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Forward-backward asymmetries in top-quark pair production at the Tevatron

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Summary. — We review the measurements of various forward-backward asymmetries in $t\bar{t}$ production in $p\bar{p}$ collisions by the CDF and D0 collaborations.

PACS `14.65.Ha` – Top quarks.

1. – Introduction and motivation

As the heaviest of the known elementary quanta of the standard model of particle physics (SM), the top quark offers many opportunities to search for new phenomena beyond the SM (BSM). Puzzling discrepancies between data and SM predictions were found in measurements of forward-backward asymmetries (A_{FB}s) in $t\bar{t}$ production at the Fermilab Tevatron Collider. These asymmetries arise from the $p\bar{p}$ initial state of the Tevatron, and are less accessible at the LHC [1].

The forward-backward asymmetries answer the question: is it the top quark or antiquark that is more likely to be produced in the direction (up to $\pi/2$) of the incoming proton? Measurements exist for several choices of the angular variable and the frame of reference. For each choice we count the number (N_{F}) of "forward" events, *i.e.* those with an angle smaller than $\pi/2$, and the number (N_{B}) of "backward" events. From them we define the corresponding asymmetry:

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}\,. \tag{1}$$

The motivation for measuring such quantities lies in the SM and its history. According to the SM, $t\bar{t}$ production at the Tevatron is dominated (85–90%) by quark-antiquark collision and an asymmetry arises from a correlation between the direction of the produced top (anti)quark and the direction of the incoming (anti)quark. Hence, the asymmetry can be phrased in terms of the angle of deflection of the strong ("color") charge carried by the incoming (anti)quark and transfered to the outgoing top (anti)quark. The predicted

SM asymmetry does not appear in the leading order of $t\bar{t}$ production, α_s^2, but only in at order α_s^3, as elucidated in ref. [2], which started the current interest in these observables. There, the top pair production asymmetry was calculated to be $A_{\mathrm{FB}} \approx 5\%$. Current state of the art calculations [3-6], yield (in the $t\bar{t}$ frame) $A_{\mathrm{FB}} = 7$–9%. For more details, see elsewhere in these proceedings [7].

$t\bar{t}$ production may already be asymmetric at leading order in BSM scenarios, so these measurements probe a wide variety of BSM scenarios [8]. A similar historical precedent is the evidence for the SM's Z boson, found in the production asymmetry of the process $e^+e^- \to \mu^+\mu^-$ in energies well below the Z resonance mass [9].

2. – The basic observable

The basic asymmetry is defined according to the rapidity difference between the top quark and antiquark: $\Delta y = y_t - y_{\bar{t}}$. This asymmetry was measured by D0 in the l+jets [10] channel (decay chain $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}q\bar{q}'l\nu$) and by CDF in both the l+jets [11] channel and di-lepton [12] channel (decay chain $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}l^+l^-\nu\nu$).

The l+jets measurements use events that contain the following objects. At least one electron or muon with $E_T > 20\,\mathrm{GeV}$ and $|\eta| < 1.1$, with the D0 analysis also including muons out to $|\eta| = 2.0$, increasing its sensitivity to most BSM scenarios. At least four jets with $E_T > 20\,\mathrm{GeV}$ and either $|\eta| < 2.0$ (CDF) or $|\eta| < 2.5$ (D0). At least one of these jets must be tagged as containing a b hadron. A transverse momentum imbalance, as measured by the calorimetry, $\not{E}_T > 20\,\mathrm{GeV}$. The CDF analysis selects 1260 events, and estimates that 977 events are signal (78% pure); the D0 analysis selects 1581 events, and estimates that 1126 events are signal (71% pure).

Both l+jets measurements use a χ^2 test statistic to assign reconstructed objects to the final state partons from top decay. The χ^2 statistic accounts for experimental resolutions, and the observed b tags, and is constrained by the known W boson and top quark masses. The CDF analysis also accounts for the natural widths of these resonances, but neglects the angular resolutions. The D0 analysis propagates the variations of the observed objects that minimize the χ^2 to the rest of the analysis, a "kinematic fitter". After this assignment, the event is fully reconstructed under the $t\bar{t}$ hypothesis.

The CDF analysis follows their previous cross-section measurement [13], and uses its background estimate to perform background subtraction and then calculates the A_{FB} for $t\bar{t}$ production. This is shown by the black and green lines in fig. 1, and yields a detector-level A_{FB} of $(7.5 \pm 3.6)\%$. The D0 analysis estimates the background using a discriminant trained to separate $t\bar{t}$ from W+jets production without biasing Δy, in a simultaneous fit of the sample composition and A_{FB}. This yields a detector-level A_{FB} of $(9.2 \pm 3.7)\%$. The sample composition and data Δy distributions are shown in fig. 2. Such detector-level results were central to the previous D0 measurement [14], but are inconvenient as they can not be compared directly to theory calculations. Nevertheless, this is possible either as detailed in ref. [14] or in the approach of ref. [15]. As predicted in the SM, the detector-level A_{FB}, *e.g.* in D0 data, are positive in the exactly-four jets subsample $((12.2 \pm 4.3)\%)$ and negative in the five-or-more jets subsample $((-3.0 \pm 7.9)\%)$. But the statistical strength of this observation is marginal at best.

Production-level results are derived by correcting for acceptance and resolution effects. The former are quantified by an acceptance matrix (diagonal), and the latter by a migration matrix. CDF use 4-by-4 matrix inversion, while D0 uses a more detailed description of the migration with a 26-by-50 matrix. The latter requires regularized unfolding, performed using curvature of probability density regularization. Both methods

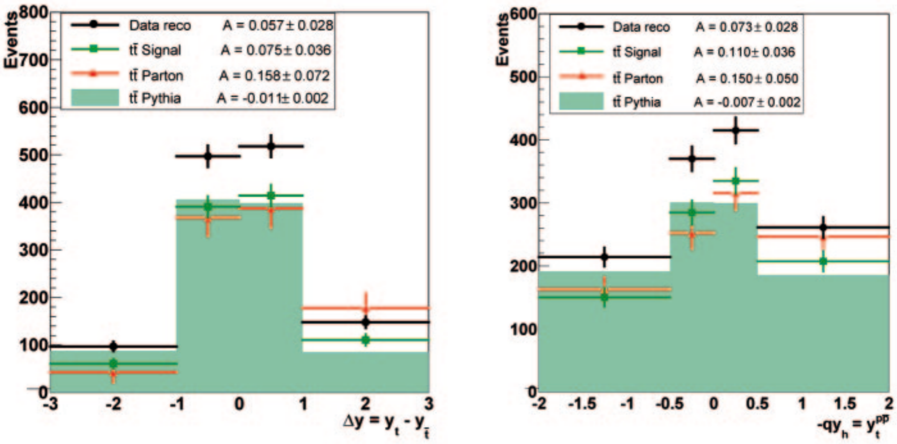

Fig. 1. – (Colour on-line) Reconstructed angular distributions from CDF.

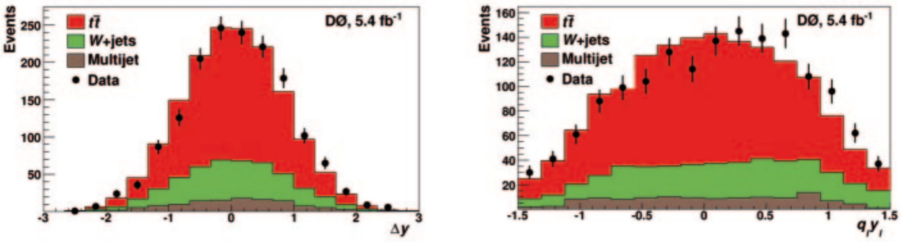

Fig. 2. – Reconstructed angular distributions from D0.

are validated using SM simulations and various viable BSM scenarios, which are also used to quantify the systematic uncertainties involved in the correction procedures(¹). The unfolded results are shown in fig. 3.

Both collaborations also report breakdowns of the asymmetry by $m_{t\bar{t}}$ and $|\Delta y|$ regions. At detector-level D0 find no significant dependence, as shown in fig. 4. CDF find significant dependences, and so report corrected results as shown in fig. 5. In particular, at high $m_{t\bar{t}}$ CDF measure an A_{FB} value that is 3.4 SD above the SM calculation. This statistical significance is unaffected by the unfolding procedure. The cut value of $m_{t\bar{t}} = 450\,\mathrm{GeV}$ was chosen by CDF *a priori*, using simulated BSM signals. The D0 analysis used the same cut. The di-lepton analysis, described below, also hints at an $m_{t\bar{t}}$ dependence, with a raw difference (*i.e.* before background-subtraction) of $\Delta A_{\mathrm{FB}}{}^{\mathrm{raw}} = (11 \pm 12)\%$. This despite having less experimental sensitivity to $m_{t\bar{t}}$.

The di-lepton measurement uses events that contain the following objects. At least two electrons or muons with $E_T > 20\,\mathrm{GeV}$ and either $|\eta| < 1.1$ or, for electrons, $1.2 < |\eta| < 2.8$. At least two jets with $E_T > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$. $\not{E}_T > 25\,\mathrm{GeV}$ or 50 GeV,

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(¹) Narrow s-channel resonances are particularly difficult for both procedures. However, such resonances are ruled out by direct searches.

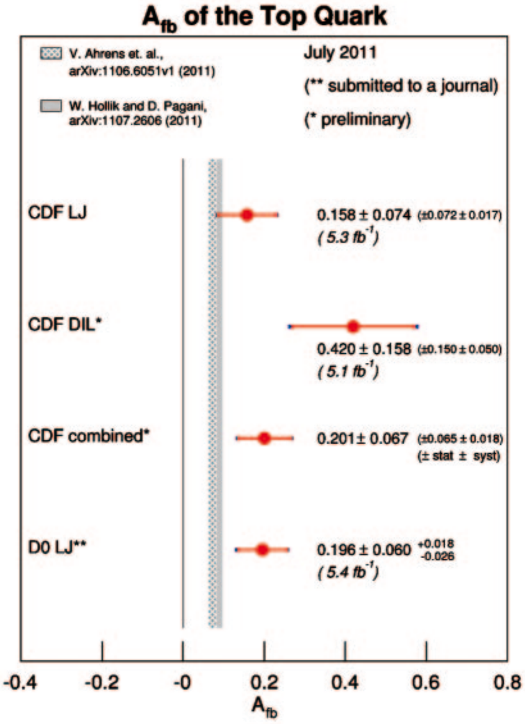

Fig. 3. – Summary of inclusive Δy-based A_{FB} measurements.

depending on the angular separation between the momentum imbalance and the selected jets and lepton. To further suppress background, events are also required to have a sum of object transverse energies, $H_T > 200\,\mathrm{GeV}$. 334 events are selected, with an estimated purity of $\approx 75\%$.

Event reconstruction is more difficult than in the l+jets channel as there are fewer observables. To compensate, *a priori* distributions of the $t\bar{t}$ system's kinematic variables (namely, $p_T^{t\bar{t}}$, $p_z^{t\bar{t}}$, and $m_{t\bar{t}}$) are used in a kinematic fit. The fit then yields excellent Δy reconstruction. The reconstructed Δy distribution is shown in fig. 6.

After background subtraction, CDF find $A_{\mathrm{FB}} = (21 \pm 7)\%$. The production-level asymmetry is extracted assuming that A_{FB} is linear in Δy. The procedure was validated for various SM and BSM models. At production-level, CDF find $A_{\mathrm{FB}} = (42 \pm 15(\mathrm{stat.}) \pm 4(\mathrm{syst.}))\%$, which is 2.6 SD away from no asymmetry, and 2.3 SD above the SM calculation used.

3. – Other observables

Asymmetries were also defined using lepton-based observables. The excellent experimental resolutions on these observables greatly simplifies unfolding and interpretation. They are sensitive to the $t\bar{t}$ A_{FB}, and to the top polarization [16].

In the di-lepton channel, CDF also measure an A_{FB} defined for $\Delta\eta_l = \eta_{l^+} - \eta_{l^-}$ (see fig. 7). After background subtraction CDF find $A_{\mathrm{FB}} = (21 \pm 7)\%$.

In the l+jets channel, D0 measure an A_{FB} defined according to the lepton charge and direction: $q_l y_l$ (see fig. 2). After background subtraction D0 find $A_{\mathrm{FB}} = (14.2 \pm 3.8)\%$.

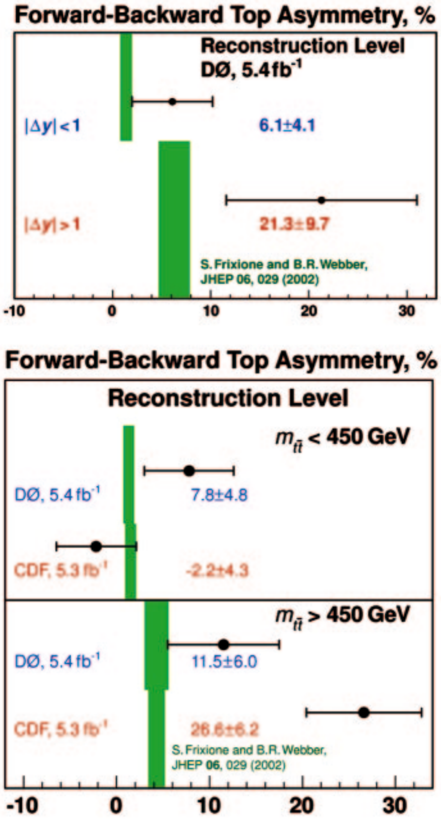

Fig. 4. – Reconstruction-level Δy-based A_{FB} measurements for selected subsamples.

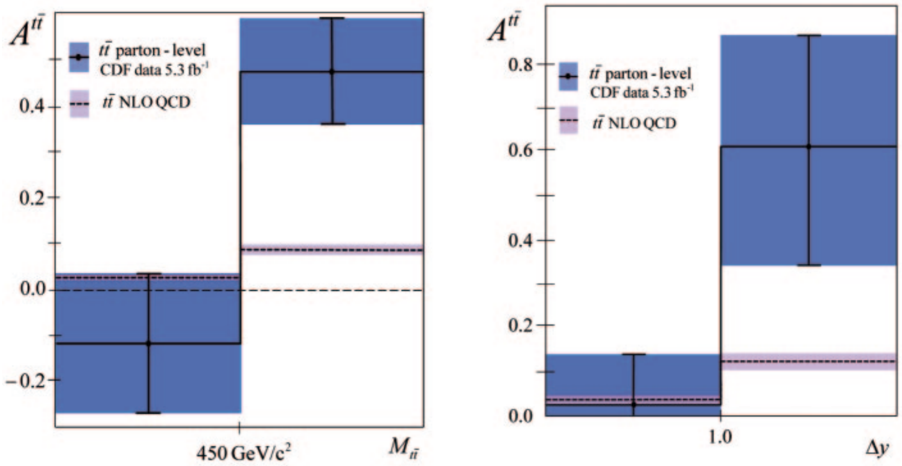

Fig. 5. – Generator-level Δy-based A_{FB} measurements for selected subsamples.

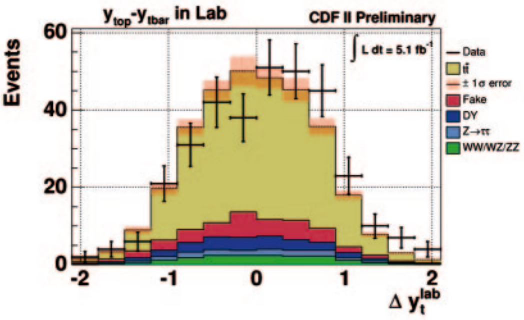

Fig. 6. – Reconstructed Δy distribution in di-lepton channel.

Due to the excellent lepton resolution, only acceptance corrections are needed. The production-level asymmetry is $A_{\mathrm{FB}} = (15.2 \pm 4.0)\%$, which is more than 3 SD above the MC@NLO [17] prediction $A_{\mathrm{FB}} = 2.1\%$.

In the CDF l+jets analysis, another observable is used, that offers experimental resolution superior to that on Δy. It is the reconstructed hadronic rapidity, signed by the lepton change, as shown in fig. 1. This observable is sensitive to the collision frame's boost, but this is compensated for by the superior resolution, which also leads to a more stable unfolding. A weaker mass dependence is observed for this angular variable.

4. – The top pair transverse momentum

The leading source of systematic uncertainty in the D0 analysis is the simulated correlation between the Δy-based A_{FB} and $p_T^{t\bar{t}}$. The MC@NLO simulation predicts a sizable dependence. This was further studied using the PYTHIA simulation [18], which highlighted that such a dependence can arise from the angular ordering of the initial state showers according to the direction of the hard scatter (see fig. 8). D0 also presents a rough check of the simulation of $p_T^{t\bar{t}}$, which indicates that the amount of additional radiation may be oversimulated (see fig. 9).

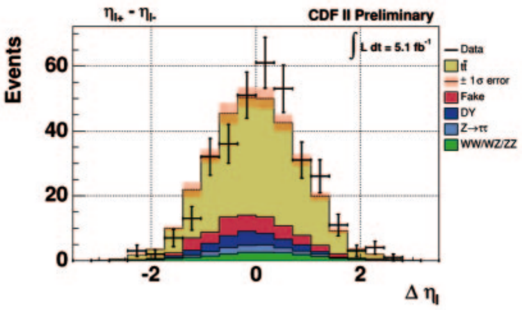

Fig. 7. – Reconstructed lepton pseudo-rapidity difference in di-lepton channel.

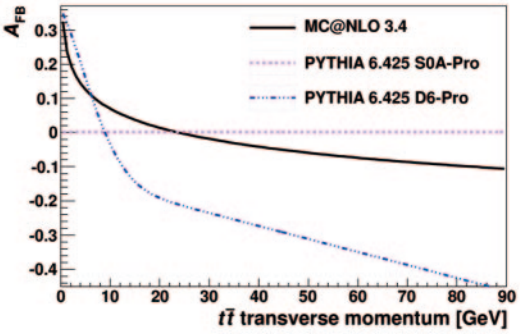

Fig. 8. – Simulated dependences of A_{FB} on $p_T^{t\bar{t}}$.

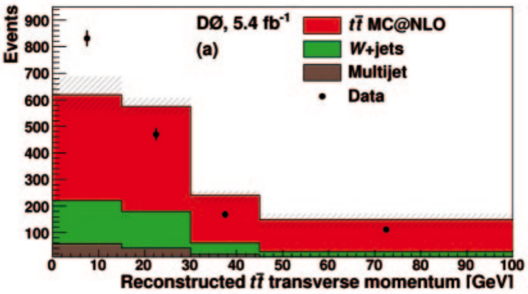

Fig. 9. – Reconstructed $p_T^{t\bar{t}}$ distribution. The hatched area represents systematic uncertainties due to jet reconstruction.

5. – Summary

Several forward-backward asymmetries in $t\bar{t}$ production were measured at the Tevatron. All are higher than calculated in the SM. The two biggest discrepancies, above three SD, are from the CDF high-$m_{t\bar{t}}$ measurement of the standard Δy-based A_{FB}, and from the D0 measurement of a lepton-based A_{FB}. Both collaborations measure, at production-level, inclusive Δy-based A_{FB}s of $\approx (20 \pm 6)\%$. A simple Gaussian combination suffices to show that taken together, these are roughly three SD higher than the SM calculations.

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