New Color-Octet Vector Boson?

Bo Xiao\(^1\), You-kai Wang\(^1\), and Shou-hua Zhu\(^1,2\)

\(^1\) Institute of Theoretical Physics & State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
\(^2\) Center for High Energy Physics, Peking University, Beijing 100871, China

(Dated: November 2, 2010)

Both CDF and D0 at Tevatron reported the measurements of forward-backward asymmetry in top pair production, which showed possible deviation from the standard model QCD prediction. In this paper, we show that a new color-octet massive vector boson with mass just above twice that of top quark can simultaneously account for the asymmetry and differential distribution \(d\sigma/dM_{t\bar{t}}\) in top pair production, without conflict with other measurements for example di-jet production. The new particle can be discovered and studied at the more powerful Large Hadron Collider.

PACS numbers: 14.65.Ha, 12.38.Bx

Discovering new particle is one of the most important goals for higher and higher energy colliders, such as Tevatron at Fermilab and Large Hadron Collider (LHC) at CERN. Top quark was discovered in 1995 at Tevatron. Since the important discovery, measuring properties of top quark is one of the most active field in high energy physics. The endeavor is justified because the top quark is the heaviest ever known fermion and is thought to be related to mechanism of electro-weak symmetry breaking and physics beyond the standard model (SM). Most of measured properties such as mass, width, production rate are consistent with SM predictions, however the CDF and D0 Collaboration have observed possible deviation on forward-backward (FB) asymmetry in top pair production. In this paper we will show that the deviation can be due to the new color-octet massive vector boson.

At \(t\bar{t}\) frame the FB asymmetry in top quark pair production \(A_{FB}\) is defined as

\[
A_{FB} = \frac{\sigma(\Delta Y > 0) - \sigma(\Delta Y < 0)}{\sigma(\Delta Y > 0) + \sigma(\Delta Y < 0)} = \frac{\sigma_A}{\sigma},
\]

where \(\Delta Y \equiv Y_t - Y_{\bar{t}}\) is the difference between rapidity of the top and anti-top quark, which is invariant under \(t\bar{t}\) or \(p\bar{p}\) rest frame.

The measurements of CDF and D0 are \(^1\)\(^2\),

\[
A_{FB}^{CDF} = 0.158 \pm 0.072 \pm 0.017, \text{ with } 5.3 \, fb^{-1};
\]

\[
A_{FB}^{D0} = 0.08 \pm 0.04 \pm 0.01, \text{ with } 4.3 \, fb^{-1}.
\]

These discussions can be roughly classified into two categories. One category is by introducing a \(Z'\) or \(W'\) which have flavor changing couplings with fermions. The flavor changing coupling among \(Z'\), top and up quarks can induce a \(t\)-channel diagram \(u\bar{u} \to t\bar{t}\) which contributes to \(A_{FB}\) via the interference with usual QCD tree diagrams. The other category is by introducing a heavy(\(> 1\, TeV\)) axial-gluon. It induces a \(s\)-channel diagram \(q\bar{q} \to t\bar{t}\) which contributes to \(A_{FB}\) via the interference with usual QCD tree diagrams and/or itself. However, for the new physics in the first category, \(d\sigma/dM_{t\bar{t}}\) distribution for top pair production is violated greatly \(^1\), even after including more higher-order effects \(^2\). Other severe constraint comes from the measurement of same-sign top production rate at Tevatron \(^4\)\(^23\). For the second category of new physics, the suitable parameters to account for all existing measurements can hardly be found \(^2\)\(^24\)\(^2\), especially to satisfy the constraint from the high \(M_{t\bar{t}}\) region. The lesson from these investigations \(^12\)\(^21\) is that it is very difficult to account for \(A_{FB}\) without distorting the shape of \(d\sigma/dM_{t\bar{t}}\). Totally new idea is indispensable. How about to introduce \(s\)-channel diagram induced by a low mass color-octet vector boson? In this case, the \(A_{FB}\) can be induced by interference with the corresponding QCD diagrams, at the same time the shape of \(d\sigma/dM_{t\bar{t}}\) for high \(M_{t\bar{t}}\) is minimally affected. In this paper we will show that by introducing a new color-octet massive vector boson (denoted by \(Z_{C}\) hereafter) with the mass \(M_{C}\) just above \(2m_t\), the measured \(A_{FB}\) and \(d\sigma/dM_{t\bar{t}}\) can be accounted for. Furthermore such kind of new particle are compatible with all other measurements.

In Fig. 1 the measurements \(^23\) and predictions in the SM for \(A_{FB}\) and \(d\sigma/dM_{t\bar{t}}\) are depicted. From the figures it is quite natural to expect that extra contributions to both \(A_{FB}\) and \(d\sigma/dM_{t\bar{t}}\) are in the low \(M_{t\bar{t}}\) region. Adopting the central values, the extra asymmetric cross section \(\sigma_A\) of \(\sim 800 \, fb\) is required. At the same time additional \(\sim 700 \, fb\)

---

\(^*\)E-mail: homenature@pku.edu.cn
\(^\dagger\)E-mail: wangyk@pku.edu.cn
\(^\ddagger\)E-mail: shzhu@pku.edu.cn
cross section $\delta \sigma$ is also required in the 350-400 GeV bin, which is hardly accommodated by threshold resummation \[3,11\]. The resummation effects will increase the distribution evenly over the whole $M_{tt}$ region.

For example in supersymmetric models there is physics beyond the SM (BSM) is nothing new. $M$ above or below a specific 'above' and 'below' represent that $A_{FB}$ and $d\sigma/dM_{tt}$ as a function of $M_{tt}$ in the SM and $Z_C+SM$. For the new particle $Z_C$, $M_C = 360$ GeV is chosen. Other allowed $M_C$ induces the similar behavior. Experimental data is also shown. Here 'above' and 'below' represent that $A_{FB}$ is calculated above or below a specific $M_{tt}$ and $m_t = 170.9$ GeV.

Color-octet massive particle conjectured in physics beyond the SM (BSM) is nothing new. For example in supersymmetric models there is gluino, namely the supersymmetric partner of gluon. Gluinos couple with the color particle in the strength of strong interaction which is well described by QCD. Another example is the above-mentioned axial-gluon which is the mediator for the new gauge group. Such axigluon has been proposed to account for the FB asymmetry in top pair production with the mass of axial-gluon at $O(1)$ TeV. However imposing the constraints from differential distribution of top pair invariant mass, dijet production measurement, as well as other low energy measurements, such proposals seem to be disfavored. The failure to account for FB asymmetry in top pair production utilizing axial-gluon lies in the implicit assumption of the couplings with top quark and light quarks, which are at $O(g_s)$ i.e. the strong coupling constant.

In the phenomenological model we introduce a new color-octet axial massive vector boson $Z_C$. The coupling with the top-quark is taken to be $-ig_t \gamma^\mu \gamma^5 T^a$, and coupling with other quarks to be $-ig_q q^\mu \gamma^5 T^a$.

In this model, $\delta \sigma_A$ arises from the left diagram and $\delta \sigma$ the right one in Fig. 2. The analytical expression of $\sum_{\text{Color,Spin}} |M|^2$ for the left diagram can be written as

$$32\pi C_A C_F g_t g_t \frac{(s - M_C^2) s}{(s - M_C^2)^2 + \Gamma_C^2 M_C^2 \cos \theta \beta}, \quad (3)$$

where $C_A = 3$, $C_F = 4/3$, $\beta \equiv \sqrt{1 - 4m_t^2/s}$ and $\Gamma_C$ is the total width of $Z_C$

$$\Gamma_C = \sum_{2m_t < M_C} \frac{g_t^2 C_F}{4\pi} \frac{1}{8} \frac{(s - M_C^2)^2}{\frac{1}{2} \Delta^2 M_C^2} (1 + \cos^2 \theta) \beta^2.$$

$\sum_{\text{Color,Spin}} |M|^2$ for the right diagram can be written as

$$2C_A C_F (g_t g_t)^2 \frac{s^2}{(s - M_C^2)^2 + \Gamma_C^2 M_C^2} (1 + \cos^2 \theta) \beta^2.$$

In the following we will determine the model parameters namely $M_C$ and the two couplings constants $g_t$ and $g_q$, utilizing the $\delta \sigma_A = 800$ fb and $\delta \sigma = 700$ fb. The procedure is divided into two steps.

Step one: Determining the parameters using $\delta \sigma_A$ and $\delta \sigma$. There are three additional free parameters $M_C$, $g_t$, $g_q$. For the convenience of numerical analysis, we first transform the three free

1 In the realistic model, bottom quark is usually grouped with top quark. The assumption here does not change our main results.
parameters into $M_C$, $g_t g_q$ and $g_q / g_t$. All possible $g_q / g_t$, $M_C$ and $g_t g_q$ can be found by scanning the parameter space.

Step two: Limiting the parameters $g_q / g_t$, $M_C$ and $g_t g_q$ by requiring that the extra contribution from $Z_C$ can improve the agreement between theoretical predictions and experimental measurements, namely the distributions of $d\sigma/dM_{t\bar{t}}$ and $A_{FB}$. The possible parameter $g_q / g_t$ is confined to a very narrow region $0.0040 \leq g_q / g_t \leq 0.0044$. At the same time, $M_C$ and $g_t g_q$ are approximately written as

$$g_q g_t \simeq 0.2 \frac{M_C - 290[GeV]}{m_t}; 350\text{ GeV} \leq M_C \leq 380\text{ GeV}.$$ 

In Fig. 1 we show the excellent agreement between theoretical predictions and data after including extra contributions from $Z_C$ with the possible parameter set $M_C = 360$ GeV, $g_q / g_t = 0.0042$ and $g_t g_q = 0.082$. As for $g_q$, extra constraint may arise from the measurements of di-jet production [26]. However it is obviously that the required $g_q$ here is much less than the limit.

We should emphasize that the numerical results here is just for the illustration purpose. The generic features for other allowed $\delta\sigma_A$ and $\delta\sigma$ due to the uncertainties of measurements are the same, namely (1) color octet vector boson with mass just above $2m_t$ can improve the agreement between the predictions and data; (2) the coupling among new vector boson with top is much larger than that of light quarks; (3) the couplings of $Z_C$ should be axial-vector like. The third point can be understood as follow. If taking the more generic coupling of $Z_C$ as $(g_V \gamma^\mu + g_A \gamma^\mu \gamma^5)$ in the beginning, we find that $g_V$ has to be much smaller than $g_A$ in order to account for $\delta\sigma$ and $\delta\sigma_A$ simultaneously.

The underlying reason is very simple. The $|M|^2$ of $\delta\sigma_A$ brought by $g_A$ is proportional to $\beta$ (cf. Eq. 3), while the $|M|^2$ of $\delta\sigma$ brought by $g_V$ doesn’t have this feature. For $M_{t\bar{t}}$ in 350-400 GeV, $\beta$ is small, therefore $g_V$ has to be much smaller than $g_A$ in order not to bring much more $\delta\sigma$ than $\delta\sigma_A$. It is the observed $\delta\sigma$ and $\delta\sigma_A$ that fix the coupling $g_V$ much less than $g_A$.

The key difference between the proposed model and the axial-gluon model introduced in Ref. 12 is that, for the latter the mass of axial-gluon is quite heavy ($O(1)$ TeV) so the the axial couplings with top and other quarks have the *opposite* sign in order to induce the positive $A_{FB}$ from interference, while in this model, the $M_C$ is assumed just above $2m_t$ and the axial-vector couplings with top-quark and the other quarks have the *same* sign.

Tevatron has shown sign of the new color-octet vector boson, and it is quite natural to explore how to discover and study such kind of new particle at the more powerful LHC. In Fig. 3 we show the differential cross section $d\sigma/dM_{t\bar{t}}$ as a function of $M_{t\bar{t}}$ in $Z_C$ model. It is clear that the top-antitop production cross section is larger than that of in the SM, especially in the low $M_{t\bar{t}}$ region via the sub-process $qq \to t\bar{t}$ at LHC. Due to the Yang theorem, on-shell $Z_C$ does not contribute to top pair production in gluon-gluon fusion, which is the main production mechanism in the SM. The bump of $Z_C$ at $M_{t\bar{t}}$ should appear after collecting enough data samples.

The coupling properties of new particle can be studied via the angular distributions. However the usual forward-backward asymmetry defined at Tevatron is not applicable at LHC. The reason is that LHC is the proton-proton collider, there is no preferred direction which is contrary to the proton anti-proton collider Tevatron. Fortunately, there are some solutions [6, 8, 27, 28]. Based on Ref. 28 we will study the one-side forward-backward asymmetry in the $Z_C$ model. The differential one-side asymmetric cross-section $d\sigma^{A_{OFB}}/dM_{t\bar{t}}$ is shown in Fig. 3 which is important to distinguish $Z_C$ model from other possible contributions. The integrated one-side asymmetric cross sections $\sigma^{A_{OFB}}$ are depicted in Tab. 1. Also shown is the signal significance $Sig$ which is defined as

$$Sig = \frac{\sigma^{A_{OFB}}_{Z_C} - \sigma^{A_{OFB}}_{SM}}{\sqrt{\sigma_{SM}}},$$

where $\mathcal{L}$ is taken to be 10 fb$^{-1}$. In order to beat the huge QCD backgrounds, especially the ones
from gluon-gluon fusion, selection cuts are necessary both for $\sigma$ and for $\sigma^{A_{OFB}}$ [28]. The optimal choice of cuts is $P_{t,\text{cut}} = 600$ GeV for LHC at 7 TeV and $P_{t,\text{cut}} = 1.2$ TeV for LHC at 14 TeV [28]. From the figure and table, LHC can discover and measure the coupling nature of such kind of $Z_C$ with quite low integrated luminosity.

To summarize, both CDF and D0 at Tevatron reported the measurements of forward-backward asymmetry in top pair production. Theoretically such asymmetry is due to the higher-order QCD processes in the SM. The measurements showed possible deviation from the theoretical prediction. In this paper a phenomenological model which contains the new color-octet massive vector boson $Z_C$ is proposed. When the mass of $Z_C$ is just above twice that of top quark and the couplings are appropriately chosen, the asymmetry and distribution of $M_\ell$ in top pair production can be explained simultaneously, without conflict with other measurements for example di-jet production.

We would like to emphasize the implications of our study for model-building. The requirements for the new massive color-octet vector boson $Z_C$ are (1) $M_C$ is just above $2m_t$; (2) the nature of couplings among $Z_C$ and quarks is axial-vector-like; (3) the axial coupling of $Z_C$ with top quark is much larger than that with light quarks, but are of the same sign, which is contrary to the conventional axial-gluon models. These features indicate that $Z_C$ can be intimately correlated with conjectured top quark pair condensate, and even the mechanism of electro-weak symmetry breaking. We are not aware of any models in literature which have such features. Hopefully the Tevatron asymmetry measurements are the sign for the new particle and true underlying mechanism will be uncovered at the LHC.

Acknowledgements: This work was supported in part by the Natural Sciences Foundation of China (Nos. 10775001, 10635030 and 11075003).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\text{process} & \text{SM} & \text{A}\_{OFB} & \text{obs} \\
\hline
$M_C = 600, 1650$ fb & $355.0, 360.0, 370.0$ & $26.69, 28.13, 29.85$ \\
\hline
\end{tabular}
\caption{Total one-side asymmetric cross section (fb) in $Z_C$+SM. In the SM, $\sigma_{\text{SM}}(M_C = 600, 1650)$ fb and $\sigma_{\text{A}_{OFB}}(M_C = 600, 1650)$ fb are used for all the $\sigma$ and $\sigma^{A_{OFB}}$ calculations.}
\end{table}