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Low energy exclusive e^+e^- cross sections and inclusive charged hadron production with the Babar detector

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Recent results on exclusive hadronic cross sections from the Babar Collaboration at SLAC are presented. Specifically, we present results on the $e^+e^- \to K^+K^-(\gamma)$ and $e^+e^- \to p\bar{p}$ cross sections. The observations are performed using events with initial-state photon radiation, which allows the cross sections to be measured at low energy and over an extended energy range. In addition, we present results on the inclusive momentum spectra of identified charged pions, kaons, and protons at a center-of-mass energy of 10.54 GeV, which allow new tests of QCD calculations.

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1. Introduction

The Babar experiment operated at the PEP-II asymmetric-energy e^+e^- collider at SLAC from 1999-2008. The data analysis is still very active, with around 30 physics publications expected in 2013. Most data were collected at the energy of the $\Upsilon(4S)$ resonance, just above the threshold to produce a $B\overline{B}$ bottom-quark meson pair. The $B\overline{B}$ event sample was (and still is being) used to study CP violation and to probe the physics of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. Babar also collected large samples of $e^+e^- \to c\bar{c}$ and $e^+e^- \to \tau^+\tau^-$ events and has many results on charm meson and tau lepton physics. The topics of the current presentation are something yet different, however: events with initial-state photon radiation (ISR), which give access to measurements of low-energy exclusive e^+e^- cross sections, and recent results on the inclusive production of identified charged hadrons ($\pi^\pm$, $K^\pm$, p) at the fixed center-of-mass energy of 10.54 GeV.

2. The $e^+e^- \to K^+K^-(\gamma)$ cross section and charged kaon form factor

Our recent measurement of the $e^+e^- \to K^+K^-(\gamma)$ cross section [1] fits into a broad Babar ISR program to provide a precise low-energy measurement of the inclusive $e^+e^- \to$ *hadrons* cross section by summing exclusive channels. One measures the $\sigma(e^+e^- \to X\gamma_{ISR})$ cross section, with "X" the exclusive state, as a function of the mass $\sqrt{s'} = m_X$ of the state, where $\sqrt{s'}$ is the effective c.m. energy. The sum of exclusive channels provides a more accurate determination of the cross section than a measurement based on the inclusive recoil against the ISR photon γ_{ISR} because it yields better mass ($\sqrt{s'}$) resolution. With the K^+K^- results presented here, Babar covers essentially the complete set of significant exclusive channels.

The low-energy $e^+e^- \to$ *hadrons* inclusive cross section is needed for the calculation of the hadronic correction to the vacuum polarization contribution to the muon magnetic anomaly a_μ, namely for the standard model prediction of the muon $g-2$ value. Note that a_μ cannot be calculated perturbatively. Instead one uses the measured low-energy $e^+e^- \to$ *hadrons* inclusive cross section in conjunction with dispersion relations.

We measure the number of $K^+K^-(\gamma)$ events in intervals of $\sqrt{s'}$. We allow the possibility of an additional photon "(γ)," beyond the ISR photon, in order to keep the uncertainty of the event acceptance below 10^{-3}. The luminosity is monitored by measuring the number of $\mu^+\mu^-(\gamma)$ events within the same data sample. Thus knowledge of the absolute luminosity is not necessary, and there is no reliance on theoretical expressions for radiator functions, reducing systematic uncertainties.

Events are required to contain two charged tracks consistent with a K^+K^- pair. The photon with highest energy is identified as the ISR photon. The ISR photon must have at least 3 GeV in the c.m. frame and lie within 0.3 radians of the missing momentum vector formed from all other reconstructed particles in the event (this last requirement strongly suppresses non-ISR events). Background events, which mostly arise from other ISR processes, are subtracted, and the data are corrected to account for finite detector resolution.

The measured cross section is shown in Fig. 1 (left). The Babar results cover a large energy range compared with previous experiments and six orders of magnitude in cross section. The precision of the results is emphasized in Fig. 1 (right), which shows the Babar results in a zoomed energy range in comparison with results from other experiments. Concerning the muon anomaly, the

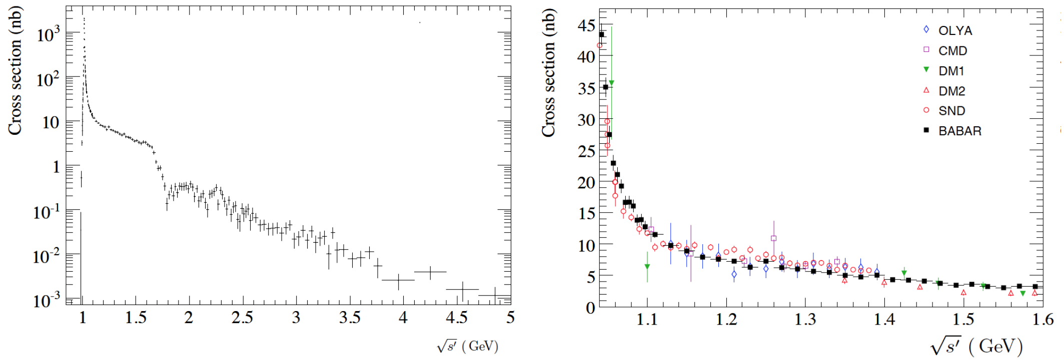

Figure 1: Babar results for the $e^+e^- \to K^+K^-(\gamma)$ cross section, (left) over the full energy range probed and (right) in the $1.04 \leq \sqrt{s'} \leq 1.60$ GeV region.

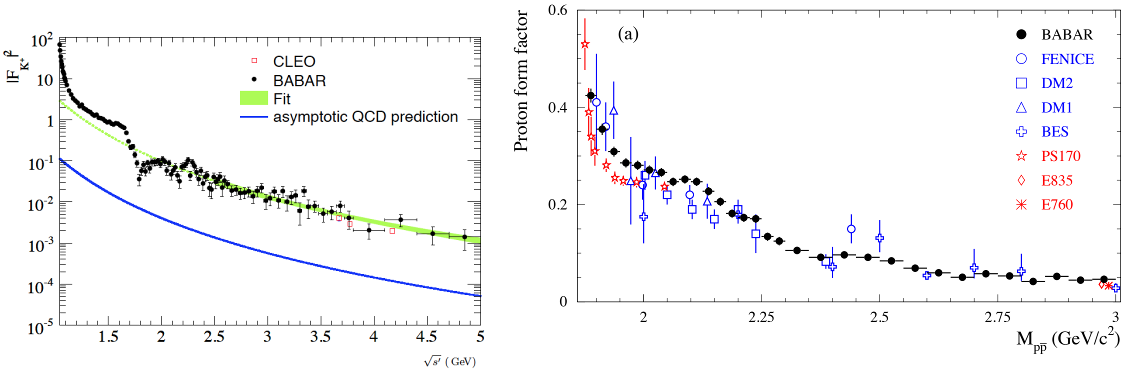

Figure 2: (left) The charged kaon form factor measurement from Babar. The solid green line shows the result of a fit of the QCD shape $\alpha_S(s')/s'$ to the data. The solid blue line shows the QCD result including the predicted absolute normalization. (right) Babar measurement of the proton form factor in comparison with previous results.

Babar results yield $a_\mu^{\mathrm{KK,LO}} = 22.93 \pm 0.18(\mathrm{stat.}) \pm 0.22(\mathrm{syst.})$, compared with the previous result $a_\mu^{\mathrm{KK,LO}} = 21.63 \pm 0.27(\mathrm{stat.}) \pm 0.68(\mathrm{syst.})$, and thus improve the precision of the KK contribution by about a factor of three.

We also extract the charged kaon form factor, shown in Fig. 2 (left). In the $\sqrt{s'} \geq 2.5$ GeV region above the hadron resonances, the shape of the QCD prediction $\alpha_S(s')/s'$ (with α_S the strong coupling strength) agrees with the data. However the predicted normalization is wrong by an order of magnitude. The Babar measurements agree with those from the CLEO experiment [2], shown by the three red squares in Fig. 2 (left). CLEO has results at three energy points only because they use fixed c.m. energies rather than the ISR method.

3. The proton form factor

A similar ISR technique to that described above for $e^+e^- \to K^+K^-(\gamma)$ events is used to select and study $e^+e^- \to p\bar{p}$ events [3]. These $p\bar{p}$ results update those of a previous Babar publication [4] using twice as much data and improved analysis techniques.

The new Babar results for the proton form factor are shown in Fig. 2 (right). The results confirm the enhancement of the $e^+e^- \to p\bar{p}$ cross section just above the $p\bar{p}$ threshold. Similar to the K^+K^- study, the Babar $p\bar{p}$ measurements provide precise results over a wider energy range than previous experiments.

4. Identified charged hadron production

The final topic concerns the inclusive production of identified charged pions, kaons, and protons at $E_{c.m.} = 10.54$ GeV [5], with $E_{c.m.}$ the c.m. energy. The multiplicity and momentum spectra of identified charged hadrons provide a basic characterization of multihadronic events, and information on how hadronization depends on hadron mass, strangeness, and baryon number.

Precise measurements of identified charged hadron spectra at energies around 91 GeV were provided by the LEP and SLD experiments. However, until the present work and and roughly contemporaneous results from the Belle Collaboration [6], the only results on identified charged hadrons at $E_{c.m.} \approx 10$ GeV were from the ARGUS experiment [7]. The BES experiment presented distributions of inclusive charged particle multiplicity and momentum for c.m. energies between around 2 and 5 GeV [8], but not results for identified hadrons.

The Babar analysis makes use of 0.91 fb^{-1} of data collected in the e^+e^- continuum region at 10.54 GeV. This is only about 0.2% of the total Babar data sample but is sufficient because the uncertainties are dominated by systematic terms. Charged tracks are required to have momenta above 200 MeV so that the particle identification (PID) efficiencies are well determined. In total, 2.2 million events are selected. As for the other studies discussed here, MC-derived track-selection and PID efficiencies are corrected to account for data-MC discrepancies using control samples in the data. The background, which primarily arises from $e^+e^- \to \tau^+\tau^-$ events, is subtracted. We mostly use prompt particles in presenting results, which means that the decay products of K^0_S mesons and weakly decaying baryons are not included. This differs from the convention generally used by the LEP and SLD experiments.

The results for the inclusive identified charged hadron spectra are shown in Fig. 3 (left). The data are displayed in bins of $x_p = 2p^*/E_{c.m.}$, where p^* is the c.m. particle momentum. The results are shown (from top to bottom) for charged pions, kaons, and protons. The corresponding results from ARGUS are also shown. The Babar and ARGUS data agree once the small difference in c.m. energy is accounted for. The Babar data for kaons and protons are seen to be far more precise than those of ARGUS.

The precise low energy Babar data allow the scaling behavior to be investigated. Figure 3 (right) shows the Babar data (black points) for charged pions (top) and protons (bottom) in comparison with the corresponding results from SLD at 91.2 GeV [9] (green points). Intermediate-energy results from the TASSO experiment [10] are also shown. Clear scaling violations are observed, i.e., the Babar and SLD data do not agree with each other. At large values of x_p, the scaling violation is attributed to the running of the strong coupling strength α_S, while at small x_p it is a hadron-mass effect. Shown in comparison with the data are predictions from the Jetset [11] Monte Carlo event generator. The green and black Jetset curves correspond to $E_{c.m.} = 10.54$ and 91.2 GeV, respectively. For charged pions (top right plot of Fig. 3), the black curve goes through the black points and the green curve through the green points, so the scaling behavior is well described. For protons,

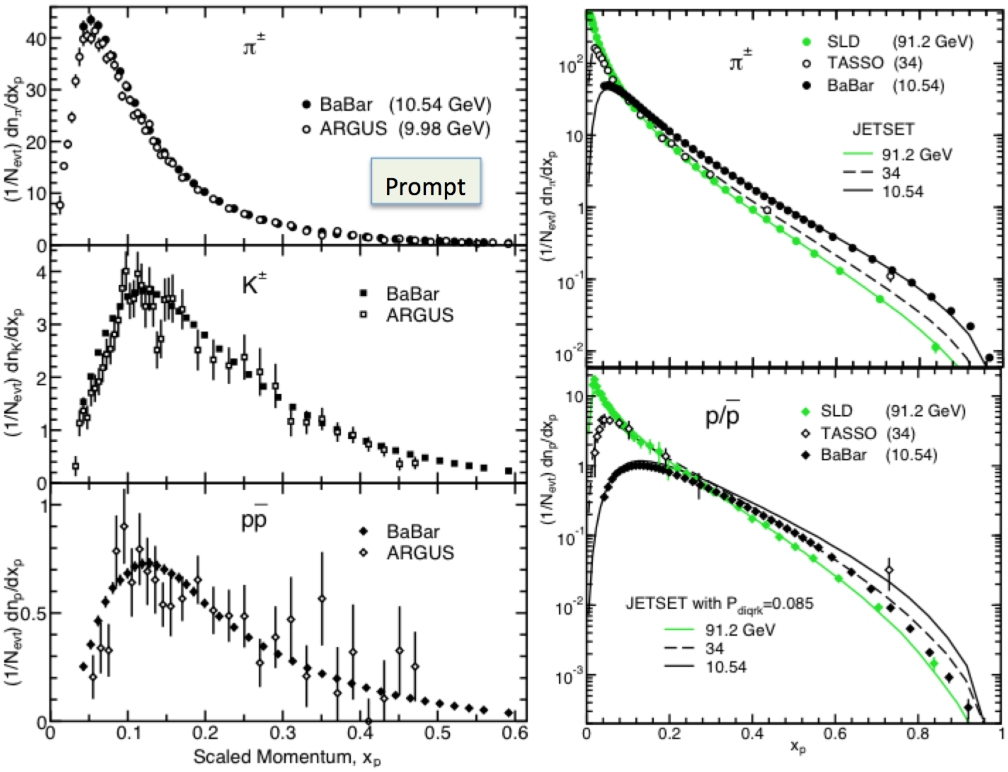

Figure 3: (left) Scaled momentum spectra for charged pions, kaons, and protons; (right) Comparison of the scaled momentum spectra of charged pions and protons for the SLD, TASSO, and Babar experiments.

however (bottom right plot of Fig. 3), the black curve lies above the black points, indicating that the scaling violation is overestimated by the simulation.

Following the lead of LEP, we also plot the data in terms of the $\xi = -\ln(x_p)$ variable. In the modified leading-logarithm approximation (MLLA), taken together with the local parton-hadron duality conjecture (which states that hadron-level distributions are the same as parton-level distributions up to the normalization factor), the ξ distributions are predicted to be Gaussian in the region around the peak. The results, shown in Fig. 4 (left), agree with this prediction. We next consider the peak position of the ξ distribution, denoted ξ^*. The MLLA predicts that ξ^* should increase logarithmically with c.m. energy for a given hadron type, and that – for a fixed c.m. energy – ξ^* should decrease exponentially with hadron mass value. Figure 4 (right) shows the ξ^* results. For the protons (green points), we draw a straight line between the high-precision Babar and SLD points (at 10.54 and 91.2 GeV, respectively). The results of intermediate-energy experiments are seen to be consistent with this line. Analogous results are found for protons (black solid line and diamonds). Furthermore, the slopes of the pion and proton curves are consistent with each other. Also, the ξ^* values of protons lie well below those of pions, consistent with the expected mass dependence of ξ^*. All these results are consistent with the MLLA prediction. However, the slope for the corresponding kaon curve [see the open squares and dashed black line in Fig. 4 (right)] differs from that for pions and kaons, and the ξ^* values of kaons hardly differ from those of protons. The different slope for kaons can be explained by the rapidly changing strange-quark content of events

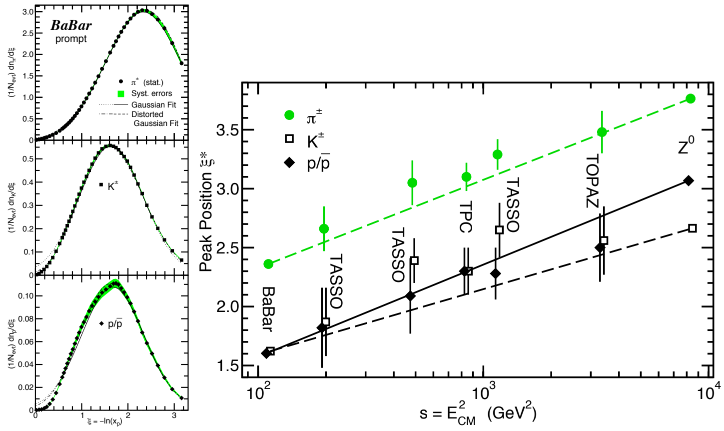

Figure 4: (left) Distributions of $\xi = -\ln(x_p)$ with $x_p = 2p^*/\mathrm{E}_{\mathrm{c.m.}}$ for (from top to bottom) charged pion, kaons, and protons. (right) The peak position ξ^* of the ξ distributions as a function of $\mathrm{E}_{\mathrm{c.m.}}$ for Babar and other experiments.

between 10 and 91 GeV, which is not accounted for in the QCD calculations.

5. Summary

Babar has a strong and comprehensive program in the measurement of exclusive $\mathrm{e}^+\mathrm{e}^- \to$ *hadrons* cross sections at low c.m. energies using the ISR method. Summing the exclusive channels yields improved results for the inclusive cross section, which is having an impact on the precision of the standard model prediction for the muon anomaly a_μ. First results for the $\mathrm{e}^+\mathrm{e}^- \to \mathrm{K}^+\mathrm{K}^-(\gamma)$ cross section are shown, as are updated results for the proton form factor.

Precise measurements of the inclusive momentum spectra of identified charged pions, kaons, and protons $\mathrm{E}_{\mathrm{c.m.}} = 10.54$ GeV allow new tests of QCD predictions, both for scaling violations and MLLA calculations.

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