Part I: Heavy baryon forward-backward asymmetries in $p\bar{p}$ collisions. Part II: Confirmation of the exotic state $X(5568) \rightarrow B_s^0 \pi^\pm$ in $p\bar{p}$ collisions.

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The DØ Collaboration presents measurements of forward-backward asymmetries of baryon production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Also presented is a confirmation of the exotic state $X(5568) \rightarrow B_s^0 \pi^\pm$ with $B_s^0$ reconstructed in the semi-leptonic decay $B_s^0 \rightarrow \mu^\mp D_s^\pm X$. 

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1. Part I: Heavy baryon forward-backward asymmetries in \( p\bar{p} \) collisions

Measurements of forward-backward production asymmetries in \( p\bar{p} \) collisions are a legacy of the Tevatron that test models of forward production.

In the coordinate system in which the \( z \) axis is aligned with the proton beam direction we define the rapidity \( y \equiv \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \), where \( p_z \) is the \( \Lambda \) or \( \bar{\Lambda} \) momentum component in the \( z \) direction and \( E \) is its energy in the \( p\bar{p} \) center of mass frame. The \( \Lambda \) (\( \bar{\Lambda} \)) is defined as “forward” if its longitudinal momentum is in the \( p \) (\(\bar{p}\)) direction. We obtain the numbers \( N_F(\Lambda) \) and \( N_B(\Lambda) \) \( (N_F(\bar{\Lambda}) \) and \( N_B(\bar{\Lambda})) \) of reconstructed \( \Lambda \)'s (\( \bar{\Lambda} \)'s) in the “forward” and “backward” categories, respectively, in bins of \( |y| \). The forward-backward asymmetry is defined as

\[
A_{FB}(\Lambda, \bar{\Lambda}) = \frac{N_F(\Lambda) - N_B(\Lambda) + N_F(\bar{\Lambda}) - N_B(\bar{\Lambda})}{N_F(\Lambda) + N_B(\Lambda) + N_F(\bar{\Lambda}) + N_B(\bar{\Lambda})},
\]

(1.1)

The DØ detector is well suited to measure forward-backward asymmetries because the initial state is the CP eigenstate \( p\bar{p} \), and the solenoid and toroid magnetic fields can be reversed periodically allowing studies and cancellations of systematic uncertainties. The measurements are based on 10.4 fb\(^{-1} \) of \( p\bar{p} \) collision data at \( \sqrt{s} = 1.96 \) TeV collected by the D0 experiment at the Fermilab Tevatron collider.

Figure 1: Left: Forward-backward asymmetries \( A_{FB}(\Lambda, \bar{\Lambda}) \) measured with three data sets: zero bias, and data triggered on \( J/\psi \) or \( \mu \) [1]. Right: Comparison of \( \bar{\Lambda}/\Lambda \) production ratios in \( pp \) collisions with \( \left[ 1 - A_{FB}(\Lambda, \bar{\Lambda}) \right] / \left[ 1 + A_{FB}(\Lambda, \bar{\Lambda}) \right] \) measured in \( p\bar{p} \) collisions (see references in [1]).

Figure 1 presents measurements of \( A_{FB}(\Lambda, \bar{\Lambda}) \) in \( p\bar{p} \) collisions, and compares these results with \( \bar{\Lambda}/\Lambda \) production ratios measured by several \( pp \) collision experiments. A summary of forward-backward asymmetry measurements of \( \Lambda, \Xi^- , \Omega^- , B^- \), and baryons containing a \( c \) quark or a \( b \) quark is presented in Fig. 2. Note the hierarchy of the forward-backward asymmetries of baryons at a given rapidity \( |y| \): \( A_{FB}(H_c, \bar{H}_c) > A_{FB}(\Lambda, \bar{\Lambda}) > A_{FB}(H_b, \bar{H}_b) \) with \( A_{FB}(H_b, \bar{H}_b) \) consistent with zero. \( H_c \) are baryons containing a \( c \) quark, and \( H_b \) are baryons containing a \( b \) quark. In Fig. 2 the \( H_c \) are prompt, i.e. exclude \( H_b \) decays, and the \( \Lambda \) exclude \( H_c \) and \( H_b \) decays. The forward-backward asymmetry of \( \Lambda_b \) is presented in Ref. [6].
Forward-backward asymmetries, and $X(5568)$

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2. Part II: Confirmation of the exotic state $X(5568) \rightarrow B_s^0 \pi^\pm$ in $p\bar{p}$ collisions

The DØ experiment has found evidence of a $B_s^0 \pi^\pm$ resonance at $M = 5568$ MeV, slightly above threshold [7]. See Fig. 4. The $B_s^0$ was reconstructed in the hadronic channel

$$B_s^0 \rightarrow J/\psi \phi, \quad J/\psi \rightarrow \mu^+ \mu^-, \quad \phi \rightarrow K^+ K^-.$$  \hspace{1cm} (2.1)
The $B^0_s$ is fully mixed so its quark anti-quark composition is undetermined. The non-zero width of the resonance $21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV implies a strong decay.

**Figure 4:** Left: Invariant mass of $X(5568) \to B^0_s \pi^+$ with $B^0_s$ reconstructed in the hadronic channel $B^0_s \to J/\psi \phi$. Right: Same with cone cut $\Delta R(B^0_s, \pi) = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$ [7].

The interpretation of the resonance as a molecular state, e.g. a colorless $B^0_d(b\bar{d})$ loosely coupled to a colorless $K^+(u\bar{s})$, should have a mass close to $m(B^0_d) + m(K^+) = 5773$ MeV, and therefore is disfavored. A tightly bound tetraquark e.g. $(bd)(\bar{s}\bar{u}), (bu)(\bar{s}\bar{d}), (su)(\bar{b}\bar{d})$, or $(sd)(\bar{b}\bar{u})$ has been considered. See also Ref. [8] for a scalar-scalar diquark-antidiquark $0^+$ state.

**Figure 5:** Left: $X(5568) \to B^0_s \pi^+$ with $B^0_s$ decaying in the semi-leptonic channel $B^0_s \to m \mp D^\pm_s X, D^\pm_s \to \phi \pi^\pm, \phi \to K^+ K^-$. Right: $m(K^+ K^- \pi^\pm)$ for right sign $\mu \mp \phi \pi^\pm$ showing $D^\pm$ and $D^+_s$ meson decays, and wrong sign combination [9].

This $B_s \pi^\pm$ resonance is now confirmed with $B^0_s$ reconstructed in the semi-leptonic channel [9].

$$B^0_s \to \mu^+ D^+_s X, \quad D^+_s \to \phi \pi^\pm, \quad \phi \to K^+ K^-. \quad (2.2)$$

See Figs. 5, 6 and 7. The requirement $4.5 \text{ GeV} < m(\mu^+ D^-_s) < m(B^0_s)$ reduces the $\nu_\mu$ contribution to the mass resolution. The hadronic and semileptonic channels have independent events, signals, backgrounds and triggers. A comparison of the two measurements is presented in Table 1.
Forward-backward asymmetries, and \(X(5568)\)

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Figure 6: Weighting MC in \(p_T(\mu)\) and \(p_T(\mu D_s)\) to fit data [9].

Figure 7: Semileptonic channel (no cone cut is applied) [9].

<table>
<thead>
<tr>
<th>Mass [MeV]</th>
<th>5566.5(\pm)3.4 (\pm)3.4</th>
<th>5567.8(\pm)2.9(\pm)1.9</th>
<th>5567.8</th>
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<tr>
<td>Width [MeV]</td>
<td>6.0(\pm)0.6(\pm)0.6</td>
<td>21.9(\pm)6.4(\pm)2.5</td>
<td>21.9</td>
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<td>133(\pm)31(\pm)15</td>
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<td>5.1(\sigma)</td>
<td>3.9(\sigma)</td>
</tr>
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<td>Fraction**</td>
<td>7.3(\pm)2.8(\pm)0.6%</td>
<td>8.6(\pm)1.9(\pm)1.4%</td>
<td></td>
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Table 1: Comparison of measurements of the \(B^0_s\pi^+\) resonance with \(B^0_s\) reconstructed in the hadronic and semi-leptonic channels [9]. The combined semi-leptonic and hadronic channel significance with (without) hadronic channel cone cut is 5.7\(\sigma\) (4.7\(\sigma\)), including systematics and look-elsewhere-effect (LEE). * With systematics, and LEE for the hadronic channel. ** Fraction of \(B^0_s\) from \(X(5568)\).
In conclusion, the DØ experiment has found evidence of a $B^0_s\pi^\pm$ resonance in $p\bar{p}$ collisions with $B^0_s$ reconstructed in hadronic and semi-leptonic channels. This resonance has not been confirmed by LHCb or CMS in $pp$ collisions.

References


