B Physics: Theory Overview

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1 Introduction

A great deal of work on B physics has been done over the past 15-20 years. At first, it was mostly in the context of the B factories BaBar and Belle. This included finding methods for measuring the standard model (SM) parameters, examining ways of looking for new physics (NP), analyzing the results, etc. Unfortunately, most of the measurements at the B factories agreed with the SM. Although there were several hints of NP, mostly in $\bar{b} \to \bar{s}$ transitions, there were no statistically-significant signals.

CDF and DO then demonstrated that B physics can be done at hadron colliders. They made a number of measurements involving B_s^0 mesons, in particular B_s^0-$\overline{B}_s^0$ mixing.

The LHC will continue this exploration of B physics. They will focus mainly on B_s^0 mesons, but may well be able to repeat (and perhaps improve upon?) some of the measurements made at BaBar and Belle. As always, the hope is to find a signal of NP. It seems clear now that very large signals are ruled out. But the LHC may well have the precision to detect even small deviations from the SM. In this talk, I will discuss a number of B-physics measurements to be made at the LHC that have the potential for revealing NP.

2 B_s^0-$\overline{B}_s^0$ Mixing

In the presence of B_s^0-$\overline{B}_s^0$ mixing, the mass eigenstates B_L and B_H [L (H) corresponds to "light" ("heavy")] are admixtures of the flavour eigenstates B_s^0 and $\overline{B}_s^0$:

$$
\begin{aligned}
|B_L\rangle &= p\left|B_s^0\right\rangle + q\left|\overline{B}_s^0\right\rangle , \\
|B_H\rangle &= p\left|B_s^0\right\rangle - q\left|\overline{B}_s^0\right\rangle ,
\end{aligned}
\tag{1}
$$

with $|p|^2 + |q|^2 = 1$. The initial flavour eigenstates oscillate into one another according to the Schrödinger equation with $H = M^s - i\Gamma^s/2$ (M^s and Γ^s are the dispersive and

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absorptive parts of the mass matrix), and lead to the time-dependent states $B_s^0(t)$ and $\overline{B}_s^0(t)$. The off-diagonal elements M_{12}^s and Γ_{12}^s are generated by B_s^0-$\overline{B}_s^0$ mixing.

Defining $\Delta M_s \equiv M_H - M_L$ and $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$, we have

$$\Delta M_s = 2|M_{12}^s| \ , \quad \Delta\Gamma_s = 2|\Gamma_{12}^s|\cos\phi_s \ , \quad \frac{q}{p} = e^{-2i\beta_s} \ , \tag{2}$$

where $\phi_s \equiv \arg(-M_{12}^s/\Gamma_{12}^s)$ is the CP phase in $\Delta B = 2$ transitions. The weak phases ϕ_s and $2\beta_s$ are independent. The SM predicts that both ϕ_s and $2\beta_s$ are very small (but $\phi_s \neq -2\beta_s$!). $\Delta\Gamma_s$ is sizeable and is positive in the SM. In the presence of NP, one can have $2\beta_s \neq 0$ and $\Delta\Gamma_s < 0$.

$\boldsymbol{J/\psi\phi}$: In 2008 CDF and DO measured the indirect CP asymmetry in $B_s^0 \to J/\psi\phi$, and found a hint for CPV. The 2011 update gives (at 68% C.L.) [1]

$$\begin{aligned} 2\beta_s^{\psi\phi} &\in [2.3°, 59.6°] \cup [123.8°, 177.6°] \ , & \text{CDF} \ , \\ &\in [9.7°, 52.1°] \cup [127.9°, 170.3°] \ , & \text{DO} \ . \end{aligned} \tag{3}$$

Note that the measurement is insensitive to the transformation $(2\beta_s^{\psi\phi}, \Delta\Gamma_s) \leftrightarrow (\pi - 2\beta_s^{\psi\phi}, -\Delta\Gamma_s)$. This implies that $2\beta_s^{\psi\phi}$ has a twofold ambiguity, which is reflected in the two ranges of possible solutions above.

LHCb has greatly improved upon this result. First, the twofold discrete ambiguity has been removed by measuring $\text{sign}(\Delta\Gamma_s)$: $\Delta\Gamma_s = 0.120 \pm 0.028$ ps^{-1} [2]. This is done using the decay $B_s^0 \to J/\psi\phi(\to K^+K^-)$, and looking at the interference between the s- and p-wave K^+K^- angular momentum states.

Second, they find [3]

$$2\beta_s^{J/\psi\phi} = (-0.06 \pm 5.77 \text{ (stat)} \pm 1.54 \text{ (syst)})° \ , \tag{4}$$

in agreement with the SM. Still, the errors are large enough that NP cannot be excluded.

To completely search for NP, LHCb has to measure B_s^0-$\overline{B}_s^0$ mixing in as many different decays as possible. This has already begun:

$\boldsymbol{J/\psi f_0(980)}$: LHCb has measured $\beta_s^{J/\psi f_0} = (-25.2 \pm 25.2 \pm 1.1)°$ [4]. The advantage of this decay is that, because the $f_0(980)$ is a scalar, no angular analysis is needed. The disadvantage is that, because the $f_0(980)$ is not a pure $s\bar{s}$ state, there are possibly other contributions to the decay, leading to hadronic uncertainties [5].

$\boldsymbol{J/\psi\pi^+\pi^-}$: LHCb has measured $\beta_s^{J/\psi\pi^+\pi^-} = (-1.09^{+9.91+0.23}_{-9.97-0.17})°$ [6]. *A priori*, since this is a 3-body state, its CP can be $+$ or $-$, and so it cannot be used to cleanly extract weak-phase information. However, it has been shown that the $J/\psi\pi^+\pi^-$ state is almost purely CP $-$ [7], so that there is little error due to the CP $+$ state.

Other final states that are potentially of interest include (i) $\boldsymbol{D_s^\pm K^\mp}$ [8] – here one extracts $(2\beta_s + \gamma)$, (ii) $\boldsymbol{D_s^+ D_s^-}$ [9] – here one has to deal with penguin pollution, (iii) $\boldsymbol{D_{CP}^0 K\overline{K}}$ [10] – here one requires a Dalitz-plot analysis.

Finally, $B_s^0 \to K^{(*)0}\overline{K}^{(*)0}$ is a pure $\bar{b} \to \bar{s}$ penguin decay whose amplitude in the SM is $A = V_{tb}^* V_{ts} P_{tc}' + V_{ub}^* V_{us} P_{uc}'$. The second term is doubly Cabibbo suppressed with respect to the first term. If it is neglected, the indirect CP asymmetry vanishes in the SM, so that its measurement could reveal NP. However, $V_{ub}^* V_{us} P_{uc}'$ is not entirely negligible. Including it, it is found that indirect CPV measures $|\beta_s^{eff}| \leq 14.9°$ in the SM [11]. If a larger value of $|\beta_s^{eff}|$ is measured, this would imply NP.

3   Like-sign Dimuon Asymmetry

DO has reported an anomalously large CP-violating like-sign dimuon charge asymmetry in the B system. The updated measurement is [12]

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(7.87 \pm 1.72 \pm 0.93) \times 10^{-3} \;, \qquad (5)$$

a 3.9σ deviation from the SM prediction, $A_{\rm sl}^{b,{\rm SM}} = (-2.3_{-0.6}^{+0.5}) \times 10^{-4}$.

Now, it has been shown that, if this anomaly is real, it implies NP in B_s^0-$\overline{B}_s^0$ mixing. Such NP effects can appear in M_{12}^s and/or Γ_{12}^s. In fact, it has been argued that NP in Γ_{12}^s should be considered as the main explanation for the above result [13].

In the SM, the dominant contribution to Γ_{12}^s is $\bar{b} \to \bar{s}c\bar{c}$. Significant NP contributions, i.e. comparable to that of the SM, can come mainly from $\bar{b} \to \bar{s}\tau^+\tau^-$. This is (in principle) straightforward to detect – if $\mathcal{B}(B_s^0 \to \tau^+\tau^-)$ is observed to be at the percent level, this will be a clear indication of NP (in the SM, $\mathcal{B}(B_s^0 \to \tau^+\tau^-) = 7.9 \times 10^{-7}$). Thus, this is one decay that LHCb should try to measure.

4 $B_s^0 \to V_1 V_2$ Decays

$B_s^0 \to V_1 V_2$ is really 3 decays. Being vector mesons, V_1 and V_2 can have relative orbital angular momentum $l = 0$, 1 or 2 (s, p or d wave). This is taken into account by decomposing the decay amplitude into components in which the polarizations of the final-state vector mesons are either longitudinal (A_0), or transverse to their directions of motion and parallel ($A_{\|}$) or perpendicular ($A_{\perp}$) to one another.

(1) f_T, f_L: Naively, one expects $f_T \ll f_L$, where f_T (f_L) is the fraction of transverse (longitudinal) decays in $B \to V_1 V_2$. However, it was observed that $f_T f L \simeq 1$ in $B \to \phi K^*$ [14]. One explanation of this "polarization puzzle" is that the $1/m_B$ penguin-annihilation (PA) contributions are important [15]. PA can be sizeable within QCD factorization (QCDf).

There are two penguin decay pairs whose amplitudes are the same under flavour SU(3), and for which there is a good estimate of SU(3) breaking within QCDf: ($B_s^0 \to$

$\phi\phi$, $B_d^0 \to \phi K^{0*}$) and ($B_s^0 \to \phi \overline{K}^{0*}$, $B_d^0 \to \overline{K}^{0*} K^{0*}$) [16]. Given the polarization in the B_d^0 decay, can predict the polarization in the B_s^0 decay, and thus test PA.

This has been partially done – $B_s^0 \to \phi\phi$ has been measured:

$$\text{predict}: \quad \frac{f_T(B_s^0 \to \phi\phi)}{f_T(B_d^0 \to \phi K^{0*})} = 1.36 \pm 0.59 \ ,$$

$$\text{expt}: \quad \frac{f_T(B_s^0 \to \phi\phi)}{f_T(B_d^0 \to \phi K^{0*})} = 1.25 \pm 0.11 \ . \tag{6}$$

The theoretical error is large, but there is reasonable agreement.

(2) Triple Product (TP): In the B rest frame, the TP takes the form $\vec{q} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)$, where $\vec{q}$ is the difference of the two final momenta, and $\vec{\varepsilon}_1$ and $\vec{\varepsilon}_2$ are the polarizations of V_1 and V_2. The TP is odd under both P and T, and thus constitutes a potential signal of CPV. There are two TP's: $A_T^{(1)} \propto \text{Im}(A_\perp A_0^*)$ and $A_T^{(2)} \propto \text{Im}(A_\perp A_\parallel^*)$.

The statement that "TP's are a signal of CP violation" is not quite accurate. The A_i ($i = 0, \parallel, \perp$) possess both weak (CP-odd) and strong (CP-even) phases. Thus, $\text{Im}(A_\perp A_0^*)$ and $\text{Im}(A_\perp A_\parallel^*)$ can both be nonzero even if the weak phases vanish. In order to obtain a true signal of CP violation, one has to compare the B and $\overline{B}$ decays.

The TP's for the $\overline{B}$ decay are $-\text{Im}(\overline{A}_\perp \overline{A}_0^*)$ and $-\text{Im}(\overline{A}_\perp \overline{A}_\parallel^*)$, in which $\overline{A}_0$, $\overline{A}_\parallel$, and $\overline{A}_\perp$ are equal to A_0, $A_\parallel$, and $A_\perp$, respectively, but with weak phases of opposite sign. $A_\perp$ is pure p wave ($l = 1$), and so the additional minus sign is generated when CP is applied and $A_\perp \to \overline{A}_\perp$. The true (CP-violating) TP's are then given by $\frac{1}{2}[\text{Im}(A_\perp A_0^*) + \text{Im}(\overline{A}_\perp \overline{A}_0^*)]$ and $\frac{1}{2}[\text{Im}(A_\perp A_\parallel^*) + \text{Im}(\overline{A}_\perp \overline{A}_\parallel^*)]$.

Now, CPV requires the interference of two amplitudes. The common way to look for CPV is via a nonzero rate difference between a decay and its CP-conjugate decay (direct CPV). The direct CP asymmetry is proportional to $\sin\phi \sin\delta$, where ϕ and δ are the relative weak and strong phases of the two amplitudes. That is, direct CPV requires a nonzero strong-phase difference. On the other hand, the true TP is proportional to $\sin\phi \cos\delta$, so no strong-phase difference is necessary. This helps in the search for NP. Also, in the SM, true TP's are generally small (or zero) [17], so that TP's are a good way to find NP.

CDF and LHCb have measured the true TP asymmetries in $B_s^0 \to \phi\phi$ [18]:

$$
\begin{aligned}
A_u \ (\perp \parallel) &= -0.007 \pm 0.064 \ (\text{stat}) \pm 0.018 \ (\text{syst}) \quad \text{CDF} \ , \\
&= -0.064 \pm 0.057 \ (\text{stat}) \pm 0.014 \ (\text{syst}) \quad \text{LHCb} \ , \\
A_v \ (\perp 0) &= -0.120 \pm 0.064 \ (\text{stat}) \pm 0.016 \ (\text{syst}) \quad \text{CDF} \ , \\
&= -0.070 \pm 0.057 \ (\text{stat}) \pm 0.014 \ (\text{syst}) \quad \text{LHCb} \ .
\end{aligned} \tag{7}
$$

These agree with the SM prediction ($A_u = A_v = 0$).

There are also fake (CP-conserving) TP's, due only to the strong phases of the A_i's. These are given by $\frac{1}{2}[\text{Im}(A_\perp A_0^*) - \text{Im}(\overline{A}_\perp \overline{A}_0^*)]$ and $\frac{1}{2}[\text{Im}(A_\perp A_\parallel^*) - \text{Im}(\overline{A}_\perp \overline{A}_\parallel^*)]$.

In the SM, certain fake TP's are very small [19]. This implies that one can partially distinguish the SM from NP through the measurement of the fake $A_T^{(2)}$ TP. This applies to $B \to \phi K^*$ and $B_s^0 \to \phi\phi$.

5   Measuring U-spin/SU(3) Breaking

Consider charmless $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ decays whose amplitudes are equal under U spin ($d \leftrightarrow s$). There are four observables: the CP-averaged $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ decay rates B_d and B_s, and the direct CP asymmetries A_d and A_s. In the U-spin limit, $X = 1$, where $X \equiv -(A_s/A_d)(B_s/B_d)$. Thus, by measuring the four observables, and computing the deviation of X from 1, one can *measure* U-spin breaking [20].

This can be applied to 4 decay pairs involving B_s^0 decays: $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$, $B_s^0 \to \pi^+K^-$ and $B_d^0 \to \pi^-K^+$, $B_d^0 \to K^0\overline{K}^0$ and $B_s^0 \to \overline{K}^0K^0$, $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$. The first (second) decay is $\bar{b} \to \bar{d}$ ($\bar{b} \to \bar{s}$).

If one neglects annihilation- and exchange-type diagrams, there are 12 additional pairs of decays to which this analysis can be applied. These are not related by U spin, but are instead related by flavour SU(3).

6   Conclusions

In the past, there were a number of hints of NP in some B decays, usually in $\bar{b} \to \bar{s}$ transitions. Unfortunately, with recent LHCb measurements, most of these have gone away. This suggests that, if NP is present, very large signals are unlikely.

Still, the LHC has the precision to detect small deviations from the SM predictions. To this end, it is best to make measurements of as many different processes as possible. In this talk, I have mentioned a number of different possibilities (some of which have already been measured). Hopefully, when these measurements are made, we will see a sign of NP.

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