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Recent QCD results from the *BABAR* experiment

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We report some of the most recent results in studying different aspects of QCD with about 500 fb^{-1} of data collected by the *BABAR* experiment at the e^+e^- B-factory PEP-II, located at SLAC National Accelerator Laboratory. In particular, we present the Dalitz plot analyses of the hadronic three-body J/ψ decays to $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, and $K_SK^\pm\pi^\mp$ using an isobar model and a Veneziano model. From the isobar analyses of the modes $J/\psi \to K^+K^-\pi^0$ and $J/\psi \to K_SK^\pm\pi^\mp$, a broad structure has been observed in the low-mass region of the $K\bar{K}$ invariant mass spectra and found to be consistent with the neutral and charged resonances $\rho(1450)$. Moreover, for the first time the branching fraction ratio of the decay $\rho(1450)^0 \to \pi^+\pi^-$ over $\rho(1450)^0 \to K^+K^-$ is measured to be $(0.307 \pm 0.084 \pm 0.082)$. We then show the results of a search for the B-meson decay to four baryons $B^0 \to pp\bar{p}\bar{p}$, which might help shedding some light on the mechanism of hadron fragmentation into baryons, and on the experimental difference between the inclusive branching fraction of B-meson decay to baryons and the sum of the exclusive baryonic B decays. A signal yield of 10.4 ± 4.3 events is observed, corresponding to a statistical significance of 3σ, and the upper limit is computed to be 2×10^{-7} at 90% confidence level.

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1. The *BABAR* experiment

The results presented here are based on the analysis of the data collected with the *BABAR* detector [1] at the electron-positron asymmetric-energy collider PEP-II. Charged-particle momenta are precisely measured by means of a five-layer double-sided silicon vertex tracker and a 40-layer multiwire drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. A CsI(Tl) crystal electromagnetic calorimiter (EMC) measures photons, neutral particles and identified electrons thanks to the absorption of the produced electromagnetic showers. The particle identification (PID) for protons, kaons and pions uses the specific energy loss measured in the tracking devices and the measurement of the Cherenkov angle provided by the internally reflecting, ring-imaging Cherenkov detector.

2. The Dalitz-plot Analysis

The dataset used for this analysis [2] corresponds to 519 fb^{-1} collected at the centre-of-mass (CM) energy of $\Upsilon(nS)$ resonances, with $n = 2,3,4$. Initial State Radiation (ISR) processes $e^+e^- \to J/\psi\gamma_{ISR}$ are selected to provide clean J/ψ samples with undetected forward photons γ_{ISR}. The conservation of the initial-state quantum numbers $J^{PC} = 1^{--}$ is exploited to study multiquark resonances, which are predicted by the QCD to populate the low-mass region of the hadron mass spectrum. The J/ψ decay is reconstructed into different three-body hadronic channels, $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $K_SK^\pm\pi^\mp$, and for all of them the Dalitz-plot analysis is performed. Only poorly measured branching fractions and preliminary results from previous Dalitz-plot analyses already existed for these modes [3].

2.1 Method

The event reconstruction is similar for all the three channels. Starting from the initial four-momenta of the beam particles (p_{e-}, p_{e+}), the recoil mass $M^2_{rec} = (p_{e-} + p_{e+} - p_{h1} - p_{h2} - p_{h3})^2$ is calculated, which is expected to peak around zero, since in ISR events it corresponds to the ISR photon mass, treated as a missing particle. Background is rejected by accepting only events in the window $|M^2_{rec}| < 2$ GeV/c^2 and by reconstructing, from the final-state four-momenta, the invariant mass for the three-hadron system, which should peak at the J/ψ mass for signal events. For each mode, the signal yield is extracted by fitting the mass spectrum with a Monte Carlo resolution function, corresponding to the sum of a Gaussian function and a Crystal ball shape function [4]. The fitted signal yields are reported in Table 1 and the branching fraction ratios for the modes $J/\psi \to K^+K^-\pi^0$ and $J/\psi \to K_SK^\pm\pi^\mp$, normalized to $J/\psi \to \pi^+\pi^-\pi^0$, are computed, giving respectively $(0.120 \pm 0.003_{stat} \pm 0.009_{sys})$ and $(0.265 \pm 0.005_{stat} \pm 0.021_{sys})$.

2.2 Results

For the mode $J/\psi \to \pi^+\pi^-\pi^0$ the Dalitz-plot analysis is performed on the events in the signal region indicated in Table 1, using two different models, the isobar and the Veneziano models. The second approach assumes that the low-energy spectrum is dominated by resonances and they can be described thanks to the resonance-Regge duality [5]. The two fits are reported in Figure 1, where the dominant contribution among the fitted fractions is due to the $\rho(770)\pi$ resonance, giving an isobar

J/ψ decay mode	Signal region (GeV/c^2)	Event yields	Purity %
$\pi^+\pi^-\pi^0$	$3.028 - 3.149$	20417	91.3 ± 0.2
$K^+K^-\pi^0$	$3.043 - 3.138$	2102	88.8 ± 0.7
$K_S K^\pm \pi^\mp$	$3.069 - 3.121$	3907	93.1 ± 0.4

Table 1: For each analysed mode, the results from the invariant mass spectrum fit is reported in the third column. In the second column, the fitting range is shown for each channel, while in the last column the purity is given.

fraction of $(114.2 \pm 1.1 \pm 2.6)\%$ and a Veneziano fraction of $(133.1 \pm 3.3)\%$. Both models provide similar representation of data, even though the better data-fit agreement shown by the Veneziano model might indicate the presence of further resonances. For the other two analysed modes, the

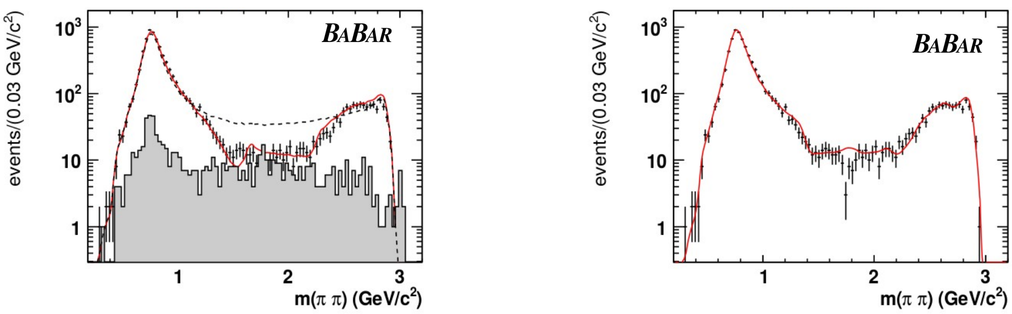

Figure 1: The $\pi\pi$ mass projection for all the three $\pi\pi$ charge combinations. The dashed line (left) is the result from the fit with only the $\rho(770)\pi$ amplitude. The fit in the left plot uses the isobar model and the shaded histogram shows the background distribution estimated from the J/ψ sidebands. On the right, the fit with the Veneziano model is shown.

available statistics is not enough to perform the fit with the Veneziano model and only the isobar fit results are provided (Figure 2). For the decay $J/\psi \to K^+K^-\pi^0$ the dominant contribution to the fitted fractions comes from the $K^*(892)K^\pm$ resonance, while in the low-mass region of the $K\bar{K}$ invariant mass spectrum, a broad structure is found to be compatible with the $\rho^0(1450)$. Similarly for the mode $J/\psi \to K_S K^\pm \pi^\mp$, the fit with the isobar model is dominated by the $K^*(892)\bar{K}$ and by the $K_2^*(1430)\bar{K}$ resonances. Also in this case, a broad structure in the low-mass region of the $K_S K^\pm$ spectrum is observed to be consistent with the $\rho(1450)^\pm$ resonance. Finally, the branching fraction ratio of the decay modes $\rho(1450)^0 \to K^+K^-$ to $\rho(1450)^0 \to \pi^+\pi^-$ is measured for the first time to be $(0.307 \pm 0.084 \pm 0.082)$.

3. The search for the $B^0 \to pp\bar{p}\bar{p}$ decay

Due to its large mass, the B meson decays also into final states containing baryons and therefore it is an optimal tool to study the mechanism of baryonic fragmentation of hadrons, only poorly

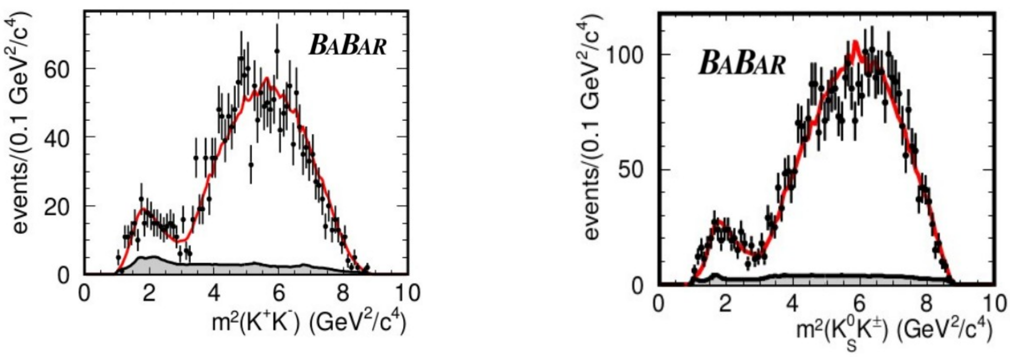

Figure 2: The Dalitz plot projections respectively for the mode $J/\psi \rightarrow K^+K^-\pi^0$ (right) and for $J/\psi \rightarrow K_S K^{\pm}\pi^{\mp}$ (left). The superimposed curves result from the fit with the isobar model and the shaded regions show the background estimates obtained by interpolating the results of the Dalitz-plot analyses of the sideband regions.

understood. The inclusive branching fraction (BF) of B mesons decaying into baryonic final states is approximately 7% [6] and it is not covered by the sum of the measured exclusive baryonic channels of the B meson. Indeed, this puzzle motivates the search for unmeasured B meson decays to baryons. Main open issues in baryonic B decays are related to the hierarchy of the branching fractions, due to resonant subchannels, and the threshold enhancement effect. So far, the only four-baryon final state studied by the BABAR collaboration is the decay mode $\bar{B}^0 \rightarrow \Lambda_c^+ p\bar{p}\bar{p}$ [7], for which no event was observed and the upper limit on the branching fraction at 90% CL was calculated to be 2.8×10^{-6}.

3.1 Method

The dataset analysed for the search of the decay $B^0 \rightarrow pp\bar{p}\bar{p}$ corresponds to 424 fb^{-1} recorded by the BABAR detector at the centre-of-mass (CM) energy of $\Upsilon(4S)$ resonance, $\sqrt{s} = 10.58$ GeV/c^2 (on-peak data). The event is reconstructed combining 4 oppositely charged tracks identified as protons and antiprotons and kinematically fitted to a common vertex, with a fit probability larger than 0.1%. Cuts are also applied to the kinematic variables $m_{ES}= \sqrt{(E^*_{beam})^2 - (\vec{p}_B{}^*)^2}$ and $\Delta E= E^*_B - E^*_{beam}$ [8], related to the momentum, $\vec{p}_B{}^*$, and the reconstructed energy, E^*_B, of the B-candidate and to the beam energy, E^*_{beam}, in the CM reference frame. The PID efficiency for protons is excellent for this analysis ($> 99\%$) and mis-identification rates for wrongly assigning the proton identity to kaons and pions are lower than 1%. Real protons coming from continuum hadronization processes ($e^+e^- \rightarrow q\bar{q}$) are expected to be the main source of combinatoric background. Further background is rejected by cutting on the output of a multivariate analysis method, the Boosted Decision Tree (BDT), whose response is evaluated on the input variable distributions ΔE, $cos\theta^*_B$, θ^*_B being the flight polar angle of the B meson in the centre-of-mass frame, and two event-shape variables which discriminate between the spherical shape of a signal event ($e^+e^- \rightarrow B\bar{B}$) and a jet-like $q\bar{q}$ event. The signal efficiency, computed on the signal MC sample as the ratio of the number of selected to generated events, is assessed to be $\varepsilon = 0.207 \pm 0.005$. The associated uncertainty is systematic and takes into account the contributions from the PID and the tracking efficiencies, and

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the BDT selection. The signal yield is extracted from an extended unbinned maximum likelihood fit to the selected events in the range $5.2 < m_{ES} < 5.3$ GeV/c^2. The shape of the signal and of the background components is fixed in the fit to the results of the modeling studies performed on both MC samples and on the sideband region data.

3.2 Results

The result from the fit to the on-peak data is reported in Figure 3. It provides a signal yield

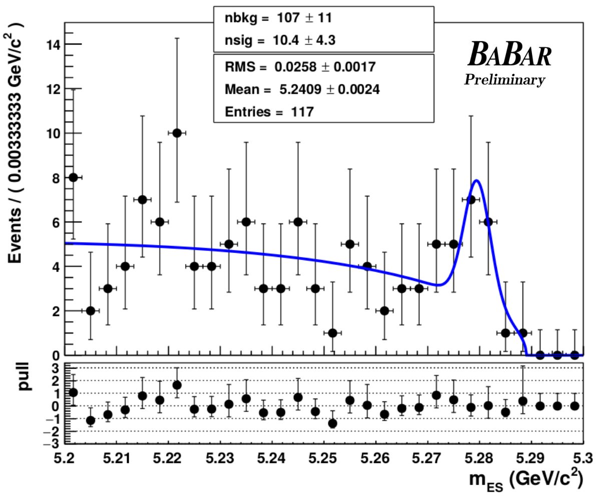

Figure 3: Preliminary result from the fit (blue line) to unblinded data. The signal yield $N_{sig} = 10.4 \pm 4.3$ is extracted by fitting the on-peak data (black dots) in the whole reconstruction range $5.2 < m_{ES} < 5.3$ GeV/c^2, after the final selection is applied.

of $N_{sig} = 10.4 \pm 4.3$ and the corresponding branching fraction is calculated as $\mathscr{B}(B^0 \to pp\bar{p}\bar{p}) = \frac{N_{sig}}{\varepsilon \cdot N_{B\bar{B}}} = (1.1 \pm 0.5_{stat} \pm 0.2_{sys}) \times 10^{-7}$, where the experimental inputs are N_{sig}, ε and the number of B meson pairs $N_{B\bar{B}}$. The largest contribution to the total uncertainty on the branching fraction comes from the low number of fitted signal events.

3.3 Upper limit calculation

This measurement is statistically limited by the low number of fitted signal events. To obtain the statistical significance we compare the logarithms of the likelihood from the fits with and without the signal hypothesis, resulting in a significance of 3.16σ. Since available data are not sufficient to claim a 5σ discovery, the upper limit at 90% CL on the branching fraction is computed by integrating the likelihood function projected on N_{sig}, up to the value of N_{sig}^{UL} such that the equality $\int_0^{N_{sig}^{UL}} L(n_{sig}) dn_{sig} = 0.90 \int_0^{+\infty} L(n_{sig}) dn_{sig}$ is verified. This calculation is based on the Bayesian approach, assuming a flat prior for $N_{sig} > 0$ and 0 otherwise, and it results in an upper limit on the signal yield of $N_{sig}^{UL} = 18$. We therefore obtain the upper limit for the searched branching fraction to be $\mathscr{B}(B^0 \to pp\bar{p}\bar{p}) < 2 \times 10^{-7}$ at 90% CL.

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