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Unexpected features of $e^+e^- \to p\overline{p}$ and $e^+e^- \to \Lambda\overline{\Lambda}$ cross-sections near threshold

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Abstract. Unexpected features of the BaBar data on $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$ cross-sections ($\mathcal{B}$ stands for baryon) are discussed. These data have been collected, with unprecedented accuracy, by means of the initial-state radiation technique, which is particularly suitable in giving good acceptance and energy resolution at threshold. A striking feature observed in the BaBar data is the non-vanishing cross-section at threshold for all these processes. This is the expectation due to the Coulomb enhancement factor acting on a charged fermion pair. In the case of $e^+e^- \to p\overline{p}$ it is found that Coulomb final-state interactions largely dominate the cross-section and the form factor is $|G^p(4M_p^2)| \sim 1$, which could be a general feature for baryons. In the case of neutral baryons an interpretation of the non-vanishing cross-section at threshold is suggested, based on quark electromagnetic interaction and taking into account the asymmetry between attractive and repulsive Coulomb factors. Besides strange baryon cross-sections are compared to U-spin invariance predictions.

PACS. 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 13.40.Gp Electromagnetic form factors – 13.40.Ks Electromagnetic corrections to strong- and weak-interaction processes

1 $\sigma(e^+e^- \to \mathcal{B}\overline{\mathcal{B}})$ at threshold

The significance of baryon time-like form factors (FF) has been pointed out and looked for in $p\overline{p} \to e^+e^-$ a long time ago [1]. However, only recently an exhaustive set of data has been achieved by BaBar, showing unexpected features even if in part predicted on the basis of fundamental principles. Space-like FF behaviors are also driven by basic principles as was anticipated [2, 3], but only after thirty years experimentally recognized [4]. Therefore baryon FFs are still a lively topical subject.

Unexpected features are pointed out in the following, concerning recent cross-section measurements of

$$e^+e^- \to p\overline{p}$$

and

$$e^+e^- \to \Lambda\overline{\Lambda},\ \Sigma^0\overline{\Sigma^0},\ \Lambda\overline{\Sigma^0}$$

in the corresponding threshold energy regions. BaBar has measured these cross-sections [5, 6] (fig. 1), with unprecedented accuracy, up to an invariant mass of the $\mathcal{B}\overline{\mathcal{B}}$ system: $W_{\mathcal{B}\overline{\mathcal{B}}} \sim 4\,\mathrm{GeV}$, by means of the initial-state radiation technique (ISR), in particular detecting the photon radiated by the incoming beams.

There are several advantages in measuring processes at threshold in this way:

- even exactly at the production energy the efficiency is quite high and, in case of charged particles collinearly produced, the detector magnetic field provides their separation;
- a very good invariant-mass resolution is achieved, $\Delta W_{p\overline{p}} \sim 1\,\mathrm{MeV}$, comparable to what is achieved in a symmetric storage ring;
- a full angular acceptance is also obtained, even at 0° and 180°, due to the detection of the radiated photon.

In Born approximation the differential cross-section for the process $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$ is

$$\frac{\mathrm{d}\sigma(e^+e^- \to \mathcal{B}\overline{\mathcal{B}})}{\mathrm{d}\Omega} = \frac{\alpha^2\beta C}{4W_{\mathcal{B}\overline{\mathcal{B}}}^2}\left[(1+\cos^2\theta)|G_M^{\mathcal{B}}(W_{\mathcal{B}\overline{\mathcal{B}}}^2)|^2 + \frac{4M_{\mathcal{B}}^2}{W_{\mathcal{B}\overline{\mathcal{B}}}^2}\sin^2\theta|G_E^{\mathcal{B}}(W_{\mathcal{B}\overline{\mathcal{B}}}^2)|^2\right], \qquad (1.1)$$

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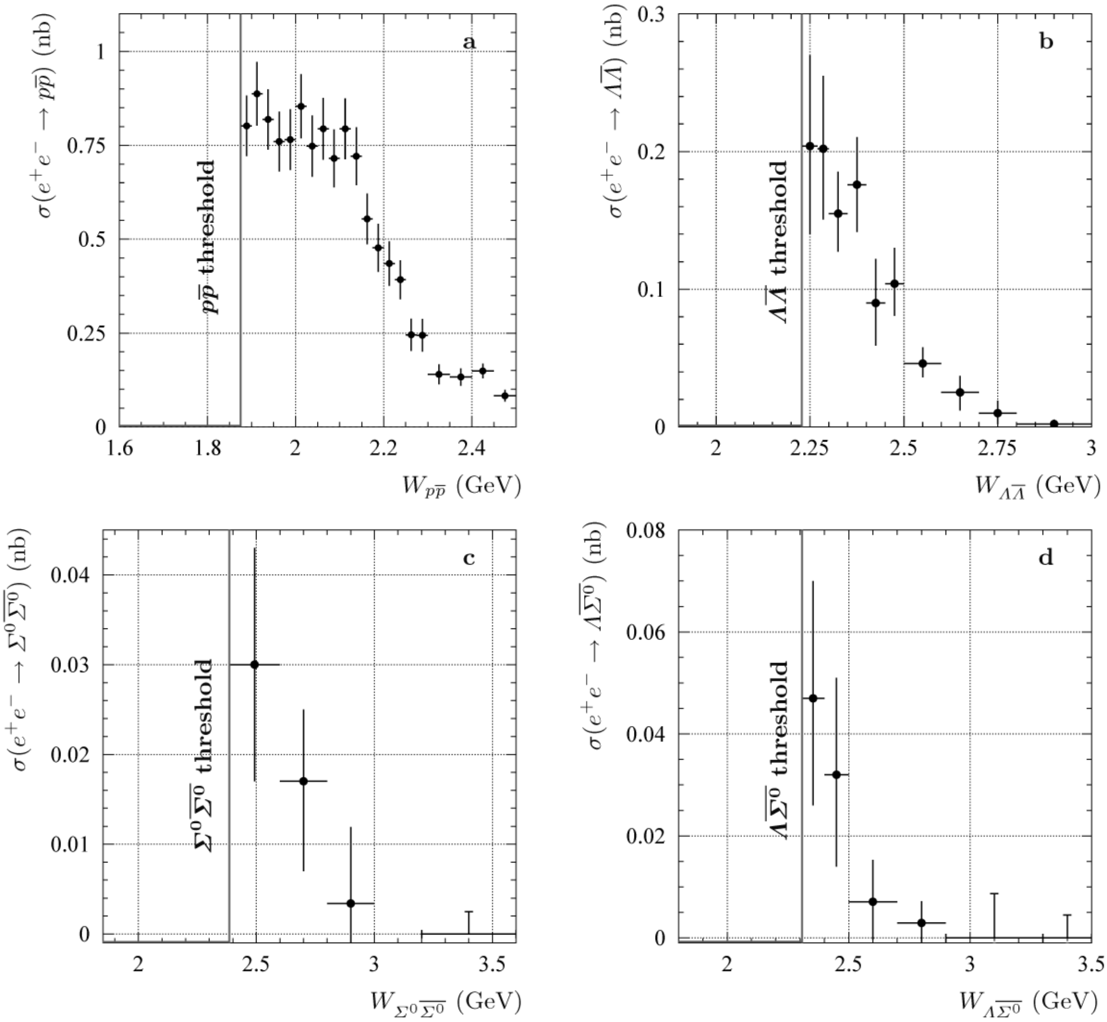

Fig. 1. $e^+e^- \to p\overline{p}$ (a), $e^+e^- \to \Lambda\overline{\Lambda}$ (b), $e^+e^- \to \Sigma^0\overline{\Sigma^0}$ (c), and $e^+e^- \to \Lambda\overline{\Sigma^0}$ (d) total cross-sections measured by the BaBar experiment [5,6]. The gray vertical lines indicate the production thresholds.

where $W_{\mathcal{B}\overline{\mathcal{B}}}$ is the $\mathcal{B}\overline{\mathcal{B}}$ invariant mass, β is the velocity of the outgoing baryon, C is a Coulomb enhancement factor, that will be discussed in more detail in the following, θ is the scattering angle in the center-of-mass (c.m.) frame and $G_M^{\mathcal{B}}$ and $G_E^{\mathcal{B}}$ are the magnetic and electric Sachs FFs. At threshold it is assumed that, according to the analyticity of the Dirac and Pauli FFs as well as the S-wave dominance, there is one FF only: $G_E^{\mathcal{B}}(4M_{\mathcal{B}}^2) = G_M^{\mathcal{B}}(4M_{\mathcal{B}}^2) \equiv G^{\mathcal{B}}(4M_{\mathcal{B}}^2)$.

The following peculiar features have been observed, in the case of $e^+e^- \to p\overline{p}$ [5]:

- as is shown in fig. 1a, the total cross-section $\sigma(e^+e^- \to p\overline{p})$ is suddenly different from zero at threshold, being 0.85 ± 0.05 nb (by the way it is the only endothermic process that has shown this peculiarity);
- data on $\sigma(e^+e^- \to p\overline{p})$ show a flat behavior, within the experimental errors, in an interval of about 200 MeV above the threshold and then drop abruptly;
- the angular distribution, averaged in a 100 MeV interval above the threshold, has a behavior like $\sin^2\theta$, *i.e.* dominated by the electric FF, and then a behavior like $(1 + \cos^2\theta)$, *i.e.* dominated by the magnetic FF (see eq. (1.1) and fig. 2).

Similar features have been observed by BaBar in the cases of $e^+e^- \to \Lambda\overline{\Lambda}$, $\Sigma^0\overline{\Sigma^0}$, $\Lambda\overline{\Sigma^0}$ [6] (fig. 1b, c, d), even if within much larger experimental errors, in particular, the cross-section $\sigma(e^+e^- \to \Lambda\overline{\Lambda})$ is different from zero at threshold, being 0.20 ± 0.05 nb.

Of course, extremely sharp rises from zero cannot be excluded and the relationship between data and predictions, reported in the following, could be accidental.

A long time ago it has been pointed out that final-state Coulomb corrections to the Born cross-section have to be taken into account in the case of point-like charged fermion pair production [8]. This Coulomb correction has been usually introduced as an enhancement factor, C in eq. (1.1). It corresponds to the squared value of the Coulomb scattering wave function at the origin, assumed as a good approximation in the case of a long-range interaction added to a short-range one, the so-called Sommerfeld-Schwinger-Sakharov

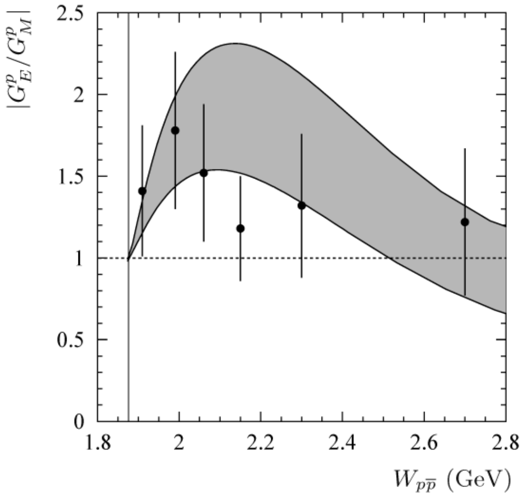

Fig. 2. BaBar data on the ratio $|G_E^p/G_M^p|$ extracted by studying the angular distribution of the $e^+e^- \to p\overline{p}$ differential cross-section (eq. (1.1)). The strip is a calculation [7] based on a dispersion relation relating these data and the space-like ratio, as recently achieved at JLAB and MIT-Bates [4].

rescattering formula [8,9]. This factor has a very weak dependence on the fermion pair total spin, hence it is the same for G_E and G_M and can be factorized. The Coulomb enhancement factor is

$$C(W_{\mathcal{B}\overline{\mathcal{B}}}) = \begin{cases} 1, & \text{for neutral } \mathcal{B}, \\ \dfrac{\pi\alpha/\beta}{1-e^{-\pi\alpha/\beta}}\,, & \text{for charged } \mathcal{B}, \end{cases} \qquad (1.2)$$

$$\beta = \sqrt{1-\frac{4M_{\mathcal{B}}^2}{W_{\mathcal{B}\overline{\mathcal{B}}}^2}}\,.$$

In ref. [10] a similar formula is obtained, but $1/\beta \to 1/\beta - 1$; however that does not affect the following considerations. Very near threshold the Coulomb factor is $C(W^2_{\mathcal{B}\overline{\mathcal{B}}} \to 4M^2_{\mathcal{B}}) \sim \pi\alpha/\beta$, so that the phase space factor β is cancelled and the cross-section is expected to be finite and not vanishing even exactly at threshold. However, as is shown in fig. 3, as soon as the fermion relative velocity is no more vanishing, actually few MeV above the threshold, it is $C \sim 1$ and Coulomb effects can be neglected.

In the case of $e^+e^- \to p\overline{p}$ the expected Coulomb-corrected cross-section at threshold is

$$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\cdot|G^p(4M_p^2)|^2 = 0.85\cdot|G^p(4M_p^2)|^2\,\text{nb},$$

in striking similarity with the measured one. Therefore Coulomb interaction dominates the energy region near threshold and it is found

$$|G^p(4M_p^2)| \sim 1.$$

In the following this feature is suggested to be a general one for baryons. It looks as if the FF at threshold, interpreted as $\mathcal{B}$ and $\overline{\mathcal{B}}$ wave function static overlap, coincides with the baryon wave function normalization, taking

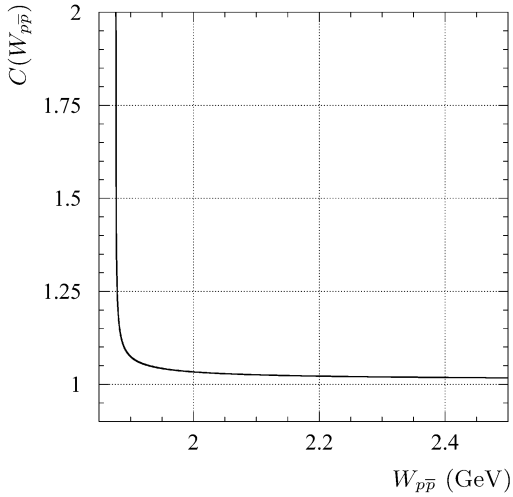

Fig. 3. Coulomb enhancement factor as a function of the $p\overline{p}$ c.m. energy from eq. (1.2).

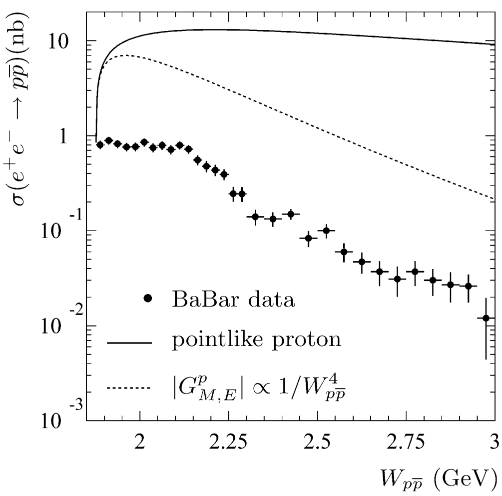

Fig. 4. BaBar cross-section $e^+e^- \to p\overline{p}$ in comparison with expected behaviors in case of pointlike protons (solid line) and assuming asymptotic FFs (dashed line).

into account that the S-wave is peculiar of fermion pairs at threshold. In the case of meson pairs total angular-momentum conservation requires a P-wave, that vanishes at the origin, hence this Coulomb enhancement factor too, and the cross-section has a β^3 behaviour near threshold. Tiny Coulomb effects in the case of meson pairs have been extensively pursued [11].

The reason why $\sigma(e^+e^- \to p\overline{p})$ is so flat above the threshold has to be explained as well as its following sharp drop. As a reference, in fig. 4, the cross-sections in the case of a pointlike proton (solid curve) and in the case of $|G^p_{M,E}| \propto 1/W^4_{p\overline{p}}$, *i.e.* $\sigma(e^+e^- \to p\overline{p}) \propto 1/W^{10}_{p\overline{p}}$ (dashed curve) are shown in comparison with the BaBar data. A non-trivially structured electric and magnetic FFs (eq. (1.1)) have to be included to get this cross-section. In particular the different behavior at threshold and the dominance of the electric FF are consistent with a sud-

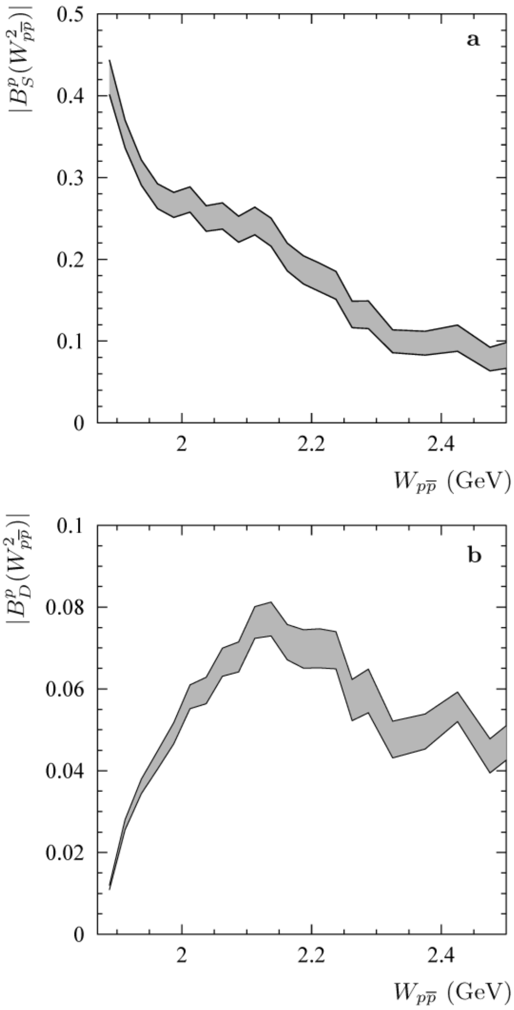

Fig. 5. S-wave (a) and D-wave (b) as extracted from ref. [7].

den and important D-wave contribution. In fact, angular momentum and parity conservation allow, in addition to the S-wave, also the D-wave contribution. Using the results of ref. [7], where the relative phase between G_E^p and G_M^p has been obtained by means of a dispersion relation applied to the space-like ratio G_E^p/G_M^p and to the BaBar time-like $|G_E^p/G_M^p|$ (fig. 2), the S- and D-wave complex FFs, B_S^p and B_D^p have been extracted. In terms of G_E^p and G_M^p they are:

$$B_S^p = (G_M^p W_{p\overline{p}}/M_p + G_E^p)/3,$$
$$B_D^p = (G_M^p W_{p\overline{p}}/2M_p - G_E^p)/3.$$

S-wave and D-wave opposite trends, as shown in fig. 5, produce the observed plateau.

2 An interpretation of $\sigma(\mathrm{e}^+\mathrm{e}^- \to \Lambda\overline{\Lambda})$ at the quark level

In the case of $e^+e^- \to \Lambda\overline{\Lambda}$, being Λ a neutral baryon, final-state Coulomb effects should not be taken into account and a finite cross-section at threshold is not expected. Nevertheless the $e^+e^- \to \Lambda\overline{\Lambda}$ cross-section data (fig. 1b) show a threshold behavior quite similar to that of $\sigma(e^+e^- \to p\overline{p})$ (fig. 1a), also the ratio $|G_E^\Lambda/G_M^\Lambda|$ (not shown) has a trend similar to $|G_E^p/G_M^p|$ (fig. 2).

Assuming that this Coulomb dominance is not a mere coincidence, one might investigate what is expected at the quark level. Valence quarks only are considered in the following. The baryon pair relative velocity is equal to the quark pair average relative velocity. The quark velocity spread inside the baryon should come mostly from the relative velocity among the different quark pairs. Hence for each pair there is a Coulomb attractive amplitude times the quark electric charge and each amplitude has a phase taking into account the displacement of the quark inside the baryon. In addition to the quark pair Coulomb interaction there are contributions from quarks belonging to different pairs. There are several suppression factors for them: relative phase, velocity spread and moreover most of them, coming from quarks having charges of the same sign, are repulsive ones. There is no symmetry between repulsive and attractive Coulomb interactions and this asymmetry might explain why there is a non-vanishing cross-section at threshold even for neutral baryon pairs. In fact in the case of the repulsive Coulomb interaction the Sommerfeld formula is (charges Q_q and $Q_{\overline{q}'}$ have the same sign):

$$C(W_{p\overline{p}}) = \frac{-\pi\alpha|Q_q Q_{\overline{q}'}|/\beta}{1-\exp(+\pi\alpha|Q_q Q_{\overline{q}'}|/\beta)} \xrightarrow[W_{p\overline{p}}^2 \to 4M_p^2]{} 0,$$

i.e. $C = 0$ at threshold. Therefore at the quark level, considering only Coulomb enhancement factors due to quark pairs, it is expected:

$$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}(2Q_u^2 + Q_d^2)\cdot|G^p(4M_p^2)|^2 = 0.85\cdot|G^p(4M^2)|^2\,\text{nb},$$

in the proton case, and

$$\sigma(e^+e^- \to \Lambda\overline{\Lambda})(4M_\Lambda^2) = \frac{\pi^2\alpha^3}{2M_\Lambda^2}(Q_u^2+Q_d^2+Q_s^2)\cdot|G^\Lambda(4M_\Lambda^2)|^2 = 0.4\cdot|G^\Lambda(4M_\Lambda^2)|\,\text{nb},$$

in the Λ baryon case.

The expectation for $e^+e^- \to p\overline{p}$, at quark level as well as at hadron level, is the same, namely the total cross-section is 0.85 nb (assuming $|G^p(4M_p^2)|^2 \sim 1$) to be compared to the experimental value: $\sigma(e^+e^- \to p\overline{p}) = 0.85 \pm 0.05$ nb at threshold. In the case of $e^+e^- \to \Lambda\overline{\Lambda}$ the expectation range is (0–0.4) nb (still assuming $|G^\Lambda(4M_\Lambda^2)| \sim 1$) to be compared to the experimental value at threshold: $\sigma(e^+e^- \to \Lambda\overline{\Lambda}) = 0.20 \pm 0.05$ nb.

3 Other baryon form factor measurements

The cross-sections $\sigma(e^+e^- \to \Sigma^0\overline{\Sigma^0})$ and $\sigma(e^+e^- \to \Lambda\overline{\Sigma^0})$ have been measured by the BaBar Collaboration for the first time [6], although with large errors. At threshold, assuming a smooth extrapolation from the first data point, it is $\sigma(e^+e^- \to \Sigma^0\overline{\Sigma^0}) = 0.03 \pm 0.01\,\text{nb}$ and $\sigma(e^+e^- \to \Lambda\overline{\Sigma^0}) = 0.047 \pm 0.023\,\text{nb}$. The expectation, according to U-spin symmetry and some additional hypotheses on the interaction Hamiltonian [12], is that Λ and Σ^0 have opposite (equal in modulus) magnetic moments as well as FFs at threshold, apart from mass corrections. Hence, on the basis of the $e^+e^- \to \Lambda\overline{\Lambda}$ cross-section it should be $\sigma(e^+e^- \to \Sigma^0\overline{\Sigma^0}) \sim \sigma(e^+e^- \to \Lambda\overline{\Lambda}) \cdot (M_\Lambda/M_{\Sigma^0})^2 \sim 0.18\,\text{nb}$, by far greater than the experimental one. Although at least the small mass difference among neutral strange baryons implies small corrections to U-spin conservation, full U-spin invariance should hold at enough high Q^2. A milder version of the U-spin invariance [13], obtained under the assumption of negligible electromagnetic transitions between U-spin triplet and singlet, like the photon, is explored in the following. Therefore, neglecting Λ and Σ^0 mass difference and extrapolating the magnetic-moment relations to the FFs at threshold, it should be:

$$G_{\Sigma^0} = G_\Lambda - \frac{2}{\sqrt{3}} G_{\Lambda\overline{\Sigma^0}}\,, \tag{3.1}$$

that is, assuming real FFs at threshold or no relative phase

$$\sigma_{\Sigma^0\overline{\Sigma^0}} = \left[\frac{M_\Lambda}{M_{\Sigma^0}}\sqrt{\sigma_{\Lambda\overline{\Lambda}}} - \frac{2}{\sqrt{3}}\frac{\overline{M_{\Lambda\overline{\Sigma^0}}}}{M_{\Sigma^0}}\sqrt{\sigma_{\Lambda\overline{\Sigma^0}}}\right]^2. \tag{3.2}$$

In terms of adimensional quantities, the previous relation can also be written as

$$M_{\Sigma^0}\sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}} - M_\Lambda\sqrt{\sigma_{\Lambda\overline{\Lambda}}} + \frac{2}{\sqrt{3}}\overline{M_{\Lambda\overline{\Sigma^0}}}\sqrt{\sigma_{\Lambda\overline{\Sigma^0}}} = 0.$$

Entering the BaBar results we get the following prediction for the $\sigma_{\Sigma^0\overline{\Sigma^0}}$ cross-section at threshold:

$$\sigma_{\Sigma^0\overline{\Sigma^0}} = \left[\frac{M_\Lambda}{M_{\Sigma^0}}\sqrt{\sigma_{\Lambda\overline{\Lambda}}} - \frac{2}{\sqrt{3}}\frac{\overline{M_{\Lambda\overline{\Sigma^0}}}}{M_{\Sigma^0}}\sqrt{\sigma_{\Lambda\overline{\Sigma^0}}}\right]^2 = 0.03 \pm 0.03\,\text{nb}. \tag{3.3}$$

This value, which is quite lower than the $\sigma_{\Lambda\overline{\Lambda}}$ cross-section, is consistent with the measured one. Using eq. (3.2) with the BaBar data for the cross-sections at threshold

$$M_{\Sigma^0}\sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}} - M_\Lambda\sqrt{\sigma_{\Lambda\overline{\Lambda}}} + \frac{2}{\sqrt{3}}\overline{M_{\Lambda\overline{\Sigma^0}}}\sqrt{\sigma_{\Lambda\overline{\Sigma^0}}} = (-0.1 \pm 2.0) \times 10^{-4}$$

still in agreement with the minimal U-spin invariance prediction, within the experimental error. The asymmetry between Λ and Σ^0 FFs with respect to the proton case can be settled assuming that a suitable combination is the one properly normalized.

The aforementioned experimental evidence, *i.e.* $e^+e^- \to p\overline{p}$ and $e^+e^- \to \Lambda\overline{\Lambda}$ are dominated by the Coulomb enhancement factor and remain almost constant even well above their threshold, has to be tested in the case of

$$e^+e^- \to \Sigma^+\overline{\Sigma^+}.$$

According to U-spin expectation it should be

$$\sigma(e^+e^- \to \Sigma^+\overline{\Sigma^+}) \sim \sigma(e^+e^- \to p\overline{p}) \cdot \left(\frac{M_p}{M_{\Sigma^+}}\right)^2 \sim 0.53\,\text{nb}.$$

This measurement has not yet been done, but it is within the BaBar or Belle capabilities by means of ISR.

Another important process to understand the nucleon structure is

$$e^+e^- \to n\overline{n}.$$

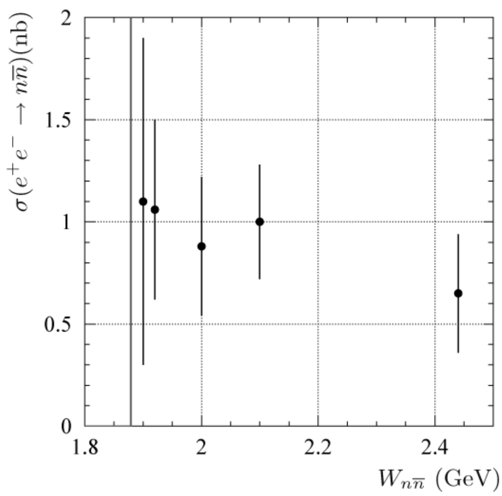

Fig. 6. The $e^+e^- \to n\overline{n}$ total cross-section as measured by the FENICE Collaboration [14]. The gray vertical line indicates the production threshold.

The cross-section $\sigma(e^+e^- \to n\overline{n})$ has been measured only once, long time ago by the FENICE experiment at the e^+e^- storage ring ADONE [14], that found above threshold $\sigma(e^+e^- \to n\overline{n}) \sim 1\,\text{nb}$, as shown in fig. 6. According to the above-mentioned minimal assumption on U-spin invariance it should be

$$G_n = \frac{3}{2}G_\Lambda - \frac{1}{2}G_{\Sigma^0}\,,$$

hence

$$\sigma(e^+e^- \to n\overline{n}) = \frac{1}{4}\left(3\sqrt{\sigma_{\Lambda\overline{\Lambda}}}M_\Lambda - \sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}}M_\Sigma\right)^2 \frac{1}{M_n^2} = 0.5 \pm 0.2\,\text{nb} \tag{3.4}$$

lower than the FENICE results, but not in contradiction because of their large errors.

Unfortunately it is very unlike that BaBar or Belle will ever be able to measure this process by means of ISR. However, BESIII at the τ/charm Factory in China and in part VEPP2000 in Russia can do that in the c.m. as well as by means of ISR at lower energies.

As mentioned before full U-spin symmetry in electromagnetic interactions of members of a $SU(3)$ flavor

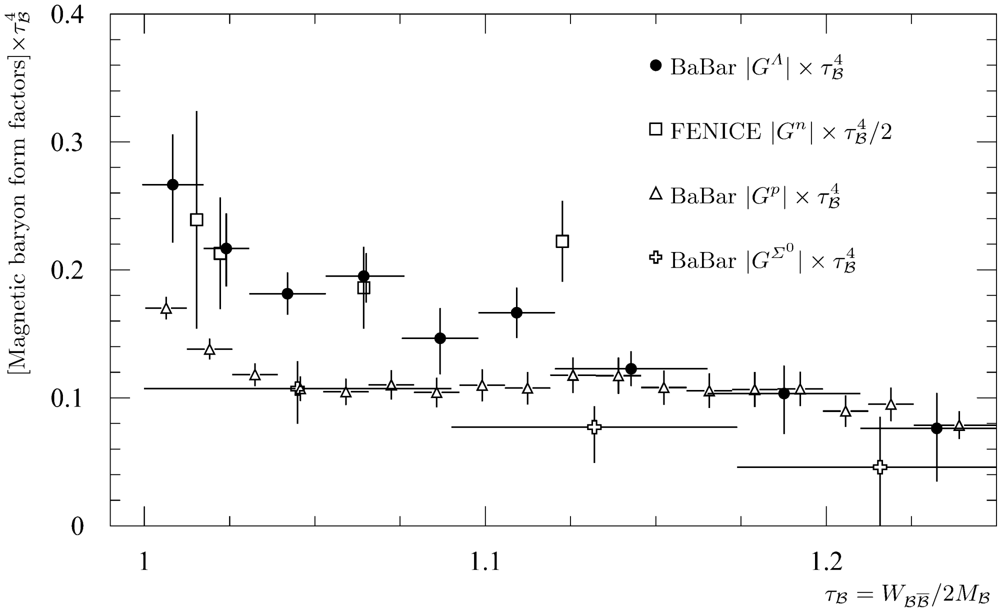

Fig. 7. Comparison among $|G^{\Lambda}|$, $|G^{\Sigma^0}|$, $|G^p|$ and $|G^n|/2$ scaled by the fourth power of the c.m. energy normalized to the mass of the final states: $\tau_{\mathcal{B}} = W_{\mathcal{B}\overline{\mathcal{B}}}/2M_{\mathcal{B}}$ ($\mathcal{B} = \Lambda$, Σ^0, n, p).

multiplet should hold at enough high energy, at least when strange and non-strange mass differences become negligible. In this limit it is predicted $G^{\Lambda} \sim -G^{\Sigma^0}$ and $G^{\Lambda} \sim 0.5\, G^n$, as already mentioned. In fig. 7 data on magnetic FFs, scaled by the fourth power of $\tau_{\mathcal{B}} = W_{\mathcal{B}\overline{\mathcal{B}}}/2M_{\mathcal{B}}$ are shown as a function of $\tau_{\mathcal{B}}$. Strange baryon FFs are obtained under the hypothesis $|G_E^{\mathcal{B}}| = |G_M^{\mathcal{B}}|$, that of the neutron assuming $|G_E^n| = 0$, while the proton magnetic FF, more properly, is achieved by means of dispersion relations using also the proton angular-distribution measurements. The data show a trend in agreement with the full U-spin symmetry predictions. By the way, Λ data and U-spin symmetry confirm the unexpected high cross-section $\sigma(e^+e^- \to n\overline{n})$, with respect to $\sigma(e^+e^- \to p\overline{p})$. However, data on both G^{Σ^0} and G^n are quite poor and much better measurements are demanded, in particular in the case of $e^+e^- \to n\overline{n}$. Various theoretical models and phenomenological descriptions make predictions on baryon time-like FF [15]. In particular the BaBar cross-section, angular distributions and $e^+e^- \to n\overline{n}$ cross-section have been reproduced, modeling final-state interactions by means of a suitable potential [16].

4 Conclusions

All the $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$ cross-sections, as measured by the BaBar Collaboration, do not vanish at threshold. In the case of $e^+e^- \to p\overline{p}$ this behavior is explained by the $p\overline{p}$ Coulomb enhancement factor and the form factor normalization: $|G^p(4M_p^2)| \sim 1$. This cross-section is remarkably flat near threshold; it turns out that S- and D-wave have opposite trends, producing this peculiar behavior. In the case of $e^+e^- \to \Lambda\overline{\Lambda}$, as well as $e^+e^- \to p\overline{p}$ the non-vanishing cross-section at threshold is consistent with a valence quark Coulomb enhancement factor. A framework concerning strange baryon FFs is obtained requiring the suppression of electromagnetic transitions between U-spin singlet and triplet. Neutron and Σ^+ FFs are demanded to check this new picture of baryon FFs.

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