The top quark forward-backward asymmetry at CDF

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Summary. — The top forward-backward asymmetry at the Tevatron is larger than predicted by the standard model. We measure the inclusive asymmetry, the asymmetry of the lepton in semi-leptonic top quark pair decays, and the moments of the top quark angular distribution. We observe a consistency among these measurements, and an excess linear term in the differential cross section $d\sigma/d\cos\theta_t$.

14.65.Ha, 11.30.Er, 12.38.Qk

1. – Inclusive $A_{\mathbf{FB}}$

The large mass of the top quark may indicate that it is somehow connected to new phenomena, and so the detailed study of the top quark is a large and active area of research in particle physics. One of the most interesting topics under study is the forward-backward asymmetry in top quark pair production at the Tevatron.

The Tevatron produced top quark pairs from a proton-antiproton initial state. This state is a CP-even eigenstate, and so any charge-asymmetric features of top quark pair production would manifest as a forward-backward asymmetry at the Tevatron.

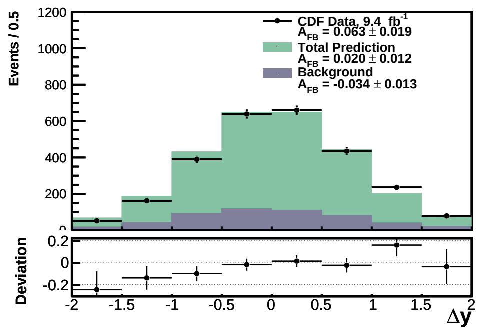

Fig. 1. – Δy at the detector level

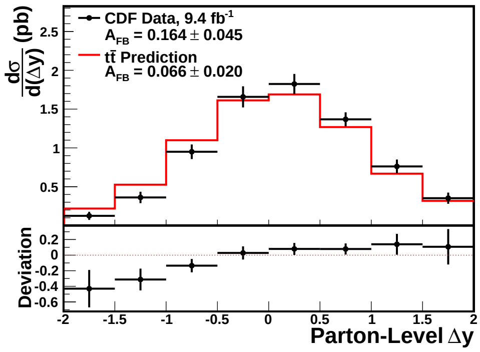

Fig. 2. – Δy at the parton level

We select a sample of events from the CDF data which is expected to be enriched in top quark pair production and we reconstruct the top quark and top anti-quark four-vectors from their decay products, as documented in [1]. The asymmetry is defined as

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

where Δy is the rapidity difference $y(t) - y(\bar{t})$. This quantity is invariant under boosts along the beamline, and so is convenient to use at a hadron collider. At next-to-leading order (NLO) in the standard model (SM), the A_{FB} is predicted to be $(6.6 \pm 2.0)\,\%$ [2].

The distribution of Δy is shown in fig. 1. This distribution includes the effects of non-$t\bar{t}$ backgrounds, events failing the selection requirements or falling outside the geometric acceptance of the detector, and the finite resolution of the detector. In order to compare the A_{FB} to theoretical predictions, we must correct for these effects. We subtract the backgrounds from the data and correct to the parton level using a singular-value-decomposition unfold [3]. The unfolded result is shown in fig. 2. At parton-level,

$$A_{\mathrm{FB}} = (16.4 \pm 4.5)\,\%,$$

which is 2.2 standard deviations larger than the SM prediction at NLO.

It is also important to investigate the A_{FB} as a function of various kinematics, such as the mass of the $t\bar{t}$ pair and the absolute value of Δy. These are shown in fig. 3, also corrected to the parton level. The data and the prediction both show an approximately linear dependence on each variable, but the slope in the data exceeds the slope in the prediction by 2.3 standard deviations. Fig. 4 shows the dependence of the A_{FB} on the transverse momentum of the $t\bar{t}$ system. This is sensitive to various soft QCD effects, and we note that the shape of the dependence is predicted correctly, but the overall magnitude of the asymmetry is not.

2. – Leptonic asymmetry

The direction of the charged lepton from top quark decay is kinematically correlated with the direction of the parent top quark. Because the reconstructed direction of the

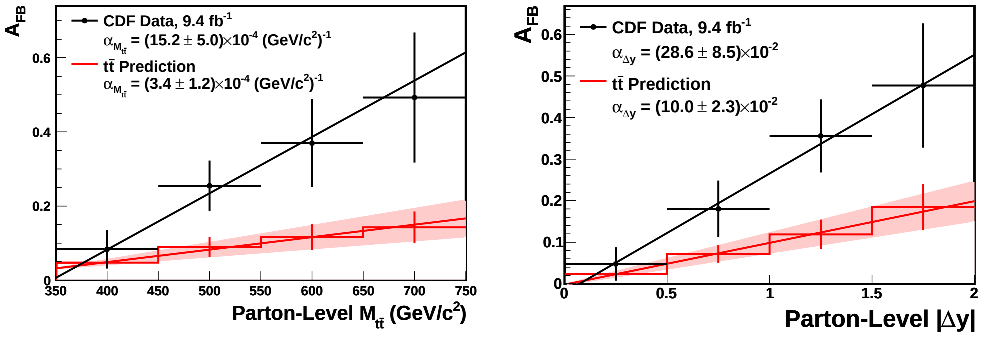

Fig. 3. – Dependence of A_{FB} on $M_{t\bar{t}}$ and on $|\Delta y|$

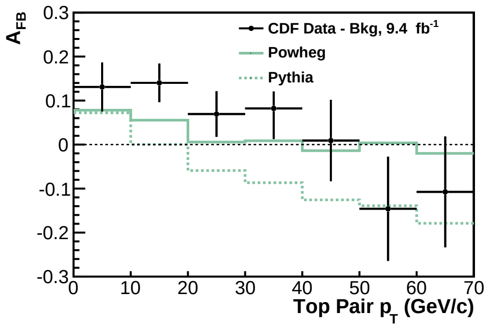

Fig. 4. – Dependence of A_{FB} on $p_T(t\bar{t})$

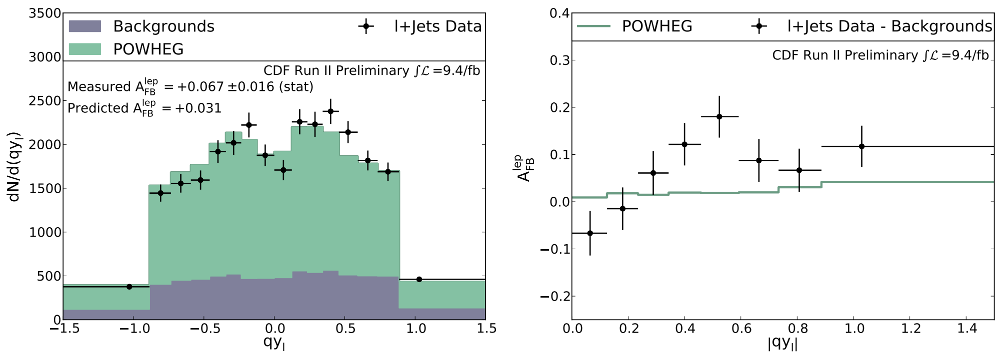

Fig. 5. – The charge-weighted lepton rapidity distribution and lepton asymmetry as a function of $|y_\ell|$

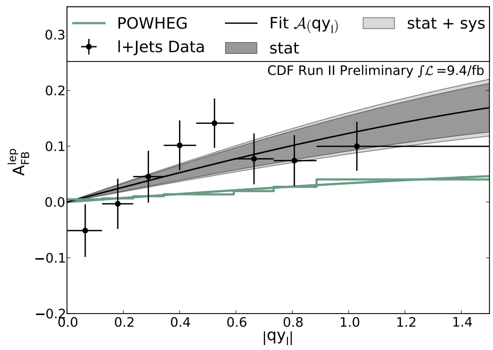

Fig. 6. – Leptonic asymmetry after correction for backgrounds and selection inefficiencies, along with fit to hyperbolic tangent model

charged lepton does not depend on the $t\bar{t}$ reconstruction procedure, a measurement of the leptonic forward-backward asymmetry, $A^{\ell}_{\rm FB}$, provides a means to verify that the observed top quark pair $A_{\rm FB}$ is not an artifact of our reconstruction procedure. Due to the kinematic correlations, we expect

$$A^{\ell}_{\rm FB} \simeq 7\,\%,$$

given the measured $t\bar{t}$ $A_{\rm FB}$. The NLO SM predicts $A^{\ell}_{\rm FB} = (3.6 \pm 0.2)\,\%$ [4].

As in the measurement of the $t\bar{t}$ $A_{\rm FB}$, we must account for effects arising from non-$t\bar{t}$ backgrounds and from inefficiencies in selecting $t\bar{t}$ events. In order to do this, we measure the distribution of the lepton rapidity multiplied by its charge, qy_ℓ, subtract the backgrounds from the data, and find the $A^{\ell}_{\rm FB}$ as a function of the absolute value of the lepton rapidity (fig. 5). We then correct for selection-efficiency effects and fit $A^{\ell}_{\rm FB}(|y_\ell|)$ to a model $a\tanh(qy_\ell/2)$ (fig. 6). From the fitted parameters, we extract the inclusive leptonic asymmetry,

$$A^{\ell}_{\rm FB} = 9.4 \pm 2.4^{+2.2}_{-1.7}\%.$$

This compares favorably with the expectation from the $t\bar{t}$ $A_{\rm FB}$, and is in excess of the NLO SM prediction by 2.3 standard deviations.

3. – Angular differential cross section

The full differential cross section for $t\bar{t}$ production in various models (including both the standard model and models of new physics), are parameterized by the mass scale of the interaction, $\hat{s}$, and the production angle, $\cos\theta_t$. The production angle is the angle between the momenta of the incoming parton (from the proton) and the outgoing top quark, as measured in the center-of-mass frame.

In particular, each of the various models exhibits a distinct behavior as a function of $\cos\theta_t$ (fig. 7). The SM at leading order predicts that the differential cross section should have constant and quadratic terms, while the NLO corrections produce additional terms at all polynomial degrees. Models with a new particle which produces $t\bar{t}$ in the s-channel

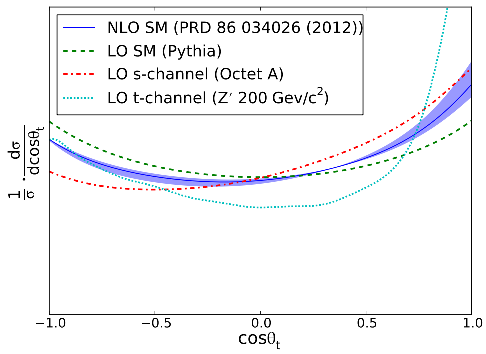

Fig. 7. – Differential cross section in several models

(such as a heavy, axial-vector copy of the gluon) predict an additional term which is linear in $\cos\theta_t$. Models with a new particle which produces $t\bar{t}$ in the t-channel (such as a flavor-changing Z' with u–Z'–t coupling) predict an additional term $\hat{s}/\hat{t} \sim 1/(1-\cos\theta_t)$ [5]. A measurement of the differential cross section $d\sigma/d\cos\theta_t$ may then be able to discriminate among these models.

We employ the orthonormal Legendre polynomials [6], which are integral to the theory of scattering and angular momentum, to characterize the shape of the differential cross section. Projecting the predictions of the models described above onto the Legendre polynomials,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_t} = \sum_{\ell} a_\ell P_\ell(\cos\theta_t),$$

results in the Legendre moments a_ℓ (coefficients multiplying each Legendre polynomial) shown in fig. 8. We scale all the moments so that the zeroth moment, a_0, is unity. The leading order SM prediction has a non-zero 2nd moment, and the NLO SM has additional contributions at all degrees. The s-channel model has an excess first moment,

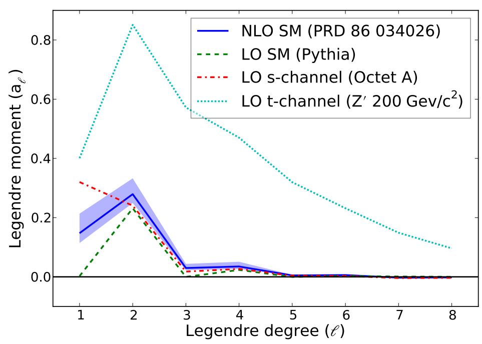

Fig. 8. – Legendre moments of several models

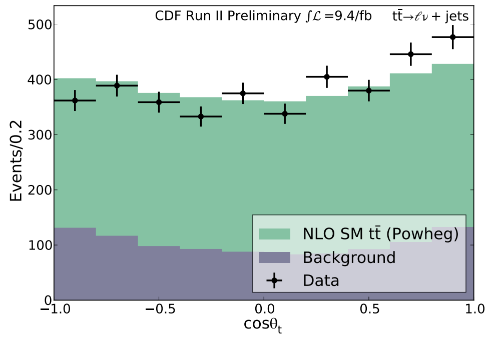

Fig. 9. – Distribution of $\cos\theta_t$ before any corrections for detector resolution and acceptance effects

a_1, compared to the leading order SM, and the t-channel model has large moments at all degrees.

We project the detector-level $\cos\theta_t$ distribution (fig. 9) onto the Legendre polynomials, subtract the Legendre moments of the backgrounds, and then correct to the parton level following a similar procedure to that used for the inclusive A_{FB}. The correction procedure for the Legendre moments does not employ any regularization, in contrast to the inclusive A_{FB}. The parton-level Legendre moments are shown in fig. 10. We observe good agreement with the NLO SM prediction, with the exception of an excess first moment. The first moment is 2.2 standard deviations larger than predicted.

Because the A_{FB} must arise from some feature of the differential cross section, it is also of interest to explore which features of the measured differential cross section account for the asymmetry. The even-degree Legendre polynomials are symmetric, and so contribute no asymmetry. The odd-degree polynomials are anti-symmetric, and so the asymmetry must be explained by some combination of non-zero odd-degree Legendre moments. Fig. 11 shows the contribution of each measured Legendre moment to the A_{FB}, and the contribution of the linear term against the contribution of all the non-linear terms

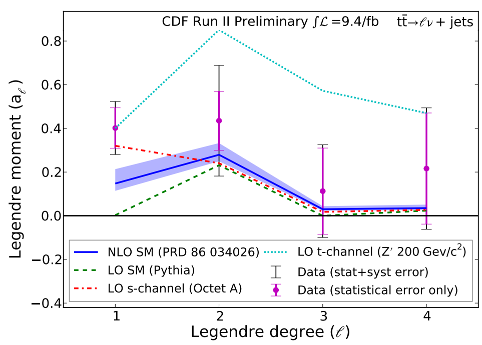

Fig. 10. – Measured Legendre moments after correction to parton level

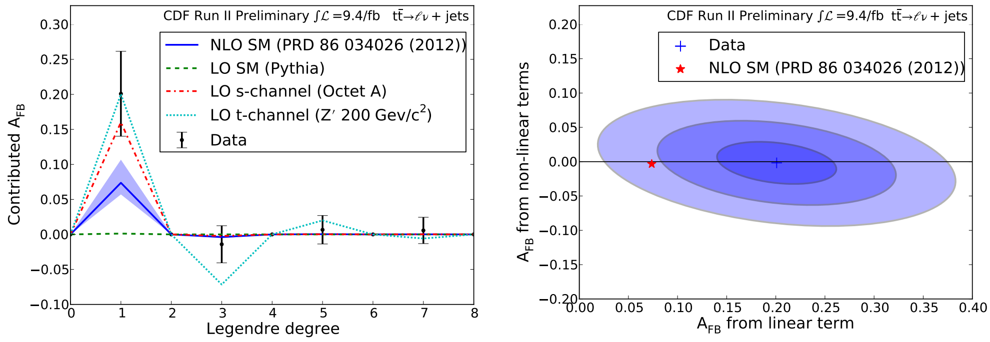

Fig. 11. – Contribution of each moment to the asymmetry, and contribution of the linear term and the non-linear terms to the asymmetry.

to the A_{FB}. The linear term dominates the asymmetry.

4. – Conclusion

The top quark pair forward backward asymmetry is larger than predicted by the standard model. It depends approximately linearly on the top quark pair mass and on the top quark pair rapidity difference. The shape of the dependence of the A_{FB} on the top quark pair transverse momentum is predicted by the SM, but the magnitude of the asymmetry is not. When examining only the lepton in the semi-leptonic $t\bar{t}$ decay, we observe an asymmetry which is consistent with the top quark pair asymmetry. We observe an excess linear term in the differential cross section $d\sigma/d\cos\theta_t$ which is sufficient to explain the asymmetry.

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[6] We normalize the Legendre polynomials so that $\frac{2\ell+1}{2}\int_{-1}^{1} \mathrm{d}x P_\ell(x) P_{\ell'}(x) = \delta_{\ell\ell'}$.