Exploring the three-dimensional structure of the proton and nuclei

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Context and goals

Hadrons and nuclei ↔ quarks, antiquarks, gluons

- \( q, \bar{q}, g \) only manifest at short distance/short times
  \( \sim \) 'snapshots' of a strongly interacting system
  rather than 'structure' in a static sense

- several difficult and interesting aspects:
  confinement, gluon self coupling, chiral symmetry breaking
  highly relativistic system \( (p \neq uud) \)

- aim: study quantitatively
  how hadrons and nuclei 'look like'/behave at parton level
  how partons interact inside hadrons and nuclei

1. to make progress in understanding QCD dynamics
   measurements ↔ physical picture ↔ theory

2. in some cases: use to improve quantitative description of
   \( pp/pA/AA \) collisions
Dynamics at short vs. long distances

- hard processes involve both short and long distance dynamics (inevitably have hadrons in initial and final state)
- parton splitting

- important aspect of dynamics in several contexts
- evolution eqs. in resolution scale (DGLAP) or in rapidity (BFKL, BK, etc)
- perturbative calculations, largely well understood

- but what about sea quarks/antiquarks generated by non-perturbative mechanisms?
  - different behavior of \( s \) vs. \( \bar{s} \), \( \bar{u} \) vs. \( \bar{d} \)
  - role of pion/kaon fluctuations (connected with chiral dynamics)
Longitudinal vs. transverse

- hard processes single out (at least) one spatial direction

\[ r \times p \]

holds both in collision c.m. and in target rest frame

- different roles played by longitud. and transv. directions

\[ \sim \] lose manifest 3dim rotation symmetry in target rest frame

- usual parton densities: **longitudinal** information

  aims: achieve high precision, details of flavor structure, 
  \( q \) vs. \( \bar{q} \), polarization, nuclear effects

- **transverse** structure: much less well known

  in first instance aim to see general trends/patterns
  but often also requires high-precision measurements

- new d.o.f.: *orbital angular momentum* (classically: \( L = r \times p \))
Transverse structure: momentum vs. position

- variables related by 2d Fourier transforms, e.g.
  - quark fields \( \tilde{\psi}(k_T, z^-) = \int d^2 z_T e^{i z_T k_T} \psi(z_T, z^-) \)
  - proton states \( |p^+, b_T\rangle = \int d^2 p_T e^{-i b_T p_T} |p^+, p_T\rangle \)

\[ \text{with } z^- = z^0 - z^3 \text{ and } p^+ = p^0 + p^3 \]

- fully relativistic description: localize only in 2 dimensions in 3d can only localize object within its Compton wavelength

- at level of squared amplitudes/probabilities

\[ \bar{\psi}(k_T)\psi(l_T) = \int d^2 y_T d^2 z_T e^{-i(y_T k_T - z_T l_T)} \bar{\psi}(y_T)\psi(z_T) \]

\[ y_T k_T - z_T l_T = \frac{1}{2} (y_T + z_T) (k_T - l_T) + \frac{1}{2} (y_T - z_T) (k_T + l_T) \]

- 'average' transv. momentum \( \leftrightarrow \) position difference
  - transv. momentum transfer \( \leftrightarrow \) 'average' position

- 'average' transv. mom. and position not Fourier conjugate

- Wigner phase space distributions \( W(x, k_T, b_T) \) give probabilities

\[ \int d^2 k_T W = f(x, b_T) \text{ and } \int d^2 b_T W = f(x, k_T) \]
Access to transverse position: exclusive processes

- **DVCS and meson production** → generalized parton distrib’s

  - similar theory as for usual parton densities
  - have factorization proofs, evolution in resolution scale $Q$
  - longit. mom. transfer → two parton mom. fractions $x \pm \xi$
  - to LO in $\alpha_s$ measure $\text{GPD}(x, \xi = x, \Delta_T)$

- '1st stage' imaging: $\text{Fourier} \rightarrow \text{GPD}(x, \xi = x, b_T)$

  - no probability interpretation, but $b_T$ = well defined transverse distance
Access to transverse position: exclusive processes

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- longit. mom. transfer $\leadsto$ two parton mom. fractions $x \pm \xi$
  to LO in $\alpha_s$ measure $GPD(x, \xi = x, \Delta_T)$

- ’2nd stage’: $GPD(x, \xi = x, b_T) \rightarrow GPD(x, \xi = 0, b_T)$

- density interpretation: $GPD(x, \xi = 0, b_T) = f(x, b_T)$
- access only via $\alpha_s$ effects $\leadsto$ $Q^2$ dependence
- presently unclear how strongly extrapolation to $\xi = 0$ will depend on theoretical assumptions
Small $x$ formulation: the dipole representation

- amplitude $N(x, r_T, b_T)$ for scattering of dipole on target naturally in $b$ space

Fourier transf. gives $r_T \rightarrow k_T$ of quark, $b_T \rightarrow \Delta_T$ of target

- valid for small $x$ (empirically $\lesssim 10^{-2}$)
  “$x$” and “$\xi$” do not appear as independent variables

- comparison with collinear (= GPD) formalism:
  - dipole formalism: small $x$ limit, predicts $x$ dependence
    large $Q$ limit not taken, require $Q$ large enough for pert. calc.
  - GPD form.: all $x$, large $Q$ limit, predicts $Q$ dependence
  - in double limit of large $Q$ and small $x$ approaches equivalent
Some trends, unknowns, predictions

- lattice calculations \( \langle b^2 \rangle \propto \text{const} + \alpha' \log \frac{1}{x} \) for gluons \( \alpha' \sim 0.15 \text{ GeV}^{-2} \) from HERA \( J/\Psi \) prod’n much smaller than in soft hadronic procs.
- at small \( x \) find \( \langle b^2 \rangle \propto \text{const} + \alpha' \log \frac{1}{x} \)
- at large \( b \) prediction from chiral dynamics \( \langle b^2 \rangle \sim e^{-\kappa b_T} / b_T \) with \( \kappa \sim 2m_\pi = (0.7 \text{ fm})^{-1} \)
- requires precise measurement at low \( \Delta_T \)
Nuclei

- coherent hard scattering on nucleus $\leadsto$ spatial parton distr’n
  general theme: deviation from “independent nucleon approx.”

$$f_{q/A}(x, b) = f_{q/N}(\cdot, \cdot) \otimes f_{N/A}(\cdot, \cdot)$$

- nontrivial effects in saturation dynamics

  scattering on gluons from different nuclei
  merging of gluon chains from different nuclei
Spin and orbital angular momentum

- GPD $E \leftrightarrow$ nucleon helicity flip $\langle \downarrow | O | \uparrow \rangle$

$\sim$ interference between wave functs. with $L_z$ and $L'_z = L_z \pm 1$

no direct relation with $\langle L_z \rangle$, but indicator of large $L_z$

- helicity flip $\leftrightarrow$ transverse polarization asymmetry

parton dist’s in proton polarized along $x$ are shifted along $y$:

$$f^X(x, b) = f(x, b^2) - \frac{b^y}{m} \frac{\partial}{\partial b^2} e(x, b^2)$$

$$e(x, b^2) = \text{Fourier transform of } E(x, \xi = 0, \Delta_T)$$

- connection to orbital angular momentum via $b \times p$

$\rightarrow$ talk M Burkardt, Nov 1

- shift known to be large for valence combinations $u - \bar{u}$, $d - \bar{d}$

from sum rule connecting with magnetic moments of $p$ and $n$

unknown for sea quarks and gluons
Spin and orbital angular momentum

- **GPD** $E \leftrightarrow$ nucleon helicity flip \( \langle \downarrow | \mathcal{O} | \uparrow \rangle \)

  \( \sim \) interference between wave fcts. with $L^z$ and $L'_z = L^z \pm 1$

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- $E$ key part of Ji’s angular momentum sum rule:

  \[
  2J^q = \int dx \, x[q(x) + \bar{q}(x)] + \int dx \, x[e^q(x) + e^{\bar{q}}(x)] \\
  2J^g = \int dx \, xg(x) + \int dx \, xe^g(x) \\
  e^a(x) = \int d^2 b \, e^a(x, b^2) = E^a(x, \xi = 0, \Delta_T = 0)
  \]

- other definitions of angular momentum exist

  much disc. in literature: Jaffe, Manohar '90; . . . ; Wakamatsu '10

  to my mind, non-uniqueness of “o.a.m.” reflects character of the system under study:

  - quarks and gluons interact
  - gauge fields contain phys. and unphys. d.o.f.
Aside: multi-parton interactions in hadron-hadron collisions

- hard inclusive process, e.g. $pp \rightarrow \text{jet jet + } X$
  - no impact parameter dependence
  - integrate over $b_1$ and $b_2$ independently

- secondary soft or hard interactions
  - do not affect inclusive cross section, but change event structure
  - will affect many analyses at LHC
  - sensitive to transverse distance between partons
    - but this distance not directly related to final-state variables

- information from GPDs can help description of mult. interactions
  - $b$ dependence and its interplay with momentum fraction $x$
Transverse parton momentum: distributions and fragmentation

- factorization = possibility to disentangle dynamics into
  - hard scattering \((\text{calculate})\)
  - quantities referring only to one hadron: parton distributions, fragmentation functions

  is not trivial, should not be taken for granted

- factorization where parton transv. momentum is retained
  reveals subtle properties of QCD dynamics

- close to factorization proofs for semi-inclusive DIS, Drell-Yan,
  \(e^+e^- \rightarrow \text{back-to-back hadrons} + X\)

- possibly also achievable for \(\gamma^*p \rightarrow \text{back-to-back hadrons} + X\)

- hadron-hadron collisions: not clear if can separate “partons in one hadron” from their “environment” in the process

  \(\rightarrow\) talks P Mulders, Sep 14; T Rogers, Sep 20
Transverse momentum dependent distributions

► theoretical description of transv. momenta in final state:
  • if large then generate perturbatively = hard radiation
  • for small transv. momenta (or transv. momentum differences) described by transv. mom. dependent distributions etc.
  • no sharp boundary between “intrinsic” and “radiative” but transition between the two regimes interesting and often practically relevant

► distribution of $q, \bar{q}, g$ at low $k_T$ remains largely unknown
  • lattice studies, as well as constituent quark models suggest significant difference in trv. mom. distribution of $u$ and $d$ quarks in $p$ → talk B Musch, Nov 3
  ⊳ should be open for surprises

► $k_T$ dep’t gluon distribution plays prominent role at small $x$
  rather direct access to saturation scale $Q_s(x)$
  → talks F Yuan, Sep 14; B-W Xiao, Oct 6
The relevance of gluons “accompanying” a parton

- in general, colored objects are surrounded by gluons
  profound consequence of gauge invariance
  technically implemented in Wilson lines

- $k_T$ dep’t distributions can be time reversal odd
  e.g. Sivers function: unpol. quarks in proton pol. along $x$:

$$f^X(x, k_T) = f(x, k_T^2) + \frac{k_y}{M} f_{1T}(x, k_T^2)$$

Sivers fct. has **opposite sign** when gluons couple after quark scatters (SIDIS) or before quark annihilates (DY)
would be **zero** if gluons were absent
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Sivers fct. has opposite sign when gluons couple after quark scatters (SIDIS) or before quark annihilates (DY)

- would be zero if gluons were absent

- fragment’n fct’s: similar dynamics, with important differences
Orbital angular momentum again

- Sivers fct. $\leftrightarrow$ proton helicity flip
  $\sim$ interference of config’s with $L^z$ and $L'_z = L^z \pm 1$
  another indicator of $L^z$
Orbital angular momentum again

- **Chormodynamic lensing:**
  - transverse shift in $b$ space (described by $E$)
  - $\sim$ transverse shift in $k_T$ (described by $f_{1T}^\perp$)
    - generated by gluon exchange, opposite signs for SIDIS and DY
    - no calculation in full QCD (is highly nonperturbative)
    - but seen in model calculations
  - should test experimentally for different $x$ and different parton species

- Both $E$ and $f_{1T}^\perp$ exist for quarks and gluons
  - could become sizeable at small $x$ by parton splitting,
  - provided that are not small at low scale/low $k_T$
Connection with hadron-hadron collisions

two aspects:

▶ universality of $T$ even dist’s, sign change of $T$ odd dist’s between DY and SIDIS
  $= \text{test our understanding of the role of gauge field d.o.f.}$

▶ explore and quantify expected breakdown of $k_T$ factorization in more complicated hadron-hadron processes, e.g. $pp \rightarrow \pi + X$

current understanding: not possible to disentangle “accompanying gluons” from one and the other colliding hadron
Conclusions

- semi-inclusive and exclusive procs. with measured transv. momenta
  - study trv. parton momentum and position in quantitative, theoretically controlled ways
  - require large range in $Q^2$ and $k_T$, need multi-dimensional binning
- involves many aspects, some rather concrete, others more generic
  - interplay of pert. and nonpert. phenomena
    - radiatively generated vs. nonpert. sea, flavor and spin strct.
    - transition from small to large $k_T$
  - spatial distribution of partons in hadron ↔ confinement
  - role of $\pi$ fluctuations ↔ chiral dynamics
  - spin-orbit correlations ($k_T$ or $b_T$ vs. polarization)
    - orbital angular momentum
  - dynamics of gluons that accompany any colored particle
    (Wilson lines)
- large array of possible measurements, distribution functions
  - possibility to relate phenomena and discern patterns