Searching for new physics in WW and single-W events

Jenny List[*], Ulrich Einhaus[*,†], Andre Filipe Silva[*,‡], Leonhard Reichenbach[§,¶]

[*] *Deutsches Elektronen-Synchrotron DESY,* [†] *now at: Karlsruhe Institut für Technologie KIT,* [‡] *University of Coimbra,* [§] *University of Bonn,* [¶] *CERN*

Abstract

Pair- and single-production of *W* bosons provide many opportunities to look for new physics via precision measurements, for instance via scrutinizing the involved triple-gauge vertices or by measuring CKM matrix elements in an environment very complementary to B hadron decays. This contribution presents the ongoing work based on full simulation of the ILD detector concept, exploiting the $O(10^8)$ *W* bosons produced during the $250\,\mathrm{GeV}$ stage of the ILC. The projections, which also contribute to two focus topics of the current ECFA study on future Higgs/Top/electroweak factories, promise improvements of the measurement precision of TGCs and the CKM matrix, respectively, of one to two orders of magnitude with respects to LEP.

Talk presented at the International Workshop on Future Linear Colliders (LCWS 2024), 8-11 July 2024, Tokyo.

1 Introduction

The international particle physics community agrees that the highest priority next collider should be an e^+e^- Higgs factory. At such a collider also W bosons would be produced copiously: for instance the ILC would produce 1.2×10^8 W bosons at 250 and 500 GeV, while the FCC-ee program offers similar amounts at 160 and 240 GeV. The production processes comprise W pair production and single-W production, i.e. the t-channel contribution with the tree-level Feynman diagram containing only one W, hence called the single-W channel. Both processes are highly sensitive to the beam polarisation, and both suitable to scrutinize triple-gauge vertices connecting two W bosons with a Z boson or a photon. In addition, the hadronic decays of the W bosons probe elements of the CKM matrix – a quite complementary approach to B factory measurements, in particular concerning the involved systematic uncertainties.

This contribution gives an overview of ongoing work and highlights the prospects for their measurements at a future e^+e^- collider.

2 Triple Gauge Couplings

In its most general from, the vertex between a neutral and two charged electroweak gauge bosons includes 14 complex couplings, i.e. 28 real parameters. In the Standard Model (SM), only four of them, $g_{1,Z}$, $g_{1,\gamma}$, κ_Z and κ_γ, are equal to one, while all others are predicted to be zero. Any deviation from this prediction presents a highly sensitive probe for physics beyond the SM. Due to lack of data, the number of parameters considered is strongly reduced by demanding C, P and CP invariance, as well as electromagnetic gauge and $SU(2) \times U(1)$ invariance, leaving three free parameters, e.g. $g_{1,Z}$, κ_γ and λ_γ as used at LEP, or the equivalent parameters in SMEFT. W pair production in e^+e^- collisions offers and ideal laboratory: in addition to the total polarised cross-sections, the differential cross-section in terms of the production angle as well as the two times two decay angles of the W bosons give sensitivity to the triple-gauge vertices. Any projection will depend significantly on the exact analysis technique applied: whether the analysis of the differential distributions is performed binned or un-binned, whether three or all five angles are used, whether single- and multi-parameter fits are done, and how which systematic uncertainties are included.

A number of studies on triple-gauge couplings at future colliders has been performed, from theory-level fits to optimal observables to studies in full, Geant4-based, detector simulations. The most comprehensive study, purely on theory-level, i.e. considering neither detector resolution, nor backgrounds, nor systematic uncertainties, showed that at a high-energy e^+e^- collider at $\sqrt{s} = 500$ GeV with polarised beams, including transverse polarisation, in principle all 28 real coupling parameters can be disentangled and constrained [1, 2]. More recently, the sensitivity to the three couplings of the LEP parametrisation has been studied in the context of a SMEFT fit to the Higgs and electroweak sector, also based on theory-level optimal observables [3]. This study projects an impressive improvement of the precision by about a factor of more than a 100 compared to HL-LHC. In particular for λ_γ, the sensitivity does improve significantly with energy, so that the TeV-scale energy stages of linear colliders even improve by about a factor of 1000 over HL-LHC. The effect of detector resolution and residual backgrounds on the optimal observable technique has been studied in [4], showing that these effects – if uncorrected for – lead to significaqnt biases of the central values obtained from the optimal observable technique, and demonstrating that for instance machine-learning techniques can be employed to predict the necessary corrections.

Studies based on realistic detector simulations only exist for ILC at $\sqrt{s} = 500$ GeV and 1 TeV [5, 6]. Due to the limited available capacity for Geant4-based Monte-Carlo production at the time, only W pair production and three out of the five angular observables were considered in a binned analysis, rendering the results extremely conservative. Nevertheless, the covariance matrix from the simultaneous fit of the three LEP couplings from these studies was the basis for the input to the Higgs and electroweak fits

performed e.g. in [7]. Projections for lower center-of-mass energies up to now rely on interpolations between the 500 GeV / 1 TeV projections and the actual LEP2 results [8]. These showed that at 250 GeV, the sensitivity is expected to be a factor of 4-5 worse than at 500 GeV for the same final-states considered. This study also for the first time highlighted the significant additional gain from including the single-W final states into, improving the precision of the $e\nu qq$ channel by a factor 2-3 compared to including only $WW \rightarrow e\nu qq$ events. A first comprehensive study of experimental uncertainties and how their impact on the final result can be minimised has been presented in [9]. This work showed when combining data from various 2-fermion and 4-fermion final-states, all involved physics observables (like the TGCs but also e.g. forward-backward asymmetries etc.) can be disentangled from systematic effects from e.g. luminosity, polarisation, energy, detector acceptance and others in a combined fit with physics and nuisance parameters, with very small residual impact from the systematic uncertainties on the physics observable. This observation holds in particular when both beams are polarised, providing a sufficient number of over-constraining data-sets.

3 CKM matrix determination from hadronic W decays

There is at the moment an intriguing discrepancy at the 3σ level in the value of $|V_{cb}|$ from B decays, being at $(42.19 \pm 0.78) \times 10^{-3}$ from inclusive B decays and at $(39.10 \pm 0.50) \times 10^{-3}$ from exclusive B, B_s and Λ_b decays. While this discrepancy is difficult to solve in B decays due to inherent hadronic uncertainties, these are absent in decays of real Ws. With the large QCD background, the LHC prospects of this measurement are only at the level of 10%. However, a future HTE factory would offer a clean environment with $O(10^8)$ W bosons, leading to a ideal uncertainty on the measurement of $|V_{cb}|$ of 0.15% given 100% efficiency and no backgrounds. This is accompanied by theory uncertainties expected to drop to the level of 10^{-4} until such measurement is conducted. Moreover, $|V_{cb}|$ is not the only point of interest, rather all 6 CKM matrix elements that do not involve the top quark can be determined via hadronic W decays in a manner complementary to B and D meson decays at corresponding factories. Table 1 summarises the branching ratios, expected number of W decays for 10^8 Ws and the following ideal determination uncertainty for these 6 elements. While these ideal uncertainties give us an interesting lower limit, detailed physics and detector simulations involving efficiencies and background are needed to determine how close we can get to the ideal numbers.

W^-	$\bar{u}d$	$\bar{u}d$	$\bar{u}b$	$\bar{c}d$	$\bar{c}d$	$\bar{c}b$
BR	31.8%	1.7%	4.5×10^{-6}	1.7%	31.7%	5.9×10^{-4}
N_{ev}	64×10^6	3.4×10^6	900	3.4×10^6	63×10^6	118×10^3
$\delta_{V_{ij}}^{th}$	0.0063%	0.027%	1.7%	0.027%	0.0063%	0.15%

Table 1: *W* decay branching ratios in the Standard Model, corresponding occurrence for 10^8 Ws and CKM matrix element determination precision given 100% efficiency and no backgrounds; from [10].

A first study [11] considering 2-fermion processes as background, a parametrised flavour tagging inspired by the IDEA detector concept for FCC-ee and potentially limiting systematic effects showed that for $|V_{cb}|$ a control of the flavour tagging efficiency at the level of about 0.1% would be sufficient, while $|V_{cs}|$ the efficiency would need to be controlled to better than 0.01% in order not to limit the achievable precision.

A more comprehensive set of background processes and systematic uncertainties has been considered in a full-simulation study based on the ILD version for CEPC [12]. This study showed that it is not sufficient to consider only 2-fermion backgrounds, since also 4-fermion processes contribute significantly to the final selection. It also showed that systematic uncertainties should improve by about a factor 4 over

LEP systematics in order not to limit the final result. It also showed that in terms of statistical precision, $5\,\mathrm{ab}^{-1}$ of unpolarised data give about the same result as $2\,\mathrm{ab}^{-1}$ of polarised data.

4 Ongoing work in ILD/CLD

ILD and CLD are working towards a full analysis of all *WW* and single-*W* channels. A first tool has been developed providing a unique categorisation of each event into the possible *WW* and single-*W* decay channels, hadronic, semileptonic and leptonic. This allows for any *W*-related study to be performed on overlap-free exclusive-channel samples, which are coherent between studies, in order for an easy comparison and combination of their results.

The categorisation algorithm uses the number of isolated leptons in each event, as reconstructed in the ILD [13] full-simulation and reconstruction chain via isolated lepton tagging algorithms (for electrons and muons) and a dedicated τ finder. This also allows for for a sub-categorisation of the semileptonic channel into the three lepton flavours. Furthermore, a cut on the event invariant mass is used to tag so-called invisible semileptonic events, where the electron from the leptonically decaying *W* is very forward and outside of the detector acceptance.

This basic categorisation already delivers decent results, but can be easily improved by employing cuts on the event properties number of reconstructed particles, invariant mass, missing energy and missing transverse momentum in order to re-categorise events. The result is shown in Figure 1, with the numbers on the diagonal indicating the efficiencies of the category reconstruction. On first view, the dominant diagonality shows a good overall categorisation. The hadronic and leptonic channels are reconstructed with very high efficiency of 98% and the semileptonic muonic channel with 92%. The semileptonic channels with an electron are categorised moderately well at around 77%, with both channels where the simulated electron is inside or outside or the detector acceptance ($\cos\theta < 0.994$) having some confusion with each other, but also with other channels, in particular the semileptonic one with tauons. This channel itself also only has a moderate efficiency at 62%, 'losing' mostly to the semileptonic-invisible channel. For a future refinement of this matrix, these points of confusion can serve as a starting point, in particular the τ finder.
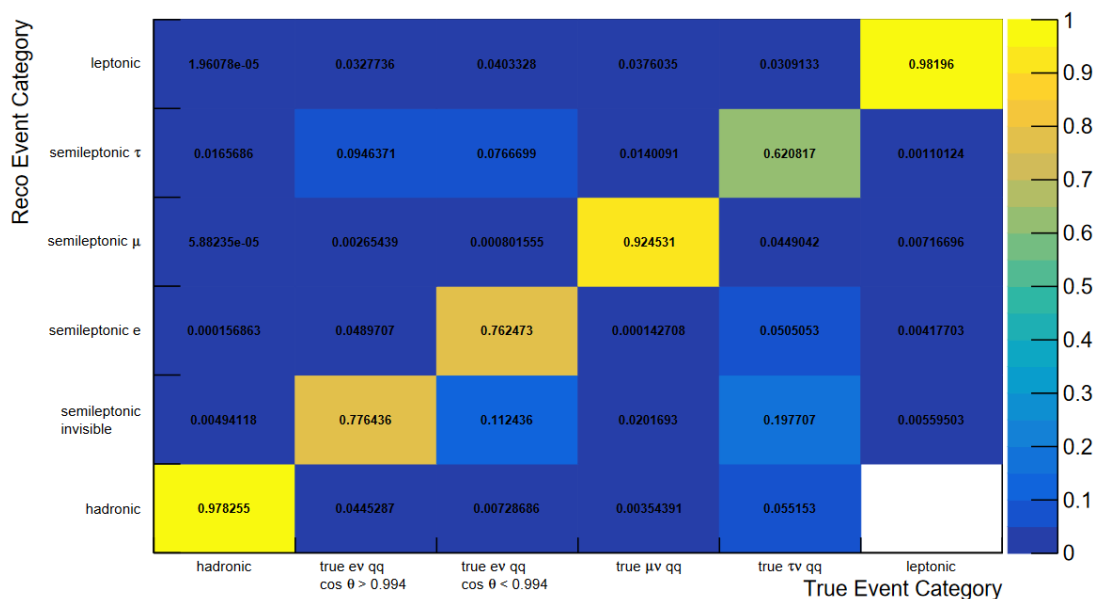
Figure 1: Confusion matrix of the *WW* categorisation.

The confusion between the visible and invisible semileptonic electron channels play an important role

in particular in the *W* differential cross section measurement, since the angular cut-off in reconstruction is in the region of the largest contribution of the single-*W* channel. Dedicated studies of forward-electron reconstruction are being performed, in order to alleviate this confusion and, ideally, improve the overall reconstruction efficiency. This is also shown in Figure 2, where in a first step, the same performance evaluation in Key4hep [14] has been applied to CLD and ILD full-simulation data. One crucial issue is misreconstruction due to bremsstrahlung, which may be reduced through Gaussian sum filters. The goal here is to implement these in ACTS in key4hep and then apply the same tracking framework to all Higgs factory detector concepts that provide full detector simulation.
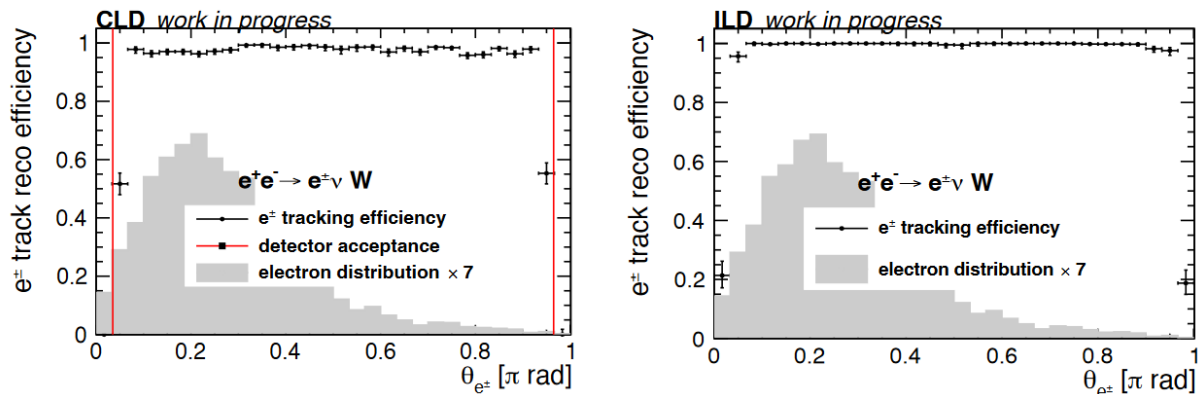
Figure 2: Electron angular tracking efficiency, assessed with the same performance evaluation for CLD and ILD.

The measurement of CKM matrix elements from hadronic *W* decays requires excellent flavour tagging, including dedicated strange tagging. Several new flavour taggers which are all utilising modern machine learning techniques are under development and can address this question. One of these [15], based on ParticleNet, is being adapted to allow for strange tagging. This is enabled by utilising particle identification (PID), in particular kaon ID, since jets from strange quarks have a higher average fraction of strange hadrons, in particular after weighting with momentum. The PID information is provided by the new tool CPID [16] and both this and the inference part of the flavour tagger have been recently implemented in the ILD reconstruction chain.

5 Conclusion

This contribution gave an overview on existing results and ongoing work quantifying the capabilities of future e^+e^- in the areas of constraining triple gauge couplings and CKM matrix elements from *W* boson production. In both areas, very significant progress is expected beyond today's state-of-the-art, as well as with regard to expectations from HL-LHC and *B* factories. For some of the observables, the ability to measure at the higher center-of-mass energies offered only by linear colliders gives a distinct advantage. The measurements require the clean environment of an e^+e^- collider and are not expected to be superseeded by a future hadron collider.

References

[1] M. Diehl, O. Nachtmann, and F. Nagel. *Triple gauge couplings in polarized e- e+ —> W- W+ and their measurement using optimal observables*. Eur. Phys. J. C, 27:375–397, 2003. http://dx.doi.org/10.1140/epjc/s2002-01096-y.

[2] M. Diehl, O. Nachtmann, and F. Nagel. *Probing triple gauge couplings with transverse beam*

polarisation in e+ e- —> W+ W-. Eur. Phys. J. C, 32:17–27, 2003. http://dx.doi.org/10.1140/epjc/s2003-01339-5.

[3] J. de Blas, Y. Du, C. Grojean, J. Gu, V. Miralles, M. E. Peskin, J. Tian, M. Vos, and E. Vryonidou. Global SMEFT Fits at Future Colliders. In *Snowmass 2021*, 6 2022. http://arxiv.org/abs/2206.08326.

[4] S. Chai, J. Gu, and L. Li. *From optimal observables to machine learning: an effective-field-theory analysis of $e^+e^- \to W^+W^-$ at future lepton colliders*. JHEP, 05:292, 2024. http://dx.doi.org/10.1007/JHEP05(2024)292.

[5] I. Marchesini. *Triple gauge couplings and polarization at the ILC and leakage in a highly granular calorimeter*. PhD thesis, Hamburg U., 2011.

[6] T. Behnke et al., editors. *The International Linear Collider Technical Design Report - Volume 4: Detectors*. 2013. ILC-REPORT-2013-040.

[7] T. Barklow, K. Fujii, S. Jung, R. Karl, J. List, T. Ogawa, M. E. Peskin, and J. Tian. *Improved Formalism for Precision Higgs Coupling Fits*. Phys. Rev. D, 97(5):053003, 2018. http://dx.doi.org/10.1103/PhysRevD.97.053003.

[8] R. Karl. *From the Machine-Detector Interface to Electroweak Precision Measurements at the ILC — Beam-Gas Background, Beam Polarization and Triple Gauge Couplings*. PhD thesis, Hamburg U., Hamburg, 2019. http://dx.doi.org/10.3204/PUBDB-2019-03013.

[9] J. Beyer. *Achieving electroweak precision at future electron-positron colliders*. PhD thesis, U. Hamburg (main), Deutsches Elektronen-Synchrotron, DESY, Hamburg, Hamburg U., 2022. http://dx.doi.org/10.3204/pubdb-2023-00837.

[10] J. de Blas et al. *Focus topics for the ECFA study on Higgs / Top / EW factories*, 2024. http://arxiv.org/abs/2401.07564.

[11] D. Marzocca, M. Szewc, and M. Tammaro. *Direct CKM determination from W decays at future lepton colliders*. 5 2024. http://arxiv.org/abs/2405.08880.

[12] H. Liang, L. Li, Y. Zhu, X. Shen, and M. Ruan. *Measurement of CKM element $|V_{cb}|$ from W boson decays at the future Higgs factories*. 6 2024. http://arxiv.org/abs/2406.01675.

[13] The ILD Collaboration. *International Large Detector: Interim Design Report*. 2020. http://arxiv.org/abs/2003.01116.

[14] P. Fernandez Declara et al. *The Key4hep turnkey software stack for future colliders*. PoS, EPS-HEP2021:844, 2022. http://dx.doi.org/10.22323/1.398.0844.

[15] M. Meyer. *Machine Learning Flavour Tagging for Future Higgs Factories*, 2023, https://agenda.infn.it/event/34841/contributions/207748/.

[16] U. Einhaus et al. *Implementation, performance and physics impact of particle identification at Higgs factories*. PoS, EPS-HEP2023:598, 2024. http://dx.doi.org/10.22323/1.449.0598.