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Asymmetries in the angular distributions in the $t\bar{t}$ system

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We review the status of the forward–backward asymmetry measurements in the pair production of top and antitop in proton–antiproton collisions. We also comment on the charge asymmetry in the production of the $t\bar{t}$ system in the proton–proton collisions.

Keywords: Top quark; asymmetry; QCD.

1. Introduction

Asymmetries in the pair production of top–antitop quarks in hadronic collisions have gained a lot of attention because the size of the effect exceeded the predictions based on the Standard Model (SM). To understand the basis for these predictions as well as the importance of this measurement and its experimental subtleties, it is instructive to review its historic predecessor — the asymmetry of fermion pair production in electron–positron collisions. One of the first indications of the existence of the Z-boson was an observation of the forward–backward asymmetry in the production of muon pairs in e^+e^- collisions observed at PETRA at the center-of-mass energy of 30 GeV/c,[1] significantly below the Z-boson mass. The observed negative asymmetry of -8% indicated that the mediator of the electroweak interaction has a nonzero axial coupling to fermions, or in other words, its coupling to left-handed fermions is not equal to that to right-handed fermions. By analogy, should a strong interaction be left–right asymmetric, as was hypothesized in some models, it would be manifested in the forward–backward asymmetry of quark–antiquark production in $p\bar{p}$ collisions.[2] Since the top quark is the heaviest known quark, measuring asymmetry in top-pair production probes the nature of strong interactions at the highest energy scale.

The raw negative measured asymmetry in muon pair production was corrected for a small positive asymmetry expected purely due to the next-to-leading (NLO) order quantum electrodynamics (QED) effect,[3] which is an electromagnetic attraction of the final state positive muon to the initial state electron and its repulsion from the initial state positron, as well as its charge conjugate terms. The fact that the weak contribution to the asymmetry was of the opposite sign to that of the expected one which is purely from QED made it easier to establish that the effect is due to the exchange of a new particle — Z-boson. Similarly, a positive asymmetry in the quark-pair production in proton–antiproton collisions is expected at the NLO due to the Coulomb-like strong attraction of quarks to antiquarks. The first estimation of this effect in the production of top–antitop pairs was done using a simple scaling from the calculation of the asymmetry due to electromagnetic interaction.[4] The effect is more significant for strong interactions due to a larger coupling constant and the number of possible color combinations. Thus, from the theoretical point of view, there is a direct parallel between the asymmetries in $e^+e^- \to \mu^+\mu^-$ and $p\bar{p} \to t\bar{t}$ processes. Both are due to the NLO exchange of the vector mediators (photons or gluons) and a potential exchange of mediators with an axial component (Z-boson or a hypothetical new particle — axigluon). From the experimental point of view, measuring the asymmetry in top-pair production is far more challenging. First of all, unlike electrons, protons are composite particles and the center-of-mass system of the initial state quark–antiquark is not defined in a straightforward way. Second, unlike muons whose trajectory is directly observed by the detectors, top quarks are reconstructed from their decay products with the resultant ambiguities.

In this review, we discuss measurements of the forward–backward asymmetry in $p\bar{p} \to t\bar{t}$ production at the center-of-mass energy of 1.98 TeV at the Tevatron performed by CDF and D0. We also cover the results of the charge asymmetry measurement in $pp \to t\bar{t}$ process obtained by the large hadron collider (LHC) experiments Atlas and CMS. All four experiments are general purpose devices designed to identify muons, electrons and photons, register tracks from charged particles, and measure energy of the particles interacting with the calorimeter material.

2. Definitions

In e^+e^- collisions, the angle θ between the positive muon direction and the incoming positron is used to describe the angular distributions. The forward–backward asymmetry is defined as the difference between the number of events with positive $\cos(\theta)$ and the ones with negative $\cos(\theta)$, divided by the total number of events. In hadronic collisions, rapidity, y,[a] is commonly used instead of angle θ. This variable is invariant under the boost along the z-axis. As a result, the asymmetry defined using the difference in rapidity of top (y_t) and antitop quarks ($y_{\bar{t}}$) in the laboratory frame is equivalent to asymmetry in the $t\bar{t}$ rest frame, and is identical to the definition using $\cos(\theta)$:

[a] The rapidity y is defined as $yt(\theta, \beta) = \frac{1}{2}\ln[(1 + \beta\cos(\theta))/(1 - \beta\cos(\theta))]$, where θ is the polar angle and β is the ratio of a particle's momentum to its energy. The angle $\theta = 0$ corresponds to the direction of the incoming proton.

$$\Delta y = y_t - y_{\bar{t}}\,, \tag{1}$$

$$A_{\rm FB} = \frac{N_f - N_b}{N_f + N_b}\,, \tag{2}$$

where N_f is the number of "forward" events, i.e. the ones having $\Delta y > 0$ and N_b is the number of "backward" events with $\Delta y < 0$.

Experimental ambiguities result in both smearing and bias of the top-quark rapidity determination and thus affect asymmetry measurement. It is convenient to define the asymmetry at the reconstruction level as well as at production, with the former typically being smaller than the later. In our discussion, we will refer to the asymmetry defined using reconstruction level objects as reconstructed asymmetry, while the asymmetry that uses top-quark kinematics at production is referred to as generated asymmetry. Experimentally generated asymmetry is obtained from the reconstructed distributions using a special technique called "unfolding".

In addition to asymmetry defined for the fully reconstructed $t\bar{t}$ system, we define an asymmetry of leptons from top decay with rapidity y_l and charge q_l, $A^l_{\rm FB}$. In this case, forward events are the ones that have $q_l y_l > 0$ and backward events are the ones for which this quantity is negative. This leptonic asymmetry is simpler to reconstruct, yet it is correlated with the fully reconstructed asymmetry and thus serves as a valuable cross-check. It is also sensitive to the top-quark polarization, which helps to distinguish between different models.

In the dilepton channel it is possible to define an asymmetry $A^{ll}_{\rm FB}$, based on the difference in rapidity of positive (y_{l^+}) and negative (y_{l^-})leptons: ($\Delta y_{ll} = y_{l^+} - y_{l^-}$). In this case the forward events are the ones with $\Delta y_{ll} > 0$, and the backward events are the ones with $\Delta y_{ll} < 0$.

3. Theoretical Predictions

There are several good reviews of the theoretical developments on the subject,[5] here we just give a short overview.

3.1. *Standard Model*

In the perturbative QCD calculation, the first nonzero contribution to the forward–backward asymmetry in the $t\bar{t}$ system appears at the α_s^3 order, where α_s is the strong coupling constant. At this order, there are two classes of events with nonzero asymmetry. Tree-level production (α_s^2) results in events that show no preference for forward or backward directions. The box diagram (α_s^4) describes the Coulomb-like strong attraction of tops to incoming antiquarks and repulsion from incoming quarks, which leads to the preferred production of forward events. The interference between the tree-level diagram and the box diagram (α_s^3) gives rise to the first class of the $t\bar{t}$ events. They contribute to the positive asymmetry. The second class of events, which results from the interference of the diagrams that include radiation of gluons in the initial or final state, exhibits slight preference to the production of backward events leading to negative asymmetry. Color coherence in gluon radiation leads to the gluon being irradiated predominantly between the direction of the top quark and the incoming quark, or antitop and the incoming antiquark. Backward events, where the top direction is closer to that of the incoming antiquark rather than quark, have more phase space for such correlated irradiation and, thus, are more probable. If the irradiated gluon is sufficiently hard and within the detector acceptance, it may be reconstructed as an extra jet in addition to those from the $t\bar{t}$ decay. These events are also characterized by a higher transverse momentum of the $t\bar{t}$ system than events of the first class due to the recoil from the irradiated gluon. The overall asymmetry is positive, but the expected asymmetry depends on the jet multiplicity and the transverse momentum of the $t\bar{t}$ system.

Until recently the $t\bar{t}$ cross-section has been calculated only at the α_s^3 order. Since the asymmetry only appears at this order, no full NLO treatment of this effect is available. Recently the calculation of the full $t\bar{t}$ cross-section at the α_s^4 order was performed,[6] yet the asymmetry predictions are still pending. Several attempts were made to calculate the most significant contributions,[7] including those due to electroweak interaction,[8] resulting in a variety of predictions ranging from 5% to 9%. Some authors argue that the interaction of the top quark with the proton remnants cannot be considered negligible, leading to asymmetry predictions as large as 12%.[9] For simplicity in this review, we compare the experimental results to the MC@NLO simulation,[10] which predicts an overall asymmetry of 5% in $p\bar{p}$ collisions.

3.2. *Beyond Standard Model*

Since the experimental results are higher than the prediction using the Standard Model, a number of Beyond Standard Model (BSM) scenarios were suggested to explain the effect. They can be divided into two classes of models, the ones where the $t\bar{t}$ production is mediated by heavy particle that has nonzero axial coupling to quarks in the s-channel,[11] and the ones that involve $t\bar{t}$ production in the t-channels,[12] in which case the mediating current does not need to have an axial component.

In $p\bar{p}$ collisions, the $t\bar{t}$ system is four times more likely to be produced in the annihilation of $u\bar{u}$ quarks than of $d\bar{d}$ quarks.[b] To explain positive asymmetry using an s-channel mediator, there are two possible scenarios — either the mediator axial coupling to u- and t-quarks have an opposite sign and the probed center-of-mass energies are predominantly below the resonances mass, or the mediator axial coupling to u- and t-quarks have the same sign, but its mass is below the energies probed. The $t\bar{t}$ production is dominated by the energies close to the threshold, which is about 350 GeV. Resonances of such mass can elude discovery only if they are very broad, which excludes models predicting Z' type of resonance.[13] Axigluons, hypothetical particles that arise in the SM extensions that predict axial strong currents, can potentially be broad and thus escape the detection to date.[14]

[b]In pp collisions, it is only twice as likely.

4. Reconstruction of $t\bar{t}$ Events

A $t\bar{t}$ event is reconstructed from the top and antitop-decay products. Almost, a top quark always decays to a bottom quark and a W-boson: $t \to bW$. A W-boson can decay either hadronically: $W \to q\bar{q}'$, or leptonically: $W \to l\bar{\nu}_l$. Events are classified based on the mode of W-boson decay. A channel where both W-bosons decay hadronically is called "alljets". Events with both W-bosons decaying leptonically are referred to as "dileptons". An event with one of the W-bosons decaying leptonically and the other one hadronically is referred to as "lepton + jets" ($l +$jets). For the asymmetry measurement, it is essential to distinguish top quark from antitop. Lepton from W-boson decay tags the sign of the leptonically decaying top quark. Thus, only $l +$ jets and dilepton channels are suitable for the asymmetry measurement. In the $l +$ jets channel, hadronically decaying top is assumed to have the charge opposite to the leptonically decaying top. For the asymmetry measurement, full top- and antitop-quark kinematics must be reconstructed which implies that reconstructed objects must be uniquely matched to top decay products.

4.1. *Lepton + jets channel*

The $l +$ jets final state contains two b-quarks from top decay, two light quarks from the hadronic W-boson decay and a lepton and a neutrino from the leptonic W-boson decay. Since the reconstruction of the fast decaying τ-lepton is usually challenging, experimentalists mostly limit themselves to muons and electrons from top decay. Quarks hadronize as jets of charged and neutral particles, reconstructed in the tracking systems and in the calorimeters. b-jets can be identified by the presence of a displaced vertex or several tracks with a significant impact parameter with respect to the interaction vertex. $l +$ jets is an ideal system to measure the $t\bar{t}$ asymmetry. Leptons provide a highly reliably charge determination. About 40% of $t\bar{t}$ events decay this way, so the statistics is high. The information about the lost neutrino is recovered using the missing transverse energy measurement and the top and W-boson mass constraints.[15] These constraints can also be used to match quarks from the $t\bar{t}$ decay products to the reconstructed jets and to improve the jet energy measurements.[16] Thus, the kinematics of the $t\bar{t}$ system can be fully reconstructed providing measurements of the four-vectors of both top and antitop quarks necessary for the asymmetry definition.

The main challenges of the asymmetry measurement are associated with the kinematic reconstruction of the $t\bar{t}$ system. Even, if all four jets associated with quarks from $t\bar{t}$ are present and correctly assigned, the experimental resolution leads to smearing of the rapidity of the top quark and antiquark. If, on the other hand, the kinematic fitting technique incorrectly assigns jets to quarks, the Δy is both smeared and biased. Thus, migrations from the forward event category to backward and vice versa can occur, leading to the reduction of the original asymmetry. The situation gets even more complex if one of the jets used in the kinematic fitting is not from the $t\bar{t}$ decay, but rather is associated with a gluon from the initial or final state radiation. In this case, the misreconstruction of the top and antitop rapidities is even more significant, leading to a higher fraction of the events being misclassified. Since backward events are more likely to contain extra jets, as discussed in the theory section, they are also more likely to be misclassified, while forward events are more likely to stay within their category, thus, the asymmetry is biased towards positive values. Moreover, backward events being somewhat more boosted, that is having higher transverse momentum of the $t\bar{t}$ system, have a somewhat higher probability to be selected to have at least four jets in the final state compared to forward events. This effect leads to the acceptance bias. Allowing for events with only three jets in the final state reduces this bias, but presents reconstruction challenges in the system where one of the jets from the $t\bar{t}$ decay is lost.[17]

The asymmetry measured on the reconstructed events must be corrected for the discussed effects. This is usually done using a technique called the unfolding. It seeks to find a binned distribution in generator level Δy given the reconstruction level distribution, which is also binned. The simulation provides the probability to migrate from one bin into another and the probability for an event to be accepted as a function of Δy. If bins of the input distribution are sufficiently wide, the statistical fluctuations of data pose no problem. This is the procedure followed by CDF.[18] At the same time, the migration probability in each bin is a single number averaged over the bin width. This approximation is particularly problematic for events close to the $\Delta y = 0$ boundary, where the probability for an event to be misclassified as forward or backward changes rapidly with Δy. To deal with this feature, D0 employed finer bins close to the $\Delta y = 0$ boundary and coarser bins for large Δy, where the statistics is limited.[19] As a result, the statistical fluctuations make the unfolding procedure unstable and regularization needs to be employed. Regularized unfolding imposes some prior knowledge about the generator level distribution, namely that it is expected to be smooth. LHC measurements of the asymmetries in the $t\bar{t}$ system also use the regularized unfolding technique.[21,22] To study the dependence of the asymmetry on the kinematic parameters, e.g. on the invariant mass of the $t\bar{t}$ system, $m_{t\bar{t}}$, the unfolding must be done in two dimensions (Δy versus $m_{t\bar{t}}$).

4.2. *Dilepton channel*

$t\bar{t}$ event reconstruction in the dilepton system, which contains two undetectable neutrinos, pose even greater challenges. Different methods were developed to optimize the use of the available information.[24] Typically, additional information is used to resolve the ambiguity due to neutrino momenta, e.g. the shape of the longitudinal and transverse momentum of the $t\bar{t}$ system, the invariant mass of the $t\bar{t}$ system, and the proton structure functions. The statistics of $t\bar{t}$ events in dileptons is smaller than that in the $l +$ jets system, resulting in higher uncertainties in the asymmetry measurement. At the same time, two leptons in each event provides two leptonic asymmetry measurements, or one measurement of the asymmetry based on the rapidity difference between the two leptons.

Table 1. Forward–backward asymmetry in pair production of top quark in $p\bar{p}$ collisions, A_{FB}. First uncertainty is statistical, second systematic.

Experiment/channel	$\int L$, fb^{-1}	A_{FB}, %	Comment
Superseded:			
D0/l + jets[23]	0.9	$12 \pm 8 \pm 1$	at reco level
CDF/l + jets[18]	1.9	$24 \pm 13 \pm 4$	unfolded
CDF/l + jets[25]	5.3	$15.8 \pm 7.2 \pm 1.7$	"
Current:			
CDF/dilepton[24]	5.1	$42 \pm 15 \pm 5$	"
D0/l + jets[19]	5.4	$19.5 \pm 6.0^{+1.8}_{-2.6}$	"
CDF/l + jets[26]	9.4	$16.4 \pm 3.9 \pm 2.6$	"
Theory:			
MC@NLO[10]		5.0 ± 0.2	
QCD NLO + EW[8]		8.7 ± 0.2	

5. Overview of the Tevatron Results

5.1. *Fully reconstructed forward–backward asymmetry*

The Tevatron results on the inclusive asymmetry measurement are summarized in Table 1. First, results on the $t\bar{t}$ asymmetry were produced by the Tevatron based on about 1 fb^{-1} of the integrated luminosity by D0 (Ref. 23) and by CDF.[18] The central value obtained by both experiments exceeded the theoretical predictions available to that date. The experiments chose different approaches to present their results. D0 presented the reconstructed asymmetry, which was compared to the theoretical prediction propagated through the full D0 simulation and reconstruction. To allow for a comparison with different models, D0 presented dilution (a probability to correctly identify the event as forward or backward) as a function of the generated difference between the rapidities of top and antitop quarks. Taking model's specific distribution in Δy and multiplying it by the dilution function, one obtains a distribution in Δy, which can be summarized into a single quantity — the forward–backward asymmetry, and compared to the experimentally observed one. CDF on the other hand, chose to unfold the reconstructed Δy distribution into the generated one, which can be characterized by the unfolded asymmetry, directly comparable to theoretical predictions. Since using the dilution function did not prove to be popular, D0 presented its results updated to a higher statistics using a fine-bin regularized unfolding technique.[19]

The high-energy community was puzzled by the update of the Tevatron results using 5 fb^{-1} of data not only because of their high values, but also because CDF reported a rise of the asymmetry with the invariant mass of the $t\bar{t}$ system, much stronger than predicted by the SM.[25] The mass dependence of the asymmetry

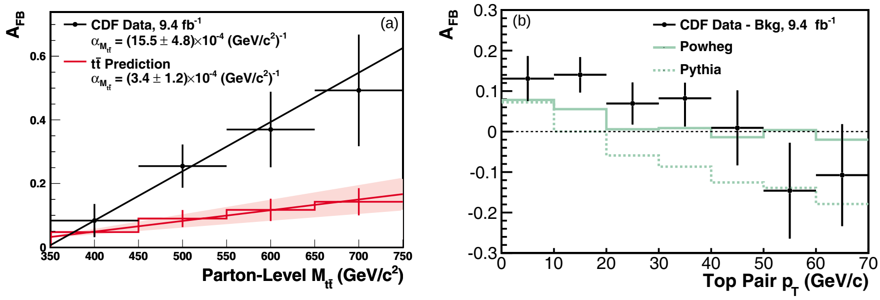

Fig. 1. (a) The dependence of the fully reconstructed and unfolded asymmetry on the invariant mass of the $t\bar{t}$ system measured by CDF in $l+$jets channel. (b) The comparison of the CDF data to the predictions of POWHEG[27] and Pythia[28] generators for the dependence of the asymmetry on the transverse momentum of the $t\bar{t}$ system at the reconstruction level.

reported by D0 was between the SM prediction and the CDF results are in statistical agreement with both. In the same publication, D0 pointed out the dependence of the asymmetry on the transverse momentum of the $t\bar{t}$ system. CDF updated its results using the full statistics of the Tevatrons Run II.[26] The overall asymmetry measured in the $l+$jets channel is still considerably higher that the prediction and the strong dependence on the invariant mass of the $t\bar{t}$ system, shown in Fig. 1(a) is persistent. CDF also compared the dependence of the reconstruction level asymmetry on the transverse momentum of the $t\bar{t}$ system to the predictions based on POWHEG and Pythia simulations, as shown in Fig. 1(b).

Despite the overall effect being larger than predicted, the sign of the effect and the kinematics dependencies are in qualitative agreement with the SM prediction, i.e. the asymmetry increases with $m_{t\bar{t}}$, and decreases with p_T of the $t\bar{t}$ system. These properties make it tangible to attribute the effect to new physics. Comparison to α_s^4 calculations, once available would shed a new light on the nature of the forward–backward asymmetry.

In addition to summarizing the properties of the $t\bar{t}$ angular distribution in a single number, the forward–backward asymmetry, CDF performed an analysis of this distribution using a Legendre polynomial expansion of the angular distribution over $\cos(\theta_t)$, where angle θ_t is between top and proton direction in the $t\bar{t}$ rest frame.[29] The data distribution over the $\cos(\theta_t)$ is presented in Fig. 2(a). The power of these polynomials is sensitive to the spin of a s-channel mediator. It was found that the access (with a significance of about two standard deviations) over the SM prediction is concentrated solely in the first power polynomial, which corresponds to a spin-1 mediator that has an axial component, as shown in Fig. 2(b).

5.2. *Asymmetries in the angular distributions of leptons from $t\bar{t}$ decay*

Any asymmetry in the $t\bar{t}$ production would result in asymmetry in the angular distribution of leptons. Experimentally, measuring the asymmetry in the lepton

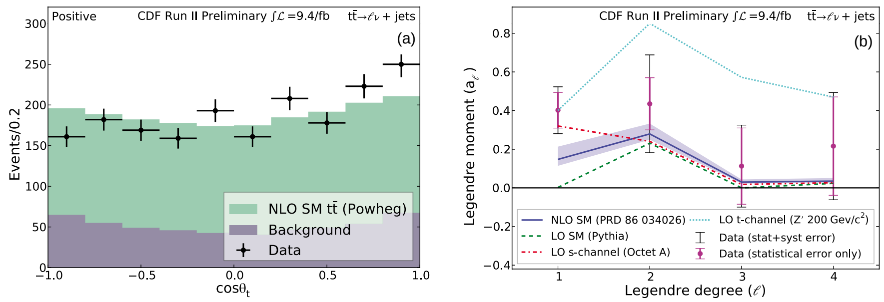

Fig. 2. (a) Distribution over $\cos(\theta_t)$ (defined in text) measured by CDF in l + jets channel, (b) coefficient in front of ith Legendre polynomial measured in data.

angular distribution, $A^l_{\rm FB}$ is far less challenging compared to the asymmetry in the fully reconstructed $t\bar{t}$ system. This measurement does not require a full reconstruction of the $t\bar{t}$ system, and the resolution on lepton direction is usually excellent. Originally, this measurement was suggested as a cross-check of the fully reconstructed asymmetry.[19] Later, it was pointed out that the leptonic asymmetry is interesting in its own right since it is also sensitive to the top decay dynamics, namely the polarization of the top quark.[30] The SM predicts tops to be produced unpolarized, while BSM scenarios suggest different values of the polarization. Thus, measuring the leptonic asymmetry together with the fully reconstructed one provides additional discrimination between the SM and different BSM scenarios. Moreover, kinematic dependence of the two asymmetries (e.g. on $m_{t\bar{t}}$ or p_T of the lepton), discriminates between the models even further.[31]

Measuring $A^l_{\rm FB}$ is not without challenge. W-boson production in association with jets, which is the main background to the $t\bar{t}$ signal, results in asymmetrically distributed leptons, and extra care must be taken to properly normalize this background, understand its kinematic dependencies and the lepton asymmetry associated with this process. The asymmetry of leptons from W-boson decay is a well-established effect. It is caused first by weak axial couplings of W-bosons to up- and down-quarks and to a lepton and its neutrino, and second by the fact that an up-quark carries somewhat higher energy fraction of the proton, x, compared to a down-quark. Because of the sensitivity to the second effect, the leptonic forward–backward asymmetries are used to constrain the proton parton density functions (PDFs). These PDFs are typically used to model the W-boson production in $p\bar{p}$ collisions. Since the simulation is tuned to the data, one might expect the leptonic asymmetry in W production to be modeled well. This is true for the inclusive W-boson production, dominated by the annihilation of valence up- and down-quarks. Yet, in the production of W-bosons in association with jets, the quark–gluon interactions play much more significant role. Moreover, the fraction of the quark–gluon initial state is dependent on the transverse momentum of the lepton. The PDFs of the gluons with high x are measured with large uncertainties and thus

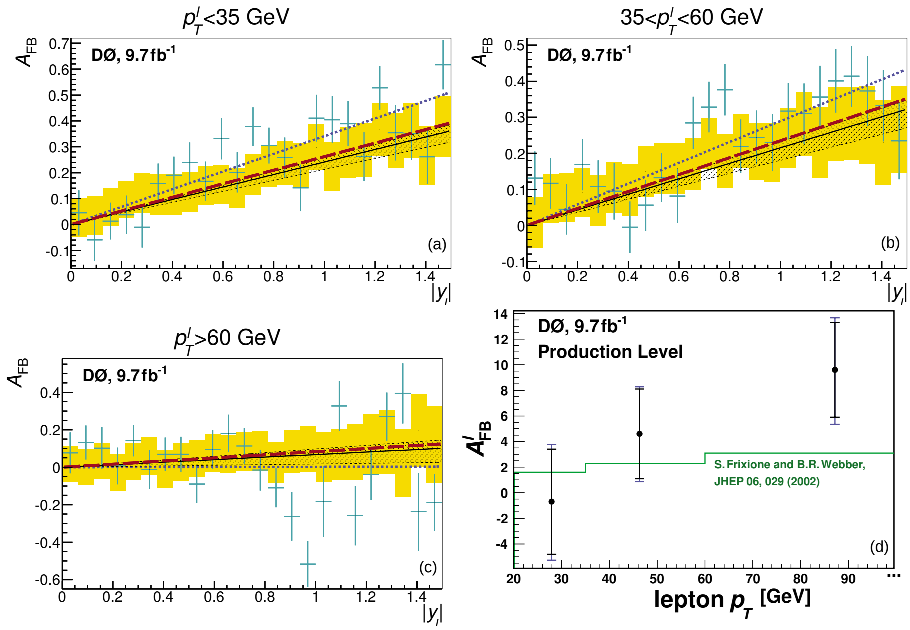

Fig. 3. Distribution over lepton $|y_l|$ measured by D0 in lepton + jets channel in control sample (three jets and zero b-tags) for leptons with low p_T (a), medium range of p_T (b), high p_T (c) and dependence of A^l_{FB} on lepton p_T (d).

are a source of the significant systemic uncertainty in the measurement of the lepton asymmetry from $t\bar{t}$ decay and its kinematic dependence. For its measurement of the leptonic asymmetry dependence on lepton's p_T, D0 chose to calibrate the asymmetry of leptons from W-boson decay using a control data set with zero b-tags, depleted in $t\bar{t}$ signal.[35] This calibration is shown in Figs. 3(a)–(c). Using these distributions, event weights are defined as a function of $|y_l|$ and applied to the simulated $W+$jets events. The dependence of the measured asymmetry of leptons from $t\bar{t}$ decay on the transverse momentum of the lepton is shown in Fig. 3(d).

Another subtlety in the leptonic asymmetry measurement is an extrapolation from the fiducial region determined by the acceptance of the detector to leptons to the full phase space. Such an extrapolation is necessarily model dependent. For an unbiased comparison to different models, it is best to use the results defined within a certain pseudorapidity[c] η region and compare it to the respective theoretical prediction.

The inclusive A^l_{FB} results are summarized in Table 2. D0 was the first to present the lepton-based asymmetry, which exceeded the SM expectation. The asymmetry in the leptons production measured by CDF using the full Run II dataset also exceeds the SM prediction. Both collaborations also presented results in the dilepton

[c]The pseudorapidity η is defined as $-\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$.

Table 2. Forward–backward asymmetry of leptons from top quark decay in $p\bar{p}$ collisions, $A^l_{\rm FB}$. First uncertainty is statistical, second systemic.

Experiment/channel	$\int L$, fb^{-1}	$A^l_{\rm FB}$, %	Comment
Superseded:			
D0/l + jets[19]	5.4	$15.2 \pm 3.8^{+1.0}_{-1.3}$	$\lvert\eta_{\rm lep}\rvert < 1.5$
D0/dilepton[32]	5.4	$5.8 \pm 5.1 \pm 1.3$	extrapolated to full acceptance
Current:			
CDF/l + jets[24]	9.4	$9.4 \pm 2.4^{+2.2}_{-1.7}$	"
D0/dilepton[34]	9.7	$4.1 \pm 3.5 \pm 1.0$	"
D0/l+jets[35]	9.7	$4.8 \pm 2.7^{+1.4}_{-1.8}$	"
CDF/dilepton[33]	9.4	$7.2 \pm 5.2 \pm 3.0$	"
Theory:			
MC@NLO[10]		3.6 ± 0.3	
QCD NLO + EW[8]		8.7 ± 0.2	

Table 3. Forward–backward asymmetry based on the rapidity difference between two leptons in the dilepton channel, $A^{ll}_{\rm FB}$. First uncertainty is statistical, second systemic.

Experiment/channel	$\int L$, fb^{-1}	$A^{ll}_{\rm FB}$, %	Comment
Superseded:			
D0/dilepton[32]	5.4	$5.3 \pm 7.6 \pm 2.9$	extrapolated to full acceptance
Current:			
D0/dilepton[34]	9.7	$12.3 \pm 5.4 \pm 1.5$	"
CDF/dilepton[33]	9.7	$7.6 \pm 7.2 \pm 3.1$	"
Theory:			
QCD NLO + EW[8]		4.8 ± 0.4	

channels, where it is possible to measure the asymmetry based on each lepton individually (two measurements per event), or based on the difference in rapidity of the two leptons, summarized in Table 3.

6. $t\bar{t}$ Charge Asymmetry Measurements at the LHC

Forward–backward asymmetry in the $t\bar{t}$ production in $p\bar{p}$ collisions probes the difference in behavior of top quark versus antitop quark, or in other words, the charge asymmetry in the $t\bar{t}$ system. Since proton–proton collisions are forward–backward symmetric it is impossible to define the corresponding asymmetry in the $t\bar{t}$ production, yet it is still possible to probe the charge asymmetry in the quark–antiquark annihilation process. Since initial state quarks participating in the $t\bar{t}$ production are mostly valence quarks, while antiquarks are sea quarks, the whole system is usually boosted in the direction of the initial state quark rather than antiquark. Thus, the same physics that leads to positive forward–backward asymmetry in $p\bar{p}$ collisions results more forward production of top quarks in pp collisions compared to more central production of the antitop quarks. This is described by the charge asymmetry defined based on the difference in absolute rapidities of top and antitop:

$$\Delta|y| = |y_t| - |y_{\bar{t}}|\,, \tag{3}$$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}\,. \tag{4}$$

Note that this is a different quantity than forward–backward asymmetry defined in $p\bar{p}$ system. The results between the Tevatron and LHC can only be compared within the framework of a certain model.

Most of the $t\bar{t}$ events in LHC are produced via gluon fusion, the process that is charge symmetric. There is also a possibility that $t\bar{t}$ can be produced in a quark–gluon reaction, in which case there is an additional jet in the final state. This process exhibits some non-negligible charge asymmetry, which must be taken into account when comparing the LHC results to the theoretical model or to the Tevatron results. Both gluon fusion and quark–gluon interaction can be considered as background processes to $t\bar{t}$ production via quark–antiquark annihilation, which makes the charge asymmetry measurement at the LHC to be quite challenging. To make the situation even worse, gluon radiation is more probable from the initial state that contains gluons rather than quarks. Since, in the $l+\text{jets}$ channel at least four jets in the final state are selected, it gives preference to the $t\bar{t}$ events produced in the gluon fusion and in quark–gluon interaction rather than $q\bar{q}$ annihilation.

Experimentally, LHC analyses follow the same strategy as at the Tevatron — the full kinematics of the $t\bar{t}$ system is reconstructed using kinematic fitting techniques, the reconstruction level distributions in $\Delta|y|$ are unfolded to the generator level and then summarized into A_C. Table 4 summarizes the results from LHC experiments on the $t\bar{t}$ charge asymmetry measurement in the $l+\text{jets}$ and dilepton channels. Unlike Tevatron results, LHC measurements show no access over the SM prediction. The comparison of the Tevatron measurements of the A_{FB} and the A_C measurements from the LHC are shown in the framework of several BSM scenarios in Fig. 4. Experimental bands correspond to one standard deviation, so models that lie outside these bands cannot be considered as an excluded one at 95% C.L. For a true analysis of the excluded models, experimental results must be combined and acceptance biases are understood. Qualitatively, it appears that though a large number of models, in particular Z' class of models are incompatible with the data, still there is a significant number of BSM scenarios that are in agreement with the results from both colliders.

Table 4. Charge asymmetry in pair production of top quarks in pp collisions, A_C. First uncertainty is statistical, second systemic.

Experiment/channel	$\sqrt{s}$, TeV	$\int L$, fb^{-1}	A_C, %
Current:			
CMS/dilepton[36]	7	5.0	$1.0 \pm 1.5 \pm 0.6$
Atlas/dilepton[20]	7	4.7	$5.7 \pm 2.4 \pm 1.5$
CMS/l + jets[21]	7	4.9	$0.4 \pm 1.0 \pm 1.1$
Atlas/l + jets[22]	7	4.7	0.6 ± 1.0
CMS/l + jets[37]	8	19.7	$0.5 \pm 0.7 \pm 0.6$
Theory:			
MC@NLO[10]			0.6 ± 2.0
QCD NLO + EW[8]			0.6 ± 2.0

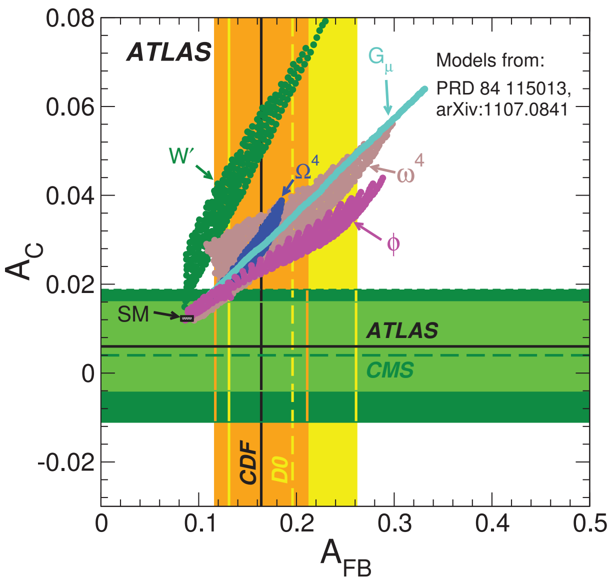

Fig. 4. The comparison of the Tevatron measurements of the $A_{\rm FB}$ and the A_C measurements from the LHC are shown in the framework of several BSM scenarios, described in Ref. 38. Vertical and horizontal bands for experimental results represent one standard deviation. The models that fall outside of this band cannot be considered to be excluded at 95% C.L.

7. Conclusions

The forward–backward asymmetry in the $t\bar{t}$ production measured by the Tevatron experiments exceeds the predictions based on the QCD α_s^3 calculations. The dependence of the asymmetry on the invariant mass of the $t\bar{t}$ system shows a stronger rise than predicted by the SM. In accordance with the SM expectation, the asymmetry decreases with the transverse momentum of the $t\bar{t}$ system. LHC experiments reported the charge asymmetry in the $t\bar{t}$ system that is in agreement with the SM predictions. A full analysis of the BSM scenarios excluded by a combination of the Tevatron and LHC results is pending, yet it is clear that there is a large number of models, including the SM, that is consistent with the experimental results from both colliders.

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References

1. B. Adeva *et al.*, *Phys. Rev. Lett.* **48**, 1701 (1982).
2. J. C. Pati and A. Salam, *Phys. Lett. B* **58**, 333 (1975); L. J. Hall and A. E. Nelson, *ibid.* **153**, 430 (1985); P. H. Frampton and S. L. Glashow, *ibid.* **190**, 157 (1987); *Phys. Rev. Lett.* **58**, 2168 (1987); M. Bauer, F. Goertz, U. Haisch, T. Pfoh and S. Westhoff, *JHEP* **1011**, 039 (2010).
3. W. Bartel *et al.*, *Phys. Lett. B* **92**, 206 (1980).
4. J. H. Kuhn and G. Rodrigo, *Phys. Rev. Lett.* **81**, 49 (1998).
5. E.g. S. Westhoff, arXiv:1311.1127.
6. M. Czakon, P. Fiedler and A. Mitov, *Phys. Rev. Lett.* **110**, 252004 (2013).
7. L. G. Almeida, G. F. Sterman and W. Vogelsang, *Phys. Rev. D* **78**, 014008 (2008); N. Kidonakis, *ibid.* **84**, 011504 (2011).
8. W. Bernreuther and Z.-G. Si, *Phys. Rev. D* **86**, 034026 (2012) and references therein.
9. S. J. Brodsky, *Annu. Rev. Nucl. Part. Sci.* **2012.62**, 1 (2012).
10. S. Frixione and B. R. Webber, *JHEP* **0206**, 029 (2002); S. Frixione, P. Nason and B. R. Webber, *ibid.* **0308**, 007 (2003).
11. G. Marques Tavares and M. Schmaltz, *Phys. Rev. D* **84**, 054008 (2011); P. Frampton, J. Shu and K. Wang, *Phys. Lett. B* **683**, 294 (2010).
12. S. Jung, H. Murayama, A. Pierce and J. D. Wells, *Phys. Rev. D* **81**, 015004 (2010).
13. CMS Collab. (S. Chatrchyan *et al.*), *Phys. Rev. D* **87**, 114015 (2013); G. Aad *et al.*, *Phys. Lett. B* **708**, 37 (2012).
14. B. Gripaios, A. Papaefstathiou and B. Webber, *JHEP* **1311**, 105 (2013); M. Gresham, J. Shelton and K. M. Zurek, *ibid.* **1303**, 008 (2013).
15. B. A. Betchart, R. Demina and A. Harel, arXiv:1305.1878.
16. S. Snyder, Measurement of the top quark mass at D0, Ph.D. thesis, State University of New York at Stony Brook (1995); I. Volobouev, arXiv:1101.2259.
17. R. Demina, A. Harel and D. Orbaker, arXiv:1310.3263.
18. CDF Collab. (T. Aaltonen *et al.*), *Phys. Rev. Lett.* **101**, 202001 (2008).
19. D0 Collab. (V. Abazov *et al.*), *Phys. Rev. D* **84**, 112005 (2011).
20. ATLAS-CONF-2012-057.
21. CMS Collab. (S. Chatrchyan *et al.*), *Phys. Lett. B* **717**, 129 (2012).
22. ATLAS-CONF-2013-078.
23. D0 Collab. (V. M. Abazov *et al.*), *Phys. Rev. Lett.* **100**, 142002 (2008).
24. CDF Collab. (T. A. Aaltonen *et al.*), *Phys. Rev. D* **88**, 072003 (2013).

25. CDF Collab. (T. A. Aaltonen *et al.*), *Phys. Rev. D* **83**, 112003 (2011).
26. CDF Collab. (T. Aaltonen *et al.*), *Phys. Rev. D* **87**, 092002 (2013).
27. S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **1006**, 043 (2010).
28. T. Sjöstrand *et al.*, *Comput. Phys. Commun.* **135**, 238 (2001).
29. CDF Collab. (T. Aaltonen *et al.*), arXiv:1306.2357.
30. D. Choudhury, R. M. Godbole, S. D. Rindani and P. Saha, *Phys. Rev. D* **84** 014023 (2011); E.L. Berger, Q.-H. Cao, C.-R. Chen and H. Zhang, *ibid*. **88**, 014033 (2013).
31. A. Falkowski *et al.*, *Phys. Rev. D* **87**, 034039 (2013); A. Carmona *et al.*, CERN-PH-TH/2014-005.
32. D0 Collab. (V. M. Abazov *et al.*), *Phys. Rev. D* **87**, 011103(R) (2013).
33. CDF Conference Note 11035.
34. D0 Collab. (V. M. Abazov *et al.*), accepted by *Phys. Rev. D* (2013).
35. R. Demina, *EPJ Web Conf.* **49**, 07004 (2013).
36. CMS PAS TOP-12-010.
37. CMS-PAS-TOP-12-033.
38. J. A. Aguilar-Saavedra and M. Perez-Victoria, *Phys. Rev. D* **84**, 115013 (2011).