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Study of semi-inclusive production of η' mesons in B decays

The *BABAR* Collaboration

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Abstract

We report a measurement of the rate for $B \to \eta' X_s$ transitions where the η' meson has center-of-mass momentum in the range 2.0 to 2.7 GeV/c and X_s represents a system comprising a kaon and up to four pions. Our study is based on 22.2 million $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ with the *BABAR* detector at the Stanford Linear Accelerator Center. We find $\mathcal{B}(B \to \eta' X_s) = (6.8^{+0.7}_{-1.0}(stat) \pm 1.0(syst)^{+0.0}_{-0.5}(bkg)) \times 10^{-4}$ assuming that the signal is due to $b \to sg^*$ transitions.

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1 Introduction

The study of B decay modes involving gluonic penguin transitions $b \rightarrow sg^*$ is important both for obtaining a better understanding of the mechanisms contributing to B decays and as a sensitive place to search for direct *CP* violation effects. Exclusive modes such as $B^+ \rightarrow \eta' K^+$ or $B^0 \rightarrow K^+\pi^-$ are expected to be dominated by penguin amplitudes [1] and may show direct *CP*-violating charge asymmetries [2]. The study of a collection of decay modes $B \rightarrow \eta' X_s$, where X_s denotes a set of decay particles containing an s quark, is another attractive method for obtaining inclusive information about $b \rightarrow sg^*$ transitions.

In this paper, we report an application of this last approach to obtain a semi-inclusive measurement of the rate for $B \rightarrow \eta' X_s$ for center-of-mass momentum $p^*_{\eta'}$ of the η' ranging from 2.0 to 2.7 GeV/c. In this high momentum interval, η' production from $b \rightarrow c \rightarrow \eta'$ cascades, such as $B \rightarrow D_s X$ with $D_s \rightarrow \eta' X$, $B \rightarrow D^+ X$ with $D^+ \rightarrow \eta' X$, $B \rightarrow D^0 X$ with $D^0 \rightarrow \eta' X$, $B \rightarrow \Lambda_c X$ with $\Lambda_c \rightarrow \eta' X$, is suppressed, although it is important to note that other B decay processes, such as $b \rightarrow u$ decays ($B \rightarrow \eta'\pi$, $\eta'\rho$, $\eta' a_1$) and internal spectator $b \rightarrow c$ decays ($\overline{B}^0 \rightarrow \eta' D^{0(*)}$) may still contribute. Figure 1 shows the momentum distribution for the relevant processes. The various contributions can be distinguished by kaon identification and by examining the mass spectrum of the system recoiling against the η' ($M(X_s)$). This is possible if the recoiling hadronic system is reconstructed with a semi-inclusive set of possible decay modes. CLEO used such a semi-inclusive reconstruction technique to obtain the branching fraction $\mathcal{B}(B \rightarrow \eta' X_s) = (6.2 \pm 1.6(stat) \pm 1.3(syst)^{+0.0}_{-1.5}(bkg)) \times 10^{-4}$ for $2.0 < p^*_{\eta'} < 2.7$ GeV/c [3]. This rate is large in comparison with available predictions [4]. Our analysis uses a similar technique, although with improved kaon identification and different Monte Carlo models.

2 The *BABAR* detector and dataset

The data used in this analysis were collected with the *BABAR* detector [5] at the PEP-II storage ring [6] located at the Stanford Linear Accelerator Center. The study presented here is based on an integrated luminosity of 20.2 fb^{-1} corresponding to a sample of 22.2 million $B\overline{B}$ pairs at the $\Upsilon(4S)$ resonance (on-resonance) and 2.6 fb^{-1} collected with center of mass energy 40 MeV below this resonance (off-resonance).

The asymmetric beam configuration in the laboratory frame provides a boost to the $\Upsilon(4S)$ increasing the momentum range of the B-meson decay products up to 4.3 GeV/c. Charged particles are detected and their momenta are measured by a combination of a silicon vertex tracker consisting of five double-sided layers and a 40-layer drift chamber, both operating in a 1.5-T solenoidal magnetic field. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter, which provides excellent angular and energy resolution with high efficiency for energies above 20 MeV.

Charged particle identification is provided by measurements of the average energy loss dE/dx in the tracking devices and the Cherenkov angle in the detector for internally reflected Cherenkov light (DIRC). The Cherenkov angle determination provides K-π separation of better than 4σ below 3 GeV/c and 2.5σ for the highest momenta.

3 Event selection

In order to select $B\overline{B}$ events, we use the following requirements:

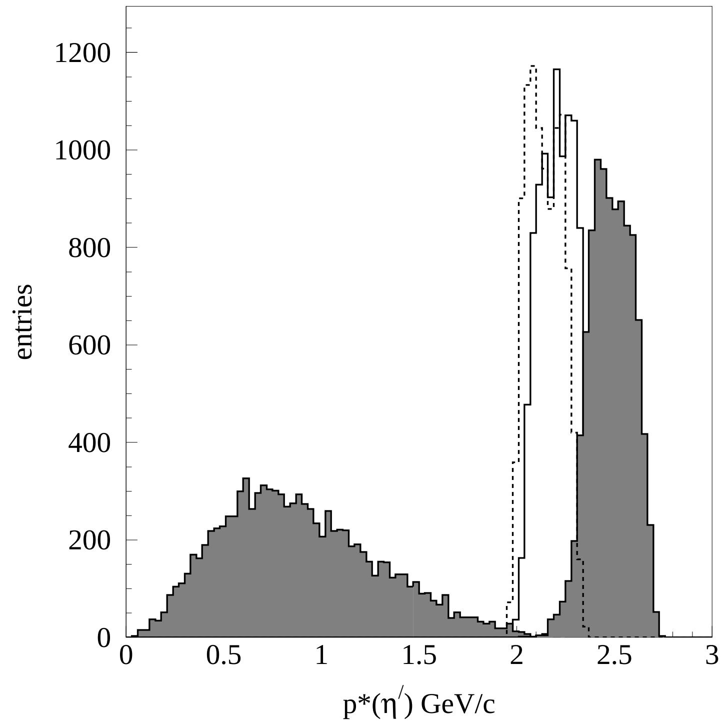

Figure 1: Distribution of $p^*_{\eta'}$ from Monte Carlo simulation of various $b \to sq\overline{q}$ processes, such as $B \to \eta' K$, $\eta' K^*$ (horizontally hatched histogram), η' from a mixture of $B\overline{B}$ sources dominated by $b \to c$ cascade contributions (diagonally hatched histogram), $\eta' D^0$ (open histogram) and $\eta' D^{*0}$ (dashed histogram) samples.

- There must be at least four charged tracks per event, in order to suppress low multiplicity events such as $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$.
- R_2, the ratio of the second to the zeroth Fox-Wolfram moment [7], must be less than 0.5. The distribution of this variable, which varies from 0 to 1, is peaked at low values for spherical $B\overline{B}$ events while it is broader and shifted toward intermediate values for $e^+e^- \to q\overline{q}$ events ($q = u, d, s, c$).
- The total energy of charged and neutral particles is required to be at least 5 GeV and below 15 GeV. Events having a significant missing energy due to neutrinos, such as $\tau^+\tau^-$ events where one τ decay to a higher multiplicity hadronic mode, such as $\tau \to \pi\pi\pi\nu_\tau$, are highly suppressed by this cut.

The efficiency of this selection is $(98 \pm 1)\%$ for $B\overline{B}$ Monte Carlo events.

4 Semi-inclusive analysis

We form combinations of a charged kaon or a K^0_S, an η' and as many as four pions of which at most one is a π^0. Sixteen decay modes and their charge conjugates are considered:

$$
\begin{array}{l}
B^{\pm} \to \eta' K^{\pm}(+\pi^0(+\pi^+\pi^-)) \\
B^0/\overline{B}^0 \to \eta' K^0_S(+\pi^0(+\pi^+\pi^-)) \\
B^{\pm} \to \eta' K^0_S\pi^{\pm}(+\pi^0(+\pi^+\pi^-)) \\
B^0/\overline{B}^0 \to \eta' K^{\pm}\pi^{\mp}(+\pi^0(+\pi^+\pi^-))
\end{array}
$$

The η' is reconstructed in the $\eta\pi^+\pi^-$ channel, from $\eta \to \gamma\gamma$ candidates only. We require a minimum energy of 50 MeV for photons from $\eta \to \gamma\gamma$. Photons are rejected if they are consistent with originating from a π^0 having an energy above 200 MeV. Candidates with invariant mass within 3σ of the η mass are kinematically fitted to the nominal η mass and then combined with two charged tracks to form an η' candidate.

To identify the s quark in the X_s system, we select events either with a track consistent with a charged kaon or with a reconstructed K^0_S in the $\pi^+\pi^-$ channel. The charged kaon selection has been optimized to reduce background from $B \to \eta'\pi$, $\eta'\rho$, and $\eta' a_1$ decays without losing too much efficiency for the signal. For the K^0_S, we consider the two-dimensional angle α between the momentum of the K^0_S candidate and the flight direction, which is peaked near zero for a true K^0_S. We require $\alpha < 0.05$ rad. Selected K^0_S candidates with invariant mass within 3σ of the K^0_S mass are kinematically fitted to the nominal K^0_S mass.

4.1 B candidate selection

Candidates for $B \to \eta' X_s$ are reconstructed in the 16 modes listed above. They are required to be consistent with a B decay based on the energy substituted mass [5],

$$M_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$$

and the energy difference

$$\Delta E = (E_i E_B - \mathbf{p}_i \cdot \mathbf{p}_B - s/2)/\sqrt{s}$$

where $\sqrt{s}$ is the total e^+e^- center-of-mass energy. The initial-state four-momentum $(E_i, \mathbf{p}_i)$ derived from the beam kinematics and the four-momentum $(E_B, \mathbf{p}_B)$ of the reconstructed B candidate are all defined in the laboratory. The calculation of $M_{\rm ES}$ only involves the three-momenta of the decay products, and is therefore independent of the masses assigned to them. An additional variable, the cosine of the angle in the center of mass frame between the thrust axis of the B candidate and the thrust axis of the remainder of the event, $\cos\theta_T$, is used to remove continuum background. The selection criteria applied are the following:

- $M_{ES} > 5.265\,{\rm GeV}/c^2$ and $|\Delta E| < 0.1\,{\rm GeV}$, *i.e.,* consistent with the nominal B mass and known production energy; and
- $|\cos\theta_T| < 0.8$ to reduces the large continuum background, which is concentrated near $\cos\theta_T = \pm 1$ while the expected signal is uniformly distributed in this variable.

For each event, we select only a single candidate in a given decay mode. The selected candidate is the one with the smallest χ^2 defined as $\chi^2 = (M_{\rm ES} - M_B({\rm PDG}))^2/\sigma({\rm M_B^2}) + \Delta{\rm E}^2/\sigma(\Delta{\rm E}^2)$, where the widths $\sigma(M_B^2)$ and $\sigma(\Delta E^2)$ are obtained from Monte Carlo simulation.

4.2 Determination of the X_s mass spectrum

To explore the raw X_s mass distribution, we first select the B candidates for which the mass of the η' daughter is within 3 sigma of the known value, and subtract the off-resonance contribution, rescaled by the luminosity ratio, from the on-resonance distribution. The resultant mass distributions for all B modes and separately for the B^0 modes are shown in Fig. 2. Both distributions can be seen to peak above $2\,\mathrm{GeV}/c^2$. We can also examine the X_s mass spectrum for a possible signal for the internal spectator charmed decays ($X_s = D^{0(*)}$ with $D^{*0} \to D^0\pi^0$, $D^0 \to K\pi$, $K\pi\pi\pi$, $K\pi\pi^0$). In particular, for the B^0 modes, there is no evidence for a narrow D^0 signal near $1870\,\mathrm{MeV}/c^2$ (see Fig. 3 for predicted distribution), although statistics are low.

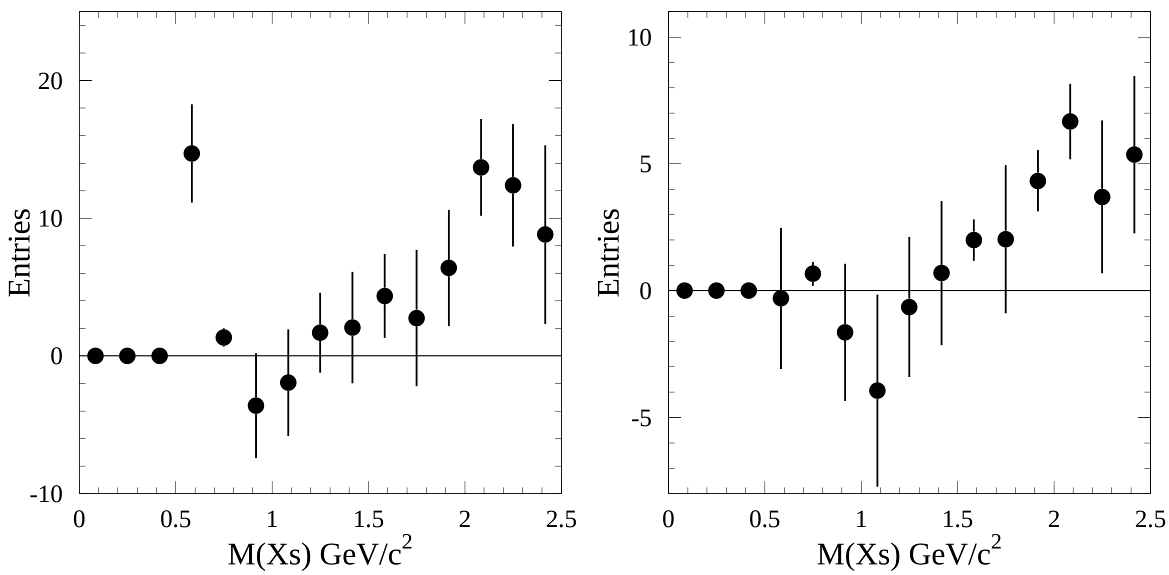

Figure 2: Continuum-subtracted $M(X_s)$ spectrum for all B modes (left) and B^0 modes alone (right)

To obtain the decay X_s spectrum we first fit the η' mass distribution in bins of X_s mass. For masses above $2.32\,\mathrm{GeV}/c^2$, corresponding to the kinematic limit $p^*_{\eta'} < 2\,\mathrm{GeV}/c$, the yield is dominated by the $b \to c \to \eta'$ contribution. The differential branching fraction for the region $M(X_s) < 2.5\,\mathrm{GeV}/c^2$, where we expect $b \to sg^*$ to be dominant, is shown in Fig. 4. The signal tends to peak towards higher mass values, and remains substantial between 2 and $2.5\,\mathrm{GeV}/c^2$. The experimental resolution for $M(X_s)$ has been estimated with the Monte Carlo simulation to be 80–90 MeV/c^2 around $1.5\,\mathrm{GeV}/c^2$, rising to 170–180 MeV/c^2 for $2\,\mathrm{GeV}/c^2$ and above.

Looking specifically at the two-body decay modes alone ($X_s = K^\pm, K^0_S$), we find no significant signal for $\eta' K^0_S$ but observe 36.2 ± 6.6 events for $\eta' K^\pm$ (see Fig. 5). This corresponds to a branching fraction of $(5.6 \pm 1.0(stat)) \times 10^{-5}$, in good agreement with our recent exclusive measurement of $(7.0 \pm 0.8(stat) \pm 0.5(syst)) \times 10^{-5}$ [10], thereby confirming the consistency of the semi-inclusive method.

4.3 Extraction of η' signal

The $B \to \eta' X_s$ yields are determined by fitting the observed η' signals, after all selection criteria have been applied in the range $2.0 < p^*_{\eta'} < 2.7\,\mathrm{GeV}/c$. We fit separately the $K^\pm$ modes and the

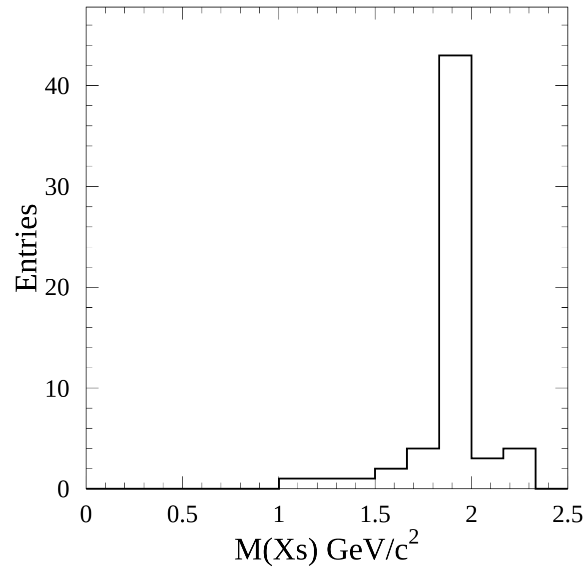

Figure 3: $M(X_s)$ spectrum predicted from simulation of $\overline{B}^0 \to \eta' D^0$ decays

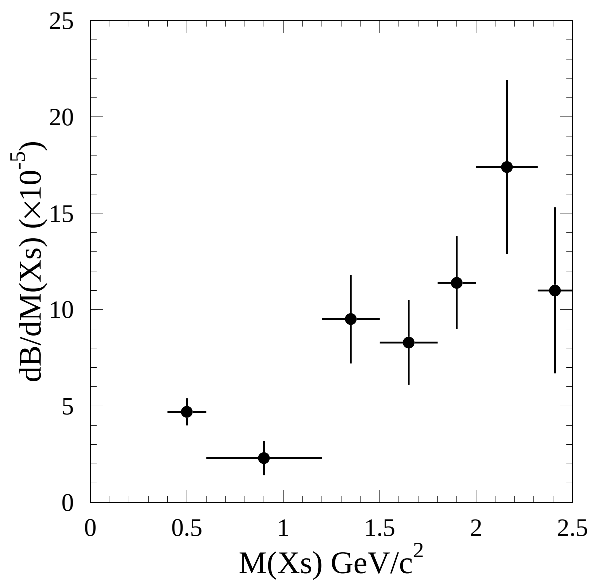

Figure 4: Distribution of $d\mathcal{B}(B \to \eta' X_s)/dM(X_s)$ (statistical errors only) as a function of $M(X_s)$ for all B modes.

K_S^0 modes with results as shown in Fig. 6. We find 188.8 ± 21.5 events for the $K^{\pm}$ modes and 57.1 ± 14.7 events for the K_S^0 modes in on-resonance data. For off-resonance data, we find $0.0^{+2.5}_{-0.0}$ for $K^{\pm}$ modes and $0.0^{+3.0}_{-0.0}$ for K_S^0 modes.

The efficiencies have been computed with two main Monte Carlo simulations to study model dependence. One involves a mixture of resonant modes, $\eta' K$, $\eta' K_1$, $\eta' K_2^*$, $\eta' K_3^*$, and $\eta' K_4^*$, and

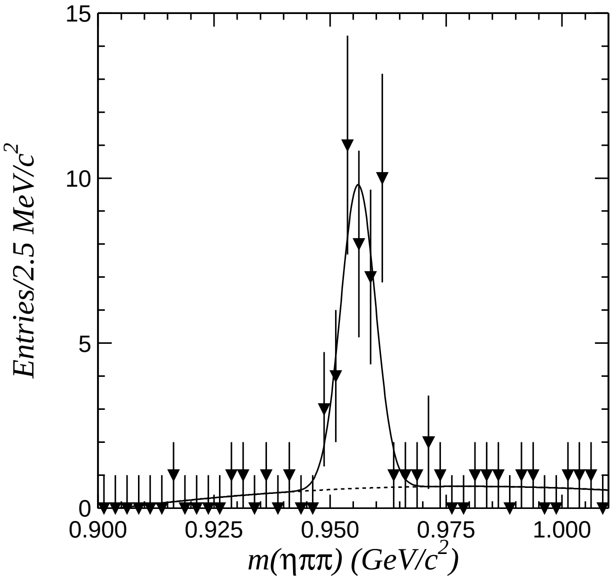

Figure 5: η' mass for $X_s = K^{\pm}$.

the other uses an X_s pseudo particle decaying to $s\overline{q}g$ ($q = u, d$). In the latter, we use a $M(X_s)$ distribution derived from the η' QCD anomaly theoretical prediction [8, 9].

For a given K mode ($K^{\pm}$ or K^0_S), the efficiency is computed as:

$$\epsilon = \frac{N_{\text{fit}}}{N_{\text{gen}}}$$

where N_{fit} and N_{gen} are, respectively, the numbers of fit and generated events. The efficiencies are estimated (statistical errors only) to be $(7.6 \pm 0.4)\%$ for $K^{\pm}$ modes and $(3.3 \pm 0.2)\%$ for K^0_S modes, including the $K^0_S \to \pi^+\pi^-$ branching fraction.

4.4 Semi-inclusive branching fraction and interpretation

The semi-inclusive rate for the high momentum region, $2.0 < p^*_{\eta'} < 2.7\,\text{GeV}/c$, is computed by performing a weighted average of the results obtained in the $K^{\pm}$ modes and the K^0_S modes. The detection efficiencies given in Section 4.3 are corrected to account for the η' and η branching fractions to the channel we observe (17.4%), and the $K^0 \to K^0_S$ projection (1/2). The final state X_s includes both K^+- and K^0-tagged decays, and both charged and neutral B mesons contribute to the observed yields. The total number of produced B mesons of both charges is 45.5 million. Computing the weighted average of the K^+- and K^0-tagged decays, assuming that their branching fractions are equal, we obtain $\mathcal{B}(B \to \eta' X_s) = (6.8^{+0.7}_{-1.0}(stat) \pm 1.0(syst)^{+0.0}_{-0.5}(bkg)) \times 10^{-4}$. Our measurement confirms, with higher precision, the CLEO result, $(6.2 \pm 1.6(stat) \pm 1.3(syst)^{+0.0}_{-1.5}(bkg)) \times 10^{-4}$.

Sources of systematic error included in this result are summarized in Table 1. The largest uncertainty arises from our ability to model the X_s system. This contribution is estimated by determining the efficiency with different Monte Carlo generators, as described in Section 4.3. The efficiency from the X_s pseudo-particle model tends to be lower than that obtained with the mixture of resonant decays, the difference is smaller when we increase the amount of heavier resonances (K^*_3,

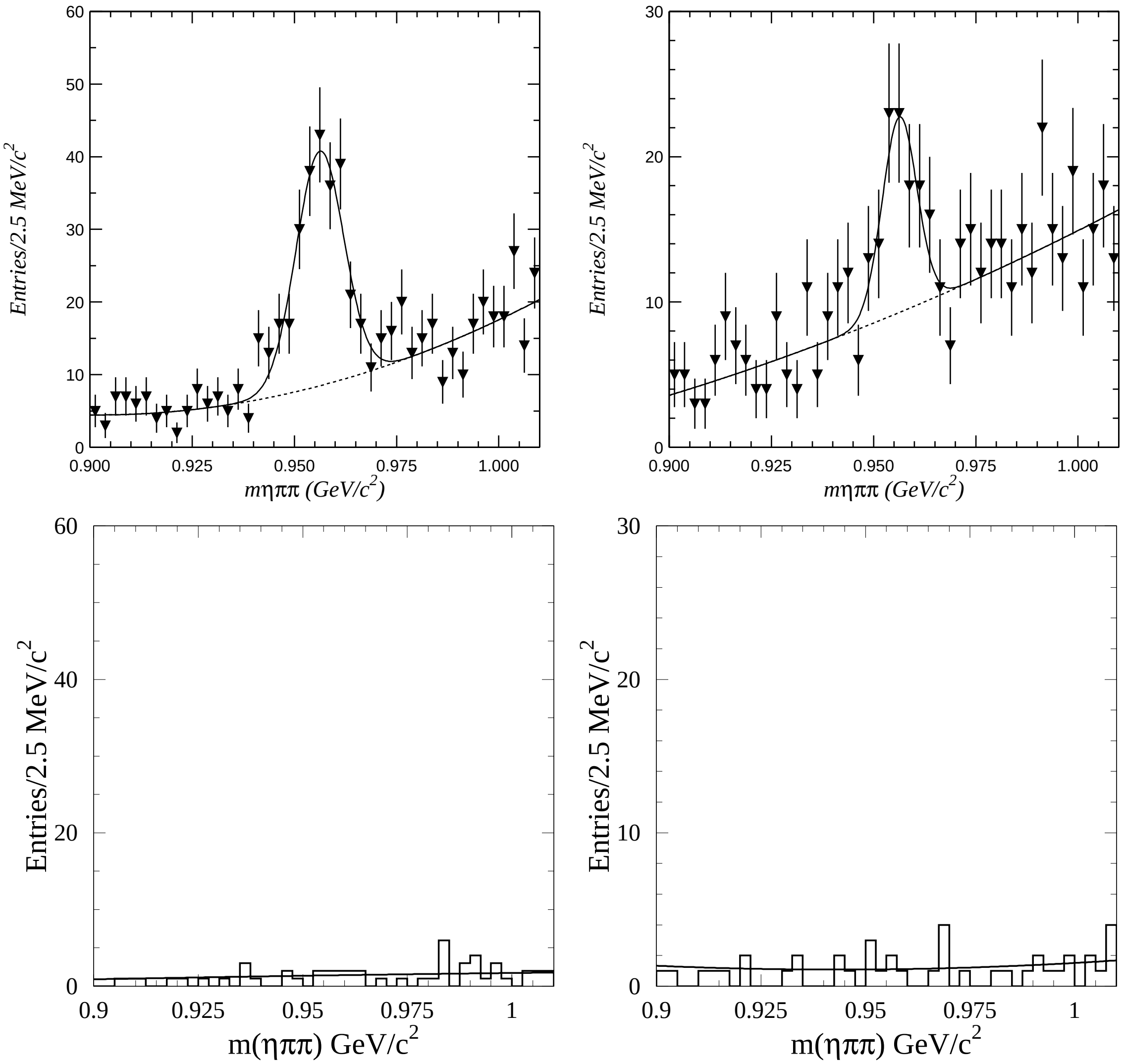

Figure 6: Semi-inclusive η' mass spectra for $K^{\pm}$ (upper left: on-resonance, lower left: off-resonance) and K^0_S (upper right: on-resonance, lower right: off-resonance) modes, in the momentum range $2.0 < p^*_{\eta'} < 2.7\,\mathrm{GeV}/c$

K^*_4) in the model. Other systematic uncertainties are contributed by the event shape requirement, $B\overline{B}$ counting, tracking and photon detection efficiencies, and kaon identification efficiencies.

We have also considered a possible contribution from internal spectator decays $\overline{B}^0 \to \eta' D^{0(*)}$ as an additional source of systematic error. Early branching fraction predictions for these modes were in the range $(1.5 - 6.0) \times 10^{-5}$ [11] while more recent predictions [12] find $(3 - 5) \times 10^{-5}$, assuming that only the quark content of the η' contributes to the tree diagram. The efficiency computed for these modes is 2%, which implies a contribution of (1.4-4.6)% to the observed yield. To conservatively account for the theoretical uncertainty, we use a branching fraction of 9.0×10^{-5} in determining the systematic error contribution.

Several models have been proposed to explain η' production at high $p^*_{\eta'}$ in B decays:

Table 1: Systematic errors for $\mathcal{B}(B \to \eta' X_s)$

Source	$K^{\pm}$ modes	K^0_S modes
Model dependency	$\pm 10\%$	$\pm 10\%$
Event shape	$\pm 1\%$	$\pm 1\%$
B counting	$\pm 1.6\%$	$\pm 1.6\%$
Tracking	$\pm 5\%$	$\pm 7\%$
Photon detection	$\pm 6.8\%$	$\pm 7.2\%$
$\mathcal{B}(\eta' \to \eta\pi\pi) \times \mathcal{B}(\eta \to \gamma\gamma)$	$\pm 3.4\%$	$\pm 3.4\%$
$K^{\pm}$ identification	$\pm 2.6\%$	–

- Introduction of $b \to sq\overline{q}$ operators with constructive interference between $u\overline{u}$, $d\overline{d}$ and $s\overline{s}$ components of the η' [4]; however the expected branching fraction from such processes is much lower than we observe.

- A $b \to c\overline{c}s$ enhancement through a possible $c\overline{c}$ content in the η' wave function [13, 14]; however, more recent calculations [15] do not support such a wave function component.

Both of these mechanisms predict an X_s mass spectrum peaking near $1.5\,\mathrm{GeV}/c^2$, lower than suggested by the data. The branching fraction and mass spectrum in data do appear to be consistent with a model incorporating an η' QCD anomaly [8, 9] that couples the η' to gluons, $b \to sg^*$, $g^* \to g\eta'$.

5 Summary

We have measured a semi-inclusive η' branching fraction using fully reconstructed final states consisting of an η' and a system comprising one kaon and up to four pions to reduce the background from other B decays. We find $\mathcal{B}(B \to \eta' X_s) = (6.8^{+0.7}_{-1.0}(stat) \pm 1.0(syst)^{+0.0}_{-0.5}) \times 10^{-4}$ for $2.0 < p^*_{\eta'} < 2.7\,\mathrm{GeV}/c$. This measurement confirms the surprisingly large branching fraction found by CLEO, but with much improved precision. This and the shape of the X_s mass distribution are consistent with the η' QCD anomaly model.

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