Recent progress for Linear Collider SM/BSM Higgs/Electroweak Symmetry Breaking Calculations

Jürgen Reuter[1] *

DESY Theory Group -
Notkestr. 85, D-22603 Hamburg, Germany

In this paper I review the calculations (and partially simulations and theoretical studies) that have been made and published during the last two to three years focusing on the electroweak symmetry breaking sector and the Higgs boson(s) within the Standard Model and models beyond the Standard Model (BSM) at or relevant for either the International Linear Collider (ILC) or the Compact Linear Collider (CLIC), commonly abbreviated as Linear Collider (LC).

1 General Remarks

Most of the work on the electroweak symmetry breaking sector can be grouped into the following three categories: 1) Precision calculations for the Higgs mass within the SM and in BSM models, 2) precision calculations for electroweak (EW) processes relevant to the EW sector, and 3) Higgs production processes. Each of the categories comprises studies and calculations within the SM as well as in BSM models. The first category on precision calculations for the Higgs mass is still one of the most important issues for the reduction of the theory error on the Higgs mass prediction which is highly relevant for the Higgs searches and potential measurements at the Large Hadron Collider (LHC). This part and also the third part, the precision calculations for specific Higgs production (and decay) channels are not covered, mainly because there has not been done much on these subjects in the past three years, or the results are covered elsewhere. Several topics that fit in the context of this document have also been covered by other people during the LCWS conference in Granada like Higgs production in SUSY decays [1], composite Higgs physics [2], the non-minimal flavor-violating (NMFV) MSSM [3], precision studies of the 2HDM [4], or also the Higgs sector of a pure $B-L$ model [5].

2 Precision calculations to SM Higgs and Background Processes

2.1 Electroweak Triboson Production

Two of the most important processes to check and overconstrain the sector of electroweak symmetry breaking both at LHC as well as a future linear collider are triboson production and vector boson scattering. The processes $e^+e^- \to WWZ, mZZZ$ are commonly viewed as a logical continuation of the physics from WW production at

LEP. In Ref [6] it was shown that both processes at a 1 TeV ILC allow for a precision measurement of the quartic gauge couplings (QGC) and a possible determination anomalous QGCs or constraining them much better than the projected measurement capabilities at the LHC. The WWZ channel alone enables one to constrain the parameter space in the $\alpha_{4/5}$ anomalous QGC parameters, while combining this with the ZZZ measurement shrinks

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[*] Dedicated to the memory of our friend Uli Baur.

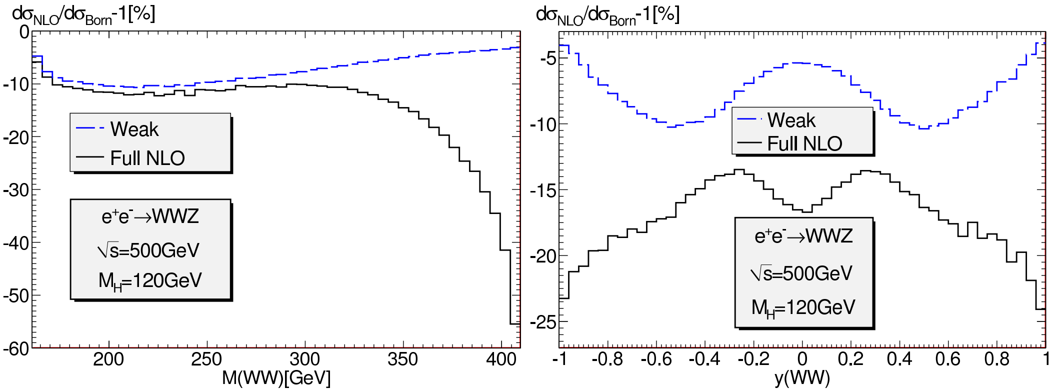

Figure 1: Differential M_{WW} and y_{WW} distributions for $ee \to WWZ$. The black line are the full NLO corrections, while the blue line shows the genuine weak corrections.

the confidence level ellipses besides its much lower statistics by a factor three to four. To determine deviations from the SM QGC with an integrated luminosity of 1 fb^{-1} a theoretical precision of at the per-mil level. There have been three different groups calculating the NLO corrections to the two triboson production processes $e^+e^- \to WWZ, ZZZ$, [7–9]. In the 't Hooft-Feynman gauge used in Ref. [7] the NLO corrections comprise 2700 diagrams for the WWZ channel including 109 pentagon diagrams, while the corresponding ZZZ process has roughly 1800 diagrams containing 64 pentagons. They used two different independent codes, both based on the `FeynArts/FormCalc` package [11, 12]. The calculation has been performed in the kinematic regime where M_{WW} is below the Higgs threshold, using the on-shell renormalization scheme, the Passarino-Veltman tensor reduction [13], and the method proposed in [14] to avoid numerical instabilities from vanishing inverse Gram determinants. They compared the Catani-Seymour dipole subtraction method [15, 16] as well as a phase-space slicing method to treat the soft-collinear divergencies, which agree until the soft-collinear approximation breaks down. Both groups [7–9] compared their results with each other and found agreement. The dominant electroweak corrections come from QED initial state radiation (ISR), which can be subtracted to obtain the genuine weak corrections based either on the Catani-Seymour method or on an experimental extraction from ZZZ. The peak cross section $\sigma_{\text{peak}}(WWZ) \sim 50$ fb is much larger than the corresponding $\sigma_{\text{peak}}(WWZ) \sim 1.2$ fb. The full EW corrections including QED ISR are negative and amount to -30 % of the cross section, while the genuine EW corrections are of the order of -7 to -18 %, cf. Fig. 1 This calculation is consistent with estimates from EW double-logarithmic Sudakov corrections [17].

The authors of [10] have studied the influence of finite-width effects in the near-threshold production at the ILC. They find that using finite widths for EW gauge bosons as well as the Higgs could alter the lineshape of the process cross sections at the level of 20-30 per cent. However, a proper treatment using resummation would be highly desirable here.

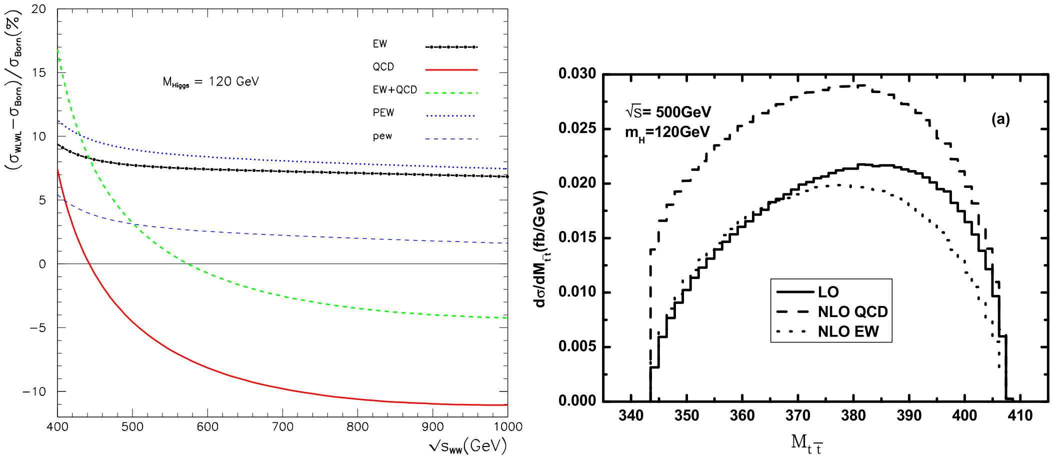

Figure 2: Left: relative NLO corrections for the process $WW \to tt$: the dashed green line are the full corrections, the black line the EW and the red the QCD corrections, respectively. Right: The tt invariant mass distribution at LO (dark line), the dashed line gives the NLO QCD corrections, while the dotted one shows the NLO EW corrections.

2.2 Vector Boson Scattering

As has been also shown in [6], vector boson scattering is an even more powerful tool to examine and (over)constrain the EWSB sector (for an overview how to describe resonances in the EW sector for center-of-mass energies of 1 TeV and larger see e.g. [18]). The top Yukawa coupling might play a special role in the SM as the only coupling of order one, hence, it is an interesting topic to study vector boson scattering to a top quark pair. In [19], the authors have calculated the QCD and EW NLO corrections to this scattering process $WW, ZZ \to t\bar{t}$ in the on-shell scheme. They find that the corrections grow with rising Higgs mass and that the EW corrections mostly cancel the QCD corrections such that the total corrections over most of the mass range are only of the order of ±5 %, cf. the left plot in Fig. 2. The calculations are for the $2 \to 2$ scattering process, and the final results have been obtained in the effective W approximation (EWA), i.e. using structure functions for the W/Z as a parton in the electron. Such a description is known to give rise to deviations of differential cross sections from irreducible background from W/Z bremsstrahlung. This effect can be even larger than the NLO corrections [18].

2.3 Top-Antitop Associated Production

At ILC or CLIC, $t\bar{t}h$ associated production is an important process to measure precisely the properties of the Higgs boson after it has been discovered, specifically its Yukawa coupling to the top quark. For this process and a light Higgs boson which predominantly decays into bottom quarks the process $e^+e^- \to t\bar{t}Z$ is one of the most severe backgrounds. Hence, it is important to know this background at NLO. The QCD and EW NLO corrections have been calculated in the paper [20] based on `FeynArts/FormCalc` [11, 12]. The on-shell scheme has been used and a trivial CKM matrix was assumed throughout the calculation which has been performed for a fixed Higgs mass of 120 GeV. Lei et al. used photon and gluon

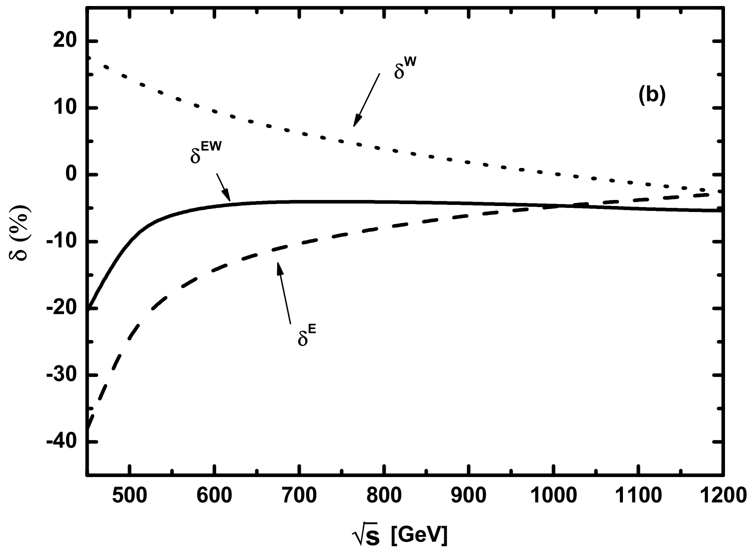

Figure 3: NLO corrections to ttZ production at an ILC: The dashed curve shows the electric corrections, the dotted one the pure electroweak and the full line the sum of the two.

masses, respectively, to regulate infrared singularities. For this process, as expected, the QCD corrections dominate and are positive, ∼ 40 %, while the EW corrections are negative of size $\sim -4 - 8$ %, see the right plot in Fig. 2. The relative size of purely electromagnetic as well as purely weak corrections are shown in Fig. 3.

2.4 Charged Higgs production

Within the Two-Higgs-doublet model, either the generic one, or in the context of the MSSM, charged Higgs pair production might not be in the kinematical of a 1 TeV ILC. It is nevertheless worthwhile to study the production where only one of the two is on-shell and then goes into a top-bottom pair, hence the process: $e^+e^- \to t\bar{b}H^-$. This is specifically important in the high Higgs mass region and in the decoupling limit. The SM QCD NLO corrections for that process have been calculated in [21]. Quite recently, the SUSY QCD NLO corrections for that process have been calculated by [22]. They found that the corrections are enhanced in the parameter region of large $\tan\beta$ which can as usual be accounted for by a resummed bottom Yukawa coupling. The residual SUSY QCD corrections are of the order of -10 to -15 %. In addition, the authors checked a completely analytical calculation by a method using a numerical evaluation of both loop and phase-space integrals based on Bernstein-Tkachov [23, 24]. This method which has been used before only for up to $2 \to 2$ processes [25], is here for the first time applied to a $2 \to 3$ kinematics. The authors found no particular gain in speed/performance or a simpler treatment compared to the fully analytic approach.

2.5 Trilinear Higgs coupling

The trilinear Higgs coupling is the main recent focus on investigations in SM Higgs physics, as it might give the only possible handle to the Higgs potential itself, which is the true trigger for the EWSB. Most of the relevant investigations about measuring the triple Higgs coupling at the ILC can be found in [26,27]. More recently, in [28] the processes $e^+e^- \to HHb\bar{b}, HHt\bar{t}$ have been studied with the main purpose to look for possible interference effects from the continuum production and the diagram containing the trilinear Higgs coupling. As expected, the interferences are tiny, of the order 3 %, for these processes. A very extensive investigation of the question whether and how well the trilinear Higgs coupling will be measurable at ILC has been done by Baur [29].

Baur found that the WW fusion process with the final state $\nu\bar{\nu}HH$ dominates over the Higgsstrahlung process with final state ZHH (note that the first is partially also contained in the second one regarding the invisible Z decay, but not in the kinematical region considered here). The paper simulates the full final states taking all interferences into account using the `WHIZARD` generator [30,31]. Off-shell and interference effects are known to be generically crucial in electroweak production at an ILC, specifically if heavier Higgses are to be extracted via cut-based analyses from their SM backgrounds [32]. Despite this, these effects are not overly important for that particular process here. The main conclusion of the paper is that the trilinear Higgs coupling λ_{HHH} can be measured for a Higgs mass in the range of 120-180 GeV at a 1 TeV ILC with a precision from 20-80 %, while a 3 TeV CLIC could even achieve a precision of 10-20 %. The result although has to be taken with a small grain of salt as neither ISR nor beamstrahlung have been included in the study; but they both can have quite large effects on such signal-to-background investigations (cf. e.g. [32]). The largest background to the signal comes from the $jjbbcc$ final state with two light jets, two b jets and two charm jets with charm mistagged as a bottom quark. The di-Higgs invariant mass in the fully reconstructible final state $jjbbcc$ is shown for two different Higgs masses (120 and 140 GeV) in Fig. 4.

3 EW processes in BSM models

Many studies on BSM models have been done, historically with a strong focus or even bias to supersymmetric models like the MSSM (cf. e.g. [33–35]. Here, I will not cover any EW calculations or studies related to supersymmetric theories, some work presented during this conference can be found in [1]. The investigations summarized in this report deal with a SM with a fourth generation, technicolor and topcolor-assisted technicolor, Little Higgs models as well as twin-Higgs models.

3.1 SM with a fourth generation

A fourth SM family is already heavily constrained by LHC data, not so much by the direct searches but by the Higgs search. However, such a possibility is still not completely ruled out. In the paper [36] special type of dimension six interactions between the light SM quarks, the 4th generation up-type quark (t') and the SM gauge bosons are introduced which resemble magnetic moment-type interactions. Such operators like $\mathcal{L} = \sum_u \frac{\kappa}{\Lambda} \overline{t'} \sigma_{\mu\nu} q_u F^{\mu\nu}$ could even dominate the chiral SM interactions, and are hence easy, but also worthwile to study. These couplings allow for a single production of the t' states in $e^+e^- \to t'q \to Wbq$. The authors

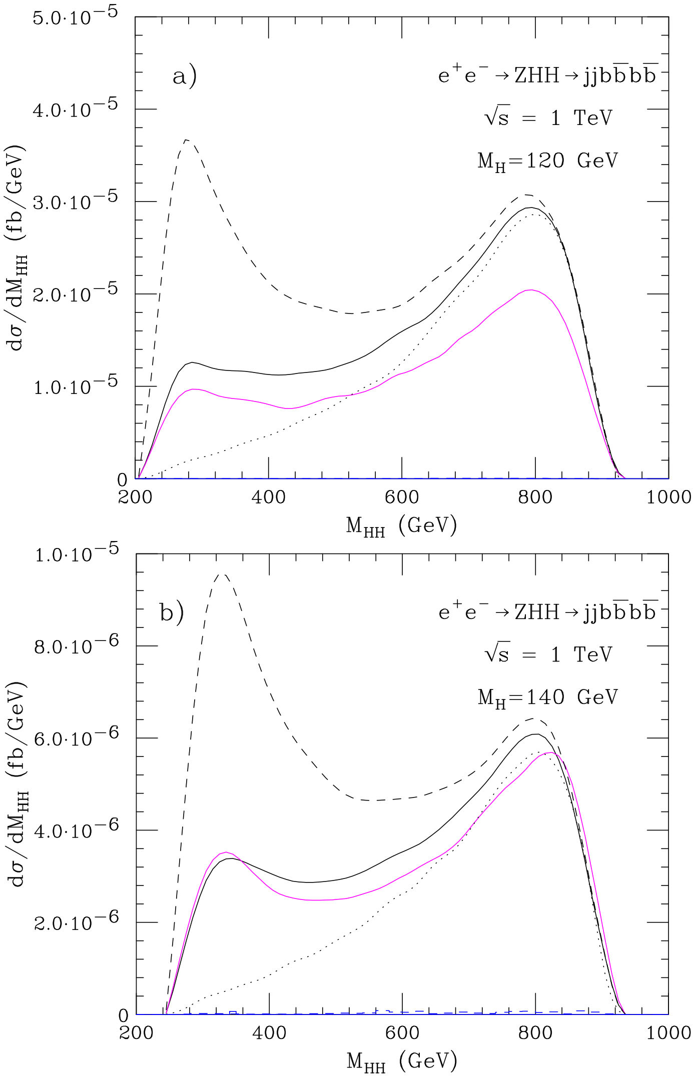

Figure 4: HH invariant mass in the fully reconstructible final state $jjbbcc$ for Higgs masses of 120 GeV (upper) and 140 GeV (lower). The dashed line is for enhancing the trilinear coupling by a factor of 2, the dotted line is setting it to zero. The blue line shows the factorized process without interferences.

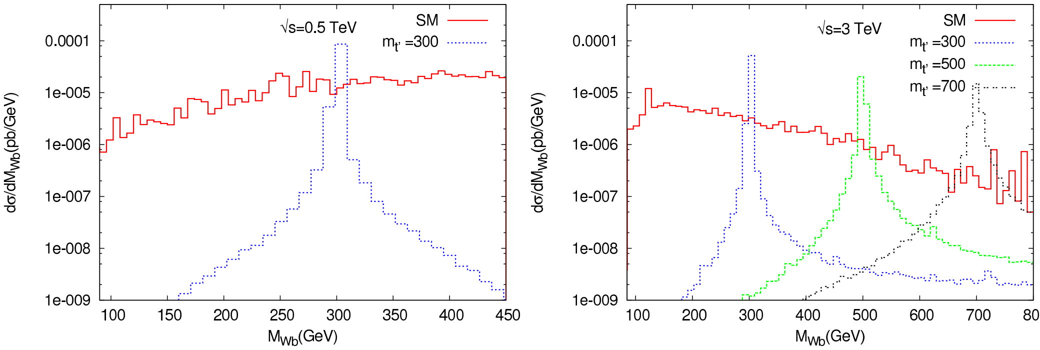

Figure 5: The Wb invariant mass for center-of-mass energies of 500 GeV (left) and 3 TeV (right). The red line shows the SM background, the peaks are the t' signals for different masses.

study the detectability at ILC in these final states as a function of the t' mass, shown in Fig. 5, where the Wb invariant mass is shown for a 500 GeV ILC and a 3 TeV CLIC for different t' masses.

3.2 Technicolor and Top-Color assisted Technicolor

Technicolor is a model where there are new matter constituents (techniquarks) and the corresponding force carriers (technigluons) of new strong dynamics at the TeV scale [37, 38]. These models are having difficulties to be reconciled with the electroweak precision observables, with flavor, and the generation of fermion masses. However, they gained a big revival in the context of dual models in the sense of the adS/CFT correspondence. Topcolor, on the other side, is a model where there is a new strong interaction of only the top quark which makes it condense and triggers EW symmetry breaking [39, 40]. Topcolor-Assisted Technicolor (TC2) is a mixture of both (extended) technicolor as well as topcolor, where one is forced to introduce a vacuum "tilted" in the $U(1)$ charges to avoid phenomenologically catastrophical $b\bar{b}$ condensates (for more details cf. [41]).

In these models there are emergent top pions with masses naturally of the order of the top quark, $m_\pi \sim m_t$, a top-pion decay constant of $f_\pi \sim 60$ GeV, and a corresponding "Yukawa" coupling $g_{tb\pi} \sim m_t/sqrt2 f_\pi \sim 2.5$. So basically, these models are like a 2HDM in the decoupling limit, with the pseudoscalar top-pions and a scalar called the top-Higgs as decoupled states. In [42] the authors calculated the pair production in the processes $\pi_t\pi_t$ and $\pi_t h_t$ both for the LHC as well as for the ILC. The indirect bounds together with the searches from Tevatron (which had almost never been able to see these states) yield a lower bound like $m_\pi, m_h \sim 220$ GeV. Even with present LHC data presumably only the low-mass region is left non-excluded, but searches for these states at the LHC are difficult. The authors calculated the tree-level cross sections as well as the NLO vertex correections using the `LoopTools` package [12]. They found small K-factors of 1.05. The cross section for $e^+e^- \to \pi_t\pi_t$ at a 1.5 TeV linear collider is of the order 20 fb.

For the two processes $e^+e^- \to \pi_t\pi_t$ and $e^+e^- \to \pi_t h_t$ there is a discrepancy with two earlier NLO calculations, Ref. [43] and [44]. The main backgrounds for these processes are SM triboson production which can however effectively be suppressed by a cut-based analysis.

Another paper [45] calculates the pair production cross sections of topcolor pions in photon-induced processes, both at the LHC and at the ILC. Together with the tree-level result they also calculate the leading NLO contribution. For the photon-induced toppion pair production, $e^+e^- \to \gamma\gamma \to \pi_t\pi_t$ the K-factor is again 1.05, while the cross section is of the order of one pb at a 1.5 TeV linear collider. For the toppion/top-Higgs pair production the corresponding cross section is $\lesssim$ 10 fb. The main conclusions from here are that the ILC (at least in the 1.5 TeV version) can detect top-pions, but cannot compete with the LHC detection capabilities. For all of these papers mentioned here, an investigation of a realistic ILC environment together with ISR and beamstrahlung is missing as well as a more thorough study of the ILC capability as a function of the parameter spaces of the TC models. Note that there was also another independent NLO calculation for $\gamma\gamma \to \pi_t^+\pi_t^-$ in Ref. [42].

Further calculations dealt with the process $e^+e^- \to W^+\mu_t^-\pi_t^0$ [46], where the cross sections are only in the range of a few femtobarns. The main background is $ttbcW$ which is very complicated final state with high multiplicity. Such a signal will be quite difficult to dig out of the background. Also note that such cross sections are not reliable any more for center-of-mass energies $\sqrt{s} \gtrsim 1$ TeV, as in the case of non-unitarized multi-pion scattering. Ref. [46] also studied the associated production $e^+e^- \to Z\pi_t^+\pi_t^-$. Again, the cross sections are of the order of roughly a femtobarn and only marginally visible. All these calculations have also been performed for the case of photon-induced processes, $ee \to \gamma\gamma \to X$. Another publication [47] also included production of a top-Higgs in association with top quarks in gamma-induced collisions, $e^+e^- \to \gamma\gamma \to t\bar{t}h_t$.

3.3 Little Higgs models

Little Higgs models [48–50] are a variant of strongly interacting models that are in better agreement with EW precision data, as they manage to have a weakly interacting sector at the TeV scale. These models have as generic properties an extended global symmetry together with an extended scalar sector compared to the SM, an extended gauge symmetry and hence new heavy vectors (Z', W'), as well as new heavy fermions, especially a heavy top quark T. Some of these models have a discrete symmetry, called T-parity in order to further ameliorate EW precision observables. This allows then for dark matter. Generically, there are two types of models, the product group model, where the scalars are in an irreducible representation (irrep), while the weak gauge group is a product group, and the simple group models, where the weak gauge group is simple and the scalar modes are in a product group representation. The most important model of the first class is the Littlest Higgs [49], and the Simplest Little Higgs [51] of the second class, respectively. In the Littlest Higgs, the essential parameters of these models are the intermediate scale which sets the mass for the additional weakly interacting states as well as the Higgs triplet vacuum expectation value (vev). Constraints from EW precision observables demand $f \gtrsim 3-4$ TeV, and $v' \lesssim 10^{-2}$ GeV [52–54]. As the Goldstone bosons from the complex Higgs triplet of that model are difficult to see at the LHC, Ref. [55]. The cross section largely suffers from phase space as well as the decoupling limit, Fig. 6. The authors focus on the fermiophobic limit which is favored by EW precision observables. The main SM background is Ztt, but no realistic detectability study has been done (yet).

In many of these models, there are global $U(1)$ symmetries rather naturally which lead to single light pseudoscalar Goldstone bosons [56], which could serve as a discriminator between different Little Higgs model classes [57]. Recently, the top quark-associated production of

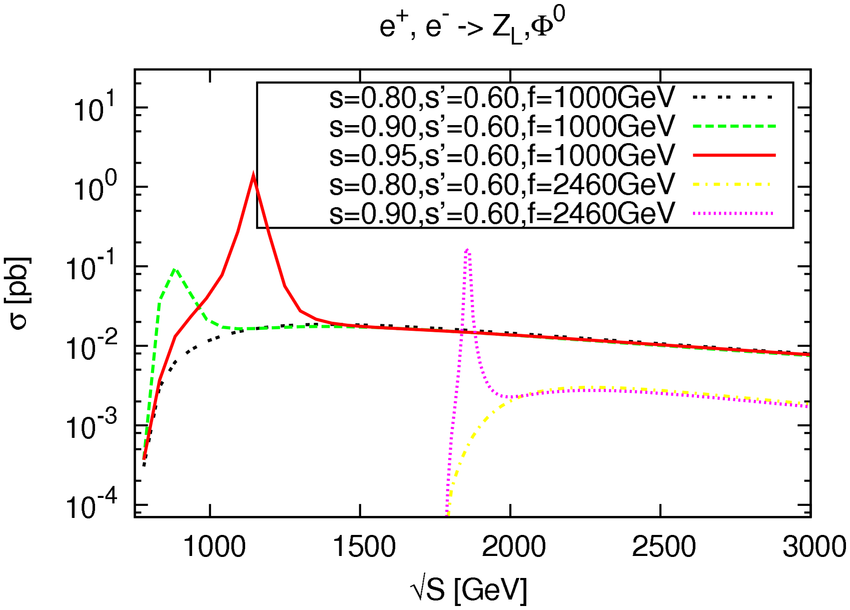

Figure 6: The cross section for the pair production of $Z\Phi$ in the Littlest Higgs model as a function of the center-of-mass, the two mixing angles in the gauge sector as well as the model scale, f.

such a pseudo-axion has been revisited for the Simplest Little Higgs with T-parity [58]. The cross sections are compatible with the corresponding $ee \to tth$ cross sections from the SM or the MSSM, namely roughly 1 fb. The authors also added the $tt\eta$ production from $\gamma\gamma$-induced interactions. Generically, all these cross sections are not too promising but they add an additional source for measurements within the Simplest Little Higgs.

3.4 Twin-Higgs models

Twin-Higgs models are extensions of the SM by a discrete (parity) symmetry. This could be either a mirror symmetry [59], or a discrete left-right exchange symmetry [60–62]. These models are similar to Little Higgs as there are Goldstone bosons arising from the breaking of a large(r) global symmetry. The parity doubling is responsible for the cancellation of the quadratic divergencies. The special thing about these models is that they have no new colored states, hence they are notoriously difficult to discover at the LHC. It is only the Higgs which communicates to the mirror sector. Drell-Yan production is possible but suffers from large backgrounds. In the left-right symmetric twin-Higgs model (LRTH) [63] there is a $U(4)_1 \times U(4)_2$ global symmetry, and a gauge left-right symmetry, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The Higgs spectrum consists of the standard scalar Higgs, a charged Higgs $\phi^\pm$, a pseudoscalar ϕ^0 and a heavy doublet (h_1^+, h_2^0). In Ref. [64] the pair production of $h\phi^0$ has been calculated in the LRTH. The cross sections are marginal and even close to threshold not larger than one fb, but can give rise to Z' resonances at CLIC in the range above 1 TeV. As the predominant decay is $\phi^0 \to b\bar{b}$, these states are only limited by the detector resolution. Another publication estimated the corrections to (multiple)

Higgsstrahlung $e^+e^- \to ZH, ZHH$ in the LR Twin-Higgs model, [65]. As has been studied in the context of Little Higgs models, extensions of the EW Higgs sector can drastically enhance these processes [57]. The enhancement auf these cross sections makes the processes available as discovery modes at an ILC or CLIC.

4 Summary and Conclusions

Screening the literature and work on electroweak and Higgs physics (precision) calculations of the last couple of years with emphasis on a Future Linear Collider shows that we are well prepared for the physics at such a machine. Basically all signal and most background processes are known at next-to-leading order, while some of the open processes like vector boson scattering and triboson production have been calculated at NLO recently. These processes are the cornerstone of the high-luminosity and/or high-energy physics program, and they are at the heart of EW symmetry breaking. One of the final open tasks after a possible discovery of a SM-like Higgs boson and its precision taxonomy at LHC and ILC/CLIC will be the mapping out of the Higgs potential to find out whether this is indeed as given in the SM or has some deeper mechanism leading to its generation.

Concerning beyond the Standard Model (BSM) physics, the focus in the recent years was on EW symmetry breaking-related processes in mostly strongly interacting models like Little Higgs, technicolor, topcolor and twin-Higgs models. Specifically multiple production of scalar particles as well as production in association with top quarks or the EW gauge bosons have been the driving forces of the investigations. Generically, one can say that guidance is needed from the Higgs-sector measurements and the high-energy phase of LHC to know in which direction to turn for a future ILC/CLIC.

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