PRECISE MEASUREMENT OF LIGHT-QUARK ELECTROWEAK COUPLINGS AT FUTURE COLLIDERS*

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Electroweak Precision Measurements are stringent tests of the Standard Model and sensitive probes to new physics. Accurate studies of the Z-boson couplings to the first-generation quarks could reveal potential discrepancies between the fundamental theory and experimental data. Future lepton colliders offering high statistics of Z bosons would be an excellent tool to perform such a measurement based on a comparison of radiative and non-radiative hadronic decays of the Z boson. Due to the difference in quark charge, the relative contribution of the events with final-state radiation (FSR) directly reflects the ratio of up- and down-type quark decays. Such an analysis requires a proper distinction between photons coming from different sources, including initial-state radiation (ISR), FSR, parton showers, and hadronisation. In our paper, we will show how to extract the values of the Z couplings to quarks and present preliminary results of the analysis for ILC.

1. Motivation

The Standard Model (SM) of particle physics is the most successful theory describing interactions at the fundamental level. Despite its ability to explain experimental data from various experiments, several cosmological observations suggest that it is not the ultimate theory. Many convincing

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arguments, such as the density of dark matter, the baryon–antibaryon asymmetry or the very early history of the Universe, point towards the existence of a more fundamental model. Furthermore, the SM is a theory consistent with data only when a considerable number of internal parameters, including particle masses and couplings, is set to some specific values. Thus, precise measurements of the parameters are needed to probe the structure of the SM and possibly find any discrepancies revealing connections to more general models incorporating explanations for effects unpredicted by the SM.

Electroweak precision observables, including couplings of the SM fermions to photons, Z and W bosons, are among the best-measured parameters of this fundamental theory. The predictivity of the electroweak interactions at collider scales allows for comparing theoretical calculations with experimental data even at per-mille precision; for instance, the partial width of the Z boson decaying into $b\bar{b}$ pairs is known to 0.3%, while the partial width for the c-quark channel is constrained up to 1.7% [1]. On the other hand, the partial widths for the lighter quarks remain only poorly constrained due to the lack of proper tagging algorithms. Their values can however be extracted in another way, namely by studying radiative and non-radiative decays separately. Future Higgs factories operating at the Z pole would offer production of numerous, 10^9–10^{12} Z bosons making the measurement a sensitive probe of the quark-flavour universality [2]. In this paper, we presented prospects for measuring the light-quark couplings at colliders of this type.

2. Measurement idea

The measurement has already been performed at LEP [3–7]. The general idea is based on the fact that up- and down-type quarks differ in electric charge. The coupling strength of the Z boson to a given fermion f is conventionally defined as

$$c_f = v_f^2 + a_f^2 \,, \tag{1}$$

where v_f (a_f) is the vector (axial) coupling. They are determined in the SM by the third component of the fermion weak isospin and its charge

$$v_f = 2I_{3,f} - 4Q_f \sin^2\theta_{\mathrm{W}} \,, \qquad a_f = 2I_{3,f} \,, \tag{2}$$

where θ_{W} is the weak mixing angle. The total width of the Z boson to hadrons, Γ_{had}, reads

$$\Gamma_{\mathrm{had}} = N_c \frac{G_\mu M_Z^3}{24\pi\sqrt{2}} \left(1 + \frac{\alpha_{\mathrm{s}}}{\pi} + \mathcal{O}\left(\alpha_{\mathrm{s}}^2\right)\right)(3c_d + 2c_u) \,, \tag{3}$$

where N_c is the number of colours, G_μ is the Fermi constant, M_Z is the mass of the Z boson, α_{s} is the strong coupling constant, and c_d (c_u) is the

coupling to down-type (up-type) quarks [4, 7]. The total width to radiative hadronic decays, $\Gamma_{\text{had}+\gamma}$, is given by

$$\Gamma_{\text{had}+\gamma} = N_c \frac{G_\mu M_Z^3}{24\pi\sqrt{2}} f(y_{\text{cut}}) \frac{\alpha}{2\pi} \left(3q_d^2 c_d + 2q_u^2 c_u\right) , \tag{4}$$

where $f(y_{\text{cut}})$ is a form factor depending on the arbitrary parameter y_{cut} incorporating the isolation criteria for photons, α is the electromagnetic coupling constant, and q_d (q_u) is the electric charge of down-type (up-type) quarks. Since $q_d \neq q_u$, the expressions for the radiative and the total hadronic widths include different coupling combinations and the couplings of the up- and down-type quarks can be disentangled.

Specifically, given excellent heavy-flavour tagging envisioned for future e^+e^- colliders [8], one may assume for simplicity that $b\bar{b}$ and $c\bar{c}$ events can be fully separated from the light-flavour production data. Then, the "light" hadronic cross section for $Z \to q\bar{q}$, $q = u, d, s$, can be expressed as

$$\sigma_{Z\to\text{lhad}} = \mathcal{C}_1 \left(2c_d + c_u\right), \tag{5}$$

where $\mathcal{C}_1$ is a constant. Similarly, the radiative hadronic cross section is given by

$$\sigma_{Z\to\text{lhad}+\gamma} = \mathcal{C}_2 \left(c_d + 2c_u\right), \tag{6}$$

where $\mathcal{C}_2$ is another constant (if the reconstruction parameters are fixed to some particular values). By fitting the experimental data to theoretical calculations and simulations, the values of $\mathcal{C}_1$ and $\mathcal{C}_2$ can be extracted, and one can disentangle c_d and c_u.

Naturally, the two constants are connected and the radiative cross section can be rewritten as

$$\sigma_{Z\to\text{lhad}+\gamma} = \sigma_{Z\to\text{lhad}} \frac{c_d + 2c_u}{2c_d + c_u} \frac{\alpha}{\pi} F(y_{\text{cut}}) . \tag{7}$$

The form factor $F(y_{\text{cut}})$ may depend on an arbitrarily chosen cut parameter describing the separation between the final-state quarks and emitted photons. The function can be extracted from precise theoretical calculations at fixed order. For illustrative purposes, the leading-order value has been obtained in Whizard 3.1 [9, 10] and is shown in figure 1, where y_{cut} is taken to be the photon transverse momentum with respect to the closest quark axis.
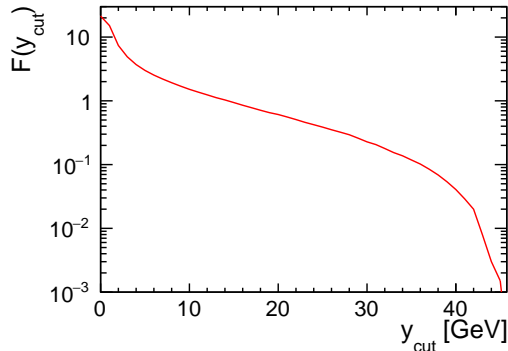
Fig. 1. The form factor $F(y_{\mathrm{cut}})$ as a function of the photon transverse momentum with respect to the closest quark axis. The results were obtained in Whizard 3.1.

3. Simulation of events

The measurement relies on precise Monte Carlo generation of data samples. The process of $e^+e^- \to q\bar{q}$ is often perceived as a benchmark point for testing Monte Carlo tools and typically does not pose a challenge for the generators. However, the requirement of reconstruction of isolated photons introduces several complications. One has to consider not only the final-state photons (FSR) from matrix elements (ME) but also to model properly the initial-state radiation (ISR), match fixed-order calculations to parton showers and separate photons occurring from hadronisation. As a recipe, one can generate data samples using fixed-order ME calculations, with exclusive emissions of hard photons, and match them with ISR structure function and FSR showers accounting for collinear and soft emissions. A similar problem has been tackled in [11] where dark-matter production at lepton colliders has been considered. A matching procedure for simulating photons using both ME calculations (for hard emissions) and ISR structure function (for soft emissions) has been developed for Whizard [9, 10], a Monte Carlo generator incorporating many features important for future lepton colliders, including beam polarisation, beamstrahlung, and ISR spectra. We followed and extended this approach to account for effects present for hadronic final states. For this purpose, the internal interface of Whizard to PYTHIA 6 [12] was employed to include parton showers and hadronisation. In the future, we plan to compare our results with those from PYTHIA 8 [13], Herwig 7 [14], and KKMC 5 [15] to assess systematic uncertainties coming from the Monte Carlo modelling.

The matching in [11] relied on two variables, q_- and q_+, defined as

$$q_- = \sqrt{4E_0 E_\gamma} \, \sin \frac{\theta_\gamma}{2} \,,$$
$$q_+ = \sqrt{4E_0 E_\gamma} \, \cos \frac{\theta_\gamma}{2} \,, \tag{8}$$

where E_0 is the nominal beam energy, E_γ is the energy of the emitted photon, and θ_γ is its emission angle. The variable q_- (q_+) corresponds to the virtuality of a single photon emitted from the electron (positron) line. The procedure assumes that all the photons with $q_\pm > 1$ GeV and $E_\gamma > 1$ GeV are generated via fixed-order calculations, while all the softer emissions are taken into account via the built-in ISR structure function in Whizard. As shown in figure 2 taken from [11], the procedure allows for restoring similar photon multiplicities as those obtained in KKMC [16], a Monte Carlo code for $e^+e^- \to f\bar{f}$ employing the YFS exponentiation [17] for exclusive photon emissions.

(a) All generated photons   (b) Hard photons only
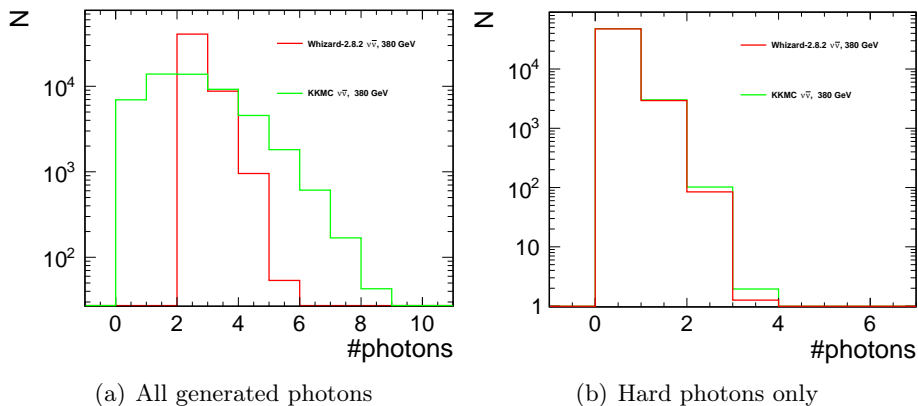
Fig. 2. Distributions of the photon multiplicities for the process of $e^+e^- \to \nu\bar{\nu}$ at the collision energy of 380 GeV simulated in Whizard and KKMC (the Z-pole run was not considered in that study [11]). The left plot shows the multiplicity for all photons generated by the MC codes and the right one, the multiplicity of the photons passing selection criteria ("hard photons", observable in the detector). As the final state is electrically neutral, only initial-state photons are expected in this process. The distributions are normalised to the number of events expected for an integrated luminosity of 1 fb^{-1}.

The procedure described above has been developed for dark-matter pair-production, *i.e.* for the case when final-state particles have been assumed to be chargeless (electrically neutral and colourless). When considering

hadronic Z decays, QCD and QED showers need to be included for the hadronic final state and thus, the procedure had to be extended. For the separation of *hard* and *soft* final-state radiation domains, we use an additional criterion based on the invariant mass of the photon-jet pairs, $M_{\gamma j}$. The *hard* photons, *i.e.* those fulfilling all the criteria simultaneously

— $q_\pm > 1$ GeV,

— $E_\gamma > 1$ GeV,

— $M_{\gamma j_{1,2}} > 1$ GeV

were generated using fixed-order ME calculations and *soft* photons (not meeting at least one of the criteria) were simulated via the internal structure function (for ISR) and the PYTHIA 6 parton shower (for FSR). Events with at least one ISR or FSR photon passing *hard* photon selection were rejected (the matching procedure was established to avoid double counting). In figure 3, we show the fraction of rejected events for different quark flavours (normalised to the cross section per flavour) for ISR and FSR. As expected, the rejection efficiency for ISR does not depend on the quark flavour, while the rejection efficiency for FSR distinguishes up- and down-type quarks and differs by a factor of 4 between the two cases, which corresponds to the difference in the quark charge squared.
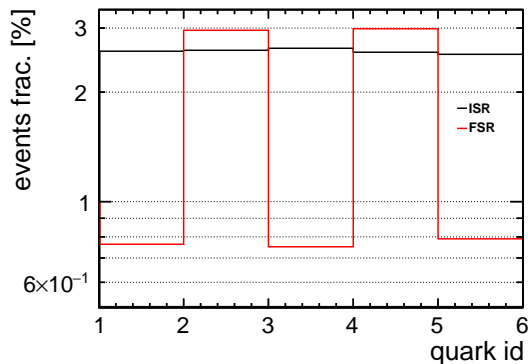

Fig. 3. (Colour on-line) Fraction of events rejected by the matching procedure for different quark flavours (normalised to the cross section per flavour) for ISR (black) and FSR (red/grey).

4. Analysis procedure

As explained in the previous section, measurable photons originate from different processes, including ISR, FSR, and hadronisation. The matching procedure developed for this study allows for removing double counting of

photons generated explicitly at fixed order and those coming from structure functions and showers. However, the separation of the FSR photons, providing insight into quark charges and thus, opening the path towards flavour tagging, has to be handled at the analysis level to emulate physical conditions of future experiments. At the Z pole, the contribution from ISR is strongly suppressed due to the small phase space for photon emissions. However, the impact of photons coming from hadronic decays is non-negligible and forms the main part of the background in this analysis.

To illustrate the issue, we generated 0- and 1-ME-photon samples in Whizard 3.1 according to the matching procedure described above. Higher photon multiplicities have been neglected for now, as the cross section for the 2-ME-photon sample is about 30 times smaller than that for the 1-ME-photon sample. We performed a fast detector simulation with Delphes 3.5 [18] using the default *ILCgen* cards employing the Durham algorithm [19] in the exclusive two-jet mode. For analysis, we accepted only two-jet events with exactly one reconstructed photon with transverse momentum $p_\gamma^{\mathrm{T}} > 2$ GeV and pseudorapidity $|\eta| < 2.5$. More stringent cuts can help reject photons coming from hadronisation and their optimisation has been left for future studies.

In figure 4, we compare cross sections for 0- and 1-ME-photon samples taking into account photons coming from hadron decays, as well as all the reconstructed photons. The comparison clearly shows that photons in the 0-ME-photon sample originate entirely from decays of neutral hadrons, while in the 1-ME-photon sample, they form only about 10% of all the photons. The composition of the hadron-decay background for different quark flavours
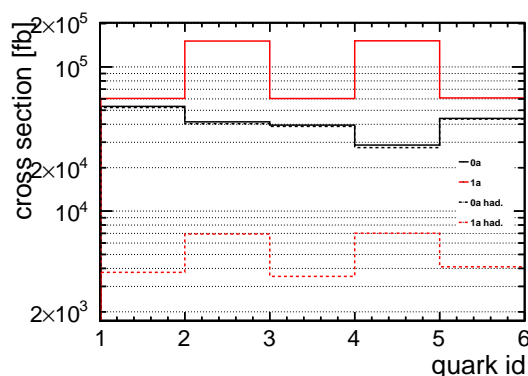

Fig. 4. (Colour on-line) Cross sections for 0- (black) and 1-ME-photon (red/grey) samples for different quark flavours. The solid lines indicate all the reconstructed events, while the dashed lines stand for the photons coming from hadron decays only.

for the 0-ME-photon sample is presented in Table 1. For all the flavours, π^0 decays are dominant; another important contribution comes from η decays. For the heavy quarks, one also has to include D- and B-meson decays.

Table 1. Composition of the hadron-decay background for different quark flavours for the 0-ME-photon sample, based on the hadronisation model implemented in PYTHIA 6.

[%]	d	u	s	c	b
π^0	94	94	94	93	88
η	4.5	4.5	4.3	3.7	3.6
D mesons	—	—	—	1.9	2.0
B mesons	—	—	—	—	5.6

The severe background coming from hadron decays points towards the necessity of elaborated studies not only on the analysis cuts but also on the dedicated photon reconstruction criteria. As elucidated in Section 2, the isolation parameter y_{cut} can be chosen arbitrarily, for instance, to minimise the systematic error of the measurement. We plan to optimise the reconstruction criteria in the future.

5. Conclusions and outlook

Future e^+e^- colliders operating at the Z pole will effectively constrain the Standard Model parameters. Thanks to very high data statistics, they can allow for performing precision measurements of the Z-boson couplings to fermions, including those of light quarks. In our study, we established a dedicated generation procedure accounting for photons coming from different sources, including ISR, FSR, hadronisation, and hadron decays. We performed preliminary studies on the experimental cuts and their efficiency. In the next steps, we plan to study photon isolation criteria, which are crucial for reducing the background originating from decays of neutral particles, and the uncertainty coming from the Monte Carlo simulation. The ultimate goal of the study is to estimate the uncertainty of the measurement at different future machines depending on the reconstruction criteria and experimental cuts.

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