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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 $A_{\text{FB}}^{\bar{t}t} = 0.128 \pm 0.025$. 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, $A_{\text{FB}}^{\bar{t}t}$, 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 ($\ell + \text{jets}$), 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 ($\ell\ell$) 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 $\ell + \text{jets}$ 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 $A_{\text{FB}}^{\bar{t}t}$ [13]. In the $\ell\ell$ channel, CDF used several kinematic distributions to minimize the expected total uncertainty [14], while D0 carried out a simultaneous measurement of $A_{\text{FB}}^{\bar{t}t}$ 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, $A_{\text{FB}}^{\bar{t}t}$ is defined by

$$A_{\text{FB}}^{\bar{t}t} = \frac{N(\Delta y_{\bar{t}t} > 0) - N(\Delta y_{\bar{t}t} < 0)}{N(\Delta y_{\bar{t}t} > 0) + N(\Delta y_{\bar{t}t} < 0)}, \quad (1)$$

*Full author list given at the end of the article.

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where $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$ is the rapidity difference [17] between the t and \bar{t} 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 \bar{t} quarks to the parton level.

The asymmetry in t and \bar{t} 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

$$A_{\text{FB}}^{\ell\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}, \quad (2)$$

where q_ℓ is the sign of the electric charge and η_ℓ the pseudorapidity of the lepton in the laboratory frame. For the $\ell\ell$ channel, the dilepton asymmetry is defined as

$$A_{\text{FB}}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}, \quad (3)$$

where $\Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$ is the pseudorapidity difference between the positive- and negative-charge lepton. The asymmetries obtained using top quarks and leptons are correlated, as a positive rapidity difference between a t and a \bar{t} quark is likely to produce a positive pseudorapidity difference between a positive- and negative-charge decay lepton.

Inclusive and differential measurements of $A_{\text{FB}}^{\bar{t}t}$ at the Tevatron were reported in Refs. [12,13] for the $\ell + \text{jets}$ channel and in Refs. [14,15] for the $\ell\ell$ channel. Measurements of $A_{\text{FB}}^{\ell\ell}$ for the $\ell + \text{jets}$ channel are given in Refs. [19,20] and in Refs. [21,22] for the $\ell\ell$ channel. Measurements of $A_{\text{FB}}^{\ell\ell}$ 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 $A_{\text{FB}}^{\bar{t}t}$, $A_{\text{FB}}^{\ell\ell}$, and $A_{\text{FB}}^{\ell\ell}$, each extrapolated to the full phase space relying on corresponding Monte Carlo simulations, and the differential asymmetry of $A_{\text{FB}}^{\bar{t}t}$ 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 $A_{\text{FB}}^{\bar{t}t}$ as a function of $|\Delta y_{t\bar{t}}|$. 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 $A_{\text{FB}}^{\bar{t}t}$ as a function of $m_{t\bar{t}}$. The CDF and D0 differential asymmetries, $A_{\text{FB}}^{\ell\ell}$ as a function of $q_\ell \eta_\ell$ and

$A_{\text{FB}}^{\ell\ell}$ as a function of $\Delta\eta$ are not combined, but are displayed together for ease of comparison.

Predictions of inclusive and differential $A_{\text{FB}}^{\bar{t}t}$ 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 $A_{\text{FB}}^{\bar{t}t}$ calculations [1,26]. The combined inclusive-lepton asymmetries $A_{\text{FB}}^{\ell\ell}$ and $A_{\text{FB}}^{\ell\ell}$ 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 $D0\ell + \text{jets}$ [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 $A_{\text{FB}}^{\bar{t}t} = 0.128 \pm 0.021(\text{stat}) \pm 0.014(\text{syst})$, consistent with the NNLO QCD + NLO EW prediction of 0.095 ± 0.007 [2] within 1.3 standard deviations (SD). The combination has a χ^2 of 1.7 for 3 degrees of freedom (DOF). BLUE also provides the weights in the combination for the CDF $\ell + \text{jets}$, D0 $\ell + \text{jets}$, 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 $A_{\text{FB}}^{\bar{t}t}$ asymmetries as a function of $m_{t\bar{t}}$ are measured only for the $\ell + \text{jets}$ channel. We combine the D0 bins in the range of $350 < m_{t\bar{t}} < 550 \text{ GeV}/c^2$ to provide uniform, 100-GeV/ c^2 -wide, bins

TABLE I. Combined differential $A_{\text{FB}}^{\bar{t}t}$ values in bins of $m_{\bar{t}t}$, with the probability (Prob.) for the CDF and D0 inputs to agree with each other, with statistical (Stat.), systematic (Tot. syst.), and total uncertainties. The systematic uncertainties are broken down into uncertainties in the distribution of the background (Bkd. distr.), background normalization (Bkd. norm.), signal modeling (Signal), detector modeling (Det.), measurement method (Meth.), and parton distribution function (PDF).

$m_{\bar{t}t}$ (GeV/ c^2)	$A_{\text{FB}}^{\bar{t}t}$	Prob.	Uncertainty								
			Total	Stat.	Meth.	Signal	PDF	Det.	Bkd. distr.	Bkd. norm.	Tot. syst.
350–450	0.081	95%	0.037	0.031	0.009	0.012	0.004	0.007	0.010	0.003	0.020
450–550	0.195	22%	0.048	0.042	0.010	0.016	0.007	0.006	0.007	0.006	0.023
550–650	0.258	98%	0.093	0.063	0.008	0.062	0.017	0.017	0.006	0.008	0.068
> 650	0.319	8%	0.147	0.123	0.018	0.065	0.021	0.026	0.019	0.019	0.080

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 $m_{\bar{t}t}$ 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 between -1 and $+1$ has negligible impact on the combined result because the statistical uncertainties dominate.

The combined $A_{\text{FB}}^{\bar{t}t}$ values, and their statistical and systematic uncertainties for each category, are given in Table I, which also reports the probabilities for the CDF and D0 inputs to agree with each other in each mass bin. Overall, the differential combination has a χ^2 of 5.2 for 4 DOF. The correlations in the total uncertainties between $m_{\bar{t}t}$ bins are given in Ref. [31]. The values of $A_{\text{FB}}^{\bar{t}t}$ as a function of $m_{\bar{t}t}$ 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 $A_{\text{FB}}^{\bar{t}t}(m_{\bar{t}t}) = \alpha_{m_{\bar{t}t}}(m_{\bar{t}t} - 450 \text{ GeV}/c^2) + \beta_{m_{\bar{t}t}}$ taking into account the correlations (see Table IV in Ref. [31]). The linear fit yields a slope of $\alpha_{m_{\bar{t}t}} = (9.71 \pm 3.28) \times 10^{-4} \text{ GeV}^{-1}c^2$ with an

intercept at a $m_{\bar{t}t}$ value of 450 GeV/ c^2 of $\beta_{m_{\bar{t}t}} = 0.131 \pm 0.034$. The fit has a χ^2 of 0.3 for 2 DOF. The values predicted at NNLO QCD + NLO EW are $\alpha_{m_{\bar{t}t}}^{\text{SM}} = (5.11_{-0.64}^{+0.42}) \times 10^{-4} \text{ GeV}^{-1}c^2$ and an intercept of $\beta_{m_{\bar{t}t}}^{\text{SM}} = 0.087_{-0.006}^{+0.005}$. 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 $A_{\text{FB}}^{\bar{t}t}$ and of the corresponding slope parameters agree with the combined experimental results to within 1.3 SD.

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

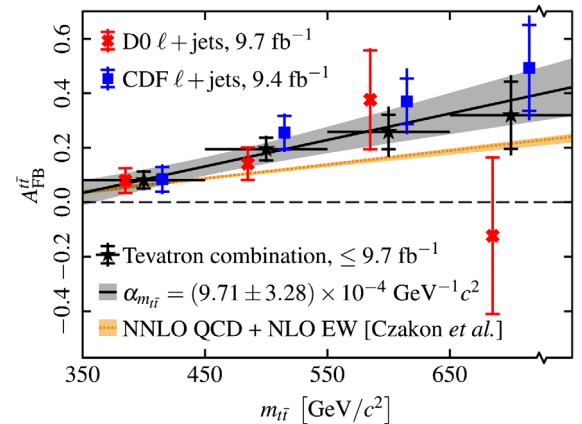


FIG. 1. Results for $A_{\text{FB}}^{\bar{t}t}$ vs $m_{\bar{t}t}$ for the individual CDF and D0 measurements and for their combination. The inputs to the combination are displaced at different abscissa values within each $m_{\bar{t}t}$ bin for ease of visibility. The inner error bar indicates the statistical 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.

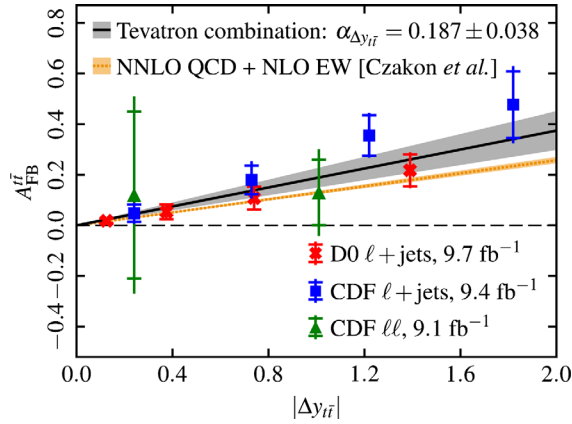


FIG. 2. Measurements of the differential asymmetries A_{FB}^{τ} vs $|\Delta y_{\tau}|$ with data points displayed at the distribution-weighted center of the bins. The inner error bar indicates the statistical uncertainty, while the outer error bar corresponds to the total uncertainty, including the systematic uncertainty added in quadrature. The combined linear dependence for all the experimental results is given by the solid black line, with the 1 SD total uncertainty on the one-parameter fit given by the shaded gray area. The dashed orange line shows the NNLO QCD + NLO EW prediction [1,2,26], while the shaded orange area reflects its 1 SD uncertainty.

a simultaneous least-squares fit to a linear function $A_{\text{FB}}^{\tau}(|\Delta y_{\tau}|) = \alpha_{\Delta y_{\tau}} |\Delta y_{\tau}|$ for all available measurements, employing a combined 10×10 covariance matrix C_{ij} . We define $\chi^2(|\Delta y_{\tau}|) = \sum_{ij} [y_i - f_i(|\Delta y_{\tau}|)] C_{ij}^{-1} [y_j - f_j(|\Delta y_{\tau}|)]$, with y_i and y_j representing the bin i and j of each of the three measurements, and $f_i(|\Delta y_{\tau}|)$ and $f_j(|\Delta y_{\tau}|)$ representing the expectations from a linear function. The definition of the asymmetry ensures that $A_{\text{FB}}^{\tau} = 0$ at $\Delta y_{\tau} = 0$. The correlations of the systematic uncertainties among analysis channels and experiments are assumed to be equal to those in the A_{FB}^{τ} vs $m_{\tau\bar{\tau}}$ measurements. Figure 2 shows the individual measurements and the result of the linear fit. The linear dependence for the combination is measured to be $\alpha_{\Delta y_{\tau}} = 0.187 \pm 0.038$ with a χ^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 $\alpha_{\Delta y_{\tau}}^{\text{SM}} = 0.129^{+0.006}_{-0.012}$. The prediction and the combined result differ by 1.5 SD.

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

The combined fit to the CDF and D0 inclusive $A_{\text{FB}}^{\ell\ell}$ measurements yields $A_{\text{FB}}^{\ell\ell} = 0.108 \pm 0.043(\text{stat}) \pm 0.016(\text{syst})$. The fit has a χ^2 of 0.2 for 1 DOF, and the

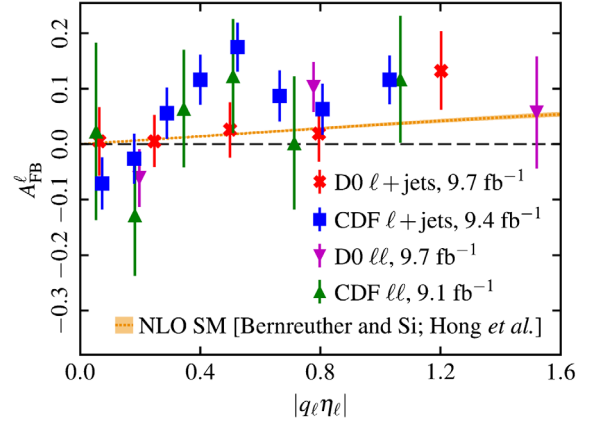


FIG. 3. Comparison of the differential asymmetries A_{FB}^{ℓ} as a function of $|q\ell\eta\ell|$ displayed at the center of the bins. The left-most data point of the CDF $\ell + \text{jets}$ data is slightly moved right to avoid direct overlap with the left-most data point of the D0 $\ell + \text{jets}$ data. Each error bar represents the total experimental uncertainty. The dashed orange line shows the NLO SM prediction [3,32], while the shaded orange area shows its 1 SD uncertainty.

result is consistent with the NLO QCD + NLOEW prediction of 0.048 ± 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 $A_{\text{FB}}^{\ell\ell}$ 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 $A_{\text{FB}}^{\tau} = 0.128 \pm 0.025$ compared to the prediction at NNLO QCD + NLO EW of 0.095 ± 0.007 . All three inclusive observables agree with the existing SM

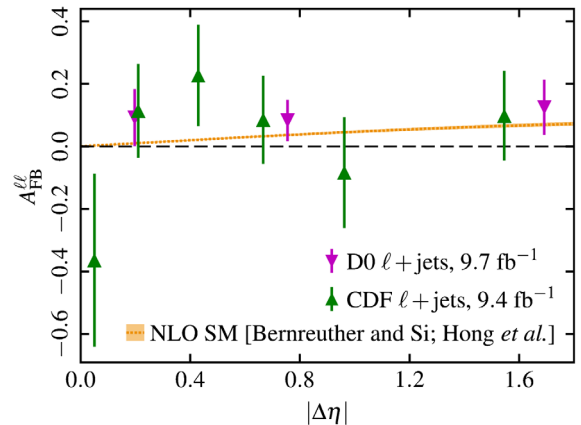


FIG. 4. Comparison of the differential asymmetries $A_{\text{FB}}^{\ell\ell}$ as a function of $|\Delta\eta|$ displayed at the center of the bins. Each error bar represents the total experimental uncertainty. The dashed orange line shows the NLO SM prediction [3,32], while the shaded orange area shows its 1 SD uncertainty.

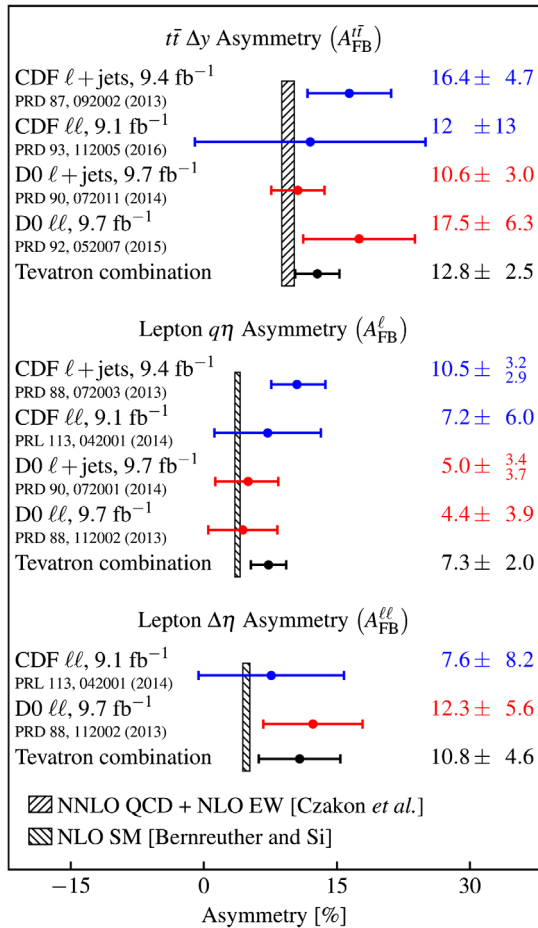


FIG. 5. Summary of inclusive forward-backward asymmetries in $t\bar{t}$ events in percents at the Tevatron.

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. The reported consistency is the result of an intense effort of refining the experimental and theoretical understanding, which started in 2010, when significant departures of the first Tevatron measurements [8,9] from the predictions suggested potential contributions from BSM dynamics.

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T. Aaltonen,^{21,†} V. M. Abazov,^{13,‡} B. Abbott,^{115,‡} B. S. Acharya,^{79,‡} M. Adams,^{97,‡} T. Adams,^{96,‡} J. P. Agnew,^{93,‡} G. D. Alexeev,^{13,‡} G. Alkhazov,^{87,‡} A. Alton,^{31,kk,‡} S. Amerio,^{39a,39b,†} D. Amidei,^{31,†} A. Anastassov,^{15,w,†} A. Annovi,^{17,†} J. Antos,^{12,†} G. Apollinari,^{15,†} J. A. Appel,^{15,†} T. Arisawa,^{51,†} A. Artikov,^{13,†} J. Asaadi,^{47,†} W. Ashmanskas,^{15,†} A. Askew,^{96,‡}

S. Atkins,^{105,‡} B. Auerbach,^{2,†} K. Augsten,^{61,‡} A. Aurisano,^{47,†} V. Aushev,^{90,‡} Y. Aushev,^{90,‡} C. Avila,^{59,‡} F. Azfar,^{38,†}
 F. Badaud,^{64,‡} W. Badgett,^{15,†} T. Bae,^{25,†} L. Bagby,^{15,‡} B. Baldin,^{15,‡} D. V. Bandurin,^{122,‡} S. Banerjee,^{79,‡}
 A. Barbaro-Galtieri,^{26,†} E. Barberis,^{106,‡} P. Baringer,^{104,‡} V. E. Barnes,^{43,†} B. A. Barnett,^{23,†} P. Barria,^{41a,41c,†} J. F. Bartlett,^{15,‡}
 P. Bartos,^{12,†} U. Bassler,^{69,‡} M. Bauce,^{39a,39b,†} V. Bazterra,^{97,‡} A. Bean,^{104,‡} F. Bedeschi,^{41a,†} M. Begalli,^{56,‡} S. Behari,^{15,†}
 L. Bellantoni,^{15,‡} G. Bellettini,^{41a,41b,†} J. Bellinger,^{53,†} D. Benjamin,^{14,†} A. Beretvas,^{15,†} S. B. Beri,^{77,‡} G. Bernardi,^{68,‡}
 R. Bernhard,^{73,‡} I. Bertram,^{91,‡} M. Besançon,^{69,‡} R. Beuselinck,^{92,‡} P. C. Bhat,^{15,‡} S. Bhatia,^{107,‡} V. Bhatnagar,^{77,‡}
 A. Bhatti,^{45,†} K. R. Bland,^{5,†} G. Blazey,^{98,‡} S. Blessing,^{96,‡} K. Bloom,^{108,‡} B. Blumenfeld,^{23,†} A. Bocci,^{14,†} A. Bodek,^{44,†}
 A. Boehnlein,^{15,‡} D. Boline,^{112,‡} E. E. Boos,^{85,‡} G. Borissov,^{91,‡} D. Bortoletto,^{43,†} M. Borysova,^{90,vv,‡} J. Boudreau,^{42,†}
 A. Boveia,^{11,†} A. Brandt,^{119,‡} O. Brandt,^{74,‡} L. Brigliadori,^{6a,6b,†} M. Brochmann,^{123,‡} R. Brock,^{32,‡} C. Bromberg,^{32,†}
 A. Bross,^{15,‡} D. Brown,^{68,‡} E. Brucken,^{21,†} X. B. Bu,^{15,‡} J. Budagov,^{13,†} H. S. Budd,^{44,†} M. Buehler,^{15,‡} V. Buescher,^{75,‡}
 V. Bunichev,^{85,‡} S. Burdin,^{91,ii,‡} K. Burkett,^{15,†} G. Busetto,^{39a,39b,†} P. Bussey,^{19,†} C. P. Buszello,^{89,‡} P. Butti,^{41a,41b,†}
 A. Buzatu,^{19,†} A. Calamba,^{10,†} E. Camacho-Pérez,^{82,‡} S. Camarda,^{4,†} M. Campanelli,^{28,†} F. Canelli,^{11,ee,†} B. Carls,^{22,†}
 D. Carlsmith,^{53,†} R. Carosi,^{41a,†} S. Carrillo,^{16,i,†} B. Casal,^{9,j,†} M. Casarsa,^{48a,†} B. C. K. Casey,^{15,‡} H. Castilla-Valdez,^{82,‡}
 A. Castro,^{6a,6b,†} P. Catastini,^{20,†} S. Caughron,^{32,‡} D. Cauz,^{48a,48b,48c,†} V. Cavaliere,^{22,†} A. Cerri,^{26,e,†} L. Cerrito,^{28,r,†}
 S. Chakrabarti,^{112,‡} K. M. Chan,^{102,‡} A. Chandra,^{121,‡} A. Chapelain,^{69,‡} E. Chapon,^{69,‡} G. Chen,^{104,‡} Y. C. Chen,^{1,†}
 M. Chertok,^{7,†} G. Chiarelli,^{41a,†} G. Chlachidze,^{15,†} K. Cho,^{25,†} S. W. Cho,^{81,‡} S. Choi,^{81,‡} D. Chokheli,^{13,†} B. Choudhary,^{78,‡}
 S. Cihangir,^{15,§,‡} D. Claes,^{108,‡} A. Clark,^{18,†} C. Clarke,^{52,†} J. Clutter,^{104,‡} M. E. Convery,^{15,†} J. Conway,^{7,†} M. Cooke,^{15,uu,†}
 W. E. Cooper,^{15,‡} M. Corbo,^{15,z,†} M. Corcoran,^{121,§,‡} M. Cordelli,^{17,†} F. Couderc,^{69,‡} M.-C. Cousinou,^{66,‡} C. A. Cox,^{7,†}
 D. J. Cox,^{7,†} M. Cremonesi,^{41a,†} D. Cruz,^{47,†} J. Cuevas,^{9,y,†} R. Culbertson,^{15,†} J. Cuth,^{75,‡} D. Cutts,^{118,‡} A. Das,^{120,‡}
 N. d'Ascenzo,^{15,v,†} M. Datta,^{15,hh,†} G. Davies,^{92,‡} P. de Barbaro,^{44,†} S. J. de Jong,^{83,84,‡} E. De La Cruz-Burelo,^{82,‡} F. Déliot,^{69,‡}
 R. Demina,^{44,‡} L. Demortier,^{45,†} M. Deninno,^{6a,†} D. Denisov,^{15,‡} S. P. Denisov,^{86,‡} M. D'Errico,^{39a,39b,†} S. Desai,^{15,‡}
 C. Deterre,^{93,mm,‡} K. DeVaughan,^{108,‡} F. Devoto,^{21,†} A. Di Canto,^{41a,41b,†} B. Di Ruzza,^{15,p,†} H. T. Diehl,^{15,‡} M. Diesburg,^{15,‡}
 P. F. Ding,^{93,‡} J. R. Dittmann,^{5,†} A. Dominguez,^{108,‡} S. Donati,^{41a,41b,†} M. D'Onofrio,^{27,†} M. Dorigo,^{48a,48d,†}
 A. Driutti,^{48a,48b,48c,†} A. Drutskoy,^{33,‡} A. Dubey,^{78,‡} L. V. Dudko,^{85,‡} A. Duperrin,^{66,‡} S. Dutt,^{77,‡} M. Eads,^{98,‡} K. Ebina,^{51,†}
 R. Edgar,^{31,†} D. Edmunds,^{32,‡} A. Elagin,^{11,†} J. Ellison,^{95,‡} V. D. Elvira,^{15,‡} Y. Enari,^{68,‡} R. Erbacher,^{7,†} S. Errede,^{22,†}
 B. Esham,^{22,†} H. Evans,^{100,‡} A. Evdokimov,^{97,‡} V. N. Evdokimov,^{86,‡} S. Farrington,^{38,†} A. Fauré,^{69,‡} L. Feng,^{98,‡} T. Ferbel,^{44,‡}
 J. P. Fernández Ramos,^{29,†} F. Fiedler,^{75,‡} R. Field,^{16,†} F. Filthaut,^{83,84,‡} W. Fisher,^{32,‡} H. E. Fisk,^{15,‡} G. Flanagan,^{15,t,†}
 R. Forrest,^{7,†} M. Fortner,^{98,‡} H. Fox,^{91,‡} J. Franc,^{61,‡} M. Franklin,^{20,†} J. C. Freeman,^{15,†} H. Frisch,^{11,†} S. Fuess,^{15,‡}
 Y. Funakoshi,^{51,†} C. Galloni,^{41a,41b,†} P. H. Garbincius,^{15,‡} A. Garcia-Bellido,^{44,‡} J. A. García-González,^{82,‡} A. F. Garfinkel,^{43,†}
 P. Garosi,^{41a,41c,†} V. Gavrilov,^{33,‡} W. Geng,^{66,32,‡} C. E. Gerber,^{97,‡} H. Gerberich,^{22,†} E. Gerchtein,^{15,†} Y. Gershtein,^{109,‡}
 S. Giagu,^{46a,†} V. Giakoumopoulou,^{3,†} K. Gibson,^{42,†} C. M. Ginsburg,^{15,†} G. Ginther,^{15,‡} N. Giokaris,^{3,§,†} P. Giromini,^{17,†}
 V. Glagolev,^{13,†} D. Glenzinski,^{15,†} O. Gogota,^{90,‡} M. Gold,^{34,†} D. Goldin,^{47,†} A. Golossanov,^{15,†} G. Golovanov,^{13,‡}
 G. Gomez,^{9,†} G. Gomez-Ceballos,^{30,†} M. Goncharov,^{30,†} O. González López,^{29,†} I. Gorelov,^{34,†} A. T. Goshaw,^{14,†}
 K. Goulianos,^{45,†} E. Gramellini,^{6a,†} P. D. Grannis,^{112,‡} S. Greder,^{70,‡} H. Greenlee,^{15,‡} G. Grenier,^{71,‡} Ph. Gris,^{64,‡}
 J.-F. Grivaz,^{67,‡} A. Grohsjean,^{69,mm,‡} C. Grosso-Pilcher,^{11,†} S. Grünendahl,^{15,‡} M. W. Grünewald,^{80,‡} T. Guillemin,^{67,‡}
 J. Guimaraes da Costa,^{20,†} G. Gutierrez,^{15,‡} P. Gutierrez,^{115,‡} S. R. Hahn,^{15,†} J. Haley,^{116,‡} J. Y. Han,^{44,†} L. Han,^{58,‡}
 F. Happacher,^{17,†} K. Hara,^{49,†} K. Harder,^{93,‡} M. Hare,^{50,†} A. Harel,^{44,‡} R. F. Harr,^{52,†} T. Harrington-Taber,^{15,m,†}
 K. Hatakeyama,^{5,†} J. M. Hauptman,^{103,‡} C. Hays,^{38,†} J. Hays,^{92,‡} T. Head,^{93,‡} T. Hebbeker,^{72,‡} D. Hedin,^{98,‡} H. Hegab,^{116,‡}
 J. Heinrich,^{40,†} A. P. Heinson,^{95,‡} U. Heintz,^{118,‡} C. Hensel,^{55,‡} I. Heredia-De La Cruz,^{82,nn,‡} M. Herndon,^{53,†} K. Herner,^{15,‡}
 G. Hesketh,^{93,pp,‡} M. D. Hildreth,^{102,‡} R. Hirosky,^{122,‡} T. Hoang,^{96,‡} J. D. Hobbs,^{112,‡} A. Hocker,^{15,†} B. Hoeneisen,^{63,‡}
 J. Hogan,^{121,‡} M. Hohlfield,^{75,‡} J. L. Holzbauer,^{107,‡} Z. Hong,^{47,w,†} W. Hopkins,^{15,f,†} S. Hou,^{1,†} I. Howley,^{119,‡}
 Z. Hubacek,^{61,69,‡} R. E. Hughes,^{35,†} U. Husemann,^{54,†} M. Hussein,^{32,cc,†} J. Huston,^{32,†} V. Hynek,^{61,‡} I. Iashvili,^{111,‡}
 Y. Ilchenko,^{120,‡} R. Illingworth,^{15,‡} G. Introzzi,^{41a,41e,41f,†} M. Iori,^{46a,46b,†} A. S. Ito,^{15,‡} A. Ivanov,^{7,o,†} S. Jabeen,^{15,ww,‡}
 M. Jaffré,^{67,‡} E. James,^{15,†} D. Jang,^{10,†} A. Jayasinghe,^{115,‡} B. Jayatilaka,^{15,†} E. J. Jeon,^{25,†} M. S. Jeong,^{81,‡} R. Jesik,^{92,‡}
 P. Jiang,^{58,§,‡} S. Jindariani,^{15,†} K. Johns,^{94,‡} E. Johnson,^{32,‡} M. Johnson,^{15,‡} A. Jonckheere,^{15,‡} M. Jones,^{43,†} P. Jonsson,^{92,‡}
 K. K. Joo,^{25,†} J. Joshi,^{95,‡} S. Y. Jun,^{10,†} A. W. Jung,^{15,yy,‡} T. R. Junk,^{15,†} A. Juste,^{88,‡} E. Kajfasz,^{66,‡} M. Kambeitz,^{24,†}
 T. Kamon,^{25,47,†} P. E. Karchin,^{52,†} D. Karmanov,^{85,‡} A. Kasmi,^{5,†} Y. Kato,^{37,n,†} I. Katsanos,^{108,‡} M. Kaur,^{77,‡} R. Kehoe,^{120,‡}
 S. Kermiche,^{66,‡} W. Ketchum,^{11,ii,†} J. Keung,^{40,†} N. Khalatyan,^{15,‡} A. Khanov,^{116,‡} A. Kharchilava,^{111,‡} Y. N. Kharzheev,^{13,‡}
 B. Kilminster,^{15,ee,†} D. H. Kim,^{25,†} H. S. Kim,^{15,bb,†} J. E. Kim,^{25,†} M. J. Kim,^{17,†} S. H. Kim,^{49,†} S. B. Kim,^{25,†} Y. J. Kim,^{25,†}

Y. K. Kim,^{11,†} N. Kimura,^{51,†} M. Kirby,^{15,†} I. Kiselevich,^{33,‡} J. M. Kohli,^{77,‡} K. Kondo,^{51,§,†} D. J. Kong,^{25,†} J. Konigsberg,^{16,†}
 A. V. Kotwal,^{14,†} A. V. Kozelov,^{86,‡} J. Kraus,^{107,‡} M. Kreps,^{24,†} J. Kroll,^{40,†} M. Kruse,^{14,†} T. Kuhr,^{24,†} A. Kumar,^{111,‡}
 A. Kupco,^{62,‡} M. Kurata,^{49,†} T. Kurča,^{71,‡} V. A. Kuzmin,^{85,‡} A. T. Laasanen,^{43,†} S. Lammell,^{15,†} S. Lammers,^{100,‡}
 M. Lancaster,^{28,†} K. Lannon,^{35,x,†} G. Latino,^{41a,41c,†} P. Lebrun,^{71,‡} H. S. Lee,^{81,‡} H. S. Lee,^{25,†} J. S. Lee,^{25,†} S. W. Lee,^{103,‡}
 W. M. Lee,^{15,§,‡} X. Lei,^{94,‡} J. Lellouch,^{68,‡} S. Leo,^{22,†} S. Leone,^{41a,†} J. D. Lewis,^{15,†} D. Li,^{68,‡} H. Li,^{122,‡} L. Li,^{95,‡} Q. Z. Li,^{15,‡}
 J. K. Lim,^{81,‡} A. Limosani,^{14,s,†} D. Lincoln,^{15,‡} J. Linnemann,^{32,‡} V. V. Lipaev,^{86,§,‡} E. Lipeles,^{40,†} R. Lipton,^{15,‡} A. Lister,^{18,a,†}
 H. Liu,^{120,‡} Q. Liu,^{43,†} T. Liu,^{15,†} Y. Liu,^{58,‡} A. Lobodenko,^{87,‡} S. Lockwitz,^{54,†} A. Loginov,^{54,†} M. Lokajicek,^{62,‡}
 R. Lopes de Sa,^{15,‡} D. Lucchesi,^{39a,39b,†} A. Lucà,^{17,15,†} J. Lueck,^{24,†} P. Lujan,^{26,†} P. Lukens,^{15,†} R. Luna-Garcia,^{82,qq,†}
 G. Lungu,^{45,†} A. L. Lyon,^{15,‡} J. Lys,^{26,§,‡} R. Lysak,^{12,d,†} A. K. A. Maciel,^{55,‡} R. Madar,^{73,‡} R. Madrak,^{15,†} P. Maestro,^{41a,41c,†}
 R. Magaña-Villalba,^{82,‡} S. Malik,^{45,†} S. Malik,^{108,‡} V. L. Malyshev,^{13,‡} G. Manca,^{27,b,†} A. Manousakis-Katsikakis,^{3,†}
 J. Mansour,^{74,‡} L. Marchese,^{6a,jj,†} F. Margaroli,^{46a,†} P. Marino,^{41a,41d,†} J. Martínez-Ortega,^{82,‡} K. Matera,^{22,†} M. E. Mattson,^{52,†}
 A. Mazzacane,^{15,†} P. Mazzanti,^{6a,†} R. McCarthy,^{112,‡} C. L. McGivern,^{93,‡} R. McNulty,^{27,i,†} A. Mehta,^{27,†} P. Mehtala,^{21,†}
 M. M. Meijer,^{83,84,‡} A. Melnitchouk,^{15,‡} D. Menezes,^{98,‡} P. G. Mercadante,^{57,‡} M. Merkin,^{85,‡} C. Mesropian,^{45,†} A. Meyer,^{72,‡}
 J. Meyer,^{74,ss,†} T. Miao,^{15,†} F. Miconi,^{70,‡} D. Mietlicki,^{31,†} A. Mitra,^{1,†} H. Miyake,^{49,†} S. Moed,^{15,†} N. Moggi,^{6a,†}
 N. K. Mondal,^{79,‡} C. S. Moon,^{15,z,†} R. Moore,^{15,ff,gg,†} M. J. Morello,^{41a,41d,†} A. Mukherjee,^{15,†} M. Mulhearn,^{122,‡}
 Th. Muller,^{24,†} P. Murat,^{15,†} M. Mussini,^{6a,6b,†} J. Nachtman,^{15,m,†} Y. Nagai,^{49,†} J. Naganoma,^{51,†} E. Nagy,^{66,‡} I. Nakano,^{36,†}
 A. Napier,^{50,†} M. Narain,^{118,‡} R. Nayyar,^{94,‡} H. A. Neal,^{31,‡} J. P. Negret,^{59,‡} J. Nett,^{47,†} P. Neustroev,^{87,‡} H. T. Nguyen,^{122,‡}
 T. Nigmanov,^{42,†} L. Nodulman,^{2,†} S. Y. Noh,^{25,†} O. Normiella,^{22,†} T. Nunnemann,^{76,‡} L. Oakes,^{38,†} S. H. Oh,^{14,†} Y. D. Oh,^{25,†}
 T. Okusawa,^{37,†} R. Orava,^{21,†} J. Orduna,^{118,‡} L. Ortolan,^{4,†} N. Osman,^{66,‡} C. Pagliarone,^{48a,†} A. Pal,^{119,‡} E. Palencia,^{9,e,†}
 P. Palni,^{34,†} V. Papadimitriou,^{15,†} N. Parashar,^{101,‡} V. Parihar,^{118,‡} S. K. Park,^{81,‡} W. Parker,^{53,†} R. Partridge,^{118,oo,‡}
 N. Parua,^{100,‡} A. Patwa,^{113,tt,‡} G. Pauletta,^{48a,48b,48c,†} M. Paulini,^{10,†} C. Paus,^{30,†} B. Penning,^{92,‡} M. Perfilov,^{85,‡} Y. Peters,^{93,‡}
 K. Petridis,^{93,‡} G. Petrillo,^{44,‡} P. Pétrouff,^{67,‡} T. J. Phillips,^{14,†} G. Piacentino,^{15,q,†} E. Pianori,^{40,†} J. Pilot,^{7,†} K. Pitts,^{22,†}
 C. Plager,^{8,†} M.-A. Pleier,^{113,‡} V. M. Podstavkov,^{15,‡} L. Pondrom,^{53,†} A. V. Popov,^{86,‡} S. Poprocki,^{15,f,†} K. Potamianos,^{26,†}
 A. Pranko,^{26,†} M. Prewitt,^{121,‡} D. Price,^{93,‡} N. Prokopenko,^{86,‡} F. Prokoshin,^{13,aa,†} F. Ptohos,^{17,g,†} G. Punzi,^{41a,41b,†} J. Qian,^{31,‡}
 A. Quadt,^{74,‡} B. Quinn,^{107,‡} P. N. Ratoff,^{91,‡} I. Razumov,^{86,‡} I. Redondo Fernández,^{29,†} P. Renton,^{38,†} M. Rescigno,^{46a,†}
 F. Rimondi,^{6a,§,‡} I. Ripp-Baudot,^{70,‡} L. Ristori,^{41a,15,†} F. Rizatdinova,^{116,‡} A. Robson,^{19,†} T. Rodriguez,^{40,†} S. Rolli,^{50,h,†}
 M. Rominsky,^{15,‡} M. Ronzani,^{41a,41b,†} R. Roser,^{15,†} J. L. Rosner,^{11,†} A. Ross,^{91,‡} C. Royon,^{62,‡} P. Rubinov,^{15,‡} R. Ruchti,^{102,‡}
 F. Ruffini,^{41a,41c,†} A. Ruiz,^{9,†} J. Russ,^{10,†} V. Rusu,^{15,†} G. Sajot,^{65,‡} W. K. Sakumoto,^{44,†} Y. Sakurai,^{51,†}
 A. Sánchez-Hernández,^{82,‡} M. P. Sanders,^{76,‡} L. Santi,^{48a,48b,48c,†} A. S. Santos,^{55,rr,†} K. Sato,^{49,†} G. Savage,^{15,‡}
 V. Saveliev,^{15,v,†} M. Savitskiy,^{90,‡} A. Savoy-Navarro,^{15,z,†} L. Sawyer,^{105,‡} T. Scanlon,^{92,‡} R. D. Schamberger,^{112,‡}
 Y. Scheglov,^{87,§,‡} H. Schellman,^{117,99,‡} P. Schlabach,^{15,†} E. E. Schmidt,^{15,†} M. Schott,^{75,‡} C. Schwanenberger,^{93,‡}
 T. Schwarz,^{31,†} R. Schwienhorst,^{32,‡} L. Scodellaro,^{9,†} F. Scuri,^{41a,†} S. Seidel,^{34,†} Y. Seiya,^{37,†} J. Sekaric,^{104,‡} A. Semenov,^{13,†}
 H. Severini,^{115,‡} F. Sforza,^{41a,41b,†} E. Shabalina,^{74,‡} S. Z. Shalhout,^{7,†} V. Shary,^{69,‡} S. Shaw,^{93,‡} A. A. Shchukin,^{86,‡}
 T. Shears,^{27,†} P. F. Shepard,^{42,†} M. Shimojima,^{49,u,†} O. Shkola,^{90,‡} M. Shochet,^{11,†} I. Shreyber-Tecker,^{33,†} V. Simak,^{61,‡}
 A. Simonenko,^{13,†} P. Skubic,^{115,‡} P. Slattery,^{44,‡} K. Sliwa,^{50,†} J. R. Smith,^{7,†} F. D. Snider,^{15,†} G. R. Snow,^{108,‡} J. Snow,^{114,‡}
 S. Snyder,^{113,‡} S. Söldner-Rembold,^{93,‡} H. Song,^{42,†} L. Sonnenschein,^{72,‡} V. Sorin,^{4,†} K. Soustruznik,^{60,‡} R. St. Denis,^{19,§,†}
 M. Stancari,^{15,†} J. Stark,^{65,‡} N. Stefaniuk,^{90,‡} D. Stentz,^{15,w,†} D. A. Stoyanova,^{86,‡} M. Strauss,^{115,‡} J. Strologas,^{34,†} Y. Sudo,^{49,†}
 A. Sukhanov,^{15,†} I. Suslov,^{13,†} L. Suter,^{93,‡} P. Svoisky,^{122,‡} K. Takemasa,^{49,†} Y. Takeuchi,^{49,†} J. Tang,^{11,†} M. Tecchio,^{31,†}
 P. K. Teng,^{1,†} J. Thom,^{15,f,†} E. Thomson,^{40,†} V. Thukral,^{47,†} M. Titov,^{69,‡} D. Toback,^{47,†} S. Tokar,^{12,†} V. V. Tokmenin,^{13,‡}
 K. Tollefson,^{32,†} T. Tomura,^{49,†} D. Tonelli,^{15,e,†} S. Torre,^{17,†} D. Torretta,^{15,†} P. Totaro,^{39a,†} M. Trovato,^{41a,41d,†} Y.-T. Tsai,^{44,‡}
 D. Tsybychev,^{112,‡} B. Tuchming,^{69,‡} C. Tully,^{110,‡} F. Ukegawa,^{49,†} S. Uozumi,^{25,†} L. Uvarov,^{87,‡} S. Uvarov,^{87,‡}
 S. Uzunyan,^{98,‡} R. Van Kooten,^{100,‡} W. M. van Leeuwen,^{83,‡} N. Varelas,^{97,‡} E. W. Varnes,^{94,‡} I. A. Vasilyev,^{86,‡}
 F. Vázquez,^{16,l,†} G. Velev,^{15,†} C. Vellidis,^{15,†} A. Y. Verkheev,^{13,‡} C. Vernieri,^{41a,41d,†} L. S. Vertogradov,^{13,‡} M. Verzocchi,^{15,‡}
 M. Vesterinen,^{93,‡} M. Vidal,^{43,†} D. Vilanova,^{69,‡} R. Vilar,^{9,†} J. Vizán,^{9,dd,†} M. Vogel,^{34,†} P. Vokac,^{61,‡} G. Volpi,^{17,†}
 P. Wagner,^{40,†} H. D. Wahl,^{96,‡} R. Wallny,^{15,j,†} M. H. L. S. Wang,^{15,‡} S. M. Wang,^{1,†} J. Warchol,^{102,§,‡} D. Waters,^{28,†}
 G. Watts,^{123,‡} M. Wayne,^{102,‡} J. Weichert,^{75,‡} L. Welty-Rieger,^{99,‡} W. C. Wester III,^{15,†} D. Whiteson,^{40,c,†} A. B. Wicklund,^{2,†}
 S. Wilbur,^{7,†} H. H. Williams,^{40,†} M. R. J. Williams,^{100,xx,‡} G. W. Wilson,^{104,‡} J. S. Wilson,^{31,†} P. Wilson,^{15,†} B. L. Winer,^{35,†}
 P. Wittich,^{15,f,†} M. Wobisch,^{105,‡} S. Wolbers,^{15,†} H. Wolfmeister,^{35,†} D. R. Wood,^{106,‡} T. Wright,^{31,†} X. Wu,^{18,†} Z. Wu,^{5,†}
 T. R. Wyatt,^{93,‡} Y. Xie,^{15,‡} R. Yamada,^{15,‡} K. Yamamoto,^{37,†} D. Yamato,^{37,†} S. Yang,^{58,‡} T. Yang,^{15,†} U. K. Yang,^{25,†}

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. Zennaro,^{111,‡} T. G. Zhao,^{93,‡} B. Zhou,^{31,‡} C. Zhou,^{14,†} J. Zhu,^{31,‡} M. Zielinski,^{44,‡} D. Zieminska,^{100,‡}
 L. Zivkovic,^{68,zz,‡} and S. Zucchelli^{6a,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, ICREA, Universitat Autònoma 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*Glasgow University, Glasgow G12 8QQ, United Kingdom*

²⁰*Harvard University, 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-00014 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, D-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 Energéticas Medioambientales y Tecnológicas, 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*

^{39a}*Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

^{39b}*University of Padova, I-35131 Padova, Italy*

⁴⁰*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

^{41a}*Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy*

- ^{41b}University of Pisa, I-56127 Pisa, Italy
^{41c}University of Siena, I-56127 Pisa, Italy
^{41d}Scuola Normale Superiore, I-56127 Pisa, Italy
^{41e}INFN Pavia, I-27100 Pavia, Italy
^{41f}University of Pavia, I-27100 Pavia, Italy
⁴²University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
⁴³Purdue University, West Lafayette, Indiana 47907, USA
⁴⁴University of Rochester, Rochester, New York 14627, USA
⁴⁵The Rockefeller University, New York, New York 10065, USA
^{46a}Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy
^{46b}Sapienza Università di Roma, I-00185 Roma, Italy
⁴⁷Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
^{48a}Istituto Nazionale di Fisica Nucleare Trieste, I-33100 Udine, Italy
^{48b}Gruppo Collegato di Udine, I-33100 Udine, Italy
^{48c}University of Udine, I-33100 Udine, Italy
^{48d}University of Trieste, I-34127 Trieste, Italy
⁴⁹University of Tsukuba, Tsukuba, Ibaraki 305, Japan
⁵⁰Tufts University, Medford, Massachusetts 02155, USA
⁵¹Waseda University, Tokyo 169, Japan
⁵²Wayne State University, Detroit, Michigan 48201, USA
⁵³University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
⁵⁴Yale University, New Haven, Connecticut 06520, USA
⁵⁵LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ 22290, Brazil
⁵⁶Universidade do Estado do Rio de Janeiro, Rio de Janeiro, RJ 20550, Brazil
⁵⁷Universidade Federal do ABC, Santo André, São Paulo, SP 09210, Brazil
⁵⁸University of Science and Technology of China, Hefei 230026, People's Republic of China
⁵⁹Universidad de los Andes, Bogotá 111711, Colombia
⁶⁰Faculty of Mathematics and Physics, Center for Particle Physics, Charles University, 116 36 Prague 1, Czech Republic
⁶¹Czech Technical University in Prague, 116 36 Prague 6, Czech Republic
⁶²Institute of Physics, Academy of Sciences of the Czech Republic, 182 21 Prague, Czech Republic
⁶³Universidad San Francisco de Quito, Quito 170157, Ecuador
⁶⁴LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, F-63178 Aubière Cedex, France
⁶⁵LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France
⁶⁶CPPM, Aix-Marseille Université, CNRS/IN2P3, F-13288 Marseille Cedex 09, France
⁶⁷LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay Cedex, France
⁶⁸LPNHE, Universités Paris VI and VII, CNRS/IN2P3, F-75005 Paris, France
⁶⁹CEA Saclay, Irfu, SPP, F-91191 Gif-Sur-Yvette Cedex, France
⁷⁰IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France
⁷¹IPNL, Université Lyon 1, CNRS/IN2P3, F-69622 Villeurbanne Cedex, France
and Université de Lyon, F-69361 Lyon CEDEX 07, France
⁷²III. Physikalisches Institut A, RWTH Aachen University, 52056 Aachen, Germany
⁷³Physikalisches Institut, Universität Freiburg, 79085 Freiburg, Germany
⁷⁴II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen, Germany
⁷⁵Institut für Physik, Universität Mainz, 55099 Mainz, Germany
⁷⁶Ludwig-Maximilians-Universität München, 80539 München, Germany
⁷⁷Panjab University, Chandigarh 160014, India
⁷⁸Delhi University, Delhi-110 007, India
⁷⁹Tata Institute of Fundamental Research, Mumbai-400 005, India
⁸⁰University College Dublin, Dublin 4, Ireland
⁸¹Korea Detector Laboratory, Korea University, Seoul 02841, Korea
⁸²CINVESTAV, Mexico City 07360, Mexico
⁸³Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands
⁸⁴Radboud University Nijmegen, 6525 AJ Nijmegen, The Netherlands
⁸⁵Moscow State University, Moscow 119991, Russia
⁸⁶Institute for High Energy Physics, Protvino, Moscow region 142281, Russia
⁸⁷Petersburg Nuclear Physics Institute, St. Petersburg 188300, Russia
⁸⁸Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), 08193 Bellaterra (Barcelona), Spain
⁸⁹Uppsala University, 751 05 Uppsala, Sweden

- ⁹⁰Taras Shevchenko National University of Kyiv, Kiev 01601, Ukraine
⁹¹Lancaster University, Lancaster LA1 4YB, United Kingdom
⁹²Imperial College London, London SW7 2AZ, United Kingdom
⁹³The University of Manchester, Manchester M13 9PL, United Kingdom
⁹⁴University of Arizona, Tucson, Arizona 85721, USA
⁹⁵University of California Riverside, Riverside, California 92521, USA
⁹⁶Florida State University, Tallahassee, Florida 32306, USA
⁹⁷University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁹⁸Northern Illinois University, DeKalb, Illinois 60115, USA
⁹⁹Northwestern University, Evanston, Illinois 60208, USA
¹⁰⁰Indiana University, Bloomington, Indiana 47405, USA
¹⁰¹Purdue University Calumet, Hammond, Indiana 46323, USA
¹⁰²University of Notre Dame, Notre Dame, Indiana 46556, USA
¹⁰³Iowa State University, Ames, Iowa 50011, USA
¹⁰⁴University of Kansas, Lawrence, Kansas 66045, USA
¹⁰⁵Louisiana Tech University, Ruston, Louisiana 71272, USA
¹⁰⁶Northeastern University, Boston, Massachusetts 02115, USA
¹⁰⁷University of Mississippi, University, Mississippi 38677, USA
¹⁰⁸University of Nebraska, Lincoln, Nebraska 68588, USA
¹⁰⁹Rutgers University, Piscataway, New Jersey 08855, USA
¹¹⁰Princeton University, Princeton, New Jersey 08544, USA
¹¹¹State University of New York, Buffalo, New York 14260, USA
¹¹²State University of New York, Stony Brook, New York 11794, USA
¹¹³Brookhaven National Laboratory, Upton, New York 11973, USA
¹¹⁴Langston University, Langston, Oklahoma 73050, USA
¹¹⁵University of Oklahoma, Norman, Oklahoma 73019, USA
¹¹⁶Oklahoma State University, Stillwater, Oklahoma 74078, USA
¹¹⁷Oregon State University, Corvallis, Oregon 97331, USA
¹¹⁸Brown University, Providence, Rhode Island 02912, USA
¹¹⁹University of Texas, Arlington, Texas 76019, USA
¹²⁰Southern Methodist University, Dallas, Texas 75275, USA
¹²¹Rice University, Houston, Texas 77005, USA
¹²²University of Virginia, Charlottesville, Virginia 22904, USA
¹²³University of Washington, Seattle, Washington 98195, USA

[§]Deceased.

^aVisitor from University of British Columbia, Vancouver, BC V6T 1Z1, Canada.

^bVisitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.

^cVisitor from University of California Irvine, Irvine, CA 92697, USA.

^dVisitor from Institute of Physics, Academy of Sciences of the Czech Republic, 182 21, Czech Republic.

^eVisitor from CERN, CH-1211 Geneva, Switzerland.

^fVisitor from Cornell University, Ithaca, NY 14853, USA.

^gVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.

^hVisitor from Office of Science, U.S. Department of Energy, Washington, DC 20585, USA.

ⁱVisitor from University College Dublin, Dublin 4, Ireland.

^jVisitor from ETH, 8092 Zürich, Switzerland.

^kVisitor from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.

^lVisitor from Universidad Iberoamericana, Lomas de Santa Fe, México, C.P. 01219, Distrito Federal.

^mVisitor from University of Iowa, Iowa City, IA 52242, USA.

ⁿVisitor from Kinki University, Higashi-Osaka City, Japan 577-8502.

^oVisitor from Kansas State University, Manhattan, KS 66506, USA.

^pVisitor from Brookhaven National Laboratory, Upton, NY 11973, USA.

^qVisitor from Istituto Nazionale di Fisica Nucleare, Sezione di Lecce, Via Arnesano, I-73100 Lecce, Italy.

^rVisitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.

^sVisitor from University of Melbourne, Victoria 3010, Australia.

^tVisitor from Muons, Inc., Batavia, IL 60510, USA.

^uVisitor from Nagasaki Institute of Applied Science, Nagasaki 851-0193, Japan.

^vVisitor from National Research Nuclear University, Moscow 115409, Russia.

^wVisitor from Northwestern University, Evanston, IL 60208, USA.

^xVisitor from University of Notre Dame, Notre Dame, IN 46556, USA.

- ^yVisitor from Universidad de Oviedo, E-33007 Oviedo, Spain.
- ^zVisitor from CNRS-IN2P3, Paris, F-75205 France.
- ^{aa}Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.
- ^{bb}Visitor from Sejong University, Seoul 143-747, Korea.
- ^{cc}Visitor from The University of Jordan, Amman 11942, Jordan.
- ^{dd}Visitor from Universite catholique de Louvain, 1348 Louvain-La-Neuve, Belgium.
- ^{ee}Visitor from University of Zürich, 8006 Zürich, Switzerland.
- ^{ff}Visitor from Massachusetts General Hospital, Boston, MA 02114 USA.
- ^{gg}Visitor from Harvard Medical School, Boston, MA 02114 USA.
- ^{hh}Visitor from Hampton University, Hampton, VA 23668, USA.
- ⁱⁱVisitor from Los Alamos National Laboratory, Los Alamos, NM 87544, USA.
- ^{jj}Visitor from Università degli Studi di Napoli Federico II, I-80138 Napoli, Italy.
- ^{kk}Visitor from Augustana University, Sioux Falls, SD 57197, USA.
- ^{ll}Visitor from The University of Liverpool, Liverpool L69 3BX, UK.
- ^{mm}Visitor from Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, Germany.
- ⁿⁿVisitor from Consejo Nacional de Ciencia y Tecnologia (Conacyt), M-03940 Mexico City, Mexico.
- ^{oo}Visitor from SLAC, Menlo Park, CA 94025, USA.
- ^{pp}Visitor from University College London, London WC1E 6BT, UK.
- ^{qq}Visitor from Centro de Investigacion en Computacion - IPN, CP 07738 Mexico City, Mexico.
- ^{rr}Visitor from Universidade Estadual Paulista, São Paulo, SP 01140, Brazil.
- ^{ss}Visitor from Karlsruher Institut für Technologie (KIT) - Steinbuch Centre for Computing (SCC), D-76128 Karlsruher, Germany.
- ^{tt}Visitor from Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA.
- ^{uu}Visitor from American Association for the Advancement of Science, Washington, D.C. 20005, USA.
- ^{vv}Visitor from National Academy of Science of Ukraine (NASU) - Kiev Institute for Nuclear Research (KINR), Kyiv 03680, Ukraine.
- ^{ww}Visitor from University of Maryland, College Park, MD 20742, USA.
- ^{xx}Visitor from European Organization for Nuclear Research (CERN), CH-1211 Genève 23, Switzerland.
- ^{yy}Visitor from Purdue University, West Lafayette, IN 47907, USA.
- ^{zz}Visitor from Institute of Physics, Belgrade, CS-11080 Belgrade, Serbia.