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MULTIPLE PHOTON EMISSION AND b QUARK ASYMMETRIES *,**

S. Jadach
Institute of Physics, Jagellonian University, Krakow, Poland
and
B.F.L. Ward
SLAC, Stanford, CA 94305, USA,
Department of Physics and Astronomy, University of Tennessee,
Knoxville, Tennessee 37996-1200, USA,
and
International Centre for Theoretical Physics, Trieste, Italy.

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ABSTRACT

We discuss the effects of multiple photon final states in high precision tests of the $SU_{2L} \times U_1$ model wherein one measures the b quark asymmetries at a very high luminosity Z^0 factory, such as the possible high luminosity upgrade of the CERN LEP Collider. The specific asymmetries analyzed are the forward-backward asymmetry A_{FB}, the left-right polarized asymmetry A_{LR} and the polarized forward-backward asymmetry $A_{FB,pol.}$. The radiative effects are found to be significant for A_{FB} as expected, but they are not as large, on a percentage basis, as the corresponding result for muons.

1. INTRODUCTION

Recently we have introduced methods [1] based on the formalism of Yennie, Frautschi and Suura [2] (YFS) for realizing, at the level of an event-by-event simulator, the effects of multiple photon emission in Z^0 physics scenarios relevant to the SLC and LEP. And, indeed, the respective Monte Carlo fortran programs for the processes $e^+e^- \to f\bar{f} + n(\gamma)$, $f \neq e$, and $e^+e^- \to e^+e^- + n(\gamma)$ are in fact available from us, for example, for the interested reader. We have illustrated[2] the respective multiple photon effects in the case that $f = \mu$ and in the Bhabha scattering case (the latter case is dealt with only at the low angle scattering regime relevant to luminosity simulations). Here, we focus on the case $e^+e^- \to b\bar{b} + n(\gamma)$ in the high precision regime. Such high precision considerations may be relevant to a high luminosity upgrade of the LEP Collider, for example. Such a high luminosity upgrade of the SLC appears more remote at this time, according to the lore.

Specifically, we will first review the elements of the methods we shall employ in the next section. We then discuss in the third Section, the multiple photon emission effects on the b-quark asymmetries of interest to us here. The interplay of the radiative effects and the detector cuts is realized by applying MkII-type detector cuts. Here, in order to make the comparison with our earlier work on $\mu\bar{\mu} + n(\gamma)$ final states immediate, we impose the same μ-like cuts on our b-quark. We realize that, in doing this, some of what we gain in immediacy we may lose in the proximity to reality. In any event, we do not lose contact with the effects of interest to us. Finally, we conclude with some summary remarks in Section 4.

2. REVIEW OF THE MONTE CARLO-BASED YFS METHODS

Here, we review our Monte Carlo-based YFS methods. The starting points are the two key theorems of YFS concerning multiple-photon emission in a process like $e^+e^- \to f\bar{f} + n(\gamma)$.

More precisely, the first theorem of YFS shows that the virtual infrared singularities in the amplitude M for $e^+e^- \to f\bar{f} + n(\gamma)$ may be extracted as an overall factor of the exponential type, $\exp[\alpha B]$, where B is a known infrared divergent function. The second theorem of YFS shows that the rate associated with the virtual-infrared-finite part of M, $m \equiv \exp[-\alpha B]M$, suffers real infrared divergences in a controlled way, so that it may be expressed as

$$|m|^2 = \tilde{S}(k_1)\ldots\tilde{S}(k_n)\beta_0 + \ldots + \sum_i \tilde{S}(k_i)\beta_{n-1}(k_1,\ldots,k_{i-1},k_{i+1},\ldots,k_n)$$
$$+ \beta_n(k_1,\ldots,k_n) \qquad (1)$$

where β_j are free of all infrared divergences and $\tilde{S}$ is the famous [2] real infrared emission factor. In this way, we arrive finally at the classic YFS result

$$d\sigma_{YFS} = \exp(2\alpha(\mathrm{Re}B + \tilde{B}))(1/(2\pi)^4) \int d^4y \exp[iy(P_e + P_{\bar{e}} - P_{X'}) + D]$$
$$\{\beta_0 + \sum_{n=1}^{\infty} (1/n!) \int \prod_{j=1}^{n} (d^3k_j/k_j)\exp(-iyk_j)\beta_n\} dE_{X'}\, d^3P_{X'} \qquad (2)$$

where $X' = f\bar{f}$ and

$$D \equiv \int d^3k(\exp(-iyk) - \theta(K_{max} - k))\tilde{S}(k)/k . \qquad (3)$$

In Refs.1, we have realized this result via the Monte Carlo method so that, for each event, one obtains, among the final particle 4-vector list, the actual 4-vectors of the multiple photons themselves. Here, we will illustrate these Monte Carlo methods on the processes $e^+e^- \to b\bar{b} + n(\gamma)$. To these we turn in the next section.

3. b QUARK ASYMMETRIES

One of the fundamental parameters of the standard $SU_{2L} \times U_1$ model is the parameter $\sin^2\theta_W \equiv 1 - M_W^2/M_{Z^0}^2$ Indeed, tests of the model can be construed as comparing different determinations of $\sin^2\theta_W$ from different measurements, with due attention to the respective higher order corrections to the tree level relationships between these determinations. In this light, the b quark angular asymmetries may play a significant role, affording as as they do yet another path to $\sin^2\theta_W$.

It follows then, that in this role, the higher order radiative corrections to the b quark angular asymmetries are of some interest; and, we wish to take-up here those corrections associated with multiple photon emission by the initial state in $e^+e^- \to Z^0 \to b\bar{b} + n(\gamma)$ on the Z^0 pole. The specific asymmetries which we consider are then

$$A_{FB} \equiv (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B) , \qquad A_{LR} \equiv (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R) ,$$

and

$$A_{FB,pol.} \equiv (\sigma_{LF} - \sigma_{LB} - (\sigma_{RF} - \sigma_{RB}))/(\sigma_{LF} + \sigma_{RF} + \sigma_{LB} + \sigma_{RB}), \quad (4)$$

where σ_A, A = F,B, is the cross-section for $\cos\theta_b > 0$ (< 0) for A = F(B) and σ_H, H = L,R, is the cross-section for electrons of handedness H. Here, θ_x is the x production angle relative to the e^- direction in the e^+e^- c.m. system. Thus, these are just the usual asymmetries.

In order to make immediate contact with our work on $e^+e^- \to \mu\bar{\mu} + n(\gamma)$, we impose MkII-like "muon" cuts on our b quark final states: $|\cos\theta_b| < 0.8$, $|\cos\theta_\gamma| < 0.95$, $E_\gamma > 0.2$ GeV, $E_{VIS} > 0.1\sqrt{s}$, where E_{VIS} is the total visible energy in the respective event. Here, we simulate $\sim 10^5$ $b\bar{b} + n(\gamma)$ events, with $M_{Z^0} = 91.0$ GeV, $\sin^2\theta_W \cong 0.2354$, and $m_t \cong 50$ GeV. (If $t \to H^+ + b$, the latter value is still not excluded even by the recent hadron-hadron collider data [3].) In this way, we arrive finally at the results in Table I using our Monte Carlo program YFS2 Fortran [1] for $b\bar{b} + n(\gamma)$ production in $e^+e^- \to X$. What we see is that the multiple photon emission does indeed affect significantly $A_{FB}(b)$, although we should note that it is not as pronounced as the corresponding effect on $A_{FB}(\mu)$ for the $\mu\bar{\mu} + n(\gamma)$ process. The effects on the polarized asymmetries are substantially reduced compared to that on $A_{FB}(b)$; this is consistent with what was found for $\mu\bar{\mu} + n(\gamma)$ production and with the lore. We should note that our primary purpose for illustrating the polarized beam results is one of pedagogy; for, the practical aspects of simultaneously achieving both high luminosity and longitudinal polarization appear quite challenging, both at the SLC and at LEP. However, we do not know of a no-go theorem here. And, indeed, we see that the polarized asymmetries are again quite attractive because of their stability to multiple photon emission, even in the presence of cuts. We note that an acollinearity cut is helpful in reducing the respective corrections but that in $b\bar{b}$ production, such a cut is not so useful[4].

We conclude that in a high statistics measurement of the b quark asymmetries in $e^+e^- \to Z^0 \to b\bar{b} + n(\gamma)$ it is indeed necessary to account properly for the attendant radiative effects associated with multiple photon emission. Our Monte Carlo based YFS methods permit us to effect such an accounting.

4. CONCLUSION

We have considered the effects of multiple photon radiation on the fundamental b quark asymmetries in $e^+e^- \to Z^0 \to b\bar{b} + n(\gamma)$ in the context of high precision tests of the standard $SU_{2L} \times U_1$ model at a high luminosity Z^0 factory, such as the proposed high luminosity upgrade of the CERN LEP Collider. We have found that the radiative effects are significant.

Specifically, $A_{FB}(b)$ is the most strongly affected by the multiple photon radiation when compared with A_{LR} and $A_{FB,pol.}$. The effects on $A_{FB}(b)$ are at the level of $\sim$ 5%, whereas the analogous effects on $A_{FB}(\mu)$ are $\sim$ 100 %. Hence, the practical implications are somewhat different in passing from $b\bar{b} + n(\gamma)$ to $\mu\bar{\mu} + n(\gamma)$. The $b\bar{b} + n(\gamma)$ case involves a correction which is big on the scale of α, but which nonetheless is essentially well-known in our simulations after $\sim 10^5$ events. The $\mu\bar{\mu} + n(\gamma)$ case involves a correction which is much larger (in percentage of the attendant asymmetry) than that in the $b\bar{b} + n(\gamma)$ case, and which yields a net asymmetry which is still not known well after 10^5 events. Thus, from this perspective, $A_{FB}(b)$ indeed looks encouraging; however, we say here nothing about b-tagging, QCD fragmentation effects, etc. Such matters will be taken-up elsewhere [5].

The polarized b quark asymmetries track those of $\mu\bar{\mu}$ production in being stable against the $n(\gamma)$ radiative effects. We encourage further work by the machine physics community in realizing truly high luminosity longitudinally polarized Z^0 factories.

In summary, a large data sample of $e^+e^- \to Z^0 \to b\bar{b} + n(\gamma)$ events, such as that envisioned in the high luminosity LEP upgrade, would indeed require the proper implementation of the higher order radiative corrections, most ideally on an event-by-event basis. We have shown that our Monte Carlo program YFS2 Fortran (or the more complete program KORALZ Fortran, which includes YFS2 as a submodule) does indeed permit such an implementation.

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5. See recent work by A. Djouadi et al., MPI-PAE/48/89.

TABLE I

b QUARK ASYMMETRIES

1. NO RADIATIVE CORRECTIONS

$A_{FB} = 0.0708 \qquad A_{LR} = 0.116 \ , \qquad A_{FB,pol.} = 0.609$

2. RADIATIVE EFFECTS

5×10^5 events (YFS2)

$A_{LR} = 0.1126 \pm 0.0012$

$A_{FB,pol.} = 0.6143 \pm 0.0013$

$A_{FB} = 0.0672 \pm 0.0012$, No Acol. Cut

$A_{FB} = 0.0689 \pm 0.0012$, 1^{o} Acol. Cut

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