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Top-quark pair production close to threshold at hadron colliders: an update

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QCD and weak corrections for top-antitop production at the LHC are presented with emphasis on their behaviour in the threshold region.

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1. Introduction

Top-quark pair production close to threshold is considered as ideal option for an electron-positron collider. However, although technically more difficult, a number of closely related questions can also be investigated at a hadron collider like the LHC. Concerning QCD, it may be possible to exploit the subtle differences between production of $t\bar{t}$ colour singlet and colour octet configurations, respectively, and thus investigate the subtleties of top-antitop interactions. In principle this might allow to disentangle attractive and thus closely bound from repulsive $t\bar{t}$ systems. The impact of these effects on various differential distributions is investigated.

A second, equally important issue are the weak corrections to $t\bar{t}$ production at a hadron collider, and their impact on the total cross section for top-quark pair production and on differential distributions. In particular, we investigate the influence of weak corrections on transverse momentum and rapidity distributions and the interplay between Higgs boson exchange and the Yukawa potential between top and antitop. We observe a pronounced sensitivity of the threshold cross section on an enhanced Yukawa coupling.

2. QCD corrections in the $t\bar{t}$ threshold region

QCD corrections for $t\bar{t}$ production in the threshold region have reached a remarkable level of precision, as far as electron-positron annihilation is concerned. The first papers based on leading order Greens functions were written more than twenty years ago [1, 2, 3, 4]. In the meantime these calculations were pushed to next-to-next-to-next-to leading order (N^{3}LO) [5], leading to a precision which will allow to even get access to subtle effects like those originating from the Yukawa interaction between the top and the antitop quark and which is particularly strong in the threshold region [6, 7]. In total a precision of the top-mass determination around 50 MeV may well be within reach.

For the time being, however, experiment is limited to hadron colliders. Top-mass determinations have been made originally by the Tevatron and more recently by the LHC with a cms-energy of up to 13 TeV. Abundant top-quark production has been observed. However, the precision of the top-mass determination is still limited to about 1 GeV. This is a natural consequence of the fact that the kinematical reconstruction is based on decays of colour triplet quarks with a mass, which is presumably close, but not identical to the pole mass.

The lowest order processes for hadronic top-pair production are

$$q + \bar{q} \to g^* \to t + \bar{t} \tag{2.1}$$

with $t\bar{t}$ in a repulsive colour octet configuration, and

$$g + g \to t + \bar{t} \tag{2.2}$$

with $t\bar{t}$ either in a (repulsive) color octet or an (attractive) colour singlet configuration. In next-to-leading order (NLO) the QCD potential can be cast into the following form

$$\tilde{V}^{[1,8]}(\vec{q}) = -\frac{4\pi\alpha_s(\mu_r)C^{[1,8]}}{\vec{q}^2}\left[1 + \frac{\alpha_s(\mu_r)}{4\pi}\left(\beta_0 \ln\frac{\mu_r^2}{\vec{q}^2} + a_1\right)\right], \tag{2.3}$$

with $C^{[1]} = C_F = 4/3$ and $C^{[8]} = C_F - C_A/2 = -1/6$ as colour coefficients and $a_1 = (31/9)C_A - (20/9)T_F n_f$.

It is well known that the relatively large width of the top quark of around 1.36 GeV [8] is comparable to the Rydberg constant of the $t\bar{t}$-system, $(C^{[1]}\alpha_s)^2 m_t/4 \approx 1.5$ GeV. This leads to a merging of the higher S-states and a moderate enhancement of the 1S peak as far as the $t\bar{t}$ colour singlet configuration is concerned. The repulsive color octet combination, on the other hand, is significantly suppressed (Fig.1). Including QCD corrections of order α_s, the cross section of the

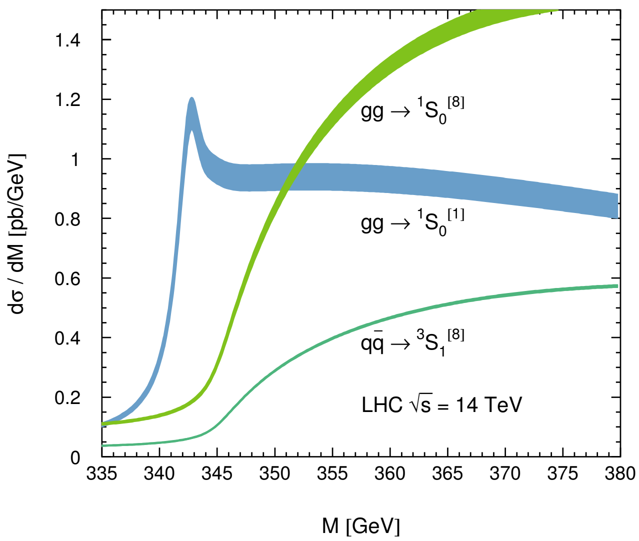

Figure 1: Invariant mass distribution for the leading subprocesses.

reaction $i + j \to t + \bar{t}(+X)$ can, at parton level, be cast into the following form [9]

$$M\frac{d\hat{\sigma}_{ij\to t\bar{t}}}{dM}(\hat{s}, M^2, \mu_f^2) = F_{ij\to T}(\hat{s}, M^2, \mu_f^2)\,\frac{1}{m_t^2}\,\mathrm{Im}\,G^{[1,8]}(M + i\Gamma_t)\,. \tag{2.4}$$

The first factor, $F_{ij\to t\bar{t}}$, can be evaluated purely perturbatively

$$\begin{aligned} F_{ij\to T}(\hat{s}, M^2, \mu_f^2) &= \mathscr{N}_{ij\to t\bar{t}}\,\frac{\pi^2\alpha_s^2(\mu_r)}{3\hat{s}}\left(1 + \frac{\alpha_s(\mu_r)}{\pi}\mathscr{C}_h\right) \\ &\quad\times\left[\delta_{ij\to t\bar{t}}\,\delta(1-z) + \frac{\alpha_s(\mu_r)}{\pi}\left(\mathscr{A}_c(z) + \mathscr{A}_{nc}(z)\right)\right]. \end{aligned} \tag{2.5}$$

and depends obviously on the specific initial state configuration, characterized by i and j. The second factor, Im$G^{[1]}$ or Im$G^{[8]}$, characterizes the final state, which may appear in a color singlet or octet configuration. Note, that also reactions like $qg \to t\bar{t}q$ contribute in NLO. Let us also note that the factor $\mathscr{N}_{ij\to t\bar{t}}$ characterizes the normalisation, $\mathscr{C}_h$ the hard virtual correction, $\mathscr{A}_c$ the collinear part of the real corrections and $\mathscr{A}_{nc}$ non-collinear real emission. The explicite analytic results for all these quantities can be found in [9]. The complete prediction for producing the dominant $t\bar{t}$ states in the threshold region are shown in Fig. 1. Here $^3S_1^{[8]}$ stands for the spin triplet, color octet S-wave state, and $^1S_0^{[1]}$ for the spin singlet, color singlet S-wave state. The corresponding result, including, however, all production channels, is shown in Fig. 2. This analysis is strictly speaking, only valid

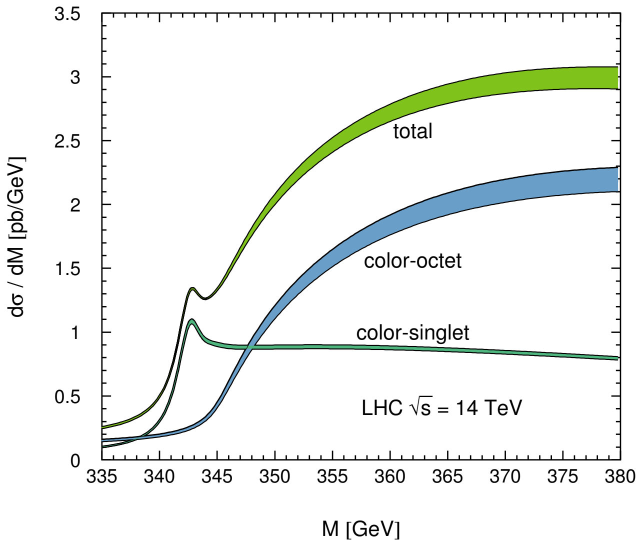

Figure 2: Invariant mass distribution close to threshold including all partonic production channels.

in the threshold region. Nevertheless it can be compared to a NLO calculation which completely ignores bound-state effects (Fig. 3) Good qualitative agreement is observed from threshold up to

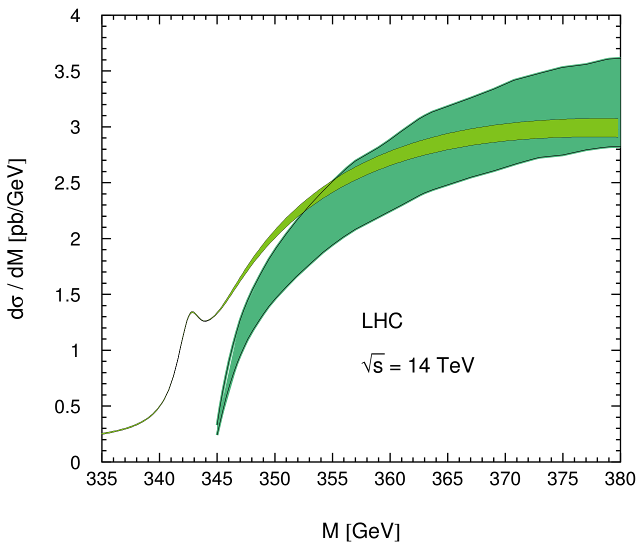

Figure 3: Comparison of threshold resummed results with fixed order QCD predictions.

several tens of GeV above. However, the parton cross section without bound-state effects obviously vanishes below the nominal threshold $2m_t = 344.8\text{GeV} \pm \mathcal{O}(1\text{GeV})$, and the subtle effects leading to a difference between color singlet and and color octet production are obviously absent.

To summarize: The differential distribution for top-quark production has been calculated which differs significantly from the one based on stable top quarks and which ignores the differences between color singlet and color octet bound-states. The additional threshold enhancement of around 10pb is small compared to the total cross section of roughly 800pb (for 14 TeV) but may, nevertheless, be noticeable, if one investigates specifically the threshold region. Note, that these subtle threshold effects are ignored in present theory predictions, even those extending to NNLO.

3. Weak corrections to $t\bar{t}$ production

With increasing precision of $t\bar{t}$ measurements at hadron colliders weak corrections will start to become relevant. The leading QCD Born amplitude for $q\bar{q} \to t\bar{t}$ is of order g_s^2, the leading weak amplitude of order g_w^2. Hence one might expect the dominant weak correction to arise from the interference term and thus to be of order $g_s^2 g_w^2$. However, upon closer inspection one finds that the first correction is in fact of order $g_s^4 g_w^2$ and thus remains to be relatively small, i.e. typically about one percent. There are, however, two regions where an enhancement can be expected [10, 11]:

i.) The region of very large $\hat{s}$, say above 1 TeV, and similarly large momentum transfer $-\hat{t}$, where sizable negative corrections can be observed, a consequence of the large negative "Sudakov" logarithms. For quark-antiquark induced processes these are about a factor two larger than those for gluon-induced processes, a consequence of the fact that for quark induced processes weak charges are present both in the initial and the final state.

ii.) Very close to the $t\bar{t}$ threshold, say between 340 GeV and 400 GeV the attractive force between t and $\bar{t}$, induced by the Higgs-boson exchange, plays an important role. This might offer the unique possibility of measuring the Higgs coupling to top quarks, at least if a precision of six percent or better can be achieved.

Let us demonstrate these effects in the following. The total cross section for $t\bar{t}$ production at the LHC depends only marginally on m_H with a relative weak correction varying between -1.8% and -2.3% for m_H between 120 GeV and 1000 GeV. The effect is significantly enhanced, once events are selected with large $t\bar{t}$ masses (e.g. $M_{t\bar{t}} > 2$TeV and large transverse momenta. Let us therefore discuss the implementations of these corrections on individual distributions. The total cross section receives a correction of around 1.8% for a Higgs boson mass of roughly 120 GeV. The size of the corrections to the $M_{t\bar{t}}$- and p_t-distributions, that can be determined by experiment, increases with increasing transverse momenta. The corrections are always negative and amount to ten percent and more, if the invariant mass of the $t\bar{t}$ system reaches 2 TeV and if events with large transverse momenta of the top quark are required (Fig. 4).

The other kinematic configuration of interest is the region close to threshold, say between $2m_t \approx 350$ GeV and 400 GeV. In this case the dominant effect is induced by the Yukawa potential

$$V_Y(r) = -\frac{\kappa}{r} e^{-r/r_Y} \tag{3.1}$$

with

$$\kappa = \frac{g_Y^2}{4\pi} = \frac{\sqrt{2} G_F m_t^2}{4\pi} \approx 0.034 \tag{3.2}$$

and $r_Y = 1/M_H$. The range of the potential r_Y is still small compared to the size of the bound state $r_{\text{Bohr}} = \langle \frac{4}{3} \alpha_s \frac{M_t}{2} \rangle^{-1}$ with $r_Y/r_{\text{Bohr}} \approx 1/6$. This leads to an enhancement of roughly $(1 + \kappa \frac{m_t}{m_H}) \approx 1.05$. This effect vanishes quickly with increasing $\hat{s}$ and is practically absent for $\hat{s} = 400$GeV. (Fig. 5)

The Yukawa coupling that is employed in this context is fixed to the Standard model value $g_Y^2 = \sqrt{2} G_F m_t^2$. It remains to be seen, whether the experimental mass resolution and the normalization of

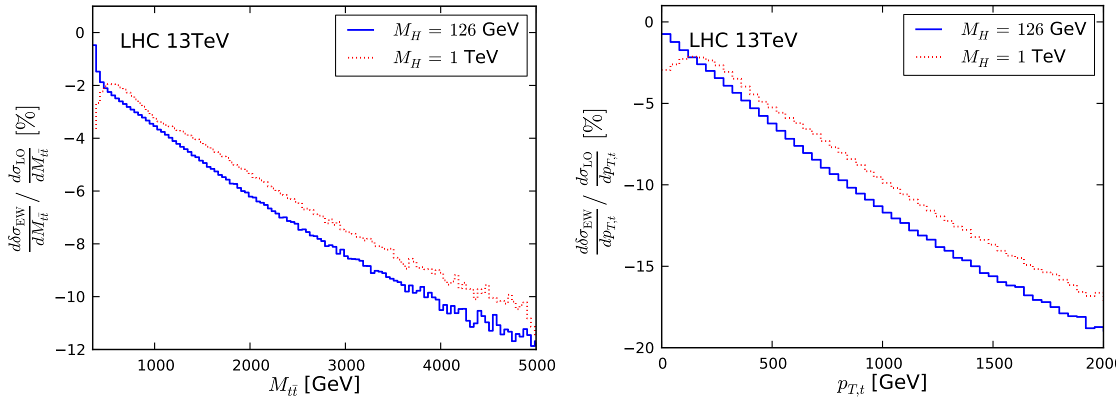

Figure 4: Impact of weak corrections on differential distributions at large momentum transfer.

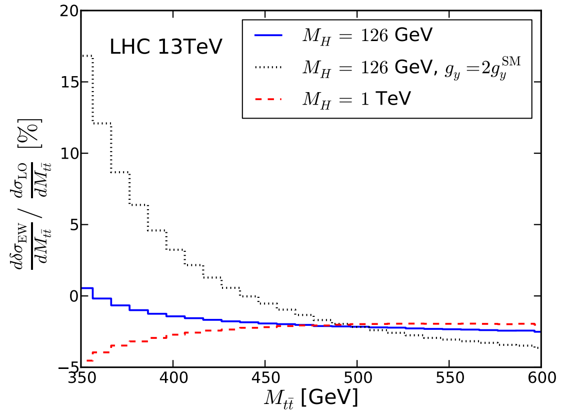

Figure 5: Threshold corrections due to attractive Yukawa interaction.

the cross section will be sufficiently precise to pin down this 5% effect and thus determine directly the Yukawa coupling. However, in any case this approach should allow to provide an upper limit on modifications of g_Y that might be postulated in theories beyond the Standard Model [10]. The relevance of such a limit can be best seen from Fig. 5 where an enhancement of the top-Higgs Yukawa coupling by a factor two has been assumed, leading to an increase of the correction by a factor four and thus to a significant enhancement of the cross section in the threshold region.

4. Summary

Top-quark pair production in the threshold region will be a unique laboratory to pin down subtle effects related to mass generation and spontaneous symmetry breaking. This holds true for hadronic interactions, where the difference between attractive and repulsive top-antitop interaction may lead to visible modifications of the cross section. Weak interactions, on the other hand, in particular the exchange of Higgs bosons between top and antitop quarks, will lead to a modification of the cross section amounting to several percent in the Standard Model. These effects are particularly sensitive to the Yukawa coupling between the top quark and the Higgs boson and could lead to a non-trivial limit on the strength of this until now quite elusive coupling.

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