Prospects for Differential Cross-Section and Optimal Observable Measurements in W-pair and single-W Production at Future $e^+ e^-$ Colliders

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This contribution describes an ongoing study of W-pair and single-W production at future $e^+ e^-$ colliders with the aim to evaluate the prospects for measuring the relevant differential cross-sections as well as optimal observables for the extraction of triple gauge couplings. The study is performed based on detailed, Geant4-based simulations of the CLD and ILD detector concepts, using Monte-Carlo samples generated at $\sqrt{s}$=250 GeV.

1 Introduction

At any Higgs Factory, W bosons will be produced copiously: for instance, the ILC would produce 1.2×10^8 W bosons at 250 and $500\,\mathrm{GeV}$, while the FCC-ee program offers similar amounts at 160 and $240\,\mathrm{GeV}$. 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. Both processes are susceptible to beam polarisation and offer an ideal laboratory for scrutinizing triple-gauge vertices connecting two W bosons with a Z boson or a photon: 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 gives 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.

In its most general form, 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. Since the LEP data were not sufficient to constrain the full set of TGCs, the number of parameters usually 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 LEP2 [1], or the equivalent parameters in SMEFT.

Several studies on triple-gauge couplings at future colliders have been performed. The most comprehensive study, purely on the theory level, i.e. considering neither detector resolution, nor backgrounds, nor systematic uncertainties, showed that at a high-energy e^+e^- collider at $\sqrt{s} = 500\,\mathrm{GeV}$ with polarised beams, including transverse polarisation, all 28 real coupling parameters can be disentangled and constrained [2, 3]. 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 [4]. This study projects an impressive improvement of the precision by about a factor of more than 100 compared to HL-LHC. The effect of detector resolution and residual backgrounds on the optimal observable technique has been studied in [5], showing that these effects can lead to significant biases of the central values obtained, and demonstrating that machine-learning techniques can be employed to predict the necessary corrections.

Studies based on realistic detector simulations only exist for the ILC at $\sqrt{s} = 500\,\mathrm{GeV}$ and $1\,\mathrm{TeV}$ [6, 7]. Due to the limited available capacity for GEANT4-based Monte-Carlo production at that time, only W pair production and three out of the five angular observables were considered in a binned analysis, rendering the results extremely conservative. These studies were used as inputs for the fits performed e.g. in [8]. So far, projections for lower centre-of-mass energies rely on interpolations between the $500\,\mathrm{GeV}$ / $1\,\mathrm{TeV}$ projections and the actual LEP2 results [9]. These showed that at $250\,\mathrm{GeV}$, the sensitivity is expected to be a factor of 4-5 worse than at $500\,\mathrm{GeV}$ when considering the same final states. This study also highlighted the significant additional gain from including the single-W final states, improving the precision of the $e\nu q\overline{q}$ channel by a factor 2-3 compared to including only W pair events. A first comprehensive study of experimental uncertainties and the minimisation of their impact on the final result has been presented in [10]. This work showed when combining data from various 2-fermion and 4-fermion final-states, all involved physics observables (TGCs but also 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 works particularly well if both beams are polarised, providing a sufficient number of over-constraining data sets.

2 Towards a first analysis at 240/250 GeV in full simulation of ILD and CLD

The analysis is based on fully simulated event samples comprising all Standard Model processes. For ILD, we used data from the recent mass production [11]. For CLD, the data was prepared similarly, i.e. generated with WHIZARD, showered through PYTHIA 6 and then GEANT4 simulated using ddsim, albeit with newer software versions than in the ILD case. In both cases, the reconstruction was based on MARLIN, in the CLD case run using the Key4hep Marlin wrapper [12]. The event samples will be mixed andf re-weighted to unpolarised data for the FCC-ee case and easier comparison to LEP2 results, as well as to polarised data for the ILC case.

In the narrow-width approximation and for a detector isotropic in ϕ, the kinematics of W-pair events are fully defined by the production angle of the W^-, $\cos\theta_{W^-}$, defined as the angle between the beam e^- and the W^-, as well as the decay angles of the two W bosons, $\cos\theta^*_{f/\bar{f}}$, $\phi^*_{f/\bar{f}}$, the polar and azimuthal angles of the fermion/anti-fermion in the rest frame of the parent W^-/W^+. These five angular observables are best measurable in the semi-leptonic decay of the W-pair to $l\nu q\bar{q}$ with $l = e, \mu$, where the W charges can be tagged from the lepton and only one neutrino has to be reconstructed from the missing energy of the event. We restrict ourselves to these two final states in this study. In the context of other analyses, though, it has been shown that also quark / anti-quark separation is possible with quite high efficiency and purity when exploiting the full information offered by ILD [13].

Dedicated studies of forward-electron reconstruction were performed, to gauge the detector acceptance requirements and, ideally, improve the overall reconstruction efficiency in the single-W case. This is shown in Figure 1, where, as a first step, the same performance evaluation in Key4hep [14] has been applied to CLD and ILD full-simulation data.

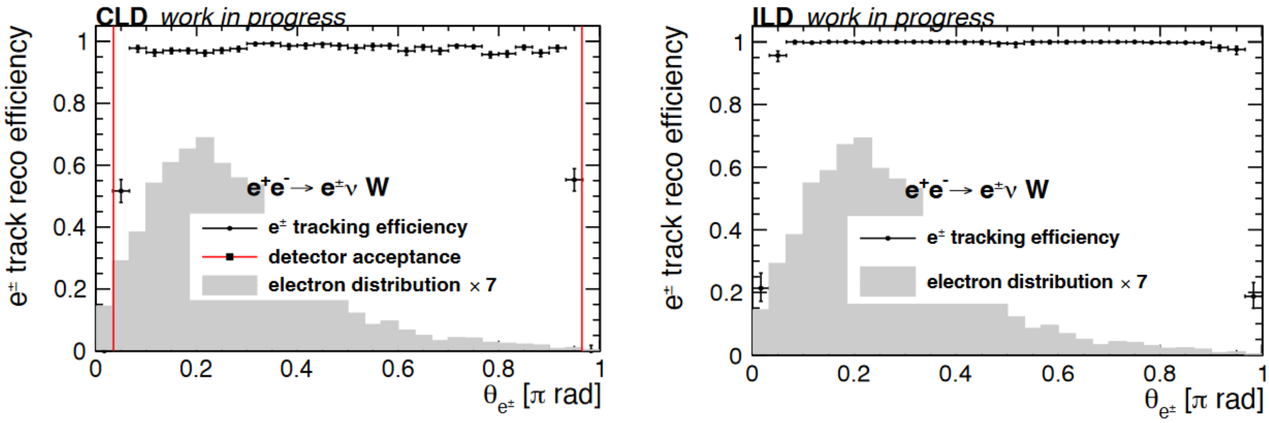

Figure 1: Electron angular tracking efficiency, assessed with the same performance evaluation for CLD and ILD. [PLACEHOLDER, TO BE UPDATED by JAN 24]

A simple preselection rejects the vast majority of backgrounds and performs a unique categorisation of each event into the possible W^+W^- 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, for an easy comparison and combination of their results. Afterwards, a channel-specific main selection and dedicated kinematic reconstruction follow, resulting in estimates of the four-vectors of the fermions / anti-fermions from the W decays, which allow to calculate production and decays angles and additionally the optimal observables as derived in [2].

Figure 2 shows projected measurements of the angular distributions, compared to the corresponding differential cross-section measurements from LEP2 [1]. This illustrates the immense increase in precision expected

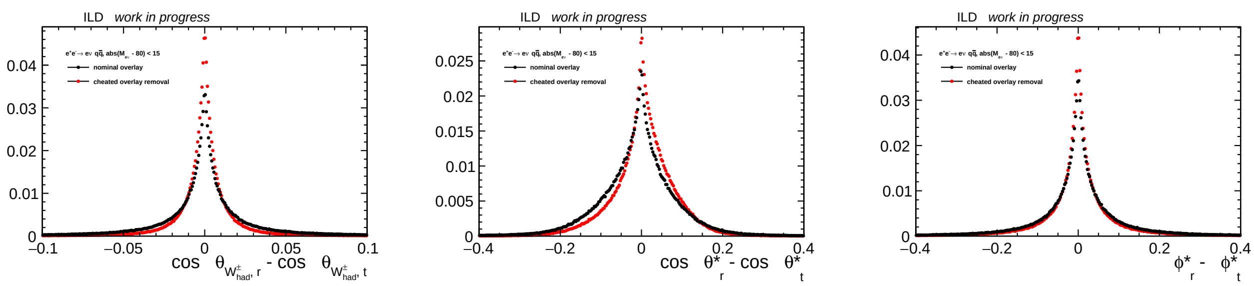

Figure 2: PLACEHOLDER, to be replaced by Jan 24

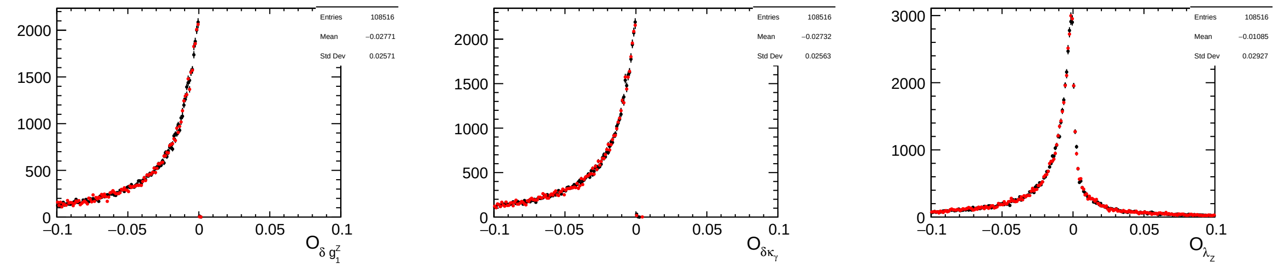

Figure 3: PLACEHOLDER, to be replaced by Jan 24

at future Higgs factories. The extraction of constraints of triple gauge couplings is best performed using optimal observables. Figure 3 shows the expected reconstruction of the optimal observables of the subset of couplings which can be separated without transverse beam polarisation. The first three correspond to the three couplings of the so-called LEP parameterisation, also used in linear 6D SMEFT fits.

3 References

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