Four Jets as a Probe of O(100 GeV) Physics beyond Standard Model at Hadron Colliders

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Abstract

O(100 GeV) physics beyond the standard model (BSM) could be overlooked provided that it is hidden in the untouched Higgs sector or jets. The top quark forward-backward asymmetry measurements and di-jet bump, which is observed in the associated production with charged lepton plus missing energy (supposed arising from W decay), may indicate the existence of a new color-octet axial-vector $Z_C$ with a mass about 145 GeV. Here $Z_C$ decays into two jets with a certain branching ratio. In this paper we investigated the possibility to discover $Z_C$ pair via analyzing the four jets as the final states, which are heavily polluted by huge QCD background. Our simulation showed that, however, both Tevatron and LHC have the excellent chance to discover $Z_C$ through analyzing the four jets events with accessible integrated luminosity and good control of QCD background.

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I. INTRODUCTION

The Standard Model (SM) of particle physics has been extensively tested at the LEP, Tevatron, and current running LHC with $\sqrt{s} = 7$ TeV. Even though several anomalies between theoretical prediction and experimental measurement persisted, such as the forward-backward asymmetry of $b$-quark pair production at LEP [1, 2], the forward-backward asymmetry of top-quark pair production at Tevatron [3–7], and the di-jet anomalous bump debated between CDF and D0 of Tevatron [8, 9], most of measurements are still consistent with the SM predictions and no obvious deviations have been discovered yet.

Why is the SM so successful? As usually conjectured, provided that the physics beyond the SM (BSM) does exist, BSM must be at O(TeV) scale or even higher. Discovering such kind of BSM is one of the main goals of high energy LHC. Another possible answer to the question is that the scale of BSM is not so high but hidden in the untouched sector of the SM, the Higgs sector, or the not-so-well measured objects, namely jets. The first case is due to the small signal rate and the latter one is due to the huge QCD background, especially when the BSM scale is at O(100 GeV). In this paper, we will pursue the second possibility and concentrate on the BSM with one new color-octet vector boson $Z_C$, which decays into two jets with a certain branching ratio. We should emphasize that the study on $Z_C$ is just for the purpose of demonstration. The multi-jet events can be acted as the probe, in the much broader sense, to investigate the BSM at O(100 GeV) at the Tevatron and the LHC.

The new color-octet vector boson $Z_C$ was initially proposed [10, 11] to account for the forward-backward asymmetry of top-quark pair production at Tevatron. The forward-backward asymmetry obtains the required contribution from the interference among the s-channel $Z_C$-mediating diagram and the usual QCD ones. At the same time, if the $Z_C$ couples with the quarks axial-like, the theoretical predictions are still consistent with the experimental measurements of the differential and total cross section of top pair production. Later, $Z_C$ was utilized to explain the anomalous di-jet bump discovered by CDF [12]. The di-jet is associated production with $W$. It should be noted that such di-jet bump is not confirmed by D0 [13]. However it is quite interesting to search such di-jet bump at LHC and at Tevatron with more accumulated data (roughly $10fb^{-1}$) and investigate the different capacities to isolate the different mechanism to produce such di-jet bump. For example at LHC the main contributions may come from gluon-gluon contributions while at Tevatron
the quark contributions are larger. In a sense Tevatron can be a better collider to observe the multi-jet signal arising from quark annihilation. This is one of the reasons why we still keep on focusing on the detail searching strategies of multi-jet events at Tevatron.

The new color-octet particle can be potentially discovered via di-jet measurement. However due to huge QCD background, the di-jet is not always an excellent final states to probe new particle. For example at Tevatron the constraint for particle with mass less than 200 GeV is weak [14]. However the earlier and less energetic experiments at UA2 can provide the strictest constraints [15–19], as also shown in Refs. [12, 20]. Based on above observations, pair production of new color-octet particle with mass less than 200 GeV can be a useful mode. Provided that a new particle decays into di-jet, the pair production will induce four jets. With more jets one can utilize new handles, which depend on the characteristics of physics to be investigated, to suppress corresponding QCD background. To investigate how to suppress the huge QCD background is one of the main topics in this paper. In Ref. [21], the authors have investigated the possibility of observing four jets from massive color-octet scalar boson pair at the Tevatron/LHC [22]. Experimentally, at Tevatron there were several analysis of six jets events in order to find low mass squarks and gluinos [23–25]. Recently ATLAS [26] released measurements for low mass pair-produced color-octet scalar particles, which subsequently decaying into the four-jet final state. Due to the low integrated luminosity, the constraints from ATLAS are still weak. Based on the measurements from Ref. [26], we will set limit for our model parameters after considering the different acceptances for pair production of scalar and vector particles.

The paper is organized as following. In section II, we describe briefly the coupling among $Z_C$ and quarks as well as gluon. The phenomenology of $Z_C$ is also investigated in this section. In Section III, we simulate the signal and background of the four-jet events at Tevatron and LHC with $\sqrt{s} = 7$ TeV and 14 TeV respectively and study the useful cuts to suppress the QCD background. Section IV contains our conclusions and discussions.
II. $Z_C$ AND ITS PHENOMENOLOGY

A. Interactions of $Z_C$

The new color-octet vector can easily appear if one extends the color gauge group $SU(3)_C$ to the larger group, for example $SU(3)_1 \otimes SU(3)_2$ with the gauge couplings $h_1$ and $h_2$ respectively. Introducing scalar field $\Phi(3,\bar{3})$ under $SU(3)_1 \otimes SU(3)_2$ with vacuum expectation $M \times I_{3 \times 3}$, we could break down $SU(3)_1 \otimes SU(3)_2$ to the usual $SU(3)_C$.

The interactions of $Z_C$ and gluons can be written as

$$\frac{1}{2} g_s^2 f^{abc} f^{ade} Z_C^{\mu \nu} \left( G_\nu^d (Z_C^{c \mu} G_\mu^a + Z_C^{a \mu} G_\mu^c) + Z_C^{e \mu} G_\mu^c G_\nu^d \right)$$

$$+ g_s f^{abc} Z_C^{a \mu} \left( (\partial^\mu Z_C^{b \nu} - \partial^\nu Z_C^{b \mu}) G_\nu^e - Z_C^{b \mu} \partial^\nu G_\nu^e \right)$$

(1)

Here $g_s$ is the usual strong coupling constant, $f^{abc}$ are the $SU(3)$ structure constants, $G_\mu$ is the gluon field. The color-octet new particles have been searched by experiment. Recently ATLAS \[26\] has measured the four-jet cross section. From their measurement the limit of the cross section times the branching ratio to four-jet final states for color-octet scalar \[27, 28\] is roughly 1nb when the mass is 145\,GeV. In order to deduce the limit of the vector $Z_C$, we simulate the scalar and vector at the same time and apply the same cuts as those of ATLAS experiment \[26\]. Furthermore, in order to compare the difference between scalar-octet and vector-octet, we illustrate the $\cos \theta^*$ distribution in Fig.\[1\]. Theoretically $\theta^*$ is the open angle between $Z_C$ and beam in the center-of-mass frame of final states. We find that in the signal region ($|\cos(\theta^*)| < 0.5$) the vector-octet’s contribution is almost the same as scalar-octet, and in the background region ($|\cos(\theta^*)| > 0.7$), although the vector-octet’ contribution is larger, they are in the same order. Based on this, the limit cross section times the branching ratio to four-jet final states for the vector-octet is safely to be the same as the scalar-octet’, which is 1nb at 145 \,GeV. Then we set the branching ratio to four-jet final states to be $Br^2 = 0.06$, which $Br$ denotes $Br(Z_C \to jj)$. The branching ratio of $Z_C$ into two-jet final states naturally arise from many complete model construction to guarantee the gauge anomaly cancelation by introducing exotic states. The nature of these exotic particles is model dependent. In other words, the branching ratio of $Z_C$ into two-jet final states is a free parameter.
FIG. 1: Distributions of scalar-octet and vector-octet as the function of \( \cos \theta^* \) with the same cross section after applying \( p_T, \Delta R, \) and mass difference cuts. The detailed description can be found in Ref. [26].

The effective Lagrangian of \( Z_C \) and quarks can be written as

\[
\Delta \mathcal{L}_q = \beta g_s Z^{\mu a}_C J^5_{\mu}^a ,
\]

where \( J^5_{\mu}^a \) is the axial vector color current

\[
J^5_{\mu} = \sum_f \bar{q}_f \gamma_\mu \gamma_5 \frac{\lambda^a}{2} q_f
\]

with \( \lambda^a \) the Gell-Mann color matrices. Such axial-vector current can account for the top quark forward-backward asymmetry and the di-jet anomalous bump simultaneously [10–12], although by introducing the branching ratio of \( Z_C \) into two jets, the di-jet bump’s significance will decrease. To evade the limit from the di-jet measurements by UA2, similar to the case in Ref. [12], \( \beta \) will be less than 0.3, which could be obtained according to the model construction in [21]. In our following numerical evaluation, we set \( \beta \) to be 0.2.
As the color-octet particle, $Z_C$ can decay only into quarks, i.e. jets, if kinematically allowed. The main production mechanism at hadron colliders is the single $Z_C$ production via $q\bar{q} \rightarrow Z_C$. However, as emphasized in Introduction, for $m_{Z_C} < 200$ GeV, the QCD backgrounds at Tevatron and LHC are overwhelming.

$Z_C$ can be associated production with $\gamma, W$ and $Z$. In fact the $WZ_C$ production mode is assumed to be the origin of di-jet anomalous bump observed by CDF. In Ref. [12], we have investigated this channel. Our study showed that $WZ_C$ mode can act as the discovery channel with low integrated luminosity. $Z_C$ can be associated production with light quarks and gluons and the final states will be three jets. One can expect such signal is very likely buried by huge QCD backgrounds, similar to the case of di-jet. In this paper we will focus on the $Z_C$ pair production and the final states are four jets. Though the QCD background is still very large, we can find ways to suppress them greatly, as shown below.

![Graph](image.png)

**FIG. 2:** The cross sections of $Z_C$ pair production as a function of $m_{Z_C}$ induced by $q\bar{q}$ and gluon-gluon sub-processes at Tevatron with the parameter introduced in Eq. 2

The signal cross sections of $q\bar{q}(gg) \rightarrow Z_CZ_C$ as a function of $m_{Z_C}$ are depicted in Fig. 2.
FIG. 3: Same with Fig. 2 except at LHC with $\sqrt{s} = 7$ and 14 TeV respectively.

at Tevatron and Fig. 3 at LHC. From the curves it is obvious that the $Z_C$ pair production is mainly from $q\bar{q}$ sub-processes at Tevatron while from gluon-gluon fusion at LHC. Thus Tevatron and LHC play the different role to identify the different production mechanisms. The signal cross sections at Tevatron and LHC are both large. Provided that the QCD backgrounds can be controlled, the signal will be easily identified. This will be the topic of next section.

III. DETAILED SIMULATION

In order to suppress the huge QCD background, we will study the different behaviors of signal and background and find the optimized cuts to isolate the signal. In the simulation, $m_{Z_C}$ is set to be 145 GeV. We use MadGraph \cite{29, 30} to generate four jets events arising from signal and QCD background. The resulting events are put into Pythia and PGS packages to do fragmentation, hadronization and detector simulation.
A. ZC at Tevatron

The basic cut are chosen as

\[ p_{T,j} \geq 50 GeV; \quad \eta_j \leq 2.8; \quad \Delta R_{jj} \geq 0.4 \]  

(4)

After carefully analyzing the event samples of the signal and QCD background, we apply the optimal selection cuts as following.

- The four jets arising from QCD processes tend to be softer than that of signal, thus we choose the first cuts as:

\[ p_{T,j} \geq 60 GeV; \quad \eta_j \leq 1.8; \quad N_j = 4. \]  

(5)

- After rearranging the four jets by the descending order of transverse momentum, we apply the second cuts:

\[ p_{T,j_1} \geq 100 GeV; \quad p_{T,j_2} \geq 80 GeV \]  

(6)

- We pair the four jets into two groups by the criteria that minimizes the quantity \(|m_{j_1j_2} - m_{j_3j_4}|\) and relabel the jets that \(j_1\) and \(j_2\) make up the first pair, and \(j_3\) and \(j_4\) make up the second pair.

- Similar to the analysis conducted by ATLAS Collaboration [26], we draw the \(\Delta R_{jj}\) of paired jets distribution in Fig. 4.

  From the figure, we can see that the paired jets’ \(\Delta R_{jj}\) distributions of the signal and background are totally different. Thus we choose the third cuts as:

\[ \Delta R_{jj} \leq 1.6 \]  

(7)

- In order to show clearly how the proper \(\Delta R_{jj}\) cut can greatly suppress the QCD background at the Tevatron, we show the di-jet invariant mass distribution of the signal and background before and after the third cuts in Figs. 5 and 6.

- In order to isolate signal from backgrounds further, we apply the fourth cut, namely taking a mass window at the peak:

\[ \Delta m_{jj} < 30 GeV \]  

(8)
FIG. 4: $\Delta R_{jj}$ distributions of signal and backgrounds at Tevatron. The luminosity is $10 fb^{-1}$.

FIG. 5: Di-jet invariant mass distribution of signal and background at Tevatron before $\Delta R_{jj}$ cut. The luminosity is $10 fb^{-1}$.
The luminosity is $10^{fb}$.

The signal and background event numbers vary after applying cuts conditions of Eqs. (4, 5, 6, 7, 8), which are shown in Table I. In the real experiment, there are uncertainties for backgrounds estimation because of the experiments’ equipments and other analysis processes. For jets, the uncertainties are very large. In order to properly include such effects, we adopt the following formula to estimate significance of signal over background

$$S \sqrt{B + \gamma B}.$$  \hspace{1cm} (9)

Here the coefficient $\gamma$ is an empirical parameter which is conservatively set to 0.3.

From the table, we can see that the proper selection cuts can effectively reduce the QCD background from $3.6 \times 10^6$ to about $5.5 \times 10^3$, while the signal from $4.5 \times 10^4$ to about $9 \times 10^3$. With already accumulated $10 \ fb^{-1}$ data, Tevatron has an excellent chance to discover such kind of new particle in the four jets events.

B. \textit{Z} at LHC

Similarly we simulate the signal and background at the LHC with $\sqrt{s} = 7$ and 14 TeV respectively. We find that the selection cuts for Tevatron are also suitable for LHC, so we use the same cuts in the analysis of LHC cases. In Figs. 7 and 8 the $\Delta R_{jj}$ distributions of
TABLE I: Event numbers for signal, QCD background, S/B and $\frac{S}{\sqrt{B}+\gamma B}$ after applying cuts of Eqs. (4, 5, 6, 7, 8) respectively at Tevatron. The integrated luminosity is $10 fb^{-1}$.

| Selection cuts | Signal | $\sigma_{signal}$ | QCD background | $\sigma_{QCD}$ | $\frac{S}{B}$ | $\frac{S}{\sqrt{B}+\gamma B}$ |
|----------------|--------|-------------------|----------------|---------------|---------------|----------------|
| Basic cuts     | 45300  | 4.53pb            | 3670000        | 367pb         | 0.01          | 0.04            |
| 1st cuts       | 20964  | 2.10pb            | 463007         | 46.3pb        | 0.04          | 0.15            |
| 2nd cuts       | 18681  | 1.87pb            | 330080         | 33pb          | 0.06          | 0.19            |
| 3rd cuts       | 11592  | 1.16pb            | 52187          | 5.22pb        | 0.22          | 0.74            |
| 4th cuts       | 8950   | 0.90pb            | 5517           | 0.55pb        | 1.62          | 5.40            |

The signal and background with $\sqrt{s} = 7$ and 14 TeV respectively are depicted. From figures, we can see the QCD background is much greater than that of signal. Though the signal is much larger than that at Tevatron, as also shown in Fig. 3 the QCD background at LHC becomes even larger.

FIG. 7: The $\Delta R_{jj}$ distribution of the signal and background at the LHC with $\sqrt{s} = 7$ TeV. The luminosity is $10 fb^{-1}$.
FIG. 8: The $\Delta R_{jj}$ distribution of the signal and background at the LHC with $\sqrt{s} = 14$ TeV. The luminosity is $1 fb^{-1}$.

In order to show how the third cuts can suppress the QCD background at the LHC, we show the di-jet invariant mass distributions for signal and background before and after the third cuts in Fig. 9 and Fig. 10 for $\sqrt{s} = 7$ TeV with $10 fb^{-1}$ luminosity, as well as Fig. 11 and Fig. 12 for $\sqrt{s} = 14$ TeV with $1 fb^{-1}$ luminosity.

After applying all the optimized cuts, we list the final results in Table II at the LHC with $\sqrt{s} = 7$ and 14 TeV respectively. From the table, we can see that LHC-14 with $1 fb^{-1}$ data can discover the new color-octet particle with large significance. Compared with Tevatron, due to the larger QCD background, the capacity to discover the new particle at LHC is not better. Such results are not strange if one compares the capacity to measure di-jet events of CDF/D0 and UA2.

IV. CONCLUSION AND DISCUSSION

To summarize, we demonstrate in this paper that high energy hadron colliders, namely Tevatron and current running LHC, can be utilized to investigate the O(100 GeV) physics beyond the standard model via the four jets events. We simulated the signal and the cor-
FIG. 9: Di-jet invariant mass distribution of signal and background at LHC with $\sqrt{s} = 7$ TeV before $\Delta R_{jj}$ cut. The luminosity is $10 fb^{-1}$.

FIG. 10: Di-jet invariant mass distribution of signal and background at LHC with $\sqrt{s} = 7$ TeV after $\Delta R_{jj}$ cut. The luminosity is $10 fb^{-1}$.
FIG. 11: Di-jet invariant mass distribution of signal and background at LHC with $\sqrt{s} = 14$ TeV before $\Delta R_{jj}$ cut. The luminosity is $1 fb^{-1}$.

FIG. 12: Di-jet invariant mass distribution of signal and background at LHC with $\sqrt{s} = 14$ TeV after $\Delta R_{jj}$ cut. The luminosity is $1 fb^{-1}$.
TABLE II: Signal, background, S/B and $\sqrt{S\bigoplus\gamma B}$ at the LHC after applying all optimized cuts of Eqs. (4,5,6,7,8).

| $LHC$   | Signal  | $\sigma_{Signal}$ | QCD background  | $\sigma_{QCD}$ | $\frac{S}{\sqrt{B\bigoplus\gamma B}}$ | $\frac{S}{\gamma B}$ |
|---------|---------|-------------------|-----------------|----------------|--------------------------------------|---------------------|
| 7TeV(10$fb^{-1}$) | 347710 | 34.77 pb | 620690 | 62.07 pb | 0.56 | 1.87 |
| 14TeV(1$fb^{-1}$) | 300000 | 300 pb | 265518 | 265.5 pb | 1.13 | 3.77 |

responding background for the previously proposed new color-octet axial-vector $Z_C$ with a mass of 145 GeV, as indicated by CDF di-jet bump. At the same time $Z_C$ can also accommodate the top quark forward-backward asymmetry measurements by Tevatron, which showed certain deviation from the SM prediction. Our results showed that both Tevatron and LHC have the excellent chance to discover $Z_C$ through analyzing the four jets events with accessible integrated luminosity and good control of QCD background. Moreover we pointed out that Tevatron and LHC can play a role to identify the different production mechanisms, namely at LHC $Z_C$ pair production comes from gluon-gluon contributions while at Tevatron the quark contributions are larger. In a sense Tevatron can be a better collider to observe the multi-jet signal arising from quark annihilation. On the other hand, with the higher energy and the integrated luminosity, LHC has the power to give the better result.

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