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Higgs effects in top anti-top production near threshold in e^+e^- annihilation

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Abstract

The completion of the third-order QCD corrections to the inclusive top-pair production cross section near threshold demonstrates that the strong dynamics is under control at the few percent level. In this paper we consider the effects of the Higgs boson on the cross section and, for the first time, combine the third-order QCD result with the third-order P-wave, the leading QED and the leading non-resonant contributions. We study the size of the different effects and investigate the sensitivity of the cross section to variations of the top-quark Yukawa coupling due to possible new physics effects.

1. Introduction

Top anti-top quark production near threshold in e^+e^- collisions provides a unique opportunity to measure the top-quark mass precisely, due to the well-defined center-of-mass energy and the enhancement of the cross section due to the strong-interaction Coulomb force. Whether the required theoretical precision on the cross section can be achieved has been an open question, since the second order (non-relativistic) QCD calculations revealed unexpectedly large corrections and uncertainties [1,2]. After many years of work, the third-order QCD calculation has been

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recently finished [3], resulting in a largely reduced theoretical uncertainty. With QCD effects under control, the emphasis shifts to other effects which must be addressed for a realistic cross section prediction. The most important are Higgs effects associated with the top-quark Yukawa coupling, general electromagnetic and electroweak corrections, non-resonant production of the final state $W^+W^-b\bar{b}$ in the center-of-mass region near twice the top-quark mass, $2m_t$, and photon initial-state radiation.

In this paper, we mainly focus on Higgs-boson effects and the sensitivity to the top-quark Yukawa coupling. The Yukawa potential generated by Higgs exchange [4], one-loop Higgs corrections to $t\bar{t}$ production [5], and both together [6] have been considered long ago, but these early calculations do not reach the precision that corresponds to the third-order QCD calculation in the non-relativistic power-counting scheme. Third-order Higgs corrections to the production vertex and the energy and wave-function at the origin of a hypothetical S-wave toponium resonance have been computed in [7], but the $t\bar{t}$ cross section has not yet been considered. We supply this missing piece here. We also add for the first time the P-wave contributions [8] and the leading non-resonant contributions [9,10] to the third-order S-wave QCD calculation. We then allow the top-quark Yukawa coupling y_t to deviate from the Standard Model relation[1] $m_t = y_t v/\sqrt{2}$ and investigate the sensitivity to such deviations given the current theoretical uncertainties.

2. Higgs effects at NNNLO

The contribution of the Higgs boson to the top pair production cross section $e^+e^- \to t\bar{t}$ introduces two new parameters, the Higgs mass m_H, and top-quark Yukawa coupling y_t. To set up the calculation we have to fix their relation to m_t and the strong and electroweak couplings, α_s and $\alpha_{\rm EW}$, to establish the power counting. Recall that it is customary to count $\alpha_s \sim v$ and $\alpha_{\rm EW} \sim \alpha_s^2$, where $v = [(\sqrt{s} - 2m_t)/m_t]^{1/2}$ is the small top-quark velocity. A contribution of order α_s^k (or, equivalently, v^k) according to this counting is called "N^{k}LO" or "kth order". We opt for counting $y_t^2 \sim \alpha_{\rm EW} \sim \alpha_s^2$ and $m_H \sim m_t$. Other options would be to count the top–Yukawa coupling like the strong coupling, $y_t^2 \sim \alpha_s$, or the Higgs mass $m_H \sim m_t v$, or both. Clearly, with $m_t \approx 173$ GeV, $m_H \approx 125$ GeV and $v \sim 1/10$, the counting $m_H \sim m_t$ is more appropriate. In the terminology of non-relativistic effective theory and the threshold expansion, the Higgs mass is of order of the hard scale, and not the potential scale, which has significant impact on the structure of the contributions. On the other hand, the counting of the coupling simply determines at which orders in the expansion the Higgs contributions appear and we will justify our choice below.

The effective field theory setup is described in detail in [11]. We recall that the dominant S-wave production cross section is proportional to the imaginary part of the spectral function of the vector current

$$\Pi^{(v)}(q^2) = \frac{3}{2m_t^2} c_v^2 G(E) + \ldots, \tag{2.1}$$

where c_v is the hard matching coefficient of the vector current, $E = \sqrt{s} - 2m_t$, and $G(E)$ is the Green function in potential-nonrelativistic QCD (PNRQCD), i.e. the propagator of a non-relativistic top anti-top pair. The Higgs contributions to c_v are discussed in Section 2.1. To compute the corrections to the Green function the Higgs contributions to the PNRQCD Lagrangian

[1] The symbol v is used for the Higgs vacuum expectation value and the top-quark velocity, see below. The meaning should be clear from the context.