Top-quark as a probe of physics beyond the Standard Model

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Summary. — We provide a qualitative and quantitative unified picture of the charge asymmetry in top quark pair production at hadron colliders in the SM and beyond, and summarise the most recent experimental measurements.

PACS `14.65.Ha` – Top quarks.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS `12.10.Dm` – Unified theories and models of strong and electroweak interactions.

1. – Introduction

The top quark being the heaviest known elementary particle – it weights almost the same as a single gold atom – plays a fundamental role in many extensions of the Standard Model (SM) and in alternative mechanisms for the electroweak symmetry breaking (EWSB). Since its discovery in 1995 at Tevatron, many properties of the top quark, such as mass and total cross-section, have been measured with high precision, allowing also to set strong limits on physics beyond the SM.

An interesting property in top quark pair production in hadronic collisions is the charge asymmetry, namely a difference in the angular distribution of the top quarks with respect to that of the antiquarks, due to higher order corrections in the Standard Model (SM). Since 2007, sizable differences were observed between theory predictions [1, 2, 3] and measurements by the CDF [4, 5, 6, 7, 8, 9] and the D0 [10, 11, 12] collaborations at the Tevatron. This discrepancy was particularly pronounced for the subsample of $t\bar{t}$ pairs with large invariant mass, $m_{t\bar{t}} > 450$ GeV, and the asymmetry defined in the $t\bar{t}$ rest-frame, where a 3σ effect was advocated [8]. These anomalies triggered a large number of theoretical investigations speculating about possible new physics contributions [3, 13, 14, 15, 16, 17, 18]. Recent analysis, however, lower this discrepancy, particularly at D0 [12].

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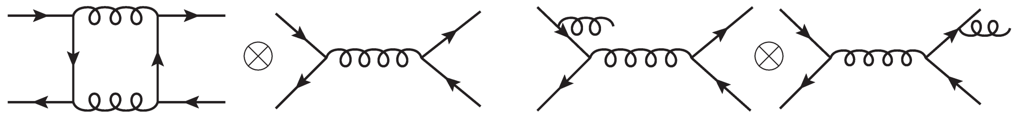

Fig. 1. – Origin of the QCD charge asymmetry.

Also, measurements at the LHC [19, 20, 21, 22, 23, 24, 25] are in good agreement with the SM prediction.

The $t\bar{t}$ asymmetry is often called forward–backward asymmetry at the Tevatron and charge asymmetry at the LHC, but in fact, although the kinematical configurations of the two machines are different the physical origin of the asymmetry in both cases is the same. In this talk, we provide a qualitative and quantitative unified picture of this property in the SM and beyond, and summarize the experimental measurements.

2. – The charge asymmetry in the SM

The dominant contribution to the charge asymmetry (see Fig. 1) originates from $q\bar{q}$ annihilation [1] due to the interference between the Born amplitudes for $q\bar{q} \to t\bar{t}$ and the one-loop amplitudes, which are antisymmetric under the exchange of the heavy quark and antiquark (box and crossed box). To compensate the infrared divergences, these virtual corrections are combined with the interference between initial and final state radiation. Diagrams with the triple gluon coupling in both real and virtual corrections give rise to symmetric amplitudes and can be ignored. A second contribution to the asymmetry from quark-gluon scattering ("flavor excitation") hardly contributes to the asymmetry at the Tevatron. At the LHC, it enhances the asymmetry in suitable chosen kinematical regions [1]. CP violation arising from electric or chromoelectric dipole moments of the top quark do not contribute to the asymmetry.

The inclusive charge asymmetry is proportional to the symmetric colour factor $d_{abc}^2 = 40/3$, and positive, namely the top quarks are preferentially emitted in the direction of the incoming quarks at the partonic level [1]. The colour factor can be understood from the different behaviour under charge conjugation of the scattering amplitudes with the top and antitop quark pair in a colour singlet or colour octet state. The positivity of the inclusive asymmetry is a consequence of the fact that the system will be less perturbed, and will require less energy, if the outgoing colour field flows in the same direction as the incoming colour field. On the contrary, the asymmetry of the $t\bar{t}$+jet sample is negative because radiation of gluons requires to decelerate the colour charges.

At Tevatron, the charge asymmetry is equivalent to a forward–backward asymmetry as a consequence of charge conjugation symmetry, and arises from the collision of valence quarks and antiquarks of similar momenta. Thus, top quarks are preferentially emitted in the direction of the incoming protons. The LHC is a proton-proton symmetric machine and obviously a forward–backward asymmetry vanishes, however, the same charge asymmetry as defined at the Tevatron arises from the small $t\bar{t}$ sample produced by annihilation of valence quarks with sea antiquarks [1, 3]. Figure 2 shows a qualitatively and not to scale picture of the rapidity distributions of the top and the antitop quarks at the Tevatron (left) and the LHC (centre, right). Since valence quarks carry on average more momentum than sea antiquarks, production of top quarks with larger

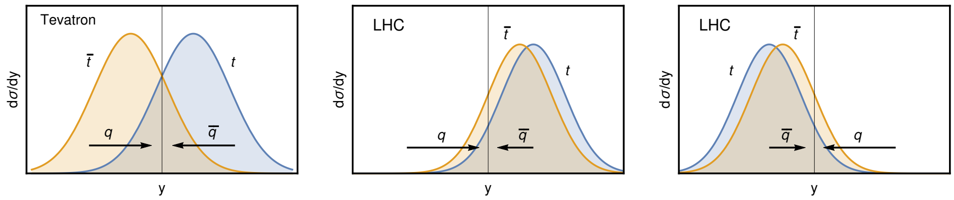

Fig. 2. – Not to scale partonic rapidity distributions of top and antitop quarks at the Tevatron (left) and the LHC (centre, right).

rapidities is preferred in the SM, and antitop quarks are produced more frequently at smaller rapidities.

Mixed QED-QCD and EW-QCD corrections [1] enhance the QCD asymmetry by about twenty percent at the Tevatron [26, 27], and by 0.13 at the LHC [26]. The difference is due to the fact that contrary to QCD, the QED and EW corrections depend on the flavour of the incoming quarks, being the flavour asymmetries of opposite sign for up and down quarks. While the relative importance of $u\bar{u}$ versus $d\bar{d}$ annihilation is $4:1$ at the Tevatron, it is $2:1$ at the LHC. This leads to an small decorrelation in the SM, that can be exploited to explain the observed discrepancies at the Tevatron with respect to the LHC in some beyond the SM scenarios [28].

3. – Theoretical predictions and measurements at the Tevatron and the LHC

The charge asymmetry at the Tevatron (aka forward–backward asymmetry) in the laboratory frame is given by either of the following definitions:

$$A_{\text{lab}} = \frac{N(y_t > 0) - N(y_t < 0)}{N(y_t > 0) + N(y_t < 0)} = \frac{N(y_t > 0) - N(y_{\bar{t}} > 0)}{N(y_t > 0) + N(y_{\bar{t}} > 0)} = 0.056(7) \ , \tag{1}$$

requiring to measure the rapidity of either t or $\bar{t}$ for each event. Equivalenty, the charge asymmetry can be defined in the $t\bar{t}$ rest-frame though the variable $\Delta y = y_t - y_{\bar{t}}$:

$$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.087(10) \ , \tag{2}$$

which requires to determine both rapidities simultaneously. It is important to stress that although Δy is invariant under boosts, the size of the asymmetry changes from one frame to another. Systematics are also different. The difference between the SM predictions in Eq. (1) and Eq. (2) is not due to any improvement of the theoretical calculations, but $A_{\text{lab}} < A_{t\bar{t}}$ (A_{FB} in the literature) due to the fact that the boost into the laboratory frame partially whashes out the partonic asymmetry [3].

At the LHC, the charge asymmetry is defined through $\Delta|y| = |y_t| - |y_{\bar{t}}|$:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} = \begin{cases} 0.0115(6)@7\text{TeV} \\ 0.0102(5)@8\text{TeV} \\ 0.0059(3)@14\text{TeV} \end{cases} . \tag{3}$$

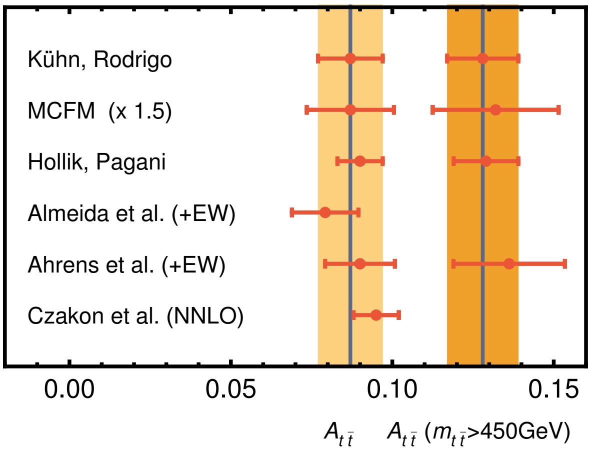

Fig. 3. – Summary of theoretical predictions for the inclusive charge asymmetry at the Tevatron in the $t\bar{t}$ rest-frame, $A_{t\bar{t}}$, and in the large invariant mass region $A_{t\bar{t}}(m_{t\bar{t}} > 450$ GeV).

$\Delta|y|$ is positive (negative) if the product $(y_t + y_{\bar{t}})\Delta y$ is positive (negative). The factor $Y_{t\bar{t}} = (y_t + y_{\bar{t}})/2$, is the average rapidity of the $t\bar{t}$ system, and determines whether the event is mostly forward ($Y_{t\bar{t}} > 0$) or backward ($Y_{t\bar{t}} < 0$), and Δy is the same variable which is used to measure the asymmetry at the Tevatron (see again Fig. 2).

At the LHC, $t\bar{t}$ production, contrary to what happens at the Tevatron, is dominated by gluon fusion which is symmetric. Also, the asymmetry at the LHC decreases at higher energies because of the larger gluon fusion contribution. Therefore, in order to reach a sizable asymmetry at the LHC it is necessary to introduce selection cuts to suppress as much as possible the contribution of gluon fusion events, and to enrich the sample with $q\bar{q}$ events. In particular, gluon fusion is dominant in the central region and can be suppressed by e.g. introducing a cut in the average rapidity $Y_{t\bar{t}}$, selecting events with large $m_{t\bar{t}}$ or tagging $q\bar{q}$ events with initial state radiation of W bosons [29]. Obviously this is done at the price of lowering the statistics, which, however, will not be a problem at the LHC at long term.

A similar asymmetry effect is also expected in bottom quark production, although it is affected by a higher gluon fusion dilution even at the Tevatron [1]. A sizable effect is only obtained at large invariant masses of the bottom quark pair, or close to the Z-pole where the tree-level EW asymmetry, which is highly supressed in top quark pair production, is enhanced. First analysis have been published [30, 31, 32] which are compatible with the SM still with large errors.

The charge asymmetry is the ratio of the antisymmetric cross-section to the symmetric cross-section. The leading order contribution to the antisymmetric cross-section is a loop effect, but the leading order contribution to the symmetric cross-section appears at the tree-level. This suggest that the charge asymmetry should be normalised to the Born cross-section [1], and not the NLO cross-section, in spite of the fact that the later is well known, and is included in several Monte Carlo event generators such as MCFM [33]. This procedure is furthermore supported by the fact that theoretical predictions resuming leading logarithms (NLL [34] and NNLL [35]) do not modify significantly the central

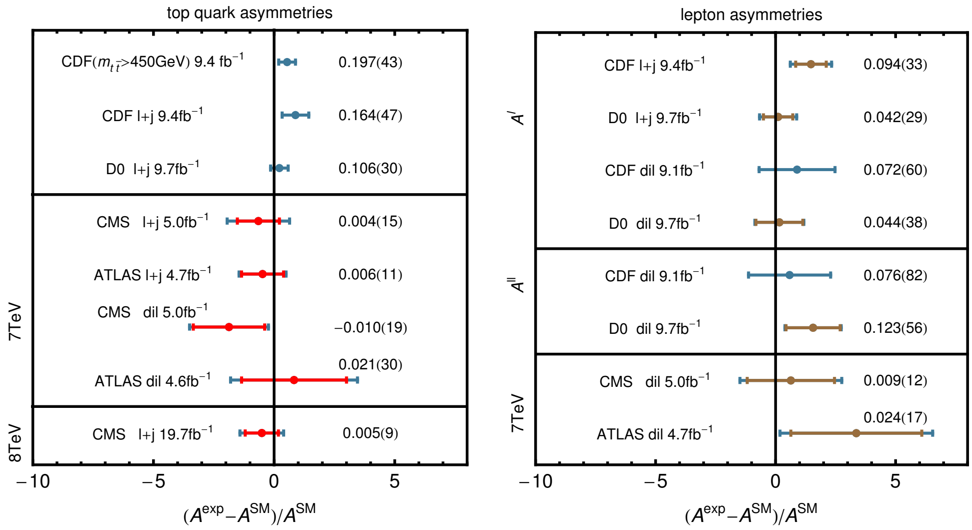

Fig. 4. – Summary of experimental measurements for the top quark and lepton asymmetries in the Tevatron and the LHC in comparison with the corresponding theoretical predictions.

prediction for the asymmetry, and are less sensitive to the normalisation. Recent results on the asymmetry at NNLO [36], $A_{t\bar{t}} = 0.095(7)$, are within the error bar in Eq. (2), and confirm the robustness of the approximation adopted in Ref. [1].

Figure 3 summarizes the state-of-the-art SM predictions for the inclusive asymmetry in the $t\bar{t}$ rest-frame, and in the large invariant mass region, $m_{t\bar{t}} > 450$ GeV, from different authors [26, 8, 27, 34, 35]. In order to have a coherent picture, EW corrections have been added to the predictions presented in [8, 34, 35], which amount to a factor of about 1.2, and the Monte Carlo based prediction has also been corrected by an extra factor of 1.3 to account for the normalisation to the NLO cross-section. A nice agreement if found among the different theoretical predictions. The small differences are only due to the choice of the factorisation and renormalisation scales; the asymmetry is proportional to the strong coupling.

The asymmetry can be defined also through the decay products in the dilepton and lepton+jets channels [22, 25, 38, 39, 40, 41, 42]. The direction of the lepton (antilepton) is correlated with the direction of the top quark (top antiquark), particularly for very boosted tops. The same asymmetries as in Eq. (1) to Eq. (3) can be used with the substitutions $y_t \to y_\ell$, $\Delta y \to \Delta y_\ell$, and $\Delta|y| \to \Delta|y_\ell|$. Leptons are well measured experimentally, however the asymmetries are diluted by roughly a factor two [37], at least in the SM where the top quarks are produced almost unpolarised. BSM contributions might polarise the top quarks, then altering the correlation of the top asymmetries with the lepton asymmetries and spin correlations in BSM scenarios.

A summary of the most recent experimental measurements in comparison with the respective theoretical predictions in the SM is presented in Fig. 4 (left) for the top quark asymmetries, and in Fig. 4 (right) for the lepton asymmetries. A good agreement is found with the SM with the exception of very few mild discrepancies.

4. – Summary

The most recent measurements of the top quark asymmetries at the Tevatron are closer to the SM, although a few mild anomalies still persist which cannot unfortunately be clarified with further data. The agreement is, however, not due to relevant enhancements of the SM predictions. The theoretical predictions have not changed significantly since the pionering works, if the correct frame is chosen for comparison with data; the bulk of the QED and EW corrections were already included in Ref. [1] and the recent reevaluations increase the central value by only +0.008. Very recent NNLO results lie within the previously quoted theoretical error band and confirm the appropriateness of the long discussed question about the normalisation of the asymmetries. Although the current measurements leave a very small window for BSM, the existence of these anomalies since 2007 have clearly boosted a better understanding of the properties of the top quark, both for model building and precision physics. Plenty of room for further analysis of the top quark, lepton and bottom quark asymmetries at the next run of the LHC exists. In particular, asymmetries are sensitive to BSM and still complementary to other observables for BSM searches.

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