Measurement of time-like baryon electromagnetic form factors in processes with initial state radiation

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Abstract. Initial state radiation processes can be effectively used to measure $e^+e^-$ annihilation at high luminosity storage rings, such as the $B-$factory PEP-II in Stanford and the tau-charm factory BEPC-II in Beijing. The BaBar Collaboration has measured with unprecedented accuracy the channels $e^+e^-\rightarrow pp, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0, \Lambda\Sigma^0$, produced with initial state radiation at $\sqrt{s}=10.6$ GeV. BES-III aims to collect a luminosity of $10 fb^{-1}$ at $\sqrt{s}=3.77$ GeV in the next years. The measurements of the baryon electromagnetic form factors published by BaBar are summarized here together with the expectations of BES-III for the same channels.

1. Introduction
Electromagnetic form factors (FFs) account for the non point-like structure of hadrons. The vertex operator $\Gamma^\mu(q)$ describing the hadronic current in the Feynman diagrams of Fig. 1 can be written in terms of the so called Dirac and Pauli FFs, $F_1$ and $F_2$:

$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_N} F_2(q^2),$$

with $m_N$ the mass of the nucleon $N$ or spin-1/2 baryon. The FFs are analytic functions of the momentum transfer $q^2$. They are real for the space-like (SL) region ($q^2<0$) and complex in the (time-like) TL region ($q^2>0$) for $q^2>4m^2_N$. The use of the so-called Sachs FFs has become conventional:

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m^2_N} F_2(q^2), \quad G_M(q^2) = F_1(q^2) + F_2(q^2),$$

with $G_E(0) = G_M(0)/\mu_N = 1$ and $\mu_N$ the nucleon magnetic moment. Form factors for $q^2<0$ are determined by elastic scattering of electrons from hadrons available as targets. Form factors for $q^2>0$ are measured in annihilation processes $e^+e^- \rightarrow NN$.

2. Initial State Radiation
The process of $e^+e^-$-annihilation can be accompanied by the emission of one or several photons from the initial state (ISR) giving rise to annihilations into a hadron pair $e^+e^- \rightarrow h^+h^-\gamma_{ISR}$. The following equation relates the differential cross section of $e^+e^- \rightarrow NN\gamma_{ISR}$ and the cross section of $e^+e^- \rightarrow NN$:

$$\frac{d\sigma_{e^+e^- \rightarrow NN\gamma_{ISR}}}{dq^2} = \frac{1}{s} \cdot W(s, x, \theta^\gamma_r) \cdot \sigma(q^2),$$

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where $q^2 = m^2$ is the momentum transfer of the virtual photon, $x = 2E^{*}_\gamma/\sqrt{s} = 1 - m^2/s$, $\sqrt{s}$ is the center of mass energy of the collider, and $E^{*}_\gamma$ and $\theta^{*}_\gamma$ are the energy and polar angle of the ISR photon in the $e^+e^-$ center of mass (c.m.). The radiator funtion $W(s, x, \theta^{*}_\gamma)$ [1], describes the probability of the ISR photon emission

$$W(s, x, \theta^{*}_\gamma) = \frac{\alpha}{\pi x} \left( \frac{2 - 2x + x^2}{\sin^2\theta^{*}_\gamma} - \frac{x^2}{2} \right),$$

with $\alpha$ the electromagnetic fine structure constant. This function favors the emission of the ISR photon at small c.m. polar angle and with low energy. The differential cross section of the annihilation process $e^+e^-\rightarrow N\overline{N}$ in c.m. reads [2]

$$\frac{d\sigma(q^2, \theta^{*}_N)}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2} \left[ (1 + \cos^2\theta^{*}_N)|G_M(q^2)|^2 + \frac{1}{\tau} \sin^2\theta^{*}_N |G_E(q^2)|^2 \right],$$

where $\theta^{*}_N$ is the polar angle of the nucleon in c.m., $\tau = 4m^2/q^2$, $\beta = \sqrt{1-1/\tau}$, $C = y/(1 - \exp(-y))$, $y = \pi\alpha/\beta$ and the Coulomb factor $C$ accounts for the electromagnetic $N\overline{N}$ interactions [3]. Angular integration of the previous equation gives the total cross section:

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

From the measurement of $q^2 = m^2$ for the process $e^+e^-\rightarrow N\overline{N}$ with ISR. Eq. 5 and Eq. 6 for the process $e^+e^-\rightarrow N\overline{N}$ can be extracted for the $q^2$ range starting from the $N\overline{N}$ threshold $4m_N^2$, and up to $\sqrt{s}$. The analysis of the angular differential cross section of Eq. 5 allows the independent extraction of $G_E$ and $G_M$ for different momentum transfers in a single experiment. The rate for ISR production of a given channel is suppressed by at least a factor $\alpha/\pi$ with respect to the cross section without ISR photon (Eq. 3). However, this loss of cross section is compensated in high luminosity experiments like BaBar [4] and BES-III [5], located in $e^+e^-$ storage rings.

**3. Tagged and untagged ISR measurements in BaBar and BES-III**

There are two approaches for studying ISR events. In the first approach, the untagged one, the ISR photon is not detected, but all the final hadrons must be detected and fully reconstructed. In the second approach, the tagged one, the ISR photon and the hadrons must be detected and fully reconstructed. Since the differential cross section for ISR events increases significantly for photons with small $\theta^{*}_\gamma$ (Eq. 4), the untagged approach offers much larger statistics than the tagged one. The fact that the ISR photon in BES-III is much less energetic than in BaBar for the hadronic invariant masses of interest, opens up the possibility for untagged measurements.
in BES-III. This is not possible for BaBar, where the hadrons of the final state are highly boosted in the opposite direction to the ISR photon and can only reach the detector if the ISR photon also does. Fig. 2 shows the expected BES-III statistics for the $p\bar{p}$ and $n\pi$ ISR channels (sum of tagged and untagged events). Fig. 3 shows the corresponding statistics for the $\Lambda\bar{\Lambda}$ ISR channel. An integrated luminosity of 10 fb$^{-1}$ and $\sqrt{s} = 3.77$ GeV has been assumed here. For comparison, the event yield for the BaBar $p\bar{p}$ and $\Lambda\bar{\Lambda}$ ISR channels (only tagged events) for an integrated luminosity of 232 fb$^{-1}$ and $\sqrt{s} = 10.6$ GeV is shown as well. The Phokhara event generator [6, 7] was used for these simulations and the geometrical acceptance in the c.m. polar angle of the detectors used was $22^{\circ} < \theta < 137^{\circ}$ for the hadrons and the ISR photon in BES-III, and $47^{\circ} < \theta^* < 157^{\circ}$ for the hadrons and $40^{\circ} < \theta^* < 157^{\circ}$ for the ISR photon in BaBar.

4. BaBar measurement of $e^+e^- \rightarrow p\bar{p}$ via ISR

BaBar analyzed a data sample corresponding to 232 fb$^{-1}$ from which 4025 $e^+e^- \rightarrow p\bar{p}$ events were selected [8]. Events were tagged by detecting a photon radiated at polar angle $22^{\circ} < \theta < 137^{\circ}$ in the laboratory frame. After all selection criteria, a background contamination of about 5% for $m_{p\bar{p}} < 2.5$ GeV/c$^2$, increasing with $m_{p\bar{p}}$ and consistent with 100% above 4.5 GeV/c$^2$ was estimated. The main background source were $e^+e^- \rightarrow p\bar{p}n^0$ events with a soft photon lost or two overlapping $\gamma$. From the measurement of $\sigma(e^+e^- \rightarrow p\bar{p})$, the effective FF defined as:

$$|F(q^2)|^2 = \frac{2\tau |G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau + 1}$$  \hspace{1cm} (7)$$

was extracted. This effective FF can be directly compared to previous measurements of $|G_M(q^2)|$, all obtained under the working hypothesis that $|G_E(q^2)| = |G_M(q^2)|$ (Fig. 4). A general consistency among all these data was observed. In particular the precise data by BaBar and by the PS170 experiment at LEAR [9], show a similar rise of the effective FF when the energy approaches the $p\bar{p}$ threshold. There are several possible explanations for this feature [10, 11, 12, 13]. A similar behavior has been observed in $m_{p\bar{p}}$ in other processes with different dynamics [14, 15, 16, 17, 18]. The dashed line in Fig. 4 is the result of a QCD inspired fit [19]. The fit curve is about a factor 2 higher than the corresponding curve in the SL region, while QCD and analyticity predict that asymptotically $|G_E^0(q^2)| = |G_E^0(-q^2)|$. 

![Figure 2. Expected yield of $p\bar{p}$ (red) and $n\pi$ (black) ISR events in BES-III and of $p\bar{p}$ ISR events in BaBar (blue).](image1)

![Figure 3. Expected yield of $\Lambda\bar{\Lambda}$ ISR events in BES-III (red) and in BaBar (blue).](image2)
The ratio of electric to magnetic form factor was extracted from the analysis of the distribution of the proton helicity angle in the \( p\bar{p} \) rest frame. The mass region from \( p\bar{p} \) threshold up to 3 GeV/\( c^2 \) was divided in six intervals. For each one of these bins, BaBar measured values of \( |G_E/G_M| \) greater than unity, in disagreement with the previous results from experiment PS170 (Fig 5). The PS170 data had a non complete angular acceptance and strong angular dependence of the detection efficiency. In the same figure, the expectations for the expected BES-III statistics under the assumption that \( G_E/G_M = 1 \) are also shown.

5. BaBar measurements of strange-baryon form factors via ISR

BaBar measured the production via ISR of the following strange baryon pairs: \( e^+e^- \rightarrow \Lambda\bar{\Lambda}, \Sigma^+\Sigma^0, \Lambda\Sigma^0(\Sigma^0\bar{\Lambda}) \) by tagging the ISR photon [20]. Fig. 6 shows a summary of the strange-baryon effective FFs measured by BaBar. It is seen that the \( \Lambda, \Sigma^0, \) and \( \Sigma^0\Lambda \) FFs are of the same order. The same figure reports, by comparison, the effective proton FF measured by BaBar. A fit to the \( \Lambda \) FF with the power-law function \( F(Q^2) \sim Q^{-n} \) returned \( n \approx 9 \), showing that the asymptotic regime \( n = 4 \) predicted by perturbative-QCD is not reached in the energy range below 3 GeV. The ratio \( |G_{E(\Lambda)}/G_{M(\Lambda)}| \) was measured from the angular distribution of the produced \( \Lambda \) in the \( \Lambda\bar{\Lambda} \) channel for two different mass intervals. The results are shown in Fig. 7 together with BES-III expectations for this channel. The values are consistent with unity within large errors. BaBar also tried to extract the relative phase \( \Phi \), between \( G_{E(\Lambda)} \) and \( G_{M(\Lambda)} \) by measuring the polarization of the outgoing \( \Lambda \), perpendicular to the scattering plane of the \( e^+e^- \) process. Under the assumption \( |G_{E(\Lambda)}| = |G_{M(\Lambda)}| \), the measured lambda polarization was translated in an interval for the relative phase between the two FFs: \(-0.76 < \sin\Phi < 0.98\).

6. Prospects for time-like baryon FFs measurements in BES-III

The BEPC-II accelerator is designed to have the highest instantaneous luminosity on the \( \Psi(3770) \) resonance. Peak luminosities of \( 6 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) have been achieved (\( \sim 60\% \) of design value). Background conditions appear to be optimal for data taken on the \( \Psi(3770) \) resonance, on which 2.9 fb\(^{-1}\) of integrated luminosity have already been taken and for which 10 fb\(^{-1}\) are expected in the coming years. Feasibility studies show, that the expected statistics at BES-III will be competitive with the existing BaBar measurements (see Figs. 5 and 6). A determination of the FFs of the neutron seems feasible as well at BES-III. The precision remains to be investigated.
7. Conclusions

Compared to the SL sector, where precision measurements of FFs have been achieved on the percent level, the data base of TL FFs is rather scarce. A major improvement has been achieved by introducing the initial state radiation technique at BaBar obtaining an effective proton form factor with unprecedented precision and covering a wide $q^2$ range. The BaBar result concerning the ratio of the proton electric to the magnetic FFs is still limited by statistical uncertainties, and it is in conflict with a previous measurement at PS170. It is expected, that BES-III improves the achieved accuracy of BaBar by a factor 3 to 4 in the proton and hyperons FFs by using also the ISR technique at the $\Psi(3770)$ resonance. Moreover, at the BEPC-II accelerator a new precision measurement of the time-like baryon FFs over a wide energy range between 2.0 to 4.5 GeV is foreseen [21]. From new facilities at Novosibirsk and FAIR/Darmstadt we can expect significantly improved results [22].

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