IL NUOVO CIMENTO **42 C** (2019) 111
DOI 10.1393/ncc/i2019-19111-1

Colloquia: EuNPC 2018

Baryon time-like form factors at BESIII

M. Bertani on behalf of the BESIII Collaboration
INFN Laboratori Nazionali di Frascati - Frascati, Italy

received 5 February 2019

Summary. — The BESIII experiment, operating at the Beijing e^+e^- collider BEPCII, has collected large data sets at center-of-mass energies between 2.0 and 4.6 GeV allowing the measurement of baryon electromagnetic form factors in the time-like region employing different experimental techniques. An overview of the BESIII results on proton, hyperon form factors are presented together with future perspectives.

1. – Introduction

Electromagnetic form factors (EMFF) are fundamental quantities which describe the modification of the point-like photon-hadron vertex due to the structure of hadrons, therefore they provide information on the intrinsic electric and magnetic distribution of the hadrons. The structure of a non point like particle of spin S is parametrized by (2S+1) form factors. The two EMFF of a baryon B, spin 1/2 particle, can be measured in the time-like region through the annihilation reaction $e^+e^- \leftrightarrow B\bar{B}$ using the energy scan technique: the c.m. energy $(\sqrt{s})$ is varied systematically, and at each energy point a measurement of the associated cross section is carried out. In the Born approximation the differential cross section for the annihilation reaction $e^+e^- \to B\bar{B}$ is expressed as a function of the baryon EMFF $|G_E|$ and $|G_M|$as [1]:

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

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

where α is the electromagnetic coupling constant, θ (M) is the scattering angle (the mass) of the baryon. The Coulomb factor C makes the cross section non zero at threshold [2], it is expressed as the product between the enhacement factor ε and a resummation term R, i.e.the so called Sommerfeld-Shwinger-Sakharov rescattering formula. In the limit $\beta \to 0$

the Coulomb factor behaves like the enhacement factor ε so that the factor β is cancelled and the cross section at threshold becomes finite. It is assumed that the interaction between baryons and leptons occurs through the exchange of a virtual photon carrying a momentum transfer squared q^2.

The measurement of the differential cross section, eq.(1) at a fixed energy allows the determination of the form factors ratio $R = |G_E|/|G_M|$. The quantity usually measured when the angular distribution cannot be precisely studied due to low statistics, is the effective form factor G_{eff}, a linear combination of $|G_E|^2$ and $|G_M|^2$.

The total cross section, integrated over the full range of polar angle θ and G_{eff} are:

$$\sigma(q^2) = \frac{2\pi\alpha^2\beta C}{3q^2\tau}(2\tau|G_M|^2 + |G_E|^2), G_{eff} = \sqrt{\frac{2\tau|G_M|^2 + |G_E|^2}{2\tau + 1}} \tag{2}$$

The e^+e^- annihilation at high energies is often accompanied by the emission of one or several photons from the Initial State Radiation (ISR), thus allowing the reduction of the invariant mass of the baryon-antibaryon system and hence the measurement of the baryon form factors over a wide range of q^2 below $\sqrt{s}$. Depending on the energy of the ISR photon the hadronic mass of 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.

2. – The BESIII detector

The BESIII detector [3] is a magnetic spectrometer located at the Beijing Electron-Positron Collider (BEPCII). The cylindrical-shaped detector has a geometrical acceptance of 93% of the full solid angle and has four main components: a small-cell, helium-based (60% He, 40% C_3H_8) main drift chamber (MDC), a time-of-flight system (TOF) based on 5-cm-thick plastic scintillators, an electromagnetic CsI(Tl) calorimeter (EMC) and the muon counter (MUC) based on Resistive Plate Chambers. BESIII is providing the world's largest data sample of e^+e^- collisions in the τ-charm region.

3. – Measurement of the Proton Form Factors

A first data set for the measurement of $e^+e^- \to p\bar{p}$ was taken in 2012 corresponding to 156.9 pb^{-1} at 12 c.m. energy values between 2.2 and 3.7 GeV [4]. A world leading data sample between 2.0 nd 3.08 GeV was then collected in 2015 at 16 c.m. energy points corresponding to a luminosity of 688.5 pb^{-1}, allowing a great improvement in the precision of previous measurements.

The Born cross section is determined for each energy point by:

$$\sigma_{born} = \frac{N_{obs} - N_{bck}}{L\varepsilon(1+\delta)} \tag{3}$$

where N_{obs} is the number of selected events, N_{bck} is the estimated number of background events, L is the integrated luminosity determined at each c.m. energy, ε is the detection efficiency of the signal and $(1+\delta)$ is the radiative correction function calcolated using CONEXC event generator [5]. The corresponding effective form factor of the proton is extracted from the measured cross section using eq.(2). The results from 2012 data [4] and the preliminary results from 2015 data are shown in fig.1 for $\sigma_{p\bar{p}}$ and G_{eff}.

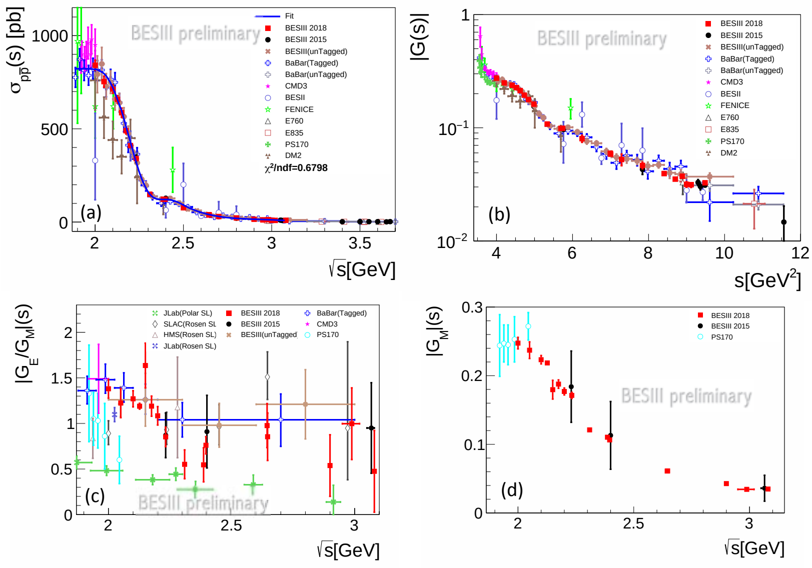

Fig. 1. – Preliminary results from BESIII including statistical and systematic uncertainties, together with other existing measurements, for (a) the $e^+e^- \to p\bar{p}$ cross section; (b) the effective proton form factor, (c) $R = |G_E/G_M|$ of the proton; (d) the magnetic FF of the proton $|G_M|$.

For the first time in the time-like region the precision in the cross section and effective form factor is dominated by systematic uncertainty for most scan points at low and medium energy, thus providing improvement in the resolution of the measurement. The best accuracy is between 3% and 4.2% at lower energy points, less then 1.7% at higher energy. For both the cross section and the form factor there is good agreement with existing measurements.

The form factor ratio $R = |G_E/G_M|$ is extracted from the fit to the distribution of the proton polar angle at several $\sqrt{s}$ values, R is compatible with unity and consistent with BABAR data in the same energy region. The absolute value of G_M was also measured for the first time (fig.1) over a wide energy range. Precision for both R and G_M is greatly improved with respect to previous measurements.

High statistics data samples at c.m. energies at and above the peak of $\psi(3770)$ resonance have been exploited to study the proton EMFF using the ISR technique: $e^+e^- \to p\bar{p}\gamma$. A data set of 7.4 fb^{-1} at $\sqrt{s} = 3.773$ GeV and 4.6 GeV has been analyzed using both the tagged and untagged ISR methods. In the tagged method the proton and antiproton system have to be detected togeher with the ISR photon in the BESIII apparatus. On the other hand in the untagged method only the proton and anti-proton are detected in the apparatus while the ISR photon escapes detection being emitted along the beam axis. BESIII has preliminary results on the untagged method while the tagged analysis is being reviewed. The untagged analysis requires two oppositely charged tracks being identified as protons, the missing momentum of the $p\bar{p}$ system is required to have a small polar angle assuming it is due to a photon escaping detection along the beam pipe. Correspondingly, the candidate events must yield a small missing mass. In this

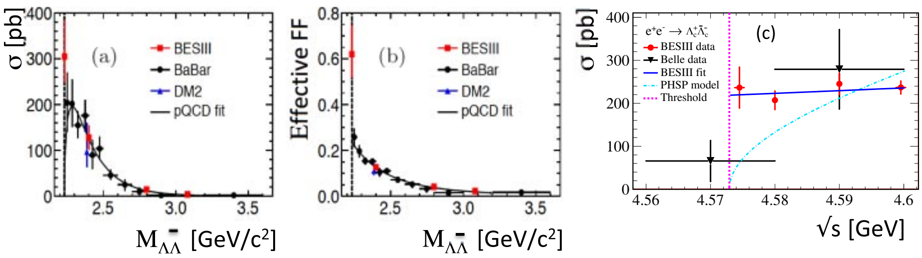

Fig. 2. – Results from BESIII for $e^+e^- \to \Lambda\bar{\Lambda}$ cross section (a), Λ effective form factor (b), the $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ cross section (c).

way the Born cross section of $e^+e^- \to p\bar{p}$ and the effective EMFF can be investigated in 30 bins from $\sqrt{s} = 2.0$ to 3.0 GeV. The preliminary results for the untagged ISR method are shown in fig.1 together with the scan results. They are consistent with each other and with BABAR results. The accuracy is competitive with previuos measurements.

4. – Hyperon form factors at BESIII

4·1. *Measurement of* Λ_c *Form Factor*. – The c.m. energy region accessible to BESIII barely allows the study of the threshold region of the charmed hyperon Λ_c through the reaction $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ at four c.m. energies: $\sqrt{s} = 4.5745, 4.580, 4.590, 4.5995$ GeV [6]. The hyperons are reconstructed from ten Cabibbo-favoured decay modes and the cross sections are determined as the weighted avarage of the individual decay modes obtained in the analysis. The results for the cross section [6] are reported in fig.2(c): as it can be seen there is tension between the result obtained by BELLE [7] and the BESIII one. While the BELLE measurement is compatible with a vanishing cross section, BESIII result suggests a plateau in the cross section and a not vanishing value at threshold. The BELLE results, obtained by ISR technique, has a coarse binning and the lowest mass bin extends below the $\Lambda_c\bar{\Lambda}_c$ threshold which may distort the distribution. As a conclusion, more data with high precision are necessary to understand the charmed baryon production at threshold.

At $\sqrt{s} = 4.5745, 4.5995$ GeV the statistics is sufficient to determine the EMFF ratio R in an angular analysis of the differential cross section: $R = 1.14 \pm 0.14 \pm 0.07$ and $R = 1.23 \pm 0.05 \pm 0.03$ respectively. This is the first determination of the EMFF ratio for the charmed hyperon.

4·2. *Measurement of* Λ *Form Factor*. – The 2012 energy scan data has been usefull to study the Λ cross section and EMFF close to threshold: $\sqrt{s} = 2.2324, 2.4, 2.8, 3.08$ GeV, with the first data point being only 1 MeV above the $\Lambda\bar{\Lambda}$ production threshold. Hyperons are generally reconstructed from their decay to $p\pi$ but at threshold a different strategy is necessary since the low energy nucleons are stopped in the beam pipe. Therefore the decay mode $n\pi^0$ is exploited and the annihilation vertices of $\bar{p}$ and $\bar{n}$ at the beam pipe are used to tag the decay of the $\bar{\Lambda}$. The results for cross section and effective EMFF [8] are shown in fig.2(a), (b). In contrast with the expectation of a vanishing cross section at threshold, the BESIII result reveals a steep increase at threshold which hints a more complex underlying physics scenario, requiring further detailed studies of hyperon production. The points at higher energies are consistent with previous results with improved precision.

4·3. *Measurement of the relative phase of* Λ *Form Factor*. – As a part of the hyperon studies performed by BESIII, a 2015 data set of 66.9 pb^{-1} at $\sqrt{s} = 2.369$ GeV allows the determination of the EMFF ratio as well as the relative phase of the EMFF of the Λ. The hyperon pairs are exclusively reconstructed in the final state $e^+e^- \to \Lambda\bar{\Lambda} \to p\bar{p}\pi^+\pi^-$. The preliminary results of the exctracted cross section and EMFF are consistent with the BESIII result [8]. The EMFF ratio R and the relative phase $\Delta\Phi$ are determined following the approach suggested by Faldt and Kupsc [9] and the preliminary results are: $R = 0.94 \pm 0.16 \pm 0.03 \pm 0.02(\alpha_\Lambda)$ and $\Delta\Phi = 42^\circ \pm 16^\circ \pm 8^\circ \pm 6^\circ(\alpha_\Lambda)$, where the last uncertainty reflects the deviation of the recent determination of the Λ decay constant [10] from the PDG value [11]. A non-zero phase has polarization effect on the baryons: $P_y \propto \sin\Delta\Phi$. This is the first measurement ever of the relative phase of hyperon EMFF in the time-like region.

5. – Summary and prospects

BESIII is an excellent laboratory for the measurement of baryon EMFF since both ISR and scan energy methods can be exploited and the kinematical thresholds of the different baryon production are covered. The proton EMFF has been studied with unprecedented precision. The measurement of the EMFF of the hyperons Λ, Λ_c has been published and a preliminary result of the first measurement of the relative phase of Λ EMFF is available. New results on neutron form factors and of other hyperons will be available soon.

REFERENCES

[1] A.Zichichi *et al.*, *N.Cimento* **24**, 170 (1962).
[2] C.Tzara, *Nucl. Phys. B* **18**, 216-252 (1970).
[3] M. Abilikim *et al.* [BESIII Collaboration], *Nucl. Instru. Meth. A* **614**, 345 (2010).
[4] M.Ablikim *et al.* [BESIII Collaboration], *Phys.Rev. D* **91**, 112004 (2015).
[5] R.G.Ping, *Chin.Phys. C* **38**, 083001 (2014).
[6] M. Ablikim *et al.* [BESIII Collaboration], *Phys. Rev. Lett.* **120**, 132001 (2018).
[7] Pakhlova *et al.* [BELLE Collaboration], *Phys. Rev. Lett.* **101**, 17001(2008),0807.
[8] M. Ablikim *et al.* [BESIII Collaboration],*Phys. Rev. D* **97**, 032013 (2018).
[9] G.Faldt, A.Kupsc, *Phys.Lett B* **772**, 16 (2017), 1702.07288.
[10] M. Ablikim *et al.* [BESIII Collaboration] (2018), 1808.08917.
[11] C.Patrignani *et al.* [Particle Data Group], *Chin. Phys.C* **40** (2018), 170.00150.