Nuclear physics with a high–luminosity medium–energy ep/eA collider at JLab

C. Weiss, EIC@JLab Study Group, JLab User Group Workshop, 09-Jun-09

$s_{ep} \sim 1000\,\text{GeV}^2$

$\mathcal{L} \approx \text{few} \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$

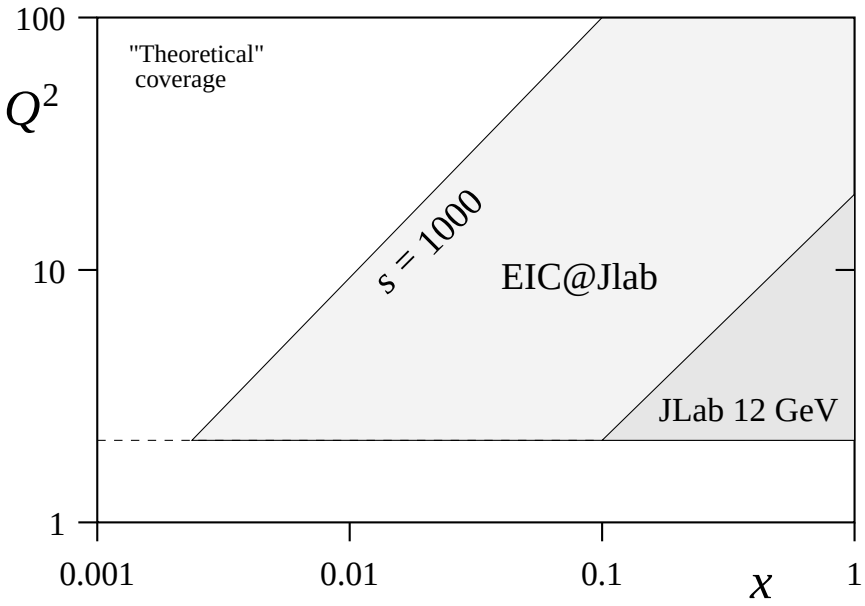
$E_e/E_p = 5/30 - 60\,\text{GeV}$

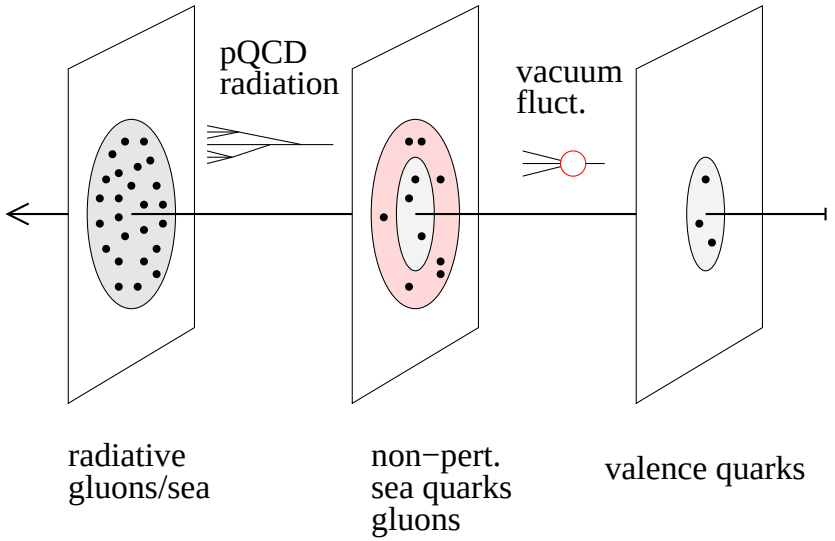
Polarization, nuclear beams

- Sea quark and gluon imaging of nucleon
- Nucleon spin: Quark/gluon orbital motion
- Nuclei in QCD: Gluons, new short–distance probes
- QCD vacuum in hadron structure and creation

"Next step"
after 12 GeV. . .
into qualitatively
new domain!

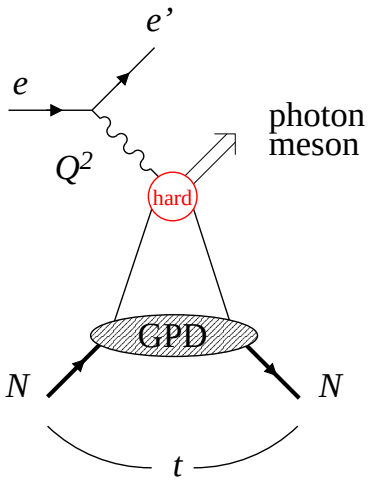
Nucleon structure in QCD: Landscape

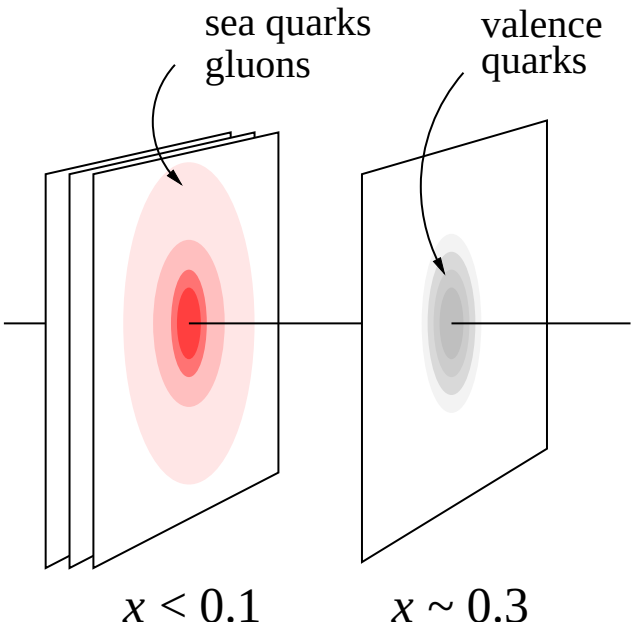




- Nucleon in QCD many–body system: Rich structure, different dynamics
- JLab 12 GeV: Valence quark spin/flavor/spatial distributions
- EIC@JLab: Gluons and sea quark spin/flavor/spatial distributions
  - → multiparticle dynamics
  - → role of gluons in structure
  - → non–pert. QCD vacuum, meson cloud
- High–energy collider (HERA): small–x gluons
  - → perturbative QCD radiation
  - → high parton densities, "saturation"

Quark/gluon imaging of nucleon





- How are quarks/gluons in nucleon distributed in transverse space?

  → Fundamental characteristics, cf. form factors

  → Dynamics: valence quarks, pion cloud, . . .

  → Visualization: 3D Images

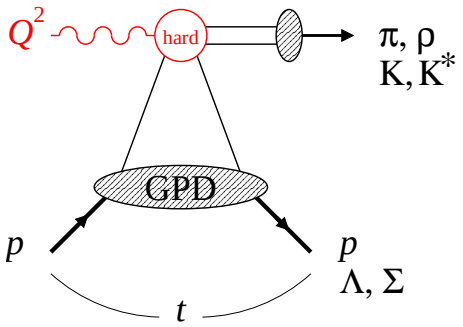
  → Lattice results

- JLab 12 GeV: GPDs in valence quark region from DVCS

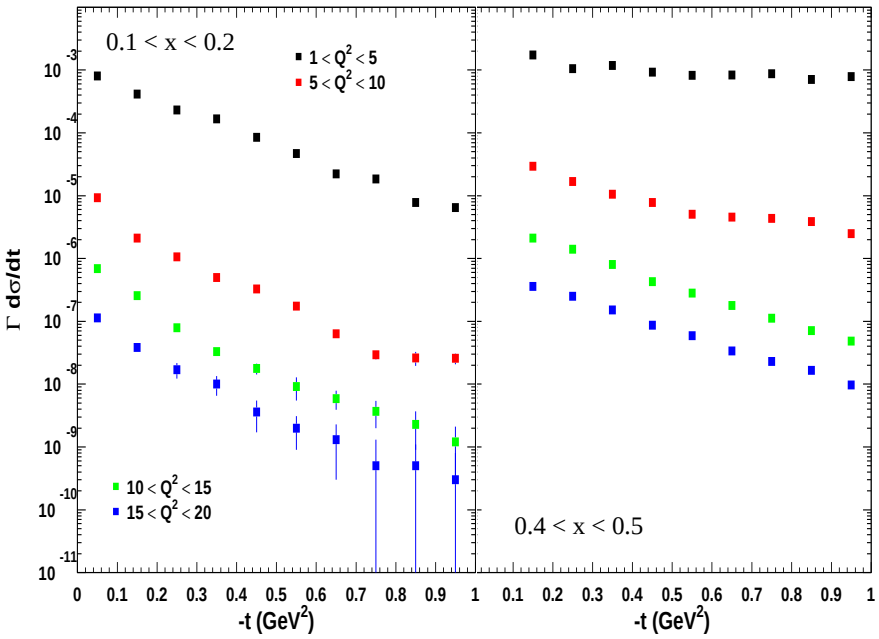
  Sea quarks? Gluons?

  Full spin/flavor separation?

EIC: Sea quark imaging with exclusive mesons



Exclusive $\pi,^+$ 5/50 GeV, 10^34, 100 days [T. Horn et al. 08]



- Meson production needs $Q^2 \sim 10\,\mathrm{GeV}^2$ for GPD description to be fully effective [cf. HERA]

- Unprecedented access to individual spin/flavor components

  $\rightarrow$ Flavor separation $\bar{d} \leftrightarrow \bar{u}$

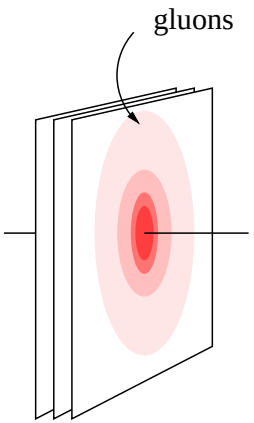
  $\rightarrow$ Polarization $\Delta q, \Delta\bar{q}$

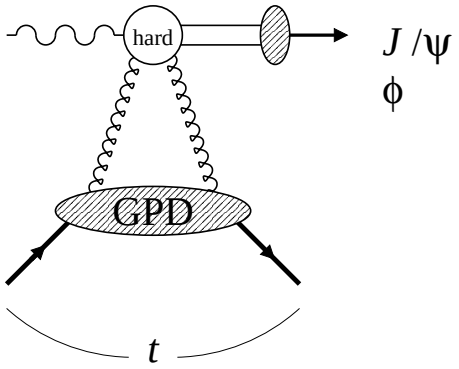
  $\rightarrow$ Strangeness $s, \bar{s}$

Small cross sections, differential measurements require high luminosity

Exclusivity: energy resolution, recoil detection

EIC: Gluon imaging with exclusive J/ψ



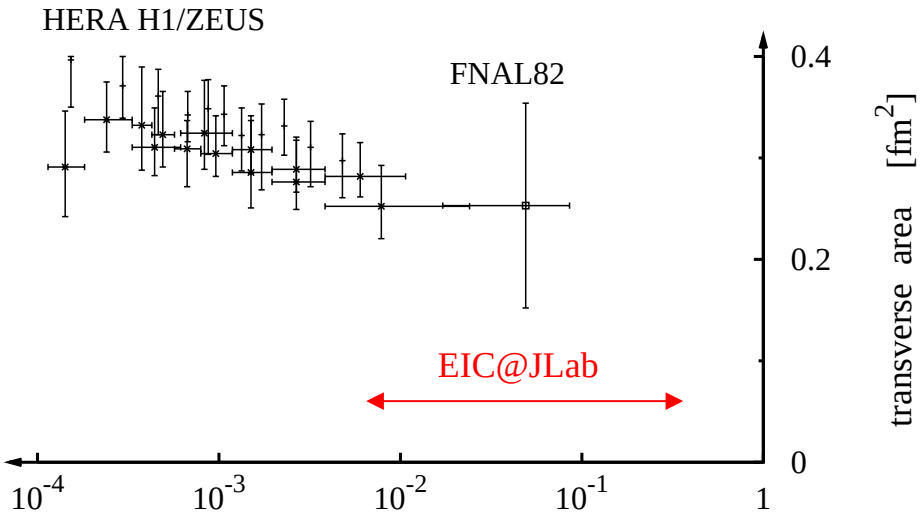


- Gluons essential part of structure . . . not just at small x!

  30% of momentum at $Q^2 \sim 0.5\,\mathrm{GeV}^2$

  Mass generation $\leftrightarrow$ vacuum structure

  "Next generation" of nucleon models

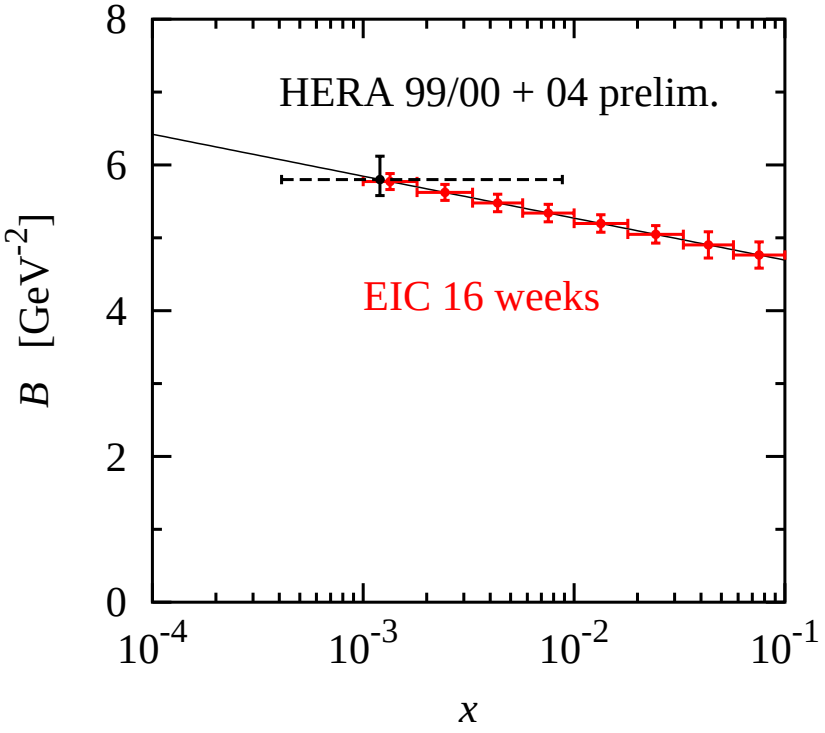


- Transverse gluon imaging through exclusive J/ψ

  HERA: Small x, overall area only

  $x > 10^{-2}$: No precise information!

Better t–resolution with more symmetric collider!



Simulation for 10/250 GeV, $10^{33}\text{cm}^{-2}s^{-1}$

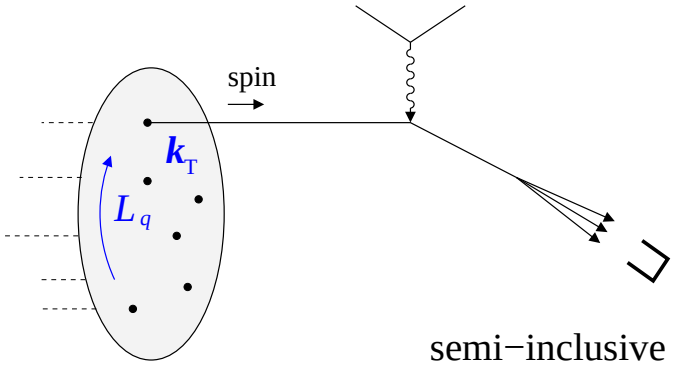
Even better results with high–luminosity medium-energy EIC@JLab!

Adapted from A. Sandacz (2007)

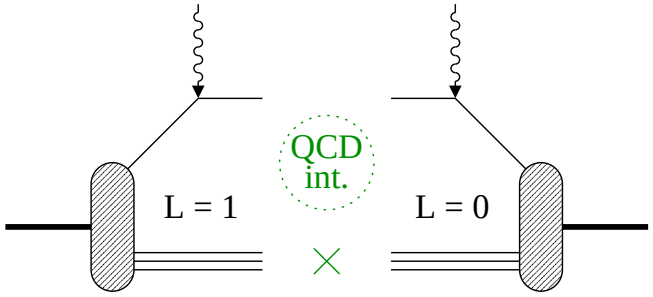
- Example: Transverse quark/gluon imaging with DVCS

  Sensitive quark and gluons in region $x < 10^{-1}$

Quark/gluon spin and orbital motion



semi−inclusive



Interference structure functions (Sivers)

- How does nucleon spin arise from QCD degrees of freedom?

  ΔG likely small at low scales, new focus on L_q, L_g . . . needs comprehensive approach!

- Quark/gluon orbital motion

  Emerging theoretical framework: TMDs

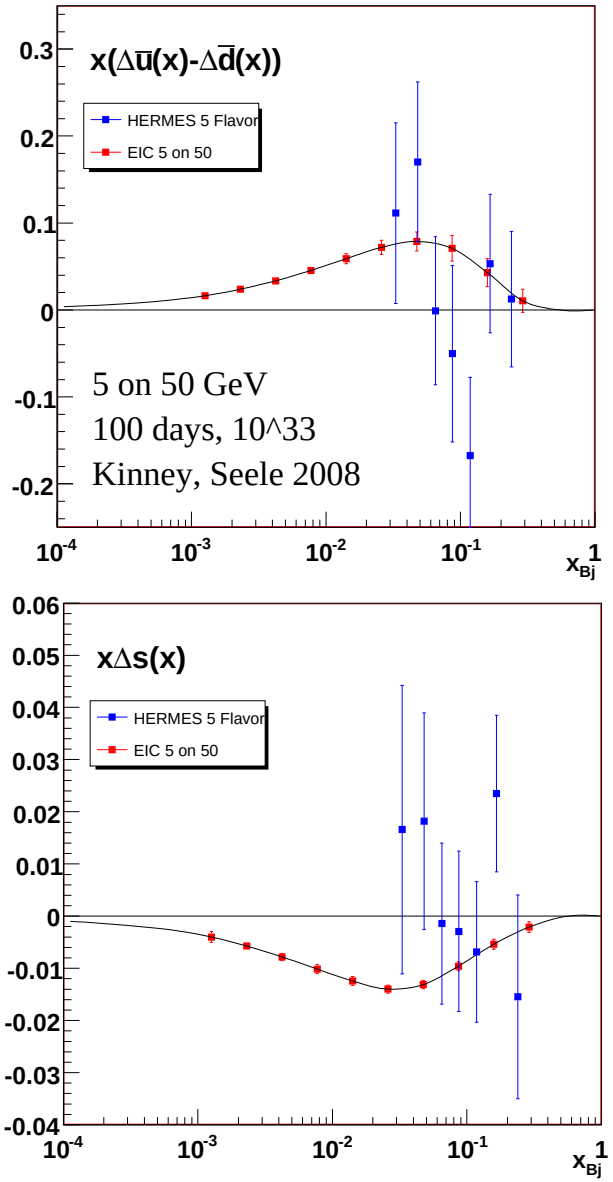
  Interference structures in semi–inclusive DIS: Orbital angular momentum, QCD dynamics

- Flavor decomposition $\Delta q, \Delta\bar{q}$, transversity

- 12 GeV: Inclusive spin structure in valence region $\rightarrow \Delta q, \Delta G$ from global fits, large x, growing semi–inclusive/TMD program

  Need higher Q^2, W to realize full potential of semi-inclusive DIS!

EIC: Quark/gluon spin and orbital motion



- Unprecedented semi–inclusive DIS capabilities: x, Q^2, W' coverage, transverse polarization

  $\rightarrow$ Flavor separation $\Delta q \leftrightarrow \Delta\bar{q}$

  $\rightarrow$ L_q from interference structures: indirect access, expect progress

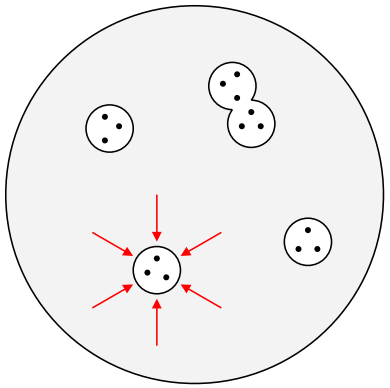
  $\rightarrow$ TMDs, quark orbital motion

  $\rightarrow$ Transversity distributions

- ΔG from inclusive spin structure (global fits), open charm

- Also possible: J_q from GPDs
  Model–dependent; await 12 GeV results

Nuclei in QCD



- How does nuclear binding influence quark/gluon structure?

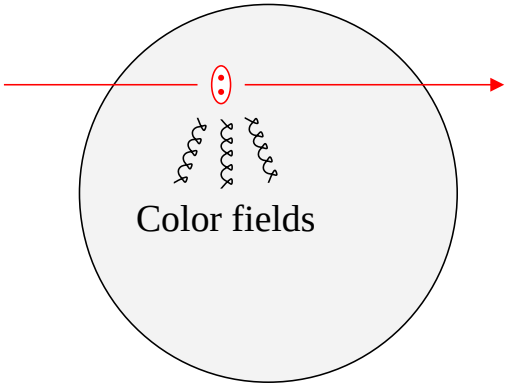
  $\rightarrow$ Long–range forces in QCD, effective theories

  $\rightarrow$ Short–range NN interaction, dense matter

- How do small–size quark/gluon configurations interact with hadronic matter?

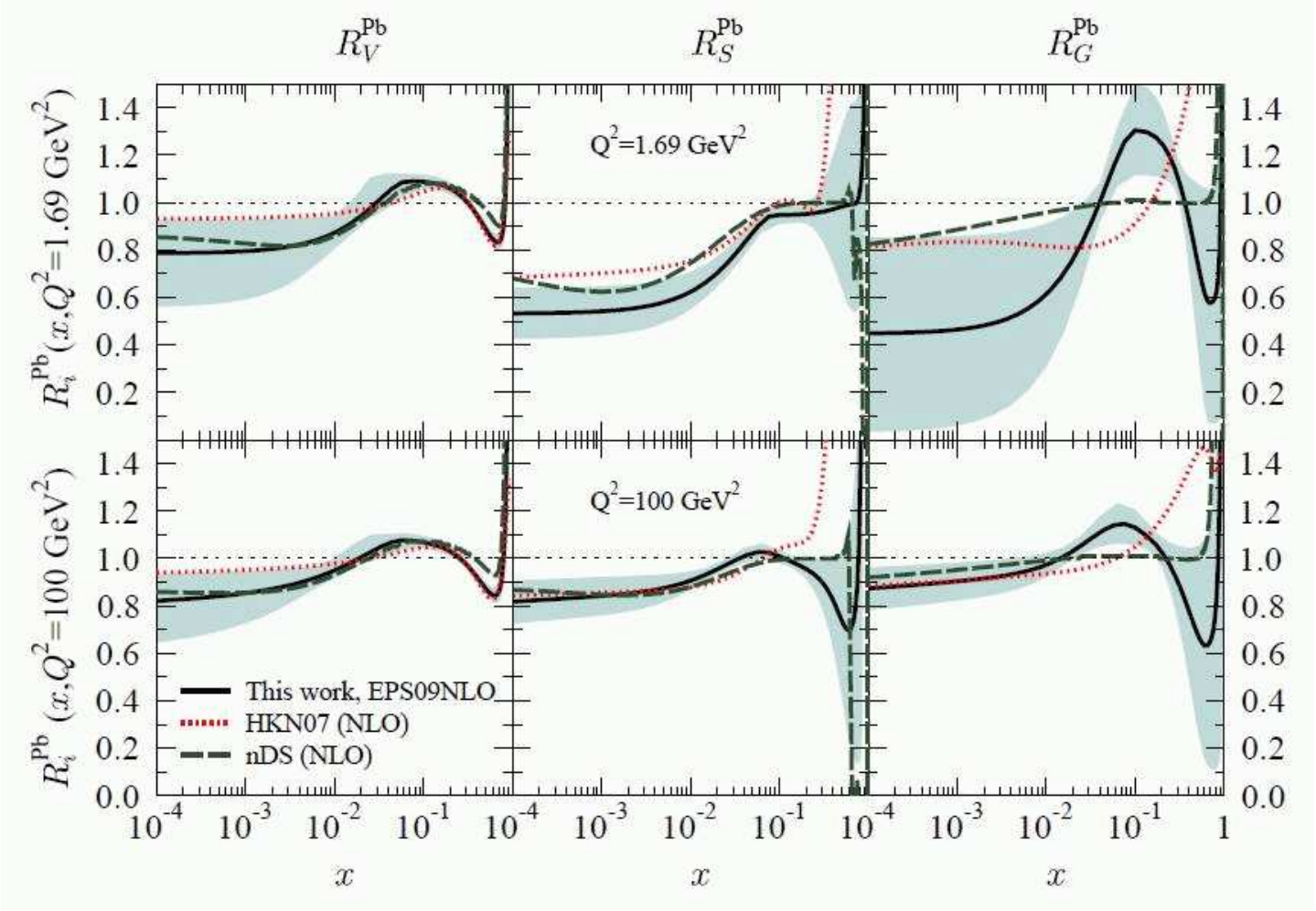
  $\rightarrow$ Local color fields in nuclei

  $\rightarrow$ Coherence effects



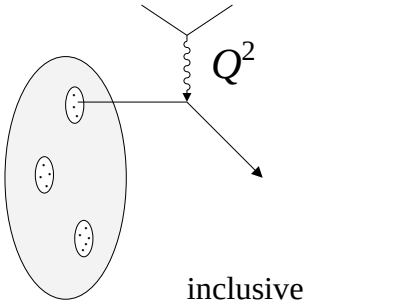
- JLab 6/12 GeV: EMC effect of valence quarks, short–range correlations, transparency

  Sea quarks, gluons? Coherence?

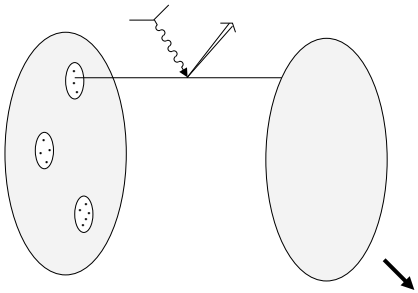


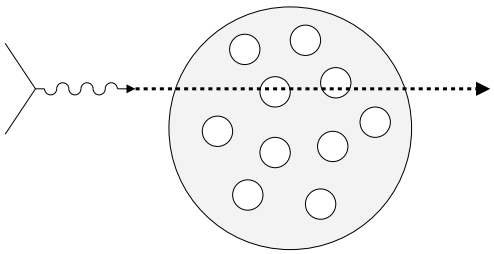
- Example: Uncertaintanties of present nuclear parton densities
  [Eskola et al. 2009, EPS09]

EIC: Quark/gluon structure of the nucleus



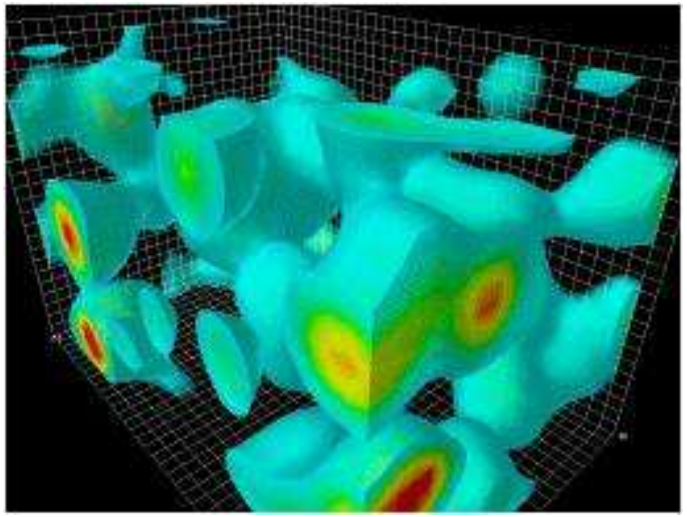
inclusive

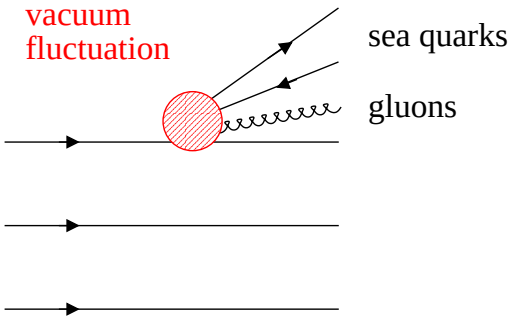

coherent


transparency

- Nuclear gluons and sea quarks from inclusive DIS: "EMC effect"
  - Gluons: Q^2 dependence, longit. structure F_L
  - Sea quarks: Isospin dependence, polarization
  - large x, Q^2 coverage
- Neutron structure from spectator tagging in $D(e, e'p)X$
  - Sea quarks: isospin dependence
  - forward p/n detection
- Fundamental quark/gluon radii from coherent nuclear processes $A(e, e'M)A$
  - New class of "QCD form factors"
  - luminosity, recoil detection – challenging!
- Color transparency in meson production
  - Color fields in nuclei
  - luminosity; x range $\rightarrow$ coherence length

QCD vacuum structure



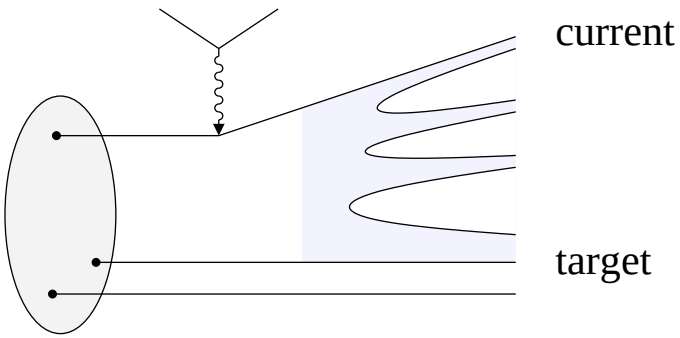


- QCD vacuum: Ground state of complex many–body system!
  - $q\bar{q}$ pairs, strong gluon fields
    Lattice: progress in simulation/visualization
  - Spontaneous chiral symmetry breaking:
    Mass generation, collective excitations
  - Topological excitations:
    Global structure of gauge group

- Explore vacuum through hadron structure
  - Sea quarks, gluons in partonic wavefn
  - Quark/gluon correlations: "Higher twist"

    EIC: Inclusive/semi-inclusive/exclusive DIS
    [→ earlier]

EIC: QCD vacuum and hadron creation



- How do hadrons emerge from QCD vacuum?

  $\rightarrow$ Mechanism? Mass scales? Quantum numbers?

  $\rightarrow$ Energy–mass conversion

- Semi–inclusive DIS: Quark fragmentation functions

  Charge/flavor dependence: Much more than $e^+e^- \rightarrow$ hadrons!

  Energy, luminosity

- Particle correlations within/between jets

  Detailed study of mechanism.
  Target fragmentation: Flavor structure, quark–quark correlations.

  Fully differential measurements, forward detection

Summary

- High–luminosity, intermediate–energy ep/eA collider provides unique combination of capabilities for nucleon/nuclear structure

  x, Q^2 coverage for sea quarks, gluons, QCD processes
  Luminosity: Rare processes, differential measurements
  Detectability: Energy resolution, particle ID, forward direction

- "Next generation" of nucleon structure experiments

  Nucleon quark/gluon imaging
  Origin of nucleon spin
  QCD and nuclear binding
  QCD vacuum in hadron structure and creation

- Possible electroweak program. . . high luminosity!

A major opportunity for the nuclear physics community!