

Constraints on four-fermion interactions from the $t\bar{t}$ charge asymmetry at hadron colliders

M. Perelló Roselló^a, M. Vos^b

IFIC (UVEG/CSIC), Apartado de Correos 22085, 46071 Valencia, Spain

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Abstract The charge asymmetry in top quark production at hadron colliders is sensitive to beyond-the-Standard-Model four-fermion interactions. In this study we compare the sensitivity of $t\bar{t}$ cross-section and charge asymmetry measurements to effective operators describing four-fermion interactions and study the limits on the validity of this approach. A fit to a combination of Tevatron and LHC measurements yields stringent limits on the linear combinations C_1 and C_2 of the four-fermion effective operators.

1 Introduction

Since the discovery of the top quark, its properties and interactions have been characterized in some detail. Run I of the LHC, with a top quark pair production of several million events, is extending the programme initiated at the Tevatron in several ways. The larger center-of-mass energy of the LHC moreover gains access to measurements of known processes involving top quarks in an unexplored kinematic regime and to entirely new processes (i.e. associated production: $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$).

All measurements so far are in good agreement with the Standard Model predictions. The most notorious exception is the measurement of the forward-backward asymmetry in $p\bar{p}$ collisions at 1.96 TeV at the Tevatron [1, 2] and its dependence on the kinematics of the $t\bar{t}$ system [3–7]. Excitement has decreased considerably in recent years, as the discrepancy failed to grow as additional Tevatron data were added. Taking into account the EW correction [8] and the full next-to-next-to-leading-order (NNLO) QCD corrections [9] the remaining tension of the inclusive measurements at the Tevatron with the SM prediction is down to the 1.5σ level. Measurements of a related charge asymmetry in 7 TeV [10–13]

and 8 TeV [14–16] pp collisions at the LHC by ATLAS and CMS are consistent with the SM prediction.

We assume in the following that all data on the top quark, including the Tevatron A_{FB} puzzle, is in reasonable agreement with the SM description. Remains the task of deriving the most comprehensive constraints on extensions of the Standard Model. The large number of related measurements requires a sophisticated multi-parameter treatment. The effective field theory paradigm seems an adequate solution to recast the wealth of measurements into a manageable number of constraints. First steps in the direction of a global fit to the top sector were recently set by the TopFitter collaboration [17, 18].

In this paper we derive constraints on beyond-the-Standard-Model (BSM) four-fermion operators involving top quarks from measurements at hadron colliders. In Fig. 1 the Feynman diagram for the relevant four-fermion operator is shown, as well as the Born-level Standard Model diagram for $q\bar{q} \rightarrow t\bar{t}$ production.

We compare the sensitivity of available and future cross-section and charge asymmetry measurements, signalling the complementarity of both types of measurements. We study the limits to the validity of the effective operator approach for a number of measurements and propose a practical solution to guarantee valid results with the current data and in the foreseeable future. Finally, we derive constraints on the four-fermion operators from Tevatron and LHC data and present the prospects for an addition of future measurements.

2 Effective operator setup

A general effective Lagrangian expands around the Standard Model in terms of Λ^{-2} :

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}(\Lambda^{-4}), \quad (1)$$

^a e-mail: martin.perello@ific.uv.es

^b e-mail: marcel.vos@ific.uv.es

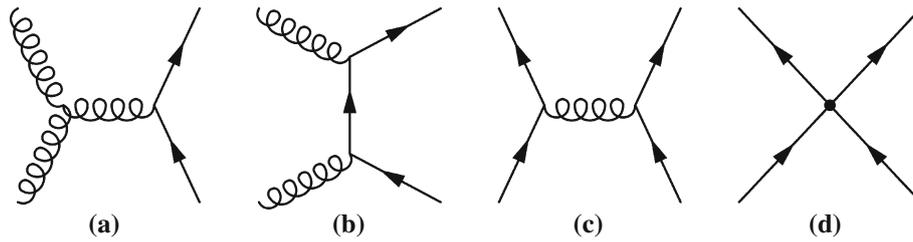


Fig. 1 Feynman diagrams for top quark pair production at hadron colliders. At the Born level SM production proceeds through gluon-initiated diagrams **a** and **b** and the $q\bar{q}$ annihilation process in **c**. The BSM diagram **d** corresponds to the $q\bar{q} \rightarrow t\bar{t}$ process through a four-fermion operator

where the O_i and C_i denote dimension-6 operators and their Wilson coefficients. We use $\bar{C}_i = C_i \times v^2/\Lambda^2$, with $v = 246$ GeV the Higgs vacuum expectation value, throughout the paper. The scale of new physics Λ has to be taken to several TeV for the effective operator paradigm to hold. We limit our analysis to contributions proportional to Λ^{-2} (i.e. the interference of the Standard Model with dimension-6 operators). In Sect. 5 we do, however, estimate the size of the Λ^{-4} terms by calculating the contribution of the square of the dimension-6 operators.

In Ref. [19] a basis is given for a complete set of dimension-six operators. As we are interested in the four-fermion operators involved in $t\bar{t}$ production at the LHC, operators including leptonic initial states are not included. The reduced group of seven four-fermion operators is listed in Table 1. Operators with the form $(\bar{q}\lambda^A u^i)(\bar{u}^j \lambda^A q)$ can be turned into a linear combination of $O_{qu}^{(1)}$ and are not included. We note that the operators involving left-handed quarks (those with the subscript q in Table 1) can be constrained by precision electroweak observables. These seven operators can be reduced to four by using a flavour-specific linear combination [20]:

$$\begin{aligned}
 C_1^u &= C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)} \\
 C_2^u &= C_{qu}^{(1)} + C_{qt}^{(1)} \\
 C_1^d &= C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)} \\
 C_2^d &= C_{qd}^{(1)} + C_{qt}^{(1)}
 \end{aligned}
 \tag{2}$$

A further reduction of the basis for four-fermion operators to two effective operators is achieved by assuming $C_1^u = C_1^d = C_1$ and $C_2^u = C_2^d = C_2$. This reduction is valid in models where the new massive states couple to u -type and d -type quarks with the same strength. Among the models that satisfy this requirement the axigluon [21] has received most attention in the context of the $t\bar{t}$ charge asymmetry measurements at the Tevatron and the LHC. We note that the assumption is also valid for models that are not strictly flavour-universal, such the axigluon with an opposite-sign coupling top quarks ($g_t = -g_q$), that can give rise to positive

Table 1 Four-fermion operators involved in $t\bar{t}$ production at hadron colliders in the notation from [20], where q is the left-handed quark doublet, u and d correspond to the up and down right-handed quarks of the first two families, and t represents the right-handed top quark

Operator
$O_{qq}^{(8,1)} = \frac{1}{4} (\bar{q}^i \gamma_\mu \lambda^A q^j) (\bar{q} \gamma^\mu \lambda^A q)$
$O_{qq}^{(8,3)} = \frac{1}{4} (\bar{q}^i \gamma_\mu \tau^I \lambda^A q^j) (\bar{q} \gamma^\mu \tau^I \lambda^A q)$
$O_{ut}^{(8)} = \frac{1}{4} (\bar{u}^i \gamma_\mu \lambda^A u^j) (\bar{t} \gamma^\mu \lambda^A t)$
$O_{dt}^{(8)} = \frac{1}{4} (\bar{d}^i \gamma_\mu \lambda^A d^j) (\bar{t} \gamma^\mu \lambda^A t)$
$O_{qu}^{(1)} = (\bar{q} u^i) (\bar{u}^j q)$
$O_{qd}^{(1)} = (\bar{q} d^i) (\bar{d}^j q)$
$O_{qt}^{(1)} = (\bar{q} t) (\bar{t} q)$

Superscripts i, j are used to denote the first two generations

contributions to the asymmetry, and the Kaluza Klein gluon as realized in Randall-Sundrum warped extra-dimensions in Refs. [22,23], the main benchmark for direct searches for resonant signals in $t\bar{t}$ production.

3 Measurements

To constrain the four-fermion effective operator coefficients simultaneously we need at least four independent measurements with good sensitivity to these operators. We choose the inclusive forward-backward asymmetry measured at Tevatron, and the charge asymmetry measured at the LHC at $\sqrt{s} = 8$ TeV. The inclusive $t\bar{t}$ production cross-section at the Tevatron and at the LHC at $\sqrt{s} = 8$ TeV are also included. The datasets are summarized in Table 2.

The selection of Table 2 emphasizes inclusive measurements that integrate over all kinematic regimes. The use of differential measurements, especially of the production of high-mass $t\bar{t}$ pairs, may offer greater sensitivity to high-scale physics beyond the SM [31]. We therefore include a recent ATLAS result for the charge asymmetry in events where the top quark pair is produced with a large invariant mass [29], which we take as a proxy for measurements in boosted

Table 2 Measurements considered in this analysis [30]

	SM prediction	Measurement
Tevatron, 1.96 TeV $p\bar{p}$, CDF+D0, inclusive σ	7.16 ± 0.26 pb [24]	7.60 ± 0.41 pb [25]
Tevatron, 1.96 TeV $p\bar{p}$, CDF+D0, inclusive A_{FB}	9.5 ± 0.7 % [9]	13 ± 2.3 % [4,5]
LHC, 8 TeV pp , ATLAS+CMS inclusive σ	245.80 ± 10.56 pb [24]	241.50 ± 8.54 pb [26]
ATLAS 8 TeV pp , inclusive A_C	1.11 ± 0.04 % [27]	0.9 ± 0.5 % [16]
CMS 8 TeV pp , inclusive A_C	1.11 ± 0.04 % [27]	0.3 ± 0.4 % [15]
ATLAS 8 TeV pp , differential A_C ($m_{t\bar{t}} > 0.75$ TeV)	1.60 ± 0.04 % [28]	4.2 ± 3.2 % [29]

The Tevatron A_{FB} measurement corresponds to a naive combination between D0 and CDF experiments. A combination of the ATLAS and CMS measurements of the inclusive asymmetry at 8 TeV is not yet available, so both measurement are kept as independent constraints

top quark pair production that become available at the LHC.¹

4 Sensitivity to effective operators

We generate $t\bar{t}$ samples at parton-level with the Monte Carlo generator Madgraph5_aMC@NLO [37] using the UFO [38] model TopEffTh [39] to calculate the impact of the effective operators on the cross-section and charge asymmetry.

The dependence of the top quark pair production cross section and the charge asymmetry on the four-fermion operator coefficients is parameterized² using the linear dependence of Eq. (3):

$$\frac{(\sigma - \sigma^{SM})}{\sigma^{SM}} = \left[\alpha_u (C_1^u + C_2^u) + \alpha_d (C_1^d + C_2^d) \right] \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2, \quad (3)$$

and (4):

$$(A_C - A_C^{SM}) = \left[\beta_u (C_1^u - C_2^u) + \beta_d (C_1^d - C_2^d) \right] \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2 \quad (4)$$

Equation (3) shows that the cross section is proportional to $C_1 + C_2$, while the asymmetry in Eq. (4) is proportional to

¹ ATLAS and CMS have also published differential cross section measurements at $\sqrt{s} = 7$ and 8 TeV [32–36]. These are not included in the fit as the measurements at low mass (or top p_T) provide a weak constraint, while the measurement at very high mass strongly restricts the validity interval (as discussed in Sect. 5).

² As we use a leading order calculation for the Standard Model contribution σ^{SM} in Eq. (3) corresponds to the Born-level result. The charge asymmetry appears only at next-to-leading order in the SM, so the leading-order asymmetry in Eq. (4) is vanishes, $A_C^{SM, Born} = 0$. For the comparison with data NNLO+NNLL predictions are used for the purely Standard Model contribution, while the charge asymmetry A_C at the LHC is only available to NLO precision.

$C_1 - C_2$. Therefore, the combination of the two measurements provides a very powerful constraint on both C_1 and C_2 operators. The complementarity is illustrated in Fig. 2a, where the bands representing the constraint from the asymmetry measurement cross the cross-section bands at a straight angle.

The results for the coefficients of Eqs. (3) and (4) are presented in Table 3. The coefficients α_u and α_d are defined such that they are proportional to the contribution of new interactions to the cross-section divided by the SM cross section. As such the size of $\alpha_{u/d}$ in different measurements offers a good indication of the sensitivity of the measurements (assuming the *relative* precision of all measurements is equal, condition that is approximately met for the measurements in the Table). The $\beta_{u/d}$ coefficients indicate the strength of the constraint for charge asymmetry measurements of the same absolute precision.

For all measurements the coefficients α_u and β_u for the u-type operators are larger than α_d and β_d , that apply to d-type operators. The ratios α_u/α_d and β_u/β_d are largest at the Tevatron, where a naive estimate based on the valence quark content of the proton and anti-proton would yield a factor of four. The large ratio at the Tevatron is quite powerful to derive simultaneous constraints on u-type and d-type operators. The Tevatron bands in C_1^u and C_1^d space in Fig. 2b cross at more favourable angles than the LHC bands. At the LHC (where the naive estimate would yield a ratio of two) the u-type and d-type operator coefficients are much closer.

Among the inclusive measurements, the Tevatron clearly offers a much greater sensitivity to four-fermion operators than the LHC at 8 TeV, reflecting the much larger dilution by gluon-initiated processes at the LHC. The impact of the dilution is most clearly observed in the cross-section bands in Fig. 2a. Even if ATLAS and CMS have managed to reduce the uncertainty on the pair production cross-section measurement to approximately 4 % (compared to 5 % for the Tevatron combination) the constraint from the LHC 8 TeV cross-section data is quite weak. The gluon-gluon contribution to the cross-section reaches nearly 90 % at 13 TeV, reducing the sensitivity even further.

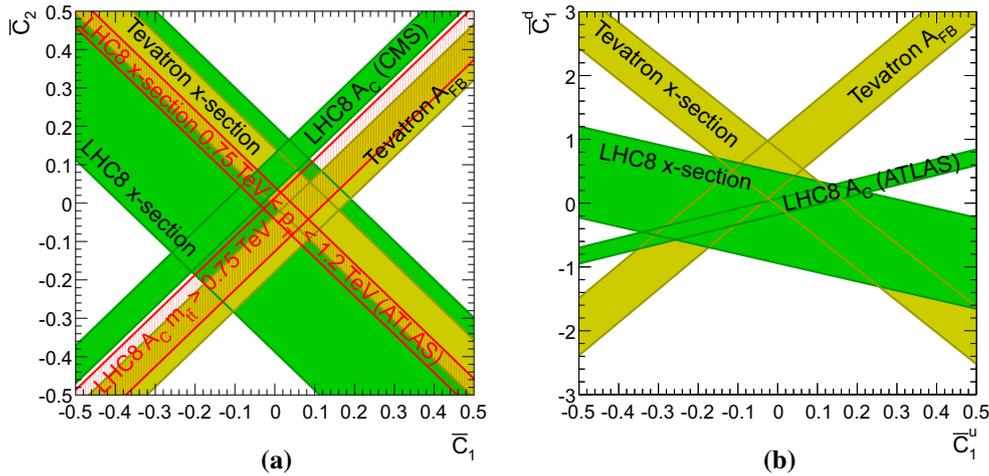


Fig. 2 The 68% confidence level constraints on pairs of effective operators from several cross-section and charge asymmetry measurements. The bands represent in **a** represent the constraints on C_1 and C_2 (assum-

ing $C_1^u = C_1^d = C_1$ and $C_2^u = C_2^d = C_2$). The bands in **b** represent the constraints on C_1^u and C_1^d

Table 3 Parameterization of the coefficients α and β of Eqs. (3) and (4), that govern the impact of non-zero effective operators on the cross-section and the charge asymmetry, respectively

	α_u [%]	α_d [%]	β_u [%]	β_d [%]
Tevatron 1.96 TeV $p\bar{p}$ inclusive	5.19 ± 0.02	1.05 ± 0.02	1.66 ± 0.09	0.32 ± 0.09
LHC 8 TeV pp inclusive	1.02 ± 0.02	0.71 ± 0.02	0.37 ± 0.09	0.24 ± 0.09
LHC 8 TeV pp ($m_{t\bar{t}} > 0.75$ TeV)	3.03 ± 0.09	1.56 ± 0.09	2.16 ± 0.09	0.6 ± 0.09
LHC 13 TeV inclusive	0.73 ± 0.02	0.48 ± 0.02	0.26 ± 0.09	0.27 ± 0.09
LHC 13 TeV ($m_{t\bar{t}} > 1.2$ TeV)	6.61 ± 0.02	3.60 ± 0.02	6.09 ± 0.09	2.78 ± 0.09

The u/d subscripts indicate whether the coefficients correspond to u -type or d -type quarks

Table 3 suggests a way to restore the sensitivity of the LHC to the level of the Tevatron and beyond. The differential measurements listed in the table correspond to the cross-section and charge asymmetry for boosted top quark production. For 8 TeV operation the phase space is limited to events with an invariant mass of the $t\bar{t}$ system $m_{t\bar{t}} > 750$ GeV. For 13 TeV the cut on $m_{t\bar{t}}$ is raised to 1.2 TeV. We see that the α and β coefficients of these differential measurements are indeed an order of magnitude larger than those of the inclusive measurements at the same center-of-mass energy. Therefore, the measurement of the charge asymmetry at high mass can provide a competitive constraint, even with an uncertainty that is an order of magnitude larger than that of the inclusive charge asymmetry measurement. The measurements of the charge asymmetry and cross section in boosted top quark production of Refs. [29] and [33], indicated as red dashed bands in Fig. 2, provide quite competitive constraints. These measurements are still statistically limited in run I, with a non-negligible contribution from modelling uncertainties in these relatively unexplored corners of phase space. With the large $t\bar{t}$ samples that become available in run 2 of the LHC there is consid-

erable margin for improvement of this and other differential measurements.

5 Validity of the effective operator approach

The charge asymmetry is reported by several authors (see for instance Ref. [40]) to receive relatively large contributions from terms that are proportional to Λ^{-4} . As a full treatment of all these terms (including the contribution of the interference between dimension-8 operators with the SM and the interference between two dimension-6 operators vertices and the SM) is not feasible at present, this poor convergence may jeopardize the effective operator paradigm in this area. In this Section we estimate the size of the Λ^{-4} contributions by calculating the contribution of the dimension-6 operator squared (i.e. $|BSM|^2$), which is accessible in the TopEffTh model. We then have:

$$\left(O_i - O_i^{SM}\right) = AC_i \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 + A'C_i^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4. \quad (5)$$

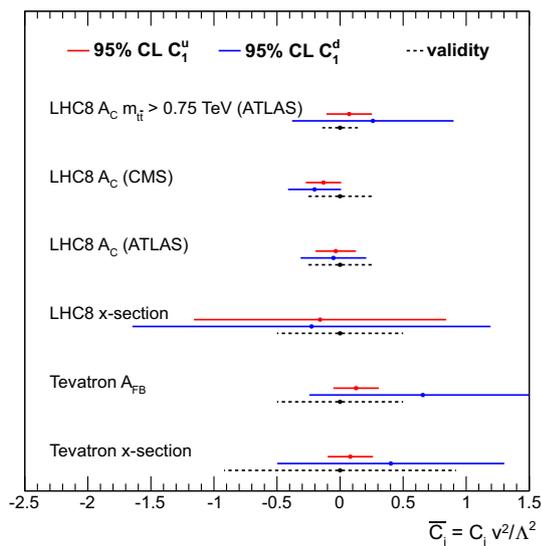


Fig. 3 The interval of validity and 95 % CL limits of cross-section and charge asymmetry measurements at hadron colliders. The interval of validity is given as a black dashed line. For each measurement the 95 % CL limits on the coefficients of the effective operators involving u-type and d-type quarks are indicated as error bars. Operators are fit one by one, with all other non-SM operators are set to 0

For each measurement and each operator from Table 1 we determine the ratio A/A' . The results we obtain for the different operators in Table 1 are generally in good agreement for a given measurement, but vary from one measurement to the next. We therefore present a unique interval for each measurement. Following Ref. [40] the region of validity is given by the interval of the coefficient C_i where the (Λ^{-2}) linear term is at least twice as large as the quadratic (Λ^{-4}) term (i.e. $A/A' > 2C_i (\frac{1\text{TeV}}{\Lambda})^2$).

In Fig. 3 the range of validity for each measurement is compared to the 95 % CL constraint on C_1^u and C_1^d derived from that measurement (assuming vanishing contributions from all other operators). To guarantee valid results we require that the 95 % CL interval is fully contained in the $A/A' > 1 C_i (\frac{1\text{TeV}}{\Lambda})^2$ band.³

The interval of validity shrinks with the increase in center-of-mass energy: at the 8 TeV LHC it is typically a factor two smaller than at the Tevatron. In combination with the reduced sensitivity to four-fermion operators of the LHC data there is a risk that adding a measurement may reduce the interval of validity more than the 95 % CL interval. The differential measurements can see a very strong reduction of the interval of validity, in particular once we enter the regime of boosted top quark pair production. However, in this case the sensi-

tivity grows to compensate the reduced interval of validity. Therefore, a differential measurement of sufficient precision may prove to be useful in the fit.

The same trend towards smaller interval of validity for increasing center-of-mass energy is observed for the cross section and the charge asymmetry. The interval of validity of the charge asymmetry is generally somewhat smaller than that of the cross section, but the difference is small compared to that between the Tevatron and the LHC, or between inclusive and differential measurements. For the inclusive measurements at the 8 TeV LHC the tension between interval of validity and the 95 % CL interval on individual coefficients is much more pronounced for the cross-section measurement than for the charge asymmetry.

6 Multi-parameter fit

So far we have evaluated constraints on one coefficient at the time, assuming all others have a vanishing contribution. In this Section we generalize the fit to all four-fermion operators (but still keep the remaining effective operators related to two-fermion interactions equal to 0). Using the parameterization, and the datasets from Table 2, we construct an overall χ^2 function:

$$\chi^2 = \sum_i \left(\frac{O_i(\{C_i\}) - O_i^{exp}}{\Delta_i^{exp}} \right)^2, \tag{6}$$

where $O_i(\{C_i\})$ corresponds to the parameterisation of Eq. (3) or Eq. (4) and O_i^{exp} and Δ_i^{exp} to the difference between the measurement and the SM prediction. The sum runs over all measurements i defined in Table 2.

We minimize the χ^2 function using the root package MINUIT [41] in order to extract the parameters $\{C_i\}$.

The simultaneous fit of the four effective operators $\bar{C}_1^u, \bar{C}_2^u, \bar{C}_1^d$ and \bar{C}_2^d using all data in Table 2 yields tight constraints on the former two, that correspond to interactions initiated by u-type quarks. The 95 % CL limits are contained within the interval of validity. As we anticipated in Sect. 4 the constraint on operators corresponding to d-type quarks is much weaker, where the marginalized 95 % CL constraints from the four-parameter fit on \bar{C}_1^d and \bar{C}_2^d are 3–5 times weaker than the limits on single operators. The marginalized 95 % CL intervals extend beyond the interval of validity. The exact level of tension between range of validity and limits depends somewhat on which measurements are included in the fit, but the qualitative conclusion remains true for all combinations of the data in Table 2: none of the combinations of the cross-section and charge asymmetry data yield meaningful marginalized limits on \bar{C}_1^d and \bar{C}_2^d . A similar observation was made in Ref. [18] for \bar{C}_2^d .

³ This requirement ensures that the χ^2 evaluation on the 68 % CL interval is within the $A/A' > 2 C_i (\frac{1\text{TeV}}{\Lambda})^2$ interval where the Λ^{-4} is of minor importance. This is therefore equivalent to the criterion of Ref. [40].

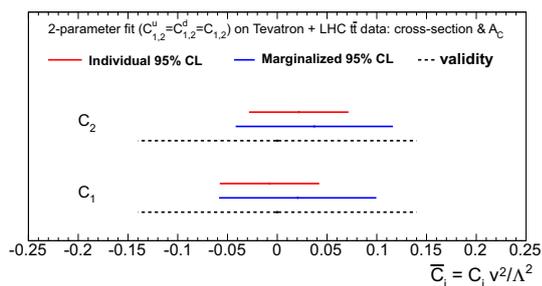


Fig. 4 The 95 % CL limits on the four-fermion operators C_1 and C_2 extracted from cross-section and charge asymmetry measurements at hadron colliders. The *individual* limits are obtained assuming all other non-SM operators are 0, while the *marginalized* limits are obtained from a two-parameter fit that floats both operator coefficients simultaneously

Much stronger constraints are obtained when we assume $C_1^u = C_1^d = C_1$ and $C_2^u = C_2^d = C_2$. In this case, the interval is within the tightest interval of validity of the measurements used in the fit.⁴ We therefore present the constraints obtained with the two-parameter fit as the main result of this study.

7 Constraints on four-fermion operators

The result of the two-parameter fit of the coefficients $C_1 = C_1^u = C_1^d$ and $C_2 = C_2^u = C_2^d$ of the four-fermion operators to $t\bar{t}$ production cross section and charge asymmetry measurements at hadron colliders is presented in Fig. 4. All other dimension-6 effective operators are assumed to have negligible impact. The allowed intervals at 95 % confidence level are $-0.06 < \bar{C}_1 < 0.1$ and $-0.04 < \bar{C}_2 < 0.11$. The allowed intervals are contained within the region where the Λ^{-2} contribution of the dimension-6 operators dominates over an estimate of the Λ^{-4} contribution (indicated as a black line labelled “validity”).

As discussed in Sect. 4 the charge asymmetry and cross-section measurements provide complementary constraints. Indeed, the simultaneous fit of C_1 and C_2 yields very similar results to the limits obtained when a single operator is floated in the fit.

A fit of the two linear combinations $\bar{C}_+ = \bar{C}_1 + \bar{C}_2$ and $\bar{C}_- = \bar{C}_1 - \bar{C}_2$ yields limits $-0.09 < \bar{C}_+ < 0.2$ and $-0.07 < \bar{C}_- < 0.04$. In this case the results are readily related to the measurements. We see that the \bar{C}_- constraint, driven by the charge asymmetry, is nearly three times stronger than

⁴ The matching of the intervals of validity of different measurements is quite delicate in a multi-parameter fit. For instance, we do not include the last bins of the differential cross section measurement of Ref. [33] in our fit. Even if the cross section measurements provides a powerful constraint on C_+ , as shown in Fig. 2a, the current charge asymmetry measurements cannot provide an equally stringent bound and the overall validity of the fit would be compromised.

the constraint on \bar{C}_+ , that is dominated by the cross-section measurements. The central value of C_+ is 0.06, due to the Tevatron cross-section of Refs. [4,5] that slightly exceeds the SM prediction. The C_- fit is pulled towards negative values by the CMS measurement in Ref. [15]. This measurement, 2σ below the SM value, is able to compensate the positive pull from the Tevatron experiments. We propose the constraint on $\bar{C}_- = \bar{C}_1 - \bar{C}_2$ as a benchmark for charge asymmetry measurements: the extent of the 95 % CL allowed region is a good figure-of-merit to relate the sensitivity to high-scale new physics of measurements with different initial states (i.e. Tevatron vs. LHC), different center-of-mass energies and in different kinematic regimes. Similarly, the constraint on $\bar{C}_+ = \bar{C}_1 + \bar{C}_2$ is a good indicator of the sensitivity of cross section measurements to high-scale new physics in processes initiated by a quark and anti-quark.

The limits on the four-fermion operators presented in this paper are stronger than those of the global fit to the top sector presented in Refs. [17, 18]. The prize to pay for this gain in precision is a loss of generality: the limits we derive are valid only under the assumption of equal coefficients for the four-fermion operators involving u-type and d-type quarks: $C_1 = C_1^u = C_1^d$ and $C_2 = C_2^u = C_2^d$. We believe, however, that this may be the most practical way to guarantee the validity of the effective operator approach with the current data sets. In the long run more precise data from LHC run 2 should allow to constrain the separate four-fermion operators of up-type and down-type quarks to safe intervals.⁵

8 Comparison to a concrete new physics model

The limits on C_- can be recast into limits on the mass of a flavour-universal axigluon [21] (with equal couplings to all quarks) using the relation $(C_1 - C_2)/\Lambda^2 = -4g_s^2/m_A^2$ from Ref. [39]. The 95 % CL lower limit on the axigluon mass is 2.0 TeV. The axigluon with opposite-sign couplings to light and top quarks ($g_t = -g_q$), that makes a positive contribution to the charge asymmetry, is even more strongly constrained: $m > 2.8$ TeV. These limits extend the exclusion of earlier studies [42] considerably.

Both limits are well in excess of the 1.5 TeV that Ref. [39] quotes as the lower limit for application of the effective-operator analysis. We stress once more that these limits are valid only under the assumption that there are no new degrees of freedom below the scale Λ .

⁵ Ideally, one would float all four degrees of freedom in the fit when extracting the coefficients of the two-fermion operators, so as to avoid an artificial reduction of the uncertainty on these parameters. Then, the four-fermion operator constraints can be obtained under the assumption $C_1 = C_1^u = C_1^d$ and $C_2 = C_2^u = C_2^d$.

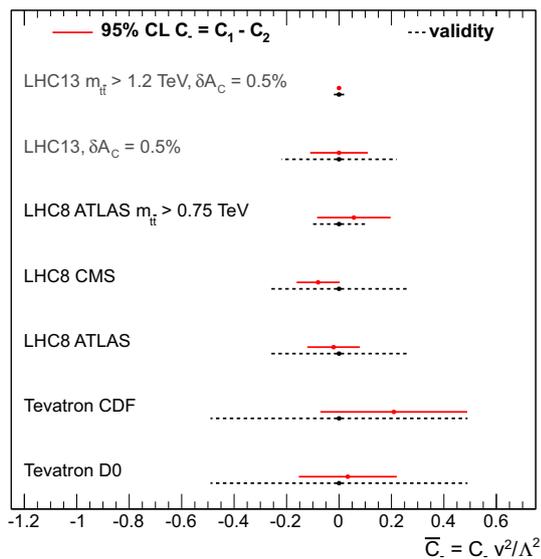


Fig. 5 The 95 % CL limits on the linear combination of four-fermion operators $\bar{C}_- = \bar{C}_1 - \bar{C}_2$ extracted from charge asymmetry measurements at hadron colliders. The entries labelled as LHC13 present the prospects of a charge asymmetry measurement with an uncertainty of 0.5 % and a central value in exact agreement with the SM prediction

With LHC run I the sensitivity for observation of a narrow signal on the SM $t\bar{t}$ background has entered the sub-pb regime for a multi-TeV resonance. The ATLAS and CMS searches [43,44] yield a 95 % CL lower limit on the axigluon mass of order 2 TeV. Limits from di-jet resonance searches at 13 TeV provide even stronger limits on this particular model [45].

9 Outlook to LHC run 2

During the preparation of this paper the analysis of LHC run 2 data is in full swing. CMS has published a first $t\bar{t}$ cross-section measurement [46], while ATLAS has produced a preliminary result [47]. It is instructive to consider the effect of the inclusion of the 13 TeV results in the fit.

The constraints on \bar{C}_- of past and present measurements and the prospects for future measurements of charge asymmetries are shown in Fig. 5.

In 13 TeV pp collisions the $q\bar{q} \rightarrow t\bar{t}$ process is further diluted by the increase in gluon-gluon-initiated $t\bar{t}$ production. Therefore, the sensitivity of inclusive measurements to four-fermion operators is limited. In Fig. 5 the expected uncertainty on \bar{C}_- from the 13 TeV inclusive charge asymmetry measurement with a precision of 0.5 % is larger than that of the current LHC8 measurements with a similar precision. With the current uncertainty of approximately 15 % (dominated by the 10 % uncertainty of the preliminary estimate of the integrated luminosity) the cross-section measurements

add no value to the fit. For inclusive measurements the interval of validity at 13 TeV is reduced only slightly, to $-0.22 < \bar{C}_X < 0.22$, and a two-parameter fit (with the assumption $C_u = C_d$) on measurements of comparable precision to those at 8 TeV is expected to yield a limit that remains within the interval of validity.

We already signalled in Sect. 4 that the excellent sensitivity to four-fermion operators of differential measurements, in particular measurements in the regime of boosted $t\bar{t}$ pair production, compensates for their (current) relatively poor precision. As an example, consider highly boosted top quark pair production with $m_{t\bar{t}} > 1.2$ TeV, the top entry in Fig. 5. If a charge asymmetry is performed to 0.5 % precision an extremely tight constraint on four-fermion interactions can be derived. A problem for the inclusion of such measurements is the limited range of validity of the effective operator analysis for such measurements (due to large contributions from the Λ^{-4} terms that are only partially known). Requiring that the Λ^{-2} term dominates over Λ^{-4} term reduces the interval accessible to the effective operator analysis to $|\bar{C}_X| < 0.03$, well below the current limits. To constrain the measurement the measurement of both \bar{C}_1 and \bar{C}_2 operators to this level would require a (relative) cross section measurement in the boosted regime with a precision of 4 % and a charge asymmetry measurement with a precision of 0.5 %, which is definitely challenging, but may not be impossible.

10 Summary

Top quark pair production data at hadron colliders provides a constraint on four-fermion interactions. Analyzing the relative sensitivities of pair production measurements at the Tevatron and the LHC we find that the cross-section and charge asymmetry measurements provide complementary constraints, where the latter are more powerful at the LHC. The sensitivity to four-fermion operators is strongly enhanced for measurements in the boosted regime.

Several authors [17,39,40] have signalled the importance of higher-dimension contributions of order (Λ^{-4}) to high-energy collision data. We have ensured explicitly that these contributions, whose size is estimated as the contribution of the dimension-6 operator squared, are subdominant in our fit.

We have extracted limits on the dimension-6 operators C_1 and C_2 , under the assumption of that the coupling strengths to up- and down-type quarks are identical (i.e. $C_1 = C_1^u = C_1^d$ and $C_2 = C_2^u = C_2^d$). The allowed intervals at 95 % CL, $-0.06 < C_1 \times v^2 / \Lambda^2 < 0.10$ and $-0.04 < C_2 \times v^2 / \Lambda^2 < 0.11$, are in good agreement with the SM prediction $C_1 = C_2 = 0$. These form stricter limits than those obtained from a global fit that includes the same data [17] (at what we believe is an acceptable loss of generality).

For an explicit UV completion such as the axigluon model these limits correspond to a lower limit on the mass in excess of 2 TeV, which is a competitive constraint when compared to direct limits from resonance searches.

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