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FSR CORRECTIONS TO THE PROCESS $e^+e^- \to \bar{p}p\gamma$*

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Newly developed model of the nucleon form factors is described and the role of the final state emission in the reaction $e^+e^- \to \bar{p}p\gamma$ is discussed.

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1. Introduction

The nucleon electromagnetic form factors play an important role in our understanding of strong interactions at low energies and attract a lot of attention. A recent review of this subject can be found in [1]. One of the important sources of experimental information is the radiative return method advocated to be used in this context in [2] and the nucleon final states were added to Monte Carlo event generator PHOKHARA to help the form factor extractions from the data. With more and more accurate experiments, the radiative corrections including the photon emission from final charged nucleons and better modelling of the form factors are indespensible. This subject will be addressed in detail in [3] and here we give a short overview of the obtained results. In Section 2 we describe our notation and adopt a simple model nucleons form factors relaying on SU(2) isospin symmetry. In Section 3 we give some details about fits of the model to the experimental data. In Section 4 the impact of the final state radiation on the cross section for the process $e^+e^- \to \bar{p}p\gamma$ is shortly summarized.

2. Form factors

Within QED, the hadronic current has the following form

$$F_\mu = -ie\bar{v}(p_2)\left(F_1^N\left(Q^2\right)\gamma_\mu - \frac{F_2^N\left(Q^2\right)}{4m_N}[\gamma_\mu, \not{Q}]\right)u(p_1)\,, \qquad (1)$$

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where F_1 is a Dirac form factor and F_2 is a Pauli form factor. It is convenient to express cross section and distribution for the process $e^+e^- \to \bar{p}p$ in terms of electric and magnetic Sachs form factors, which have the following form

$$G_{\mathrm{M}}^N = F_1^N + F_2^N \,, \qquad G_{\mathrm{E}}^N = F_1^N + \tau F_2^N \,, \tag{2}$$

where $\tau = Q^2/4m_N^2$.

Nucleons form factors can be decomposed into isoscalar (F_i^{s}) and isovector (F_i^{v}) contributions. One can write the Pauli and Dirac form factors in the following form

$$F_{1,2}^p = F_{1,2}^{\mathrm{s}} + F_{1,2}^{\mathrm{v}} \,, \qquad F_{1,2}^n = F_{1,2}^{\mathrm{s}} - F_{1,2}^{\mathrm{v}} \,. \tag{3}$$

We assume here, for simplicity, an exact SU(2) isospin symmetry, thus no contributions coming from particles containing s-quarks are considered.

We have modelled the isovector and isoscalar contributions using Breit–Wigner functions with constant widths as propagators and assume complex couplings, which partly take into account final states interactions. To fulfil the theoretical constraints and fit the experimental data, it was necessary to consider four radial excitations. We have fixed the masses and widths at the PDG [4] values. Considered contributions have the following form

$$F_1^{\mathrm{s}} = \frac{1}{2}\frac{\sum_{n=0}^{3} c_n^1 \mathrm{BW}_{\omega_n}(s)}{\sum_{n=0}^{3} c_n^1} \,, \tag{4}$$

$$F_1^{\mathrm{v}} = \frac{1}{2}\frac{\sum_{n=0}^{3} c_n^2 \mathrm{BW}_{\rho_n}(s)}{\sum_{n=0}^{3} c_n^2} \,, \tag{5}$$

$$F_2^{\mathrm{s}} = -\frac{1}{2}b\frac{\sum_{n=0}^{3} c_n^3 \mathrm{BW}_{\omega_n}(s)}{\sum_{n=0}^{3} c_n^3} \,, \tag{6}$$

$$F_2^{\mathrm{v}} = \frac{1}{2}a\frac{\sum_{n=0}^{3} c_n^4 \mathrm{BW}_{\rho_n}(s)}{\sum_{n=0}^{3} c_n^4} \,, \tag{7}$$

$$\tag{8}$$

where the Breit–Wigner function is defined as

$$\mathrm{BW}_i = \frac{m_i^2}{m_i^2 - s - i m_i \Gamma_i} \,. \tag{9}$$

Parameters a and b come from the normalization of the electric and magnetic form factors in the limit of $s = 0$ to electric charges and magnetic moments of nucleons, and read

$$a = \mu_p - \mu_n - 1 \,, \tag{10}$$

$$b = -\mu_p - \mu_n + 1 \,. \tag{11}$$

We have imposed the asymptotic (large s) behaviour of the form factors to fulfil the QCD predicted [5] power laws

$$F_1(s) \sim \frac{1}{(s)^2}\,, \qquad F_2(s) \sim \frac{1}{(s)^3}\,. \tag{12}$$

This gives relations between the couplings and only twelve parameters survive to be determined using experimental data.

3. Fits of the theoretical model to experimental data

The free parameters were determined by fits to the measured observables. This fit was done for all available experimental data including the cross section for the process $e^+e^- \to \bar{N}N$, where N denote nucleons as well as the inverse process. We have used also the data for the ratio of electric and magnetic form factors in the space-like and time-like regions, and also the form factors extracted in the space-like region. The experiments are listed in Table I.

TABLE I

Values of the chi-squared distribution and number of measured points for particular experiments.

Experiment	Type	Number of points	chi-squared value
BaBar [6]	cross section $e^+e^- \to p\bar{p}$	38	39.69
FENICE [7]	cross section $e^+e^- \to p\bar{p}$	5	4.42
DM2 [8]	cross section $e^+e^- \to p\bar{p}$	7	24.52
DM1 [9]	cross section $e^+e^- \to p\bar{p}$	4	1.23
Adone [10]	cross section $e^+e^- \to p\bar{p}$	1	0.46
BES [11]	cross section $e^+e^- \to p\bar{p}$	8	13.58
CLEO [12]	cross section $e^+e^- \to p\bar{p}$	1	0.127
JLab 2005 [13]	proton ratio	10	18.47
JLab 2002 [14]	proton ratio	4	5.32
JLab 2001 [15]	proton ratio	13	9.52
MAMI [16]	proton ratio	3	2.08
JLab 2010 [17]	proton ratio	3	3.63
PS 170 [18]	proton ratio	5	5.98
BaBar [6]	proton ratio	6	22.27
PS170 [19]	cross section $p\bar{p} \to e^+e^-$	8	8.07
PS170 [20]	cross section $p\bar{p} \to e^+e^-$	3	1.8
E760 [21]	cross section $p\bar{p} \to e^+e^-$	3	1.05
E835 [22]	cross section $p\bar{p} \to e^+e^-$	5	3.51
E835 [23]	cross section $p\bar{p} \to e^+e^-$	2	0.08
JLab [24]	neutron ratio	3	3.64
BLAST [25]	neutron ratio	4	6.07
FENICE [7]	cross section $e^+e^- \to n\bar{n}$	4	15.26

The χ^2 values are also given in this table showing good, but not excellent agreement of the considered model with the data. We show here two plots only. First of them is cross section for the process $e^+e^- \to \bar{p}p$ as a function of $\sqrt{s}$ shown in figure 1. Measured values of considered cross section are presented as points with error bars. Solid/blue line represents fitted value of mentioned cross section. For this observable, the theoretical model is able to reproduce the data with the exception of DM2 experiment, where for the 7 experimental points, the full chi-squared value is equal 24.52. Ratio of the electric and magnetic form factors in the space-like region for proton is shown in figure 2. Measured values of this ratio are presented as points with error bars. The solid/blue line represent fitted value of considered ratio. For the data for the process $\bar{p}p \to e^+e^-$ overall value of chi-squared is very small and this data were fitted perfectly. In the case of the ratio of electric and magnetic form factors in the time-like region, the chi-squared value is quite big. This observable was measured by two experiments PS170 and BaBar, which are evidently inconsistent thus the wrong fit. When we have finished our fits, the new data from the experiment BaBar emerged and we have checked that the considered model of the nucleons form factor do not reproduce well the data. An extension of the presented model considering also ϕ-meson contributions to the nucleons form factors is required to fit this data appropriately [3].

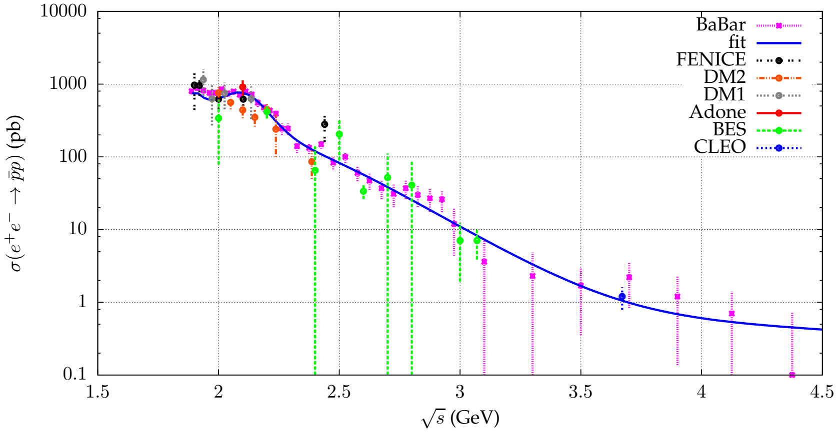

Fig. 1. Measured and fitted cross section for the process $e^+e^- \to \bar{p}p$.

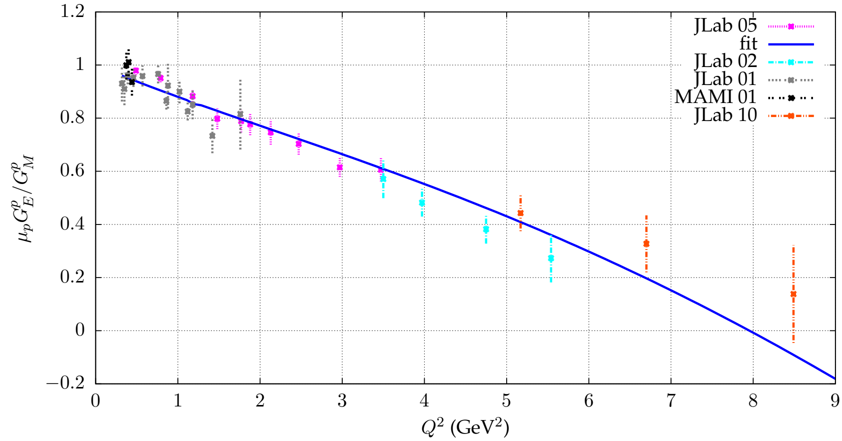

Fig. 2. Measured and fitted ratio of electric and magnetic form factors in space-like region.

4. FSR radiative corrections

We have investigated the impact of the final state radiation on cross section for the process $e^+e^- \to \bar{p}p\gamma$. The model of the form factor which is described in previous sections was used in this studies. Implementation of the final state radiation for the proton and antiproton channel was done in the same way as it was done for muons in [26]. Calculated differential cross section includes also the Columb factor. Relative difference between the

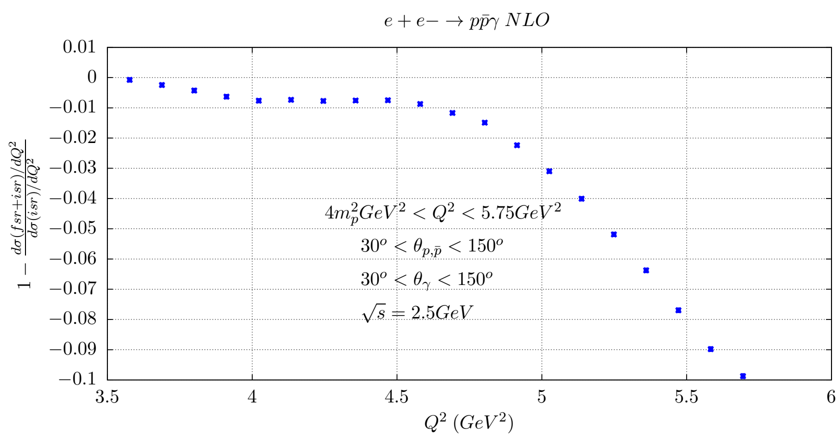

Fig. 3. Relative difference between the differential cross section which includes FSR and ISR and which includes only ISR.

differential cross section, as a function of proton–anti-proton pair invariant mass (Q^2), which includes only ISR and which includes ISR and FSR is shown in figure 3 for energy $\sqrt{s} = 2.5$ GeV. We have used here following angular cuts on photon, proton and antiproton $30^\circ < \theta_\gamma < 150^\circ$. The influence of the final state radiation depends on value of Q^2. For small Q^2, the contribution of the FSR is smaller than 1%, while for large Q^2, can grow up to 10%. A detailed studies of final state radiation will be presented in [3].

5. Conclusions

A new model of the nucleons form factors was developed fitting all data but the newly published very accurate BaBar data in the time-like region. The final state radiation from protons was considered, which gives up to 10% contribution to the radiative return cross section in the region large proton–anti-proton pair invariant masses.

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