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Recent Results of Baryon Electromagnetic Form Factors at BESIII

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This contribution reports on the recent measurements of baryon electromagnetic form factors at BESIII experiment. The electric and magnetic structure of hadrons is described by electromagnetic form factors, which are basic observables that offer crucial insights into the internal structure of baryons, such as protons, neutrons, and hyperons, and contribute to our understanding of strong interactions governed by Quantum Chromodynamics (QCD). The results are presented with examples focused on but not limited to the nucleon (proton and neutron), the strangeness hyperons (Λ, Σ, Ξ and Ω), and the charmed hyperon Λ_c. The cross sections for $e^+e^- \to \Lambda\bar{\Lambda}$ and $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ are measured near threshold with unprecedented precision. There are also preliminary findings on the initial measurement of the Λ_c factor ratio $|G_E|/|G_M|$. The cross section and form factor measuring results for the Σ, Ξ and Ω hyperons are also shortly summarized in this proceeding.

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*Speaker

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1. Introduction

Baryons are a class of subatomic particles made up of three valence quarks, bound together by the strong force, mediated by gluons. They have an internal structure, and their spatial distributions of charge and magnetization are described by their $2s + 1$ electromagnetic form factors (FFs) for spin-s baryons. In case of the spin-$\frac{1}{2}$ baryon (B), the differential cross section of the annihilation reaction $e^+e^- \to B\bar{B}$ in the Born approximation is expressed as a function of the baryon electromagnetic FFs as [1]:

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2], \tag{1}$$

$$\beta = \sqrt{1-\frac{1}{\tau}}, \quad \tau = \frac{q^2}{4m_B^2}, \quad C = \frac{y}{1-e^{-y}}, \quad y = \frac{\alpha\pi}{\beta}$$

where α is the electromagnetic coupling constant, and θ is the baryon scattering angle in the e^+e^- center-of-mass (c.m.) frame. C is the Coulomb correction factor to the one-photon exchange that makes the cross section nonzero (for charged baryons) at the threshold. Due to the fact that annihilation of e^+e^- is mostly accompanied by emission of one or several photons from the initial state, the high luminosity at the e^+e^- collider experiments allows for a complementary approach, the initial-state radiation (ISR) return method, to the energy scan technique in hadron cross section measurements.

2. Nucleon (p and n) From Factors

Space-like proton form factors have been extensively studied to understand the internal structure of the proton [2, 3]. The BESIII produced the most precise measurements of the modulus of the electric-to-magnetic form factor ratio $|G_E|/|G_M|$ at center-of-mass energies between 2.0 and 3.08 GeV [4, 5]. Experimentally, the Born cross section of $e^+e^- \to p\bar{p}$ is calculated by

$$\sigma_{Born} = \frac{N_{obs} - N_{bkg}}{\mathcal{L}.\epsilon.(1+\delta)} \tag{2}$$

where N_{obs} is the observed number of candidate events, N_{bkg} is the expected number of background events, $\mathcal{L}$ is the integrated luminosity, ϵ is the detection efficiency, and $(1+\delta)$ is the radiative correction factor. The time-like form factors of the proton have also been measured [6, 7] by BESIII using the Initial State Radiation (ISR) technique. The BESIII measurements are shown Fig. 1. The most precise measurements on the ratio $|G_E|/|G_M|$ at 2.125 GeV with direct annihilation [5].

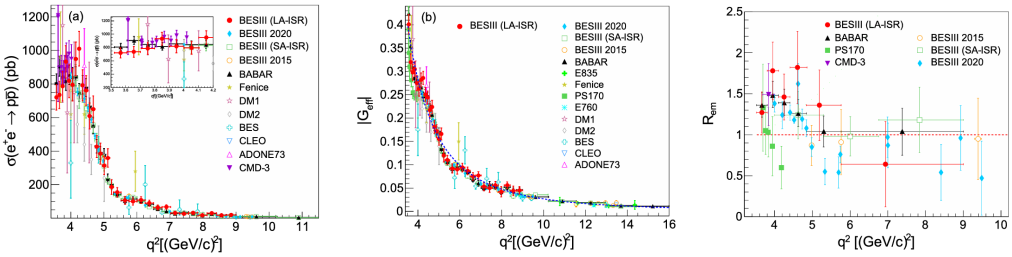

Figure 1: (left) The cross sections for $e^+e^- \to p\bar{p}$, (middle) $|G_{eff}|$ and (right) the ratio $|G_E|/|G_M|$ [7].

In 2021, the BESIII published groundbreaking results on Born cross sections of $e^+e^- \to n\bar{n}$ and measured that the ratio $R_{np} = \sigma_{n\bar{n}}/\sigma_{p\bar{p}}$ is consistently less than 1 at all energy points in the scanned range of 2.0 to 3.08 GeV [8]. Interestingly, there is also an oscillating behavior in the neutron effective form factor. The BESIII published the latest results on neutron EMFFs recently [9]. It is instructive that the dispersion

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relations (DR) model [10] exhibits the best consistency with the findings of BESIII, as this suggests that the measurement of the form factor is well described by a framework that accounts for the complex interactions between hadrons and their excited states, as illustrated in Fig. 2.

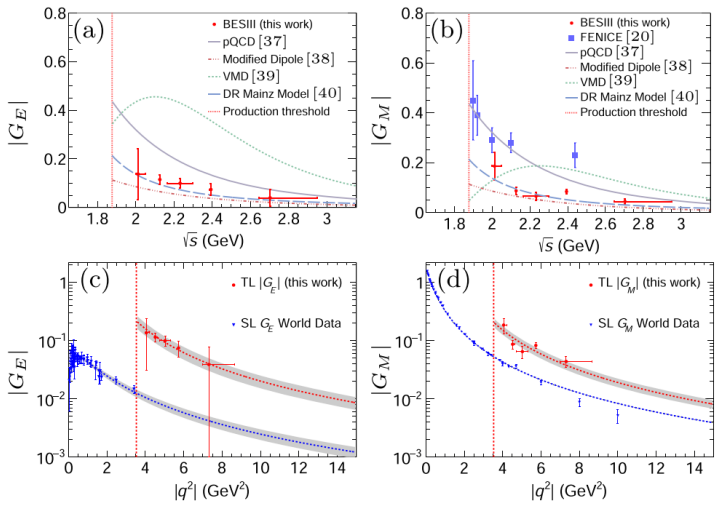

Figure 2: Results of Neutron FFs: (a) G_E, (a) G_M, (c) G_E compares with SL (d) GM comapre with SL [9].

3. Hyperon Form Factor

3.1 Lambda (Λ and Λ_c) From Factors

The EMMFs form factors for hyperons are much less well known compared to the nucleon case, and experimental data are only available in the timelike region due to the difficulties in providing stable hyperon beams or targets [11, 12]. The BESIII experiment has studied the process $e^+e^- \to \Lambda\bar{\Lambda}$ in detail [13–15]. The BESIII detector was used to track the decay products of the Λ-hyperons, such as protons and pions, to identify and reconstruct the event. The results of these measurements are presented in Fig. 3. The BESIII has conducted measurements of the relative phase of the Λ baryon, confirm the complex form of EMFFs: $|\frac{G_E}{G_M}| = 0.96 \pm 0.14 \pm 0.02$ and relative phase $\Delta\phi = 37^\circ \pm 12^\circ \pm 6^\circ$ at the center of mass energy 2.396 GeV. A nonzero relative phase between electric $|G_E|$ and magnetic $|G_M|$ leads to the polarization of Λ in the process $e^+e^- \to \Lambda\bar{\Lambda}$ even though the initial states e^+e^- are not polarized [16].

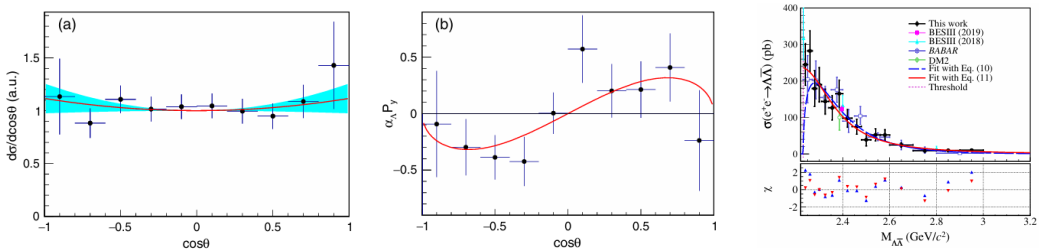

Figure 3: Relative phase of Λ (left and middle) [13] and the cross section for the $e^+e^- \to \Lambda\bar{\Lambda}$ (extreme right) [14].

The BESIII experiment made a precise measurement of the cross section for the process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and $|\frac{G_E}{G_M}|$ using 631.3 pb^{-1} of the data [17]. No obvious signal for Y(4660) was found unlike the results from the Belle experiment [18]. In 2023, BESIII studied $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ with unprecedented precision at the twelve centers of mass energies from 4.6119 to 4.9509 GeV [19] using the decay process $\Lambda_c \to pK^-\pi^+$. For

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the first time, the energy dependence of the form factor ratio $|\frac{G_E}{G_M}|$ is observed for the Λ_c hyperon, which can be well described by an oscillatory function. The results are summarized in Fig. 4.

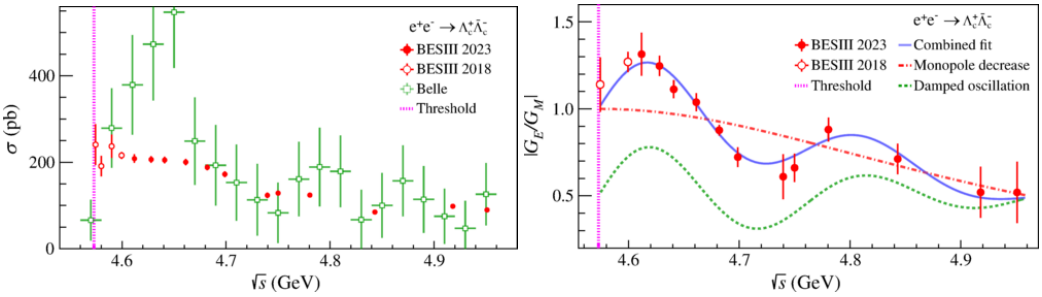

Figure 4: Comparison of the cross sections of the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ (left) and measured $|\frac{G_E}{G_M}|$ (right) [19].

Recently, BESIII has also measured $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^-$ + c.c. and $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^-$ + c.c. for the first time at center of mass energies of $\sqrt{s}$ = 4918.0 and 4950.9 MeV [20]. Non-zero cross sections are observed very close to the production threshold.

3.2 Omega (Ω) From Factors

The BESIII reported a measurement of the Born cross section and the effective form factor for the process $e^+e^- \to \Omega^-\bar{\Omega}^+$ based on data samples collected at eight c.m. energies close to the $\Omega^-\bar{\Omega}^+$ production threshold [21] without an obvious signal due to the low statistics and production cross section. Despite the absence of a clear signal, the study established an upper limit for the effective form factor $|G_{eff}|$ of the Ω^- hyperon. The interaction of a virtual photon (γ^*) with the Ω^- hyperon and its antiparticle ($\bar{\Omega}^+$) is described by four electromagnetic form factors (FFs) [22]: Spatial charge distribution ($|G_{E0}|$), Spin-dependent magnetic properties ($|G_{M1}|$), Shape deformation ($|G_{E2}|$) and higher-order magnetic interactions ($|G_{M3}|$). The cross section and upper limits of effective FF values are summarized in the Fig. 5.

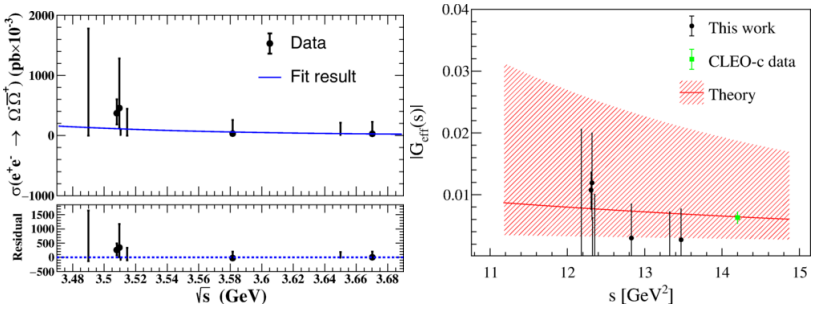

Figure 5: The cross section (left) and upper limits of effective FF (right) values for the $e^+e^- \to \Omega^-\bar{\Omega}^+$ [21].

3.3 Xi (Ξ) and (Σ) From Factors

The BESIII collaboration conducted detailed investigations into the production of $\Xi\bar{\Xi}$ hyperons near the production threshold using the processes $e^+e^- \to \Xi^-\bar{\Xi}^+$ [23] and $e^+e^- \to \Xi^0\bar{\Xi}^0$ [24]. The observed ratio of Born cross sections between the neutral and charged channels, $e^+e^- \to \Xi^0\bar{\Xi}^0$ and $e^+e^- \to \Xi^-\bar{\Xi}^+$ was found to be consistent with isospin symmetry predictions, as shown in Fig. 6.

The BESIII measured the time-like EMFFs of Σ^+ and Σ^- over the energy range $\sqrt{s}$ = 2.3864 to 3.0200 GeV [25, 26]. An asymmetry in Born cross sections σ_{Born} is observed for the production of Σ -baryon triplet (Σ^+, Σ^0 and Σ^-) in $e^+e^- \to \Sigma\bar{\Sigma}$, with the ratio measured as: $(9.7 \pm 1.3) : 3.3 \pm 0.7 : 1$. BESIII has also measured EMFFs of Σ in the timelike region using the untagged initial-state radiation technique [27] using data with an integrated luminosity of 12 fb^{-1}. Recently BESIII has extracted EMFFs and relative phase

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for the first time by studying the decay mode $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ with an improved precision of $|\frac{G_E}{G_M}|$[28]. The measured results for Σ hyperons are shown in Fig. 7.

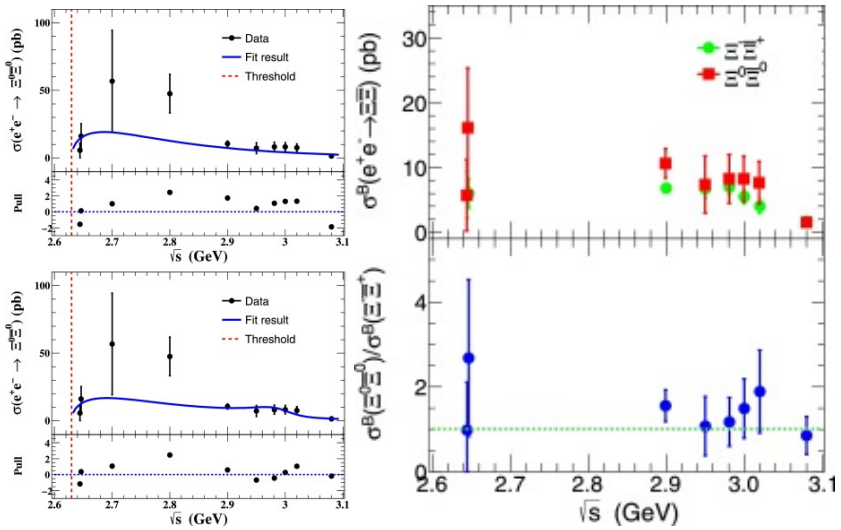

Figure 6: Results of Ξ FFs for $e^+e^- \to \Xi^0\bar{\Xi}^0$ (left) and $e^+e^- \to \Xi^+\bar{\Xi}^+$ (right) [24].

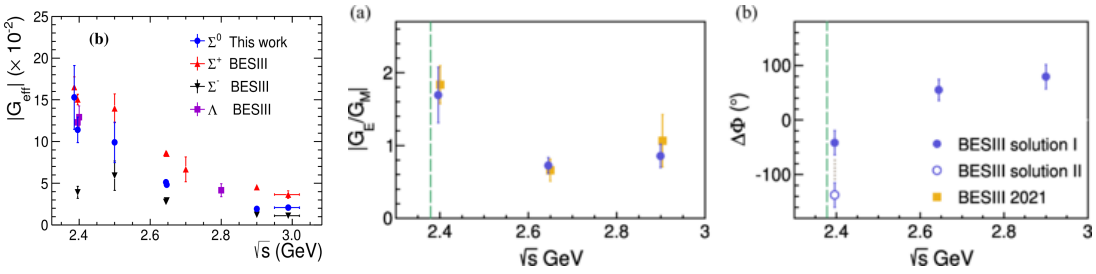

Figure 7: $|G_{eff}|$ of Σ^0 (left) [26], results for $|\frac{G_E}{G_M}|$ (middle) and the relative phase $\Delta\phi$ (right) [28].

4. Summary and Outlook

Recent advancements in the field of Electromagnetic Form Factors (EMFFs) have indeed made significant strides, especially through e^+e^- collider experiments utilizing both energy scan and Initial State Radiation (ISR) methods. Many measurements are available for each baryon from baryon octet, but BESIII just started exploring candidates from baryon decuplet as there are hardly data available for these studies. Time-like form factors are important for understanding the structure of baryons when they are produced in e^+e^- annihilations. The measurements of the proton form factors in the time-like region have been a significant achievement in hadronic physics. The neutron has been more difficult to study than the proton because of its lack of electric charge and its not easy to detect and identify in the detectors. However, BESIII has achieved unprecedented precision in measuring the neutron time-like form factor. The observation that all the cross-section lineshapes for various baryon-antibaryon pairs, including those for singly strange baryons, exhibit a plateau starting from the baryon-pair production threshold is an interesting feature and indicates specific dynamics in the production process. These findings have shown oscillations in reduced form factors, and fluctuations in the $|\frac{G_E}{G_M}|$. Studies have successfully confirmed that the relative phases between various contributing processes (such as in the production of baryon-antibaryon pairs) match the predictions of pQCD-based models. Future electron-ion colliders and electron-positron colliders will significantly improve our understanding of baryon form factors by providing high-precision data in both space- and time-like regions.

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