

## BaBar results on $e^+e^- \rightarrow p \bar{p}$ by means of ISR

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BaBar has measured with unprecedented accuracy the  $e^+e^- \rightarrow p\bar{p}$  cross section from the threshold up to  $Q_{p\bar{p}}^2 \sim 20 \text{ GeV}^2/c^4$ , finding out an unexpected cross section, with plateaux and negative steps. Evidence for a ratio  $|G_E/G_M| > 1$  has also been found as well as a sudden variation in  $|G_M|$  just above the threshold.

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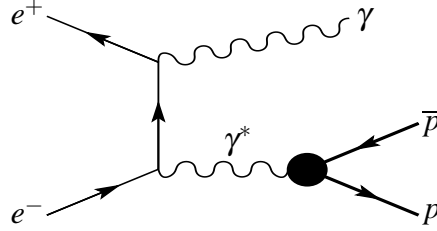
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BaBar has measured with unprecedented accuracy the cross section  $\sigma(e^+e^- \rightarrow p\bar{p}\gamma)$  from the threshold up to a  $p\bar{p}$  c.m. total energy squared  $Q_{p\bar{p}}^2 \sim 20 \text{ GeV}^2/c^4$  by means of the initial state radiation (ISR), as in Fig.1. In fact it has been shown [1] that at a  $m_e/E_e$  precision level it is:

$$\frac{d\sigma}{d\Omega_\gamma dE_\gamma}(e^+e^- \rightarrow p\bar{p}\gamma) = P(s, E_\gamma, \Omega_\gamma) \cdot \sigma(Q_{p\bar{p}}^2), \quad (1)$$

where  $s$  is the  $e^+e^-$  total c.m. energy squared,  $E_\gamma$  and  $\Omega_\gamma$  are energy and angles of the ISR photon in the  $e^+e^-$  c.m. frame,  $P$  is the density function for ISR emission, computed according to QED as in Fig.1, and  $\sigma(Q_{p\bar{p}}^2)$  is the  $e^+e^- \rightarrow p\bar{p}$  cross section at the  $p\bar{p}$  c.m. energy squared  $Q_{p\bar{p}}^2$ .



**Figure 1:** The diagram of the  $e^+e^- \rightarrow p\bar{p}\gamma$  process.

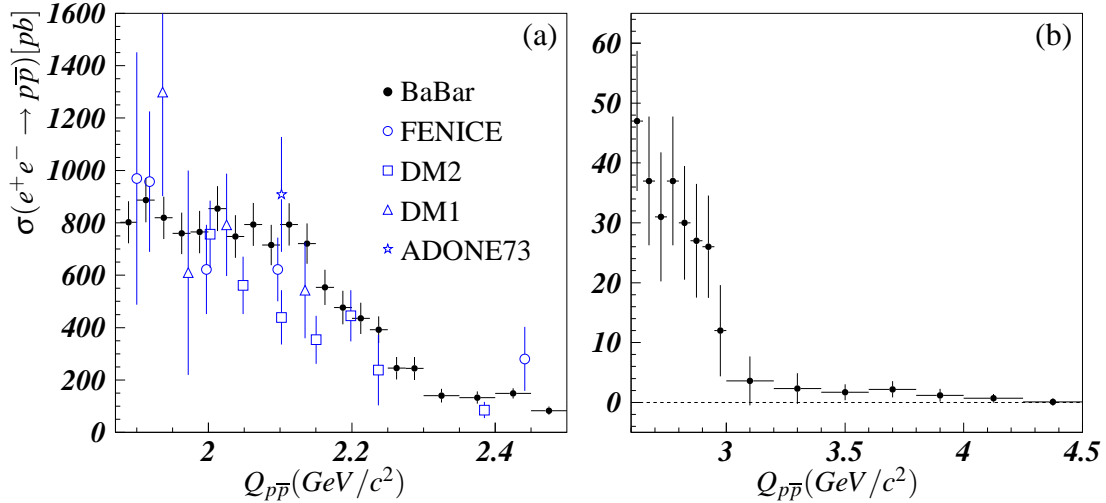
In the Born approximation it is given by [2]:

$$\frac{d\sigma(e^+e^- \rightarrow p\bar{p})}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2Q_{p\bar{p}}^2} \left[ (1 + \cos^2\theta) |G_M(Q_{p\bar{p}}^2)|^2 + \frac{4M_p^2}{Q_{p\bar{p}}^2} \sin^2\theta |G_E(Q_{p\bar{p}}^2)|^2 \right]. \quad (2)$$

All quantities are evaluated in the  $p\bar{p}$  c.m. frame:  $\theta$  is the azimuthal proton emission angle,  $\beta$  is the proton velocity,  $C$  is a factor introduced in the final state distorted wave approximation to take into account the Coulomb interaction [3],  $G_E$  and  $|G_M|$  are the analytical time-like continuation of the corresponding electric and magnetic form factors (FF), as defined in the process  $ep \rightarrow ep$ , where the exchanged  $Q_{p\bar{p}}^2$  is space-like. Recently the knowledge of the nucleon has been shaken to the roots by the new measurement of  $G_E/G_M$  for space-like  $Q_{p\bar{p}}^2$  [4], which is not constant at all, as believed for many decades, in spite of early theoretical predictions [5, 6]. At  $Q_{p\bar{p}}^2 = 4M_p^2$  it is expected  $G_E/G_M = 1$ , assuming that electric, magnetic, Dirac and Pauli FF are all analytical functions with respect to  $Q_{p\bar{p}}^2$ , hence continuous across the  $p\bar{p}$  threshold. The same expectation is achieved assuming at threshold there is the  $S$  wave only. Actually this expectation has been extended to the whole  $Q_{p\bar{p}}^2$  explored range [7–13], lacking high statistics measurements in particular concerning  $G_E$ . Actually what is quoted is  $|G_M|$ , also because at high  $Q_{p\bar{p}}^2$  its contribution is the dominant one. Concerning time-like  $Q_{p\bar{p}}^2$  the first [7] and the most relevant measurements at low [8] and at high  $Q_{p\bar{p}}^2$  [9], previous to BaBar, has been performed by means of the inverse process  $p\bar{p} \rightarrow e^+e^-$ . Under the aforementioned hypothesis concerning  $|G_M|$  they have shown a very steep increase approaching the threshold and a  $1/Q_{p\bar{p}}^4$  overall behaviour, even earlier than asymptotically expected according to PQCD [14].

In the following ISR events have been selected by asking the ISR photon is detected, to get rid of the non ISR multihadronic background. A rather large fraction of events is lost in this way, however in this case BaBar has the advantage over a conventional c.m.  $e^+e^-$  collider that the cross section can be measured even at threshold, with a  $\sim 1 \text{ MeV}/c^2$   $Q_{p\bar{p}}$  invariant mass resolution and with almost full  $p\bar{p}$  angular coverage. The B-factory PEP II ( $9\text{ GeV}/c^2$   $e^-$  colliding with

3.1  $GeV/c^2$   $e^+$ ) and the BaBar detector have been described in detail several times [15]. For the present purposes charged particle tracking (a 5 layer silicon vertex, SVT, and a 40 layer drift chamber, DCH) and identification (by means of an internally reflecting ring imaging Cherenkov, DIRC, of ionization in SVT and DCH and energy deposition in the calorimeter) systems are the main components. Muons are identified by means of the instrumented iron flux return. The ISR photon is detected and must be in the range  $22^\circ < \theta_\gamma < 137^\circ$  in the lab frame, however photon information has not been used in the kinematical fit. The Monte Carlo (MC) event generator is based on the code described in [16]. Extra ISR soft photons are generated according to the structure function method [17].



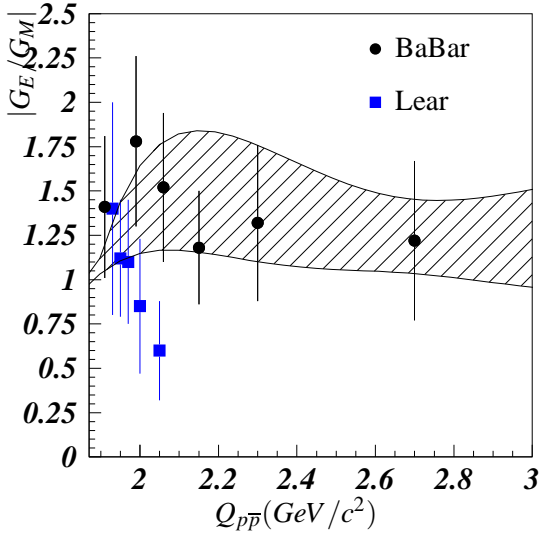
**Figure 2:** The  $e^+e^- \rightarrow p\bar{p}$  cross section in comparison with previous experiments: FENICE [13], DM2 [12], DM1 [11] and ADONE73 [10].

At present a data sample related to  $232fb^{-1}$  total integrated luminosity has been analyzed. Event selection has required an energetic photon and two opposite sign charged tracks, originated from the interaction point with a polar angle within the DIRC acceptance. Radiative Bhabha events are rejected if for each track it is  $0.9 < E_{cal}/P_{tr} < 1.1$ , between the energy deposition  $E_{cal}$  in the calorimeter and the DCH momentum  $P_{tr}$ . To get rid of the huge ISR  $\pi^+\pi^-\gamma$ ,  $\mu\mu\gamma$ ,  $K^+K^-\gamma$  background both charged tracks are required to be well identified as proton candidates by means of a tight cut, leading to a loss of about 30% of signal events. A kinematical fit is performed adding further tight cuts, that is to be compatible only with proton masses hypothesis, leading to a further loss of about 25%. The overall detection efficiency is about 18% with a mild dependence on  $Q_{p\bar{p}}$ . In the surviving events there is no evidence of a peak at the  $\rho$  mass or a peak at the  $\Phi$  mass in a pion or kaon pair masses hypothesis and the estimated remaining contamination is negligible. Angular and energy photon distributions are consistent with the ISR expectation. Final state radiation is expected to be very small and there is no interference term, due to the different charge parity. The most important and subtle source of background is the process  $e^+e^- \rightarrow p\bar{p}\pi^0$ , where easily a soft photon is lost or the two photons are merged and not disentangled by the pattern recognition. Since there are no experimental information on this process, events  $e^+e^- \rightarrow p\bar{p}\pi^0$  with a fully reconstructed  $\pi^0$  are identified and the contamination in the selected sample of  $e^+e^- \rightarrow p\bar{p}$  candidate events is evaluated according to the MC expectation. These estimated background events are about

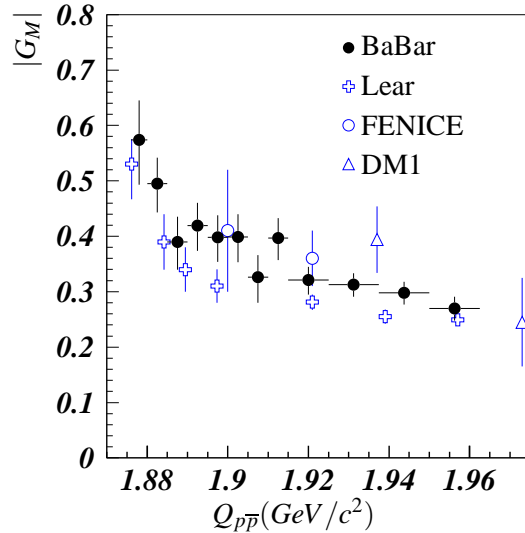
5% of the selected candidate events when  $Q_{p\bar{p}}^2 < 6 \text{ GeV}^2/c^4$ , about 10% if  $6 < Q_{p\bar{p}}^2 < 9 \text{ GeV}^2/c^4$  and become consistent with 100% above  $Q_{p\bar{p}}^2 \sim 20 \text{ GeV}^2/c^4$ .

The ISR luminosity is calculated using the total integrated luminosity and the probability density function for ISR photon emission, as in eq.(1), taking into account the angular cuts. The luminosity, that has been integrated, depends on the  $Q_{p\bar{p}}$  invariant mass bin width, varying from  $\sim 0.5 \text{ pb}^{-1}$  at  $Q_{p\bar{p}}^2 \sim 2 \text{ GeV}^2/c^2$  up to  $\sim 1 \text{ pb}^{-1}$  at  $Q_{p\bar{p}}^2 \sim 3 \text{ GeV}^2/c^2$  for a  $10 \text{ MeV}/c^2$  bin width.

Radiative corrections have been evaluated according the structure function method. They do not include corrections due to vacuum polarization. Hence what is quoted here is the so called “dressed” cross section. The invariant mass resolution has been unfolded, however the chosen bin widths exceed the resolution. With all these ingredients the calculated cross section  $\sigma(e^+e^- \rightarrow p\bar{p})$  is shown in Fig.2, statistical and systematic errors are quoted, including the uncertainties in detection efficiency, integrated luminosity and radiative corrections. For comparison some previous measurements are also shown. The emerging cross section shape is an unexpected one: a flat plateau from the threshold up to  $Q_{p\bar{p}}^2 \sim 5 \text{ GeV}^2/c^4$ , followed by a step and then a second step at  $Q_{p\bar{p}}^2 \sim 8.5 \text{ GeV}^2/c^4$ . At present no simple explanation has been found concerning this behaviour.



**Figure 3:** The measured ratio  $|G_E/G_M|$  in comparison with the Lear data [8].



**Figure 4:** The proton magnetic form factor in comparison with other experiments.

The angular distributions have been fitted, according to eq.(2) to extract the ratio  $|G_E/G_M|$ . The fitted ratios are reported in the Fig.3 . BaBar results are not in agreement with the APPLE [8] results at LEAR, while they are in qualitative agreement with an expectation, updated, based on dispersion relations and on the JLAB space-like  $|G_E/G_M|$  measurements [18]. There is no clear evidence for an asymmetry, i.e. two photon exchange contribution, but there is not enough statistics to draw any conclusion. As previous experiments did,  $|G_M|$  is evaluated from the total cross section as shown in Fig.4, under the hypothesis  $G_E = G_M$ , which is at odd with the aforementioned results by the way. The asymptotic  $1/(Q_{p\bar{p}}^2)^2$  behaviour found in  $p\bar{p} \rightarrow e^+e^-$  is confirmed as well as a very steep slope very near threshold. The  $C$  factor in the cross section formula has a very steep slope too and is relevant only very near threshold, diverging as  $1/\beta$  so that the cross section should be finite at threshold. It has been introduced to get rid of the pointlike Coulomb interaction, since the FF definition should demand that the pointlike cross section has been factorized. However this

receipt concerning Coulomb interaction has been questioned [19] and a better evaluation might affect the steep threshold behaviour of the FF. It may be worthwhile to remind that no Coulomb corrections are expected in the  $e^+e^- \rightarrow n\bar{n}$  process. Alternative interpretations are peculiar  $p\bar{p}$  final state interactions, like one  $\pi$  exchange, as suggested in the  $J/\psi$  radiative decay into a pseudoscalar  $p\bar{p}$  pair [20], or a narrow  $p\bar{p}$  vector state below threshold as obtained by means of dispersion relations in the unphysical region [21].

In conclusion BaBar has measured with unprecedented accuracy the  $e^+e^- \rightarrow p\bar{p}$  cross section from the threshold up to  $Q_{p\bar{p}}^2 \sim 20 \text{ GeV}^2/c^4$ , finding out unexpected negative steps. Evidence for a ratio  $|G_E/G_M| > 1$  has also been found just above the threshold as well as a sudden variation in  $|G_M|$ .

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