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Z-boson couplings to quarks at Higgs factories

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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 e^+e^- colliders running at the Z pole 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 measurement uncertainties.

This work was carried out in the framework of the ILD Concept Group

Contents

1 Introduction

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. Furthermore, 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 included in the SM.

Future Higgs factories operating at the Z-pole would produce $10^9 - 10^{12}$ Z bosons, allowing for precise measurement of the Z-boson couplings to fermions. In this contribution, we present prospects for measuring electroweak couplings of quarks, especially highlighting the measurement for light quarks.

2 Measurement idea

A similar measurement has already been performed at LEP [1–5]. 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, c_f, is conventionally defined as a sum of its squared vector and axial couplings. The total width of the Z boson to hadrons, Γ_{had}, is proportional to the sum of the couplings for down- and up-type quarks:

$$\Gamma_{had} \sim (3c_d + 2c_u). \tag{1}$$

Analogously, the total width to radiative hadronic decays for exactly one photon emission, $\Gamma_{had+\gamma}$, scales as

$$\Gamma_{had+\gamma} \sim \frac{\alpha}{2\pi} f(y_{cut}) \left(3Q_d^2 c_d + 2Q_u^2 c_u\right), \tag{2}$$

where α is the electromagnetic coupling constant, $f(y_{cut})$ is a form factor depending on an arbitrary parameter y_{cut} incorporating the isolation criteria for photons and Q_d (Q_u) is the electric charge of down-type (up-type) quarks. In the following, we will assume y_{cut} is the photon transverse momentum with respect to the jet direction, q^T. 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.

In our approach, we collect two-jet events inclusively and classify them into 10 categories, corresponding to all the combinations of 4 possible jet tags ("light", s, c, b). Additionally, we tag events with exactly one isolated photon. To estimate the statistical precision, we fit cross sections to minimise the χ^2-test statistic by comparing the numbers of expected and "measured" events, where the second number is drawn from the Poisson distribution.

3 Monte Carlo event generation

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, but the reconstruction of isolated photons

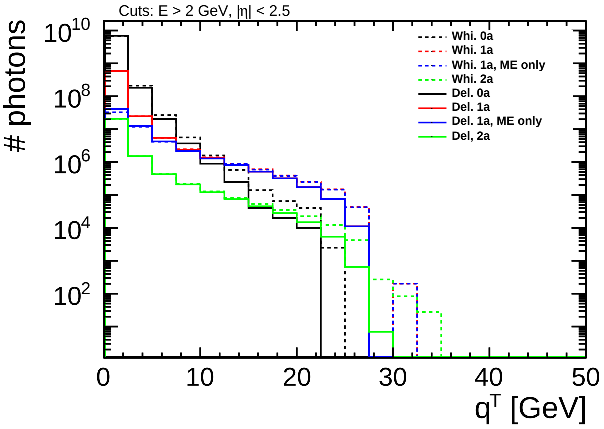

Figure 1: The number of photons visible in the detector as a function of q^T. See text for details.

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. Building upon [6], we have developed a dedicated matching procedure for simulating photons using both ME calculations (for hard emissions) and ISR structure function and FSR showers (for soft emissions) in WHIZARD [7, 8].

4 Experimental prospects

The difference in quark charges affects only the photons emitted from the final state and hence, experimental selection should be optimised to enhance the numbers of measured photons of this kind and suppress the other contributions (ISR and decays of hadronisation products). To simulate detector effects, we used DELPHES 3.5.0 [9] with the *ILCgen* cards. The steering cards were modified to cluster all the photons into jets. It allowed for testing photon isolation criteria independently of the current assumptions.

In Figure 1, we compare the distributions of photons at the generator and detector level for different generated photon multiplicities. Besides the distributions for 0, 1 and 2 ME-photon samples, we plot the distribution of the 1 ME-photon sample when only "proper" photons (those generated in the full ME picture, not coming from showers or hadronisation) are tagged. The plot shows that above 10 GeV, the 1-ME-photon sample becomes dominant.

To optimise the cut, we studied 7 sources of uncertainties: luminosity of 0.01%, acceptance of radiative (non-radiative) events of 5% (50%), and tagging of b jets of 1%, c jets of 2%, s jets of 5%, light quarks of 10%. The assumptions are preliminary and were used as a “proof of concept” of our statistical framework. Figure 2 shows preliminary results for the uncertainty of the measurement of the couplings and the ratio of light-quark couplings, depending on the cut on q^T. The precision reaches the sub-percent level for light quarks (u and d) and the sub-permille level for heavier quarks. The study will be continued to estimate the uncertainties in greater detail.

5 Conclusions

Future e^+e^- colliders operating at the Z-pole will further constrain the Standard Model parameters. Precision measurements of the Z-boson couplings to quarks 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 and estimated the statistical and systematic uncertainties of the measurement. Preliminary results suggest that a sub-percent precision will be achievable for light quarks while for heavier quarks, a sub-permille precision is envisioned.

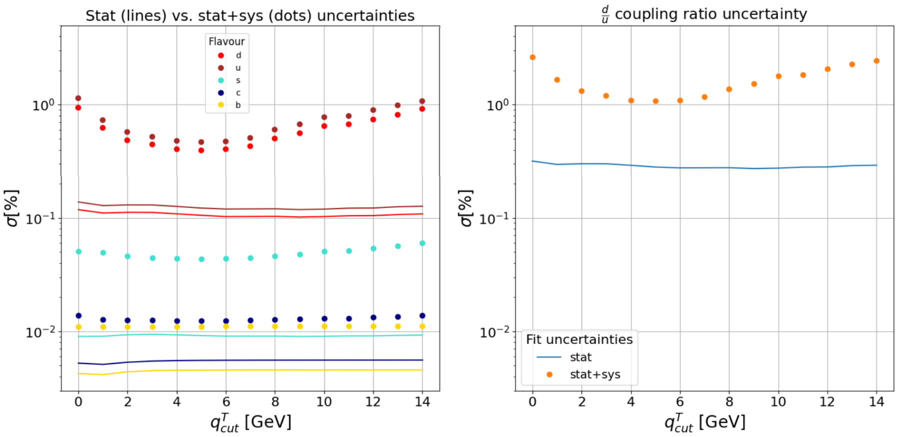

Figure 2: Preliminary results for the uncertainty of the Z-boson couplings to quarks (left) and the ratio of the u and d couplings (right) as a function of the cut on q^T. Solid lines indicate statistical precision only, while dots stand for a sum of statistical and systematic uncertainties.

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