Forward backward asymmetry in $\mathbf{e^+e^- \to t\bar{t}}$ at $\sqrt{\mathrm{s}} = 500\,\mathrm{GeV}$ for fully hadronic decays of the $\mathbf{t\bar{t}}$ pair

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Abstract

We determine the statistical precision for the forward back asymmetry A^t_{FB} in $e^+e^- \to t\bar{t}$ for the fully hadronic decay mode $t\bar{t} \to (bq\bar{q})(\bar{b}q\bar{q})$ at $\sqrt{s} = 500\,\mathrm{GeV}$. Results are given for the beam polarisations $P(e^-, e^+) = (-80\%, +30\%)$ and $P(e^-, e^+) = (+80\%, -30\%)$ for an integrated luminosity of $250\,fb^{-1}$ for each polarisation. Only signal events are used for the analysis, with $\gamma\gamma$ overlay. The expected precisions are 2.9% in case of $P(e^-, e^+) = (-80\%, +30\%)$ and 3.2% in case of $P(e^-, e^+) = (+80\%, -30\%)$.

1 Introduction

Top quark physics is one of the most important channels at ILC. The forward backward asymmetry A^t_{FB} for fully hadronic decays of the top or t quarks was determined in the Letter of Intent of the ILD concept [1] for the beam polarisations $P, P' = -0.8, +0.3$ of the incoming electron and positron beams, respectively. The charge was to repeat this analysis for the detector DBD. Therefore, the analysis presented in this short note follows closely the procedure described in [2]. It is also a test for the updated software packages mainly `ILCSoft` and `LCFIPlus`.

2 Event selection

The present study assumes a centre-of-mass energy of $\sqrt{s} = 500\,\mathrm{GeV}$ and a luminosity of $\mathcal{L} = 500\,\mathrm{fb}^{-1}$ equality shared between the beam polarisations $P, P' = \pm 0.8, \mp 0.3$ of the incoming electron and positron beams.

We use the data generated with `WHIZARD 1.95`. The analysis is carried out on samples with fully polarised beams and then corrected for the realistic case of non-full beam polarisation. *We select the signal events for analysis, for which a $t\bar{t}$ pair is required to be present in the generated event record. For more details about the input samples, please read the Technical Remarks at the end of this note.* The software version `ILCSoft 01-16` is used for event reconstruction. The package `LCFIPlus v00-05-02` is used for flavor tagging and vertex charge reconstruction.

The t quark decays nearly exclusively into a pair of b quarks and W bosons. The b quarks hadronise into a jet, called b jet hereafter, which contains a B meson. The six jet final state is reconstructed using the Durham jet finder. Subsequently the jets are analysed with the `LCFIPlus` package, which assigns a b likeness called b -tag to the jet. The two jets with the highest b-tag values are considered to be the jets from the b quarks. Events for which one of the b-tag values is smaller than 0.3 are rejected. The two W bosons are reconstructed from the remaining four jets. A combination of two jets, which are closest to the W mass, m_W, is defined to be W_1 while the remaining two are combined into W_2.

After having reconstructed the jets from W bosons and b quark jets, the jets are combined to form t quarks. Out of four possible combinations of two b jets with these Ws, $Top = W_i + b_k$ with $i, k = (1, 2)$, two tops are reconstructed with the minimal χ^2.

$$\chi^2 = \left(\frac{m_t - 174}{\sigma_{m_t}}\right)^2 + \left(\frac{E_t - 250}{\sigma_{E_t}}\right)^2 + \left(\frac{p_b^* - 69}{\sigma_{p_b^*}}\right)^2,$$

with

$$p_b^* = \gamma p_b (1 - \beta_t \cdot \cos(\theta_{tb}))$$

being the momentum of the b quark in the rest frame of the t quark, E_t the energy of the t quark candidate and m_t the mass of the t quark.

The defined χ^2 is a quality criterium for the events and only events that satisfy $\chi_1^2 < 20$ and $\chi_2^2 < 40$ are retained. Finally, events are selected for which both t quarks and both W bosons are in the range $50 < m_t < 200$ GeV and $60 < m_W < 100$ GeV

After having selected the t quarks, the b quark charge Q_b at the vertex is determined to identify whether it came from a t or $\bar{t}$ quark. The charge at the vertex is reconstructed as the sum of the charge of all particles related to this vertex. For both jets $|Q_b| < 5$ is required, otherwise the event is rejected.

In order to verify the charge reconstruction it is compared with b quark and $\bar{b}$ quark in the Monte Carlo record. Additionally, a cross check is performed using B mesons, which are formed from the b quark. The Fig. 1 shows in its left part the measured jet charges originating from b or $\bar{b}$ quarks. The right hand part is the same but now the reference charge is given by a B meson in the jet. For the majority of the events the charge of the original particle is reconstructed correctly. The distributions are compatible with those shown in Ref. [2]. It should at this point be emphasised that the `LCFIPlus` package is so far not optimised for the charge measurement. This means that further improvement can be expected in the future.

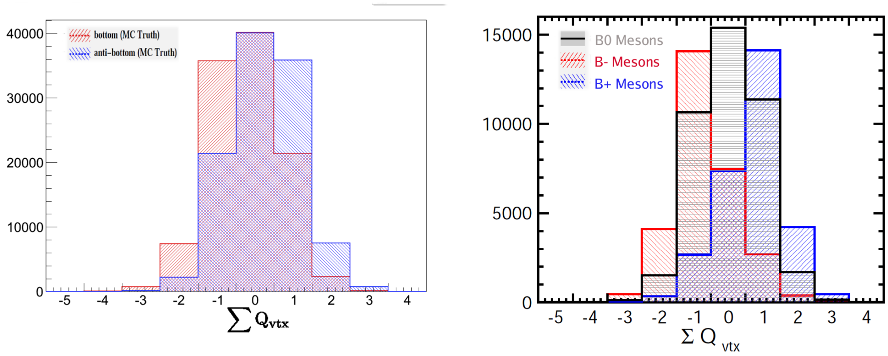

Figure 1: *Left: Reconstructed charge for jets originating from b or $\bar{b}$ quarks. Right: The charge of the B meson is taken as a reference for the verification of the vertex charge measurement.*

For the association of the b jets b_1 and b_2 having charge Q_{b_1} and Q_{b_2} to t or $\bar{t}$ the event charge $C = Q_{b_1} - Q_{b_2}$ is defined. The Fig. 2 shows the distribution of the event charge. As expected, most of the events have a non-zero C value, which in turn implies that we can distinguish between a t quark and a $\bar{t}$ quark. The following criteria are applied

- In case $C = 0$ an event is discarded;
- If $C < 0$ the b_1 is assumed to be produced in the decay of a t quark;
- If $C > 0$ the b_1 is assumed to be produced in the decay of a $\bar{t}$ quark.

All introduced event selection criteria are summarised in Table 1.

Cut number	*Type*
1	b tag$_{1,2} > 0.3$
2	$\chi_1^2 < 20$ and $\chi_2^2 < 40$
3	$50 < m_t < 200$ GeV
4	$60 < m_W < 100$ GeV
5	$Q_b < 5$
6	$C \neq 0$

Table 1: *Cuts as applied in this analysis in the sequence as they appear in the text.*

The final selection efficiency is about 13% independent for both beam polarisations. This is about 8% smaller than reported in [2]. The main reason for this is the relatively hard cut on the W boson mass, see Sec. 4 for further discussion.

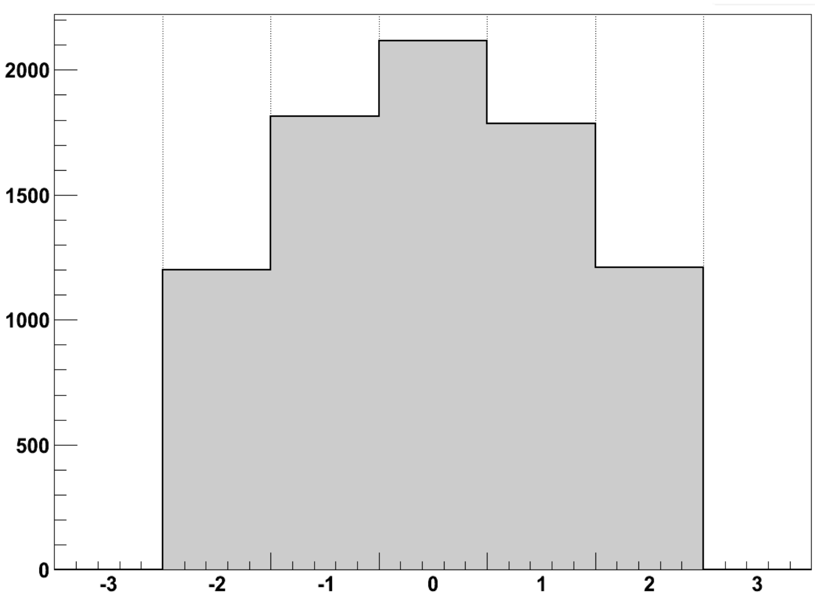

Figure 2: *Event Charge* $C = Q_{b_1} - Q_{b_2}$, *the variable used to identify the charge of top quark.*

3 Determination of the forward backward asymmetry $\mathbf{A^t_{FB}}$

The forward backward asymmetry is defined as follows

$$A^t_{FB} = \frac{N(0 < \theta_{top} \leq \frac{\pi}{2}) - N(\frac{\pi}{2} < \theta_{top} \leq \pi)}{N(0 < \theta_{top} \leq \frac{\pi}{2}) + N(\frac{\pi}{2} < \theta_{top} \leq \pi)}$$

The polar angle θ_{top} is defined w.r.t. to the incoming electron beam. The quantity N is the number of events in the different detector hemispheres.

For convenience the asymmetry is given for t quarks only and the angle of $\bar{t}$ is inverted by π to add it to t.

$$\cos\theta_t = -1 * \cos\theta_{\bar{t}}$$

The Fig. 3 shows the forward backward asymmetry for the polarisation $P, P' = -1, +1$ after the selection described in the previous section. A clear asymmetry is visible. The measured charge of the b quark is compared with the MC truth and remaining events with a wrong charge assignment are identified. These events are also indicated in Fig. 3.

For about 65% of the t quarks selected according to Sec. 2 the charge is measured correctly. For the final result events with wrong charge assignment are subtracted from the number of observed events. The resulting

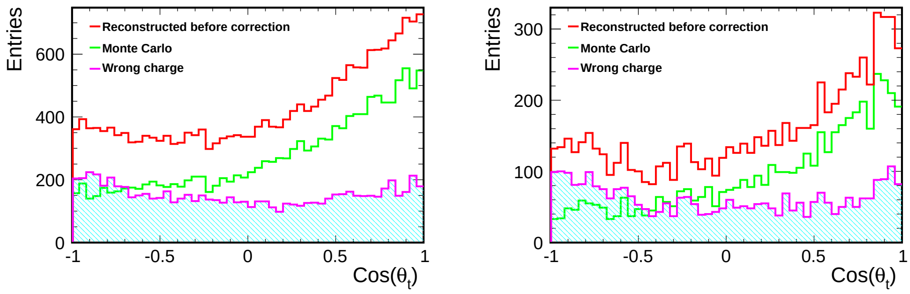

Figure 3: *Left: Asymmetry for $P, P' = -1, +1$ after application of cuts in Tab. 1. The figure shows in addition the generated distribution and the events for which the b quark charge is incorrectly reconstructed. Right: The same as left but for $P, P' = +1, -1$*

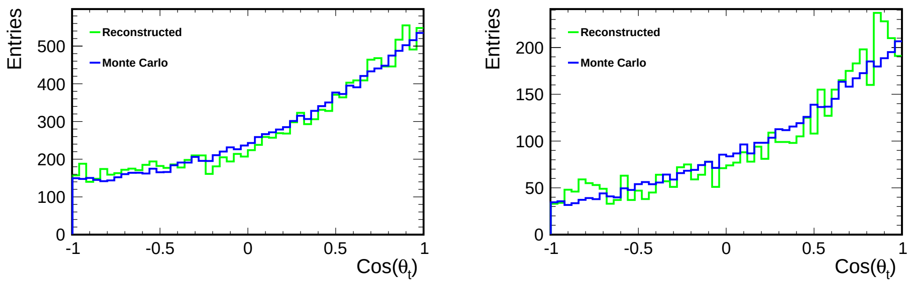

Figure 4: *Left: Asymmetry for $P, P' = -1, +1$ after application of cuts in Tab. 1 and correction for events in which the b quark charge was incorrectly reconstructed. The corrected result is compared with the generated distribution. Right: The same as left but for $P, P' = +1, -1$*

asymmetries for both beam polarisations are shown in Fig. 4 and the results are summarised in Tab. 2. Note, that 1/4 of the difference between generated and reconstructed A^t_{FB} is taken as the systematic error. The statistical error is given for the number of events expected for $250\,\mathrm{fb}^{-1}$ and $P, P' = \pm 0.8, \mp 0.3$

P, P'	$(A^t_{FB})_{gen.}$	A^t_{FB}	$(\delta_{A_{FB}}/A_{FB})_{stat.}$ [%]	$(\delta_{A_{FB}}/A_{FB})_{syst.}$ [%]
$-1, +1$	0.355	0.344	2.9 (corrected to $P, P' = -0.8, +0.3$)	0.8
$+1, -1$	0.438	0.443	3.2 (corrected to $P, P' = +0.8, -0.3$)	0.3

Table 2: *Precisions expected for A^t_{FB} for different beam polarisations.*

4 Discussion of results

The selection efficiency in the present analysis is about 8% smaller than this was case for the LOI study. The reason is mainly the tighter selection cuts on the W boson mass. The analysis cuts have been varied within reasonable limits. The efficiency can be increased to about 20% and better while the absolute result of A^t_{FB} changes by less than 6%. It might also be required to define different selection cuts for the two configurations of the beam polarisation. Clearly, the definition of an optimal cut scenario is a task for further studies. A major source of systematic error is that the final correction for wrongly measured b quark charges is based on Monte Carlo truth information. This is turn would require a perfect modeling of the final state. The error of the charge measurement may however be controlled in situ with semi-leptonic events. More studies on the optimisation of the measurement b or charge are needed in the future.

5 Summary and outlook

A repetition of the LOI analysis of the asymmetry A^t_{FB} in fully hadronic decays of the t quark is presented. The asymmetry A^t_{FB} can be measured with a precision of about 3%. The obtained result is within statistical limits compatible with what ILD has presented in the LOI. The analysis may be improved by means of an optimisation of the analysis cuts. The new `LCFIPlus` package is not yet optimised for the measurement of the b quark charge. Yet it gives already results, which are at least similar to those of the LOI. This promises future improvement of the study. In order to control systematic effects due to a non-perfect modeling of the final state, the charge measurement can be studied using semi-leptonic events. In general it is clearly attractive to investigate how the fully hadronic and semi-leptonic analysis can be combined in the future. In addition the full SM background will have to be included. Due to reasons of limited time this was not possible up to now. In the LOI analysis it was however shown that this is no major concern.

Technical remarks

The events are generated with version 1.95 of the `WHIZARD` event generator [3, 4] in form of six fermion final states. The generated events are then passed to the PYTHIA simulation program to generate parton shower and subsequent hadronisation. For this events are selected for which the difference between the invariant masses of the three fermion systems forming a t quark from WHIZARD and the input t quark mass to WHIZARD of 174 GeV is smaller than $5\Gamma_t$. Here Γ_t is the total decay width of the t quark. By this only about

70% of the events generated by WHIZARD are recognised as $t\bar{t}$ events and treated accordingly. The analysis is based on the described sub-selection of events. In reality only the six fermion final state is available. The relation between the measurement of the six fermion final state and e.g the couplings of the t quark to the photon and the Z^0 boson remains to be established.

References

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