

# Top physics at high-energy lepton colliders

*Summary of TopLC15, IFIC Valencia, 30<sup>th</sup> June - 2<sup>nd</sup> July, 2015*

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## Abstract

A summary is presented of the workshop “top physics at linear colliders” that was held at IFIC Valencia from the 30<sup>th</sup> of June to the 3<sup>rd</sup> July 2015. We present an up-to-date status report of studies into the potential for top quark physics of lepton colliders with an energy reach that exceeds the top quark pair production threshold, with a focus on the linear collider projects ILC and CLIC. This summary shows that such projects can offer very competitive determinations of top quark properties (mass, width) and its interactions with other Standard Model particles, in particular electroweak gauge bosons and the Higgs boson. In both areas the prospects exceed the LHC potential significantly - often by an order of magnitude.

## 1 Introduction

Whereas hadron colliders have dominated the landscape of high-energy particle physics for well over a decade, high-energy lepton colliders feature prominently on the roadmap for the future of particle physics. Their precision physics programme forms an ideal complement to the discovery reach of the LHC.

A mature, shovel-ready project exists for a linear  $e^+e^-$  collider that can reach a center-of-mass energies from several 100 GeV to approximately 1 TeV (the International Linear Collider or ILC [1], to be hosted at the Kitakami site in Japan). Extensive R&D into high-gradient acceleration has moreover opened up the possibility of a relatively compact multi-TeV collider (Compact Linear Collider, or CLIC [2]). More recently, renewed attention has been devoted to the possibility of a large circular  $e^+e^-$  collider, the triple-LEP [3]. An  $e^+e^-$  collider with center-of-mass energy up to the  $t\bar{t}$  threshold could form the first stage of the Future Circular Collider (FCC) at CERN. In China an only slightly less ambitious project is being pursued [4], that could host a 250 GeV  $e^+e^-$  collider (CEPC) in its initial stage. A muon collider [5] is explored for a more remote future. In this report the focus is on the linear collider projects, for which detailed experimental studies have been performed. Quite often, however, conclusions apply to  $e^+e^-$  colliders in general. Wherever relevant studies are available from circular machines, we will include them in the discussion.

The case for a high-energy lepton collider rests strongly on the potential to characterize the couplings of the Higgs boson discovered in 2012 to sub-percent precision [6]. Also the potential of lepton colliders to open a complementary window on new physics (from leptophilic dark matter to sleptons) is well established [7]. The third pillar of the programme is a detailed scrutiny of the top quark [8].

The TopLC15 workshop in Valencia is the third in a series of workshops devoted to top physics at future lepton colliders <sup>1</sup>. The aim of the series is to enhance the cohesion of the global effort to understand the top physics potential of lepton collider fully. In particular, we hope the TopLC workshops bring together theorists and experimentalists. This summary report aims to provide an up-to-date reference and bibliography.

The focus of the workshop was on several measurements of top quark properties and interactions where detailed prospect studies exist, such as the mass measurement at the pair production threshold and the measurements of the top quark couplings to the Higgs boson [9] and the photon and  $Z$ -boson [10]. Sections 2, 3 and 4 present an up-to-date status report for these studies. In Section 5 we enter a less explored area, discussing recent parton-level studies of the potential of the linear collider projects to detect Flavour Changing Neutral Current (FCNC) decays of the top quark. The impact of reconstruction algorithms on the top quark physics potential is discussed in Section 6, with a focus on the reconstruction of tracks and jets. The final Section 7 presents a brief summary and outlook.

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<sup>1</sup>Previous editions were organized in the greater Paris area, by LAL Orsay and LPNHE. The fourth workshop will be held at KEK in Tsukuba, Japan, from 6-8 July 2016.

## 2 Top quark mass

The top quark mass is one of the key parameters of the Standard Model of particle physics. A precise determination enables stringent tests of the self-consistency of the theory. A precise measurement is needed to verify the relation between the top quark mass and the Higgs boson and W-boson masses predicted by the SM (see, for instance, Ref. [11]). The value of the top quark mass moreover has a strong impact on the stability of the vacuum when the Higgs potential is extrapolated to large scales [12]. In the following we present the current precision and the prospects of the complete LHC programme. We also discuss the uncertainties that affect the interpretation of the *direct* measurement of the top quark mass and alternatives pursued by the LHC experiments. We then present the ultimate precision achievable at a lepton collider that scans its center-of-mass energy through the top quark pair production threshold region. After a brief presentation of two recent theory milestones, the calculation of the NNNLO correction to the cross-section at threshold and the four-loop relation between different mass schemes, we discuss the remaining theory uncertainty. We finalize this Section with the most up-to-date prospects of the linear collider for the top quark mass determination, including realistic estimates for the theoretical and experimental systematic uncertainties.

### 2.1 LHC, state of the art and prospects

The current world average for the top quark mass based on *direct* measurements at hadron colliders have attained a precision of better than 0.5% [13]. The most precise measurements by CMS and D0 achieve 500 MeV uncertainty per measurement. After three years of operation at approximately half the design energy the ATLAS and CMS already exceed the expectations [14] drawn up before the start of the LHC.

With the large  $t\bar{t}$  samples collected at the LHC the statistical uncertainty on the measurement ceases to be relevant. The current measurements at the LHC are already dominated by systematic uncertainties, with the most important contributions coming from the uncertainties on the jet energy scale and in the modelling of the  $t\bar{t}$  signal. It is therefore far from straightforward to draw up reliable prospects for the future evolution of the uncertainty. Expectations range from a pessimistic 500 MeV [15] after the complete LHC programme to 200 MeV [16]. These estimates explicitly exclude the theoretical uncertainty from the total error budget. An additional uncertainty must be added to account for the ambiguity in the interpretation of the top mass parameter in the Monte Carlo generators in terms of a rigorous field-theoretical mass scheme, as discussed in the next section.

Alternative mass determinations at hadron colliders include a determination of the top quark mass from a fully corrected cross-section measurement. The cross-section measurements by ATLAS and CMS in the di-lepton ( $e\mu$ ) channel on the 7

and 8 TeV data [17, 18] reach a precision of approximately 4% and have a negligible dependence on the (MC) mass assumed in the correction of the acceptance. The pole mass is extracted by comparing the observed cross-section to the NNLO calculation of Ref. [19] with NNLL resummation, which reduces the scale uncertainty on the cross-section to the level of 3%. An uncertainty of 1.7–1.8% is assigned to the cross-section to account for the uncertainty in the LHC beam energy. The value of the top quark pole mass that is determined is in agreement within the uncertainty of approximately 2 GeV with the result of the *direct* mass measurement. Further progress is expected from improved PDF fits.

Adrian Irlles presented the result of a new pole mass measurement on 7 TeV LHC data by ATLAS [20], where the mass is extracted from the differential cross-section in top quark pair production in association with a hard jet, following the method proposed in Ref. [21]. The result is again in good agreement (within an uncertainty of 2.3 GeV) with the other determinations. As this measurement is not limited by the systematic uncertainty of relating the MC mass to the top quark mass, an analysis of the 8 TeV and 13 TeV data sets can bring a strong improvement of the precision.

## 2.2 Top quark mass, theory and interpretation

The most precise measurements of the top quark mass at hadron colliders extract the top quark mass by comparing distributions generated using Monte Carlo (MC) generators to the data. In the standard interpretation the MC mass parameter is identified with the pole mass. This interpretation has an ambiguity that is estimated to be  $\mathcal{O}(1 \text{ GeV})$  [15, 22, 23, 24, 25]. The uncertainties cited by the experiments include contributions for the modelling of  $t\bar{t}$  production and decay, non-perturbative corrections, colour reconnection, etc. At the precision of today’s measurements these may adequately cover the intricacies in the standard interpretation of the top quark mass, but for progress towards a 200 MeV top quark mass measurement a more sophisticated treatment seems required.

Several theory groups are performing studies to elucidate the relation between the MC mass parameter and field theory mass definitions [24, 25]. At the workshop Andre Hoang showed preliminary results from a study that compare the predictions of mainstream Monte Carlo generators (such as Pythia [26]) to hadron-level QCD calculations. The latter are based on the work in Refs. [27, 28, 29] in Soft Collinear Effective field Theory (SCET) and account for perturbative and non-perturbative effects. A comparison of both predictions yields a relation between the mass parameter of the Monte Carlo generator and the quark mass in the calculation. The distributions under study include the thrust in  $e^+e^- \rightarrow b\bar{b}$  and  $e^+e^- \rightarrow t\bar{t}$  pair production at different center-of-mass energies. These preliminary results indicate that the relation between MC mass and field theoretical top quark mass definitions may be established to a precision of 500 MeV for bottom quarks and better than 1 GeV for top quarks.

Alternative measurements, such as those discussed in the previous section, form an independent cross-check of the interpretation of the *direct* measurement, provided they can achieve sub-GeV precision.

### 2.3 The $e^+e^- \rightarrow t\bar{t}$ production threshold: theory status

The top quark pair production threshold at electron-positron colliders has been identified long ago [30] as a key element in the programme of high-energy lepton colliders. The position of the threshold is related to the top quark mass  $m_t$ , the slope of the rise in cross section around the threshold reflects its natural width. The cross section in the threshold region is moreover sensitive to the top quark Yukawa coupling and the strong coupling constant  $\alpha_s$ . A precise measurement of the shape of the sharp rise of the cross-section around  $\sqrt{s} = 2m_t$  can provide competitive measurements of these parameters.

To take advantage of the potential of a threshold scan precise predictions of the threshold shape are crucial. As QCD bound-state effects become sizeable, the calculations must be organized as a combined perturbative series in terms of the top quark velocity and  $\alpha_s$ . The state-of-the-art fixed-order NNNLO calculation [31] presented at the workshop by Martin Beneke and Yuichiro Kiyo achieve a precision of approximately 3% on the cross section. More importantly, when using the PS or 1S mass schemes, the peak position shows excellent convergence: the NNNLO correction represents a 65 MeV shift. Higgs boson exchange [32], the known non-resonant contribution at NLO [33] and electromagnetic corrections are included in the NNNLO description, but not yet the known electro-weak corrections.

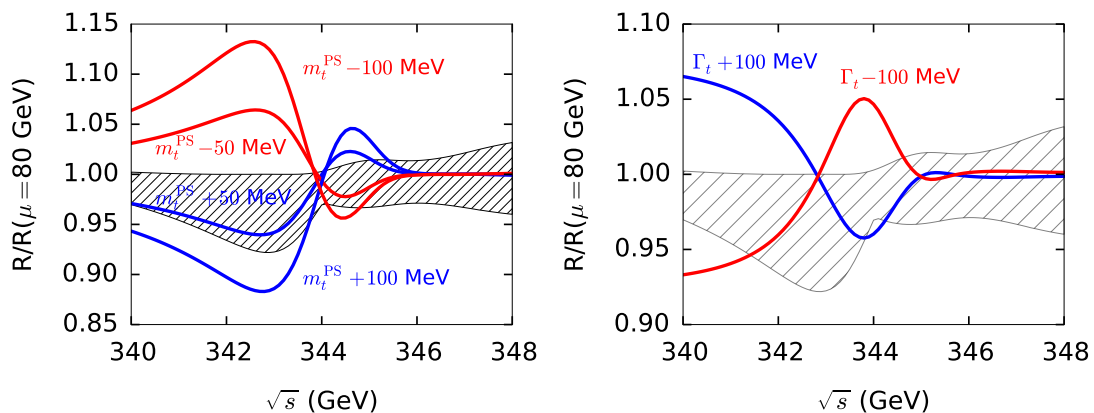


Figure 1: The uncertainty on the  $t\bar{t}$  threshold shape at NNNLO precision from Ref. [31]. In the leftmost plot the change in the shape due to a shift of the top quark mass is superposed, in the rightmost plot the effect of a change in the top quark width.

The uncertainty band on the NNNLO calculation is presented in Fig. 1. From a comparison of the width of the error band with the variation of the top quark mass by 50 MeV one can estimate that the systematic uncertainty on the top quark due to this uncertainty is of the order of tens of MeV and likely smaller than 50 MeV<sup>2</sup>. A rigorous propagation of the uncertainty in a realistic fit is to be performed in the near future.

In Ref. [34] Hoang and Stahlhofen have performed a renormalization group improved next-to-next-to leading logarithmic (NNLL) calculation of the threshold shape in the framework of velocity Non-relativistic QCD (vNQCd) which also accounts for the resummation of logarithms of the top quark velocity. A combination of the NNLL renormalization-group improved results with the NNNLO fixed-order calculation has the potential to further reduce the theoretical uncertainty.

A description of the QCD effects at the pair production threshold with NLO accuracy is included in recent versions of the matrix element generator WHIZARD [35]. The model *tt threshold* allows for the generation of fully differential distributions. In the  $\sqrt{s}$  region immediately above the threshold the bound-state QCD effects gradually die out. For a reliable estimation of the cross-section in this region the threshold calculation must be matched to the continuum predictions. Preliminary results from this effort were presented in the contribution by Jürgen Reuter.

## 2.4 Lepton collider prospects

A threshold scan, a scan of the center-of-machine energy of the machine to map out the top quark pair production threshold, is part of the programme of all electron-positron collider projects with sufficient energy reach. Typically, a ten-point scan is envisaged in a narrow (10 GeV) region around the position of the would-be 1S resonance. Mostly, equidistant points are assumed with approximately 10 fb<sup>-1</sup> per scan point. A threshold scan with these characteristics can be performed in a fraction of a year.

The shape of the threshold region is affected by several effects, such as Initial State Radiation (which is equal for all machines) and the beam energy spread (where each machine has its own characteristic profile). The resulting threshold shapes of three  $e^+e^-$  projects are shown in Fig. 2. Even if the 1S peak is washed out to different degrees, a one-parameter fit of the top mass to the threshold shape (ten points, 10 fb<sup>-1</sup>each. no polarization) yields a quite similar statistical accuracy of approximately 20 MeV for all projects [36]. These difference are small compared to several of the systematic uncertainties evaluated in the next Section, such that the specific profile of each machine has a negligible impact on the precision that can be reached.

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<sup>2</sup>In agreement with the estimate based on the NNLL renormalization group improved calculations of Ref. [34].

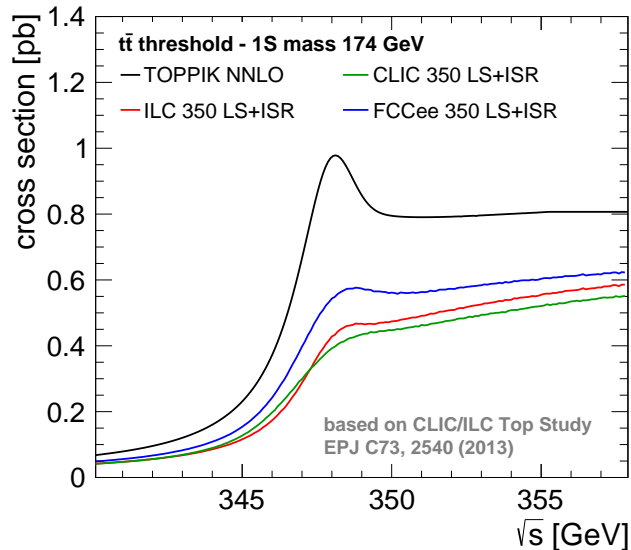


Figure 2: Realistic  $t\bar{t}$  threshold shapes for several  $e^+e^-$  collider projects. The theory curve from the NNLO calculation available in the TOPPIK code is folded with the luminosity spectrum (LS), which includes an estimate of the beam energy spread and the effect of beamstrahlung in the linear collider projects, and Initial-State-Radiation (ISR).

The statistical uncertainty on the mass depends on the number of fit points and on the number of floating parameters. An optimization of the location of the fit points can save considerable running time. In a one-parameter fit of the threshold shape one achieves identical precision on the top quark mass with three wisely chosen points (i.e.  $30 \text{ fb}^{-1}$ ) as with the full ten-point scan. The situation is more complex as soon as more than one parameter is floated. The uncertainty increases by a factor three when, apart from the mass, the top quark width and the strong coupling constant  $\alpha_s$  are extracted.

## 2.5 Systematic uncertainties

Several groups have evaluated systematic uncertainties on the top quark mass extraction. A number of experimental sources of uncertainty, including the impact of non- $t\bar{t}$  background, are evaluated in Ref. [37]. The largest contribution is expected to stem from the uncertainty in the beam energy, where a residual uncertainty of 1 part in 10.000 yields a 30 MeV uncertainty in the top quark mass. The uncertainty due to an imperfect knowledge of the luminosity spectrum was revised based on the work of Ref. [38] and is expected to be of the order of 10 MeV [39]. Ref. [33] has

shown that the non-resonant contribution is approximately constant: its impact can be reduced to less than 30 MeV with a simple correction [40]. While a complete and systematic evaluation of the systematics is still missing, this patchwork of results yields an experimental systematic uncertainty of the order of 40 MeV.

The theory uncertainty on the top quark mass has two main contributions. The theory uncertainty in the NNNLO description of the threshold shape discussed in the previous Section (see Fig. 2) is expected to be below 50 MeV. A full-fledged fit that includes the uncertainty band has been performed since the workshop and indeed yields a theory uncertainty of approximately 45 MeV [36]. An additional uncertainty in the conversion of the threshold mass to the  $\overline{MS}$  scheme is discussed in the next Section.

## 2.6 Conversion to the $\overline{MS}$ mass

Another highlight of the theory effort is the calculation by Marquard et al. [41] of the conversion between different mass schemes to four loops. The translation of the threshold (1S or PS) mass obtained from the fit to the threshold shape to a short distance mass such as the  $\overline{MS}$  mass is an intrinsic part of the measurement procedure. In the three-loop conversion the theory uncertainty in this step was in fact the dominant uncertainty on the mass (approximately 100 MeV). With the addition of the fourth loop the scale uncertainty is reduced to the level of 10 MeV. A non-negligible parametric uncertainty due to the uncertainty of the strong coupling constant remains, however.

The uncertainty in the current (2014) world average [42] for  $\alpha_s$  at the Z boson mass is 0.0006. Today, the uncertainty in the conversion therefore amounts to approximately 40 MeV. In a somewhat unusual turn of events the  $\alpha_s$  uncertainty is expected to increase by a factor two [43] in the next world average. The potential for future improvement is somewhat uncertain [3, 44]. For a detailed discussion the reader is referred to Ref. [43] and references therein.

The strong coupling constant affects the extraction of the top quark  $\overline{MS}$  mass from the threshold in the standard scheme in two ways:  $\alpha_s$  plays a role in the prediction of the line shape that is used to extract a threshold mass (1S or PS mass, a larger value of  $\alpha_s$  leads to a larger prediction for the cross section) and in the conversion of the threshold mass to the  $\overline{MS}$  mass. The threshold shape itself provides a measurement of  $\alpha_s$ , but that constraint is somewhat weaker than the world average. In Figure 3 the precision on the  $\overline{MS}$  mass  $\overline{m}_t(\overline{m}_t)$  is shown as a function of the uncertainty of the  $\alpha_s$  prior. The contributions from the uncertainty on the line shape and the parametric uncertainty in the mass conversion are added in quadrature. A coherent use of  $\alpha_s$  in the mass fit and conversion leads to a partial cancellation between both terms, such that the curve in Figure 3 should be considered as conservative upper limit.

At the workshop Yuichiro Kiyo showed that the shifts in the peak position due to



scale variations are reduced when the NNNLO calculation is performed in the  $\overline{MS}$  scheme than with the PS mass. This demonstrates that indeed some cancellations occur. A direct extraction of the  $\overline{MS}$  mass may then be interesting [45]. A detailed study of both schemes in a realistic environment, and with a coherent treatment of the  $\alpha_s$  uncertainty, is encouraged.

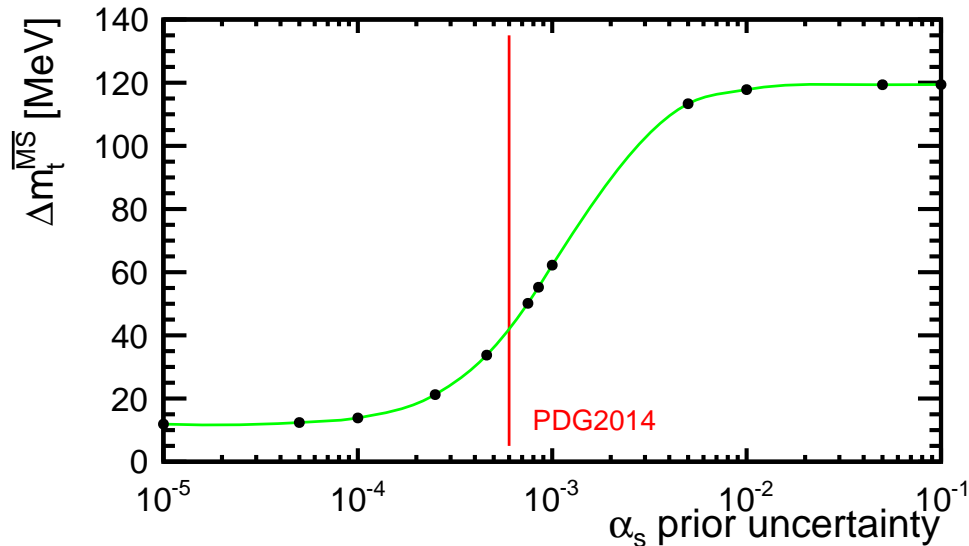


Figure 3: The uncertainty on the  $\overline{MS}$  mass of the top quark obtained from a threshold scan as a function of the uncertainty on the value of the strong coupling constant  $\alpha_s$  that is used as a prior in the fit and the conversion of the threshold mass to a short-distance mass. Courtesy of M. Perello and M. Vos.

## 2.7 Mass measurement in the continuum

Mass measurements in continuum  $t\bar{t}$  production at center-of-mass energies above the threshold are interesting for a number of reasons. First, the threshold scan is not scheduled as the first step of ILC or CLIC programme. Even if the measurement in the continuum is ultimately superseded by the threshold scan it may provide the best top quark mass at the time. The measurement of the top quark mass at a scale different from the  $t\bar{t}$  threshold may provide access to the running of the top quark mass.

The full-simulation study of Ref. [37] establishes the statistical precision of the top quark mass measurement using the *direct* measurement in the ILC operated at 500 GeV with an integrated luminosity of  $500 \text{ fb}^{-1}$ . As the mass extraction is based on

Monte Carlo templates, as it is at the LHC, the interpretation in a rigorously defined mass scheme remains problematic. By the same token, a precise measurement at a lepton collider may prove to be a valuable tool to elucidate the interpretation of this top quark mass measurement.

At the workshop an alternative method was presented by Marca Boronat and Pablo Gomis, that extracts the top quark mass from the  $s'$  ( $s' = s(1 - 2E_\gamma/\sqrt{s})$ ) distribution in  $t\bar{t} + \gamma$  or  $t\bar{t} + \text{jet}$  production. The rate of energetic ISR photons (and FSR gluons) depends strongly on the top quark mass. A comparison of a precise measurement of the differential cross-section to a fixed-order calculation allows for a mass extraction with a rigorous interpretation in the mass scheme of choice. Preliminary, parton-level results indicate that a precision of 100 MeV may be feasible with the  $t\bar{t} + \gamma$  analysis using  $500 \text{ fb}^{-1}$  at 380 GeV. At higher energy larger samples are required: the same precision is reached only after accumulating  $4000 \text{ fb}^{-1}$  at 500 GeV. The statistical uncertainty of the  $t\bar{t} + \text{jet}$  analysis is better than this, but a detailed study of the identification of the additional jet is required.

At lepton colliders with a center-of-mass energy beyond 500 GeV the top quark mass can be extracted from the shape of boosted top quark jets, as proposed in Refs. [46, 47].

## 2.8 Summary

The possibility of lepton colliders to scan their center-of-mass energy through the  $t\bar{t}$  production threshold is one of the most exciting prospects of such a machine. The threshold scan allows for a top quark mass measurement with a statistical uncertainty of order 10 MeV and a total uncertainty below 50 MeV. Further progress in theory and  $\alpha_s$  may improve these prospects. Measurements of the mass using data sets acquired at center-of-mass energies well above the threshold can reach a statistical precision of better than 100 MeV. New methods that maintain a clean interpretation are being developed.

## 3 Top quark couplings to the Higgs boson

The top quark and the Higgs boson form a *dream couple* for precision measurements. The heaviest particle in the Standard Model, the top quark, is tightly coupled to the Higgs boson with a Yukawa coupling of the order of unity. As the top quark is one of the main drivers of the instability of the Higgs boson mass it is quite conceivable that the interaction between the top quark and the Higgs boson is intimately connected to new physics. Many extensions of the Standard Model indeed reserve a special role for this couple, in the form of top quark partners, a composite top and Higgs sector, etc. A direct measurement of the coupling of these two particles is therefore desirable.

### 3.1 LHC status and prospects

Gluon fusion Higgs production at the Large Hadron Collider proceeds primarily through a top quark loop. The same is true for the decay to a photon, one of the most prominent channels behind the discovery of the Higgs boson in 2012. The ATLAS and CMS experiments therefore have good indirect sensitivity to the top quark coupling to the Higgs boson. In the 7-parameter fit that is currently the de facto standard, the couplings to up- and down-type quark are allowed to vary independently, but the couplings of the quarks of a given type (i.e., down-type quarks d,s and b, or up-type quarks u,c and t) are assumed to be identical. These fits achieve a precision of approximately 20%, which is expected to improve to the level of 7-10% [6].

A more direct probe of the top quark Yukawa coupling is found in the associated production of a top quark pair and a Higgs boson. The production cross section is nearly 1 pb at  $\sqrt{s} = 13$  TeV, significantly smaller than top quark pair production (nearly 1 nb) and other Higgs boson production processes (up to 100 pb). After run I of the LHC the ATLAS and CMS experiment have reported first evidence for  $t\bar{t}H$  production. Combining all decay channels and the two experiments, the significance is approaching the  $5\sigma$  threshold. The best fit signal strength  $\mu_{t\bar{t}H} = \sigma/\sigma_{SM} = 2.3^{+0.7}_{-0.8}$  of the ATLAS + CMS combination in Ref. [48] is somewhat larger than in the Standard Model.

In a complex final state such as  $t\bar{t}H$ , with large systematics associated to the modelling of the background, a prediction of the LHC potential is prone to large uncertainties. The Snowmass Higgs report [6] expects the direct measurement of the top Yukawa coupling in  $t\bar{t}H$  production at the LHC to reach a precision of 14-15% after  $300 \text{ fb}^{-1}$  at  $\sqrt{s} = 14$  TeV. The full LHC programme, including the luminosity upgrade, could reduce this to 7-10% (depending on the assumptions on the evolution of systematic uncertainties) after accumulating  $3000 \text{ fb}^{-1}$ .

### 3.2 Lepton Collider prospects

At electron-positron colliders  $t\bar{t}H$  production proceeds through the s-channel, with the Higgs boson radiated off one of the top quarks (i.e.  $e^+e^- \rightarrow Z/\gamma^* \rightarrow t\bar{t}H$ ). The cross section of Figure 4 displays a sharp threshold at approximately 500 GeV. At the threshold, production is significantly enhanced by QCD bound-state effects [49]. The result is a broad maximum that extends to about a TeV. At linear colliders, with an instantaneous luminosity that grows approximately linearly with the center-of-mass energy, the optimum energy is typically somewhat higher than the maximum of the cross section.

Philipp Roloff reviewed the ILC and CLIC studies of  $t\bar{t}H$  production. The two projects have performed full-simulation studies [9, 50, 51] at several center-of-mass energies, from as low as 500 GeV to 1.4 TeV. Several final states are analysed. The jet

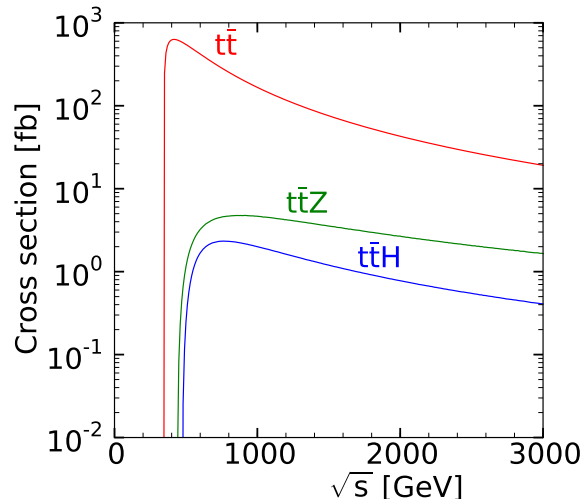


Figure 4: The cross section as a function of the center-of-mass energy of lepton colliders. The three curves correspond to top quark pair production (the upper, red curve) and to associated production of a top quark pair with a  $Z$ -boson (the central, green curve) or a Higgs boson (the lowest, blue curve).

multiplicity and combinatorics ranges from moderate (i.e.  $e^+e^- \rightarrow t\bar{t}H \rightarrow l^+\nu b l^-\bar{\nu}\bar{b}\bar{b}$  with four b-jets) to extremely challenging (i.e.  $e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}'bq''\bar{q}'''WW \rightarrow 10$  jets). According to the ILC studies a precision of 18% can be achieved with  $500 \text{ fb}^{-1}$  at  $\sqrt{s} = 500 \text{ GeV}$ . After the complete programme, which includes  $4000 \text{ fb}^{-1}$  at  $\sqrt{s} = 500 \text{ GeV}$ , the precision improves to 6%. Operation of the ILC at  $\sqrt{s} = 550 \text{ GeV}$  (with the same luminosity) would improve the prospects considerably: the  $e^+e^- \rightarrow t\bar{t}H$  cross section increases by a factor of nearly four and the statistical precision by a factor two (i.e. to 9% after  $500 \text{ fb}^{-1}$  and 3% after the nominal programme). At still higher energy there are several competing effects (cross section, instantaneous luminosity, experimental response). The expected precision after  $1 \text{ ab}^{-1}$  at 1 TeV [9] or  $1.5 \text{ ab}^{-1}$  at 1.4 TeV in CLIC [52, 50, 51] turns out to be very similar, with an uncertainty on the Yukawa coupling of approximately 4%.

The linear collider prospect studies have so far been limited to extractions of the Yukawa coupling from the total cross section for  $t\bar{t}H$  production. More sophisticated analyses may find better constraints by analyzing differential distributions. These may also provide more insight into the potential for a determination of other properties of the Higgs boson (for instance its CP structure [54]).

Table 1: The expected precision on the top quark Yukawa coupling extraction from the cross section for associated production of a top quark pair with a Higgs boson. For the LHC measurement at  $\sqrt{s} = 8$  TeV the value for  $\mu_{t\bar{t}H}$  is given, the ratio of the measured associated production rate and the Standard Model prediction.

Collider	LHC			ILC			CLIC
$\sqrt{s}$ [TeV]	8	14	14	0.5	0.55	1	1.4
$\int L$ [fb $^{-1}$ ]	20	300	3000	500 (4000)	500 (4000)	1000	1500
source	[48]	[8]	[8]	[53]	[53]	[9]	[52, 50, 51]
precision [%]	$\mu = 2.3_{-0.6}^{+0.7}$	14-15	7-10	18 (6)	9 (3)	4	4

### 3.3 Yukawa coupling from a $t\bar{t}$ threshold scan

The top quark pair production process is sensitive to the exchange of a Higgs boson between the top and anti-top quark. According to Ref. [55] this leads to a 9% effect on the cross section, that is approximately independent of the center-of-mass energy in the vicinity of the threshold. A precise measurement of the cross section then allows for an extraction of the Yukawa coupling. In Ref. [55] the top quark properties are extracted in a simultaneous fit of the top quark mass, the top quark width and the Yukawa coupling to several distributions (cross section,  $A_{FB}$ , top quark momentum) in the usual ten-point threshold scan. The fit yields a statistical uncertainty on the Yukawa coupling of 4.2% (assuming two different polarizations).

The authors of Ref. [32] scrutinize the theory uncertainty of this measurement. A propagation of the current theory uncertainty would yield an uncertainty on the Yukawa coupling of approximately 30%. (ignoring the parametric error due to the uncertainty in the strong coupling constant  $\alpha_s$ ). Further progress in theory is therefore required to fully take advantage of the statistical power of the threshold scan. In the words of Ref. [32] “once theoretical uncertainties are taken into account, it is unlikely that such a high precision [i.e. 4.2%] can be achieved” in practice. That said, the extraction of the top quark Yukawa coupling from the threshold scan remains an interesting possibility, that should be pursued. This is particularly true for circular machines, where the  $t\bar{t}$  threshold may be accessible if a large enough ring is built, while the  $t\bar{t}H$  production process seems out of reach. In that case the threshold scan provides the most direct access to the top quark Yukawa coupling.

### 3.4 Summary

The top quark Yukawa coupling can be determined to 4% statistical uncertainty, at the  $t\bar{t}$  production threshold. The total uncertainty of this measurement is expected to be approximately 20%, dominated by the uncertainty in the cross section in the threshold region. Observation of the associated production of a top quark pair with

a Higgs boson is possible at lepton colliders with a center-of-mass energy greater than 500 GeV. In the nominal luminosity scenarios ILC and CLIC can provide a very competitive precision of approximately 4%. This direct extraction of the top quark Yukawa coupling thus approaches (but does not quite reach) the precision of the constraint on the top quark Yukawa coupling that can be obtained indirectly in a seven-parameter fit with  $\kappa_u = \kappa_c = \kappa_t$ .

## 4 Top quark electro-weak couplings

The measurement of the couplings of quarks to neutral electro-weak gauge boson at lepton colliders has proven to be a powerful probe of new physics. Tight constraints on extensions of the Standard Model can be derived from the precision measurements of the  $Zb\bar{b}$  coupling at LEP and SLD. The study of the top quark pair production process in  $e^+e^-$  collisions finally extends this precision programme to the top quark sector.

### 4.1 Impact of BSM physics

The couplings of the top quark to the  $Z$ -boson and the photon are very sensitive to effects from massive unknown particles. A precise characterization of the  $Zt\bar{t}$  vertex is therefore a powerful handle to discover new physics at a scale well beyond the direct reach of the machine, or to constrain extensions of the Standard Model. The possible impact of several new physics scenarios is illustrated in Fig. 5, that was shown by Stefania de Curtis in her overview of composite Higgs models and their imprint on top physics. Large deviations - up to tens of % - are allowed in the left-handed and right-handed coupling of the top quark to the  $Z$ -boson. The large, purple markers indicate several models with extra spatial dimensions collected in Ref. [56]. The cloud of smaller, black markers correspond to different realizations of the model of Ref. [57].

The sensitivity that can be gained through the study of associated production of a top quark pair with a  $Z$ -boson at the LHC is indicated by the large shaded ellipse, following the study of Ref. [58]. The much tighter constraints from lepton colliders is indicated by the small ellipses at the origin. The estimates for the experimental studies from Refs. [10, 58] are detailed in the following sections.

### 4.2 LHC status and prospects

Hadron colliders gain sensitivity to the couplings of the top quark to neutral electro-weak gauge bosons through the study of the associated production processes  $pp(p\bar{p}) \rightarrow t\bar{t}Z$  and  $pp(p\bar{p}) \rightarrow t\bar{t}\gamma$ . The production cross sections for these processes have proven to be prohibitively small at the Tevatron. At the LHC the Standard Model predicts

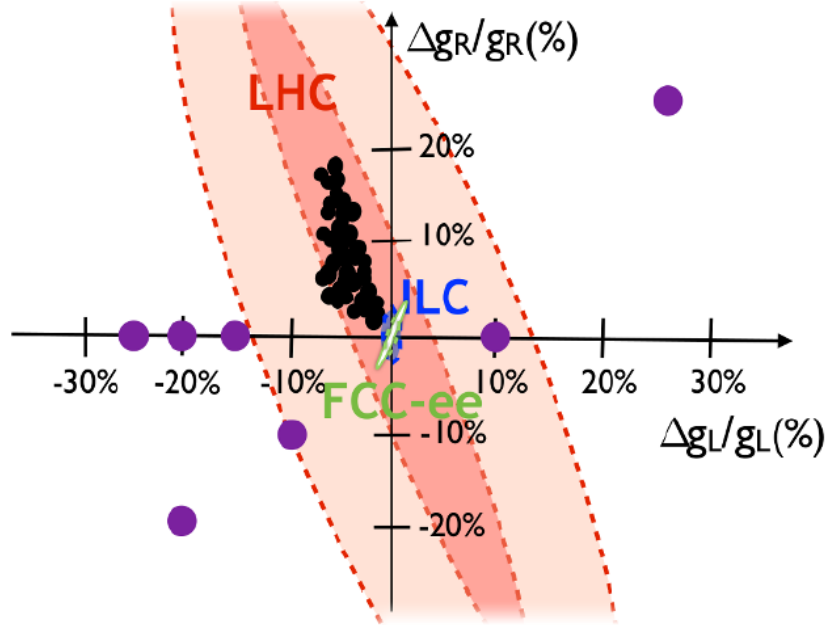


Figure 5: Deviations from the SM predictions of the left-handed and right-handed couplings of the top quark to the  $Z$ -boson in several BSM scenarios. The large, purple markers indicate several models with extra spatial dimensions collected in Ref. [56]. The cloud of smaller, black markers correspond to different realizations of the model of Ref. [57]. The experimental prospects are discussed in the text.

cross sections of order 100 fb. Indeed, after Run I of the LHC at 7/8 TeV the ATLAS and CMS experiments have isolated the signal of both processes (and of the  $pp \rightarrow t\bar{t}W$  process) with a significance of greater than  $5\sigma$  [59, 60, 61, 62]. The first measurements of the production rates are in good agreement with the Standard Model expectations. CMS has taken advantage of this observation to present the first preliminary limits on the top quark couplings to the  $Z$ -boson.

Many measurements have been performed of further electro-weak processes involving top quarks and the  $W$ -boson, such as single top quark production, and top quark decay ( $t \rightarrow Wb$ ). The interpretation of all measurements in a global fit to a complete set of dimension-6 operators related to the top sector is taking off [63, 64, 65, 66, 67]. The results of Ref. [65] include (still weak) limits on electro-weak operators, even if they are not yet fully incorporated into the global fit framework.

While the early observation of the associated production processes bodes well for the remainder of the LHC programme, current constraints are quite weak. So far, the LHC collaborations have refrained from presenting prospects for the sensitivity of

these measurements in Run II and after a luminosity upgrade of the LHC. Therefore, the results of Ref. [58] remain a reference. Recent work by Röntsch and Schulze [68] shows that inclusion of the NLO correction for the  $t\bar{t}Z$  production process reduces the uncertainties by 25–40%. Assuming a residual theoretical uncertainty of 15% at NLO they estimate that with  $300 \text{ fb}^{-1}$  of data at 13 TeV the vector and axial couplings can be constrained to  $C_V = 0.24_{-0.85}^{+0.39}$  and  $C_A = -0.6_{-0.18}^{+0.14}$  at 95% confidence level (the central values are set to the SM prediction).

### 4.3 Status of SM predictions

Predictability is a key ingredient of the precision physics programme of lepton colliders. The rate of the  $e^+e^- \rightarrow Z/\gamma^* \rightarrow t\bar{t}$  process is predicted with %-level precision already today (see Ref. [69] and references therein). Calculation of further orders in  $\alpha_s$  can bring the QCD corrections to the per-mil level. This should be compared to the uncertainty of approximately 4% on the  $t\bar{t}$  cross section at the LHC [19].

At the workshop Nhi Quach presented the status of the ongoing effort of the GRACE collaboration to determine higher-order electro-weak corrections to top quark pair and  $t\bar{t}\gamma$  production at lepton colliders with polarized beams [70, 71]. The EW correction is sizeable not only on the total cross section, but can also affect differential results, such as the forward-backward asymmetry. Using the narrow-width approximation the EW corrections can be determined also for the  $e^+e^- \rightarrow t\bar{t} \rightarrow W^+bW^-\bar{b}$  including top quark decays.

To accommodate for NLO QCD corrections, the WHIZARD generator uses external virtual matrix element from one-loop providers, while providing real radiation and subtraction terms for a finite integration internally. Processes relevant for top physics that have been scrutinized already are  $e^+e^- \rightarrow t\bar{t}$  and  $e^+e^- \rightarrow t\bar{t}h$  and some the  $2 \rightarrow 3$ ,  $2 \rightarrow 4$ ,  $2 \rightarrow 5$  and  $2 \rightarrow 6$  processes that arise when the decays are included (i.e.  $tWb, WbWb, WbWbh, bb\nu\nu$ ). In the context of this summary, the WHIZARD generator provides a description of the full  $e^+e^- \rightarrow W^+bW^-\bar{b}$  process, including diagrams with a single top quark and diagrams without  $Wb$  resonance, at Next-to-Leading-Order in QCD [72]. The integration of this calculation in a matrix element generator allows for evaluation of arbitrary differential distributions and a (POWHEG-)matching to the parton shower. The latter is again provided in WHIZARD for arbitrary processes.

### 4.4 Linear Collider prospects

At lepton colliders running well above the top quark pair production threshold the dominant top quark production process is  $e^+e^- \rightarrow Z/\gamma^* \rightarrow t\bar{t}$ . With the decay  $t \rightarrow Wb$ , and  $W \rightarrow q\bar{q}'$  or  $W \rightarrow l\nu$  this is indeed the dominant six-fermion process.



The potential for the measurement of the CP conserving form factors of the  $t\bar{t}Z$  and  $t\bar{t}\gamma$  vertices is well established by studies that include a full simulation of the detector response in a realistic environment [10] at the ILC operated at 500 GeV. A precise measurement of the cross section and the forward-backward asymmetry for data taken with  $e_L^-e_R^+$  and  $e_R^-e_L^+$  polarization allows to constrain the vectorial and axial form factors of the  $Z$ -boson and photon to sub-% precision [10], exceeding the expected precision of the LHC by an order of magnitude or more. The potential remains excellent at energies closer to the pair production threshold. Only the sensitivity to the  $F_{1A}$  form factor is degraded considerably due to the reduced boost of the top quarks.

Roman Pöschl presented preliminary results from the IFIC-LAL team for CP violating couplings. These can be extracted from the asymmetries in observables proposed by Bernreuther et al. [73, 74] (in lepton+jets events observables are used that are based on the directions of the charged lepton, the recoiling hadronic top system and the incoming electron beam). Experimental uncertainties on these observables are expected to be smaller than the statistical uncertainty after collecting  $500 \text{ fb}^{-1}$ , thus validating the prospects of %-level determinations of the real and imaginary parts of  $F_{2A}$  derived at parton-level from the TESLA TDR [75] study [76].

Alternative approaches to the measurement of top quark couplings are being pursued by several groups [71, 77]. Both groups have presented promising results in parton-level studies, where they show that a comparison of the observed final state to the full matrix element can simultaneously constrain all form factors to good precision.

## 4.5 Summary

The couplings of the top quark to the  $Z$ -boson and photon are a flagship measurement of any lepton collider that is able to produce top quark pairs. The sub-% precision on anomalous couplings yields sensitivity to new physics at scales well beyond the direct reach of the machine. The top quark pair production process moreover presents a sensitive probe for CP violation in the top quark sector.

## 5 Exotic top quark decays

The potential of hadron colliders for the search for exotic flavour-changing neutral current decays of the top quark is well established (for a recent overview see Ref. [8]). The prospects of high-energy lepton collider experiments are much less explored. The rate of top quark pair production clearly favours the LHC. It is therefore expected that for decays where the final state presents distinctive signatures that are readily spotted among the large backgrounds the LC projects are not competitive. They can,

however, provide quite competitive limits in some cases. Lepton colliders offer the possibility to study the FCNC coupling also in production (i.e.  $e^+e^- \rightarrow Z/\gamma^* \rightarrow t\bar{q}$ ). A second advantage is the much cleaner environment (lower background rates, better detector performance). This may give the LC a clear advantage if the top quark decays to final states with less distinctive features. In the following we evaluate one example, the decay  $t \rightarrow cH$ , followed by the dominant decay  $H \rightarrow b\bar{b}$ , in some detail.

## 5.1 FCNC top decays in two Higgs doublet models

In the Standard Model FCNC top decays are strongly suppressed by the GIM mechanism and the CKM matrix. Typical branching fractions for  $t \rightarrow Zq$ ,  $t \rightarrow gq$ ,  $t \rightarrow \gamma q$  and  $t \rightarrow Hq$  are of the order  $10^{-15} - 10^{-12}$ . In extensions of the Standard Model these branching fractions can be much enhanced and may be detectable at collider experiments. Scenarios can be found in the most popular BSM families (supersymmetry, models with additional spatial dimensions), where the branching fractions for these decays is enhanced by orders of magnitude. In the models considered in Ref. [8] the decay the FCNC branching fraction is largest for  $t \rightarrow cH$  decay for several two-Higgs-doublet models and the Randall Sundrum model with warped extra dimensions<sup>3</sup> The authors quote a maximum branching fraction of order 0.1% in the flavour-violating 2HDM model.

Gauhar Abbas presented an investigation into the possible enhancement of the branching ratios of  $t \rightarrow cH$  decay within the aligned two Higgs doublet model (A2HDM). Assuming that the 125 GeV Higgs-like boson corresponds to the lightest CP-even state  $h$  of the CP-conserving A2HDM and taking into account constraints coming from the measurements of the 125 GeV Higgs properties, searches for a light charged Higgs via top decays, and the flavour physics, the  $t \rightarrow cH$  fraction remains well below the expected sensitivity of the LHC and ILC, across all of the parameter space considered [78].

Miguel Nebot presented allowed ranges of branching ratios for the decays  $t \rightarrow Hc$  and  $H \rightarrow \tau e, \tau\mu$  in a class of two Higgs doublet models (by Branco, Grimus, Lavoura, or BGL) where flavour changing neutral scalar currents occur at tree level [79]. In such models flavour violating top and Higgs decays can occur at discovery level at per mil or even percent level, within reach of the LHC and future colliders.

## 5.2 LHC status and prospects

Current limits from the LHC (after analysis of the 8 TeV data set) on flavour changing neutral current top quark decays range from a few % for decays to a photon and a quark to  $3 \times 10^{-5}$  for  $t \rightarrow gu$  (derived from a search for  $qg \rightarrow t$  production).

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<sup>3</sup>The exception is the R-parity violating SUSY model, where the preferred channels are  $Zq$  and  $gq$ .

The ATLAS and CMS experiments have presented limits on the branching fraction  $\text{BR}(t \rightarrow cH) <$  of 0.56% (CMS) and 0.79% (ATLAS).

The prospects for improvements in the next two decades are presented in Ref. [8]. The completion of the LHC programme and its luminosity upgrade is expected to yield improvements in the limits to the level of  $10^{-6} - 10^{-4}$ . An extrapolation yields an expected limit on  $\text{BR}(t \rightarrow cH)$  of  $5 \times 10^{-4}$ .

### 5.3 LC prospects

The TESLA studies reported in Ref. [80] provide an estimate of the expected sensitivity to  $t \rightarrow \gamma q$  and  $t \rightarrow Zq$  of a linear collider experiment that collects  $500 \text{ fb}^{-1}$  at  $\sqrt{s} = 500 \text{ GeV}$ . The sensitivity of searches for single top production in association with a light quark is quite competitive with that of the full LHC programme, reaching a BR of  $6.4 \times 10^{-6}$  for the branching fraction to a photon and a quark. The authors of Ref. [8] note that a competitive limit is possible even with the low-energy stage at 250 GeV of a linear collider.

### 5.4 FCNC decay $t \rightarrow cH$

The prospects for the decay  $t \rightarrow cH$  are least solidly established. The estimate for the LHC in Ref. [8] is based on an extrapolation, while no results are presented for the LC potential. At the TopLC15 workshop A.F. Żarnecki presented a recent LC study at parton level. The  $t \rightarrow cH$  signal is isolated among the large background of top quark pairs with  $t \rightarrow Wb$  decays in the lepton+jets and fully hadronic final states by a series of cuts, including the requirement of 3 b-tagged jets and a comparison of the  $\chi^2$  values of a kinematic fit to the signal and background hypotheses. Even if this study is based on a simplified description of the detector the author has shown that the result is relatively robust against a degradation of the assumed jet energy resolution and flavour tagging performance of the experiment. The expected 95% C.L. limits for three different center-of-mass energies are presented as a function of integrated luminosity in Figure 6. In this result, an energy resolution of  $50\%/\sqrt{E[\text{GeV}]}$  is assumed.

The expected limits improve roughly inversely proportional to the number of top quarks produced in the experiment. For this reason, center-of-mass energies close to the maximum of the cross-section (i.e. approximately 420 GeV) offer greater potential. The larger instantaneous luminosity that can be achieved at higher-energy linear colliders does not make up for the loss in cross section.

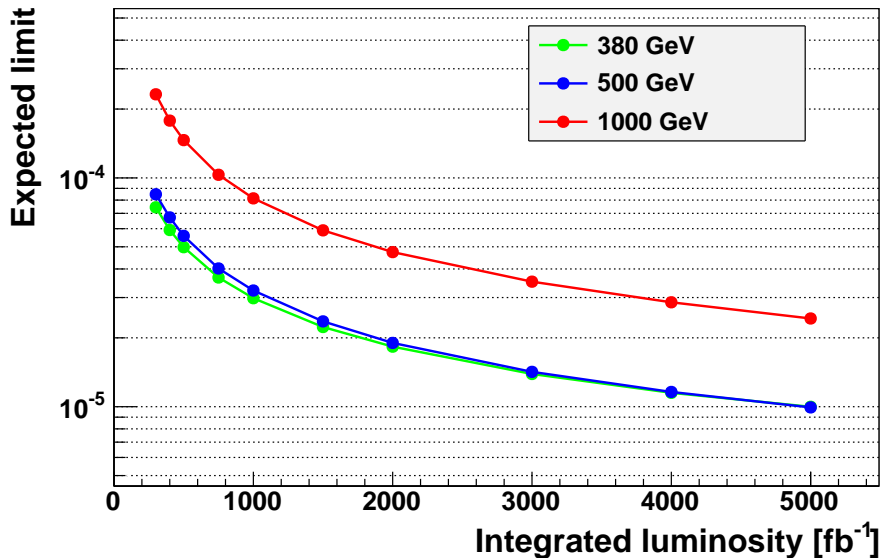


Figure 6: The sensitivity of lepton colliders for the FCNC decay  $t \rightarrow cH$ . The expected limit on the branching fraction  $t \rightarrow cH$  is shown as a function of integrated luminosity for  $e^+e^-$  colliders operated at 380 GeV, 500 GeV and 1 TeV.

## 5.5 Summary

Lepton colliders may provide competitive constraints on the rates of exotic decays of the top quark even after the full LHC programme. Preliminary, parton-level results indicate that ILC or CLIC can achieve a sensitivity for the  $t \rightarrow cH$  decay down to a branching of  $10^{-5}$ .

## 6 Reconstruction

The top quark physics programme at lepton colliders poses stringent requirements on the performance of the detector and the reconstruction software. The ILD and SiD detector concepts [81, 82, 83] for the ILC and the CLIC detector [2] provide a detailed detector model in GEANT4 [84]. These designs are based on decades of experience and are backed up by characterizations of the performance of key technologies in beam tests.

In an overview talk at the workshop Jenny List identified the key challenges in the development of reconstruction algorithms for top physics: jet reconstruction, flavour tagging and vertex charge reconstruction. This overview was followed by focused contributions by Junping Tian, Sviatoslav Bilokin and Masakazu Kurata.

Jet clustering at future lepton colliders is a considerable challenge. Reconstruction

of the six- or eight-fermion final states that arises from the decay of a top quark pair or  $t\bar{t}H$  event requires excellent clustering. The higher  $Q^2$  available at high-energy colliders increases the depth of the parton shower: the distance within a given shower may well exceed the distance between two jets. At the same time, the presence of *pile-up* due to the  $\gamma\gamma \rightarrow \text{hadrons}$  production forces to carefully preselect tracks and clusters (see, for instance, Refs. [85] and [86] for, respectively, the ILC and CLIC case) and to limit the exposed jet area, especially in the forward region of the experiment. Most analyses have resorted to the longitudinally invariant  $k_t$  algorithm [87, 88] to provide more robust clustering, but several groups have proposed new algorithms [89, 90, 91]. An exhaustive comparison of the performance is still lacking.

The performance of flavour tagging and vertex charge determination are crucial to top physics. The former is key in isolating the  $t\bar{t}$  signal, the latter provides a tag of top and anti-top quarks in fully hadronic events. Excellent track reconstruction, with high efficiency and negligible fake rate, lies at the heart of both. The LC detector concepts have demonstrated good performance in a realistic environment for prompt, central tracks with a momentum greater than 1 GeV. The main challenge is to extend the pattern recognition performance to low-momentum tracks in the forward detector, that are too often missed by the pattern recognition. A recovery procedure presented by Sviatoslav Bilokin has shown some potential to improve the vertex charge determination, but more work is needed to improve the track reconstruction for this category of particles.

## 7 Summary and outlook

The TopLC15 workshop at IFIC in Valencia in July 2015 brought together the theory and experimental communities with an interest in the top physics of future high-energy lepton colliders. This summary of the contributions provides an essentially complete status report from ongoing studies into the potential of the linear  $e^+e^-$  collider projects (ILC and CLIC) to measure top quark properties and to study the interactions of the top quark with other Standard Model particles.

The case for a top quark mass measurement at threshold with a statistical precision of order 20 MeV and a total uncertainty of less than 50 MeV rests on increasingly solid ground. This precision includes the theory uncertainty - based on today's state-of-the-art NNNLO description of top quark pair production at threshold and the four-loop conversion of the threshold mass to the  $\overline{MS}$  mass. Also experimental uncertainties are estimated. The workshop saw a renewed interest in mass measurements in the continuum, where the mass may be extracted from the cross section for associated  $t\bar{t} + \text{photon}$  or  $t\bar{t} + \text{jet}$  production.

The top quark Yukawa coupling can be determined at threshold, to a precision that is likely limited by theory uncertainties ( $\sim 20\%$  with the current theory). Col-

liders operated above the  $t\bar{t}H$  threshold at approximately 500-550 GeV can achieve a precision of approximately 4%.

The measurement of the top quark electro-weak couplings are another pillar of the top physics programme. Sizeable ( $O(10\%)$ ) deviations from the Standard Model predictions are expected in a broad range of extensions of the SM, whereas a percent-level measurement is feasible with the nominal ILC and CLIC programmes.

Lepton colliders can provide competitive limits on rare top quark decays that are not easily distinguished from the dominant (hadronic) backgrounds at the LHC. A good example is the preliminary result of a parton-level study that predicts a sensitivity to  $t \rightarrow cH$  to a branching fraction of the order of  $10^{-5}$ .

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