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Running of the charm-quark mass from HERA deep-inelastic scattering data

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ABSTRACT

Combined HERA data on charm production in deep-inelastic scattering have previously been used to determine the charm-quark running mass $m_c(m_c)$ in the $\overline{\text{MS}}$ renormalisation scheme. Here, the same data are used as a function of the photon virtuality Q^2 to evaluate the charm-quark running mass at different scales to one-loop order, in the context of a next-to-leading order QCD analysis. The scale dependence of the mass is found to be consistent with QCD expectations.

1. Introduction

The Standard Model of particle physics is based on Quantum Field Theory, which can provide predictions that rely on a perturbative approach. In the $\overline{\text{MS}}$ renormalisation scheme of perturbative quantum chromodynamics (pQCD), the values of all basic QCD parameters depend on the scale μ at which they are evaluated. The most prominent example is the scale dependence, i.e. running, of the strong coupling constant α_s, a by now well established property of pQCD. It has, for example, been determined from measurements of hadronic event shapes or jet production at e^+e^- colliders [1,2], and from measurements of jet production at HERA [3], Tevatron [4] and LHC [5].

The scale dependence of the mass m_Q of a heavy quark in the $\overline{\text{MS}}$ scheme can likewise be evaluated perturbatively, using the renormalisation group equation

$$\mu^2 \frac{d}{d\mu^2} m_Q(\mu) = m_Q(\mu)\, \gamma_{m_Q}(\alpha_s)\ , \qquad (1)$$

which is governed by the mass anomalous dimension $\gamma_{m_Q}(\alpha_s)$ known up to five-loop order [6] in perturbation theory. The running of the $\overline{\text{MS}}$ beauty-quark mass has already been successfully investigated from measurements at the LEP e^+e^- collider [7]. Heavy-flavour production in deep-inelastic scattering (DIS) at HERA is particularly sensitive to heavy-quark pair production at the kinematic threshold. A recent determination of the beauty-quark mass $m_b(m_b)$ [8] by the ZEUS experiment at HERA was reinterpreted as a measurement of $m_b(\mu = 2m_b)$ using the solution of Eq. (1) at one loop. The comparison [9–11] of this result with the measurements from LEP and the PDG world average [12,13] shows consistency with the expected running of the beauty-quark mass.

An explicit investigation of the running of the charm-quark mass has not been performed yet. Combined HERA measurements [14] on charm production in deep-inelastic scattering have already been used for several determinations of the charm-quark mass $m_c(\mu = m_c)$ in the $\overline{\text{MS}}$ renormalisation scheme [14–18]. Fig. 1 shows the measured reduced cross section for charm production [14] as a function of the Bjorken variable x_{Bj} in 12 bins of photon virtuality Q^2 in the range 2.5 GeV$^2 < Q^2 <$ 2000 GeV^2. In this paper, these data are used to investigate the running of the charm-quark mass with the same treatment of the uncertainties of the combination as in Ref. [14]. The fixed flavour number scheme (FFNS) is used at next-to-leading order (NLO) with $n_f = 3$ active flavours. This scheme gives a very good description of the charm data [14,19], as shown in Fig. 1. Calculations of next-to-next-to-leading order corrections with massive coefficient functions [18,19] have not yet been completed, and are therefore not used in this paper.

2. Principle of the $m_c(\mu)$ determination

The theoretical reduced cross section for charm production is obtained from a convolution of charm-production matrix elements with appropriate parton density functions (PDFs). The latter are obtained from inclusive DIS cross sections, which include a charm contribution. Thus both, matrix elements and PDFs, depend on the value of the charm-quark mass. The scale dependence of the charm-quark mass is evaluated by subdividing the charm cross-section data [14] into several subsets corresponding to different individual scales, as indicated by different rows in Fig. 1. In contrast, in the evaluation of the PDFs, data spanning a large scale range such as the inclusive HERA DIS data [20,21] must be used in order to get significant PDF constraints. A subdivision into individual scale ranges is thus not possible for the PDF determination. On the other hand, it has been established that, apart from the strong constraint which the charm measurements impose on the charm-quark mass [14], their influence on a combined PDF fit of both inclusive and charm data is small [21]. Therefore, the PDFs extracted from inclusive DIS can be used for investigations of charm-quark properties, provided that the same charm-quark mass is used throughout, recognising that thereby some correlation between the mass and PDF extractions is induced. The influence of this correlation on the determination of the charm-quark mass running is minimised as described in section 4.

To obtain the charm-quark mass at different scales, the charm data are subdivided into six kinematic intervals according to the virtuality of the exchanged photon. Each measurement in a given range in Q^2, as listed in Table 1 and shown in Fig. 1, is performed with charm data originating from collisions at a typical scale of $\mu = \sqrt{Q^2 + 4m_c^2}$. The actual scale used for each interval is defined according to

$$\log \mu = \left\langle \log \left(\sqrt{Q^2 + 4m_c^2} \right) \right\rangle, \qquad (2)$$

where the brackets indicate the logarithmic average of the considered range. The resulting value for each Q^2 range is also listed in Table 1.

Technically, a value of $m_c(m_c)$ is extracted separately from a fit to each interval. The value of $m_c(m_c)$ is obtained assuming the running of both α_s and m_c as predicted by QCD. To that end, Eq. (1) is solved using the one-loop dependence on the scale μ, as relevant

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