Effects Of Kaluza-Klein Excited $W$
On Single Top Quark Production At Tevatron

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Abstract

In extra dimension theories if the gauge bosons of the standard model propagate in the bulk of the extra dimensions then they will have Kaluza-Klein excitations that can couple to the standard model fermions. In this paper we study the effects of the first excited Kaluza-Klein mode of the $W$ on single top production at the Tevatron. We find that the cross section for the single top production can be significantly reduced if the mass of the first Kaluza-Klein excited $W \sim 1$ TeV. Hence, a measurement of the single top production cross section smaller than the standard model prediction would not necessarily imply $V_{tb} < 1$ or evidence of extra generation(s) of fermions mixed with the third generation.

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1 Introduction

An important issue in high energy physics is to understand the mechanism of mass generation. In the standard model, a fundamental complex Higgs scalar is introduced to break the electroweak symmetry and generate masses. However, arguments of triviality and naturalness suggest that the symmetry breaking sector of the standard model is just an effective theory. The top quark, with a mass of the order of the weak scale, is singled out to play a key role in probing the new physics beyond the standard model (SM) \cite{1}. The electroweak interactions of the top quark are particularly interesting and can be probed in the single top production and top decays. In this work we focus on the single top production at the Tevatron.

Single top production at the Tevatron occurs within the SM in three different channels, the $s$-channel $W^*$ production, $q\bar{q}' \to W^* \to t\bar{b}$ \cite{2, 3, 4, 5, 6, 7}, the $t$-channel $W$-exchange mode, $bq \to tq'$ \cite{6, 7, 8, 9, 10, 11, 12, 13, 14} (sometimes referred to as $W$-gluon fusion), and through $tW^-$ production \cite{15}.

The process $q\bar{q} \to t\bar{b}$, compared to the single top production via $W$-gluon fusion has the advantage that the cross section can be calculated reliably because the quark and antiquark structure functions at the relevant values of $x$ are better known than the gluon structure functions that enter in the calculation for the $W$-gluon cross section. Measurement of single top production cross section has been discussed in detail in Refs\cite{6, 7, 16}. In these references it is estimated that single top production can be measured with an experimental error, at the one sigma level, of $\pm 19\%$ at Run 2 (now called Run 2a) with an integrated luminosity of $2 fb^{-1}$. The measured cross section can then be used to extract the CKM element $V_{tb}$ with a combined theoretical and experimental error of $\pm 12-19\%$ in Run 2a depending on how one estimates the theoretical error. In Refs\cite{6, 7, 16} it was mentioned that there may be a Run 3 producing $30 fb^{-1}$ of data and if only the $s$-channel $W^*$ production, $q\bar{q}' \to W^* \to t\bar{b}$ is used, then $V_{tb}$ could be extracted at Run 3 with an error (including
theoretical error) of about ± 5%. At present Run 2a is expected to start next year and achieve ultimately an integrated luminosity of 2 fb$^{-1}$. The run beyond an integrated luminosity of 2 fb$^{-1}$ is no longer called Run 3 but is a continuation of Run 2 (Run 2b) and may achieve an integrated luminosity of 15 fb$^{-1}$ or higher. Update of the estimate on the precision in single top measurement at Run 2 since Refs[6, 7, 16] is not yet available [17]. As a rough estimate for the errors in measuring $V_{tb}$ in Run 2b, operating at an integrated luminosity of 15 fb$^{-1}$, one can multiply the estimate in “Run 3” presented in Refs[6, 7, 16] by a factor of $\sqrt{2}$.

The unitarity of the CKM matrix leads to a value of $V_{tb} \sim 1$. Hence a measurement of $V_{tb}$ which differs from unity would indicate presence of new physics. For instance a measurement of $V_{tb} < 1$ is commonly taken to indicate the existence of new generation of fermions mixed with the third generation.

Thus, it is possible that the effects of new physics will be revealed in single top production [19]. In this paper we consider effects that extra dimension theories can produce in single top production at the Tevatron. If in such theories, the gauge fields of the Standard Model(SM) live in the bulk of the extra dimensions then they will have Kaluza-Klein(KK) excitations. The possibility that the masses of the lowest lying of these states could be as low as $\sim$ a few TeV or less (of the order of the inverse size of the compactification radius) leads to a very rich and exciting phenomenology at future and, possibly, existing colliders [20]. Limits on the masses of the lowest lying excitations obtained from direct $Z'/W'$ and dijet bump searches at the Tevatron from Run 1 indicate that they must lie above $\simeq 0.85$ TeV [21]. A null result for a search made with data from Run 2 will push this limit to $\simeq 1.1$ TeV. Model dependent limits can also be placed on the masses of the excitation from low energy observables and precision electroweak measurements [22, 23, 24]. For instance in Ref [22] global fits to the electroweak observables, with certain assumptions, were found to provide lower bounds on the compactification scale, $M_c$, (which is equal to the mass of the first excited KK gauge boson) which were generically in the 2-5 TeV range depending on which standard model fermions,
as well as the higgs boson, live in the bulk of the extra dimensions or are localized at different points of it. In fact Ref[22] found scenarios where global electroweak fits give a 95% C.L upper and lower bounds on $M_c$ in the range $0.95 \text{ TeV} \leq M_c \leq 3.44 \text{ TeV}$. Note the analysis of Ref[23] assumed the standard model fermions to be stuck at the boundary of the extra dimension.

In addition to the various assumptions, mentioned above, that are involved in putting bounds on $M_c$ from global electroweak fits there is another very important assumption made in all these analyses. In all these analyses it is assumed that the only new physics beyond the standard model arise from the the physics of the KK excitations of the standard model fields. For instance, as mentioned in Ref[23], in all these analyses the gravity induced processes are assumed not to significantly affect the electroweak observables. Note that, in general, the gravity induced processes will affect electroweak observables, changing the bound on $M_c$ from electroweak data, but will not affect single top production at tree level. In fact it is quite likely that there are additional new physics effects which may easily change the bounds on $M_c$ obtained from global fits to electroweak data. One can represent the effects of this additional new physics in terms of higher dimensional operators in the effective Lagrangian framework. Recent studies have clearly demonstrated that the presence of higher dimensional operators can significantly effect global fits to the electroweak observables [18]. In light of the above discussion we do not strictly enforce the bounds on $M_c$ from global electroweak fits in a specific model but rather assume that $M_c$ is in the same ballpark as obtained from global electroweak fits. In other words we assume that $M_c \sim \text{ TeV}$.

In this work we consider the contribution of the first excited KK mode of the $W$, denoted by $W_{KK}$, on the s-channel mode for the single top production at the Tevatron. This channel is more sensitive to the presence of a new charged resonance than the t-channel $W$-gluon fusion mechanism as was discussed in Ref[25]. This is because the momentum of the the s-channel resonance is time-like which leads to larger interference with the standard model amplitude than the t-channel process where the momentum of the $W_{KK}$ is space-like. For the s-channel process there can be a
resonant enhancement of the amplitude which does not occur in the t-channel process. Note that the additional new physics effects, discussed above, which are not of gravitational origin may also affect single top production and has been extensively studied in Ref. [19] and we do not consider these effects in this work. However, if the additional new physics is from gravity induced processes then there is no effect, at the tree level, on the s-channel mode for single top production which is mediated by the exchange of a charged boson.

The paper is organized as follows. In section II, we calculate the effects of the excited Kaluza-Klein $W$ state on the single top production. In section III, we present our results and conclusions.

2 Effect of KK excited $W$ in the single top production rate at Tevatron

To study the physics of the KK excited $W$ we use a model which is based on a simple extension of the SM to 5 dimensions (5D) [22, 27]. However, as discussed above, we do not assume that this model represents all the physics beyond the standard model. The 5D SM is probably a part of a more fundamental underlying theory.

In the 5D SM model the fifth dimension $x_5$ is compactified on the orbifold $S^1/Z_2$, a circle of radius $R$ with the identification $x_5 \rightarrow -x_5$. This is a segment of length $\pi R$ with two 4D boundaries, one at $x_5 = 0$ and another at $x_5 = \pi R$ (the two fixed points of the orbifold). The SM gauge fields live in the 5D bulk, while the SM fermions, $\psi$, and the Higgs doublets, can either live in the bulk or be localized on the 4D boundaries. We do not consider gravity in our analysis. It is possible that gravity might propagate in more extra dimensions than the SM fields. We do not expect gravity to affect single top production at the Tevatron.

If the standard model fields live in the bulk then they will have KK excitations. The fields living
in the bulk can be Fourier-expanded as

\[ \Phi_+(x_\mu, x_5) = \sum_{n=0}^{\infty} \cos \left( \frac{n x_5}{R} \right) \Phi_+^{(n)}(x_\mu), \]

\[ \Phi_-(x_\mu, x_5) = \sum_{n=1}^{\infty} \sin \left( \frac{n x_5}{R} \right) \Phi_-^{(n)}(x_\mu), \]

(1)

where \( \Phi_\pm^{(n)} \) are the KK excitations of the 5D fields and the fields have been defined to be even or odd under the \( Z_2 \)-parity, i.e. \( \Phi_\pm(x_5) = \pm \Phi_\pm(-x_5) \).

As mentioned above the gauge fields live in the bulk. They are assumed to be even under the \( Z_2 \) parity. Their (massless) zero modes correspond to the standard model gauge fields. If the Higgs boson lives in the bulk then it is assumed to be even under the \( Z_2 \) parity also. Fermions in 5D have two chiralities, \( \psi_L \) and \( \psi_R \), that can transform as even or odd under the \( Z_2 \). The precise assignment is a matter of definition. It is assumed that \( \psi_L (\psi_R) \) components of fermions \( \psi \), which are doublets (singlets) under SU(2)_L have even \( Z_2 \) parity and consequently only the \( \psi_L \) of SU(2)_L doublets and \( \psi_R \) of SU(2)_L singlets have zero modes. The fermions in this model couple to the KK excited gauge bosons only if they are localized on the 4D boundaries. The Lagrangian along with additional details and low energy phenomenology of this model can be found in \[22, 23, 27\] and will not be presented in this paper. For simplicity we will assume that there is one higgs doublet which along with the fermions that participate in the s-channel process for the single top production are localized on the 4D boundary at \( x_5 = 0 \).

The effective four dimensional Lagrangian can be obtained after integrating over the fifth dimension. The piece of this Lagrangian relevant to our calculation is the charged electroweak sector and is given by

\[ \mathcal{L}^{ch} = \sum_{a=1}^{2} \mathcal{L}_a^{ch} + \mathcal{L}_{\text{new}} \]  

(2)
with

\[ L^{ch}_a = \frac{1}{2} m_W^2 W_a \cdot W_a + \frac{1}{2} M_c^2 \sum_{n=1}^{\infty} n^2 W_{a}^{(n)} \cdot W_{a}^{(n)} \]

\[ - g W_a \cdot J_a - g \sqrt{2} J_{a}^{KK} \cdot \sum_{n=1}^{\infty} W_{a}^{(n)}, \]

where \( m_W^2 = g^2 v^2 / 2 \), the weak angle \( \theta \) is defined by \( e = g s_\theta = g' c_\theta \), while the currents are

\[ J_{a\mu} = \sum_\psi \bar{\psi}_L \gamma_\mu \sigma_a \frac{1}{2} \psi_L, \]

\[ J_{a\mu}^{KK} = \sum_\psi \varepsilon_{\psi} \bar{\psi}_L \gamma_\mu \sigma_a \frac{1}{2} \psi_L. \]

(3)

Here \( \varepsilon_\psi \) takes the value 1(0) for the \( \psi_L \) living in the boundary(bulk). The mass of the \( n^{th} \) excited KK state of the \( W \) is given by \( n M_c = n / R \) where \( R \) is the compactification radius. In this work we consider only the \( n = 1 \) state. The term \( L_{new} \) represents the additional new physics beyond the 5 dimensional standard model the structure of which remains unknown till the full underlying theory is understood. The coupling of KK excited \( W \) to the standard model is determined in terms of the Fermi coupling, \( G_F \), up to corrections of \( O(m_Z^2/M_c^2) \) [22, 23]. For \( M_c \sim \text{TeV} \) the \( O(m_Z^2/M_c^2) \) effects are small for single top production and therefore we do not include these effects in our calculations. We have ignored the mixing of the \( W \) with \( W_{KK} \) which is also an \( O(m_Z^2/M_c^2) \) effect. Thus, assuming the \( W_{KK} \) decays only to standard model particles, the predicted effect of \( W_{KK} \) on single top production depends, in addition to the SM parameters, only on the unknown mass of the \( W_{KK} \).

The cross section for \( pp \rightarrow t\bar{b}X \) is given by

\[ \sigma(p\bar{p} \rightarrow t\bar{b}X) = \int dx_1 dx_2 [u(x_1) \overline{d}(x_2) + u(x_2) \overline{d}(x_1)] \sigma(u\overline{d} \rightarrow t\bar{b}). \]

(5)

Here \( u(x_i), \overline{d}(x_i) \) are the \( u \) and the \( \overline{d} \) structure functions, \( x_1 \) and \( x_2 \) are the parton momentum fractions and the indices \( i = 1 \) and \( i = 2 \) refer to the proton and the antiproton. The cross section for the process

\[ u(p_1) + \overline{d}(p_2) \rightarrow W^* \rightarrow \overline{b}(p_3) + t(p_4), \]
is given by

\[ \sigma = \sigma_{SM} \left[ 1 + 4 \frac{A}{D} + 4 \frac{C}{D} \right], \]

\[ A = (s - M_W^2)(s - M_W^2) + M_W M_{W_{KK}} \Gamma_W \Gamma_{W_{KK}}, \]

\[ C = (s - M_W^2)^2 + (M_W \Gamma_W)^2, \]

\[ D = (s - M_{W_{KK}}^2)^2 + (M_{W_{KK}} \Gamma_{W_{KK}})^2, \] (6)

and

\[ \sigma_{SM} = \frac{g^4}{384 \pi s^2} \frac{(2s + M_t^2)(s - M_t^2)^2}{(s - M_W^2)^2 + (M_W \Gamma_W)^2}. \] (7)

Here \( s = x_1 x_2 S \) is the parton center of mass energy while \( S \) is the \( p\bar{p} \) center of mass energy. To calculate the width of the \( W_{KK} \) we will assume that it decays only to the standard model particles. The \( W_{KK} \) will then have the same decays as the \( W \) boson but in addition it can also decay to a top-bottom pair which is kinematically forbidden for the \( W \) boson. The width of the \( W_{KK}, \Gamma_{W_{KK}} \), is then given by

\[ \Gamma_{W_{KK}} \approx \frac{2M_{W_{KK}}}{M_W} \Gamma_W + \frac{2M_{W_{KK}}}{3M_W} \Gamma_W \cdot X, \]

\[ X = (1 - \frac{M_t^2}{M_{W_{KK}}^2})(1 - \frac{M_t^2}{2M_{W_{KK}}^2} - \frac{M_t^4}{M_{W_{KK}}^4}). \] (8)

where \( \Gamma_W \) is the width of the \( W \) boson and we have neglected the mass of the \( b \) quark along with the masses of the lighter quarks and the leptons.

### 3 Results

In Fig. 1, we plot \( \Delta \sigma / \sigma \) versus \( M_{W_{KK}} \), the mass of the first excited KK \( W \) state, where \( \Delta \sigma \) is the change in the single top production cross section in the presence of \( W_{KK} \) and \( \sigma \) is the standard model cross section[1]. We have used the CTEQ [28] structure functions for our calculations and

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6 We have not included the QCD and Yukawa corrections to the single top quark production rate. They will enhance the total rate, but not change the percentage of the correction of new physics to the cross section.
obtain a standard model cross section of 0.30 pb for the process \( p\bar{p} \rightarrow t\bar{b}X \) at \( \sqrt{S} = 2 \text{TeV} \). We observe from Fig. 1 that the presence of \( W_{KK} \) can lower the cross section by as much as 25% for \( M_{W_{KK}} \sim 1 \text{TeV} \). This has an important implication for the measurement of \( V_{tb} \) using the s-channel mode at the Tevatron. It was pointed out in Ref[25] that there could be models where the presence of an additional \( W' \) (denoted as \( W' \)) could lead to a measurement of the cross section for the s-channel \( p\bar{p} \rightarrow t\bar{b}X \) smaller than the standard model prediction. A specific example of such a model with a \( W' \) that causes a significant decrease of the single top cross section can be found in Ref[26]. This could, as pointed out in Ref [23], lead one to conclude that \( V_{tb} < 1 \) which could then be wrongly interpreted as evidence for the existence of new generation(s) of fermions mixed with the third generation. Our work provides another specific example of such a model and our results clearly demonstrates that a measurement of the cross section for the s-channel \( p\bar{p} \rightarrow t\bar{b}X \) smaller than the standard model prediction would not necessarily imply \( V_{tb} < 1 \) or evidence of extra generation(s) of fermions mixed with the third generation. Note that, as mentioned above, the predicted effect of \( W_{KK} \) on single top production depends, in addition to the SM parameters, only on the unknown mass of the \( W_{KK} \), while in most other \( W' \) models the predictions for single top production depend, in addition to the SM parameters, on the unknown mass of the \( W' \) as well as on unknown mixing parameter(s).

Note that the \( W_{KK} \) can also be searched at the Tevatron through its decay into a high energy lepton and a neutrino if it couples to the leptons. Searches for this resonance at the Tevatron allow discovery at 1.11 TeV and 1.34 TeV with 2 \( fb^{-1} \) and 20 \( fb^{-1} \) for \( \sqrt{S} = 2 \text{TeV} \) [23]. In this energy range, as shown in Fig. 1, there will be significant effects on the single top production rate. If the SM leptons are allowed to live in the bulk then they will not couple to \( W_{KK} \) and so it is no longer possible to search for this resonance through its decay to leptons. In such a scenario, single top production could be a very effective probe of the \( W_{KK} \) resonance.

In Fig.2 we show the \( t\bar{b} \) invariant mass distribution \( \frac{da}{dM_{tb}} \), where \( M_{tb} \) is the invariant mass of the
$t\bar{b}$ pair for various values of $M_{W_{KK}}$. We see a significant decrease in the signal at $M_{W_{KK}} \sim 1$ TeV for lower values of $M_{tb}$. For lower $M_{tb}$, the interference term ($\frac{A}{D}$) in Eq. (6) has a stronger effect than the direct term ($\frac{C}{D}$) which leads to a reduction of the signal. In Fig. 3 we show the $t\bar{b}$ invariant mass distribution $\frac{d\sigma}{dM_{tb}}$ for an extended range of $M_{tb}$ for $M_{W_{KK}} = 1$TeV. As we go to larger values of $M_{tb}$, close to the resonance region, the direct term in Eq. (6) becomes dominant. This leads to a bump in the resonance region. However, the signal is considerably reduced because of smaller parton distributions.

In conclusion, we have studied the effects of a KK excited $W$ on the cross section of the single top production at the Tevatron. The model of $W_{KK}$ considered in this work leads to a definite structure for its coupling to the standard model fields. Moreover, the prediction for single top production, up to very small corrections, depend only on one additional unknown parameter, the mass of the $W_{KK}$. This is unlike the usual $W'$ models, which require extending the standard model gauge group and the predictions for single top production depend on the unknown mass of the $W'$ as well as on additional unknown mixing parameter(s). Our results show that the cross section for s channel single top quark production can be significantly reduced, by about 25%, from the standard model value for $M_{W_{KK}} \sim 1$TeV. Therefore the s channel single top production could be a very effective probe of the $W_{KK}$ resonance with a mass $\sim$ TeV at the Tevatron.

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Figure 1: $\Delta \sigma / \sigma_{SM}$ versus $M_{W_{KK}}$ the mass of the first KK excited $W$. 
Figure 2: The distribution $\frac{d\sigma}{dM_{tb}}$ for various values of $M_{W_{KK}}$ for a limited range of $M_{tb}$. 
Figure 3: The distribution \( \frac{d\sigma}{dM_{tb}} \) for \( M_{W_{KK}} = 1 \, \text{TeV} \) for an extended range of \( M_{tb} \).