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Forward-backward asymmetry of top quark production at the Tevatron in warped extra dimensional models

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The CDF and D0 experiments have reported on the measurement of the forward-backward asymmetry of top quark pair production at the Tevatron and the result is that it is more than 2 standard deviations above the predicted value in the standard model. This has to be added to the long-standing anomaly in the forward-backward asymmetry for bottom quark production at LEP which is 3 standard deviations different from the standard model value. The discrepancy in the bottom asymmetry can be accounted for by the contributions of Kaluza-Klein excitations of electroweak gauge bosons at LEP in warped extra-dimensional models in which the fermions are localized differently along the extra dimension so that the gauge interactions of heavy third generation fermions are naturally different from that of light fermions. In this paper, we show that it is more difficult to elaborate a model generating a significant top asymmetry through exchanges of Kaluza-Klein gluons at the Tevatron due to the indirect constraints originating from precision electroweak data.

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Apparently, something is indeed rotten in the kingdom of third generation quarks. Adding to the long-standing anomaly of the forward-backward (FB) asymmetry for b-quark jets $A_{\rm FB}^{b}$ measured in Z boson decays at LEP [1,2], which differs by 3 standard deviations from the standard model (SM) value [3], the CDF and D0 Collaborations have reported results [4,5] on the measurement of the FB asymmetry of top quark pairs produced at the Tevatron, $A_{\rm FB}^{t}$, that are not consistent with the SM expectation. In particular, the latest and most precise result from the CDF Collaboration [4], using 3.2 $\rm fb^{-1}$ data, gives for this asymmetry in the $p\bar{p}$ laboratory frame

$$A_{\rm FB}^{t} = 0.19 \pm 0.065({\rm stat}) \pm 0.024({\rm syst}). \qquad (1)$$

In the SM, this asymmetry is predicted to be vanishing at first order in QCD. Indeed, a very nice feature of the Tevatron is that it is almost a $q\bar{q}$ collider for top quark pair production as the process occurs mainly through virtual gluon exchange in $q\bar{q}$ annihilation, with only a small contribution from the initiated gluon-gluon fusion channel. As gluons have only vectorlike couplings to quarks, the process does not generate an asymmetry between quarks and antiquarks and thus, $A_{\rm FB}^{t}$ is identically zero [6]. The asymmetry is then generated at next-to-leading order (NLO) in QCD by diagrams involving an extra gluon radiation and (anti)quark-gluon annihilation as well as from the interference between the Born gluon exchange with one-loop box diagrams. These NLO contributions lead to the expected value in the SM of [7]

$$A_{\rm FB}^{t} = 0.05 \pm 0.015. \qquad (2)$$

In the absence of large higher order contributions [8], this leads to a 2 standard deviation between the experimentally measured and the theoretically predicted values. This is in contrast to the total $p\bar{p} \to t\bar{t}$ production cross section at the Tevatron, which is measured to be [9]

$$\sigma(t\bar{t})^{\rm ex} = 7.0 \pm 0.63 \text{ pb}, \qquad (3)$$

in a good agreement with the SM expectation [10,11],

$$\sigma(t\bar{t})^{\rm th} = 7.0^{+0.71}_{-0.79} \text{ pb}. \qquad (4)$$

As in the case of the LEP $A_{\rm FB}^{b}$ anomaly (see, Ref. [12] and references therein), it is very difficult to explain this discrepancy, without affecting significantly the well-behaved $t\bar{t}$ cross section, in well-motivated extensions of the SM such as supersymmetric models for instance [13]. Among the very few attempts that have been made, examples are the exchange of TeV mass axigluons [7], colored gauge bosons which have axial-vectorial couplings to quarks; another possibility discussed in Ref. [14], would be flavor universal colorons which occur in gauge group models with an extended color such as topcolor or topcolor assisted technicolor models. These extensions do note cure the LEP $A_{\rm FB}^{b}$ anomaly, though.

In Ref. [12] it has been shown that the discrepancy between the LEP measured value of $A_{\rm FB}^{b}$ and the theoretical prediction can be resolved in the context of variants of the Randall-Sundrum (RS) extra-dimensional model [15] in which the SM fermion and bosonic fields are propagating in the bulk, except for the Higgs boson that is confined on the so-called TeV-brane. This allows a new interpretation of SM fermion mass hierarchies, if these fermions are localized differently along the extra dimension depending on their nature. One can then naturally obtain electroweak (EW) interactions for the heavy third generation fermions that are different from the ones of the light fermions. More precisely, the Z boson will mix with its Kaluza-Klein (KK) excitations and only its overall couplings to third generation fermions are significantly altered, due to the higher KK gauge boson coupling to the heavy flavors. An adequate choice of the b-quark localization allows one to explain the 3σ deviation of $A_{\rm FB}^b$, while keeping all other precision measurements unaltered.

In this paper, we show how the same warped extra-dimensional scenario that resolves the LEP $A_{\rm FB}^b$ anomaly could in principle also soften the discrepancy between the measured value of $A_{\rm FB}^t$ at the Tevatron and its theoretical value. Here again, the apparent $A_{\rm FB}^t$ anomaly could be addressed thanks to the naturally larger KK gauge boson couplings to the third generation quarks, but when trying to construct a realistic scenario respecting all the precision electroweak measurements we find it more tricky to significantly enhance $A_{\rm FB}^t$.

The RS warped extra-dimensional scenario [15] was originally proposed as a solution to the gauge hierarchy problem. It consists of a five-dimensional theory where the warped extra dimension is compactified over a $S^1/\mathbb{Z}_2$ orbifold. The fermions possess five-dimensional masses, quantified by the parameters c_f associated to each multiplet. These various masses determine the fermion localizations along the extra dimension. A possible way to avoid large deviations from the KK states in the set of high precision EW observables [1,2], while keeping the mass of the first KK weak gauge boson excitations (that are nearly equal to the KK gluon mass $M_{\rm KK}$) as low as the TeV scale, is to extend the SM group by gauging the custodial symmetry $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X$ in the bulk [16]. In particular, an additional KK Z' boson then arises with a coupling constant $g_{Z'}$ that is related to the mixing angle between the Z and Z' bosons.

In the SM sector of the gauge bosons and light fermions $f \neq b,\ t$, if the fermion localization and hence the c_f parameters are such that $c_{\rm light} \gtrsim 0.5$ [17], they lead to an acceptable fit of EW data provided that $M_{\rm KK} \approx 3$ TeV in the case of the bulk custodial symmetry [16]. In contrast, for third generation $Q = t$ and b quarks, the parameters for right- and left-handed states c_{t_R}, c_{b_R}, and $c_{Q_L} = c_{b_L} = c_{t_L}$ [as a result of SU(2) symmetry] should be chosen smaller, $c_Q \lesssim 0.5$, in order to produce relatively large quark masses [17]. Thus, the corrections to the crucial observables of the heavy b-quark sector at LEP, namely $A_{\rm FB}^b$ and the partial Z boson decay width $\Gamma(Z \to b\bar{b})$, and the Tevatron observables in top quark production, $A_{\rm FB}^t$ and $\sigma(t\bar{t})$, have to be treated separately.

We consider the scenario consisting of the quark multiplets given in [18], which corresponds to our previous choice of representation [12] (RSb model). For the parameter values, we have found it interesting to take $M_{\rm KK} \simeq 2.75$ TeV and

$$c_{Q_L} = 0.35, \quad c_{b_R} = 0.49; \quad c_{\rm light} \gtrsim 0.5; \quad g_{Z'} = 3.1, \quad (5)$$

which leads to a good fit of the observables in the b-quark sector at LEP [namely, $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ and $A_{\rm FB}^b(\sqrt{s})$ at the different energies]: a $\chi^2 \simeq 16$ compared to $\chi^2 \simeq 21$ in the SM [12,19], and a bottom quark mass $m_b \simeq 4$ GeV, which is acceptable keeping in mind that a full three-flavor treatment (beyond our scope here and left for a future study) would even improve the value. Moreover, for the *non bottom-top* quark EW observables, it allows one to obtain a global fit that is better than in the SM as shown in [19].

Generically in the RS model, the pair production of top quarks in $q\bar{q}$ annihilation does not proceed through gluon exchange (and gluon-gluon fusion) only, but also via the exchange of the KK gluon. The couplings of the first KK excitation of the gluon to left- and right-handed $q \equiv u, d$ quarks are different and proportional to $g_S Q(c_{q_{L/R}})$ where g_S is the usual QCD coupling and the charges $Q(c_{q_{L/R}})$ are the geometrical factors giving the ratio to the four-dimensional effective coupling of the gluon to $q_{L/R}$; for a light quark q with $c_q \gtrsim 0.5$ one has $Q(c_q) \approx -0.2$, while for the heavy third generation t, b quarks, $Q(c_{t,b})$ can be taken close to or larger than unity. Thus, the KK gluon coupling to quarks is not vectorial anymore, but has also an axial-vectorial component, $v_q/a_q \propto Q(c_{q_R}) \pm Q(c_{q_L})$. It is this axial-vector component of the KK gluon coupling which will generate a FB asymmetry for top quark pair production at the tree level. The angular distribution of the subprocess $q\bar{q} \to t\bar{t}$ is then given by

$$\begin{aligned}\frac{d\hat{\sigma}}{d\cos\theta_t^*} \propto\ & 2 - \beta_t^2 \sin^2\theta^* + \hat{s}^2 |\mathcal{D}|^2 [8 v_q v_t a_q a_t \beta_t \cos\theta^* \\ & + (a_q^2 + v_q^2)(v_t^2(2 - \beta_t^2 \sin^2\theta^*) \\ & + a_t^2 \beta_t^2 (1 + \cos^2\theta^*))] + \hat{4}s\,\mathrm{Re}(\mathcal{D}) \\ & \times \left[v_q v_t \left(1 - \frac{1}{2}\beta_t^2 \sin^2\theta^*\right) + a_q a_t \beta_t \cos\theta^* \right], \quad (6)\end{aligned}$$

where $\hat{s}$ is the effective c.m. energy of the subprocess, θ^* the scattering angle in the $q\bar{q}$ frame, $\beta_t = \sqrt{1 - 4m_t^2/\hat{s}}$ is the velocity of the top quark and $\mathcal{D} = (\hat{s} - M_{\rm KK}^2 + i\Gamma_{\rm KK} M_{\rm KK})^{-1}$ the propagator of the KK gluon with mass $M_{\rm KK}$ and total width $\Gamma_{\rm KK}$. To obtain the $p\bar{p}$ hadronic cross section σ, one must then integrate over the angle θ^*, sum over all contributing initial quarks and convolute with their parton distribution functions.

The FB asymmetry of the top quark is then defined as

$$A_{\rm FB}^t = \frac{\sigma(\cos\theta_t > 0) - \sigma(\cos\theta_t < 0)}{\sigma(\cos\theta_t > 0) + \sigma(\cos\theta_t < 0)}, \quad (7)$$

where now θ_t is the angle between the reconstructed top quark momentum relative to the proton beam direction. It is proportional to the factor in front of $\cos\theta^*$ in Eq. (6),

$$A_{\rm FB}^t \propto a_q a_t \beta_t \hat{s} |\mathcal{D}|^2 [(\hat{s} - M_{\rm KK}^2) + 4 v_q v_t \hat{s}], \quad (8)$$

which originates from the interference between the gluon and the KK gluon contributions and also from the pure KK gluon diagram. Note that $A_{\rm FB}^t$ is nonzero only if both axial-vector couplings of $g_{\rm KK}$, a_q, and a_t are nonzero. The product $a_q a_t$ should be negative along with $\hat{s} < M_{\rm KK}^2/(1 + 2v_q v_t)$, to have a positive $A_{\rm FB}^t$ below the $g_{\rm KK}$ resonance, as is the case with $M_{\rm KK} \approx 3$ TeV. Thus, one needs to maximize $a_q a_t$ while keeping $v_q v_t$ reasonable to achieve a large asymmetry. However, if $a_q a_t$ is too large, it will significantly alter $\sigma(t\bar{t})$ which is in accord with the SM. A judicious choice of the couplings a_q and a_t of the $g_{\rm KK}$ excitation is thus required.

Note that at NLO, there are additional contributions to $A_{\rm FB}^t$, e.g., stemming from the interference of the diagram with KK gluon exchange and the SM box diagrams; these small corrections will not be considered here.

The numerical results that we obtain are summarized in Fig. 1, which displays the contour levels in the plane $[c_{q_L}, c_{t_R}]$ corresponding, typically, to the maximum $A_{\rm FB}^t$ asymmetry as well as the associated $\sigma(t\bar{t})$ values (within $\approx 1.65\sigma$ of the experimental value, i.e., at the 90% C.L.). Note that the domain $c_{t_R} < -0.6$ corresponds typically to too light custodians. In the figure, we have fixed the c values of the right-handed first generation quarks to $c_{u_R} \approx c_{d_R} \approx 0.8$. The chosen range for c_{q_L} with much smaller values than $c_{u_R} \approx c_{d_R}$, allows substantial parity violating couplings of first generation quarks to the KK gluon and, hence, a sizable $A_{\rm FB}^t$. It seems that this choice $c_{q_L} < 0.5$ requires a certain flavor structure among five-dimensional

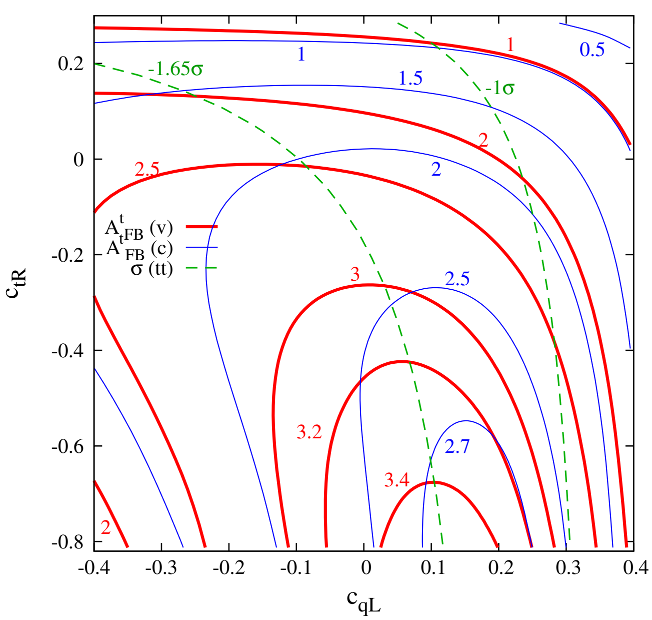

FIG. 1 (color online). Contour levels in the plane $[c_{q_L}, c_{t_R}]$ (c_{q_L} is for first generation) for the total cross section $\sigma(t\bar{t})$ (dashed lines) and the forward-backward asymmetry $A_{\rm FB}^t$ (in %) for constant (thin solid lines) and variable (thick solid lines) total decay width for the KK gluon; the other parameters are as in Eq. (5).

Yukawa couplings for reproducing quark mixing angles. A study dedicated to the complete three-flavor structure will be performed in [20].

The decrease of $\sigma(t\bar{t})$ with both c_{q_L} and c_{t_R} is caused by the increase of the $g_{\rm KK}$ couplings to $\bar{q}_L q_L$ and $\bar{t}_R t_R$ states which dominantly enhance the total $g_{\rm KK}$ decay width. The increase of $A_{\rm FB}^t$ with the decrease of c_{t_R}, which amplifies the difference between c_{t_R} and the fixed c_{Q_L}, finds its origin in the larger parity violation effect on the four-dimensional $g_{\rm KK}\bar{t}t$ coupling. $A_{\rm FB}^t$ can thus reach sizable values in regions where $\sigma(t\bar{t})$ has values consistent with Tevatron data at the 1.65σ level.

In the region $c_{t_R} \simeq -0.5$, $c_{q_L} \sim 0.4$, the order of magnitude obtained for top quark mass, $m_t \approx 10^2$ GeV, is acceptable while, despite the atypically large $Q(c_{q_L})$ values for first generation quarks (we also had to take $c_{s_R} \simeq 0.47 < 0.5$), the $Z\bar{q}q$ couplings are in good agreement with all precision data: the measurements at LEP [2], the NuTeV results [1,21], as well as, with the less accurate Tevatron and HERA data on u/d quarks [22]. This separate analysis of precision constraints on the first two generation quarks will be described in details elsewhere [20]; the reasons why these constraints can be respected are the relatively low c_{q_L} value and the existence of cancellations (e.g., the small deviations to the Z hadronic width result from an approximate cancellation of the Z'-induced corrections to u_L and d_L due to isospin [23]).

The deviations to this cancellation are compensated by the corrections induced by the KK Z bosons and the other quark chiralities/generations (controlled by other parameters). Interestingly, the NuTeV discrepancy on g_L^2 for first generation quarks at 1.9σ in the SM decreases here down to 0.7σ, while we obtain g_R^2 at 0.6σ only (weaker experimental accuracy). This significant change with respect to SM is allowed by the absence of correction compensation among different quark chiralities/generations, in contrast with the case of the Z hadronic width.

One must remark that for our parameters the total decay width of $g^{\rm KK}$ turns out to be quite large, $\Gamma_{\rm KK} \approx 30\% M_{\rm KK}$. For such a broad resonance, at least the energy dependent width, if not the full set of radiative corrections to the $p\bar{p} \to t\bar{t}$ process, should be used, in much the same way as for the ρ vector-meson exchange in $e^+e^- \to \pi^+\pi^-$ [24]. We have checked that by doing so, the contribution to the $A_{\rm FB}^t$ from $g^{\rm KK}$ exchange is increased as illustrated on the figure (thick solid contour lines).

In the acceptable region considered above ($c_{t_R} \simeq -0.5$, $c_{q_L} \sim 0.4$), the contribution from $g^{\rm KK}$ exchange is $A_{\rm FB}^t \simeq 2\%$ as shown by the contours of Fig. 1 [25]. Adding this contribution to the SM NLO value, one obtains a total of $A_{\rm FB}^t|^{\rm RS+SM} \approx 7\%$, which represents a relative improvement over the SM results. The significant gap remaining between the experimental $A_{\rm FB}^t$ value and its theoretical prediction could be explained by the still uncalculated QCD corrections at NNLO, possibly important. Note finally that there is no fine-tuning of parameters as in a large range of c values, a sizable A^t_{FB} is obtained.

In order to illustrate the importance of the indirect precision electroweak constraints, we just mention that different choice of quark representations [26] could lead to a more important A^t_{FB} increase but in which it seems impossible to obtain realistic values simultaneously for the observables on $Z\bar{q}q$ vertex coming from the atomic parity violation and the quark asymmetry Q_{FB} [1]. Here, the effects of KK quark mixing [19,27] in the first generation sector should be studied in more details.

At this stage, a few important remarks are in order:

(i) The differential cross section with respect to the pair invariant mass [recently computed at next-to-next-to-leading order (NNLO) in the SM [28]] is in good agreement with Tevatron data [29]. It seems thus difficult to generate a significant effect on A^t_{FB} in RS without spoiling the cross section fit. Nevertheless, a computation at NNLO also for the asymmetry would be necessary to conclude on the KK contributions.

(ii) The contribution to A^t_{FB} and $\sigma(t\bar{t})$ from the exchange of the KK excitations of EW gauge bosons are not dominant for the model considered here.

(iii) At the Large Hadron Collider, top charge asymmetry could be measured, possibly confirming or invalidating the present scenario [30].

In conclusion, we have proposed a RS extra-dimensional scenario in which the theoretical value of A^t_{FB} is relatively closer to the value measured at the Tevatron, compared to the SM case. If the deviation on A^t_{FB} persists in upcoming data and the relevant higher order corrections to A^t_{FB} in the SM explain the experimental result only partially, then the warped extra dimensions could play a role in the interpretation of this discrepancy. Nevertheless, as a result of the indirect precision electroweak constraints, it would be difficult to elaborate a RS scenario generating a significant top asymmetry that explains entirely the present data,

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[26] The b_R and b_L multiplets could be, respectively, in $(\mathbf{1},\mathbf{3})$ and $(\mathbf{2},\mathbf{4})$ representations of the $SU(2)_L \times SU(2)_R$ symmetry. The t_R and t_L multiplets could be embedded in $(\mathbf{1},\mathbf{2})$ and $(\mathbf{2},\mathbf{1})$ representations. The b_L and t_L multiplets then mix, giving rise to the SM $SU(2)_L$ doublet Q_L that is mainly composed from the t_L multiplet. No such mixing would occur for the first quark generations which are here in $(\mathbf{2},\mathbf{3})$ for left-handed quarks ($I_{3R}(q_L) = -1$) and $(\mathbf{1},\mathbf{4})$ for right-handed ones.

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