Dijet Signature of Low Mass Strings in the Early LHC Data

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Abstract

We have examined the dijet production at the LHC as a hint to discovery of string Regge excitations of Standard Model particles. If the fundamental string mass scale is in the TeV range, the influence of string effects on the $pp$ interaction can arise as new resonances in the dijet invariant mass distribution. Near the first resonant pole we investigate the impact of the subprocesses with quark-gluon and four-gluon separately. We show that the LHC is able to probe the string mass scale $\sim$5 TeV with only 2 pb$^{-1}$ of integrated luminosity at $E_{CM} = 14$ TeV.

1 Introduction

Daily operation of the LHC brings us closer to the discovery of new physics. Many new physics scenarios – supersymmetry, large or warped extra dimensions, technicolor, little Higgs models, etc.– offered a solution of existing unsolved problems of the Standard Model(SM) around the TeV mass scale. The space-time with more than four dimensions[1] can explain the weakness of gravity and resolve the hierarchy problem[2], which is one of the main motivations for physics beyond the SM. The goal is achieved by adding $N_{ED}$ flat large extra dimensions of space, which are transparent only for gravitons. The Planck mass $M_P$ and fundamental gravitational scale $M$ in this case are related as

$$M_P^2 = 8\pi M^{2+N_{ED}} R^{N_{ED}}, \quad (1)$$

where all $N_{ED}$ flat extra dimensions are compactified to a radius $R$. If one puts $M \sim \mathcal{O}(1$ TeV) to avoid the hierarchy problem, $R$ becomes very large for $N_{ED} = 1$ ($R \sim 10^8$ km) and varies from $\sim$0.1 mm to a few fm when $N_{ED}$ ranges from 2

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to 7. This speculation leads to the distortion of the usual inverse square law of gravity at $r < R$. Within this scenario it was shown that the tower of graviton states with nonzero momentum (Kaluza-Klein (KK) excitations) couples to SM particles\[3, 4, 5, 6\]. The summation over the whole tower of KK states makes graviton interactions with SM particles stronger. This leads to the observable effects in SM processes.

Global fits to electroweak observables provide lower bounds on $1/R$ in the 2-5 TeV range\[7\]. Experimentally allowed values for the compactified radius of extra dimensions must be smaller than 44 $\mu$m\[8\], which implies that the fundamental gravitational scale is larger than 3.2 TeV.

Since the mid-1980s the string theory (see, e.g. \[9, 10\] and references therein) has been regarded as an elegant theory of Nature which is able to unify gravity and all other fundamental interactions\[1\]. In the string theory everything is made up of vibrating strings and D-branes are dynamical hypersurfaces that play an essential role in building models of particle interactions. The string tension $\alpha'$ satisfies the linearly rising Regge trajectory

$$j(s) = j_0 + \alpha's,$$

(2)

for recurrences with the angular momentum $j$ and the square of the center-of-mass (CM) energy $s$. The string theory is naturally based on the extra dimensions of space.

The scenario with large enough transverse extra dimensions\[2\] (see, e.g. \[12\]) implies that the fundamental string mass scale

$$M_S^2 = \alpha'^{-1},$$

(3)

is also of the order of few TeVs\[3\].

If the string mass scale is close to 1 TeV, the tower of string excitation states of the graviton and SM particles will open at the energies accessible to the LHC. To date, there is no experimental evidence that the string theory itself has relation to the correct description of Nature. The detection of these states would open the door to the testability of the string theory.

Direct searches for decays of string resonances into quark-quark, quark-gluon and gluon-gluon pairs at the CMS\[14\] at the integrated luminosity of 2.9 pb$^{-1}$ have ruled out the masses $M_S < 2.5$ TeV at the 95% confidence level.

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1 Some string theory criticism can be found in[11] and references therein.
2 (transverse to the branes, the string has Dirichlet boundary conditions)
3 It was shown that low scale nonsupersymmetric string models can radiatively provide the generation of electroweak symmetry breaking[13].
The rest of this paper is organized as follows. The next section gives a brief description of string phenomenology in parton-parton interactions. Section 3 gives the description of signal and background events modeling in the generic LHC detector. In Section 4 we present our results on the dijet signature of string Regge excitations. We also make an estimate of the signal-to-background ratio for the early stage of LHC running. We end with the conclusions in Section 5.

2 String point of view on parton scattering processes

In this analysis we explore the dijet production at LHC energies affected by the TeV scale string. The processes we consider are

\[ qq \to qq, \]
\[ q\bar{q} \to q\bar{q}, \]
\[ gg \to q\bar{q}, \]
\[ q\bar{q} \to gg, \]
\[ gg \to qq, \]
\[ gg \to gg. \]

Comprehensive investigation of string parton-parton scattering amplitudes was done in\cite{15,16}. The main concept of the model considered is the extensions of the SM based on open strings ending on D-branes. The interactions occur between gauge bosons as strings attached to stacks of D-branes and chiral matter as strings stretching between intersecting D-branes\cite{10}. All relevant tree level 2→2 scattering amplitudes of the SM particles were computed with the requirement that the string theory is weakly coupled and on the assumption of the low string mass scale. It was shown that the amplitudes of the processes involving four gauge bosons or two bosons and two fermions had the compactification-model-independent, universal character. These amplitudes only depend on the local intersection properties of D-brane stacks and string effects lead to the common Veneziano formfactors

\[ V(\hat{s}, \hat{t}, \hat{u}, M_S) \sim \frac{\Gamma(1 - \hat{s}/M_S^2)\Gamma(1 - \hat{u}/M_S^2)}{\Gamma(1 + \hat{t}/M_S^2)} \] (10)

which correspond to an infinite sum over s-channel poles at the masses of the string Regge excitations. Here \( \hat{s}, \hat{t}, \hat{u} \) are the Mandelstam invariants for the subprocesses. It was pointed out\cite{15} that at the partonic CM energies \( \sqrt{\hat{s}} \ll M_s \)
the formfactors \( V(s, t, u, M_S) \sim 1 - \frac{\pi^2}{6} s\hat{u}/M_S^4 \) and the string contributions are suppressed.

At the partonic CM energies above the low string mass scale, \( \sqrt{s} > M_S \), the lowest Regge recurrences of SM particles can be manifested by contributions to the 2\( \rightarrow \)2 SM parton cross sections. But even at the partonic CM energies below the threshold virtual Regge recurrences will impact on the SM parton interaction cross sections.

The exchange of graviton KK excitations in dijet production at \( pp \) interactions occurs at the next order in perturbation theory and hence is significantly suppressed with respect to the string exchange\[17\].

3 Signal and background simulations for low string mass scale in dijet events

In order to study the ability of the LHC to observe string dijet events in \( pp \) collisions at \( E_{CM} = 7 \) and 14 TeV we used the PYTHIA6.4\[18\] event generator. As an SM background, the partonic subprocesses (4)-(9) were enabled. The signal events also involve subprocesses (4)-(9), where the string influence on (6)-(9) was incorporated in PYTHIA over squared amplitudes at the leading order in string perturbation theory\[15, 16\]. Thus, the SM dijet events involving the contributions from string Regge recurrences will be regarded as signal events. Note that the ratio of the cross section of subprocesses (4)-(5) to the cross section of (4)-(9) for the leading-order SM predictions is 0.091(0.061) for \( E_{CM} = 7(14) \) TeV. The initial- and final-state QCD and QED radiation and multiple interactions were enabled. We used the leading-order parton distribution function set from CTEQ6L1\[19\].

The LHC detector performance was simulated by using the publicly available PGS-4\[20\] with the parameter chosen to mimic a generic ATLAS-type detector. Jets were reconstructed down to \( |\eta| \leq 3 \) using the anti-\( k_T \) algorithm\[21\] which we implemented in PGS-4. We chose \( D = 0.7 \) for the jet resolution parameter and required that both leading jets carried a transverse momentum larger than \( p_{T,min}^{1,2} > 100 \) GeV. This puts the lower limit \( \sqrt{s_{min}} = 200 \) GeV.

We use the simplified output from PGS-4, namely, a list of two most energetic jets.

We simulated each signal event set at the rates of \( \sim 2.2 \cdot 10^7 \). 5.2(3.2)\( \cdot 10^7 \) SM background events were simulated for \( E_{CM} = 7(14) \) TeV. The data were normalized to 100 and 20 pb\(^{-1} \) for \( E_{CM} = 7 \) and 14 TeV, respectively.
Figure 1: The dijet invariant mass distributions in $pp$ interactions with quark-gluon (upper panels) and four-gluon (lower panels) subprocesses for different values of $M_S$, $\hat{s} \geq \hat{s}_{\text{min}}$ (see the text). The left (right) panels corresponds to $E_{CM} = 7 (14)$ TeV. The Standard Model prediction is shown in all panels (the black histogram).

4 Results

We first perform a comparison of the dijet invariant mass $M_{jj} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$ distributions of the signal and the SM background. The system was composed of two leading jets in $pp$ collisions at the LHC with subprocesses (4)-(9).

The upper panels in Fig. 1 present the dijet invariant mass distribution predictions for the subprocesses with two quarks and two gluons for different $M_S$ and $E_{CM} = 7$ and 14 TeV. The lower panels show the same for the $gg \to gg$ subprocess only for $M_S = 3$ and 4 TeV at $E_{CM} = 7$ and 14 TeV, respectively. The relation between $\hat{s}$ and $M_S^2$ is not regulated in any way. Comparing the plots in Fig. 1 we
Figure 2: The expected total cross section of $pp$ interactions with quark-gluon(blue) and four-gluon(red) subprocesses as a function of $\alpha^2$(see the text). The left(right) panel corresponds to $E_{CM} = 7(14)$ TeV and $M_S = 3(4)$ TeV.

Figure 3: The influence of the first Regge recurrences on the dijet invariant mass distributions in $pp$ interactions for different $\beta$ (see the text). $E_{CM} = 14$ TeV, $M_S = 4$ TeV.

can see that string Regge recurrences in the $gg \to gg$ subprocess lead to unreasonable high cross sections throughout the $M_{jj}$ interval if we do not restrict $\hat{s}$. Even for the subprocesses with two quarks and two gluons the resonance contributions do not disappear towards to high $M_{jj}$ far from $M_S$.

Further we study the effect of restriction of $\hat{s}$ on the cross sections of string-
induced quark-gluon and four-gluon events. The blue(red) curve in Fig. 2 is the total cross section of \( pp \) interactions for (6)-(8)((9)) channels as a function of \( \alpha^2 \), where \( \hat{s} \geq \alpha^2 M_S^2 \). The lower bounds on \( \hat{s} \) range from \( \hat{s}_{\text{min}} \) to \( M_S^2 \). The left(right) panel in Fig. 2 is for \( E_{CM} = 7(14) \) TeV. There is no \( \alpha^2 \) dependence for the subprocesses with two quarks and two gluons. The cross section of the \( gg \rightarrow gg \) channel vary by more than two orders of magnitude with \( \alpha^2 \).

To avoid confusion we will limit ourselves to the region near the first Regge recurrence threshold \( \hat{s} \approx M_S^2 \). In Fig. 3 we plot the dijet mass distributions for different upper bounds of the variable

\[
\beta = \frac{|(\hat{s} - M_S^2)|}{\hat{s}}. \tag{11}
\]

Figure 3 displays the contributions of subprocesses (4)-(9) to the \( pp \) interaction for \( E_{CM}=14 \) TeV and \( M_S=4 \) TeV. The SM prediction is also shown. The resonances are easily observable above the SM background in the wide range of \( \beta \). As expected, the signal increases with \( \beta \).

Figure 4: The expected dijet invariant mass distributions for \( pp \) interactions involving all subprocesses with the first Regge recurrences for different \( M_S \) and \( \beta = 0.0025 \). The left(right) panel corresponds to \( E_{CM} = 7(14) \) TeV.

In Fig. 4 we show the influence of string contributions from subprocesses (6)-(9) to the dijet invariant mass distribution for the upper bound of \( \beta = 0.0025 \) and different \( M_S \). This choice of \( \beta \) comes from the \( \sim 5\% \) resolution of the dijet
| $E_{CM}$ | 7 TeV | 7 TeV | 14 TeV | 14 TeV | 14 TeV | 14 TeV |
|---------|-------|-------|--------|--------|--------|--------|
| $M_S$   | 3.5 TeV | 3.5 TeV | 4 TeV | 4.5 TeV | 5 TeV |

$S/\sqrt{S+B} = 15.2$ | 4.0 | 83.2 | 50.1 | 31.5 | 20.6 |

Table 1: Signal significances for the first Regge recurrences for the early LHC data of 100(20) pb$^{-1}$ and $E_{CM} = 7(14)$ TeV.

mass for ATLAS near 5 TeV. The left(right) panel in Fig. 4 corresponds to $E_{CM} = 7(14)$ TeV. The corresponding signal significances $S/\sqrt{(S+B)}$, where the signal (S) and background (B) rates estimated in the invariant dijet mass window $[M_S - 2\Gamma, M_S + 2\Gamma]$, are demonstrated in Table 1. The string resonance decay widths into SM particles $\Gamma$ were calculated from the string amplitudes in [22]. We find that the first Regge recurrences at $M_S = 3.5(5)$ TeV might be observed with the early data of 170(2) pb$^{-1}$ at $E_{CM} = 7(14)$ TeV with significance $> 5\sigma$.

In Fig. 5 we plot separate and simultaneous influence of low mass string production of the quark-gluon and four-gluon subprocesses on the dijet invariant mass distributions for $pp$ interactions with all string-influenced subprocesses(green), quark-qluon(red), and four-gluon(blue) subprocesses. $E_{CM} = 14$ TeV, $M_S = 4$ TeV.

The ratios of the signal events corresponding to different values of $\beta$ (see Fig. 3) are

$$0.2 : 0.4 : 1.0 : 2.1 : 4.1.$$
mass distribution in \( pp \) interactions at 14 TeV and \( M_S = 4 \) TeV. The SM predictions are also demonstrated in Fig. 5. It is obvious that the four-gluon signal strongly dominates the quark-gluon signal. The respective signal significances for subprocesses (4)-(8), (9), (4)-(9) are 5.14, 48.8 and 50.1.

5 Conclusions

High energy experimental physics again becomes a wonderful arena to look at the past, present and future of our universe. The ATLAS and CMS detectors now observe particle collisions at the energies never reached before.

The string theory could be the ultimate description of Nature, but it is not experimentally substantiated yet. In this paper, we have examined the dijet production at LHC as a window to the discovery of low mass strings.

We show that if the string scale is low, the model-independent part of string signatures, namely, processes involving four gauge bosons or two bosons and two fermions, could be manifested through resonances in the dijet invariant mass distributions in the early LHC data. The major part of the resonances comes from the subprocesses with four bosons. We find that the LHC is capable of probing the string mass scale \( \geq 3.5(5) \) TeV with only 170(2) pb\(^{-1}\) of integrated luminosity at \( E_{CM} = 7(14) \) TeV.

The low mass string scenario correctly explains\[23\] the anomaly in the dijet invariant mass distributions of dijet events produced in association with a \( W \) boson\[24\].

Another signature of the low string scale and large extra dimensions would be the discovery of mini black holes.

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