Implications of the CDF $t\bar{t}$ Forward-Backward Asymmetry for Hard Top Physics

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Abstract

The CDF collaboration has recently reported a large deviation from the standard model of the $t\bar{t}$ forward-backward asymmetry in the high invariant mass region. We interpret this measurement as coming from new physics at a heavy scale $\Lambda$, and perform a model-independent analysis up to $O(1/\Lambda^4)$. A simple formalism to test and constrain models of new physics is provided. We find that a large asymmetry cannot be accommodated by heavy new physics that does not interfere with the standard model. We show that a smoking gun test for the heavy new physics hypothesis is a significant deviation from the standard model prediction for the $t\bar{t}$ differential cross section at large invariant mass. At $M_{t\bar{t}} > 1$ TeV the cross section is predicted to be at least twice that of the SM at the Tevatron, and for $M_{t\bar{t}} > 1.5$ TeV at least three times larger than the SM at the LHC.

1 Introduction

The top quark is the most massive point-like particle known to exist. As a consequence, within the Standard Model (SM), the top is largely responsible for the hierarchy problem. Furthermore, in most natural models it is linked to electroweak symmetry breaking. Therefore, there is strong motivation to search for new physics effects associated with top physics.

The CDF collaboration has recently announced several intriguing new measurements that exhibit large deviations from the corresponding SM predictions. Evidence for an anomalous forward-backward $t\bar{t}$ production asymmetry was observed for large invariant mass of the $t\bar{t}$ system \cite{1}:

$$A_{450}^{t\bar{t}} = A^{t\bar{t}}(M_{t\bar{t}} \geq 450 \text{ GeV}) = +0.475 \pm 0.114,$$

(to be compared with the SM prediction \cite{2,3,4}, $A_{450}^{t\bar{t}} = +0.09 \pm 0.01$). Previous D0 and CDF measurements of the inclusive $t\bar{t}$ asymmetry \cite{5,6} also show deviation from the SM prediction. Another recent CDF analysis in the dilepton channel \cite{7} supports this deviation, and furthermore finds a rising $M_{t\bar{t}}$ dependence for the forward-backward asymmetry.

Additionally, the CDF collaboration has recently made progress in studying the mass distribution of highly boosted jets ($p_T > 400$ GeV for the leading jet) \cite{8}, and found a hint for an excess of events in the high mass region \cite{9}.

The above measurements suggest that new physics affecting the top sector is present. Our approach in this work is the following. We interpret the measurement of $A_{450}^{t\bar{t}}$ in terms of new physics, checking the consistency of such a scenario with other measurements that do not show
any significant deviation from the SM predictions. We further discuss the effects of such new physics on ultra-massive boosted jets at the Tevatron. We then make predictions for the invariant mass distributions of top pairs soon to be measured at the Tevatron and LHC.

Several works have interpreted the recent CDF measurement of $A_{t\bar{t}450}$ within specific models of new physics [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Similarly, model-independent analyses were performed [24, 25, 26] and new physics models were invoked [27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41] to explain earlier D0 and CDF measurements of the inclusive asymmetry [5, 6].

We focus on the class of models in which the scale of new physics is well above the scale $M_{t\bar{t}}$ relevant to the CDF measurements. The effects of such new physics can then be described from a low energy model-independent perspective, using the language of effective field theory. Ref. [42] performed a similar analysis, further assuming that the dominant contribution to the forward-backward asymmetry comes from interference between the new physics and SM contributions to top pair production. Denoting the scale of new physics by $\Lambda$, Ref. [42] found that in the presence of an axial octet operator producing a pair of tops from a pair of up quarks at $\mathcal{O}(1/\Lambda^2)$, the observed $t\bar{t}$ forward-backward asymmetry can be accounted for. Here we relax the assumption of interference and consider all operators contributing to $t\bar{t}$ production up to order $1/\Lambda^4$. We provide a simple formalism that enables one to easily obtain constraints and predictions for models consistent with our framework. We derive model-independent predictions regarding near future measurements that will sharply test our general underlying assumptions.

The paper is organized as follows. In Section 2 we review the data relevant to our study. Section 3 defines the set of operators in our effective Lagrangian. Section 4 relates the operators to the observables. Our results are presented in Section 5. In Section 6 we discuss predictions for hard top physics at the Tevatron and LHC. We conclude in Section 7.

2 Relevant Data

In this work we analyze the effect of heavy new physics on the forward-backward asymmetry at large $M_{t\bar{t}}$. Roughly, we aim to account for a new physics contribution of

$$A_{t\bar{t}450} = +0.40 \pm 0.11,$$

assuming that the rest of the asymmetry in Eq. (1) comes from the SM.

Other top-related measurements do not show significant deviations from the SM predictions. Consequently, they provide constraints on the parameter space of the effective Lagrangian. The first such observable is the $t\bar{t}$ differential cross section, which we choose to represent by the following large $M_{t\bar{t}}$ bin [43]

$$\sigma_{700} \equiv \sigma^{t\bar{t}}(700 \, \text{GeV} < M_{t\bar{t}} < 800 \, \text{GeV}) = 80 \pm 37 \, \text{fb},$$

as in [42]. This is consistent with the SM prediction [4, 44], $\sigma_{700} = 80 \pm 8 \, \text{fb}$. In [42], the inclusive $t\bar{t}$ cross section was also used as a constraint. However, the theoretical estimation of the cross section originating from threshold effects is still under investigation (compare [45, 46, 47] with [44]). Furthermore, the dynamics of our heavy new physics naturally affects the measurement at large invariant masses more significantly. Thus in our study we do not use the inclusive $t\bar{t}$ cross section to constrain our parameter space. (Note though that our results below are within the combined theoretical and experimental uncertainties for the inclusive observables.) The same
argument leads us to refrain from considering $A^t\bar{t}$ in the low invariant mass region, as well as the inclusive asymmetry. We therefore use a theoretically-cleaner observable, also relevant for $A^t\bar{t}_{450}$, related to the cross section above 450 GeV, $\sigma_{450}$. Note that there seems to be some discrepancy in [3] between the measurement in this range and the SM prediction. However, in a more recent measurement reported in [1] (but not translated to the partonic level) this discrepancy is not present. We thus assume that the SM prediction agrees with the measured value of the cross section above 450 GeV. For concreteness, we use the relative uncertainty reported in [1] for the 450-500 GeV $M_{t\bar{t}}$ bin (see below), which dominates the uncertainty in the $M_{t\bar{t}}>450$ GeV range.

In order to minimize the impact of next to leading order (NLO) corrections to the new physics (NP) contributions, we normalize the latter to the SM one. We assume that the $K$-factors are universal, so that the NP/SM ratios at leading order and next to leading order are the same. This assumption is reasonable for the effective operators generated in the SM after the highly virtual gluon is integrated out [42]. Additional NLO corrections are formally down by $O(\alpha_s/\pi)$ and are henceforth neglected. In practice, log-enhancements of these contributions might be present which could modify the analysis. A full NLO computation of the effective theory is yet to be done, and is beyond the scope of this work. However, as a self consistency check of our analysis, we find below that the SM-like operators indeed account for the dominant part of the forward-backward asymmetry (see Fig. 2), supporting the above assumption.

Combining in quadrature the experimental and theoretical uncertainties, we represent Eq. (3) and the uncertainty on the cross section above 450 GeV as follows:

$$|N_{700}| \equiv \left| \sigma_{NP}^{700}/\sigma_{SM}^{700} \right| \lesssim 0.5 , \quad |N_{450}| \equiv \left| \sigma_{NP}^{450}/\sigma_{SM}^{450} \right| \lesssim 0.2 . \quad (4)$$

It is also intriguing to explore the implications of the new physics in the context of the CDF boosted jets study [8, 9]. The cross section for ultra-massive boosted jets (not coming from QCD events) can be estimated as follows [42]

$$\sigma_b \sim \left[ 21 - (8.7 \pm 3.1) R_{mass}^{-1} \right] \text{ fb} , \quad (5)$$

where $\sigma_b$ is the cross section of hadronically-decaying $t\bar{t}$ with a $p_T$ cut of 400 GeV on the leading jet and $R_{mass}$ is a parameter that determines the QCD background, as defined in [42, 48]. (An assumption of naive factorization of the jet mass distribution yields $R_{mass} = 1$, while matched Monte-Carlo simulations give $R_{mass} = 0.87$ [42, 48] with an excellent agreement on this value between the different generators.) The SM prediction for the top contribution is $\sigma_b^{SM} = 2.0 \pm 0.2$ fb [49]. We interpret the excess as top pairs, generated by the new physics source. The magnitude of this effect is then [42]

$$N_b \equiv \sigma_b^{NP}/\sigma_b^{SM} = 5 \pm 2 , \quad (6)$$

where $\sigma_b^{NP}$ is the new physics contribution to the boosted cross section, assuming $R_{mass} = 0.87$.

3 The Operator Basis

As stated above, the basic assumption that we employ is that the new physics is characterized by a scale $\Lambda$ that is larger than the invariant mass of the top pair $M_{t\bar{t}}$ in the measurements which we consider. The natural approach is then to use a set of effective operators to describe the new physics. These operators must lead from an initial $u\bar{u}$ state to a final $t\bar{t}$ state, and as such appear
at dimension six and higher. (The contribution of $d\bar{d} \to t\bar{t}$ at the Tevatron is at most 15% that of $u\bar{u} \to t\bar{t}$ for $M_{tt}$ above 450 GeV, as relevant for the observables that we consider.)

At $\mathcal{O}(1/\Lambda^2)$, there are only two four-quark operators that interfere with the SM:

$$\mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u) (\bar{t}\gamma_\mu T^a t), \quad \mathcal{O}_A^8 = (\bar{u}\gamma_\mu \gamma^5 T^a u) (\bar{t}\gamma_\mu \gamma^5 T^a t),$$  \hspace{1cm} (7)

where the superscript 8 denotes an octet color structure. Allowing for contributions that do not interfere with the SM, there are two more vector octet operators at this order:

$$\mathcal{O}_{AV}^8 = (\bar{u}\gamma_\mu \gamma^5 T^a u) (\bar{t}\gamma_\mu T^a t), \quad \mathcal{O}_{VA}^8 = (\bar{u}\gamma_\mu T^a u) (\bar{t}\gamma_\mu \gamma^5 T^a t).$$  \hspace{1cm} (8)

There are four additional orthogonal combinations of color contractions, given by:

$$\mathcal{O}_V^1 = (\bar{u}\gamma_\mu u) (\bar{t}\gamma_\mu t), \quad \mathcal{O}_A^1 = (\bar{u}\gamma_\mu \gamma^5 u) (\bar{t}\gamma_\mu \gamma^5 t),$$

$$\mathcal{O}_{AV}^1 = (\bar{u}\gamma_\mu \gamma^5 u) (\bar{t}\gamma_\mu t), \quad \mathcal{O}_{VA}^1 = (\bar{u}\gamma_\mu u) (\bar{t}\gamma_\mu \gamma^5 t).$$  \hspace{1cm} (9)

The list of dimension six operators is concluded with eight scalar and two tensor operators:

$$\mathcal{O}_{S}^{1,8} = (\bar{u} T_{1,8} u) (\bar{t} T_{1,8} t), \quad \mathcal{O}_{P}^{1,8} = (\bar{u} T_{1,8} \gamma^5 u) (\bar{t} T_{1,8} \gamma^5 t),$$

$$\mathcal{O}_{SP}^{1,8} = i (\bar{u} T_{1,8} u) (\bar{t} T_{1,8} \gamma^5 t), \quad \mathcal{O}_{PS}^{1,8} = i (\bar{u} T_{1,8} \gamma^5 u) (\bar{t} T_{1,8} t),$$

$$\mathcal{O}_{T}^{1,8} = (\bar{u} T_{1,8} \sigma^{\mu\nu} u) (\bar{t} T_{1,8} \sigma_{\mu\nu} t),$$  \hspace{1cm} (10)

with $T_1 \equiv 1$ and $T_k \equiv T^a$. The above dimension six operators contribute to top pair production at $\mathcal{O}(1/\Lambda^4)$ as well, via the square of their amplitudes. Another type of contribution at $\mathcal{O}(1/\Lambda^4)$ comes from chirality-conserving dimension eight operators that interfere with the SM. These can be constructed by applying two covariant derivatives in various ways to the operators in Eq. (7). However, naive dimensional analysis shows that their value is given by $c^2/(16\pi^2)$, where $c$ is the coefficient of any dimension six operator. This condition generically holds in case of strongly-coupled new physics, i.e. when the NP scale is roughly 5-10 TeV [42]. Moreover, even in models with a lower scale (e.g. a ~2 TeV s-channel resonance), producing a large value for $A_{t\bar{t}}^{\Lambda_{450}}$ typically leads to a suppression of the dimension eight contributions compared to the square of the dimension six amplitudes. We thus neglect these dimension eight contributions in what follows.

Note that in principle there are also dimension six chromo-magnetic/electric $u$ and $t$ dipole operators that can be considered. Their effects at $\mathcal{O}(1/\Lambda^2)$ in the hard $M_{tt}$ regime were shown to be negligible in [42]. As they involve chirality flips, their contributions at order $1/\Lambda^4$ are suppressed by at least $(m_t/\Lambda)$ compared to their $1/\Lambda^2$ effects. There are also chirality-flipping dimension eight operators which interfere with the SM, and are again suppressed by the same factor.

To conclude, we describe the hard region of the $t\bar{t}$ physics by the following effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i,$$  \hspace{1cm} (11)

where the $c_i$ are real coefficients and the operators $\mathcal{O}_i$ are listed in Eqs. (7)-(10). Below for simplicity of notation, $c_i$ will denote $c_i/\Lambda_{\text{TeV}}^4$, where $\Lambda_{\text{TeV}} \equiv \Lambda/\text{TeV}$. In our analysis we perform all calculations at leading order and neglect renormalization group running and mixing. Consequently, we also do not discuss the contribution from operator mixing to dijet production at the LHC [13]. In principle, the NP can couple to light and heavy quarks with different strengths. Generically, the operators discussed above can be characterized by a
mixed coupling of NP to light and heavy quarks, \( g_{u\bar{u}} \times g_{t\bar{t}} \), whereas the constraints from dijets are sensitive to operators characterized by a strength \( g_{u\bar{u}}^2 \). Examining the present bounds from dijet production at the LHC \[50, 51\], a hierarchy of \( g_{u\bar{u}}/g_{t\bar{t}} \sim 1/5 \) is required in order to comply with the data.

4 Relating Operators to Data

We now write the contribution of the operators to the various observables of interest. We first focus on the vector operators of Eqs. (7)-(9).

It is natural within the vector sector to distinguish between the operators that interfere with the SM and those that do not. The latter set of operators can be parameterized by:

\[
\begin{align*}
 w_+^2 &\equiv \frac{1}{2} \left( (c_{VA}^8 \pm c_{AV}^8)^2 + \frac{9}{2} \left[ (c_V^1 \pm c_A^1)^2 + (c_{VA}^4 \pm c_{AV}^4)^2 \right] \right), \\
 R^2 &\equiv w_+^2 + w_-^2, \\
 \tan \theta &\equiv w_-/w_+.
\end{align*}
\]

The relevant observables of Sec. 2 then take the simple form

\[
N_X \simeq a_X c_V^8 + b_X (c_A^8)^2 + d_X (c_A^8)^2 + e_X R^2,
\]

\[
A_{450}^{t\bar{t}} = \left( \alpha c_A^8 + \beta c_A^8 c_V^8 + \frac{\beta}{2} R^2 \cos 2\theta \right) (1 + N_{450})^{-1},
\]

where the subscript \( X = 450, 750, b \) and in \( N_X \) we neglect a term which is proportional to \( \sin 2\theta \) and suppressed by \( 4m_t^2/M_{t\bar{t}}^2 \). The coefficients \( (a, b, d, e)_X \) and \( \alpha, \beta \) are pure kinematical factors given by

\[
\begin{align*}
(a, b, d, e)_{450} &= 0.35, 0.043, 0.023, 0.033, \\
(a, b, d, e)_{700} &= 0.76, 0.16, 0.11, 0.14, \\
(a, b, d, e)_b &= 1.5, 0.57, 0.46, 0.51, \\
\alpha, \beta &= 0.17, 0.043,
\end{align*}
\]

where we use the MSTW parton distribution functions \[52\] at leading order in this calculation. The physical interpretation of \( R \) is very clear — it parameterizes the overall size of the operators which do not interfere with the SM. The angle \( \theta \) controls how much these operators project on the asymmetry. For a given \( R \), the asymmetry is maximized for \( \cos 2\theta = 1 \), justifying the omission of the \( \sin 2\theta \) term above.

It is useful to obtain relations between the various observables, allowing for a simple estimation of the new physics contributions in terms of the constraints. One such relation is between the boosted tops enhancement factor and the two cross section constraints, given by

\[
N_b = -0.12 c_V^8 + 5.6 N_{700} - 7.5 N_{450},
\]

such that

\[
|c_V^8 + 10| < 10\sqrt{1 + N_{450} - 0.21 N_{700}} \quad \text{and} \quad |c_V^8 + 21| > 15.6\sqrt{1.8 + N_{450} - 0.24 N_{700}}.
\]

The constraints in Eq. \[20\] define the range in which \( R \geq 0 \) and \( c_A^8 \) is real.
Another useful relation is between $A_{450}^t$ and the constraints $N_{450}$ and $N_{700}$. To obtain this, we can substitute $c_A^8$ for $N_{700}$ using Eq. (13), yielding

\[
(1 + N_{450}) \times A_{450}^t = \left(0.51 + 0.13 c_V^8 \right) \sqrt{N_{700}} - \left[0.76 c_V^8 + 0.16 (c_V^8)^2 + 0.14 R^2 \right] + 0.022 R^2 \cos 2 \theta .
\]

(21)

This relation is only valid for $c_A^8 \geq 0$, and indeed, as we show below, accounting for $A_{450}^t$ as in Eq. (2) requires $c_A^8 > 0$.

We would now like to comment on the most general case where the scalar and tensor operators of Eq. (10) are also present. It is straightforward to show that the effects of the latter can be captured by our Eqs. (13)-(18) with the following redefinitions

\[
\cos 2 \theta \rightarrow F(\theta, \psi, \theta_{ST}) \equiv \cos 2 \theta \cos^2 \theta_V + \sqrt{\frac{2}{3}} \cos 2 \psi \sin^2 \theta_V \cos^2 \theta_{ST},
\]

(22)

\[
R^2 \rightarrow R^2 \equiv w_+^2 + w_-^2 + r_{ST}^2 + r_P^2,
\]

(23)

with $|F| \leq 1$, and where we defined

\[
r_{ST}^2 \equiv y_+^2 + y_-^2, \quad y_\pm \equiv \left(c_T^8 \pm \sqrt{\frac{3}{8}} c_S^8 \right)^2 + \frac{9}{2} \left(c_T^1 \pm \sqrt{\frac{3}{8}} c_S^1 \right)^2,
\]

(24)

\[
r_P^2 \equiv \frac{3}{4} \left[(c_P^8)^2 + (c_{SP}^8)^2 + (c_{PS}^8)^2 + \frac{9}{2} \left[(c_P^1)^2 + (c_{SP}^1)^2 + (c_{PS}^1)^2 \right] \right],
\]

(25)

and

\[
\sqrt{w_+^2 + w_-^2} \equiv R \cos \theta_V, \quad r_{ST} \equiv R \sin \theta_V \cos \theta_{ST}, \quad r_P \equiv R \sin \theta_V \sin \theta_{ST}, \quad \tan \psi \equiv y_+/y_-.
\]

(26)

The physical interpretation of the additional parameters is as follows. $r_{ST,P}$ represent the overall size of the scalar/tensor and pseudo-scalar operators; $R$ being now the overall size of all of the non-interfering operators. The angles $\theta_{V,ST}$ determine the distribution of $R$ among the vector, scalar/tensor and pseudo-scalar operators, while the angle $\theta$ ($\psi$) parameterizes how much the vector (scalar/tensor) operators project on the asymmetry. Note that in the case where vector operators are absent, one has $|F| \leq \sqrt{2/3}$.

5 The Forward-Backward Asymmetry

The stage is now set to study the parameter space that explains the large forward-backward $t\bar{t}$ asymmetry $A_{450}^t$ while satisfying the constraints from the differential cross section. We further comment on the contribution to boosted top pair production. We consider several interesting limiting cases. The first is when there is no interference with the SM. Next the cases where the interference comes from only one operator are analyzed. Finally, we discuss the general scenario.

5.1 No Interference: $c_A^8 = c_V^8 = 0$

In models of heavy new physics which does not interfere with the SM, a simple relation between $A_{450}^t$ and $N_{700}$ can be obtained from Eqs. (13) and (14):

\[
A_{450}^t = \frac{0.16 \cos 2 \theta N_{700}}{1 + 0.24 N_{700}}.
\]

(27)
Using the bound on $N_{700}$ from Eq. (4) (which automatically satisfies the constraint from $N_{450}$), we find $A_{450}^{t\bar{t}} \lesssim 0.07$. From this we learn that the large $t\bar{t}$ asymmetry measured by CDF cannot be explained by a heavy new physics sector which does not interfere with the SM. This is consistent with the findings of [19], obtained directly from the data. Additionally, the maximal excess in the high-$p_T$ $t\bar{t}$ cross section is $N_b \sim 2$.

5.2 Vector Interference: $c_A^8 = 0$ and $c_V^8 \neq 0$

It is clear from Eq. (14) that $O_A^8$ by itself does not contribute directly to $A_{450}^{t\bar{t}}$ if $c_A^8 = 0$. However, taking $c_V^8 < 0$ can relax the constraints from $N_{450}$ and $N_{700}$, thus allowing for a larger contribution to $A_{450}^{t\bar{t}}$ from other operators, i.e. $R \neq 0$. Substituting $R^2$ for $N_{700}$ and $|c_V^8|$ for $N_{450}$ via Eq. (13) into the expression for $A_{450}^{t\bar{t}}$ of Eq. (14) yields

$$ (1 + N_{450}) \times A_{FB}^h = \cos 2\theta \left( 1.65 N_{700} - 6.15 N_{450} - 19.67 + 14.65 \sqrt{1.8 + N_{450}} - 0.24 N_{700} \right). \quad (28) $$

Plugging in the constraints from Eq. (4), we find that the maximal value for $A_{450}^{t\bar{t}}$ is 0.26, which is $1.3\sigma$ below the mean value in Eq. (2). Regarding the boosted top cross section, an excess as large as $N_b \sim 4$ can be obtained.

![Figure 1: The observables under consideration presented in the $R - c_A^8$ plane for $c_V^8 = \theta = 0$: The solid curve describes the mean value of $A_{450}^{t\bar{t}}$ from Eq. (2), while the shaded region corresponds to the $1\sigma$ range. The red-shaded region is the overlap of the latter with the $1\sigma$ constraints on $N_{450}$ and $N_{700}$ in Eq. (4).](image)

5.3 Axial Interference: $c_A^8 \neq 0$ and $c_V^8 = 0$

Ref. [42] showed that it is possible to explain the forward-backward asymmetry measurement with only $O_A^8$. It is instructive to examine the addition of non-interfering operators. Fig. 1 shows the region in the parameter space of $c_A^8$ and $R$ satisfying Eqs. (2) and (4). Interestingly, this region
is rather narrow, corresponding to $c_A^8 \sim 2$ and $R \lesssim 1$. Moreover, only the lower 1$\sigma$ range of $A_{450}^{t\bar{t}}$ can be accounted for in this case. (Note that the central value $A_{450}^{t\bar{t}} \sim 0.4$ requires a deviation of $\sim 1.8\sigma$ in $N_{700}$, agreeing with [42] modulo the inclusion of $1/\Lambda^4$ effects.) As concerns the high-$p_T$ $t\bar{t}$ cross section, a maximal excess of $N_b \sim 2$ can be achieved (with $R = 0$) along with the 1$\sigma$ range for $A_{450}^{t\bar{t}}$.

5.4 The General Case

We now explore the general parameter space accounting for the observables at hand. In Fig. 2 we show the allowed region in the $c_V^8 - c_A^8$ plane for various values of $R$. We learn the following:

- As $R$ grows, the allowed region becomes smaller, and the maximal possible value is $R \simeq 3.1$.
- The allowed range for the vector octet operator is $-2 \lesssim c_V^8 \lesssim 0$.
- The allowed range for the axial octet contribution is $0.3 \lesssim c_A^8 \lesssim 3.3$.

![Figure 2: The observables under consideration presented in the $c_V^8 - c_A^8$ plane: Each region corresponds to the overlap of the 1$\sigma$ ranges for $A_{450}^{t\bar{t}}$, $N_{450}$ and $N_{700}$ in Eqs. (2) and (4), for different values of $R$.](image)

We conclude that:

- In order to explain the measurement of the $t\bar{t}$ forward-backward asymmetry for $M_{t\bar{t}} > 450$ GeV within 1$\sigma$, a minimal contribution of the operator $\mathcal{O}_A^8$ is necessary, $c_A^8 \simeq 0.3$. (This point in the parameter space corresponds to $c_V^8 \simeq -1.9$ and $R \sim 3.1$.)
- The maximal enhancement of the boosted top pair cross section is $N_b \sim 4$. Interestingly, this is consistent with $A_{450}^{t\bar{t}}$ within 1$\sigma$.
- Accounting for the high mass $t\bar{t}$ forward-backward asymmetry within 1$\sigma$ dictates a minimal excess of $N_b \simeq 0.5$. 

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• Restricting the parameter space to include only an operator of definite chirality for each color structure, the maximal $A_{450}^{tt}$ is $\sim 0.1$. An excess of $N_b \sim 4$ can still be obtained.

6 Predictions for Near-Future Measurements

Thus far we focused on existing data from the Tevatron. This data could have interesting implications on future Tevatron and LHC measurements. To illustrate this, we consider the $t\bar{t}$ differential cross section within our framework. We emphasize that our results below are general and include in particular the contributions from scalar and tensor operators. Fig. 3 depicts the $M_{tt}$ distribution at the Tevatron and LHC. The plotted regions correspond to the predicted enhancement relative to the SM, defined by

$$N_{tot} \equiv \frac{d\sigma^{SM+NP}}{dM_{tt}} / \frac{d\sigma^{SM}}{dM_{tt}},$$

scanning over the entire parameter space obeying the $1\sigma$ constraints of Eqs. (2) and (4).

![Graph](image)

Figure 3: The ratio between the total and SM differential cross sections of top pair production as a function of $M_{tt}$ at the Tevatron (left) and the LHC at 7 TeV (right), calculated at leading order. The upper shaded regions correspond to the mean value of $A_{450}^{tt} \sim 0.4$, scanning over the allowed range for $N_{450}$ and $N_{700}$ defined in Eq. (4). The lower shaded regions correspond to the lower $1\sigma$ range of $A_{450}^{tt}$. The thick black curves at the bottom of the shaded regions correspond to $R = 0$, $c_8^V \simeq -0.85$, $c_8^A \simeq 1.7$. We learn that if the latest high mass $t\bar{t}$ forward-backward asymmetry measurement persists and is accounted for by heavy new physics, then a significant enhancement of the $t\bar{t}$ differential cross section compared to the SM is expected at both the Tevatron and LHC. Specifically, at $M_{tt} \sim 1$ TeV, a minimal factor of two enhancement is expected at the Tevatron. Similarly, at $M_{tt} \sim 1.5$ TeV, the LHC should find a $t\bar{t}$ cross section of at least a factor of three higher than within the SM. In both cases the minimal enhancement is obtained for $R = 0$, $c_8^V \simeq -0.85$, $c_8^A \simeq 1.7$. To summarize:

$$N_{tot}(M_{tt} = 1 \text{ TeV}) \gtrsim 2 \quad \text{at the Tevatron},$$

$$N_{tot}(M_{tt} = 1.5 \text{ TeV}) \gtrsim 3 \quad \text{at the LHC with } \sqrt{s} = 7 \text{ TeV}.$$
7 Outlook

We have performed a model independent analysis regarding the $t\bar{t}$ forward-backward asymmetry, assuming heavy new physics. Any corresponding high scale new physics model can be mapped to our formalism to obtain constraints and predictions. We find a robust prediction in the form of enhancement in hard top physics at the Tevatron and LHC. The observation of such an enhancement would be exciting, and our analysis would assist in interpreting the signal and extracting microscopic information on the underlying physics. An equally intriguing possibility would be the absence of such an enhancement, assuming the asymmetry is established. Our findings would then imply the presence of sub-TeV new physics. Consequently, the new physics search strategy should be modified to include precision analysis in the 100-1000 GeV energy regime.

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