

Instantons in lepton pair production

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Abstract

We consider QCD instanton-induced contributions to lepton pair production in hadron–hadron collisions. We relate these contributions to those known from deep inelastic scattering and demonstrate that they can be calculated reliably for sufficiently large momentum transfer. We observe that the instanton contribution to the angular distribution of the lepton pairs at finite momentum transfer strongly violates the Lam–Tung relation—a relation between coefficient functions of the angular distribution which is valid within the framework of ordinary perturbation theory. The drastic violation of this relation, as seen in experimental data, might be related to such instanton-induced effects.

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1. Introduction

The Standard Model of electroweak (quantum flavor dynamics (QFD)) and strong (QCD) interactions is extraordinarily successful. This success is largely based on the possibility to apply ordinary perturbation theory to the calculation of hard, short-distance dominated scattering processes, since the relevant gauge couplings are small. Certain processes, however, cannot be described by ordinary perturbation theory, no matter how small the gauge coupling is. These processes are associated with axial anomalies [1] and manifest themselves as anomalous violation of baryon plus lepton number ($B + L$) in QFD and chirality (Q_5) in QCD [2]. They are induced by topological fluctuations of the non-Abelian gauge fields, notably by instantons [3].

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A number of nonperturbative issues in the Standard Model can be understood in terms of such topological fluctuations and the associated anomalous processes. On the one hand, QCD instantons seem to play an important role in various long-distance aspects of QCD, such as providing a possible solution to the axial $U(1)$ problem [2] or being at work in chiral symmetry breaking [4]. In QFD, on the other hand, analogous topological fluctuations of the gauge fields and the associated $B + L$ violating processes are very important at high temperatures [5] and have therefore a crucial impact on the evolution of the baryon and lepton asymmetries of the universe [6].

Are manifestations of such topological fluctuations also directly observable in high-energy scattering processes? This question has been seriously considered in the late 1980s, originally in the context of QFD [7]. But, despite considerable theoretical [8] and phenomenological [9] efforts, the actual size of the cross-sections in the relevant, tens of TeV energy regime was never established (for recent attempts, see Ref. [10]). Meanwhile, the focus switched to quite analogous QCD instanton-induced hard scattering processes in deep inelastic scattering [11], which are calculable from first principles within instanton-perturbation theory [12], yield sizeable rates for observable final state signatures in the fiducial regime of the latter [13,14], and are actively searched for at HERA [15]. Moreover, it has been argued that larger-size QCD instantons, beyond the semiclassical, instanton-perturbative regime, may well be responsible for the bulk of inelastic hadronic processes and build up soft diffractive scattering [16]. It was emphasized for the first time in Ref. [17] that single photon or single W production at large transverse momentum offers a possibility to study QCD instanton-induced effects from first principles at the LHC. Unlike the processes considered in the present paper, the dominant subprocess for this dedicated instanton search at high energies at the LHC [17,18] is induced by gluon fusion, e.g., $gg \rightarrow V + X$, $V = \gamma^* \rightarrow \ell^+ \ell^-$. Moreover, the kinematical region is remarkable different from our region of interest, i.e., the available transverse momenta and virtualities are significantly larger than those we concentrate on throughout this paper.

In this paper, we consider QCD instanton-induced contributions to lepton pair production in hadron–hadron collisions² (cf. Fig. 1). We relate these contributions to the ones previously calculated for deep inelastic scattering [12], thereby demonstrating that the former—like the latter—can be calculated from first principles. In particular, as already emphasized in Ref. [17], the typical inverse hard transverse momentum scale $q_\perp^{-1}$ in lepton pair production provides a dynamical infrared cutoff for the instanton size parameter ρ , thereby allowing for a controlled semiclassical approximation, which rests on the smallness of the QCD coupling at the effective momentum scale $1/\langle\rho\rangle$: $\alpha_s(1/\langle\rho\rangle) \ll 1$. Hence, in addition to deep inelastic scattering, lepton

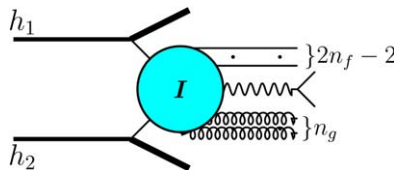


Fig. 1. QCD instanton-induced contribution to lepton pair production in hadron–hadron collisions, $h_1 + h_2 \rightarrow (n_f - 1)[\bar{q}_R + q_R] + \ell^+ + \ell^- + n_g g + X$, corresponding to n_f light flavours.

² This is often called the Drell–Yan process [19]. Instanton contributions to this process have been first discussed in Ref. [20] at a qualitative level.

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