Combined Forward-Backward Asymmetry Measurements in Top-Antitop Quark Production at the Tevatron

T. Aaltonen et al.†

(CDF Collaboration)‡
(D0 Collaboration)‡

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The CDF and D0 experiments at the Fermilab Tevatron have measured the asymmetry between yields of forward- and backward-produced top and antitop quarks based on their rapidity difference and the asymmetry between their decay leptons. These measurements use the full data sets collected in proton-antiproton collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. We report the results of combinations of the inclusive asymmetries and their differential dependencies on relevant kinematic quantities. The combined inclusive asymmetry is $A_{\text{FB}}^t = 0.128 \pm 0.025$. The combined inclusive and differential asymmetries are consistent with recent standard model predictions.

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The production of top and antitop quark ($t\bar{t}$) pairs at the Tevatron proton-antiproton ($p\bar{p}$) collider at Fermilab is dominated by the $q\bar{q}$ annihilation process, which can lead to asymmetries, $A_{\text{FB}}^t$, in the number of top quarks produced within the hemisphere centered on the beam proton (forward) relative to those that are produced within the antiproton hemisphere (backward). In the standard model (SM), no forward-backward asymmetries are expected at leading order in perturbative quantum chromodynamics (QCD). However, contributions to the asymmetry from interference of leading order and higher-order amplitudes, and smaller offsetting contributions from the interference of initial- and final-state radiation, combine to yield a nonzero asymmetry $[1-5]$. Compared to older predictions $[6]$ of the inclusive asymmetry at next-to-leading order (NLO) QCD, the latest higher-order corrections in QCD and electroweak (EW) theory are almost of the same size as the inclusive prediction at NLO QCD. Measurements of the inclusive asymmetries and their dependence on kinematic quantities of top quarks and their decay leptons are used to probe the $t\bar{t}$ production mechanism. Beyond-the-SM (BSM) interactions $[7]$ can significantly alter the dynamics, even such that differential asymmetries can be strikingly changed while inclusive asymmetries are only marginally affected.

Inclusive and differential measurements $[8,9]$ by the CDF $[10]$ and D0 $[11]$ Collaborations in 2011 were only marginally consistent with each other, and with then-existing SM predictions $[6]$. Both collaborations have since completed measurements using the full Tevatron Run II $p\bar{p}$ collision data, corresponding to integrated luminosities between 9 and 10 fb$^{-1}$. Assuming SM $t$ and $\bar{t}$ decays, they have measured asymmetries using events containing a single charged lepton ($l^+ +$ jets), where one $W$ boson from a top quark decays to a charged lepton and a neutrino and the other decays to a quark and an antiquark that evolve into jets and in events containing two charged leptons ($l^+l^-$) where both $W$ bosons decay leptonically. Both collaborations have measured inclusive and differential asymmetries as functions of kinematic quantities of the top quarks and their decay leptons. More refined analysis techniques have been employed since the initial measurements. In the $l^+ +$ jets channel, CDF performed a detailed investigation of the inclusive and differential $t\bar{t}$ asymmetries $[12]$, and D0 used a novel partial event reconstruction for the inclusive and differential measurement of $A_{\text{FB}}^t$ $[13]$. In the $l^+l^-$ channel, CDF used several kinematic distributions to minimize the expected total uncertainty $[14]$, while D0 carried out a simultaneous measurement of $A_{\text{FB}}^t$ and the top quark polarization $[15]$.

We present the combinations of the final CDF and D0 measurements and compare them with current SM calculations $[16]$. Careful assessment of the correlations of systematic uncertainties between analysis channels and experiments is required for comparing the data with predictions.

For reconstructed top and antitop quarks, $A_{\text{FB}}^t$ is defined by

$$A_{\text{FB}}^t = \frac{N(\Delta y_{\ell\ell} > 0) - N(\Delta y_{\ell\ell} < 0)}{N(\Delta y_{\ell\ell} > 0) + N(\Delta y_{\ell\ell} < 0)},$$

($1$)
where $\Delta y_{ll} = y_l - y_l^t$ is the rapidity difference [17] between the $t$ and $l$ quark, and $N$ is the signal yield in a particular configuration. Typically, measurements of $t\bar{t}$ forward-backward asymmetries require reconstruction of top and antitop quarks using all available information associated with the final-state particles [18]. Background contributions are subtracted from the yield of $t\bar{t}$ candidates, thereby providing the $t\bar{t}$ signal. The latter is corrected for detector effects, so as to unfold from the reconstructed $t$ and $t$ quarks to the parton level.

The asymmetry in $t$ and $l$ quark production also leads to asymmetries in their decay leptons which, while smaller in magnitude, do not need unfolding, but must be corrected for acceptance effects. The single-lepton asymmetry is defined by

$$A^{\ell\ell}_{FB} = \frac{N(q, \eta_{\ell} > 0) - N(q, \eta_{\ell} < 0)}{N(q, \eta_{\ell} > 0) + N(q, \eta_{\ell} < 0)},$$

where $q_{\ell}$ is the sign of the electric charge and $\eta_{\ell}$ the pseudorapidity of the lepton in the laboratory frame. For the $\ell\bar{\ell}$ channel, the dilepton asymmetry is defined as

$$A^{\ell\ell}_{FB} = \frac{N(\Delta \eta > 0) - N(\Delta \eta < 0)}{N(\Delta \eta > 0) + N(\Delta \eta < 0)},$$

where $\Delta \eta = \eta_{\ell} - \eta_{\ell}^t$ is the pseudorapidity difference between the positive- and negative-charge lepton.

Inclusive and differential measurements of $A^{\ell\ell}_{FB}$ at the Tevatron were reported in Refs. [12,13] for the $\ell +$ jets channel and in Refs. [14,15] for the $\ell\ell$ channel. Measurements of $A^{\ell\ell}_{FB}$ for the $\ell +$ jets channel are given in Refs. [19,20] and in Refs. [21,22] for the $\ell\ell$ channel. Measurements of $A^{\ell\ell}_{FB}$ are reported in Refs. [21,22].

We combine the following CDF and D0 results using the best linear unbiased estimator (BLUE) [23–25]: the inclusive asymmetries $A^{\ell\ell}_{FB}$, $A^{\ell\ell}_{FB}$, and $A^{\ell\ell}_{FB}$, each extrapolated to the full phase space relying on corresponding Monte Carlo simulations, and the differential asymmetry of $A^{\ell\ell}_{FB}$ as a function of the invariant mass of the $t\bar{t}$ system ($m_{t\bar{t}}$). For combinations of inclusive asymmetries, the input uncertainties are symmetrized, while they are treated as asymmetric in the case of the combination of the asymmetry as a function of $m_{t\bar{t}}$. A mutually compatible classification of all systematic uncertainties is not available for $A^{\ell\ell}_{FB}$ as a function of $m_{t\bar{t}}$. Hence, we provide results of a simultaneous least-squares fit to determine the slope parameter of the asymmetry in the CDF and D0 data, assuming a linear dependence. A similar fit is also provided for $A^{\ell\ell}_{FB}$ as a function of $m_{t\bar{t}}$. The CDF and D0 differential asymmetries, $A^{\ell\ell}_{FB}$, as a function of $q_{\ell}\eta_{\ell}$ and $A^{\ell\ell}_{FB}$ as a function of $\Delta \eta$ are not combined, but are displayed together for ease of comparison.

Predictions of inclusive and differential $A^{\ell\ell}_{FB}$ distributions at next-to-next-to-leading order (NNLO) QCD calculations are available from Ref. [1]. The contribution from EW NLO corrections to the NLO QCD asymmetries are not negligible [3]. Hence, we compare the measurements to the latest NNLO QCD + NLO EW inclusive and differential $A^{\ell\ell}_{FB}$ calculations [1,26]. The combined inclusive-lepton asymmetries $A^{\ell\ell}_{FB}$ and $A^{\ell\ell}_{FB}$ are compared to the NLO QCD + NLO EW predictions of Ref. [3].

To accommodate correlations among analysis channels and between experiments, we classify systematic uncertainties into the following categories.

(i) Background modeling. The uncertainties in the distribution and normalization of the background are assumed to be uncorrelated since the backgrounds are estimated differently in different analyses, and in the two experiments.

(ii) Signal modeling. The uncertainties in modeling the signal, parton showering [27], initial- and final-state radiation [28], and color connections [29] are taken to be fully correlated among analysis channels and experiments because they all rely on the same assumptions.

(iii) Detector modeling. The uncertainties in jet-energy scale [30] and the modeling of the detector are fully correlated within each experiment and uncorrelated between the two experiments.

(iv) Method. The uncertainties in the methods used to correct for detector acceptance, efficiency, and potential biases in the reconstruction of top quark kinematic properties are mostly taken to be uncorrelated between experiments and analysis channels. However, the uncertainties on the phase-space correction procedures for the leptonic asymmetry in the D0 $\ell +$ jets [13] and $\ell\ell$ [15] analyses are estimated using the same methods and are, therefore, correlated with each other but are uncorrelated with the CDF results.

(v) Parton-density distribution functions. The uncertainties in parton-density distribution functions (PDF) and the pileup in energy from overlapping $p\bar{p}$ interactions are treated as fully correlated between the analysis channels and the two experiments, because they characterize the same potential systematic biases.

The combined inclusive asymmetry is $A^{\ell\ell}_{FB} = 0.128 \pm 0.021$ (stat) $\pm 0.014$ (syst), consistent with the NNLO QCD + NLO EW prediction of $0.095 \pm 0.007$ [2] within 1.3 standard deviations (SD). The combination has a $\chi^2$ of 1.7 for 3 degrees of freedom (DOF). BLUE also provides the weights in the combination for the CDF $\ell +$ jets, D0 $\ell +$ jets, CDF $\ell\ell$, and D0$\ell\ell$ results, which are 0.25, 0.64, 0.01, and 0.11, respectively.

The CDF and D0 differential $A^{\ell\ell}_{FB}$ asymmetries as a function of $m_{t\bar{t}}$ are measured only for the $\ell +$ jets channel. We combine the D0 bins in the range of $350 < m_{t\bar{t}} < 550$ GeV/$c^2$ to provide uniform, 100-GeV/$c^2$-wide, bins...
for the combination. For the two measurements, we use covariance matrices [31] that take into account the bin-to-bin correlations from the unfolding of differential distributions. The correlations in systematic uncertainties among channels and experiments for each $m_{t\bar{t}}$ bin are assumed to be equal to those in the inclusive measurements. However, the uncorrelated background uncertainties for the differential asymmetries are subdivided into two separate components, one for the overall normalization and one for the differential distribution (shape) of the background. According to the different experimental methodologies, these are treated as correlated between bins for the CDF measurement and as uncorrelated for the D0 measurement. We verify that changing the correlations of systematic uncertainties among bins are given in Ref.[31]. The values of $A_{FB}$ as a function of $m_{t\bar{t}}$ for each experiment and their combination are shown in Fig. 1, together with the NNLO QCD + NLO EW predictions [26].

The counter-intuitive value of the combined asymmetry in the 550–650 GeV/$c^2$ mass bin is due to the specific pattern of the CDF and D0 bin-to-bin correlations stemming from different choices in the regularized matrix unfolding. The opposite correlations observed between the 550–650 GeV/$c^2$ and the > 650 GeV/$c^2$ mass bins in the CDF (large and positive) and D0 (small and negative) measurements give rise to a combined asymmetry in the 550–650 GeV/$c^2$ mass bin that is smaller than that found in either measurement [31].

To reduce the correlations between the slope and the intercept, we use a linear fit of the form $A_{FB}^\ell(m_{t\bar{t}}) = \alpha_{m_{t\bar{t}}} (m_{t\bar{t}} - 450 \text{ GeV}/c^2) + \beta_{m_{t\bar{t}}}$ taking into account the correlations (see Table IV in Ref. [31]). The linear fit yields a slope of $\alpha_{m_{t\bar{t}}} = (9.71 \pm 3.28) \times 10^{-4}$ GeV$^{-1}$c$^2$ with an intercept at a $m_{t\bar{t}}$ value of 450 GeV/$c^2$ of $\beta_{m_{t\bar{t}}} = 0.131 \pm 0.034$. The fit has a $\chi^2$ of 0.3 for 2 DOF. The values predicted at NNLO QCD + NLO EW are $\alpha_{m_{t\bar{t}}}^{SM} = (5.11 ^{+0.42}_{-0.64}) \times 10^{-4}$ GeV$^{-1}$c$^2$ and an intercept of $\beta_{m_{t\bar{t}}}^{SM} = 0.087 ^{+0.005}_{-0.006}$. The predicted dependence is determined by a linear fit to the binned prediction from Ref. [26]. The NNLO QCD + NLO EW binned predictions of the differential $A_{FB}^\ell$ and of the corresponding slope parameters agree with the combined experimental results to within 1.3 SD.

The differential $t\bar{t}$ asymmetry as a function of $|\Delta y_{t\bar{t}}|$ is available from CDF for both the $\ell +$ jets and $\ell\ell$ channels, and from D0 for the $\ell +$ jets channel. The choice of binning differs for these measurements. We perform

![Graph showing results for $A_{FB}$ vs $m_{t\bar{t}}$ for the individual CDF and D0 measurements and for their combination. The inputs to the combination are displaced at different abscissa values within each $m_{t\bar{t}}$ bin for ease of visibility. The inner error bar indicates the statistical uncertainty, while the outer error bar corresponds to the total uncertainty including the systematic uncertainty added in quadrature. The value of the combined data point for the mass region of 550–650 GeV/$c^2$ is discussed in Ref. [31] in more detail. The linear dependence of the combined result is given by the solid black line together with the 1 SD total uncertainty of the two-parameter fit given by the shaded gray area. The dashed orange line shows the NNLO QCD + NLO EW prediction of Refs. [1,2,26], while the shaded orange area reflects its 1 SD uncertainty.](https://example.com/graph.png)
a simultaneous least-squares fit to a linear function $A_{FB}^{ij}(\Delta y_\ell|\eta) = \alpha_{\Delta y_\ell} |\Delta y_\ell|$ for all available measurements, employing a combined $10 \times 10$ covariance matrix $C_{ij}$. We define $\chi^2(\Delta y_\ell|\eta) = \sum_{i,j} [y_i - f_i(|\Delta y_\ell|)]C_{ij}^{-1}[y_j - f_j(|\Delta y_\ell|)]$, with $y_i$ and $y_j$ representing the bin $i$ and $j$ of each of the three measurements, and $f_i(|\Delta y_\ell|)$ and $f_j(|\Delta y_\ell|)$ representing the expectations from a linear function. The definition of the asymmetry ensures that $A_{FB}^{ij} = 0$ at $\Delta y_\ell = 0$. The correlations of the systematic uncertainties among analysis channels and experiments are assumed to be equal to those in the $A_{FB}^{ij}$ vs $m_\ell$ measurements. Figure 2 shows the individual measurements and the result of the linear fit. The linear dependence for the combination is measured to be $\alpha_{\Delta y_\ell} = 0.187 \pm 0.038$ with a $\chi^2$ of 10.9 for 9 DOF. A fit to the binned NNLO QCD + NLO EW predictions of Ref. [1,2,26] gives the slope $\alpha_{\Delta y_\ell} = 0.129^{+0.006}_{-0.012}$. The prediction and the combined result differ by 1.5 SD.

The combined fit to the CDF and D0 inclusive single-lepton asymmetries gives $A_{FB}^{\ell} = 0.073 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$. The fit has a $\chi^2$ of 2.2 for 3 DOF, and the result is consistent with the NLO QCD+ prediction of $0.038 \pm 0.003$ [3] to within 1.6 SD. The weights of the CDF $\ell +$ jets, D0$\ell +$ jets, CDF $\ell\ell$ and D0$\ell\ell$ results in the fit are 0.40, 0.27, 0.11, and 0.23, respectively. The individual CDF and D0 measurements of $A_{FB}^{\ell}$ as a function of $|q_\ell \eta|\ell$ are shown in Fig. 3.

The combined fit to the CDF and D0 inclusive $A_{FB}^{\ell}$ measurements yields $A_{FB}^{\ell} = 0.108 \pm 0.043(\text{stat}) \pm 0.016(\text{syst})$. The fit has a $\chi^2$ of 0.2 for 1 DOF, and the result is consistent with the NLO QCD + NLO EW prediction of $0.048 \pm 0.004$ [3] to within 1.3 SD. The weights of the CDF and D0$\ell\ell$ results in the fit are 0.32 and 0.68, respectively. The individual CDF and D0 measurements of $A_{FB}^{\ell\ell}$ as a function of $\Delta \eta$ are shown in Fig. 4.

In summary, we report combinations of the measurements of top-antitop quark forward-backward asymmetries performed in a $p\bar{p}$ collision sample corresponding to 9–10 fb$^{-1}$ collected by the CDF and D0 experiments at the Tevatron. The resulting combined inclusive asymmetry is $A_{FB}^{\ell} = 0.128 \pm 0.025$ compared to the prediction at NNLO QCD + NLO EW of $0.095 \pm 0.007$. All three inclusive observables agree with the existing SM prediction to within 1.6 SD.
predictions to within 1.6 standard deviations. The differential asymmetries as a function of \( m_{t \bar{t}} \) and \( \Delta y_{t \bar{t}} \) agree to within 1.5 standard deviations. All measurements favor somewhat larger positive asymmetries than the predictions, but none of the observed differences are larger than 2 standard deviations. Hence, we conclude that the measurements and their combinations, shown in Fig. 5, are consistent with each other and with the SM predictions.

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The rapidity

V. M. Abazov

T. Aaltonen

G. D. Alexeev


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The rapidity is defined as $y(\beta,\phi) = 1/2 \ln \left\{ (1 + \beta \cos(\theta))/\left[ 1 - \beta \cos(\theta) \right] \right\}$, where $\theta$ is the polar angle relative to the proton beam and $\beta$ is the ratio of a particle’s momentum to its energy. The pseudorapidity is defined as $\eta = y(\theta, 1)$.


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Y. C. Yang,25,† W.-M. Yao,26,† T. Yasuda,15,‡ Y. A. Yatsunenko,13,‡ W. Ye,112,‡ Z. Ye,15,‡ G. P. Yeh,15,† K. Yi,15,m,† H. Yin,15,‡ K. Yip,113,‡ J. Yoh,15,† K. Yorita,51,† T. Yoshida,37,k,† S. W. Youn,15,‡ G. B. Yu,14,† I. Yu,25,† J. M. Yu,31,‡ A. M. Zanetti,48a,† Y. Zeng,14,† J. Zennamo,111,‡ T. G. Zhao,93,‡ C. Zhou,14,‡ J. Zhu,31,‡ M. Zielinski,44,‡ D. Zieminska,100,‡ L. Zivkovic,68,zz,‡ and S. Zucchelli6a,6b,† (CDF Collaboration) (D0 Collaboration)

1 Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China
2 Argonne National Laboratory, Argonne, Illinois 60439, USA
3 University of Athens, 157 71 Athens, Greece
4 Institut de Fisica d’Altes Energies, ICER, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain
5 Baylor University, Waco, Texas 76798, USA
6a Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy
6b University of Bologna, I-40127 Bologna, Italy
7 University of California, Davis, Davis, California 95616, USA
8 University of California, Los Angeles, Los Angeles, California 90024, USA
9 Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain
10 Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
11 Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
12 Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia
13 Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
14 Duke University, Durham, North Carolina 27708, USA
15 Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
16 University of Florida, Gainesville, Florida 32611, USA
17 Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
18 University of Geneva, CH-1211 Geneva 4, Switzerland
19 University of California, Davis, Davis, California 95616, USA
20 University of Cambridge, Cambridge, Massachusetts 02138, USA
21 Division of High Energy Physics, Department of Physics, University of Helsinki, FIN-00014, Helsinki, Finland; Helsinki Institute of Physics, FIN-0014 Helsinki, Finland
22 University of Illinois, Urbana, Illinois 61801, USA
23 The Johns Hopkins University, Baltimore, Maryland 21218, USA
24 Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
25 Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; Sungkyunkwan University, Suwon 440-746, Korea; Korea Institute of Science and Technology Information, Daejeon 305-806, Korea; Chonnam National University, Gwangju 500-757, Korea; Chonbuk National University, Jeonju 561-756, Korea; Ewha Womans University, Seoul 120-750, Korea
26 Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
27 University of Liverpool, Liverpool L69 7ZE, United Kingdom
28 University College London, London WC1E 6BT, United Kingdom
29 Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
30 Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
31 University of Michigan, Ann Arbor, Michigan 48109, USA
32 Michigan State University, East Lansing, Michigan 48824, USA
33 Institute for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
34 University of New Mexico, Albuquerque, New Mexico 87131, USA
35 The Ohio State University, Columbus, Ohio 43210, USA
36 Okayama University, Okayama 700-8530, Japan
37 Osaka City University, Osaka 558-8585, Japan
38 University of Oxford, Oxford OX1 3RH, United Kingdom
39 Centro Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
40 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
41 Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy
University of Pisa, I-56127 Pisa, Italy
University of Siena, I-56127 Pisa, Italy
Scuola Normale Superiore, I-56127 Pisa, Italy
INFN Pavia, I-27100 Pavia, Italy
University of Pavia, I-27100 Pavia, Italy
University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
Purdue University, West Lafayette, Indiana 47907, USA
University of Rochester, Rochester, New York 14627, USA
The Rockefeller University, New York, New York 10065, USA
Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy
Sapienza Università di Roma, I-00185 Roma, Italy
University of Tsukuba, Tsukuba, Ibaraki 305, Japan
Tufts University, Medford, Massachusetts 02155, USA
Waseda University, Tokyo 169, Japan
Wayne State University, Detroit, Michigan 48201, USA
University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
Yale University, New Haven, Connecticut 06520, USA
LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ 22290, Brazil
Universidade do Estado do Rio de Janeiro, Rio de Janeiro, RJ 20550, Brazil
Universidade Federal do ABC, Santo André, São Paulo, SP 09210, Brazil
University of Science and Technology of China, Hefei 230026, People’s Republic of China
Universidad de los Andes, Bogotá 111711, Colombia
Faculty of Mathematics and Physics, Center for Particle Physics, Charles University, 116 36 Prague 1, Czech Republic
Czech Technical University in Prague, 116 36 Prague 6, Czech Republic
Institute of Physics, Academy of Sciences of the Czech Republic, 182 21 Prague, Czech Republic
Universidad San Francisco de Quito, Quito 17015, Ecuador
LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, F-63178 Aubière Cedex, France
LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France
CPPM, Aix-Marseille Université, CNRS/IN2P3, F-13288 Marseille Cedex 09, France
LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay Cedex, France
LPNHE, Université Paris VI and VII, CNRS/IN2P3, F-75005 Paris, France
CEA Saclay, Irfu, SPP, F-91191 Gif-Sur-Yvette Cedex, France
IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France
IPNL, Université Lyon 1, CNRS/IN2P3, F-69622 Villeurbanne Cedex, France
and Université de Lyon, F-69361 Lyon CEDEX 07, France
III. Physikalisches Institut A, RWTH Aachen University, 52056 Aachen, Germany
Physikalisches Institut, Universität Freiburg, 79085 Freiburg, Germany
II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen, Germany
Institut für Physik, Universität Mainz, 55099 Mainz, Germany
Ludwig-Maximilians-Universität München, 80539 München, Germany
Panjab University, Chandigarh 160014, India
Delhi University, Delhi-110 007, India
Tata Institute of Fundamental Research, Mumbai-400 005, India
University College Dublin, Dublin 4, Ireland
Korea Detector Laboratory, Korea University, Seoul 02841, Korea
CINVESTAV, Mexico City 07360, Mexico
Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands
Radboud University Nijmegen, 6525 AJ Nijmegen, The Netherlands
Moscow State University, Moscow 119991, Russia
Institute for High Energy Physics, Protvino, Moscow region 142281, Russia
Petersburg Nuclear Physics Institute, St. Petersburg 188300, Russia
Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), 08193 Bellaterra (Barcelona), Spain
Uppsala University, 751 05 Uppsala, Sweden
Visitor from Universidad de Oviedo, E-33007 Oviedo, Spain.
Visitor from CNRS-IN2P3, Paris, F-75205 France.
Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.
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