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Measurement of R value - direct and ISR

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At BESIII, the data samples for the R value measurement have been taken in the full energy region from 2.0 to 4.6 GeV that BEPCII could reach. The status of R value measurement is briefly reviewed. The cross section of $e^+e^- \to \pi^+\pi^-$ in the mass range between 600 and 900 MeV/c^2 has been measured with a 2.93 fb^{-1} data set taken at the center-of-mass energy 3.773 GeV with ISR method. The two-pion contribution to the hadronic vacuum polarization contribution to $(g-2)_\mu$ is calculated to be $a_\mu^{\pi\pi,LO}(600-900)\mathrm{MeV}/c^2 = (3.68.2 \pm 2.5_{stat} \pm 3.3_{sys}) \times 10^{-10}$.

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1. Introduction

The Standard Model (SM) has been tested in the last few decades by comparing its predictions with very precise experimental data. The remarkable agreement between the precise measurements of electroweak observables and their SM predictions is a striking experimental confirmation of the theory, even if there are a few observables where the agreement is not so satisfactory. On the other side, there are strong theoretical arguments hinting at the presence of physics beyond the SM. So we need more precise theoretical predictions. Precise SM predictions require precise input parameters. A number of excellent reviews on this subject are available [1, 2, 3]. One of the basic input parameters is the fine-structure constant α. However, physics at nonzero squared momentum transfer s is actually described by an effective electromagnetic coupling $\alpha(s)$ which is of interest for a wide range of energies, well know example is $\alpha(M_Z)$. While electroweak effects like lepton contribution are calculable in perturbation theory, for the strong interaction part ($\Delta\alpha_{\rm had}(M_Z^2)$) perturbation theory fails and a dispersion integral over e^+e^- data encoded in

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} \tag{1.1}$$

provides a reliable approach to estimate the non-perturbative effects. Fig. 1 shows the relative contributions from different e^+e^- cms energy regions to $\Delta\alpha_{\rm had}(M_Z^2)$, both in magnitude and uncertainty. The more details could be found in Tab. 1.

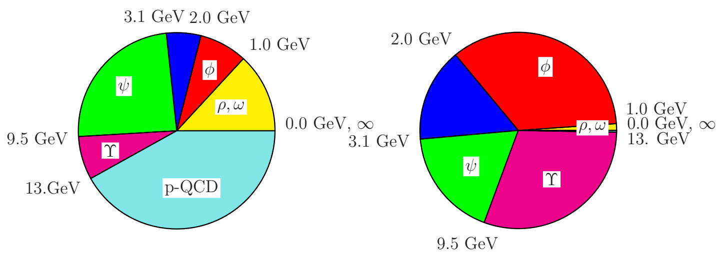


Figure 1: $\Delta\alpha_{\rm had}(M_Z^2)$: contributions (left) and squared errors (right) from different $\sqrt{s}$ regions (from Ref. [2]).

Table 1: Contributions for $\Delta\alpha_{\rm had}(M_Z^2)\times 10^4$ (direct integration method) with relative (rel) and absolute (abs) error in percent (from Ref. [2]).

Energy range	$\Delta\alpha_{\rm had}(M_Z^2)\times 10^4$	rel [%]	abs [%]
ρ,ω ($E < 2M_K$)	36.23 [13.1](0.24)	0.7	1.1
$2M_K < E < 2$ GeV	21.80 [7.9](1.33)	6.1	34.9
2 $GeV < E < M_{J/\psi}$	15.73 [5.7](0.88)	5.6	15.4
$M_{J/\psi} < E < M_\Upsilon$	66.95 [24.3](0.95)	1.4	18.0
$M_\Upsilon < E < E_{\rm cut}$	19.69 [7.1](1.24)	6.3	30.4
$E_{\rm cut} < E$ pQCD	115.66 [41.9](0.11)	0.1	0.3
$E < E_{\rm cut}$ data	160.41 [58.1](2.24)	1.4	99.7
total	276.07 [100.0](2.25)	0.8	100.0

During the last few years, in a sequence of increasingly precise measurements, the E821 Collaboration at Brookhaven has determined $a_\mu = (g_\mu - 2)/2$ with a fabulous relative precision of 0.54 parts per million (ppm) [4], allowing us to test all sectors of the SM and to scrutinise viable alternatives to this theory [5]. The present world average experimental value is $a_\mu^{\text{EXP}} = 116\,592\,089\,(63) \times 10^{-11}$ (0.54 ppm) [4]. In the theoretical prediction, a_μ^{SM} is usually split into three parts: QED, electroweak and hadronic. Like the effective fine-structure constant at the scale M_Z, the SM determination of the anomalous magnetic moment of the muon is presently limited by the evaluation of the hadronic vacuum polarisation and, in turn, by our knowledge of the low-energy total cross-section for e^+e^- annihilations into hadrons. Indeed, the hadronic leading-order contribution a_μ^{HLO}, due to the hadronic vacuum polarisation correction to the one-loop diagram, involves long-distance QCD effects which can not be computed perturbatively. However, using analyticity and unitarity, it was shown long ago that this term can be computed from hadronic e^+e^- annihilation data via the dispersion integral [6]

$$a_\mu^{\text{HLO}} = (1/4\pi^3)\int_{4m_\pi^2}^{\infty} ds\,K(s)\sigma^{(0)}(s) = (\alpha^2/3\pi^2)\int_{4m_\pi^2}^{\infty} ds\,K(s)R(s)/s. \tag{1.2}$$

The kernel function $K(s)$ decreases monotonically for increasing s. This integral is similar to the one entering the evaluation of the hadronic contribution $\Delta\alpha_{\text{had}}(M_Z^2)$. Here, however, the weight function in the integrand gives a stronger weight to low-energy data. About 91% of the total contribution to a_μ^{HLO} is accumulated at center-of-mass energies (cms) $\sqrt{s} < 1.8$GeV and the two-pion channel contributes more than 70% of a_μ^{HLO}. In summary, to achieve higher precision, more experimental effort is required to measure $\sigma(e^+e^- \to \text{hadrons})$ precisely both at low and intermediate energies [2].

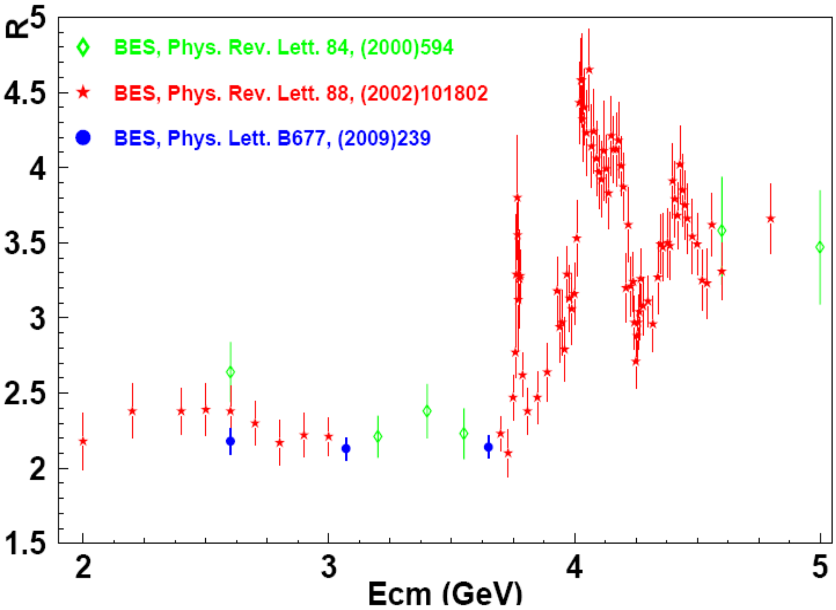
Usually, for energies below ~ 2 *GeV* exclusive cross sections are measured for individual channels, while at higher energies the hadronic final states are treated inclusively. In exclusive measurements, one directly measures the total and differential cross sections for all exclusive reactions that are kinematically allowed in that energy region. Having measured the exclusive cross sections, one can determine the total cross sections and the value of R by simply summing them. In BESIII, the ISR method could be used to measure the exclusive cross sections.

2. R value measurement status in BESIII

Figure 2 shows the measured R values below 5 GeV and the higher charmonium resonance structures measured by BES-II, which will be improved by BESIII. The precision of R value will be less than 3%, and the fit of high mass charmonium line-shape, the form factor of mesons and baryons will be measured in more precise.

BESIII Collaboration has taken data for R values measurement for 2.0 to 4.6 GeV. Three phases are performed for the data taking:

- Phase I: The data samples were taken at 2.2324, 2.4, 2.8 and 3.4 GeV with the total luminosity of about 12 pb^{-1} in 2012. These data is be used for the hadronic generator tuning and form factor measurements of large production cross section channels;



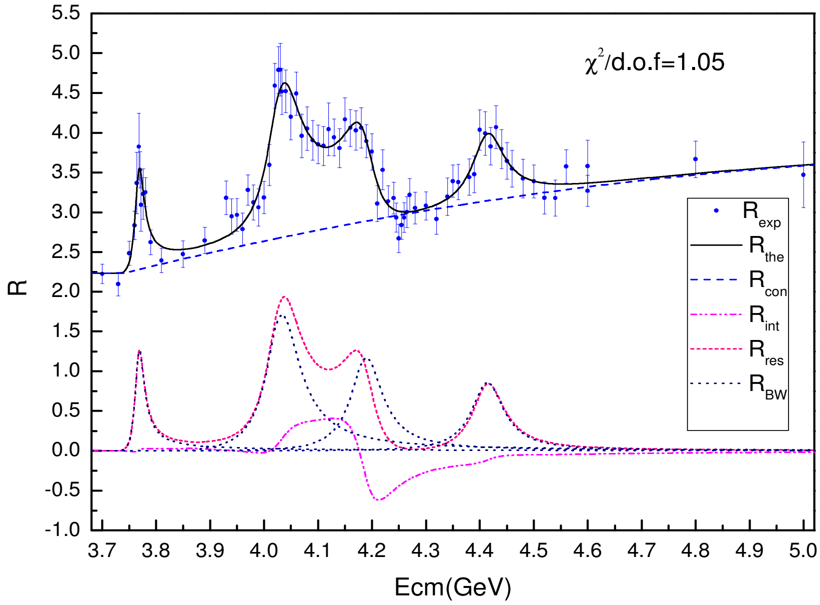


Figure 2: Upper: R values measured between 2-5 GeV. Lower: the charmoniuum resonance structures measured with BESII.

- Phase II: In 2013 and 2014, the fine scan between 3.08 and 4.59 GeV has been done for the R value measurement and high mass charmonium line-shape and resonance parameters. There are 104 energy points in energy steps (2 - 5 MeV) with the total luminosity about 800 pb^{-1}.

- Phase III: In 2015, BESIII collected 22 energy points between 2.0 and 3.08 GeV with the total luminosity about 500 pb^{-1}. These data could be used to study the threshold effect of baryons.

In experiment, R value is measured with

$$R_{exp} = \frac{N_{had}^{obs} - N_{bg}}{\sigma_{\mu\mu}^{0} \cdot L \cdot \varepsilon_{trg} \cdot \bar{\varepsilon}_{had} \cdot (1+\delta)}, \tag{2.1}$$

where N_{had}^{obs} is the number of observed hadronic events, N_{bg} the number of the residual backgrounds, L the integrated luminosity, $\bar{\varepsilon}_{had}$ the average detection efficiency for hadronic events, ε_{trg} the trigger efficiency, $(1+\delta)$ the correction factor of the initial state radiation (ISR), and $\sigma_{\mu\mu}^{0}$ the theoretical Born cross section for $e^+e^- \to \mu^+\mu^-$.

To determine the number of observed hadronic events, the event selections are optimized firstly based on MC simulation. The numbers of QED background events are determined from MC method,

$$N_{bg} = L(\varepsilon_{ee}\sigma_{ee} + \varepsilon_{\mu\mu}\sigma_{\mu\mu} + \varepsilon_{\tau\tau}\sigma_{\tau\tau} + \varepsilon_{\gamma\gamma}\sigma_{\gamma\gamma}) \tag{2.2}$$

where L is the integrated luminosity of data, σ_{ee} the cross section of Bhabha process, ε_{ee} the efficiency of Bhabha events which pass the hadronic event criteria, and other symbols have corresponding meanings. The quantum electrodynamics processes of $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ are used to determine the integrated luminosity. The integrated luminosity is measured by:

$$L = \frac{N_{obs}}{\sigma \times \varepsilon \times \varepsilon_{trig}} \tag{2.3}$$

where N_{obs} is the number of events which pass the $e^+e^- \to e^+e^-$ or $e^+e^- \to \gamma\gamma$ event selection, the σ is the cross section of $e^+e^- \to e^+e^-$ or $e^+e^- \to \gamma\gamma$, ε is the efficiency of event selection, and ε_{trig} is the trigger efficiency. The integrated luminosities of data taken from 2.2324 to 4.59 GeV at BESIII are measured with these two processes. Only for the energy point around J/ψ (from 3.093 to 3.12 GeV), the luminosity is measured by $e^+e^- \to \gamma\gamma$. The uncertainty of luminosity is about 1%. In the R value measurement, the Lund area law generator LUARLW [7] is used for determining the hadronic efficiency. LUARLW contains following constitutes: initial state radiation (ISR), string fragmentation, multiplicity and momentum-energy distribution, decay of unstable hadrons. There are many phenomenological parameters in LUARLW. In the BEPCII energy , the main parameters are those which determine the ratios of mesons and baryons with different quantum number in the string fragmentation process. In LUARLW these parameters are stored in array PARJ(1-20) as in JETSET, their default values we preset by fitting the data taken with DELPHI at LEP [8].The values of PARJ(1-20) are tuned by the experimental data taken with BESIII. Fig. 3 shows the sum of cross sections of the measured exclusive processed (red points) and the total cross section (black points), which means that only parts of exclusive processes were measured. the remained unmeasured or unknown processes use LUARLW to generate with inclusive method. Fig. 4 shows the comparison between data and MC for some selected distributions after generator tuning.

In short summary, BESIII has collected the three-phase data for the R measurement. The event selections and the luminosity has been determined with good uncertainties. The generator tuning is in process. The final uncertainties of R value measurement will be less than 3%.

3. $\pi^+\pi^-$ form factor measurement in BESIII

As the introduction part said, the cross section of $e^+e^- \to \pi^+\pi^-$ is quite important for the $(g_\mu - 2)$ measurement. There are two precision measurements for the $\sigma_{\pi^+\pi^-}$ before, KOLE Col-

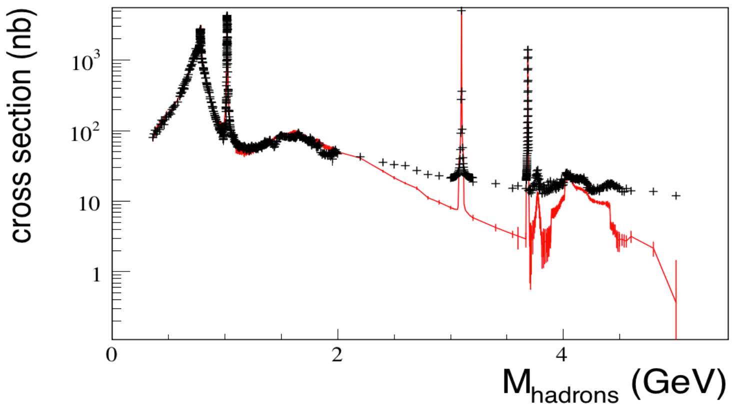


Figure 3: The Born cross section of $\sigma(e^+e^- \to \text{hadrons})$ below 5 GeV. The black points are the total inclusive cross section, the red points are the sum of the measured exclusive cross section.

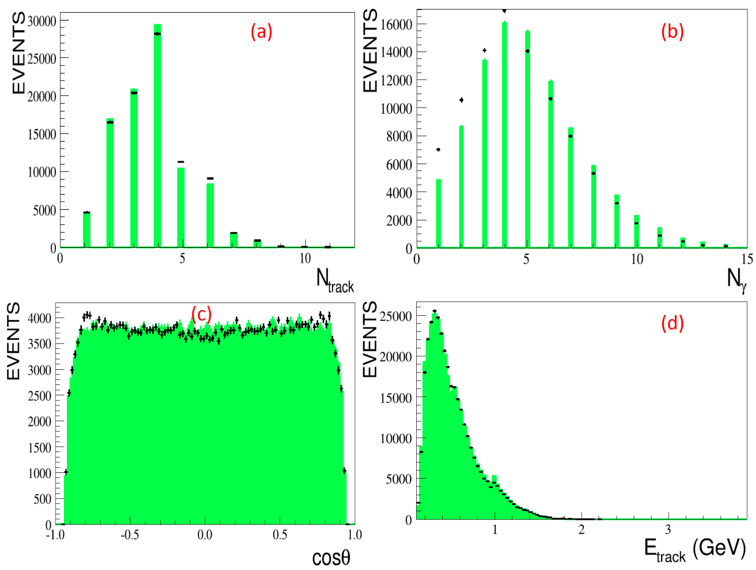


Figure 4: Comparison between data and MC at 3.65 GeV. (a) multiplicity of charged track; (b) multiplicity of photon; (c) polar angle cosθ; (d) momentum of charged track.

laboration in Frascati [9, 10, 11, 12] and BaBar Collaboration at SLAC [13]. Both of them claim the accuracy is better than 1% in the energy range less than 1 GeV. However, there is 3% discrepancy between these two measurement on the peak of $\rho(770)$ resonance. BESIII did the measurement of $\sigma_{\pi\pi}$ in the range from 600 to 900 MeV which includes the important $\rho(770)$ peak. In BESIII, the ISR method is used with the data sample collected at 3.773 GeV, and the luminosity is 2.9 pb^{-1}. With the ISR method, events are used in which one of the beam particles radiates a high-energy photon. In such a way, the available energy to produce a hadronic (or leptonic) final state is reduced, and the hadronic (or leptonic) mass range below the cms energy of the e^+e^- collider becomes available. The events of $e^+e^- \to \gamma\pi^+\pi^-$ are selected. The radiated photon should be explicitly detected in the detector. We require the presence of two charged tracks in the MDC with net charge zero. And the transverse momentums of charged tracks should be above 300 MeV/c. We also require at least one neutral cluster in the EMC without associated hits in the MDC with the energy deposited larger than 400 MeV. The Bhabha events survive the signal event selection because of its high cross section, therefore, we have to suppress this contribution. An electron particle identification algorithm is used by the information from MDC, TOF and EMC. The four-constraint kinematic fit is performed to suppress the background level, by requiring the $\chi^2_{4C} < 60$. But the $\gamma\mu^+\mu^-$ can not be suppressed by the kinematic fitting due to the limited momentum resolution of the MDC. To separate the muons with pions, the Artificial Neural Network (ANN) method, provide by the TMVA package [14], is performed after the previous selections. The ANN is trained with $e^+e^- \to \gamma\pi^+\pi^-$ and $e^+e^- \to \gamma\mu^+\mu^-$. The response value of ANN ($y_{\rm ANN}$) is calculated for distinguish pions and muons. We require that $y_{\rm ANN}$ is greater than 0.6 for each pion candidate in the event selection, yielding a background rejection of more than 90% and a signal loss of less than 30%. To calculate the $\sigma_{\pi\pi}$, there are two independent normalization methods. In the first method, we obtain the bare cross section according to the following formula:

$$\sigma^{\rm bare}_{\pi\pi(\gamma_{\rm FSR})} = \frac{N_{\pi\pi\gamma}\cdot(1+\delta^{\pi\pi}_{\rm FSR})}{L\cdot\varepsilon^{\pi\pi\gamma}_{\rm global}\cdot{\rm H(s)}\cdot\delta_{\rm vac}} \tag{3.1}$$

where $N_{\pi\pi\gamma}$ is the number of signal events found in data, L the luminosity of the dataset, H the radiator function, $\varepsilon^{\pi\pi\gamma}_{\rm global}$ the global efficiency determined by the signal MC sample, $1+\delta^{\pi\pi}_{\rm FSR}$ the FSR correction factor, and $\delta_{\rm vac}$ the vacuum polarization correction. Another method is normalized to the measured number of $e^+e^- \to \mu^+\mu^-\gamma$ events, by the formula:

$$\sigma^{\rm bare}_{\pi\pi(\gamma_{\rm FSR})} = \frac{N_{\pi\pi\gamma}}{N_{\mu\mu\gamma}}\cdot\frac{\varepsilon^{\mu\mu\gamma}_{\rm global}}{\varepsilon^{\pi\pi\gamma}_{\rm global}}\cdot\frac{1+\delta^{\mu\mu}_{\rm FSR}}{1+\delta^{\pi\pi}_{\rm FSR}}\cdot\sigma^{\rm bare}_{\mu\mu} \tag{3.2}$$

where $\varepsilon^{\mu\mu\gamma}_{\rm global}$ is the global efficiency for the $e^+e^- \to \mu^+\mu^-\gamma$ event selection, $1+\delta^{\mu\mu}_{\rm FSR}$ the FSR correction to the $\mu\mu$ final state, and $\sigma^{\rm bare}_{\mu\mu}$ the cross section of $e^+e^- \to \mu^+\mu^-$.

Fig 5 shows the comparison of the bare cross sections including FSR obtained with the first (black) and second method before unfolding(blue). The error bars are statistical only. Both method agree within uncertainties. The first method is used in this analysis, since the second one has larger statistical uncertainties which is caused by the limited $\mu^+\mu^-\gamma$ statistics in the mass range of interest.

Based on the cross section measurement, the pion form factor could be calculated via:

$$|F_\pi|^2(s') = \frac{3s'}{\pi\alpha^2\beta^3_\pi(s')}\sigma^{\rm dressed}_{\pi\pi}(s') \tag{3.3}$$

with the pion velocity $\beta_\pi(s') = \sqrt{1-4m^2_\pi/s'}$, the charged pion mass m_π, and the dressed cross section $\sigma^{\rm dressed}_{\pi\pi}(s') = \sigma(e^+e^- \to \pi^+\pi^-)(s')$ containing vacuum polarization, but corrected for FSR effect. To make comparison with other experiments, we fit the form factor with the vector meson dominance model, where the Gunaris-Sakurai parameterization [15] for the ρ resonances is adopted. The fitted result is shown in Fig. 6.

Comparison with other measurement are illustrated in Fig 7 and 8. Here, the shaded error band of the fit includes the systematic error only, while the uncertainties of the data points include the

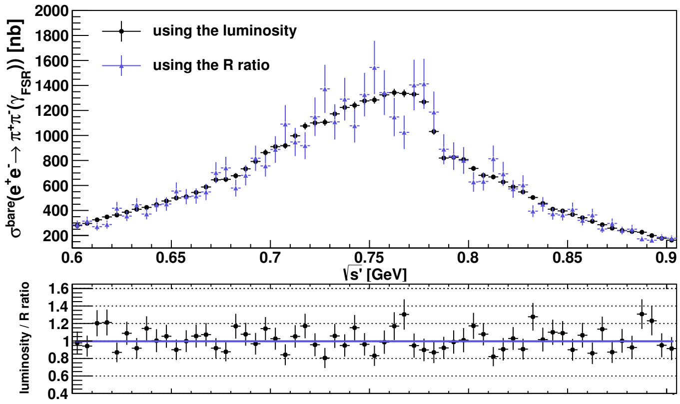


Figure 5: Comparison between the methods to extract $\sigma_{\pi\pi}$. The lower panel shows the ratio of these results together with a linear fit to quantify their difference.

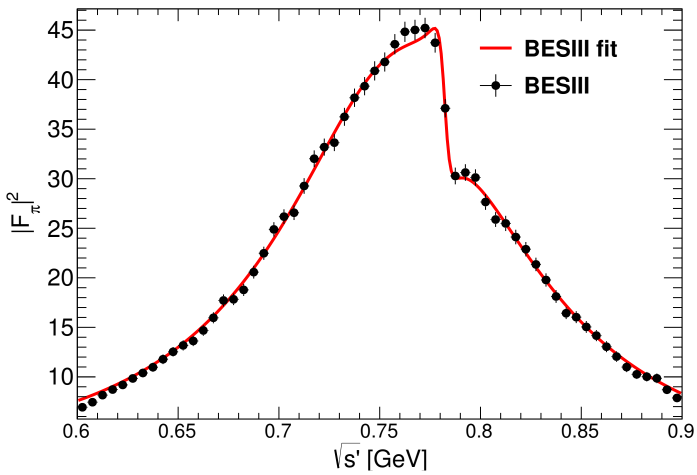


Figure 6: The measured squared pion form factor.

sum of the statistical and systematic errors. We observe a very good agreement with the KLOE 08 and KLOE 12 data sets up to the mass range of the $\rho - \omega$ interference. In the same mass range the BaBar and KLOE 10 data sets show a systematic shift, however, the deviation is, not exceeding 1 to 2 standard deviations. At higher masses, the statistical error bars in the case of BESIII are relatively large, such that a comparison is not conclusive. There seem to be a good agreement with the BaBar data, while a large deviation with all three KLOE data sets is visible. There are indications that the BESIII data and BESIII fit show some disagreement in the low mass and very high mass tails as well.

We also compute the contribution of our BESIII cross section measurement to the hadronic contribution of $(g-2)_\mu$. As summarized in Fig. 9, the BESIII result, $a_\mu^{\pi\pi,\text{LO}}(600-900\text{MeV}) = (368.2 \pm 2.5_{\text{stat}} \pm 3.3_{\text{sys}}) \cdot 10^{-10}$, is found to be in good agreement with all three KLOE values. A difference of about 1.7σ with respect to the BaBar result is observed.

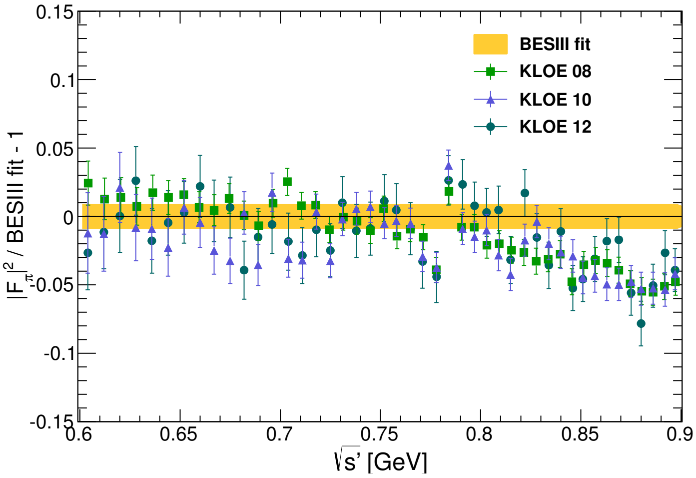


Figure 7: Relative difference of the form factor squared from KLOE and the BESIII fit.

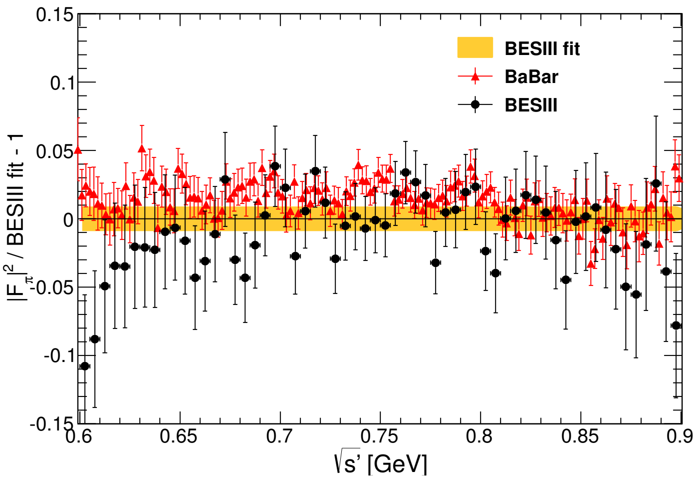


Figure 8: Relative difference of the form factor squared from BaBar and the BESIII fit.

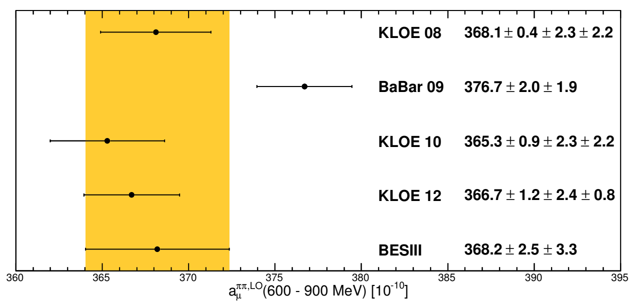


Figure 9: Our calculation of the leading-order (LO) hadronic vacuum polarization 2π contributions to $(g-2)_\mu$ in the energy range 600-900 MeV from BESIII and based on the data from KLOE 08 ,10, 12 , and BaBar, with the statistical and systematic errors. The statistical and systematic errors are added quadratically. The band shows the 1σ range of the BESIII result.

4. Summary

In BESIII, data taking plans between 2.0 - 4.6 GeV are performed which is used for R scan and QCD study. To achieve more precise measurement, many work has been done including generator tuning, event selection optimization, luminosity measurement and so on. The preliminary results of R measurement between 2.2324 - 3.671 GeV has been reported inside BESIII Collaboration, and the analysis for other energy points are in going. We also perform the cross section measurement of $\sigma_{\pi\pi}$ with ISR method, which has the accuracy of 0.9% in the dominant $\rho(770)$ mass region between 600 and 900 MeV$/c^2$. The two-pion contribution to the hadronic vacuum polarization part $(g-2)_\mu$ is determined to be $a_\mu^{\pi\pi,\mathrm{LO}}(600-900\mathrm{MeV}) = (368.2 \pm 2.5_{\mathrm{stat}} \pm 3.3_{\mathrm{sys}}) \cdot 10^{-10}$.

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