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Review

The theory of deeply inelastic scattering

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ABSTRACT

The nucleon structure functions probed in deep-inelastic scattering at large virtualities form an important tool to test Quantum Chromodynamics (QCD) through precision measurements of the strong coupling constant $\alpha_s(M_Z^2)$ and the different parton distribution functions. The exact knowledge of these quantities is also of importance for all precision measurements at hadron colliders. During the last two decades very significant progress has been made in performing precision calculations. We review the theoretical status reached for both unpolarized and polarized lepton–hadron scattering based on perturbative QCD.

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1. Introduction

Matter consists of regular structures at microscopic distances, which exhibit themselves at the crystalline, molecular, and atomic levels [1]. The discovery of α, β and γ radioactivity [2] provided new natural probes beyond the visible spectrum of light and X-rays to resolve even smaller structures of matter. In 1911 E. Rutherford discovered the atomic nucleus of a size much smaller than that of atoms through scattering of α-particles at gold [3]. Herewith the picture of matter at small distances changed dramatically rising the question for further sub-structures. The composite nature of nuclei could be explained after Chadwick's [4] discovery of the neutron and Yukawa's model for nuclear forces [5]. Another important discovery was made by Frisch and Stern in 1933 measuring the anomalous magnetic moment of the proton with a different value from that of point-particles, like electrons [6]. Later in 1939 Alvarez and Bloch measured the anomalous magnetic moment of the neutron [7], both of which constituted first evidence on the compositeness of nucleons. The current values of the nucleon magnetic moments are [8]

$$\mu_p = 2.792847356 \pm 0.000000023\, \mu_N, \qquad \mu_n = -1.9130427 \pm 0.0000005\, \mu_N, \tag{1.1}$$

with $\mu_N = e\hbar/2m_p$ the nuclear magneton.

During the 1950s the Hofstadter experiments [9] operated at virtualities being large enough to reveal the charge distribution inside nucleons, which is illustrated in Fig. 1. A positive core distribution and tail are found both for the proton and neutron, with a positive vector cloud in case of the proton and a negative one for the neutron, pointing to first details of the nucleon sub-structure. However, the specific nature of these distributions remained yet unexplained.

In 1964 Gell-Mann [11] and Zweig [12] proposed the quarks[1] as building blocks of hadrons to catalog the plethora of observed mesons and baryons. During the late 1960s the MIT-SLAC experiments [13–19] measured deep-inelastic electron–nucleon scattering at the Stanford Linear Accelerator at much shorter distances and beyond the resonance region. The important finding of these experiments were scaling and the observation that the longitudinal structure function is small, Fig. 2, confirming a prediction by Callan and Gross [20] for scattering off spin 1/2 particles. The scaling behavior of structure functions had been predicted by Bjorken using current algebra methods [21]. These new observations led Feynman to the parton model [22,23] of point-like fermionic constituents of the nucleons which react at high virtualities with the exchanged gauge bosons in the deep-inelastic process directly.

Deep-inelastic scattering off constituent quarks has been discussed as early as 1967 [24] in connection to data of that time [25]. After the discovery of scaling at SLAC also data taken in other experiments were analyzed for this behavior. One example concerns data taken at DESY at lower values of $|q^2|$ [26], cf. Fig. 3, presented using the Rittenberg–Rubinstein variable ω_W.

The parton model introduced a new level of compositeness for fermions being confined inside hadrons and related to the strong interactions. The final quantum field theory of the strong interactions developed over a series of years. Already in 1965 Nambu [27] proposed a Yang–Mills [28] $SU(3)$ gauge theory for the strong interactions, based on a three-valued charge degree of freedom [29]. Before a symmetry was introduced using para-statistics [30] which later became color. At this time it was unknown whether Yang–Mills theories could be renormalized. The formalism by Faddeev and Popov [31] needed for their quantization in covariant gauges has been found two years later only. The renormalization of massless Yang–Mills theories was proven by 't Hooft [32] and Quantum Chromodynamics (QCD) as the theory of strong interactions was proposed by Fritzsch and Gell-Mann in 1972 [33] and Fritzsch et al. [34]. In 1973 Gross and Wilczek [35] and Politzer [36] studied the running of the strong coupling constant of color octet Yang–Mills theory with color triplet quarks and found asymptotic freedom, see also [37,38]. The Lagrangian of QCD, referring to the covariant R_ξ-gauges, is given by [39]

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_{q,j}(x)\left[i\, \not{D}^{jk} - m_q\right]\psi_{q,k}(x) - \frac{1}{4}F_a^{\mu\nu}(x)F^a_{\mu\nu}(x) - \frac{1}{2\xi}\left(\partial_\mu A_a^\mu(x)\right)^2 + \partial_\mu \chi^a_\mu(x) D^{ab,\mu}\chi_b(x), \tag{1.2}$$

where $\psi_q(x)$ denotes the quark fields, $A_a^\mu(x)$ the gluon fields, $F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu + g f_{abc} A^{b,\mu} A^{c,\nu}$ the field strength tensor, f_{abc} the structure constants of $SU(3)_c$, the gauge group of QCD, $\xi \in \mathbb{R}$ the gauge parameter, $\chi_a(x)$ the ghost field, and the covariant derivatives $D_\mu^{ab} = \delta^{ab}\partial_\mu - g f^{abc} A_{c,\mu}(x)$, $\not{D}^{jk} = \gamma_\mu\left[\delta_{jk}\partial^\mu - igA_a^\mu t^a_{jk}\right]$, with t^a the generators of $SU(3)_c$. Based on this, perturbative calculations in Quantum Chromodynamics can be performed at large virtualities. Due to their high complexity these calculations are usually being performed using computer algebra programs, a first dedicated of which was `SCHOONSCHIP` by Veltman [40].

[1] G. Zweig named the hadron constituents *aces*.