Measurements of baryon form factors at BESIII

Cui Li for the BESIII Collaboration
Uppsala University, 75105 Uppsala, Sweden
E-mail: cui.li@physics.uu.se

Abstract. The momentum transfer dependence of the electromagnetic form factors is an important probe of the structure of hadrons at different scales. Using data samples collected with the BESIII detector at the BEPCII collider, we study the process of $e^+e^- \rightarrow p\bar{p}$ at 12 c.m. energies from 2232.4 to 3671.0 MeV. The Born cross section at these energy points are measured as well as the corresponding effective electromagnetic form factors. Furthermore, the ratio of electric to magnetic form factors, $|G_E/G_M|$ and $|G_M|$ are measured at the c.m. energies where the data samples are the largest. We also report preliminary results of $e^+e^- \rightarrow \Lambda\bar{\Lambda}$, which is analysed with the same method. Moreover, future prospects of the measurement of baryon electromagnetic form factors from a unique high luminosity data scan by BESIII, are given.

1. Introduction
The structure of light baryons is very important, but very difficult, to understand. Electromagnetic form factors (EMFFs) are key ingredients to describe the internal structure. The electromagnetic structure of a hadron with spin $S$ is given by $2S + 1$ form factors. Nucleon form factors can be measured by the $e^-N \rightarrow e^-N$ (space-like EMFFs), or by the $e^+e^- \rightarrow NN$ and the reversed process $NN \rightarrow e^+e^-$ (time-like EMFFs). The form factors are analytic functions of the momentum transfer squared, $q^2$, between the incident and the final states. Form factors are real in the space-like region and complex in the time-like region. This means that there is a non-zero relative phase between the electric and magnetic form factors that manifests itself in polarization of the outgoing baryons [1]. In the present context of QCD and the quark-gluon structure of hadrons, it is particularly interesting to measure form factors of hyperons which are expected to reveal the effects of SU(3) breaking. However, hyperon form factors can only be measured in the time-like region, since their short life-time make hyperon targets unfeasible. Hyperons have advantage compared to nucleons though: 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. This makes the polarisation of the hyperon experimentally accessible. As a consequence, the time-like form factors of hyperons can be fully determined.

Baryons with spin 1/2 have two electromagnetic form factors. In the experiments, the so-called Sachs form factors $G_E(q^2)$ and $G_M(q^2)$ are widely used. The Sachs form factors correspond to the Fourier transformations of the charge and magnetic spatial distributions in the Breit frame. The Born differential cross section for the process $e^+e^- \rightarrow \gamma* \rightarrow B\bar{B}$ is given by [2]

$$\frac{d\sigma_{\text{Born}}(q^2)}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2} [G_M(q^2)^2(1 + \cos^2\theta_B) + \frac{1}{\tau}G_E(q^2)^2(sin^2\theta_B)],$$

(1)
where $\alpha \approx \frac{1}{137}$ is the fine structure constant, $\theta_B$ is the polar angle of the baryon, $\beta = \sqrt{1 - \frac{1}{\tau^2}}$ is the velocity, $\tau = \frac{4m_B^2}{E}$, and $m_B$ is the mass of baryon. The Coulomb factor, $C = \frac{\pi \alpha^2}{2} \exp(-\pi \alpha/\beta)$, accounts for the electromagnetic $B\bar{B}$ interactions of point-like baryons [3] and is equal to 1 for neutral baryon pairs. This gives a total cross section of

$$\sigma_{\text{Born}}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2} \left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right].$$

The effective form factors are given by

$$|G(q^2)|^2 = \frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau + 1} = \frac{\sigma_{\text{Born}}(q^2)}{(1 + \frac{1}{2\tau})(\frac{4\pi\alpha^2\beta C}{3q^2})}$$

(3)

Above threshold, the ratio $|G_E(q^2)/G_M(q^2)|$ can be extracted from the angular distribution of baryons.

The initial state radiation (ISR) channel $e^+e^+ \rightarrow B\bar{B}\gamma_{\text{ISR}}$ also could be used to study baryon form factors. The cross section for the ISR process is two orders of magnitude smaller than for direct production [4]. However, depending on the energy of ISR photon, the hadronic mass in the final state is reduced and the hadronic cross section can be extracted for all masses below the actual c.m. energy of the collider up to the production threshold of the hadronic state. The ISR method is therefore suitable for experiments where a lot of data are collected at one single energy, e.g. the $\psi(3770)$ mass.

In this report, we present recent measurements of $e^+e^- \rightarrow p\bar{p}$ [5], $\Lambda\bar{\Lambda}$ based on data samples collected with the Beijing Spectrometer III (BESIII) at the Beijing Electron Positron Collider II (BEPCII) [6].

2. The BESIII Experiment and data sets

BEPCII is a double ring $e^+e^-$ collider operating at $2.0 - 4.6$ GeV c.m. energies with a design luminosity of $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at c.m. energy of 3.773 GeV. BESIII is a 4$\pi$ detector located at the BEPCII, and has accumulated world-leading samples of $J/\psi$, $\psi(2S)$, $\psi(3770)$ 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 form factors, and in the high mass charmonium states regions for study of $X$, $Y$ and $Z$ particles [7].

3. Nucleon Form Factors

Very recently, BESIII has published the measurement of the process of $e^+e^- \rightarrow p\bar{p}$ at 12 c.m. energies ranging from 2.2324 to 3.617 GeV [5]. These data were collected in 2011 and 2012 and the total integrated luminosity is 157 pb$^{-1}$. Experimentally, the Born cross section of $e^+e^- \rightarrow p\bar{p}$ is calculated by

$$\sigma_{\text{Born}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{L \cdot \epsilon \cdot (1 + \delta)}$$

(4)

where $N_{\text{obs}}$ is the observed number of candidate events, $N_{\text{bkg}}$ is the expected number of background events, $L$ is the integrated luminosity, $\epsilon$ is the detection efficiency, and $(1 + \delta)$ is the radiative correction factor evaluation. The accuracy in the cross section measurements is between 6.0% and 18.9% up to $\sqrt{s} < 3.08$ GeV. Results of Born cross section and the effective form factors extracted according to Eq. 3 are shown in Fig. 1 in comparisons with previous experimental results [9, 10, 11, 12, 13, 14]. Compared to previous data from BaBar [9], the precision of the Born cross section is improved by 30% for data sets fulfilling $\sqrt{s} < 3.08$ GeV.
Figure 1. Comparison of the Born cross section (a) and the effective form factors $|G|$ (b) between this measurement and previous experiments, shown on a logarithmic scale for invariant $pp$ masses from 2.20 to 3.70 GeV/c$^2$.

Figure 2. The measured ratio of electric to magnetic form factors $|G_E/G_M|$.

The precision of the corresponding effective form factors is also improved. A fit to the angular distribution of the proton is performed according to Eq. 1 and the ratio of the form factors and $|G_M|$ are determined at the data points which have the largest statistics. The corresponding results are shown in Fig. 2. A different method, named the method of moments (MM), is applied to extract the ratio $|G_E/G_M|$ and $|G_M|$. A comparison of the results obtained by the two methods is shown in Table 1. The results are well consistent and the statistical uncertainty is found to be comparable between the two different methods due to the same number of events.

At present, the precision in the ratio of the proton form factors is dominated by statistical uncertainty. In a new, unique energy scan performed in 2015, an unprecedented data sample was collected. This means that statistical uncertainties below 10% can be achieved. As a complement to the scan data, samples collected at different charmonium and XYZ states above 3.773 GeV (7.4 fb$^{-1}$), can be used, applying the ISR technique. The data sample collected by BESIII (7.4 fb$^{-1}$) corresponds to a higher effective ISR luminosity than for instance the BaBar sample of 500 fb$^{-1}$ for the study of the $e^+e^- \rightarrow pp\gamma_{ISR}$. This is thanks to the fact that BESIII can also perform untagged analysis of these events where the ISR photon emitted at very low polar angles. The lowest-lying data point is at $q = 2.0$ GeV. Comparable precision to BaBar in the form factors measurement is therefore expected from the study of $e^+e^- \rightarrow pp\gamma_{ISR}$ in BESIII. The analysis of the $e^+e^- \rightarrow pp\gamma_{ISR}$ is in progress. Experimental results on the annihilation cross section into $nn$ are very scarce [15, 16]. Like the case of proton, two different measurement are possible in BESIII: $e^+e^- \rightarrow nn$ and $e^+e^- \rightarrow nn\gamma_{ISR}$. Thus, BESIII has a unique chance to shed light on the neutron form factors.
Table 1. Results of $|G_E/G_M|$ and $|G_M|$ by fitting and by the method of moments.

| $\sqrt{s} (MeV)$ | $|G_E/G_M|$ | $|G_M| (\times 10^{-2})$ |
|-----------------|-------------|-------------------------|
|                 | Fitting     |                         |
| 2232.4          | 0.87±0.24±0.05 | 18.42±5.09±0.98         |
| 2400.0          | 0.91±0.38±0.12 | 11.30±4.73±1.53         |
| (3050.0, 3080.0) | 0.95±0.45±0.21 | 3.61±1.71±0.82         |
|                 | Method of moments |                       |
| 2232.4          | 0.83±0.24    | 18.60±5.38              |
| 2400.0          | 0.85±0.37    | 11.52±5.01              |
| (3050.0, 3080.0) | 0.88±0.46    | 3.34±1.72              |

Figure 3. Comparison of the Born cross section (a) and the effective form factors |G| (b) between this measurement and previous experiments for invariant Λ ¯Λ masses from 2.0 to 3.60 GeV/c^2.

4. Hyperon Form Factor

BESIII has preliminary results on the measurement of the channel $e^+e^- \rightarrow \Lambda\bar{\Lambda}$. The analysis is based on 40.5 pb^{-1} collected in 4 different scan points during 2011 and 2012. The lowest energy point is at 2.2324 GeV, which is just 1.0 MeV above the Λ ¯Λ threshold. The measurement of cross section at threshold by reconstructing Λ/ ¯Λ from the charged Λ → pπ^-/ ¯Λ → ¯pπ^+ and the neutral ¯Λ → nπ^0 give consistent results. The combined result is 319.5 ± 57.6 pb, which is much larger than the phase space expectations. The non-vanishing cross section confirms the measurement close to the threshold by BaBar with ISR technique [17]. Measurements of the other three energy points are performed using the charged decay mode. The preliminary results on the measurement of the Born cross section are shown in Fig. 3 together with previous measurements [?, 17].

With the higher luminosity scan data of BESIII from 2015, it is possible to fully determine the Λ form factors. A nonzero relative phase between electric $|G_E|$ and magnetic $|G_M|$ leads to the polarization of Λ in the process of $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ even though the initial states $e^+e^-$ un-polarized [1]. The polarization is highly depend on polar angle of Λ:

$$ P_n = \frac{sin2\theta_\Lambda/\sqrt{T}}{(1 + cos^2\theta_\Lambda) + R^2(1 - cos^2\theta_\Lambda)} R sin\Delta\phi $$ (5)

where $\Delta\phi$ is the relative phase and $R$ is the ratio $|G_E/G_M|$ of Λ. Thanks to the self-analyzing
weak decay, \( \Lambda \rightarrow p\pi^- \), the proton from the \( \Lambda \) decay has a tendency to be emitted along the polarization axis of the \( \Lambda \). The differential cross section of the decay proton angle is given by

\[
\frac{d\sigma}{d\cos \theta_p} = \frac{1}{2}(1 + \alpha_\Lambda P_n \cos \theta_p)
\]

where \( \theta_p \) is the angle between the decay proton in the \( \Lambda \) frame and the polarization axis of the \( \Lambda \), \( \alpha_\Lambda \) is the asymmetry parameter. The polarization could be extracted by

\[
P_n = \frac{3}{\alpha_\Lambda} < \cos \theta_p >
\]

Since \( CP \) conservation implies that \( \alpha_\Lambda = -\alpha_\bar{\Lambda} \), the \( \Lambda \) sample and \( \bar{\Lambda} \) sample could be added together which means that the statistic can be increased by a factor of 2. The polarization should be measured as a function of \( \theta_\Lambda \) since the polarization depends on this angle, which is clear from Eq. 5.

The expected statistical uncertainties of the analysis of \( e^+e^- \rightarrow \Lambda\bar{\Lambda} \) with the BESIII scan data in 2015 range between 6% and 17%. The corresponding accuracies for the ratio of the \( \Lambda \) form factors range between 14% and 29%. Similar measurements might also be possible in other hyperons like \( e^+e^- \rightarrow \Lambda\Sigma^0, \Sigma^0\Sigma^0, \Sigma^+\Sigma^-, \Sigma^-\Sigma^+, \Xi^0\Xi^0 \).

5. Summary

BESIII is an excellent laboratory for the measurement of hadron form factors, since both ISR and scan method can be performed. We have results of proton form factors with scan data which was collected in the year of 2011 and 2012 published recently. There are also preliminary results on \( \Lambda \) form factors based on scan data from 2011 and 2012. In 2015, BESIII performed a unique high luminosity scan (\( \sim 555 \text{ pb}^{-1} \)) in the energy region from 2.0 GeV to 3.08 GeV, mainly in order to measure baryon form factors with higher precision. Measurements of baryon form factors by the ISR technique based on data above 3.77 GeV are on-going.

Reference

[1] A. Z. Dubnickova, S. Dubnicka and M. P. Rekalo, Nuovo Cim. A 109 241 (1996).
[2] A. Zichichi, S. M. Berman, N. Cabibbo and R. Gatto, Nuovo Cimento 24 170 (1962).
[3] C. Tzara, Nucl. Phys. B 18 216-252 (1970).
[4] G. Bonneau and F. Martin, Nucl. Phys. B 27 381 (1971).
[5] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 91, 112004 (2015).
[6] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Meth. A 614, 345 (2010).
[7] K. Chao and Y. Wang, Physics at BESIII, Modn. Phys. A Supplement, V 24, (2009), Scientific World.
[8] R. G. Ping, Chin. Phys. C 38, 083001 (2014).
[9] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 87, 092005 (2013); J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 88, 072009 (2013).
[10] T. A. Armstrong et al. (E760 Collaboration), Phys. Rev. Lett. 70, 1212 (1993).
[11] M. Ambrogiani et al. (E835 Collaboration), Phys. Rev. D 60, 032002 (1999); M. Andreotti et al., Phys. Lett. B 559, 20 (2003).
[12] G. Bardin et al. (PS170 Collaboration), Nucl. Phys. B 411, 3 (1994).
[13] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 630, 14 (2005).
[14] T. K. Pedlar et al. (CLEO Collaboration) Phys. Rev. Lett. 95, 261803 (2005).
[15] A. Antonelli et al. (FENICE Collaboration), Nucl. Phys. B 517, 3 (1998).
[16] N. Achasov et al. (SND Collaboration), Phys. Rev. D 90, 112007 (2014).
[17] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 76, 092006 (2007).