Three-Dimensional Structure of the Nucleon and Quantum Chromodynamics

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General Scientific Meeting of the Belgian Physical Society
Ghent, 18 May 2016

QCD: *the* Theory of Strong Interaction

Quantum Chromodynamics: a renormalizable gauge quantum field theory

Fundamental Properties and Concepts of QCD

Confinement: fundamental building blocks of QCD – quarks and gluons – do not exist as free particles.
Compare with QED: photons and electrons do exist and can be detected.

Running coupling: the strong coupling α_s changes with the characteristic energy – consequence of the renormalization.
Compare with QED: the same idea.

Asymptotic freedom: at small distance the quarks and gluons are (almost) free particles and the perturbative approach is applicable.
Compare with QED: β-function has the opposite sign, hence the magnitude of the electric charge rises at small distance.

QCD Description of High-Energy Hadronic Collisions

Principal Tools to Work with QCD in the High-Energy Regime

Factorization: enables the separation of large- [essentially nonperturbative] and small-distance [perturbative hard scattering matrix elements] contributions.
Compare with QED: factorization is possible but not needed.

$$d\sigma \sim H_{\text{small distance}} \otimes S_{\text{large distance}}$$

Parton distribution functions [pdfs]: accumulate information about intrinsic structure of hadrons.
Compare with QED: one can evaluate the matrix elements for the physical final states "from the first principles".

Parton Distributions and High-Energy Processes

Inclusive processes $\to$ **collinear factorization**: one or less hadron detected; e.g., DIS, electron-positron annihilation to hadrons

Semi-inclusive processes $\to$ **TMD factorization**: two or more hadrons in the initial or final state detected; e.g., Drell-Yan, SIDIS, hadron-hadron to jets, Higgs and heavy-flavour production

Collinear factorization: longitudinal momenta of the patrons are intrinsic, transverse momenta can be created by perturbative radiation effects (parton showers) $\to$ **collinear (integrated) pdfs**

$k_\perp$**-dependent factorization:** a unifying QCD-based framework with both mechanisms of the transverse-momentum creation taken into account–intrinsic (essentially non-perturbative) and perturbative radiation $\to$ **transverse-momentum dependent (unintegrated, $3D$) pdfs**

Parton Distribution Functions

Whatever factorization framework [collinear, TMD, $k_\perp$-dependent], the **pdfs** must be

Gauge-invariant

Universal

Renormalizable

Parton Distribution Functions
Issues

Wilson lines: save gauge invariance; jeopardise universality; complicate renormalizability

Path-dependence: the structure of the Wilson lines is too complicated; universality may be broken

Factorization scale is arbitrary: transition from one scale to another (different experiments have different characteristic scales) by means of evolution equations

Evolution: DGLAP, BFKL, CCFM... TMD; development of dedicated Monte-Carlo needed [in progress]

3D Imaging of the Nucleon: PDFs beyond the collinear approximation

3-dimensional pdfs contain the information about the intrinsic longitudinal and two-dimensional transverse momenta of the quarks and gluons, are called unintegrated or

Transverse-Momentum Dependent = TMD

$3D$-structure: two sets of experimental data

high-energy DIS: $\sqrt{s} \to \infty$, momentum transfer fixed

low-q_T DY and SIDIS (polarized and unpolarized): $q_T \to 0$, invariant mass fixed

Why TMD Factorization?

low-q_T DY: $d\sigma^{Z^*}_{\rm DY}(q_T)$ in the range $60\ GeV < M < 120\ GeV \rightarrow$ High-q_T ($10^2\ GeV$), the 'peak region' ($10\ GeV$), low-q_T ($1\ GeV$). pQCD convoluted with the collinear pdf $\rightarrow d\sigma^{Z^*}_{\rm DY}(q_T)$ diverges at small q_T.

high-energy DIS: rise of the proton structure function at small-x. As parton longitudinal momentum fractions (Bjorken-x) become small, the transverse degrees of freedom becomes increasingly important. The strong corrections at small-x come from multiple radiation of gluons over long intervals in rapidity, in regions not ordered in the gluon transverse momenta $\mathbf{k}_\perp$, and are present in all higher orders of perturbation theory. TMD evolution provides an appropriate framework to resum such corrections.

Current and Future Experimental Facilities with TMD-Related Research Programms

HERMES, COMPASS: a bunch of data on polarized processes

RHIC: reactions with polarised protons and nuclei

LHC: unpolarised processes with sensitivity to polarized gluon distributions; testing resummation algorithms; Higgs, jet and heavy flavour production

Jefferson Lab: one third of approved experiments for 12 GeV Upgrade are devoted to the 3D structure of the nucleon (TMD and GPD)

Electron-Ion Collider: large-x regime, high luminosity, broad TMD program; spin effects

TMD/$3D$ Phenomenology: Identification of the benchmark observables

Polarised processes: spin asymmetries [TMD in full glory]

Low-q_T heavy particle spectra: vector and Higgs bosons, heavy flavours

High-energy limit: $s \to \infty$ for fixed momentum transfer

Further Reading:

R. Angeles-Martinez, *et al.*:
"Transverse momentum dependent (TMD) parton distribution functions: status and prospects",
Acta Phys. Pol. **B46** (2015) 2501; `arXiv:1507.05267 [hep-ph]`

E.C. Aschenauer, U. D'Alesio, F. Murgia:
"TMDs and SSAs in hadronic interactions",
`arXiv:1512.05379 [hep-ph]`

ICh., F.F. Van der Veken:
"Parton Densities in Quantum Chromodynamics", De Gruyter, Berlin (2016) [in progress]

ICh., T. Mertens, F.F. Van der Veken:
"Wilson Lines in Quantum Field Theory", De Gruyter, Berlin (2014)