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Nuclear Physics B 905 (2016) 217–230

NUCLEAR PHYSICS B

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Spin-dependent energy distribution of B-hadrons from polarized top decays considering the azimuthal correlation rate

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Received 29 September 2015; received in revised form 27 December 2015; accepted 13 February 2016

Available online 23 February 2016

Editor: Tommy Ohlsson

Abstract

Basically, the energy distribution of bottom-flavored hadrons produced through polarized top quark decays $t(\uparrow) \to W^+ + b(\to X_b)$, is governed by the unpolarized rate and the polar and the azimuthal correlation functions which are related to the density matrix elements of the decay $t(\uparrow) \to bW^+$. Here we present, for the first time, the analytical expressions for the $\mathcal{O}(\alpha_s)$ radiative corrections to the differential azimuthal decay rates of the partonic process $t(\uparrow) \to b + W^+$ in two helicity systems, which are needed to study the azimuthal distribution of the energy spectrum of the hadrons produced in polarized top decays. These spin-momentum correlations between the top quark spin and its decay product momenta will allow the detailed studies of the top decay mechanism. Our predictions of the hadron energy distributions also enable us to deepen our knowledge of the hadronization process and to test the universality and scaling violations of the bottom-flavored meson fragmentation functions.

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http://dx.doi.org/10.1016/j.nuclphysb.2016.02.014
0550-3213/

1. Introduction

In the standard model (SM), the top quark has a short lifetime ($\approx 0.5 \times 10^{-24}s$ [1]) so decays rapidly before hadronization takes place. If it was not for the confinement of color, the top quark could be considered as a free particle and due to its large mass one can safely describe its decay in perturbative theory. In fact, at the top mass scale the strong coupling constant is small, $\alpha_s(m_t) \approx 0.107$, so that all QCD effects involving the top quark are well behaved in the perturbative sense. Due to the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix element $|V_{tb}| \approx 1$ [2], at the lowest order the decay width of the top quark is almost exclusively dominated by the two-body channel; $t \to bW^+$. As it is well known, bottom quarks produced hadronize before they decay ($b \to X_b + \text{jets}$), so each X_b-jet contains a bottom-flavored hadron which most of the times is a B-meson. The bottom hadronization is indeed one of the largest sources of uncertainty in the measurement of the mass of top quark at the CERN Large Hadron Collider (LHC) [3] and the Tevatron [4], as it contributes to the Monte Carlo systematics. The LHC is a superlative top factory, which allows us to carry out precision tests of the SM and, specifically, a precise measurement of the top quark properties such as its mass m_t, total decay width Γ_t and branching fractions.

At the LHC, of particular interest is the distribution in the energy of meson produced in the top quark rest frame, so the local CMS group is now working on a determination of the top quark mass from a detailed study of the B-meson decays. The energy distribution of mesons can also provide direct access to the meson fragmentation functions (FFs).

In [5], we studied both the B-meson energy distribution produced from unpolarized top decays and the angular distribution of the W-boson decay products in the decay chain $t \to bW^+ \to Bl^+\nu_l + X$.

Since the life time of the top quark is much shorter than the typical time needed for the QCD interactions to randomize its spin, therefore its full polarization content is preserved and passes on to its decay products. Hence, the polarization of the top quark will reveal itself in the angular decay distribution and can be studied through the angular correlations between the direction of the top quark spin and the momenta of the decay products, W^+-boson and b-quark. In [6], we studied the $\mathcal{O}(\alpha_s)$ angular distribution of the scaled energy of the B/D-hadrons, by calculating the polar angular correlation in the rest frame decay of a polarized top quark into a stable W^+-boson and B/D-hadrons. We analyzed this angular correlation in a helicity coordinate system (system 1) where the event plane, including the top and its decay products, is defined in the (x, z) plane with the z-axes along the bottom quark momentum (see Fig. 1). In this system the top polarization vector ($\vec{P}_t$) was evaluated with respect to the direction of the bottom quark momentum ($\vec{p}_b$). In [7], we analyzed the same distribution in a different coordinate system (system 2) where, as in [6] the event plane is the (x, z) plane but the W^+-boson momentum ($\vec{p}_W$) is orientated along the z-axes (see Fig. 2). However, this selection makes the calculations so complicated but it provides independent probe of the polarized top quark decay dynamics.

Basically, to define the planes we need to measure the momentum directions of the momenta $\vec{p}_b$ and $\vec{p}_W$ and the polarization direction of the top quark, where the evaluation of the momentum direction of $\vec{p}_b$ requires the use of a jet finding algorithm. The top spin direction must be obtained from theoretical input. For example, in e^+e^- interactions the polarization degree of the top can be tuned with the help of polarized beams [8], so that a polarized linear e^+e^- collider may be considered as a copious source of close to zero and close to 100% polarized tops.

The azimuthal correlations between the event plane and the intersecting ones to this plane, evaluated in two aforementioned helicity systems, belong to a class of polarization observables