Measurement of $\sigma_{\text{Total}}$ in $e^+e^-$ Annihilations Below 10.56 GeV

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Abstract. Using the CLEO III detector, we measure absolute cross sections for $e^+e^-\rightarrow$ hadrons at seven center-of-mass energies between 6.964 and 10.538 GeV. $R$, the ratio of hadronic and muon pair production cross sections, is measured at these energies with a r.m.s. error <2% allowing determinations of the strong coupling $\alpha_s$. Using the expected evolution of $\alpha_s$ with energy we find $\alpha_s(M_Z^2) = 0.126 \pm 0.005^{+0.015}_{-0.011}$, and $\Lambda = 0.31^{+0.09+0.29}_{-0.08-0.21}$.

1. Introduction
Theoretically $R(s) = \sigma_0(e^+e^- \rightarrow \text{hadrons})/\sigma_0(e^+e^- \rightarrow \mu^+\mu^-)$, where $s$ is the square of the center-of-mass energy, provides a straight-forward way to measure the strong coupling $\alpha_s$, since $R(s) = R_0 \left[ 1 + C_1 \frac{\alpha_s(s)}{\pi} + C_2 \left( \frac{\alpha_s(s)}{\pi} \right)^2 + C_3 \left( \frac{\alpha_s(s)}{\pi} \right)^3 + O(\alpha_s(s))^4 \right]$, where $R_0$ is given by the number of color degrees of freedom (3) times the sum of the squares of the quark charges. The $C_i$ are determined by QCD calculations.

2. Analysis Method
The observed cross-section is the sum contributions from the bare cross-section corrected by soft photon radiation (including virtual higher order diagrams), $\sigma_{sv}$, a correction for hard photon radiation, $\sigma_{\text{hard}}$, and radiative tails from resonant states, $\sigma_{\text{res}}$. The “Born” cross-section, $\sigma_0 = \sigma_{sv}/(\epsilon(0)\delta_{sv})$, where $\epsilon(0)$ is the efficiency for events without initial state radiation and $\delta_{sv}$ accounts for soft photon emission and hadronic and leptonic vacuum polarization. More details of the analysis method and the results are available [1].

3. Selection Criteria
In order to suppress backgrounds from events other than $e^+e^- \rightarrow$ hadrons, we apply selection requirements to individual tracks and showers as well as to entire events. These cuts are not completely efficient and thus we need to calculate their efficiencies from Monte Carlo simulation, thus leading to systematic errors, that dominate the uncertainties in our results. Table 1 lists the requirements for accepting tracks and showers and individual events.

Consistency with the beam collision point is enforced by the cut on $d_0$, the distance of closest approach of the reconstructed track relative to the beam axis, and on $z_0$, the distance between that point and the average collision point on the beam axis.
Table 1. Requirements on Track & Shower Selection, and Event Selection.

| Variable                   | Allowed range | Variable                   | Allowed range |
|----------------------------|---------------|----------------------------|---------------|
| $\chi^2$/NDF              | $< 100.0$     | $|Z_{\text{vertex}}|$      | $< 6.0$ cm    |
| hit fraction               | (0.5, 1.2)    | $E_{\text{vis}}/2E_{\text{beam}}$ | $> 0.5$      |
| $|d_0|$                     | $< 3.0$ cm    | $P_{\text{miss}}^z/E_{\text{vis}}$ | $< 0.3$      |
| $|z_0|$                     | $< 18.0$ cm   | $H_2/H_0$                  | $< 0.9$      |
| error of $z_0$            | $< 25.0$ cm   | $E_{\text{cal}}/2E_{\text{beam}}$ | (0.15, 0.9) |
| $|\cot(\theta)|$           | $< 3.0424$    | $E_{\text{max}}^\gamma/E_{\text{beam}}$ | $< 0.8$      |
| error of $\cot(\theta)$  | $< 0.50$      | $N_{\text{ChargedTrack}}$  | $\geq 4$     |
| $P_{\text{track}}/E_{\text{beam}}$ | (0.01, 1.5)  | $E_{\text{shower}}/E_{\text{beam}}$ | $> 0.01$     |

4. Results

Besides estimating remaining backgrounds after these selection criteria are applied, we need to correct for beam radiation before annihilation interactions, that can then create $c\bar{c}$ and $b\bar{b}$ bound state resonances. When the resonance decays to hadrons, our observed cross section increases. For the purposes of our $R$ measurement, these contributions are sources of background and must also be subtracted.

The sources of systematic uncertainty for each continuum cross section measurement include: luminosity, radiative correction, trigger efficiency for hadronic events, multiplicity correction, and hadronic event selection criteria. The resulting measured values of $R$ as a function of energy are shown in Fig. 1.

Figure 1. CLEO $R$ measurements versus energy. The two sets of uncertainties represent combined uncorrelated and statistical uncertainties and total uncertainties; the line represents $R(s)$ with our average $\Lambda = 0.31$ GeV, and the shaded area indicates the $R$-values corresponding to one standard deviation in the uncorrelated systematic uncertainty in $\Lambda$.

Table 2 shows the resulting $\alpha_s$ values obtained at each of the seven energies. Comparing $\alpha_s$ values with the QCD predictions [2] at our energies, which assumes the combined world average of $\alpha_s(M_Z^2) = 0.1189 \pm 0.0010$, we find agreement within our quoted uncertainties.
Table 2. Measured values of \( \alpha_s(s) \) with statistical and systematic (common and uncorrelated) uncertainties, respectively.

| \( \sqrt{s} \) (GeV) | \( \alpha_s(s) \) |
|---------------------|------------------|
| 10.538              | 0.232 ± 0.003 ± 0.061 ± 0.045 |
| 10.330              | 0.142 ± 0.005 ± 0.051 ± 0.049 |
| 9.996               | 0.147 ± 0.004 ± 0.057 ± 0.038 |
| 9.432               | 0.159 ± 0.004 ± 0.058 ± 0.033 |
| 8.380               | 0.218 ± 0.022 ± 0.053 ± 0.023 |
| 7.380               | 0.195 ± 0.017 ± 0.052 ± 0.018 |
| 6.964               | 0.237 ± 0.030 ± 0.052 ± 0.018 |

To test the compatibility with other measurements of \( \alpha_s \) we use the expected running of \( \alpha_s \) with energy [3):

\[
\alpha_s(s) = \frac{4\pi}{\beta_0 \ln(s/\Lambda^2)} \left[ 1 - \frac{2\beta_1}{\beta_0^2} \ln[\ln(s/\Lambda^2)] + \frac{4\beta_2^2}{3\beta_0^4} \ln^2(s/\Lambda^2) \times \left( \ln[\ln(s/\Lambda^2)] - \frac{1}{2} \right)^2 + \frac{\beta_2\beta_0}{8\beta_1^2} - \frac{5}{4} \right],
\]

(1)

where \( n_f \) presents the number of quarks which have mass less than \( \sqrt{s}/2 \), \( \Lambda \) represents the QCD energy scale, and the \( \beta \)-functions are defined as follows: \( \beta_0 = 11 - 2n_f/3 \), \( \beta_1 = 51 - 19n_f/3 \), and \( \beta_2 = 2857 - 5033n_f/9 + 325n_f^2/27 \).

To find \( \Lambda \), we use our \( \alpha_s \) values at each energy point and solve Eq. (1), assuming \( n_f \) is equal to 4. The value of \( \Lambda \) varies from 0.11 at 10.330 GeV to 0.67 at 10.538 GeV. Using Eq. (1) with our average value of \( \Lambda \), we extract the value of the \( \alpha_s \) at \( \sqrt{s} = M_Z \). Our results for \( \alpha_s \) imply \( \Lambda = 0.31^{+0.09}_{-0.08} \) GeV and \( \alpha_s(M_Z^2) = 0.126 \pm 0.005 \pm 0.015 \), where the uncertainties represent statistical and total systematic, respectively.

Our results for \( \alpha_s(M_Z^2) \) and \( \Lambda(n_f = 4) \) agree with the world averages \( \alpha_s(M_Z^2) = 0.1189 \pm 0.0010 \) [2] and \( \Lambda(n_f = 4) = 0.29 \pm 0.04 \) GeV [4]. Kuhn et al. [5] (LTH 749) include quark mass effects and different matching between 4 and 5 flavor effective theories. They find using these data: \( \alpha_s(M_Z^2) = 0.110^{+0.010}_{-0.012} \), \( \Lambda = 0.133^{+0.011}_{-0.007} \) GeV.

Acknowledgments
This work was supported by the National Science Foundation. I thank Surik Mehrabyan, Hector Mendez, and Karl Berkelman for useful discussions.

References
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