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# INCLUSIVE HADRONIC RESULTS AT BaBar : ISR AND PENTAQUARK SEARCHES

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ABSTRACT

We present recent measurements of hadronic cross-sections from the BaBar experiment and report preliminary results on searches for pentaquark states.

## 1 Inclusive hadronic cross-section measurements using Initial State Radiation

### 1.1 Physics Motivation

The total cross-section $\sigma(e^+e^- \to \text{hadrons})$ for the production of hadrons in $e^+e^-$ annihilation is a crucial ingredient for the calculation of hadronic corrections for the running of the QED coupling constant $\Delta\alpha_{QED}^{Had}$ and for the muon anomalous magnetic moment $a_\mu^{Had}$. The hadronic contribution to the

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running of $\alpha_{QED}$, $\Delta\alpha^{Had}_{QED}$ is an input into the global standard model fits [1] which can provide an indirect measurement of the Higgs boson mass. In both cases, the hadronic contributions can be expressed as integrals of the ratio $R(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma_0(e^+e^- \to \mu^+\mu^-)$, where $\sigma_0$ denotes the Born cross-section. We have

$$\Delta\alpha^{Had}_{QED} = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} \frac{R(s)}{s}\left(\frac{m_Z^2}{s-m_Z^2}\right) \tag{1}$$

$$a_\mu^{Had} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{R(s)}{s}\left(\frac{K(s)}{s}\right), \tag{2}$$

where $K(s)$ is sharply peaked at $s = 0$. In the case of $\Delta\alpha^{Had}_{QED}$, the weight factor is almost independent of $s$ for small values of $s$, so that the entire spectrum of $R(s)$ contributes to the integral. In the case of $a_\mu$ the integral is dominated by the low $s$ region.

The error on $\Delta\alpha^{Had}_{QED}$ is dominated by the region $1\,\text{GeV} < \sqrt{s} < 7\,\text{GeV}$. Below 1 GeV, CMD-2 and KLOE have measured [2] $\sigma(e^+e^- \to \pi^+\pi^-)$ to $< 1\%$ accuracy. BES [3] has measured $R(s)$ in the range $2\,\text{GeV} < \sqrt{s} < 5\,\text{GeV}$ at 6% accuracy, but there are no recent measurements in the region $1\,\text{GeV} < \sqrt{s} < 2\,\text{GeV}$, leading to large uncertainties.

### 1.2 Initial-state Radiation at $\Upsilon(4S)$ Energies

The BaBar experiment operates at the PEP-II asymmetric $e^+e^-$ collider. While PEP-II is a fixed-energy machine, initial-state radiation (ISR), can be used to vary of the center-of-mass energy of hadron production. The full spectrum of $s'$, the reduced center-of-mass energy, is accessible. The range $0 < s' < 7\,\text{GeV}$ can be reached for ISR photon energies of $3-5.3\,\text{GeV}$ in the center-of-mass system. The photon can be detected by the BaBar electro-magnetic calorimeter (EMC) to provide a clear signature for the event. In particular, the presence of a hard photon can separate $e^+e^-$ annihilation events from beam-gas processes which constitutes an important source of background for energy-scan experiments. The hadronic system is also collimated by its recoil against a hard photon and the spectrum of the observed particles is also hardened, improving detection efficiency and reducing the dependence on the hadronization model. Requiring the ISR photon in the sensitive part of the detector further improves the fiducial containment of the hadronic system. Final-state radiation (FSR) effects are expected to be small and kinematically well-separated from ISR.

The cross-section for hadronic ISR events was evaluated using the Monte-Carlo generators. The total cross-section for $s' < 8\,\mathrm{GeV}$ in the fiducial region $15.3 < \theta_\gamma < 137.3^o$ is calculated to be 90 pb, corresponding to 18 million events in the current BaBar dataset of $200\,\mathrm{fb}^{-1}$. Of these we expect 5.7 million events for $2 < s' < 5\,\mathrm{GeV}$, to be compared with approximately 250,000 events used for the latest BES measurement in this energy range.

The main challenge of the method is the determination of the reduced center-of-mass energy $\sqrt{s'}$. This is addressed differently in the various analyses.

### 1.3 $e^+e^- \to h^+h^-h^+h^-\gamma$

BaBar performed a common analysis of the processes $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\gamma$, $e^+e^- \to K^+K^-\pi^+\pi^-\gamma$ and $e^+e^- \to K^+K^-K^+K^-\gamma$. Events with at least 4 tracks and a neutral cluster are subjected to 1C kinematic fits with the constraint $m_\gamma = 0$. A kaon identification procedure is performed on the tracks, using ionization measurements in the tracking detectors and information from the Čerenkov detector. The cross-sections are normalized using the process $e^+e^- \to \mu^+\mu^-\gamma$. Results are shown in fig. 1.

The $4\pi$ and $2K2\pi$ results agree with existing results, but are considerably more precise and cover a larger energy range. The $4K$ result is the first measurement of this quantity. In all cases, the leading uncertainties are systematic, dominated by uncertainties on the luminosity, tracking efficiency and acceptance losses. The $J/\psi$ resonance is clearly visible in all 3 cases, leading to branching fraction results of $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^+\pi^-) = (3.70\pm0.27\pm0.36)\times10^{-3}$, $\mathcal{B}(J/\psi \to K^+K^-\pi^+\pi^-) = (6.25\pm0.50\pm0.62)\times10^{-3}$, $\mathcal{B}(J/\psi \to K^+K^-K^+K^-) = (6.9 \pm 1.2 \pm 1.1) \times 10^{-3}$, assuming the PDG value for $\Gamma(J/\psi \to e^+e^-)$. These results agree with the PDG values but are significantly more precise. The $4\pi$ mode also provides a measurement of $\mathcal{B}(\psi(2S) \to J/\psi(\mu^+\mu^-)\pi^+\pi^-$ through the mis-identification of the muons as pions. Assuming the PDG values for $\Gamma(J/\psi \to \mu^+\mu^-)$, $\Gamma(\psi(2S) \to e^+e^-)$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-)$, we get $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-) = 36.1 \pm 1.5 \pm 3.7\%$.

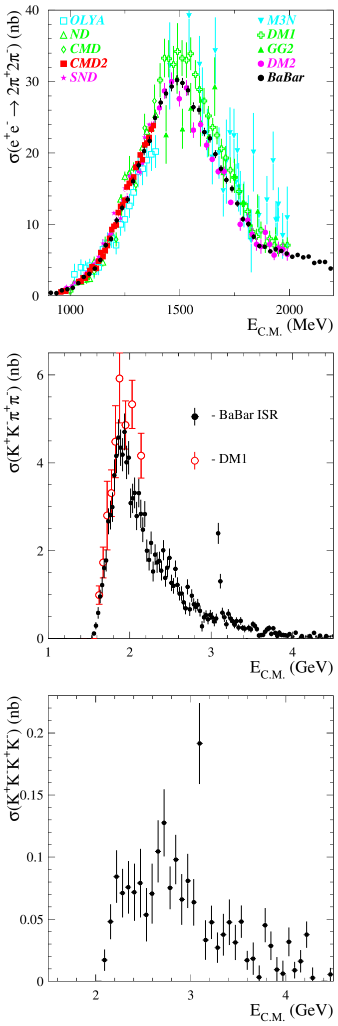


Figure 1: *Cross sections for* $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ *(top),* $K^+K^-\pi^+\pi^-$ *(center) and* $K^+K^-K^+K^-$ *(bottom) using* $89\,fb^{-1}$ *of data.*

### 1.4 $e^+e^- \to J/\psi(\mu^+\mu^-)\gamma$

The analysis of $e^+e^- \to J/\psi(\mu^+\mu^-)\gamma$ is done in similar fashion to that of the preceding section. We require energy and momentum conservation and perform a 1C kinematic fit with $m_\gamma = 0$. To reject ISR background, both tracks are required to be identified as muons.

The cross-section for $J/\psi$ production is obtained from the ratio of peak to continuum production. Assuming PDG values for $B_{\mu\mu}$ and $\mathcal{B}(J/\psi \to e^+e^-)$, we obtain $\Gamma(J/\psi \to e^+e^-) = 5.61 \pm 0.20\,\mathrm{keV}$ and the full width of the $J/\psi$ to be $\Gamma_{J/\psi} = 94.7 \pm 4.4\,\mathrm{keV}$.

### 1.5 Inclusive Analysis

Alongside the exclusive analyses presented above, a fully inclusive analysis of hadronic ISR processes is being performed, with the goal of extracting $\Delta\alpha_{QED}^{Had}$ with $3-4\%$ error. We select events with an ISR photon with center-of-mass energy greater than $3\,\mathrm{GeV}$. The various efficiency terms can all be calibrated to 1% or below; we have a triggering efficiency of 98% and a fiducial photon detection efficiency of 90%. The $s'$ integrated luminosity spectrum can be computed from the BaBar integrated luminosity, which is known to about 1%. The precision of this calculation is claimed to be less than 1%.

Leading background sources, such as radiative Bhabha, $e^+e^- \to \gamma\gamma$ and virtual Compton scattering processes can be vetoed with minimal signal losses and biases. Other modes such as $e^+e^- \to \mu^+\mu^-\gamma$ and $\tau^+\tau^-\gamma$ can be subtracted using theoretical predictions. Finally, $e^+e^- \to q\bar{q}$ events are a major source of background for $s' > 5\,\mathrm{GeV}$, mainly due to production of high-momentum $\pi^0$ and $\eta$. Event shape variables of the hadronic system can be used to suppress this background.

For this inclusive measurement, $s'$ is determined from the ISR photon energy. Due to the EMC energy resolution of about 3% for the energies considered here, the $R(s)/s$ spectrum is distorted, especially at low $s'$. However, since $\Delta\alpha_{QED}^{Had}$ is expressed as an integral in $R(s)/s$ with a weakly-varying weight factor, distortions in the spectrum do not affect the measured value for $\Delta\alpha_{QED}^{Had}$. The energy resolution therefore has minimal impact on the $\Delta\alpha_{QED}^{Had}$ measurement. The inclusive method cannot be applied to the measurement for $a_\mu^{Had}$ since the weight factor in this case is strongly peaked at $s' = 0$.

## 2 Searches for Pentaquark Resonances

Several experiments have recently claimed observations of exotic baryon resonances which seem to be composed of 5 constituent quarks. The LEPS [4] experiment has claimed observation of a resonance $\Theta^+$ at a mass of about 1540 MeV. The NA49 experiment [5] reports two degenerate states, $\Xi_5^0$ and $\Xi_5^{--}$ with masses of 1862 MeV. These resonances have been interpreted as members of a $\bar{10} + 8$ multiplet of flavor $SU(3)$, with the isospin-singlet $\Theta^+$ associated with states denoted as $N_5$, $\Sigma_5$ and $Xi_5$ in analogy with the usual baryon multiplets.

BaBar is well suited to search for these states, with excellent kaon and proton identification and excellent tracking resulting in good mass resolutions. Searches for the $\Theta^+$, $\Xi_5^0$, $\Xi_5^-$ and $\Xi_5^{--}$ states have been performed.

A search for $\Theta^+$ was done for the decay mode $\Theta^+ \to pK_S^0$. We expect a resolution of about 2 MeV on the $\Theta^+$ mass, which would be the most precise to date. However as shown in fig. 2, no peak is seen at the expected mass and only a large signal for $\Lambda_C \to pK_S^0$ is observed.

A search for the $\Xi_5^0$ and $\Xi_5^{--}$ resonances was performed using the decay chain $\Xi_5^{0/--} \to \Xi^-\pi^\pm$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$, with the proton identified as before. As shown in fig. 2, no peak is seen at the expected masses. In the $\Xi^+\pi^-$ spectrum, prominent peaks for the $\Xi^*(1530)$ and $\Xi_c^0(2250)$ are seen. No structure is observed in the exotic $\Xi^-\pi^-$ spectrum.

Searches for $\Xi_5^0 \to \Lambda K_S^0$, $N_5^0 \to \Lambda K_S^0$, $N_5^+ \to \Lambda K^+$ and $\Xi_5^- \to \Lambda K^-$, were also performed, using kaon identification and reconstructing $\Lambda \to p\pi^-$ and $K_S^0 \to \pi^+\pi^-$ as above. As shown in fig. 2 no exotic resonances were observed, while sharp peaks for $\Omega^- \to \Lambda K^-$, $\Lambda_c^+ \to \Lambda K^+$ and $\Xi_c^0 \to \Lambda K_S^0$ are clearly seen.

## 3 Conclusion

Studies of hadronic cross-sections using initial-state radiation offer promising prospects at BaBar. Many exclusive channels have already been measured, and more are in progress. A fully inclusive analysis should also offer a precise measurement of $\Delta\alpha_{QED}^{Had}$. Searches for pentaquark states have so far been negative, but they have served to highlight the potential for the study of charmed and non-charmed baryons at high-luminosity $e^+e^-$ colliders.

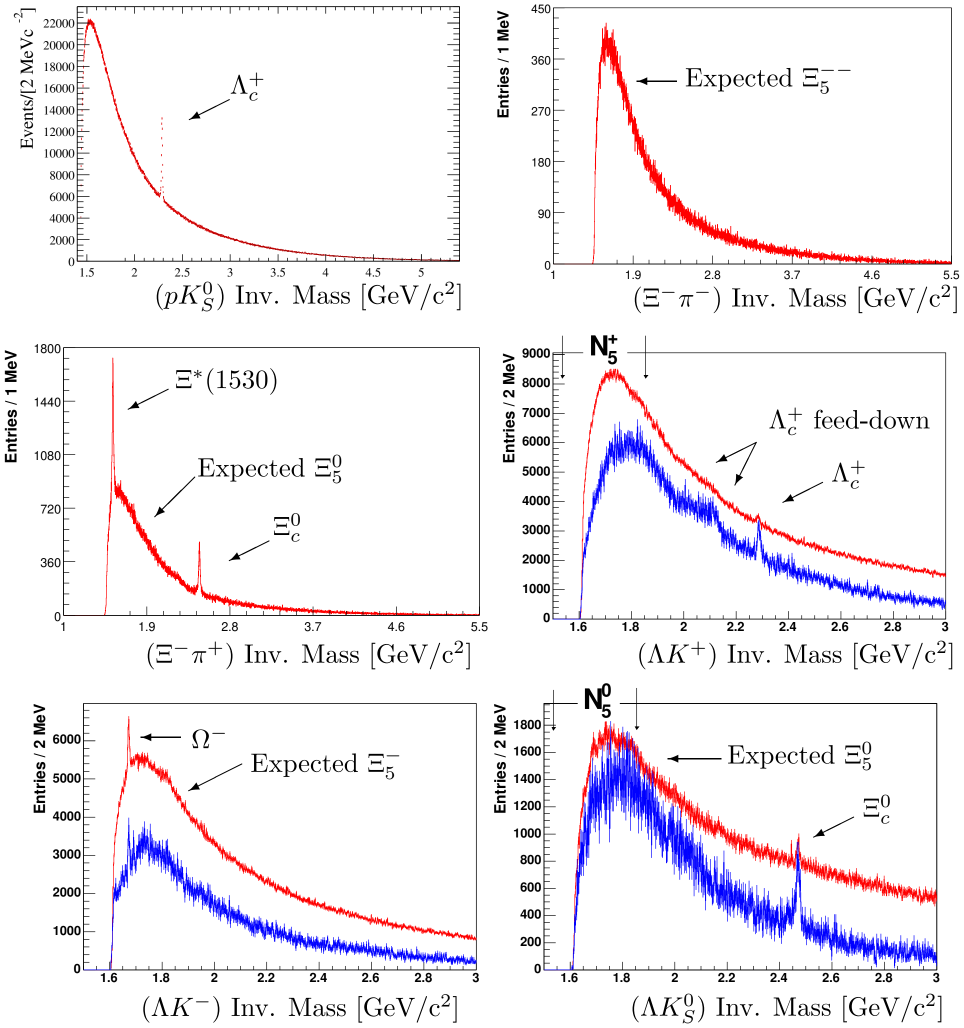


Figure 2: *Mass spectra for $pK_S^0$ and $\Xi^-\pi^-$ (top row), $\Xi^+\pi^-$ and $\Lambda K^+$ (middle row) and $\Lambda K^-$ and $\Lambda K_S^0$ (bottom row) using $123\,fb^{-1}$ of data. For the three latter plots, the upper and lower histograms correspond to $\Lambda K$ center-of-mass momenta respectively smaller than and greater than $3\,GeV$, with the lower histogram scaled up by a factor of 10 for lisibility. The positions of know resonances and expected $\Xi_5$ and $N_5$ pentaquarks are shown.*

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