Probing the Ontology of Virtual Particles in QCD: The Case of the Evolution of Parton Distribution Functions

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Abstract

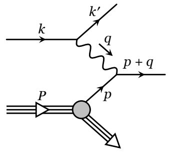
One of the well established predictions of quantum chromodynamics (QCD) is the violation of the phenomenon known as Bjorken scaling. In QCD, the corrections to Bjorken scaling are understood in terms of the evolution of the Parton distribution functions (PDF), which express the probabilities of finding various constituent particles in the hadron wave-functions. More specifically, the evolution of PDFs are described by certain integral-differential equations known as the Altarelli-Parisi equations. The PDF evolution phenomena and the interpretation of the Altarelli-Parisi equations contain important lessons for understanding both the ontology of virtual particles in quantum field theory as well as our epistemic access to them. The evolution of PDFs shows that at higher resolution, an electron appears to comprise virtual electrons, virtual electron-positron pairs, and photons. Similarly, a proton probed at short distances (high momentum) is "seen" as composed of a sea of virtual quarks, anti-quarks, and gluons. Hence, a dichotomous ontology of real versus virtual (or virtual particles as "mere" potentialities) appears problematic, as "real" particles seem to be composed of "virtual" ones. I advocate an "interventionist" approach to virtual particles (following Hacking), which stabilizes ontology through epistemic access in experimental contexts. As a result, the demonstration of scaling violation in the modern deep inelastic scattering experiments, following the form predicted by Altarelli-Parisi equations, provides strict epistemic access to virtual particles, similar to any other empirical phenomena in fundamental physics.

References:

1. Peskin and Schroeder, *Quantum Field Theory*, CRC Press, *1995.*
2. Abromowitz et. al., *Eur. Phys. J. C (2015) 75:580.*
3. Taylor, R. E. *Nucleon form factors above 6 GeV. United States:* SLAC Pub-372, 1967.
4. Hacking, Ian. *"Experimentation and Scientific Realism." Philosophical Topics,* vol. 13, no. 1, 1982, pp. 71–87.

QCD Deep Inelastic Scattering Experiments

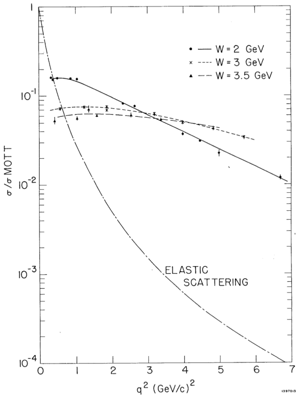
In a deep inelastic scattering experiment, one uses a virtual photon to "probe" the structure of the proton.

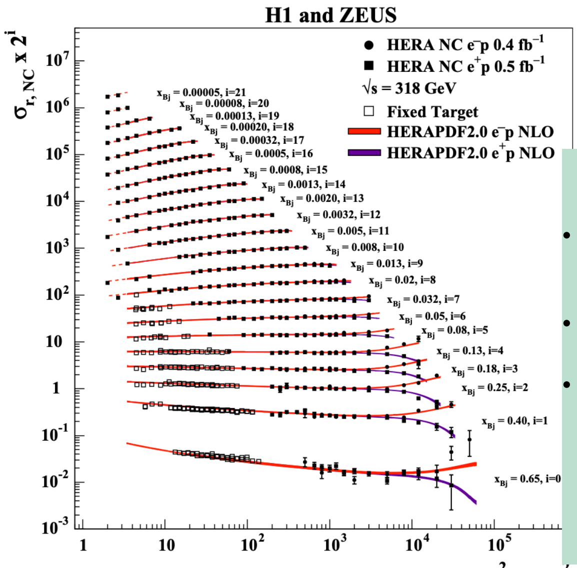


Bjorken Scaling

According to the Parton Model, hadrons are composite particles. In early experiments (electron-proton scattering), it was discovered that the structure functions of protons and neutrons were independent of the momentum transfer:

$F(x, Q^2) = F(x)$ (Generic Expression)





The Parton Model of the Proton

Scaling can be interpreted as an experimental verification of the Parton Model. From the elastic scattering experiments, we infer the *finite-size* structure of the proton, as the structure function falls rapidly with q^2 (implies a spatial distribution.)

The Violation of Scaling and the Alterelli-Parisi (AP) Equations

Bjorken Scaling implies that proton is composed of point-like constituents. However, one can also observe that the scaling is not exact: we see that for both the very small values as well as the higher values of x, the structure functions do depend on Q^2. How to understand this violation? The AP equations give an answer to this question in terms of the concept of ***Parton evolution.***

An intuitive way of understanding the drop in the structure functions is in terms of the Parton distribution function.

Probing the proton at the scale Q implies a distance resolution Q^{-1}. Thus at higher resolution, a higher number of partons come into being and so the total momentum is distributed over more "particles," hence the drop.

By considering the higher order corrections to the leading order Parton Feynman diagram, we can quantify this interpretation: *<u>At higher resolution (high momentum transfer), constituent quark—anti-quark pairs and gluons occur.</u>*

What is a Proton?

- Experiments show that the proton is composed of virtual sea quarks and gluons.
- These virtual particles' virtuality is quantified by Q^2.
- Using the distribution function at a given virtuality, once can evolve it to a higher virtuality, i.e., $Q'^2 > Q^2$.

Valence versus Sea Quarks

AP equations show how the distribution functions of quarks and gluons evolve to produce more partons at high Q. As a well known text-book states: "We can picture the proton as having more and more constituents … as its wave function is probed on finer and finer distance scales" (Peskin and Schroeder, pp. 591-592.)

$$\int_0^1 dx[f_u(x) - f_{\bar{u}}(x)] = 2$$

$$\int_0^1 dx[f_d(x) - f_{\bar{d}}(x)] = 1$$

The simple uud picture of the proton is incorrect. We need to distinguish between sea and valence quarks. The proton is composed of a sea of quark pairs.

Conclusion:

Many key questions in QCD related to the structure of the proton remain unanswered, including the mass, spin or the possible decay of the proton.

Still, the DIS experiments provide us with unequivocal access to <u>virtual quarks as real constituents of protons</u>, similar to other high energy phenomena (Higgs boson etc.)

According to Hacking's "experimental realism," "experimenters are realists about the entities that they use in order to investigate other hypotheses or hypothetical entities" (Hacking, 73.)

We use virtual photons to probe protons, and we use virtual quarks and anti-quarks (whose virtuality we control) to explain DIS experiments. Thus, we have good reasons to be experimental realists about virtual particles.