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Multi-parameter fits to the $t\bar{t}$ threshold observables at a future e^+e^- linear collider

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Abstract. A realistic study of the physics reach of a $t\bar{t}$ threshold scan at a future e^+e^- linear collider is presented. The results obtained take into account experimental and, to a large extent, theoretical systematic errors, as well as beam effects. Because of the large correlations between the physical parameters that can be extracted from the threshold scan, a multi-parameter fit is seen as mandatory. It is shown that the top mass, the top width and $\alpha_s(M_Z)$ can be extracted simultaneously with uncertainties around 20 MeV, 30 MeV and 0.0012, respectively, while the top Yukawa coupling can be measured, with the previous three parameters, to an uncertainty of about 35%, after assuming an external prior on α_s of ±0.001.

1 Introduction

The study of the top threshold scan observables in an e^+e^- linear collider environment was pointed out a long time ago [1] as a potentially high precision strategy for the determination of the top mass and eventually other relevant parameters such as the strong coupling constant, the top quark width and the top Yukawa coupling. Since then many studies with increasing levels of complexity have been performed to obtain a quantitative estimate of the attainable accuracy.

Earlier linear collider studies of the top threshold focused on the determination of the top quark mass [2–6]. A strong correlation between the top mass and the strong coupling constant, $\alpha_s(M_Z)$, was noticed, so that both quantities had to be measured at the same time, through a simultaneous two-parameter fit [2,3]. The correlation limited the experimental precision that could be achieved for the top mass to about 300 MeV. On top of it, when next-to-next-to-leading corrections to the $\bar{t}t$ cross section at threshold where computed [7], they were found to be large and to perturb the determination of the mass at the level of about 500 MeV.

In 1999 there was a substantial breakthrough when two new definitions of the top mass ("potential subtracted" [8] and "1S" [9]) were proved to be much less sensitive to higher order corrections than the pole mass used previously. As a welcome side effect, correlations between α_s and these new masses were found to be much reduced [10], so that a determination of m_t with less than 100 MeV experimental error and about 100–150 MeV theoretical uncertainty became feasible [10].

The decrease in the correlation can be understood from the fact that the most sensitive information comes from the position of the 1S resonance peak (although severely smeared after initial state radiation (ISR) and beam effects), which is at an energy $E_{1S} = 2m_t - V_{t\bar{t}}(\alpha_s)$, where m_t stands for the top pole mass, used previously, and $V_{t\bar{t}}(\alpha_s)$ stands for the $t\bar{t}$ binding potential, and depends almost linearly on α_s, therefore heavily correlating both parameters.

In order to help disentangle these two variables, the top momentum distribution due to the top Fermi motion was advocated already several years ago [11,12]. Simulation studies showed that the peak position of that distribution was quite robust against ISR and beam effects and changed linearly with the top mass while being insensitive to the strong coupling constant, providing, therefore, an additional handle for the disentangling of both variables [12,3].

Finally, in addition, the use of the top forward–backward charge asymmetry was suggested in the past as a way of getting direct information on the top quark width [14,13]. The large width of the top quark is responsible for the overlap between the 1S and 1P states whose interference causes a forward–backward charge asymmetry. Simulation studies showed that the measurement was feasible, although the attainable accuracy was rather limited [4].

In all these observables some modest sensitivity to the influence of the top Yukawa coupling, entering the $t\bar{t}$ potential was expected. Again, Monte Carlo studies showed that indeed the sensitivity was quite low [2].

For the top width and the top Yukawa coupling studies, the approach followed so far was a single parameter determination assuming no relevant uncertainty in the other parameters (top mass and strong coupling constant).

The study presented in this paper continues the work of [10], extending it and completing it. It completes it because it includes not just the cross section but also the other two relevant observables: the momentum distribution and the forward–backward asymmetry. It extends it because it explores the feasibility of extracting information about all the relevant input parameters simultaneously, that is, not just the top mass and the strong coupling constant but also the top width and the top Yukawa coupling.

The outline of this paper is as follows: in Sect. 2 the conditions in which the present analysis has been developed are summarized. In Sect. 3 the results for a "standard" two-parameter fit to the top mass and the strong coupling constant are presented and the sources of the correlations obtained are discussed. The case for a multi-parameter approach is then presented in Sect. 4 and the technical solution is described. Using this multi-parameter approach, Sect. 5 deals with the discussion on the actual sensitivity to the top quark width and Sect. 6 with the prospects for a measurement of the top Yukawa coupling. Finally, Sect. 7 summarizes the conclusions of this study.

2 Simulation input

For the present study, the simulation conditions have been assumed to be identical to the ones used in [10], namely, the TESLA beam conditions of [15] were assumed and the detector effects were simulated using the SIMDET algorithm as described in [16].

The $t\bar{t}$ observables (cross section, top momentum distribution and forward–backward charge asymmetry) have been computed using the TOPPIK code [11,13,17,18] including the latest theoretical predictions as discussed in [19][1]. For the studies presented in this work, the 1S mass definition has been used. The actual values of the input parameters used in the calculation are $m_t(1\mathrm{S}) = 175\,\mathrm{GeV}$, $\alpha_\mathrm{s}(M_Z) = 0.120$, $M_H = 120\,\mathrm{GeV}$ and the top width and Yukawa coupling as predicted in the minimal standard model. For the experimental selection studies, the signal and the relevant backgrounds have been generated using PYTHIA [22]. The event simulation is discussed in detail in [23].

For the cross section analysis, purely hadronic decays of the $t\bar{t}$ system, together with events in which only one of the top quarks decays hadronically are used. This results in an event selection efficiency of 41.2% (over the complete $t\bar{t}$ sample) with an estimated systematic uncertainty in the selection efficiency of 3% and a remaining background cross section of about 0.0085 pb. The same sample is used for the study of the top momentum distribution and, hence, the efficiency remains the same, with an estimated systematic uncertainty in the peak value of the momentum distribution of about 4%. For the forward–backward asymmetry measurement, only the sample in which one of the top decays semileptonically to an electron or a muon, allowing to tag easily the top charge, is used. This results in an event selection efficiency of about 14% with negligible background and systematic uncertainties.

For the first time, theoretical uncertainties have been included in the fit. Following [19] a 3% uncertainty in the total cross section, common to all center-of-mass energy points, has been assumed. This has to be considered as only a first attempt at quantifying the influence of the theoretical error in the results[2]. No estimate of theoretical systematics is available for either the top momentum distribution or the forward–backward charge asymmetry. However, as it will be shown below, these two observable have a rather limited weight in the final results.

The threshold scan has been assumed to consist of a luminosity of $300\,\mathrm{fb}^{-1}$ uniformly distributed in ten scan points: one of them well below threshold for a direct background determination and the other nine distributed symmetrically around the $m_t(1\mathrm{S})$ value with a 1 GeV spacing between each other[3]. Since the top mass will only be known with a moderate precision at the time the top threshold scan starts at a linear collider, it will be impossible to choose the center-of-mass energy points to lie precisely at the values we have chosen relative to $2m_t$. However, it has been checked that assuming a prior precision on m_t of around 500 MeV (coming from measurements at LHC or in the continuum region at a linear collider), the effect of not choosing the optimal values for $\sqrt{s}$ is very small.

The expectations for the three observables studied here are shown in Fig. 1 together with the corresponding expected experimental errors. It is clear from that figure that, while the measurement of cross section will be very precise, the peak of the momentum distribution will be determined with a moderate precision and the forward–backward asymmetry with a rather low precision. These uncertainties should be kept in mind when analyzing the sensitivity of each observable to the input parameters in the next sections. Both things put together will provide a feeling for which measurements are actually important for the determination of each one of the parameters discussed.

3 The top mass and the strong coupling constant

To start with, a two-parameter fit, with m_t and $\alpha_\mathrm{s}(M_Z)$, is performed, as in [10] but now using the larger integrated

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[1] A very recent update [20] of [19] results in shifts in the cross section of up to 1.5%, well within the assumed theoretical error. The new spin-independent $1/m^2$ potentials in [20] can be seen to agree with those obtained by Pineda in [21], while those in [19] disagreed

[2] For instance, we have noticed that assuming, instead, that the 3% theoretical error is totally uncorrelated between energy points (which seems rather unlikely), the effect of the theoretical error becomes much more prominent

[3] Some studies carried out in the past using just the cross section and fitting only the top mass and the strong coupling constant showed already that some modifications of the scanning strategy could allow for a decrease of some parameter errors [10]. However, when dealing with four-parameter fits, as we are doing here, the optimization of the scan strategy is not so obvious and for the moment it has not been attempted

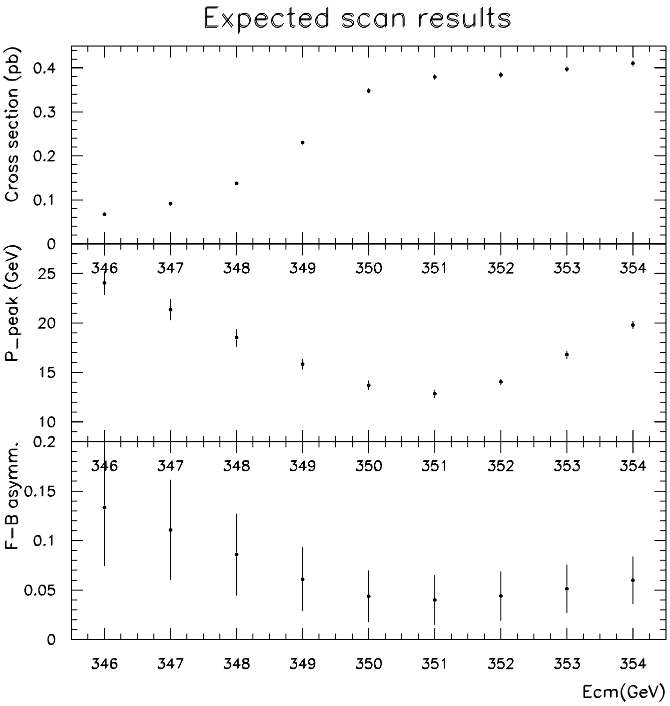

Fig. 1. The expected scan results for the cross section, the peak of the top momentum distribution and the forward–backward charge asymmetry in the conditions described in the text

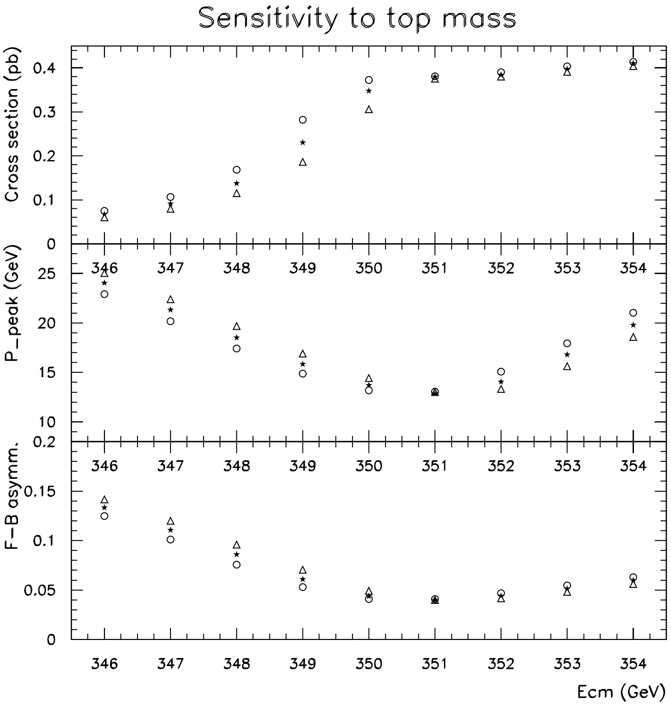

Fig. 2. Sensitivity of the observables to the top mass. The different markers correspond to $\Delta m_t = 200\,\mathrm{MeV}$ intervals

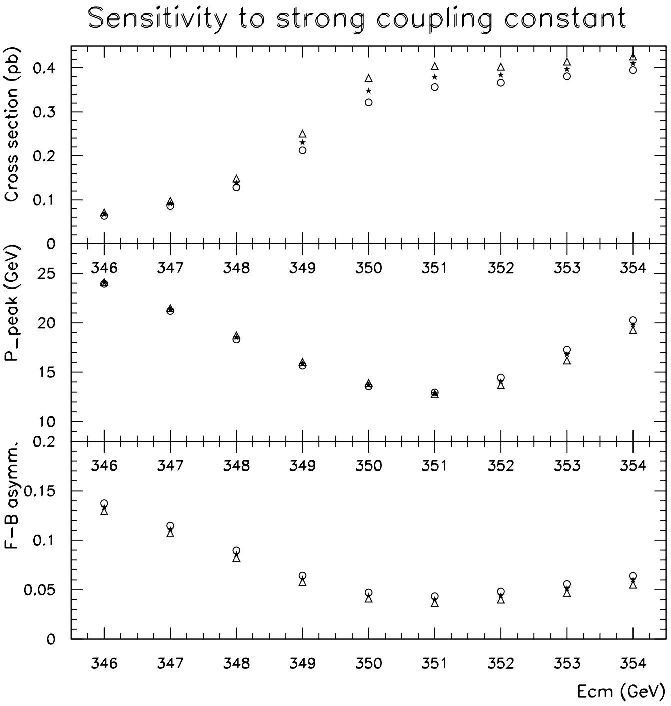

Fig. 3. Sensitivity of the observables to the strong coupling constant. The different markers correspond to $\Delta\alpha_{\mathrm{s}} = 0.004$ intervals

luminosity mentioned in the previous section and including also the information in the forward–backward charge asymmetry (A_{FB}) and position of the peak of the top momentum distribution, as outlined also in Sect. 2.

The sensitivity of each one of the observables to the top mass can be gleaned from Fig. 2, while the sensitivity to the strong coupling constant can be seen in Fig. 3. Given the scale of the experimental uncertainties shown in the previous section, it is easy to see that no relevant information in these two parameters can be expected from the forward–backward asymmetry. The peak of the momentum distribution is fairly sensitive to the top mass while rather insensitive to α_{s} and, even within the modest experimental precision, should provide valuable information on m_t. Finally, the cross section is very sensitive to both the top mass and α_{s} but, since we are using the 1S top mass definition, while most of the sensitivity to the top mass is in the (smeared) threshold position, the sensitivity to α_{s} comes mainly from the cross section above threshold. This indicates already that the top mass determination would benefit from investing the luminosity of the scan points which are above threshold in the threshold rising slope instead. The resulting uncertainties, including only experimental errors, are the following:

$$\Delta m_t = 16\,\mathrm{MeV}, \quad \Delta\alpha_{\mathrm{s}} = 0.0011, \quad \rho = 0.36, \tag{1}$$

where ρ is the correlation coefficient between m_t and α_{s}. If the 3% theoretical normalization error in the cross section is included, the results change to

$$\Delta m_t = 16\,\mathrm{MeV}, \quad \Delta\alpha_{\mathrm{s}} = 0.0012, \quad \rho = 0.33, \tag{2}$$

As can be seen, the change is extremely small. In the rest of this paper, unless explicitly said otherwise, all numbers and figures given will include the effect of the theoretical error. Figure 4 shows the correlation plot between the top mass and α_{s} resulting from the two-parameter χ^2 fit.

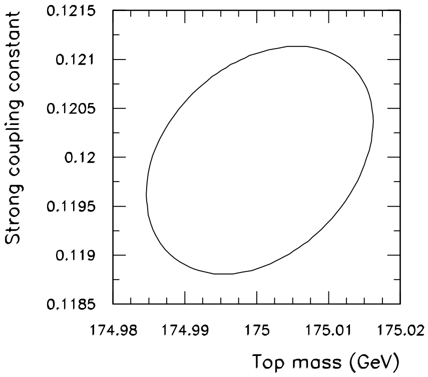

Fig. 4. $\Delta\chi^2 = 1$ contour as a function of $m_t(1\mathrm{S})$ and $\alpha_s(M_Z)$

To quantify the actual contribution of the different observables to this two-parameter fit, it has been repeated using only the cross section. In this case the results are

$$\Delta m_t = 25\,\mathrm{MeV}, \quad \Delta\alpha_s = 0.0019, \quad \rho = 0.76, \qquad (3)$$

The difference between this result and the one above has been traced back to the contribution of the peak of the momentum distribution, as expected. The sensitivity of the momentum distribution is such that it gives rise to a negative correlation between the extracted values of m_t and α_s which, when combined with the positive correlation coming from the cross section measurement, leads to substantial reductions in the overall errors of both m_t and α_s.

Once the possibility of measuring precisely the top mass and α_s with a $\bar{t}t$ threshold scan has been established one may turn the attention to measuring other quantities, like the top quark width and the top quark Yukawa coupling.

4 Multi-parameter fit strategy

So far, only single-parameter (or at most two-parameter) fits have been tried to the threshold scan observables to study the potential for the determination of the top width and Yukawa coupling. Nevertheless, as we have seen, the expected experimental error in each one of the observables strongly suggests that very likely the cross section measurement will dominate the parameter determination (with only a small improvement eventually expectable from adding the information from the forward–backward asymmetry and the top momentum distributions).

Therefore, as already stressed above, non-negligible correlations might be expected between the four parameters (top mass, strong coupling constant, top width and top Yukawa coupling) and, in this scenario, the only valid approach is a multi-parameter fit strategy.

For that, we need predictions of the three threshold observables studied in this work as a function of the four free parameters. In spite of the fact that the TOPPIK code speed has sizably improved over the previous versions, the time needed to run it after the convolution of the predictions with ISR and with the beam spectrum makes its use for a 4P fit impossible. To cure this problem and produce the necessary predictions in an affordable amount of time we have used a multi-dimensional interpolating routine based upon the algorithms of [24]. We have checked that, within the parameter intervals relevant for the fits discussed in this work, that interpolation produces results which reproduce the exact predictions with the required accuracy.

5 The top quark width

Earlier attempts have been made in studying the determination of the top quark width (Γ_t) from the $\bar{t}t$ threshold scan [4,14,25,26], with results in less than perfect agreement with each other, at least apparently.

Figure 5 shows the sensitivity of the threshold observables to the top width. As it can be seen from the figure, there is sizable sensitivity both at the peak of the cross section and at lower center-of-mass energies. For low values of the top width, the peak structure of the 1S resonance becomes apparent while for large values it disappears. The other two observables (A_{FB} and peak of momentum distribution) have an even larger sensitivity, which is enhanced in the energy points above threshold. Unfortunately, as already stressed, the accuracy of their experimental determination is much poorer. Because of that, in the scenario presented in this work, the determination of the top width can be expected to be dominated by the cross section measurement.

A three-parameter fit, with m_t, α_s and Γ_t leads to the following overall uncertainties:

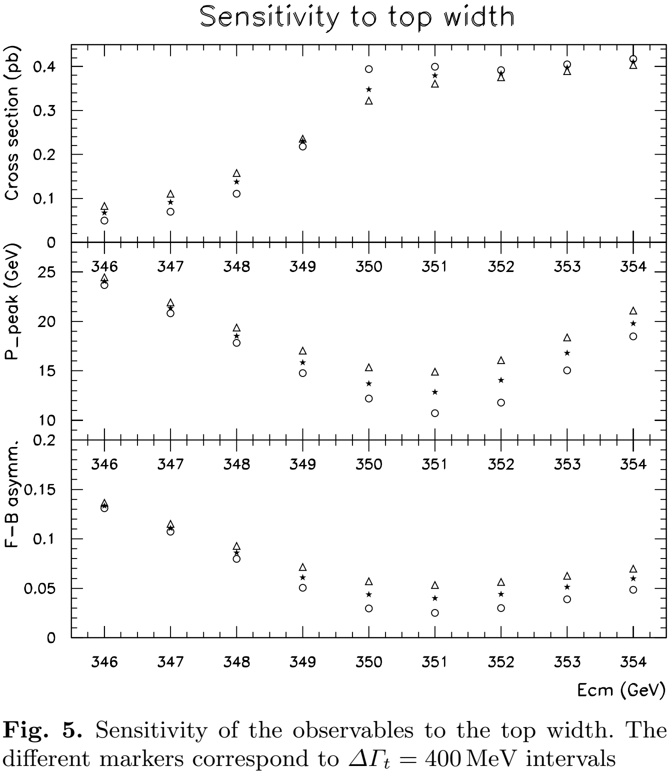

Fig. 5. Sensitivity of the observables to the top width. The different markers correspond to $\Delta\Gamma_t = 400\,\mathrm{MeV}$ intervals

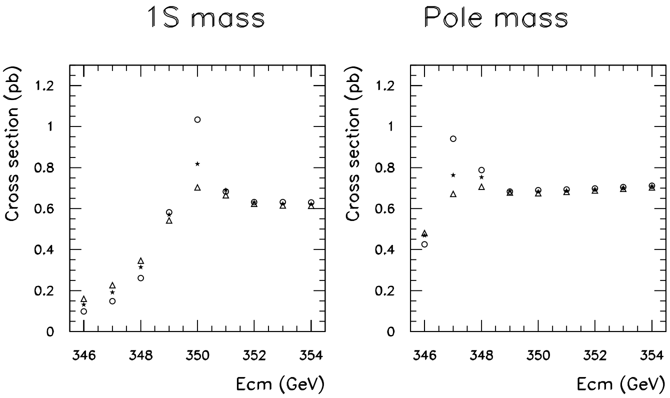

Fig. 6. The sensitivity of the cross section prediction (without ISR or beam effects) to the top width variation when the scan is centered around the top 1S mass and when it is centered around the top pole mass. The different markers correspond to $\Delta\Gamma_t = 400\,\mathrm{MeV}$ intervals

$$\Delta m_t = 19\,\mathrm{MeV}, \quad \Delta\alpha_s = 0.0012, \quad \Delta\Gamma_t = 32\,\mathrm{MeV}, \tag{4}$$

with all correlations between the three parameters being below 50%. The 32 MeV uncertainty on the top width corresponds to about a 2% measurement. This has to be compared with the 18% uncertainty reported on [4]. Several factors account for the decrease in the reported error:

(1) The integrated luminosity assumed now is six times larger than that assumed in [4] ($30\,\mathrm{fb}^{-1}$ instead of $5\,\mathrm{fb}^{-1}$ per point). This accounts for a factor ~ 2.4.

(2) The selection efficiency for top-antitop events has been taken from the work in [23], and it is about 41% while the one used in [4] was of about 25%. This accounts for a factor ~ 1.3.

(3) The present studies are based on a newer version of the TESLA machine. As a consequence the beam spectrum is now sharper than previously assumed. This results in an improvement of the top width determination by a factor ~ 1.5.

(4) A substantial part of the sensitivity in the center-of-mass energies below the maximum of the cross section was lost in the scan of [4], because, although the scan was centered around $2m_t$, the position of the peak in the cross section was shifted by about 2 GeV toward lower $\sqrt{s}$, because of the pole mass definition used for m_t. In contrast, both PS and 1S masses result, essentially by definition, in a cross section with a maximum at $2m_t$, so that the scanning strategy used here catches those energies below the maximum with substantial sensitivity to the top width. This difference can be clearly seen in Fig. 6. This accounts for a factor ~ 1.8.

When all these changes are taken into account together, a factor ~ 8.5 difference is obtained and therefore good compatibility is found between the results presented here and those in [4].

To disentangle the contribution of the different observables to the top width determination, the fit has been repeated using only the cross section. The results are

$$\Delta m_t = 34\,\mathrm{MeV}, \quad \Delta\alpha_s = 0.0023, \quad \Delta\Gamma_t = 42\,\mathrm{MeV}, \tag{5}$$

with correlations as large as 80% between the top mass and α_s. The difference between this fit and the result above can be traced back completely to the contribution of the peak of the momentum distribution in determining m_t. The contribution of the forward–backward asymmetry, introduced because it conceptually should be the cleanest observable to see the effect of the top width due to the overlap between the 1S and 1P states, is in practice negligible.

It is important to stress here that, the top quark being so heavy, a 2% determination of the top quark width can be very useful in constraining models of new physics which would predict new particles that could be produced on top quark decays. The precise determination of the top width from the threshold scan allows one to put constraints which are independent of the final state particles produced.

6 The top Yukawa coupling

Measuring the top Yukawa coupling could provide an important test of the Higgs mechanism for generating fermion masses. The exchange of a Higgs boson between the top and anti-top produced at threshold has been taken into account in the theory prediction by adding a Yukawa potential to the QCD $\bar{t}t$ potential [18]. The modified potential can have measurable effects in the observables studied here. However, Fig. 7 shows that the sensitivity of the total cross section to the Yukawa coupling is not very large and is not better in the forward–backward asymmetry while it is non-existent in the peak of the momentum distribution. Following the same arguments as given in the previous sections, we can expect that the Yukawa coupling determination will be completely dominated by the cross section measurement as well.

As an unrealistic starting point, a one-parameter fit is performed, fixing all parameters except for the top Yukawa coupling, λ_t. The fit returns an asymmetric uncertainty:

$$\frac{\Delta\lambda_t}{\lambda_t} =^{+0.18}_{-0.25}\,. \tag{6}$$

Given the lack of sensitivity, one can try to see whether there could be any gain obtained by relaxing somewhat the assumptions concerning systematic errors. In particular, the systematic error in the cross section determination has been lowered from 3% (taken from [23]) to 1%, which seems like a reasonable educated guess, given the level of understanding achieved at electron–positron machines like LEP, where selection systematics routinely achieved the few per mille level. Also, maybe with less justification, the theoretical error in the overall normalization has been lowered from 3% to 1%. Assuming the 1% errors, the uncertainty in the one-parameter fit decreases to

$$\frac{\Delta\lambda_t}{\lambda_t} =^{+0.14}_{-0.20}\,. \tag{7}$$

From now on, these lower systematic errors in selection and normalization will be assumed on all fits.

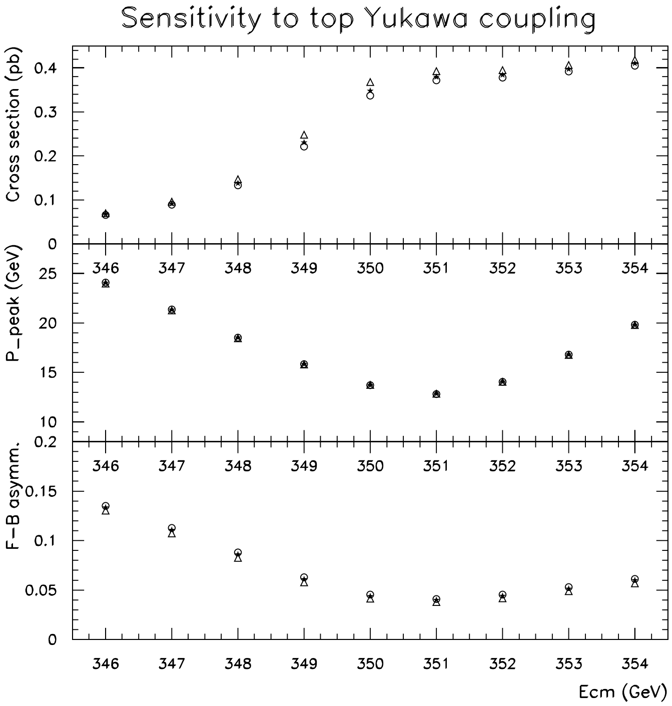

Fig. 7. Sensitivity of the observables to the top Yukawa coupling. The different markers correspond to $\Delta\lambda_t/\lambda_t = 0.50$ intervals

The next step consists on leaving the top mass and α_s free in the fit while fixing the top width to its standard model value and including an external constraint on $\alpha_s(M_Z)$ of ±0.001. The constraint should come from a different determination of α_s, like the one available, for instance, at GigaZ [27]. Under these conditions, a three-parameter fit leads to the following precisions:

$$\begin{aligned} &\Delta m_t = 27\,\mathrm{MeV}, \\ &\Delta\alpha_s = 0.001 \text{ (constraint)}, \quad \frac{\Delta\lambda_t}{\lambda_t} = {}^{+0.33}_{-0.54}, \end{aligned} \tag{8}$$

with correlations large, up to 80%, particularly among m_t and λ_t.

Finally, one could also try to leave the top width free in the fit, and perform a four-parameter fit with an external constraint on $\alpha_s(M_Z)$. The results are

$$\begin{aligned} &\Delta m_t = 31\,\mathrm{MeV}, \quad \Delta\alpha_s = 0.001 \text{ (constraint)}, \\ &\Delta\Gamma_t = 34\,\mathrm{MeV}, \quad \frac{\Delta\lambda_t}{\lambda_t} = {}^{+0.35}_{-0.65}\,. \end{aligned} \tag{9}$$

The simultaneous determination of the four parameters is possible without a large increase in the resulting uncertainties. Correlations remain similar, with a maximum of 83%, again among m_t and λ_t.

As can be seen, a realistic determination of the top Yukawa coupling, which has to be done simultaneously with that of the top mass, is very challenging, although not impossible.

7 Summary

For the first time a simultaneous four-parameter (top mass, strong coupling constant, top width and top Yukawa coupling) fit to the expectations for three $t\bar{t}$ threshold scan observables (cross section, top momentum distribution and top forward–backward charge asymmetry) has been carried out.

In a complete four-parameter fit to the expected threshold observables for a total $300\,\mathrm{fb}^{-1}$ luminosity scan using the TESLA machine, the parameter correlations obtained are very important (up to 83%), justifying the use of a full multi-dimensional approach.

The expected experimental uncertainties in each observable, as well as the sensitivity of each observable to the fitting parameters, have been scrutinized to understand in detail the origin of the correlations obtained in the parameter determination.

The outcome of the fits shows that the prediction of a high precision determination of the top mass, with an experimental accuracy better that 30 MeV and of the top width, with an accuracy at the 2% level, is quite robust.

Measuring the top Yukawa coupling with a top threshold scan looks difficult. Even with somewhat optimistic assumptions, the best error which can be expected with the above luminosity is above 30%, assuming a Higgs mass of 120 GeV. The situation should become significantly worse for heavier Higgses.

For the first time, an estimate of the theoretical error in the cross section prediction (a 3% normalization error from [19]) has been included in the fits and has been shown to have little effect on the overall result. However, a more realistic theoretical error model might lead to more severe errors, particularly on the top mass and $\alpha_s(M_Z)$.

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