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Measurements of hadron electromagnetic structure at BESIII

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Hadron form factors are fundamental observables of QCD and a powerful tool in understanding the electromagnetic structure of hadrons. In this paper, three results using data samples collected with the BESIII detector at BEPCII collider are presented: (1) the Born cross section of $e^+e^- \to p\bar{p}$ at 12 center-of-mass energies from 2232.4 to 3671.0 MeV are measured; the effective electromagnetic form factor is deduced under the assumption $|G_E| = |G_M|$; the ratio $|G_E/G_M|$ and $|G_M|$ are extracted by fitting the polar angle distribution. (2) The Born cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ at 4 center-of-mass energies are measured; the effective electromagnetic form factor is deduced under the assumption $|G_E| = |G_M|$. (3) The cross section of $e^+e^- \to \pi^+\pi^-$ in the effective center-of-mass energy region between 600 and 900 MeV is measured by the method of the initial state radiation using a 2.93 fb^{-1} data set collected at center-of-mass energy of 3773 MeV. The pion form factor $|F_\pi|^2$ is extracted and the contribution to $(g-2)_\mu$ of the measured cross section to the leading order hadronic vacuum polarization is calculated.

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1. Introduction

The structure of light baryons is very important, but very difficult, to understand. Electromagnetic form factors (FFs) are key ingredients to describe the internal structure. Nucleon FFs can be measured by the $e^-N \to e^-N$ (space-like FFs), or by the $e^+e^- \to N\bar{N}$ and the reversed process $N\bar{N} \to e^+e^-$ (time-like FFs). FFs are real in the space-like region and complex in the time-like region. In the present context of QCD and the quark-gluon structure of hadrons, it is particularly interesting to measure FFs of hyperons which are expected to reveal the effects of SU(3) breaking. However, hyperon FFs can be only measured in the time-like region. In the time-like region, a non-zero relative phase between the electric and magnetic FFs manifests itself in polarization of the outgoing baryons [1]. The weak, parity violating decay of the hyperons, that causes the decay particles to be emitted in the direction of the spin of the hyperon, makes the polarisation of the hyperon experimentally accessible. This means that for hyperons, the time-like FFs can be fully determined.

FFs can also contribute to precise prediction of the standard model (SM). The accuracy of the SM prediction of the anomalous magnetic of the muon, $(g-2)_\mu$ is entirely limited by the knowledge of the hadronic vacuum polarization contribution, which is obtained in a dispersive framework by using experimental data on $\sigma(e^+e^- \to hadrons)$ [2]. The cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ contributes to more than 70% to this dispersion relation and, hence, is the most important exclusive hadronic channel of the total hadronic cross section. Experimentally, two methods of energy-scan and initial state radiation can be used to measure electromagnetic hadron FFs.

In this report, we present recent measurements of $e^+e^- \to p\bar{p}$ [3], $\Lambda\bar{\Lambda}$ and $\pi^+\pi^-$ [4] based on data samples collected with the Beijing Spectrometer III (BESIII) at the Beijing Electron Positron Collider II (BEPCII) [5].

2. The BESIII Experiment and data sets

BEPCII is a double ring e^+e^- collider operating at $2.0-4.6$GeV center-of-mass (c.m.) energies with a design luminosity of 1×10^{33} cm^{-2}s^{-1} at c.m. energy of 3.773 GeV. BESIII is a 4π detector located at the BEPCII, and has accumulated world-leading samples of J/ψ, $\psi(2S)$, $\psi(3770)$ events for study of light hadron and charmonium spectroscopy. Furthermore, BESIII has collected the largest sample of scan data for study of *R value* and hadronic time-like FFs, and in the high mass charmonium states regions for study of X, Y and Z particles [6].

3. Measurement of $e^+e^- \to p\bar{p}$

3.1 Extraction of the Born cross section of $e^+e^- \to p\bar{p}$ and the effective FFs

The differential Born cross section of $e^+e^- \to p\bar{p}$ can be written as a function of FFs, $|G_E|$ and $|G_M|$,

$$\frac{d\sigma_{Born}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}[|G_M(s)|^2(1+cos^2\theta_p)+\frac{4m_p^2}{s}|G_E(s)|^2(sin^2\theta_p)], \tag{3.1}$$

where $\alpha \approx \frac{1}{137}$ is the fine structure constant, $\beta = \sqrt{1-\frac{4m_p^2}{s}}$ is the velocity of the proton in the e^+e^- c.m. system, $C = \frac{\pi\alpha}{\beta}\frac{1}{1-exp(-\pi\alpha/\beta)}$ is the Coulomb correction factor for a point-like proton, s

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is the square of the c.m. energy, and θ_p is the polar angle of the proton in the e^+e^- c.m. system. At threshold, $C = 1$ means that we assume that the Coulomb force acts only on the already formed hadrons and that all other effects caused by the proton being an extended, non point-like object, are parameterized by the FFs. At the energies we are considering here, this is a valid approximation. Furthermore, under the assumption of the effective FFs $|G| = |G_E| = |G_M|$ and by integrating over θ_p, it can be deduced:

$$|G| = \sqrt{\frac{\sigma_{Born}}{86.83 \cdot \frac{\beta}{s}(1 + \frac{2m_p^2}{s})}}, \tag{3.2}$$

where σ_{Born} is in nb and m_p, s in GeV.

Experimentally, the Born cross section of $e^+e^- \to p\bar{p}$ is calculated by

$$\sigma_{Born} = \frac{N_{obs} - N_{bkg}}{L \cdot \varepsilon \cdot (1+\delta)}, \tag{3.3}$$

where N_{obs} is the observed number of candidate events, N_{bkg} is the expected number of background events, L is the integrated luminosity, ε is the detection efficiency, and $(1+\delta)$ is the radiative correction factor.

Comparisons of σ_{Born} and $|G|$ to the previous experimental measurements [7]-[13] are shown in Fig. 1. Compared to previous data from BaBar [7], the precision of the Born cross section is improved by 30% for data sets fulfilling $\sqrt{s} \leq 3080.0$ MeV. The corresponding precision of effective FFs is also improved.

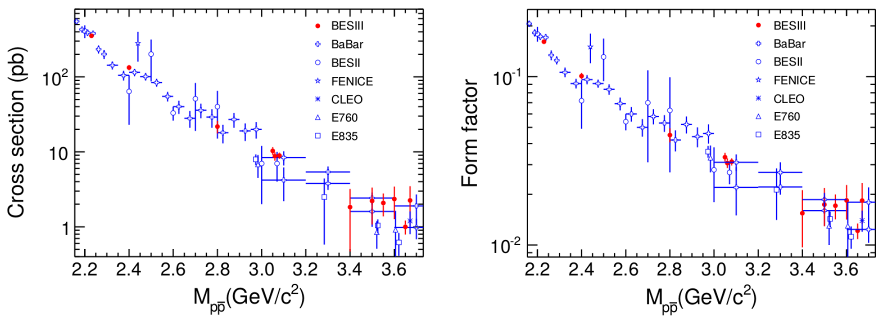

Figure 1: Comparison of the Born cross section and the effective FFs $|G|$ between this measurement and previous experiments, shown on a logarithmic scale for invariant $p\bar{p}$ masses from 2.20 to 3.70 GeV/c^2.

3.2 Extraction of the electromagnetic $|G_E/G_M|$ ratio

The distribution of the proton polar angle θ_p depends on the electric and magnetic FFs. The Eq. 3.1 can be written as:

$$F(cos\theta_p) = N_{norm}[1 + cos^2\theta_p + \frac{4m_p^2}{s}R^2(1 - cos^2\theta_p)], \tag{3.4}$$

where $R = |G_E/G_M|$ is the ratio of electric to magnetic FFs, and N_{norm} is the overall normalization factor. Both R and N_{norm} can be extracted directly by fitting the $cos\theta_p$ distributions with Eq. 3.4 for the data samples with larger statistics. The corresponding ratios R are shown in Fig. 2, and the results from the previous experiments are also presented on the same plot for comparison.

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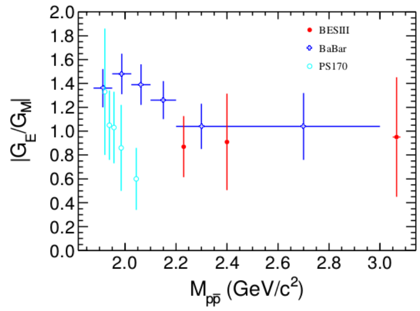

Figure 2: Comparison of the Born cross section and the effective FFs $|G|$ between this measurement and previous experiments, shown on a logarithmic scale for invariant $p\bar{p}$ masses from 2.20 to 3.70 GeV/c^2.

4. Measurement of $e^+e^- \to \Lambda\bar{\Lambda}$

Using the same method used to $e^+e^- \to p\bar{p}$, the process $e^+e^- \to \Lambda\bar{\Lambda}$ is studied using data from 4 energy points. For the first time, the cross section at the $\Lambda\bar{\Lambda}$ production threshold, 2.2324 GeV, has been measured. The measurement of cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ by reconstructing $\Lambda/\bar{\Lambda}$ from the charged $\Lambda \to p\pi^-/\bar{\Lambda} \to \bar{p}\pi^+$ and the neutral $\bar{\Lambda} \to \bar{n}\pi^0$ give consistent results. The combined result is 319.5 $\pm$ 57.6 pb, is much larger than the phase space expectations. The Born cross section and the effective FFs are also measured with the charged channel at other three c.m. energies, 2.4 GeV, 2.8 GeV and 3.08 GeV. Comparisons to the previous experimental measurements [10, 14] are shown in Fig. 3.

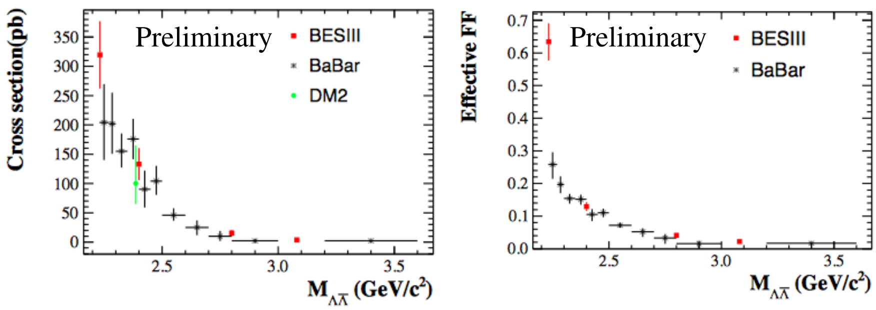

Figure 3: Comparison of the Born cross section and the effective FFs $|G|$ between this measurement and previous experiments for invariant $\Lambda\bar{\Lambda}$ masses from 2.0 to 3.60 GeV/c^2.

5. Measurement of $e^+e^- \to \pi^+\pi^-$

We exploit the method of initial state radiation (ISR) for this measurement. One of the incoming beam particles radiates a high energetic photon and, thus, the available energy to produce the hadronic $\pi^+\pi^-$ final state is reduced and the two-pion mass range $m_{\pi\pi}$ below the c.m. energy becomes available. The results for $\sigma^{bare}(e^+e^- \to \pi^+\pi^-(\gamma_{FSR}))$ as a function of $\sqrt{s'} = m_{\pi\pi}$ is shown in Fig. 4(a). The cross section is corrected for vacuum polarization effect and the final state radiation (FSR) is considered [2]. The result for pion form factor $|F_\pi|^2$ is shown in Fig. 4(b), which includes vacuum polarizations, but final state radiation effects are excluded, and the exactly the same fit formula and fit procedure are applied as described in Ref [4]. The solid line in Fig. 4(b) represents a fit to data using the Gounaris and Sakurai parametrization [15]. It is in excellent agreement with the BESIII data in the full mass range from 600 to 900 MeV/c^2, resulting in χ^2/ndf = 49.1/56.

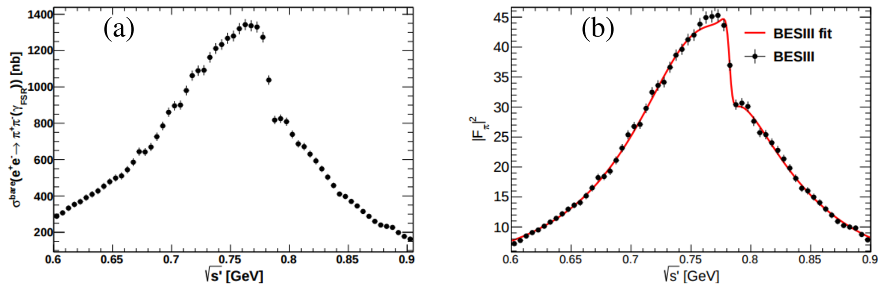

Figure 4: (a): The measured bare $e^+e^- \rightarrow \pi^+\pi^-(\gamma_{FSR})$ cross section, showing statistical errors only. (b): The pion form factor, which is fitted with the Gounaris-Sakurai parametrization.

Fig. 5 shows a normalization of the BESIII, BaBar, and KLOE pion form factor data [16]-[18] to our BESIII fit. We observe a 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, the deviation is, however, not exceeding 1 to 2 standard deviations. At higher masses the agreement with BaBar is very good, while all three KLOE data sets show a discrepancy with BESIII, which is increasing with mass and which is reaching approximately 5% at 900 MeV/c^2.

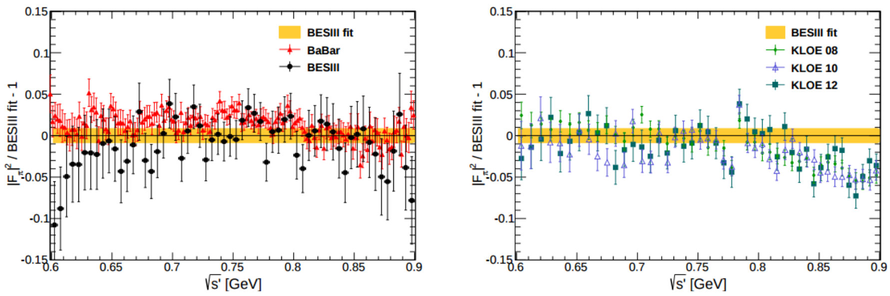

Figure 5: Relative difference of the form factor squared.

We also calculate the contribution of our cross section measurement to the hadronic contribution $(g-2)_\mu$ in the energy range between 0.6 and 0.9 GeV. As shown in Fig. 6, our result is between the values of KLOE and BaBar [16]-[18].

6. Summary

The Born cross section of $e^+e^- \rightarrow p\bar{p}$ are measured, and the effective form factors $|G|$ are extracted under the assumption $|G_E| = |G_M|$ using data at 12 energy points between 2232.4 MeV and 3671.0 MeV. The results are in good agreement with previous experiments. The observed cross section measurement of $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ near threshold is much larger than theoretical prediction. The

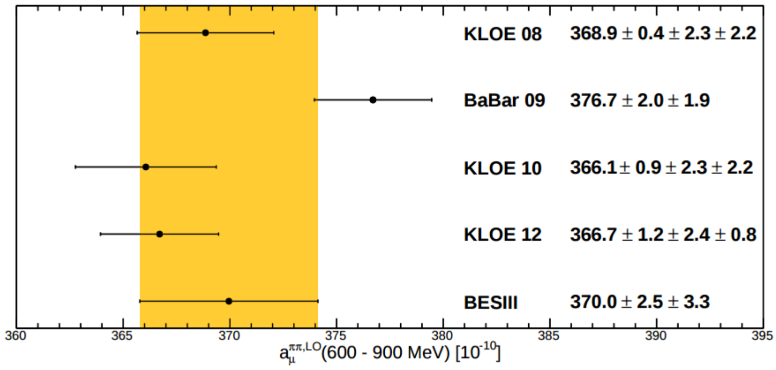

Figure 6: The contribution of BESIII cross section measurement to the hadronic contribution $(g-2)_\mu$.

Born cross section and the effective FFs are also measured at another three c.m. energies, results are in good agreement with previous experiments. Using the method of the ISR, we performed a new measurement of the $\sigma^{bare}(e^+e^- \to \pi^+\pi^-(\gamma_{FSR}))$ cross section and pion form factor with an accuracy of 0.9% in the dominant $\rho(770)$ mass region between 600 and 900 MeV/c^2 . We computed the two-pion contribution to the hadronic vacuum polarization contribution to $(g-2)_\mu$ using the vacuum polarization correction. Our result is in the middle between the corresponding values using KLOE or BaBar data in the same energy range.

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