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BABAR Analysis Document #2059, Version 4

Evidence for $X(3872) \to \psi(2S)\gamma$ in $B^{\pm} \to X(3872)K^{\pm}$ decays, and a study of $B \to c\bar{c}\gamma K$

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In a search for $B \rightarrow c\bar{c}\gamma K$ decays, where $c\bar{c}$ includes J/ψ and $\psi(2S)$, and K includes charged, neutral and excited ($K^*(892)$) kaons, we find evidence for the radiative decays $X(3872) \rightarrow J/\psi\gamma$ and $X(3872) \rightarrow \psi(2S)\gamma$ with a statistical significance of 3.8σ and 3.2σ respectively. We measure the product of branching fractions $\mathcal{B}(B^\pm \rightarrow X(3872)K^\pm) \cdot \mathcal{B}(X(3872) \rightarrow J/\psi\gamma) = (2.9 \pm 0.8 \pm 0.2) \times 10^{-6}$ and $\mathcal{B}(B^\pm \rightarrow X(3872)K^\pm) \cdot \mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma) = (8.5 \pm 2.8 \pm 1.0) \times 10^{-6}$ where the uncertainties are statistical and systematic, respectively. These results are obtained from (465 ± 5) million $B\overline{B}$ decays collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II B Factory at SLAC.

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The $X(3872)$ state discovered by the Belle Collaboration in the decay $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$ [1] is now well established [2]. It has recently been observed decaying to $\overline{D}^{0}D^{*0}$ [3]. BABAR has also seen evidence for the decay $X(3872) \rightarrow J/\psi\gamma$, a result which implies positive C-parity [4]. An angular analysis performed by CDF [5] indicates that the $X(3872)$ state has a quantum number assignment $J^{PC} = 1^{++}$ or 2^{-+}.

A variety of theoretical interpretations [6] exist for the $X(3872)$, including exotic QCD proposals such as a $\overline{D}^{0}D^{*0}$ molecule [7], or a diquark-antidiquark state [8]. The $X(3872)$ is not considered to be a conventional charmonium state since the only two obvious options, $\chi_{c1}(2^{3}P_{1})$ or $\eta_{c2}(1^{1}D_{2})$, are disfavored by its low mass and its decay to $J/\psi\gamma$, respectively. While $\overline{D}^{0}D^{*0}$ molecular proposals can accommodate decays to $J/\psi\gamma$, decays to $\psi(2S)\gamma$ are presupposed to proceed via annihilation of the $u\overline{u}$ quarks, for which the branching fraction is expected to be very small [10]. The $\chi_{c1}(2P)$ state could potentially decay to $\psi(2S)\gamma$ at a rate many times higher than to $J/\psi\gamma$ [9].

We present a study of the decay $B \rightarrow XK$, where the notation X represents any state decaying radiatively to $J/\psi\gamma$ or $\psi(2S)\gamma$ (the $\chi_{c1,2}$ and $X(3872)$ states in particular), and K encompasses $K^{\pm}$, K^{0}_{S}, $K^{*\pm}$ (892) and K^{*0} (892). We consider J/ψ decaying to $e^{+}e^{-}$ or $\mu^{+}\mu^{-}$, and $\psi(2S)$ decaying to $e^{+}e^{-}$, $\mu^{+}\mu^{-}$ or $J/\psi\pi^{+}\pi^{-}$. Kaons are required to decay to final states consisting of charged particles; $K^{0}_{S} \rightarrow \pi^{+}\pi^{-}$, $K^{*\pm} \rightarrow K^{0}_{S}(\pi^{+}\pi^{-})\pi^{\pm}$, and $K^{*0} \rightarrow K^{\pm}\pi^{\mp}$.

The data sample for this analysis consists of (465 ± 5) million $B\overline{B}$ pairs collected with the BABAR detector at the PEP-II asymmetric $e^{+}e^{-}$ collider. This represents $424\,\mathrm{fb}^{-1}$ of data taken at the $\Upsilon(4S)$ resonance. The BABAR detector is described in detail elsewhere [11].

The choice for most of the selection criteria values is optimized using simulated Monte Carlo (MC) samples by maximizing $n_{\mathrm{S}}/\sqrt{n_{\mathrm{S}} + n_{\mathrm{B}}}$, where n_{S} and n_{B} are numbers of signal and background events, respectively. For purposes of optimization, we make the assumption that the branching fractions for $X(3872)$ to $J/\psi\gamma$ and $\psi(2S)\gamma$ are the same and equal to the previous measurement [4].

The $J/\psi \rightarrow e^{+}e^{-}$ candidates are formed with electrons (and bremsstrahlung photons) with $2.96 < m(e^{+}e^{-}(\gamma)) < 3.15$ GeV/c^{2}. Candidates for $J/\psi \rightarrow \mu^{+}\mu^{-}$ require a muon pair with $3.06 < m(\mu^{+}\mu^{-}) < 3.13$ GeV/c^{2}. The $\psi(2S) \rightarrow \ell^{+}\ell^{-}$ candidates are reconstructed in a similar manner, requiring $3.61 < m(e^{+}e^{-}(\gamma)) < 3.73$ GeV/c^{2} and $3.65 < m(\mu^{+}\mu^{-}) < 3.72$ GeV/c^{2}. The $\psi(2S) \rightarrow J/\psi\pi^{+}\pi^{-}$ candidates are composed of J/ψ candidates decaying as described but with a tighter mass requirement of $3.01 < m(e^{+}e^{-}(\gamma)) < 3.15$ GeV/c^{2}. To form a $\psi(2S)$, the J/ψ candidate is mass-constrained to the nominal PDG value [12] and combined with a pair of oppositely charged tracks requiring $0.4 < m(\pi^{+}\pi^{-}) < 0.6$ GeV/c^{2}, $3.68 < m(J/\psi\pi^{+}\pi^{-}) < 3.69$ GeV/c^{2}, and all three particles to be constrained to the same decay vertex.

The $X \rightarrow c\overline{c}\gamma$ candidate is reconstructed from a mass-constrained J/ψ ($\psi(2S)$) candidate combined with a photon with an energy E_{γ} greater than 30(100) MeV. Additional selection criteria are applied to the shape of the lateral distribution ($0.001 < LAT < 0.5$) [13] and azimuthal asymmetry (as measured by the Zernike moment ($A_{42} < 0.1$)[14]) of the photon-shower energy deposited in the electromagnetic calorimeter. For $X \rightarrow J/\psi\gamma$, the radiative γ candidate is rejected if, when combined with any other γ from the event, it has an invariant mass consistent with the π^{0} mass, $124 < m_{\gamma\gamma} < 146\,\mathrm{MeV}/c^{2}$.

The K^{0}_{S} candidates are reconstructed from the decay to oppositely charged tracks within $\pm 17\,\mathrm{MeV}/c^{2}$ of the nominal K^{0}_{S} mass [12], and the significance of the distance of the reconstructed vertex from the primary vertex must be $> 3.7\sigma$. The charged excited kaons, $K^{*\pm}$ (892), are reconstructed from their decay to $K^{0}_{S}\pi^{\pm}$, with K^{0}_{S} candidates as defined above. Neutral excited kaons, K^{*0} (892), are reconstructed from their decay to $K^{\pm}\pi^{\mp}$. The excited kaons are required to fall within the mass range $0.7 < m(K^{*}) < 1.1$ GeV/c^{2}. For K^{0}_{S}, $K^{*\pm}$, and K^{*0} candidates associated with $X \rightarrow \psi(2S)\gamma$, additional requirements are placed on their χ^{2} vertex probability, $P(\chi^{2}) > 0.001, > 0.02$ and > 0.002, respectively.

The final B candidate is formed from an X candidate and a kaon constrained to the same vertex. To identify B candidates, we use two kinematic variables, m_{B} and m_{miss}. The unconstrained mass of the reconstructed B candidate $m_{B} = \sqrt{E^{2}_{B}/c^{4} - p^{2}_{B}}$, where E_{B} and p_{B} are obtained by summing the energies and momenta of the particles in the candidate B meson. The missing mass is defined through $m_{\mathrm{miss}} = \sqrt{(p_{e^{+}e^{-}} - \hat{p}_{B})^{2}}$, where $p_{e^{+}e^{-}}$ is the four-momentum of the beam $e^{+}e^{-}$ system and $\hat{p}_{B}$ is the four-momentum of the B candidate after applying a B mass constraint. These variables are uncorrelated by construction, and are advantageous for analyzing B decays in which a particle in the final state has poorly measured energy (e.g., a photon). Events with a correctly reconstructed B decay should have values equal to the nominal B mass [12] for both kinematic variables. A loose requirement of $5.2 < m_{\mathrm{miss}} < 5.3\,\mathrm{GeV}/c^{2}$ for B candidates is applied. For $X \rightarrow J/\psi\,(\psi(2S))\gamma$ events, we require m_{B} to be within $^{+30}_{-36}$ $(\pm 20)\,\mathrm{MeV}/c^{2}$ of the nominal B mass [12]. Our B candidate selection is further refined by imposing criteria on the χ^{2} probability for the B vertex; for all $X \rightarrow J/\psi\gamma$ modes $P(\chi^{2}) > 0.0001$, and for $X \rightarrow \psi(2S)\gamma$ modes, $P(\chi^{2}) > 0.01$ for the $K^{\pm}$ mode, > 0.002 for the K^{0}_{S} mode, and > 0.05 for both K^{*}

modes. The ratio of the second and zeroth Fox-Wolfram moments ($R_2 < 0.45$) [15] is used to separate isotropic B events from typically anisotropic continuum background events. Once a B candidate has been established, it and its daughter decays are refit with the B mass constrained to the known value [12].

We perform a one(two)-dimensional unbinned extended maximum-likelihood (UML) fit to $m_{\rm miss}$ (and m_{K^*}, if applicable), and then use the ${}_s$Plot formalism [16] to project our signal events into m_X, the invariant mass of the X candidate. The ${}_s$Plot of the UML fit displays the number of $B \to XK$ signal-like events as a function of m_X. We extract the number of signal events for a given decay mode by fitting this resultant m_X distribution with MC-determined Gaussian shapes for signal events plus a linear shape to account for peaking background events. Only the height of the Gaussian peak and the parameters of the linear component are allowed to float in the fit to m_X.

The signal event probability density functions (PDFs) are determined from MC-simulated $B \to \chi_{c1} K$ and $B \to X(3872)K$ events. Only reconstructed events matching the true generated decay chain particles are used to parameterize the signal PDFs. The $m_{\rm miss}$ distribution is modeled with a Crystal Ball function [17], m_X with a single Gaussian for the χ_{c2} decay modes and narrower "core" Gaussian plus a second wider Gaussian sharing the same mean for all other signal modes, and m_{K^*} with the convolution of a Breit-Wigner and a Gaussian. The PDF shapes for $B \to \chi_{c2} K$ are taken to be the same as χ_{c1}, with the exception of the m_X distribution.

The background PDFs are fitted to events from generic B^+B^-, $B^0\overline{B}^0$, $q\overline{q}$ ($q = u, d, s, c$), and $\tau^+\tau^-$ MC samples. The backgrounds are dominated by events from $B\overline{B}$ decays that include a J/ψ or $\psi(2S)$ in their decay chain. Based on MC, the important backgrounds to the $X(3872)$ decay modes are found to be of the type $B \to J/\psi K^{(*)}(\pi)$ and $B \to \psi(2S)K^{(*)}(\pi)$, where a random photon is picked up by the reconstruction and/or a pion is lost or gained in the reconstruction. "Cross feed" events where one signal mode is misreconstructed as another (mainly K plus π to form K^*, or vice versa), are found to be a negligible source of background. Background from the misreconstruction of $X(3872) \to J/\psi\pi^+\pi^-$ decays is also found to be negligible.

For the $B^\pm \to XK^\pm$ and $B^0 \to XK^0_S$ decay modes, the background in $m_{\rm miss}$ consists of two parts: a "flat" combinatoric component modeled with an ARGUS function [18], and a peaking component that shares the Crystal Ball parameterization used for signal events. These backgrounds are modeled as linear in m_X.

The K^* decay modes have three background components: events that peak in $m_{\rm miss}$ but are flat in m_{K^*} ("non-resonant") and vice versa ("K^* combinatoric"), and those that do not peak in either distribution ("combinatoric"). The peaking $m_{\rm miss}$ and m_{K^*} distributions use the same parameterization and values found by fitting for the signal modes. The non-peaking $m_{\rm miss}$ distributions are fit with an ARGUS function, while the non-peaking m_{K^*} distribution is modeled with a linear function. The two combinatoric background types are similarly flat in m_X, while the non-resonant backgrounds, typically $B \to XK\pi$, have both a flat and peaking component in m_X. However, because these non-resonant events are not signal-like in both $m_{\rm miss}$ and m_{K^*}, they are not present in the ${}_s$Plot projection in m_X.

The effectiveness of the signal extraction method is validated on MC samples for $\chi_{c1,2}$ and $X(3872)$ signal events, and toy samples generated from the MC background distribution. Successful performance of the fit is verified on simulated datasets assuming $n_{\rm S}$ and $n_{\rm B}$ from the known branching fractions and efficiencies. For the $X(3872)$ and χ_{c2} modes, we test the signal extraction covering the range from a null result up to the $\mathcal{B}(B \to \chi_{c2}K)$ upper limits [12] or using $\mathcal{B}(X(3872) \to \psi(2S)\gamma)$ several times higher than $\mathcal{B}(X(3872) \to J/\psi\gamma)$. Small biases found in the results of the MC fit validation are applied as a correction to the determination of the efficiency and final results.

The efficiency is determined by calculating the fraction of the events generated in MC simulation that survive the analysis selection criteria and are returned by the fitting procedure. Standard *BABAR* corrections are applied to account for particle identification differences found between simulation and data. These corrections are at the level of a few percent. The efficiencies for each mode are given in Table I.

We calculate the branching fraction for each decay mode using $\mathcal{B}(B \to XK) = N_S/(N_{B\overline{B}} \times \epsilon \times f)$ where N_S is the bias-corrected number of signal events from the fit to the m_X ${}_s$Plot, $N_{B\overline{B}}$ is the number of $B\overline{B}$ pairs in the data set, ϵ is the total signal extraction efficiency, and f represents all secondary branching fractions. The fit results and derived branching fractions are summarized in Table I.

For $\mathcal{B}(B \to \chi_{c1}K)$, the largest source of systematic uncertainty is due to the uncertainties on the secondary branching fractions beyond the control of this analysis ($\sim 6\%$); the second-most is uncertainty associated with particle identification ($\sim 4\%$). In the case of $B^0 \to \chi_{c2}K^{*0}$, the largest systematic error by far comes from a lack of adequate MC for determining the fit efficiency ($\sim 20\%$). For the remaining $B \to \chi_{c2}K$ and $B \to X(3872)K$ decay modes, statistical uncertainty tends to completely dominate systematic effects. For $X(3872) \to J/\psi\gamma$, the largest source of systematic uncertainty is due to uncertainties associated with particle identification ($\sim 4\%$). The predominant systematic uncertainty for $X(3872) \to \psi(2S)\gamma$ comes from MC/data differences in modeling the background $m_{\rm miss}$ and m_X shapes ($\sim 11\%$).

Figure 1 shows the fit to m_X in the mass range $3.411 < m_X < 3.611$ GeV/c^2. We observe all of the ex-

TABLE I: Summary of the analysis results. N_S is the bias-corrected number of signal events extracted from the m_X ${}_s$Plot, σ is the statistical significance defined as square root of the difference in χ^2 values between the fit result to the data and a result assuming zero signal events, ϵ is the total efficiency for the decay mode, and Derived $\mathcal{B}$ is the measurement (with 90% confidence level upper limit in parentheses) of $\mathcal{B}(B \to \chi_{c1,2}K)$ or $\mathcal{B}(B \to X(3872)K) \cdot \mathcal{B}(X \to c\bar{c}\gamma)$ with statistical and systematic uncertainty.

Decay Mode	N_S	σ	$\epsilon(\%)$	Derived $\mathcal{B}$
χ_{c1}				$\times 10^{-4}$
$\chi_{c1}K^{\pm}$	1021 ± 35	31	11.0	$4.6 \pm 0.2 \pm 0.3$
$\chi_{c1}K^{0}$	242 ± 16	14	8.7	$4.1 \pm 0.3 \pm 0.3$
$\chi_{c1}K^{*\pm}$	71 ± 13	4.9	5.7	$2.7 \pm 0.5 \pm 0.3$
$\chi_{c1}K^{*0}$	255 ± 25	11	7.9	$2.5 \pm 0.2 \pm 0.2$
χ_{c2}				$\times 10^{-5}$
$\chi_{c2}K^{\pm}$	14.4 ± 7.7	1.8	12.3	$1.0 \pm 0.6 \pm 0.3 (< 1.8)$
$\chi_{c2}K^{0}$	6.5 ± 3.9	0.6	11.0	$1.5 \pm 0.9 \pm 0.3 (< 2.8)$
$\chi_{c2}K^{*\pm}$	1.4 ± 4.7	0.2	4.2	$1.2 \pm 4.3 \pm 6.2 (< 13)$
$\chi_{c2}K^{*0}$	40.6 ± 10.5	3.6	8.6	$6.4 \pm 1.7 \pm 1.7$
$X(J/\psi\gamma)$				$\times 10^{-6}$
$X(3872)K^{\pm}$	23.3 ± 6.4	3.8	14.5	$2.9 \pm 0.8 \pm 0.2$
$X(3872)K^{0}$	5.4 ± 3.6	1.4	11.0	$2.6 \pm 1.7 \pm 0.2 (< 4.9)$
$X(3872)K^{*\pm}$	0.6 ± 2.3	0.0	6.9	$0.7 \pm 2.6 \pm 0.1 (< 4.7)$
$X(3872)K^{*0}$	2.8 ± 5.2	0.8	10.4	$0.7 \pm 1.4 \pm 0.1 (< 2.8)$
$X(\psi(2S)\gamma)$				$\times 10^{-6}$
$X(3872)K^{\pm}$	21.9 ± 7.2	3.2	10.4	$8.5 \pm 2.8 \pm 1.0$
$X(3872)K^{0}$	8.0 ± 3.8	2.0	8.4	$11.5 \pm 5.5 \pm 1.1 (< 19)$
$X(3872)K^{*\pm}$	1.6 ± 3.0	0.6	5.0	$5.5 \pm 10.4 \pm 8.4 (< 21)$
$X(3872)K^{*0}$	-1.4 ± 3.3	–	6.7	$-1.3 \pm 3.1 \pm 0.5 (< 4.4)$

pected $B \to \chi_{c1}K$ decay modes and find good agreement with previous measurements, in all cases improving upon the existing results. We find 3.6σ statistical evidence for $B^0 \to \chi_{c2}K^{*0}$, and set upper limits for the remaining $B \to \chi_{c2}K$ decays.

Fits to m_X in the range $3.772 < m_X < 3.972$ GeV/c^2 are shown in Fig. 2 for decays to $J/\psi\gamma$. We confirm evidence for the decay $X(3872) \to J/\psi\gamma$ in $B^{\pm} \to X(3872)K^{\pm}$, measuring $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \cdot \mathcal{B}(X(3872) \to J/\psi\gamma) = (2.9 \pm 0.8(stat.) \pm 0.2(syst.)) \times 10^{-6}$ with a significance of 3.8σ. This value is in good agreement with the previous *BABAR* result [4], which it supersedes, and represents the best measurement of this branching fraction to date. We find no significant signal for $B \to X(3872)K, X(3872) \to J/\psi\gamma$ in the other decay modes.

Figure 3 shows the fit to the m_X distribution for $X \to \psi(2S)\gamma$ in the range $3.772 < m_X < 3.972$ GeV/c^2. In our search for $X(3872) \to \psi(2S)\gamma$ in $B^{\pm} \to X(3872)K^{\pm}$, we find the first evidence for this decay with a significance of 3.2σ. We derive $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \cdot \mathcal{B}(X(3872) \to \psi(2S)\gamma) = (8.5 \pm 2.8(stat.) \pm 1.0(syst.)) \times 10^{-6}$. We find no significant results in any of the other decays modes in this search.

Finally, in Fig. 4, we present the m_X distribution above 3.8 GeV/c^2. The results from all decay modes in this analysis have been summed together without correcting for branching fractions or efficiency. While the $X(3872)$ signal features prominently, there are no indications of any other signals.

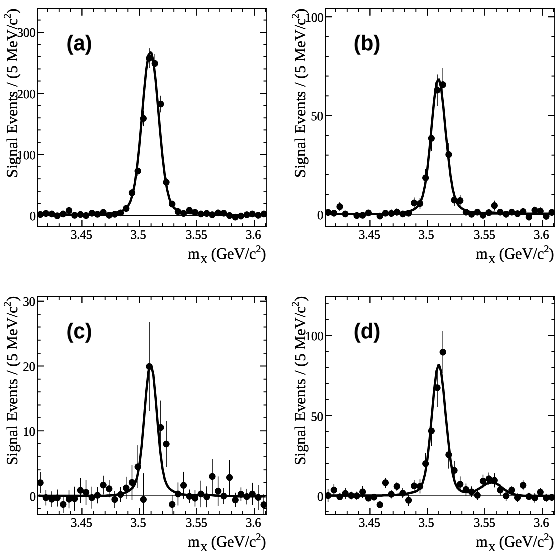

FIG. 1: ${}_s$Plot projection of the number of signal events versus m_X for (a) $B^{\pm} \to \chi_{c1,2}K^{\pm}$, (b) $B^0 \to \chi_{c1,2}K^0_S$, (c) $B^{\pm} \to \chi_{c1,2}K^{*\pm}$, and (d) $B^0 \to \chi_{c1,2}K^{*0}$. The solid curve is the fit to the data.

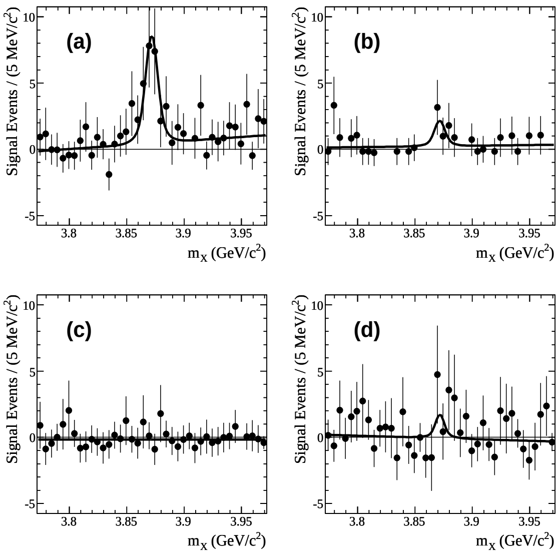

FIG. 2: ${}_s$Plot projection of the number of extracted signal events versus m_X for (a) $B^{\pm} \to X(3872)K^{\pm}$, (b) $B^0 \to X(3872)K^0_S$, (c) $B^{\pm} \to X(3872)K^{*\pm}$, and (d) $B^0 \to X(3872)K^{*0}$, where $X(3872) \to J/\psi\gamma$. The solid curve is the fit to the data.

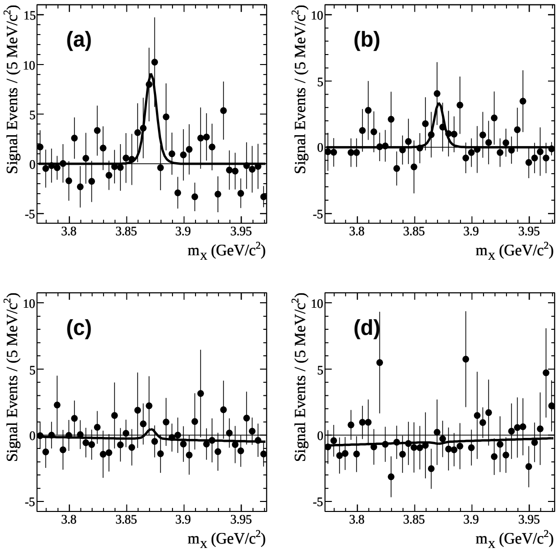

FIG. 3: $_s$Plot projection of the number of extracted signal events versus m_X for (a) $B^\pm \to X(3872)K^\pm$, (b) $B^0 \to X(3872)K^0_S$, (c) $B^\pm \to X(3872)K^{*\pm}$, and (d) $B^0 \to X(3872)K^{*0}$, where $X(3872) \to \psi(2S)\gamma$. The solid curve is the fit to the data.

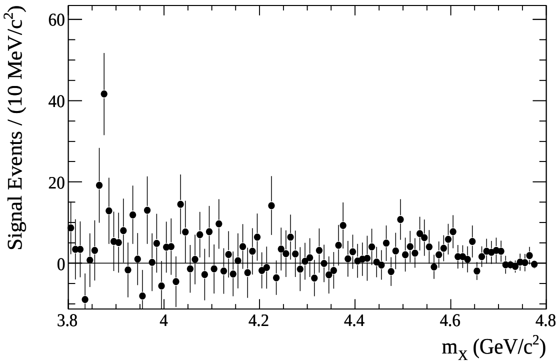

FIG. 4: $_s$Plot projection for the entire m_X range above $3.8\,\mathrm{GeV}/c^2$, summing all modes in this analysis.

In summary, we present first evidence for the decay $X(3872) \to \psi(2S)\gamma$ in $B^\pm \to X(3872)K^\pm$, and updated measurements of the $X(3872) \to J/\psi\gamma$, and $B \to \chi_{c1,2}K$ decays. We find evidence of $B^0 \to \chi_{c2}K^{*0}$, an expectedly factorization-suppressed decay [19], although we see no evidence for decays of this type in the other $\chi_{c2}K$ decay modes. Taking the statistical and systematic errors in quadrature, we find a ratio of $\frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J/\psi\gamma)} = 3.0 \pm 1.3$. Comparing to the branching fraction $\mathcal{B}(B^\pm \to X(3872)K^\pm)$ [20] with the errors again in quadrature, we find the ratios $\frac{\mathcal{B}(X(3872)\to J/\psi\gamma)}{\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)} = 0.3 \pm 0.1$ and $\frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4$. This relatively large branching fraction for $X(3872) \to \psi(2S)\gamma$ is generally inconsistent with $\overline{D}^0D^{*0}$ molecular interpretations of the $X(3872)$, and could indicate a significant amount of $c\overline{c}$-$\overline{D}^0D^{*0}$ mixing [9].

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