Recent Tevatron results on heavy flavors

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Summary. — CDF presents the first measurement of the $B^+_c$ cross section and D0 presents the observation of a new $B^0_s\pi^\pm$ state based on the full $\sim10$ fb$^{-1}$ Run II data set at the Fermilab Tevatron 1.96 TeV $p\bar{p}$ collider.

1. — Brief descriptions of the CDF and D0 detectors

The CDF [1] and D0 [2] detectors for Run II are illustrated in fig. 1. The results presented here are based on an integrated luminosity of $\sim10$ fb$^{-1}$ for 1.96 TeV $p\bar{p}$ collisions, representing the full Tevatron Run II data sets which were taken from 2001–2011.

Both the CDF and the D0 detectors have solenoidal magnetic fields of 1.4 tesla and 1.9 tesla, respectively, and excellent lepton coverage, detection, identification, and triggering. Both have silicon vertex detectors to study displaced vertices from decays of particles containing $b$- or $c$-quarks. In addition, the CDF II detector features a fast displaced vertex trigger and particle identification by energy loss $dE/dx$ in the central drift chamber and time of flight TOF. The studies presented here rely only on the muon detectors to reconstruct $J/\psi \to \mu^+\mu^-$ (not $J/\psi \to e^+e^-$). CDF detects the muons from $J/\psi$ decay over the range $|\eta|<1.0$ and the third muon from the $B_c$ decay over $|\eta|<0.6$. D0 detects muons over $|\eta|<2$. The rapidity of a produced particle is defined as $y=1/2\ln((E+p_{||})/(E-p_{||}))$, where $E$ is the energy and $p_{||}$ is the longitudinal momentum along the proton beam direction of the produced particle. The pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$ where $\theta$ is the polar angle of the produced particles relative to the proton beam direction.
2. CDF: Measurement of the $B^\pm_c$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

The $B^+_c (b\bar{c})$ is the most massive meson with two un-like quarks. It is only accessible at hadron colliders. CDF [3] measures the ratio

$$R = \frac{\sigma(B^+_c)B(B^+_c \rightarrow J/\psi\mu^+\nu)}{\sigma(B^+)B(B^+ \rightarrow J/\psi K^+)}$$

for the same kinematics of the $B^\pm_c$ and $B^+$. $B$ is the branching fractions into the observed final state. Since there is a missing neutrino in the semi-leptonic decay of the $B^+_c$, the mass spectrum of $J/\psi\mu^+$ is a broad peak centered at approximately $4.65$ GeV/$c^2$ as shown in fig. 2 (left). The signal region is defined as $4 < M(J/\psi\mu^+) < 6$ GeV/$c^2$, and sidebands for validating the modeling of the backgrounds are defined as $3 < M(J/\psi\mu^+) < 4$ GeV/$c^2$ and $6$ GeV/$c^2 < M(J/\psi\mu^+)$. There are $1370$ $B^+_c$ candidate events within the signal mass window, $132$ events in the lower sideband region, and $208$ events in the upper sideband region. There are $14338 \pm 125$ fitted number of events in the mass spectrum for the $B^+ \rightarrow J/\psi K^+$ normalization mode shown in fig. 2 (right). The spectrum also contains a fixed $3.83\%$ component due to the reflection of $B^+ \rightarrow J/\psi\pi^+$ mis-identified as $B^+ \rightarrow J/\psi K^+$, which is also illustrated in fig. 2 (right).

The backgrounds under the $B_c$ signal consist of: misidentified 3rd muons; misidentified $J/\psi$; correlated $b\bar{b}$ backgrounds where, for example, the $b \rightarrow J/\psi X$ and the $\bar{b} \rightarrow 3$rd $\mu X$; and other modes where $B^+_c \rightarrow \mu^+\mu^-\mu^X$.

Figure 3 (left) shows the $M(J/\psi\mu^+)$ including these background components along with the normalized Monte Carlo simulation. Out of the $1370 \pm 37$ $B_c$ candidates in the signal region, $630.5 \pm 20$ candidates can be attributed to these backgrounds, leaving $769.5 \pm 45.3$ (combined statistical and systematic uncertainties) $B_c \rightarrow J/\psi\mu\nu$ events. The normalization of the Monte Carlo simulation is fixed by the total number of observed events in the signal region, then compared with the number of events observed in the upper and lower mass sideband regions, showing good agreement in the table in fig. 3.
RECENT TEVATRON RESULTS ON HEAVY FLAVORS

Fig. 2. – Left: invariant mass ($J/\psi \mu$) for $B_c^+$ candidates; right: invariant mass for $B^+ \to J/\psi K^+$ candidates with fixed 3.83% component of mis-identified $B^+ \to J/\psi \pi^+$. 

The ratio $R$ can be written as

$$R = \frac{N_{B_c}/\epsilon_{B_c}}{N_{B^+}/\epsilon_{B^+}} = 0.211 \pm 0.012 \text{(stat)} \pm 0.021 \text{(syst)}$$

for $p_T(B_c^+) > 6 \text{ GeV}/c$ and $|y| < 0.6$, and where the efficiencies $\epsilon(B_c^+ \to J/\psi \mu^+ \nu) = (0.175 \pm 0.001)\%$ including the trigger efficiency for the 3rd muon, $\epsilon(B^+ \to J/\psi K^+) = (0.688 \pm 0.002)\%$ including the trigger efficiency for the $K^+$, and $\epsilon(3\text{rd} \mu) = 0.962 \pm 0.007 \text{ (stat)} \pm 0.021 \text{ (syst)}$. Continuing the calculation using $B(B^+ \to J/\psi K^+) = (1.027 \pm 0.031) \times 10^{-3}$ [4] and $\sigma(B^+, p_T < 6, |y| < 1) = (2.78 \pm 0.24) \mu\text{b}$ from prior CDF measurement [5] and assuming $R(|y| < 1) = R(|y| < 0.6)$, CDF measures $\sigma(B^+, p_T > 6, |y| < 1)B(B^+ \to J/\psi K^+) = (0.602 \pm 0.034 \text{(stat)} \pm 0.060 \text{ (syst)} \pm 0.055 \text{ (other)}) \text{ nb}$. Combining statistical and systematic uncertainties $\sigma(B_c^+)B(B_c^+ \to J/\psi \mu^+ \nu) = (0.60 \pm 0.09) \text{ nb}$. The range of theoretical predictions [6] for the Branching Fraction $B(B_c^+ \to J/\psi \mu^+ \nu) = (1.15 - 2.37)\%$ gives $\sigma(B_c^+, p_T > 6, |y| < 1) \approx (25 \pm 4 \text{ to } 52 \pm 8) \text{ nb}$.

Fig. 3. – Left: $M(J/\psi \mu)$ spectrum showing background components and $B_c^+$ candidates; right: table of backgrounds and $B_c^+$ for signal region and sidebands.
3. – D0: Observation of a new $B^0_s \pi^\pm$ state

D0 [7] observes a previously unobserved structure in the mass spectrum of $B^0_s \pi^\pm$ where $B^0_s \to J/\psi \phi$ and $J/\psi \to \mu^+ \mu^-$ and $\phi \to K^+ K^-$. The selection cuts for the $B_s$ required $p_T(K^\pm) > 0.7$ GeV/c, and the significance of the transverse separation of the $B_s$ decay vertex relative to the primary $p\bar{p}$ interaction vertex of $L_{xy}/\sigma_{L_{xy}} > 3$. This produced the $J/\psi \phi$ invariant mass plot in fig. 4 (left), which, when fitted, produced a sample of $5582 \pm 100$ $B_s$ events plus a continuum polynomial background. The shaded regions were selection for the signal and sideband samples. The signal region within $\pm 2\sigma$ of the $B_s$ mass peak consists of two components: a combinatorial background component (below the polynomial background curve), which is modeled by the sidebands in the data, and the genuine $B_s$ peak (above the polynomial background curve), modeled by Monte Carlo simulation. The relative fractions of combinatorial $B_s$ events to genuine $B_s$ are 29% and 71%, respectively.

A single pion (either $\pi^+$ or $\pi^-$) was added to the $B_s$ candidates in the shaded signal region of fig. 4 (left). The selection criteria for this $\pi^\pm$ included $p_T(\pi) > 0.5$ GeV/c, the two dimensional transverse impact parameter for the pion relative to the primary $p\bar{p}$ interaction vertex $IP_{xy} < 0.02$ cm; and the three dimensional impact parameter, including the two transverse plus longitudinal separations, relative to the primary $p\bar{p}$ interaction vertex of $IP_{3D} < 0.12$ cm. The $B_s \pi$ combination was required to have $p_T(B_s \pi) > 10$ GeV/c. Finally, a “cone” cut $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = \sqrt{(\eta_{B_s} - \eta_{\pi})^2 + (\phi_{B_s} - \phi_{\pi})^2} < 0.3$ was applied, where $\phi$ is the azimuthal angle of the $B_s$ or $\pi$. This quantity $\Delta R$ approximates the angle between the $B_s$ and the $\pi$ directions in the $p\bar{p}$ center-of-mass reference frame. The analysis was also repeated, removing and varying the $\Delta R$ cut.

The background distributions for the $B_s \pi$ mass spectra were calculated as the sum of two components: random combinatorial backgrounds for the $B_s$ which was modeled using the data, combining a sideband $M(J/\psi \phi)$ events in fig. 4 (left) with a random $\pi$ in the same data event satisfying the above selection criteria; and the random coincidence of a genuine $B_s$ and a random $\pi$, both of which were generated by the PYTHIA Monte Carlo generator. The shape of these backgrounds are compared for no $\Delta R$ cut in fig. 4 (right), showing almost perfect agreement. These were combined in the 71%/29% ratio described above for the background shape to be used in the later fits. Figure 5 (left)
Fig. 5. – Left: combined $B_s \pi$ background (29% sideband + 71% “genuine” $B_s$) derived as illustrated in fig. 4, compared to the sideband backgrounds in the data for events with no $\Delta R$ cut and for events with $\Delta R < 0.3$; right: efficiency of the $\Delta R < 0.3$ cut as a function of $m_{B_s \pi}$.

shows the background shapes, both with the $\Delta R$ cut (filled points) and without the $\Delta R$ cut (open points). Both of these background shapes are fit using the form

$$F_{bg}(m_{B_s \pi}) = (C_0 + C_2 \cdot m_0^2 + C_4 \cdot m_0^4) \times \exp(C_5 + C_6 \cdot m_0^2),$$

where $m_0 = m_{B_s \pi} - m_{B_s} - m_{\pi}$.

The observed mass spectrum for $B_s \pi$ for the $\Delta R < 0.3$ cut is shown in fig. 6 (left). The fit consists of a fixed shape (but variable normalization) for the background, from fig. 5 (left), plus an $S$-wave relativistic Breit-Wigner resonance, with variable width, convoluted with the Monte Carlo calculated mass resolution of $\sigma = 3.9$ MeV/c$^2$. The resonance mass $M_X$, natural width $\Gamma_X$, and the normalization $N_X$ (number of events) of the resonance, along with the normalization for the background were varied in the fit. This fit ($\chi^2 = 32$ for 46 degrees of freedom) determined the parameters $M_X = 5567.8 \pm 2.9$ (stat) $^{+1.0}_{-1.9}$ (syst) MeV/c$^2$, $\Gamma_X = 21.9 \pm 6.4$ (stat) $^{+5.0}_{-5.9}$ (syst) MeV/c$^2$, and $N_X = 133 \pm 100$ events.

The local significance of this signal, using the likelihood ratio, $\sqrt{-2 \ln(L_0/L_{max})} = \sqrt{43.56}$ corresponds to 6.6$\sigma$. Applying the Gross and Vitells [8] prescription for the Look Elsewhere Effect (LEE), over the range $M_{\text{threshold}}(B_s \pi) \leq M(B_s \pi) \leq M_{\text{threshold}}(BK)$, the global significance of this signal corresponds to 6.1$\sigma$.

The systematic uncertainties were studied and illustrated in table I.

Applying the $\pm 11.3\%$ systematic uncertainty to $N_X$, the yield of $X(5568)$, the significance is reduced to $5.1 \sigma$ including both LEE and the systematic uncertainties in the yield.

Figure 6 (right) shows the $M(B_s \pi)$ data without the $\Delta R$ cut and the fit, using the fixed background shape, and the Breit-Wigner with $M_X$ and $\Gamma_X$ fixed to the values found for the $\Delta R < 0.3$ fit of fig. 6 (left), allowing the normalizations for the background and resonance to vary. Due to not-well-modeled background for $M(B_s \pi) > 5.7$ GeV/c$^2$, the fit was terminated at that point, giving $\chi^2 = 18$ for 23 degrees of freedom, and $N_X = 106 \pm 25$ events. Even without the $\Delta R$ cut, a peak in the $B_s \pi$ mass spectrum is observed with a local significance of 4.8$\sigma$.

Figure 7 shows that the fitted value of $M_X$ is independent of the $\Delta R$ cut, demonstrating that the existence of the $X$ particle and the position of its mass peak are not generated by the application of this cone cut.
### Table I. - Systematic uncertainties for the observed $X(5568)$ state mass, natural width and number of events.

<table>
<thead>
<tr>
<th>Source</th>
<th>Mass, MeV/c$^2$</th>
<th>Width, MeV/c$^2$</th>
<th>Rate, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Background shape</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC samples with soft or hard $B_s^0$</td>
<td>+0.2; −0.6</td>
<td>+2.6; −0.0</td>
<td>+8.2; −0.0</td>
</tr>
<tr>
<td>Sideband mass ranges</td>
<td>+0.2; −0.1</td>
<td>+0.7; −1.7</td>
<td>+1.6; −9.3</td>
</tr>
<tr>
<td>Sideband mass calculation method</td>
<td>+0.1; −0.0</td>
<td>+0.0; −0.4</td>
<td>+0.0; −1.3</td>
</tr>
<tr>
<td>MC to sideband events ratio</td>
<td>+0.1; −0.1</td>
<td>+0.5; −0.6</td>
<td>+2.8; −3.1</td>
</tr>
<tr>
<td>Background function used</td>
<td>+0.5; −0.5</td>
<td>+0.1; −0.0</td>
<td>+0.2; −1.1</td>
</tr>
<tr>
<td>$B_s^0$ mass scale, MC and data</td>
<td>+0.1; −0.1</td>
<td>+0.7; −0.6</td>
<td>+3.4; −3.6</td>
</tr>
<tr>
<td><strong>Signal shape</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detector resolution</td>
<td>+0.1; −0.1</td>
<td>+1.5; −1.5</td>
<td>+2.1; −1.7</td>
</tr>
<tr>
<td>Non-relativistic BW</td>
<td>+0.0; −1.1</td>
<td>+0.3; −0.0</td>
<td>+3.1; −0.9</td>
</tr>
<tr>
<td>$P$-wave BW</td>
<td>+0.0; −0.6</td>
<td>+3.1; −0.0</td>
<td>+3.8; −0.0</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binning</td>
<td>+0.6; −1.1</td>
<td>+2.3; −0.0</td>
<td>+3.5; −3.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+0.9; −1.9</td>
<td>+5.0; −2.5</td>
<td>+11.4; −11.2</td>
</tr>
</tbody>
</table>

The production rate of this new $X(5568)$ state can be estimated by

$$\text{Ratio} = \frac{\sigma(X) \times \mathcal{B}(X \to B_s \pi)}{\sigma(B_s)}.$$  

Since we use the same $B_s$ decay modes for the numerator and denominator of this ratio,

$$\text{Ratio} = \frac{\sigma(X) \times \mathcal{B}(X \to B_s \pi)}{\sigma(B_s)} = \frac{N(X \to B_s \pi)}{N(B_s)} \frac{1}{\epsilon(\pi)},$$

where $\epsilon(\pi)$, the average efficiency of this pion over the range $10 < p_T(B_s) < 30 \text{ GeV/c}$, is 34%, giving $\sigma(X) \times \mathcal{B}(X \to B_s \pi)/\sigma(B_s) = (8.6 \pm 1.9 \text{ (stat)} \pm 1.4 \text{ (syst)})\%$.

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Fig. 6. – Left: $M(B_s \pi)$ spectrum for $\Delta R < 0.3$ cut, illustrating fitted background and $S$-wave relativistic Breit-Wigner signal; right: $M(B_s \pi)$ spectrum without the $\Delta R$ cut, illustrating fitted normalizations of background and $S$-wave relativistic Breit-Wigner signal (fixed $M_X$ and $\Gamma_X$, truncating fit at 5.7 GeV).
4. – Interpretation

We assume that $X$ is the ground state with orbital angular momentum $L = 0$. If this state has the direct decay $X(5568) \rightarrow B_{s0}^0 \pi^{\pm}$, then its spin-parity would be $J^P = 0^+$ and would be a counterpart of the $a_0^+(980)$ meson, replacing the $s\bar{s}$ quark components by $b\bar{s}$. If this state is really the result of the decay via $X(5568) \rightarrow B_{s0}^0 \pi^{\pm}$ where the $B_{s0}^0 \rightarrow B_{s0}^0 \gamma$, where the $\gamma$ is undetected, then the parent mass would be shifted upward by $\sim 49 \text{ MeV}/c^2$ to $5617 \text{ MeV}/c^2$ and have spin-parity of $J^P = 1^-$ and would be the counterpart of $Z_0^+ \rightarrow \Upsilon(nS)\pi^+$ [9], replacing the $b\bar{b}$ by $b\pi$.

What can this $B_{s}\pi$ state be? Since it has a resonance width $\Gamma_X = 22 \pm 8 \text{ MeV}$, it must be a strongly decaying state. Since $B_{s0}^0\pi^{\pm}$ consists of a $b\bar{u}\bar{d}$ set of valence quarks, it is clearly an exotic state. A brief bibliography of recent tetraquark and pentaquark observations is provided in reference [7]. The $X(5568)$ state is unique in that it is the first state observed containing four different quarks, and does not decay directly into a heavy $q\bar{q}$-onia meson. It could be one of the 4-quark (tetraquark) states speculated on by Gell-Mann [10]; a loosely-bound $B - K$ molecular state [11]; or a combination of bound di-quarks considered by Maiani, et al. [12]. Since the $Q$-value of the $X(5568)$ state is only $62 \text{ MeV}$ above the $B_{s}\pi$ threshold mass, and would have $206 \text{ MeV}$ binding energy, its interpretation as a bound $B - K$ molecule is disfavored.

Since the presentation of this D0 observation, LHCb has presented preliminary results [13] of a search for this new $B_{s}\pi$ state in $pp$ collisions using the $B_{s} \rightarrow J/\psi \phi$ and $B_{s} \rightarrow D_{s}^- \pi^+$ decay modes. LHCb did not confirm the D0 signal, quoting an upper limit as $90\% \text{ CL}(\sigma(X) \times B(X \rightarrow B_{s}\pi)/\sigma(B_{s})) < 1.6\%$ for $p_T(B_{s}) > 10 \text{ GeV}/c$.

D0 awaits the similar studies by CDF and the other LHC experiments.

5. – Summary and conclusions

CDF has presented the first measurement of the cross section for $B_s^+$ production at $|y| < 0.6$ and $p_T > 6 \text{ GeV}/c$ in $p\bar{p}$ production at 1.96 TeV. D0 has presented the first evidence of an exotic state $X(5568) \rightarrow B_{s} \pi^{\pm}$ consisting of four different quarks ($b, s, u, d$), with $M_X = 5567.8 \pm 2.9 \text{ (stat)}^{+0.9}_{-1.3} \text{ (syst)} \text{ MeV}/c^2$, and $\Gamma_X = 21.9 \pm 6.4 \text{ (stat)}^{+5.0}_{-2.5} \text{ (syst)} \text{ MeV}/c^2$, with a significance of $5.1\sigma$ taking into account the Look Elsewhere Effect and the systematic uncertainties in the yield of the $X(5568)$.
The CDF and D0 Collaborations thank the staffs at Fermilab and collaborating institutions, and acknowledge support of the many international funding agencies which made these experimental programs possible. D0 also thanks E. Gross and O. Vittels for useful discussions.

REFERENCES


[13] LHCb Collaboration (Aaij R. et al.), Search for structure in the $\mathcal{B}_s^0\pi^{\pm}$ invariant mass spectrum, LHCb-CONF-2016-004 (March, 2016). (This is not in arXiv).