Spinning the top quark

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We propose to measure the threshold lepton asymmetry, that is the forward-backward asymmetry of the charged lepton in $t\bar{t}$ events near the production threshold. At threshold, top quark pairs are produced in an s-wave. Angular momentum conservation then implies that the top spins equal the spin of the initial state which—in the case of quarks—is uniquely fixed by the chirality of the initial quarks. Thus, measuring final-state top spins determines the chirality of the quarks which produced them. Information about the top spins can be extracted by measuring the angular distribution of the charged lepton in semileptonic or dileptonic decays of the top pair. One such distribution, the threshold lepton asymmetry, vanishes in tree-level QCD but is nonzero if new physics modifies the relative contribution of right-handed and left-handed quarks to top pair production. This is interesting because realistic models addressing the anomalous $t\bar{t}$ asymmetry have chiral couplings to light quarks. Models with identical $t\bar{t}$ asymmetries at the Tevatron can be distinguished by their threshold lepton asymmetries, which range between plus and minus 25% in realistic models.

I. INTRODUCTION

The top quark's large mass of order the electroweak scale suggests it may have a significant coupling to new physics in the sector which breaks electroweak symmetry. This makes top quark physics a natural place to test the consistency of the Standard Model (SM) and to search for effects of new physics. Experiments at the Tevatron and the LHC have targeted several properties of top quarks, such as the single and pair production cross sections, pair production asymmetries, polarization, and spin correlations. So far only one of these measurements—the forward-backward asymmetry of $t\bar{t}$ pair production at the Tevatron $A_{\mathrm{FB}}^{t\bar{t}}$—has shown a significant deviation from the SM. Both CDF [1] and DØ [2] Collaborations report inclusive $A_{\mathrm{FB}}^{t\bar{t}}$ with central values of order 20% and more than 2σ away from the prediction based on next-to-leading order (NLO) QCD [3,4]. Moreover, CDF (though not DØ [2]) observes a strong dependence of $A_{\mathrm{FB}}^{t\bar{t}}$ on the invariant mass of the top pair [5]. The forward-backward asymmetry of the charged lepton in semileptonic [2] and dileptonic [6] $t\bar{t}$ events is also larger than the SM prediction. It is intriguing that despite noticeable differences between the individual measurements, they show a large positive asymmetry that cannot be accounted for by known SM processes.[1] Generating sizable $A_{\mathrm{FB}}^{t\bar{t}}$ requires the presence of a new particle with chiral couplings not only to the top but also to the light (up and/or down) quarks. This implies that models that generate large $A_{\mathrm{FB}}^{t\bar{t}}$ also predict that

observables related to top quark polarization will be affected [8–11].

In this paper we point out that it is interesting to investigate the forward-backward asymmetry of the charged lepton in $q\bar{q} \rightarrow t\bar{t}$ events near the production threshold. This observable has a simple and intuitive theoretical interpretation, namely it measures the relative contribution of $q_R\bar{q}_R$ and $q_L\bar{q}_L$ to top pair production at threshold. The reason is that at threshold the top pair has no orbital angular momentum, therefore the top spins are determined by the chiralities of the quarks which produced them. As usual, the top spins can be statistically measured by looking at the angular distribution of the charged lepton, which is preferentially emitted along the top quark spin and oppositely to the antitop quark spin.[2] At tree level the SM predicts equal contributions from $q_R\bar{q}_R$ and $q_L\bar{q}_L$ to $t\bar{t}$ production and therefore a vanishing threshold lepton asymmetry. On the other hand, new physics models predicting large $A_{\mathrm{FB}}^{t\bar{t}}$ always involve different couplings to left- and right-handed light quarks (for a review and references, see Refs. [13,14]) and therefore predict positive or negative values for the threshold lepton asymmetry. We argue that in many cases the threshold lepton asymmetry offers a stronger discriminating power than previously considered measures of top polarization. From the experimental point of view the measurement is relatively straightforward, especially at the Tevatron where $q\bar{q}$ is the dominant top production mode and where a large fraction of the $t\bar{t}$ pairs are produced close to threshold, $v_{\mathrm{top}} \ll c$. Unlike the

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[1]There is still room for improving the precision of SM predictions, especially concerning the effects of experimental cuts on the measured asymmetry. For recent discussions see Ref. [7].

[2]The analyzing power of top spins has long been understood; see for example Ref. [12].

measurement of spin correlations, the lepton asymmetry only requires looking at a single lepton independently of the rest of the event. Therefore it can be measured in semileptonic as well as in dileptonic top events. Given the size of the top sample accumulated by the Tevatron, the threshold lepton asymmetry can be measured with a reasonably small statistical error.

II. THE ARGUMENT

Consider top quark production in a collision of ultra-relativistic quarks with definite helicity or, equivalently, with definite chirality. In principle, there are four distinct chirality configurations of the quark-antiquark pair: $q_L \bar{q}_L$, $q_L \bar{q}_R$, $q_R \bar{q}_L$, $q_R \bar{q}_R$. In a given physics model only a subset of initial states may lead to $t\bar{t}$ production. For example, ignoring the light quark masses, QCD produces $t\bar{t}$ pairs only from the $q_L \bar{q}_L$ and $q_R \bar{q}_R$ initial states.

For definiteness, we first focus on the initial state $q_R \bar{q}_R$. A right-chirality quark has spin in the direction of its motion, i.e., positive helicity. Right-handed antiquarks have negative helicity. Therefore, quark and antiquark have opposite helicities, and since they are moving in opposite directions, their spins are aligned. Thus, the initial state has total spin 1 and polarization in the direction of the incoming quark (we will call this direction the positive z direction). Since the incoming quarks do not have orbital angular momentum in the z direction, the z component of the total angular momentum is also 1. Using angular momentum conservation, the final state must have angular momentum 1 in the positive z direction. But at threshold the top quarks have no relative velocity and no orbital angular momentum; in other words, the production process proceeds through s wave, independently of assumptions about the interactions (i.e., QCD or new physics). It follows that the top spins must be aligned and point in the z direction in order to equal the spin of the initial state.

The spins of top quarks can be determined statistically by measuring the direction of the decay products. In particular, it is well known that the charged lepton in leptonic top decays is a "perfect" top spin analyzer. For the top, the direction of the positively charged lepton follows the distribution

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + \cos\theta), \qquad (1)$$

where θ is the angle between the momentum of the outgoing lepton and the top spin in a reference frame where the top quark is at rest. For the antitop the situation is reversed: the negative lepton has a $1 - \cos\theta$ distribution with respect to the antitop spin. Thus, a process in which $t\bar{t}$ pairs are produced at rest from an initial state with right-handed initial quark chiralities predicts a distinctive angular distribution in semileptonic or dileptonic decays: the positively charged leptons are predicted to go mostly in the positive z direction with the distribution Eq. (1), whereas

negatively charged leptons are emitted mostly in the negative z direction. To quantify this effect, one can define the lepton asymmetry,

$$A_{\mathrm{FB}}^{\ell} = \frac{N_l(q_l \cos\theta_l > 0) - N_l(q_l \cos\theta_l < 0)}{N_l(q_l \cos\theta_l > 0) + N_l(q_l \cos\theta_l < 0)}. \qquad (2)$$

Here θ_l is the angle between the lepton and the incoming quark directions. For the $q_R \bar{q}_R \rightarrow t\bar{t}$ process in the $t\bar{t}$ rest frame (where both the top and antitop are at rest at threshold) we obtain the threshold lepton asymmetry $A_{\mathrm{FB}}^{\ell}(\sqrt{s} = 2m_t) = +50\%$.

If the initial state consists of left chirality quarks, $q_L \bar{q}_L$, all spins are reversed. In this case the $t\bar{t}$ pair at threshold has spins in the negative z-direction and $A_{\mathrm{FB}}^{\ell}(\sqrt{s} = 2m_t) = -50\%$. More generally, by measuring the angular distribution of the charged leptons in semileptonic or dileptonic top decays one can determine what fraction of $t\bar{t}$ events at threshold originated from left- or right-handed initial quarks. Of course, QCD is parity symmetric and predicts equal admixture of left- and right-chiral initial quarks. Thus, the QCD prediction is $A_{\mathrm{FB}}^{\ell}(\sqrt{s} = 2m_t) = 0$ at the tree level (in fact, this holds for arbitrary $\sqrt{s}$). If, however, there are new physics contributions to $t\bar{t}$ production for which the couplings to left- and right-chiral fields differ, one expects a nonvanishing lepton asymmetry.

Several comments are in order.

(i) At threshold the $t\bar{t}$ pairs are at rest, therefore the forward-backward asymmetry is ill defined. In contrast the leptons are always boosted as a result of the decay of the massive top, and the lepton threshold asymmetry can be defined. In this sense, the threshold lepton asymmetry A_{FB}^{ℓ} is independent of the $t\bar{t}$ forward-backward asymmetry $A_{\mathrm{FB}}^{t\bar{t}}$. In fact, it is easy to construct models in which the inclusive $A_{\mathrm{FB}}^{t\bar{t}}$ and A_{FB}^{ℓ} have opposite signs. The threshold lepton asymmetry is also distinct from spin correlations. The latter are sensitive to the relative directions of the spins of top and antitop, and at threshold it takes the same value ($+1$) regardless of whether the top pair is produced by $q_R \bar{q}_R$ or $q_L \bar{q}_L$. At a practical level, note that the spin correlation requires the decay products of *both* top and antitop as an input, whereas in the case of the lepton asymmetry it is sufficient to look only at the lepton from either the top or antitop. In particular, the lepton asymmetry can be measured in semileptonic events. Finally, there are important differences between the threshold and inclusive lepton asymmetries. As we discussed, the former depends only on the chirality of the initial quarks, while the latter is also sensitive to the chiralities and the forward-backward asymmetry of the final state tops. Again, there exist models where the threshold and inclusive asymmetries have opposite signs.

(ii) Apart from the lepton asymmetry it is interesting to study the dilepton asymmetry which can be defined in events in which both top quarks decay leptonically,

$$A_{\text{FB}}^{\ell\ell} = \frac{N(\eta_{\ell_+} > \eta_{\ell_-}) - N(\eta_{\ell_+} < \eta_{\ell_-})}{N(\eta_{\ell_+} > \eta_{\ell_-}) + N(\eta_{\ell_+} < \eta_{\ell_-})}, \quad (3)$$

where η is the pseudorapidity. At the $t\bar{t}$ threshold, the dilepton asymmetry, much as the single lepton one, directly measures the initial quark helicities. In particular, for a purely $q_R\bar{q}_R$ initial state, it takes the value $+2/3$, while for $q_L\bar{q}_L$ it is $-2/3$, independently of other details of the production process. Thus the threshold dilepton asymmetry is an even more sensitive probe of light quark polarization than the single lepton one, at least in theory. Moreover, the dilepton asymmetry has the advantage of being invariant under longitudinal boosts. On the other hand, the disadvantages of the dilepton observable are a more challenging $t\bar{t}$ invariant mass reconstruction and smaller statistics.

(iii) While the argument given above applies at the strict $t\bar{t}$ threshold it is clear that corrections to our analysis scale like a model-dependent power of v_{top}. As long as the top quarks are nonrelativistic, we expect the correlation of the top spins with the beam direction to persist. We will present numerical examples which quantify this in the next section.

(iv) The analysis presented here is only valid at leading order and higher order corrections, for instance due to emission of extra gluons, would change our analytic results. However, we do not expect these effects to change the qualitative argument discussed above. Next-to-leading-order corrections to the spin analyzing power of the lepton daughter or the spin-spin correlation coefficient were recently discussed in Ref. [15] and found to be important but still subdominant.

(v) The spin effect discussed here does not depend on the chirality of the top quarks produced. In fact, since the top quarks are at rest their chirality is not a good quantum number, only the top spins matter and these are completely determined by the initial quarks.

(vi) The size of the effect predicted here is diluted by production of $t\bar{t}$ pairs from initial state gluons, which clearly does not lead to any asymmetry. At the Tevatron this is not expected to be a big effect as within the SM 80% of the top production is from initial quark antiquark annihilation. At the LHC, due to the domination of the gluon contribution and the symmetric initial state, more complicated extraction techniques are needed [16].

(vii) Events initiated by $q_L\bar{q}_R$ or $q_R\bar{q}_L$ pairs would lead to tops with zero total spin at threshold and thus to a vanishing threshold lepton asymmetry, an important information by itself. We note that in this situation the spin correlation observable has opposite sign compared to the $q_L\bar{q}_L$ and $q_R\bar{q}_R$ initiated events.

(viii) Near threshold, one expects the new physics contributions to be subdominant so that the largest effect will come from interference with standard model processes. In the SM the dominant production is induced from up quarks. Thus, the threshold lepton asymmetry is most sensitive to new physics with two operator structures [17]: $(\bar{u}\gamma^\mu T^a u)(\bar{t}\gamma^\mu T^a t)$ and $(\bar{u}\gamma^\mu \gamma_5 T^a u)(\bar{t}\gamma^\mu \gamma_5 T^a t)$, where T^a is an SU(3) generator in the fundamental representation. Note that the "t-channel" structures of the form $|\bar{u}\Gamma t|^2$ are in the present context equivalent to the previous ones via Fierz transformations.

III. EXAMPLE MODELS

A. Toy model, chiral QCD

To illustrate our point, let us start with a toy model where the spin effects that were discussed so far can be clearly isolated. The model is a chiral version of QCD where a massless chiral gluon has arbitrary couplings to left- and right-handed quarks,

$$\mathcal{L} \supset (g_{q_L}\bar{q}\bar{\sigma}^\mu A_\mu q + g_{q_R}q^c\sigma^\mu A_\mu \bar{q}^c + g_{t_L}\bar{t}\bar{\sigma}^\mu A_\mu t + g_{t_R}t^c\sigma^\mu A_\mu \bar{t}^c). \quad (4)$$

Consider the top production process from a pair of light quarks colliding at a fixed CM energy $\sqrt{s}$. The amplitude can be written as

$$\mathcal{M}(q_i\bar{q}_j \to t_k\bar{t}_l) = \left(\delta_{ik}\delta_{jl} - \frac{1}{3}\delta_{ij}\delta_{kl}\right)F(s_q, s_{\bar{q}}|s_t, s_{\bar{t}}), \quad (5)$$

where $i\ldots l$ are color indices and s_x are the quark spins, $(+/-)$ for spin in the positive/negative z direction. At threshold, $\sqrt{s} = 2m_t$, we find

$$F(+, +|+, +) = -\frac{g_{q_R}(g_{t_L} + g_{t_R})}{2},$$
$$F(-, -|-, -) = -\frac{g_{q_L}(g_{t_L} + g_{t_R})}{2}, \quad (6)$$

while for other spin configurations the amplitude vanishes at threshold. In agreement with our previous discussion, at threshold the spin state of the top pair equals that of the incoming quark, thus, the top spins probe the coupling of the chiral gluon mediator to the light quarks. For example, if the chiral gluon couples only to right-handed light quarks, $g_{q_L} = 0$, $g_{q_R} \neq 0$, then both the top and the antitop quark end up with the spin $+1/2$. In that situation the threshold lepton asymmetry will take the maximal value of $+50\%$. Conversely, for $g_{q_L} \neq 0$ and $g_{q_R} = 0$ the threshold lepton asymmetry will be -50%.
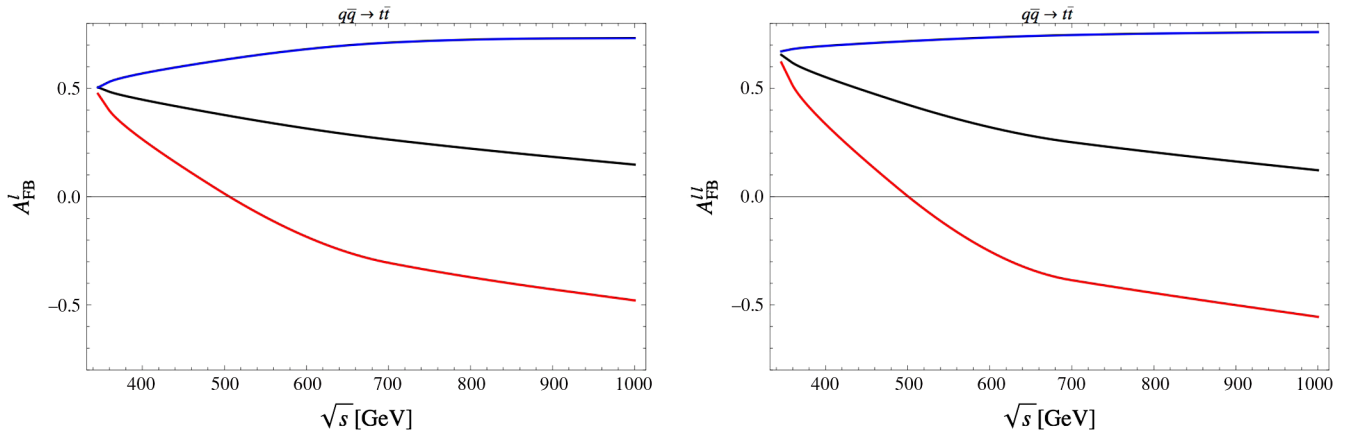
FIG. 1 (color online).   Lepton (left) and dilepton (right) forward-backward asymmetry in the $q\bar{q} \to t\bar{t}$ process as a function of the center-of-mass production energy in the chiral-QCD toy model. The asymmetries are defined at the parton level in the rest frame of the collision. We assumed purely right-handed couplings of the chiral gluon to the light quarks, and left-handed (RL), right-handed (RR) and vector (RV) couplings to the top quark. In all three cases the threshold lepton asymmetry is $+50\%$ and the threshold dilepton asymmetry is $+66\%$.

In Fig. 1 we plot the lepton asymmetry as the function of the center-of-mass $t\bar{t}$ production energy for purely right-handed coupling of the chiral gluon to the light quarks, and for three different couplings to the top quarks. We see that at threshold the lepton asymmetry is indeed always $\sim 50\%$, independently of the coupling to the top.[3] At higher $\sqrt{s}$, the $t\bar{t}$ final state has orbital angular momentum and there is no longer a one-to-one correspondence between the spins of the light quarks and of the tops, leading to A_{FB}^{ℓ} different from 50%. In fact, at very high $\sqrt{s}$ when the tops have large velocities, the lepton asymmetry approaches the value of the top forward-backward asymmetry which is positive (negative) for right-handed (left-handed) coupling of the chiral gluon to the top, and which is zero if that coupling is vectorlike. The dilepton asymmetry has a very similar qualitative behavior, the main difference being the threshold value of $\sim 66\%$.

We stress again that the lepton forward-backward asymmetry at threshold is independent of the top forward-backward asymmetry; in particular, for $g_{t_L} = g_{t_R}$ the latter is zero, while the former can be anywhere between -50% and 50%, depending on the relative magnitude of g_{q_L} and g_{q_R}. Furthermore, we underline the difference between the threshold and inclusive lepton asymmetries. In our example with $g_{q_L} = g_{t_R} = 0$ (marked as RL in the plot), the inclusive lepton asymmetry would be very small after convoluting with Tevatron PDFs, while the threshold lepton asymmetry is $\sim 50\%$.

B. Some realistic models

So far we have discussed a simple toy model where the contributions to the threshold lepton asymmetry are easily understood and calculated. Going to realistic new physics models, several new effects may complicate the picture. First of all, there will be the QCD contribution to the $t\bar{t}$ production, which is always symmetric. Thus, the threshold lepton asymmetry is not expected to be maximal, unlike in the toy model, unless the new physics completely dominates the $t\bar{t}$ production at threshold (which is unlikely given experimental constraints). Typically, new physics will interfere with QCD, changing the relative contributions of $q_L\bar{q}_L$ and $q_R\bar{q}_R$ to the top production rate, leading to a moderate positive or negative threshold lepton asymmetry. Moreover, there is always the gluon initial state contribution to the $t\bar{t}$ production which cannot favor any polarization direction. Of course, any effect present at the parton level is expected to be further smeared out by detector and reconstruction effects. In the same vein, the single lepton asymmetry measured in the LAB frame will be smeared out after PDFs are taken into account due to the random boost of the $t\bar{t}$ system, while the measurement in the $t\bar{t}$ rest frame implies additional reconstruction uncertainties. Finally, focusing on the threshold asymmetry inevitably increases statistical uncertainties, as only a fraction of $t\bar{t}$ pairs are produced with small momentum.

Nevertheless, the effect discussed above should be observable in physically interesting models, in particular, in many models addressing the anomalous $t\bar{t}$ forward-backward asymmetry reported by CDF and DØ. To demonstrate it, we study lepton asymmetry in several models which have been proposed in the literature. Quite generally, these models predict new particles with sizable chiral couplings to quarks which contribute to top production in the s channel [18,19], t/u channel [20], or both [21,22].

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[3]For axial couplings to the top the leading order amplitude vanishes at threshold. In that case the production cross-section at threshold is dominated by higher order terms in v_{top} expansion of the amplitude, and A_{FB}^{ℓ} ends up being less than 50%. Higher-order QCD corrections, not discussed in this work, could also alter this result.

TABLE I. The predicted Tevatron lepton forward-backward asymmetry calculated using MADGRAPH [23] for several benchmarks defined in the text. The asymmetry is integrated for three different m_{tt} intervals from threshold up. In each entry, we give the four observables $A_{FB}^{t\bar{t}}//A_{FB}^{\ell}$ (LAB frame)/A_{FB}^{ℓ}($t\bar{t}$ rest frame)/$A_{FB}^{\ell\ell}$. All numbers are fully inclusive (no cuts), parton level (no showering and detector effects), and tree level (in particular, purely SM NLO contributions are not included). The last line in the table gives the approximate fraction of the total $t\bar{t}$ rate falling into the corresponding m_{tt} interval.

Benchmark	$\sqrt{s} < 375$ GeV	$\sqrt{s} < 450$ GeV	Inclusive
AxR	4//13/18/21%	8//14/17/21%	11//14/17/21%
AxL	5//−10/−13/−18%	9//−8/−10/−13%	11//−6/−7/−9%
AxA	6//2/2/2%	10//3/3/5%	12//5/6/7%
SdR	0//−7/−10/−13%	2//−6/−7/−9%	5//−3/−4/−4%
SdL	2//8/10/14%	3//8/10/12%	6//9/11/13%
Fraction	17%	60%	100%

For our numerical study we pick five benchmark points and show the predicted lepton asymmetries near threshold in Table I. Three of these benchmarks belong to a model of a light ($m_{G'} \lesssim 2m_t$) s-channel color octet, an "axigluon," having flavor universal coupling to quarks. This model is capable of producing large enough contributions to $A_{FB}^{t\bar{t}}$ without violating the constraints from other Tevatron and LHC observables as long as the axigluon mass is not too far above the $t\bar{t}$ threshold and has a large width [19]. We choose $m_{G'} = 200$ GeV, $\Gamma_{G'} = 50$ GeV, and flavor and isospin universal axigluon couplings to the quarks as $g_R = 0.8g_s$, $g_L = 0$ (AxR), $g_R = 0$, $g_L = 0.8g_s$ (AxL), and $g_R = -g_L = 0.4g_s$ (AxA). Each variant of the model predicts $\Delta A_{FB}^{t\bar{t}} \approx 11\%$.[4]

Looking at the table it is clear that the sign of the lepton asymmetry at threshold reflects the polarization of the light quarks that couple to the axigluon. In particular, for AxR A_{FB}^{ℓ} near threshold is large and positive (because $t\bar{t}$ production from right-handed quarks is enhanced), while it is large and negative for AxL (because $t\bar{t}$ production from left-handed quarks is enhanced). The sign carries over to the inclusive lepton asymmetry, as noticed in Ref. [11]; however, for the inclusive asymmetry the discriminating power between different benchmarks is somewhat weaker due to a stronger correlation of A_{FB}^{ℓ} and $A_{FB}^{t\bar{t}}$ away from the production threshold. The benchmark AxA with the axial couplings of the axigluon to quarks is different. As remarked earlier, in this case the axigluon contribution to the amplitude is $\mathcal{O}(v)$ and thus completely vanishes at the threshold. Therefore, the top pair production at the threshold is dominated by the SM where no polarization effects are present, resulting in a vanishing threshold lepton asymmetry. For this benchmark, the nonvanishing inclusive A_{FB}^{ℓ} is simply a consequence of the nonzero $A_{FB}^{t\bar{t}}$ through kinematics of the top decay, much as in the SM. Quantitatively similar results would be obtained in a model

of a heavy ($m_{G'} \gg 2m_t$) axigluon with flavor nonuniversal couplings [18].

We also studied a model featuring an electroweak doublet scalar S coupled to the quarks via the flavor-violating Yukawa couplings $y_R S Q_3 u^c + y_L S Q_1 t^c$ [13,24]. In this model the scalar contributes to the $u\bar{u} \rightarrow t\bar{t}$ process in the t channel, and for a light enough mass it produces a positive contribution to $A_{FB}^{t\bar{t}}$. For our benchmark points we choose $m_S = 170$ GeV and $y_R = 1.5$, $y_L = 0$ (SdR) or $y_R = 0$, $y_L = 1.5$ (SdL), which leads to $\Delta A_{FB}^{t\bar{t}} \approx 6\%$. Here, somewhat counterintuitively, the lepton asymmetry at threshold is negative (positive) when the scalar couples to right-handed (left-handed) up quarks. What happens is that the scalar t-channel exchange interferes destructively with QCD, thus, for moderate y_R (y_L) couplings, the contribution of the right-handed (left-handed) quarks to the top production rate gets suppressed. Note that this sort of behavior is possible because the interference between the SM and new physics dominates the contributions to the forward-backward asymmetries for these benchmarks, whereas pure new physics contributions are subdominant.[5]

IV. EXISTING RELATED DATA

The threshold lepton asymmetry has not been tackled experimentally so far, but there are two measurements of the inclusive lepton asymmetry in $t\bar{t}$ events. In Ref. [2] DØ reports the measurement of the single lepton asymmetry in semileptonic top events. At the production (parton) level the result is

$$A_{FB}^{\ell} = (15.2 \pm 4.0)\%, \qquad (7)$$

compared to 2% predicted by the SM at the NLO. Interestingly, this measurement's departure from the SM

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[4]Throughout we refer to the longitudinal boost invariant $t\bar{t}$ asymmetry defined as $A_{FB}^{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_t < y_{\bar{t}})}{N(y_t > y_{\bar{t}}) + N(y_t < y_{\bar{t}})}$.

[5]This is also true for the axigluon benchmarks and quite generically for models that comply with the constraints coming from the $t\bar{t}$ cross-section measurements at the Tevatron. That new physics explanations of the asymmetry should be dominated by the interference terms was established model-independently in Ref. [21].

prediction is statistically more significant than the deviation in the $t\bar{t}$ asymmetry measured in the same sample, $A_{\mathrm{FB}}^{t\bar{t}} = 19.6 \pm 6.5\%$.

The other result is thanks to the CDF Collaboration [6] who measured the lepton asymmetry in dileptonic top events. At the reconstruction level after subtracting non-$t\bar{t}$ background, CDF obtains

$$A_{\mathrm{FB}}^{\ell} = (21 \pm 7)\%, \qquad (8)$$

which is similar to the measured $t\bar{t}$ asymmetry at the reconstruction level and strikingly smaller than the parton level $A_{\mathrm{FB}}^{t\bar{t}} = (42 \pm 15)\%$ in that channel [6].[6] Finally, recall that combining the semileptonic and dileptonic channels at CDF, one finds the inclusive parton level $A_{\mathrm{FB}}^{t\bar{t}} = (20 \pm 7)\%$ [1], very close to the $D\!\!\!/O$ value. Thus, both collaborations find that the inclusive lepton asymmetry has the same sign as the inclusive $t\bar{t}$ asymmetry which provides a handle for discriminating between different new physics models. In fact, the published $D\!\!\!/O$ and CDF measurements already strongly disfavor models predicting negative inclusive lepton asymmetries, such as our AxL and SdR benchmarks in Table I. Moreover, we observe that for both CDF and $D\!\!\!/O$ the measured lepton asymmetry is smaller than the parton level $t\bar{t}$ asymmetry. This fits best with the models predicting comparable contributions of $q_R \bar{q}_R$ and $q_L \bar{q}_L$ to the top production, such as our AxA benchmark, although at this point a moderate domination of $q_R \bar{q}_R$ cannot be excluded. Measuring the threshold lepton asymmetry would provide a valuable piece of information, allowing a better discrimination between competing models.

V. CONCLUSIONS AND OUTLOOK

We have argued that lepton forward-backward asymmetry in $t\bar{t}$ events at threshold carries direct information of the production mechanism. In particular, when top pairs are produced from purely right-handed (left-handed) quarks, a positive (negative) threshold lepton asymmetry is predicted. To our knowledge, this simple argument has not been explicitly made in the earlier literature and has not been explored in experimental studies.

Threshold lepton asymmetry is independent of the top couplings and may be present even when the $t\bar{t}$ forward-backward asymmetry vanishes. It may be studied for a single lepton in semileptonic or dileptonic events in which

case it does not require looking at the decay products of the other top. One may also study the threshold dilepton asymmetry in dileptonic events which carries the same information. The threshold asymmetry can be very different from the inclusive asymmetry. Charged leptons from tops at threshold probe the chirality of the initial quarks, whereas for highly boosted tops the lepton direction is correlated with the direction and chirality of the top. The inclusive lepton asymmetry is thus a convolution of several distinct effects. Furthermore, the threshold lepton asymmetry is complimentary to the spin-spin correlation measurement [9,10]; the latter does not distinguish $q_R \bar{q}_R$ and $q_L \bar{q}_L$ initiated events but is more sensitive to an admixture of $q_R \bar{q}_L$ and $q_L \bar{q}_R$ initiated events.

In this paper we studied lepton asymmetry at the Tevatron only. At the LHC that asymmetry of course vanishes due to the symmetric initial state. However, by focusing on events in which the center of mass of the $t\bar{t}$ pair is highly boosted, one can, in principle, gain access to the asymmetry. Highly boosted events (with the $t\bar{t}$ pair still at rest relative to each other) are much more likely to have originated from quarks than from gluons, and the direction of the boost provides a statistical tag for the direction of the initial quark [25]. The asymmetry to be measured at the LHC would then be an asymmetry of the lepton with respect to the direction of the overall longitudinal boost of the event. Whether the threshold lepton asymmetry can be realistically observed at the LHC is a nontrivial question that deserves further study.

Note that our simulations were restricted to the parton level. The effects of showering and detector resolution should be taken into account, although they are not expected to be as important as in the case of $t\bar{t}$ asymmetry. A separate question is the impact of NLO QCD and bound state corrections on the predictions of the threshold lepton asymmetry. In this paper we purposefully avoided these issues. However, one expects lepton angular distributions to be robust against soft QCD effects. This has been demonstrated in the related cases of polarized $e^+e^- \rightarrow t\bar{t}$ production [26] and $\gamma\gamma \rightarrow t\bar{t}$ production [27].

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[6]Note, however, that due to the rather hard leptonic p_T cuts and missing E_T applied in this analysis, it should not be considered a fully inclusive asymmetry measurement.

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