IL NUOVO CIMENTO Vol. 37 C, N. 6 Novembre-Dicembre 2014
DOI 10.1393/ncc/i2015-11862-1

Colloquia: LaThuile14

On measuring the leptonic forward-backward asymmetry at the Tevatron and recent results from CDF

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ricevuto il 31 Luglio 2014

Summary. — The larger-than-expected forward-backward asymmetry of the top-quark pairs produced in proton-antiproton collisions is suggestive of new physics. The forward-backward asymmetry of the charged leptons from the cascade decay of top-quark pairs serve as an complementary test for evidence for or against new physics. We provide a detailed study of the methodology used to measure the leptonic asymmetry at CDF, and measure the leptonic asymmetry in leptonic top quark pair decays, as well as the CDF combination of the leptonic asymmetry. The CDF leptonic asymmetry combination shows a 2 standard-deviation larger value than the next–to–leading-order standard model expectation.

PACS `14.65.Ha` – Top quarks.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS `12.38.Qk` – Experimental tests.

1. – Introduction

The forward-backward asymmetry of the $t\bar{t}$ system produced at the Fermilab Tevatron can be defined as

$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}\,, \tag{1}$$

where N is the number of events, y is the rapidity of the (anti-)top quark, and $\Delta y = y_t - y_{\bar{t}}$. Previous measurements of $A_{\mathrm{FB}}^{t\bar{t}}$ at CDF with $9.4\,\mathrm{fb}^{-1}$ and at D0 with $5.4\,\mathrm{fb}^{-1}$ data in the final state with only one charged lepton and hadronic jets (lepton+jets final state) have indicated a larger $A_{\mathrm{FB}}^{t\bar{t}}$ [1,2] than would be expected from the standard model (SM) [3-5]. The asymmetry in the differential cross section of the $t\bar{t}$ system has also been probed in other ways. For example, the angular distribution of cross section of $t\bar{t}$ system has been studied in the lepton+jets final state at CDF [6], observing an excess in the coefficient of the linear dependent term of $\cos\theta_t$ in the $t\bar{t}$ differential cross section, where $\cos\theta_t$ is the angle between the top-quark momentum and the incoming proton momentum as measured in the $t\bar{t}$ center-of-mass frame. This is of great interest, as new particles or interactions could cause the $A_{\mathrm{FB}}^{t\bar{t}}$ to be different from SM-only predictions [7-26].

As the large-than-expected $A_{\mathrm{FB}}^{t\bar{t}}$ is suggestive for physics beyond the SM, we can look for more evidence for or against new physics with a separate set of observables defined with the charged leptons from the cascade decays of the top-quark pairs, A_{FB}^{l} and A_{FB}^{ll} [27, 28]. We can define the A_{FB}^{l} as

$$A_{\mathrm{FB}}^{l} = \frac{N(q_l\eta_l > 0) - N(q_l\eta_l < 0)}{N(q_l\eta_l > 0) + N(q_l\eta_l < 0)}\,, \tag{2}$$

where N is the number of leptons, q is the lepton charge, and η is the pseudorapidity of the lepton. Similarly, since there are two leptons detected in each event in the final state with two charged leptons (dilepton final state), the A_{FB}^{ll} can be defined as

$$A_{\mathrm{FB}}^{ll} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}\,, \tag{3}$$

where $\Delta\eta = \eta_{l^+} - \eta_{l^-}$.

This set of observables is of equal importance, since the forward-backward asymmetry of the charged leptons can originate from the asymmetry in the production direction of their parent top quarks. In addition, the A_{FB}^{l} and A_{FB}^{ll} can deviate further from their SM predictions in the scenarios that the top quarks are produced with a certain polarization. For example, the resonant production of $t\bar{t}$ pairs via a hypothetical gluon with axial couplings ("axigluons") could cause the $A_{\mathrm{FB}}^{t\bar{t}}$ to deviate from its SM value; various axigluon couplings to the top quarks could produce the same value of $A_{\mathrm{FB}}^{t\bar{t}}$, but with very different values of A_{FB}^{l} and A_{FB}^{ll} [29].

2. – Leptonic asymmetry measurement methodology

Due to the limited detector coverage ($|\eta| < 2$ for electrons and $|\eta| < 1.1$ for muons), the imperfect detector acceptance, the smearing due to detector response and contamination from non-$t\bar{t}$ sources, a correction and extrapolation procedure is needed to measure the inclusive parton-level A_{FB}^{l} and A_{FB}^{ll} from data. Note that while we will be using the same methodology for measuring the A_{FB}^{l} as well as the A_{FB}^{ll}, our description in this section will only mention A_{FB}^{l} explicitly.

The measurement of A_{FB}^{l} at CDF in the lepton+jets final state [28] was based on the asymmetric distribution of the $q_l\eta_l$ spectrum (differential asymmetry), defined as

$$\mathcal{A}(q_l\eta_l) = \frac{\mathcal{N}(q_l\eta_l) - \mathcal{N}(-q_l\eta_l)}{\mathcal{N}(q_l\eta_l) + \mathcal{N}(-q_l\eta_l)}\,. \tag{4}$$

The differential asymmetry was modeled with an empirically determined function of the form of

$$\mathcal{A}(q_l\eta_l) = a \cdot \tanh\left(\frac{1}{2}q_l\eta_l\right), \tag{5}$$

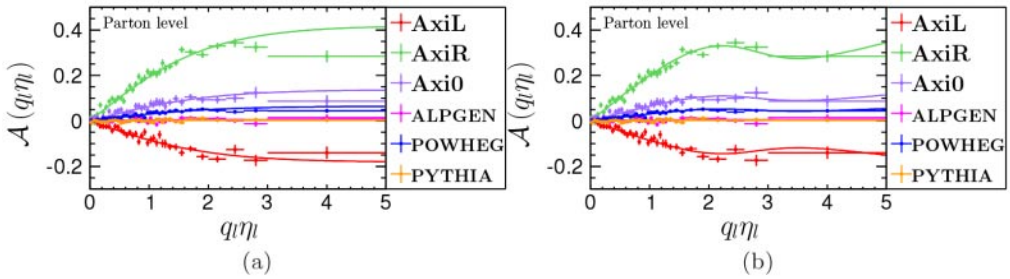

Fig. 1. – The differential asymmetry from various physics models. The lines correspond to the best fits from (a) the $a \cdot \tanh$ model and (b) the double-Gaussian model.

where a is a free parameter that is directly related to the final asymmetry. This $a \cdot \tanh$ function was used to correct for the detector response and extrapolate to the inclusive parton-level asymmetry. This methodology was very successful albeit purely empirical. Here we provide a partial explanation of why this functional form works. For more details see ref. [30].

To illustrate and test the measurement methodology, we employed a series of Monte Carlo simulated $t\bar{t}$ samples. Samples generated with ALPGEN [31], PYTHIA [32] and POWHEG [33-36] serve as estimates of the SM, and three $t\bar{t}$ MC samples that include a class of relatively light and wide axigluons (with masses at $200\,\mathrm{GeV}/c^2$ and widths at $50\,\mathrm{GeV}$) with left-handed, right-handed, and axial axigluon couplings to the quarks [29] serve as benchmark simulation samples to model various SM extensions. These samples have various A^l_{FB} in the rage between -6% and 15% [30]. The differential asymmetry from these samples are shown in fig. 1(a). Best fits of the data to the $a \cdot \tanh$ model from eq. (5). are also shown in this figure. While the differential asymmetry is well modeled in the region where $|q_l\eta_l| < 2.5$, it is not as good above 2.5.

We find that the sum of two Gaussian functions with a common mean works very well at describing the data, even at large values of $q_l\eta_l$, as shown in fig. 2. This double-Gaussian description appears good for all the samples we test on. The shape of the $q_l\eta_l$ spectrum is nearly identical for all the simulated samples, while the A^l_{FB} comes from a shift in the mean of the distribution. In addition, in the region of A^l_{FB} we are interested in, A^l_{FB} appears linearly related with the mean of the double-Gaussian distribution.

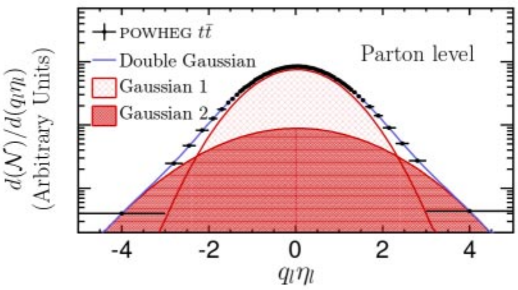

Fig. 2. – The $q_l\eta_l$ distribution from the POWHEG $t\bar{t}$ sample at parton level, overlaid with the double-Gaussian fit.

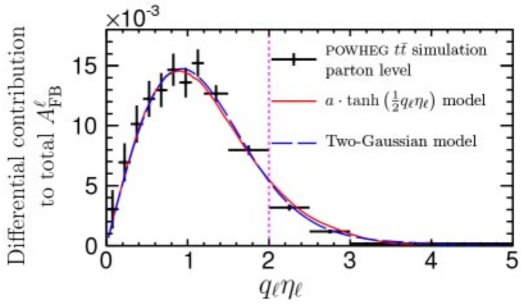

Fig. 3. – Comparison of the differential contribution to the A^l_{FB} between the $a \cdot \tanh$ model and the double-Gaussian model to the data from the POWHEG simulation.

Figure 1(b) shows the double-Gaussian model fit to the differential asymmetry for the simulated samples. A comparison with fig. 1(a) shows that the double-Gaussian model matches all the simulated samples better than the $a \cdot \tanh$ model. However, the differences are mostly in the high-$q_l\eta_l$ region where the contribution to the inclusive A^l_{FB} is small. The systematic uncertainty introduced by the $a \cdot \tanh$ fit is at the permil level while the typical dominant uncertainty (statistical) at the Tevatron experiments is at the percent level. The differential asymmetry is still the most sensitive way to determine the total A^l_{FB}, since it has the benefit of cancelling out most of the systematic uncertainties due to the acceptance of the detector.

Another way to visualize the asymmetry is to look at a description of how much contribution there is to the total asymmetry as a function of $q_l\eta_l$ (the differential contribution to the total A^l_{FB}) as shown in fig. 3. With this, we learn that the asymmetry mostly comes from region where $|\eta| < 2.0$, which is the place where the detectors offer best coverages. The shape of the differential contribution to the total A^l_{FB} is very stable among all samples, which allows for a robust extrapolation from the detected asymmetry to the parton-level inclusive asymmetry. We also note that the $a \cdot \tanh$ parametrization is excellent for $|q_l\eta_l| < 2.5$. This is more than good enough for the current measurement at the Tevatron, thus we can move forward with confidence.

3. – CDF result of A^l_{FB} and A^{ll}_{FB}

We use the full dataset collected by the CDF detector during Run II of the Tevatron, corresponding to an integrated luminosity of $9.1\,\mathrm{fb}^{-1}$, to measure the A^l_{FB} and A^{ll}_{FB} and summarize the results presented in ref. [37]. We focus on the sample in the dilepton final state, and follow the event selection criteria that was used in measuring the top-pair cross section in the same final state [38], with the dilepton invariant mass ($\mathrm{m_{ll}}$) requirement raised to $10\,\mathrm{GeV}/c^2$ to prevent potential mismodelling in low dilepton invariant mass region. The key features of this event selection criteria are requiring two opposite charged leptons, at least two jets and large $\not{E}_T$.

Figure 4 shows the $q_l\eta_l$ and $\Delta\eta$ distributions from the data along with comparisons to the SM using the POWHEG MC. Figure 5 shows the differential asymmetry as a function of $q_l\eta_l$ and $\Delta\eta$ calculated from the data after subtracting off the expected background contributions, with fits to the $a \cdot \tanh$ model. After evaluating the systematic uncertainties, the results are $A^l_{\mathrm{FB}} = 0.072 \pm 0.052(\mathrm{stat}) \pm 0.030(\mathrm{syst}) = 0.072 \pm 0.060$ and $A^{ll}_{\mathrm{FB}} = 0.076 \pm 0.072(\mathrm{stat}) \pm 0.039(\mathrm{syst}) = 0.076 \pm 0.082$, to be compared with the

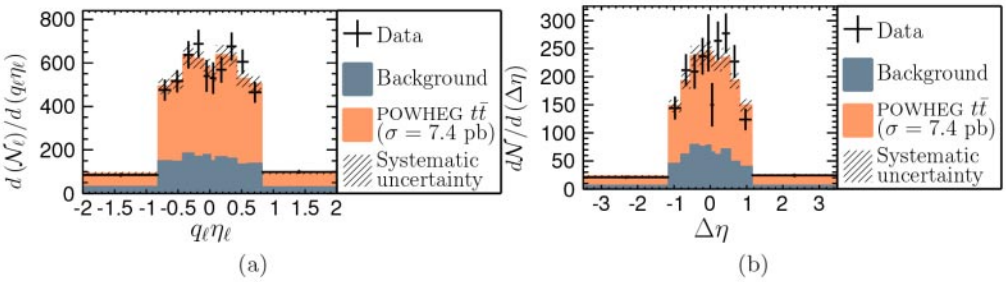

Fig. 4. – The distribution of (a) $q_l\eta_l$ and (b) $\Delta\eta$ of SM expectation overlaid with observation from data.

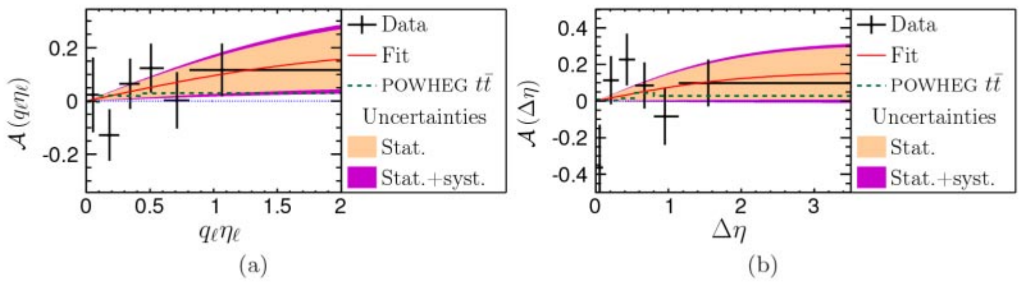

Fig. 5. – The differential asymmetry as a function of (a) $q_l\eta_l$ and (b) $\Delta\eta$ from data after background subtraction. The green line shows expectation from POWHEG MC.

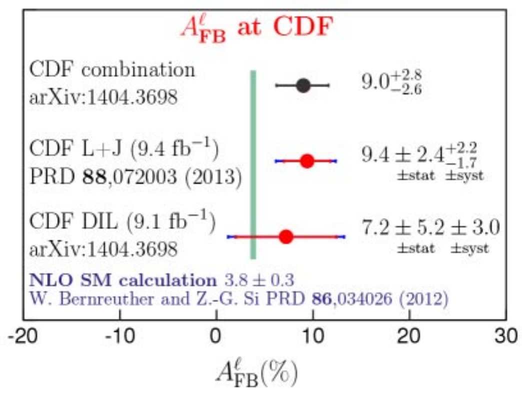

Fig. 6. – Comparison among A^l_{FB} measured in the lepton+jets and dilepton final states and the combination.

prediction from the SM at the next-to-leading order (NLO) at $A^l_{\mathrm{FB}} = 0.038 \pm 0.003$ and $A^{ll}_{\mathrm{FB}} = 0.048 \pm 0.004$ [39], respectively. The dominant uncertainty in both measurements are statistical uncertainties. Both results are consistent with the SM predictions.

We take one step further and combine the A^{l}_{FB} measured in the dilepton final state described in the previous sections and the same measurement in the lepton+jets final state in ref. [28]. The combination is based on the *best linear unbiased estimates* (BLUE) [40-42] method. In order to deal with the asymmetric uncertainties in the measurement, we followed the approach of Asymmetric Iterative BLUE (AIB) [43]. The combined A^{l}_{FB} is $A^{l}_{\mathrm{FB}} = 0.090^{+0.028}_{-0.026}$. This measurement is 2 standard deviations larger than the NLO SM calculation at $A^{l}_{\mathrm{FB}} = 0.038 \pm 0.003$. The comparison among A^{l}_{FB} measured in the lepton+jets and dilepton final states and the combination is shown in fig. 6.

4. – Conclusion

The measurements of the forward-backward asymmetry of the top-pair production at the Tevatron continues to produce exciting results. Our presented result cover both improved understanding of the methodology used to measure the A^{l}_{FB} as well as improved measurements and combination of multiple measurements. We measure the A^{l}_{FB} and A^{ll}_{FB} in the dilepton final state using full data collected during CDF Run II to be $A^{l}_{\mathrm{FB}} = 0.072 \pm 0.052(\mathrm{stat}) \pm 0.030(\mathrm{syst}) = 0.072 \pm 0.060$ and $A^{ll}_{\mathrm{FB}} = 0.076 \pm 0.072(\mathrm{stat}) \pm 0.039(\mathrm{syst}) = 0.076 \pm 0.082$. The results are consistent with the prediction from NLO SM of $A^{l}_{\mathrm{FB}} = 0.038 \pm 0.003$ and $A^{ll}_{\mathrm{FB}} = 0.048 \pm 0.004$ [39]. Furthermore we obtained the best measurement of the A^{l}_{FB} from CDF by combining the measurement in the lepton+jets final state with the measurement in the dilepton final state. The combined result is $A^{l}_{\mathrm{FB}} = 0.090^{+0.028}_{-0.026}$. This result is 2 standard deviation larger than the NLO SM calculation. CDF is continuing the effort in measuring $A^{t\bar{t}}_{\mathrm{FB}}$ in the dilepton final state and further CDF and Tevatron combinations.

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We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

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