Prospects for constraining light-quark electroweak couplings at Higgs factories

Krzysztof Mękała[1,2,*], *Daniel* Jeans[3], *Jürgen* Reuter[1], *Junping* Tian[4], and *Aleksander Filip* Żarnecki[2]

[1]Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[2]Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
[3]KEK, 1-1 Oho Tsukuba, Ibaraki 305-0801, Japan
[4]International Center for Elementary Particle Physics ICEPP, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Abstract. 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 e^+e^- colliders running at the Z-pole and around the ZH threshold would be an excellent tool to perform such a measurement, unlike the LHC where hadronic Z decays are only available in boosted topologies. The measurement is based on comparison of radiative and non-radiative hadronic decays. Due to the difference in quark charge, the relative contribution of the events with final-state radiation (FSR) directly reflects the ratio of decays involving up- and down-type quarks. Such an analysis requires proper modeling and statistical discrimination between photons coming from different sources, including initial-state radiation (ISR), FSR, parton showers and hadronisation. In our contribution, we show how to extract the values of the Z couplings to light quarks and present the estimated uncertainties of the measurement.

1 Motivation

The Standard Model (SM) of particle physics describes fundamental interactions in the most successful way. Even though it efficiently explains data from various experiments, several cosmological observations, including the density of dark matter or the baryon-antibaryon asymmetry, suggest that it is not the ultimate theory. Moreover, the SM is a theory consistent with data only when many internal parameters, such as particle masses and couplings, are set to some particular values. They have to be measured experimentally and thus, precision studies are needed to complete our knowledge of the SM and possibly find any discrepancies hinting towards more general models explaining the observations not explained by the SM.

Electroweak precision observables allow for probing the parameters of this theory, including couplings of the fermions to photons, Z and W bosons. The experiments at LEP achieved permille precision in some measurements; for instance, the partial width of the Z-boson decaying into $b\bar{b}$ pairs has been constrained to 0.3%, while the partial width for the c-quark

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[*] e-mail: k.mekala@uw.edu.pl

channel is known up to 1.7% [1]. Modern heavy-quark tagging algorithms are expected to help to improve these results at future colliders. However, due to the lack of proper tagging algorithms, measurements for light quarks are challenging and the couplings have only been weakly constrained. An alternative approach is required; one can study hadronic decays employing radiative and non-radiative signatures which are dominated by different quark types due to the difference in their couplings and charges. Future Higgs factories operating at the Z-pole would produce 10^9 – 10^{12} Z bosons and offer an excellent environment for such studies. In this talk, we presented prospects for measuring the light-quark couplings at colliders of this type.

2 Measurement idea

A similar measurement has already been performed at LEP [2–6]. The main idea relies on the fact that up- and down-type quarks differ in electric charge and thus, their electromagnetic couplings are distinguishable. 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. In the SM, they are expressed in terms of the third component of the fermion weak isospin ($I_{3,f}$) and its charge (Q_f):

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

where θ_W stands for the weak mixing angle. The total width of the Z boson to hadrons, Γ_{had}, is given at first order in α_s by

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

where N_c is the number of colours, G_μ is the Fermi constant, M_Z is the mass of the Z boson and c_d (c_u) is the coupling to down-type (up-type) quarks [3, 6]. For simplicity, we assume all couplings are universal among quarks of the same type but the assumption can be lifted by including heavy-flavour tagging. The total width to radiative hadronic decays, $\Gamma_{had+\gamma}$, can be expressed as

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

where $f(y_{cut})$ 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 potentially be disentangled.

Using the above, the hadronic cross section for $Z \to q\bar{q}$, $q = u, d, s, c, b$, can be expressed as

$$\sigma_{Z\to had} = C_1 \cdot (3c_d + 2c_u), \tag{5}$$

where C_1 is a constant. Similarly, the radiative hadronic cross section is given by

$$\sigma_{Z\to had+\gamma} = C_2 \cdot (3c_d + 8c_u), \tag{6}$$

where C_2 is another constant (assuming the photon isolation criteria are fixed). By fitting the experimental data to theoretical calculations and simulations, the values of C_1 and C_2 can be extracted, and one can disentangle c_d and c_u.

3 Simulation of events

A realistic and precise Monte Carlo simulation is crucial for the measurement. The process of $e^+e^- \to q\bar{q}$ is often perceived as a benchmark point for Monte Carlo generators. However, the reconstruction of isolated photons poses several challenges. Not only does the final-state photon radiation (FSR) from Matrix Elements (ME) have to be included but also the initial-state radiation (ISR), as well as their matching to parton showers and hadronisation modeling. 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 issue has been investigated in [7] 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 [8, 9], a Monte Carlo generator incorporating many features suitable for future lepton colliders, including beam polarisation, beamstrahlung and ISR spectra. We follow and extend this approach to include effects occurring for hadronic final states. Partonic-level events are generated with Whizard and Pythia 6 [10] is employed to simulate parton showers and hadronisation. In the future, we plan to compare our results with those from Pythia 8 [11], Herwig 7 [12] and KKMC 5 [13] to assess systematic uncertainties coming from the simulation.

The matching in [7] relies on two variables, q_- and q_+, defined as:

$$
\begin{aligned}
q_- &= \sqrt{4E_0E_\gamma}\,\sin\frac{\theta_\gamma}{2},\\
q_+ &= \sqrt{4E_0E_\gamma}\,\cos\frac{\theta_\gamma}{2},
\end{aligned}
$$

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. According to the procedure, all the photons with $q_\pm > q_{min}$ and $E_\gamma > E_{min}$ are generated via fixed-order calculations while all the softer emissions are modeled via the built-in ISR structure function in Whizard.

The procedure described above has been developed for chargeless particles in the final state (electrically neutral and colourless). As for the hadronic Z decays, the procedure has to be extended to include QCD and QED showers. 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:

- $q_\pm > 0.5$ GeV,
- $E_\gamma > 0.5$ GeV,
- $M_{\gamma j_1},\ M_{\gamma j_2} > 1$ GeV,

are generated using fixed-order ME calculations and *soft* photons (those not meeting at least one of the criteria) are simulated via the internal structure function (for ISR) and the Pythia6 parton shower (for FSR). Events with at least one ISR or FSR photon passing *hard* photon selection are rejected to avoid double counting. Figure 1 shows the fraction of rejected events with no photons generated at the matrix-element level (the “0-ME-photon sample”) for different quark flavours (normalised to the cross section per flavour) for ISR and FSR. As expected, the rejection efficiency for the ISR does not depend on the quark flavour while the rejection efficiency for the 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.

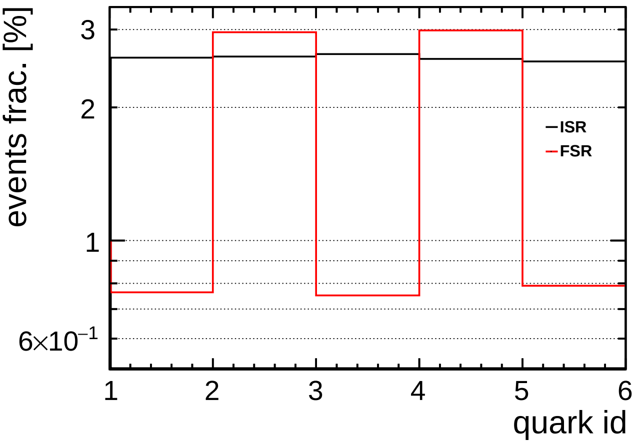

Figure 1. The fraction of events rejected by the matching procedure for different quark flavours (normalised to the cross section per flavour) for ISR (black) and FSR (red)

4 Analysis procedure

At the Z-pole, the contribution from ISR is 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. Thus, the photon reconstruction criteria shall be optimised to enhance the contribution from events with proper FSR photons.

Working at the generator level, we define the photon isolation parameter to be

$$y_{cut} = E_\gamma \sin\theta^{min}_{\gamma q_i}, \tag{7}$$

where E_γ is the photon energy and $\theta^{min}_{\gamma q_i}$ is the angle between the photon and the closest quark. The variable corresponds to the photon transverse momentum with respect to the quark direction.

To illustrate the distribution of the variable, we generated 0-, 1- and 2-ME-photon samples in WHIZARD 3.1 according to the matching procedure described above. Higher photon multiplicities have been neglected, as the cross section for the 2-ME-photon sample is already about 30 times smaller than that for the 1-ME-photon sample. The detector acceptance was mimicked by considering only those events with exactly one reconstructed photon with transverse momentum $p^T_\gamma > 5$ GeV and pseudorapidity $|\eta| < 2.5$, corresponding to the angular acceptance between about 10° and 170°. Proper assessment of detector effects has been left for future studies. Figure 2 shows the distribution of u- and d-type events with exactly one reconstructed photon for the y_{cut} set to a given value. The number of events corresponds to a future e^+e^- collider collecting 100 fb^{-1} of data. For low values of y_{cut}, the total distribution is dominated by the 0-ME-photon sample (for which the reconstructed photons come from hadronisation) while for larger values the 1-ME-photon sample becomes dominant. One can assume that a reasonable cut value should be close to about 10 GeV.

The effect of changing the detector-acceptance cuts to other values can be seen in Figure 3. The figure shows the ratio of the u- and d-type events as a function of y_{cut} for different cuts

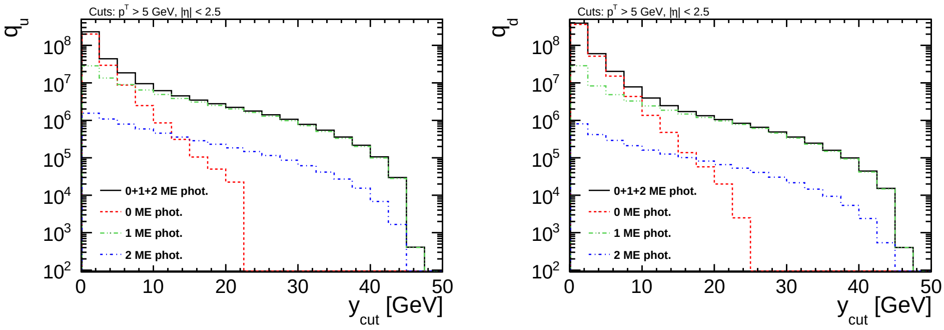

Figure 2. The distribution of the u- (left) and d-type (right) events as a function of y_{cut}. The black solid line stands for all the events, the red dashed one for the 0-ME-photon sample, the green dash-double-dotted one for the 1-ME-photon samples and the blue dash-dotted one for the 2-ME-photon sample.

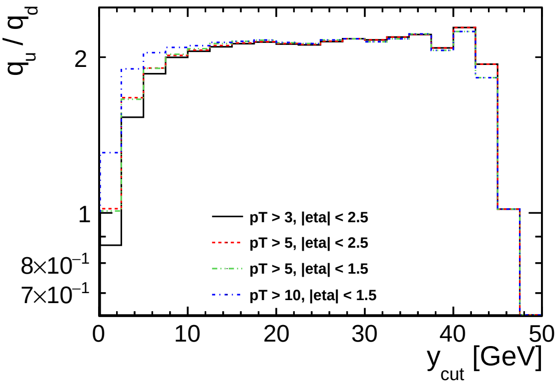

Figure 3. The ratio of the u- and d-type events as a function of y_{cut} for different detector acceptance cuts: ($p_\gamma^T > 3$ GeV, $|\eta| < 2.5$) – black solid line, ($p_\gamma^T > 5$ GeV, $|\eta| < 2.5$) – red dashed line, ($p_\gamma^T > 5$ GeV, $|\eta| < 1.5$) – green dash-double-dotted line, ($p_\gamma^T > 10$ GeV, $|\eta| < 1.5$) – blue dash-dotted line.

on the transverse momentum and pseudorapidity. The expected value

$$\frac{q_u}{q_d} = \frac{2}{3} \cdot \left(\frac{Q_u}{Q_d}\right)^2 \cdot \frac{c_u}{c_d} \approx 2.1 \tag{8}$$

is restored, irrespectively of the particular value of the detector cuts, confirming the reasonable cut value to be above 10 GeV.

5 Conclusions and outlook

Future e^+e^- colliders operating at the Z-pole will further constrain the Standard Model parameters. Precision measurements of the Z-boson couplings to fermions will be possible thanks to very high data statistics. In this study, we established a dedicated event generation procedure including photons coming from different sources – ISR, FSR, hadronisation and hadron decays. We studied photon isolation criteria preliminarily. We expect to extend the analysis to consider experimental effects and ultimately, estimate the uncertainty of the measurement of $u-$ and $d-$type-quark couplings to the Z boson at various future machines operating at different energy stages and elaborate on the reconstruction criteria and selection cuts.

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