IDENTIFICATION OF A SAMPLE OF $e^+e^- \rightarrow q\bar{q}$ EVENTS FOR THE PRECISE MEASUREMENT OF $\alpha_S$ IN HIGH ENERGY ELECTRON–POSITRON COLLIDERS

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Abstract
Based on the PYTHIA physics simulation package, and a fast simulation of the proposed detector for the Next Linear Collider, a set of cuts is identified which leads to a sample of $e^+e^- \rightarrow q\bar{q}$ events appropriate for the precise measurement of $\alpha_S$ in $e^+e^-$ annihilation at $\sqrt{s} = 500$ GeV/$c^2$. Using these cuts, the systematic uncertainty on $\alpha_S$ associated with correcting for selection cut biases and remaining non-$e^+e^- \rightarrow q\bar{q}$ ($q \neq t$) contamination is expected to be less than $\pm 1\%$. This work was done as part of a study of the prospects for the precise measurement of $\alpha_S$ at future High Energy Physics facilities, undertaken for the 1996 Snowmass Workshop on New Directions in High Energy Physics.
Introduction

The approach of measuring $\alpha_S$ via the reconstruction of hadronic observables in the process $e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ at high energy is thought to be an ideal place to perform a high $Q^2$ measurement of $\alpha_S$. With the calculation of these observables done to next-to-next-to-leading order in perturbative QCD – a very likely prospect on the time scale of data taking at the NLC – it is expected that theoretical uncertainties associated with the truncation of the perturbative series, as well as uncalculated non-perturbative effects, will be on the order of $\pm 1\%$ [1]. Thus, it is important that expectations for the size of experimental uncertainties associated with the measurement of $\alpha_S$ in high energy $e^+e^-$ collisions not exceed $\pm 1\%$. This paper discusses the results of a study in which event cuts were identified for which the systematic uncertainty on $\alpha_S$ associated with correcting for selection cut biases and remaining non-$e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ contamination is expected to be less than $\pm 1\%$. This work was done as part of a study of the prospects for the precise measurement of $\alpha_S$ at future High Energy Physics facilities, undertaken for the 1996 Snowmass Workshop on New Directions in High Energy Physics.

The European Linear Collider QCD Working Group Event Selection

At $\sqrt{s} = 500\text{GeV}$ in $e^+e^-$ collisions, the Born-level event rate is dominated by annihilation to $W^+W^-$ pairs (7.0 pb). Annihilation to light quark (udscb) pairs, the process of interest for most approaches to measuring $\alpha_S$ at a high energy linear collider, has a cross section smaller by a over factor of two (3.1 pb). Annihilation to top pairs (0.3 pb) and $Z^0Z^0$ pairs (0.4 pb) also form backgrounds which need to be suppressed when identifying a sample of events for QCD analyses.

In a study performed by the European Working Group on QCD at a High Energy Linear $e^+e^-$ Collider [2], a set of cuts was identified which result in an 83% pure sample of $e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ events. These cuts are presented in Table 1, which is reproduced from Reference [2]. In particular, a ‘hemisphere mass’ cut, requiring that at least one of the two thrust hemispheres have an invariant mass less than 13% of the total visible energy in the event, was included to suppress $e^+e^- \rightarrow t\bar{t}$ and boson pair events. After the application of the cuts, backgrounds to $e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ in the event sample are dominated by $W$-pair (11%) and $e^+e^- \rightarrow t\bar{t}$ (6%) events. This sample is appropriate for many QCD analyses in $e^+e^-$ annihilation at $\sqrt{s} = 500\text{GeV}$.

The cuts, in particular the hemisphere mass cut, introduce a moderate bias against hard gluon radiation which must be corrected for after the sample is analyzed. For example, Figure 1 show a Monte Carlo comparison (to be described in more detail below) of the $E0$ algorithm [3] three jet rate as a function of $y_{\text{cut}}$ for $e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ events between a sample of events for which no selection cuts have been applied, and a sample for which the European Working Group cuts have been
Table 1. European Working Group event selection cuts, reproduced from Reference [2]. The NLC Working Group cuts, which are the subject of this paper, are identical to these cuts up to the replacement of the hemisphere mass cut with a heavy quark anti-tag, and the removal of all events produced with nominally left-handed electron beam polarization.

| Cut                        | Value                      |
|---------------------------|---------------------------|
| Particle multiplicity     | $N_{\text{charged}} \geq 8$ |
| Polar angle of thrust axis| $|\cos(\theta_T)| < 0.8$        |
| Visible energy            | $\frac{E_{\text{vis}}}{E_{\text{cm}}} > 0.5$ |
| Longitudinal momentum balance | $\frac{|\sum p_z|}{E_{\text{vis}}} < 0.4$ |
| Minimum hemisphere mass   | $M_1$ and $M_2 > 3 \text{ GeV}$ |
| Hemisphere multiplicity   | $N^{1,2}_{\text{charged}} \geq 4$ |
| Hemisphere mass           | $(\frac{M_1}{E_{\text{vis}}}$ or $\frac{M_2}{E_{\text{vis}}}) < 0.13$ |

Fig. 1. Comparison of E0 algorithm [3] three jet rate before (dashed lines) and after (open circles) the European Working Group event selection cuts, as a function of $y_{\text{cut}}$. To emphasize the effects of event selection bias, the effects of non-$e^+e^- \rightarrow q\bar{q}$ ($q \neq t$) contamination, initial state radiation, and beamstrahlung are not included in the comparison.
applied. To isolate the effect of event selection bias, the effects of initial state radiation and of backgrounds from $t\bar{t}$ and boson pair production have not been included in this plot. In the region $10^{-2} < y_{cut} < 10^{-1}$ relevant for the measurement of $\alpha_S$, biases of 10-20% in the three jet rate are observed, adequate for a measurement of $\alpha_S \sim \pm 5\%$.

The NLC QCD Working Group Event Selection

Recently, considerable interest has been generated in the possibility of a precise measurement of $\alpha_S$, for which the uncertainty of the value of $\alpha_S$ (at the scale $Q^2 = M_Z^2$) would approach the level of $\pm 1\%$ [4]. This paper reports the results of a study in which the European Working Group cuts were modified in order provide a sample of $e^+e^- \rightarrow q\bar{q}$ $(q \neq t)$ events for which the uncertainty in the corrections for event selection bias and background contamination are consistent with this goal. This was achieved by conducting a Monte Carlo study for which the hemisphere mass cut was removed, replacing it with a cut on events which exhibit heavy quark decay characteristics (to suppress $e^+e^- \rightarrow t\bar{t}$ backgrounds), and by using events produced by right-hand polarized electron beam only (to suppress W-pair production). Otherwise, the event selection followed precisely that developed by the European Working Group. In this paper, this modified set of cuts will be referred to as the ‘NLC Working Group’ cuts.

Simulation Procedure

The various $e^+e^-$ annihilation channels discussed above were simulated with the PYTHIA 5.7 Monte Carlo [5]. Events were analyzed at the stable hadron level, with detector simulation parameterized as discussed below. The effects of local initial state radiation (that component of ISR independent of beam currents and densities) were included in the event simulation via the MSTP(11) flag. The complementary component of initial state radiation, commonly referred to as ‘beamstrahlung’, is not available within Pythia, and thus was not simulated. However, the Pythia simulation using local ISR only accurately reproduced the European Working Group results, which included a beamstrahlung simulation. This supports the notion that the relative contributions from the various $e^+e^-$ annihilation processes should be roughly independent of the amount of beamstrahlung radiation generated by the collisions.

A final state particle from the Pythia event generation was included in the calorimeter analysis if it was stable and interacting, had an $|\cos(\theta)|$ relative to the beam direction of less than 0.97, and, if charged, a transverse momentum relative to the beam direction of greater than 300 MeV/c. A charged track was included in the tracking analysis provided it had an $|\cos(\theta)|$ of less than 0.9.
Lifetime Antitag

In this study, events were not included in the QCD sample if they showed substantial evidence of the presence of heavy quarks in the final state. The primary purpose of this requirement was to suppress $e^+e^- \rightarrow t\bar{t}$ events from the final sample, particularly after the removal of the hemisphere mass cut. This cut was also very efficient in removing $e^+e^- \rightarrow b\bar{b}$ events from the sample, even though these latter events are suitable for the $\alpha_S$ analysis. Before the lifetime antitag, $e^+e^- \rightarrow b\bar{b}$ events comprised approximately 15% of all $e^+e^- \rightarrow q\bar{q} (q \neq t)$ events.

Specifically, an event was considered to contain heavy quarks if it produced four or more tracks with impact parameters relative to the $e^+e^-$ collision point which differed from 0 by $3\sigma$ or greater in either the $r-\phi$ or $r-z$ view. The impact parameter resolution assumed for the tracking system was that of the proposed NLC detector, which is as follows [6]: in the $r-\phi$ view, 2.6 $\mu$m and 13.7 $\mu$m for the asymptotic and multiple scattering terms, respectively, and in the $r-z$ view, 10 $\mu$m and 30 $\mu$m for the asymptotic and multiple scattering terms. After applying all of the European Working Group cuts except the hemisphere mass cut, the application of this lifetime antitag removed 95% of the remaining $e^+e^- \rightarrow t\bar{t}$ events, 19% of the remaining $e^+e^- \rightarrow W^+W^-$ events, and 47% of the remaining $e^+e^- \rightarrow Z^0 Z^0$ events, while retaining 68% of the remaining $e^+e^- \rightarrow q\bar{q} (q \neq t)$ signal events.

Table 2. Expected left-right cross section asymmetry $A_{LR} \sqrt{s} = 500$ GeV for various $e^+e^-$ annihilation processes.

| Process                  | $A_{LR}$ |
|--------------------------|----------|
| $e^+e^- \rightarrow q\bar{q} (q \neq t)$ | 0.45     |
| $e^+e^- \rightarrow W^+W^-$            | $>0.99$  |
| $e^+e^- \rightarrow t\bar{t}$            | 0.35     |
| $e^+e^- \rightarrow Z^0 Z^0$            | 0.30     |

Use of Right Handed Electron Beam to Suppress $e^+e^- \rightarrow W^+W^-$ Background

Table 2 shows the left-right asymmetry $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$ expected at $\sqrt{s} = 500$ GeV for the four $e^+e^-$ annihilation processes under consideration in this study. Processes with $A_{LR} > 0$ are suppressed, with a degree proportional
Fig. 2. Composition of the event sample resulting from the NLC Working Group event cuts, as a function of electron beam polarization.

to the magnitude of $A_{LR}$; for running exclusively with right handed electron beam. Running exclusively right handed electron beam with a substantial polarization is thus an effective way to suppress $e^+e^- \rightarrow W^+W^-$ events.

Figure 2 shows the resulting NLC Working Group event sample as a function of electron beam polarization. For a beam polarization of 80%, currently available in the SLAC LINAC, the resulting event sample is 82% pure, with contaminations of 13% for $e^+e^- \rightarrow W^+W^-$, 4.0% for $e^+e^- \rightarrow Z^0Z^0$, and 1.2% for $e^+e^- \rightarrow t\bar{t}$ events. Research and development on high polarization cathodes continues at SLAC. For a 90% electron beam polarization, these fractions become 87%, 7.8%, 4.3%, and 1.3%, respectively.

Three Jet Rates for the NLC Working Group Sample

Figure 3 shows the corresponding plot to Figure 1 for the NLC Working Group event selection, isolating the effect of event selection bias on hard gluon radiation. Differences between the unselected sample three jet rate and that of the sample after NLC Working Group event selection (with the effects of backgrounds and initial state radiation excluded) are at the few percent level. Thus, it is projected that the uncertainty in correcting for the event selection bias will be less than $\pm 1\%$.

Figure 4 is a plot similar to Figure 3, but with the effects of ISR and event sample backgrounds included. In this and all subsequent plots, an electron beam polarization of 80% is assumed. Substantial differences between the true three jet rate (dotted
Fig. 3. Comparison of E0 algorithm [3] three jet rate before (dashed lines) and after (open circles) the NLC Working Group event selection cuts, as a function of $y_{\text{cut}}$. Again, to emphasize the effects of event selection bias, the effects of non-$\text{e}^+\text{e}^- \to q\overline{q}$ ($q \neq t$) contamination, initial state radiation, and beamstrahlung are not included in the comparison.

Fig. 4. Comparison of the ‘raw’ three jet rate ($\text{e}^+\text{e}^- \to q\overline{q}$ ($q \neq t$) events at $\sqrt{s} = 500\text{GeV}$ only; no event cuts or detector simulation), with the three jet rate expected for the NLC Working Group selection, including initial state radiation and all non-$\text{e}^+\text{e}^- \to q\overline{q}$ ($q \neq t$) backgrounds.
line) and the expected experimental three jet rate (points) are observed. As will be discussed immediately below, however, the source of these differences are expected to be relatively straightforward to model or measure from complementary data samples, resulting in a correction to $\alpha_S$ with an uncertainty on the order of $\pm 1\%$.

The emission of a beamstrahlung or prompt radiated photon prior to annihilation acts to lower the effective cms energy of the $e^+e^-$ collision, and to give the annihilation event a boost in the laboratory frame. With the European/NLC working group cuts applied, the median fractional energy loss due to initial state radiation is of order 50 GeV. Both prompt radiation and beamstrahlung are well-understood physical processes, and can be modelled via QED and classical electrodynamics. The uncertainty incurred by the correction for these effects is expected to be small.

Figure 5 shows a comparison of true and expected experimental three jet rates after correcting for initial state radiation, assuming the correction is known precisely. The remaining disagreement, due in this plot to non-$e^+e^- \rightarrow q\overline{q}$ ($q \neq t$) backgrounds and event selection bias, is substantially smaller, particularly in the region $10^{-2} < y_{cut} < 10^{-1}$.

![Graph showing comparison of jet rates](image)

**Fig. 5.** Comparison of the ‘raw’ three jet rate ($e^+e^- \rightarrow q\overline{q}$ ($q \neq t$) events at $\sqrt{s} = 500\text{GeV}$ only; no event cuts or detector simulation), with the three jet rate expected for the NLC Working Group selection, including non-$e^+e^- \rightarrow q\overline{q}$ ($q \neq t$) backgrounds, but excluding the effects of initial state radiation.

Correcting for the $\sim 4\% e^+e^- \rightarrow Z^0Z^0$ background should also be systematically clean, given the wealth of precise data on $Z^0 \rightarrow jets$ available from $e^+e^-$ annihilation
at the $Z^0$ pole. Figure 6 shows the three jet comparison after correcting for $e^+e^- \rightarrow Z^0Z^0$ contamination, again assuming the correction is known precisely.

Finally, Figure 7 shows the three jet comparison after correcting for the $\sim 10\%$ $e^+e^- \rightarrow W^+W^-$ contamination. Depending on the magnitude of the right-handed electron beam polarization, this is a relative correction of 5-10% on the three jet rate. In order that the uncertainty on $\alpha_S$ due to this correction be small compared to $\pm 1\%$, it is necessary to know the magnitude of the correction to 10-20% of itself. Again, though, $W$ boson decay jet rates can be constrained directly with experimental data – for example, from jet rates observed opposite to purely leptonic $W$ decays in $e^+e^- \rightarrow W^+W^-$ events at high cms energy.

The remaining discrepancy observed in Figure 7, due to the effects of $e^+e^- \rightarrow t\bar{t}$ contamination and event selection bias, is not easily constrained by data. On the other hand, the size of this discrepancy is less than 5% (relative) over most of the range in $y_{\text{cut}}$ shown in the Figure. Thus, correcting for these two final sources of discrepancy between the true and observed three jet rate should also result in an uncertainty on $\alpha_S$ of less than 1%.

**Conclusion**

In the study reported in this paper, a set of event selection cuts was identified which is expected to contribute a relative uncertainty of no more than $\pm 1\%$ to a measurement of $\alpha_S$ in high energy $e^+e^-$ annihilation. This event selection is a modification to a set of cuts identified earlier by the European Linear Collider QCD Working Group, with the following changes: the hemisphere mass cut was removed, and replaced by a heavy quark anti-tag, and all events produced with (nominally) left-handed electron beam are discarded. Doing this reduces difficult to constrain effects on the three jet rate from event selection bias and $e^+e^- \rightarrow t\bar{t}$ contamination to manageable levels. Other backgrounds, including $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow Z^0Z^0$ events remaining after the event selection cuts, while somewhat substantially altering the three jet rate, can be well constrained with existing or concurrent data, and thus are not expected to contribute substantial systematic error to the measurement of $\alpha_S$ via three jet rates.

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Fig. 6. Comparison of the ‘raw’ three jet rate ($e^+e^- \rightarrow q\bar{q} \ (q \neq t)$) events at $\sqrt{s} = 500\text{GeV}$ only; no event cuts or detector simulation), with the three jet rate expected for the NLC Working Group selection, including all non-$e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ backgrounds except $e^+e^- \rightarrow Z^0 Z^0$, and excluding the effects of initial state radiation.

Fig. 7. Comparison of the ‘raw’ three jet rate ($e^+e^- \rightarrow q\bar{q} \ (q \neq t)$) events at $\sqrt{s} = 500\text{GeV}$ only; no event cuts or detector simulation), with the three jet rate expected for the NLC Working Group selection, excluding all non-$e^+e^- \rightarrow q\bar{q} \ (q \neq t)$ backgrounds except $e^+e^- \rightarrow t\bar{t}$, and excluding the effects of initial state radiation.
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