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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 Fourrier 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, Université 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, Irfu, 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) H. 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) Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), 08193 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 charged \( \Xi \) and \( \Omega \) baryons produced 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 \( \Xi^\mp \equiv \Xi^- \) and \( \Omega^+ \equiv \Omega^- \). 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

\[
A_{FB} \equiv \frac{\sigma_F(\Xi^-) - \sigma_B(\Xi^-) + \sigma_F(\Xi^+) - \sigma_B(\Xi^+)}{\sigma_F(\Xi^-) + \sigma_B(\Xi^-) + \sigma_F(\Xi^+) + \sigma_B(\Xi^+)},
\]

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 [3], 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.

![Fig. 1: Invariant mass distributions of reconstructed $\Xi^{-} \rightarrow \Lambda \pi^{-}$ (circles) and $\Xi^{+} \rightarrow \bar{\Lambda} \pi^{+}$ (triangles) for $p\bar{p} \rightarrow \mu \Xi^{\mp} X$ data.](image1)

![Fig. 2: Invariant mass distributions of reconstructed $\Omega^{-} \rightarrow \Lambda K^{-}$ (circles) and $\Omega^{+} \rightarrow \bar{\Lambda} K^{+}$ (triangles) for $p\bar{p} \rightarrow \mu \Omega^{\mp} X$ data.](image2)

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 $10.4 \, \text{fb}^{-1}$, collected from 2002 to 2011, using two data sets (i) $p\bar{p} \rightarrow \Xi^{\mp} X$, 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. [8,4]. 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 $\Xi^{+} \rightarrow \bar{\Lambda} \pi^{+}$, and $\Omega$ baryons through their decays $\Omega^{-} \rightarrow \Lambda K^{-}$ and $\Omega^{+} \rightarrow \bar{\Lambda} K^{+}$, 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 (IP) with respect to the $p\bar{p}$ interaction vertex with a significance of at least two standard deviations. The proton (pion) mass is assigned to the daughter track with larger (smaller) total momentum since the decay $\Lambda \rightarrow p\pi^{-}$ is just above threshold. The invariant mass of the ($p, \pi^{-}$) or ($\bar{p}, \pi^{+}$) pair is required to be in the interval $1.105 < M(p\pi) < 1.125 \, \text{GeV}$ [1]. We require $\Lambda$ and $\bar{\Lambda}$ candidates with $1.5 < p_T < 25 \, \text{GeV}$ 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 $\Xi^{\mp}$ or $\Omega^{\mp}$ 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 $\Lambda$ and $\Xi^{+}$ or $\Omega^{+}$) are required to be greater than 4 mm. The invariant mass for the $\Xi^{\mp}$ candidate is required to be in the interval $1.2 < M(\Lambda\pi) < 1.5 \, \text{GeV}$ and $1.55 < M(\Lambda K) < 1.85 \, \text{GeV}$ for $\Omega^{\mp}$ candidates. The kinematic selections for the $\Xi^{\mp}$ and $\Omega^{\mp}$ candidates are $p_T > 2.0 \, \text{GeV}$ 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 $\Xi^{+} \rightarrow \bar{\Lambda} \pi^{+}$ are shown in Fig. [1] and for the decays $\Omega^{-} \rightarrow \Lambda K^{-}$ and $\Omega^{+} \rightarrow \bar{\Lambda} K^{+}$ in Fig. [2].
RAW ASYMMETRIES AND DETECTOR EFFECTS

We obtain the numbers $N_F(\Xi^\mp)$ and $N_B(\Xi^\mp)$ of reconstructed $\Xi^\mp$ 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 $1.6575 < M(\Lambda K) < 1.6875$ GeV, and the sideband regions are $1.630 < M(\Lambda K) < 1.645$ GeV and $1.700 < M(\Lambda K) < 1.715$ GeV.

The normalization factor $N$ and the three raw asymmetries $A_{FB}', A_{NS}', A_{E}'$ are defined by

$$N_F(\Xi^-) = N(1 + A_{FB}') (1 - A_{NS}') (1 + A_{E}'),$$
$$N_B(\Xi^-) = N(1 - A_{FB}') (1 + A_{NS}') (1 + A_{E}'),$$
$$N_F(\Xi^+) = N(1 + A_{FB}') (1 + A_{NS}') (1 - A_{E}'),$$
$$N_B(\Xi^+) = N(1 - A_{FB}') (1 - A_{NS}') (1 - A_{E}'),$$

(2)

and similarly for $\Omega$. The raw asymmetries $A_{FB}', A_{NS}', A_{E}'$ have contributions from the physical asymmetries $A_{FB}, A_{NS}, A_{E}$, 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 $A_{E}$ is the relative excess of negatively charged over positively charged baryons.

The initial $p\bar{p}$ state is invariant with respect to CP conjugation, which changes the sign of $A_{NS}$ and $A_{E}$, while $A_{FB}$ remains unchanged. A non-zero value of $A_{NS}$ or $A_{E}$ 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 $A_{E}'$.

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

$$A_{FB}' = A_{NS}' A_{E}'$$

(3)

$$A_{NS}' = A_{FB}' A_{E}'$$

(4)

$$A_{E}' = A_{FB}' A_{NS}'$$

(5)

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 $A_{E}'$ are dominated by detector effects. The quadratic term $A_{NS}' A_{E}'$ is due to CP violation. The sum $A_{NS}' A_{E}'$ in Eq. (3) corrects $A_{FB}'$ for the detector effects $A_{NS}'$ and $A_{E}'$ on the particle counts $N_F(\Xi^-)$ and $N_B(\Xi^+)$. We can therefore set $A_{FB}' = A_{FB}$ where $A_{FB}$ is defined in Eq. (1).
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. 3 and the corresponding raw asymmetries $A'_{FB}$, $A'_{NS}$, and $A'_{Z}$ in Fig. 4. These asymmetries are calculated using Eqs. 8 and 9, neglecting the quadratic terms since they are small compared to the statistical uncertainties. The correction $A'_{NS} A'_Z$ 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 $A'_{NS} A'_Z$ as the systematic uncertainty on the measurement of $A_{FB}$. The results are summarized in Table I.

**MUON SAMPLE EVENTS $p\bar{p} \rightarrow \mu\Xi^+X$ AND $p\bar{p} \rightarrow \mu\Omega^+X$**

To study the asymmetries using a larger data set, we consider $p\bar{p} \rightarrow \mu\Xi^+X$ and $p\bar{p} \rightarrow \mu\Omega^+X$ 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 $2.2 \times 10^9$ candidates with transverse momentum in the range $1$ GeV.

### Table I: Forward-backward asymmetry $A_{FB}$ of $\Xi^+$ baryons with $p_T > 2$ GeV in minimum bias events, $p\bar{p} \rightarrow \Xi^+X$, and muon events $p\bar{p} \rightarrow \mu\Xi^+X$, and $A_{FB}$ of $\Omega^+$ and $\Omega^+$ baryons with $p_T > 2$ GeV in muon events $p\bar{p} \rightarrow \mu\Omega^+X$. The first uncertainty is statistical, the second is systematic due to the detector asymmetry $A'_{NS} A'_Z$.

| $|y|$ | $A_{FB} \times 100 (\Xi^+, \text{min. bias})$ | $A_{FB} \times 100 (\Xi^+, \text{with } \mu)$ | $A_{FB} \times 100 (\Omega^+, \text{with } \mu)$ |
|------|----------------|----------------|----------------|
| 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 | $5.09 \pm 9.00 \pm 1.64$ | $-1.14 \pm 2.05 \pm 0.27$ | $5.75 \pm 10.86 \pm 5.70$ |

### Figures

**Fig. 4:** Asymmetries $A'_{FB}$, $A'_{NS}$, and $A'_{Z}$ of reconstructed $\Xi^+$ and $\Xi^+$ candidates with $p_T > 2$ GeV, as a function of $|y|$, for the minimum bias data sample $p\bar{p} \rightarrow \Xi^+X$. The uncertainties are statistical.

**Fig. 5:** Distributions of rapidity $y$ for reconstructed $\Xi^-$ (circles) and $\Xi^+$ candidates (triangles) in events with a (a) positively or (b) negatively charged muon for $\Xi^+$ candidates with $p_T > 2$ GeV.
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 $p\bar{p} \to µΞ^- X$ events. 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. 5. 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 $Ξ^\mp µ^\pm$ than $Ξ^\mp µ^\mp$ events. An example of a process with a correlated $Ξ^\mp µ^\mp$ pair is the decay $Ξ^0 \to Ξ^- µ^+ X$. 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 $p\bar{p} \to µΩ^\mp X$ events are shown in Fig. 8 and the corresponding asymmetry $A_{FB}$ is presented in Fig. 9. The $Ξ^\mp$ and $Ω^\mp$ asymmetries are summarized in Table 1.

FIG. 7: Asymmetry $A'_{FB} = A_{FB}$ as a function of $|y|$ for $p\bar{p} \to µΞ^\mp X$ 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.

CONCLUSIONS

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

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (United States of America); Alternative Energies and Atomic Energy Commission and National Center for Scientific Research/National Institute of Nuclear and Particle Physics (France); Ministry of Education and Science of the Russian Federation, National Research Center “Kurchatov Institute” of the Russian Federation, and Russian Foundation for Basic Research (Russia); National Council for the Development of Science and Technology and Carlos Chagas Filho Foundation for the Support of Research in the State of Rio de Janeiro (Brazil); Department of
FIG. 8: Distributions of $p_T$, $p_z$, and $y$ of reconstructed $\Omega^-$ (circles) and $\Omega^+$ (triangles) with $p_T > 2$ GeV, for the data sample $p\bar{p} \rightarrow \mu \Omega^\mp X$.

[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 $\Lambda^0_b$ and $\bar{\Lambda}^0_b$ 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.