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MEASUREMENTS OF R_{hadron} AT $5 \leq E_{c.m.} \leq 8$ GeV AS A TEST OF QCD.

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Abstract

The hadron yield in e^+e^- annihilation normalized to the lowest order μ-pair cross section (R_h) is measured with systematic errors of ±6-8%, using the Crystal Ball detector at SPEAR. In the energy range of this measurement (5.2-7.0 GeV), the prediction of QCD for R_h, calculated to second order, is tested.

Résumé

La production de hadrons dans l'annihilation e^+e^- a été mesurée avec le détecteur "Crystal Ball". La mesure de la section efficace, normalisée à la production de muons (R_h), a une erreur systèmatique de ±6-8%. La prédiction de QCD calculée jusqu'au deuxième ordre testée dans le domaine d'énergie 5.2-7.0 GeV.

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I. Introduction

Presently, theory guides us to the use of R_{hadron}, (R_h), as a fundamental test of QCD, where R_h is defined to be the ratio of the annihilation of an electron and positron via a single virtual photon into hadrons divided by the theoretical lowest order point μ-pair production cross section (see figure 1). In such a ratio the straightforward effects of QED are cancelled revealing the QCD structure of the hadronic vertex.

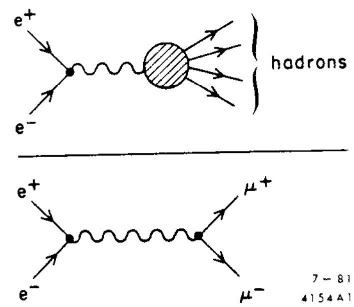

Figure 1. Feynman graphs for e^+e^- annihilation into hadrons (numerator) and μ-pairs (denominator). In this ratio (R_h), purely QED effects are divided out.

The prediction of QCD for R_h has been calculated, correct to second order in the theory, and is given by the expression,[2]

$$R_{qcd} = \sum Q_i^2[1 + \alpha_s(s)/\pi + C_2(\alpha_s(s)/\pi)^2 + \ldots] \qquad (1)$$

where in the $\overline{ms}$ renormalization scheme,[3]

$$C_2 = 1.98 - 0.115n_f \qquad (2)$$

and,

$$\alpha_s(s) = \alpha_s^o(s)[1 - (\beta_1/(4\pi\beta_o))\alpha_s^o(s)\ln\ln(s/\Lambda_{\overline{ms}}^2) + \ldots] \qquad (3)$$

and also,

$$\alpha_s^o(s) = 4\pi/(\beta_o \ln(s/\Lambda_{\overline{ms}}^2)) \qquad (4)$$

$$\beta_o = 11 - 0.667n_f \qquad (5)$$

$$\beta_1 = 102 - 38/3\ n_f \qquad (6)$$

in this QCD renormalization scheme.

We define, $s = E_{c.m.}^2$ and n_f is the number of flavors, 4 in the s-range discussed here.

Deep inelastic scattering studies using electrons, muons, and neutrinos have yielded values of Λ between 0.05 GeV and 0.5 GeV (c.f., the many reports at this conference); we take the range 0.2 GeV to 0.45 GeV in the comparison to experiment shown in this paper. Note that for s and $\Lambda_{\overline{ms}}$ with values 36 GeV^2 and 0.3 GeV, respectively, $C_2 = 1.64$ and $\alpha_s(36) = 0.202$. Thus the second order QCD contribution to R_h in the energy range considered here is 6.8×10^{-3}, i.e., about 0.2%. Presently, experiments are unable to measure such small discrepancies.

The motivation for the Crystal Ball collaboration's program to measure R_h in the high energy range of available SPEAR energies came primarily from two sources. Figure 2 shows a comparison of data from the Mark I collaboration[4] with the theoretical prediction described above (equations 1-6) and in reference 2. Barnett et al. suggest that the observed difference between the prediction of QCD and experiment might be real. If true, the ΔR_h implied might be signaling the existence of a threshold caused by some new phenomenon; which new phenomenon this might be is discussed in detail in their paper. Other possibilities discussed are experimental error and problems with QCD.

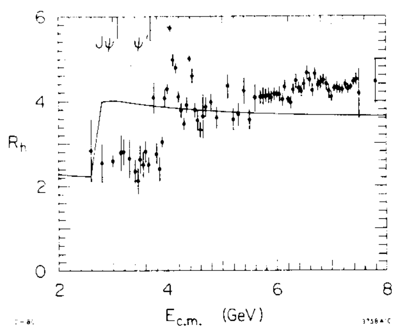

Figure 2. Measurements of R_h from the Mark I collaboration (Ref. 4). The data has been τ-subtracted and radiatively corrected. Only statistical errors are shown. Systematic errors are estimated to be ±10%. The curve is the QCD prediction for R_h (Ref. 2) with $\Lambda_{\overline{ms}}$ = .45 GeV.

The deviation observed between theory and experiment of about 16% is not very convincing given the reported systematic errors of ±10% in the Mark I experiment; clearly, better experiments were needed. The Mark II detector has also made measurements of R_h at SPEAR,[4] but these were limited to $E_{cm} \leq 5.8$ GeV, not high enough to check the disagreement between theory and experiment.

II. The Crystal R_h Program at SPEAR

The Crystal Ball detector is a device well suited to the measurement of R_h. This is due to a number of features of the detector:[5]

a) 98% of 4π coverage with NaI(tℓ) and charged particle identification.

b) Good calorimetry, particularly in the SPEAR energy range.

   i) 100% of the gamma energy is well measured.

   ii) About 50% of the charged particle energy is contained for SPEAR energies.

   iii) Some measurement of $n, \bar{n}$ K^0_ℓ energy is made since the detector has one absorption length of NaI(tℓ).

c) An independent small-angle precision luminosity monitor and a measurement of the luminosity using the central detector.

d) Many redundant event triggers, each separately having a high efficiency for multihadron events, in particular, one requiring only 1.2 GeV energy deposition into 85% of 4π.

In order to check the discrepancy between theory and experiment, we need experiments with an absolute accuracy of $\simeq \pm 5\%$ and with negligible statistical errors. This paper is a progress report of results from an ongoing Crystal Ball collaboration program to obtain measurements with the requisite errors (see table 1).

Table 1

Data Taking Schedule for R_h Measurement by the Crystal Ball

1) First run 1979--very limited, results reported previously.[6]

2) Second run 1980--results reported here.

$E_{c.m.}$ (GeV)	$\int L$ (nb^{-1})	# hadrons
5.2	76	980
6.0	96	920
6.5	96	766
7.0	122	905

3) Third run 1981--ten times more data, still being analyzed.

$E_{c.m.}$ (GeV)	$\int L$ (nb^{-1})	expected # hadrons	Comments
5.00	172	2400	extensive separated beam data taken at all energies
5.25	190	2400	
5.50	209	2400	
5.75	228	2400	
6.00	249	2400	
6.25	270	2400	
6.50	292	2400	
6.75	315	2400	
7.00	339	2400	
7.40	1072	6800	polarized beams, $\langle P \rangle \simeq 0.7$

III. Data Analysis

When extracting a value of R_h from the data obtained at SPEAR using the Crystal Ball detector, four major topics are studied in the analysis. These topics are luminosity, separation of hadronic events from background, Monte Carlo estimates of hardonic final state efficiency, and finally radiative corrections. We shall briefly discuss each of these topics.

a) Luminosity

The luminosity is measured in two ways. An estimate of the luminosity is first obtained from an independent small-angle luminosity monitor[5] which precisely measures the small-angle Bhabha scattering cross section at angles around 5° to the beam direction. The statistical errors of the measurement are negligible compared to the statistical error on the number of hadrons obtained. Secondly, the sum of the Bhabha and two-photon annihilation cross sections are measured in the main detector using 94% of 4π. The shape of the angular distribution obtained is compared to a Monte Carlo simulation of the QED processes which is correct to second order.[7] The $\cos\theta$ distributions of data and Monte Carlo are used to obtain the absolute normalization of data to Monte Carlo, and hence the luminosity. Figure 3 shows a comparison of the two distributions, normalized by area for data obtained at an $E_{c.m.}$ of 7 GeV. The luminosity used in the determination of R_h is an average of the values obtained by the two methods. Figure 4 shows the ratio of the luminosity determined by the central detector to the luminosity determined by the small angle luminosity monitor (R_{lum}). The error bars are primarily due to the statistical errors on the Monte Carlo estimate of the QED cross section for the central detector. On average, the two determinations of the luminosity agree to better than 1.5%; however, given the errors in the ratio, we presently estimate a ±3% systematic error for the luminosity determination.

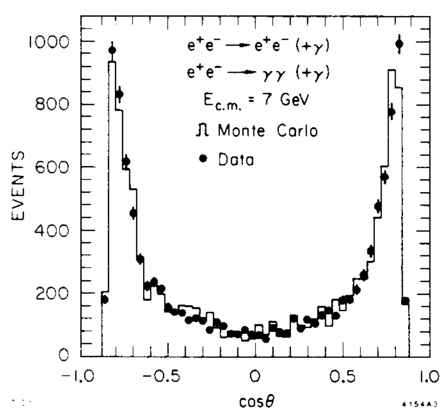

Figure 3. Angular distribution with respect to the beam (e^+) direction of e^+, e^- and γ tracks from the QED reactions $e^+e^- \to e^+e^-\gamma$ or $e^+e^- \to \gamma\gamma\gamma$ as seen in the Crystal Ball experiment (data points with statistical error bars). Each track is required to have an energy $>.5^*E_{beam}$ and each event is required to be planar within 10 degrees. For comparison, 1100 events from Monte Carlo simulations of these QED processed (Ref. 7) are shown (histogram). The histogram is normalized by area to the data points and the two shapes are in agreement with a χ^2-confidence level of 96%.

b) Separation of hadronic events from background.

There are five major backgrounds to single photon annihilation to hadrons. These backgrounds are cosmic rays, beam gas interactions, QED processes,

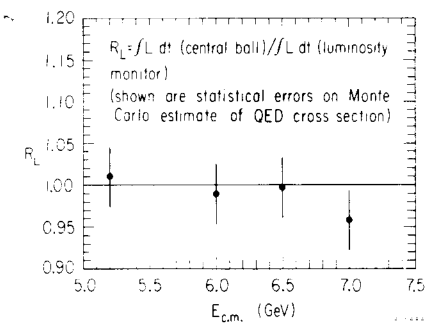

Figure 4. Ratio of luminosity as determined from the large-angle QED processes described in Fig. 3 to the luminosity as seen in the small angle detector (Ref. 5) plotted vs. $E_{c.m.}$. The error bars are dominated by the statistical uncertainty in the Monte Carlo estimate of the QED yield into the central detector.

$\tau\bar{\tau}$ production, and two-photon hadronic production. In order to separate these backgrounds from the desired hadronic events, pure samples of each background type, obtained from actual data or Monte Carlo simulation, were examined and cuts were designed to remove that background with high efficiency, while having minimal effect on the final hadronic sample. Any residual background left after cuts was substracted from the full data sample after cuts; however, typical subtractions were less than 10% after cuts for each background source (see table 3).

First consider the cosmic ray background. The trigger rate for cosmics is about 1.5 Hz for the experiment; a typical total trigger rate for the experiment is 3-4 Hz. The real hadronic event trigger rate averaged about 0.05 Hz. Cosmic rays thus represent a large potential background for a device like the Crystall Ball which presently is not able to use time-of-flight measurements to completely separate them. The first step in removing the cosmic ray background is to obtain a pure sample of cosmic ray events in the detector. This was accomplished by cutting on timing relative to the beam cross signal so as to safely exclude prompt beam-beam events. This background can be essentially completely removed with cuts which leave 98 ± 2% of the good hadronic events. In order to cut the cosmic events out, the pseudo sphericity tensor, ε_i^j , is used.

$$\varepsilon_i^j = \sum(-E_i E^j + \delta_i^j E^2) \tag{7}$$

where the sum in equation (7) is taken over all the NaI(tℓ) crystals in the detector having deposited energy E, and projected deposited energy along the x, y, z axes of $E_i = E\cos\theta_i$, or E^j, with i, j taking the directions x, y, z. The tensor ε_i^j is then diagonalized obtaining three eigenvalues, λ_α. The pseudo-sphericity is then,

$$\Pi = 3\lambda_3/(\lambda_1 + \lambda_2 + \lambda_3) \tag{8}$$

where λ_3 is the smallest eigenvalue. The eigenvector of λ_3 is taken as the jet axis, and ${p_{\perp jet}}^2$ to this jet axis is taken as equal to λ_3.

In addition, an energy asymmetry is defined for each event as,

$$A = \sqrt{((\sum E_1)^2 + (\sum E_2)^2 + (\sum E_3)^2)}/\sum E \qquad (9)$$

where again the sum is taken over all the NaI(tℓ) crystals.

The distribution of cosmic ray data in A vs. $p_{\perp jet}{}^2$ is shown in figure 5 as a scatter plot. Also shown as the solid lines in the figure are the cuts used to remove cosmics from the final data sample. The resulting timing distribution of events relative to the beam cross is shown after a (very small) beam gas subtraction in figure 6. Before cuts the cosmic ray background forms a plateau between abscissa values of about 290 to 490; after cuts essentially only the prompt beam-beam signal remains as shown in figure 6.

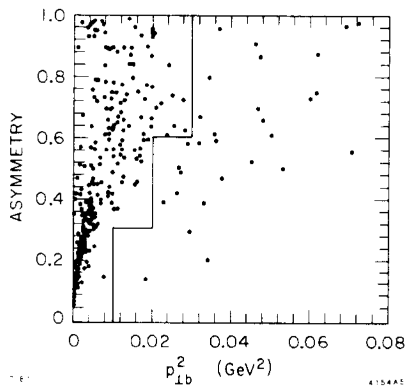

Figure 5. Correlation of energy asymmetry (A) and $p^2_{\perp jet}$ in events which are not coincident with the beam-beam crossing (cosmic ray data). A and $p^2_{\perp jet}$ are defined in section III.b of the main text. The solid curve is the cut used to remove the cosmic ray background from in-time colliding beam events.

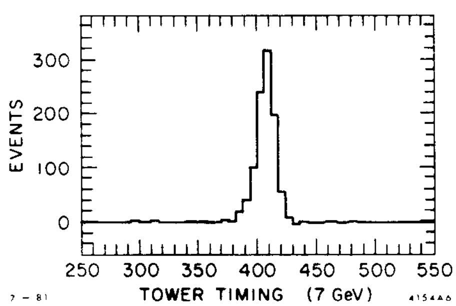

Figure 6. Timing distribution of events relative to the beam-beam crossing after the subtraction of cosmic ray background.

The most serious source of background is beam-gas interactions. Due to limitations in the tracking chambers, we are not able to subtract this background by using interaction region cuts along the z (i.e., beam) axis, as other detectors typically do. Thus, extensive separated beam data are needed to remove this background, with careful monitoring of storage ring currents and vacuum pressures a necessity. In the measurements presented here of R_h the monitoring of storage ring parameters was not optimal; the 1981 data sample has superior monitoring of these important parameters. Thus, very conservative cuts were applied to the data presented here to bring the final beam-gas subtractions to $\lesssim$12%. These cuts are the major source of inefficiency in the detection of the final hadronic data sample (typically 13 ± 4% inefficiency).

The cuts used were determined by examining separated beam data. The most powerful cut for removing this background was on pseudo $p^2_{\perp beam}$, given by the expression,

$$p^2_{\perp beam} = \sum \left(E_1^2 + E_2^2\right) \tag{10}$$

where again the sum is taken over all crystals in the detector. Events were typically required to have $p^2_{\perp beam} > 0.1$ GeV^2 to be accepted as good events; however, a smaller sample of the events as determined from other multiple criteria were required to satisfy $p^2_{\perp beam} > 0.2$ GeV^2. In addition one identified (as opposed to tracked) charged particle was also required for most events to be included in the final hadronic sample. For the remaining events, about 25% of the final sample of hadrons which had total deposited energy less than typically 3 GeV, two identified charged particles were required.

QED processes were the next most difficult process to remove from the hadronic sample. A set of cuts involving leading particle energy and the number of particles observed in an event removed these processes to a negligible level as estimated using Bhabha scattering and $\mu\mu\gamma$ Monte Carlo simulations. The effect on hadronic event efficiency of these cuts was on the few percent level.

The study of backgrounds arising from the process $e^+e^- \rightarrow e^+e^-$ + hadrons was implemented by using a Monte Carlo simulation of the process. The model used had $\#\pi^+ = \#\pi^- = \#\pi^o$, with $\langle N_{ch} \rangle = a + b\ln s$, a and b determined from e^+e^- single photon annihilation into hadrons; $\sigma_{\gamma\gamma} = 300 + 800/\sqrt{s}$ nb is taken as the cross section for this process.[8] The cuts described above plus additional cuts removing events with most of their energy deposited in the endcap regions of the detector were very effective in removing this background with only a few percent additional inefficiency for the signal.

Finally, the production of $\tau\bar{\tau}$ was subtracted by applying no additional cuts to the data. A Monte Carlo simulation of most $\tau\bar{\tau}$ final states, obtained from the Mark II collaboration, was used to subtract the residual $\tau\bar{\tau}$ contribution, typically 10%.

The result of the above process is shown in figures 7-10. The distributions show the energy deposited for each event, E_{tot}, plotted vs. the number of events. Each figure is for one of the energies for which a value of R_h is presented, and each figure has four parts, a-d. Part a shows colliding beam data with all cuts described above applied. Part b shows separated beam data with the same cuts, not properly normalized. Part c shows $\tau\bar{\tau}$ Monte Carlo with the same cuts, not properly normalized. Part d shows Part a - c1 (part b) - c2 (part c), where c1 and c2 properly normalize the subtractions. In addition a 1% to 3% subtraction

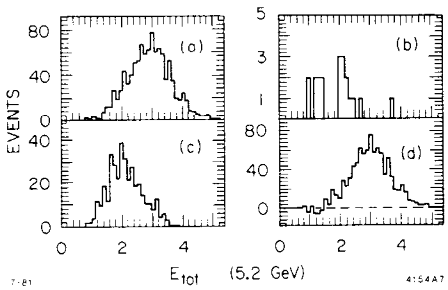

Figure 7. Total energy (E_{tot}) distributions for cuts applied and E_{beam} = 2.6 Gev:
(a) Unsubtracted colliding beam data;
(b) Separated beam data;
(c) Monte Carlo $\tau\bar{\tau}$ events;
(d) Final background-subtracted hadron data sample.

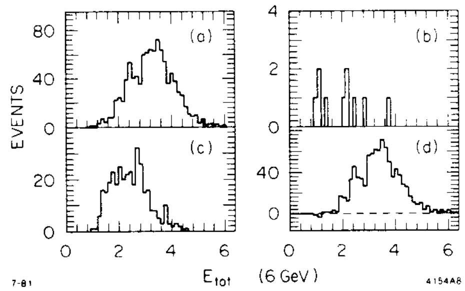

Figure 8. Total energy (E_{tot}) distributions for cuts applied and E_{beam} = 3.0 GeV:
(a) Unsubtracted colliding beam data;
(b) Separated beam data;
(c) Monte Carlo $\tau\bar{\tau}$ events;
(d) Final background-subtracted hadron data sample.

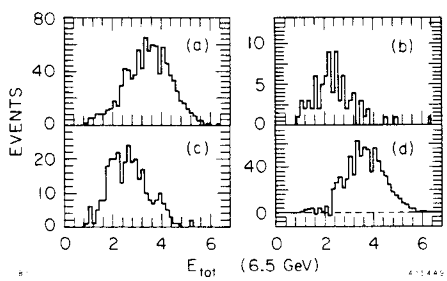

Figure 9. Total energy (E_{tot}) distributions for cuts applied and E_{beam} = 3.25 GeV:
(a) Unsubtracted colliding beam data;
(b) Separated beam data;
(c) Monte Carlo $\tau\bar{\tau}$ events;
(d) Final background-subtracted hadron data sample.

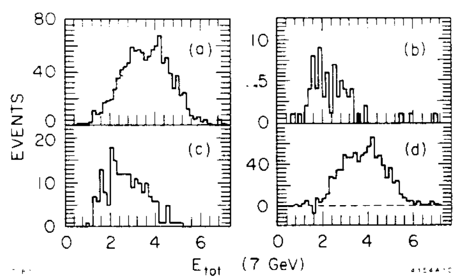

Figure 10. Total energy (E_{tot}) distributions for cuts applied and E_{beam} = 3.5 GeV:
(a) Unsubtracted colliding beam data;
(b) Separated beam data;
(c) Monte Carlo $\tau\bar{\tau}$ events;
(d) Final background-subtracted hadron data sample.

is made for $e^+e^- \to$ hadrons final states, the subtraction becoming larger as $E_{c.m.}$ increases. The final hadronic distributions for E_{tot} reasonably resemble Monte Carlo simulations of the single photon annihilation hadronic final states (the agreement between Monte Carlo and data is generally not so good when other variables are considered, see section III.). In particular, there is no excess of events at large energy deposition which might arise from QED backgrounds, and also, no excess or depletion of events at low deposited energy which might result from the incorrect subtraction of the other backgrounds (beam-gas, etc.). See table 3 for the amount of background subtraction at each energy. A systematic error of ±30% is estimated for each subtraction; these estimates of systematic error are added in quadrature to obtain the final estimate of systematic error in the number of good hadronic events. The total systematic error obtained is typically ±4%.

III. Monte Carlo Simulation of Hadronic Final States

The Monte Carlo simulations we have used of the single photon annihilation to hadrons have evolved from those used in the past by the Mark I and Mark II collaborations at SPEAR.[9] The general characteristics of these models are given in the reference and in table 2. As is shown in the table, a variety of models of this general type were used to estimate the hadronic final state efficiency. The Monte Carlo was implemented as follows. Events were generated using one of the models, JET0-JET4. The generated events were passed through a computer program which simulates the Crystal Ball detector's response to photons, electrons, and hadrons. This program also simulates the detector acceptance and charged particle identification and tracking efficiency. The event data output by this program closely resembles real event data. The output events are then passed through the entire analysis chain as real data would be. The resulting distributions of variables of interest are then compared to the hadronic samples obtained from real data (e.g., figures 7-10 d). The efficiencies used to correct the real data are obtained by comparing the number of Monte Carlo events which pass all cuts to those which are input to the analysis programs. These efficiencies, ε, shown in table 2, have a mean value of .85 for $E_{c.m.} = 7$ GeV.

The comparison of one important quantity, the observed average energy deposited per hadronic event divided by $E_{c.m.}$, $\langle E_{tot}\rangle / E_{c.m.}$, is shown in figure 11. The Monte Carlo used was JET4, JET4 generally gave the best agreement with the actual data. We have found that none of the models we have used give good agreement with all the distributions obtained from the real data. Thus we have placed a systematic error on the efficiency obtained from the Monte Carlo of $\pm 0.3\ (1-\varepsilon)$. This estimate has been arrived at in two ways. First, given that 5 models have been used, we can obtain a standard deviation of ε from all the models. For 7 GeV the standard deviation for ε is 5.7%, i.e., about $0.3\ (1-\varepsilon)$. We have also performed a parametric study on the real data, varying the cuts and noting the change in the number of events obtained as compared to the predicted change from the Monte Carlo. This estimate of error is also consistent with $0.3\ (1-\varepsilon)$. We expect that the use of more sophisticated models,

Table 2

Hadron Monte Carlo Efficiency (ε) Estimate
for $E_{c.m.}$ = 7 GeV

1) Limited Transverse Momentum ("JET") Models.
2) Initial State Radiation Included.
3) $1 + \cos^2\theta$ JET Axis Angular Distribution.

Model	$\langle P_t \rangle$ (GeV)	$\langle N_{tot} \rangle$	ε
"JET0" All π. 25% $\pi^{\pm}$ 50% π^{o}	.261	10.2	.90
"JET1" 25% ν equal π^+ π^- π^o	.261	10.2	.75
"JET2" π K ν (from D) and heavy particles (η)	.340	7.70	.87
"JET3" π K ν and heavy particles (ω)	.340	7.70	.85
"JET4" π K ν and heavy particles ($\eta \rightarrow 3\pi$)	.310	7.70	.86

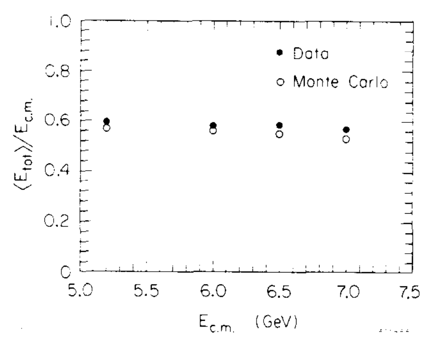

Figure 11. A comparison of (a) the average energy fraction deposited per event $\langle E_{tot} \rangle / E_{c.m.}$

such as Feynman-Field, will lead to generally better agreement between real data and Monte Carlo; we will be able to reduce our error estimate if this proves to be the case.

IV. Radiative Corrections

The radiative corrections used when obtaining R_h consist of two parts. The first we have already discussed, the radiative corrections of the QED processes used to obtain the luminosity. For the central detector estimate of luminosity, we have included the vacuum loop corrections arising from e, μ, τ, and hadron (obtained from R_h) loops, as is contained in the currently available QED Monte Carlo simulation of Berends and Kleiss[7] (see figure 12a). These corrections are important for large-angle QED processes at the energies we are considering (and higher); however, the small-angle Bhabha scattering radiative correction is not sensitive to the inclusion of the higher mass loop diagrams at our energies.

The hadronic radiative correction is accomplished in two steps. The Monte Carlo for the annihilation to hadrons has radiation effects built in. Thus events are radiatively degraded with the correct relative frequency and kinematics (the radiated photon goes down the beam pipe). The model is automatically scaled to the relevant s to yield the correct hadronic final state characteristics, e.g., particle multiplicity. Thus the efficiency calculated from the Monte Carlo properly takes into account the radiative effects. The hadronic yield is divided by the Monte Carlo efficiency, ε, before the next stage of radiative correction is done. The radiated cross section (corrected for efficiency) is then radiatively corrected using the techniques described in reference 11. Reference 11 only includes the vacuum polarization loop of the e. Thus to obtain a radiative correction consistent with that done for the luminosity, the loops for μ, τ and hadrons must be included. This has been done using results of R. M. Barnett[11] (see figure 12b). The correction due to radiative effects lowers the efficiency corrected observed cross section by typically 11%. We have assigned a systematic uncertainty of ±20% of the correction.

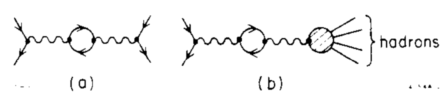

Figure 12. Vacuum-polarization corrections involving e, μ, τ and hadron loops to (a) lowest order Bhabha scattering (only timelike diagram is shown) and (b) hadron production.

V. Results and Conclusions

Table 3 shows the final R_h values obtained, the corrections made to obtain each value, and the statistical errors and systematic error estimates. Also shown are the estimates of systematic error relative to the 5.2 GeV cross section point, which are somewhat smaller than the absolute systematic error estimates. The latter systematic errors can be used to put limits on the size of steps in the energy range considered (relative to the R_h value at 5.2 GeV).

Figure 13 shows the values of R_h from table 3 plotted vs. E_{cm} together with values from Mark I and Mark II[12], and PLUTO[13], and the 1979 Crystal Ball Measurement at 5.2 GeV.[6] Also shown is the prediction of QCD[14] for $\Lambda_{\overline{ms}}$ equal to 0.45 GeV and 0.2 GeV.

Given our overall systematic errors of ±6-8%, we are consistent with the results of the Mark I with systematic errors of ±10%, and the Mark II with

Table 3

R_h Values and Errors

$E_{c.m.}$ (GeV)	R_{had}	$\Delta R_{stat.}$ [a]	$\Delta R_{syst\ 1}$ [b]	$\Delta R_{syst\ 2}$ [c]
5.2	4.00	0.14	0.34	0.00
6.0	4.00	0.14	0.28	0.08
6.5	3.93	0.15	0.30	0.17
7.0	4.28	0.15	0.32	0.18

R_h Correction Factors[d]

$E_{c.m.}$ (GeV)	Monte Carlo ε	Beam Gas	$\tau\bar{\tau}$	Rad. Cor.	$\sigma_{\gamma\gamma \to hadrons}$
5.2	1.29	0.949	0.893	0.890	0.987
6.0	1.20	0.972	0.902	0.890	0.976
6.5	1.18	0.882	0.900	0.888	0.973
7.0	1.18	0.885	0.903	0.889	0.964

[a] The statistical error on R_h.
[b] The overall systematic error estimate on R_h.
[c] The systematic error estimate on R_h relative to R_h at 5.2 GeV.
[d] The factors all multiply the uncorrected R_h to obtain the corrected R_h.

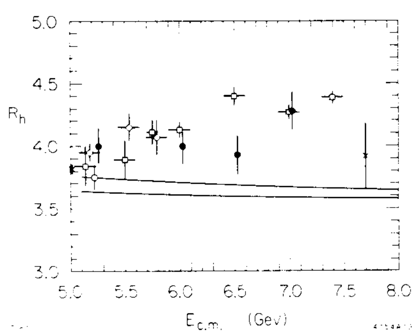

Figure 13. Radiatively corrected and τ-subtracted R_h values from various experiments are shown with statistical error bars only: Mark I (open squares); Mark II (open diamonds); PLUTO (crosses); previous results from the Crystal Ball (open circles); current results from the Crystal Ball (closed circles). The second order QCD calculations (Ref. 14) with $\Lambda_{\overline{ms}} = .2$ GeV (lower curve) and $\Lambda_{\overline{ms}} = .45$ GeV (upper curve) are shown for comparison.

systematic errors of ±8%. Within an overall scale uncertainty of 10%, our R_h values are in agreement with the second-order QCD calculations of reference 14. We see no compelling evidence for an R_h threshold near 5 GeV. We expect that the analysis of much more extensive data recently obtained using the Crystal Ball at SPEAR will yield R_h values with significantly smaller errors than the measurements reported here.

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