Top quark forward-backward asymmetry from the 3 − 3 − 1 model

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Abstract
The forward-backward asymmetry $A_{FB}$ in top quark pair production, measured at the Tevatron, is probably related to the contribution of new particles. The Tevatron result is more than a 2σ deviation from the standard model prediction and motivates the application of alternative models introducing new states. However, as the standard model predictions for the total cross section $\sigma_{tt}$ and invariant mass distribution $M_{tt}$ for this process are in good agreement with experiments, any alternative model must reproduce these predictions. These models can be placed into two categories: One introduces the s-channel exchange of new vector bosons with chiral couplings to the light quarks and to the top quark and another relies on the t-channel exchange of particles with large flavor-violating couplings in the quark sector. In this work we employ a model which introduces both s- and t-channel nonstandard contributions for the top quark pair production in proton antiproton collisions. We use the minimal version of the $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ model (3-3-1 model) that predicts the existence of a new neutral gauge boson, called $Z'$. This gauge boson has both flavor-changing couplings to up and top quarks and chiral coupling to the light quarks and to the top quark. This very peculiar model coupling can correct the $A_{FB}$ for top quark pair production for two ranges of $Z'$ mass while leading to cross section and invariant mass distribution quite similar to the standard model ones. This result reinforces the role of the 3-3-1 model for any new physics effect.

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1 Introduction

The experimental results from LEP, SLD (Slac Large Detector) and the Tevatron are in accordance with all the predictions of the standard model (SM) and, apart from the Higgs particle, all predicted particles have been discovered. However, some indications that the SM cannot explain all of the experimental results come, for example, from neutrino oscillations data that require different masses for the three neutrino kinds and mixing among them. Another indication of experimental difficulties faced by the SM comes from the forward-backward top quark asymmetry $A_{FB}$ measured at the Tevatron in the top pair production process. On the other hand, it is believed that the SM is not the complete theory because it does not explain some theoretical features, for example, the family replication and the value of the Weinberg angle $\theta_W$.

It would be interesting to study the top pair production process within a theoretical framework being an extension of the SM that presents an issue for the family replication problem and for the bound on the Weinberg angle. This is the motivation of the present work: to use the framework of the minimal version of the 3-3-1 model [1, 2] in order to calculate the forward-backward top quark asymmetry in the top pair production in proton-antiproton collisions at Fermilab energy.

The discrepancy in the $A_{FB}$ we are referring to is more than $2\sigma$ because the SM calculation, including next-to-leading order QCD corrections, is $A_{FB} = 5.0 \pm 1.5\%$ [3], while CDF obtained $0.158 \pm 0.075 \text{ (stat+syst)}$ in $t\bar{t}$ rest frame [4] and D0 obtained $8 \pm 4 \text{ (stat)} \pm 1 \text{ (syst)} \%$ [5].

There are some proposed models to explain the observed discrepancies between the Tevatron result and SM calculations. A larger $A_{FB}$ than predicted by the SM is obtained in models where the $s$-channel exchange includes a new vector boson with chiral coupling to the light quarks [6] or in models where a large flavor-violating particle is exchanged in the $t$ channel [7, 8]. The 3-3-1 model is a possible solution for the present problem because it provides the two kind of contributions, namely, a new neutral gauge boson contribution in the $s$ channel, as well as the expected flavor-changing neutral-current (FCNC) contribution in the $t$ channel. In this work we use the 3-3-1 model to calculate some distributions related to the top quark pair production in
We present the total cross section and the invariant mass and transverse momentum distributions for three different $Z'$ mass values. Our main result is a large $A_{FB}$ while keeping other signatures of the process similar to those predicted by the SM. The paper includes a section where the main ingredients of the model are presented followed by the results and conclusion section.

2 Model

The 3-3-1 model is a gauge theory with a larger group of symmetry than the SM. It is based on the semisimple gauge group $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ and, as a consequence, it contains new gauge bosons ($W_\mu^1, \ldots, W_\mu^8$ and $B_\mu$), fermions, and scalars. These particles were until now not experimentally observed, but their existence can lead to interesting signatures. An important motivation to study the 3-3-1 model is that the predicted new particles are expected to occur at energies near the breaking scale of the SM. Moreover this model offers an explanation of family replication following from the anomaly cancellation procedure and establishes a bound for the Weinberg angle [9].

In the 3-3-1 model, the electric charge operator is defined as

$$Q = T_3 + \beta T_8 + XI$$  \hspace{1cm} (1)

where $T_3$ and $T_8$ are two of eight generators satisfying the $SU(3)$ algebra

$$[T_i, T_j] = if_{ijk}T_k \quad i, j, k = 1..8;$$  \hspace{1cm} (2)

$I$ is the unit matrix, and $X$ denotes the $U(1)$ charge before the symmetry breaking.

The electric charge operator determines how the fields are arranged in each representation and depends on $\beta$. Among the choices, $\beta = -\sqrt{3}$ corresponds to the minimal version of the model, largely explored in phenomenological applications [1, 2]. The choice $\beta = -1/\sqrt{3}$, which avoids exotic charged fields, leads to a version with right-handed neutrinos [10].

In its minimal version (3-3-1 MIN), with $\beta = -\sqrt{3}$, the model has five additional gauge bosons beyond the SM ones. They are a neutral $Z'$ and four heavy charged bileptons $Y^{\pm\pm}, V^\pm$ with lepton number $L = \mp 2$.

We define the $\gamma$, $Z$, and the new $Z'$ fields as

$$A_\mu = s_w W_\mu^3 - \sqrt{3} s_w W_\mu^8 + \sqrt{1 - 4 s_w^2} B_\mu.$$

pp collisions.
\[ Z_\mu = c_w W_\mu^3 + \sqrt{3} s_w t_w W_\mu^8 - t_w \sqrt{1 - 4 s_w^2} B_\mu, \]
\[ Z'_\mu = \frac{1}{c_w} \sqrt{1 - 4 s_w^2} W_\mu^8 + \sqrt{3} t_w B_\mu, \]  
\[ (3) \]

where \( c_w = \cos \theta_w \), \( s_w = \sin \theta_w \), and \( t_w = s_w / c_w \).

Two quark families \((m = 1, 2)\) and the third one are accommodated in \( SU(3)_L \) antitriplet and triplet representation respectively:

\[ Q_m L = (d_m u_m j_m)_{T_L} \sim (3, 3^*, -1/3), \quad Q_3 L = (u_3 d_3 J)_{T_L} \sim (3, 3, 2/3). \]  
\[ (4) \]

The right-hand components of the quark fields are \( SU(3)_L \) singlets:

\[ u_\alpha R \sim (3, 1, 2/3), \quad d_\alpha R \sim (3, 1, -1/3), \]
\[ J_R \sim (3, 1, 5/3), \quad j_m R \sim (3, 1, -4/3), \]  
\[ (5) \]

\( j_1, j_2, \) and \( J \) are exotic quarks with, respectively, \(-4/3, -4/3, \) and \( 5/3 \) units of positron charge and \( \alpha = 1, 2, 3, \) and the values in the parentheses denote quantum numbers relative to \( SU(3)_C, SU(3)_L, \) and \( U(1)_X \) transformations.

As referred to before, in the 3-3-1 model, one family must transform with respect to \( SU(3) \) rotations differently than the other two. This requirement manifests itself when we collect the quark currents in a part with universal coupling with \( Z' \) similar to the SM and another part corresponding to the nondiagonal \( Z' \) couplings. The transformation of these nondiagonal terms, in the mass eigenstates basis, leads to the flavor-changing neutral Lagrangian

\[ \mathcal{L}_{FCNC} = \frac{g c_w}{\sqrt{3 - 12 s_w^2}} \left( \bar{U}_L \gamma^\mu U_L^\dagger B U_L U_L + \bar{D}_L \gamma^\mu V_L^\dagger B V_L D_L \right) Z'_\mu. \]  
\[ (6) \]

where

\[ U_L = (u~ c~ t)^T_L, \quad D_L = (d~ s~ b)^T_L \quad \text{and} \quad B = \text{diag} (1~ 0~ 0). \]

The mixing matrices \( U \) (for \( up \)-type quark) and \( V \) (for \( down \)-type quark) come from the Yukawa Lagrangian that gives rise to the quark masses, and they are related to the Cabibbo-Kobayashi-Maskawa matrix as

\[ U^\dagger V^d = V_{CKM}, \]  
\[ (7) \]

In the SM the \( up \)-type quark mass eigenstates are the weak eigenstates, so \( U = I \). For the 3-3-1 model, there are more states than the SM one and also
\(Z'\) couples differently to one of the three families. In this model, the \(up\)-type weak and the mass eigenstates are different inducing \(Z'\) flavor changing, so \(U\) must be \(\neq I\) \[1\].

In the Table I, we present \(Z\) and \(Z'\) couplings to the \(u\)- and \(d\)-type quarks. \(U\) matrix elements are free parameters; however, some limits for \(V\) elements have been obtained from \(Z'\) rare decay bounds in Refs. PRO,SHE,GOM. In the results section, we show the values of the relevant matrices elements used in our calculation.

|          | Vector couplings                     | Axial-vector couplings              |
|----------|--------------------------------------|-------------------------------------|
| \(Z'cu\) | \(\frac{U_{21}U_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) | \(\frac{U_{21}U_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) |
| \(Z'tu\) | \(\frac{U_{31}U_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) | \(\frac{U_{31}U_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) |
| \(Z'tc\) | \(\frac{U_{31}U_{12} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) | \(\frac{U_{31}U_{12} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) |
| \(Z'\tilde{d}s\) | \(\frac{V_{12}V_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) | \(\frac{V_{12}V_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) |
| \(Z'\tilde{b}d\) | \(\frac{V_{13}V_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) | \(\frac{V_{13}V_{11} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) |
| \(Z'\tilde{b}s\) | \(\frac{V_{13}V_{12} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) | \(\frac{V_{13}V_{12} \cos^2 \theta_W}{\sqrt{3} - 12 \sin^2 \theta_W}\) |

Table 1: The flavor-changing vector and axial-vector couplings to quarks (\(u\)- and \(d\)-type ) induced by \(Z'\) in the 3-3-1 model.
3 Results and Conclusions

The asymmetry for top quark pair production is defined as

\[ A_{FB} = \frac{N_t(\cos \theta \geq 0) - N_{\bar{t}}(\cos \theta \geq 0)}{N_t(\cos \theta \geq 0) + N_{\bar{t}}(\cos \theta \geq 0)}, \]

where \( \theta \) is the top quark momentum direction with respect to the beam axis in the \( t\bar{t} \) rest frame.

We use the CompHep package \[15\] with CTEQ6 parton distribution functions, by fixing the top quark mass as 175 GeV, and we adopt for \( M_{Z'} \) the values from 300 to 1000 GeV; the corresponding \( Z' \) widths are shown in the Table II. In order to calculate the total cross section and to present the invariant mass and transverse momentum distributions, we have to fix some model parameters and to introduce kinematical cuts \( (p_T > 20 \text{ GeV} \text{ and } |\eta| < 2 \) for top and antitop) corresponding to the Tevatron conditions, where the proton antiproton collide at \( \sqrt{s} = 1.96 \text{ TeV} \).

As discussed before, the up-type quark mixing leads to flavor-changing \( Z' \) coupling in both \( s \) and \( t \) channels. The elements of the mixing matrix are not fixed by experiments, and the values \( U_{11} = 0.933 \) and \( U_{13} = 0.766 \) have been used in the evaluation of the bilepton pair production cross section from the 3-3-1 model \[16\] in order to respect the unitarity constraint. We have verified that it is possible to vary \( U_{11} \) in the range 0.698 – 0.841, keeping the correct elementary cross section behavior of the cited process, and that the result is not sensitive for \( U_{13} \) variation. We present our results for two additional values for \( U_{11} \) (0.841 and 0.698).

Figures 1 and 2 present the invariant mass and transverse momentum distributions, for \( M_{Z'} = 800 \text{ GeV} \) and 1000 GeV, respectively, which are similar to the SM ones, whereas for \( M_{Z'} = 500 \text{ GeV} \) the invariant mass distribution presents some enhancement for \( M_{tt} \) larger than 450 GeV.

We display, in Figure 3, the total cross section as a function of \( M_{Z'} \) for three values of \( U_{11} \). We observe that for \( U_{11} = 0.933 \) it is possible to reproduce the experimental total cross section result within 1\( \sigma \) deviation, for \( M_{Z'} \) from 350 to 420 GeV and from 525 to 650 GeV. Moreover, the tiny dependence of the total cross section with the matrix mixing parameters is quite clear.

Next, we study the angular distribution in order to obtain the forward-backward asymmetry \( A_{FB} \) for top quark pair production. Our result is shown in Figure 4. We observe that for \( M_{Z'} = \{350, 420\} \text{ GeV} \) and \( U_{11} = 0.841 \)
and 0.933 the asymmetry is close with the central values measured by D0, whereas for $M_{Z'} = \{525, 650\}$ GeV with $U_{11} = 0.814$ and 0.933 it is possible to reproduce the CDF $A_{FB}$ measurement. For the mixing parameter $U_{11} = 0.698$, the asymmetry is small for all studied $Z'$ mass.

The calculated $A_{FB}$, for two small ranges of $M_{Z'}$ combined with the total cross section and invariant mass distribution makes the 3-3-1 model a good candidate to describe the discrepancy between the SM prediction and Fermilab result probably related to new physics.

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Figure 2: Top transverse momentum distribution for the process $p + \bar{p} \rightarrow t + \bar{t} + X$ ($\sqrt{s} = 1.96$ TeV) for the 3-3-1 model considering some $M_{Z'}$ values.
Figure 3: The total cross section for the process $p + \bar{p} \rightarrow t + \bar{t} + X$ ($\sqrt{s} = 1.96 \text{ TeV}$) as a function of $M_{Z'}$ for three values of $U_{11}$ mixing parameters with $U_{13}$ fixed. The horizontal lines correspond to the SM value within $1\sigma$ deviation.
Figure 4: The forward-backward asymmetry $A_{FB}$ for the process $p + \bar{p} \rightarrow t + \bar{t} + X \ (\sqrt{s} = 1.96 \text{ TeV})$ as a function of $M_{Z'}$ for three values of $U_{11}$ mixing parameters with $U_{13}$ fixed. The horizontal lines correspond to the central values measured by the CDF and D0 Collaborations.
Table 2: The widths corresponding to different values for $M_{Z'}$.

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