The role of the top mass in $b$-production at future lepton colliders

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Abstract

We compute the one loop contribution coming from vertex and box diagrams, where virtual top quarks are exchanged, to the asymptotic energy behaviour of $b\bar{b}$ pair production at future lepton colliders. We find that the effect of the top mass is an extra linear logarithmic term of Sudakov type that is not present in the case of $(u, d, s, c)$ production. This appears to be particularly relevant in the case of the $b\bar{b}$ cross section.
A well known feature of $b\bar{b}$ production at the $Z$ peak is the fundamental role of the top quark mass. Its effect in the $Zb\bar{b}$ vertex generates a contribution to the partial $Z$ width into $b\bar{b}$ pairs $\Gamma_b$ that contains a quadratic term (and, also, an almost equally important logarithmic term) in the top mass $\approx \alpha m_t^2/M_Z^2$ [1]. Numerically, this turns out to be of a relative few percent size for $m_t \approx 175$ GeV, well beyond the experimental accuracy of the related measurement [2]. Thus, neglecting the top mass in this special vertex would induce a catastrophic error in the theoretical prediction [3].

One might wonder whether this fundamental top mass role is retained when one moves away from the $Z$ peak and considers the generalization of that process, lepton-antilepton into a fermion-antifermion pair, at higher energies. Here one must make a preliminary observation. Away from the $Z$ peak, $Z$ exchange is no longer necessarily dominant. In fact, the photon exchange acquires a certain relevance (in the case of muon pair production it actually becomes the leading contribution). This introduces new diagrams to be considered at the one loop level, where virtual tops can be exchanged. Moreover, the role of box diagrams appears to be also increasing with energy [4], and such diagrams contain virtual top contributions as well. Therefore, one expects in full generality to find several effects of the top mass at higher energies in the considered four-fermion processes.

The general procedure for computing 1-loop effects in the massive $f\bar{f}$ case exists in the literature [5]. The detailed study done for the special case of $t\bar{t}$ production [5] confirms the idea that the role of the top mass might also be relevant in the process of $b\bar{b}$ production. To verify this feeling, several types of contributions, besides those that were effective at the $Z$ peak, must be carefully computed.

A partial reduction of these effects is provided by the observation that a special theoretical framework, based on ”$Z$-peak subtraction” [6], can be used to study these processes. In this approach, those one-loop effects that appear at the $Z$ resonance are automatically reabsorbed into new theoretical input data. In this way, that component of the $Zb\bar{b}$ vertex whose dependence on $m_t$ is constant with energy disappears, i.e. is incorporated into the partial width $\Gamma_b$. Thus, the ”effective” $m_t$ dependence, which is in our approach, we repeat, the one which cannot be eliminated by LEP1, SLC measurements, will be given by those components of self-energies and vertices whose dependence on the top mass varies with energy, and by a set of box diagrams, that by construction cannot be reabsorbed by $Z$-peak measurements.

One might ask under which conditions, a priori, such $m_t$ effects should be interesting at future $l^+l^-$ colliders. In principle, one would expect from the $Z$-peak situation effects of the few percent size; these might be relevant if the experimental accuracy were (at least) comparable with the remarkable LEP1,SLC level.

A further motivation for considering these $m_t$ exchanges is provided, in our opinion, by the conclusions of recent works [7, 8] where the effects of asymptotic leading contributions (essentially, vertices and boxes with $W$ exchange) is studied for four-fermion processes in the $TeV$ region. As shown in those papers, at such energies new electroweak effects of ”Sudakov-type” arise that are of linear and squared logarithmic type, typically $\ln \frac{q^2}{M_W^2}$, $\ln^2 \frac{q^2}{M_W^2}$ where $q^2$ is the squared c.m. energy. Such terms become separately rather large (typically, at the relative ten percent level) in the considered energy region, although
a cancellation process is at work that reduces their overall effect. The analysis of ref.[8] was performed in the Feynman-t’Hooft ξ = 1 gauge, ignoring systematically possible massive virtual top exchanges in vertices and boxes, the only diagrams responsible for Sudakov-type effects. Given the fact that small modifications can in principle alter the cancellation mechanism, we feel that such exchanges might have some relevance for what concerns b production in this energy regime.

The purpose of this paper is precisely that of showing to what extent this feeling is actually correct. With this aim, we shall start from a series of theoretical formulae whose origin can be immediately found in ref.[8], to which we defer in order to make this short article not too much filled with repetitions and definitions.

To begin our analysis, we recall briefly what is the origin of the ”Sudakov-type” effects in the considered four-fermion processes. Briefly, for massless virtual quark exchanges, in the Feynman-t’Hooft gauge they are originated from the set of vertex- and box-type diagrams shown in Fig.1. At high energies, the double ln’s are generated by vertices with one W, Z exchange and by boxes. Linear ln’s are generated by all diagrams depicted in Fig.1. In general, these ln’s add to those that can be associated to the RG ”running” of the various couplings. The latter ones are originated by self-energy diagrams and by the universal ”pinch” component of the vertex with two W’s.

The asymptotic expansions, valid in a region where q^2 >> M_Z^2, of four-fermion observables was derived in ref.[8] treating, we repeat, all virtual quark exchanges contributing Fig.1, including the top one, as if all quarks were massless. In other words, the predictions for the b\bar{b} production were identical with those for d\bar{d}, s\bar{s} quarks.

Taking now properly into account the virtual top exchange corresponds to performing an accurate estimate of the vertex and box diagrams shown in Fig.2 in the case of the final b\bar{b} production. As one sees, one must add a new set of diagrams that correspond to charged would-be Goldstone boson Φ± exchanges, whose contribution in the ξ = 1 gauge where we are working is essential. Although the computational procedure is very similar to that illustrated in ref.[8], there is one feature that, we feel, deserves the small dedicated discussion that follows.

Let us begin with a consideration of the first diagram of Fig.2. Then we must discuss separately the two cases of single W± and of single Φ± (charged would-be Goldstone boson) exchange. We remind the reader that our calculations are performed in the t’Hooft ξ = 1 gauge. Since we are dealing systematically and by construction with gauge-independent combinations of diagrams, we can set M_{Φ+} = M_{W+} from now on, without prejudice on the total observable contributions, as discussed exhaustively in ref.[8].

The calculation of the asymptotic limit of the diagram with one W leads to the conclusion that, for this case, the two leading logarithmic terms in the expression for the final b\bar{b} pairs are the same as those for d\bar{d}, s\bar{s} pairs. In other words, there is no extra ”Sudakov top” effect in this case. This conclusion is to a certain extent not unexpected if one remembers that a completely similar property was valid at the Z peak, where W exchange was not generating any \simeq m_t^2 contribution. In fact, the same property was also characteristic of the diagram with two W exchange at the Z peak, and one would thus expect to find it again in the next two W diagram of Fig.2.
The diagram with one $\Phi^+$ exchange leads to a "genuinely" new top effect. In fact, it produces a linear logarithmic term that is proportional to $\simeq \alpha \frac{m_t^2}{M_W^2} \ln \frac{q^2}{m_t^2}$. With the notation of ref.\cite{4,6} we find the leading contribution to the $\gamma$ or $Z - b\bar{b}$ vertices:

$$\Gamma_{\mu,b}(\Phi^+) = C_{\gamma} \frac{|e| \alpha}{32\pi s_W} \left(\frac{m_t^2}{M_W^2}\right) \ln \left(\frac{q^2}{m_t^2}\right) \gamma_\mu (1 - \gamma_5)$$

(1)

with $C_{\gamma} = Q_t$ and $C_Z = \frac{-2 s_W}{3 c_W}$.

Note that, in practice, one could "bargain" $m_t$ with $M_W$ in the logarithm, and the difference would be embodied by a constant $\ln \frac{m_t}{M_W}$, that would be asymptotically negligible. In the limit $m_t >> M_W$, the single $W$ exchange diagram also gives terms of order $\ln^2 (m_t^2/M_W^2)$. We postpone the discussion of "constant" ($q^2$-independent) contributions to the end of the paper. From now on, though, we shall retain the notation $\simeq \ln \frac{q^2}{m_t^2}$ to remind the origin of the logarithmic term.

The calculation of the second diagram leads to the conclusion that we have anticipated. The two $W$ exchange leads to the same asymptotic expansion for either $b$ or $d, s$ pairs. The (one $W$ + one $\Phi$) exchanges give contributions which vanish asymptotically like $m_t^2/q^2$. The two $\Phi$ exchange leads to a linear logarithmic term, again of the form $\simeq \alpha \frac{m_t^2}{m_t^2} \ln \frac{q^2}{m_t^2}$.

$$\Gamma_{\mu,b}(\Phi^+\Phi^-) = C_{\gamma} \frac{|e| \alpha}{32\pi s_W} \left(\frac{m_t^2}{M_W^2}\right) \ln \left(\frac{q^2}{m_t^2}\right) \gamma_\mu (1 - \gamma_5)$$

(2)

with $C_{\gamma} = 1$ and $C_Z = \frac{1-2 s_W}{2 c_W}$.

Finally, we consider the box diagram with two $W$ exchange. Here there is no $Z$-peak analogue, which prevents us from having a related theoretical prejudice. In fact, an accurate calculation leads to the conclusion that, again, there are no extra logarithmic terms with respect to the $d, s$ cases, exactly like in the $W$, two $W$ vertex situations.

Keeping in mind the previous discussion, and following the same procedure as in ref.\cite{8}, we can now write the "corrected" expressions for the various observables containing a final $b\bar{b}$ pair.

Using $m_t = 175\, GeV$, the theoretical expansion of $\sigma_b$, the cross section for $b\bar{b}$ production is given by:

$$\sigma_b = \sigma_b^R[1 + \frac{\alpha}{4\pi}(10.88N - 53.82) \ln \frac{q^2}{\mu^2}$$

$$+ (76.75 \ln \frac{q^2}{M_W^2} + 11.98 \ln \frac{q^2}{M_Z^2} - 8.41 \ln \frac{q^2}{m_t^2})$$

$$- (7.10 \ln^2 \frac{q^2}{M_W^2} + 2.45 \ln^2 \frac{q^2}{M_Z^2})] + \ldots \ldots \ldots \ldots$$

(3)

the cross section for production of the five "light" ($u, d, s, c, b$) quarks $\sigma_5$:

$$\sigma_5 = \sigma_5^R[1 + \frac{\alpha}{4\pi}(9.88N - 42.66) \ln \frac{q^2}{\mu^2}$$
+(46.58 \ln \frac{q^2}{M_W^2} + 7.25 \ln \frac{q^2}{M_Z^2} - 1.21 \ln \frac{q^2}{m_t^2}) \\
- (6.30 \ln^2 \frac{q^2}{M_W^2} + 2.03 \ln^2 \frac{q^2}{M_Z^2}) \right] + \ldots \ldots , \quad (4)

the forward-backward $b$-asymmetry

\begin{align*}
A_{FB,b} &= A_{FB,b}^B + \frac{\alpha}{4\pi} \left\{ (0.56N - 6.13) \ln \frac{q^2}{\mu^2} \\
+ (17.23 \ln \frac{q^2}{M_W^2} + 0.96 \ln \frac{q^2}{M_Z^2} - 0.36 \ln \frac{q^2}{m_t^2}) \\
- (0.31 \ln^2 \frac{q^2}{M_W^2} + 0.08 \ln^2 \frac{q^2}{M_Z^2}) \right\} + \ldots \ldots . \quad (5)
\end{align*}

For initial polarized leptons, we can consider the longitudinal polarization $b$ asymmetry:

\begin{align*}
A_{LR,b} &= A_{LR,b}^B + \frac{\alpha}{4\pi} \left\{ (1.88N - 20.46) \ln \frac{q^2}{\mu^2} \\
+ (27.91 \ln \frac{q^2}{M_W^2} + 1.92 \ln \frac{q^2}{M_Z^2} - 2.39 \ln \frac{q^2}{m_t^2}) \\
- (2.35 \ln^2 \frac{q^2}{M_W^2} + 0.52 \ln^2 \frac{q^2}{M_Z^2}) \right\} + \ldots \ldots , \quad (6)
\end{align*}

and the longitudinal polarization asymmetry for five light quark production $A_{LR,5}$:

\begin{align*}
A_{LR,5} &= A_{LR,5}^B + \frac{\alpha}{4\pi} \left\{ (2.11N - 22.95) \ln \frac{q^2}{\mu^2} \\
+ (24.07 \ln \frac{q^2}{M_W^2} + 1.63 \ln \frac{q^2}{M_Z^2} - 0.53 \ln \frac{q^2}{m_t^2}) \\
- (3.12 \ln^2 \frac{q^2}{M_W^2} + 0.55 \ln^2 \frac{q^2}{M_Z^2}) \right\} + \ldots \ldots . \quad (7)
\end{align*}

In all eqs. (3-7) the index $B$ refers to the ”Born” term computed with the ”Z-peak subtracted” inputs, and the dots on the r.h.s. correspond to residual ”non leading” asymptotic terms, that are either constant or vanishing with $q^2$, whose role will be discussed later on. We have written in ”boldface” the genuine terms arising from the contributions $\simeq \alpha \frac{m_t^2}{M_W^2} \ln \frac{q^2}{m_t^2}$ discussed above.

For practical purposes it may be convenient to consider, rather than $\sigma_b$, the ratio $R_b = \sigma_b/\sigma_5$, that generalizes the analogous quantity defined at the Z peak, For this
observable we would find the following expression:

\[
R_b = R_b^{B}[1 + \frac{\alpha}{4\pi} \{(N - 11.16) \ln \frac{q^2}{\mu^2}
+ (30.17 \ln \frac{q^2}{M_W^2} + 4.73 \ln \frac{q^2}{M_Z^2} - 7.20 \ln \frac{q^2}{m_t^2})
- (0.80 \ln \frac{q^2}{M_W^2} + 0.42 \ln \frac{q^2}{M_Z^2})\} + \ldots .\]

(8)

Eqs.(3-8) are the main result of this paper. They show in detail what is the extra effect of Sudakov-type coming from the proper consideration of the actual top mass in the high energy regime (terms in boldface). To give them a more quantitative meaning, we have computed the relative top effect in the energy range between 1 TeV and 10 TeV, where we know from a previous analysis performed in ref.[8] that the asymptotic logarithmic expansion (without the top effect) is well reproducing the main features of an exact one-loop calculation. For sake of completeness, we have also compared the relative top effects with the overall logarithmic effect (that also includes the RG contributions).

The results of our investigation are shown in Table 1. From inspection of that Table, the following conclusions may be drawn:

a) The Sudakov top effect is sizeable in \(R_b\) (this is practically due to the \(b\) cross section \(\sigma_b\) in the numerator). At 1 TeV, the size of the relative shift is beyond the “reference” one percent limit; at 500 GeV, the expected energy of the next LC, one finds a relative effect of one percent. This would be clearly visible at the aimed luminosity of the machine [11].

b) in all four remaining observables, the Sudakov top effect is largely diluted and, practically, hardly visible at an accuracy of few permille. A possible exception to this statement might be offered by the longitudinal polarization asymmetry \(A_{LR,b}\) provided that the available luminosity is of the few hundred \(fb^{-1}\) size; this might be kept in mind if longitudinal polarization became available.

c) The top contribution is systematically negative. Its inclusion modifies the overall logarithmic expansion, but does not alter dramatically its essential features. In other words, the discussion of ref.[8] related to the order of magnitude of the various logarithmic effects and of the total effect remains completely valid.

One sees therefore a final picture that resembles very much the corresponding situation already met at the \(Z\) peak, where neglecting the top contribution to \(R_b\) from the "non oblique" diagram would have been a theoretical disaster. This is, we believe, the main lesson that may be learned from this paper.

To conclude this work, we want now to present, in the same spirit of ref.[8], an “effective” parametrization that describes the energy dependence of the unpolarized observables \(R_b, A_{FB,b}\) and \(\sigma_5\) in an energy region below 1 TeV, where a priori the asymptotic expansions might not be suitable. The conclusions of ref.[8] were that, somehow surprisingly, the same expressions that were derived for the asymptotic regime were able, with the simple addition of a constant term, to reproduce the exact results of the program TOPAZ0[12]
within a few permille at most. In the specific case of $\sigma_b$, $A_{FB,b}$, $\sigma_5$, we have thus repeated the same procedure of comparison. This time, for self-consistency reasons, we have limited our analysis to a range from about 500 $GeV$ to 1 $TeV$, where the ratio $\frac{q^2}{m_t^2}$ is (at least) larger then ten.

A comparison of the logarithmic terms in the asymptotic expansion with the output of TOPAZ0 (of course, without initial state and final state QED corrections) gives the dashed curves shown in Fig.3. They are a rather poor approximation in this energy range, although they reproduce well the qualitative behaviour of the observables as functions of the energy. Motivated by the analysis in [8], we improve the expansion by adding suitable constants $c_5$, $c_b$ and $c_{FB,b}$ according to the formulas:

\[ \sigma_{5,b} = \sigma_{5,b}^B (1 + \frac{\alpha}{\pi} (c_{5,b} + \text{logarithms})) \]  
\[ A_{FB,b} = A_{FB,b}^B + \frac{\alpha}{\pi} (c_{FB,b} + \text{logarithms}) \]  

where, ”logarithms” stands for the logarithms arising from the asymptotic expansion and $\sigma_{5,b}^B$, $\sigma_b^B$, $A_{FB,b}^B$ are the Born level expressions of the observables. With the following values

\[ c_5 = -28.9, \quad c_b = -26.7, \quad c_{FB,b} = -2.2, \]  

we obtain the full lines in Fig.3. As in [8], the agreement is very good and the percentual deviation is below the expected experimental accuracy for all the three observables. In more details, $\sigma_5$ and $A_{FB,b}$ are precise at the 5 permille level; $\sigma_b$ displays a larger 1 % deviation which can be explained in terms of the dominance of the top mass scale and of the large constant terms $\sim \ln \frac{m_t^2}{M_W^2}$.

As a final comment on our investigation, we would like to stress the following fact. At the considered one loop level, the linear logarithmic contribution of the top quark can be considered as a “subleading” asymptotic effect, compared with the quadratic Sudakov logarithm. As we have shown, the origin of this top term is of Yukawa type and thus proportional to $\sigma_{5,b}^B \alpha m_t^2 \ln \frac{q^2}{m_t^2}$.

In a very recent and interesting paper [13], the “leading” squared logarithms of Sudakov type have been computed beyond the one loop approximation. In that analysis, all the “subleading” single logarithmic contributions have been systematically neglected. In particular, the top contribution that we have computed is not considered in that approach. At the TeV energies on which we have concentrated our analysis, this contribution, although of “subleading” kind, is nonetheless quite relevant and cannot be neglected.

The same qualitative remark should apply in our opinion to all the “subleading” logarithmic terms. At the one loop level, the complete calculation of $\sigma_{5,b}^B$ shows that the numerical weights of the linear Sudakov logarithms, in the TeV region, is of the same size (with opposite sign) as that of the “leading” quadratic logarithms. This makes us feel that, to obtain a fully satisfactory prediction, the calculation of all “subleading” logarithms beyond the one loop level should be included.
Table 1: Logarithmic contributions to various observables
(1) without top effects \((b \equiv d \equiv s)\); (2) with top effects; (3) top effects alone.

| \( \sqrt{q^2} \) (TeV) | \( \delta \sigma_b/\sigma_b \) | \( \delta R_b/R_b \) | \( \delta \sigma_5/\sigma_5 \) | \( \delta A_{FB,b} \) | \( \delta A_{LR,b} \) | \( \delta A_{LR,5} \) |
|-------------------------|-------------------------------|-------------------|-------------------------------|-------------------|-------------------|-------------------|
| 0.3 (1)                 | 0.0723                        | 0.0391            | 0.0332                        | 0.0213            | 0.0145            | 0.0018            |
| 0.3 (2)                 | 0.0667                        | 0.0344            | 0.0324                        | 0.0211            | 0.0130            | 0.0015            |
| 0.3 (3)                 | -0.0056                       | -0.0048           | -0.0008                       | -0.0002           | -0.0016           | -0.0004           |
| 0.5 (1)                 | 0.0778                        | 0.0513            | 0.0265                        | 0.0284            | 0.0128            | -0.0069           |
| 0.5 (2)                 | 0.0669                        | 0.0420            | 0.0250                        | 0.0280            | 0.0097            | -0.0075           |
| 0.5 (3)                 | -0.0109                       | -0.0093           | -0.0016                       | -0.0005           | -0.0031           | -0.0007           |
| 1 (1)                   | 0.0656                        | 0.0653            | 0.0003                        | 0.0373            | 0.0045            | -0.0262           |
| 1 (2)                   | 0.0475                        | 0.0498            | -0.0023                       | 0.0366            | -0.0007           | -0.0273           |
| 1 (3)                   | -0.0181                       | -0.0155           | -0.0026                       | -0.0008           | -0.0052           | -0.0011           |
| 2 (1)                   | 0.0307                        | 0.0764            | -0.0457                       | 0.0453            | -0.0106           | -0.0542           |
| 2 (2)                   | 0.0054                        | 0.0547            | -0.0493                       | 0.0442            | -0.0178           | -0.0558           |
| 2 (3)                   | -0.0253                       | -0.0217           | -0.0036                       | -0.0011           | -0.0072           | -0.0016           |
| 5 (1)                   | -0.0502                       | 0.0866            | -0.1368                       | 0.0544            | -0.0411           | -0.1046           |
| 5 (2)                   | -0.0851                       | 0.0568            | -0.1419                       | 0.0529            | -0.0510           | -0.1068           |
| 5 (3)                   | -0.0348                       | -0.0298           | -0.0050                       | -0.0015           | -0.0099           | -0.0022           |
| 10 (1)                  | -0.1377                       | 0.0910            | -0.2288                       | 0.0602            | -0.0720           | -0.1529           |
| 10 (2)                  | -0.1798                       | 0.0550            | -0.2348                       | 0.0584            | -0.0839           | -0.1555           |
| 10 (3)                  | -0.0420                       | -0.0360           | -0.0061                       | -0.0018           | -0.0119           | -0.0027           |
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Figure 1: Triangle and box diagrams for final light quark pairs.
Figure 2: Triangle and box diagrams for final $b\bar{b}$ quarks. $\Phi^\pm$ are the charged would-be Goldstone bosons.
Figure 3: Comparison between TOPAZ0 and the logarithmic expansion. For the two cross sections $\sigma_5$ and $\sigma_b$ we show the relative percentual deviation with and without constant terms. In the case of the asymmetry $A_{FB,b}$ the shown deviation is absolute and not relative.