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## Charge asymmetry: A theory appraisal

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**Summary.** — The most recent measurements at Tevatron of the charge asymmetry in top-antitop quark pair production reduce the discrepancy with the Standard Model from  $2\sigma$  to  $1.7\sigma$ , and open a little window, at 95% CL, for negative contributions to the charge asymmetry beyond the SM. We update our analysis for colour octet gauge bosons or axigluons in flavour universal and flavour non-universal scenarios. We review other possible models and make an educated guess on their parameter space allowed by the new measurements. Finally, we comment on the prospects to measure the charge asymmetry at the LHC.

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PACS 12.10.Dm – Unified theories and models of strong and electroweak interactions.

### 1. – Introduction

The top quark, being the heaviest known elementary particle, 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 limits on physics beyond the SM.

The LHC plans to collect  $1 \text{ fb}^{-1}$  of data at 7 TeV centre-of-mass energy by the end of 2011. At that energy the total cross-section for top-antitop quark pair production is about 160 pb [1]; thus a sample of about  $10^5$  top quark pairs will be available by the end of 2011 to perform high-precision measurements, besides offering new opportunities to probe new physics in the top quark sector. Moreover, a significant fraction of top-antitop quark events will be produced in association with jets.

Several models predict the existence of new electroweak  $W'$  and  $Z'$  gauge bosons, colour-octet gauge bosons, coloured scalars or gravitons that should be detectable in top-antitop quark events, particularly in those models where the coupling of the new

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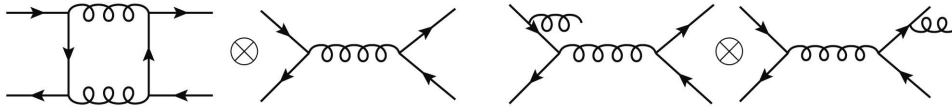


Fig. 1. – Origin of the QCD charge asymmetry.

states to the third generation is enhanced with respect to the lighter fermions. Direct searches at Tevatron [2] set lower bounds on the mass of colorons and flavour universal axigluons at about 1.2 TeV, at about 700 to 800 GeV for extra weak boson, and at about 500 GeV for gravitons. An interesting and powerful observable to distinguish among different models is the charge asymmetry.

## 2. – Charge asymmetry in QCD

At leading order in QCD the differential distributions of top and antitop quarks are identical. But due to higher-order radiative corrections (fig. 1) a charge asymmetry is generated at  $\mathcal{O}(\alpha_s^3)$  in  $q\bar{q}$  events, and top quarks become more abundant in the direction of the incoming light quarks. At Tevatron, the charge asymmetry is equivalent to a forward-backward asymmetry, due to the charge conjugation symmetry. Chromoelectric and chromomagnetic contributions do not generate any asymmetry. The QCD prediction for Tevatron, including a small mixed QCD-electroweak contribution, is [3-5]

$$(1) \quad A^{p\bar{p}} = \frac{N_t(y \geq 0) - N_{\bar{t}}(y \geq 0)}{N_t(y \geq 0) + N_{\bar{t}}(y \geq 0)} = 0.051(6),$$

where  $y$  denotes the rapidity. The charge asymmetry can also be defined through  $\Delta y = y_t - y_{\bar{t}}$ , which is equivalent to evaluate the asymmetry in the  $t\bar{t}$  rest frame because  $\Delta y$  is invariant under boosts. In that frame the asymmetry is about 50% larger [3]:  $A^{t\bar{t}} = 0.078(9)$ . Recent threshold resummations [1, 6] shift the central values for the inclusive asymmetries by a few per mille only.

The most recent measurements from CDF [7], with  $5.3 \text{ fb}^{-1}$ , are in both frames

$$(2) \quad \begin{aligned} A^{p\bar{p}} &= 0.150 \pm 0.050_{\text{stat.}} \pm 0.024_{\text{syst.}}, \\ A^{t\bar{t}} &= 0.158 \pm 0.072_{\text{stat.}} \pm 0.017_{\text{syst.}}, \end{aligned}$$

respectively. The measurement presented by D0 [8], with  $4.3 \text{ fb}^{-1}$  and in the observed region, is

$$(3) \quad A_{\text{obs.}}^{t\bar{t}} = 0.08 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}}$$

With respect to the previously published results [9, 10], the new measurements are more in agreement with the SM. If we take the CDF result as reference, the discrepancy with respect to the SM has been reduced from  $2\sigma$  to  $1.7\sigma$ . Moreover, while vanishing or negative contributions to the asymmetry were disfavoured at 95% CL previously, the new measurements open a little window for negative asymmetries beyond the SM.

### 3. – Colour-octet gauge bosons

Colour-octet gauge bosons appear in chiral colour models [11], where the SM colour group has been extended to  $SU(3)_R \otimes SU(3)_L$ , and the symmetry breaking to the diagonal  $SU(3)_C$  generates the massive axigluon, which couples to quarks with a pure axial-vector structure and the same strength as QCD. Chiral colour models require also the existence of extra fermions to cancel anomalies, and extra Higgs bosons to break the enlarged gauge symmetry. The extra states, however, are usually assumed to be arbitrary heavy. Those models can also be generalised by considering different coupling constants associated with each  $SU(3)$  component [12-15], thus generating both vector and axial-vector couplings of the axigluon to quarks. If the two copies of the  $SU(3)$  group are non-chiral, the new gauge boson is known as coloron and couple only vectorially to quarks [16, 17]. Massive gluons also appear as Kaluza-Klein [18] excitations in models of extra dimensions [19].

In the most general scenario a colour-octet resonance  $G_\mu^a$  interacts with quarks with arbitrary vector  $g_V^{q_i}$  and axial-vector  $g_A^{q_i}$  strength relative to the strong coupling  $g_S$ :

$$(4) \quad \mathcal{L} = g_S t^a \bar{q}_i (g_V^{q_i} + g_A^{q_i} \gamma_5) \gamma^\mu G_\mu^a q_i.$$

In explicit models, parity, gauge invariance or orthonormality of field profiles prevent a direct coupling of  $G_\mu^a$  to an even number of gluons; thus it is natural to assume that the extra gauge bosons do not modify gluon-gluon fusion.

The Born cross-section for  $q\bar{q}$  annihilation into top quarks in the presence of a colour-octet vector resonance reads [20]

$$(5) \quad \frac{d\sigma^{q\bar{q} \rightarrow t\bar{t}}}{d \cos \hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi \beta}{2\hat{s}} \left\{ 1 + c^2 + 4m^2 \right. \\ + \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2) + 2g_A^q g_A^t c] \\ + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} [((g_V^q)^2 + (g_A^q)^2) \\ \left. \times ((g_V^t)^2 (1 + c^2 + 4m^2) + (g_A^t)^2 (1 + c^2 - 4m^2)) + 8g_V^q g_A^q g_V^t g_A^t c \right\},$$

where  $\hat{\theta}$  is the polar angle of the top quark with respect to the incoming quark in the centre-of-mass rest frame,  $\hat{s}$  is the squared partonic invariant mass,  $T_F = 1/2$ ,  $N_C = 3$  and  $C_F = 4/3$  are colour factors,  $\beta = \sqrt{1 - 4m^2}$  is the velocity of the top quark, with  $m = m_t/\sqrt{\hat{s}}$ , and  $c = \beta \cos \hat{\theta}$ . The parameters  $g_V^q (g_V^t)$  and  $g_A^q (g_A^t)$  represent, respectively, the vector and axial-vector couplings of the excited gluons to the light quarks (top quarks). Colour-octet vector resonances are naturally broad:  $\Gamma_G/m_G = \mathcal{O}(\alpha_S)$ .

The terms in eq. (5) that are odd in  $c$  generate the charge asymmetry. Due to the factor  $(\hat{s} - m_G^2)$  the charge asymmetry generated in flavour universal models,  $g_A^q = g_A^t$ , is in general negative. A positive asymmetry can be generated if  $g_A^q g_A^t < 0$  [21-23], or if the term  $8g_V^q g_A^t g_V^q g_A^t c$  dominates over the interference.

In figs. 2 and 3, we update our analysis from refs. [21, 22] with the new measurement of the asymmetry in eq. (2). The new measurements do not disfavour completely axigluons (and colorons), at 95% CL; there is still some room for negative (or vanishing) contributions beyond the SM (fig. 2). In the flavour universal scenario, fig. 3 left, large

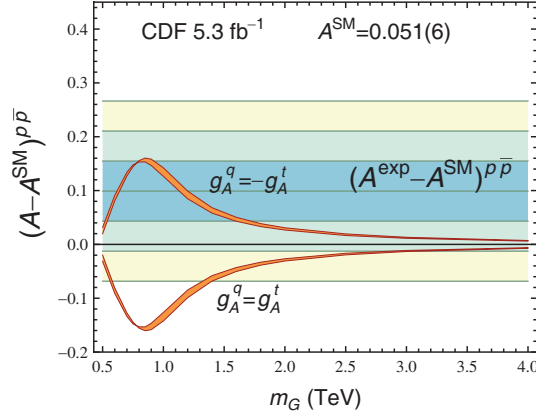


Fig. 2. – Comparison of the axigluon contribution ( $g_V^q = g_V^t = 0, g_A^q = g_A^t = 1$ ) to the top quark charge asymmetry with the  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  contours as a function of the axigluon mass. The case  $g_A^q = -g_A^t = 1$  is also shown.

vector couplings at favoured at 90% CL, although at 95% CL the allowed parameter space is much larger. In the flavour non-universal scenario, fig. 3 right, there are not significant changes, although the allowed parameter space is again larger. We have not considered here possible further constraints from flavour observables [24].

#### 4. – Coloured scalars

Besides additional gauge bosons, Grand Unified Theories (GUT) based on larger gauge groups, *e.g.*,  $SU(5)$ ,  $SO(10)$ , and  $E_6$ , often introduce new coloured scalar states. For

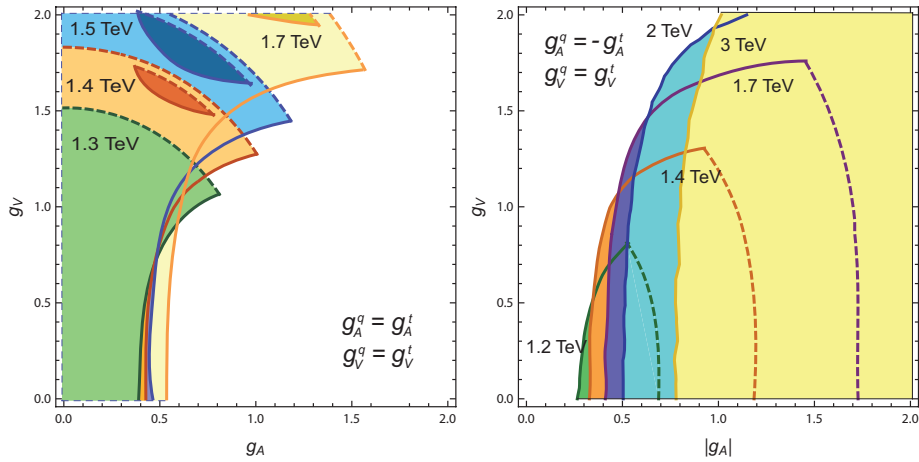


Fig. 3. – Contours at 90% and 95% CL as a function of the vector and axial-vector couplings for different values of the resonance mass for flavor universal couplings (left plot), and flavor non-universal couplings (right plot, only at 90% CL).

example, in  $SU(5)$ , the Higgs boson multiplets are made of the following field components:

$$(6) \quad \begin{aligned} 5_H &= (1, 2, 1/2) + (3, 1, -1/3), \\ 24_H &= (8, 1, 0) + (1, 3, 0) + (3, 2, -5/6) + (\bar{3}, 2, 5/6) + (1, 1, 0), \\ 45_H &= (8, 2, 1/2) + (\bar{6}, 1, -1/3) + (3, 3, -1/3) + (\bar{3}, 2, -7/6) + (3, 1, -1/3) \\ &\quad + (\bar{3}, 1, 4/3) + (1, 2, 1/2). \end{aligned}$$

Although, most of these states lie at, or close to, the unification scale, gauge coupling unification and proton decay might force some of them to be light [25, 26], and at reach at the LHC.

Exchange of coloured scalars in the  $s$ -channel do not generate a charge asymmetry; hence  $t$ -channel contributions and thus flavour-violating couplings need to be introduced to explain a large asymmetry. Several authors [26-30] have considered scalar colour singlet  $(1, 2, -1/2)$ , triplet  $(\bar{3}, 1, 4/3)$ , sextet  $(6, 1, 4/3)$  and octet  $(8, 2, -1/2)$  exchange in the  $t$ -channel. Other scalar states, like  $(6, 3, 1/3)$  and  $(\bar{3}, 3, 1)$ , have not been analysed because they are more constrained from flavour observables. The most general up quark-top quark-scalar interaction is given by [27]

$$(7) \quad \mathcal{L} = t^a \bar{t}(g_S + g_P \gamma_5) \phi^a u$$

and the generated asymmetry depends only on the following combination of scalar  $g_S$  and pseudoscalar  $g_P$  couplings:

$$(8) \quad y = \sqrt{g_S^2 + g_P^2}.$$

In general, triplet [26-28, 30] and sextet [27] appear to be in agreement with a large asymmetry, although requiring large flavour-violating couplings, while singlet [27, 30] and octet [26, 27] fail to accommodate the asymmetry. These models have to deal with potential  $uu \rightarrow tt$ , or same sign dileptons, which are quite constrained by Tevatron.

## 5. – Extra weak gauge bosons

Extra weak gauge bosons appear in GUT, topcolor models, left-right models, or as Kaluza-Klein excitations of the SM weak bosons in extra-dimensional models [31]. The amplitude for top production through  $Z'$  exchange in the  $s$ -channel does not interfere with the SM amplitude at hadron colliders, and thus its charge asymmetry is suppressed. In order to generate a large charge asymmetry several authors have considered  $Z'$  and  $W'$  in the  $t$ -channel [30, 32-35]. As for scalars, this requires to introduce large flavour-violating couplings:

$$(9) \quad \mathcal{L} = \bar{t}(g_V^{Z'} + g_A^{Z'} \gamma_5) \gamma^\mu Z'_\mu u + \bar{t}(g_V^{W'} + g_A^{W'} \gamma_5) \gamma^\mu W'_\mu d.$$

Furthermore, since weak bosons in the  $t$ -channel are more efficient than scalars in generating a large charge asymmetry, and in order to avoid  $uu \rightarrow tt$  (same sign dileptons), the extra gauge bosons need to be relatively light, having masses of the order of 200 GeV.

## 6. – The charge asymmetry at the LHC

Top quark production at the LHC is forward-backward symmetric in the laboratory frame as a consequence of the symmetric colliding proton-proton initial state. Nevertheless, it is still possible to find a charge asymmetry in suitable defined kinematic regions. QCD predicts that top quarks are preferentially emitted in the direction of the incoming quarks. But since quarks in the proton carry, on average, more momenta than antiquarks the partonic asymmetry will be translated into an excess of top quarks in the forward and backward regions due to the boost into the laboratory frame [5]. Similar arguments apply to the charge asymmetry generated at the partonic level from any other model. Thus, we define the integrated central charge by selecting events in a given range of rapidity in the central region [3, 20]:

$$(10) \quad A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)}.$$

The central asymmetry  $A_C(y_C)$  obviously vanishes if the whole rapidity spectrum is integrated, while a non-vanishing asymmetry can be obtained over a finite interval of rapidity.

In contrast with Tevatron, top quark production at LHC is dominated by gluon-gluon fusion (70% at 7 TeV and 90% at 14 TeV), which is charge symmetric under higher-order corrections. The charge antisymmetric contributions to top quark production are thus screened at LHC due to the prevalence of gluon-gluon fusion. This is the main handicap for that measurement. The amount of events initiated by gluon-gluon collisions can nevertheless be suppressed with respect to the  $q\bar{q}$  and  $gq(\bar{q})$  processes, the source of the charge asymmetry, by introducing a lower cut on the invariant mass of the top-antitop quark system  $m_{t\bar{t}}$ ; this eliminates the region of lower longitudinal momentum fraction of the colliding partons, where the gluon density is much larger than the quark densities. The charge asymmetry of the selected data samples is then enhanced, although at the price of lowering the statistics.

In refs. [20, 22] we have analyzed the magnitude of the asymmetry and its statistical significance at the LHC, in QCD and in the presence of a colour-octet vector boson (see eq. (4)). The statistical significance of the measurement can be maximised by tuning the maximum rapidity  $y_C$  in eq. (10) and by selecting events with a minimal top-antitop quark pair invariant mass,  $m_{t\bar{t}}^{\min}$ . We found that around  $y_C = 0.7$  the statistical significance is maximised. In QCD, statistics compensate for the smallness of the charge asymmetry, and indeed it is not necessary to introduce any cut in  $m_{t\bar{t}}$ . In models with extra massive gluons, a cut at about half (or even below) of the mass of the heavy gluon that is probed maximises the statistical significance. This is a very interesting feature because softer top and antitop quarks should be identified more easily than the very highly boosted ones [36].

The production of top quark pairs together with one jet reach roughly half of the total inclusive cross-section calculated at next-to-leading order (NLO) [37]. The charge asymmetry in  $t\bar{t}$ +jet is produced by the interference of initial- with final-state real gluon emission (fig. 1). This charge asymmetry is of similar size, but of opposite sign to the total  $t\bar{t}$  inclusive asymmetry [5]. The exclusive charge asymmetry suffers, however, from huge higher-order corrections [38]. In ref. [39] we have extended our analysis to  $t\bar{t}$ +jet, particularly for Kaluza-Klein gluons where  $g_A^q = 0$  for light quarks [19], where the inclusive asymmetry vanishes at LO. It is interesting to stress that, contrary to the

SM, where top quarks contribute to the asymmetry only when they are in a colour-singlet state (colour factor equal to  $d_{abc}^2$ ), there are also colour-octet contributions proportional to the colour factor  $f_{abc}^2$  in  $t\bar{t}$ +jet.

## 7. – Conclusions

The new measurements of the top quark charge asymmetry at the Tevatron reduce the discrepancy with the SM from  $2\sigma$  to  $1.7\sigma$ , and do not disfavour completely vanishing or negative contributions beyond the SM at 95% CL. The new measurements thus relax some of the exclusion constraints obtained by several studies. We have updated our analysis for colour octet vector resonances and found that large vector couplings are still favoured at 90% CL in flavour universal scenarios, with a larger than before allowed parameter space at 95% CL. In flavour non-universal scenarios, with  $g_A^q g_A^t < 0$  there is not a significant change, although again the allowed parameter space is slightly larger.

From the analysis of other authors, scalar colour triplet and sextet states with large flavour-violating couplings are compatible with a large charge asymmetry, while colour singlet and octet fail to account for the data. Extra weak bosons in the  $t$ -channel again require large flavour-violating couplings, and would exhibit masses close to the electroweak scale. Since the new measurement of the charge asymmetry is closer to the SM prediction, one can anticipate that smaller flavour-violating couplings will be needed to account for the new measurement in these models.

The measurement of the charge asymmetry from  $t\bar{t}$  events, with or without associated jets, at the LHC seems promising, although challenging. The measurement requires to select relatively low boosted top quark events, which is certainly an advantage. Although  $1\text{ fb}^{-1}$  should be enough for a first measurement, most probably several tens of  $\text{fb}^{-1}$  of data will be necessary to distinguish among models.

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