Eur. Phys. J. A (2012) **48**: 33
DOI 10.1140/epja/i2012-12033-6

THE EUROPEAN PHYSICAL JOURNAL A

Letter

No Sommerfeld resummation factor in $e^+e^- \longrightarrow p\overline{p}$?

R. Baldini Ferroli[1,2], S. Pacetti[3,a], and A. Zallo[2]

[1] Museo Storico della Fisica e Centro Studi e Ricerche "E. Fermi", Rome, Italy
[2] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[3] INFN and Dipartimento di Fisica, Università di Perugia, Perugia, Italy

Received: 14 December 2011 / Revised: 27 January 2012
Published online: 20 March 2012

Communicated by J. Bijnens

Abstract. The Sommerfeld rescattering formula is compared to the $e^+e^- \to p\overline{p}$ *BABAR* data at threshold and above. While there is the expected Coulomb enhancement at threshold, two unexpected outcomes have been found: the modulus of the proton form factor is normalized to one at threshold, *i.e.* $|G^p(4M_p^2)| = 1$, as a pointlike fermion, and, moreover, data show that the resummation factor in the Sommerfeld formula is not needed. Other $e^+e^- \to$ baryon-antibaryon cross-sections show similar behavior near threshold.

Many recent papers, mostly concerning evidence of Dark Matter [1], are related to the so-called Sommerfeld rescattering formula [2,3] (eq. (2)). In this letter, the unexpected lack of the resummation term in the Sommerfeld rescattering formula in the present $e^+e^- \to p\overline{p}$ cross-section data, as well as other unexpected features of $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$ ($\mathcal{B}$ stands for baryon), are emphasized, namely:

- in $e^+e^- \to p\overline{p}$, the cross-section is not vanishing at threshold, as already pointed out [4,5] and it is fully dominated by the Coulomb final-state enhancement and $|G^p(4M_p^2)| = 1$, as a pointlike fermion, where G^p is the common value of electric and magnetic proton form factors (FF) at the production threshold;
- in $e^+e^- \to p\overline{p}$, the cross-section above threshold is consistent with no Sommerfeld resummation factor, as will be shown in detail in the following;
- other charged baryon pair cross-sections data, $e^+e^- \to \Lambda_c\overline{\Lambda_c}$ and $e^+e^- \to p\overline{N}(1440)$ + c.c., show similar features, even if within large errors, as well as the present puzzling data on neutral baryon pair cross-sections.

These cross-sections have been measured by means of the initial-state radiation technique. This procedure has several advantages in the case of a hadron pair production. In particular, at threshold, in the hadronic center of mass (CM):

- the efficiency is quite high;
- a very good invariant-mass resolution, $\Delta W_{p\overline{p}} \sim 1\,\mathrm{MeV}$, is achieved, comparable to what is obtained in a symmetric storage ring.

[a] e-mail: `simone.pacetti@pg.infn.it`

In the Born approximation, the cross-section for the process $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$, in the case of charged baryons, is

$$\sigma_{\mathcal{B}\overline{\mathcal{B}}}(W^2_{\mathcal{B}\overline{\mathcal{B}}}) = \frac{4\pi\alpha^2\beta}{3W^2_{\mathcal{B}\overline{\mathcal{B}}}}\,\mathcal{C} \times \left[\left|G_M^{\mathcal{B}}(W^2_{\mathcal{B}\overline{\mathcal{B}}})\right|^2 + \frac{2M^2_{\mathcal{B}}}{W^2_{\mathcal{B}\overline{\mathcal{B}}}}\left|G_E^{\mathcal{B}}(W^2_{\mathcal{B}\overline{\mathcal{B}}})\right|^2\right], \quad (1)$$

where $W_{\mathcal{B}\overline{\mathcal{B}}}$ is the $\mathcal{B}\overline{\mathcal{B}}$ invariant mass, β is the velocity of the outgoing baryon, $\mathcal{C}$ is the Coulomb factor,

$$\mathcal{C} = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)}, \quad (2)$$

that takes into account the electromagnetic $\mathcal{B}\overline{\mathcal{B}}$ final-state interaction, $G_M^{\mathcal{B}}$ and $G_E^{\mathcal{B}}$ are the magnetic and electric Sachs FF's, and $M_{\mathcal{B}}$ is the baryon mass.

Because of parity conservation S and D waves only are allowed. At threshold it is assumed that, according to the analyticity of the Dirac and Pauli FF's as well as according to the S-wave dominance, $G_E^{\mathcal{B}}$ and $G_M^{\mathcal{B}}$ coincide and there is only one FF: $G^{\mathcal{B}}(4M^2_{\mathcal{B}}) \equiv G_E^{\mathcal{B}}(4M^2_{\mathcal{B}}) = G_M^{\mathcal{B}}(4M^2_{\mathcal{B}})$. The definition of the partial-wave FF's $G_S^{\mathcal{B}}$ and $G_D^{\mathcal{B}}$ in terms of $G_E^{\mathcal{B}}$ and $G_M^{\mathcal{B}}$ is the following:

$$G_S^{\mathcal{B}} = \frac{2G_M^{\mathcal{B}}\sqrt{W^2_{\mathcal{B}\overline{\mathcal{B}}}/4M^2_{\mathcal{B}}} + G_E^{\mathcal{B}}}{3},$$
$$G_D^{\mathcal{B}} = \frac{G_M^{\mathcal{B}}\sqrt{W^2_{\mathcal{B}\overline{\mathcal{B}}}/4M^2_{\mathcal{B}}} - G_E^{\mathcal{B}}}{3}, \quad (3)$$

and $G_D^{\mathcal{B}}(4M^2_{\mathcal{B}}) = 0$. For pointlike fermions it is $G_E(Q^2) = G_M(Q^2) \equiv 1$.

The Coulomb factor, $\mathcal{C}$, is usually introduced as an enhancement factor $\mathcal{E}$ times a resummation term $\mathcal{R}$, *i.e.* the so-called Sommerfeld-Schwinger-Sakharov rescattering formula [6,2,3]: $\mathcal{C} = \mathcal{E} \times \mathcal{R}$. It has a very weak dependence on the fermion pair total spin and corresponds to the modulus squared of the wave function, solution of the Schrödinger equation with Coulomb potential, at the origin. It is assumed as a good approximation of the Coulomb final-state interaction, in the zero-velocity limit when baryons are produced at rest in their CM. In such an approximation, the factor $\mathcal{C}$ should affect the S-wave only, because the D-wave vanishes at the origin. For the same reason, a Coulomb enhancement is not expected when pseudoscalar meson pairs are produced via e^+e^- annihilation; these processes occur only in the P-wave. The cross-section formula should be more properly written in terms of S- and D-wave FF's as:

$$\sigma_{\mathcal{B}\overline{\mathcal{B}}}(W^2_{\mathcal{B}\overline{\mathcal{B}}}) = 2\pi\alpha^2\beta\,\frac{4M^2_{\mathcal{B}}}{W^4_{\mathcal{B}\overline{\mathcal{B}}}} \times\Big[\mathcal{C}\,|G^{\mathcal{B}}_S(W^2_{\mathcal{B}\overline{\mathcal{B}}})|^2 + 2|G^{\mathcal{B}}_D(W^2_{\mathcal{B}\overline{\mathcal{B}}})|^2\Big]. \qquad (4)$$

The enhancement factor is

$$\mathcal{E} = \frac{\pi\alpha}{\beta}, \qquad (5)$$

so that, in the limit $\beta \to 0$, the D-wave FF vanishes, the Coulomb factors tends to $\mathcal{E}$ and hence the phase space factor β in eq. (4) is cancelled, and the cross-section is expected to be finite and *not vanishing even exactly at threshold*. As the resummation factor is

$$\mathcal{R} = \frac{1}{1-\exp\left(-\pi\alpha/\beta\right)}, \qquad (6)$$

it follows that few MeV above the threshold it is $\mathcal{C} \sim 1$, the phase space factor is restored and Coulomb effects can be neglected.

Concerning P and D waves, a further degree of approximation could be applied by means of the derivative at the origin or by means of a different approach [7–10].

The $e^+e^- \to p\overline{p}$ cross-section [11] in fig. 1 shows the following peculiar features:

– it is suddenly different from zero at threshold, being (0.85 ± 0.05) nb (this is the only known endothermic process that shows this peculiarity);
– it is flat above threshold, within the experimental errors, in a CM energy interval of about 200 MeV and then it drops abruptly.

In the $p\overline{p}$ case, the expected Coulomb-corrected cross-section at threshold is (see eq. (1))

$$\sigma_{p\overline{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\cdot|G^p(4M_p^2)|^2 = 0.85\cdot|G^p(4M_p^2)|^2\,\mathrm{nb}, \qquad (7)$$

in striking similarity with the measured mean value close to the threshold, if

$$|G^p(4M_p^2)| = 1.00 \pm 0.05,$$

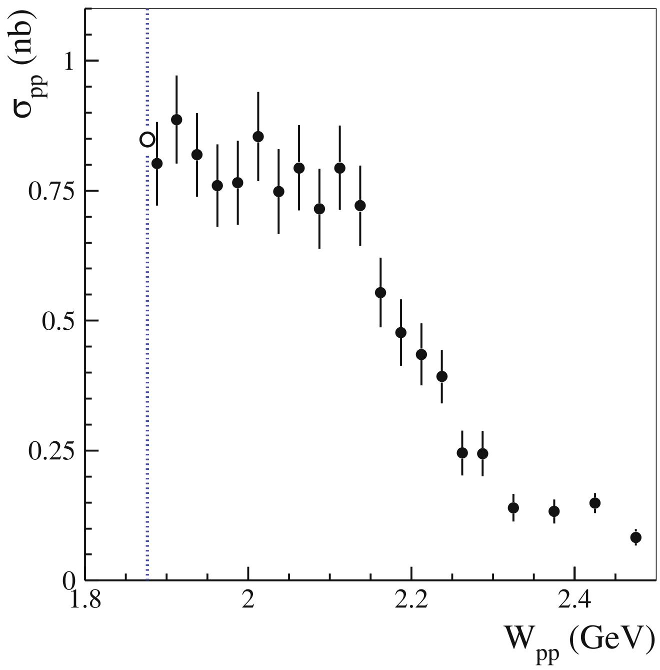

Fig. 1. The $p\overline{p}$ cross-section obtained by *BABAR* (solid circles). The dotted line represents the threshold and the empty circle is the Coulomb-enhanced threshold cross-section, assuming $|G^p(4M_p^2)| = 1$.

as for a pointlike fermion. The Coulomb interaction dominates the energy region at threshold.

Above threshold the moduli $|G^p_S|$ and $|G^p_D|$ have already been achieved [12], according to eq. (3) by means of the proton angular distribution and using a dispersion relation procedure applied to space-like and time-like data on the modulus of the ratio $|G^p_E|/|G^p_M|$. Dispersion relations are needed to have access to the relative phase between G^p_S and G^p_D. In the CM energy range where the cross-section is flat, G^p_S is found to be real and positive, while G^p_D is real and negative.

In spite of the fact that the D-wave FF is subdominant, the angular distribution and hence the ratio $|G^p_E|/|G^p_M|$ are very sensitive to it. Indeed, following the definitions of eq. (3), the G^p_D contribution to G^p_E is positive and weighted by a factor of two while that to G^p_M is negative.

For the purposes of this letter, G^p_S and G^p_D have been re-evaluated according to eq. (4), keeping, from ref. [12], the only result concerning the relative phase between G^p_S and G^p_D which is vanishing (the outcome is essentially the same achieved according to eq. (1)).

Figure 2 shows the near-threshold data on the modulus of the ratio G^p_E/G^p_M and $p\overline{p}$ total cross-section that have been used to extract $|G^p_S|$ and $|G^p_D|$, that are reported in fig. 3, where $|G^p_S|$ is compared to the inverse of the square root of the resummation factor, given in eq. (6) and it is

$$|G^p_S(4M_p^2 - 4\,\mathrm{GeV}^2)| \simeq \frac{1}{\sqrt{\mathcal{R}}} = \sqrt{1-\exp(-\pi\alpha/\beta)}\,.$$

The agreement, within the errors, is striking. In other words: *if the resummation factor is introduced in the Cou-*

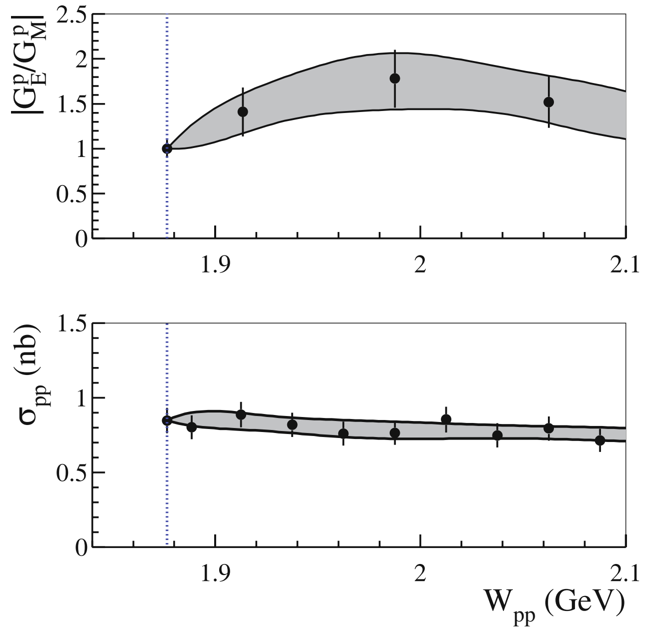

Fig. 2. Top: modulus of the ratio $|G_E^p/G_M^p|$. Bottom: $p\overline{p}$ cross-section. The gray bands are the fits and the dotted line is the threshold.

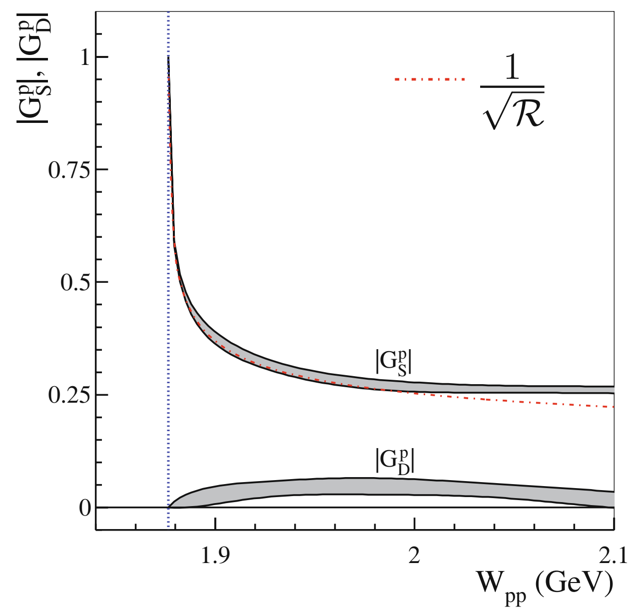

Fig. 3. $|G_S^p|$ and $|G_D^p|$ obtained using the ratio $|G_E/G_M|$, the total $p\overline{p}$ cross-section, and assuming a relative phase $\phi = \pi$, see text. The dot-dashed curve is the inverse of the square root of the resummation factor of eq. (6).

lomb correction then the inverse of the resummation factor is demanded in $|G_S^p|^2$ *by the data*, strongly suggesting that it is an *unnecessary factor*. If the resummation factor is not taken into account, it is $|G_S^p| \sim 1$ in a ~ 200 MeV CM energy interval above threshold and then it drops abruptly.

This conclusion could have been already foreseen on the basis of the flat cross-section above threshold and the expected steep increase above threshold due to the phase space factor. There must be a cutoff to the Coulomb dominance, but, what proton data are showing is that the energy scale for a baryon pair is hundred times greater than that expected for pointlike charged fermions.

In light of this, in any baryon-antibaryon channel we could consider a Coulomb correction with the only enhancement factor $\mathcal{E}$. The effective proton time-like FF, extracted from the *BABAR* cross-section data, is shown in fig. 4, assuming the usual Coulomb correction in red and only the enhancement factor in black.

Finally, fig. 5 shows the mean value of the inverse resummation factor $\mathcal{R}^{-1}$ over an interval of the baryon-antibaryon invariant mass ΔW, *i.e.* the quantity

$$\overline{\mathcal{R}^{-1}} = \frac{1}{\Delta W}\int_0^{\Delta W} \mathcal{R}^{-1}\mathrm{d}W$$
$$= \frac{1}{\Delta W}\int_0^{\Delta W} \left[1 - \exp\left(\frac{-\pi\alpha}{\sqrt{1-4M_P^2/W^2}}\right)\right]\mathrm{d}W.$$

Such a value indicates the scale factor experimentally introduced on the threshold data when a ΔW wide bin is considered. For instance, using a 2 MeV wide initial bin, the first data point will be scaled by a factor ~ 0.55. This is the reason why the threshold datum of the *BABAR* effective proton FF, red points in fig. 4, is ~ 0.6 instead of 1 as computed directly from the cross-section in eq. (7).

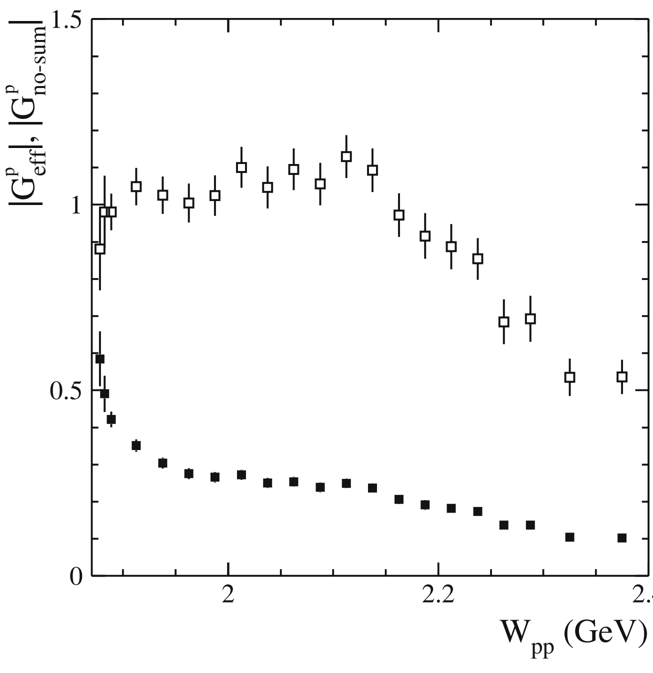

Fig. 4. Effective proton time-like FF extracted from the *BABAR* cross-section data. Solid squares show the FF assuming the usual point-like Coulomb correction of eq. (2), while the empty squares represent the FF obtained using the only enhancement factor of eq. (5).

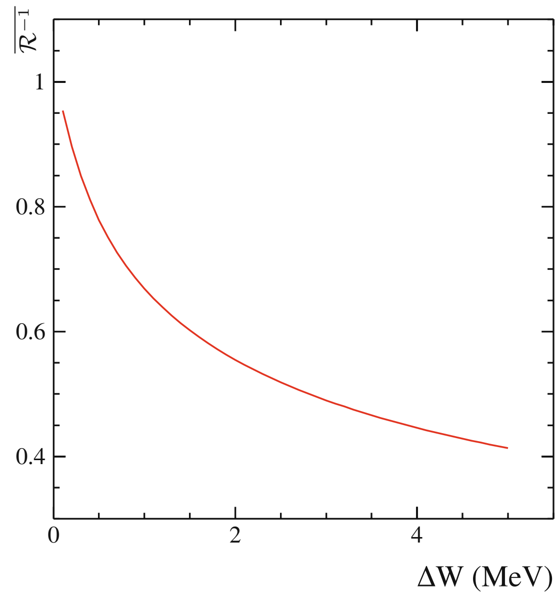

Fig. 5. Mean value of the inverse resummation factor.

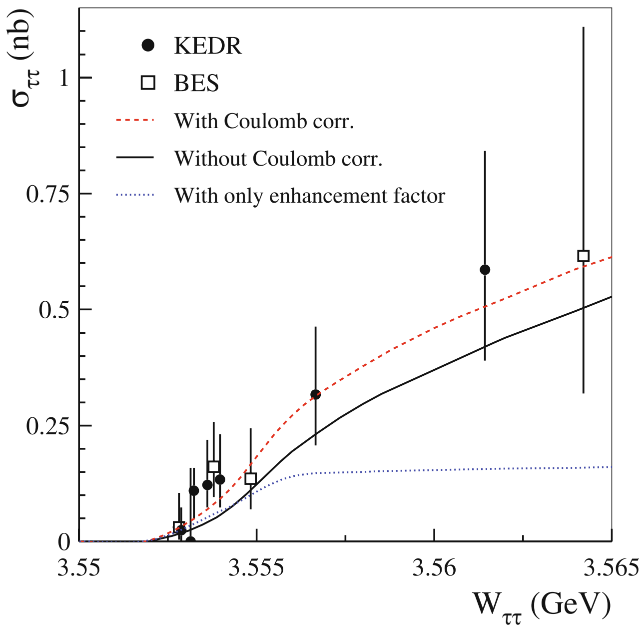

Fig. 6. The $e^+e^- \to \tau^+\tau^-$ cross-section data, from BES and KEDR experiments, compared with predictions obtained with and without the Coulomb correction, dashed and solid curves, and including the only enhancement factor $\mathcal{E}$ of eq. (5), dotted curve.

In the case of a pure QED process, like $e^+e^- \to \tau^+\tau^-$, present data [13–16] show a fair agreement with both, the enhancement and the resummation factors. In fig. 6 these data are compared to the predictions with (dashed curve) and without (black solid curve) these factors, including initial-state radiation and colliding beam energy spread, as in the data. Because of that, the expected step at threshold is smoothed out, but the aforementioned agreement is still visible.

Unfortunately, at present, there are no $e^+e^- \to \mu^+\mu^-$ cross-section data so close to threshold to see any Coulomb effects, however, the KLOE Collaboration [17] is studying the possibility to access this energy region via initial-state radiation.

Also in the case of $e^+e^- \to \Lambda_c\overline{\Lambda_c}$, see fig. 7, as already pointed out [5], the cross-section measured by the Belle Collaboration [18] is not vanishing at threshold. If there is no resummation factor there is no major dependence on the mass resolution and the expected cross-section at threshold can be directly compared to the data, once the Coulomb enhancement is taken into account as well as assuming $|G^{\Lambda_c}(4M^2_{\Lambda_c})| = 1$. There is a fair agreement, within the errors.

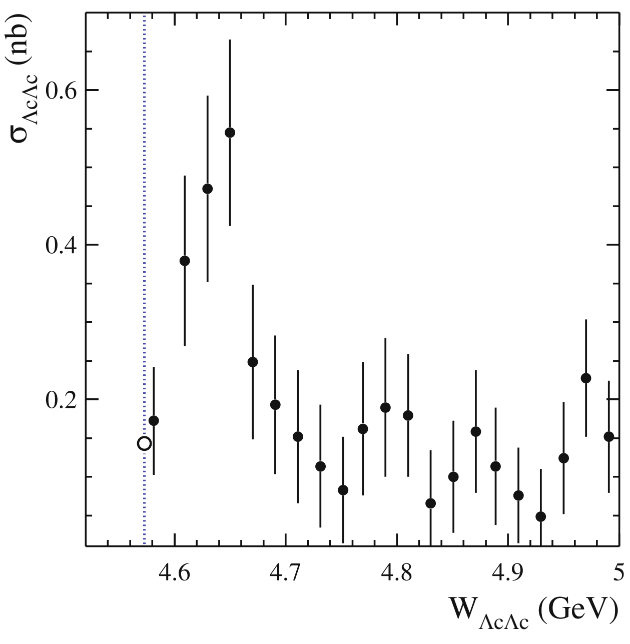

Fig. 7. The $\Lambda_c\overline{\Lambda_c}$ cross-section obtained by Belle (solid circles). The dotted line represents the threshold and the empty circle is the cross-section value Coulomb enhanced at threshold, assuming $|G_c^{\Lambda}(4M^2_{\Lambda_c})| = 1$.

Measuring $e^+e^- \to p\overline{p}$ *BABAR* has also measured the cross-section of $e^+e^- \to p\overline{N}(1440)$ + c.c. (see fig. 8 of ref. [11]), being a significant background to $e^+e^- \to p\overline{p}$. To get from these data a cross-section at threshold, a procedure has been exploited to avoid $N(1440)$ finite-width effects. The $N(1440)$ width as well as the $e^+e^- \to p\overline{N}(1440)$ + c.c. are simulated. For each simulated event the $N(1440)$ momentum is evaluated and a new CM energy is achieved assuming a zero width. The cross-section obtained in this way is compared, in fig. 8, to the pointlike cross-section, Coulomb enhanced at threshold. Even though such a procedure is not so rigorous, there is still agreement, suggesting that at threshold baryon pair production cross-section behaves in a universal way.

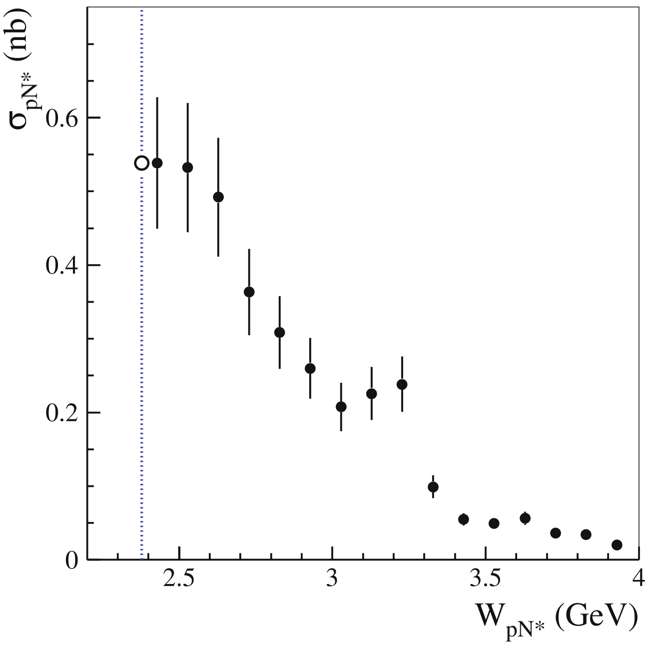

Fig. 8. The $e^+e^- \to p\overline{N}(1440)$ + c.c. cross-section obtained by *BABAR* (solid circles). The dotted line represents the threshold and the empty circle is the cross-section value Coulomb enhanced at threshold, assuming $|G^{pN(1440)}[(M_p + M_{N(1440)})^2]| = 1$.

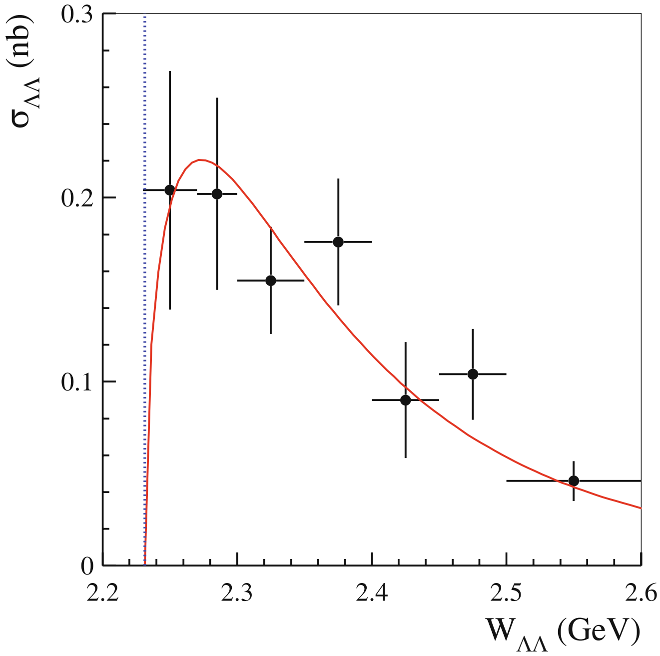

Fig. 9. The $\Lambda\overline{\Lambda}$ cross-section obtained by *BABAR*. The dotted line represents the threshold and a fit is reported, obtained including the outgoing baryon velocity factor and by means of an effective FF behaving like a dipole.

At last, 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. 9) show a threshold behavior similar to that of $\sigma_{p\overline{p}}$.

Other intriguing relations among threshold values of baryon-antibaryon production cross-sections can be obtained for the four channels: $\Lambda\overline{\Lambda}$, $\Sigma^0\overline{\Sigma^0}$, $\Lambda\overline{\Sigma^0}$ and $n\overline{n}$, where the strange baryon cross-sections have been measured by the *BABAR* Collaboration [19] and that of $e^+e^- \to n\overline{n}$ by the FENICE Collaboration [20].

Remnants of Coulomb interactions at the quark level have been invoked to explain non-vanishing threshold values in the case of neutral baryon production cross-sections.

Nevertheless, the present accuracy of the data cannot exclude a steep rising, according to the baryon velocity, for these cross-sections. As an example, fig. 9 shows a fit of the $\Lambda\overline{\Lambda}$ cross-section performed using a dipole effective FF in the eq. (1) with no Coulomb correction, *i.e.* $\mathcal{C} = 1$. A much better accuracy is needed to settle this issue.

In conclusion:

- the *BABAR* data on the $e^+e^- \to p\overline{p}$ cross-section clearly show the effect of the expected Coulomb correction at threshold, where it manifests itself as the only *enhancement factor* of eq. (5);
- the modulus of the proton FF is one at threshold as for a pointlike fermion;
- phenomenologically the data disprove the presence of the resummation factor of eq. (6);
- other charged baryon pair cross-sections show near threshold a similar behavior, within the errors.

New data near threshold are coming from CMD2 and SND at VEPP2000 and on a larger interval from BESIII at BEPCII by means of initial-state radiation, as well as a detailed test of the Sommerfeld rescattering formula in $e^+e^- \to \tau^+\tau^-$.

The investigation of the time-like behavior of nucleon FF's has been carried out by many authors using different approaches, models and phenomenological descriptions; in ref. [21–48] we report only an incomplete list. However, the result we present in this letter is a pure statement of fact and hence completely model independent. Possible interpretations, phenomenological explanations as well as other S-wave pair production at threshold are under study [49].

We warmly acknowledge A. Zichichi, G. Altarelli, G. Pancheri and Y. Srivastava for their strong support and the *BABAR* Collaboration, in particular Budker Institute colleagues, who achieved most of the experimental results.

References

1. Search at `http://inspirehep.net/` using command line: `find k dark matter and fulltext ''sommerfeld enhancement''`.
2. A. Sommerfeld, *Atombau und Spektralliniem* Vol. **2** (Vieweg, Braunschweig, 1944) p. 130.
3. J. Schwinger, *Particles, Sources, and Fields*, Vol. **III** (Westview Press, 1998) p. 80.
4. R. Baldini, S. Pacetti, A. Zallo, A. Zichichi, Eur. Phys. J. A **39**, 315 (2009) arXiv:0711.1725 [hep-ph].
5. R.B. Baldini, S. Pacetti, A. Zallo, arXiv:0812.3283 [hep-ph].
6. A.D. Sakharov, Zh. Eksp. Teor. Fiz. **18**, 631 (1948) (Sov. Phys. Usp. **34**, 375 (1991)).
7. M.B. Voloshin, Mod. Phys. Lett. A **18**, 1783 (2003).
8. S. Dubynskiy, A. Le Yaouanc, L. Oliver, J.C. Raynal, M.B. Voloshin, Phys. Rev. D **75**, 113001 (2007) arXiv:0704.0293 [hep-ph].
9. G.P. Lepage, Phys. Rev. D **42**, 3251 (1990).
10. D. Atwood, W.J. Marciano, Phys. Rev. D **41**, 1736 (1990).
11. BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D **73**, 012005 (2006) arXiv:hep-ex/0512023.
12. S. Pacetti, Eur. Phys. J. A **32**, 421 (2007).
13. BES Collaboration (J.Z. Bai *et al.*), Phys. Rev. D **53**, 20 (1996).
14. KEDR Collaboration (V.V. Anashin *et al.*), JETP Lett. **85**, 347 (2007).
15. KEDR Collaboration (V.V. Anashin *et al.*), Nucl. Phys. Proc. Suppl. **169**, 125 (2007) arXiv:hep-ex/0611046.
16. A.G. Shamov *et al.*, Nucl. Phys. Proc. Suppl. **189**, 21 (2009).
17. F. Bossi, private communication.
18. Belle Collaboration (G. Pakhlova *et al.*), Phys. Rev. Lett. **101**, 172001 (2008) arXiv:0807.4458 [hep-ex].
19. BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D **76**, 092006 (2007) arXiv:0709.1988 [hep-ex].
20. A. Antonelli *et al.*, Nucl. Phys. B **517**, 3 (1998).
21. B.O. Kerbikov, A.E. Kudryavtsev, Nucl. Phys. A **558**, 177C (1993).
22. G.V. Meshcheryakov, V.A. Meshcheryakov, Mod. Phys. Lett. A **9**, 1603 (1994).
23. V.A. Meshcheryakov, G.V. Meshcheryakov, Phys. Atom. Nucl. **60**, 1265 (1997) (Yad. Fiz. **60**, 1400 (1997)).
24. V.F. Dmitriev, A.I. Milstein, Nucl. Phys. Proc. Suppl. **162**, 53 (2006) arXiv:nucl-th/0607003.
25. V.F. Dmitriev, A.I. Milstein, Phys. Lett. B **658**, 13 (2007).
26. Y. Yan, K. Khosonthongkee, C. Kobdaj, P. Suebka, J. Phys. G **37**, 075007 (2010) arXiv:0906.5234 [hep-ph].
27. F. Iachello, Q. Wan, Phys. Rev. C **69**, 055204 (2004).
28. R. Bijker, F. Iachello, Phys. Rev. C **69**, 068201 (2004) arXiv:nucl-th/0405028.
29. R. Bijker, F. Iachello, Phys. Rev. C **69**, 068201 (2004) arXiv:nucl-th/0405028.
30. E. Tomasi-Gustafsson, F. Lacroix, C. Duterte, G. I. Gakh, Eur. Phys. J. A **24**, 419 (2005) arXiv:nucl-th/0503001.
31. E. Tomasi-Gustafsson, G.I. Gakh, Eur. Phys. J. A **26**, 285 (2005) arXiv:hep-ph/0511077.
32. C. Adamuscin, E.A. Kuraev, E. Tomasi-Gustafsson, F.E. Maas, Phys. Rev. C **75**, 045205 (2007) arXiv:hep-ph/0610429.
33. M. Mirazita, Nucl. Phys. Proc. Suppl. **174**, 151 (2007).
34. S. Furuichi, H. Ishikawa, K. Watanabe, Phys. Rev. C **81**, 045209 (2010) arXiv:0809.3334 [hep-ph].
35. E. Tomasi-Gustafsson, M.P. Rekalo, arXiv:0810.4245 [hep-ph].
36. O.D. Dalkarov, P.A. Khakhulin, A.Y. Voronin, Nucl. Phys. A **833**, 104 (2010) arXiv:0906.0266 [nucl-th].
37. G. Hohler, E. Pietarinen, I. Sabba Stefanescu, F. Borkowski, G.G. Simon, V.H. Walther, R.D. Wendling, Nucl. Phys. B **114**, 505 (1976).
38. P. Mergell, U.-G. Meissner, D. Drechsel, Nucl. Phys. A **596**, 367 (1996) arXiv:hep-ph/9506375.
39. H.W. Hammer, U.-G. Meissner, D. Drechsel, Phys. Lett. B **385**, 343 (1996) arXiv:hep-ph/9604294.
40. H.W. Hammer, D. Drechsel, U.-G. Meissner, Phys. Lett. B **586**, 291 (2004) arXiv:hep-ph/0310240.
41. H.W. Hammer, U.-G. Meissner, Eur. Phys. J. A **20**, 469 (2004) arXiv:hep-ph/0312081.
42. M.A. Belushkin, H.W. Hammer, U.-G. Meissner, Phys. Lett. B **633**, 507 (2006) arXiv:hep-ph/0510382.
43. J. Haidenbauer, H.W. Hammer, U.-G. Meissner, A. Sibirtsev, Phys. Lett. B **643**, 29 (2006) arXiv:hep-ph/0606064.
44. M.A. Belushkin, H.W. Hammer, U.-G. Meissner, Phys. Rev. C **75**, 035202 (2007) arXiv:hep-ph/0608337.
45. R. Baldini, S. Dubnicka, P. Gauzzi, S. Pacetti, E. Pasqualucci, Y. Srivastava, Eur. Phys. J. C **11**, 709 (1999).
46. S.J. Brodsky, C.E. Carlson, J.R. Hiller, D.S. Hwang, Phys. Rev. D **69**, 054022 (2004) arXiv:hep-ph/0310277.
47. S. Dubnicka, Nuovo Cimento A **100**, 1 (1988).
48. A.Z. Dubnickova, S. Dubnicka, M.P. Rekalo, Nuovo Cimento A **109**, 241 (1996).
49. R. Baldini, S. Pacetti, A. Zallo, in preparation.