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FORWARD–BACKWARD ASYMMETRIES FOR $e^+e^- \rightarrow Z^0 \rightarrow \bar{b}b, \bar{t}t$ AND PHYSICS BEYOND THE STANDARD MODEL*

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ABSTRACT

We study the properties of $A_{FB}^{b,t}$, the forward-backward asymmetry, and of $A_{polFB}^{b,t}$, the polarized forward-backward asymmetry, for the processes $e^+e^- \rightarrow Z^0 \rightarrow \bar{b}b, t\bar{t}$ in the presence of new gauge interactions. It turns out that a measurement of A_{polFB}^{b} can determine the strength of $B^0 - \bar{B}^0$ mixing without any appreciable impact from new gauge interactions. A measurement of A_{FB}^{b} has the potential to reveal such new forces, however only in a semi-quantitative fashion unless $B^0 - \bar{B}^0$ mixing is well determined in an independent way. On the other hand A_{FB}^{t} can quantitatively measure the effects of new currents, because $T^0 - \overline{T}^0$ mixing is expected to be very small. We show that the additional kinematic factors which appear in expression for A_{FB}^{t} do not suppress the effects of new gauge structures.

The process $e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-$, readily measured at SLC/LEP, will yield large statistics without the uncertainties of strong interactions. Therefore, A_{LR}, the polarization asymmetry, A^{μ}_{FB}, the forward-backward asymmetry and A^{μ}_{polFB}, the polarized forward-backward asymmetry, will be measured with a high accuracy for this reaction. The above asymmetries are defined as:

$$A_{LR} = \frac{\sigma(e^-(L)e^+ \rightarrow \bar{f}f) - \sigma(e^-(R)e^+ \rightarrow \bar{f}f)}{\sigma(e^-(L)e^+ \rightarrow \bar{f}f) + \sigma(e^-(R)e^+ \rightarrow \bar{f}f)} \tag{1}$$

$$A^{f}_{FB} = \frac{\int d\phi(\int_0^1 - \int_{-1}^0)d\cos\theta \frac{d\sigma(e^+e^- \rightarrow \bar{f}f)}{d\Omega}}{\sigma(e^+e^- \rightarrow \bar{f}f)} \tag{2}$$

$$A^{f}_{polBF} = \frac{\int d\phi(\int_0^1 - \int_{-1}^0 d\cos\theta \; \frac{d\sigma(e^-(L)e^+ \rightarrow \bar{f}f)}{d\Omega}}{\sigma(e^-(L)e^+ \rightarrow \bar{f}f)} \tag{3}$$

Here f refers to the final state fermions, $d\sigma$ and σ denote a partial cross-section and total cross-section measured on the Z^0 resonance, respectively, while $e^-(L)$ and $e^-(R)$ refer to the left-polarized and right-polarized electron, respectively. The 100% polarization is assumed.

Deviation of the measured asymmetries from the values predicted in the standard model will give indirect evidence for new physics above the standard model, *e.g.*, the radiative electro-weak correction due to the new particle content[1] and/or the new gauge interactions.[2]

It has been shown[1] that the effect of radiative corrections due to new particle content is in general less that 1%. On the other hand the new guage structure can change the value of the asymmetries significantly,[2] *i.e.*, there is a deviation of more than 1% when the mass of the additional neutral gauge boson(s), $m_{Z'}$, is less than $\mathcal{O}(10)\, m_Z$. Therefore a precise measurement of different asymmetries will impose a new upper bound on the mass of additional neutral gauge bosons.

In Ref. 2 one has constructed a quantity Δ^q, which unambiguously measures the effect of new currents only. Δ^q is a particular linear combination of δq_{LR} and δA^q_{polFB}, which are deviations of the measured values for A_{LR} and A^q_{polFB} from the standard model predictions. In the previously considered cases[2] with $q = c, b$, the hadronization effects were not included. In principle this amounts to an oversimplification of the phenomena of $D^\circ - \overline{D}^\circ$ and $B^\circ - \overline{B}^\circ$ mixing which affect the expression for A^q_{FB} and A^q_{polFB}, and therefore also Δ^q.

Very little $D^\circ - \overline{D}^\circ$ mixing is expected, and the experimental upper limit on its strength is roughly 1%. Thus $e^+e^- \to Z^0 \to \bar{c}c$ presents in principle a very clean case. In practice however it will pose considerable technical problems to tag c events because $2m_c \ll m_Z$.

In this note we shall study in detail the processes

$$e^+e^- \to Z^0 \to \bar{b}b,\, \bar{t}t \quad , \tag{4}$$

in the presence of additional gauge interactions.

Those will be the two processes readily measured at SLC/LEP because the b and t quarks have a chance to be tagged more easily than the light c quark. First we examine the effect of $B^\circ - \overline{B}^\circ$ mixings on A^b_{FB} and A^b_{polFB} . We propose that this effect could be determined by measuring A^b_{polFB} and show how it affects A^b_{FB} in the presence of new gauge interactions. In the second part we discuss how the finite top mass ($m_t \gtrsim 20$ GeV) affects A^t_{polFB} and A^t_{FB} .

1. $e^+e^- \rightarrow Z^0 \rightarrow \bar{b}b$

When attempting to measure A^b_{FB} and A^b_{polFB} in $e^+e^- \rightarrow \bar{b}b$, one employs flavor-tagging (usually via direct leptons) for a dual purpose: first to (hopefully) insure that bottom states have been produced and secondly to determine the direction of flight of b in contrast to that of $\bar{b}$. Bottom quarks, however, do not decay as such; they first evolve into hadrons which finally decay weakly. Yet if $B^\circ - \overline{B}^\circ$ mixing occurs, then any procedure to establish the direction of flight of the b quark will unavoidably lead to some errors. There exists[3,4] the following simple relation between $A^b_{polFB,FB}$, *i.e.*, the theoretical forward-backward asymmetries on the quark level, and $A^B_{polFB,FB}$, which is actually measured

$$A^B_{polFB,FB} \; = \; \frac{1}{1+\bar{r}} \, A^b_{polFB,FB} \quad . \tag{5}$$

Here, $\bar{r}$ denotes the weighted average over $B_d - \overline{B}_d$ and $B_s - \overline{B}_s$ mixing with $B_q = (b\bar{q})$. The parameter $\bar{r}$ can be represented as follows

$$\bar{r} \; = \; \frac{2\left(r_d + \rho_s r_s \frac{1+r_d}{1+r_s}\right)}{2 + \rho_s \frac{(1-r_s)(1+r_d)}{1+r_s}} \quad , \tag{6}$$

with

$$\rho_s \; = \; \frac{\text{number of } B_s}{\text{number of } B^-} \tag{7}$$

and

$$r_{d,s} \; = \; \frac{\Gamma\left(B_{d,s} \rightarrow \ell^+ X\right)}{\Gamma\left(B_{d,s} \rightarrow \ell^- X\right)} \quad . \tag{8}$$

Conventionally, one expects[4]

$$r_d \simeq 0\ , \qquad \rho_s \sim \frac{1}{3} - \frac{1}{2}, \qquad r_s \sim 0.3 - 1 \tag{9}$$

and therefore

$$\bar{r} \sim 0.1 - 0.25 \quad . \tag{10}$$

A priori no better calculation of $\bar{r}$ can be undertaken; in particular since m_t is unknown and ρ_s at best poorly known.

In Fig. 1, $A^B_{polFB}\,(i)$ and $A^B_{FB}\,(ii)$ are plotted as functions of $m_{Z'}/m_Z$ for a generic example of the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge structure. The Higgs fields transform under the gauge group as

$$\Delta_L \sim (\underline{3},\ \underline{1},\ 2),\ \Delta_R \sim (\underline{1},\ \underline{3},\ 2),\ \phi \sim (\underline{2},\ \underline{2},\ 0) \tag{11}$$

and they have the following vacuum expectation values[5,6] (VEV's):

$$\langle \Delta_L \rangle \simeq 0\ , \quad \langle \Delta_R \rangle > \langle \phi \rangle = \begin{bmatrix} k & 0 \\ 0 & k' \end{bmatrix}\ , \quad k \ll k' \quad . \tag{12}$$

It turns out that for other VEV patterns and/or other gauge structures *e.g.*, $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$, the qualitative features of A^B_{polFB} and A^B_{FB} remain the same.

The value for $\bar{r}$ is chosen to be 0 (dots), 0.1 (solid) and 0.25 (dashes).

From Fig. 1 one can infer that the effect of $B^\circ - \overline{B}^\circ$ mixing is more significant for A^B_{polFB} than for A^B_{FB} because A^b_{polFB} (~ 0.7) $\gg A^b_{FB}$ (~ 0.15). Also, A^B_{polFB} is much less sensitive to the effects of additional gauge structures than A^B_{FB}.

Therefore, A^B_{polFB} is a good candidate for determining $\bar{r}$. On the other hand, measurement of A^B_{FB} may indicate new gauge interactions. However, this would be only a qualitative indication until a precise measurement of $\bar{r}$ is done. Note also that Δ^b, a linear combination of δA_{LR} and δA^b_{polLR}, which measures the effect of new currents only, cannot be determined to an accuracy of few percentage unless $\bar{r}$ is determined to within 20%.

2. $e^+e^- \ \longrightarrow \ Z^0 \ \longrightarrow \ \bar{t}t$

This process is interesting (for $2m_t < m_Z$, of course), because t–quarks can be probably tagged more easily than c quarks in a similar process. On the other hand this process has very low statistics as $2m_t \to m_Z$. However, for $m_t \ \lesssim \ 40$ GeV the measurement of this process may yield a clear signal with enough statistics, and therefore it is important to see how $A^t_{polFB,FB}$ are affected in the presence of new gauge interactions.

It can safely be predicted that $T^0 - \overline{T}^0$ mixing will be so small ($< 1\%$) and it can be completely ignored for our purposes. Then the main uncertainty entering is of a kinematical nature. Namely, for $m_t \ \gtrsim \ 20$ GeV one has:

$$\beta \ \equiv \ \left[1 - \left(\frac{2m_t}{m_Z}\right)^2\right]^{1/2} \ \approx 0.9 < 1 \quad , \tag{13}$$

and therefore the approximation with $\beta = 1$ is not valid anymore. Thus, in evaluating $A^t_{polFB,FB}$ we have used:

$$\frac{d\sigma}{d\Omega}\left\{ \, e^+e^-{}_{\binom{L}{R}} \ \rightarrow \ Z^0 \ \rightarrow \ \bar{t}t\right\}$$

$$\propto \ \beta\left(v_e \mp a_e\right)^2\left\{\left(a_t^2 + v_t^2\right) \ \beta^2\left(1+\cos^2\theta\right) + 2v_t^2\ \left(1-\beta^2\right) \pm 4a_t v_t\,\beta\cos\theta\right\} \quad , \tag{14}$$

with v_f, a_f denoting the vector and axial vector fermionic currents. Parameter β is given by Eq.(13).

In Fig. 2, $A^t_{polFB}(i)$ and $A^t_{FB}(ii)$ are given as a function of $m_{Z'}/m_Z$ for $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge structure with VEV's (12). The top mass is chosen to be 32 GeV (dots), 35 GeV (solid) and 38 GeV (dashes). Qualitatively similar results are obtained for other VEV patterns and/or other gauge groups.

The following comments are in order. Observing the top via $e^+e^- \to Z^0 \to t\bar{t}$ will presumably allow us to determine its mass only up to ± 2 GeV. This introduces very little uncertainty into $A^t_{polFB,FB}$, as shown in Fig. 2. Again, A^t_{polFB} is not very sensitive to new gauge interactions. On the other hand, measurement of A^t_{FB} can be used successfully to obtain a lower bound on $m_{Z'}$. Namely, the finite top mass, *i.e.*, $\beta < 1$, does not suppress the effect of additional gauge interactions for A^t_{FB}.

One should also note that now the quantity Δ^t, which would measure the effects of new currents only, should be modified due to the additional kinematic factors [see Eq.(11)].

In conclusion, the measurement of processes $e^+e^- \to Z^\circ \to \bar{b}b$, $\bar{t}t$ at SLC/LEP will be important in extracting new physics beyond the standard model, in particular the new gauge interactions. We showed that the effect of $B^\circ - \overline{B}{}^\circ$ mixing on the forward-backward asymmetry is significant. Since A^B_{polFB} is not too sensitive to the effects of the new gauge structures, its determination may yield an independent measurement of the $\bar{r}$ parameter. On the other hand, A^B_{FB} can indicate qualitatively the effect of new structures even when $\bar{r}$ is not determined precisely. Regarding A^t_{FB}, it *is* sensitive to the new gauge structure, and the additional kinematic factors arising from the finite top quark mass ($\beta \neq 1$) do not suppress these effects. Also, the uncertainty in m_t to within 3 GeV does not affect the results significantly.

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FIGURE CAPTIONS

Fig. 1. $A^B_{polFB}(i)$ and $A^B_{FB}(ii)$ as a function of $m_{Z'}/m_Z$. The gauge structure is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with the Higgs content of [Eq. (11)] and VEV's of [Eq. (13)]. The value of $\bar{r} = 0$ (dots), 0.1 (solid), and 0.25 (dashes).

Fig. 2. $A^B_{polFB}(i)$ and $A^B_{FB}(ii)$ as a function of $m_{Z'}/m_Z$ for the gauge symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with the Higgs content of [Eq. (11)] and the VEV pattern of [Eq. (13)]. The top masses are $m_t = 32$ GeV (dots), 35 GeV (solid) and 38 GeV (dashes).

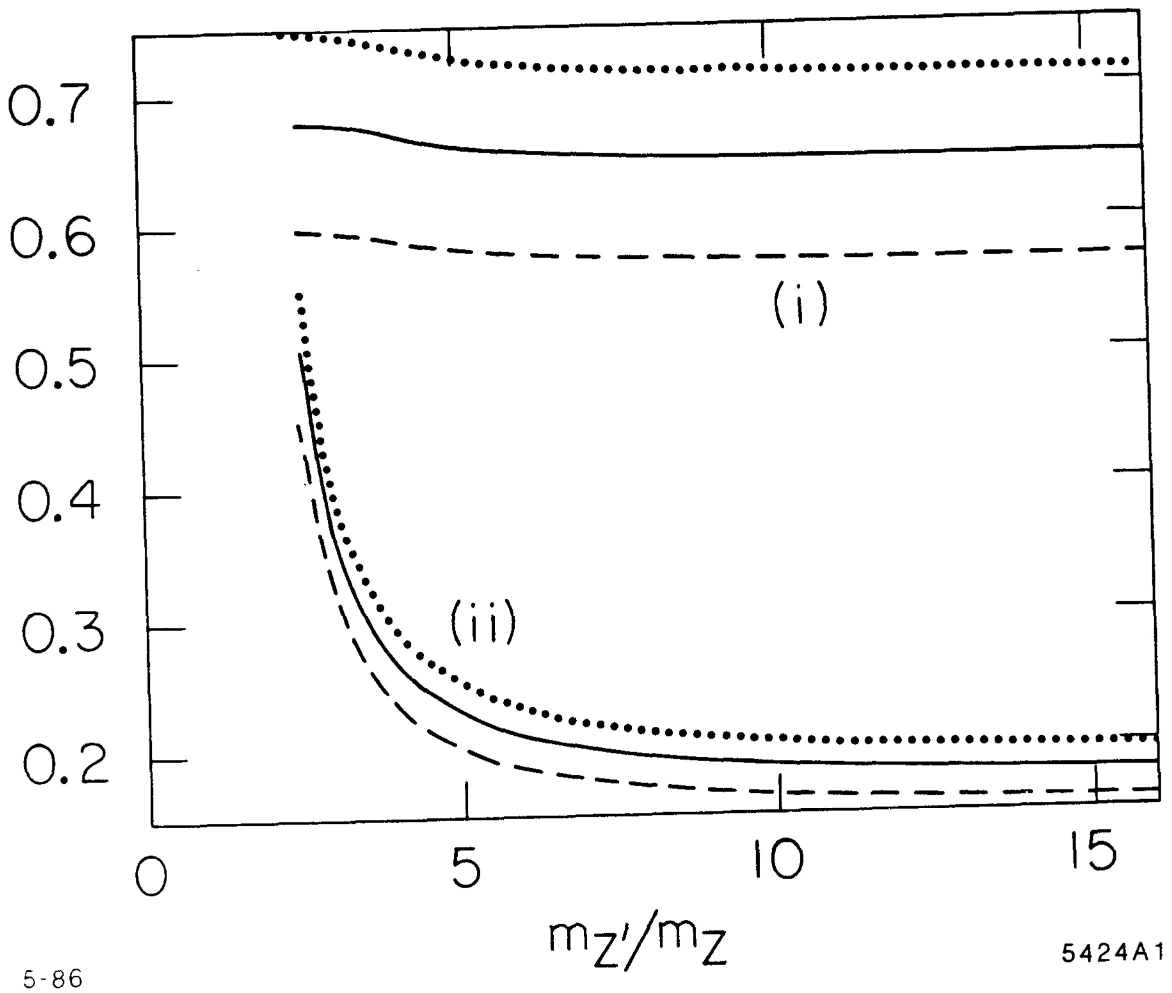

Fig. 1

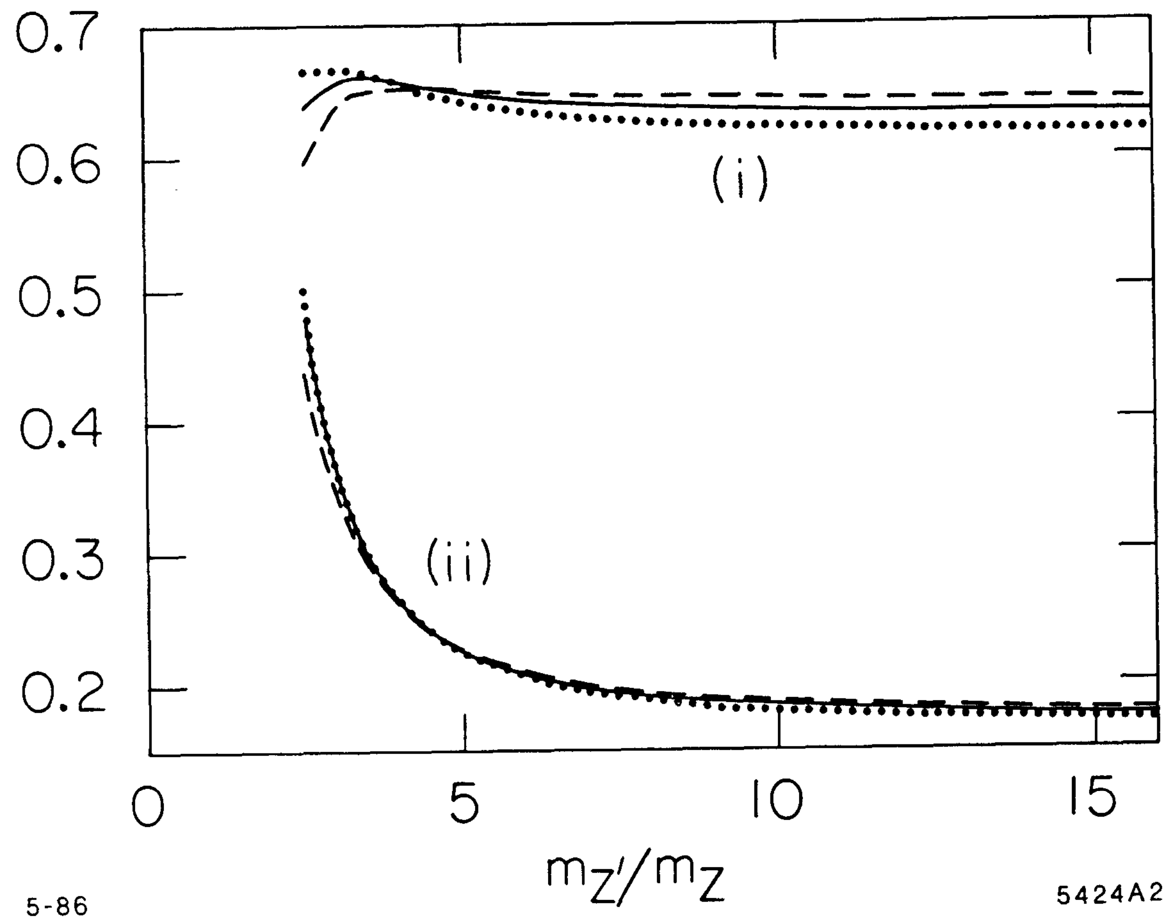

Fig. 2