Measurement of the forward-backward asymmetries in the production of $\Xi$ and $\Omega$ baryons in $p\bar{p}$ collisions


1 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ 22290, Brazil  
2 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, RJ 20550, Brazil  
3 Universidade Federal do ABC, Santo André, SP 09210, Brazil  
4 University of Science and Technology of China, Hefei 230026, People’s Republic of China  
5 Universidad de los Andes, Bogotá, 111711, Colombia  
6 Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, 116 36 Prague 1, Czech Republic  
7 Czech Technical University in Prague, 116 36 Prague 6, Czech Republic  
8 Institute of Physics, Academy of Sciences of the Czech Republic, 182 21 Prague, Czech Republic  
9 Universidad San Francisco de Quito, Quito, Ecuador  
10 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, F-63178 Aubière Cedex, France  
11 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France  
12 CPPM, Aix-Marseille Université, CNRS/IN2P3, F-13288 Marseille Cedex 09, France  
13 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay Cedex, France  
14 LPNHE, Universités Paris VI and VII, CNRS/IN2P3, F-75005 Paris, France  
15 CEA Saclay, Ifyu, SPP, F-91191 Gif-Sur-Yvette Cedex, France  
16 IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France  
17 IPNL, Université Lyon 1, CNRS/IN2P3, F-69622 Villeurbanne Cedex, France and Université de Lyon, F-69361 Lyon CEDEX 07, France  
18 III. Physikalisches Institut A, RWTH Aachen University, 52056 Aachen, Germany  
19 Physikalisches Institut, Universität Freiburg, 79085 Freiburg, Germany  
20 II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen, Germany  
21 Institut für Physik, Universität Mainz, 55099 Mainz, Germany  
22 Ludwig-Maximilians-Universität München, 80539 München, Germany  
23 Panjab University, Chandigarh 160014, India  
24 Delhi University, Delhi-110 007, India  
25 Tata Institute of Fundamental Research, Mumbai-400 005, India  
26 University College Dublin, Dublin 4, Ireland  
27 Korea Detector Laboratory, Korea University, Seoul, 02841, Korea  
28 CINVESTAV, Mexico City 07360, Mexico  
29 Nikhef, Science Park, 1098 XG Amsterdam, the Netherlands  
30 Radboud University Nijmegen, 6525 AJ Nijmegen, the Netherlands  
31 Joint Institute for Nuclear Research, Dubna 141980, Russia  
32 Institute for Theoretical and Experimental Physics, Moscow 117259, Russia  
33 Moscow State University, Moscow 119991, Russia  
34 Institute for High Energy Physics, Protvino, Moscow region 142281, Russia  
35 Petersburg Nuclear Physics Institute, St. Petersburg 188300, Russia  
36 Instituto Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Fisica d’Altes Energies (IFAE), 08913 Bellaterra (Barcelona), Spain  
37 Uppsala University, 751 05 Uppsala, Sweden  
38 Taras Shevchenko National University of Kyiv, Kiev, 01601, Ukraine  
39 Lancaster University, Lancaster LA1 4YB, United Kingdom  
40 Imperial College London, London SW7 2AZ, United Kingdom  
41 The University of Manchester, Manchester M13 9PL, United Kingdom  
42 University of Arizona, Tucson, Arizona 85721, USA  
43 University of California Riverside, Riverside, California 92521, USA  
44 Florida State University, Tallahassee, Florida 32306, USA  
45 Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA  
46 University of Illinois at Chicago, Chicago, Illinois 60607, USA  
47 Northern Illinois University, DeKalb, Illinois 60115, USA  
48 Northwestern University, Evanston, Illinois 60208, USA  
49 Indiana University, Bloomington, Indiana 47405, USA  
50 Purdue University Calumet, Hammond, Indiana 46323, USA  
51 University of Notre Dame, Notre Dame, Indiana 46556, USA  
52 Iowa State University, Ames, Iowa 50011, USA  
53 University of Kansas, Lawrence, Kansas 66045, USA  
54 Louisiana Tech University, Ruston, Louisiana 71272, USA
We present a study of the forward-backward asymmetries $A_{FB}$ for the production of charged $\Xi$ and $\Omega$ baryons in $p\bar{p}$ collisions at a center of mass energy $\sqrt{s} = 1.96$ TeV, recorded by the D0 detector at the Fermilab Tevatron collider.

We previously performed a study of $A_{FB}$ for $\Lambda$ and $\bar{\Lambda}$ production [1], where $A_{FB}$ is defined as the relative excess of $\Lambda$ ($\bar{\Lambda}$) baryons produced with longitudinal momentum $p_z$ in the $p$ ($\bar{p}$) direction. These results are in agreement with the observations in a wide range of proton collision experiments that the $\Lambda$/$\bar{\Lambda}$ production ratio follows a universal function of the “rapidity loss” $y_p - y$ between the beam proton and the produced $\Lambda$ or $\bar{\Lambda}$ baryon which does not depend significantly on $\sqrt{s}$ or on the nature of the target $p$, $\bar{p}$, Be, or Pb (see Ref. [1] and references therein). These results support the view that a strange quark produced directly in the hard scattering of point-like partons, or indirectly in the subsequent showering, can coalesce with a diquark remnant of the beam particle to produce a $\Lambda$ baryon with a probability that increases as the rapidity difference between the incoming proton and outgoing $\Lambda$ baryon decreases.

If this hypothesis is correct, we also expect $A_{FB} > 0$ for $\Lambda_c$ ($\bar{\Lambda}_c$), and $\Lambda_b$($\bar{\Lambda}_b$) production in which a $c$ or $b$ quark can coalesce with a diquark form the proton. For the $B$ mesons and $\Xi$ and $\Omega$ baryons, we expect $A_{FB} \approx 0$ since these particles do not share a diquark with the proton. Previous D0 measurements include $A_{FB}(B^-, B^+) [2]$ and $A_{FB}(\Lambda_b, \bar{\Lambda}_b) [3]$.

In this article, we present measurements of the forward-backward asymmetries of $\Xi^\mp$ and $\Omega^\mp$ production, where we use the notation $\Xi^\mp \equiv \Xi^- \mp \Xi^+$ and $\Omega^\mp \equiv \Omega^- \mp \Omega^+$. The $\Xi^-$ and $\Xi^+$ baryons are defined as “forward” if their $p_z$ points in the $p$ or $\bar{p}$ direction, respectively. The asymmetry $A_{FB}$ is defined as

$$A_{FB} \equiv \frac{\sigma_F(\Xi^-) - \sigma_B(\Xi^-) + \sigma_F(\Xi^+) - \sigma_B(\Xi^+)}{\sigma_F(\Xi^-) + \sigma_B(\Xi^-) + \sigma_F(\Xi^+) + \sigma_B(\Xi^+)}, \quad (1)$$

where $\sigma_F$ and $\sigma_B$ are the forward and backward cross sections of $\Xi^-$ or $\Xi^+$ production, and similarly for $\Omega^\mp$ baryons. The measurements include $\Xi^\mp$ and $\Omega^\mp$ baryons that are either directly produced or decay products of heavier hadrons. The measurement strategy for the asymmetry $A_{FB}$ of $\Xi^\mp$ and $\Omega^\mp$ baryons presented here...
closely follows the analysis method used to determine $A_{FB}$ for $\Lambda$ and $\bar{\Lambda}$ baryons in Ref. [1].

DETECTOR AND DATA

The D0 detector is described in detail in Refs. [4,7]. The collision region is surrounded by a central tracking system that comprises a silicon microstrip vertex detector and a central fiber tracker, both located within a 1.9 T superconducting solenoidal magnet [4], surrounded successively by the liquid-argon/uranium calorimeters, a layer of the muon system [5], comprising drift chambers and scintillation trigger counters, the 1.8 T magnetized iron toroids, and two additional muon detector layers after the toroids.

The longitudinal momentum $p_z$ and the rapidity $y \equiv \ln [(E + p_z)/(E - p_z)]/2$ are both measured with respect to the proton beam direction in the $p\bar{p}$ center of mass frame where $E$ is the energy of the baryon. We present results for the full integrated luminosity of 10.4 fb$^{-1}$, collected from 2002 to 2011, using two data sets (i) $p\bar{p} \rightarrow \Xi^\pm X$, and (ii) $p\bar{p} \rightarrow \mu \Xi^\mp X$. The first data set is unbiased since it is collected using a pre-scaled trigger on beam crossing (“zero bias events”) or with a pre-scaled trigger on energy deposited in the forward counters (“minimum bias events”). The second data set is selected with a suite of single muon triggers which implies that most events contain heavy-quark ($b$ or $c$) decays. This data set is defined using the same muon triggers and muon selections as in Ref. [8,9]. The muon data provides a sizable data set that adds additional statistics for the analysis. For $\Omega$’s there are fewer events, so we only present results for the set $p\bar{p} \rightarrow \mu \Omega^\mp X$.

We observe $\Xi$ baryons through their decays $\Xi^- \rightarrow \Lambda\pi^-$ and $\Xi^+ \rightarrow \Lambda\pi^+$, and $\Omega$ baryons through their decays $\Omega^- \rightarrow \Lambda K^-$ and $\Omega^+ \rightarrow \Lambda K^+$, with $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ in both cases. The $\Lambda$ and $\bar{\Lambda}$ candidates are reconstructed from pairs of oppositely curved tracks with a common vertex ($V^0$). Each track is required to have a non-zero impact parameter in the transverse plane with signifi-

cance greater than two standard deviations and a good transverse plane from the primary vertex with significance greater than three standard deviations. The observed decay lengths in the transverse plane of the $\Lambda$ and $\Xi^-$ or $\Omega^-$ (or $\bar{\Lambda}$ and $\Xi^+$ or $\Omega^+$) are required to be greater than 4 mm. The invariant mass for the $\Xi^+$ candidate is required to be in the interval $1.105 < M(p\pi^-) < 1.125$ GeV [1]. We require $\Lambda$ and $\bar{\Lambda}$ candidates with $1.5 < p_T < 25$ GeV and pseudorapidity $|\eta| < 2.2$ [10], and their IP must be non-zero with a significance greater than two standard deviations.

The $\Lambda$ ($\bar{\Lambda}$) candidate is combined with a negatively (positively) charged-particle track with separation in the transverse plane from the primary vertex with significance greater than three standard deviations and a good vertex with the $\Lambda$ ($\bar{\Lambda}$) candidate. This track is assigned the pion mass for $\Xi$’s or the kaon mass for $\Omega$’s. The $\Xi^+$ or $\Omega^+$ candidates are required to have an IP consistent with zero within three standard deviations. The observed decay lengths in the transverse plane of the $\Lambda$ and $\Xi^-$ or $\Omega^-$ (or $\bar{\Lambda}$ and $\Xi^+$ or $\Omega^+$) are required to be greater than 4 mm. The invariant mass for the $\Xi^+$ candidate is required to be in the interval $1.2 < M(\Lambda\pi^-) < 1.5$ GeV and $1.55 < M(\Lambda K^-) < 1.85$ GeV for $\Omega^+$ candidates. The kinematic selections for the $\Xi^+$ and $\Omega^+$ candidates are $p_T > 2.0$ GeV and $|\eta| < 2.2$. The pion or kaon track and the two daughter tracks of the $\Lambda$ baryon are required to be different from any track associated to a muon. The invariant mass distributions for the decays $\Xi^- \rightarrow \Lambda\pi^-$ and $\Xi^+ \rightarrow \Lambda\pi^+$ are shown in Fig. [1] and for the decays $\Omega^- \rightarrow \Lambda K^-$ and $\Omega^+ \rightarrow \Lambda K^+$ in Fig. [2].
We obtain the numbers \( N_F(\Xi^-) \) and \( N_B(\Xi^+) \) of reconstructed \( \Xi^- \) baryons in the forward and backward categories in each bin of \( |y| \) by counting \( \Xi^\mp \) candidates in the signal region, \( 1.305 < M(\Lambda\pi) < 1.335 \) GeV, and subtracting the counts in two sideband regions, defined by \( 1.2775 < M(\Lambda\pi) < 1.2925 \) GeV and \( 1.3475 < M(\Lambda\pi) < 1.3625 \) GeV. The signal region for \( \Omega^\mp \) candidates is \( 1.6575 < M(\Lambda\Lambda) < 1.6875 \) GeV, and the sideband regions are \( 1.630 < M(\Lambda\Lambda) < 1.645 \) GeV and \( 1.700 < M(\Lambda\Lambda) < 1.715 \) GeV.

The normalization factor \( N \) and the three raw asymmetries \( A'_{FB}, A'_{NS}, \) and \( A'_\Xi \) are defined by

\[
\begin{align*}
N_F(\Xi^-) &= N(1 + A'_{FB})(1 - A'_{NS})(1 + A'_\Xi), \\
N_B(\Xi^-) &= N(1 - A'_{FB})(1 + A'_{NS})(1 + A'_\Xi), \\
N_F(\Xi^+) &= N(1 + A'_{FB})(1 + A'_{NS})(1 - A'_\Xi), \\
N_B(\Xi^+) &= N(1 - A'_{FB})(1 - A'_{NS})(1 - A'_\Xi),
\end{align*}
\]

and similarly for \( \Omega \). The raw asymmetries \( A'_{FB}, A'_{NS}, \) and \( A'_\Xi \) have contributions from the physical asymmetries \( A_{FB}, A_{NS}, \) and \( A_\Xi \), and from detector effects. The forward-backward asymmetry \( A_{FB} \) measures the relative excess of \( \Xi^- (\Xi^+) \) baryons with \( p_z \) in the \( p (\bar{p}) \) direction. The asymmetry \( A_{NS} \) is given by the relative excess of the sum of \( \Xi^- \) and \( \Xi^+ \) baryons with \( p_z \) in the \( \bar{p} \) beam direction (north) with respect to the \( p \) beam direction (south). The asymmetry \( A_\Xi \) is the relative excess of negatively charged over positively charged baryons.

The initial \( pp \) state is invariant with respect to \( CP \) conjugation, which changes the sign of \( A_{NS} \) and \( A_\Xi \), while \( A_{FB} \) remains unchanged. A non-zero value of \( A_{NS} \) or \( A_\Xi \) would indicate \( CP \) violation.

The asymmetry \( A'_{NS} \) is mainly due to differences in the product of the acceptance and efficiency between the northern hemisphere of the DØ detector with respect to the southern hemisphere. The difference in reconstruction efficiencies of \( \Xi^- \) and \( \Xi^+ \) baryons caused by the different inelastic interaction cross-sections of \( p \) and \( \bar{p} \) with the detector material creates the additional asymmetry \( A'_\Xi \).

The raw asymmetries including terms up to second-order in the asymmetries are given by

\[
\begin{align*}
A'_{FB} &= A'_{NS} A'_\Xi, \\
A'_{NS} &= A'_{FB} A'_\Xi, \\
A'_\Xi &= A'_{FB} A_{NS},
\end{align*}
\]

and

\[
\begin{align*}
A'_{FB} &= A'_{NS} A'_\Xi, \\
A'_{NS} &= A'_{FB} A'_\Xi, \\
A'_\Xi &= A'_{FB} A_{NS},
\end{align*}
\]

The raw asymmetry \( A_{FB} \) has negligible contributions from detector effects after averaging over solenoid and toroid magnet polarities. The raw asymmetries \( A_{NS} \) and \( A_\Xi \) are dominated by detector effects [1]. The quadratic term \( A_{NS} A_\Xi \) in Eq. 5 corrects \( A_{FB} \) for the detector effects \( A_{NS} \) and \( A_\Xi \) on the particle counts \( N_F(\Xi\mp) \) and \( N_B(\Xi\mp) \). We can therefore set \( A_{FB} = A_{FB} \) where \( A_{FB} \) is defined in Eq. 1.
TABLE I: Forward-backward asymmetry $A_{FB}$ of $\Xi^+$ baryons with $p_T > 2$ GeV in minimum bias events, $pp \to \Xi^+$, and muon events $p\bar{p} \to \mu\Xi^+$, and $A_{FB}$ of $\Omega^-$ and $\Omega^+$ baryons with $p_T > 2$ GeV in muon events $p\bar{p} \to \mu\Omega^\mp$. The first uncertainty is statistical, the second is systematic due to the detector asymmetry $A'_{NS}A'_\Xi$.

| $|y|$  | $A_{FB} \times 100$ ($\Xi^+$, min. bias) | $A_{FB} \times 100$ ($\Xi^+$, with $\mu$) | $A_{FB} \times 100$ ($\Omega^\mp$, with $\mu$) |
|------|-------------------------------------|-------------------------------------|-------------------------------------|
| 0.0 to 0.5 | $-2.78 \pm 3.20 \pm 0.34$ | $-0.20 \pm 0.72 \pm 0.01$ | $-3.43 \pm 2.90 \pm 0.13$ |
| 0.5 to 1.0 | $5.23 \pm 2.85 \pm 0.55$ | $-0.13 \pm 0.66 \pm 0.03$ | $3.25 \pm 2.78 \pm 0.10$ |
| 1.0 to 1.5 | $2.61 \pm 3.75 \pm 0.45$ | $1.55 \pm 0.77 \pm 0.05$ | $0.46 \pm 3.52 \pm 0.14$ |
| 1.5 to 2.0 | $5.09 \pm 9.00 \pm 1.64$ | $-1.14 \pm 2.05 \pm 0.27$ | $5.75 \pm 10.86 \pm 5.70$ |

FIG. 4: Asymmetries $A'_{FB} = A_{FB}$, $A'_{NS}$ and $A'_{\Xi}$ of reconstructed $\Xi^-$ and $\Xi^+$ candidates with $p_T > 2$ GeV, as a function of $|y|$, for the minimum bias data sample $p\bar{p} \to \Xi^+$.

The uncertainties are statistical. The asymmetry $A'_{NS}$ is needed to obtain $A'_{FB} = A_{FB}$ is measured to be consistent with zero within statistical uncertainties, see Figs. 4 (b) and (c). Thus, we choose not to apply this correction, but rather take the full measured detector asymmetry $A'_{NS}A'_{\Xi}$ as the systematic uncertainty on the measurement of $A_{FB}$. The results are summarized in Table I.

MINIMUM BIAS SAMPLE EVENTS $p\bar{p} \to \Xi^+$

The minimum bias sample contains $3.7 \times 10^3$ reconstructed $\Xi^+$ candidates with $p_T > 2$ GeV. Distributions of $p_T$, $p_z$, and $y$ for the $\Xi^+$ candidates are shown in Fig. 4 and the corresponding raw asymmetries $A'_{FB} = A_{FB}$, $A'_{NS}$ and $A'_{\Xi}$ in Fig. 5. These asymmetries are calculated using Eqs. 4, neglecting the quadratic terms since they are small compared to the statistical uncertainties. The correction $A'_{NS}A'_{\Xi}$ needed to obtain $A'_{FB} = A_{FB}$ is measured to be consistent with zero within statistical uncertainties, see Figs. 5 (b) and (c). Thus, we choose not to apply this correction, but rather take the full measured detector asymmetry $A'_{NS}A'_{\Xi}$ as the systematic uncertainty on the measurement of $A_{FB}$. The results are summarized in Table I.

MUON SAMPLE EVENTS $p\bar{p} \to \mu\Xi^+$ AND $p\bar{p} \to \mu\Omega^\mp$

To study the asymmetries using a larger data set, we consider $p\bar{p} \to \mu\Xi^+$ and $p\bar{p} \to \mu\Omega^\mp$ events taken from the single muon trigger sample. Charged particles with transverse momentum in the range $1.5 < p_T < 25$ GeV and $|y| < 2.2$ are considered as muon candidates. Muon candidates are further selected by matching central tracks with a segment reconstructed in the muon system and by applying tight quality requirements aimed at reducing false matching and background from cosmic rays and beam halo. To ensure that the muon candidate traverses the detector, including all three layers of the muon system, we require either $p_T > 4.2$ GeV or $|p_z| > 5.4$ GeV [8, 9]. The inclusive muon sample contains $2.2 \times 10^9$.
FIG. 6: Asymmetries $A'_{FB} = A_{FB}$, $A'_{NS}$ and $A'_{Ξ}$ of reconstructed $Ξ^-$ and $Ξ^+$ candidates with $p_T > 2$ GeV, as a function of $|y|$, for $p\bar{p} \rightarrow µΞ^±X$ events. The uncertainties are statistical.

FIG. 7: Asymmetry $A'_{FB} = A_{FB}$ as a function of $|y|$ for $p\bar{p} \rightarrow µΞ^±X$ events with (a) $2.0 < p_T < 4.0$ GeV, (b) $4.0 < p_T < 6.0$ GeV, and (c) $p_T > 6.0$ GeV. The uncertainties are statistical.

reconstructed muons and $7.7 \times 10^4$ reconstructed $Ξ^-$ and $Ξ^+$ candidates with $p_T > 2$ GeV, as well as $1.4 \times 10^4$ reconstructed $Ω^-$ and $Ω^+$ candidates.

Rapidity distributions for reconstructed $Ξ^-$ and $Ξ^+$ candidates are shown in Fig. 6. From these distributions we observe that (i) the detection efficiency for $Ξ^-$ baryons is larger than for $Ξ^+$ baryons as explained above, and (ii) there are more $Ξ^± µ^{±}$ than $Ξ^± µ^{±}$ events. An example of a process with a correlated $Ξ^± µ^{±}$ pair is the decay $Ξ_0^{±} \rightarrow Ξ^± µ^{±}X$. We find that the asymmetry $A'_{FB}$ obtained with events containing a $µ^{±}$ is consistent with the corresponding asymmetry with $µ^{±}$ within statistical uncertainties. We therefore combine the $µ^{±}$ and $µ^{±}$ samples to obtain the asymmetries presented in Figs. 6 and 7.

The $p_T$, $p_z$, and $y$ distributions for $p\bar{p} \rightarrow µΩ^{±}X$ events are shown in Fig. 8 and the corresponding asymmetry $A_{FB}$ is presented in Fig. 9. The $Ξ^{±}$ and $Ω^{±}$ asymmetries are summarized in Table I.

CONCLUSIONS

We have measured the forward-backward asymmetries $A_{FB}$ in $p\bar{p} \rightarrow Ξ^{±}X$, $p\bar{p} \rightarrow µΞ^{±}X$, and $p\bar{p} \rightarrow µΩ^{±}X$ events using $10.4$ fb$^{-1}$ of integrated luminosity recorded with the D0 detector. We find that $A_{FB}$ for $Ξ^{±}$ and $Ω^{±}$ are consistent with zero within uncertainties.

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


[3] V.M. Abazov et al. (D0 Collaboration), Measurement of the forward-backward asymmetry in $\Lambda_c^0$ and $\bar{\Lambda}_c^0$ baryon production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 91, 072008 (2015).


[10] The pseudorapidity is given by $\eta = -\ln[\tan(\theta/2)]$, where $\theta$ is the polar angle with respect to the proton beam direction.