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Measurement of hadronic cross sections with the BABAR detector

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Abstract. A program of measuring exclusive e^+e^- to light hadrons processes is in place at BABAR with the aim to improve the calculation of the hadronic contribution to the muon $g-2$. We present the most recent results obtained with the full data set of about 470 fb^{-1} collected by the BABAR experiment. In particular, we report the result on the channel $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$, which gives the main uncertainty on the total cross section in the energy region between 1 and 2 GeV. We have also completed the studies of the final states with two neutral or charged kaons.

1. Motivation

The measurement of the leptonic anomalous magnetic moment, $a_\ell = (g_\ell - 2)/2$, where g_ℓ is the gyromagnetic factor, provides a precise test of QED, as both predicted and measured values are obtained with extremely high precision. However, for the muon anomalous magnetic moment, there is a long standing discrepancy, at more than 3σ , between the theoretical prediction [1] and the experimental result [2] from spin precession by the E821 experiment at BNL:

$$a_\mu^{th.} = (11659180.2 \pm 4.9) 10^{-10} \text{ and } a_\mu^{exp.} = (11659208.9 \pm 6.3) 10^{-10}. \quad (1)$$

New measurements of $(g_\mu - 2)$ at Fermilab and at J-PARC should reduce the uncertainty on the measured value by at least a factor four in the years to come. So it is crucial to reduce also the uncertainty on the calculated value, obtained mostly from QED, with hadronic corrections and weak interaction corrections. The dominant correction and dominant uncertainty in the theoretical predictions come from the leading order hadronic vacuum polarization term [1]:

$$a_\mu^{LO had.} = (692.3 \pm 4.2) 10^{-10}. \quad (2)$$

This correction to the virtual photon propagator is linked to the production of hadrons in e^+e^- annihilations via dispersion relations. Its calculation needs as experimental inputs the total hadronic cross section, which at low energies is determined from a finite sum of exclusive modes. The BABAR Collaboration pursues a comprehensive study of these exclusive modes. The experiment was installed on the high-intensity energy-asymmetric PEP-II collider at SLAC. It took nearly 0.5 ab^{-1} of data in the region of the Υ resonances over ten years from 1999 to 2008. It has recently measured the following final states produced in e^+e^- annihilations: $\pi^+\pi^-\pi^0\pi^0$ [3], $\pi^+\pi^-\eta$ [4], $K_S^0 K_L^0 \pi^0$, $K_S^0 K_L^0 \pi^0 \pi^0$, and $K_S^0 K_L^0 \pi^0 \eta$ [5], and $K_S^0 K^\pm \pi^\mp \pi^0$ and $K_S^0 K^\pm \pi^\mp \eta$ [6].



2. Initial state radiation

In events with initial state radiation (ISR), a photon is emitted from the colliding electron or positron. This process allows to measure cross sections in a wide range of energies well below the collider center-of-mass energy $\sqrt{s} \sim 10$ GeV and down to threshold. The effective energy $\sqrt{s'}$ is calculated event by event from the ISR photon energy E_γ according to $s' = s(1 - 2E_\gamma/\sqrt{s})$.

An energetic photon is detected in the calorimeter in coincidence with hadrons in the BABAR detector. The hadronic system is boosted and back to back with the photon, which gives a good reconstruction efficiency even at threshold. The ISR photon is chosen as the highest energy photon over 3 GeV. A kinematic fit of the hadronic system improves the energy resolution.

3. The $\pi^+\pi^-\pi^0\pi^0$ mode

In the $\pi^+\pi^-\pi^0\pi^0$ analysis [3], we also ask for exactly two tracks with opposite sign and identified as pion and at least four photons in addition to the ISR photon to reconstruct the two π^0 s in their decay into two photons. About 150 000 signal events are obtained. The small fraction of background surviving the selection requirements is estimated from simulations and then subtracted from the data. However, a major issue in this mode is the background from the $\pi^+\pi^-\pi^0\pi^0$ ISR channel, which was not well known and consequently not well simulated. A dedicated analysis was performed to measure this background directly in the BABAR data.

Figure 1 shows, as a function of energy, the cross section of the $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ process, which peaks at about 32 nb around 1.5 GeV. The systematic uncertainty on the cross section is about 3% in the peak region and 7% in the tail region. The results from the BABAR experiment are much more precise than previous measurements in the region up to 2.2 GeV and cover a previously unexplored energy range, from 2.2 GeV up to 4.5 GeV. Intermediate resonances have been searched for. A fraction of $(32.1 \pm 0.2 \pm 2.6)\%$ is found to proceed through $\omega\pi^0$, with the ω decaying into three pions. The cross section of this process is shown in figure 2.

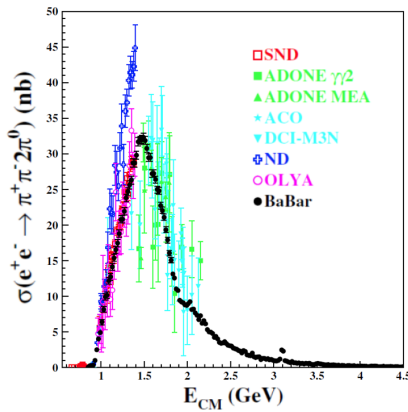


Figure 1. Cross section as a function of energy of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ from BABAR (black circles with statistical uncertainties) and previously published results.

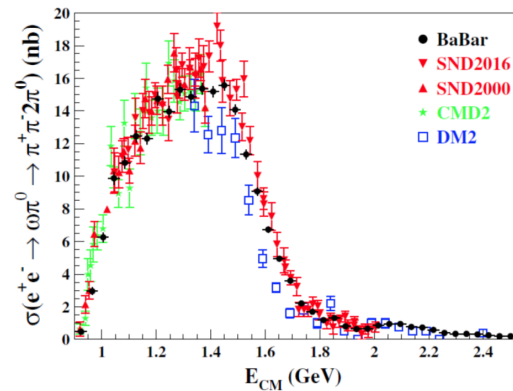


Figure 2. Cross section of $e^+e^- \rightarrow \omega\pi^0$ as a function of energy from BABAR (black circles with statistical uncertainties) and previously published results.

Among the channels relevant for the calculation of $(g_\mu - 2)$, $\pi^+\pi^-\pi^0\pi^0$ had one of the least known cross section. The new BABAR result improves by a factor 2.5 the knowledge on the contribution of this channel (all contributions of specific modes are given in the energy range from threshold up to 1.8 GeV) in the calculation of $(g_\mu - 2)$ to a precision of 3.2%:

$$a_\mu(\pi^+\pi^-\pi^0\pi^0) = (17.9 \pm 0.1 \pm 0.6) 10^{-10}. \quad (3)$$

4. The $\pi^+\pi^-\eta$ mode

The $\pi^+\pi^-\eta$ final state has been studied [4], with the η reconstructed in its decay into two photons. The number of signal events is 8065 ± 101 . The cross section of this process dominated by the $\rho\eta$ mode is shown in figure 3 as a function of energy up to 2 GeV and above 2 GeV. It peaks at about 4 nb slightly above 1.5 GeV and presents a bump around 1.75 GeV. The systematic uncertainty varies from 5% at the peak to 12% in the tail. The cross section measured by BABAR is in agreement with previous measurements and more precise especially at high energy, where the covered range is extended up to 3.5 GeV. The new BABAR result reduces the uncertainty on the correction to the calculation of $(g_\mu - 2)$ from this mode by nearly a factor two to 5%:

$$a_\mu(\pi^+\pi^-\eta) = (1.18 \pm 0.03 \pm 0.06) 10^{-10}. \quad (4)$$

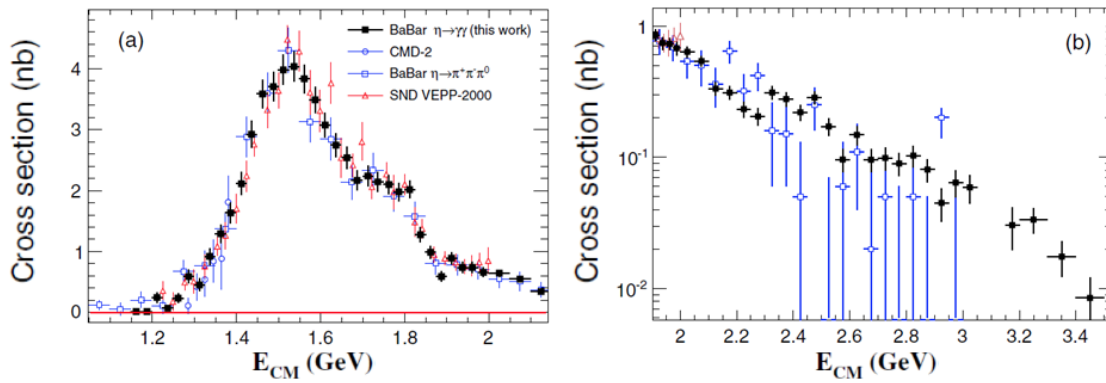


Figure 3. Cross section of $e^+e^- \rightarrow \pi^+\pi^-\eta$ as a function of energy at (a) low and (b) high energy from BABAR (black circles with statistical uncertainties) and previously published results.

5. Modes with kaons

Charged kaons are identified as tracks selected with particle identification information coming mainly from the DIRC Cherenkov detector. K_S^0 are reconstructed from $\pi^+\pi^-$ decays as pairs of tracks with opposite sign and a displaced vertex. K_L^0 are detected as isolated energy clusters of more than 0.2 GeV in the calorimeter, which give the direction of the K_L^0 candidates. Their energy however is determined in the kinematic fit of the event. The method has been validated by studying the recoil mass against the $K_S^0\gamma$ system in the $\gamma\phi$ channel with the ϕ decaying into $K_S^0K_L^0$. In the channels under study, the resolution in the invariant mass of the hadronic system is about 25 MeV/ c^2 . Backgrounds from known ISR processes account for about half of the background in data. The additional one is estimated from sideband regions in the χ^2 of the kinematic fit.

With 3669 signal events, the BABAR Collaboration has obtained the first measurement of the $e^+e^- \rightarrow K_S^0K_L^0\pi^0$ cross section [5] as a function of energy between 1 and 4 GeV, as illustrated in figure 4. The cross section peaks at roughly 3 nb around 1.7 GeV, rising sharply from threshold around 1.4 GeV and decreasing quickly up to 2 GeV and then more slowly up to the 3 GeV region, where the J/ψ contribution can be seen. The systematic uncertainty is about 10% in the peak region and 30% around 3 GeV. Resonant substructures have been searched for in the $K_S^0\pi^0$ and $K_L^0\pi^0$ invariant mass distributions, which show a high $K^{*0}(892)$ peak and a much smaller one corresponding to $K^{*0}(1430)$, as illustrated in figure 5. So, similarly to what was observed in the $K^+K^-\pi^0$ channel, the $K_S^0K_L^0\pi^0$ mode is dominated by $K^{*0}(892)\bar{K}$, which accounts for about 90% of the decays, with in addition small amounts of $K^{*0}(1430)\bar{K}$ and $\phi\pi^0$.

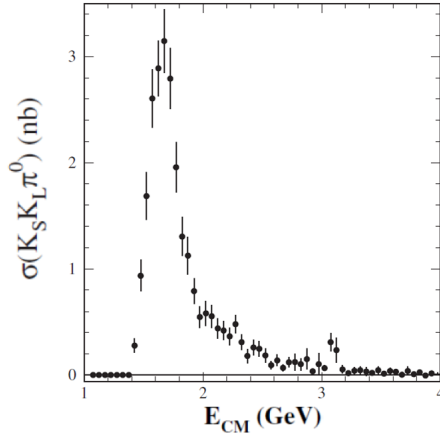


Figure 4. The cross section of $e^+e^- \rightarrow K_S^0 K_L^0 \pi^0$ as a function of energy. The error bars show the statistical uncertainties.

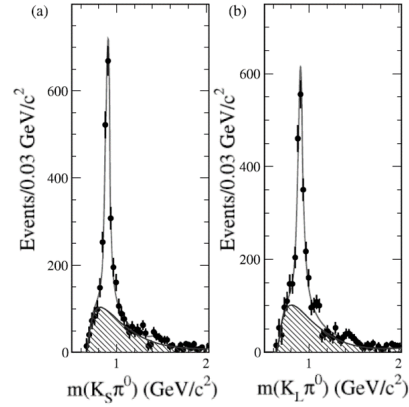


Figure 5. Invariant mass of (a) $K_S^0 \pi^0$ and (b) $K_L^0 \pi^0$ in $e^+e^- \rightarrow K_S^0 K_L^0 \pi^0$. The points show the data and the curve the result of a fit with resonant $K^{*0}(892)$ and $K^{*0}(1430)$, and (hatched) non-resonant components.

The BABAR Collaboration has also measured for the first time the cross sections of the $e^+e^- \rightarrow K_S^0 K_L^0 \eta$ and $e^+e^- \rightarrow K_S^0 K_L^0 \pi^0 \pi^0$ processes [5], based respectively on 864 ± 43 and 392 ± 55 signal events, from threshold up to 4 GeV. As shown in figure 6, the $K_S^0 K_L^0 \eta$ cross section peaks at about 1 nb around 1.7 GeV. It is dominated by the $\phi\eta$ mode under 2 GeV. The systematic uncertainties range roughly linearly from 15% at the peak to 30% at 3 GeV. The $K_S^0 K_L^0 \pi^0 \pi^0$ cross section peaks at about 0.5 nb near 1.8 GeV, as illustrated in figure 7. The systematic uncertainties increase from 25% in the peak region to 60% around 2 GeV and 100% in the high energy region. This channel includes a large fraction of $K^{*0}(892)\bar{K}^0\pi^0$.

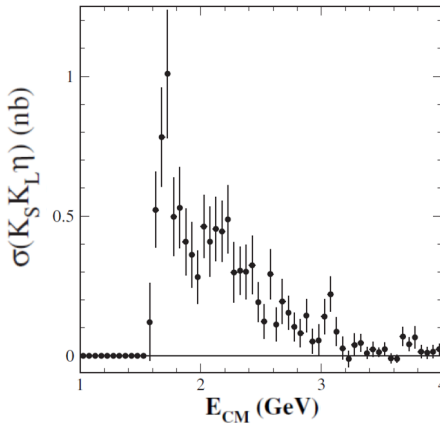


Figure 6. Cross section as a function of energy of $e^+e^- \rightarrow K_S^0 K_L^0 \eta$ with statistical uncertainty.

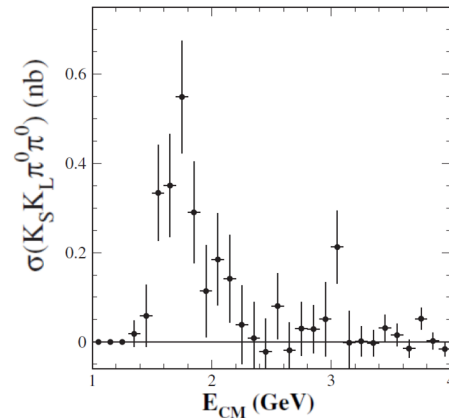


Figure 7. Cross section as a function of energy of $e^+e^- \rightarrow K_S^0 K_L^0 \pi^0 \pi^0$ with statistical uncertainty.

Modes with a K_S^0 , a charged kaon, a charged pion, and either a π^0 or an η meson have also been measured for the first time [6], based respectively on 6430 ± 90 and 358 ± 24 signal events, from threshold up to 4 GeV. After a slow rise from threshold, the cross section of $e^+e^- \rightarrow K_S^0 K^\pm \pi^\mp \pi^0$ increases steeply from 1.6 GeV to a peak value of 2.3 nb near 1.9 GeV,

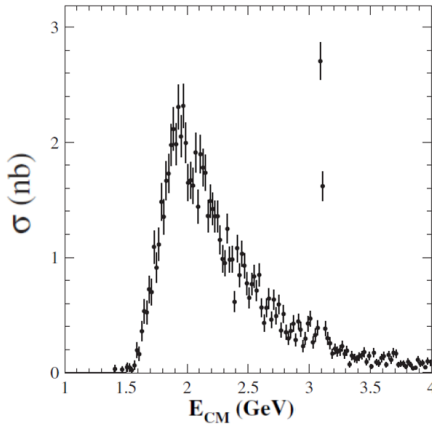


Figure 8. Cross section as a function of energy of $e^+e^- \rightarrow K_S^0 K^\pm \pi^\mp \pi^0$ with statistical uncertainty.

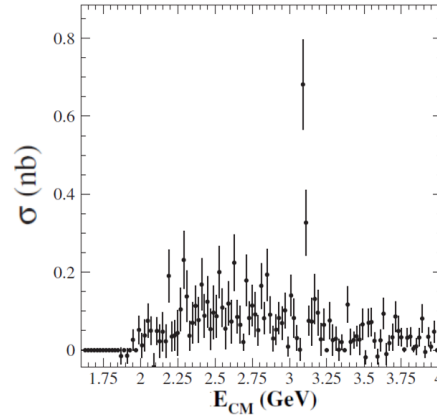


Figure 9. Cross section as a function of energy of $e^+e^- \rightarrow K_S^0 K^\pm \pi^\mp \eta$ with statistical uncertainty.

followed by a slow decrease with energy, except for a strong J/ψ signal, as illustrated in figure 8. The cross section is measured with a systematic uncertainty of 6% around the peak and 12% in the tail region. Many intermediate resonant states are present, among which $K_S^0 K^\pm \rho^\mp(770)$, $K^{*0}(892) K^\pm \pi^\mp$, $K^{*\pm}(892) K^\mp \pi^0$, $K^{*0}(892) K_S^0 \pi^0$, and $K^{*+}(892) K^{*-}(892)$. The cross section of $e^+e^- \rightarrow K_S^0 K^\pm \pi^\mp \eta$ is obtained with a systematic uncertainty varying from 13% below 3 GeV to 19% above. As illustrated in figure 9, it is much smaller with a value consistent with 0.1 nb over a wide range around 2.5 GeV and shows a broad shape with no peak, except at the J/ψ mass. The dominant intermediate resonances are from $K^{*\pm}(892) K^\mp \eta$ and $K^{*0}(892) K_S^0 \eta$.

All the accessible $KK\pi$ and $KK\pi\pi$ channels have now been covered by BABAR. With the measurement of $K_S^0 K_L^0 \pi^0$, the precision on the contribution of all $KK\pi$ modes for $(g_\mu - 2)$ has been improved by 20%, reaching 6%. The contribution of the $KK\pi\pi$ modes was previously calculated with only the two $K^+ K^-$ channels and isospin relations. Including the four additional modes involving a K_S^0 gives a precision of 6%, improving it by as much as a factor eight.

$$a_\mu(\text{all } KK\pi) = (2.45 \pm 0.15) 10^{-10} \text{ and } a_\mu(\text{all } KK\pi\pi) = (0.85 \pm 0.05) 10^{-10}. \quad (5)$$

6. Conclusion

The ISR technique allows a comprehensive study of low energy e^+e^- annihilations in a single experiment. BABAR has recently measured the cross sections of $\pi^+\pi^-\pi^0\pi^0$, a large contributor to the uncertainty on $a_\mu^{LO\text{had.}}$, and modes with two kaons that had never been measured before.

Within a few years, by using all the new experimental results, the uncertainty on the hadronic correction (from equation 2 to equation 6) has decreased by 20% [7]. The difference between the prediction and the measured value of $(g_\mu - 2)$ stays at about 3.5σ :

$$a_\mu^{LO\text{had.}} = (693.1 \pm 3.4) 10^{-10}. \quad (6)$$

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