NON ABELIAN GAUGE COUPLINGS IN
FOUR FERMION PROCESSES AT LEP

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The LEP data on four fermion processes are presently used to study the non abelian gauge couplings of the Standard Model. The present theoretical error for two classes of processes, single-$W$ production and radiative four fermion final states, is discussed according to the results of the four fermion working group of the LEP2 Monte Carlo Workshop held at CERN.

1 Introduction

The center of mass (c.m.) energy reached at LEP2 allows to test directly the non abelian gauge couplings in $e^+e^-$ collisions. The most copiously produced final states are four fermion final states, which, apart from being very important in the measurement of the $W$ properties such as mass and width\footnote{Presented by Fulvio Piccinini at IVth Rencontres du Vietnam: International Conference on Physics at Extreme Energies (Particle Physics and Astrophysics), Hanoi, Vietnam, 19-25 July 2000.}, contain information on the interactions among the gauge vector bosons. In order to study the trilinear gauge couplings, also other processes are presently considered, such as single-$W$ production and $e^+e^-\rightarrow\nu\bar{\nu}\gamma$. These two processes are very sensitive to the $WW\gamma$ vertex and are useful to disentangle the $WWZ$ from the $WW\gamma$ interactions present in the four fermion final states. At present also hypothetical self-interactions among the neutral vector bosons are looked for in the LEP experiments through the analysis of the neutral current four fermion final states and the radiative fermion pair production. At LEP there is also the opportunity to directly study, for the first time in $e^+e^-$ collisions, the quartic gauge couplings, which are a window on the symmetry breaking mechanism. In particular, the quartic vertices involving at least one photon can be studied through the analysis of the radiative four fermion...
processes, the $\gamma\gamma + E$ and the $f\bar{f}\gamma\gamma$ final states. In order to establish possible departures from the Standard Model (SM) predictions of the gauge boson self-interactions, it is extremely important to have sufficiently precise theoretical predictions to exploit the experimental precision. For this reason, within the four fermion working group of the LEP2 Monte Carlo Workshop, the $4f$, single-$W$ and $4f + \gamma$ final states have been studied with the aim of assessing the present theoretical accuracy of the SM predictions. In the present contribution some issues related to single-$W$ and radiative four fermion final states will be reviewed.

2 Single-$W$

Being the foreseen accuracy of final LEP2 data of the order of few per cent, all the theoretical effects on this scale need to be taken into account in the calculations. Due to the particular kinematical configuration with one electron/positron in the very forward region, the single-$W$ process is very challenging from the theoretical point of view. Actually it requires a massive treatment of the phase space and of the matrix element, due to strong cancellations in the region of the very small electron/positron scattering angles.

Several programs have been developed to treat this particular process, such as CompHEP, GRACE, NEXTCALIBUR, SWAP, WHACT, WTO, each of them adopting an independent approach for the calculation of the matrix element and of the kinematics. Such a plethora of programs allowed to reach a very high technical precision, at the 0.1% level, after careful tuned comparisons. In order to avoid integration singularities, it is mandatory to include the gauge boson width in the propagator. In general this introduces a violation of gauge invariance. This problem has been extensively studied and several options to address it have been explored. The most theoretically appealing procedure is the fermion loop scheme, which preserves $U(1)$ and $SU(2)$ Ward identities. Recently, this scheme has been generalized to the case of massive external fermions, both in its minimal version, which considers the imaginary parts of the fermion loops (IFL), and in its full realization with real and imaginary parts. In particular, a numerical investigation has been performed, showing no significant difference between the IFL and the fixed width scheme, even in the region most sensible to $U(1)$ gauge invariance, thus justifying the use of the fixed width for simplicity reasons. The complete fermion loop scheme, containing also the real part of the corrections, allows to evaluate the effects of the running couplings, which in the case of single-$W$ amount to about 5-7%, depending on the channel and the adopted selection criteria. However, being the leading dynamics given by the $W$ fusion diagram and by the $W$ bremsstrahlung diagram, with a $t$-channel photon, it is quite natural to ascribe the main contribution of the correction to the running of the electromagnetic coupling $\alpha_{QED}$. According to this, a simple prescription follows, which amounts to calculate the matrix element with the FW scheme, and rescale the differential cross section as $d\sigma/dt \to (\alpha^2(t)/\alpha^2_{G_F}) d\sigma/dt$, where $\alpha_{G_F}$ is the electromagnetic coupling calculated according to the input parameter scheme, while $\alpha(t)$ is the coupling calculated at the typical scale of the process. This very simple prescription have been proved to work very well for the semileptonic signature, with high invariant mass cut (which is a realistic event selection), while it differs of about 2% for the fully leptonic sample, for the cuts which enhance the contribution of the peripheral diagrams. This difference is however of the order of the intrinsic precision of the fermion loop scheme.

A further relevant issue is given by radiative corrections due to photon radiation. Given the particular kinematical configuration of the single-$W$ process with a charged particle lost in the beam pipe, the question naturally arises whether a Leading Log (LL) description is meaningful. Actually, by looking at the tree-level differential distribution of the virtual photon four-momentum transfer $t$, the largest part of the events are characterized by a ratio $t/m_e^2 \gg 1$. This allows to adopt the LL approximation, where, according to the factorization theorems, the
QED corrected cross section of a generic process can be written as a convolution of the form

$$\sigma = \prod_i \int dx_i D(\Lambda_i^2, x_i) \sigma_0,$$

where the index $i$ denotes a generic charged external line. The choice of the scales $\Lambda_i$ is not dictated by general arguments. A generally adopted attitude is given by the comparison of the $O(\alpha)$ expansion of the above convolution with a diagrammatic calculation which reproduces the correct LL contribution. Typical simple examples are $e^+e^- \rightarrow f\bar{f}$, with $f \neq e$ and Bhabha scattering, for which an exact $O(\alpha)$ perturbative calculation exist. In the case of single-$W$ production, the exact $O(\alpha)$ perturbative calculation is still missing, so a general strategy for the evaluation of the scales $\Lambda_i$ is needed. As a first step, a LL diagrammatic calculation, taking into account soft and collinear photon bremsstrahlung and its virtual counterpart, and, in the case of a calorimetric measurement of the energy of the final-state (FS) particles, also hard radiation collinear to the FS particles themselves, can be performed. Then the comparison between the result of such a calculation and the $O(\alpha)$ expansion of the SF QED corrected cross section allows to fix the scales $\Lambda_i$. If a calorimetric measurement of the energies of the FS particles is performed, only the IS legs need to be corrected by the SF’s. Furthermore, since the electron is scattered in the very forward region, the interference between the electron line and the rest of the process is very small. This allows a natural sharing of the logarithms between the two SF’s associated to the colliding electron and positron, whose scales read

$$\Lambda_-^2 = 4E^2 \frac{(1-c_-)^2}{\delta^2}, \quad \Lambda_+^2 = 2 \frac{4}{9} E^2 \frac{(1-c_d)(1-c_u)^2}{(1-c_{ud})^2 \delta^2},$$

where $\delta$ is the half-opening angle of the calorimetric resolution. By using the above scales in the calculation of the total cross section leads to a QED correction of about 7-8%, depending on the c.m. energy, lower (higher) of about 4% with respect to a calculation which adoptes $s$ ($t$) as scale for both SF’s. Similar quantitative conclusions have been reached independently by the GRACE group.

To summarize, the total theoretical error associated with single-$W$ production has been conservatively estimated within the four fermion working group to be $\pm 5\%$, even if some authors consider realistic a theoretical error of the order of $3\%$.

3 Radiative four fermion processes

Also in the case of $4f + \gamma$ final states, several computational tools have been developed, such as CompHEP, GRACE, NEXTCALIBUR, PHEGAS/HELAC, RacoonWW, WRAP. By means of these programs a technical precision at the 0.1\% level has been reached in cross sections as well as distributions. The tuned comparisons have been performed by adopting the massless approximation for the outgoing fermions. However, fermionic mass terms can become important, due to the collinear “singularities” associated with photons emitted from the external legs, i.e. fermion mass effects are expected to be relevant for small angular separation cuts photon-charged fermions. For instance, for the process $e^+e^- \rightarrow \mu^+\nu_\mu c\bar{s}\gamma$ at $\sqrt{s} = 200$ GeV and with a minimum angle of $5^\circ$ between photon and quarks, the relative difference between a massless calculation and a massive one is $1.9\%$ for $\theta_{\min}^{\gamma\mu} = 1^\circ$, and reaches $9.3\%$ for $\theta_{\min}^{\gamma\mu} = 0.1^\circ$. Moreover, in the case of a final state muon, the separation cut can realistically be even $0^\circ$, and only a massive calculation can deal with this phase space region.

Due to the presence of an observed photon in the final state, the treatment of initial state radiation (ISR) (which in the LEP2 energy range gives a reduction of the cross section of the order of $15\%$) in terms of collinear SF’s can become inadequate because affected by multiple counting
between the pre-emission photons, described by the SF’s, and the observed one, described by the hard-scattering matrix element. A general strategy to deal with such a problem has been proposed for the $\nu\bar{\nu}\gamma$ final states, by using $p_\perp$ dependent SF’s \cite{15}. The same approach has been adopted in the code WRAP \cite{14}, to deal with the signature $4f + \gamma$. As a result of a preliminary investigation, i.e. by neglecting the contribution of final state radiation, the multiple counting contained in the predictions obtained with collinear SF’s, affects the theoretical prediction at the 5\% level with a minimum angle between charged fermions and photon of 10$^\circ$ and $E_\gamma^\text{min} = 1\text{ GeV}$\cite{14}. Summarizing, the present theoretical error on radiative four fermion final states has been estimated to be at the 2.5\% level, due to the unknown missing non logarithmic terms of an exact $O(\alpha)$ calculation, to be compared with a final expected experimental error at the 5\% level, obtained by combining the data of the four LEP experiments.

4 Conclusions

At LEP there is the opportunity to directly measure the trilinear and quadrilinear gauge couplings, through the analysis of several processes. In order to fully exploit the experimental precision, the theoretical predictions should be known with the highest possible accuracy. To this aim, at CERN it has been held in 1999 the four fermion working group of the LEP2 Monte-Carlo Workshop, where the present theoretical accuracy of the (SM) predictions has been discussed for several processes. In this contribution some theoretical aspects concerning single-$W$ production and radiative four fermion final states have been reviewed. In particular, as far as single-$W$ is concerned, the issue of gauge invariance, the effect of the running couplings and the proper scales in the SF’s for the treatment of ISR have been discussed, summarizing the most recent work yielding a conservative estimate of the theoretical error of $\pm$5\%. Regarding the $4f + \gamma$ final states, the effects of finite fermion masses and the problem of the correct treatment of ISR have been pointed out. The resulting theoretical error can be estimated to be of the order of 2.5\%.

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