IL NUOVO CIMENTO Vol. 35 C, N. 1 Gennaio-Febbraio 2012
DOI 10.1393/ncc/i2012-11163-3

Colloquia: LaThuile11

Forward-backward asymmetry in $t\bar{t}$ production

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(ricevuto il 29 Settembre 2011; pubblicato online il 2 Febbraio 2012)

Summary. — We present new measurements of the forward-backward asymmetry in $t\bar{t}$ production, performed with 5 fb^{-1} of Tevatron p$\bar{\text{p}}$ collisions at center of mass energy 1.96 TeV, recorded and analyzed at CDF. Significant inclusive asymmetries are observed in both the lepton+jets and the dilepton decay modes of the $t\bar{t}$ pair. In the dilepton mode, the asymmetry is observed in the reconstructed top rapidity, and in the lepton rapidity difference which is independent of any top reconstruction. In the lepton plus jets sample, the full reconstruction of the top kinematics is used to measure the dependence of the asymmetry on the rapidity difference Δy and the invariant mass $M_{t\bar{t}}$ of the $t\bar{t}$ system, and the asymmetry is found to be most significant at large rapidity and mass.

PACS 14.65.Ha – Top quarks.

1. – Introduction

Top quark pair production is a test of QCD at large momentum transfer. This strong process is symmetric at leading order (LO), but has a small charge asymmetry (O(6%)) arising at order α_s^3 [1]. The top quark production angle or rapidity is measured in reconstructed lepton+jets events and used to calculate the simple asymmetry $A_{\text{FB}} = \frac{F-B}{F+B}$ which is corrected for backgrounds, acceptance and resolution effects to yield a "parton-level" asymmetry to be compared to theory.

In 2008 CDF and D0 published asymmetry measurements in the lepton+jets mode with 1–2 fb^{-1} that both found large positive asymmetries with large uncertainties [2]. CDF has recently completed a new series of measurements in which we update the sample to 5.3 fb^{-1} and explore both the lepton+jets and dilepton decay modes, and the charge, rapidity, and mass dependence of the asymmetry [3, 4].

These measurements have stimulated a number of models for new interactions in the top sector [5]. In one class of theories the gluon interferes with new axial s-channel objects arising from an extended strong gauge group or extra dimensions. Consistency with the measured top cross section and $M_{t\bar{t}}$ distribution requires masses greater than $\sim 2\,\text{TeV}/c^2$. Another broad class of theories posits potentially light t-channel objects with non-standard u-t or d-t flavor couplings, with the asymmetry then arising from dominance of the flavor-change into the forward Rutherford peak. Although the asymmetry itself is challenging to observe in the pp collisions of the LHC, many of these theories predict other new phenomena that can be detected at the Tevatron and LHC.

2. – Inclusive measurement in lepton+jets mode

We select 1260 "lepton+jets" events with a central e or μ with $p_T > 20\,\text{GeV}$, $\not{E}_{\text{T}} > 20\,\text{GeV}$, four or more jets with $E_T > 20\,\text{GeV}$, and at least one secondary vertex "b-tag". Non-$t\bar{t}$ background shapes and normalizations are understood in precision $t\bar{t}$ cross-section measurements [6] which predict 283 ± 91 non-$t\bar{t}$ events. The $t\bar{t}$ kinematics are reconstructed with a χ^2-based comparison of the jet-parton matching and neutrino solutions along with the constraints that $M_W = 80.4\,\text{GeV}/c^2$, $M_t = 172.5\,\text{GeV}/c^2$, and b-tagged jets are matched to b-partons.

We measure the frame-independent rapidity difference of the leptonic and hadronic top decay systems, Δy_{lh}. When weighted by the lepton charge q, this gives the top-antitop rapidity difference: $q\Delta y_{lh} = q(y_l - y_h) = y_t - y_{\bar{t}} = \Delta y$. In the limit of small $t\bar{t}$ system p_T this is simply related to the top quark rapidity in the $t\bar{t}$ rest frame: $y_t^{t\bar{t}} = \frac{1}{2}\Delta y$. The total asymmetry in the $t\bar{t}$ rest frame is

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

In QCD at NLO, a small charge asymmetry arises from the interference of q$\bar{\text{q}}$ processes behaving differently under charge conjugation. We use MCFM to predict a parton-level asymmetry of 0.058 ± 0.009. We also use the event generator MC@NLO with the CDF detector simulation and standard non-$t\bar{t}$ background models to predict a "data-level" asymmetry of 0.017 ± 0.004. (MCFM and MC@NLO calculations include 15% scale dependence uncertainty.) The data-level prediction is less than the statistical error of the current data set, so PYTHIA remains a good approximation of the standard model. To test our methods in the presence of large asymmetries we developed a simple coloron model with MADGRAPH and the CDF simulation, tuning the octet mass and couplings to produce an inclusive asymmetry similar to the data while minimizing the impact on $M_{t\bar{t}}$ and the $t\bar{t}$ cross-section.

The left plot in fig. 1 shows the distribution Δy in the data compared to Monte Carlo predictions. In the data, $A^{t\bar{t}} = 0.057 \pm 0.028$. The Δy_{lh} asymmetries in the separate lepton-charge species (not shown) are $A_{+}^{t\bar{t}} = 0.067 \pm 0.040$ and $A_{-}^{t\bar{t}} = -0.048 \pm 0.039$. With large errors, these are equal in magnitude and opposite in sign, as expected for a CP conserving charge asymmetry.

The Δy distribution can be corrected to the $t\bar{t}$ "signal-level" by subtracting backgrounds. Further correcting the signal for selection, acceptance, and resolution distortions provides "parton-level" measurements that can be compared to theoretical predictions. The correction is a simple linear unfold of Δy using a response matrix based on Pythia, and tested on an alternate Pythia sample, MC@NLO, and the color octet models. The raw and corrected asymmetries are shown in table I. At all levels the asymmetry exceeds the prediction with modest significance. The signal level is consistent with the value of 0.08 ± 0.04 recently reported by D0 [7]. The corrected $q\Delta y$ distribution can be used to calculate a crude rapidity dependent asymmetry in two bins of $q\Delta y$. In the $t\bar{t}$ rest frame we measure fully corrected asymmetries of $A^{t\bar{t}}(|\Delta y| < 1.0) = 0.026 \pm 0.118$

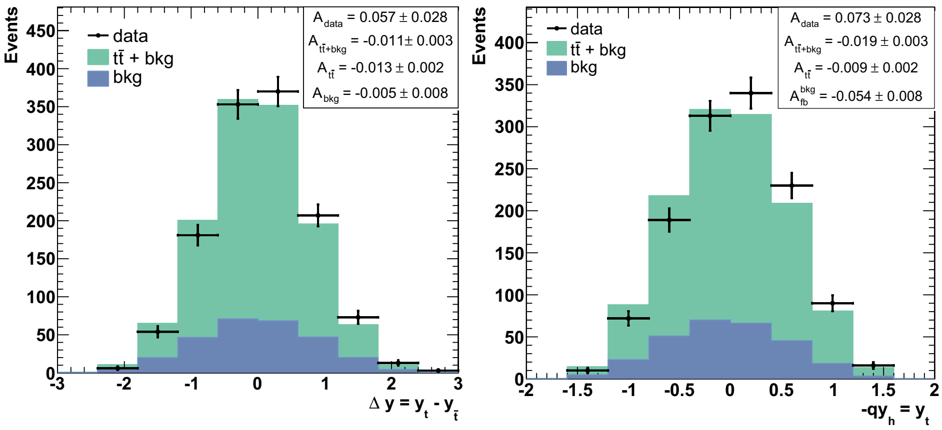

Fig. 1. – Charge-weighted rapidities and asymmetries in data and models. Left: Δy. Right: $-qy_h$.

and $A^{t\bar{t}}(|\Delta y| \geq 1.0) = 0.611 \pm 0.256$, compared with MCFM predictions of 0.039 ± 0.006 and 0.123 ± 0.008 for these Δy regions respectively.

3. – Asymmetry in dilepton mode

CDF has recently measured the inclusive $t\bar{t}$ forward-backward asymmetry in the dilepton decay mode [4]. We select 334 events with two opposite sign central leptons (e or μ) with $p_T > 20\,\text{GeV}$ and mass inconsistent with a Z-boson $m_{ll} = [75, 105]\,\text{GeV}/c^2$, $\not{E}_\text{T} > 25\,\text{GeV}$, two or more jets with $E_T > 20\,\text{GeV}$, and total scalar energy $H_t > 200\,\text{GeV}$. The non-$t\bar{t}$ background is estimated to be 87 ± 17 events.

The difference of the lepton pseudo-rapidities $\Delta\eta = \eta_+ - \eta_-$, is correlated with Δy and has none of the multijet, $\not{E}_\text{T}$, and b-tagging vagaries of the lepton+jets sample. We define the inclusive asymmetry

$$A^{\Delta\eta} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}\,. \tag{2}$$

The $A^{\Delta\eta}$ measurement is tested in large Z-boson samples as a function of associated jet multiplicity and yields the expected electroweak asymmetries with very good

TABLE I. – *Summary of lepton+jet asymmetries $A^{t\bar{t}}$ at data, signal, and parton level.*

Sample	Level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004
data	signal	0.075 ± 0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005
data	parton	0.158 ± 0.074
MCFM	parton	0.058 ± 0.009

TABLE II. – *Asymmetries $A^{\Delta\eta}$ in the dilepton selection. Statistical errors only.*

Selection	$= 0$ jets	$= 1$ jet	≥ 2 jets
reco data	-0.038 ± 0.047	0.040 ± 0.057	0.138 ± 0.054
MC@NLO	-0.026 ± 0.037	-0.009 ± 0.053	-0.022 ± 0.022

precision. With the top like selection including Z-veto and missing E_T, we measure in $\Delta\eta$ while controlling the multiplicity of jets. Events with 0 jets are dominated by W-pair production, while those with 1 jet are a mix of WW, Drell-Yan, $Z \to \tau\tau$, and $W+$ jets with a fake lepton. Events with 2 jets are the $t\bar{t}$ selection. $A^{\Delta\eta}$ for each category, along with the prediction, are shown in table II. The background dominated 0 and 1 jet events have small asymmetries consistent with prediction (and 0), while the $t\bar{t}$ dominated 2 jet sample shows a significant positive asymmetry. The $\Delta\eta$ distribution in the 2 jet sample is shown in fig. 2.

A simple transformation to the parton-level value is derived based on the minimal assumption that $A(\Delta y)$ is proportional to Δy. The reconstructed parton level asymmetry is found to be $A^{t\bar{t}} = 0.475 \pm 0.114$. The asymmetry is positive by $\sim 3\sigma$, like the lepton+jets sample. The asymmetries of the dilepton and lepton plus jets samples differ by 1.7σ

4. – Mass dependence in lepton+jets mode

We generally expect the $M_{t\bar{t}}$ dependence to contain information on the fundamental asymmetry mechanism. The NLO QCD asymmetry grows linearly to 15% at $M_{t\bar{t}} \sim 800\,\text{GeV}/c^2$ and other models predict alternative mass dependences [5]. Using the full reconstruction in the lepton+jets sample, a mass-dependent asymmetry $A^{t\bar{t}}(M_{t\bar{t}})$ is found by dividing the data into bins of mass $M_{t\bar{t},i}$ and examining the Δy distribution in each:

$$A^{t\bar{t}}(M_{t\bar{t},i}) = \frac{N(\Delta y > 0, M_{t\bar{t},i}) - N(\Delta y < 0, M_{t\bar{t},i})}{N(\Delta y > 0, M_{t\bar{t},i}) + N(\Delta y < 0, M_{t\bar{t},i})}. \tag{3}$$

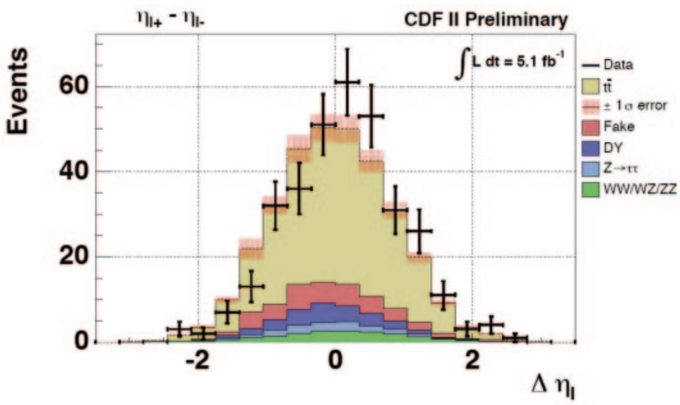

Fig. 2. – $\Delta\eta$ distribution in the 2-jet top selection. $A^{\Delta\eta} = 0.138 \pm 0.054$.

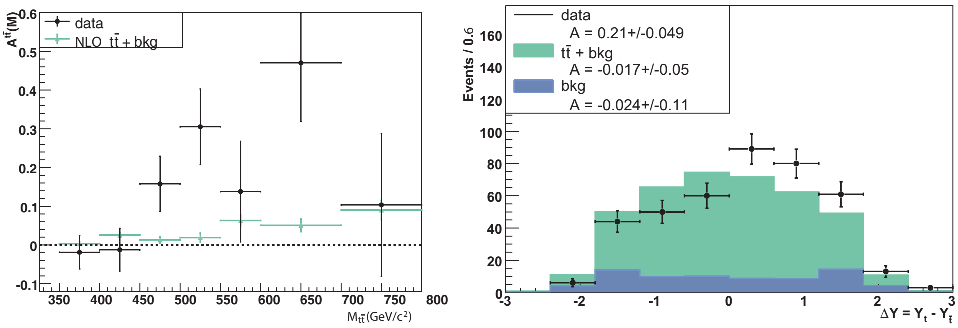

Fig. 3. – Left: Asymmetry Δy in bins of $M_{t\bar{t}}$, compared to the prediction of MC@NLO $t\bar{t}$ + backgrounds. Statistical errors only. The last bin includes all $M_{t\bar{t}} \geq 700\,\mathrm{GeV}/c^2$. Right: Δy for events with $M_{t\bar{t}} > 450\,\mathrm{GeV}/c^2$

The measured $A^{t\bar{t}}(M_{t\bar{t},i})$ is shown on the left in fig. 3, compared to the prediction (MC@NLO + bkg). At high mass the asymmetry is consistently above the prediction. To quantify $A^{t\bar{t}}(M_{t\bar{t}})$ in a simple, statistically robust way, we use a compact representation of $A^{t\bar{t}}(M_{t\bar{t},i})$ into just two $M_{t\bar{t}}$ bins, below and above a given mass boundary. In the color-octet samples, which have $A^{t\bar{t}}(M_{t\bar{t},i})$ distributions that are comparable to the data, the significance of the asymmetry at high mass is maximized when the bin division is at $M_{t\bar{t}} = 450\,\mathrm{GeV}/c^2$, and we adopt this boundary.

The first lines of table III show the high and low mass asymmetries and the MC@NLO prediction. At low mass the asymmetry is consistent with zero. At high mass the reconstructed asymmetry $A^{t\bar{t}} = 0.210 \pm 0.049$ is more than three standard deviations above the prediction. The right panel in fig. 3 shows the Δy distribution for the $M_{t\bar{t}} > 450\,\mathrm{GeV}/c^2$.

The asymmetries in Δy_{lh} for separate lepton charge species are given in the bottom part of table III. Under the interchange of lepton charge, the asymmetry at high mass is reversed in a manner consistent with CP conservation. This argues against a false positive arising in event selection or $t\bar{t}$ reconstruction, as neither contains information on the lepton charge.

5. – Asymmetry in the laboratory frame

The well-measured rapidity of the hadronic top decay system y_h, multiplied by the opposite of the lepton charge, yields the top rapidity in the laboratory frame. The

TABLE III. – *Asymmetries at the data-level in the l+jets sample. Data has statistical errors only.*

Selection	All $M_{t\bar{t}}$	$M_{t\bar{t}} < 450\,\mathrm{GeV}/c^2$	$M_{t\bar{t}} \geq 450\,\mathrm{GeV}/c^2$
reco data	0.057 ± 0.028	-0.016 ± 0.034	0.210 ± 0.049
MC@NLO	0.017 ± 0.004	0.012 ± 0.006	0.030 ± 0.007
A^{+}_{lh}	0.067 ± 0.040	-0.013 ± 0.050	0.210 ± 0.066
A^{-}_{lh}	-0.048 ± 0.039	0.020 ± 0.047	-0.210 ± 0.071

TABLE IV. – *Reconstruction level asymmetries $A^{\mathrm{p\bar{p}}}$ in the laboratory frame. Data has statistical errors only.*

Selection	All $M_{t\bar{t}}$	$M_{t\bar{t}} < 450\,\mathrm{GeV}/c^2$	$M_{t\bar{t}} \geq 450\,\mathrm{GeV}/c^2$
data reco	0.073 ± 0.028	0.059 ± 0.034	0.103 ± 0.049
MC@NLO +bkg	0.001 ± 0.003	-0.008 ± 0.005	0.022 ± 0.007
A_h^+	-0.070 ± 0.040	-0.028 ± 0.050	-0.148 ± 0.066
A_h^-	0.076 ± 0.039	0.085 ± 0.047	0.053 ± 0.072

inclusive $-qy_h$ distribution is shown in the right plot of fig. 1 and the data level asymmetries are shown in table IV. Because the backgrounds in the lab frame enter with a negative asymmetry, the predicted lab frame asymmetry is $A^{\mathrm{p\bar{p}}} \sim 0$. The measurement is 2.6σ above that prediction. The NLO effect predicts that $A^{\mathrm{p\bar{p}}} < A^{t\bar{t}}$, which is not seen in the inclusive measurement, although the uncertainty is large. At high mass, the ratio $A^{\mathrm{p\bar{p}}}/A^{t\bar{t}} = 0.49 \pm 0.23$ is less than the MC@NLO prediction of 0.74, but the uncertainty is again large. With improved precision, the ratio $A^{\mathrm{p\bar{p}}}/A^{t\bar{t}}$ may provide discrimination between NLO QCD and other models for the asymmetry.

6. – Conclusion

A significant forward-backward asymmetry is measured in inclusive $t\bar{t}$ production in two different decay modes. In the lepton+jets mode, there is evidence that the asymmetry arises from the small population of events at large Δy and $M_{t\bar{t}}$, and a suggestion that asymmetries in the lab frame and $t\bar{t}$ frame contain independent information. If the asymmetry is real it could be evidence for new interactions in the top sector or unexpected behavior of QCD at higher order.

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We thank the organizers for including this special talk and also for a stimulating and enjoyable conference. We acknowledge the assistant of T. TAIT with the MADGRAPH model of the color octet.

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