R-values in Low Energy e^+e^- Annihilation

Zhengguo Zhao

Institute of High Energy Physics of Chinese Academy of Sciences
Beijing 100039, P.R.C.

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Abstract

The QED running coupling constant $\alpha(s)$ and the anomalous magnetic moment of muon a_{μ} are two fundamental quantities for the precision test of the Standard Model. The current uncertainties on $\alpha(s)$ and a_μ are dominated by the contribution from the R-values measured about 20 years ago with uncertainties of 15-20% in the energy region below 5 GeV. This presentation summarizes the measurements of R-values in low energy e^+e^- annihilation. The new experiments aiming at reducing the uncertainties in R-values performed with the upgraded Beijing Spectrometer (BESII) at Beijing Electron Positron Collider (BEPC) and with CMD-2 and SND at VEEP-2 in Novosibirsk are reviewed and discussed.

1. Introduction

1.1 Definition of R

R-value I'm going to discuss is one of the most fundamental quantities in particle physics. According to quark-parton model, hadrons produced via e^+e^- collision are characterized by the annihilation of e^+e^- into a virtual γ or Z^0 boson. In the lowest order, the cross section for the (QED) processes $e^+e^-\rightarrow\gamma\rightarrow q\bar{q}$ is related to the that for $e^+e^-\rightarrow\gamma\rightarrow\mu^+\mu^-$.

$$\sigma(e^+e^- \rightarrow q\bar{q}) = 3Q_f^2\sigma(e^+e^- \rightarrow \mu^+\mu^-),$$

where Q_q is the fractional charge of the quark, and three in front records the three colors for each flavor. Summing over all the quark flavors, one define the ratio of the rate of hadron production to that for muon pairs as

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \gamma \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-)} = 3\sum_f Q_f^2 .$$

The cross section of the pure QED process $e^+e^-\rightarrow\gamma\rightarrow\mu^+\mu^-$ can be precisely calculated, which is the Born cross section $\sigma(e^+e^-\rightarrow\gamma\rightarrow\mu^+\mu^-)=4\pi\alpha^2/3s$. Thus, a measurement of total e^+e^- annihilation cross section into hadron counts directly the number of quarks, their flavor and colors. The R-value is expected to be constant so long as the center-of-mass energy of the annihilated e^+e^- does not overlap with resonances or thresholds for the production of new quark flavors. One has

$$
\begin{aligned}
R &= 3[(2/3)^2+(1/3)^+ +(2/3)^2] = 2 && \text{for u, d, s,} \\
&= 2 \quad + 3(2/3)^2 = 10/3 && \text{for u, d, s, c,} \\
&= 10/3 + 3(1/3)^2 = 11/3 && \text{for u, d, s, c, b.}
\end{aligned}
$$

These R-values are only based on the leading order process $e^+e^- \to q\bar{q}$. However, one should also accommodate the contributions from diagrams where the quark and anti-quark radiate glues. The higher order QCD corrections to R has been calculated in complete 3rd order perturbation theory [1], and the results can be expressed as

$$R = 3\sum_q Q_q^2\left[1+\left(\frac{\alpha_s(s)}{\pi}\right)+1.411\left(\frac{\alpha_s(s)}{\pi}\right)^2-12.8\left(\frac{\alpha_s(s)}{\pi}\right)^3+\cdots\right],$$

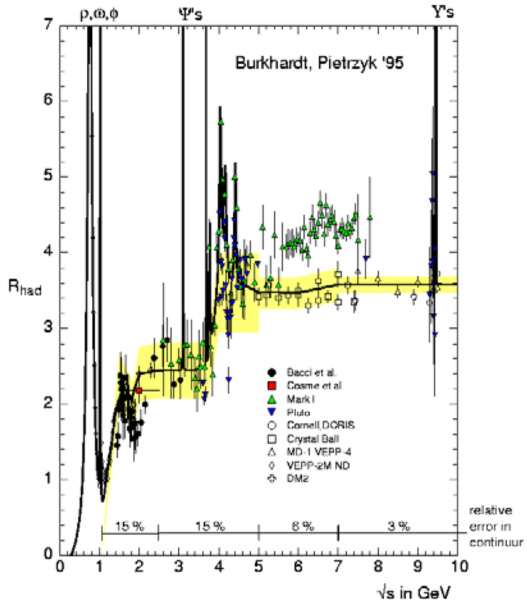
where $\alpha_s(s)$ is the strong coupling constant. Precise measurement of R at higher energy can be employed to determine α_s according to e.q. 1.3, which exhibits a QCD correction known to $O(\alpha_s^3)$. In addition, at low c.m. energy, non-perturbative corrections (resonances ···) could be important.

1.2 Current status of the experimental R-value

R-value has been measured by many laboratories in the energy region covering from hadron production threshold to the Z^0 pole and recently to the energy of W pair production[2, 2']. The experimental R-values are in general consistent with theoretical predictions, which are impressive confirmation of the hypothesis of the three color degrees of freedom for quarks.

The uncertainties of R in different energy region are summarized in table 1. At center-of-mass energy less than 5 GeV, the measurements of R were performed 15 to 20 years ago by Orsay, Frascati and SLAC with uncertainties of 15-20% [3, 4, 5, 6]. Between the charm and bottom thresholds, i.e., about 5-10.4 GeV, R were measured by Mark I, DASP, PLUTO, Crystal Ball, LENA, CLEO, CUSB, and DESY-Heidelberg collaborations [41]. Their systematic normalization uncertainties were about 5-10%. Above bottom threshold, the measurements were from PEP, PETRA and LEP with uncertainties of 2-7%.

Fig. 2 quoted from Ref. [15] shows the R-values for center-of-mass energies up to 10 GeV, including resonances. The relative errors of the continuum contribution on R is shown as a band and given in numbers at the bottom of the figure.



We emphases that for c.m.e below 5 GeV, the uncertainties in R-values is about ~15% in average; and there are ambiguous structures in the energy region between 3.7-5 GeV. The R-values and the ambiguous structures are inconsistent from different measurements made by different detectors.

Table 1. R in low energy measured by different laboratories

Place	Ring	Detector	E_{cm} (GeV)	Points	Year
Beijing	BEPC	BESII	2.0-5.0	106	1998-1999
Novosibirsk	VEPP-2M VEPP-2	CMD2 SND Olya, ND CMD	0.6-1.4 0.3-1.4	Exclusive channels	1997-1999
SLAC	Spear	MarkI	2.8-7.8	78	1982
Frascati	Adone	γγ2, MEA Boson,BCF	1.42-3.09	31	1978
Orsay	DCI	M3N DM1, DM2	1.35-2.13	33	1978
Hamburg	Doris	DASP PLUTO	3.1-5.2 3.6-4.8	64 27	1979 1977

1.3 $\alpha(M_Z^2)$ and the Standard Model fits

A remarkable progress has been made in precision test of the Standard Model (SM) during the last decade[?].. For the analysis of electroweak data in the SM [8, 9] one starts from the input parameters. Some of them, like $\alpha(M_Z^2)$, G_F, and M_Z are very well known, and some others, m_{light} and $\alpha_s(M_Z)$ are only approximately determined while m_t is poorly known. M_H is almost unknown. Constrain on m_t and M_H can be derived by comparing the measured observables with theoretical predictions that has been calculated to full one-loop accuracy and partial two-loop precision, a sufficient precision to match the experimental capabilities.

Out of the three accurately determined quantities $\alpha(s)$, G_F, and M_Z, the largest uncertainty comes from the running of QED coupling constant $\alpha(s)$ from $s = 0$, where it is known to 0.04 ppm, up to the Z pole, which is the scale relevant for the electroweak precision test. The running of $\alpha(s)$ as a function of $s=\sqrt{q^2}$ is shown in fig. 3. When relating measurements performed at different energy scales, and if the relation involves $\alpha(s)$, one has to know the running of $\alpha(s)$ in different energy scale. The uncertainty in $\alpha(M_Z^2)$ arises from the contribution of light quarks to the photon vacuum polarization $\Delta\alpha(s) = -\prod_{\gamma\gamma}(s)$ at the Z mass scale. They are independent of any particular initial or final states and can be absorbed in $\alpha(s)$

$$\alpha(s) = \alpha / [1- \Delta\alpha(s)] , \qquad 1.4$$

with the fine-structure constant α=1/137.035 989 5(61) and

$$\Delta\alpha(s) = -4\pi\alpha \mathrm{Re}[\Pi_\gamma'(s)-\Pi_\gamma'(0)]$$

where $\Pi_\gamma'(s)$ is the photon vacuum polarization function

$$i\int d^4 x e^{iq\cdot x}\left\langle 0 \,|\, T j^\mu_{em}(x) j^\nu_{em}(0) \,|\, 0 \right\rangle = -(q^2 g^{\mu\nu} - q^\mu q^\nu \Pi_\gamma'(q^2))$$

and $j^\mu_{em}(x)$ is the electromagnetic current.

$\Delta\alpha$ receives the contribution of the leptonic loops and the quark loops to the running

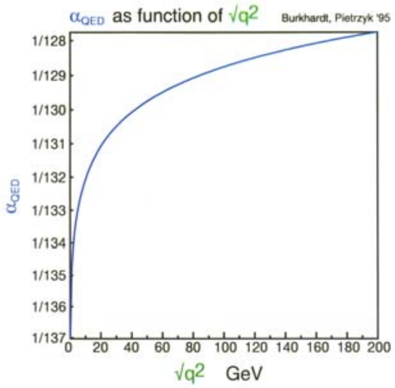
$$\Delta\alpha = \Delta\alpha_{lepton} + \Delta\alpha_{had},$$

where the leptonic part

$$\Delta\alpha_{lepton}(s) = \sum_{l=e,\mu,\tau} \frac{\alpha}{3\pi}\left[\ln(s/m_l^2) - \frac{5}{3} + O(m_l^2/s)\right]$$

$$= 0.013142 \text{ for } s = M_Z^2$$

is relative precisely calculated analytically according to perturbation theory because free lepton loop are affected by small electromagnetic corrections[Jeglhler?]. Whereas, the hadronic part $\Delta\alpha_{had}$ cannot be entirely calculated from QCD because of ambiguities in defining the light quark masses m_u and m_d as well as the inherent non-perturbative nature of the problem at small energy scale (the free quark loops are strongly modified by strong interactions at low energy). An ingenue way [10] is to relate $\Delta\alpha_{had}$ from quark loop diagram to R_{had}, making use of unitarity and the analyticity of $\Pi_\gamma'(s)$.



$$\Delta\alpha_{had}^{(5)}(s) = -\frac{\alpha s}{3\pi} P\left(\int_{4m_\pi^2}^{E_{cut}^2} ds' \frac{R_\gamma^{data}(s')}{s'(s'-s)} + \int_{E_{cut}^2}^{\infty} ds' \frac{R_\gamma^{PQCD}(s')}{s'(s'-s)} \right)$$

where

$$R_\gamma(s) \equiv \sigma(e^+e^- \to \gamma^* \to \text{hadrons}) / \sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = 12\pi \, \text{Im}\Pi_\gamma'(s)$$

and P is the principal value of the integral.

A lot of independent work has recently been done on the subject to evaluate α(s) at the energy of Z pole. So far, the uncertainty of Δα(s) is dominant by the R-values in low energy (E_{cm}<5 GeV) were measured with an average uncertainties of ~15%, as indicated in fig. ?. Recently there is a theoretical driven tendency to extend the PQCD to the energy down to 1.7 GeV in order to avoid using the R-values measured 20 years ago with large uncertainty. However, such a tendency is not deter the experimentalists to improve R measurements, which can test such a kind of calculation base on QCD. Table ? summarized the evaluated $\alpha(M_Z^2)$ values by different authors

Table 2. Summary of the evaluated $\Delta\alpha(M_Z^2)$ and $\alpha^{-1}(M_Z)$. Only the published values are listed. The value in the last row is from purely theoretical calculation based on QCD sum rules.

$\Delta\alpha(M_Z)$	$\alpha^{-1}(M_Z)$	Author	Year and Ref.
0.0285 ± 0.0007	128.83 ± 0.09	Jegerlhner	1986, [11]
0.0283 ± 0.0012	128.86 ± 0.16	Lynn et al.	1987, [12]
0.0287 ± 0.0009	128.80 ± 0.12	Burkhardt et al.	1989, [13]
0.0282 ± 0.0009	128.87 ± 0.12	Jegerlhner	1991, [14]
0.02732± 0.00042	128.99 ± 0.06	Martin et al.	1995, [16]
0.0280 ± 0.0007	128.89 ± 0.09	Burkhardt et al	1995, [15]
0.0280 ± 0.0007	128.90 ± 0.09	Eidelmann et al.	1995, [52]
0.02752± 0.00046	128.96 ± 0.06	Swartz	1996, [7]
0.0267 ± 0.0011	129.04 ± 0.05	N. F. Nasrallah	1997, [42]

0.02817±0.00062	128.878 ± 0.085	Michel Davier et. al.	1997, [54]
0.02778±0.00026	128.923 ± 0.036	Michel Davier et. al.	1997, [55]
0.02778±0.00017	128.928 ± 0.023	J.H. Kuehn et. al.	1998, [56]
0.02789±0.00045	128.907 ± 0.062	S. Groote, et. al.	1998, [57]
0.02763±0.00016	128.933 ± 0.021	A. Hoecker, e,al.	1998, [58]

A serious problem in the determination of $\Delta\alpha(M_Z^2)$ and thus $\alpha(M_Z^2)$ is that the low energy contributions from the 5 light quarks to $\Delta\alpha(M_Z^2)$ cannot be calculated reliably from perturbative QCD, one has to rely on the hadronic e^+e^- annihilation data to evaluate $\Delta\alpha(M_Z^2)$ with the help of e.q. 1.8, to which the $R_{had}(s)$ values determined by old measurements in low energy region with a typical precision of 15-20%, as discussed before, has to be used as inputs. Fig. 4 shows the relative contributions to the value and the related uncertainties of $\alpha(M_Z^2)$. As shown in fig. 4(b), more than half of the over all uncertainty comes from the hadronic contribution at center-of-mass energies between 1-5 GeV.

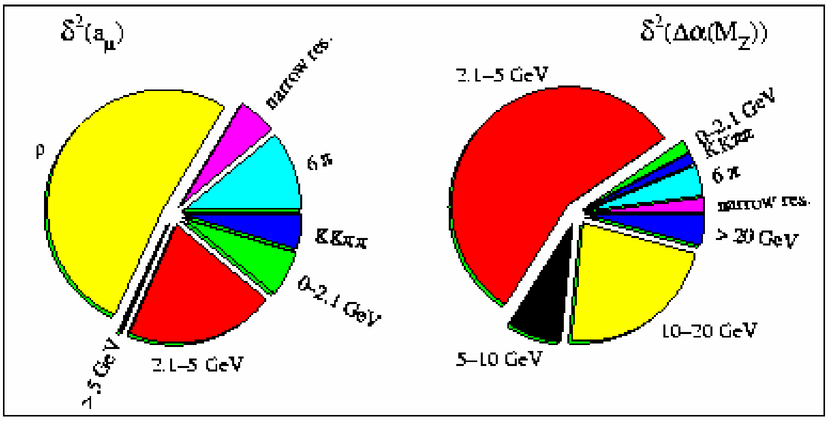


Figure ?. The relative contribution of the uncertainties in (a) a_μ and (b) $\Delta\alpha(M_Z^2)$[M. Davier?].

Besides the problems arising from the poor precision data for the hadronic production in the processes of $e^+e^-\to\gamma\to$hadrons, the structure in the charm threshold region is not well known. DASP group [17] inferred the existence of narrow resonance at 4.04 GeV and 4.16 GeV. In addition to the resonance at 3.77 GeV, Mark I data [18] shown a broad enhancement at 4.04, 4.2 and 4.4 GeV. The resonance at 4.4 GeV was also observed by PLUTO [19], but the height and width of the resonance were reported differently. New cross section measurement in the charm threshold region is expected to clarify the structure, which is important for the knowledge of the charmonium itself, and contribute to the precision determination of $\alpha(M_Z^2)$.

The electroweak mixing angle $\sin^2\theta_W$ is very often characterized by experimental results deduced from the *Z* mass and other *Z*-pole observables, the W mass and neutral-current processes. Its value depends on the renormalization prescription, of which all relate to $\alpha(M_Z^2)$. For example, $\sin^2\theta_W$ can be calculated by using relatively precise measured parameters G_F, M_Z and $\alpha(M_Z^2)$

$$\sin^2 2\theta = \frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2} \cdot \frac{1}{1-\Delta r}$$

where Δr includes the radiative correction relating α, $\alpha(M_Z^2)$, G_F, M_Z and M_W.

One sees that $\alpha(M_Z^2)$ is universally important to the radiative correction in the SM fit. Recently there has been an increasing interest in the electroweak phenomenology to reduce the uncertainty in $\alpha(M_Z^2)$ which at present seriously limits the further progress in the determination of the Higgs mass from radiative correction in the SM fit. Fig.?-Fig.? illustrate the influence of the uncertainty of $\alpha(M_Z^2)$ to the SM parameters $m_{H,}$ m_W and $sin^2\,\theta_{eff}^{lept}$.

4 plots here
m_H-sin\theta^2, m_H-m_W, m_H-m_t, kai^2-m_H

Figure ? (a)
The $\Delta\chi^2 \equiv \chi^2\text{-}\chi^2_{min}$ distribution of the SM fit of m_H can be made by constraining the fit with the measured top mass m_t =175±6 [21] as shown in fig. ?. Fig. ? SM fit to m_t and m_H with $\alpha(M_Z^2)$ varying by $\pm\sigma$ [?B. Pietrzyk and H. Burkhard]

The E.W. data from high energy are now so precise that the radiative correction gives rise to the precision tests of the E.W. theory. In particular, the indirectly determination of m_H depends critically on the precision of $\alpha(M_Z^2)$

The value of $\alpha(M_Z^2)$ influences the determination of electroweak corrections relating to m_W, m_H and $\sin^2\theta_{eff}^{lept}$. $\sin^2\theta_{eff}^{lept}$ is the most sensitive observable for Higgs mass determination so far. The experimental error on $\sin^2\theta_{eff}^{lept}$ due to $\alpha(M_Z^2)$ in the prediction of this quantity is equal to the experimental error, implying that *the SM interpretation to the improved measurements of $sin^2\,\theta_{eff}^{lept}$ would be limited by current precision of $\alpha(M_Z^2)$. An improved uncertainty for the value of $\alpha(M_Z^2)$ would result in an improved constraint on m_H.*

Because of the above arguments, Dr. ?? made an strong statement at ICHEP95, claiming that the re-measurement of hadronic cross section in the energy region of 1-5 GeV is has as much weight as all measurements of $\sin^2\theta_{eff}^{lept}$ put together[39].

Fig. ? shows the results of the SM fit on m_t and m_H, exhibiting the change of the m_t and m_H in the SM fit as $\alpha(M_Z^2)$ varies within its 1 σ error.

1.4 g-2 of the lepton

According to the Dirac theory, an lepton is point-like and possesses a magnetic moment

$$\mu = g\, \mu_B\, s,$$

where $\mu_B = e\hbar / 2m_e c$ is Bohr magneton and ***s*** the lepton spin. g = 2 for particles of s = 1/2 is predicted by the Dirac theory.

Anomalous magnetic moment of leptons $a_{lepton} \equiv (g\text{-}2)/2$ receives radiative contributions that can in principle be sensitive to new degree of freedom and interactions. The weak interaction and the vacuum polarization effects are too small to observe for electron because of m_l^2-dependence. The measurement of a_τ is very difficult due to its short lifetime. However, benefited from its larger mass and relatively long lifetime the anomalous magnetic moment of muon a_μ has been measured with very high precision at the CERN Muon Storage Ring [22, 23, 24], which is one of the best measured quantities in physics. Theoretically, a_μ is sensitive to large energy scales and very high order radiative corrections [25, 26]. It therefore provides an extremely clean test of electroweak theory and may give us hints on possible deviations from the SM [27, 28, 29]. The experimental and the theoretical prediction on a_μ are well summarized by Dr. Robet Lee in his talk given at LP99[Robert Lee]

According to different source of contribution, a_μ can be decomposed as

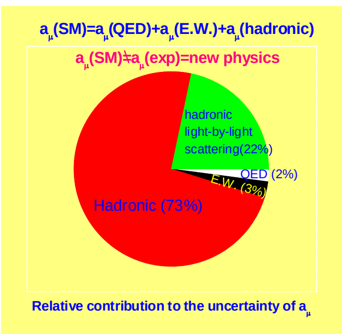
$$a_\mu(SM) = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak},$$

where the QED contribution a_μ^{QED}, the largest term among all, has been calculated to $O(\alpha^5)$, including the contribution from τ vacuum polarization. a_μ^{weak} includes the SM effects due to virtual W, Z and Higgs particle exchanges. a_μ^{had} denotes the virtual hadronic (quark) contribution determined by QCD, part of which corresponds to the effects representing the contribution of running $\alpha(s)$ from low energy to high energy scale. It can not be calculated from first principle but relates to the experimentally determined $R_{had}(s)$ through the expression

$$a_\mu^{had} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s^2} R_{had}(s),$$

where K(s) is a kernel varying from 0.63 at $s = 4m_\pi^2$ to 1.0 at $s = \infty$.

Figure ? illustrates the relative contributions from QED, weak and hadronic effecs to the uncertainty of a_μ..



The hadronic vacuum polarization is the most uncertain one of all the SM contributions to a_μ, presently 154×10^{-11}. For several scenarios, it has been claimed recently that "*the physics achievement of the effort to re-measure the cross section of $e^+e^-\to$ hadrons that brings down the uncertainty of a_μ to 60×10^{-11} is equivalent to that of LEP2 or even LHC*"[27, 43].

Near the threshold, as seem from e.q. 1.8 and e.q. 1.12, the a_μ^{had} integration is proportional to R_{had}/s^2, whereas the $\Delta\alpha(M_Z)$ integration is proportional to R_{had}/s. This implies that a_μ^{had} is more sensitive to the lower energy than to the higher one. Further measurement in the energy region of 0.5-1.5 GeV from VEPP-2M in Novosibirsk and φ factory at DAϕNE will contribute to the interpretation of *g-2* measurement at Brookhaven [31] and luminosity measurement at CERN [39]. However, their contribution to the precision determination of $\alpha(M_Z)$ is limited. The improved R value from BESII at BEPC in the energy region of 2-5 GeV will make the major contribution to evaluate $\alpha(M_Z)$, and also partly contribute to the interpretation of *g-2*.

Recent measurements of R in low energy e^+e^-

There are two different approaches to the measurement of R. One is to study the exclusive hadronic final states, i.e. to measure the production cross section of each individual channel $\sigma^{exp}(e^+e^-\to hadrons)_j$. One has the value of R by summing over the measured hadron production cross section of all individual channels. This method demands that the detector has good particle identification and requires the understanding of each channel. It is usually used for the center-of-mass energy below 2 GeV. Figure ? indicates different individual channels and their production thresholds.

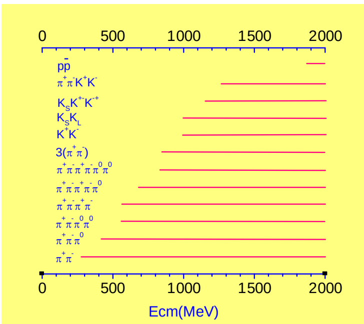


Figure ?. Production threshold of different hadronic final states.

Another method treats the hadronic final states inclusively. It measures R by dealing with all the hadronic events simultaneously, and suitable for the energy region where a reliable event generator for hadron production is available. With an improved LUND model[B. Andersson and Haiming], we may be able to extend the c.m. energy region down to 2 GeV. This method relies on MC generator to obtain acceptance-corrected values of R. Experimentally, the R value is defined as

$$R \equiv \frac{\sigma^0_{hadron}(s)}{\sigma^0_{\mu^+\mu^-}(s)} = \frac{1}{\sigma^0_{\mu^+\mu^-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

where N_{had} and N_{bg} are the observed hadronic events and all kind of background respectively; L represents the integrated luminosity of the colliding beam; δ is the radiative correction to hadron production, and ε_{had} the detection efficiency for the hadronic events.

The typical features of hadron production below 5 GeV are:\\
\cdot the are many resonances in this energy region, such as, ρ, ω, φ, ρ', ω', φ'; $c\bar{c}$ and charmed mesons J/ψ, ψ(2S), D^+D^-, D_s^+ D_s^-; and $\tau^+\tau^-$, baryon-antibaryon pair production \\
\cdot small number of final states and low charged multiplicity, $N_{ch} \lesssim 6$\\

The experimental challenge here is how to subtract the beam-associated background and select N_{had}.

In the following section, I'll discuss first some new measurements done by CMD-2 and SND at VEPP-2M in Novosibirsk, which based on exclusive analysis of the hadron production in the energy region around 0.4-1.4 GeV. Then I'll concentrated on discussing the R scan done by BESII at BEPC in the energy region from 2-5 GeV, which measure the R values by dealing with hadronic final states inclusively.

Measurements from CMD-2 and SND at VEPP-2M (Novosibirsk)

VEPP-2M, the e^+e^- collider with maximum luminosity of $\sim 5\times10^{30}$ $cm^{-2}s^{-1}$ at E_{beam}=510 MeV, has been operating since 1974 in the energy region E_{cm}=0.4-1.4 GeV (ρ, ω, φ-meson region). SND \cite{V.M. Aulchenko et al., Proc. Workshop on Physics and detectors for DAϕNE, Frascati, Italy, April 9-12 (1991), p605.} and CMD2 \cite{1. E.V. Anashkin et al., ICFA Instrumentation Bulletin 5 (1988)
2. R.R. Akhmetshing et al., Preprint BINP 99-11, Novosibirsk, 1999} are the two detectors carrying out experiments at VEPP-2M. Since 1994, VEPP-2M performed a series scans from 0.38 GeV to 1.38 GeV. \cite{hep-exp/9904027, 26 April 1999}. With these data, SND measured the cross section for the channels $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, K_SK_L, and CMD2 measured the cross section for the channels $\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0$, $\gamma\gamma\pi^+\pi^-$.

Recent results from SND

SND is described in detail in [M.N. Achasov et al., e-print hep-ex/9909015, submitted to Nucl. Instr. And Meth.]. The three layer spherical electromagnetic calorimeter consisting of 1620 $NaI(TI)$ crystals with total mass of 3.6 tones is its main part. The calorimeter covers 90\% of 4π steradian solid angle. Its energy resolution for the photons is can $\sigma_E(E)/E = 4.2\%/E (GeV)^{1/4}$, and the angular resolution is $~1.5^0$. The two cylindrical drift chambers covering 95\% of 4π solid angle measures the angle of the charged particles to the accuracy of $~0.4^0$ and $~2.0^0$ in azimuth and polar direction respectively. As an low energy neutral detector, SND is good at detecting γ.

\cdot Study of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^+\pi^-$

As illustrated in Fig. ?, the four pions final states produced via the e^+e^- annihilation in $E_{cm}=1~2 GeV$ energy region dominates and determine the main part of the hadronic contribution into the g-2 of the muon and the QCD sum rules. Besides, these processes are important sources of information for the understanding of the hadron spectroscopy, in particular for the study of ρ-meson radial excitation \cite{PDG Review of Particle Physics. Part I and II. Phys. Rev. D, Particles and Fields. V.54 (1996)}

These processes were studied at VEPP-2M [9809013, 15, 47, 48], DCI[49] and ADONE[50] colliders. The statistical errors of these measurements was ~5\%, and systematic error ~15\%. There was ~20\% discrepancy among the different experiments.

For the process of $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^- $, the systematic error is ~15\%, mainly comes from the event selection and the luminosity determination. For
$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ channel, the backgrounds are mainly from $e^+e^- \rightarrow K^+K^-$, QED processes $e^+e^- \rightarrow e^+e^- e^+e^-, e^+e^-\gamma\gamma$, as well as cosmic rays and beam associated background. The systematic error is ~15\%, of which ~5\% arise out of the variation of the detection efficiency shown from the simulation of the intermediate states like $\omega \pi^0$ $\rho^0 \pi^0 \pi^0$ and Lorentz-invariant phase space simulation(LIPS).

\cdot The investigation of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

This process was measured by ND at VEPP-2M in the energy region up to 1.1 GeV[15]. The measured cross section is significantly higher than that predicted by the Vector Dominance Model (VDM). However, it is well know that VDM is able to well describe the cross section near the ω and ϕ resonances for the processes $e^+e^- \rightarrow \omega,~ \phi \rightarrow \rho \pi \rightarrow \pi^+\pi^-\pi^0$.t is therefore necessary to perform new precise measurement in non-resonance region to investigate the limitation of VDM and determine possible contributions from heavier intermediate states like $\omega(1120)$ or $\omega(1600)$[11].

The systematic error from the detection efficiency, luminosity measurement and the background subtraction are 10\%, 5\% and 5\% respectively, giving a total systematic error of ~12\%. The result from the new measurement agrees with the old ND data.

Invariant masses of π-meson pairs in the final 3π state was measured to investigate the intermediate state in the $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ process. The intermediate states might be $\rho \pi$ and much less probable $\omega \pi$ with decay $\omega \rightarrow 2\pi$. Comparing the mass spectrum of $\pi^+\pi^-$ and $\pi^0 \pi^{\pm}$, one can observe the interference between the two intermediate states. The clear peak shown in $\pi^+\pi^-$ mass spectrum of the experimental data proves the $\rho \omega$ interference in 3π final state, and the phase measured to be zero agrees the VDM prediction.

\cdot cross section measurement for $e^+e^- \rightarrow K_S K_L$

The cross section of $e^+e^- \rightarrow K_S K_L$ reaction was measured in 1982 by OLYA(Novosibirsk) and DM1(Orsay) in the energy region $E_{cm}=1.06-1.40 GeV$ and $E_{cm}=1.40-2.20$ GeV respectively[53, 52]. It's desirable to re-measure this channel since the accuracy reached by both experiments is not good enough.

So far ~1.8 pb^{-1} data has been analyzed, utilizing $K_S \rightarrow \pi^0 \pi^0$ from $e^+e^- \rightarrow K_S K_L$. $e^+e^- \rightarrow \omega \pi^0 \rightarrow \pi^0 \pi^0 \gamma$ is the main background source. In addition, cosmic rays and beam associated background also contribute. The cross section measured is illustrated in Fig. ?, together with the result from OLYA for comparison.

Recent results from CMD-2

Fig. ? sketches the layout of the CMD-2, a general purpose detector consisting of drift chamber, proportional Z-chamber, CsI barrel and BGO endcap electromagnetic calorimeter and muon range system [hep-ex/9904027 7, 8, 9]. A thin superconducting solenoid supplying a B field of 10 KGs, inside which are the drift chamber, the Z-chamber and the endcap calorimeter. The basic parameters for CMD-2 are:

The drift chamber has 560 sense wire and 80 jet-like cells. The spatial resolution reached are $\sigma_{R-\phi}=250\mum$ and $\sigma_{z}=5~mm$. The dE/dx and momentum resolution are $\sigma_{dE/dx}=0.2 \times E$ and $\sigma_p/p=(90\times p^2[GeV]+7)^{1/2})\%$ respectively. The Z-chamber has two layers with 2 $\times$ 32 sector of sense wires and 512 strips, covering a solid angle of $0.8 \times 4 \pi$ steradian. The resolution for Z is $\sigma_Z=250 \mu m ~1 mm$. The barrel electromagnetic calorimeter is consist of 892 CsI crystals with a thickness of 8.1 radiation lengths. The energy resolution is $\sigma_E/E=8~10\% \sqrt E (GeV)$ and angular resolution $\sigma_{\theta, \phi}= 0.02$. The endcap BGO calorimeter has 680 crystals with thickness of 13.4 radiation lengths. The energy and spatial resolutions are $\sigma_E/E=6\% \sqrt E (GeV)$ and $\sigma_{\theta, \phi}= 0.02/\sqrt E (GeV)$. The solid angle covered by both calorimeters is $0.92 \times 4 \pi$ steradian. The μ counter has two double layers of streamer tube and gives a spatial resolution of 5-7 cm in Z component.

CMD-2 measured cross sections for the reactions $e^+e^- \rightarrow \pi^+\pi^-, \omega \pi^+ \pi^-(\omega \rightarrow \pi^+\pi^-\pi^0), \eta \pi^+ \pi^-(\eta \rightarrow \pi^+\pi^-\pi^0, or \gamma \gamma)$ and $e^+e^- \rightarrow 4 \pi$. Fig. ? , ? plot the cross section measured for $\omega \pi^+ \pi^-$ and $\eta \pi^+ \pi^-$, together with what measured by DM2. The new measurement significantly reduced the uncertainties though the systematic errors are still as high as ~15\%. Here I will review a little bit more in detail about the $e^+e^- \rightarrow \pi^+\pi^-, 4\pi$ measurements.

Based on an integrated luminosity of ~$5.8pb^{-1}$ data collected at the energies between 1.05 and 1.38 GeV, CMD-2 measured the energy dependence of the processes $e^+e^- \rightarrow \pi^+ \pi^- 2\pi^0$ and $e^+e^- \rightarrow 2\pi^+

2\pi^-$, as shown in Fig. ? and Fig. ?.(hep-ex/9904024 fig. 10, 11, 12). They find that the dominant contribution to the cross section of the process $e^+e^- \rightarrow \pi^+ \pi^- 2\pi^0$ comes from $\omega \pi^0$ and $\rho^{\pm} \pi^{\mp} \pi^0$ intermediate states, whereas the $\rho^{\pm} \pi^0 \pi^0$ state is not observed. The $\rho^{\pm} \pi^{\mp} \pi^0$ states is saturated completely by the $a_1(1260) \pi$ intermediate state. This is also the dominant contribution to the cross section for the process $e^+e^- \rightarrow 2\pi^+ 2\pi^-$. The theoretical predictions for the differential distributions and the total cross sections can be dramatically changed if one take into account the interference of different amplitudes with various intermediate states but the identical final states. This can be illustrated by comparing the experimental data with that of the calculations.

The cross section of $e^+e^- \rightarrow 4\pi$ can be related to the hadronic spectra in correspondent with the four π decays of the τ-lepton through the hypothesis of CVC [hep-ex/9904024 ref. 2], which has been experimentally tested to be valid within the accuracy of 3-5\% [hep-ex/9904024 ref. 3]. The observed $a_1(1260) \pi$ dominance should be taken into account in the τ decays.

Fig. ?(hep-ex/9904024 fig. 11) shows the measured total cross section for $e^+e^- \rightarrow \pi^+ \pi^- 2\pi^0$ process. The error bar indicates only the statistical error. The systematic uncertainties are mainly come from event reconstruction, radiative correction and the determination of luminosity. The overall systematic uncertainty is estimated to be ~15\%. The cross section measured by this experiment is consistent with what measured with OLYA[hep-ex/9904024 ref. 21] and recent result from SND [hep-ex/9904024 ref. 22]. But the cross section from all three measurements is apparently lower than that given by ND [hep-ex/9904024 ref. 23, 24]. For comparison, the results from Orsay[15, 25] and Frascati above 1.4 GeV are also shown in the figure.

The total cross section for $e^+e^- \rightarrow 4\pi$ is illustrated in Fig. ?(hep-ex/9904024 fig. 12). Only the statistical errors are shown. The systematic uncertainties are also attributed to the luminosity measurement, the event reconstruction and selection and the radiative correction as well. The estimated total systematic uncertainty is ~15\%.

The cross section of the process $e^+e^- \rightarrow \pi^+ \pi^-$ is given by
\begin{equation}
\sigma = \frac{\pi \alpha^2}{3s} \beta_{\pi}^3 abs{F_{\pi}(s)}^2,
\end{equation}
where $F_{\pi}(s)$ is the pion form factor at the center-of-mass energies $\sqrt(s)$. β_{π} is the velocity of the pion. A precision measurement of the pion form factor is necessary for determine the R value in an exclusive way. As we discussed previously and as shown in the Fig. ? that the R values with high precision is required to evaluate the hadronic contribution to the $(g-2)_{\mu}$. The relative uncertainty contribution is dominated by the $e^+e^- \rightarrow \pi^+ \pi^-$ channel with $\sqrt(s)$<2 GeV [hep-ex/9904027 ref. 1,2,3]. The famous E821 experiment at BNL [LP99 Robert Lee] has measured $(g-2)_{\mu}$ to a precision of ~1ppm (confirm with Lee's talk) and will further improve the accuracy to about 0.4 ppm. In order to

explain the measurement with such a high accuracy, the uncertainty in R should be below 0.5 \% in this energy region. Therefore a new measurement of the pion form factor with smaller uncertainty is important for the interpretation of E821 measurement.

The pion form factor was measured by OLYA and MMD groups at VEPP-2M [hep-ex/9904027 ref. 5] about twenty years ago[hep-ex/9904027 ref. 6]. 24 points from 360 to 820 MeV were studied by CMD with a systematic uncertainty of about 2\%. The OLYA measurement scanned 640-1400 MeV with small steps, giving a systematic uncertainty from 4\% at the ρ-meson peak to 15\% at 1400 MeV.

The pion form factor is one of the major experiments planned at CMD-2. 128 energy points in total were scanned in the whole VEPP-2M energy region (0.36-1.38 GeV) in six runs performed from 1994 to 1998 [hep-ex/9904027]. The results from this experiment to be discussed will based on the data taken from the first 3 runs with 43 energy points ranging from 0.61-0.96 GeV. The small energy scan step 0.01 GeV in this energy region allows the calculation of the hadronic contribution in a model-independent way. In order to investigate the ω-meson parameters and the $\rho - \omega$ interference, the energy steps were 2-6 MeV in the energy region near the $\omeag$-meson. The beam energy was measured with the resonance depolarization technique for almost all the energy points, which significantly reduced the systematic error arising from the energy uncertainty. The Charged trigger makes use of the information from the drift chamber and the Z-chamber and requires at least one track. There was an additional trigger criteria for the energy points between 0.81 and 0.96 GeV, which asks for the total energy deposited in the calorimeter to be great than 20-30 MeV. The neutral trigger , served for monitoring the trigger efficiency, is based on the information only from the calorimeter.

The background is mainly from cosmic muons. Bhabha and dimuon production are also the background source. The shape of the energy deposition was carefully studied for the event separation and selection. The event vertex was also applied to reject the cosmic muons effectively.

To take the fact that the radiative correction for $e^+e^- \rightarrow \pi^+ \pi^-$ depends on the energy behavior of the cross section of $e^+e^- \rightarrow \pi^+ \pi^-$ itself into account, the radiative correction factor was calculated literately. The existing $|F_{\pi}(s)|^2$ data was used as the first iteration for the calculation. $|F_{\pi}(s)|^2$ values was found to be stable after 3 iterations.

The corrections for the pion losses due to decays in flight and nuclear interaction, as well as the background from $\omega \rightarrow 3 \pi$ were done, using Monte Carlo simulation.

The total systematic uncertainty was estimated to be 1.5\% and 1.7\% for the energy region 0.78-0.784 GeV and 0.782-0.94 GeV respectively, and 1.4\% for all the other points. Table ? summarizes the main systematic error sources. \\

Table ? hep-ex/9904027 table 2. Main source of systematic errors.

Except the leading contribution from $\rho(770)$ and $\omega(782)$, the resonances $\rho(1450)$ and $\rho(1700)$ should be taken into account to describe the data for the determination of the pion form factor. In addition, the model based on the Hidden Local Symmetry (HLS), which predicts a point-like coupling $\gamma \pi^+ \pi^-$, can well describe the experimental data below 1 GeV. Both the Gounaris-Sakurai (GS) parameterization and the HLS parameterization approaches [hep-ex/9904027 ref. 6, 21] were used to fit the form factor.
Only the higher resonance $\rho(1450)$ was taken into account in fitting the pion form factor in the relatively narrow energy region 0.61-0.96 GeV. Fig. ? shows the fit of the pion form factor for the data taken in 1994-1995, and the table ? summarizes the corresponding results.

Fig. ? [hep-ex/9904027 fig. 25] Fit of the pion form factor with CMD-2 94, 95 data according to GS and HLS models. Both theoretical curves are indistinguishable.

Table ? [hep-ex/9904027 page 50 (29)]. Results of the pion form factor fit of CMD-2 94, 95 data. PGG data is also shown for comparison.

With the rest data collected, CMD-2 hopes to reduce the systematic error presented here by a factor of two. To achieve this goal, new approach for the calculation of the radiative correction must be developed.

The new cross section measurements from Novosibirsk significantly improve the accuracy and are the precision measurements. It would be more contributing if the energy region could be extended to 2 GeV, which link up to the lowest energy of BEPC.

R scan done with BESII at BEPC in 2-5 GeV (Beijing)

Since late 1980s', BEPC has been the only e^+e^- machine covering the c.m. energy of 2-5 GeV in the world[?] . Its upgrade program was finished in 1999. Improvements included moving the insertion quadrupoles closer to the interaction point and increasing the total RF voltage. The bunch length was shortened, and the vertical beta function at the interaction point
was reduced. So far a factor of 1.5~2 improvement in the luminosity, to $3\times 10^{30}~cm^{-2}s^{-1}$ at the J/ψ peak,has been achieved. The beam background has been significantly decreased because of the replacement of the thick(?) aluminum beam pipe with thin beryllium one. The performance of the upgraded BEPC, including the linac, is much better than it was, especially at the low energy end of the R scanning range.
BES, a conventional detector, has been described in detail in ref. [36]. It was upgraded from 1995 to 1999[Li Jin, NIM]. The upgrades included replacement of the central drift chamber with a vertex chamber composed of 12 tracking layers. The vertex chamber was rebuilt from the Mark III endplates and beryllium beam pipe and provides a spatial resolution of about 90 μm. A new barrel time-of-flight counter with an array of 48 plastic scintillators that are read out by fine mesh photomultiplier tubes situated in the 0.40~T magnetic field volume provids 180 ps resolution. A new main drift chamber

replaces the aging original. It has 10 superlayers, each with four sublayers of sense wires. It provides dE/dx information for
particle identification and has a momentum resolution of
$\sigma_p/p=1.8\%\sqrt{(1+p^2)}$ for charged tracks with momentum p in GeV. The sampling-type barrel electromagnetic calorimeter (BSC), which covers 80\% of 4π solid angle, consists of 24 layers of self-quenching streamer tubes interspersed with lead and with each layer having 560 tubes. The BSC has an energy resolution of $\sigma_E/E=21 \%/\sqrt{E}$ (E in GeV) and a spatial resolution of 7.9 mrad in ϕ and 3.6 cm in z. The outermost component of BESII is a μ identification system consisting of three double layers of proportional tubes interspersed in the iron flux return of the magnet. These measure coordinates along the muon trajectories with resolutions of 3 cm and 5.5 cm in $r\phi$ and z, respectively. In addition, the new DAQ system shorten the data accumulation dead time from 20 ms/event to 10 ms/event. Fig. ? is the layout of the BESII detector.

Figure ? BESII

With the upgraded machine and detector, BES collaboration performed two scans to measure R in the energy region of 2-5 GeV in 1998 and 1999. The first run scanned 6 energy points covering the energy from 2.6 to 5 GeV in the continuum. Separated beam operation at each energy points were carried out in order to subtract the beam associated background correctly from the data \cite{PRL R paper}. The main goal of the first R scan was to understand the trigger and hadronic event acceptances, as well as the hadronic events selection and the background subtraction, which are central to a total cross section measurement. The second run scanned about 85 energy points in the energy region of 2-4.8 \cite{CERN Courier 99}, almost the extreme energy region that BEPC can cover. Data were taken at 85 egergy points in the scan. To subtract beam associated background, separated beam operation were performed at 26 energy points and single beam operation for both e^- and e^+ were carried out at 7 energy points distributing in the whole scanned energy region. Special runs were taken at J/ψ to determine the trigger efficiency. J/ψ and $\psi(2S)$ resonances were scanned in the beginning and at the end of the R scan for the energy calibration.

As discussed previously, the R values from the BESII scan date are measured by observing the final hadronic events inclusively, i.e. the value of R is determined from the number of observed hadronic events (N^{obs}_{had}) by the relation
\begin{eqnarray*}
R=\frac{ N^{obs}_{had} - N_{bg} - \sum_{l}N_{ll} - N_{\gamma\gamma} }
{ \sigma^0_{\mu\mu} \cdot L \cdot \epsilon_{had} \cdot \epsilon_{trg}
\cdot (1+\delta)},
\end{eqnarray*}
where N_{bg} is the number of beam associated background events;
$\sum_{l}N_{ll},~(l=e,\mu,\tau)$ and $N_{\gamma\gamma}$ are the
numbers of misidentified lepton-pairs from one-photon and two-photon processes events; L is the integrated luminosity; δ is the radiative correction; and ϵ_{had} and ϵ_{trg} represent the detection and trigger efficiency for
hadronic events.

\subsection{Hadronic event selection and background subtraction}

The task of the hadronic event selection is to identify one photon multi-hadron production from all other possible contamination mechanisms. The events selection should make full use of all the information from each sub-detector of BESII, namely, the vertex position, the measured charged-particle momentum, the related time of flight, the associated pulse height and shape of the electromagnetic calorimeter, and the hits in muon counter.

Two categories of events will be selected, i.e. the lepton pair production $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^{--}$ and the production of three or more hadronic particles $e^+e^- \to \gamma \to$ *hadron*s. Events with three or more prongs forming a vertex should be selected as hadronic events. Two prong events with total charge zero may be treated as hadronic events if the track momentum and azimuthal angle are clearly out of the categories of the Bhabha and dimuon events as described below.

The backgrounds involved in our measurement are mainly from cosmic ray, lepton pair production $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$; two-photon processes, beam associated process, i.e. the interaction between beam and gas, or beam and pipe. The cosmic rays and part of the lepton pair production events are directly removed according to the vertex position, the time of flight and the collinear angle of the selected tracks, as well as the associated hits on muon counter. The remaining background from the lepton pair production and two-photon processes is then subtracted out statistically according to Monte Carlo simulation.

The lepton pair productions are QED processes and can be calculated to the precision of $O(\alpha^3)$ for e and μ pair production.

The $\tau^+\tau^-$ pair events are difficult to be separated from hadronic events sample because of its hadronic decay and short life time, and should be therefore treated by a background subtraction with the help of Monte Carlo simulation, in which all the possible decay modes and the corresponding branching ratio should be taken into account according to the PDG. The fraction of τ events surviving the hadronic events criteria is energy dependent and is high. It was about ?% and the overall magnitude of the τ-subtraction was about ?%, due to which the total contribution to the error in R was estimated to be ±?% [PRL R98].

Two-photon processes is a higher-order electromagnetic processes where both electron and positron emit a quasi real photon, the two photons giving rise to an object with mass m usually appreciably smaller than \$\sqrt{s}\$ and which decays through $e^+e^- \to l^+l^-\gamma$, $e^+e^- \to l^+l^-e^+e^-$, $e^+e^- \to l^+l^-\mu^+\mu^-$ and $e^+e^- \to e^+e^- + hadrons$ ($l = e, \mu$). The cross section of the other two photon processes are small as compared to $e^+e^- \to l^+l^-e^+e^-$ [33, 17, 18]. The typical features of the produced final particles via two-photon processes are that they are pretty much favoring the direction along the beam pipe, and poses a very small momentum. [kill ref 44 and 45]

The beam associated background sources are complicated. They may mainly come from beam-gas, beam-wall interaction, synchrotron radiation and lost beam particles. The salient features of the beam associated background are that their tracks are very much along the beam pipe direction, the energy deposited in BSC is small, and most of the tracks are protons.

Separated-beam runs at each energy is necessary for the subtraction of beam associated background**.** Most of the beam associated background events are rejected by vertex and energy cuts \cite{cuts}. Applying the same hadronic events selection criteria to the separated-beam data, one can obtain the number of separated-beam events N_{sep} surviving these criteria. The number of beam associated events N_{bg} in the corresponding hadronic events sample is given by

$$N_{bg} = f \cdot N_{sep} ,$$

where f , the constant of proportionality, can be determined by the ratio of the pressure at collision region times beam current integrated over time measured for both colliding- and separated-beam running, i.e.,

$$f = \frac{\int_{colliding} dt \cdot P(t) \cdot [I_{e^+}(t) + I_{e^-}(t)]}{\int_{separate-beam} dt \cdot P(t) \cdot [I_{e^+}(t) + I_{e^-}(t)]}$$

To subtract beam associated background in this way, the variation of the pressure in the collision region and the beam current must be recorded for both colliding- and separated-beam running at each energy to be measured.

\subsection{Detection efficiency}

The detection efficiency is defined as the probability that a hadronic event is observed in the detector and passes all the selection criteria. The detection efficiency, which depends on the angular and momentum distribution, and the particle multiplicity as well, will be determined by Monte Carlo simulation in combination with the selected hadronic-event sample.

The tasks of the Monte Carlo simulation are to generate physical events from e^+e^- annihilation and simulate the response of the detector to the generated events. For the measurement of the cross section $\sigma(e^+e^- \rightarrow \gamma \rightarrow \text{hadrons})$, model calculations that generate complete final states are essential for the investigation of background and the determination of detection efficiency.

It is not known dynamically how the hadronic final states are produced by e^+e^- . Only phenomenological hadronization models are available to describe the transition of quarks and glues into final hadrons. The *yellow book* 'Z Physics at LEP-I' has overall described the QCD plus hadronization models. Table 8 lists the most commonly used models in e^+e^- annihilation. To our knowledge, the JETSET [34] parton shower model gives the overall best description of hadronic-event production, particularly for the center-of mass energy higher than 10 GeV. In the energy region of our interest, i.e., 2-5 GeV, the energy is rather low and there exist several resonances and particle production thresholds.

JETSET7.4 is used to serve as hadronic event generator for the R measurement. Parameters in the generator are tuned using \$4 \times 10^4\$ hadronic event sample collected near 3.55 GeV for the tau mass measurement done by the BES collaboration \cite{BES collaboration, J.Z. Bai et al., Phys. Rev. D 53, 20(1996)}. The parameters of the generator are adjusted to reproduce distributions of kinematic variables such as multiplicity, sphericity, transverse momentum, etc. Fig.~\ref{fig:lund} shows these distributions for the real and simulated event samples.

The parameters have also been obtained using the 2.6 GeV data (\$\approx 5 \times 10^3 \$ events). The difference between the two parameter sets and between the data and the Monte Carlo data based on these parameter sets is used to determine a systematic error of 1.9-3.2\% in the hadronic efficiency.

One must notice that the Monte Carlo simulation packet JETSET was not build in order to fully describe few body states produced by e^+e^- annihilation at a few GeV energy region, though the event shapes are consistent with that from the Monte Carlo simulation with tuned parameters at 3.5 GeV. A great effort has been putting by the LUND group and BES collaboration to develop the formalism using the basic Lund Model area law directly for the Monte Carlo simulation, which is expected to describe the data better. [area law]

The trigger efficiencies are measured by comparing the
responses to different trigger requirements in special runs taken at the J/ψ resonance. From the trigger measurements, the efficiencies
for Bhabha, dimuon and hadronic events are determined to be 99.96\%, 99.33\% and 99.76\%, respectively. As a cross check, the trigger information from the 2.6 and 3.55 GeV data samples
are used to provide independent measurements of the trigger efficiencies. These are consistent with the efficiencies determined from the J/ψ data. The errors in the trigger efficiencies for Bhabha and hadronic events are less than $\pm$0.5\%.

%\subsection{radiative correction}

The radiative effects in the final state is expected to be, to lowest order in α, $1+\alpha/\pi$, or 0.23%. Such a small correction will not be applied because the effect of final state radiation on the determination of ϵ_{had}, the averaged detection efficiency for observing hadronic events determined by Monte Carlo simulation, is not known. However, one can assign a systematic error, usually less than 0.3\% to *R* to account for the estimated uncertainty in magnitude of final state radiation.

The radiative corrections for the initial state should be taken into account to obtain the true cross section from the experimentally measured one. To obtain the leading order $[O(\alpha^2)]$ cross section σ^{0}_{had} from the observed hadronic cross section σ^{obs}_{had}, one must remove the higher-order terms of the electromagnetic coupling constant α, which is generally referred to as radiative corrections and is denoted by δ in our case. The observed cross section σ^{obs}_{had} is then related to σ^{0}_{had} by

\begin{equation}
\sigma^{obs}_{had}=\sigma^{0}_{had} \dot \epsilon_{had} \dot (1+\delta)
\end{equation}

where the radiative correction includes the initial state vertex correction, the leptonic and hadronic vacuum polarization and the bremsstrahlung radiation from one of the initial charged particles states. These corrections are represented by δ_{vert}, δ_{vert}^l (l=e, μ, τ), δ_{vac}^{had} and δ_{γ} respectively. The detailed description of the radiative correction can be found in Ref. [44….].

The uncertainties of the radiative correction are from higher-order radiative corrections; modeling of σ_{had}^0; the choice of k_{max} and the maximum photon energy fraction cutoff.   The Radiative corrections determined using four different

schemes \cite{\bibitem{13}F.A. Berends and R. Kleiss,
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\bibitem{24}C. Edwards \etal, SLAC-PUB-5160, 1990.} agreed with each other to within 1\%
below charm threshold. Above charm threshold, where resonances are important, the agreement is within $1\sim3\%$. The major uncertainties common to all models are due to errors in previously measured R-values and in the choice of values for the resonance parameters. For the measurements reported here, we use the formalism of Ref.~\cite{G. Bonneau and F. Martin, Nucl. Phys. B27, 387(1971)} and include the differences with
the other schemes in the systematic error of ~2-4\%.

The R values obtained at the six energy points scanned in 1998 are shown in Table~\ref{tab:rvalue} and graphically displayed in Fig.~\ref{fig:rvalue} with solid dots. Table~\ref{tab:rsyst} illustrates the systematic errors from different error sources. The largest systematic error is due to the hadronic event selection and is determined to be 3.8-6.0\% by varying the selection criteria. The systematic errors on the measurements below 4.0 GeV are similar and are a measure
of the amount of error common to all points. The BES collaboration has also done the analysis including only events with greater than two
charged tracks; although the statistics are smaller, the results
obtained agree well with the results shown here.
The R values for E_{cm} below 4 GeV are in good agreement with results from $\gamma \gamma 2$ \cite{gamma2} and Pluto \cite{pluto} but are below those from Mark I \cite{MarkI}.
Above 4 GeV, our values are consistent with previous measurements.

Preliminary R-values at 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3.0, 4.6 and 4.8 GeV are also plotted with stars in fig. ?. The errors, which add the statistical and systematical errors in quadrature, are all conservatively assigned to be 10\% as preliminary results. However, it's believed that these errors can be decreased to be comparable as represented by the error bars of the solid dots, i.e. ~7\% for the energy points below 3.6 GeV and ~12\% for the energy above 4.5 GeV.

The first scan repeated 3.4 GeV and the second scan repeated 2.6 and 4.6 GeV measured in the first scan. In all case, R-values obtained are consistent with each other at the same energy points.

The R scan done with BESII were well planned, and the performance was stable and the data quality is good. A great effort was invested to understand and improve the detection efficiency, to determine the trigger efficiency and to correctly subtract the beam associated background from the data with the help of the separated/single beam operation data. The uncertainty in R measured by BES in the energy region below 3.6 GeV will be decreased a factor of two, reaching ~7\% accuracy. The accuracy is not expected to be better than \10% for the energy above 4 GeV.

The new R ratio in e^+e^- presented from Novosibirsk and Beijing has a great impact on the improvement of $\alpha(M_Z^2)$. Using these new results, though some of them are still preliminary, A.D. Martin et. al. [hep-ph/9912252] re-evaluate $\alpha(M_Z^2)$ and find $\alpha(M_Z^2)^{-1}=128.973 \pm 0.035$ or 128.934 ± 0.040, according to whether inclusive or exclusive cross section are used. With the final results from Beijing inclusive measurement in the whole 2-5 GeV region and the more precise results from Novosibirsk, $\alpha(M_Z^2)$ and $(g-2)_{\mu}$ will be more precisely determined from the experimental data.\\

Future plans for the R measurement in low energy e^+e^-

A dedicated energy scan, targeting at ~1\% precision direct measurement below 1.4 GeV, planned by KLOE at DAPNE is not possible at short term since the DAFNE machine is
tuned for the phi resonance. However a machine upgrade is foreseen which will allow to do the energy scan in the year around 2004, hopefully. A possibility to measure the hadronic cross section is to measure events with Initial State Radiation (ISR). In this case one of the electrons or positrons of the beam have irradiated a hard photon and the cms energy of the hadronic system in the final state, mostly pions coming from the rho-resonance, is lowered. KLOE has already started the analysis of those events. [KLOE edc 99-24]

CMD-2 and SND at VEPP-2M in Novosibirsk is planning to scan from threshold to 1.4 GeV in 1999-2000. A R scan in the energy between 2 to 10 GeV with KEDR at VEPP-4 is proposed. A scan with such a wide energy region would be very important if the measurement could be precise. In addition, there are proposals to build ϕ and $\tau-c$ factory. Both would be nice tools to measure R precisely.

BESII at BEPC in Beijing is analyzing the second run R scan data. The preliminary R values in the whole energy region of 2-5 GeV is expected to be shown in the Spring of 2000, and the final results will be presented in the summer of 2000. The Chinese government has significantly increase the budget for the operation of BEPC/BESII. In addition, ~8 million US dollars has been approved to BEPC/BESII for their major upgrade and for the R&D for the Beijing tau-charm factory(BTCF). If the BTCF dream become true, the R values in the energy region ~2-5 GeV, particularly in 2-3.7 GeV could be measured to an accuracy of 1-3\%, which would be extremely important for the interpretation of $(g-2)_{\mu}$ experiment carrying out by E821 at BNL and for the precision determination of $\alpha(M_Z^2)$.

Summary

Being one of the most fundamental parameters in particle physics, R-values plays an important role in the development of the theory of particle physics and in testing the Standard Model. Experimental efforts to precisely measure the R-values at low energies are crucial for the future electroweak precision physics. The measurements are not only important for the evaluation of QED running coupling constant $\alpha(M_Z^2)$ and for the interpretation of $(g-2)_{\mu}$, but also necessary for the understanding of the hadron production mechanism via e^+e^-

annihilation using the data with enough statistics collecting in the continue region below 5 GeV.

A real breakthrough to the electroweak theory physics with regards to the R-values in low energy would be possible only by measuring $\sigam(e^+e^-\rightarrow hadrons)$ at 1\% accuracy. Such a level of precision requires significant improvement to both machine and detector, and need better theoretical calculation on the radiative correction and the event generator for the hadron production.

SND and CMD-2 at VEPP-2M in Novosibirsk have significantly improved the measurements of the hadron production cross section via e^+e^- collision for some of the important exclusive channels in the energy region of 0.36-1.38 GeV. Further improvement with the analysis of the existing data is forthcoming.

The R scan performed with BESII at BEPC in Beijing can significantly reduce the uncertainties in R in the energy region form 2-5 GeV. Their R-values from the first run data has already reduced the uncertainties in R from ~15-20\% to ~7\%. The R-values from the second run is expected to has the same precision and is expected to be presented in the Summer of 2000.

KLOE at DAPNE in Frascati can potentially improve the R-values to a precision ~1\% in the energy region from the hadron production threshold to 1.4 GeV. An R scan extending the energy from the threshold to 2 GeV, which links up the scan energy to the lowest done with BESII at BEPC, is highly wished to improve the measurement.

Once the R-values being measured with a precision of ~1\% in the energies covered by VEPP-2M and DAPNE, central question will then again how to further decrease the uncertainties of R measured by BESII in the energy region of 2-5 GeV, particularly from 2-3.7 GeV. This will be a big project and an attracting physics program for a $\tau-c$ factory, or any advanced $\tau-c$ facility with a luminosity of ~$10^{32} /cm^2s$ at the J/ψ resonance and a new generation detector as compared to BESII.

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Figure captions:

Figure 1. Data for R=$\sigma(e^+e^- \rightarrow$hadrons)/ =$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, together with expectations of the pure quark-parton model and with the best fit to the data, including O(α_s^3) QCD corrections and the effect of the Z^0 pole [2]. R at energies below 5 GeV are not plotted in detail.

Figure 2. Data for R at the energies below 10 GeV. The shaded band and the numbers in the lower part of the plot show the experimental uncertainties of the continuum measurement.

Figure 3. The running of $\alpha(s)$ as a function of s=$\sqrt{q^2}$.

Figure 4. Relative contribution to (a) the value of $\Delta\alpha(M_Z)$ and (b) the uncertainty of $\Delta\alpha(M_Z)$.

Figure 5. (a) The LEP and SLD measurements of $\sin^2\theta_{eff}^{lept}$ and the LEP measurements of Γ_{lepton} compared with the Standard Model prediction. The star shows the prediction if among the electroweak radiative corrections only the vacuum polarization is included. (b) The results of the Standard Model fit of m_t and M_H with $\alpha(M_Z)$±its error (1σ).

Figure 6. Results of the Standard Model fit of m_t vs. $\alpha(M_Z)$ with and with out constrain on α for electroweak data of (a) 1996 and (b) 1994.

Figure 7. $\Delta\chi^2$ distribution of the Standard Model fit of M_H with (a) the input value of $\alpha(M_Z)\pm 1\ \sigma$ error and (b) theoretical error of the M_H fit.

Figure 8. Variation of the peak luminosity in the energy region of 2-5 GeV obtained at BEPC in 1997.

where

$$P(s,m^2) = -\frac{5}{3} + \log\left(-\frac{s}{m^2}\right) . \qquad \text{B.2}$$

There are problems, however, to apply the expressions above to quarks because the quark masses are defined ambiguously and QCD corrections are large. An ingenue way is to relate the loop diagram to the total cross section σ_{tot} for the process $e^+e^- \rightarrow \gamma \rightarrow all$ as

$$\mathrm{Im}\,\Pi_{\gamma\gamma}(s) = -\frac{\alpha}{3} R_{had} \qquad \text{B.3}$$

$$\mathrm{Re}\,\Pi_{\gamma\gamma}(s) = \frac{\alpha s}{3\pi} P \int_{4m_\pi^2}^{\infty} ds' \frac{R_{had}(s')}{s'(s'-s)} . \qquad \text{B.4}$$

where P stands for the principal value of the integral and is a known analytical expression (B.2).

Appendixes C A method used by Mark I to determine the detection efficiency for hadronic particles

Denoting N_p as the number of events produced with charge multiplicity p, ε_{qp} the probability that a hadron final state with charged-particle multiplicity p be selected as hadronic events with q charge tracks, then the number of events observed with charged multiplicity q and represented by M_q is given by

$$M_q = \sum_{p=2}^{\infty} \varepsilon_{qp} N_p \,, \qquad \text{C.1}$$

where ε_{qp} can be calculated by Monte Carlo simulation of the production and detection of the final hadronic states. N_p can be determined from the observed quantity M_q by unfold the e.q. C.1 through maximum-likelihood functions defined

$$L = \prod_q \frac{\mu_q^{N_q}}{N_q} e^{-\mu_q} \qquad \text{C.2}$$

for the detected events N_q, where μ_q stands for the predicted number of detected events with multiplicity q. The average detection efficiency at a given c.m. energy is then given by

$$\bar{\varepsilon} = \frac{\sum M_q}{\sum N_p} \,. \qquad \text{C.3}$$