The potential of the $t\bar{t}$ charge asymmetry measurement at a Linear Collider with $\sqrt{s}$ in the range 500 GeV $-$ 1 TeV

I. Garcia[1], E.Ros[1], J.Trenado[2], M.Vos[1]

[1] IFIC (Univ. Valencia - CSIC), Spain
[2] Univ. Barcelona, Spain

DOI: will be assigned

Precision measurements of electroweak parameters are a sensitive probe for BSM physics. In this lecture it is shown how to extract experimentally the top forward-backward charge asymmetry at a Linear Collider with $\sqrt{s}$ in the range 500 GeV $-$ 1 TeV (even without beam polarizations). We show that ambiguities in the top reconstruction, present at $\sqrt{s}$ = 500 GeV, are removed for $\sqrt{s}$ = 1 TeV and beyond.

1 The FB charge asymmetry for top quarks

The FB charge asymmetry for top quarks is defined as

$$A_{FB}(t) = \frac{N_F - N_B}{N_F + N_B}$$

where $N_F(N_B)$ are defined as the number of events with forward (backward) outgoing top quark. The direction of the top is defined relative to the incoming electron direction. Therefore, if θ is the angle between the incoming electron and the outgoing top, N_F is the number of events with $\cos\theta > 0$ and N_B the number of events with $\cos\theta < 0$. The same holds for the incoming positron and the outgoing antitop.

The FB charge asymmetry has been extensively studied at LEP ($\sqrt{s} = M_Z$) for all fermions except top, that could not be procuced since the center-of-mass energy of LEP is below top production threshold. Table 1 shows the FB asymetries measured by LEP experiments [1]. One can notice some tension between the SM value and the measurement for b-quarks. The measurement of the left-right symmetry by SLD [] offers a complementary constraint on the $Z/\gamma^* q\bar{q}$ vertex. These two sets of measurements provide the most precise measurements of the Weinberg angle, that differ at the 3 σ level.

Table 1: FB asymmetries measured by LEP experiments at $\sqrt{s} = M_Z$.

A_{FB}	measured value	deviation (in sigmas)
e	0.0145(25)	-0.7
μ	0.0169(13)	$+0.6$
τ	0.0188(17)	$+1.6$
s	0.0976(114)	-1.4
c	0.0707(35)	$+0.8$
b	0.0992(16)	-2.3

The FB asymmetry can be shown to be sensitive for example to warped Extra Dimension models [3] and in general to a large variety of BSM models.

A top charge asymmetry can also be defined for hadron colliders [4]. Evidence for a deviation from the value predicted by the Standard Model is claimed by the CDF collaboration for events with large invariant mass ($m_{tt} > 450$ GeV [5]). The D0 collaboration finds no statistically significant enhancements of A_{FB}, neither for high $m_{t\bar{t}}$ nor for top quark pairs with a large rapidity difference.

A top charge asymmetry can be also defined at the LHC, where gluon-gluon collisions form the main source of top production. In this case one defines the asymmetry as

$$A_c = \frac{N_+ - N_-}{N_+ + N_-}$$

where $N_+(N_-)$ is the number of events with $|y_t| - |y_{\bar{t}}| > 0(< 0)$, where y_t and $y_{\bar{t}}$ are the rapidity of the top quark and anti-top quark, respectively. This quantity should vanish in the SM, except for % level higher order corrections in QCD. The first analyses of the CMS and ATLAS experiments have not observed any anomaly in this quantity:

$$A_c = -0.013 \pm 0.028^{+0.026}_{-0.031} \qquad \text{[CMS, 1.09 } fb^{-1} \text{ [7]]}$$

$$A_c = -0.024 \pm 0.016 \pm 0.023 \qquad \text{[ATLAS, 0.7 } fb^{-1} \text{ [8]]}$$

The analysis of this asymmetry, together with other observables like the total cross-section and the invariant mass spectrum, can be used to constrain a large variety of BSM models.

Concerning $A_{FB}(t)$ for a Linear Collider, it can be used as a benchnark for the sensitivity to detect a seuential Z' well beyond the $\sqrt{s}$ of the collider. This resonance will interfere with the γ/Z to produce a deviation in $A_{FB}(t)$. If we assume a precision for this asymmetry of 1.5%, the sensitivity at $\sqrt{s} = 500$ GeV is up to a mass of 3 TeV. For a Collider with $\sqrt{s} = 1$ TeV, the sensitivity goes beyond 5 TeV. In certain warped ED models [9], the sensitivity is considerably enhanced for top quarks. Technically, $A_{FB}(t)$ is more easy to measure at $\sqrt{s} = 500$ GeV due to an increased cross-section (0.6 pb, compared to 0.2 pb at 1 TeV), resulting in a statistical error of $\Delta A_{FB} = 0.4\%$ (compared to 0.7% at 1 TeV), if we assume a total integrated luminosity of 1 ab^{-1} and event acceptance od 12% for semileptonic top decays. In practice the situation is more complicated due to problems in the top reconstruction at the low energy (see next section) and to an increased sensitivity of the asymmetry to the top mass uncertainty resulting in $\Delta A_{FB} = 0.4\%$ at $\sqrt{s} = 500$ GeV, to be compared to $\Delta A_{FB} = 0.1\%$ at 1 TeV. In both cases we assume a precision of 1.6 GeV for the top mass.

We note here that the use of polarized electron and/or positron beams allows for a more precise determination of the top quark couplings than that possible with A_{FB}. This study will be extended to include a study of the left-right asymmetry, but in this note these results are not yet included.

2 Top quark reconstruction

The top quark decays to a W boson and a bottom quark with a branching fraction close to 100 %. Depending on whether the W bosons decays to a charged lepton and a neutrino or to quark anti-quark, the final state formed in $t\bar{t}$ pair production is categorized as:

- fully hadronic: both W-bosons decay to quark anti-quark, resulting in a final state with at least six jets and no isolated leptons
- one lepton + jets (or semi-leptonic): one W boson decays to a charged lepton and a neutrino, yielding a distinctive signature of an isolated lepton and missing (transverse) energy and at least four jets
- di-lepton: both W-bosons decay to a charged lepton and a neutrino, leading to a final state with two isolated leptons, missing energy with contributions from two neutrinos and two b-jets

In many analyses (at hadron colliders) final states with τ-leptons form a separate category to deal with the difficulties inherent in the isolation of hadronic τ-lepton decays and the ambiguities due to the additional neutrinos in leptonic τ-lepton decays.

Reconstruction algorithms have been developed for these different final states. In final states with at most one leptonically decaying W-boson the measurement of the missing energy can be used to reconstruct the neutrino momentum. In hadron colliders, the missing transverse energy is identified with the neutrino p_T, while the longitudinal component of the neutrino momentum is inferred (with a two-fold ambiguity) from the measured lepton momentum and the W-mass constraint. Jets are assigned to top quark candidates using a combination of b-tagging information and mass constraints. The ambiguities that inevitably arise in this procedure are studies in detail in the next section.

In the years leading up to the start-up of the LHC many authors have pointed to the experimental challenge posed by the reconstruction of highly boosted top quarks [10, 11]. Since then, new techniques have been developed that are geared particularly towards the highly collimated topologies that form in the N-body decay of highly boosted objects [12, 13]. The LHC experiments have evaluated the potential of these methods in detailed MC simulations [14] and have tested some of the crucial assumptions in analyses of the first LHC data [15, 16, 17]. We expect that these techniques will reach maturity to provide a new window on BSM physics at the LHC and future high-energy e^+e^- colliders.

3 Results for a future linear collider

In the following we present a study of top reconstruction using the PYTHIA generator, including ISR, and a fast simulation of the detector response, for both center-of-mass energies of 500 GeV and 1 TeV. Our 500 GeV simulation study gives an overall result compatible to another result presented in this workshop, using this time a full simulation based on the ILD detector [18]. We claim therefore that the reconstruction problems that we observe at the low energy (500 GeV) are intrinsic of the event configuration and cannot be removed by an improved detector resolution.

Semi-leptonic quark decays are selected by demanding a highly energetic electron ($E_l > 20$ GeV, $|\cos\theta_l| <0.996$), missing energy ($p_{miss} > 20$ GeV) and at least 4 jets in the event. Note that the missing energy is obtained from the momentum imbalance in the 3 directions x, y, z, ignoring therefore ISR, that for $t\bar{t}$ is very small, since radiative return to the Z^0 is forbidden. It is possible in this way to obtain the full momentum imbalance (i.e. the neutrino energy) and not just its transverse component as for hadron colliders. The next step in the selection is the reconstruction of the W from the leptonically decaying top-quark. This is achieved by demanding

$$|M_{inv}(l - miss) - M_W| < 25(35) \quad \text{GeV}$$

for 500 GeV and 1 TeV, respectively, $M_W = 80.4$ GeV being the W mass. The leptonic top reconstruction is achieved by demanding

$$|M_{inv}(W - j) - M_t| < 35(60) \quad \text{GeV}$$

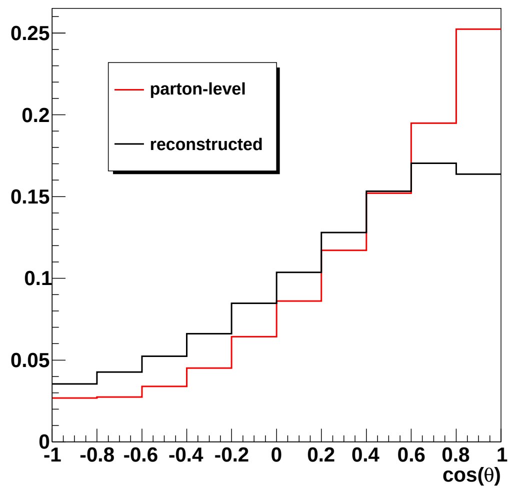
for 500 GeV and 1 TeV, respectively, $M_t = 175$ GeV being the top mass, and j a jet with $E_j > 20$ GeV and $|\cos\theta_j| < 0.996$. The jet j producing the best fit is selected as the 'b-jet' from the top semi-leptonic decay. No b-tagging requirement is imposed besides this fitting condition. The final requirement is that the total beam energy can be reconstructed from the energy of the various particles produced in the decay of the top quark, i.e.

$$|E_W + E_j - E_{beam}| < 75(200) \quad \text{GeV}$$

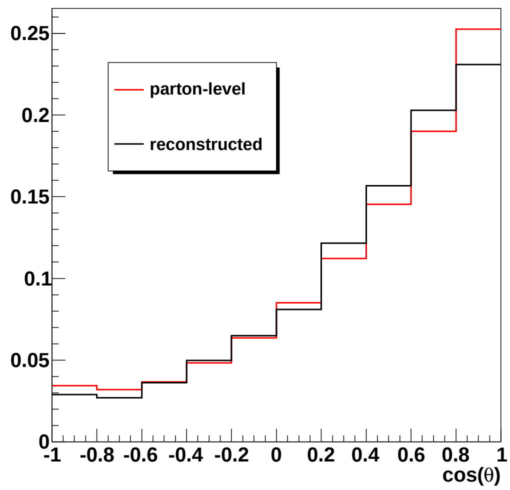
for 500 GeV and 1 TeV, respectively, E_{beam} being the beam energy of 250 (500) GeV.

Only the leptonic side of the reconstructed top is used in the analysis. The charge of the lepton can be related to the charge of the top (l^+ for top, l^- for antitop) and allows therefore the reconstruction of the scattering angle θ between the incoming e^- and the outgoing top (or between e^- and the antitop). This scattering angle (that provides the A_{FB} asymmetry) is displayed in Fig. 1a and Fig. 1b, for 500 GeV and 1 TeV, respectively.

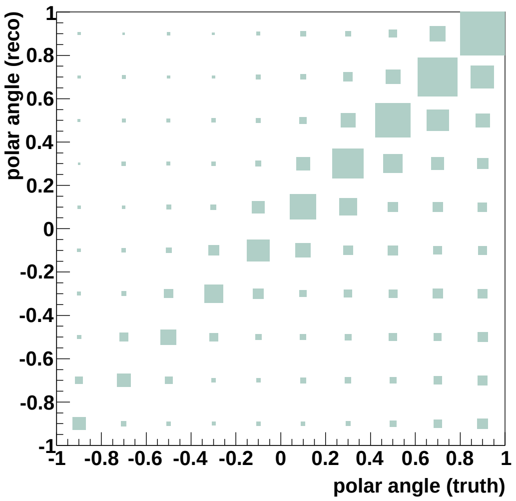
We can see that at $\sqrt{s} = 500$ GeV a very large migration in the reconstructed $\cos\theta$ distribution, leading to a reduced asymmetry of 0.22, to be compared to the partonic value of 0.40. Similar problems in mapping the reconstructed top quark direction back onto the true direction are reported by the LHC collaborations. Repeating our study for the LHC environment, we find our response matrices are in qualitative agreement with those found by ATLAS in Reference [8].



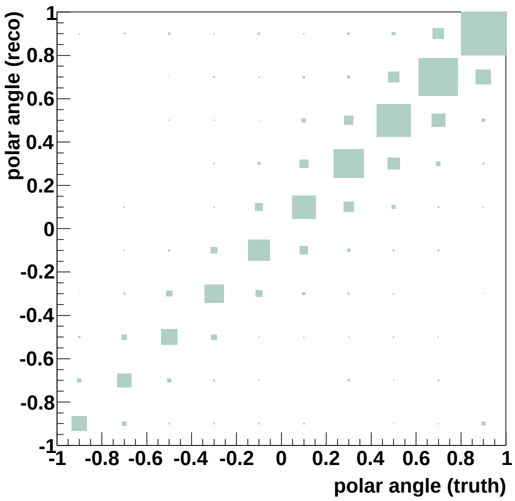
(a) 500 GeV



(b) 1 TeV



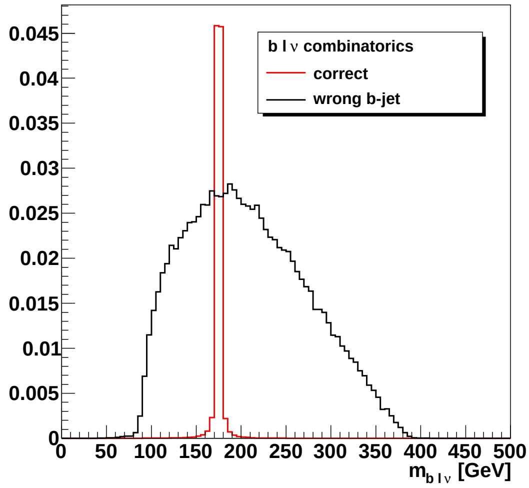
(c) 500 GeV



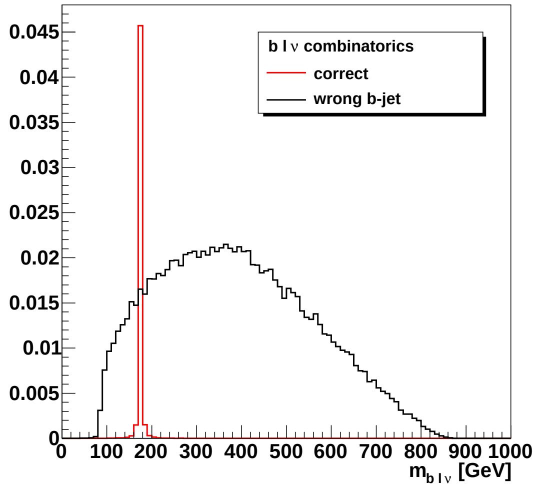
(d) 1 TeV

Figure 1: $\cos\theta$ distribution for top quark scattering at center-of-mass energies of (a) 500 GeV and (b) 1 TeV. The reconstructed distribution using a fast detector simulation is compared to the distribution obtained at the partonic level. The 2D response matrices are shown in (c) for 500 GeV and (d) for 1 TeV.

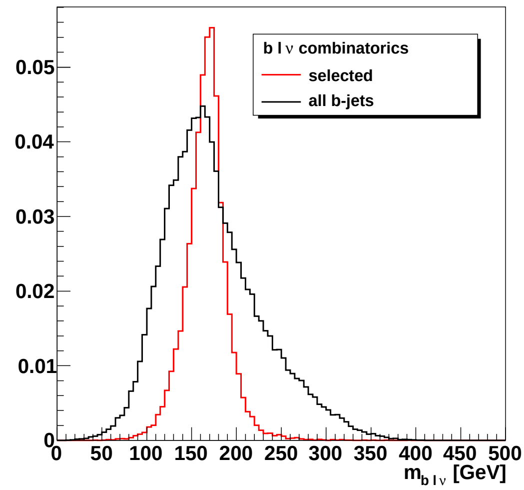
This migration effect has almost vanished at 1 TeV, where the reconstructed and partonic asymmetries are 0.52 and 0.56, respectively. In the following, we discuss the origin of this migration effect. This origin is the impossibility to select the correct b-quark from the leptonic top decay for any detector with finite resolution, as illustrated in Fig. 2a. This figure shows at parton level, and for the 500 GeV case, the reconstructed top mass using the correct b-quark and also the wrong combination. Fig. 2b shows the same result after including detector simulation. This figure shows a very large overlap between both distributions, implying a very large probability for confusing the correct and the wrong b-quarks. This probability is in fact of the order of 40%. When the wrong b-quark is selected, the direction of the reconstructed top is erratic, leading to the migration effect discussed before.



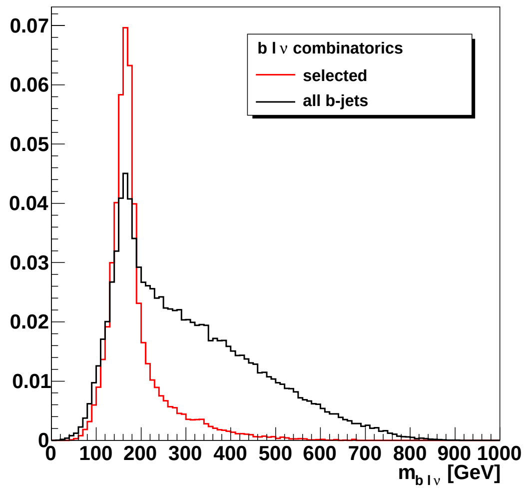
(a) 500 GeV



(b) 1 TeV



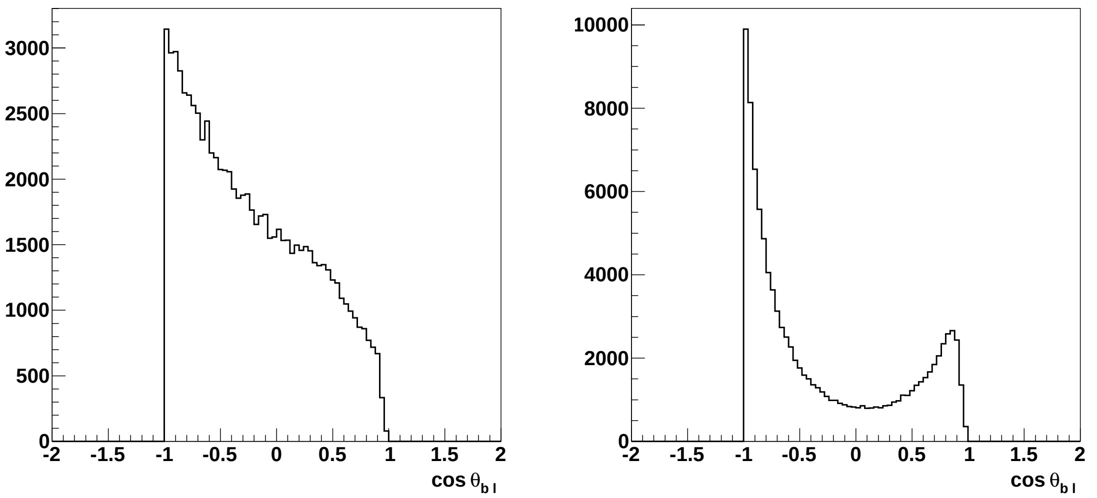
(c) 500 GeV



(d) 1 TeV

Figure 2: Reconstructed top (a,b) at parton level and (c,d) after detector simulation. In both cases the comination using the correct b-quark (red) and wrong combinatuons (black) are presented. The center-of-mass energy is 500 GeV. The same quantities, (c) and (d), are also displayed at 1 TeV.

The power of the top quark mass constraint to resolve the ambiguities increase slightly at 1 TeV, as seen in Fig. 2c and Fig. 2d. A drastic improvement is achieved using the boost of the top quarks (at 500 GeV they are nearly at rest). As a result the lepton and the correct b-quark are close together, as illustrated by Fig. 3 that shows the quantity $cos(\theta_b - \theta_l)$ at 500 GeV (a) and 1 TeV (b). A simple cut of the type $cos(\theta_b - \theta_l) > 0$ is sufficient to select the correct b-quark and therefore remove the migration effect discussed before. An improved detector resolution may have some impact in the migration effect observed at 500 GeV, as discussed in [18], where the full capabilities of the ILD detector are used. It is noted however that the migration effect is still present with this improved resolution, and is even present at the parton level.



(a) 500 GeV

(b) 1 TeV

Figure 3: $|cos(\theta_b - \theta_l)$ at 500 GeV (a) and 1 TeV (b).

4 Summary and conclusions

1) A measurement of the FB top asymmetry at ILC-1000 (or CLIC-3 TeV) is complementary in several ways to a measurement at CLIC-500, since statistical and systematic errors differ substantially, but add finally to a total value with similar uncertainty.
2) The relatively modest boost at 1 TeV is sufficient to circumvent the potentially large systematic due to ambiguities in the assignement of b-jets to top-quarks candidates.
3) These conclusions will be reinforced by repeating the analysis with full simulation and extending the number od observables to quantities like, for example, LR asymmetries.

Acknowledgements

The authors would like to thank the organizers of the LC forum for the opportunity to share these results and Franois Richard for his very helpful suggestions.

References

[1] PDG2010, K.Nakamura et al., Journal of Physics G37 (2010) 075021.
The LEP Collaborations, the LEP Electroweak Working Group, The SLD Heavy Flavour and Electroweak Working Groups, CERN-EP/2000-016, January 2000.

[2] SLD collaboration, Phys.Rev.Lett.84:5945-5949,2000.

[3] A.Djouadi, G.Moreau, F.Richard, Nucl.Phys. B773 (2007) 43.

[4] J.H.Kuhn, G.Rodrigo, Phys.Rev. D59 (1999) 054017.

[5] CDF Collaboration, Phys.Rev. D83(2011)112003.

[6] D0 Collaboration, Phys.Rev. D84(2011)112005.

[7] The CMS Collaboration CMS-TOP-11-014 [arXiv:1112.5100 [hep-ex]]

[8] The ATLAS Collaboration ATLAS-CONF-2011-106

[9] F. Coradeschi, LCWS10 workshop, Beijing (China), 2010.
M. Battaglia, LCWS11 workshop, Granada (Spain), 2011.

[10] B. Lillie, L. Randall and L. T. Wang, JHEP **0709** (2007) 074 [arXiv:hep-ph/0701166].

[11] K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D **77** (2008) 015003 [arXiv:hep-ph/0612015].

[12] A. Abdesselam *et al.*, Eur. Phys. J. C **71** (2011) 1661 [arXiv:1012.5412 [hep-ph]].

[13] A. Altheimer *et al.*, arXiv:1201.0008 [hep-ph].

[14] The ATLAS collaboration ATL-PHYS-PUB-2010-008

[15] The ATLAS collaboration ATLAS-CONF-2011-073

[16] The CMS collaboration CMS-PAS-JME-10-013

[17] The CMS collaboration CMS-PAS-EXO-11-006

[18] R.Poeschl, 'Top quark studies at 500 GeV', this workshop.