The 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 longstanding anomaly in the forward–backward asymmetry for bottom quark production at LEP which is 3 standard deviations different from the Standard Model value. In this note, we show that the two discrepancies can be accounted for by the contributions of Kaluza–Klein excitations of gauge bosons (gluons at the Tevatron and electroweak 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.

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As in the case of the LEP $A^b_{FB}$ 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 axi-gluons 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 not cure the LEP $A^t_{FB}$ anomaly, though.

In Ref. 12 it has been shown that the discrepancy between the LEP measured value of $A^t_{FB}$ and the theoretical prediction can be resolved in the context of variants of the Randall–Sundrum (RS) extra–dimensional model 13 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 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 to explain the $3\sigma$ deviation of $A^t_{FB}$, while keeping all other precision measurements unaltered.

In this letter, we show how the same warped extra dimensional scenario that resolves the LEP $A^b_{FB}$ anomaly could also (partially or in total) explain the discrepancy between the measured value of $A^t_{FB}$ at the Tevatron and the theoretical value. Here again, the apparent $A^t_{FB}$ anomaly is addressed thanks to the naturally larger KK gauge boson couplings to the third generation quarks. Some implications of this scenario are discussed.

Apparently, something is indeed rotten in the kingdom of third generation quarks. Adding to the longstanding anomaly of the forward–backward (FB) asymmetry for $b$–quark jets $A^b_{FB}$ 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, $A^t_{FB}$, that are not consistent with the SM expectation. In particular, the latest and most precise result from the CDF collaboration 4, using 3.2 fb$^{-1}$ data, gives for this asymmetry in the $p\bar{p}$ laboratory frame

$$A^t_{FB} = 0.19 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)} \,. \tag{1}$$

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 vector–like couplings to quarks, the process does not generate an asymmetry between quarks and antiquarks and thus, $A^t_{FB}$ 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 6

$$A^t_{FB} = 0.05 \pm 0.015 \,. \tag{2}$$

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

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

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

$$\sigma(t\bar{t})^{\text{th}} = 7.0^{+0.71}_{-0.72} \text{ pb} \, . \tag{4}$$
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 \(S^1/Z_2\) 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 electroweak observables \([1, 2]\), while keeping the mass of the first KK weak gauge boson excitations (that are nearly equal to the KK gluon mass \(M_{KK}\)) as low as the TeV scale, is to extend the SM group by gauging the custodial symmetry \(SU(2)_L \times SU(2)_R \times U(1)_Y\) 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 light fermions \(f \neq b\) and \(t\), if the fermion localization and hence the \(c_f\) parameters are such that \(c_{t_{	ext{light}}} \gtrsim 0.5\) \[17\], they lead to an acceptable fit of electroweak data provided that \(M_{KK} \approx 3\) 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 \(c_{t_{	ext{light}}}, c_{b_{	ext{light}}}\) 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 \(A_{FB}^t\) and the partial \(Z\) boson decay width \(\Gamma(Z \rightarrow b\bar{b})\), and the Tevatron observables in top quark production, \(A_{FB}^t\) and \(\sigma(t\bar{t})\), have to be treated separately.

In this study, we adopt a choice of parameters close to the one made in Ref. \[12\] which reproduces the correct \(t, b\) quarks, the parameters for \(b\)-quark masses as well as LEP data \[18\], taking into account the electroweak KK excitations and their mixing with the gauge bosons; we will ignore the fermion KK excitations that we assume to be too heavy \[19\]. In particular, we will consider the following point in parameter space

\[
c_{Q_L} = 0.52, c_{b_{	ext{light}}} = 0.31; g_{Z'} = 0.9; M_{KK} \approx 2.75\text{ TeV} \quad (5)
\]

which leads to a very good fit of the observables in the \(b\)-quark sector at LEP, a likelihood of \(\chi^2 \approx 15\) compared to \(\chi^2 \approx 21\) in the SM \[12, 17\], and a bottom quark mass \(m_b \approx 3\) GeV, which is acceptable keeping in mind that a full three-flavor treatment would improve the value. Moreover, for the non bottom quark electroweak observables, it allows to obtain a global fit that is better than in the SM, while keeping \(M_{KK}\) as low as possible \[19\].

In this particular 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-right-handed \(q = u, d\) 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, \(v_q/a_q \propto Q(c_{q_{L/R}}) \pm Q(c_{Q_{L/R}})\). 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 \(q\bar{q} \rightarrow t\bar{t}\) is then given by

\[
\frac{d\hat{\sigma}}{d\cos\theta_t} \propto 2 - \beta_t^2 \sin^2 \theta^* + s^2 |D|^2 \left[8 v_q v_\ell a_q a_\ell b_t \cos \theta^* + \left(a_q^2 + v_\ell^2 \left(2 - \beta_t^2 \sin^2 \theta^*\right) + a_\ell^2 \beta_t^2 (1 + \cos^2 \theta^*)\right)\right]
\]

\[
+ 4 \text{Re}(D) \left[v_q v_\ell \left(1 - \frac{1}{2} \beta_t^2 \sin^2 \theta^*\right) + a_q a_\ell b_t \cos \theta^*\right] (6)
\]

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

The FB asymmetry of the top quark is then defined as

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

where now \(\theta_t\) 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).

\[
A_{FB}^t \propto a_q a_\ell b_t \hat{s} |D|^2 \left[\left(\hat{s} - M_{KK}^2 + 4v_q v_\ell\right)\right] \quad (8)
\]

which originates from the interference between the gluon and the KK gluon contributions and also from the pure KK gluon diagram. Note that \(A_{FB}^t\) is non-zero only if both axial-vector couplings of \(g_{kk}\), \(a_q\) and \(a_\ell\) are non-zero. The product \(a_q a_\ell\) should be negative along with \(\hat{s} < M_{KK}^2/(1 + 2v_q v_\ell)\), to have a positive \(A_{FB}^t\) below the \(g_{kk}\) resonance, as is the case with \(M_{KK} \approx 3\) TeV. Thus, one needs to maximize \(a_q a_\ell\) while keeping \(v_q v_\ell\) reasonable to achieve a large asymmetry. However, if \(a_q a_\ell\) 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 \(a_\ell\) of the \(g_{kk}\) excitation is thus required.

Note that at NLO, there are additional contributions to \(A_{FB}^t\), 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.

Fixing the values of \(c_{Q_L}, c_{b_{	ext{light}}}, g_{Z'}\) and \(M_{KK}\) to those given in eq. (5), we have searched over about 20,000 different values of the set of four parameters \([c_{Q_L}, c_{b_{	ext{light}}}, c_{b_{	ext{light}}}, c_{b_{	ext{light}}}]\) using both directed random search algorithms and grid scans for selected parameters, looking for a significant FB asymmetry but a \(t\bar{t}\) cross section that is within \(\approx 1.6\sigma\) (i.e. at the 90\% confidence level) of the experimental value. The results that we obtain are summarized in Fig. 1 which displays the contour levels in the plane \([c_{Q_L}, c_{b_{	ext{light}}}]\) corresponding, typically, to the maximum \(A_{FB}^t\).
anomaly as well as the associated $\sigma(t\bar{t})$ values. In this figure, we have fixed the $c$ values of the right–handed light quarks to $c_{uR} \approx c_{dR} \approx 0.8$. The chosen range for $c_{qL}$ with much smaller values than $c_{uR} \approx c_{dR}$, allows substantial parity violation couplings of first generation quarks to the KK gluon and, hence, a sizeable $A_{FB}^{t\bar{t}}$.

![FIG. 1: Contour levels in the plane $[c_{qL}, c_{tR}]$ for the total cross section $\sigma(t\bar{t})$ (dashed lines) and the forward–backward asymmetry $A_{FB}^{t\bar{t}}$ [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. 1 with $M_{KK} = 2.75$ TeV.](image)

The decrease of $\sigma(t\bar{t})$ with both $c_{qL}$ and $c_{tR}$ is caused by the increase of the $g_{KK}$ couplings to $q_{L}q_{L}$ and $t_{L}t_{R}$ states which dominantly enhance the total $g_{KK}$ decay width. The increase of $A_{FB}^{t\bar{t}}$ with the decrease of $c_{tR}$, which amplifies the difference between $c_{tR}$ and the fixed $c_{Q{L}_{L}}$, finds its origin in the larger parity violation effect on the four–dimensional $g_{KK}t\bar{t}$ coupling. $A_{FB}^{t\bar{t}}$ can thus reach sizable values in regions where $\sigma(t\bar{t})$ has values consistent with Tevatron data at the 1.65\(\sigma\) level. Note that in the relevant region, the order of magnitude obtained for top quark mass, $m_t \approx 100$ GeV, is satisfactory while, despite of the atypically large $Q(c_{qL})$ values for light quarks, one can arrange such that the $Zq\bar{q}$ couplings are in good agreement with Tevatron/HERA data as well as with the high–precision measurements at LEP 2–21.

The largest contribution from the KK gluon exchange, assuming a fixed total decay width $\Gamma_{KK}^{c}$ is $A_{FB}^{t\bar{t}} \approx 4.3\%$ as shown by the thin contours of Fig. 1 21. Adding this contribution to the SM NLO value, one obtains a total of $A_{FB}^{t\bar{t}}^{RS+SM} \approx 9\%$, which is well within $\lesssim 1.65\sigma$ from the experimental value eq. (1), a substantial improvement over the SM result which deviates by $\approx 2\sigma$.

However, for this optimal choice of parameters, the total decay width for the KK gluon turns out to be quite large, $\Gamma_{KK} \approx 30\% M_{KK}$. For such a broad resonance, at least the energy dependent width, if not the full set of radiative corrections to the $p\bar{p} \rightarrow t\bar{t}$ process, should be used, in much the same way as for the $\rho$ vector–meson exchange in $e^+e^- \rightarrow \pi^+\pi^-$. We have checked that by doing so, the contribution to $A_{FB}^{t\bar{t}}$ from KK gluon exchange can be increased to a maximum of $\approx 5.6\%$, as shown by the thick solid contour lines in Fig. 1. This value then completely resolves the Tevatron $A_{FB}^{t\bar{t}}$ anomaly, $A_{FB}^{t\bar{t}}^{RS+SM} \approx 11\%$. Note that there is no fine–tuning of parameters as in a large range of $c$ values, a sizeable $A_{FB}^{t\bar{t}}$ is obtained.

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

i) Another puzzling feature of the CDF data is that the differential cross section with respect to the $t\bar{t}$ invariant mass is, except for the two extreme points, systematically below the SM expectation 23. In our scenario, e.g. for $c_{qL} \approx 0.1$, the negative interference between the contributions of the gluon and its KK excitation lowers the mass distribution as to fit nicely the data. We expect a tiny excess of events, $O(20\%)$, for invariant $t\bar{t}$ masses above 800 GeV; this excess is found to be more significant in other scenarios, e.g. for slightly lower $M_{KK}$ values.

ii) The contribution to $A_{FB}^{t\bar{t}}$ and $\sigma(t\bar{t})$ from the exchange of the KK excitations of electroweak gauge bosons are not dominant for the set of parameters considered in Fig. 1. However, scenarios can be found in which these contributions are significant. In particular, the KK $Z'$ boson can have large enough couplings to the initial $q\bar{q}$ and final $t\bar{t}$ states, such that it generates the bulk of $A_{FB}^{t\bar{t}}$ which, in some cases, can reach the level of $\approx 7\%$ 24.

iii) At the Large Hadron Collider, such gluon KK states could be copiously produced and $A_{FB}^{t\bar{t}}$ asymmetry could be measured 25, confirming or invalidating the present scenario; this will be, however, rather challenging. At the future $e^+e^-$ International Linear Collider, one would be more sensitive to the exchange of the KK excitations of electroweak gauge bosons in top or bottom quark pair production 12.

In conclusion, we have proposed a warped extra–dimensional scenario with specific localizations of the fermions along the extra–dimension, in which the tree level contribution of Kaluza–Klein gluon excitations with masses $\approx 3$ TeV, brings the theoretical value of the forward–backward asymmetry in top quark pair production close to the value measured at the Tevatron. This is in contrast to the Standard Model case where the predicted and measured values differ by more than two standard deviations. This is the same scenario which also cures the longstanding anomaly of the forward backward asymmetry for $b$–quarks measured at LEP. In this letter, we presented the main implications of this possibility; more details will be given in a future publication 26.

We are eagerly awaiting for a more precise experimental determination of the asymmetry, in particular from the D0 experiment. If the deviation persists and the relevant higher order corrections to the asymmetry in the Standard Model (which are mandatory to implement to have the predicted value under full control) fail to explain the experimental result, then one would have a very exciting signal of warped extra space–time dimensions.

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We have evaluated the contribution of the box diagrams involving squarks and gluinos in the minimal supersymmetric extension of the SM (MSSM) to $A_T^{FB}$ and found that, even for squark and gluino masses close to 100 GeV, the interference with the tree SM diagram with gluon exchange cannot exceed the level of $10^{-4}$.

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