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BABAR measurement of baryon time-like form factors via initial state radiation

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Abstract BABAR has measured with unprecedented accuracy the $e^+e^- \to p\overline{p}$ and $e^+e^- \to \Lambda\overline{\Lambda}$ cross sections by means of the initial state radiation technique, which has the advantages of good efficiency, good energy resolution and full angular acceptance, even exactly at threshold. A peculiar feature of these cross sections is their non-vanishing values at threshold. In the case of charged baryons, this phenomenon is expected according to the Coulomb interaction between the outgoing baryon and antibaryon. Once this Coulomb enhancement factor is taken into account, the striking result is achieved that the proton form factor at threshold is $|G^p(4M_p^2)| = 1$, that is what is expected for pointlike fermion pairs, in spite of the proton structure. However a Coulomb enhancement factor is not expected for neutral fermions, likely in contradiction with the BABAR data. Qualitatively this behaviour is consistent with Coulomb interactions at the valence quark level.

Key words baryon form factor, Initial state radiation, BABAR

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1 Introduction

Unexpected features [1] in the measurements of the $e^+e^- \to p\overline{p}$ and $e^+e^- \to \Lambda\overline{\Lambda}$ cross sections in the near threshold region are pointed out in the following. BABAR has measured these processes [2, 3] (Fig. 1), with unprecedented accuracy, from their thresholds up to $W_{\mathcal{B}\overline{\mathcal{B}}} \approx 3 \div 4$ GeV by means of the initial state radiation (ISR) technique ($W_{\mathcal{B}\overline{\mathcal{B}}}$ is the invariant mass of the baryon-antibaryon system and $\mathcal{B}$ stands for baryon).

The main advantages in measuring a two body process very near the threshold via ISR are, in the case of BABAR :

- an efficiency quite high (≈ 18%),
- a good invariant mass resolution (≈ 1 MeV),
- a full angular acceptance when the radiated photon is detected.

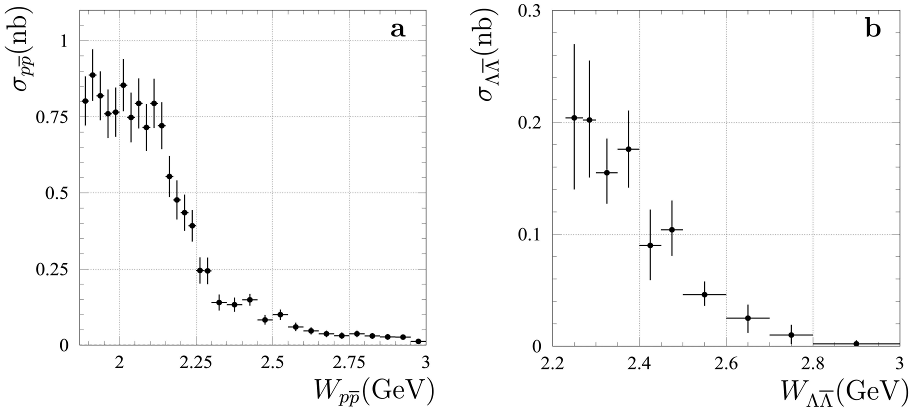

Fig. 1. The $e^+e^- \to p\overline{p}$ (a) and $e^+e^- \to \Lambda\overline{\Lambda}$ (b) total cross sections [2, 3].

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2 Interpretation of the data

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

$$\frac{d\sigma_{\mathcal{B}\overline{\mathcal{B}}}}{d\Omega}(W^2_{\mathcal{B}\overline{\mathcal{B}}}) = \frac{\alpha^2\beta C}{4W^2_{\mathcal{B}\overline{\mathcal{B}}}}\left[(1+\cos^2\theta)|G^{\mathcal{B}}_{\rm M}|^2 + 4M^2_{\mathcal{B}}/W^2_{\mathcal{B}\overline{\mathcal{B}}}\sin^2\theta|G^{\mathcal{B}}_{\rm E}|^2\right], \qquad (1)$$

where β is the baryon velocity, C is a Coulomb correction Coulomb correction that will be discussed in the following, θ is the scattering angle in the center of mass frame, and $G^{\mathcal{B}}_{\rm M}$ and $G^{\mathcal{B}}_{\rm E}$ are the magnetic and electric Sachs form factors (FF).

Analiticity and S wave at threshold require

$$G^{\mathcal{B}}_{\rm M}(4M^2_{\mathcal{B}}) = G^{\mathcal{B}}_{\rm E}(4M^2_{\mathcal{B}}) = G^{\mathcal{B}}(4M^2_{\mathcal{B}}).$$

For pointlike fermions it is $G^{\mathcal{B}}(W^2_{\mathcal{B}\overline{\mathcal{B}}}) = 1$. In the case of the $e^+e^- \to p\overline{p}$ the cross section $\sigma_{p\overline{p}}$ [2], Fig. 1a, is suddenly different from zero at threshold, being constant and ≈ 0.85 nb up to about 200 MeV above the threshold, then it drops.

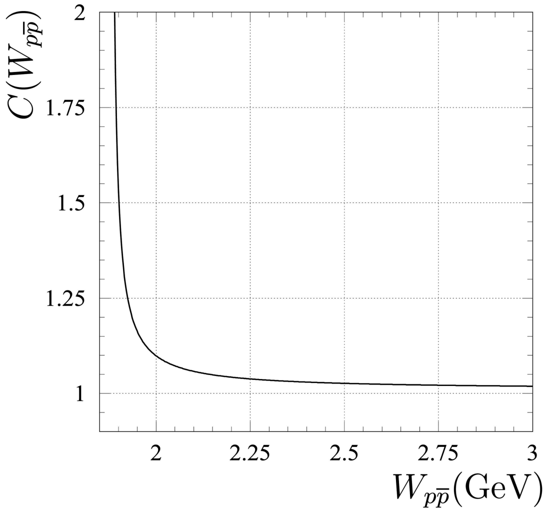

Fig. 2. Coulomb enhancement factor for the $p\overline{p}$ channel.

In principle, due to the finite energy-bin width, experiments can not exclude cross sections that vanish at threshold but with extremely sharp rises. In this case the relationship between data and predictions, reported in the following, could be accidental.

It is well known that Coulomb corrections to the Born cross section have to be accounted for in the case of production of pointlike charged fermions [4]. This correction, C in Eq. (1), should have a weak dependence on the total spin, it is the same for $G_{\rm E}$ and $G_{\rm M}$, it is $C = 1$ (no effect) for neutral fermions and with a good accuracy is $C(W_{\mathcal{B}\overline{\mathcal{B}}}) = (\pi\alpha/\beta)/(1-e^{-\pi\alpha/\beta})$ for charged fermions produced in a S wave. In the case of meson pairs, produced in a P wave, no Coulomb correction is expected in this approximation. Very near threshold the Coulomb factor behaves like $\pi\alpha/\beta$ and cancels out the phase-space β, making the cross section finite and non-zero even at $\beta = 0$. However, as it is shown in Fig. 2, as soon as the fermion velocity is no more vanishing, only few MeV above the threshold, it is $C \approx 1$ and Coulomb effects become negligible.

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

$$\begin{aligned}\sigma_{p\overline{p}}(4M^2_{\rm p}) &= (\pi^2\alpha^3/2M^2_{\rm p})\cdot|G^{\rm p}(4M^2_{\rm p})|^2 \\ &= 0.85\cdot|G^{\rm p}(4M^2_{\rm p})|^2\,\text{nb}.\end{aligned}$$

This is in striking similarity with the measured values just above threshold if $|G^{\rm p}(4M^2_{\rm p})| = 1$ within about 0.5 % accuracy. Nobody predicted this result and no explanation has been pointed out until now. A similar result has been achieved in the case of charmed baryon pairs, even if within a large error [5].

The angular distribution, in the first 100 MeV bin, is $\propto \sin^2\theta$, i.e. dominated by the electric FF $G^{\rm p}_{\rm E}$. By means of dispersion relations it is possible to relate space-like and time-like electric and magnetic form factors, to get their relative phase and S wave and D wave amplitudes. It turns out that the S wave amplitude shows a sharp decrease above threshold. Other very interesting results of this connection between space-like and time-like data are reported in details in Ref. [6].

In the case of the Λ, Coulomb effects should not be taken into account. It follows that the $e^+e^- \to \Lambda\overline{\Lambda}$ cross section is expected to vanish at threshold, in fair disagreement with the BABAR data, Fig. 1b. In particular the cross section $\sigma_{\Lambda\overline{\Lambda}}$ appears non-zero at threshold, being ≈ 0.2 nb [3]. The other strange neutral baryon cross sections measured by BABAR [3] are consistent with a similar threshold behaviour. All these strange neutral cross sections are also consistent with the U spin invariance expectations [5]. However the errors are too large to draw a conclusion.

Assuming that this Coulomb dominance is not a mere coincidence, it might be of interest to investigate, at least qualitatively, what is expected at the valence quark level. Once quark pairs are produced they experience an attractive Coulomb interaction. For each pair there is a Coulomb amplitude with a phase to account for their displacement inside the baryon. Interference terms should be suppressed by various factors, like displacement and velocity spread, and same sign Coulomb corrections vanish at threshold (same formula for C but with negative α). Therefore in the proton case, at quark level, it should be:

$$\sigma_{\mathrm{p\overline{p}}}(4M_{\mathrm{p}}^2)=(\pi^2\alpha^3/2M_{\mathrm{p}}^2)(2Q_{\mathrm{u}}^2+Q_{\mathrm{d}}^2)=0.85\,\mathrm{nb},$$

so that the pointlike result is recovered. In the case of the $\mathrm{e}^+\mathrm{e}^-\to\Lambda\overline{\Lambda}$ cross section, at quark level, the expectation would be:

$$\sigma_{\Lambda\overline{\Lambda}}(4M_{\Lambda}^2)=(\pi^2\alpha^3/2M_{\Lambda}^2)(Q_{\mathrm{u}}^2+Q_{\mathrm{d}}^2+Q_{\mathrm{s}}^2)=0.4\,\mathrm{nb}.$$

While, at hadron level, it should be $\sigma_{\Lambda\overline{\Lambda}}(4M_{\Lambda}^2)=0$. Hence the expectation range for $\sigma_{\Lambda\overline{\Lambda}}$ at threshold is $(0\div0.4)$ nb, in qualitative agreement with the BABAR data.

Some authors (e.g. Ref. [7]) emphasize that similar threshold effects, due to strong interaction, are forecast in the case of heavy quark pair production.

3 Conclusion

In conclusion BABAR data on cross sections for the processes $\mathrm{e}^+\mathrm{e}^-\to\mathrm{p\overline{p}}$, $\Lambda\overline{\Lambda}$ have been shortly reviewed. The most surprising feature is their non-zero cross section at threshold. Indeed, in Born approximation, Eq. (1), the cross section $\sigma_{\mathcal{B}\overline{\mathcal{B}}}$ is proportional to the velocity β of the baryon. However a pointlike Coulomb correction gives a factor $1/\beta$ that cancels out the phase space velocity, when charged baryons are involved. This Coulomb enhancement factor dominates the $\mathrm{e}^+\mathrm{e}^-\to\mathrm{p\overline{p}}$ cross section near threshold and, once has been introduced, the striking result is found that $|G^{\mathrm{p}}(4M_{\mathrm{p}}^2)|\approx1$, as in the case of pointlike fermions. For neutral baryons no Coulomb interaction is expected, hence the cross section should vanish at threshold, in contrast with what is observed, within the errors, in the case of $\sigma_{\Lambda\overline{\Lambda}}$, Fig. 1(b).

Coulomb interactions among the valence quarks could qualitatively explain this behaviour.

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