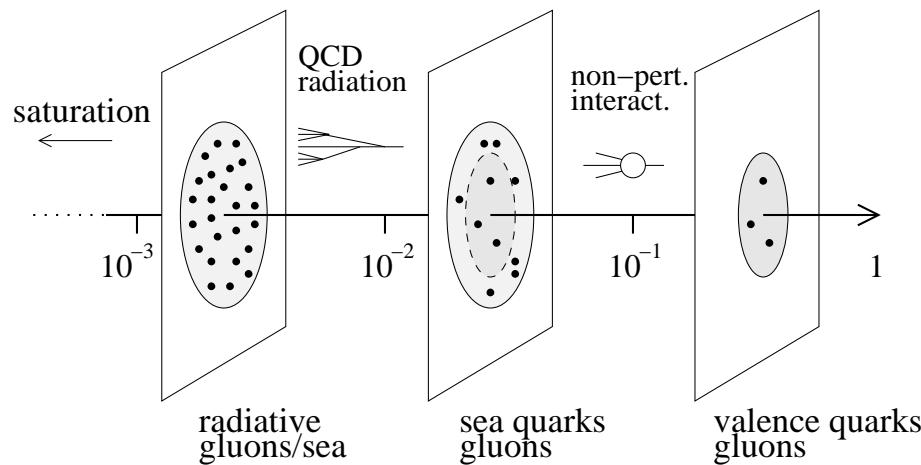
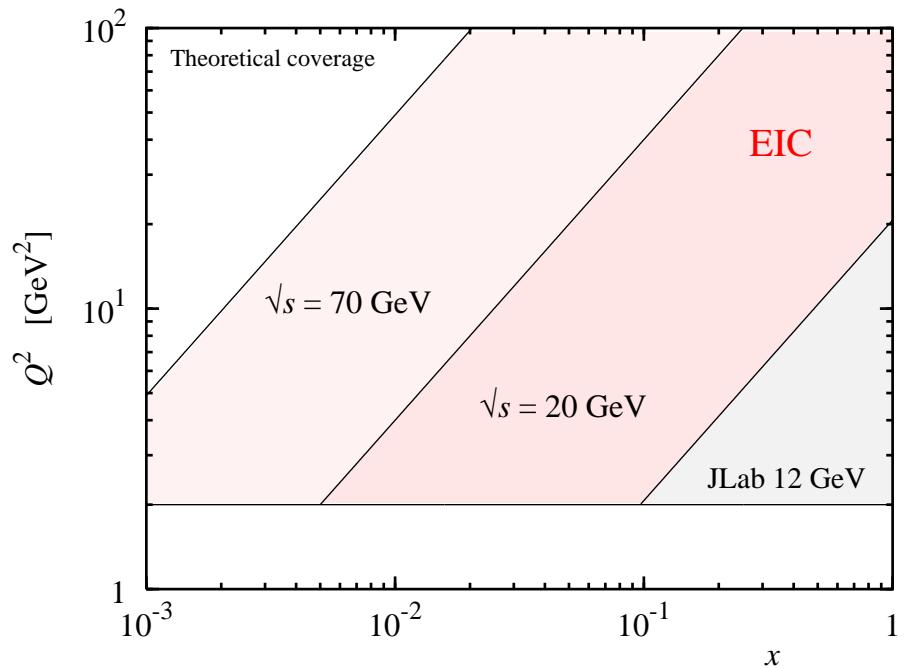
Components with different particle number

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

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



3D nucleon structure: Landscape



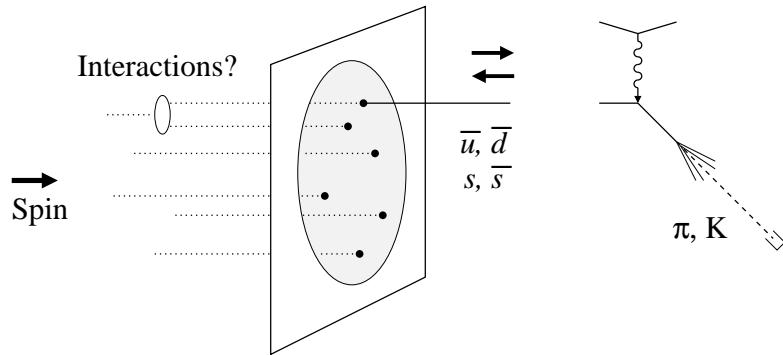
- Components probed predominantly
 - $x > 0.1$ Valence quarks: Source, quantum numbers
Also gluons at large x !
Intrinsic sea $s\bar{s}$, $c\bar{c}$?
 - $x \sim 10^{-1} - 10^{-2}$ Sea quarks, gluons: Quantum numbers
Generated by non-perturbative QCD interactions!
 - $x < 10^{-2}$ Gluons, singlet sea: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

- Quantities measured

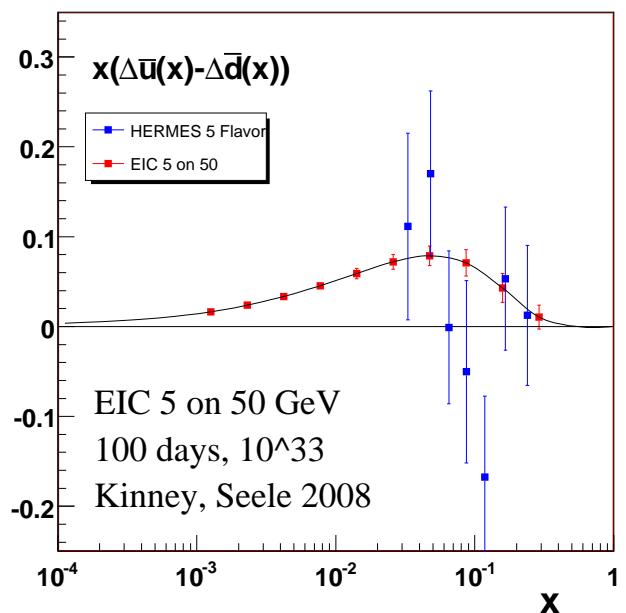
Particle number densities, incl. spin/flavor dependence	PDFs
Transverse spatial distributions	GPDs
Orbital motion, angul. momentum	TMDs
Particle correlations	MP distributions, GPDs

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

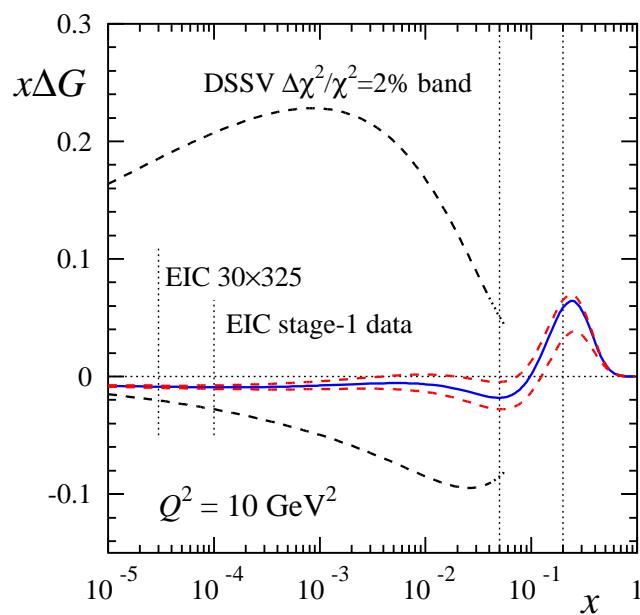
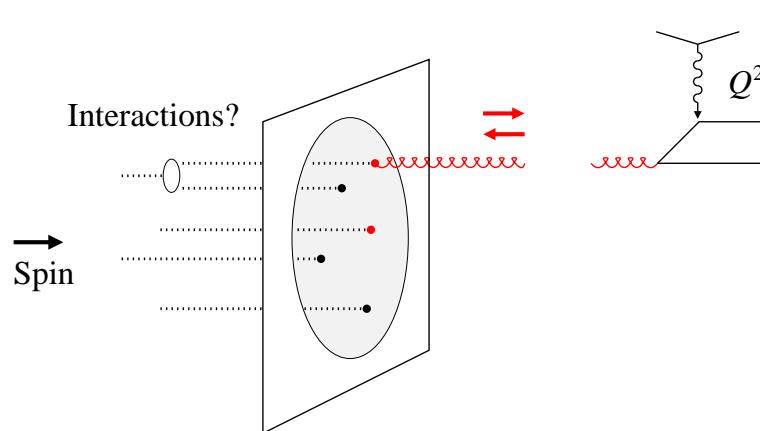
3D nucleon structure: Sea quark polarization



- 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 → Talk Stratmann

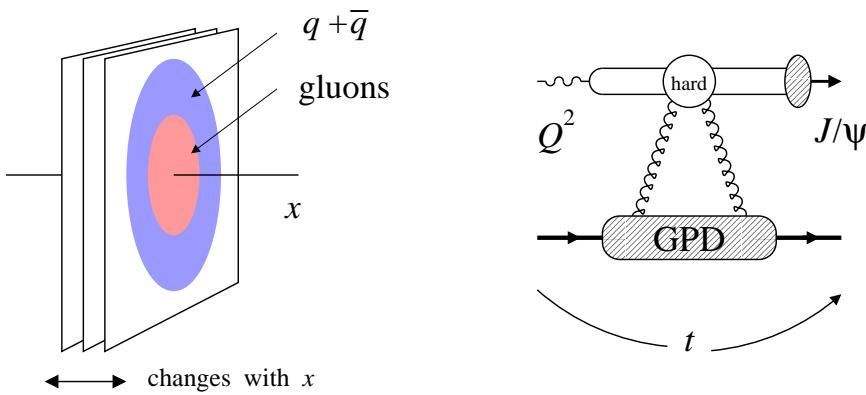
- Quark/gluon orbital angular momentum

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

Manifest in semi-inclusive spin asymmetries
e.g. Sivers effect → Talk Prokudin

Challenge to separate OAM in wave function
from QCD final-state interactions
→ Talk Burkardt

3D nucleon structure: Spatial distributions

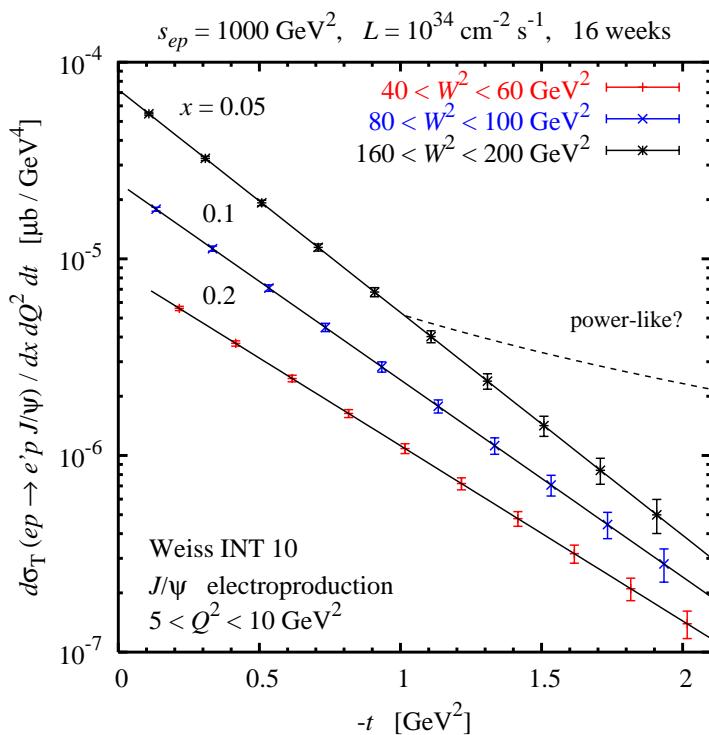


- How are quarks/gluons distributed in transverse space?

Fundamental size and “shape” of nucleon in QCD

Distributions change with x :
Diffusion, chiral dynamics

Input for saturation models,
multiparton interactions in $pp@\text{LHC}$



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

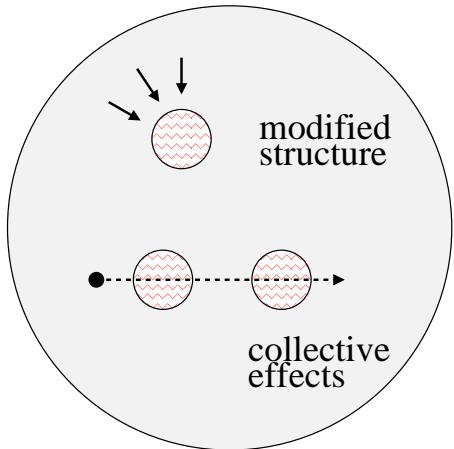
Gluonic form factor of nucleon:
Generalized parton distribution

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

- EIC: “Gluon imaging” of nucleon

Luminosity for low rates,
differential measurements

Color fields in nuclei: Physics



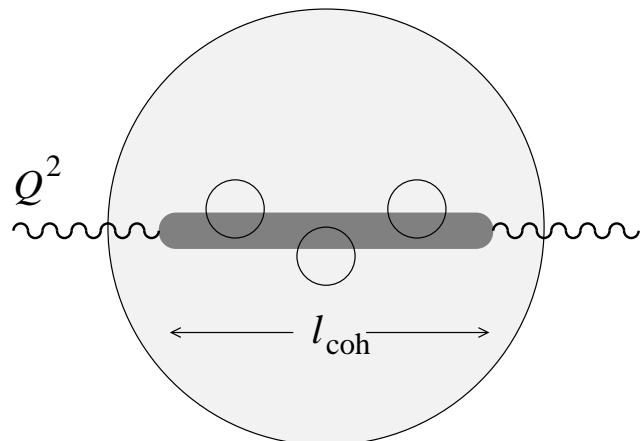
- What are the fundamental color fields in nuclei?

Modification of nucleon structure

Collective effects $A \neq \sum N$

Non-nucleonic degrees of freedom

→ QCD origin of NN interaction at different energies
→ Approach to black-disk/saturation regime



- Interaction with high-energy probe

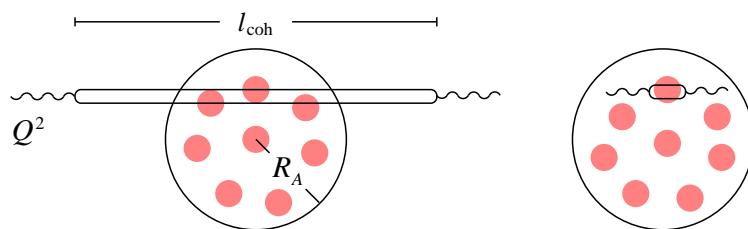
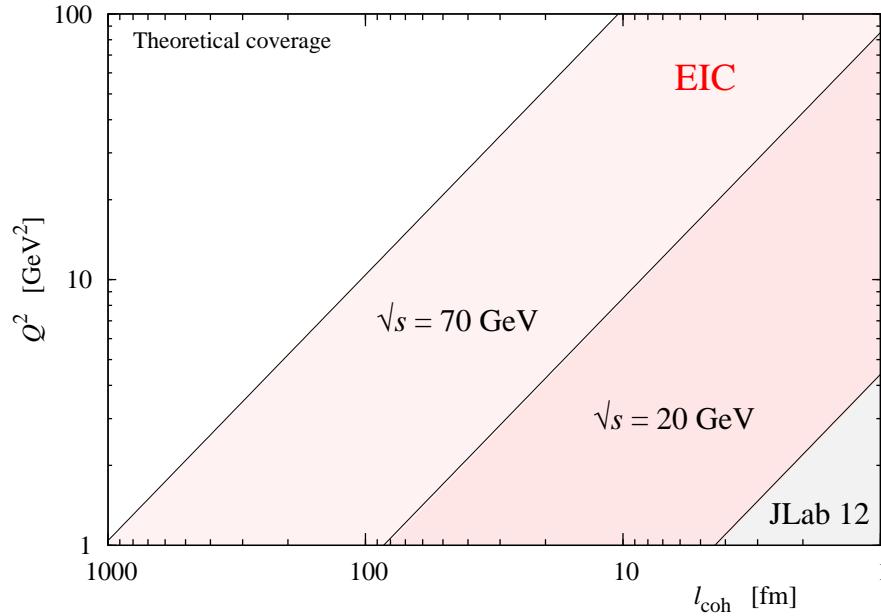
Transverse resolution $r \sim 1/Q$

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

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

Color fields in nuclei: Landscape

- Fields probed in eA



$l_{coh} \ll R_A$: Modified nucleon structure,
short-range correlations

JLab 12 GeV: EMC effect for valence quarks
EMC effect for gluons, antiquarks?

$l_{coh} \gtrsim R_A$: 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?

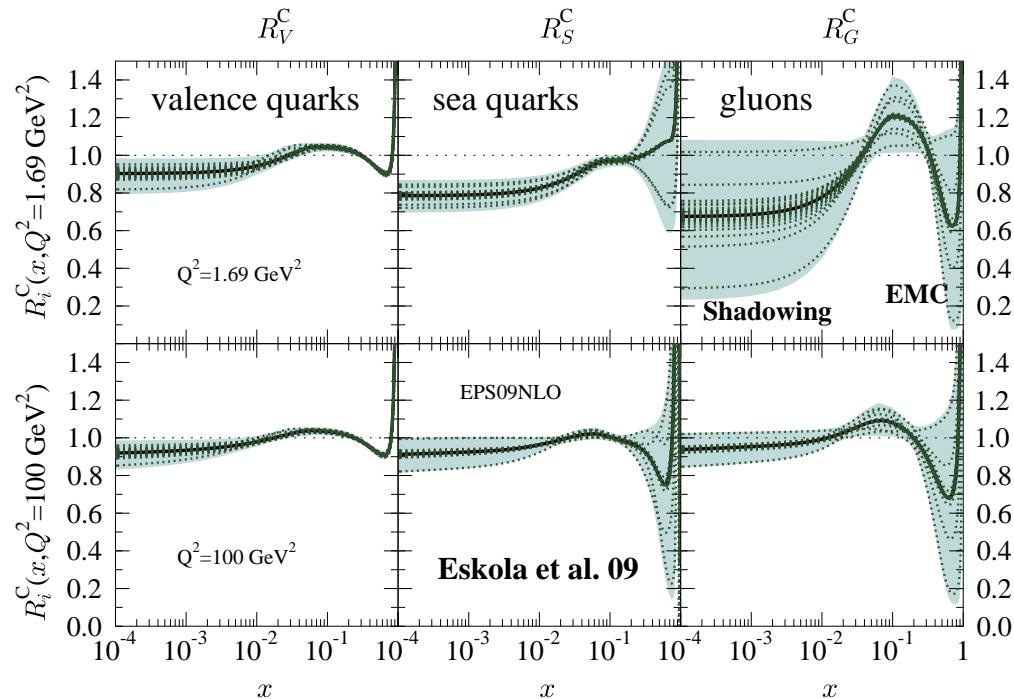
Color transparency: Disappearance of
interaction for small probes $\sigma \propto r^2$
Fundamental prediction of QCD as gauge theory

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

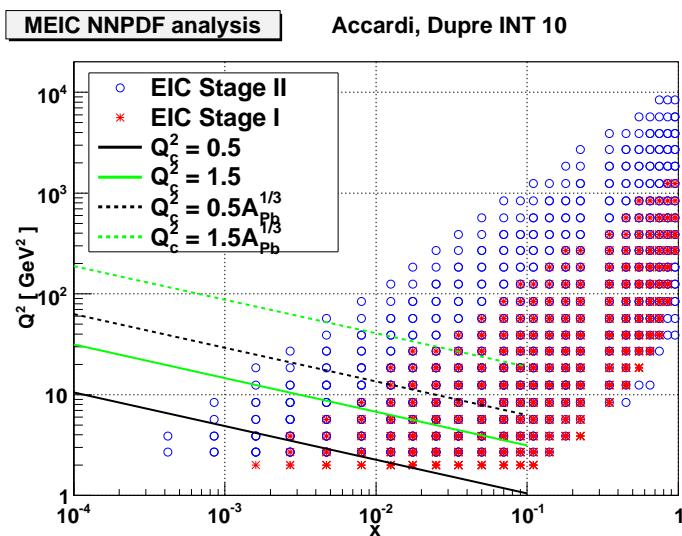


- Nuclear quark/gluon densities

$x > 0.1$ “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 $F_{2A}(x, Q^2)$



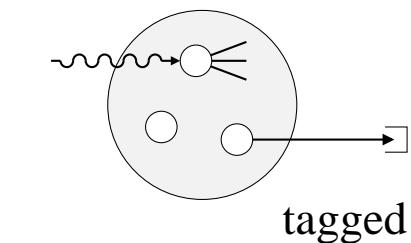
- Medium-energy EIC: Precise determination of nuclear quark/gluon densities

Wide coverage in x, Q^2

- Important for understanding approach to saturation at small x

Shadowing affects nuclear enhancement of Q_s

Color fields in nuclei: New probes with EIC

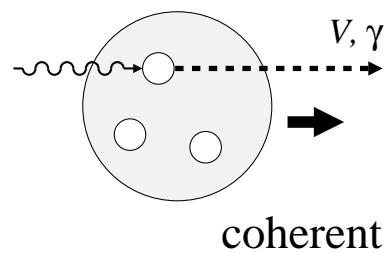


- Spectator tagging

Bound nucleon structure: EMC effect

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

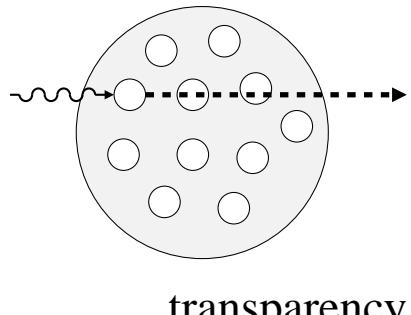
Requires forward p/n detection



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

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

Impact parameter dependent shadowing

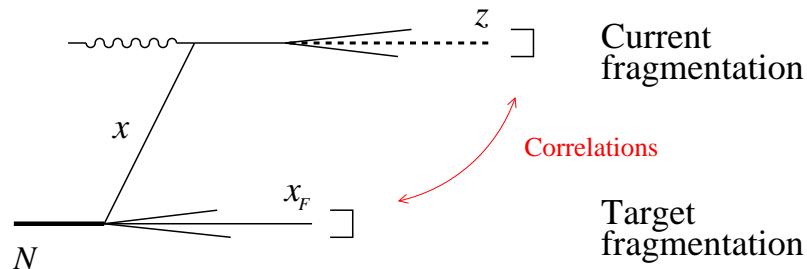
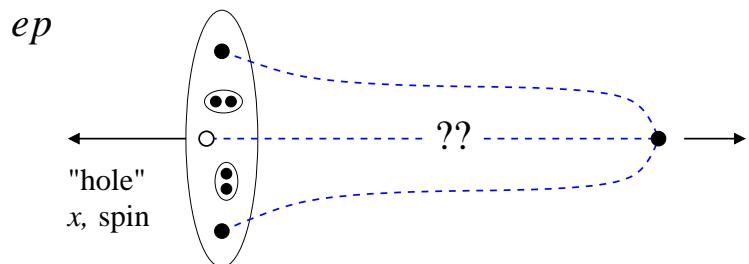
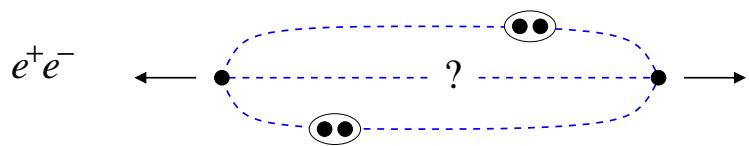


- Color transparency in meson production

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 \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

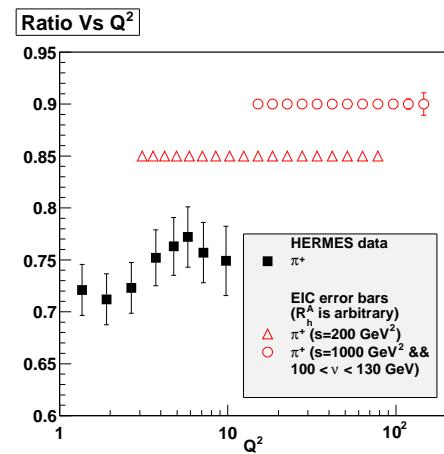
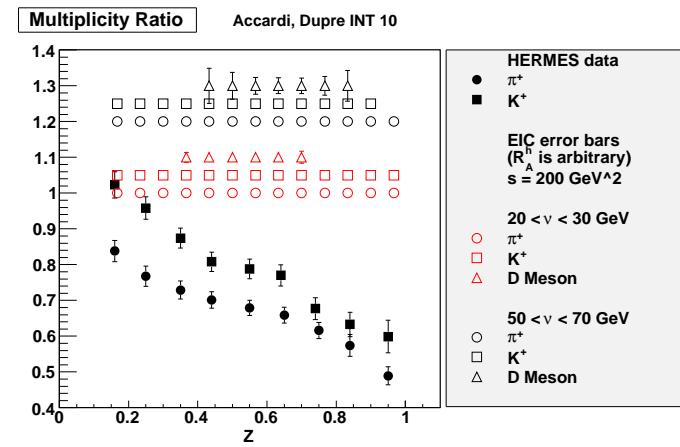
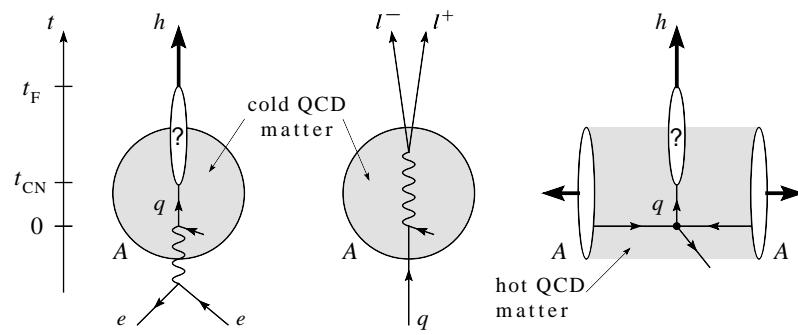
Fragmentation functions from ep :
Favored \leftrightarrow unfavored, test universality

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

Qualitatively new! Many applications! Unique for EIC

Hadrons from color charge: Matter



- How does fast color charge interact with hadronic matter?

Energy loss, attenuation

Time scales for color neutralization t_N , hadron formation t_F

Cold vs. hot matter? $eA/\gamma A \leftrightarrow \text{jets in } AA$

- EIC: Comprehensive studies

Wide range of energy $\nu = 10 - 100 \text{ GeV}$: Move hadronization inside/outside nucleus, distinguish energy loss and attenuation
Fixed-target: Correlations $\nu - Q^2$

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

$\sqrt{s} > 30 \text{ GeV}$: Study jets and their substructure in eA

Summary

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