Landscape of nucleon structure in QCD

C. Weiss (JLab), EINN 2009, Milos, 27–Sep 2009

- Parton picture as a many-body system
  - Wave function description, different components
  - Unified perspective large $x \leftrightarrow$ small $x$, $ep \leftrightarrow pp$
  - Role of QCD vacuum structure

- Physical properties
  - Momentum distributions
  - Transverse spatial structure
  - Orbital motion of partons
  - Correlations
  - PDFs
  - GPDs, form factors
  - TMDs, angular momentum
  - “Higher twist,” multiparton distributions

  cf. condensed matter, nuclei

  “expanding interest”
Nucleon structure in QCD

- **QCD vacuum not empty**
  
  Strong non-perturbative gluon fields, scale $\mu \gg 1 \text{ fm}^{-1}$
  
  $\bar{q}q$ pair condensate, $\pi$ as collective excitation

- **Slow–moving nucleon** $P \sim \mu$
  
  $\langle N|O|N \rangle$ from Euclidean correlation functions
  
  $\rightarrow$ lattice, analytic methods
  
  No concept of “particle content”

- **Fast–moving nucleon** $P \gg \mu$
  
  Closed system: Wave function description
  
  Gribov, Feynman
  
  Components with different numbers of particles
  
  Deep–inelastic processes in $ep, pp, \gamma p$:
  
  “Snapshot” with resolution $1/Q$
  
  Perturbative fluctuations $\rightarrow$ scale dependence
Nucleon structure: Landscape

- Many-body system with different components
  
  Energy of configurations $\sim 1/x$  momentum fraction

- Measurable properties
  
  Longitudinal momentum densities
  Transverse spatial distributions
  Orbital motion: $k_T$ dependence, angular momentum
  Correlations between partons
Parton densities: Unpolarized quarks and gluons

- Global QCD fits to $ep/pp$ data with controlled uncertainties
  CTEQ, MSTW, GJR, Alekhin
  “Infrastructure” for LHC

- Quark densities at large $x$ still poorly known
  Reveal basic $qqq$ configuration of N
  JLab 12 GeV $\rightarrow$ L. Cardman

- Gluon density at $x > 0.3$: Direct probes?
  High-mass jets at LHC
  $+ d/u$ from JLab 12 GeV
  Open charm at EIC?
  $\rightarrow$ H. Avakian, EIC Workshop
Parton densities: Non-singlet sea quarks

- Non-singlets $\bar{d} - \bar{u}$, $s - \bar{s}$ etc. are of non-perturbative origin
  
  Weak scale/scheme dependence

- $\bar{d} - \bar{u}$ from FNAL E866 Drell–Yan and HERMES SIDIS

  Pion cloud at distances $\sim 1/M_\pi$
  carries only $\sim 30\%$ of asymmetry
  
  Strikman, CW

- $s \neq \bar{s}$ from NuTeV CC neutrino DIS
  with $W^+ + s \rightarrow c$ tagging

  $K\Lambda$ fluctuations? Brodsky, Ma

  Semi-inclusive DIS with EIC!

  Much room for improvement!
  Direct impact on vacuum/nucleon structure
Parton densities: Polarization

- NLO QCD fits to polarized inclusive and semi-inclusive $ep$ and $pp$ data
  → D. De Florian
  New fragmentation functions DSS 07

- Gluon polarization $\Delta G(x)$ small
  Dynamical explanation?
  Nucleon spin requires quark/gluon orbital angular momenta!
  Improvement from COMPASS
  + JLab 12 GeV inclusive data
  Future EIC → D, De Florian, H, Avakian, EIC Workshop

- Polarized sea quark flavor asymmetries:
  First hint that $\Delta \bar{u} - \Delta d > 0$, large
  Non-perturbative vacuum fluctuations, chiral symmetry breaking
  Dorokhov, Kochelev; Diakonov et al.

De Florian, Sassot, Stratmann, Vogelsang 09
$Q^2 = 10$ GeV$^2$
Transverse spatial distributions: GPDs

- GPD at $x' = x$: Transverse form factor of quarks with longitudinal momentum $x$
  \[
  \text{GPD}(x, \Delta_T) \rightarrow \mathcal{F}(x, b) \text{ Burkardt}
  \]

- Nucleon’s transverse size grows with decreasing $x$

  Different mechanisms

- Hard exclusive processes $eN \rightarrow e' + M + N$: QCD factorization theorem
  Müller et al.; Ji; Radyushkin; Collins, Frankfurt, Strikman

  Pointlike in transverse space: \[
  \int d^2k_T
  \]

  Recent results $\gamma^* \gamma \rightarrow \pi^0$? Radyushkin, Polyakov

- Practical challenges

  Higher twist effects in hard process: intrinsic $k_T$, finite size of produced meson

  $x \neq x'$, non-diagonal pieces
Transverse spatial distributions: Gluons

- Transverse distribution of gluons from exclusive $J/\psi$ photoproduction
  - HERA: Small $x$, overall area only
  - $x > 10^{-2}$ poor . . . COMPASS?
  - Valence gluons: $\phi$ electroproduction with JLab 12 GeV
    - “Gluon imaging” with EIC

- Essential ingredient in small–$x$ phenomenology
  - QCD dipole model in impact parameter representation Frankfurt et al.; Kowalski et al.
  - Saturation in $ep$, nuclear enhancement $\rightarrow$ F. Gelis
Transverse spatial distributions: Quarks

- **Exclusive amplitude**: Two parts
  
  GPD contains both, related by Lorentz invariance, “polynomiality”

  Included in GPD parametrizations

  → M. Polyakov, D. Müller

- **Dynamics of $q\bar{q}$ knockout?**

  Cf. absolute cross sections

  QCD vacuum structure!

  $\pi^+$ production: Pion pole term

- **DVCS $eN \rightarrow e'N\gamma$: Both needed**

  Im/Re from spin/charge asymmetries

  → F.X. Girod, A. Mussgiller

  Dispersion approach: Im $\rightarrow$ Re, subtraction constant

→ A. Fradi: CLAS $\rho^+$
Transverse spatial distributions: Charge, current

\[ \int dx \]

- Partonic interpretation of elastic FF: Transverse charge/current density
  Burkardt, Miller
  \[ F_{\text{el}}(\Delta T) \xrightarrow{2D \text{ Fourier}} \rho_T(b) \]

- Transverse charge densities from empirical FFs
  Neutron negative at center, counter to \( \pi^- p \) picture Miller
  Deformation through transverse polarization, extension to \( N \to \Delta \) Carlson, Vanderhaeghen

- Calculable in lattice QCD:
  Local operators in \( N, \Delta \to C \), Lorce
  New insights from “old” observables

Transversely polarized \( p, n \). Carlson, Vanderhaeghen 07
**Orbital motion: Transverse momentum**

- Transverse motion, $k_T$ dependence observable in semi-inclusive DIS

- QCD factorization with $\gamma^* N$ collinear: TMDs, soft factor

  Matching of non-pert. and pert. mechanisms Ji et al., Bacchetta et al.

- Measures of parton orbital motion

  Sivers: Deformation of $k_T$ distribution by transverse nucleon spin; interference of $\Delta L = 1$ wave function components + FSI

  Pretzelosity: Deviation from spherical shape through $\Delta L = 2$ in wave function Miller

- EIC: Fully differential measurements, low ↔ high $p_T$

Phenomenological extraction of Sivers distribution from HERMES and COMPASS SIDIS data, Anselmino et al, 08

→ Workshop summary by A. Bacchetta
Orbital motion: Angular momentum

\[ J_q \sim \langle N | \mathbf{x} \times \mathbf{T} | N \rangle \]

- Two basic definitions of quark/gluon angular momentum
  - Matrix element of EM tensor in rest frame
    - Ji sum rule, GPDs
    - \( L \) in partonic wave function

- Need to understand connection!
  - Many interesting issues: Gauge dependence
    - M. Burkardt, A. Bacchetta

- Rest frame calculations of \( J_q \)
  - Lattice: Dynamical fermions, no disconnected diagrams
    - Ph. Hägler
  - Quark model at low scale
    - Myhrer, Thomas
  - Chiral quark–soliton model
    - Wakamatsu

- Requires comprehensive approach:
  - SIDIS + GPDs (Ji sum rule)
Correlations

• Transverse correlations in partonic wave function
  
  Cf. short–range NN correlations in nuclei
  JLab Hall A, CLAS
  
  Vacuum fluctuations $\rho \ll R_{\text{had}}$

• Sea quarks have intrinsic $k_T \sim \rho^{-1}$
  $\gg$ valence quarks
  
  → Semi-inclusive DIS
  → Higher twist in inclusive DIS $\sim \langle k_T^2 \rangle$ Sidorov, CW

• Observable in $pp$ through enhancement of multiple hard processes
  
  CDF 3 jet + gamma data consistent with $\rho \sim 0.3$ fm

  High rates for multijets at LHC!
Small $x$ and new correspondences $ep \leftrightarrow pp$

- **Unitarity limit and saturation** $\rightarrow F. Gelis$
  Appearance of new dynamical scale $Q_s(x) \gg \mu_{\text{vac}}$, systematic approximations!
  Nucleon/nuclear wave function develops component with $k_T \sim Q_s$ observable in particle production at RHIC, LHC, $eA$ at EIC

- **Hard diffractive scattering** $pp \rightarrow p + H + p$
  Interplay between hard process and soft spectator interactions:
  Rapidity gap survival
  Sensitive to transverse distribution of partons . . .
  probe GPDs in $pp$ scattering! LHC, Tevatron, RHIC?

- **Ultraperipheral $pA/AA$ collisions** $\rightarrow$ D. D'Enterria
  $\gamma A/\gamma\gamma$ scattering with Weizsäcker–Williams photons
  from field of heavy nucleus $Z \gg 1$ RHIC, LHC
  $\rightarrow$ Small–$x$ physics, e.g. high–$p_T$ jets $W(\gamma p) = 10$ TeV at LHC = 30× HERA!
  $\rightarrow$ Heavy quarkonium spectroscopy
  $\rightarrow$ Higher–order QED processes
Summary

- The nucleon as a many–body system – a unifying perspective
  - different probes, excitation energies, resolution scales . . .
  - physical properties

- New synergies/correspondences between $ep \leftrightarrow pp \leftrightarrow \gamma p$

- Great prospects with present and future facilities

  | COMPASS | RHIC | Ultraperipheral RHIC, LHC |
  | JLab 12 GeV | LHC | J-Parc |
  | EIC/ENC/LHeC | GSI FAIR | GlueX at JLab |