PROCEEDINGS OF SCIENCE

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

B. Hoeneisen[*†]
Universidad San Francisco de Quito
E-mail: bruce1@fnal.gov, bhoeneisen@usfq.edu.ec

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 $X(5568) \to B_s^0 \pi^{\pm}$ with B_s^0 reconstructed in the semi-leptonic decay $B_s^0 \to \mu^{\mp} D_s^{\pm} X$.

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[*]Speaker.
[†]Representing the DØ collaboration

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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 $y \equiv \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$, where p_z is the Λ or $\bar{\Lambda}$ momentum component in the z direction and E is its energy in the $p\bar{p}$ center of mass frame. The Λ ($\bar{\Lambda}$) 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 Λ's ($\bar{\Lambda}$'s) in the "forward" and "backward" categories, respectively, in bins of $|y|$. The forward-backward asymmetry is defined as

$$A_{FB}(\Lambda,\bar{\Lambda}) \equiv \frac{N_F(\Lambda) - N_B(\Lambda) + N_F(\bar{\Lambda}) - N_B(\bar{\Lambda})}{N_F(\Lambda) + N_B(\Lambda) + N_F(\bar{\Lambda}) + N_B(\bar{\Lambda})}. \tag{1.1}$$

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.

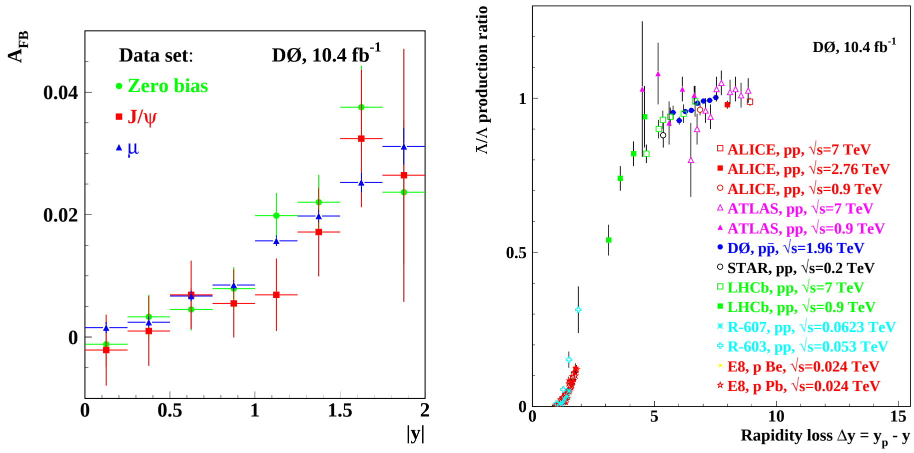

Figure 1: Left: Forward-backward asymmetries $A_{FB}(\Lambda,\bar{\Lambda})$ measured with three data sets: zero bias, and data triggered on J/ψ or μ [1]. Right: Comparison of $\bar{\Lambda}/\Lambda$ production ratios in pp collisions with $[1-A_{FB}(\Lambda,\bar{\Lambda})]\,/\,[1+A_{FB}(\Lambda,\bar{\Lambda})]$ 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 Λ, Ξ^-, Ω^-, 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 Λ exclude H_c and H_b decays. The forward-backward asymmetry of Λ_b is presented in Ref. [6].

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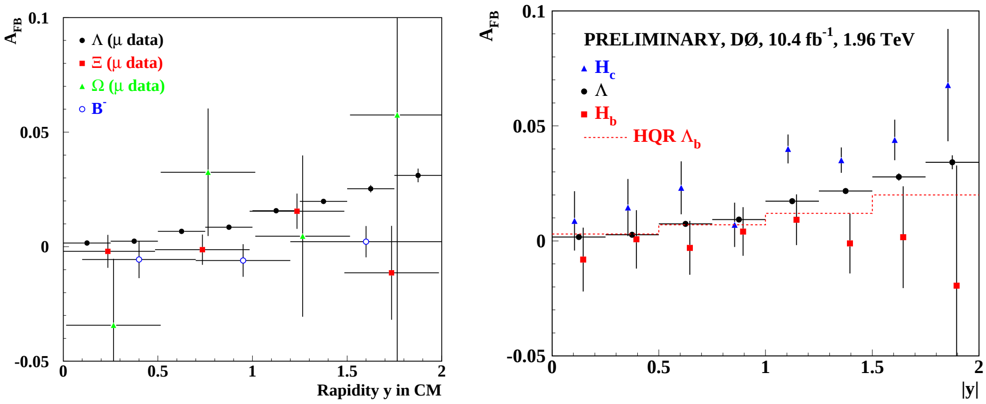

Figure 2: Left: Forward-backward asymmetry measurements of Λ, Ξ^-, Ω^-, and B^- [1, 2, 3]. Right: A_{FB} of prompt Λ, and of heavy baryons with a c or b quark (from inclusive decays $H_c \to \mu^+ \Lambda X$, and $H_b \to \mu^- H_c X$ followed by $H_c \to \Lambda X$) [4].

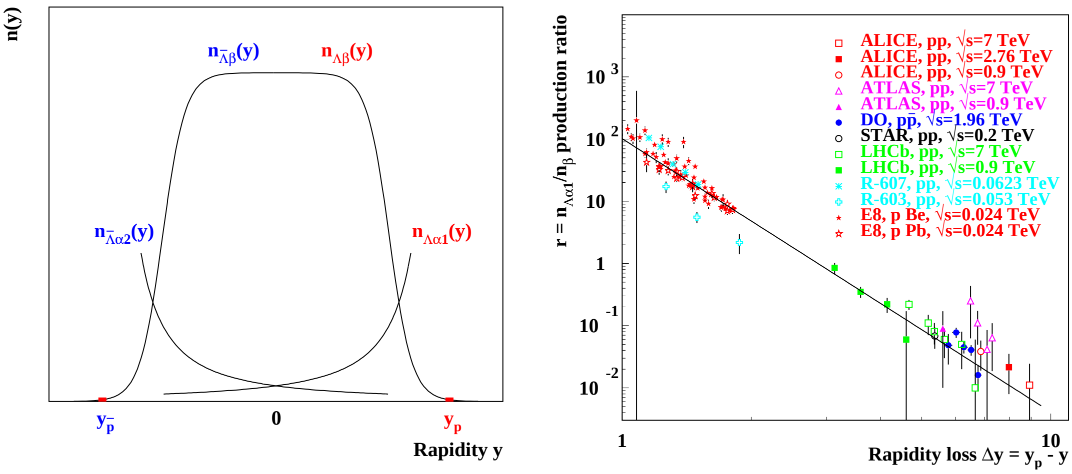

Figure 3: Left: Two Λ and $\bar{\Lambda}$ production mechanisms: "α" is forward, and "β" is central and symmetric in rapidity y. Right: Their ratio $r \equiv \alpha/\beta$ is a simple and universal function of "rapidity loss" $\Delta y = y_p - y$ [5].

We conclude that a simple two component Λ production model (central production β and forward production α) adequately represents all data, see Fig. 3 [5]. At small rapidity loss, the presence of the α component depends on having a shared (di)quark between the outgoing baryon and the parent proton.

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

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

$$B_s^0 \to J/\psi \phi, \qquad J/\psi \to \mu^+ \mu^-, \qquad \phi \to K^+ K^-. \tag{2.1}$$

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The B_s^0 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.

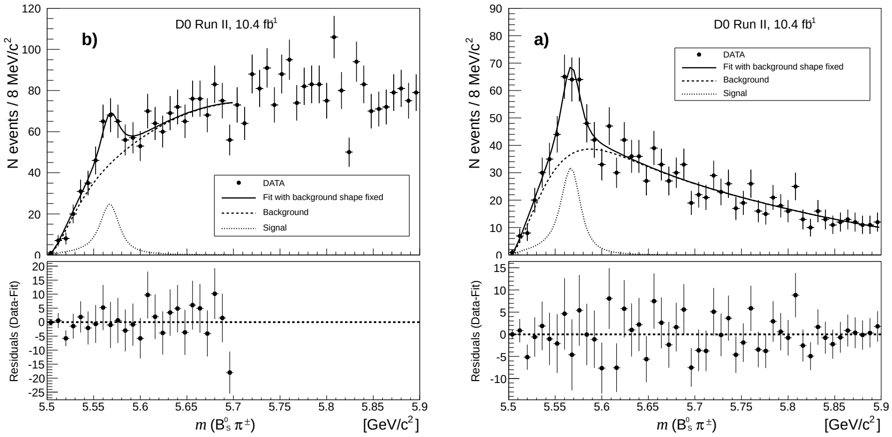

Figure 4: Left: Invariant mass of $X(5568) \to B_s^0\pi^\pm$ with B_s^0 reconstructed in the hadronic channel $B_s^0 \to J/\psi\phi$. Right: Same with cone cut $\Delta R(B_s^0, \pi) = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ [7].

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

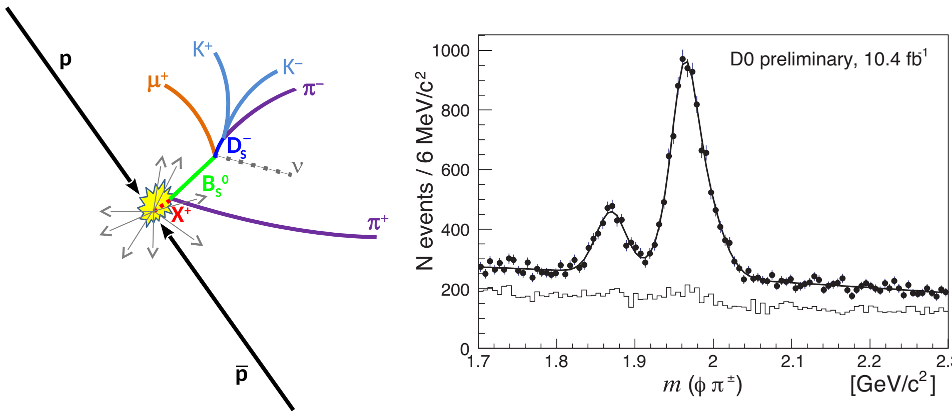

Figure 5: Left: $X(5568) \to B_s^0\pi^\pm$ with B_s^0 decaying in the semi-leptonic channel $B_s^0 \to \mu^\mp D_s^\pm X, D_s^\pm \to \phi\pi^\pm$, $\phi \to K^+K^-$. Right: $m(K^+K^-\pi^\pm)$ for right sign $\mu^\pm\phi\pi^\mp$ showing $D^\pm$ and $D_s^\pm$ meson decays, and wrong sign combination [9].

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

$$B_s^0 \to \mu^\mp D_s^\pm X, \qquad D_s^\pm \to \phi\pi^\pm, \qquad \phi \to K^+K^-. \tag{2.2}$$

See Figs. 5, 6 and 7. The requirement 4.5 GeV $< m(\mu^+ D_s^-) < m(B_s^0)$ reduces the ν_μ 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.

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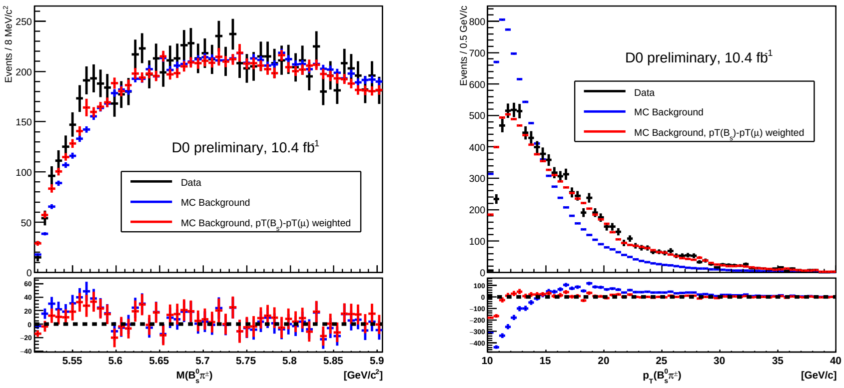

Figure 6: Weighting MC in $p_T(\mu)$ and $p_T(\mu D_s)$ to fit data [9].

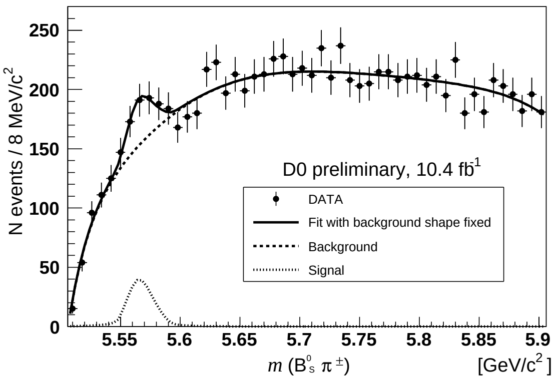

Figure 7: Semileptonic channel (no cone cut is applied) [9].

	Semileptonic	Hadronic with cone cut	Hadronic no cone cut
Mass [MeV]	$5566.7^{+3.6}_{-3.4} \pm 1.0$	$5567.8 \pm 2.9^{+0.9}_{-1.9}$	5567.8
Width [MeV]	$6.0^{+9.5+1.9}_{-6.0-4.6}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	21.9
Events	$139^{+51+10.9}_{-63-31.5}$	$133 \pm 31 \pm 15$	106 ± 23
Significance*	3.2σ	5.1σ	3.9σ
Fraction**	$7.3^{+2.8+0.6}_{-2.4-1.7}\%$	$8.6 \pm 1.9 \pm 1.4\%$	

Table 1: Comparison of measurements of the $B_s^0\pi^\pm$ resonance with B_s^0 reconstructed in the hadronic and semi-leptonic channels [9]. The combined semi-leptonic and hadronic channel significance with (without) hadronic channel cone cut is 5.7σ (4.7σ), including systematics and look-elsewhere-effect (LEE). * With systematics, and LEE for the hadronic channel. ** Fraction of B_s^0 from $X(5568)$.

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In conclusion, the DØ experiment has found evidence of a $B_s^0\pi^{\pm}$ resonance in $p\bar{p}$ collisions with B_s^0 reconstructed in hadronic and semi-leptonic channels. This resonance has not been confirmed by LHCb or CMS in pp collisions.

References

[1] V.M. Abazov et al. (D0 Collaboration), "Measurement of the forward-backward asymmetry of Λ and $\bar{\Lambda}$ production in $p\bar{p}$ collisions", Phys. Rev. **D** 93, 032002 (2016), arXiv:1511.05113.

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