Recent results from the CDF and DØ Collaborations are presented on the topic of heavy flavor from Run II operating at the \( p\bar{p} \) Tevatron Collider. Heavy flavor spectroscopy results are reviewed: orbitally and radially excited states of the \( B^0 \) and \( B_s^0 \) mesons, properties of \( b \)-flavored baryons, and a search for the \( X(4140) \) meson. Results testing for \( CP \) violation in mixing and decay of \( B \) mesons via measuring the dimuon \( CP \)-violating charge asymmetry, as well as a measurement of direct \( CP \) asymmetry in \( D^+_s \to \phi\pi^\pm \) decays are presented.

1 Heavy Flavor Spectroscopy and Properties of States

Heavy flavor spectroscopy is interesting to study because heavy quark hadrons can be considered the “hydrogen atom” of QCD, and \( b \) hadrons offer the heaviest quarks in bound systems. As shown in Fig. 1(a), in the framework of Heavy Quark Effective Theory (HQET), a \( b \) hadron can be roughly described by the heavier \( b \) quark being analogous to the nucleus of the atom, with lighter \( u, d \) or \( s \) quarks orbiting the nucleus similar to the electrons of an atom, but surrounded by a complicated, strongly interacting cloud of light quarks, antiquarks, and gluons sometimes referred to as “brown muck". Studies of these states provide very sensitive tests of potential models, HQET, and all regimes of QCD in general, including lattice gauge calculations, potential models, QCD string, etc.

The Tevatron has the capability of producing heavier states not accessible at the \( B \) factories running at the \( \Upsilon(4S) \), i.e., the heavy \( B \) mesons: \( B^0_s \) (\( \bar{b}s \), the ground state with the spins of the quarks anti-aligned), \( B^*_s \) (\( \bar{b}s \), with the spins of the quarks aligned), \( B_c \) (\( \bar{b}c \), the ground state), \( B^{**} \) (\( \bar{b}d \), with the quarks having relative orbital angular momentum), and \( B^{***} \) (\( \bar{b}s \), with the quarks having relative orbital angular momentum); and the heavy \( b \) baryons: \( \Lambda_b^0 \) (\( bud \)), \( \Sigma_b^{(*)} \) (\( buu \) and \( bdd \)), \( \Xi_b \) (\( bsd \)), and \( \Omega_b \) (\( bss \)).

1.1 Spectroscopy of Excited \( B \) Mesons

In the heavy-quark limit, the spin of the heavy quark decouples from the light degrees of freedom and the heavy and light systems can be considered separately. Given the approximation within
HQET that the heavy quark is at rest in the frame of the hadron, we can describe the heavy quark through the assignment of a spin quantum number, \( \vec{s}_Q \). The light degrees of freedom which, following the simple hydrogen atom model of HQET, can be thought of as orbiting the heavy quark are assigned a total angular momentum \( \vec{j}_q = \vec{s}_q + \vec{L} \), where \( s_q \) and \( L \) are the spin and orbital angular momentum of the light degrees of freedom. Finally the total angular momentum is given by \( \vec{J} = \vec{s}_Q + \vec{j}_q \).

\[ B^{**} \] and \( B_{s}^{**} \) mesons (also denoted \( B_J \) and \( B_{sJ} \), respectively) are composed of a heavy \( b \) quark and a lighter down or strange quark in a \( L = 1 \) state of orbital momentum, with four possible states in each case as shown in Fig. 1(c). The mass splittings are analogous to the fine and hyperfine splittings in hydrogen.

CDF has updated their measurements of the narrow \( D \)-wave orbitally excited states\(^2\). The \( B^{0/\pm} \) ground state is reconstructed in seven different final states and then a \( \pi \) or \( K \) meson added to reconstruct \( B^{**} \rightarrow B^{(*)}\pi \) and \( B_{s}^{**} \rightarrow B^{0(*)}K^0 \) as well as \( \rightarrow B^+K^- \) and then applying an artificial neural net to enhance the signal. The specific signal peaks for \( B_{s}^{**} \) are shown in Fig. 2(a). Note that in the case of having a \( B^* \rightarrow B\gamma \) in the decay chain, a second mass peak appears shifted down by \( M_{B^*} - M_B = 46 \text{ MeV} \).

When done for \( B^{**} \), the usual orbitally excited \( B_J \) states appear as shown in Fig. 2(b), plus a peak appears at higher masses identified in both the \( B^{0} + \pi \) and \( B^{\pm} + \pi \) combinations with a combined significance of 4.4\( \sigma \). From extrapolations of \( D^{**} \) and theory\(^3\), these states are consistent with a radial excitation \( 2(^3S_1) \) of the ground state \( B \) and are the first evidence of
these new states. Masses, widths, and relative production rates are updated. The properties of the orbitally excited and the new $B(5970)^{0/\pm}$ states are compatible with isospin symmetry and a number of predictions of models as summarized in Fig. 3.

Figure 3 – Summary of CDF mass measurements\(^4\) of excited states compared to various models.

1.2 \(c\) and \(b\)-Flavored Baryons

In a continued analogy with atomic systems, baryons containing a \(b\) quark can be approximated as a heavy quark filling in for the nucleus orbited by a light \(diquark\). Examples of a \(L = 0\) system would then be the \(J = 1/2 \Lambda_b\) with the \(qq\) spins anti-aligned and the \(J = 3/2 \Sigma_b\) with the light quark spins aligned as shown in Fig. 1(b). Before Run 2 of the Tevatron, only the ground-state \(\Lambda_b\) was identified, but the Tevatron has gone on to discover a host of new \(b\) baryons. With more statistics, the properties of these states can be measured with more precision.

CDF has analyzed their full Run 2 dataset updating properties measured for these heavy-flavor states\(^4\). Decays to \(J/\psi \rightarrow \mu^+\mu^-\) provide triggers without lifetime bias for measuring lifetimes, and states are reconstructed adding light baryons to the \(J/\psi\) in the final state: \(J/\psi \Lambda_b/\Xi_b/\Omega_b \rightarrow J/\psi + \Lambda/\Xi/\Omega\) that are then compared to topologically similar reference modes \(B^+ \rightarrow J/\psi K^+\) and \(B^0 \rightarrow J/\psi K^{*0}/K_0^0\). Decays to \(c\) baryons are also investigated using a two-track displaced hadron trigger that leads to lifetime biases. Decay chains \(\Xi_b^{+/0} \rightarrow \Xi_c^{0/\pm} \pi^{-/\pm}\) and \(\Omega_b \rightarrow \Omega_c^0 \pi^+\) are reconstructed with the \(c\) baryons decaying to a corresponding light baryon and \(\pi\). The long charged decay lengths of the \(\Xi_b^{\pm}\) and \(\Omega_b^\pm\) (\(c\tau = 4.9\) cm and \(2.5\) cm) allow special track reconstruction in the silicon detector. Examples of signal samples are shown in Fig. 4 along with signal yield in bins of \(ct\) to determine lifetimes, e.g., for the \(\Xi_b^-\). Results are collated in Table 1.

The \(\Lambda_b\) lifetime is closer to predictions than previous measurements, the lifetime measurements of the \(\Xi_b^\pm\) and \(\Omega_b\) baryons are unique and limited by the statistics of the samples, and the first measurement of the mode \(\Omega_b^- \rightarrow \Omega_c^0 \pi^-\) is established.

1.3 Search for \(X(4140)\)

The \(X(4140)\) resonance has been observed by a number of experimental collaborations, but others have set limits on its production as described in a detailed review\(^5\). The standard quark model does not predict a state at this mass, and its decay suggests a \(c\bar{c}\) quark content, but its mass is above the open charm threshold leading to speculation that it could be a \(D_s\bar{D}_s\) molecule, a \(q\bar{q}g\) hybrid, or a \(c\bar{c}s\bar{s}\) tetraquark state.
Figure 4 – (a-c) Signal peaks of \( b \) baryons investigated by CDF, and (d,e) rate of \( \Xi^- \) in bins of \( ct \) used to determine lifetime. Adapted from original\(^4\).

Table 1: \( \Xi \) and \( b \)-baryon mass and lifetime results. The first uncertainty listed is statistical and the second is systematic.

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Mass (MeV/c(^2))</th>
<th>Lifetime (ps)</th>
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<tr>
<td>( \Xi^- )</td>
<td>2470.85 ± 0.24 ± 0.55</td>
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<tr>
<td>( \Xi^0 )</td>
<td>2468.00 ± 0.18 ± 0.51</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_b )</td>
<td>5620.15 ± 0.31 ± 0.47</td>
<td>1.565 ± 0.035 ± 0.020</td>
</tr>
<tr>
<td>( \Xi_b^{-} )</td>
<td>5793.4 ± 1.8 ± 0.7</td>
<td>1.36 ± 0.15 ± 0.02</td>
</tr>
<tr>
<td>( \Xi_b^{0} )</td>
<td>5788.7 ± 4.3 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>( \Omega_b )</td>
<td>6047.5 ± 3.8 ± 0.6</td>
<td>1.66±0.53±0.40 ± 0.02</td>
</tr>
</tbody>
</table>

\( M(\Xi_b^{0}) - M(\Xi_b^{+}) \) = 2.85 ± 0.30 ± 0.04
\( M(\Xi_b^{-}) - M(\Xi_b^{0}) \) = 4.7 ± 4.7 ± 0.7

The DØ Collaboration has searched\(^6\) for this state by reconstructing \( B^+ \rightarrow J/\psi\phi K^+ \) as shown in Fig. 5(a). After adding decay length cuts and vetoing \( \psi(2S) \) states, a fit for the \( B^+ \) yield is made in bins of \( M(J/\psi (\phi \rightarrow K^+ K^-)) \) to look for resonances in the \( J/\psi \phi \) combination. As shown in Fig. 5(b), evidence for the \( X(4140) \) is observed at 3.1\( \sigma \) significance with a mass of \( M = 4159.0±4.3±6.6 \) GeV and width \( \Gamma = 19.9±12.6^{+1.0}_{-8.0} \) MeV as well as measuring its branching fraction compared to \( B^+ \rightarrow J/\psi\phi K^+ \). This measurement adds additional information to the puzzle of this state, including resonances at even higher masses in \( J/\psi \phi \) invariant mass.

2 Studies of CP Violation

2.1 Dimuon Charge Asymmetry

One of the few ways for direct physics to result in a pair of same-sign muons is when a neutral \( B \) meson, i.e., \( B^0_d \) or \( B^0_s \), directly decays semileptonically, while a neutral \( B \) meson from the other produced \( b \) quark oscillates before decaying semileptonically. CP violation in mixing, i.e., \( \Gamma(B^0 \rightarrow B^0 \rightarrow \mu^- X) \neq \Gamma(B^0 \rightarrow B^0 \rightarrow \mu^- X) \) can be explored by studying the semileptonic asymmetry \( \mathcal{A}_{\text{SL}} = N_b(\mu^+ \mu^-) - N_b(\mu^- \mu^-)/\text{Sum} \) by forming the raw asymmetry, correcting for background asymmetries, and determining the fraction of muons from \( b \) quarks. This asymmetry is a linear combination of the semileptonic charge asymmetries of \( B^0_d \) and \( B^0_s \),
2.2 Test for Direct CP Violation in Charm Meson Decay

Direct CP violation can occur if tree and loop (penguin) diagrams interfere with different strong and weak phases. However, no CP violation is expected in the decay $D_s^+ \rightarrow \phi \pi^+$ since all processes have the same weak phase so that an observation of CP violation would imply new physics. It is also useful to test the assumption of no CP violation in direct charm decay used in measurements of CP violation in $B_s^0$ mixing and of production asymmetries of $\sigma(D_s^0)$ measured at the LHC.

Experimentally, the DØ Collaboration has measured\(^7\) the raw asymmetry in total numbers of $D_s$ mesons of different charge signs, i.e., $A_{D_s} = N(D_s^+) - N(D_s^-)/\text{Sum}$, and applying corrections for detector and physics background asymmetries to find the CP asymmetry $A_{\text{CP}}$. In the reconstruction $D_s^+ \rightarrow \phi \pi^+$ followed by $\phi \rightarrow K^+ K^-$, the dominant kaon charge asymmetry approximately cancels. A fit to yields in the sum and difference distributions as shown in Fig. 7 after corrections results in $A_{\text{CP}} = (-0.38 \pm 0.26 \pm 0.08)\%$ that is consistent with zero and the most precise measurement of this quantity to date.

\[ A^b = C_d a^d_{s1} + C_s a^s_{s1}, \]

In a previous publication\(^7\), the DØ Collaboration measured $A^b$ with a value representing a $3.9\sigma$ deviation from the SM prediction. They have updated this analysis\(^8\) using a larger dataset, adding a more detailed study of the asymmetry dependence on the impact parameter (IP), $p_T$, and $|\eta|$ of each muon, as well as including an additional CP-violating process to interpret results\(^9\). The advantages of this analysis at the Tevatron is the $pp$ CP-invariant initial state, in contrast to the $pp$ LHC collider, and the DØ detector that regularly reversed the polarity of its solenoidal and toroidal magnets helping to cancel/reduce many detector charge asymmetries. Independent data samples are used to measure background and detector reconstruction charge asymmetries, and the charge asymmetry of single muons, as a function of IP and corrected for these effects shows no significant asymmetry, as expected. Measurements of the dimuon sample (Fig. 6(a)) with the same corrections gives a result of $A_{\text{CP}} = (-0.235 \pm 0.064 \pm 0.055)\%$ which represents a $3.6\sigma$ deviation from the SM prediction of $(-3.5 \pm 0.8) \times 10^{-4}$. Since the fractional mix of $B_s^0$ and $B_s^0$ is different in each (IP\(_1\), IP\(_2\)) bin, the semileptonic charge asymmetries can be extracted as shown in Fig. 6(b) (solid and dashed lines), which deviates from the SM by $3.0\sigma$. The results are consistent with independent DØ measurements of $a^s_{s1}$ and $a^s_{s1}$ (bands on plots)\(^10\), and the combination of all DØ results are also shown in Fig. 6(b). These are the most precise measurement of these quantities so far from a single measurement, including $\Delta \Gamma_d/\Gamma_d = (+0.79 \pm 1.15)\%$. This combination is still consistent with all other measurements, and also stresses the importance of having more independent measurements of $\Delta \Gamma_d/\Gamma_d$. 

Figure 5 – (a) $B^+$ peak from $B^+ \rightarrow J/\psi \phi K^+$ decays, and (b) following further cuts, resonances in $J/\psi \phi$ invariant mass. Adapted from original\(^6\).
Figure 6 – (a) Dimuon charge CP asymmetry $A_{\text{CP}}$ in bins of impact parameter (IP) of each of the two muons and over entire sample. (b) Result (black dashed and solid line contours) of dimuon charge asymmetry as a function of semileptonic CP charge asymmetry $a_d^s$ and $a_d^l$. Solid colored contours after combination with independent direct measurements (hashed bands) from DØ. Adapted from original.

Figure 7 – (a) Sum and (b) difference of number of $D_s^+$ and $D_s^-$ mesons in the decay mode $D_s^+ \rightarrow \phi \pi^+$. Adapted from original.

References