Towards a Precise Measurement of the Top Quark Yukawa Coupling at the ILC

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A precise measurement of the top quark Yukawa coupling is of great importance, since it may shed light on the mechanism of EWSB. We study the prospects of such measurement during the first phase of the ILC at $\sqrt{s} = 500$ GeV, focusing in particular on recent theoretical developments as well as the potential benefits of beam polarization. It is shown that both yield improvements that could possibly lead to a measurement competitive with the LHC.

1. INTRODUCTION

The top quark Yukawa coupling (λ_t) is the largest coupling of the Higgs boson to fermions. A precise measurement of it is very important since the it may help unravel the secrets of the Electroweak Symmetry Breaking (EWSB) mechanism, in which the top quark could possibly play a key role. For $m_h < 2m_t$, a direct measurement of λ_t is possible via associated $t\bar{t}h$ production, both at the LHC and a future e^+e^- International Linear Collider (ILC). At the LHC, the expected accuracy [1] is $\delta\lambda_t/\lambda_t \sim 12 - 15\%$ for $m_h \sim 120 - 200$ GeV, assuming an integrated luminosity of 300 fb^{-1}. Existing feasibility studies at the ILC [2] predict an accuracy of $\delta\lambda_t/\lambda_t \sim 6 - 10\%$ for $m_h \sim 120 - 190$ GeV, assuming $\sqrt{s} = 800$ GeV and 1000 fb^{-1}. However, currently the baseline design for the ILC only contemplates a maximum center-of-mass energy of 500 GeV. Therefore, it is very relevant to explore the prospects of this measurement during the first phase of the ILC, especially in view of the limited accuracy expected at the LHC: for a number of years, the combination of results from the LHC and ILC would yield the most precise determination of λ_t.

A preliminary feasibility study at $\sqrt{s} = 500$ GeV was performed in Ref. [3], which we briefly overview here. Indeed, the measurement of λ_t at $\sqrt{s} = 500$ GeV is more challenging than at $\sqrt{s} = 800$ GeV. On the one hand, the reduced phase-space leads to a large reduction in $\sigma_{t\bar{t}h}$ (e.g. $\sigma_{t\bar{t}h}^{Born} \simeq 0.16(2.5)$ fb at $\sqrt{s} = 500(800)$ GeV, for $m_h = 120$ GeV). On the other hand, the cross section for many background processes is significantly increased. This analysis assumed $m_h = 120$ GeV and focused on the $t\bar{t}h \rightarrow (\ell\nu b)(jjb)(b\bar{b})$ decay channel $(BR \sim 30\%)$. The dominant background is $t\bar{t}jj$, followed by $t\bar{t}Z$, although other non-interfering backgrounds (e.g. W^+W^-) were also considered. Signal and backgrounds were processed through a fast detector simulation. After basic preselection cuts, the signal efficiency was found to be $\simeq 50\%$ and the $S : B \simeq 1 : 100$. In order to increase the sensitivity, a multivariate analysis using a Neural Network (NN) with 23 variables was performed. The final selection consisted on an optimized cut on the NN distribution. Assuming an integrated luminosity of 1000 fb^{-1}, the expected total number of signal and background events was 11 and 51, respectively, resulting in $(\delta\lambda_t/\lambda_t)_{stat} \simeq 33\%$. Based on previous experience [2], the addition of the fully hadronic decay channel was expected to ultimately lead to $(\delta\lambda_t/\lambda_t)_{stat} \simeq 23\%$. While this analysis is already rather sophisticated, significant improvements are expected from e.g. the usage of a more efficient b-tagging algorithm or a more optimal treatment of the kinematic information. In the next sections we discuss additional sources of improvement which are currently under investigation.

2. THE IMPACT OF RESUMMATION EFFECTS

The precise measurement of λ_t requires accurate theoretical predictions for $\sigma_{t\bar{t}h}$. Currently, one-loop QCD and electroweak corrections are available. However, at $\sqrt{s} = 500$ GeV and for $m_h \geq 120$ GeV, the kinematic region

Table I: Comparison of the Born and NLL $\sigma_{t\bar{t}h}$ for different scenarios regarding radiative effects in the initial state.

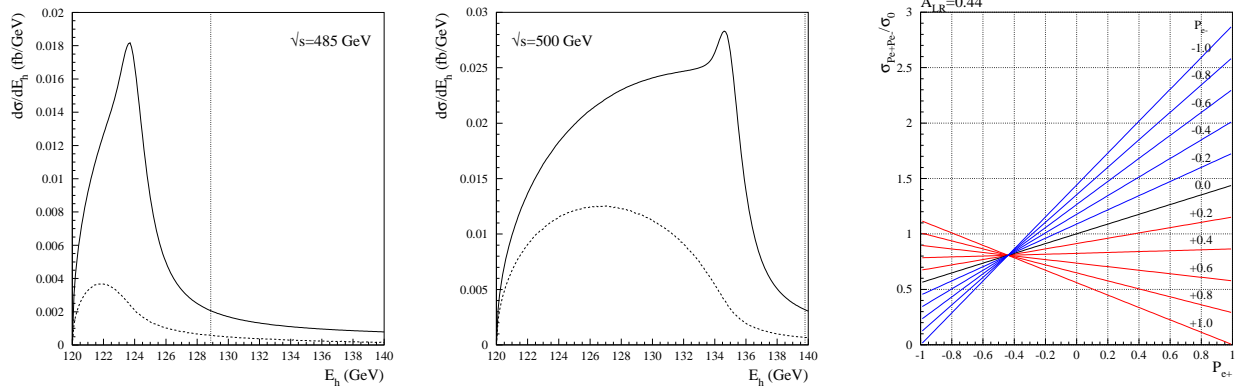| (ISR,BS)	$\sigma_{t\bar{t}h}$ (fb) (Born)	$\sigma_{t\bar{t}h}$ (fb) ("NLL-improved")	Enhancement factor
(off,off)	0.157(1)	0.357(2)	2.27
(off,on)	0.106(1)	0.252(3)	2.38
(on,on)	0.0735(8)	0.179(2)	2.44

Figure 1: Left and center: comparison of the Born (dashed) and NLL (solid) $d\sigma_{t\bar{t}h}/dE_h$ for different values of $\sqrt{s}$, assuming $m_t^{1S} = 180$ GeV and $m_h = 120$ GeV. The dotted line indicates the value of E_h^{max}. Right: ratio of polarized to unpolarized cross section for different values of (P_{e^-}, P_{e^+}).

where the $t\bar{t}$ system is non-relativistic dominates. As discussed in Ref. [4], in this regime Coulomb singularities are important and need to be resummed within the framework of the vNRQCD effective theory, leading to large enhancements factors in the cross section relative to the Born level. At the ILC, because of ISR and beamstrahlung (BS), the event-by-event center-of-mass energy ($\sqrt{\hat{s}}$) will be lower than the nominal one, thus bringing the $t\bar{t}$ system deeper into the non-relativistic regime. In order to compute the expected $\sigma_{t\bar{t}h}$ including these effects, the 11-fold Born differential cross section for $e^+e^- \to t\bar{t}h \to W^+ b W^- \bar{b} h$ was multiplied by a K-factor defined as $K(E_h, \sqrt{\hat{s}}) = (d\sigma_{t\bar{t}h}^{NLL}/dE_h)/(d\sigma_{t\bar{t}h}^{Born}/dE_h)$, where E_h stands for the Higgs boson energy in the e^+e^- rest-frame, and then folded with ISR and BS structure functions. The NLL differential cross section was kindly provided by the authors of Ref. [4]. Fig. 1(left and center) compares the Born (for off-shell top quarks) and NLL differential cross sections for different values of $\sqrt{\hat{s}}$, assuming $m_t^{1S} = 180$ GeV and $m_h = 120$ GeV. The ratio of these two curves defines $K(E_h, \sqrt{\hat{s}})$ and can be significantly larger than 1, especially for low values of $\sqrt{\hat{s}}$. Since the NLL prediction is only valid for $E_h \leq E_h^{max}$ (where E_h^{max} effectively corresponds to a cut on the top quark velocity in the $t\bar{t}$ rest-frame of $\beta_t < 0.2$), we currently set $K(E_h, \sqrt{\hat{s}}) = 1$ for $E_h > E_h^{max}$, although in practice, it should be possible to use $K(E_h, \sqrt{\hat{s}}) = (d\sigma_{t\bar{t}h}^{O(\alpha_s)}/dE_h)/(d\sigma_{t\bar{t}h}^{Born}/dE_h)$. Table I compares the predicted Born and "NLL-improved" $\sigma_{t\bar{t}h}$ for different scenarios, illustrating the large impact of radiative effects in the initial state. This underscores the importance of being able to predict these effects to the percent level. While the impact of ISR cannot be reduced, it might be possible to find an optimal operating point of the accelerator, as far as this measurement is concerned, in terms of BS and total integrated luminosity. Finally, it is found that, for $m_h = 120$ GeV, resummation effects can increase $\sigma_{t\bar{t}h}$ by a factor of ~ 2.4 with respect to the Born cross section, used in the previous feasibility study.

3. THE IMPACT OF BEAM POLARIZATION

So far, all feasibility studies of this measurement have assumed unpolarized beams. Currently, the baseline design for the ILC only includes longitudinal electron beam polarization ($|P_{e^-}| \simeq 0.8$). Positron beam polarization ($|P_{e^+}| \simeq$

0.6) is considered as an option. The ratio of the polarized cross section (for arbitrary longitudinal beam polarization) $(\sigma_{P_{e^-}P_{e^+}})$ to the unpolarized cross section (σ_0) is given by $\sigma_{P_{e^-}P_{e^+}}/\sigma_0 = (1 - P_{e^-}P_{e^+})(1 - P_{eff}A_{LR})$, where $P_{eff} = (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$ denotes the "effective polarization" and A_{LR} is the "left-right asymmetry" of the process of interest [5]. Therefore, two potential enhancement factors can in principle be exploited: the first one requires having both beams polarized, the second one requires $A_{LR} \neq 0$ and a judicious choice of the signs of P_{e^-} and P_{e^+} in order to have $P_{eff}A_{LR} < 0$. In the case of SM $t\bar{t}h$ production, $A_{LR} \simeq 0.44$, essentially independent of $\sqrt{s}$ in the range $\sim 0.5 - 1.0$ TeV. Assuming $(A_{LR})_{SM}$, Fig. 1(right) shows the cross section enhancement factor as a function of P_{e^+}, for different values of P_{e^-}. The optimal (realistic) operating point would be $(P_{e^-}, P_{e^+}) = (-0.8, +0.6)$, achieving an increase in $\sigma_{t\bar{t}h}$ by a factor of $\simeq 2.1$ with respect to the unpolarized case. Unfortunately, this choice does not help reduce the dominant background, which is increased by a similar factor. Nevertheless, the net result is still an improvement in the statistical precision on λ_t by $\sim 45\%$, which would be an argument in favor of including positron polarization in the baseline design. For $(P_{e^-}, P_{e^+}) = (-0.8, 0)$, only a modest increase in $\sigma_{t\bar{t}h}$ by a factor of ~ 1.3 would be achieved. It is important to realize that, in order to choose the sign of P_{e^-} and P_{e^+}, it is necessary to know the sign of A_{LR}. Anomalous couplings in the $tt\gamma$ and ttZ vertices could possibly lead to deviations in A_{LR} from the SM prediction. Unfortunately, due to the limited precision in the measurement of the ttZ couplings [6], the LHC is not expected to provide any useful constraints on the sign of A_{LR}. Therefore, at the ILC the first step should be to perform measurements of the polarized $\sigma_{t\bar{t}}$ in order to determine the sign of A_{LR}, and thus fix the signs of P_{e^-} and P_{e^+} (the magnitudes should be largest possible). On the other hand, admittedly the measurement of λ_t requires a percent-level and model-independent determination of the $t\bar{t}\gamma$ and $t\bar{t}Z$ couplings, which typically benefits from changing the beam polarization. Therefore, it would be desirable to optimize the running strategy to maintain the largest possible $\sigma_{t\bar{t}h}$, needed for a precise measurement of λ_t, while meeting the precision goals for measurements of top quark couplings.

4. CONCLUSIONS

We have studied the prospects of a precise measurement of the top quark Yukawa coupling during the first phase of the ILC. Taking into consideration an existing feasibility study, and the additional enhancement factors to $\sigma_{t\bar{t}h}$ discussed here, we anticipate a precision of $(\delta\lambda_t/\lambda_t)_{stat} \sim 10\%$ for $m_h = 120$ GeV, assuming $\sqrt{s} = 500$ GeV and 1000 fb^{-1}.

Acknowledgments

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