2.10 Precision Tests of QCD

Tests of QCD are both enriching and essential to the program of measurements to be made at the NLC. Since QCD *is* our theory of strong interactions it would be irresponsible not to test it at the highest energy scales available in different hard scattering processes. In addition, the precise determination of the strong coupling α_s is key to a better understanding of high energy physics. For example, the current precision of $\alpha_s(m_z^2)$ measurements, limited to 5–10%, results in the dominant uncertainty on our prediction of the energy scale at which grand unification of the strong, weak and electromagnetic forces takes place [126]. Measurements of hadronic event properties at high energies, combined with existing lower energy data, would allow one to test the gauge structure of QCD by searching for anomalous 'running' of observables, such as the 3-jet event rate, and to set limits on models which predict such effects, for example those involving light gluinos. Gluon radiation in $t\bar{t}$ events is expected to be strongly regulated by the large mass and width of the top quark; $t\bar{t}g$ events will hence provide an exciting new domain for QCD studies. Conversely, measurements of gluon radiation patterns in $t\bar{t}g$ events may provide valuable additional constraints on the top quark decay width. In addition, searches could be made for anomalous chromo-electric and chromo-magnetic moments of top quarks, which modify the rate and pattern of gluon radiation and for which the phase space increases as the c.m. energy is raised. Finally, polarized electron beams could be exploited to allow tests of symmetries using multi-jet final states.

2.10.1 Precise Measurement of α_s

Tests of QCD can be quantified in terms of the consistency of values of the yardstick $\alpha_s(m_z^2)$ measured in different experiments. Measurements of $\alpha_s(m_z^2)$ have been performed over a range of Q^2 from roughly 1 to 10^4 GeV^2 [127], and are consistent within the errors; an average yields $\alpha_s(m_z^2) = 0.117 \pm 0.006$, implying that QCD has been tested to a precision of about 5%, which is modest compared with the achievement of sub-1% level tests of the electroweak theory. This is due primarily to the *theoretical uncertainties* that dominate the measurements. These uncertainties are due to both the restriction of perturbative QCD calculations to low order, and non-perturbative ('hadronization') effects that are presently incalculable in QCD. We consider whether a measurement of $\alpha_s(m_z^2)$ at the 1%–level of precision is possible at the NLC by extrapolation of a recent measurement from e^+e^- annihilation at the Z^0 resonance by the SLD Collaboration, based on 15 hadronic event shape observables measured with a sample of 50,000 hadronic events [128]:

$$\alpha_s(m_Z^2) \quad = \quad 0.1200 \pm 0.0025\,(\text{exp.}) \pm 0.0078\,(\text{theor.})\ . \tag{2.13}$$

The experimental error is composed of statistical and systematic components of about ± 0.001 and ± 0.002 respectively, and the theoretical uncertainty has components of ± 0.003 and ± 0.007 arising from hadronization and missing higher order terms, respectively.

Based on this experience, we can estimate the errors to be expected for a similar measurement of α_s at a 500 GeV NLC:

Statistical error: At design luminosity, the NLC would deliver roughly 200,000 $q\overline{q}$ (q=u,d,s,c,b) events per year implying that a statistical error on $\alpha_s(m_z^2)$ of about $\pm$ 0.0005 could be obtained. Cuts for rejection of W$^+$W$^-$ and $t\overline{t}$ backgrounds, based on kinematic information as well as beam polarization and b-tagging, will not substantially reduce the $q\overline{q}$ sample size.

Systematic error: This results primarily from the uncertainty in modeling the jet resolution of the detector. The situation may be improved at the NLC both from an improved calorimeter and from the naturally improved calorimeter energy resolution for higher energy jets. It is not unreasonable to suppose that the current systematic error of $\pm$0.002 could be reduced by a factor of two, but more convincing demonstration of this point would require a simulation of the detector, as well as the event selection and analysis cuts [129].

Hadronization uncertainty: Since jets of hadrons, rather than partons, are observed in detectors, it is necessary to correct hadronic distributions for any smearing and bias effects that occur in the hadronization process. Such corrections are usually estimated from Monte Carlo simulations incorporating hadronization models. In Z^0 decays, they are typically at the level of 10% [128]. One can argue that non-perturbative corrections to jet final states in e^+e^- annihilation can be parametrized in terms of inverse powers of $\sqrt{s}$ [130], and that for a generic observable X the ratio of non-perturbative to perturbative QCD contributions is dominated by a term of the form:

$$\frac{\delta X^{\mathrm{non-pert}}}{X^{\mathrm{pert}}} \quad \sim \quad \frac{\log s}{\sqrt{s}} \,. \tag{2.14}$$

Increasing Q from 91 GeV to 500 GeV decreases this ratio by a factor of 5, implying that hadronization corrections should be of order 2% at NLC. Assuming that these corrections can be estimated to better than $\pm$50%, the hadronization uncertainty on $\alpha_s(m_z^2)$ should be less than $\pm$0.001.

Uncertainty due to missing higher orders: Currently perturbative QCD calculations of hadronic event measures are available complete up to $\mathcal{O}(\alpha_s^2)$. Since the data contain knowledge of all orders one must estimate the possible bias inherent in measuring $\alpha_s(m_z^2)$ using the truncated QCD series. It is customary to estimate this from the dependence of the fitted $\alpha_s(m_z^2)$ on the QCD renormalization scale, yielding a large and dominant uncertainty of about $\pm$0.007 [128]. At 500 GeV this uncertainty will be reduced only slightly to $\pm$0.006.

From this simple analysis it seems reasonable to conclude that achievement of the luminosity necessary for 'discovery potential' at the NLC will result in a $q\overline{q}$ event sample of sufficient size to measure $\alpha_s(m_z^2)$ with a statistical uncertainty of better than 1%. Construction of detectors superior in performance to those in operation today should enable reduction of systematic errors to the 1% level. Hadronization effects should be significantly smaller and imply a sub–1% uncertainty. The missing ingredient for an overall 1%-level $\alpha_s(m_z^2)$ measurement at 500 GeV is the calculation of $\mathcal{O}(\alpha_s^3)$ perturbative QCD contributions, which should be actively pursued.

2.10.2 Energy Evolution Studies

The non-Abelian gauge structure of QCD implies that the strong coupling decreases roughly as $1/\ell n\, s$. Existing hadronic final states data from e^+e^- annihilation at the PETRA, PEP, TRISTAN, SLC and LEP colliders span the range $14 \leq \sqrt{s} \leq 91$ GeV, although hadronization uncertainties are large on the data below 25 GeV [127]. A 1.5 TeV NLC would increase the lever-arm in $1/\ell n\, s$ by almost a factor of two, allowing detailed study of the energy evolution of QCD observables proportional to α_s, such as the rate of 3-jet production R_3. This would provide not only a test of the fundamental structure of the $SU(3)_c$ group, but also a search-ground for new physics that might produce 'anomalous' running. One such possibility is the existence of a light, electrically neutral colored fermion that couples to gluons, for example, a light gluino. The existence of such a particle would manifest itself via a modification of gluon vacuum polarization contributions involving fermion loops, effectively increasing the number of light fermion flavors N_f entering into the QCD β-function. For the case of a light gluino, which leads to a 10% increase in the value of R_3 at 500 Gev, a 1% measurement of α_s would allow this effect to be detected with a significance of many standard deviations.

However, data from experiments at different e^+e^- colliders contributing to this analysis, some of which were recorded more than 10 years ago, were treated differently by the various experimental groups, and have relatively large systematic errors that are at least partly uncorrelated from point to point. It is clear that the precision of searches for anomalous running of QCD observables at NLC would be improved significantly if new data were taken at lower c.m. energies with the *same* detector and analysis procedures. Table 2.13 shows the number of $q\overline{q}$ events delivered per day at various c.m. energies by the NLC operating at design luminosity; more luminosity would be delivered per day than was recorded in total by the original lower energy colliders! The ability to maintain high luminosity at low center of mass energies presents a formidable challenge to the design of the collider, but even running at lower luminosity could deliver substantial data samples, especially at the Z^0, although the high event rates would present extreme requirements on the triggering and data processing capabilities of the detector.

Table 2.13: Number of $q\overline{q}$ events per day delivered by NLC at design luminosity

CM Energy Q (GeV)	$q\overline{q}$ events/day
500	1750
91	20,000,000
60	75,000
35	150,000

2.10.3 Symmetry Tests Using Beam Polarization

For polarized e^+e^- annihilation to three hadronic jets one can define the triple-product $\vec{S_B} \cdot (\vec{k_1} \times \vec{k_2})$ ($B = \gamma, Z^0$), which correlates the boson polarization vector $\vec{S_B}$ with the normal to the three-jet plane defined by $\vec{k_1}$ and $\vec{k_2}$, the momenta of the highest- and the second-highest-energy jets respectively. The triple-product is even under reversal of CP, and odd under T_N, where T_N reverses momenta and spin-vectors without exchanging initial and final states. Standard Model T_N-odd contributions of this form at the Z^0 resonance have been investigated [131] and are found to be of order $\beta \sim 10^{-5}$; the first experimental study of this quantity has been made by SLD [132], yielding limits: $-0.022 < \beta < 0.039$. Above the Z^0 the dominant Standard Model contributions remain smaller than 2 parts in 10^5, presenting a background-free observable for new contributions from beyond the Standard Model, for example, due to rescattering of new gauge bosons that couple only to baryon number [133].

2.10.4 Gluon Radiation in $t\bar{t}$ Events; Anomalous Couplings

The large mass and decay width of the top quark serve to make the study of gluon radiation in $t\bar{t}$ events a new arena for testing QCD. The mass m_t acts as a cutoff for collinear gluon radiation, and the width Γ_t acts as a cutoff for soft gluon radiation, allowing reliable perturbative QCD calculations to be performed. We have noted in Section 3.1 the influence of the large top quark width on the rate and pattern of gluon radiation in $t\bar{t}$ events.

The existence of anomalous couplings of top quarks to gluons could manifest itself via a modification of the rate and pattern of emitted gluon radiation, beyond effects such as those just discussed. A parametrization of anomalous couplings in the strong-interaction Lagrangian may be written:

$$\mathcal{L}^{q\bar{q}g} = g_s \bar{q} T_a \left(\gamma_\mu + \frac{i\sigma_{\mu\nu} k^\nu}{2m_t} (\kappa - i\tilde{\kappa}\gamma_5) \right) q G_a^\mu \tag{2.15}$$

where κ and $\tilde{\kappa}$ represent anomalous 'chromomagnetic' and 'chromoelectric' dipole moments, respectively. The chromoelectric moment gives rise to CP-violating effects. Their effects on gluon radiation have been calculated to the leading order in α_s [134]. At $\sqrt{s} = 500$ GeV, limits of $|\kappa| \leq 0.03$ appear reachable; at $\sqrt{s} = 1.5$ TeV, one may additionally constrain $|\tilde{\kappa}| \leq 0.2$. These should be compare to a limit of $|\kappa| \leq 0.1$ which would be obtained from a measurement of the $t\bar{t}$ cross section at the Tevatron with 10 times the current integrated luminosity. A similar limit on κ from LHC would require a $t\bar{t}$ cross section measurement to better than 20%.