QED Radiative Correction for the Single-W Production using a Parton Shower Method

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Abstract
A parton shower method for the photonic radiative correction is applied to the single W-boson production processes. The energy scale for the evolution of the parton shower is determined so that the correct soft-photon emission is reproduced. Photon spectra radiated from the partons are compared with those from the exact matrix elements, and show a good agreement. Possible errors due to an inappropriate energy-scale selection or due to the ambiguity of energy scale determination are also discussed, particularly for the measurements on triple gauge-couplings.
1 Introduction

Single-$W$ production processes present an opportunity to study the anomalous triple gauge-couplings (TGC)\cite{1} in the experiments at LEP2 and at future $e^+e^-$ linear colliders. For their precise predictions of cross sections the inclusion of an initial state radiative correction (ISR) is inevitable in the event-generator. As a tool for the ISR the structure function (SF)\cite{2} and the parton shower (PS)\cite{3} methods have been widely used for $e^+e^-$ annihilation processes. For the case of the single-$W$ production processes, however, the main contribution comes from non-annihilation type diagrams. The universal factorization method used for the annihilation processes is obviously inappropriate. The main problem lies in choosing the energy scale of the factorization. A previous study on the two photon process\cite{4} has shown that the SF and QED parton shower (QEDPS) methods are able to reproduce precisely the exact $O(\alpha)$ results even for non-annihilation processes, as long as the appropriate energy scale is used.

In this report a general method to find the energy scale for SF and QEDPS is proposed. Then numerical results of testing SF and QEDPS for $e^-e^+\to e^-\bar{\nu}_e u\bar{d}$ and $e^-e^+\to e^-\bar{\nu}_\mu \mu^+\nu_\mu$ are presented. Systematic errors are also discussed.

2 Calculation method

2.1 Energy Scale Determination

The factorization theorem for QED radiative corrections in the leading-logarithmic approximation is valid independent of the structure of the matrix element of the kernel process. Hence SF and QEDPS must be applicable to any $e^+e^-$ scattering processes. However, choice of the energy scale in SF and QEDPS is not a trivial matter\cite{11}. For simple processes considered so far like $e^+e^-$ annihilation and two-photon process with only multi-peripheral diagrams, the evolution energy scale could be found by the exact perturbative calculations. However, this is not always the case when more complicated processes are concerned. Hence a way to find a suitable energy scale without knowing exact loop calculations should be established somehow.

First let us look at the general consequence of the soft photon approxi-
The cross section with radiations in the soft-photon limit is given by the Born cross section multiplied by the following factor up to the double-log term as [6]

\[
\frac{d\sigma_{\text{soft}}(s)}{d\Omega} = \frac{d\sigma_0(s)}{d\Omega} \times \exp \left[ -\frac{\alpha}{\pi} \ln \left( \frac{E}{k_c} \right) \sum_{i,j} e_ie_j \eta_i \eta_j \ln \left( \frac{1 + \beta_{ij}}{1 - \beta_{ij}} \right) \right]^2, \quad (1)
\]

where \( m_j(p_j) \) are the mass(momentum) of the \( j \)-th charged particle, \( k_c \) the maximum energy of the soft photon(the value to separate soft- and hard-photons), \( E \) the beam energy and \( e_j \) the electric charge in unit of the \( e^+ \) charge. The factor \( \eta_j \) is \(-1\) for the initial particles and \(+1\) for the final particles. The indices \((i, j)\) run over all the charged particles in the initial and final states.

For the two-photon process, \( e^-(p_-)e^+ (p_+) \rightarrow e^-(q_-)e^+ (q_+)\mu^- (k_-)\mu^+ (k_+) \), it is shown in ref.[4] that the soft-photon factor in Eq.(1) with a \((p_- \cdot q_-)\)-term reproduces the \( O(\alpha) \) corrections\[7\] up to the double-log term in the soft-photon limit. This implies that one is able to read off the possible evolution energy scale in SF from Eq.(1) without doing explicit loop calculations\[6\]. The point is the observation that the energy scale \( s = (p_- + p_+)^2 \) does not appear in the soft-photon corrections even they are included in the general formula Eq.(1). In the case of the two-photon process we have ignored those terms in SF which come from the photon bridged between different charged lines, because the contributions from the box diagrams with a photon exchange between \( e^+ \) and \( e^- \) is known to be small\[4\]. Fortunately the infrared part of the loop corrections is already included in Eq.(1) and there is no need to know the full form of the loop diagram. Let us look at two terms with, for example \((p_- \cdot p_+)\)- and \((q_- \cdot p_+)\)-terms. The momentum of \( e^- \) is almost the same before and after the scattering\( (p_- \approx q_-) \). Only the difference appears in \( \eta_j \eta_k = +1 \) for a \((p_- p_+)\)-term and \( \eta_j \eta_k = -1 \) for a \((q_- p_+)\)-term. Then these terms compensate each other after summing them up for the forward scattering which is the dominant kinematical region of this process. This is

\[\text{A similar idea is independently proposed by Montagna et al. in[8].}\]
the mechanism that the energy scale \( s = (p_- + p_+)^2 \) does not appear in the soft-photon correction despite that it exists in Eq. (1).

When some experimental cuts are imposed, for example the final \( e^- \) is tagged in a large angle, this cancellation is not perfect but partial and the energy scale \( s \) must appear in the soft-photon correction. In this case the annihilation type diagrams will also give a contribution. Then it may happen that the usual SF and QEDPS for the annihilation processes are justified to be used for the ISR with the energy scale \( s \). To find the most dominant energy scale under the given experimental cuts an easy way is to integrate numerically the soft-photon cross section given by Eq. (1) over the allowed kinematical region. Thus in order to determine the energy scale it is sufficient to know the infrared behavior of the radiative process using the soft-photon factor.

Let us determine the energy-scale of the QED radiative corrections to the single-\( W \) production process,

\[
e^-(p_-) + e^+(p_+) \rightarrow e^-(q_-) + \bar{\nu}_e(q_\nu) + u(k_u) + \bar{d}(k_d).
\]

The soft-photon correction factor in Eq. (1) is numerically integrated with the Born matrix element of the process (3) only with the \( t \)-channel diagrams without any cut on the final fermions. In order to separate the contribution from each term, we take terms up to \( O(\alpha) \) in Taylor expansion of exponential function in Eq. (1). Parameters used in the calculation will be explained in section 4. The results are shown in Table 1. One can see that the main contribution comes from an electron charged-line (\( p_- q_- \)-term) and a positron charged-line \((p_+ k_u k_d \text{-terms}=p_+ k_u \text{-term} + p_+ k_d \text{-term} + k_u k_d \text{-term})\), while all other contributions are negligibly small. Like the two-photon processes the energy scale \( s \) does not appear in the soft-photon correction. The above

| all terms | \( p_- q_- \) | \( p_+ k_u k_d \) | all other combinations |
|-----------|---------------|-----------------|-----------------------|
| 1         | 0.38          | 0.61            | \( 1.9 \times 10^{-3} \) |

Table 1: Soft-photon correction factor from sets of the charged particle combinations for the process of \( e^+ e^- \rightarrow e^- \bar{\nu}_e u d \) at the CM energy of 200 GeV. The factor from all terms is normalized to unity. \( k_c = 1 \text{GeV} \) is used. \( p_+ k_u k_d = p_+ k_u \text{-term} + p_+ k_d \text{-term} + k_u k_d \text{-term} \).
tron and positron charged-lines individually with the energy scale of their momentum-transfer squared.

2.2 Structure Function Method

The analytic solution of the DGLAP evolution function[10] in the leading-logarithmic order is known as the structure function[2]. With SF the QED corrected cross section is given by

$$\sigma_{\text{total}}(s) = \int dx_I - \int dx_F - \int dx_u \int dx_d D_e^-(x_I, -t_-) D_e^-(x_F, -t_-) D_{e^+}(x_I, -t_+) D_u(x_u, s_{ud}) D_d(x_d, s_{ud}) \sigma_0(\hat{s}),$$

where $\sigma_0$ is the Born cross section and $D$'s are the SF. The energy scales $t_- = (p_- - q_-)^2$, $t_+ = (p_+ - (k_u + k_d))^2$ and $s_{ud} = (k_u + k_d)^2$ are chosen following the result of the last section. After(before) the photon radiation the initial(final) momenta $p_\pm(q_\pm)$ become $\hat{p}_\pm(\hat{q}_\pm)$

$$\hat{p}_- = x_I p_-, \quad \hat{q}_- = \frac{1}{x_F} q_-,$$

respectively. Then the CM energy squared, $s$, is scaled as $\hat{s} = x_I x_{I+} s$.

2.3 Parton Shower Method

Instead of the analytic formula of SF a Monte Calro method based on the parton shower algorithm in QED can be used to solve DGLAP equation in the LL approximation. Its detailed algorithm of the QEDPS is found in ref.[12] for the $e^+e^-$ annihilation processes, in ref.[13] for the Bhabha process, and in ref.[4] for the two-photon process. The same energy scale as the SF method is used in QEDPS also. Significant difference between SF and QEDPS is that the QEDPS can treat the transverse momentum of the emitted photons correctly by imposing the exact kinematics at the $e \rightarrow e\gamma$ splitting. It does not affect the total cross sections so much when the final $e^-$ has no cut. However, the finite recoiling of the final $e^\pm$ can result some effects on the tagged cross sections.

In return for the exact kinematics at the $e \rightarrow e\gamma$ splitting, $e^\pm$ are no more on-shell after a photon emission. On the other hand the matrix element of the
hard scattering process must be calculated with on-shell external particles. A trick to map the off-shell four-momenta of the initial $e^\pm$ to those at on-shell is needed. The following method is used in the calculations.

1. $\hat{s} = (\hat{p}_- + \hat{p}_+)^2$ is calculated, where $\hat{p}_\pm$ are the four-momenta of the initial $e^\pm$ after the photon emission by QEDPS. $\hat{s}$ is positive even for the off-shell $e^\pm$.

2. New four-momenta of initial $e^\pm$ in their rest-frame, $\tilde{p}_\pm$, are defined as $\tilde{p}_\pm^2 = m_e^2$ (on-shell) and $\hat{s} = (\tilde{p}_- + \tilde{p}_+)^2$. All four-momenta of final particles are generated in the rest-frame of $\tilde{p}_+ + \tilde{p}_-$. 

3. All four-momenta are rotated and boosted to match the three-momenta of $\tilde{p}_\pm$ with those of $\hat{p}_\pm$.

This method respects the direction of the final $e^\pm$ rather than the CM energy of the collision. The total energy does not conserve then because of the virtuarity of the initial $e^\pm$. The violation of the energy conservation is of the order of $10^{-6}$ GeV or less, and the probability of the violation more than 1 MeV is $10^{-4}$.

3 Numerical Calculations

3.1 Cross sections with no cut

Total and differential cross sections of semi-leptonic process $e^- e^+ \rightarrow e^- \bar{\nu}_e u \bar{d}$ and leptonic one $e^- e^+ \rightarrow e^- \bar{\nu}_e \mu^+ \nu_\mu$, are calculated with the radiative correction by SF or QEDPS. Feynman diagrams of the semi-leptonic process are shown in Fig.1. Fortran codes to calculate the amplitudes are automatically produced by GRACE system[14]. All fermion-masses are kept finite in the calculations. Numerical integrations of the matrix element squared in the four-body phase space are done using BASES[15]. For a test with no experimental cuts, only the $t$-channel diagrams(non-annihilation diagrams) are taken into account. Standard model parameters used in the calculations are summarized in Table2. The on-shell relation strict at the tree-level is employed to determine weak couplings. Some of electro-weak corrections could be taken into account through the $G_F$-scheme and running coupling constant. In this report, however, we do not include those effects because here we are
interested in looking at the pure QED radiative corrections to the Born cross section. It has been pointed out that a tiny violation of the gauge invariance

\[
\begin{align*}
M_W & = 80.35 \text{ GeV} & \Gamma_W & = 1.96708 \text{ GeV} \\
M_Z & = 91.1867 \text{ GeV} & \Gamma_Z & = 2.49471 \text{ GeV} \\
\alpha & = 1/137.0359895 & \sin^2 \theta_w & = 1 - \frac{M_W^2}{M_Z^2} \\
m_e & = 0.511 \times 10^{-3} \text{ GeV} & m_\mu & = 105.658389 \times 10^{-3} \text{ GeV} \\
m_u & = 5.0 \times 10^{-3} \text{ GeV} & m_d & = 10.0 \times 10^{-3} \text{ GeV}
\end{align*}
\]

Table 2: Standard-model parameters

caused by the inclusion of a finite W-boson width results a wrong cross section for single-W production\([16, 17]\). To cure this problem the fermion-loop scheme\([17, 18, 19]\] has been proposed. It is reported in ref.\([18]\), however, that no significant difference is seen between the fermion-loop scheme and the fixed width scheme. Thus in this report the fixed width scheme, together with an appropriately modified current, described in \([16]\) is employed.

For the total energy of the emitted photons both methods, SF and QEDPS, must give the same spectrum once the same energy scale is used. This is confirmed for the semi-leptonic process as shown in Fig.2 at the CM energy of 200 GeV. We choose the same energy-evolution scale as SF described by Eq.\((4)\). Total cross sections as a function of the CM energies at LEP2 with no cuts are shown in Fig.3. The effect of the QED radiative corrections on the total cross sections are obtained to be 7 to 8% in the LEP2 energy region. If one used an inappropriate energy scale, say \(s\), in SF, the ISR effect is overestimated about 4% as seen in Fig.3. The result of SF is consistent with the QEDPS around 0.2% if the proper energy scale is employed.

There is some ambiguity to choose the energy-evolution scale in the leading-log order. For example the transverse-momentum squared or the invariant-mass squared of \(u\bar{d}\) (or \(\mu\bar{\nu}_\mu\)) systems could be a candidate of the energy scale. It is found that even these energy scales are chosen in QEDPS instead of \((p_+ - (k_u + k_d))^2\), the total cross sections change by only 0.6%, which must be allocated to the theoretical uncertainty.

The energy and angular distributions of the hard photon from QEDPS are compared with those obtained from the exact matrix elements. The
cross sections of the radiative process \(e^- e^+ \rightarrow e^- \bar{\nu}_e u d \gamma\) are calculated based on the exact amplitudes generated by GRACE and integrated numerically in five-body phase space using BASES. Again only the \(t\)-channel diagrams (non-annihilation diagrams) are taken into account. To compare the distributions the soft-photon corrections for the radiative process must be included. For this purpose QEDPS is implemented into the \(e^- \bar{\nu}_e u d \gamma\) calculations with a careful treatment to avoid a double-counting of the radiation effect. The definition of the hard photon is

1. \(E_\gamma > 1\) GeV,

2. opening angle between the photon and the nearest final-state charged particles is greater than \(5^\circ\).

The distributions of the hard photons are in good agreement as seen in Fig.4. The total cross section of the hard photon emission agrees each other in 2% level. We also calculated the radiative cross-section without soft-photon correction. If the soft-photon correction is not included in the radiative process, we find a 30% overestimation of the radiative cross-section with above experimental cuts.

### 3.2 Cross sections with experimental cut

It is also investigated how large the effects of the QED radiative corrections is for the single-\(W\) production when realistic experimental conditions are imposed. The experimental cuts applied here are \(\theta_e^- < 5^\circ\), \(M_{q\bar{q}} > 45\) GeV, \(E_\mu > 20\) GeV. For this study all the diagrams, not only the \(t\)-channel diagrams but also the \(s\)-channel, are taken into account in the calculations. The dominance of the signal from \(t\)-channel diagrams is 97%(90%) for the hadronic(leptonic) decay of the \(W\) boson, respectively. Total cross sections as a function of the CM energies at LEP2 with these cuts are shown in Fig.5. The QED radiative corrections on the total cross sections are found to be 7 to 8% in this LEP2 energy range. If one uses the inappropriate energy scale \(s\) in SF, the ISR effect is overestimated by around 5%, which is larger than those of the no-cut case. SF with the proper energy scale shows a deviation from QEDPS around 0.5% for \(e^- \bar{\nu}_e u d \gamma\) process and 1.0% for \(e^- \bar{\nu}_e \mu^+ \nu_\mu\). The agreement between QEDPS and SF becomes worse than the no-cut case, because the finite transverse-momentum of the emitted photons by QEDPS.
changes the acceptance of the above electron-veto requirement. Hence for the realistic experimental conditions the finite transverse-momentum of emitted photons should not be ignored.

Finally a possible effect of the systematic error of the ISR effect on the anomalous TGC measurements is investigated. If the inappropriate energy scale is used in the ISR tools such as the CM-energy squared, the total cross sections with the experimental cuts includes 5% systematic error. Even if one used one of proper energy scales, there is 0.6% uncertainty on the cross sections due to ambiguity of the energy scale selection. These uncertainty of the total cross sections limits the experimental sensitivity of the anomalous TGC measurements. Total cross-sections of $e\nu_e u d$ and $e\nu_e \mu \nu_\mu$ processes with experimental cuts as a function of the anomalous TGC is summarized in Fig.6. The cross sections are obtained at the CM-energy of 200 GeV with all diagrams. A bound shown in dashed lines shows $\pm5\%$ cross section variation from its standard model value. If one used the inappropriate energy scale, it affects $\pm0.05$ on $\Delta\kappa$ measurement and $\pm0.4$ on $\lambda$ measurement. The ambiguity of the energy-scale selection gives the systematic error of less than $0.01$ on $\Delta\kappa$ and $0.1$ on $\lambda$.

4 Conclusions

The method to apply the QED radiative correction to the non-annihilation process was established. The conventional method, SF with the energy scale $s$ gave about 4% overestimation in the LEP2 energies. The uncertainty due to the energy-scale determination was estimated to be about 0.6%. This uncertainty may affect the anomalous TGC measurements less than 0.01 on $\Delta\kappa$ and 0.1 on $\lambda$. If one wants to look at the hard photon spectrum, the soft-photon correction to these radiative processes are needed.

In this report we have treated two processes $e^- e^+ \rightarrow e^- \bar{\nu}_e ud$ and $e^- e^+ \rightarrow e^- \bar{\nu}_e \mu^+ \nu_\mu$. The CP conjugate processes $e^- e^+ \rightarrow e^+ \nu_e \bar{u}d$ and $e^- e^+ \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu$ give the same results and the other channels $e^- e^+ \rightarrow e\nu_e cs$ and $e^- e^+ \rightarrow e\nu_e \tau \nu_\tau$ will show slightly different results due to their masses. On the other hand the self CP-conjugate process $e^- e^+ \rightarrow e^- \bar{\nu}_e e^+ \nu_e$ has an additional complexity, because two energy scales $t_- = (p_{e^-} - q_{e^-})^2$ and $\tilde{t}_- = (p_{e^-} - q_{e^-} - q_{\bar{e}^-})^2$ can appear simultaneously.
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Figure 1: Feynman diagrams of the process $e^- e^+ \rightarrow e^- \bar{\nu}_e u d$. First ten diagrams show the s-channel diagrams and last ten the t-channel ones.
Figure 2: Differential cross section of the total energy of emitted photon(s) obtained from the QEDPS (histogram) and from the SF(circle).
Figure 3: Total cross sections and those normalized by the QEDPS results for $e\nu_e \bar{u}d$ and $e\nu_e \mu\nu_\mu$ processes without experimental cuts. The SF(t) denotes the SF with proper energy scale and the SF(s) with the inappropriate energy scale (s). Only $t$-channel diagrams (non-annihilation diagrams) are taken into account.
Figure 4: Differential cross sections of the hard photon; Energy, transverse energy w.r.t. the beam axis, cosine of the polar angle, and opening angle between photon and nearest charged-fermion. A histogram shows the QEDPS result and stars from the matrix element with soft-photon correction. Only t-channel diagrams(non-annihilation diagrams) are taken into account.
Figure 5: Total cross sections and those normalized by the QEDPS results for $e\nu_{e}u\bar{d}$ and $e\nu_{e}\mu\nu_{\mu}$ processes with experimental cuts. The SF(t) denotes the SF with proper energy scale and the SF(s) with the inappropriate energy scale (s). All diagrams are taken into account.
Figure 6: Total cross-sections of $e\nu\bar{u}d$ and $e\nu\mu\nu_{\mu}$ processes with experimental cuts as a function of the anomalous TGC. Dashed (dotted) lines show $\pm 5\%$ ($\pm 0.6\%$) cross section variation from its standard model value. The cross sections are obtained at the CM-energy of 200 GeV with all diagrams.
