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Recent results on time-like baryon electromagnetic form factors at BESIII

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Electromagnetic form factors, which parametrize the inner structure of hadrons, are fundamental observables for understanding the strong interaction. The electron-positron collider experiments are powerful tools to study the electromagnetic form factors of various baryons in time-like region via energy scan or ISR-return methods. In this contribution we report about the recent measurements of baryon electromagnetic form factors at the BESIII experiment. Taking advantage of large statistics, the moduli of the electric and magnetic form factors of n are measured separately for the first time at center-of-mass energy from 2.00-2.95 GeV. Moreover, new results about the hyperon (Λ, Σ, Λ_c, Δ, Ω) pair production cross section and form factors are presented. The anomalous threshold effect is observed in some pair production channels and an oscillation behavior is observed, for the first time, in the energy dependence of the ratio between modulus of the electric and magnetic form factor for Λ_c baryon. In addition, a complete measurement of Σ^+ form factors is achieved in a wide q^2 region.

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1. Introduction

Electromagnetic form factors (EMFFs), $G_E(q^2)$ and $G_M(q^2)$, describing the charge and magnetization distributions of hadrons, are functions of the momentum transfer q^2. According to the value of the q^2, two kinematic regions can be defined: the space-like (SL) and the time-like (TL). The SL FFs with $q^2 < 0$ can be studied in elastic lepton scattering experiments. The TL FFs with $q^2 > 0$ can be studied in Dalitz decays in low q^2 regions and lepton-antilepton annihilation processes in high q^2 regions. SL and TL FFs can be related by the dispersion theoretical analysis.

For spin-1/2 baryon (B), the cross section in the Born approximation of the one-photon-exchange process $e^+e^- \to B\bar{B}$ is expressed as [1]:

$$\sigma_B = \frac{2\pi\alpha^2\beta C}{3q^2\tau}\left(2\tau\,|G_M|^2 + |G_E|^2\right), \tag{1}$$

where α is the fine-structure constant, C is the Coulomb factor, $\beta = \sqrt{1/(1-\tau)}$, $\tau = q^2/4m_B^2$, m_B is the baryon mass. The Coulomb factor C accounts for the electromagnetic interaction between the outgoing baryon pairs. For neutral baryons, it is 1 and for charged baryons, it is $y/(1-e^{-y})$ with $y = \pi\alpha\sqrt{1-\beta^2}/\beta$. Therefore, for charged baryons, the factor β is canceled by the Coulomb factor, resulting in a nonzero cross section at threshold. However, for neutral baryons, a vanishing cross section should be expected near threshold. The combination of $|G_E|$ and $|G_M|$ defines the effective FF ($|G_{eff}|$), which is proportional to the square root of the cross section:

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

which is equivalent to $|G_M|$ under the working hypothesis $|G_M| = |G_E|$. It is often convenient to describe the process ($e^+e^- \to B\bar{B}$) in terms of $|G_{eff}|$ and the ratio $R = |G_E/G_M|$ between the electric and the magnetic FF at a given q^2. The R could be extracted by analyzing the angular distributions of the baryons in final state.

SL EMFFs are real functions of q^2, whereas the TL ones are complex. The electric and magnetic FFs of a spin-1/2 baryon have a relative phase $\Delta\Phi$, leading to a transverse polarization of the baryons even if the colliding beams are unpolarized. The polarization P depends on the relative phase and the scattering angle of the baryon as [2]:

$$P_y = -\frac{\sin 2\theta Im[G_E G_M^*]/\sqrt{\tau}}{\frac{|G_E|^2\sin^2\theta}{\tau} + |G_M|^2\left(1+\cos^2\theta\right)}, \tag{3}$$

where θ is the polar angle of the baryon. Therefore, $\Delta\Phi$ and the moduli of the EMFFs can be extracted by studying the baryon polarization.

Experimentally the FFs can be accessed by exploiting two different methods: the direct scan and the initial state radiation (ISR), which are both available at BESIII. The BESIII spectrometer is introduced in Ref. [3] and will not mentioned in this paper.

2. Neutron EMFFs

Recently, a analysis about neutron EMFFs was performed by BESIII based on a 354.6 pb^{-1} data sample collected at 12 center-of-mass (c.m.) energies ($\sqrt{s}$) from 2.0-2.95 GeV [4]. It is the first separate measurements of the $|G_E|$ and $|G_M|$, whose results are shown in Fig 1. The results are compared with various models, among which, the dispersion relations (DR) gives the best description of data. As shown in Fig 1, the results of $|G_M|$ from this work are smaller than those from FENICE [5]. The analyticity of neutron EMFFs between SL and TL regions was investigated as well. In case of $|q^2| \to \infty$, the moduli of EMFFs should approach each other. Aa a result, the ratio $R_{E,M} = \left|G^{TL}_{E,M}(q^2)/G^{SL}_{E,M}(-q^2)\right|$ goes to 1 when $|q^2| \to \infty$. BESIII searched for the asymptotic behavior of the EMFFs, as shown in Fig. 2. However, our results are $R_E = 5.18 \pm 1.18$ and $R_M = 1.72 \pm 0.14$, which is away from 1.

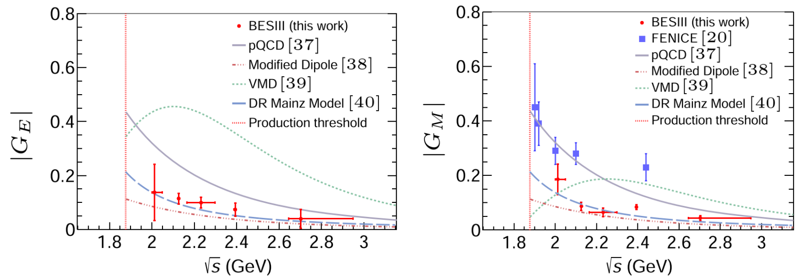

Figure 1: Electric (left) and Magnetic (right) Form Factors of the neutron as a function of $\sqrt{s}$ together with the theoretical predictions.

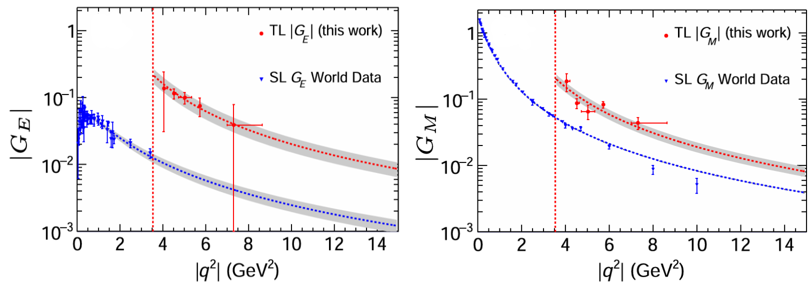

Figure 2: Electric (left) and Magnetic (right) Form Factors of the neutron as a function of q^2.

3. Hyperon EMFFs

It is difficult to study EMFFs of hyperons in the SL region due to the difficulties in providing stable hyperon beams. The hyperons can be produced in e^+e^- annihilation above their production threshold, so the investigations on EMFFs of hyperons can be performed in the TL region. Recent results on the EMFFs of Λ, Λ_c, Σ, Ω, and Δ from BESIII are presented in this section (although Λ_c and Δ are not hyperons).

3.1 Cross section measurement of $e^+e^- \to \Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$, $\Lambda_c\bar{\Lambda}_c^{(*)}$, $\Omega\bar{\Omega}$, and $\Delta\bar{\Delta}$

Using the data sample with a luminosity of 11.9 fb^{-1} collected at $\sqrt{s} = 3.773 - 4.258$ GeV, the cross sections for the processes of $e^+e^- \to \Lambda\bar{\Lambda}$ and $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ are measured by the ISR method [6, 7]. For both channels, the results are consistent with previous measurements from

BESIII and other experiments, but with improved precision. In addition, non-zero cross sections are observed near the threshold which conflict with perturbative QCD prediction, and the lineshape of the cross sections has been studied with the least chi-square fit under various assumptions as shown in Fig. 3. These results have gained some interest from some theorists.

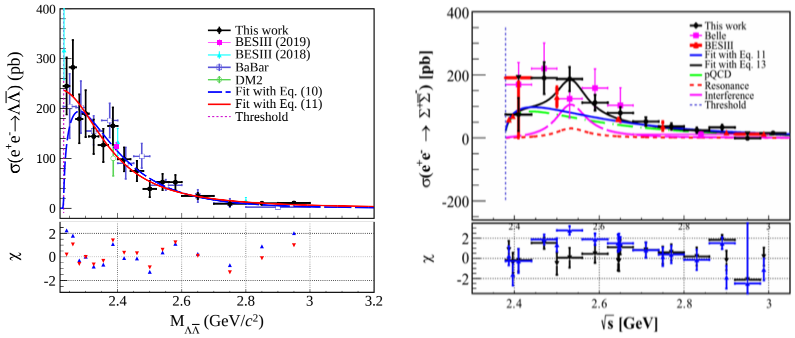

Figure 3: The cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ (left) and $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ (right).

Based on the data sample at $\sqrt{s}$ = 4.64 – 4.95 GeV, the process of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ is studied at 12 c.m. energies [8]. The Born cross sections and effective form factors are determined with unprecedented precision. Flat cross sections around 4.63 GeV are obtained (as shown in Fig. 4) and no indication of the resonant structure $Y(4630)$, as reported by Belle, is found. Analyzing the cross section together with the polar-angle distribution of the Λ_c^+ baryon at each energy point, the moduli of EMFFs ($|G_E|$ and $|G_M|$) are extracted and separated. For the first time, the energy dependence of the form factor ratio $R = |G_E/G_M|$ is observed, which can be well described by an oscillatory function, as shown in Fig. 4. The processes involved excited states of Λ_c, Λ_c^*, are also investigated with the data sets at $\sqrt{s}$ = 4.92, 4.95 GeV. Cross sections of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^- + c.c.$ and $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^- + c.c.$ processes are measured for the first time (Fig. 4), and the angular distribution parameter α_{Λ_c} and FF ratio $\frac{\sqrt{|G_M|^2+|G_E|^2}}{|G_C|}$ for $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^- + c.c.$ process are determined for the first time [9].

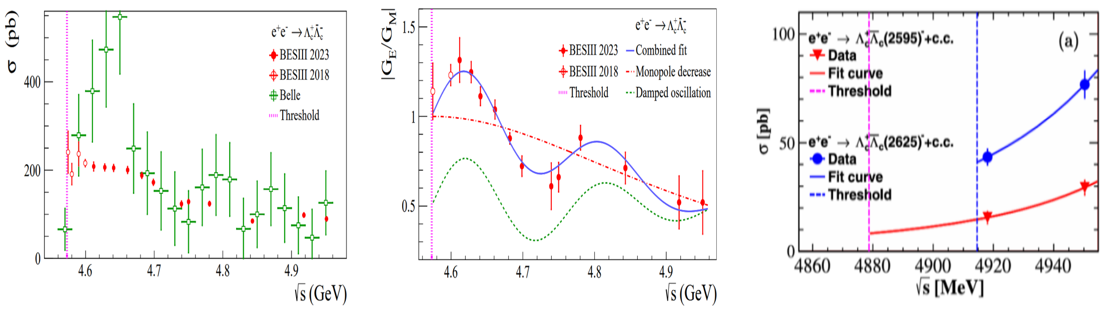

Figure 4: The cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ (left), the $R = |G_E/G_M|$ of Λ_c^+ (mid), and the cross section of $e^+e^- \to \Lambda_c\bar{\Lambda}_c^* + c.c.$ (right).

The cross sections for the processes of $e^+e^- \to \Delta^{++}\bar{\Delta}^{--}$ and $e^+e^- \to \Omega^-\bar{\Omega}^+$ are measured at $\sqrt{s}$ = 2.3094 – 2.6464 and 3.49 – 3.67 GeV, respectively [10, 11]. However, no significant signal is observed for both channels, so the upper limits of the cross sections are calculated, as shown in Fig. 5. Besides, the signal of $e^+e^- \longrightarrow \Delta^{++}p\pi^- + c.c.$ is observed and its cross section is determined.

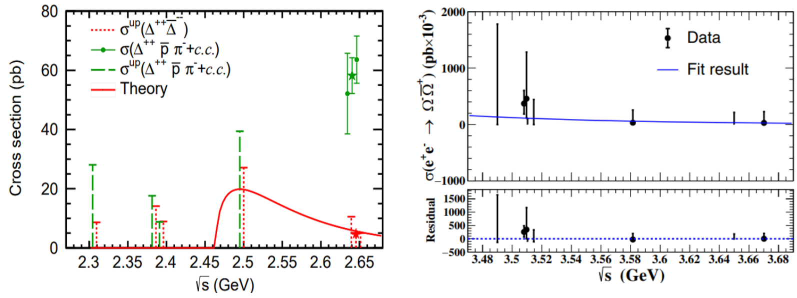

Figure 5: The cross section of $e^+e^- \longrightarrow \Delta^{++}\bar{\Delta}^{--}$ (left), and the cross section of $e^+e^- \longrightarrow \Omega^-\bar{\Omega}^+$ (right)..

3.2 Complete measurement of Σ^+ EMFFs

Benefiting from the large data samples collected by the BESIII detector, it is possible to extract the relative phase $\Delta\Phi$ between G_E and G_M, and study the polarization of hyperon, by analyzing the joint angular distribution of the cascade weak decay of hyperon. For the reaction of $e^+e^- \longrightarrow \Sigma^+(\longrightarrow p\pi^0)\bar{\Sigma}^-(\longrightarrow \bar{p}\pi^0)$, the joint decay distribution is derived in terms of $\Delta\Phi$ and a series of angular distribution parameters, see Ref. [12]. The Σ^+ transverse polarization p_y is given by:

$$p_y = \frac{\sqrt{1-\eta^2}\sin\theta\cos\theta}{1+\eta\cos^2\theta}\sin(\Delta\Phi), \tag{4}$$

where $\eta = \left(\tau - R^2\right)/\left(\tau + R^2\right)$, $R = |G_E|/|G_M|$.

BESIII reported the polarization of Σ^+ at c.m. energies of 2.396, 2.644 and 2.90 GeV with a significance of 2.2σ, 3.6σ and 4.1σ, the $\Delta\Phi$ between G_E and G_M, and the $|G_E|/|G_M|$ [13], as shown in Fig. 6.

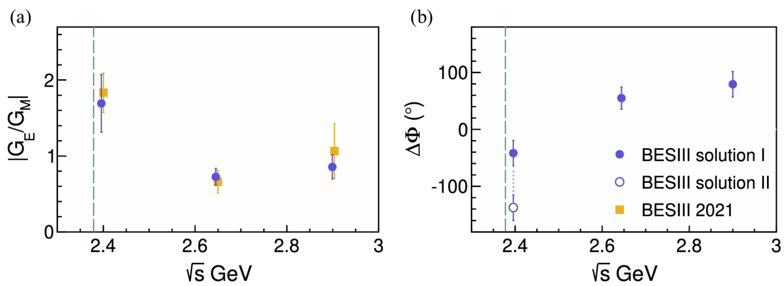

Figure 6: The ratio of $|G_E|$ and $|G_M|$ (left) and the relative phase $\Delta\Phi$ between G_E and G_M (right).

4. Summary

In summary, based on the energy scan method and ISR method, fruitful and interesting physics results for the baryon TL EMFFs from BESIII are obtained, which leads to lots of interest and discussion. More experimental data as well as theoretical investigation could shed light on baryon behavior and their structure and the exploration of BESIII is preliminary but may be a good beginning.

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