HADRONIC B MESON DECAYS
- Getting Ready for CP Violation -

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We review recent results on hadronic B meson decays including rare as well as non-suppressed modes. The main emphasis is on those channels relevant to measurement of CP violation in the coming B factories. After briefly describing flavor-tagged charm counting, we cover $B \to DK^{(*)}$, $B \to$ charmless 2-body decays, inclusive $\eta'$ production, and final-state-interaction phases in $B \to \Psi K^*$ and $B \to D^* \rho$.

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1 Flavor-tagged charm counting

According to experiments, the semileptonic branching ratio of $B$ mesons, $B_{s.l.}$, and the number of charms generated in a $B$ meson decay, $n_c$, are (the numbers are averages over $B^0$ and $B^+$)

$$B_{s.l.} = 10.41 \pm 0.29 \%, \quad n_c = 1.10 \pm 0.05, \quad (1)$$

while the corresponding theoretical predictions are

$$B_{s.l.} = \begin{cases} 12.0 \pm 1.0 \% \\
10.9 \pm 1.0 \% \end{cases}, \quad n_c = \begin{cases} 1.20 \pm 0.06 \% \\
1.21 \pm 0.06 \% \end{cases}, \quad \text{for } \mu = \begin{cases} m_b \\
m_b/2 \end{cases}, \quad (2)$$

where the errors are largely due to uncertainties in quark masses. We see that the agreement between experiment and theory is within the errors for $B_{s.l.}$ and about two sigmas for $n_c$; namely, it is inconclusive at present.

Further information can be obtained by counting $c$ and $\bar{c}$ separately for a given $b$ flavor. This is accomplished on the $\Upsilon 4S$ resonance by tagging $D^0$ and $D^+$ mesons (denoted simply as $D$) with leptons from the other $B$ meson. In the sample of $D$-lepton pairs, however, $D$ and the lepton may come from the same $B$, in which case $D$ and the lepton tend to be back-to-back. Those coming from different $B$’s would be uncorrelated ($B$ mesons decay nearly at rest). This can be used to statistically separate the two kinds of pairs. Figure 1 shows the measured angular correlations. One can see that the $D\ell^-$ (or $D\ell^+$) pairs are

![](image.png)

Figure 1: The $\cos \theta_{D-\ell}$ distribution where $\theta_{D-\ell}$ is the angle between $D$ and the lepton. The charm quantum number of $D$ and the charge of the lepton are the same for the open squares and opposite for the solid squares. If $D$ and the lepton are from the same $B$, they are mostly back-to-back. The lepton momentum is required to be greater than 1.5 GeV/c.
mostly from different $B$'s, namely, the directions of $D$ and $\ell$ are uncorrelated (flat distribution). On the other hand, the $D\ell^-$ (or $\bar{D}\ell^+$) pairs are mostly from the same $B$ (back-to-back); there is, however, a small uncorrelated component. After corrected for the $B^0\bar{B}^0$ mixing, the latter component represents the ‘wrong-sign’ $D$ meson production $b \to \bar{D}$ which can be due to the process $b \to cW^-$, $W^- \to \bar{c}s$:

$$\frac{\#(D\ell^+)_{\text{app.B}}}{\#(D\ell^-)_{\text{app.B}}} \cdot \frac{Br(\bar{B} \to DX)}{Br(B \to DX)} = 0.100 \pm 0.026 \pm 0.016.$$  \hspace{1cm} (3)

Before this measurement, $\bar{c}$ in $W^- \to \bar{c}s$ was usually assumed to hadronize either as a $D_S^-$, one of its excited states, or a charmonium. A possibility of sizable wrong-sign $D$ production, however, had been pointed out prior to the measurement.

As a byproduct, one can form the ratio of $\#(D\ell^+)_{\text{app.B}}$, which measures $Br(\bar{B} \to DX)$, to $\#(D\ell^-)_{\text{same.B}}$, which measures $Br(\bar{B} \to D\ell^-\bar{\nu})$, to obtain

$$r \equiv \frac{Br(\bar{B} \to DX)/Br(B \to X)}{Br(B \to D\ell^-\bar{\nu})/Br(B \to X\ell^-\bar{\nu})} = 0.901 \pm 0.034 \pm 0.015,$$  \hspace{1cm} (4)

where $Br(B \to X) = 1$ by definition, and $Br(\bar{B} \to X\ell^-\bar{\nu})$ is the separately-measured semileptonic branching ratio. Note that the numerator of $r$ is the probability that the $b$ quark will result in a right-sign $D$, while the denominator is the same probability given that the decay was semileptonic. If we ignore $b \to u$, $D_s^+$ production from $b \to c$, production of charmed baryon or charmonium, and $b \to 'sg'$, then we expect $r = 1$. Here, $b \to 'sg'$ stands for any quark-level transition $b \to (\text{no charm})$ other than $b \to u$. Correcting for all but $b \to 'sg'$, we get

$$Br(b \to 'sg') = 0.2 \pm 3.4 \pm 1.5 \pm 1.7\% \text{ or } < 6.8\% \text{ (90\% c.l.)}$$  \hspace{1cm} (5)

where the first error is statistical, second systematic, and the third is due to models used in the corrections. It should be noted that the ratio $r$ above is insensitive to the uncertainty in the decay branching ratios of $D$ mesons used in the analysis since it largely cancels between the numerator and the denominator.

Another ratio of interest is the denominator of $r$ itself which is expected to be unity if we ignore $\bar{B} \to D_s^+\ell^-\bar{\nu}$ and $b \to u\ell^-\bar{\nu}$. The $D$ mesons are detected by $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ where $Br(D^+ \to K^-\pi^+\pi^+)$ is normalized to $Br(D^0 \to K^-\pi^+)$. Thus, by setting the above ratio to unity after the corrections, one can extract $Br(D^0 \to K^-\pi^+)$. The result is

$$Br(D^0 \to K^-\pi^+) = 3.69 \pm 0.11 \pm 0.16 \pm 0.04\%,$$  \hspace{1cm} (6)

which may be compared to the PDG value $Br(D^0 \to K^-\pi^+) = 3.85 \pm 0.09\%$.
Along with $B \to K \pi, \pi \pi$, these are modes that we hope can be used to measure the CKM angle $\gamma$. A large CP asymmetry is possible in $B^-\to D^0 K^-$ vs. $B^+\to D^0 K^+$ ($D^0$: CP eigenstates) through interference of $B^-\to D^0 K^-$ and $B^-\to \bar{D}^0 K^-$ (and its charge conjugate modes). The original method proposed to measure these 4 modes to construct two triangles to extract the angle $\gamma$. A difficulty in measuring the 'wrong-sign' $D^0$ decay due to the doubly-Cabibbo-suppressed $D^0$ decay was pointed out by Atwood, Dunietz and Soni, who also proposed a solution for the problem even though it required a large data sample. Analyses using only the favored modes were recently proposed by Gronau and Xing. Also, the charged $B$ decays to $DK$ ($D^0\pi^0$) can be combined with their corresponding neutral $B$ to enhance sensitivities.

We detect $D^0$ in $B^-\to D^0 K^-$ in the modes $D^0\to K^-\pi^+\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$. The major background comes from the Cabibbo-favored counter part $B^-\to D^0\pi^-$. In fact, we expect

$$\frac{Br(B^-\to D^0 K^-)}{Br(B^-\to D^0\pi^-)} \sim \lambda^2 \left(\frac{f_K}{f_\pi}\right)^2 \sim 0.08,$$

where $\lambda \sim 0.225$ is the Cabibbo factor and $f_{K,\pi}$ are decay constants. The $B^-\to D^0\pi^-$ background is suppressed by the ionization loss information in the drift chamber and the fact that miss-assigning kaon mass to the pion results in the total energy greater than the expected $B$ meson energy. There is also substantial background from the continuum events, and they are reduced by cutting on the angle between the sphericity axis of the $B$ candidate and that of the rest of the event, the polar angle of $B$ in the lab frame, and a Fischer discriminant. The Fischer discriminant $F$ is a linear combination of a set of measured variables $\vec{x}$

$$F = \vec{\lambda} \cdot \vec{x}$$

where the coefficients $\vec{\lambda}$ is determined by maximizing the separation between the signal sample and the background sample:

$$S \equiv \frac{\left(\langle F \rangle_s - \langle F \rangle_b\right)^2}{\sigma_F^2} = \frac{\left[\vec{\lambda} \cdot (\langle \vec{x} \rangle_s - \langle \vec{x} \rangle_b)\right]^2}{\vec{\lambda}^T V \vec{\lambda}},$$

where $V$ is the covariant matrix of $\vec{x}$ and $\langle \rangle_{s,b}$ denotes the average over the signal or background sample. Taking $\partial S/\partial \lambda_i = 0$ gives

$$\vec{\lambda} = V^{-1}(\langle \vec{x} \rangle_s - \langle \vec{x} \rangle_b).$$
Here, $\vec{\xi}$ are the energy flows in 9 cones around the event axis, the second Fox-Wolfram event shape variable, and the polar angle in lab of $B$ candidate event axis.

The $B$ mass is calculated from the total 3-momentum $\vec{P}_{tot}$ of the daughter particles and the known beam energy $E_{beam}$ as

$$M_B \equiv \sqrt{E_{beam}^2 - \vec{P}_{tot}^2},$$

and called the beam-constrained mass. Note that the beam-constrained mass is equivalent to the absolute value of the total momentum of candidate particles. The distribution of $M_B$ after the background rejection cuts is given in Figure 2.

There is a significant excess beyond the expected background and we obtain

$$\frac{Br(B^- \rightarrow D^0 K^-)}{Br(B^- \rightarrow D^0 \pi^-)} = 0.055 \pm 0.014 \pm 0.005$$

which is consistent with the theoretical expectation.

The large background from $B^- \rightarrow D^0 \pi^-$ indicates a need for a better particle identification. One way around it is to detect the channel $B^- \rightarrow D^0 K^{*-}, K^{*-} \rightarrow K_S \pi^-$, where the background from the Cabibbo-favored counterpart $B^- \rightarrow D^0 \rho^-$ is negligible. Such analysis is currently under way,
3 \( B \to \) charmless 2-body decays

The interference of tree and penguin diagrams is expected to cause substantial CP violating decay rate asymmetries in charmless 2-body modes such as \( B \to K\pi \) and \( \pi\pi \). Many methods have been proposed to extract the CKM phase angles \( \gamma \) and \( \alpha \) using these modes.[4]

In the rest frame of \( \Upsilon 4S \), the \( B \) mesons are nearly at rest \((P_B \sim 350 \text{ MeV}/c)\), and thus the light mesons are nearly monochromatic at \( P \sim m_B/2 \). Such momentum is the highest that can be created by a \( B \) decay, and as a consequence, the background from generic \( B \) decays are small. The main background thus comes from the continuum events where the two-jet events \( e^+e^- \to q\bar{q} \) can generate particles with momenta all the way up to the beam energy. And the continuum background is suppressed by the same set of parameters as in the \( D^0K^- \) analysis discussed above.

As in the case of \( D^0K^- \), it is critical to distinguish charged kaons from charged pions and again we use the ionization loss information \((dE/dx)\) and the \( B \) meson energy shift that occurs when the light meson mass is miss-assigned. Figure 3 shows the beam constrained mass distribution for the modes \( B^- \to K^-\pi^+, h^-\pi^0, K_S\pi^- \), where \( h^- \) is either \( K^- \) or \( \pi^- \). The variable \( \Delta E \) is the total energy of the candidate particles minus the beam energy, and expected to peak at zero for the signal when the masses are correctly assigned. When the wrong mass assignment is made (namely, \( K \leftrightarrow \pi \) flip), \( \Delta E \) shifts by about 42 MeV. In the figure, the charged kaons or charged pions are selected by the ionization loss only without using \( \Delta E \). All charged tracks are assigned the pion mass and thus one sees that the \( \Delta E \) peak for \( K^-\pi^+ \) is shifted. The \( dE/dx \) also provides \( \sim 1.8\sigma \) separation between \( K^+ \) and \( \pi^+ \) at \( p = 2.6 \text{ GeV}/c \) \((2.0\sigma \) for the new dataset taken with a He-based drift chamber gas), and \( \Delta E \) gives close to \( 2\sigma \) separation for a single \( K \leftrightarrow \pi \) flip. Final numbers are obtained by likelihood fit using the beam constrained mass, \( \Delta E \), \( dE/dx \) and the set of variables used for the continuum suppression. Table 1 gives the results where all numbers are published values[15] except for the column labeled ‘ICHEP98’ which shows the values updated at the ICHEP 1998 conference.[4]

One sees that we are starting to observe quite a few modes that are important in measuring the CP violating CKM angles. Most of these modes are self-tagging and do not require measurements of decay times (including the neutral \( B \) meson modes). Studies to measure decay asymmetries of these and other modes are currently under way.

Table 2 lists the other hadronic rare modes of interest that involve \( \eta(1) \), \( \omega \), or vector mesons. There are upper limits for other modes which can be found in the references.[18,20] Some salient features one notices are: (1) the \( \eta'K^- \) rate
Figure 3: The beam-constrained mass distribution for the modes $B^{-} \rightarrow K^{-}\pi^{+}$, $h^{-}\pi^{0}$, and $K_{S}\pi^{-}$ where $h^{-}$ is $K^{-}$ or $\pi^{-}$. All charged tracks are assumed to be pion. The dotted lines show the continuum backgrounds.

is large, (2) $\eta^{' } K^{-} \rightarrow \eta K^{-}$, and (3) $\eta^{' } K \sim \eta^{' } K^{*}$.

Variety of mechanisms have been proposed to explain these features. The large $\eta^{' } K^{-}$ rate may be due to $c\bar{c}$ content of $\eta^{' }$ [23] color-octet $c\bar{c}$ contribution, [24] new physics to enhance $b \rightarrow s g$, [25] $b \rightarrow s g g$ followed by $g g \rightarrow \eta^{' }$, [26] and gluon fusion where one gluon is from valence quarks, [27] They all have something to do with gluon-$\eta^{' }$ coupling, and many are closely related; in fact, when the gluon creation is dominated by $c\bar{c}$ loop, it may be interpreted as $c\bar{c}$ content (or coupling) to $\eta^{' }$. Often, it is said that the $c\bar{c}$ content of $\eta^{' }$ would result in $\eta^{' } K^{*}/\eta^{' } K \sim 2$ which is in contradiction with the experiment. This is not necessarily so. With the value of the $c\bar{c}$ coupling needed to explain the $\eta^{' } K^{-}$ rate, this ratio is still consistent with the data. [24] The observation $\eta K^{-} \rightarrow \eta K^{-}$ can be naturally explained by the fact that gluon couples to $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ with the same amplitude, and the valence quark content of $\eta^{' }$ and $\eta$ are roughly (ignoring the mixing) $\eta^{' } = u\bar{u} + d\bar{d} + s\bar{s}$ while $\eta = u\bar{u} + d\bar{d} - 2s\bar{s}$; namely, $u\bar{u} + d\bar{d}$ and $s\bar{s}$ interfere constructively for $\eta^{' }$ and destructively for $\eta$. The
Table 1: Measured branching fractions for $B \to \pi\pi, K\pi, KK$.

|                | $N$(signal) | signif. | Br($10^{-5}$)(PRL) | Br($10^{-5}$)(ICHEP98) |
|----------------|-------------|---------|---------------------|------------------------|
| $\pi^+\pi^-$   | 9.9         | 2.2$\sigma$ | $<1.5$             | $<0.84$               |
| $\pi^+\pi^0$   | 11.3        | 2.8$\sigma$ | $<2.0$             | $<1.6$                |
| $\pi^0\pi^0$   | 2.7         | 2.4$\sigma$ | $<0.93$            |                       |
| $K^+\pi^-$     | 21.6        | 5.6$\sigma$ | $1.5^{+0.9}_{-0.4} \pm 0.1 \pm 0.1$ | $1.4 \pm 0.3 \pm 0.2$ |
| $K^+\pi^0$     | 8.7         | 2.7$\sigma$ | $<1.6$             | $1.5 \pm 0.4 \pm 0.3$ |
| $K^0\pi^+$     | 9.2         | 3.2$\sigma$ | $2.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.2$ | $1.4 \pm 0.5 \pm 0.2$ |
| $K^0\pi^0$     | 4.1         | 2.2$\sigma$ | $<4.1$             |                       |
| $K^+K^-$       | 0.0         | 0.0$\sigma$ | $<0.43$            | $<0.24$               |
| $K^+K^0$       | 0.6         | 0.2$\sigma$ | $<2.1$             | $<0.93$               |
| $K^0K^0$       | 0           | -        | $<1.7$             |                       |
| $h^+\pi^0$     | 20.0        | 5.5$\sigma$ | $1.6^{+0.7}_{-0.5} \pm 0.3 \pm 0.2$ |                       |

feature $\eta' K \sim \eta' K^*$ is predicted by many of the above mechanisms and agrees with the qualitative argument by Lipkin.\footnote{30} At the end of the day, however, one should note that the standard 4-quark operators (penguins included) can explain the observed rates within the errors.\footnote{31}

4 Inclusive $\eta'$ production

As mentioned above, the gluonic penguin process ($b \to sg$) plays a critical role in direct CP violation in $B$ decays. One signature of gluonic penguin is excess production of $\eta'$ which is believed to be ‘gluon rich’.

In searching for $\eta'$ which might be originating from $b \to sg$, one looks for them at the end point of the momentum spectrum in order to suppress $\eta'$ from $b \to c$ processes. The momentum window is chosen to be $2.0 < p_{\eta'} < 2.7$ GeV/c. The background from continuum is suppressed by the pseudo-$B$-reconstruction technique which was used previously\footnote{22} for the inclusive study of the $b \to s\gamma$ (electro-magnetic penguin) process. Namely, we explicitly reconstruct $B \to \eta' K^{\pm}(n\pi)$ where $n \leq 4$ and at most one neutral pion can be included, then the invariant mass of the decay $\eta' \to \eta\pi^{+}\pi^{-}$ ($\eta \to \gamma\gamma$) is plotted when there is at least one $B$ candidate in the signal region of $\Delta E$ vs. $M_B$. The $\eta'$ mass distributions\footnote{23} are shown in Figure 4. The effective luminosity for the continuum data relative to the on-resonance data is 0.524; namely, the continuum background in (a) is about twice the amount seen in (b). The excess in (a) after the continuum background is subtracted is $39.0 \pm 11.6$. 


Table 2: Measured branching fractions for modes with $\eta'$ and $\omega$.

| Mode              | $Br(10^{-5})$ | Significance | Ref. |
|-------------------|---------------|--------------|------|
| $\eta'K^-$        | $7.4^{+0.8}_{-1.3} \pm 0.9$ | 12.7$\sigma$ | 3    |
| $\eta'K^0$       | $5.9^{+1.8}_{-1.6} \pm 0.9$ | 7.3$\sigma$  | 5    |
| $\eta'\pi^-$     | < 1.2         |              |      |
| $\eta h^-$       | < 0.8         |              |      |
| $\eta'K^{*0}$    | < 9.9         |              |      |
| $\eta K^{*0}$    | < 3.3         |              |      |
| $\omega K^-$     | $1.5^{+0.7}_{-0.6} \pm 0.2$ | 4.3$\sigma$ | 4    |
| $\omega \pi^-$   | $1.1^{+0.6}_{-0.5} \pm 0.3$ | 2.9$\sigma$ | 4    |
| $\phi K^* \uparrow$ | $1.3^{+0.7}_{-0.6} \pm 0.2$ | 3.5$\sigma$ | 4    |
| $\phi K^-$       | < 0.53        |              |      |
| $\rho^0 K^0$     | < 3.6         |              |      |
| $K^{*+}\pi^-$    | < 4.5         |              |      |
| $K^{*+}K^-$      | < 1.1         |              |      |

†Average of $B^\rightarrow \phi K^{*-}$ and $B^0 \rightarrow \phi K^{*0}$.

The continuum-subtracted $\eta'$ signal is due to $B$ decays in general and not necessarily due to $b \rightarrow sg$. Possible backgrounds are

1. $b \rightarrow D, D_S \rightarrow \eta'$. The rates and spectra of $D$ and $D_S$ in $B$ decay are well-measured and their decays to $\eta'$ are also experimentally known reliably. The contribution from these sources are estimated to be less than 0.2 events in the signal region.

2. Color-allowed modes $b \rightarrow (DX)(\eta'X)$ where the total charge of $(\eta'X)$ is $-1$ (from $W^-$). This contribution is modeled by 3-body decay $B \rightarrow D\eta'\pi$ with flat phase space and searching for $\eta'$ at a lower momentum range. Upper limit is set at $< 1.4$ events in the signal region.

3. $b \rightarrow u \rightarrow \eta'$. Theoretical estimates predicts that $3.5 \sim 7.0\%$ of the signal is due to this source. The uncertainties, however, are large.

4. Color-suppressed modes $B \rightarrow D^{(*)0}\eta'$. Theoretical branching fractions predictions for these channels leads to $2.1 \sim 8.6\%$ of the signal being due to this source albeit with large uncertainties. Experimentally, limits can be set by searching for $D^0$ or $D^{*0}$ in the signal sample which indicates that up to $41\%$ of the signal can be due to this source.

About $10\%$ of the signal is the exclusive mode $\eta'K^-$ and for the rest the recoil mass distribution broadly peaks in the region $1.7$ GeV to $2.4$ GeV. The
Figure 4: The mass distribution for the $\eta'$ candidates for $2.0 < p_{\eta'} < 2.7$ GeV/c when there is at least one $B$ candidate in the signal region (see text). It is plotted for the on-resonance data (a) and for the continuum data (b).

fall off at the high mass end is due to the cut $p_{\eta'} > 2.0$ GeV/c. There is no signal seen for $\eta'K^*$. The branching ratio corresponding to the excess is

$$Br(B \to \eta'X_s) = (6.2 \pm 1.6 \pm 1.3^{+0.0}_{-1.3}) \times 10^{-4} \quad (2.0 < p_{\eta'} < 2.7\text{GeV}) \quad (13)$$

where the central number corresponds to the case where the backgrounds discussed above are set to zero, and the lower value of the last error corresponds to 1.5 times the worst case theoretical prediction for the backgrounds discussed above.

If the excess is indeed largely due to $b \to sg$ process, the measured $\eta'$ production is probably too large compared to the conventional process where the corresponding 4-quark penguin operators are naively coupled to $\eta'$ meson. Possible enhancement mechanisms proposed are related to those proposed for the large exclusive $\eta'K$ rates: $c\bar{c}$ content of $\eta'$ which can couple to the Cabibbo-favored transition $b \to c\bar{c}s$, color-octet $c\bar{c}$ contribution, coupling of $\eta'$ to two gluons through the QCD anomaly resulting in three-body decay $b \to \eta'\gamma g$, or two-body decay $b \to \eta's$, and new physics that enhances $b \to sg$. The 2-body decay tends to produce hard $\eta'$s (namely, small recoil mass) and seems at odd with the measurement. At this point, there appears to be no strong
evidence to force us to introduce new physics.

5 Final-state-interaction phases

Decay rate CP asymmetry in general requires interference of more than one processes having different final-state-interaction (FSI) phases as well as different weak phases. In B decays, final-state-interaction may be looked for in the re-scattering $\bar{B}^0 \rightarrow D^+\pi^- \rightarrow D^0\pi^0$ where $D^+\pi^-$ is color-favored while $D^0\pi^0$ is color-suppressed, and an enhancement of $D^0\pi^0$ beyond what is expected from naive factorization would indicate re-scattering. Currently, however, upper limit exists: $Br(B^0 \rightarrow D^0\pi^0) < 1.2 \times 10^{-4}$ while factorization predicts around $1 \times 10^{-4}$. Thus, no evidence for re-scattering is observed in this channel.

Another way is to search phase differences in helicity amplitudes for $B \rightarrow VV$ decays such as $\Psi K^*$ and $D^*\rho$. Full angular fits has been performed for both modes. The analysis of $\Psi K^*$ modes showed no evidence of FSI phase. The same analysis measured the parity content of the $\Psi K^*$ final state to be $16 \pm 8 \pm 4\%$ parity $-$. Since the final state $\Psi K^*$ has $C= +$, the CP is mostly $+$ which is opposite to the CP of the $\Psi K_S$ final state. With full angular analysis, this modes is equivalent to about $1/4$ of the $\Psi K_S$ sample in measuring the CKM angle $\beta$.

The angular distribution for $B \rightarrow D^*\rho$ is given in terms of the three helicity amplitudes $H_{\pm,0}$ by

$$\frac{32\pi}{9\Gamma} \int d\cos\theta_1 d\cos\theta_2 d\chi \frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\chi} = 4|H_0|^2 \cos^2\theta_1 \cos^2\theta_2 + (|H_+|^2 + |H_-|^2) \sin^2\theta_1 \sin^2\theta_2$$

$$+ \Re[(H_-H_+^* \cos 2\chi + \Im(H_-H_+^*) \sin 2\chi)|2\sin^2\theta_1 \sin^2\theta_2$$

$$+ \Re[(H_-H_+^* - H_+H_0^*) \cos \chi + \Im(H_-H_0^* - H_+H_+^*) \sin \chi] \sin 2\theta_1 \sin 2\theta_2$$

where $\theta_1$ ($\theta_2$) is the decay polar angle of $D$ (charged $\pi$) in the $D^*$ ($\rho$) rest frame and $\chi$ is the azimuthal angle between the two decay planes in the $B$ rest frame. Assuming CP symmetry in the decay, helicity amplitudes of $B$ and $\bar{B}$ are related by $H_\lambda(\bar{B}) = H_{-\lambda}(B)$ ($\lambda = +, -, 0$) which corresponds to flipping the sign of $\chi$. The data samples of $B$ and $\bar{B}$ are combined accordingly. By convention, $H_0$ is taken to be real and the normalization is $|H_+|^2 + |H_-|^2 + |H_0|^2 = 1$. Then, the expression is invariant under the exchange $H_\pm \leftrightarrow H_\mp$, which means that the data cannot distinguish which is $H_+$ and which is $H_-$. The $V-A$ nature of the interaction, however, indicates that $|H_+| < |H_-|$ for $\bar{B}$ and we thus define the larger of $|H_\pm|$ to be $H_-$ (opposite for $B$). Table shows the result of the fit.}
Table 3: Helicity amplitudes for $\bar{B}_0 \to D^{*+}\rho^-$ and $B^- \to D^{*0}\rho^-$. 

|                | $B^0 \to D^{*+}\rho^-$ | $B^- \to D^{*0}\rho^-$ |
|----------------|-------------------------|-------------------------|
| magnitude      |                         |                         |
| $H_0$          | 0.936                   | 0.932                   |
| $H_-$          | $0.317 \pm 0.052 \pm 0.013$ | $0.19 \pm 0.23 \pm 0.14$ | $0.283 \pm 0.068 \pm 0.039$ | $1.13 \pm 0.27 \pm 0.17$ |
| $H_+$          | $0.152 \pm 0.058 \pm 0.037$ | $1.47 \pm 0.37 \pm 0.32$ | $0.228 \pm 0.069 \pm 0.036$ | $0.95 \pm 0.31 \pm 0.19$ |

There are signs of non-zero phases. Systematics checks have been performed to confirm that it is not due to $\rho$ width, non-resonant $\pi\pi$ component, nor due to backgrounds. The angular distribution expression above indicates that the non-trivial phases results in $\sin \chi$ or $\sin 2\chi$ distributions. Thus, in principle such terms can be seen directly in 1-dimensional distributions (with proper weighting as a function of $\theta_{1,2}$). The data is unfortunately unable to demonstrate such signatures beyond statistical errors. Alternatively, one could directly obtain the coefficient of each term of the angular distribution by the moment analysis. The result shows that the coefficient $\Im(H_+H_-^*)$ is non-zero with 2.5σ significance. The non-zero phases of Table 3 are more significant, and it comes from the information contained in the relative values of the coefficients.

6 Conclusions

The ingredients required for the study of CP violation in B decays are steadily accumulating and we are closing in on actually measuring CP asymmetries. Many of the modes used in the measurements of CKM angles $\alpha$ and $\gamma$ as well as the ‘easy’ $\beta$ are already observed, and with a little more statistics we may even be able to see direct CP violation. There are strong indications that the necessary ingredients for such asymmetries - gluonic penguin and final state phases - indeed exist.

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