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Hadron form factors at BESIII

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Electromagnetic form factors provide fundamental information about the structure and dynamics of hadrons. They constitute a rigorous test of nonperturbative QCD as well as of phenomenological models. Using data samples collected with the BESIII detector at the BEPCII collider, the Born cross section of $e^+e^- \to \bar{p}p$ at the center-of-mass energy between 2.0 GeV and 3.08 GeV is measured. The from factor ratio |GE/GM| and the magnetic form factor |GM| are extracted by fitting the polar angle distribution of the proton for data samples with large statistics. For BESIII data between 3.773 and 4.6 GeV, the initial state radiation (ISR) method is used to study $e^+e^- \to \bar{p}p$ in tagged mode. The cross section of $e^+e^- \to \bar{p}p$ and ratio |GE/GM| are obtained. For $\mathrm{e^+e^-} \to \Lambda_c^+\Lambda_c^-$ process, very weak energy dependence of cross section near threshold indicates that traditional theoretical prediction, which does not take into account strong interaction, needs to be modified. With the large statistics of multiple decay modes, the ratio |GE/GM| and |GM| is extracted. Results on the cross section and effective form factor of $e^+e^- \to \bar{\Lambda}\Lambda$ are presented, improving the overall presicion. A new measurement on the cross section and effective form factor of $e^+e^- \to \pi^+\pi^-$ with the ISR technique to improve the understanding of the inconsistency between the experimental results and the theoretical prediction of the anomalolus magnetic moment of the moun are shown. Preliminary results recently obtained at the BESIII experiment for $e^+e^- \to K^+K^-$ are presented.

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1. Introduction

Electromagnetic form factors (FFs) describe the internal structure and the diynamics of the hadron. They give access to information on the intrinsic electric and magnetic distributions of hadrons in the space-like region. Electromagnetic FFs have been associated in the Time-Like (TL) region with the time evolution of these distributions [1]. The number of electromagnetic FFs is depends on the spin of the hadron. The structure of a non point-like particle of spin S is parameterized in terms of $(2S+1)$ FFs.

Baryons (Mesons) with spin 1/2 (1) can be measured in TL region through the annihilation reactions $e^+e^- \leftrightarrow \bar{B}B$ ($e^+e^- \leftrightarrow \bar{M}M$) using the energy scan technique, where the center of mass energy of the collider ($\sqrt{s}$) is scanned systematically. In the Born approximation, the differential cross section for the annihilation reaction $e^+e^- \rightarrow \bar{B}B$ ($e^+e^- \leftrightarrow \bar{M}M$) in the centre of mass system is a function of the baryon electromagnetic FFs $|G_E|$ and $|G_M|$ as [2]:

$$\sigma(q^2) = \frac{2\pi\alpha^2\beta C}{3q^2\tau}\left(2\tau|G_M|^2 + |G_E|^2\right). \tag{1.1}$$

$$\beta = \sqrt{1-\frac{1}{\tau}}, \qquad \tau = \frac{q^2}{4M^2}, \qquad C = \frac{y}{(1-exp(-y))}, \qquad y = \frac{\alpha\pi}{\beta}, \tag{1.2}$$

with α the electromagnetic coupling constant. The Coulomb factor C is responsible for the the cross section to be non zero at threshold [3]. In equation 1.1 the approximation of only one virtual photon, which carries a momentum transfer squared q^2, is supposed.

Measuring the differential cross section at a fixed energy allows the determination of the FF ratio $R = |G_E|/|G_M|$ and a following determination of the separate $|G_E|$ and $|G_M|$. Without access to the angular distributions or with small statistics the effective FF is measured instead, introduced as a linear combination of $|G_E|^2$ and $|G_M|^2$:

$$|G_{eff}| = \sqrt{\frac{2\tau|G_M|^2 + |G_E|^2}{2\tau+1}}. \tag{1.3}$$

The initial state radiation (ISR) technique introduces a complementary approach to measure hadronic cross section at high luminosity e^+e^--storage rings, such as the Beijing Electron-Positron Collider II (BEPCII). Due to the fact that annihilation of e^+e^- is mostly accompanied by emission of one or several photons from the initial state, the invatiant mass (q^2) of the $\bar{B}B$ ($\bar{M}M$) system is reduced, and hence the cross section and FFs can be measured from production threshold to $\sqrt{s}$.

2. BESIII detector and data sets

The BESIII detector [4] is a general purpose spectrometer located at BEPCII. BEPCII is a double ring e^+e^- collider running at center of mass energies ($\sqrt{s}$) between 2.0 and 4.6 GeV and reached a peak luminosity of 1.0×10^{33} cm^{-2}s^{-1} at $\sqrt{s}$ =3770 MeV. The cylindrical BESIII detector has an effective geometrical acceptance of 93% of 4π. It contains a small cell, helium-based (60% He, 40% C_3 H_8) main drift chamber (MDC) which provides momentum measurements of charged particles with a resolution of 0.5% at 1 GeV/c in a 1 Tesla magnetic field. The energy loss (dE/dx) measurement provided by the MDC has a resolution better than 6%. The time-of-flight system (TOF) consists of 5-cm-thick plastic scintillators and provides a time resolution of 80 pb in the barrel and 110 ps in the end caps. The electromagnetic calorimeter (EMC) consists of 6240 CsI (Tl) in a cylindrical structure and two end caps and is used to measure the energies of photons and electrons with an energy resolution of 2.5% in the barrel and 5.0% in the end caps for1 GeV electrons and photons. The muon system (MUC) consists of 1000 m^2 of Resistive Plate Chambers (RPC) and is used to identify muons providing a spatial resolution better than 2 cm.

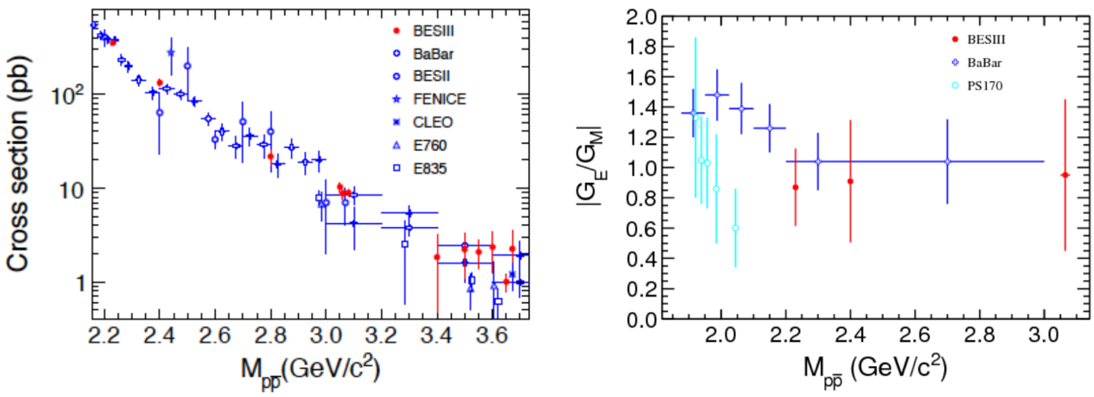
3. Proton form factors at BESIII

3.1 Measurement of the $e^+e^- \to \bar{p}p$ using the scan technique

Using 157 pb^{-1} of collected data in 2011 and 2012, BESIII measured the cross section of $e^+e^- \to \bar{p}p$ at 12 center of mass energies between 2.2 and 3.7 GeV [5]. The event selection criteria, the estimation of the background contamination and the evaluation of the signal efficiencies were obtained based on the Monte Carlo simulations for the signal and the different background processes. The Born cross section of $e^+e^- \to \bar{p}p$ is calculated by:

$$\sigma_{Born} = \frac{N_{obs} - N_{bkg}}{L\varepsilon(1+\delta)}, \tag{3.1}$$

where N_{obs} is the number of selected events, N_{bkg} is the estimated number of background events, L is the integrated luminosity determined at each center of mass energy, ε is the detection efficiency of the signal and $(1+\delta)$ is the radiative correction factor calculated using the CONEXC event generator [6]. The corresponding effective electromagnetic FF of the proton is calculated using Eq. 1.3 .The results on the Born cross section are shown in Fig. 1. This measurement improves below $\sqrt{s}$ =3.08 GeV the precision on the Born cross section by 30% compared to the BaBar measurement [7, 8]. The ratio of the proton FFs is extracted at three energies [5].

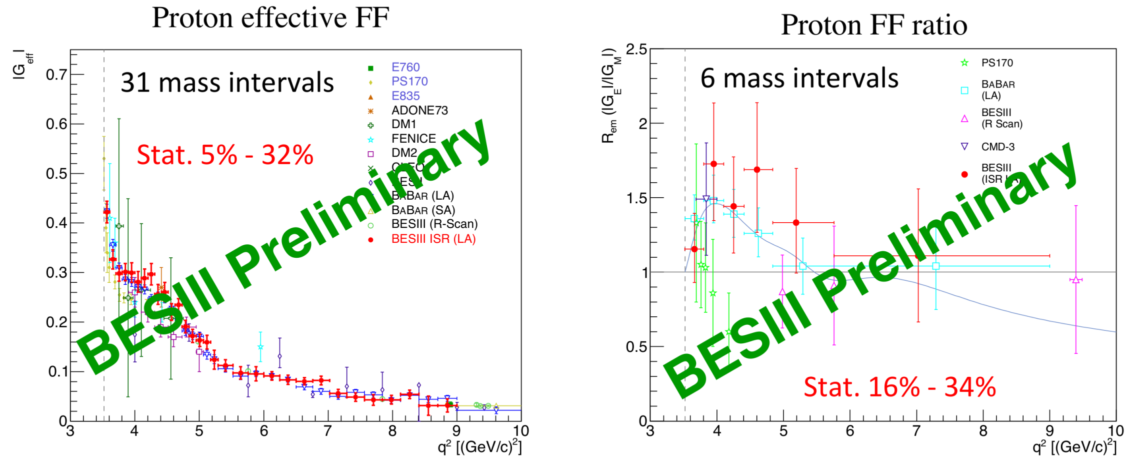


(a) (b)

Figure 1: Results for the Born cross section of $e^+e^- \to \bar{p}p$ (a) and the FF Ratio (b) [5].

3.2 Measurement of the $e^+e^- \to \bar{p}p$ using the ISR technique

Based on 7.408 fb^{-1} of data collected at BESIII with center of mass energies between 3.773 and 4.600 GeV, the proton FFs have been measured using the initial state radiation technique with the so called tagged ISR analysis where only events with ISR photons emitted within the acceptance of the EMC are selected. The ratio of the proton FFs has been extracted in six intervals of $\bar{p}p$-invariant mass from the threshold up to 3.0 GeV/c^2. The Born cross section of $e^+e^- \to \bar{p}p$ and the proton effective FF have been also measured in 31 intervals. Fig. 2 shows the preliminary results for the Born cross section and the proton FF ratio. The results are consistent with the previous experiments with the total uncertainty, dominated by statistics, between 20% and 35% for the ratio and between 10% and 64% for the Born cross section.



(a)

Figure 2: BESIII preliminary results for the Born cross section of $e^+e^- \to \bar{p}p$ (a) and the FFs ratio of proton (b) from tagged ISR analysis (BESIII ISR (LA), red points).

4. Hyperon form factors at BESIII

4.1 Measurement of the $e^+e^- \to \bar{\Lambda}\Lambda$

Preliminary results on the measurement of the $e^+e^- \to \bar{\Lambda}\Lambda$ cross section and FF have been released recently. Data samples of 40.5 pb^{-1} collected at $\sqrt{s} = 2.2324$, 2.400, 2.800 and 3.080 GeV have been analyzed. The lowest energy point, 2.2324 GeV, is only 1.0 MeV above the threshold of the $\bar{\Lambda}\Lambda$ production. The preliminary results on the Born cross section and the hyperon effective FF are shown in Fig. 3. At $\sqrt{s} = 2.2324$ GeV, the average cross section is 318 ± 60 pb, which is significantly larger than the expected value assuming no Coulomb interaction between the produced neutral hyperons. At the higher energy points, the results are consistent with the previous data. This measurement improves the precision by 10%.

4.2 Measurement of the $e^+e^- \to \bar{\Lambda}_c^- \Lambda_c^+$

The process $e^+e^- \to \bar{\Lambda}_c^- \Lambda_c^+$ was measured between $\sqrt{s} = 4.57$ and 4.6 GeV in 4 data sets with a total luminosity of 631.3 pb^{-1} collected in 2014/2015. The data is very close to the production

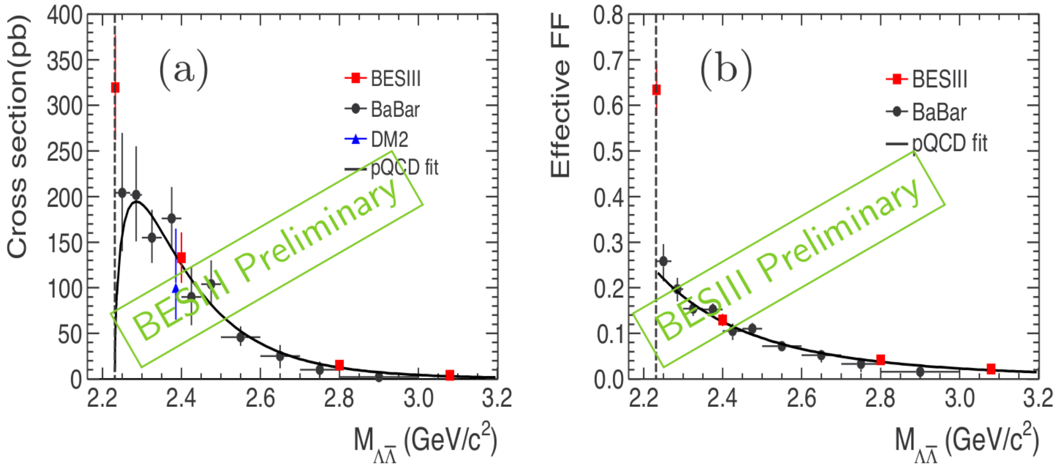


Figure 3: Preliminary results on the Born cross section of $e^+e^- \to \bar{\Lambda}\Lambda$ (a) and the Λ effective FF (b).

threshold and allows the first direct measurement of the Λ_c FF. The born cross section shown in Fig.4 was determined with an unpredicted statistical accuracy ($\sim$ 1.3% at 4.6 GeV). At the two high luminosity data sets at 4.57 and 4.6 GeV the Λ_c FF ratio was determined to be close to unity with 1.14±0.14±0.07 at 4.57 GeV and 1.23±0.05±0.03 at 4.6 GeV.

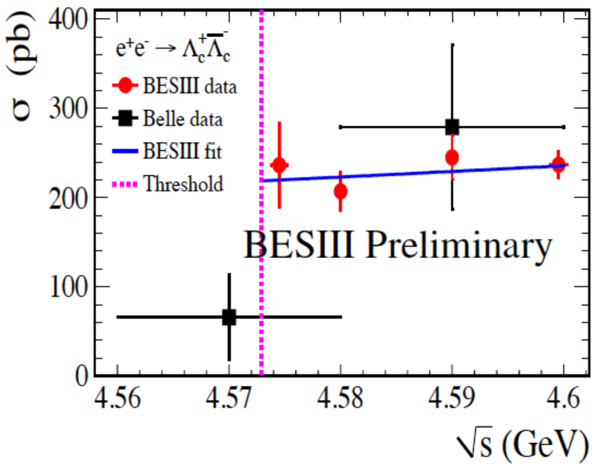
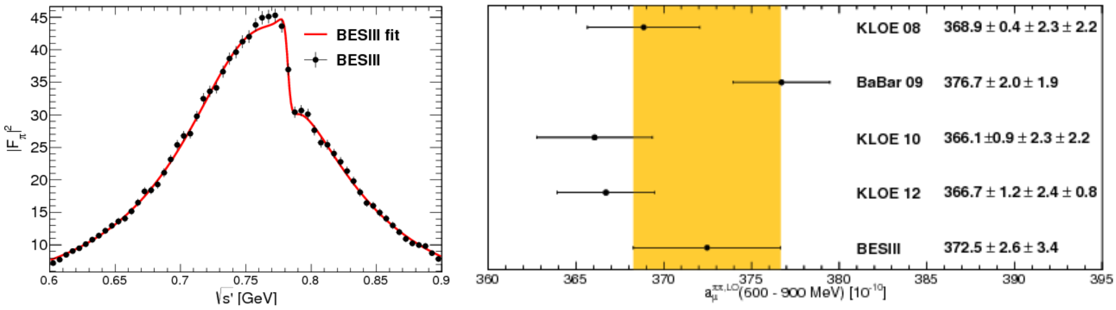


Figure 4: Preliminary results on the Born cross section of $e^+e^- \to \bar{\Lambda}_c^-\Lambda_c^+$.

5. Meson form factors at BESIII

5.1 Measurement of the $e^+e^- \to \pi^+\pi^-$ using the ISR technique

For the confirmation of the deviation of $\sim$3.6σ between the experimental results and the theoretical prediction of the anomalous magnetic moment of the moun (g$_\mu$-2), a measurement of the largest contribution to the hadronic vacuum polarization contribution α_μ^{hadr}, the $e^+e^- \to \pi^+\pi^-$ cross section, has been performed [13] to verify the deviation between theory and experiment as shown by the KLOE and BaBar experiments. The Born cross section of $e^+e^- \to \pi^+\pi^-$ has been measured in the range from 600 MeV to 900 MeV from 2.9 fb^{-1} data collected at 3.773 GeV in 2010/2011 using the ISR technique and the effective FF has been extracted. The main background $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ was supressed to be under 1% using a neural network technique. The systematic uncertainty in the cross section is 0.9% and the results on α_μ shown in Fig.5 are inbetween the KLOE and the BaBar measurements, while clearly confirming the deviation of $\sim 4\sigma$ from the standard model prediction $(g_\mu\text{-}2)^{SM}$.

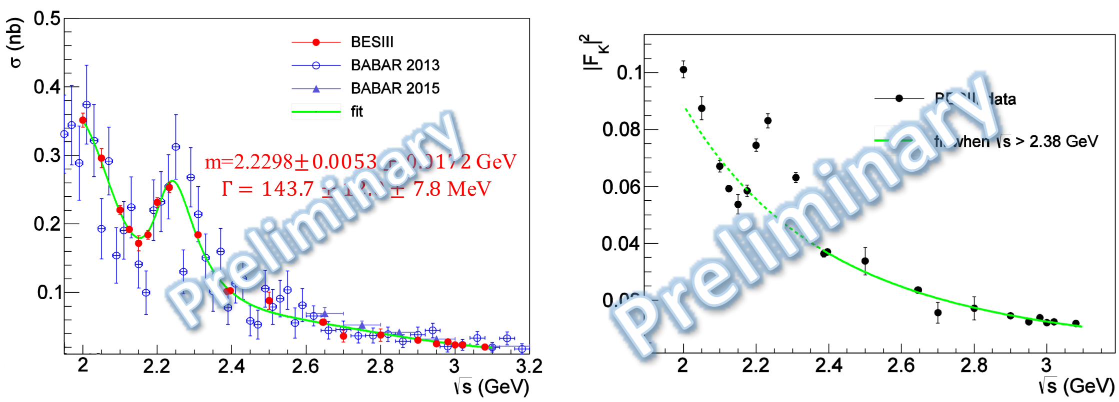


(a) (b)

Figure 5: Effective form factor of $e^+e^- \to \pi^+\pi^-$ (a) and the a_μ (b)

5.2 Measurement of the $e^+e^- \to K^+K^-$

BESIII released preliminary results on the cross section and effective FF from $e^+e^- \to K^+K^-$ based on 651 pb^{-1} of data collected in 2014/2015 at $\sqrt{s}$ between 2.0 GeV and 3.08 GeV. The results on the cross section and effective FF, measured in 22 energy points, are shown in Fig. 6. The results improve the uncertainty on this channel and are consistent with previous results from the BaBar experiment. Furthermore, the results confirm the QCD prediction for the form factor $|F_K|$ to decrease with 1/s.



(a) (b)

Figure 6: Born cross section of $e^+e^- \to K^+K^-$ (a) and the effective form factor (b)

6. Summary and prospects

The experimental measurements of the TL hadron FFs close to the threshold region shows some unexpected features [11, 12]. In this context, a precise and complete measurement of the hadrons FFs in this region is of great importance. BESIII is an excellent laboratory for the measurement of hadrons FFs, since both ISR and scan methods can be performed, and the kinematical threshold for the different hadronn pair production is covered by the available data samples.

In 2015, BESIII performed high luminosity scan in 22 energy points between 2.0 and 3.08 GeV. Based on these data samples, the proton electromagnetic FFs $|G_E|$ and $|G_M|$ can be extracted separately. The expected precision on the ratio of the proton FFs is at the level of 10%. In addition to the proton, BESIII can provide the most precise measurements of the neutron FFs with the $e^+e^- \to \bar{n}n$ and $e^+e^- \to \bar{n}n\gamma$ processes. The determination of Λ FFs, $|G_E|$, $|G_M|$ and the relative phase between them is also possible. The polarization of Λ in $e^+e^- \to \bar{\Lambda}\Lambda$, which contains information on the relative phase between $|G_E|$ and $|G_M|$, can be experimentally accessed thanks to the self-analyzing weak decay of Λ, i.e $\Lambda \to p\pi^-$. The measurement of the hyperons FFs at BESIII can be extended to other channels, i.e. $e^+e^- \to \bar{\Lambda}_{\bar{c}}\Lambda_{c^+}$, $\Lambda\bar{\Sigma}^0, \ldots$. Also meson FFs measurements, like $e^+e^- \to \pi^+\pi^-$, $K^+K^-, \ldots$ are possible at BESIII and can improve the overall precision for cross sections and FFs.

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