Annals of Physics 350 (2014) 347–378

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Spin correlations in the Drell–Yan process, parton entanglement, and other unconventional QCD effects

O. Nachtmann

Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

ARTICLE INFO

Article history:
Received 17 April 2014
Accepted 19 July 2014
Available online 25 July 2014

Keywords:
QCD vacuum structure
Drell–Yan process
Higgs-boson production

ABSTRACT

We review ideas on the structure of the QCD vacuum which had served as motivation for the discussion of various non-standard QCD effects in high-energy reactions in articles from 1984 to 1995. These effects include, in particular, transverse-momentum and spin correlations in the Drell–Yan process and soft photon production in hadron–hadron collisions. We discuss the relation of the approach introduced in the above-mentioned articles to the approach, developed later, using transverse-momentum-dependent parton distributions (TDMs). The latter approach is a special case of our more general one which allows for parton entanglement in high-energy reactions. We discuss signatures of parton entanglement in the Drell–Yan reaction. Also for Higgs-boson production in *pp* collisions via gluon–gluon annihilation effects of entanglement of the two gluons are discussed and are found to be potentially important. These effects can be looked for in the current LHC experiments. In our opinion studying parton-entanglement effects in high-energy reactions is, on the one hand, very worthwhile by itself and, on the other hand, it allows to perform quantitative tests of standard factorisation assumptions. Clearly, the experimental observation of parton-entanglement effects in the Drell–Yan reaction and/or in Higgs-boson production would have a great impact on our understanding how QCD works in high-energy collisions.

E-mail address: O.Nachtmann@thphys.uni-heidelberg.de.

http://dx.doi.org/10.1016/j.aop.2014.07.022
0003-4916/

1. Introduction

In this article we want to give a synopsis and an update of the results of [1–5] concerning some unconventional QCD effects in the Drell–Yan process and in soft-photon production in hadron–hadron collisions. In addition we shall investigate possible effects of parton entanglement for Higgs-boson production in hadron–hadron collisions. We think that our study is quite timely. On the one hand there are the current LHC experiments. On the other hand there is an experimental program under way to investigate over a large c.m. energy range the Drell–Yan process and the related Z-production reaction

$$\begin{aligned} h_1 + h_2 \rightarrow & V + X, \\ & \hookrightarrow l^+ + l^- \\ V = & \gamma^*, Z. \end{aligned} \tag{1.1}$$

Here $h_{1,2}$ are hadrons, X stands for the final hadronic state, and $l = e, \mu$ for the leptons. We shall be interested in particular in the angular distribution of the leptons where "anomalies" have first been seen by the NA10 experiment at CERN [6,7] and then confirmed by the E615 experiment at FNAL [8,9]. The interesting findings of these experiments have only recently led to great further experimental efforts. In Table 1 we list the original experiments and some recent ones which are either completed or planned. This list is *not* intended to be exhaustive, it is only meant to indicate the wide range of ongoing studies, concerning both the incoming hadrons $h_{1,2}$ in (1.1) and the c.m. energy $\sqrt{s}$. All these experiments should be very suitable for studying the unconventional QCD effects discussed in [1–5].

Our paper is organised as follows. In Section 2 we recall some ideas on the QCD vacuum structure which were developed in the 1970s and 1980s. We sketch the motivation which led to the introduction of spin correlations in the Drell–Yan process in [1,2]. In Section 3 we discuss the framework developed in [2] for treating the reaction (1.1). The relation of our framework to the one using transverse-momentum-dependent-parton distributions (TMDs) is given. We emphasise that our framework allows to investigate effects from parton entanglement which may occur, for instance, due to instantons. In Section 4 we investigate possible effects of parton entanglement – in this case for gluons – on the production of Higgs bosons in hadron–hadron collisions. Section 5 contains our conclusions. In Appendices we discuss the Drell–Yan reaction with general quark–antiquark density matrix, conventions for kinematic variables, and an example of a non-trivial two-gluon density matrix for Higgs-boson production via gluon–gluon annihilation for entangled gluons.

2. The QCD vacuum structure as a possible source of unconventional effects

In the 1970s and 1980s many interesting ideas on the QCD vacuum structure were developed. Instantons were introduced and shown to have important effects in [10–12]. Savvidy [13] showed that a colour-magnetic field will lower the energy of the vacuum state. Shifman, Vainshtein and Zakharov (SVZ) introduced the gluon condensate of the vacuum [14–16]. A particularly nice picture of the QCD vacuum was developed by Ambjørn and Olesen [17,18]; see Fig. 1(a). Note the hexagonal structure of the chromomagnetic flux tubes. For comparison we show in Fig. 1(b) the hexagonal structure of the ether of electrodynamics as envisaged by Maxwell [19] in 1861. Thus, some ideas on the QCD vacuum structure resemble strikingly the dielectric ether of the 19th century which was discarded by Einstein. Maybe, some time in the future we shall also have a deeper and simpler understanding of the QCD vacuum structure. For the present we shall take these ideas on the QCD vacuum as working hypothesis; for reviews see [20] and Chapters 6 and 8 of [21].

But let us come to the Drell–Yan (DY) reaction (1.1) with $V = \gamma^*$. In leading order we have the annihilation of a quark–antiquark pair into a virtual photon γ^* which then decays into a lepton pair; see Fig. 2. The standard description of the process is well known [34–36]. For unpolarised hadrons h_1 and h_2 the quark q and antiquark $\bar{q}$ are supposed to be also unpolarised and completely uncorrelated.

In the paper [1] of 1984 this assumption was questioned. The argument was that the $q\bar{q}$ annihilation takes place in a non-trivial background full of colour fields if we believe the ideas on the QCD vacuum.