

# Experimental status of top charge asymmetry measurements

Viatcheslav Sharyy for the D0, CDF, Atlas and CMS collaborations  
CEA, IRFU, SPP, Bat. 141, 91191 Gif-sur-Yvette, France

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The latest measurements of the asymmetry in the angular distributions of the  $t\bar{t}$  events are reviewed. The measurements of the forward-backward asymmetry  $A_{FB}$  in the  $p\bar{p}$  1.98 TeV collisions at the Tevatron show some tension with the Standard Model calculation, while results of the measurements of the charge asymmetry  $A_C$  in  $pp$  collisions at 7 TeV and 8 TeV at the LHC are compatible with Standard Model predictions.

## 1 Introduction

The measurement of the asymmetry in the angular distributions of  $t\bar{t}$  events is a powerful test of the Standard Model (SM) predictions, and allows to probe for physics beyond the SM. Different asymmetries are considered at the Tevatron and LHC. At the Tevatron, the  $t\bar{t}$  pairs are produced in the  $p\bar{p}$  collisions, so we can define the forward-backward asymmetry as

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

where  $\Delta y = y_t - y_{\bar{t}}$  is a difference in rapidity of top and antitop quarks,  $N(\dots)$  is a corresponding number of  $t\bar{t}$  events. At the LHC, the  $pp$  collisions are forward-backward symmetric, so the charge asymmetry is considered:

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

where  $\Delta|y| = |y_t| - |y_{\bar{t}}|$  is a difference in absolute rapidity of top and antitop quarks. The latest SM calculations for those quantities yield  $(8.7_{-0.5}^{+0.6})\%$  for the Tevatron,  $(1.23 \pm 0.05)\%$  for the LHC 7 TeV and  $(1.11 \pm 0.05)\%$  for the LHC 8 TeV [1]. See [2] for the discussion about details of theoretical predictions and possible contributions from the non-SM processes.

The analysis of experimental data includes several steps. After event selection the top and antitop quarks' kinematic parameters need to be reconstructed using measured parameters of leptons, jets and missing transverse energy. Two final states are usually considered for the asymmetry measurement:  $\ell$ +jets and dileptons. In  $\ell$ +jets final state the  $t\bar{t}$  pair is decaying to  $t\bar{t} \rightarrow W^+W^- b\bar{b} \rightarrow \ell\nu q\bar{q}' b\bar{b}$ , where direction and transverse momentum ( $p_T$ ) for lepton  $\ell$  and four quark jets are sufficient for reconstruction of the top and antitop parameters. Usually, more or less sophisticated kinematic reconstruction methods are used to account for the ambiguity in attributing jets to partons. These methods usually use constraints on two-jets and

three-jets invariant masses which correspond to the W-boson and to the top quark masses and improve the uncertainty on the measured jets energies. In the dilepton final state, the  $t\bar{t}$  pair decays to the final state with two non-detected neutrinos,  $t\bar{t} \rightarrow W^+W^- b\bar{b} \rightarrow \ell^+\ell^- \nu\bar{\nu} b\bar{b}$ . The reconstruction in this final state requires a “scan” of the phase space constrained by the experimental measured parameters of leptons and jets. Parameters of the top quark and antiquark are calculated as a weighted sum of reconstructed parameters in all scan points. The last step in the asymmetry measurements is an unfolding of the reconstructed distributions to the parton level. Strictly speaking, such unfolding is not required if we restrict the measurement to the inclusive asymmetry only. Usually, it is not the case, because it is also interesting to measure the asymmetry dependence from the invariant mass of  $t\bar{t}$  pair ( $m_{t\bar{t}}$ ),  $\Delta y$  or other parameters. Such differential measurement is more sensitive to the possible new physics contribution, since it is expected to contribute more in some region or phase space, e.g. at high  $m_{t\bar{t}}$ .

The procedures of reconstruction and unfolding of top quark parameters complicate quite a lot the asymmetry analyses and require a careful calibration. The alternative approach has been developed for the asymmetry measurements. Instead of measuring the quark asymmetry, we can measure asymmetry in the distributions of leptons. Since direction of leptons is measured with a good precision, no top quark reconstruction or unfolding is needed. The drawback of this approach is that the leptonic asymmetry isn't as powerful as the top quark asymmetry, because the direction of leptons is not fully correlated with the direction of top quark. For example, at the Tevatron, the leptonic asymmetry is defined as

$$A_\ell = \frac{N(q \cdot y_\ell > 0) - N(q \cdot y_\ell < 0)}{N(q \cdot y_\ell > 0) + N(q \cdot y_\ell < 0)},$$

where  $y_\ell$  and  $q$  is a lepton rapidity and charge.  $A_\ell$  is predicted to be  $(3.8 \pm 0.6\%)$  [1]. More interestingly, it was found, that the measurement of the angular distribution of leptons is complementary to the  $t\bar{t}$  asymmetry measurement. This is related to the fact, that the angular distribution of leptons is affected not only by the angular distribution of top quark but also by its polarization. In the SM the top quark polarization is zero, but could be significantly different for the non-SM contribution, e.g. in the  $t\bar{t}$  production via axigluon mechanism [3]. In the dilepton final state, we also can measure the two-lepton asymmetry, constructed analogously to the  $t\bar{t}$  asymmetry. It is defined at the Tevatron as:

$$A_{FB}^u = \frac{N(\Delta y_\ell > 0) - N(\Delta y_\ell < 0)}{N(\Delta y_\ell > 0) + N(\Delta y_\ell < 0)},$$

and at the LHC:

$$A_C^u = \frac{N(\Delta|y_\ell| > 0) - N(\Delta|y_\ell| < 0)}{N(\Delta|y_\ell| > 0) + N(\Delta|y_\ell| < 0)},$$

where difference in leptons rapidities is  $\Delta y_\ell = y_{\ell^+} - y_{\ell^-}$  and  $\Delta|y_\ell| = |y_{\ell^+}| - |y_{\ell^-}|$ .

## 2 LHC results

The results of the  $A_C$  measurement by ATLAS at 7 TeV [4, 5] as well as measurements by CMS at 7 TeV [6, 7] and 8 TeV [8] are shown in the Table 1. The measured values are all compatible with each other and with SM predictions. Measurements of the leptonic asymmetry  $A_C^{\ell\ell}$ , Table 2, also don't show any deviation from the SM expectation. The enormous statistics

Measurement				Measured Value, %	Theoretical Expectation[1],%
ATLAS	$\ell$ +jets	7 TeV	$4.7 \text{ fb}^{-1}$	$0.6 \pm 1.0$	$1.23 \pm 0.05$
	dileptons			$5.7 \pm 2.4(stat.) \pm 1.5(syst.)$	
CMS	$\ell$ +jets	5 $\text{fb}^{-1}$	$0.4 \pm 1.0(stat.) \pm 1.1(syst.)$		
	dileptons		$5.0 \pm 4.3(stat.)^{+1.0}_{-3.9} (syst.)$		
	$\ell$ +jets	8 TeV	$19.7 \text{ fb}^{-1}$	$0.5 \pm 0.7(stat.) \pm 0.6(syst.)$	$1.11 \pm 0.04$

Table 1:  $A_C$  measurements at the LHC [4, 5, 6, 8], unfolded to the parton level.

Measurement				Measured Value, %	Theoretical Expectation[1],%
ATLAS	dileptons	7 TeV	$4.7 \text{ fb}^{-1}$	$2.3 \pm 1.2(stat.) \pm 0.8(syst.)$	$0.55 \pm 0.02$
CMS			$5 \text{ fb}^{-1}$	$1.0 \pm 1.5(stat.) \pm 0.6(syst.)$	

Table 2:  $A_C^{\ell\ell}$  measurements at the LHC [5, 7].

accumulated at the LHC allows to investigate the restricted phase space regions, e.g. high velocity and high  $m_{t\bar{t}}$  mass regions. In both cases the expectation for the SM asymmetry is larger than for the inclusive asymmetry and the possible contribution from the non SM physics are also expected to be enhanced, see e.g. [9]. Both experiments have looked at the asymmetry differential distributions, but no deviation from SM has been found. For illustration, see two selected distributions in Fig. 1,2.

### 3 Tevatron results

For quite some time, measurements at the Tevatron were puzzling because of the observed 2–3 standard deviations (SD) between the measured and expected  $A_{FB}$  asymmetries. Table 3 shows that the difference between the most recent theoretical prediction and the current measurements of the CDF and D0 experiments [10, 11] are less than 2 SD. In the same time, asymmetry measured at the high  $m_{t\bar{t}}$  shows a moderate deviation from the expectation. In particular, CDF results on the measured slope of the  $A_{FB}$  asymmetry as a function of  $m_{t\bar{t}}$  (Fig. 3) show a 2.4 SD deviation between measured slope and the expected one. In the same measurement  $|\Delta y|$  dependence shows even large deviation at the level of 2.8 SD, Fig. 3. The  $|\Delta y|$  differential distribution of asymmetry has been also measured in a different way in the CDF experiment. The shape of the unfolded  $\cos(\theta)$  distribution has been fitted with the Legendre polynomial series and it was found that the contribution to the asymmetry of the first coefficient in series is different from the SM expectation, see [12] for the detailed description.

The leptonic asymmetry  $A_\ell$  is measured by both experiments with full available statistics and demonstrates an agreement at the level of 2 SD with the SM expectation (Table 4), even if the CDF measurement is slightly higher than the expectation. It exists some difficulty in the interpretation of the obtained results. It is related to the fact, that leptonic asymmetries are measured in the phase space limited by the acceptance  $|y|$  cut and then extrapolated to the full phase space. These acceptance cuts are different in different measurements, e.g. CDF

EXPERIMENTAL STATUS OF TOP CHARGE ASYMMETRY MEASUREMENTS

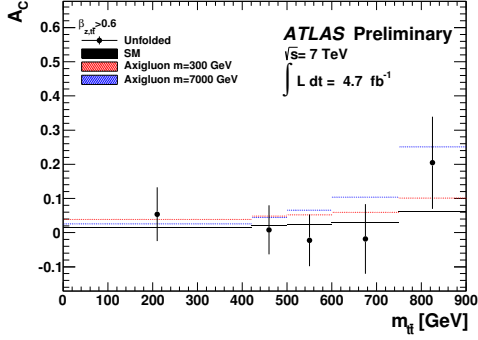


Figure 1: Charge asymmetry distribution as a function of  $m_{t\bar{t}}$  for the events with  $t\bar{t}$  velocity  $> 0.6$  as measured by the Atlas experiment [4].

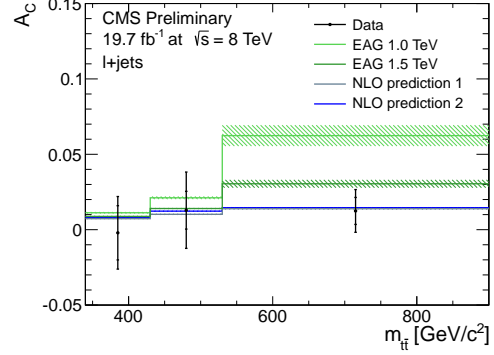


Figure 2: Charge asymmetry distribution as a function of  $m_{t\bar{t}}$  as measured by the CMS experiment [6].

Measurement		Measured Value, %	Theoretical Expectation [1], %
CDF	$9.4 \text{ fb}^{-1}$	$16.4 \pm 4.7$	$8.8 \pm 0.6$
D0	$5.4 \text{ fb}^{-1}$	$19.6 \pm 6.5$	

Table 3:  $A_{FB}$  measurements in the  $\ell$ +jets final state at the Tevatron [10, 11], unfolded to the parton level.

$\ell$ +jets measurement uses  $|y| < 1.25$ , D0  $\ell$ +jets measurement uses  $|y| < 1.5$  and asymmetry in the D0 dilepton channel is measured within the acceptance cut of  $|y| < 2.0$ . The extrapolation procedure is model dependent and done in a different way in different measurements. Currently both experiments are working on the combination of measurements and defining the most appropriate extrapolation procedure.

The dilepton final state gives an unique possibility to make a measurement of the  $A_{FB}^{\ell\ell}$  asymmetry. The D0 analysis measured it to be equal  $12.3 \pm 5.4(stat.) \pm 1.5(syst.)$  [15, 16] which is in agreement with the theoretical prediction  $4.8 \pm 0.4$  [1]. In addition, in this analysis the correlation between  $A_{FB}^{\ell\ell}$  and  $A_\ell$  measurements has been studied, see Fig 4, and the ratio of these two asymmetries has been found to be  $R = A_\ell/A_{FB}^{\ell\ell} = 0.36 \pm 0.20$  which is 2 SD away from the expectation, which could be estimated using the predicted values of  $A_{FB}^{\ell\ell}$  and  $A_\ell$  in [1]:  $R_{th} = 3.8/4.8 \sim 0.8$ . For further discussion about this measurement see [16].

Measurement			Measured Value, %	Theoretical Expectation [1], %
CDF	$\ell$ +jets	$9.4 \text{ fb}^{-1}$	$9.4^{+3.2}_{-2.9}$	$3.8 \pm 0.6$
D0	$\ell$ +jets ( $ \eta  < 1.5$ )	$9.7 \text{ fb}^{-1}$	$4.7 \pm 2.3(\text{stat.})^{+1.1}_{-1.4}(\text{syst.})$	
D0	dileptons	$9.7 \text{ fb}^{-1}$	$4.4 \pm 3.7(\text{stat.}) \pm 1.1(\text{syst.})$	

Table 4:  $A_\ell$  measurements at the Tevatron [13, 14, 15]. CDF  $\ell$ +jets and D0 dileptons measurements are extrapolated to the full phase space, but D0  $\ell$ +jets measurement is limited to the acceptance  $|\eta| < 1.5$ .

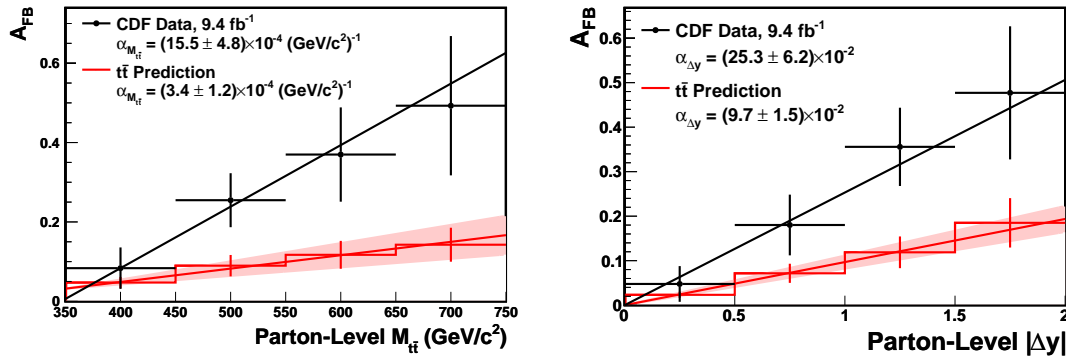


Figure 3:  $A_{FB}$  asymmetry distribution as a function of  $m_{t\bar{t}}$  and  $|\Delta y|$  as measured by the CDF experiment in the  $\ell$ +jets final state [10].

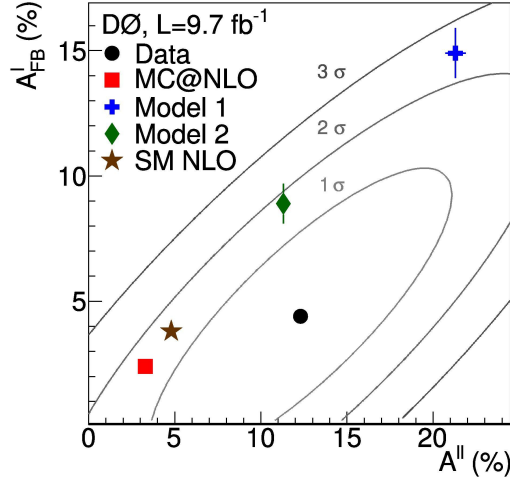


Figure 4:  $A_\ell$  vs  $A_{FB}^{\ell\ell}$  asymmetry as measured by the D0 experiment in the dilepton final state [15, 16].

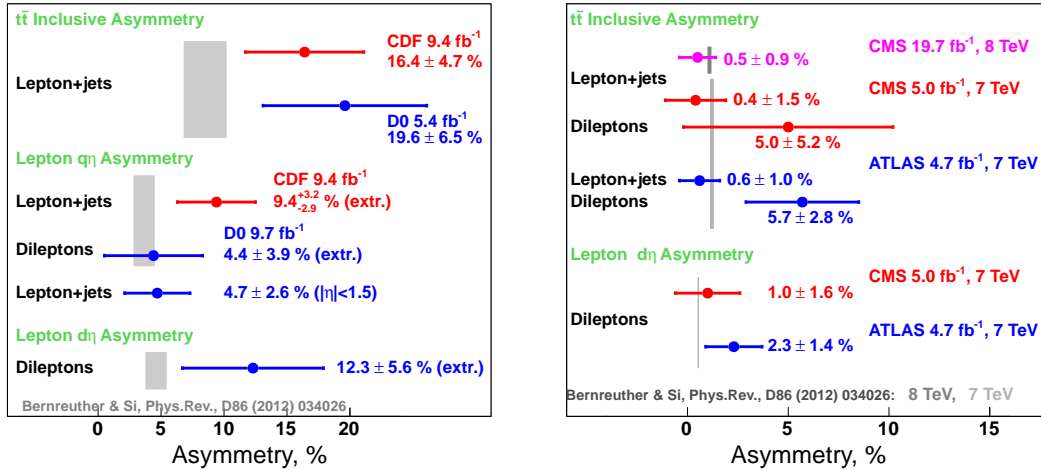


Figure 5: Summary of the asymmetry measurements at the Tevatron and LHC.

## 4 Conclusion

During the last several years Tevatron measurements of the asymmetry show an intriguing deviation from the SM calculation. The current measurements of the inclusive  $t\bar{t}$  asymmetry from the CDF and from the D0 experiments don't show any strong deviation from the recent SM calculations, but the asymmetry measurements as a function of  $m_{t\bar{t}}$  or  $|\Delta y|$  show a significant deviation from the SM at the level more than 2 standard deviations. In the same time D0 didn't yet analyze the full available statistics and hence the final conclusion about the  $t\bar{t}$  asymmetry from the Tevatron is still to come. The leptonic asymmetry measurements at the Tevatron deviate less than 2 SD from the SM model predictions, but results still need to be combined to have a more precise conclusion about the level of agreement with the expectation.

Measurements at the LHC don't show any deviation from the SM prediction, but the expected asymmetry is very low and the current precision of the measurements is about 1%, comparable with the expected asymmetry. At the LHC the most interesting direction of study is a measurement of the differential asymmetry as a function of the velocity or invariant  $t\bar{t}$  mass. The large statistics accumulated at the LHC make possible the precise measurements in regions of the phase space where both SM and non-SM asymmetries are expected to be large. For the moment, no deviation from the expectations were found. Fig. 5 summarizes current measurements of the inclusive asymmetries both at the Tevatron and LHC and compares them with the expected SM values.

## References

- [1] W. Bernreuther and Z. -G. Si, Phys. Rev. D **86** (2012) 034026, arXiv:1205.6580 [hep-ph].
- [2] S. Westhoff, arXiv:1311.1127 [hep-ph].
- [3] A. Falkowski, M. L. Mangano, A. Martin, G. Perez and J. Winter, Phys. Rev. D **87** (2013) 034039, arXiv:1212.4003 [hep-ph].

- [4] ATLAS Collaboration, ATLAS-CONF-2013-078.
- [5] ATLAS Collaboration, ATLAS-CONF-2012-057.
- [6] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **717** (2012) 129, arXiv:1207.0065 [hep-ex].
- [7] CMS Collaboration, CMS-PAS-TOP-12-010.
- [8] CMS Collaboration, CMS-PAS-TOP-12-033.
- [9] J. A. Aguilar-Saavedra and A. Juste, Phys. Rev. Lett. **109** (2012) 211804, arXiv:1205.1898 [hep-ph].
- [10] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87** (2013) 092002, arXiv:1211.1003 [hep-ex].
- [11] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **84** (2011) 112005, arXiv:1107.4995 [hep-ex].
- [12] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **111** (2013) 182002, arXiv:1306.2357 [hep-ex].
- [13] T. A. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **88** (2013) 072003, arXiv:1308.1120 [hep-ex].
- [14] V. M. Abazov *et al.* [D0 Collaboration], Conference note 6381, July 2013.
- [15] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **88** (2013) 112002. arXiv:1308.6690 [hep-ex].
- [16] A. Chapelain [D0 Collaboration], arXiv:1311.6731 [hep-ex].