3D imaging of proton and nuclei with EIC
Progress report on deep exclusive reaction program

C. Weiss (JLab), EIC Advisory Committee Meeting, JLab, 02–Nov-09

- **Gluon imaging**
  - Physics of non-perturbative glue
  - Exclusive \( J/\psi \) and \( \phi \) production
  - Importance for \( pp@LHC \), small \( x \)
  - Nuclear gluons

- **Quark imaging**
  - Sea quarks: QCD vacuum, chiral dynamics
  - Exclusive meson production, DVCS
  - Polarization

- **Meson/baryon structure**
  - Excited states \( N \rightarrow N^* \), diffraction
  - Longitudinal correlations \( \xi \neq 0 \)
  - Orbital motion
Nucleon structure: Landscape

- Nucleon in QCD many–body system
  Different components, effective dynamics

- Components probed in $ep$ scattering
  JLab 12 GeV  valence quarks
  EIC  sea quarks, gluons, $Q^2$ dependence

- Physical properties
  Parton densities
  Transverse spatial distributions: GPDs
  Orbital motion: TMDs, angular momentum
  Correlations: “Higher twist”
Nucleon structure: Transverse imaging

- Transverse imaging of nucleon through high-$Q^2$ exclusive processes $N(e, e'M)N'$
  
  GPDs ($x' = x$): Form factors of partons with longitudinal momentum fraction $x$
  
  Transverse spatial distribution of partons: Tomographic images of nucleon at fixed $x$ Burkardt
  
  → Fundamental, process–independent
  
  → Twist–2, calculable in lattice QCD

- JLab 12 GeV: Valence quark GPDs through $N(e, e'\gamma)N'$ + spin observables
  
  Transverse distributions of valence quarks
  
  Longitudinal correlations $x' \neq x$

Much more interesting information: Gluons! Sea quarks! Spin/flavor
Gluon imaging: Probes and dynamics

- Gluon imaging through exclusive $J/\psi$ and $\phi$ ($Q^2 > 10$ GeV$^2$)
  - Clean channels!
  - Transverse distribution directly from $\Delta_T$-dependence

- Physical interest
  - Valence gluons – dynamical origin?
  - Chiral dynamics at $b \sim 1/M_\pi$
  - Diffusion in QCD radiation

- Essential for future MC for $pp@LHC$, saturation $Q_s \sim$ gluons/transverse area

- Existing data
  - Transverse area $x < 0.01$ HERA
  - Larger $x$ poorly known FNAL 82, …
Gluon imaging: Valence gluons

- EIC: Precise gluon imaging through exclusive $J/\psi$ and $\phi$
  
  $x > 0.01$: Map unknown region of non-perturbative gluons!

- Needed for imaging
  
  Full $t$-distribution $\rightarrow$ Fourier
  Non-exponential? Power-like at $|t| > 1 \text{GeV}^2$?

  Electroproduction with $Q^2 > 10 \text{GeV}^2$:
  Test of reaction mechanism, different channels

- Machine requirements
  
  Recoil detection for exclusivity, $t$-measurements
  Luminosity $\sim 10^{34} \text{cm}^{-2}\text{s}^{-1}$ for $x > 0.1$,
  electroproduction, high-$t$

First gluonic images of nucleon at large $x$!
Gluon imaging: Gluon vs. quark size

- Do singlet quarks and gluons have the same transverse distribution?
  
  Hints from HERA:
  \[ \text{Area}(q + \bar{q}) > \text{Area}(g) \]

  Dynamical models predict difference:
  Pion cloud, constituent quark picture

  No difference assumed in present
  \( pp \) MC generators for LHC!

- EIC: Gluon size from \( J/\psi \),
  singlet quark size from DVCS

  \( x \)-dependence: Quark vs. gluon diffusion in wave function

  Detailed analysis: LO \( \rightarrow \) NLO Müller et al.

Detailed differential images of nucleon’s partonic structure

Sandacz, Hyde, CW
Gluon imaging: Nuclei

- Transverse distribution of gluons in nuclei from coherent $J/\psi$ production
  - Fundamental characteristic: Quark–gluon origin of nucleon–nucleon forces
  - New approach to nuclear shadowing: Thickness $\leftrightarrow$ impact parameter $b$
  - Theoretical predictions Goекe, Guzey, Siddikov 09

- Experimental challenges
  - Detection at very low $t \sim (\text{few fm})^{-2}$
  - Beam optics: Intrinsic $k_T$
  - Veto nuclear breakup, excitations (theory)
Quark imaging: Exclusive meson production

- Transverse distribution of non-perturbative sea quarks
  - Flavor structure $\bar{u} \leftrightarrow \bar{d} \leftrightarrow s, \bar{s}$
  - Longitudinal polarization $q^+ \leftrightarrow q^-$
  - $\rightarrow$ QCD vacuum structure
  - $\rightarrow$ Chiral dynamics, “pion cloud”

- Exclusive meson production $\gamma^* N \rightarrow M + B$
  - Requires $Q^2 > 10$ GeV$^2$ for dominance of “pointlike” configurations $\rightarrow$ pQCD
  - Meson quantum numbers select spin/flavor component of GPD
  - Information about meson wave function: Size, flavor structure
Quark imaging: Sea quarks

\[ e p \rightarrow e'\pi^+ n \]

- Do strange and non-strange sea quarks have the same spatial distribution?
  - \( \pi N \) or \( K\Lambda \) components in nucleon?
  - QCD vacuum fluctuations?

- EIC: Exclusive \( \pi \) and \( K \) production
  - High luminosity for low rates, differential measurements in \( x, t, Q^2 \)
  - Kinematic reach in \( Q^2, x \)
  - Recoil detection for exclusivity, \( t \)-distributions

Spatial structure of non-perturbative sea – many more examples!
Quark imaging: Polarization

- Deformation of transverse distributions by transverse polarization of nucleon
  Helicity–flip GPD, cf. Pauli FF

- EIC: Exclusive $\rho$ and $\phi$ production with transversely polarized beam
  Excellent statistics at $Q^2 > 10 \text{GeV}^2$
  Transverse polarization natural for collider

T. Horn, 4 on 60 GeV, $L = 10^{34} \text{cm}^{-2} \text{cm}^{-1}$
Exclusive processes: Why lower energies

- Example: Exclusive production \( ep \to e'\pi^+n \)
  
  Physics interest \( x > 0.01 \):
  Non-perturbative sea quarks

- Lower–energy, symmetric collider
  
  → Wider \( \pi^+ \) angular distribution:
  Detection, angular resolution

  → Wider recoil \( n \) distribution:
  \( t \)-resolution

- Detector simulations in progress

Exclusive processes at \( x > 0.01 \): Better prospects with lower–energy, more symmetric collider!
Exclusive processes: Beyond transverse imaging

- Longitudinal correlations in nucleon
  
  GPDs at $x' \neq x$: Correlated $q\bar{q}$ pairs in nucleon
  $\rightarrow$ QCD vacuum structure, relativistic nature of nucleon
  
  EIC: Reveal correlations through exclusive meson, $\gamma$ at $x > 0.1$, $Q^2$ dependence
  
  . . . needs kinematic coverage way beyond JLab 12 GeV

- Orbital motion of quarks/gluons
  
  TMDs and orbital motion from semi-inclusive DIS:
  Major component of EIC program
  
  Connection with GPDs: Unintegrated distributions, Ji sum rule
  
  . . . should be discussed together!
Exclusive processes: Baryon/meson structure

- $N^*$ resonance excitation through hard exclusive process
  
  QCD factorization: Hard process as transition operator \cite{Frankfurt, Strikman, Polyakov}
  New quantum numbers!

- New probes of meson structure
  Meson size $\leftrightarrow Q^2$ dependence, flavor structure
  “Exotics” from QCD counting rules

- Diffractive dissociation in exclusive vector meson production
  Quantum fluctuations of gluon density:
  Fundamental property of many-body system \cite{Frankfurt, Strikman, Treleani, CW}

Interesting opportunities, should be explored further!
Summary

- High-luminosity $ep/eA$ collider offers unique capabilities for gluon and quark imaging through exclusive processes

  → Fundamental QCD structure of nucleon/nuclei, non-perturbative dynamics
  → Visualization, 3D images
  → Synergy with lattice QCD: GPD moments
  → Essential input for $pp@LHC$, small-$x$

  ... Potential to become “golden experiment”

- Challenging experiments: Low rates, differential measurements, exclusivity, $t$–resolution, etc.

  → Driver of accelerator/detector requirements
  → Need to control systematics!

- Explore other interesting aspects of exclusive processes: Longitudinal correlations, meson structure, diffraction, ...