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QCD AND $\gamma\gamma$ INTERACTIONS AT A HIGH-ENERGY LINEAR e^+e^- COLLIDER

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Abstract

A summary is presented of the key strong-interaction measurements that could be made at a high-energy, high-luminosity e^+e^- collider.

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1 Introduction

Strong-interaction measurements at a future high-energy linear e^+e^- collider (LC) will form an important component of the physics programme. A 1 TeV collider has an energy reach comparable with the LHC, and offers the possibility of testing QCD in the experimentally clean, more theoretically accessible e^+e^- environment. In addition, $\gamma\gamma$ interactions will be delivered free by Nature, and a dedicated $\gamma\gamma$ collider is an additional option, allowing detailed measurements of the relatively poorly understood photon structure. Here I review the main topics; more details can be found in [1]:

- Precise determination of the strong coupling α_s.
- Measurement of the Q^2 evolution of α_s, searches for new coloured particles and constraints on the GUT scale.
- Measurements of the $t\bar{t}$(g) system
- Measurement of the total $\gamma\gamma$ cross section and the photon structure function.

Related top-quark, $\gamma\gamma$ and theoretical topics are summarised elsewhere [2, 3, 4].

2 Precise Determination of α_s

The current precision of individual $\alpha_s(M_Z^2)$ measurements is limited at best to several per cent [5]. Since the uncertainty on α_s translates directly into an uncertainty on perturbative QCD (pQCD) predictions, especially for high-order multijet processes, it would be desirable to achieve much better precision. In addition, since the weak and electromagnetic couplings are known with much greater precision, the error on α_s represents the dominant uncertainty on our 'prediction' of the scale for grand unification of the strong, weak and electromagnetic forces [6].

Several techniques for α_s determination are available at the LC:

2.1 Event Shape Observables

The determination of α_s from event 'shape' observables that are sensitive to the 3-jet nature of the particle flow has been pursued for 2 decades and is generally well understood [7]. In this method one usually forms a differential distribution, makes corrections for detector and hadronisation effects, and fits a pQCD prediction to the data, allowing α_s to vary. Examples of such observables are the event thrust and jet masses.

The latest generation of such α_s measurements, from SLC and LEP, has shown that statistical errors below the 1% level can be obtained with samples of a few tens of thousands of hadronic events. With the current LC design luminosities of 5×10^{33}/cm^2/s (NLC/JLC) and 3×10^{34}/cm^2/s (TESLA), at $Q = 500$ GeV, tens/hundreds of thousands of $e^+e^- \rightarrow q\bar{q}$ events would be produced each year, and a statistical error on α_s below the 1% level could be achieved easily.

Detector systematic errors, which relate mainly to uncertainties on the corrections made for acceptance and resolution effects, are under control at the 1-3% level (depending on the observable). If the LC detectors are designed to be very hermetic, with good tracking resolution and efficiency, as well as good calorimetric jet energy resolution, all of which are required for the search for new physics processes, it seems reasonable to expect that the detector-related uncertainties can be beaten down to the 1% level or better.

$e^+e^- \rightarrow Z^0\ Z^0$, W^+W^-, or $t\bar{t}$ events will present significant backgrounds to $q\overline{q}$ events for QCD studies, and the selection of a highly pure $q\overline{q}$ event sample will not be as straightforward as at the Z^0 resonance. The application of kinematic cuts would cause a significant bias to the event-shape distributions, necessitating compensating corrections at the level of 25% [8]. More recent studies have shown [9] that the majority of W^+W^- events can be excluded without bias by using only right-handed electron-beam produced events in the α_s analysis. Furthermore, the application of highly-efficient b-jet tagging can be used to reduce the $t\bar{t}$ contamination to the 1% level. After statistical subtraction of the remaining backgrounds (the $Z^0\ Z^0$ and W^+W^- event properties (will) have been measured accurately at SLC and LEP), the residual bias on the event-shape distributions is expected to be under control at the 1% level on α_s.

Additional corrections must be made for the effects of the smearing of the particle momentum flow caused by hadronisation. These are traditionally evaluated using Monte Carlo models. The models have been well tuned at SLC and LEP and are widely used for evaluating systematic effects. The size of the correction factor, and hence the uncertainty, is observable dependent, but the 'best' observables have uncertainties as low as 1% on α_s. Furthermore, one expects the size of these hadronisation effects to diminish with c.m. energy at least as fast as $1/Q$. Hence 10%-level corrections at the Z^0 should dwindle to less than 2% corrections at $Q \geq 500$ GeV, and the associated uncertainties should be well below the 1% level on α_s.

Currently pQCD calculations of event shapes are available complete only up to $O(\alpha_s^2)$. 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. Though not universally accepted, it is customary to estimate this from the dependence of the fitted $\alpha_s(M_Z^2)$ on the QCD renormalisation scale, yielding a large and dominant uncertainty of about ± 0.007 [10]. Since the missing terms are $O(\alpha_s^3)$, and since $\alpha_s(500$ GeV$)$ is expected to be about 25% smaller than $\alpha_s(M_Z^2)$, one expects the uncalculated contributions to be almost a factor of two smaller at the higher energy, leading to an estimated uncertainty of ± 0.004 on $\alpha_s(500$ GeV$)$. However, translating to the conventional yardstick $\alpha_s(M_Z^2)$ yields an uncertainty of ± 0.006, only slightly smaller than currently. Therefore, a 1%-level $\alpha_s(M_Z^2)$ measurement is possible experimentally, but will not be realised unless $O(\alpha_s^3)$ contributions are calculated.

2.2 The $t\bar{t}$ System

The value of α_s controls the strong potential that binds quarkonia resonances. In the case of $t\bar{t}$ production near threshold, the large top mass and decay width ensure that the top quarks decay in a time comparable with the classical period of rotation of the bound system, washing out most of the resonant structure in the cross-section, $\sigma_{t\bar{t}}$. The shape of $\sigma_{t\bar{t}}$ near threshold hence depends strongly on both m_t and α_s. Fits of next-to-leading-order (NLO) pQCD calculations to simulated measurements of $\sigma_{t\bar{t}}$ showed [11] that m_t is strongly correlated with α_s. Fixing α_s allowed the error on m_t to be reduced by a factor of 2. Since the main aim of such an exercise is to determine m_t as precisely as possible, the optimal strategy would be to *input* α_s from elsewhere.

Moreover, recent NNLO calculations of $\sigma_{t\bar{t}}$ near threshold have caused consternation, in that the size of the NNLO contributions appears to be comparable with that of the NLO contributions, and the change in the shape causes a shift of roughly 1 GeV in the value of the fitted m_t. This mass shift can be avoided by a judicious top-mass definition [3], which also reduces the m_t-α_s correlation. However, the resulting cross-section normalisation uncertainty translates into an uncertainty of ± 0.012 on $\alpha_s(M_Z^2)$, *i.e.* about 5 times larger than the estimated statistical error [2]. Although this may provide a useful 'sanity check' of α_s in the $t\bar{t}$ system, it does not appear to offer the prospect of a 1%-level measurement.

A preliminary study has also been made [12] of the determination of α_s from $R = \sigma_{t\bar{t}}/\sigma_{\mu^+\mu^-}$ *above* threshold. For $Q \sim 400$ GeV the theoretical uncertainty on R is roughly 3%; for $Q \geq 500$ GeV the exact value of m_t is much less important and the uncertainty is smaller, around 0.5%. However, on the experimental side the limiting precision on R will be given by the uncertainty on the luminosity measurement. If this is only as good as at LEPII, *i.e.* around 2%, then $\alpha_s(M_Z^2)$ could be determined with an experimental precision of at best 0.007, which is not especially useful other than as a consistency check.

Finally, there remains the possibility of determining α_s using $t\bar{t}g$ events, which have recently been calculated [13] at NLO. For reasonable values of the jet-resolution scale y_c the NLO contributions are substantial, of order 30%, which is comparable with the situation for massless quarks. The discussion of unknown higher-order contributions above is hence also valid here, and $t\bar{t}g$ events will only be useful for determination of α_s once the NNLO contributions have been calculated. If the $t\bar{t}g$ event rate can be measured precisely, the ansatz of flavour-independence of strong interactions can be tested for the top quark, and the running of m_t could be determined in a similar manner to the running b-quark mass [14]. A precision of 1% implies a measurement of $m_t(Q)$ with an error of 5 GeV.

2.3 A High-luminosity Run at the Z^0 Resonance

A LC run at the Z^0 resonance is attractive for a number of reasons. At nominal design luminosity tens of millions of Z^0 /day would be delivered, offering the possibility of a year-long run to collect a Giga Z^0 sample for ultra-precise electroweak measurements and tests of radiative corrections. Even substantially lower luminosity, or a shorter run, at the Z^0 could be useful for detector calibration.

A Giga Z^0 sample offers two additional options for α_s determination via measurements of the inclusive ratios $\Gamma_Z^{had}/\Gamma_Z^{lept}$ and $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$. Both are indirectly proportional to α_s, and hence require a very large event sample for a precise measurement. For example, the current LEP data sample of 16M Z^0 yields an error of 0.003 on $\alpha_s(M_Z^2)$ from $\Gamma_Z^{had}/\Gamma_Z^{lept}$. The statistical error could, naively, be pushed to below the 0.0005 level, but systematic errors arising from the lepton selection will probably limit the precision to 0.0016 [15]. Nevertheless this would be a very precise, reliable measurement. In the case of $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$ the experimental precision from LEP and CLEO is already at the 0.001 level on $\alpha_s(M_Z^2)$. However, there has been considerable debate about the size of the theoretical uncertainties, with estimates ranging from 0.002 to 0.006. If this situation is clarified, and the theoretical uncertainty is small, $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$ may offer a further 1%-level $\alpha_s(M_Z^2)$ measurement.

3 Q^2 Evolution of α_s

The running coupling is sensitive to the presence of any new coloured particles, such as gluinos, beneath the c.m. energy threshold via their vacuum polarisation contributions. Measurements of event shape observables at high energies, combined with existing lower energy data, would allow one to search for anomalous running. In addition, extrapolation of the running α_s can be combined with extrapolations of the dimensionless weak and electromagnetic couplings in order to try to constrain the GUT scale [6]. The highest-energy measurements, up to $Q = 200$ GeV, are currently provided by LEPII. Older data from e^+e^- annihilation span the range $14 \leq Q \leq 91$ GeV. A 0.5 - 1.0 TeV linear collider would increase significantly the lever-arm for measuring the running [1, 8].

However, over a decade from now the combination of LC data with the older data may not be straightforward, and will certainly not be optimal since some of the systematic errors are correlated among data at different energies. It would be desirable to measure *in the same apparatus, with the same technique, and by applying the same treatment to the data* at least one low-energy point - at the Z^0 or even lower - in addition to points at the W^+W^- and $t\bar{t}$ thresholds, as well as at the highest c.m. energies.

4 Other e^+e^- QCD Topics

Limited space allows only a brief mention of several important topics [1]:

• Searches for anomalous chromo-electric and chromo-magnetic dipole moments of quarks, which effectively modify the rate and pattern of gluon radiation. Limits on

the anomalous b-quark chromomagnetic moment have been obtained at the Z^0 resonance [16]. The $t\bar{t}g$ system would be important to study at the LC.
• Gluon radiation in $t\bar{t}$ events is expected to be strongly regulated by the large mass and width of the top quark. Measurements of gluon radiation patterns in $t\bar{t}g$ events may provide additional constraints on the top decay width [17].
• Polarised electron (and positron) beams can be exploited to test symmetries using multi-jet final states. For polarized e^+e^- annihilation to three hadronic jets one can define $\vec{S}_e \cdot (\vec{k}_1 \times \vec{k}_2)$, which correlates the electron-beam polarization vector $\vec{S}_e$ with the normal to the three-jet plane defined by $\vec{k}_1$ and $\vec{k}_2$, the momenta of the two quark jets. If the jets are ordered by momentum (flavour) the triple-product is CP even (odd) and T odd. Standard Model T-odd contributions of this form are expected [18] to be immeasurably small, and limits have been set for the $b\bar{b}g$ system [19]. At the LC these observables will provide a search-ground for anomalous effects in the $t\bar{t}g$ system.
• The difference between the particle multiplicity in heavy- (b, c) and light-quark events is predicted [20] to be independent of c.m. energy. Precise measurements have been made at the Z^0, but measurements at other energies are limited in precision, rendering a limited test of this important prediction. High-precision measurements at the LC would add the lever-arm for a powerful test.
• Colour reconnection and Bose-Einstein correlations are fascinating effects. They are important to study precisely since they may affect the precision with which the masses of heavy particles, such as the $W^\pm$ and top-quark, can be reconstructed kinematically via their multijet decays [21].

5 Photon Structure

Though much progress has been made in recent years at LEP and HERA, a thorough understanding of the 'structure' of the venerable photon is still lacking. Away from the Z^0 resonance the relative cross-section for $\gamma\gamma$ scattering is large, but good detector acceptance in the low-polar-angle regions is required. The LC provides an opportunity to make definitive measurements, either from the 'free' $\gamma\gamma$ events provided in the e^+e^- collision mode, or via a dedicated high-luminosity 'Compton collider' facility. From the range of interesting $\gamma\gamma$ topics [4] I mention only a few important 'QCD' measurements:
• The total cross-section, $\sigma_{\gamma\gamma}$, and the form of its rise with Q, will place constraints on models which cannot be differentiated with today's data; 'proton-like' models predict a soft rise, whereas 'minijet' models predict a steep rise.
• The photon structure function, $F_2^{\gamma\gamma}(x, Q^2)$, and the nature of its rise at low x in relation to 'BFKL' or 'DGLAP' evolution.
• Polarised structure functions, the charm content of the photon, and diffractive phenomena.

6 Summary and Conclusions

Tests of QCD will enrich the physics programme at a high-energy e^+e^- collider. Measurement of $\alpha_s(M_Z^2)$ at the 1% level of precision appears feasible experimentally, but will require considerable theoretical effort. A search for anomalous running of $\alpha_s(Q^2)$ is an attractive prospect, but presents serious requirements on the design of both the collider and detectors. Electron-beam polarisation can be exploited to perform symmetry tests using multi-jet final states. Interesting gluon radiation patterns in $t\bar{t}$ events could be used to constrain the top quark decay width. Measurement of the gluon radiation spectrum would also constrain anomalous strong top-quark couplings. Realistic hadron-level Monte Carlo simulations, including detector effects, need to be performed to evaluate these possibilities quantitatively.

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