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Search for $B \to \chi_c \, K^{(*)}$ Decays

The *BABAR* Collaboration

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Abstract

We report on the search for the factorization suppressed decays $B \to \chi_{c0} \, K^{(*)}$ and $B \to \chi_{c2} \, K^{(*)}$, with χ_{c0} and χ_{c2} decaying into $J/\psi \, \gamma$. We use a sample of 124 million $B\overline{B}$ events collected with the *BABAR* detector at the PEP-II storage ring at the Stanford Linear Accelerator Center. No significant signal is found and upper bounds for the branching fractions are obtained. All results are preliminary.

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1 INTRODUCTION

Hadronic decays of heavy mesons are not precisely described, despite the electroweak nature of the quark decay, because the initial and final states consist of mesons, not of quarks. The factorization scheme allows one to make some predictions though. Factorization assumes that a weak decay matrix element can be described as the product of two independent hadronic currents. Under the factorization hypothesis, $B \to c\ K^{(*)}$ decays are allowed when $c = J/\psi$, $\psi(2S)$ or χ_{c1}, but suppressed when $c = \chi_{c0}$ or χ_{c2} [1]. In lowest order heavy quark effective theory, there is no $J \geq 2$ operator to create the tensor χ_{c2} from the vacuum. The decay rate to χ_{c0} is zero due to charge conjugation invariance [2].

Belle has recently [3] observed $B \to \chi_{c0}\ K^+$ decays, with $\chi_{c0} \to \pi^+\ \pi^-$ or $K^+\ K^-$, with a branching fraction surprisingly large based on the expectation from factorization and measurements of the χ_{c1} branching fraction. BaBar has confirmed the observation [4] with a branching fraction somewhat lower than, but compatible with, that measured by Belle.

In this document we attempt the detection of $B \to \chi_{c,i}\ K^{(*)}$, $i = 0, 2$, using the radiative $\chi_c \to J/\psi\ \gamma$ decays.

2 THE *BABAR* DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II storage ring. They represent an integrated luminosity of 112.4 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance.

The *BABAR* detector is described elsewhere [5]. Charged particles are detected with a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) with a helium-based gas mixture, placed in a 1.5-T solenoidal field produced by a superconducting magnet. The charged-particle momentum resolution is approximately $(\delta p_T/p_T)^2 = (0.0013\,p_T)^2 + (0.0045)^2$, where p_T is the transverse momentum in GeV/c. The SVT, with a typical single-hit resolution of $10\,\mu$m, measures the impact parameters of charged-particle tracks in both the plane transverse to the beam direction and along the beam. Charged-particle types are identified from the ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) measured in the DCH and SVT, and from the Cherenkov radiation detected in a ring-imaging Cherenkov device (DIRC). Photons are identified by a CsI(Tl) electromagnetic calorimeter (EMC) with an energy resolution $\sigma(E)/E = 0.023 \cdot (E/\,\mathrm{GeV})^{-1/4} \oplus 0.019$. Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron, which return the magnetic flux of the solenoid.

3 ANALYSIS METHOD

The channels considered here are $B \to \chi_c\ K^{(*)}$ with $\chi_c \to J/\psi\ \gamma$, $J/\psi \to e^+e^-$ or $\mu^+\mu^-$; K is K^+ or $K^0_S\ (\pi^+\ \pi^-)$; $K^{*0} \to K^+\ \pi^-$ or $K^0_S\ \pi^0$; $K^{*+} \to K^+\ \pi^0$ or $K^0_S\ \pi^+$; and $\pi^0 \to \gamma\ \gamma$.

Multihadron events are selected by demanding a minimum of three reconstructed charged tracks in the polar-angle range $0.41 < \theta_{lab} < 2.54$ rad. Charged tracks have to be reconstructed in the DCH and are required to originate at the beamspot: within 1.5 cm in the plane transverse to the beam and 10 cm along the beam. Events are required to have a primary vertex within 0.5 cm of the average position of the interaction point in the plane transverse to the beamline and within 6 cm longitudinally. Electromagnetic depositions in the calorimeter in the polar-angle range $0.410 < \theta_{lab} < 2.409$ rad that are not associated with charged tracks, have an energy larger than 30 MeV, and a shower shape consistent with a photon are taken as photon candidates. A total energy larger than 4.5 GeV in the fiducial regions for charged tracks plus neutrals is required. To reduce continuum background, we require the normalized second Fox-Wolfram moment R_2 [6] of the event, calculated with both charged tracks and neutral clusters, to be less than 0.5. Charged tracks are required to be in polar-angle regions for which the PID efficiency is well-measured. For electrons, muons, and kaons the acceptable ranges are 0.40 to 2.40, 0.30 to 2.70 and 0.45 to 2.50 rad, respectively.

Event selection was optimized by maximizing $\epsilon/\sqrt{B}$, where ϵ is the signal efficiency, and B the number of events, after selection was applied. Candidates for J/ψ mesons are reconstructed in the e^+e^- and $\mu^+\mu^-$ decay modes, from a pair of identified leptons that form a good vertex. Muon candidates are identified using a neural network selector and are required to pass a loose selection for the first muon candidate and a very loose selection for the second muon candidate. Electron candidates are selected using a likelihood selector and are required to pass a loose selection. For $J/\psi \rightarrow e^+e^-$ decays, electron candidates are combined with photon candidates in order to recover some of the energy lost through bremsstrahlung. Photons are required to be within 35 mrad in polar angle from the electron track, and to have an azimuthal angle intermediate between the initial track direction (estimated by subtracting 50 mrad opposite to the bend direction of the reconstructed track) and the centroid of the EMC cluster arising from the track.

The lepton-pair invariant mass has to be between 2.95 and 3.18 GeV/c^2 for both lepton flavors. The remaining background is mainly due to genuine J/ψ's. Candidates for K^0_S consist of oppositely-charged tracks with invariant mass between 487 and 510 MeV/c^2 and are required to satisfy vertexing conditions. The K^0_S flight length has to be greater than 1 mm, and its direction must form an angle with the K^0_S momentum vector in the plane perpendicular to the beam line that is less than 0.2 rad. Charged kaon candidates are identified using a likelihood selector and are required to pass a tight selection. Photon candidates as defined above are used also for the reconstruction of $\pi^0 \rightarrow \gamma\gamma$ decays. A π^0 candidate consists of a pair of photon candidates with invariant mass in the interval $117 - 152$ MeV/c^2 and momentum larger than 350 MeV/c. K^* candidates must have a $K\pi$ invariant mass in the range $0.85 - 0.94$ GeV/c^2 around the nominal $K^*(892)$ mass [7]. The J/ψ, K^0_S, and π^0 candidates are constrained to their corresponding nominal masses [7].

The χ_c candidates are formed from J/ψ and photon candidates. The photon is required to fulfill the same shower shape requirement mentioned above, have an energy larger than 0.15 GeV, and not be part of π^0 candidates in the mass range $0.125 - 0.140$ GeV/c^2.

The χ_c and $K^{(*)}$ candidates are combined to form B candidates. Two kinematic variables are used to further remove incorrect B candidates. The first is the difference $\Delta E \equiv E^*_B - E^*_{beam}$ between the B-candidate energy and the beam energy in the $\Upsilon(4S)$ rest frame. In the absence of experimental effects, reconstructed signal candidates have $\Delta E = 0$. The second is the beam-energy-substituted mass $m_{\rm ES} \equiv (E^{*2}_{beam} - p^{*2}_B)^{1/2}$. The energy substituted mass $m_{\rm ES}$ should peak at the B meson mass 5.279 GeV/c^2.

For the signal region, ΔE is required to be between -35 MeV and $+20$ MeV for channels involving a π^0, and to be between -20 MeV and $+20$ MeV otherwise. If several B candidates are found in an event, the one having the smallest $|\Delta E|$ is retained. $m_{\rm ES}$ is required to be in the $5.274 - 5.284$ GeV/c^2 range.

Studies using simulated samples show that most of the background events in the $\chi_c\, K^*$ channels are due to non-resonant (NR) $B \rightarrow \chi_c\ (J/\psi\ \gamma) K\ \pi$ decays. Also the observation of the suppressed χ_{c2} could be complicated by the presence of the prominent χ_{c1} peak. Therefore the search is performed by the observation of the spectrum of the mass difference $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$. It was found from Monte Carlo simulation that after the non-resonant events were removed from the sample, the expected number of genuine $\chi_c \to J/\psi\ \gamma$ decays was extremely small, 0.2 ± 0.2 for the $\chi_{c2}\ K^{*0}$ $(K^+\ \pi^-)$ and $\chi_{c2}\ K^{*+}\ (K^+\ \pi^0)$ modes, and 0.0 ± 0.2 for all the other χ_{c2} modes and all the χ_{c0} modes.

The efficiencies obtained from fits to the mass difference distribution for exclusive samples, where one B decays to the final state under consideration and the other inclusively, are given in Table 1. Note that χ_{c1} exclusive simulated samples are used in the place of χ_{c2}, that were not available.

The χ_{c2} has a negligible natural width and is therefore fitted with a Gaussian. The χ_{c0} has a natural width $\Gamma = 10.1\,\mathrm{MeV}$ comparable with the measurement resolution $\sigma \approx 10\,\mathrm{MeV}/c^2$, and therefore the χ_{c0} peak is fitted with a Voigtian, the convolution of a Breit-Wigner and a Gaussian distribution.

Table 1: Efficiencies from fits of the distribution of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ for exclusive samples.

	χ_{c1}	χ_{c0}
$K^{*0}\ (K^+\ \pi^-)$	0.071 ± 0.001	0.066 ± 0.001
$K^{*0}\ (K^0_S\ \pi^0)$	0.031 ± 0.001	0.010 ± 0.000
$K^{*+}\ (K^+\ \pi^0)$	0.036 ± 0.001	0.031 ± 0.001
$K^{*+}\ (K^0_S\ \pi^+)$	0.065 ± 0.001	0.062 ± 0.001
K^+	0.144 ± 0.001	0.117 ± 0.002
K^0_S	0.158 ± 0.001	0.126 ± 0.001

We corrected for the presence of non-resonant decays under the K^* peak in the following way: the $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ distribution for the events on the plateau; i.e. $1.1 < m_{K\pi} < 1.3\,\mathrm{GeV}/c^2$, is subtracted from the $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ distribution for the events in the signal region $0.85 < m_{K\pi} < 0.94\,\mathrm{GeV}/c^2$, after rescaling by a factor $r = 0.26 \pm 0.04$, where r is the ratio obtained from Monte Carlo simulation of non-resonant events under the peak compared to the plateau. The branching fractions were then computed from:

$$BF = \frac{N}{N_B \times \epsilon \times f} \tag{1}$$

where N is the number of events obtained from fitting the $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ distribution, N_B is the number of $B\overline{B}$ events, ϵ is the selection efficiency and f is the secondary branching fraction of the B daughters. Examples of fits to the "generic" $B\overline{B}$ Monte Carlo (MC) sample, that contains a simulation of inclusive $\Upsilon(4S) \to B\overline{B}$ decays, can be seen in Fig. 1.

The free parameters in the fits are: a linear background, the overall mass difference scale, the resolutions of the gaussian taken to be the same for the 3 χ's and the amplitudes of the peaks. The fixed parameters are the natural width of the χ_{c0} and 2 mass differences, all taken from PDG.

With such fits, it was checked that the non-resonant events were subtracted correctly, and that the proximity of the χ_{c1} was not inducing any visible bias on the measurement of the nearby χ_{c2}.

4 SYSTEMATIC STUDIES

This measurement is affected by the following set of systematic uncertainties:

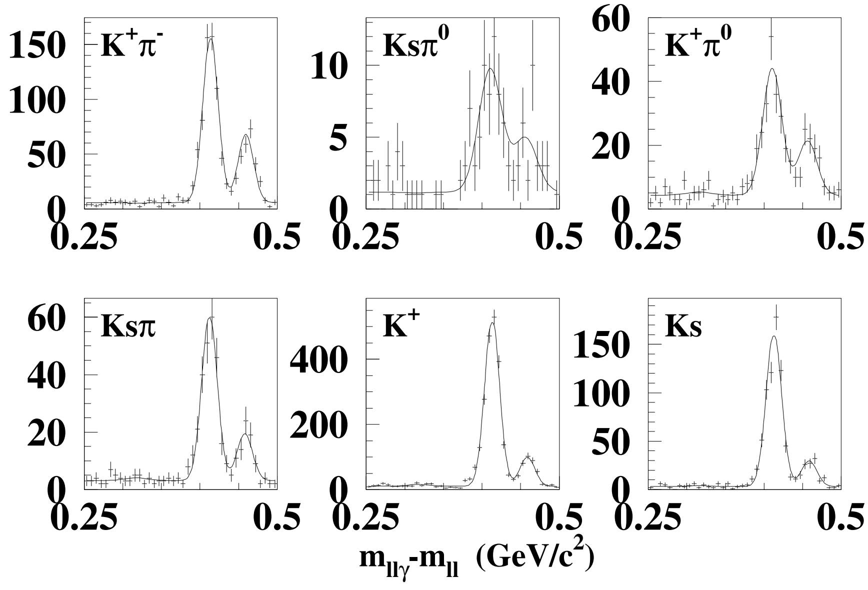

Figure 1: Distribution of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ (GeV/c^2) for generic MC samples.

- Overall uncertainty on the number of B events, 1.1%.
- Uncertainy on the secondary branching fractions: from PDG [7] (dominated by the relative uncertainty of the branching fraction of the radiative decay of the χ, 11.9 and 8.5% for the χ_{c0} and χ_{c2}, respectively).
- Tracking: 1.3% per track.
- K^0_S: a 2.5% uncertainty.
- Neutrals: 2.5% per "χ" photon, 5.0% per π^0.
- An overall 3% uncertainty on particle identification correction.
- Selection cuts: For each mass peak and for ΔE, the uncertainty of the MC-to-data shift in central value and in width are measured on the well populated χ_{c1} channels and are used to vary the selection cuts, by 1 σ. The corresponding efficiency variation, estimated on the exclusive sample, is the induced contribution to the systematics. The central value and width induced systematics are estimated independently, and are added quadratically below.

  The results for χ_{c1} MC sample and χ_{c0} MC sample are quite close to each other; an average value is used for both.
- The ratio of B^0 to B^+ production in $\Upsilon(4S)$ decays is assumed to be unity. The related uncertainty is small [9] and is neglected here.

- The NR component is probably in an S-wave Kπ state, as was observed in the J/ψ K^* system [8], with an unknown relative phase ϕ wrt the main K^* (892) P-wave peak.

  It is possible that no signal is found in the channels under consideration in this section. Therefore the systematics due to the unknown relative phase is here estimated with a MC-based method.

  The Kπ invariant mass is fitted with an amplitude that is the sum of a non-relativistic Breit-Wigner and a real amplitude that corresponds to a polynomial (parabolic) distribution for the NR (Fig. 2).

$$p(m_{K\pi}) = \left| \frac{a}{m_{pdg} - m_{K\pi} - i\Gamma/2} + b(m_{K\pi})e^{i\phi} \right|^2 \tag{2}$$

  where a and b are real quantities. The slow variation of the phase of the S wave with $m_{K\pi}$ is neglected here.

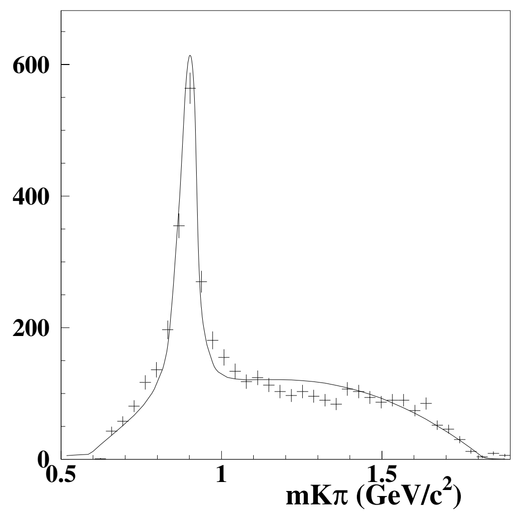

Figure 2: The distribution of $m_{K\pi}$ for the generic MC sample. A fit with a coherent sum of a polynomial NR and a non-relativistic Breit-Wigner is overlaid.

  The free parameters in the fit are the 3 degrees of freedom of the NR parabola, the magnitude of the signal, and the relative phase ϕ. As the high mass plateau is dominated by the NR contribution, no attempt is made to subtract the few combinatorial events. The fact that ϕ is unknown is dealt with by randomly generating samples of events distributed as above for each value of ϕ, and applying the NR subtraction as described above. The number of events N thus measured is normalized to that generated with the value ϕ_0 of ϕ obtained in the fit, and the ratio $R = N(\phi)/N(\phi_0)$ is plotted as a function of ϕ in Fig. 3. The medium value is 1.44 with maximal relative extention $\pm$ 35%, giving an RMS relative uncertainty of $\pm$ 20%.

- In the case of χ_{c2}, the efficiency depends on the intensity fractions to various polarization states, due to the variation of the detection efficiency with the angles describing the decay.

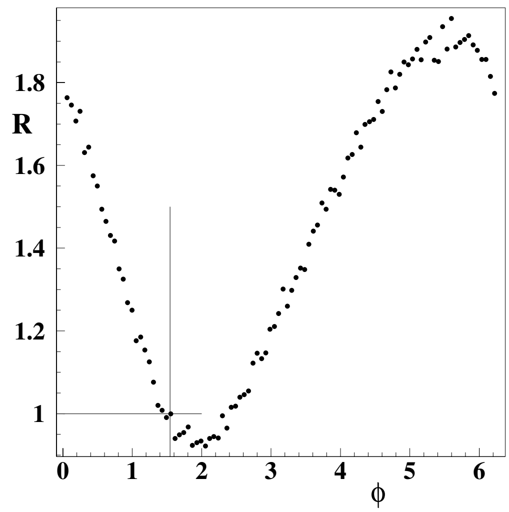

Figure 3: Number of events measured, after NR subtraction, in Toy MC samples, as a function of ϕ, normalized to the number obtained with the phase fitted on the generic sample (shown by the vertical line).

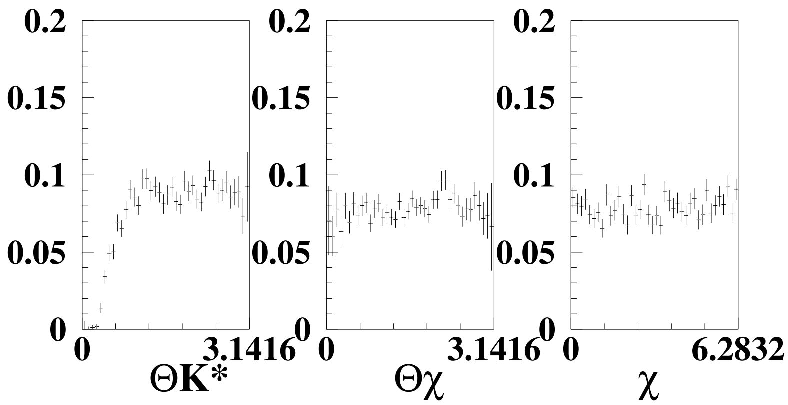

Figure 4: Signal efficiency as a function of the helicity angles for K^+ π^- channel. χ is the angle between the decay planes of the χ_c and of the K^*.

The efficiency is mainly sensitive to the K^* decay helicity angle, (Fig. 4) due to soft pions for small values of θ_{K*}.

The selection efficiency therefore depends, to 1st order, on the polarization of the K^* population, throught the angular distribution:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{K^*}} = \frac{3}{4}\left[(1-\cos^2\theta_{K^*}) + |A_0|^2(3\cos^2\theta_{K^*}-1)\right], \tag{3}$$

where $|A_0|^2$describes the fraction of longitudinal K^* polarization. The efficiency is:

$$\langle\varepsilon\rangle = \int \frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{K^*}}\varepsilon(\theta_{K^*})\mathrm{d}\cos\theta_{K^*} = a + |A_0|^2 b, \tag{4}$$

where

$$a = \frac{3}{4}\int (1-\cos^2\theta_{K^*})\varepsilon(\theta_{K^*})\sin\theta_{K^*}\mathrm{d}\theta_{K^*}, \tag{5}$$

$$b = \frac{3}{4}\int (3\cos^2\theta_{K^*}-1)\varepsilon(\theta_{K^*})\sin\theta_{K^*}\mathrm{d}\theta_{K^*}. \tag{6}$$

The values of a and b are obtained from the two above equations and from the parametrisation $\varepsilon(\theta_{K^*})$ extracted from Figure 4 and are shown in Table 2. In the case no signal is observed, the polarization is unknown, and we estimate the efficiency as $(a+0.5b) \pm (|b|/\sqrt{12})$.

Table 2: Coefficients for the calculation of amplitude dependent average efficiency for the χ_{c2} K^* channels (%).

	a	b	Efficiency	Fract. uncert.
K^{*0} (K^+ π^-)	8.68	-1.40	7.98± 0.40	5.1
K^{*0} (K^0_S π^0)	4.25	-1.66	3.43± 0.48	14.0
K^{*+} (K^+ π^0)	5.05	-1.79	4.16± 0.52	12.4
K^{*+} (K^0_S π^+)	7.83	-1.84	6.92± 0.53	7.7

As usual the effect is stronger on channels having a π^0 in the final state, as the larger background results in harsher cuts during the optimization process.

A summary of the multiplicative contributions to the systematics can be found in Table 3.

In addition to these multiplicative contributions comes a contribution from NR background subtraction. The contribution of the uncertainty of r is given in Table 4.

5 PHYSICS RESULTS

Fits on the data clearly show the presence of the factorization allowed χ_{c1}, but no signal, within uncertainty, for the factorization suppressed χ_{c0} and χ_{c2} (Table 5, Fig. 5).

Non-resonant events subtraction has been applied. The phase-related systematics estimated on the MC sample are used for the data.

Table 3: Systematics: summary of the multiplicative contributions: relative uncertainties (%).

	K^{*0} $(K^+ \ \pi^-)$	$(K^0_S \ \pi^0)$	$(K^+ \ \pi^0)$	$(K^0_S \ \pi^+)$	K^+	K^0_S
B counting	1.1	1.1	1.1	1.1	1.1	1.1
Tracking	5.2	2.6	3.9	3.9	3.9	2.6
K^0_S	–	2.5	–	2.5	–	2.5
Neutrals	2.5	7.5	7.5	2.5	2.5	2.5
Particle identification	3.0	3.0	3.0	3.0	3.0	3.0
Cut variation $\langle\rangle$	1.0	1.5	1.3	0.8	0.6	0.5
Cut variation width	7.6	13.	11.5	8.2	6.5	6.3
MC stat	1.4	2.9	1.7	1.8	1.3	1.3
phase	20.0	20.0	20.0	20.0	–	–
χ_{c0} Sec. BF	11.9	11.9	11.9	11.9	11.9	11.9
Total for χ_{c0}	25.4	28.3	27.6	25.5	14.8	14.6
χ_{c2} Sec. BF	8.5	8.5	8.5	8.5	8.5	8.5
Polar	5.1	14.0	12.4	7.7	–	–
Total for χ_{c2}	24.5	30.5	29.1	25.3	12.2	12.0

Table 4: Systematics on the measured BF's on the generic samples due to NR subtraction. (in units of 10^{-4}).

	χ_{c2}	χ_{c0}
$(K^+ \ \pi^-)$	0.0	0.5
$(K^0_S \ \pi^0)$	0.2	1.3
$(K^+ \ \pi^0)$	0.1	1.4
$(K^0_S \ \pi^+)$	0.1	1.7

Table 5: Number of events from fits of the distribution of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ for the data. (NR subtracted).

	χ_{c2}	χ_{c0}
K^{*0} $(K^+ \ \pi^-)$	0.3 ± 1.1	2.1 ± 2.5
K^{*0} $(K^0_S \ \pi^0)$	-1.7 ± 2.0	1.0 ± 0.9
K^{*+} $(K^+ \ \pi^0)$	-1.8 ± 0.6	0.1 ± 2.9
K^{*+} $(K^0_S \ \pi^+)$	-0.2 ± 1.2	12.3 ± 3.7
K^+	6.4 ± 4.8	15.1 ± 7.6
K^0_S	2.8 ± 2.6	4.5 ± 4.0

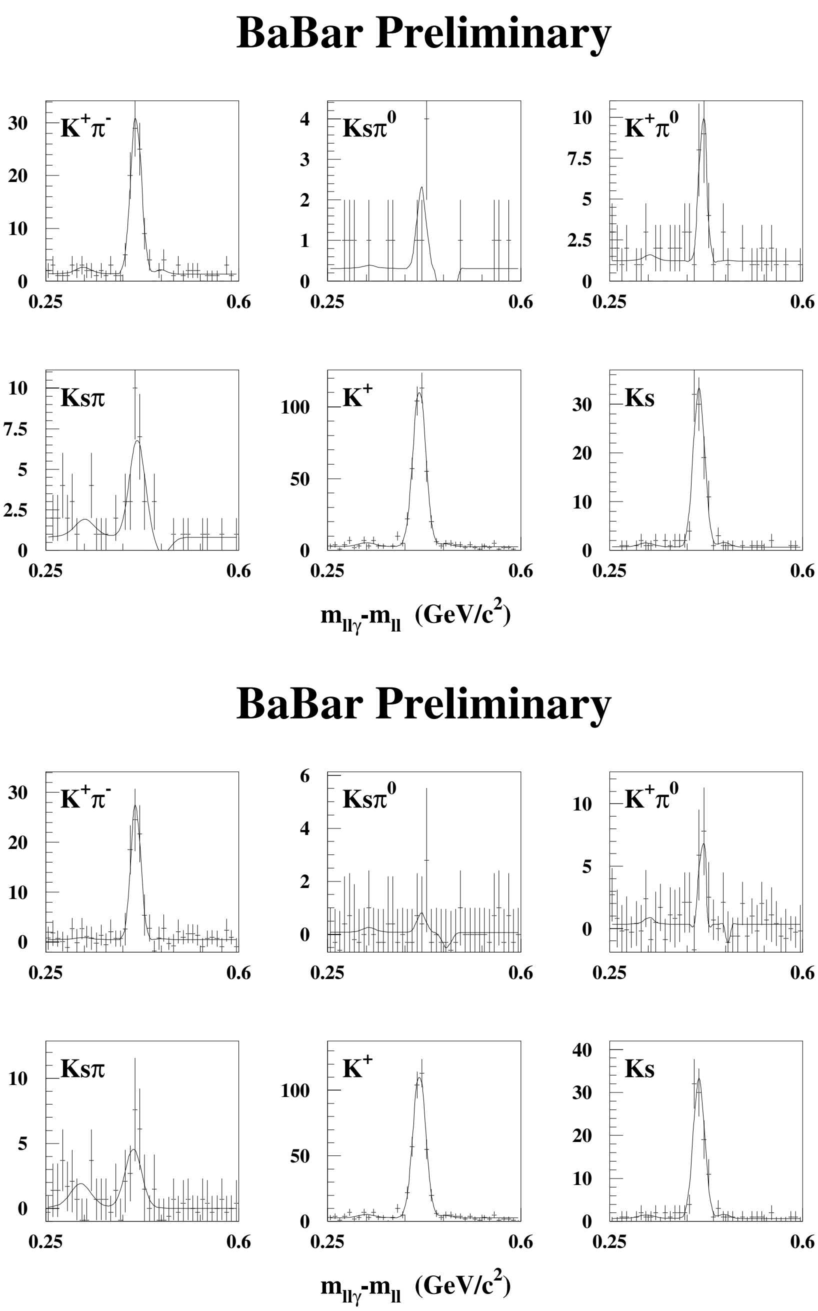

Figure 5: Distribution of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ for data. Top: raw data; Bottom: NR subtracted.

Combining the measurements of the K^* sub-modes, and under the reasonable approximation that the multiplicative efficiencies between each K^* sub-mode are fully correlated, we obtain the branching fractions for the suppressed modes listed in Table 6.

The results for the allowed χ_{c1} are found to be compatible with those of [10], an analysis optimized to the relevant BF, in contrast with this one.

Table 6: Measured Branching fractions (in units of 10^{-4}).

	χ_{c2}	χ_{c0}
K^{*0}	0.02 ± 0.07 ± 0.10	3.09 ± 3.35 ± 1.27
K^{*+}	-0.37 ± 0.15 ± 0.20	27.0 ± 11.2 ± 9.0
K^+	0.15 ± 0.11 ± 0.12	7.49 ± 3.76 ± 1.09
K^0	0.18 ± 0.16 ± 0.12	5.96 ± 5.39 ± 0.88

Upper bounds on the BF's, at 90% confidence level (CL) are obtained using a simulation, assuming gaussian statistics for the statistical uncertainties and taking into account the systematic uncertainties (Table 7). It has been assumed that the BF can only be positive.

Table 7: Branching fractions: upper bounds at 90% CL. (in units of 10^{-4}).

	χ_{c2}	χ_{c0}
K^{*0}	0.22	8.
K^{*+}	0.14	45.
K^+	0.36	12.
K^0	0.44	13.

6 SUMMARY

The upper limits obtained for decays to χ_{c2} are more than one order of magnitude lower than the branching fractions of the factorization allowed decays and of the already observed $B \rightarrow \chi_{c0} K^+$ decays. All results are preliminary.

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