MEASUREMENTS OF α_s IN e^+e^- ANNIHILATION AT $\sqrt{s}=53.3$ GeV and 59.5 GeV

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We studied the energy–energy correlation (EEC) and its asymmetry (AEEC) using e^+e^- hadronic annihilation events obtained at $\sqrt{s}=53.3$ GeV and 59.5 GeV with the TOPAZ detector at the TRISTAN collider. We used a Monte Carlo simulation combined with the QCD matrix elements by Gottschalk and Shatz and the Lund string fragmentation model. By comparing the experimental data with simulated events, we determined the strong coupling constant α_s at both energies. The results are $0.129 \pm 0.007(\text{stat}) \pm 0.010(\text{syst})$ at $\sqrt{s}=53.3$ GeV and $0.122 \pm 0.008(\text{stat}) \pm 0.010(\text{syst})$ at 59.5 GeV.

To test the energy dependence of the strong coupling constant α_s and to determine the QCD scale parameter Λ, precise measurements of α_s at different energies are essential. The electron–positron hadronic annihilation process provides a good opportunity for this purpose, since the process is theoretically well understood at the parton level. The main ambiguity comes from a fragmentation model to compare a perturbative QCD prediction with experimental data.

There are several methods to determine α_s in the process $e^+e^- \to$ hadrons in the continuum region [1]. They can be classified into two groups. The first one is a precise measurement of the ratio of the total hadronic cross section to the lowest order QED $\mu^+\mu^-$ cross section, the R ratio. The coupling constant α_s

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appears in R as the QCD correction to the naive quark model (QM), and it can be directly derived from the measured R. Since it is free from the detailed assumptions in the fragmentation model, it is a clean method from a theoretical point of view[#1]. Unfortunately, since the QCD contribution to R is small (about 4% for $\alpha_s=0.13$), a measurement with very high accuracy is required to determine α_s precisely. However, to reduce the total systematic error to a less than 1% level is almost impossible in practice. Moreover, lack of knowledge on the Z^0 mass and the Weinberg angle $\sin^2\theta_w$ results in a large uncertainty in the calculation of electroweak contribution to R at the TRISTAN energy region ($\Delta R(\mathrm{QM}) \simeq -0.10\Delta M_Z(\mathrm{GeV}/c^2) - 2.7\Delta\sin^2\theta_w$ at $\sqrt{s}=60$ GeV). It is an additional difficulty in the determination of α_s from R.

The second group is a study of various event-shape parameters which are sensitive to α_s. It can be estimated by fitting those distributions calculated from a Monte Carlo simulation program to the real data. However, the shape parameters depend on the choice of the fragmentation scheme as well as the perturbative QCD calculation in the Monte Carlo simulation. Hence, the resulting value of α_s has a large systematic uncertainty in general.

The energy–energy correlation (EEC) function, which is one of the shape parameters, has been introduced by Basham et al. [3]. The EEC is defined as the energy weighted angular correlation between two particles in a multi-hadron final state,

$$\mathrm{EEC}(\chi) = \frac{1}{N}\sum_{\mathrm{events}}^{N}\sum_i\sum_j \frac{E_iE_j}{E_{\mathrm{CM}}^2}\,\delta(\chi-\chi_{ij}) , \qquad (1)$$

where i and j run over all the particle combinations in an event. χ_{ij} is the angle between particles i and j. E_i is the energy of particle i, which was assumed to be a pion for a charged particle and a photon for a neutral particle. N is the number of hadronic events used for the analysis.

The asymmetry of the EEC (AEEC) is defined as

[#1] Recently, the next-next-to-leading $O(\alpha_s^3)$ QCD correction to R has been calculated by Gorishny et al.. The obtained correction is large, e.g., in the $\overline{\mathrm{MS}}$ scheme it is about twice larger than the next-to-leading $O(\alpha_s^2)$ correction for $\alpha_2=0.130$. Hence, the speed of the convergence of the perturbation series is controversial. See, in detail, ref. [2].

$$\mathrm{AEEC}(\chi) = \mathrm{EEC}(\pi-\chi) - \mathrm{EEC}(\chi) . \qquad (2)$$

The AEEC is a good measure of α_s, since it enhances the contribution from non-collinear hard gluon emission relative to the collinear $q\bar{q}$ contribution. In the collinear $q\bar{q}$ events, many effects of the fragmentation contribute symmetrically to the EEC, and they cancel out in AEEC.

We studied the EEC and AEEC using the hadronic annihilation events collected by the TOPAZ detector at the TRISTAN e^+e^- collider at $\sqrt{s}=52$–55 GeV and 59–60 GeV, and determined the values of α_s in these energy regions. The integrated luminosities of the data used for the analysis were 6.4 pb^{-1} at $\sqrt{s}=$ 52–55 GeV and 4.0 pb^{-1} at 59–60 GeV. The data at $\sqrt{s}=52$–55 GeV (59–60 GeV) were combined and treated as events at 53.3 GeV (59.5 GeV).

The TOPAZ detector [4] is a general purpose 4π-detector featuring a time projection chamber (TPC) as a central tracking device with an axial magnetic field of 1.0 T. The TPC provides the momentum resolution of $(\sigma_{p_t}/p_t)^2=(0.015p_t)^2+(0.016)^2$ (p_t in GeV/c) and a dE/dX resolution of 4.6%. Neutral particles are detected by the lead–glass calorimeters in the barrel region (BCL), and the gas calorimeters consisting of lead plates and proportional tubes in the end cap regions (ECL). Their energy resolutions are $(\sigma_E/E)^2=(0.08/\sqrt{E})^2+(0.025)^2$ and $(0.20/\sqrt{E})^2+(0.054)^2$ (E in GeV) for the BCL and ECL calorimeters, respectively. The inner radius of BCL is 1.76 m, and the front surface of ECL is $|z|=1.75$ m from the interaction point.

The hadronic events were selected by requiring: (a) at least 5 tracks with $p_t>0.15$ GeV/c and $|\cos\theta|\leqslant 0.83$ (with respect to the beam direction) coming from the interaction region; (b) the total visible energy E_{vis} including both charged and neutral particles had to be larger than E_{beam}; (c) the momentum balance along the beam direction defined as $|\sum p_z/E_{\mathrm{vis}}|$ had to be smaller than 0.4; (d) the larger of the invariant masses in the two hemispheres (with respect to the sphericity axis) had to be larger than 2.0 GeV; (e) no more than one cluster in the calorimeters with an energy deposit $>0.5E_{\mathrm{beam}}$; (f) the polar angle of the sphericity axis of the event in the range between 30° and 150°; and (g) no isolated hard photon (its definition is given below).

Requirements (b) and (c) are essential to remove two-photon events, (d) and (e) are to remove $\tau\bar{\tau}$ and Bhabha events, respectively. Requirement (f) is to ensure that the event is well contained in the detector, and (g) is to reduce the effect of the initial state radiation. We define an isolated hard photon by the requirement of an energy deposit of larger than 2.5 GeV and no charged particles of $p > 0.5$ GeV/c within a cone of 30° with respect to the photon direction. These cuts selected 745 events at $\sqrt{s} = 53.3$ GeV, and 540 events at 59.5 GeV. The contaminations from two-photon, $\tau\bar{\tau}$ and Bhabha events were estimated to be less then 1.2% in total by Monte Carlo simulations.

We used both charged and neutral particles in the calculation of the EEC. The charged particle was required to satisfy the p_t and $|\cos\theta|$ cuts described in requirement (a) in the hadronic event selection criteria. The neutral particle was required to have a minimum energy deposit of 500 MeV in the electromagnetic calorimeters. We required further that the neutral particle had no associated charged tracks, the energies of which were greater than the deposited shower energy, within 30 cm from the center of the hit point on the calorimeter. The EEC is calculated according to eq. (1), where we took E_{vis}, the visible energy of the event calculated from all the accepted particles, instead of E_{CM}.

The Monte Carlo simulation which we used for the determination of α_s is based on the $O(\alpha_s^2)$ QCD matrix elements calculated by Gottschalk and Shatz (GS) [5] combined with the Lund string fragmentation model (JETSET 6.3) [6]. The GS matrix elements include all the virtual corrections up to $O(\alpha_s^2)$ to the three-jet cross section. In the calculation of the jet cross sections, n-parton ($n=2$, 3, 4) cross sections were separated at $y_{ij} > y_{\mathrm{cut}} = 0.015$, where y_{ij} is the scaled invariant mass squared of a pair of partons, $y_{ij} = (p_i + p_j)^2/s$. Since the Lund string model with the symmetric function, $f(z) = z^{-1}(1-z)^a \exp(-bm_T^2/z)$, reproduces well the phenomenology of the fragmentation in the various event-shape distributions, we adopted this model [7].

The raw EEC was corrected for the effects of the initial state radiation, detector acceptance, and resolution. The correction was applied to each bin of the EEC as

$$\mathrm{EEC}_{\mathrm{corrected}}(\chi) = \frac{\mathrm{EEC}^{\mathrm{MC}}_{\mathrm{ideal}}(\chi)}{\mathrm{EEC}^{\mathrm{MC}}_{\mathrm{real}}(\chi)}\, \mathrm{EEC}_{\mathrm{raw}}(\chi)\,, \tag{3}$$

where $\mathrm{EEC}^{\mathrm{MC}}_{\mathrm{real}}$ ($\mathrm{EEC}^{\mathrm{MC}}_{\mathrm{ideal}}$) is the Monte Carlo prediction of the EEC with (without) the corrections. The correction factors were calculated for various α_s values, and the corresponding factors were used in the α_s determination procedure. Prior to the correction, the fragmentation parameters (a, b, σ_q) were tuned to reproduce our event-shape distributions. The values were $a=0.9$, $b=0.5$ GeV^{-2} and $\sigma_q = 0.4$ GeV/c. The systematic uncertainty in the correction factor was studied by varying the fragmentation parameters. We varied these parameters within the ranges of $b = 0.4$–0.7 GeV^{-2} and $\sigma_q = 0.35$–0.45 GeV/c, where the model could reasonably reproduce the event-shape distributions. The parameter a was fixed at 0.9 since the parameters a and b are strongly correlated. A typical value of the uncertainty was about 4.0%.

Fig. 1 shows the corrected EEC distributions for the selected hadronic events. Since the EEC has strong correlations between angular bins, the statistical error was estimated using the Monte Carlo simulation. We made fifty samples of simulated events, each of which had the same number of events as the experimental data. The statistical error was estimated by calculating the standard deviation of the EEC values deduced from the samples for each angular bin. The EEC distribution of the Monte Carlo events is also plotted in the figure.

We show the AEEC distributions in fig. 2. The nu-

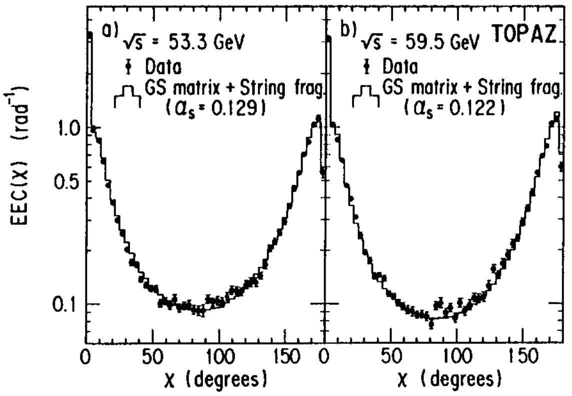

Fig. 1. The corrected EEC data at $\sqrt{s} = 53.3$ GeV (a), and 59.5 GeV (b). Only the statistical errors of the data are shown. The histograms are the Monte Carlo simulations with the best fitted α_s values.

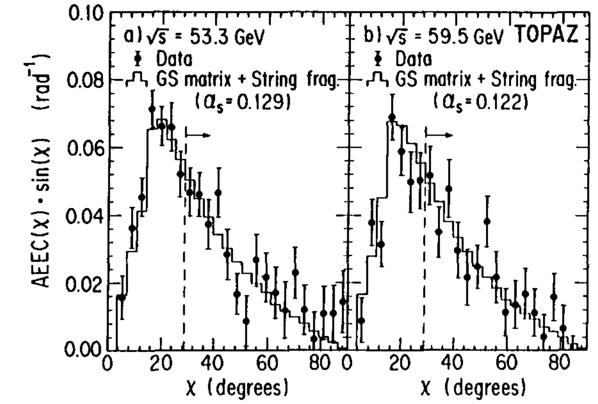

Fig. 2. The asymmetry of EEC at $\sqrt{s}=53.3$ GeV (a), and 59.5 GeV (b). The data are scaled by sin χ. Only the statistical errors of the data are shown. The histograms are the Monte Carlo simulations with the best fitted α_s values. The vertical dashed lines show the regions which we used for deducing the α_s values.

merical values of the EEC and AEEC in each bin are tabulated in table 1 (at $\sqrt{s}=53.3$ GeV) and table 2 (at 59.5 GeV). To determine α_s, we compared the measured AEEC with the AEEC calculated from high-statistics samples of Monte Carlo events generated with thirteen different α_s values at each CM energy. A chi-square was calculated for each Monte Carlo sample in the angular range of $\chi \geqslant 28.8°$, outside of a typical jet cone size, to minimize the fragmentation effects from collinear events. Only statistical errors were considered in the chi-square calculations. By fitting a parabola to the (α_s, χ^2)-points around the chi-square minimum, α_s was determined as 0.129 ± 0.007 at $\sqrt{s}=53.3$ GeV and 0.122 ± 0.008 at 59.5 GeV. The dependence of the α_s values on the fragmentation parameters (b, σ_q) was studied by varying them in a manner similar to the detector acceptance. The total systematic error in α_s was estimated to be ± 0.010, which included both the ambiguities in the correction factors and the fragmentation parameters for both energy points.

In order to compare our data with other experiments, we also derived α_s using the QCD matrix elements by Gutbrod, Kramer and Schierholz (GKS)

Table 1
Corrected EEC and AEEC at 53.3 GeV. Quoted errors are statistical only.

χ(deg.)	EEC(χ)(rad^{-1})	EEC($\pi-\chi$)(rad^{-1})	AEEC(χ)(rad^{-1})
0.0–3.6	3.247 ± 0.072	0.556 ± 0.030	-2.690 ± 0.078
3.6–7.2	0.993 ± 0.023	1.119 ± 0.038	0.126 ± 0.045
7.2–10.8	0.839 ± 0.014	1.033 ± 0.028	0.194 ± 0.031
10.8–14.4	0.642 ± 0.015	0.825 ± 0.018	0.183 ± 0.023
14.4–18.0	0.474 ± 0.011	0.705 ± 0.015	0.231 ± 0.019
18.0–21.6	0.376 ± 0.010	0.556 ± 0.013	0.180 ± 0.017
21.6–25.2	0.298 ± 0.007	0.453 ± 0.016	0.155 ± 0.018
25.2–28.8	0.250 ± 0.007	0.358 ± 0.013	0.108 ± 0.015
28.8–32.4	0.204 ± 0.006	0.291 ± 0.012	0.087 ± 0.014
32.4–36.0	0.173 ± 0.006	0.251 ± 0.009	0.079 ± 0.011
36.0–39.6	0.167 ± 0.005	0.226 ± 0.010	0.059 ± 0.011
39.6–43.2	0.138 ± 0.004	0.207 ± 0.010	0.068 ± 0.010
43.2–46.8	0.128 ± 0.004	0.167 ± 0.009	0.039 ± 0.010
46.8–50.4	0.122 ± 0.003	0.144 ± 0.006	0.022 ± 0.007
50.4–54.0	0.122 ± 0.004	0.133 ± 0.007	0.011 ± 0.008
54.0–57.6	0.101 ± 0.003	0.133 ± 0.007	0.032 ± 0.008
57.6–61.2	0.104 ± 0.004	0.129 ± 0.006	0.025 ± 0.007
61.2–64.8	0.098 ± 0.004	0.117 ± 0.005	0.019 ± 0.007
64.8–68.4	0.106 ± 0.005	0.119 ± 0.005	0.013 ± 0.007
68.4–72.0	0.095 ± 0.004	0.119 ± 0.005	0.024 ± 0.006
72.0–75.6	0.098 ± 0.004	0.110 ± 0.004	0.012 ± 0.006
75.6–79.2	0.099 ± 0.004	0.102 ± 0.005	0.004 ± 0.006
79.2–82.8	0.093 ± 0.004	0.104 ± 0.004	0.011 ± 0.006
82.8–86.4	0.092 ± 0.004	0.103 ± 0.004	0.011 ± 0.006
86.4–90.0	0.092 ± 0.005	0.106 ± 0.004	0.014 ± 0.006

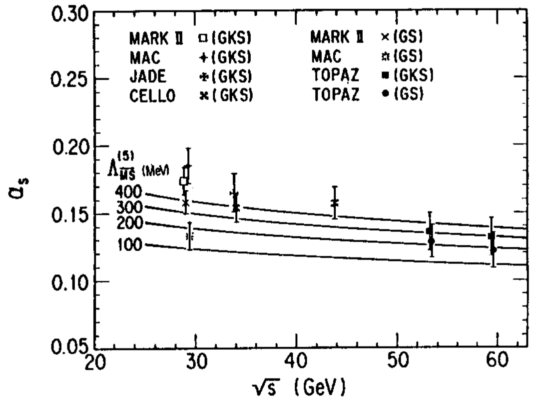

Fig. 3. Recent determinations of α_s from the e^+e^- experiments in the continuum region. Only results using the GS or GKS matrix elements and the Lund string fragmentation model are plotted. Statistical and systematic errors are added in quadrature. The solid curves show the $\sqrt{s}$ dependence of α_s for some $\Lambda^{(5)}_{\overline{MS}}$ values.

[8]. The derivation method is the same as before except for the use of the GKS matrix elements instead of the GS matrix elements. Following a similar analysis as above, we obtained α_s as $0.136 \pm 0.009(\text{stat}) \pm 0.011(\text{syst})$ at 53.3 GeV and $0.132 \pm 0.009(\text{stat}) \pm 0.011(\text{syst})$ at 59.5 GeV. The first error is statistical and the second systematic. The value of α_s are 5%–8% larger than those using the GS matrix elements.

The measured α_s values for the GKS calculation as well as the GS calculation are plotted in fig. 3 together with those from other e^+e^- experiments at lower energies [9]. The statistical and systematic errors are added in quadrature. Since the determination of α_s depends on the QCD matrix elements and the fragmentation scheme, we plot only the results using the GS or GKS matrix elements and the Lund string model. The solid curves in the figure show the QCD prediction for some values of $\Lambda^{5}_{\overline{MS}}$, which is the QCD scale parameter corresponding to the $\overline{MS}$ renormalization scheme with five flavors [10]. We have been using the two-loop β-function in the definition of $\alpha_s(Q^2)$ with the energy scale $Q^2=s$ [11],

Table 2
Corrected EEC and AEEC at 59.5 GeV. Quoted errors are statistical only.

χ(deg.)	EEC(χ)(rad^{-1})	EEC($\pi-\chi$)(rad^{-1})	AEEC(χ)(rad^{-1})
0.0–3.6	3.166 ± 0.084	0.599 ± 0.035	-2.567 ± 0.091
3.6–7.2	1.037 ± 0.027	1.108 ± 0.044	0.071 ± 0.052
7.2–10.8	0.850 ± 0.017	1.053 ± 0.032	0.202 ± 0.036
10.8–14.4	0.654 ± 0.017	0.781 ± 0.021	0.127 ± 0.027
14.4–18.0	0.470 ± 0.013	0.694 ± 0.018	0.223 ± 0.022
18.0–21.6	0.397 ± 0.012	0.557 ± 0.015	0.160 ± 0.019
21.6–25.2	0.310 ± 0.008	0.428 ± 0.019	0.117 ± 0.021
25.2–28.8	0.244 ± 0.009	0.348 ± 0.015	0.105 ± 0.017
28.8–32.4	0.194 ± 0.007	0.290 ± 0.014	0.096 ± 0.016
32.4–36.0	0.176 ± 0.007	0.235 ± 0.011	0.060 ± 0.013
36.0–39.6	0.144 ± 0.006	0.219 ± 0.012	0.075 ± 0.013
39.6–43.2	0.145 ± 0.005	0.189 ± 0.011	0.043 ± 0.012
43.2–46.8	0.139 ± 0.005	0.168 ± 0.010	0.030 ± 0.011
46.8–50.4	0.114 ± 0.004	0.146 ± 0.007	0.032 ± 0.008
50.4–54.0	0.110 ± 0.005	0.157 ± 0.008	0.047 ± 0.009
54.0–57.6	0.101 ± 0.004	0.126 ± 0.008	0.026 ± 0.009
57.6–61.2	0.097 ± 0.004	0.110 ± 0.007	0.013 ± 0.008
61.2–64.8	0.092 ± 0.005	0.107 ± 0.006	0.015 ± 0.008
64.8–68.4	0.090 ± 0.005	0.108 ± 0.006	0.018 ± 0.008
68.4–72.0	0.086 ± 0.004	0.098 ± 0.006	0.012 ± 0.007
72.0–65.6	0.087 ± 0.004	0.091 ± 0.005	0.004 ± 0.007
75.6–79.2	0.085 ± 0.004	0.101 ± 0.005	0.016 ± 0.007
79.2–82.8	0.076 ± 0.005	0.083 ± 0.005	0.007 ± 0.007
82.8–86.4	0.097 ± 0.005	0.094 ± 0.005	-0.003 ± 0.007
86.4–90.0	0.101 ± 0.006	0.089 ± 0.005	-0.012 ± 0.008

$$\alpha_s(s) = \frac{12\pi}{(33-2n_q)\ln(s/\Lambda^2_{\overline{\rm MS}})} \times\left[1-\frac{3(306-38n_q)}{(33-2n_q)^2}\frac{\ln\ln(s/\Lambda^2_{\overline{\rm MS}})}{\ln(s/\Lambda^2_{\overline{\rm MS}})}\right], \quad (4)$$

where n_q is the number of quark flavors. A fit to our data (using the GS matrix elements) gives $\Lambda^{(5)}_{\overline{\rm MS}} = 209^{+104}_{-78}$ MeV.

In conclusion, we studied the energy–energy correlation in the e^+e^- annihilation into hadrons at $\sqrt{s}=53.3$ and 59.5 GeV. From the asymmetry of the EEC, we determined α_s at these energy points. Our method was based on a Monte Carlo simulation using the $O(\alpha_s^2)$ QCD matrix elements calculated by Gottschalk and Shatz and the Lund string fragmentation model. The values of α_s are $0.129\pm0.007(\text{stat})\pm0.010(\text{syst})$ at $\sqrt{s}=53.3$ GeV and $0.122\pm0.008(\text{stat})\pm0.010(\text{syst})$ at 59.5 GeV.

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