Exclusive processes and nucleon structure

C. Weiss (JLab), EIC Workshop Rutgers, 14–Mar–2010

- Nucleon structure in QCD
  Quark/gluon transverse distributions, correlations, orbital motion

- High-$Q^2$ exclusive processes and GPDs
  Reaction mechanism and tests
  Large vs. small $x$

- Exclusive processes from 12 GeV to EIC
  DVCS: GPDs from dispersion analysis
  Meson production: Quark imaging
  $J/\psi, \phi$: Gluon imaging
  $N^*$ and meson structure
  Nuclei: Color transparency, shadowing, coherent processes
Nucleon structure: Landscape

- **Nucleon in QCD many–body system**
  
  Partonic picture: Different components, effective dynamics
  
  Correspondence with rest frame picture: Euclidean QCD, lattice, instantons

- **Components probed in \( ep \) scattering**
  
  JLab 12 GeV Valence region: 3q, 5q
  
  EIC Sea quarks, gluons, \( Q^2 \) dependence

- **Physical properties**
  
  Parton densities
  
  Transverse spatial distributions
  
  Orbital motion, angular momentum
  
  Correlations
  
  + nuclear modifications
Exclusive processes: GPDs

- $Q^2 \gg$ hadronic size$^{-2}$: Reaction pointlike, partonic mechanism
  
  QCD factorization theorem
  GPDs universal, process–independent
  Müller et al. 94; Brodsky et al. 94; Collins et al. 96; Radyushkin 96, Ji 96

- Nucleon structure from GPDs
  
  $\xi = 0$ Transverse spatial distribution of of partons with longitudinal momentum $x \rightarrow$ Miller
  
  $|x| < \xi$ $q\bar{q}$ correlations in nucleon
  
  Moments Form factors of local twist–2 operators
  EM tensor, angular momentum $\rightarrow$ Schweitzer

- Test reaction mechanism!
  
  Model–independent features: Universality, $Q^2$ scaling, kinematic dependences, . . .
  
  Finite–size corrections: Theory estimates
  Frankfurt et al 96, Kroll, Goloskokov 05+
## Exclusive processes: Large vs. small $x$

<table>
<thead>
<tr>
<th>$x \ll 0.1$</th>
<th>$x &gt; 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross sections</strong></td>
<td>Gluon/singlet quark $J/\psi$, $\phi$, $\rho^0$, $\gamma$ large vs. non-singlet quarks $\rho^+$, $\pi$, $K$ small</td>
</tr>
<tr>
<td></td>
<td>Valence quark dominance $\rho^+ \approx \rho^0$, $\phi \ll \rho^0$ → Guidal</td>
</tr>
<tr>
<td><strong>GPD interpretation</strong></td>
<td>Skewness small $\xi \ll 1$ theoretically controlled</td>
</tr>
<tr>
<td></td>
<td>$t \approx -\Delta^2_\perp$</td>
</tr>
<tr>
<td></td>
<td>Transverse imaging</td>
</tr>
<tr>
<td></td>
<td>Skewness sizable, non-perturbative</td>
</tr>
<tr>
<td></td>
<td>$t = f(\xi, \Delta_\perp)$, $t_{\text{min}}$ large</td>
</tr>
<tr>
<td></td>
<td>Transverse structure + longitudinal correlations</td>
</tr>
<tr>
<td><strong>Higher twist</strong></td>
<td>Space–time picture: Dipole model</td>
</tr>
<tr>
<td></td>
<td>HT $\sim$ finite dipole size</td>
</tr>
<tr>
<td></td>
<td>Successful phenomenology incl. absolute cross sections HERA</td>
</tr>
<tr>
<td></td>
<td>“Knockout” of $q\bar{q}$ pair</td>
</tr>
<tr>
<td></td>
<td>Sudakov suppression</td>
</tr>
</tbody>
</table>
**DVCS: Observables and analysis**

- Interference BH–DVCS allows one to access DVCS at amplitude level
  
  \[
  \text{HERMES, JLab } \quad \text{DVCS} \times \text{BH} \quad \text{from } \sigma(\text{pol}), \sigma(e^{\pm})
  \]
  \[
  \text{HERA } \quad |\text{DVCS}|^2 \quad \text{from } \sigma(\text{unpol})
  \]

- Reaction mechanism

  JLab Hall A cross sections show \(Q^2\) scaling, higher twist \(\sim M_V^2/Q^2\) → Munoz Camacho

  HERA: \(Q^2\)-scaling, \(t\)-slopes

- Theory analysis

  Leading-twist analysis developed at NLO
  Müller et al.

  Successful HERA phenomenology, \(R = \text{DVCS/DIS}\)

  Dispersion relations for hard exclusive amplitudes:
  Minimize model dependence
  Frankfurt et al. 97, Teryaev et al. 05+; Müller et al. 07; Diehl et al. 07

\[
\begin{align*}
\text{Re } \text{DVCS} &= \int \text{Im } \text{DVCS} \\
&= \text{Dispersion} \\
&\quad + \text{D-Term} \\
\text{Im } \text{DVCS} \sim \text{LT} \quad H(\xi, \xi; t) \quad \text{measurable!}
\end{align*}
\]
DVCS: Future facilities

- JLab 12 GeV: Valence quark GPDs through spin observables, $p/D \rightarrow$ Munoz Camacho
  - COMPASS: DVCS at $0.01 < x < 0.1$
    - Re DVCS from $\mu^{\pm}$ Projections Schoeffel 09
  - EIC: Great opportunities!
    - Need to quantify impact on GPD analysis
      - Simulations: Sandacz, Horn, Hyde

- Topics for discussion

  Reaction mechanism: What do we need in order to separate leading and higher twist?

  Dispersion analysis: Do we need more data at smaller $x$ or better accuracy at larger $x$?

  Neutron DVCS: What can be done with forward tagging?
Meson production: Mechanism

- Requires $Q^2 > 10 \text{GeV}^2$ for pointlike process
  - HERA: $t$–slope independent of $Q^2$, universality
  - JLab 6 GeV: Mechanism not yet fully understood → Guidal

Meson selects definite charge/spin/flavor component of GPD

$J/\psi, \phi$ gluon
$\rho^0$ gluon + singlet $q$
$\rho^+, K^*$ non-singlet $q$
$\pi, K, \eta$ non-singlet $\Delta q$

Nucleon structure interest
- Transverse imaging of quarks and gluons
- Spin/flavor structure
Meson production: Quark imaging

\[ e^+ p \rightarrow e'^+ \pi^0 n \]

- Do strange and non-strange sea quarks have the same transverse distribution?

\[ \rightarrow \pi N \text{ or } K \Lambda \text{ components in nucleon?} \]
\[ \rightarrow \text{QCD vacuum fluctuations?} \]

- EIC: Exclusive \( \pi \) and \( K \) production \( \rightarrow \) Horn

High luminosity for low rates, differential measurements in \( x, t, Q^2 \)

Kinematic reach in \( Q^2, x \)

Recoil detection for exclusivity, \( t \)-distributions

EIC simulation T. Horn et al. 09
Meson production: Gluon imaging

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

- Physical interest → Vogt, Strikman
  - Valence gluons – dynamical origin?
  - Chiral dynamics at $b \sim 1/M_\pi$
  - Diffusion in QCD radiation
  - Input for $pp@LHC$ MC, small-$x$ physics

- Existing data and plans
  - Transverse area $x < 0.01$ HERA
  - Larger $x$ poorly known FNAL 82, . . .
  - JLab 12 GeV: Exclusive $\phi$, $J/\psi$ near threshold → Chudakov
Meson production: Valence gluons

- EIC: Transverse imaging of valence gluons through exclusive $J/\psi, \phi$

- Needed for imaging
  - Full $t$–distribution → Fourier
  - Non-exponential? Power–like at $|t| > 1$ GeV$^2$?

Electroproduction with $Q^2 > 10$ GeV$^2$:
  - Test reaction mechanism, compare different channels, control systematics

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

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

- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA: $\text{Area}(q + \bar{q}) > \text{Area}(g)$
  - Difference expected from chiral dynamics: Pion cloud by Strikman, CW 09
  - 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 by Müller et al.

Detailed differential images of nucleon’s partonic structure

Sandacz, Hyde, CW
Meson production: $N^*$ and meson structure

- **$N^*$ resonance excitation through hard exclusive process**
  
  QCD factorization: Hard process as transition operator. Frankfurt, Strikman, Polyakov

  New quantum numbers!

- **New probes of meson structure**
  
  Meson size ↔ $Q^2$ dependence, flavor structure

  “Exotics” from QCD counting rules

- **Pion GPDs from “knockout” processes** → Girod

  Requires $x \ll M_\pi / M_N \sim 0.1$ for quasi-real pion

  Kinematics with $p_T(\pi) \gg p_T(N)$ suppresses production on nucleon. Strikman, CW 04
Exclusive processes with nuclei

- QCD factorization = Color Transparency
  Nuclei as filter for small–size configurations
  Explore longitudinal direction $R_A \leftrightarrow l_{\text{coh}}$

- Coherent processes: Nuclear GPDs
  Fundamental quark/gluon distributions in nucleus, matter vs. charge radii $\rightarrow$ Liuti
  Shadowing as function of impact parameter $\rightarrow$ Guzey
  Requires detection at very low $t \sim (\text{few fm})^{-2}$
  Intrinsic $k_T$ from beam optics
  Veto nuclear breakup, excitations

- Quasi–elastic processes: Neutron structure
  Neutron GPDs, medium modifications
  Requirements similar as for spectator tagging in inclusive DIS $\rightarrow$ Keppel, Hyde
Summary

• High-luminosity EIC offers many exciting opportunities to explore QCD structure of nucleon and nuclei with exclusive processes

  • DVCS over wide kinematic range
  • Valence/sea quark imaging with meson production
  • Gluon imaging with $J/\psi$ and $\phi$
  • Fundamental quark/gluon distributions in nuclei from coherent scattering

• Many processes require/favor lower energy, more symmetric collider $s \sim 1000 \text{ GeV}^2$  Cf. detailed process simulations

• “Next step” for nuclear physics after JLab 12 GeV