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String resonances at the Large Hadron Collider

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The Large Hadron Collider promises to discover new physics beyond the standard model. An exciting possibility is the formation of string resonances at the TeV scale. In this article, we show how string resonances may be detected at the LHC in the $pp \rightarrow \gamma + \text{jet}$ channel. Our study is based on event-shape variables, missing energy and momentum, maximum transverse momentum of photons and dijet invariant mass. These observables provide interesting signatures which enable us to discriminate string events from the standard model background.

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I. INTRODUCTION

Our knowledge of high energy physics is limited to energies approximately less than 1 TeV. A possible candidate for new physics above the TeV scale is supersymmetry (SUSY) [1,2]. SUSY provides a solution for the Higgs mass problem, a candidate for cold dark matter, and unification of low energy gauge couplings by introducing superpartners to standard model (SM) fields (see Ref. [1] and references therein). Alternatives to SUSY are extra-dimensional models, such as large extra dimensions [3], warped braneworlds [4] and universal extra dimensions [5]. In these models, gravity becomes strong at the TeV scale. The most astounding consequences of TeV-scale gravity would be the production of mini black holes (BHs) [6] and real/virtual gravitons [7] in particle colliders and cosmic ray showers.

Both SUSY and extra dimensions are essential ingredients of string theory [8,9]. The string scale is defined as [9]

$$l_s = \sqrt{\alpha'}, \quad (1)$$

where α' is the slope parameter with units of inverse energy squared. The strength of string interactions is controlled by the string coupling g_s . The Planck scale M_{PL} is related to the string scale M_s by

$$M_s = g_s M_{\text{PL}}. \quad (2)$$

Since string effects are expected to appear just before quantum gravity effects set in, the string coupling is generally assumed to be of order one. A small coupling also justifies the use of perturbative analysis [10]. In this scenario, the string scale is close to the Planck scale. In the presence of large extra dimensions gravity becomes strong at the TeV scale; the Planck scale and the string scale are both ~ 1 TeV. In this case, string resonances would be observed at the Large Hadron Collider (LHC) before the onset of nonperturbative quantum gravity effects.

Detection of string events at the LHC [11–13] through corrections to SM amplitudes would be the most direct evidence of this scenario.

The aim of this article is to present a detailed analysis of string resonances at the LHC in the $pp \rightarrow \gamma + \text{jet}$ channel [11]. (For a discussion of different channels see, e.g., Ref. [12].) The main result of our investigation is that string resonances may be distinguishable from the SM background.

II. STRING AMPLITUDE

The relevant process for $pp \rightarrow \gamma + \text{jet}$ events is gluon-gluon scattering: $gg \rightarrow g\gamma$. The string amplitude for this process is [11]

$$|M(gg \rightarrow g\gamma)|^2 = g_s^4 Q^2 C(N) \left\{ \left[\frac{s\mu(s, t, u)}{u} + \frac{s\mu(s, u, t)}{t} \right]^2 + (s \leftrightarrow t) + (s \leftrightarrow u) \right\}, \quad (3)$$

where s , t and u are the Mandelstam variables and

$$\mu(s, t, u) = \Gamma(1-u) \left(\frac{\Gamma(1-s)}{\Gamma(1+t)} - \frac{\Gamma(1-t)}{\Gamma(1+s)} \right). \quad (4)$$

Here $N = 3$ is the number of D branes needed to generate the eight gluons of the SM, $C(N) = \frac{2(N^2-4)}{N(N^2-1)}$ is a constant parameter, and $Q^2 = \frac{1}{6} \kappa^2 \cos^2 \theta_W \sim 2.55 \times 10^{-3}$, where $\kappa^2 = 0.02$ and θ_W are the mixing parameter and the Weinberg angle, respectively. The values of the parameters are chosen as in Ref. [11].

In the limit $s \rightarrow nM_s^2$ the string amplitude possesses poles at $n = s/M_s^2$, where n is an integer. For odd values of n the behavior of the amplitude in this limit can be written analytically as

$$|M(gg \rightarrow g\gamma)|^2 = g_s^4 Q^2 C(N) \frac{4}{(n!)^2} \frac{s^4 + u^4 + t^4}{M_s^4 [s - nM_s^2]} \times \left\{ \frac{\Gamma(t/M_s^2 + n)}{\Gamma(t/M_s^2 + 1)} \right\}^2. \quad (5)$$

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For even values of n the behavior of the amplitude at the poles is obtained from Eq. (5) with the substitution $s \rightarrow t$ and $n \rightarrow m = t/M_s^2$ in the square bracket term. Following Ref. [11], the singularities of the amplitude are smeared with a fixed width $\Gamma = 0.1$ for all $n > 1$ and as

$$|M(gg \rightarrow g\gamma)|^2 \simeq \frac{4g^4 Q^2 C(N)}{M_s^4} \left[\frac{M_s^8}{(s - M_s^2)^2 + (\Gamma^{J=0} M_s)^2} + \frac{t^4 + u^4}{(s - M_s^2)^2 + (\Gamma^{J=2} M_s)^2} \right] \quad (6)$$

for $n = 1$. Equation (6) includes a correction for spin dependent widths: $\Gamma^{J=0} = 0.75\alpha_s M_s$ and $\Gamma^{J=2} = 0.45\alpha_s M_s$ [11], where $\alpha_s = g_s^2/4\pi$ is the strong coupling constant. The presence of the poles indicates the formation of string resonances. The total cross section for the $pp \rightarrow \gamma + \text{jet}$ event is obtained by integrating the parton cross section over the CTEQ6D parton distribution functions of the protons $f(x_i, Q)$ [14]

$$\sigma_{pp \rightarrow \text{string} \rightarrow \gamma + \text{jet}} = \int dx_1 \int dx_2 \int dt f_1(x_1, Q) f_2(x_2, Q) \frac{d\sigma}{dt}, \quad (7)$$

where x_i is the fraction of the total momentum carried by parton i , Q is the four-momentum transfer squared and

$$\frac{d\sigma}{dt} = \frac{|M(gg \rightarrow g\gamma)|^2}{16\pi s^2}. \quad (8)$$

The limits of integration on x_1 and x_2 are (0, 1). The limits on t are fixed by the conditions $s + u + t = 0$ and $|t||u|/s \geq P_{T\min}^2$. The choice of CTEQ6D parton distribution functions allows direct comparison of our results to those of Ref. [11]. The left panel of Fig. 1 shows the differential cross section of the $pp \rightarrow \gamma + \text{jet}$ process with total center-of-mass energy E_{CM}

$$\frac{d\sigma}{ds} = \int dx_2 \int dt \frac{2\sqrt{s}}{x_2 E_{\text{CM}}^2} f_1(x_1, Q) f_2(x_2, Q) \frac{d\sigma}{dt}. \quad (9)$$

The differential cross section is characterized by reso-

nances at $s = nM_s^2$. The middle panel of Fig. 1 shows the total cross section as a function of the minimum transverse momenta of the two outgoing particles of the 2×2 scattering, $P_{T\min}$. The string cross section for $M_s = 1$ TeV (solid red line) and the cross section for $M_s = 2$ TeV (dashed green line) are $\sim 10^3$ and 5×10^4 times less than the SM cross section, respectively. Our sample run of 10^7 events produced ~ 9300 (220) string events for $M_s = 1(2)$ TeV, with an integrated LHC luminosity of 1 fb^{-1} .

Before ending this section we briefly discuss the discovery reach of string resonances at the LHC. The right panel of Fig. 1 shows the signal-to noise ratio for two values of the integrated luminosity and E_{CM} as a function of M_s when $P_{T\min} = 50$ GeV. The instantaneous luminosity is assumed to be the LHC design luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The integrated luminosities of $\sim 1300 \text{ fb}^{-1}$ (solid red line and dotted blue line) and 300 fb^{-1} (dashed green line and finely dotted pink line) will be achieved in 4 years and 1 yr, respectively. However, the LHC is expected to reach the design luminosity only after 2 years of operation in the luminosity range of $10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ [15].

III. ANALYSIS

String resonances at the LHC are simulated with a Fortran Monte Carlo code interfaced with PYTHIA [16]. Event-shape variables are a powerful discriminator of string events from the SM background. Their effectiveness is further increased by an analysis of events with high- P_T photons. String events are characterized by high values of visible energy and missing transverse momentum as the photon and the jet originate directly from the 2×2 interaction. Isolated photons provide a further means to extract string signals. Being directly produced from the string resonance, isolated photons from string interactions are harder than SM photons.

We fix $P_{T\min} = 50$ GeV for both string and SM events which results into a signal-to-background ratio of ~ 73 . This choice is justified as follows. For low values of $P_{T\min}$

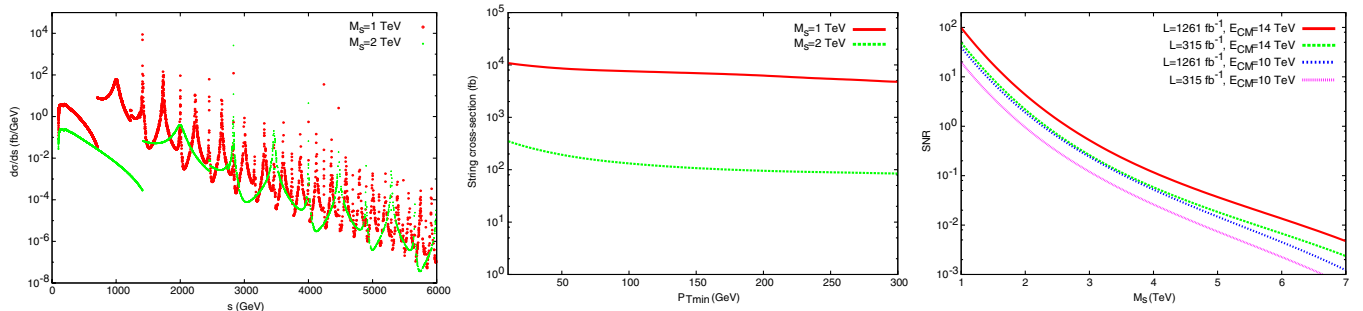


FIG. 1 (color online). Left Panel: Differential cross section of string events for $M_s = 1$ TeV (red dots) and $M_s = 2$ TeV (green crosses) with $P_{T\min} = 50$ GeV. String resonances are clearly seen when $s = nM_s^2$. Middle Panel: String cross section for $M_s = 1$ TeV (red dots) and $M_s = 2$ TeV (green crosses) with $P_{T\min} = 50$ GeV. The cross section for $M_s = 1$ TeV is ~ 44 times larger than the cross section for $M_s = 2$ TeV. Right Panel: Signal-to-noise ratio (SNR) for an integrated luminosity of 1300 fb^{-1} (solid red line and dotted blue line) and 300 fb^{-1} (dashed green line and finely dotted pink line), respectively.

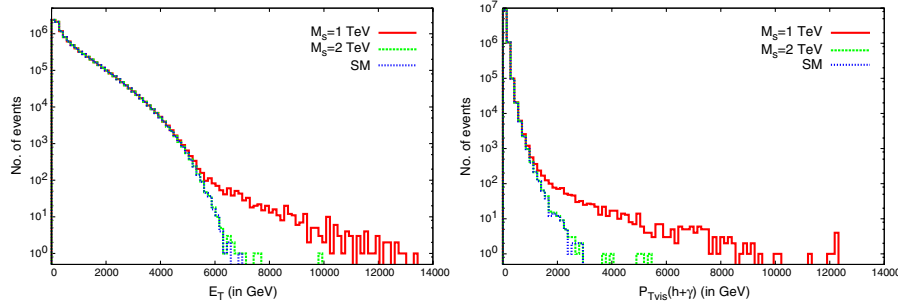


FIG. 2 (color online). Left Panel: Visible energy distribution for string + SM and SM-only events. The result for string resonances is shown by the solid red histogram ($M_s = 1$ TeV) and by the dashed green histogram ($M_s = 2$ TeV). String events can be identified from the high- E_T tail for $M_s = 1$ TeV. Right Panel: Distribution of visible P_T for γ + hadrons. The high- P_T tail is a strong indicator of the presence of string resonances.

the string cross section is highly suppressed *w.r.t.* the SM cross section, for example $\frac{\sigma_{\text{string}}}{\sigma_{\text{SM}}} \sim 10^{-5}$ for $P_{T\text{min}} = 10$ GeV. Therefore, discrimination of string events from the SM background is difficult for events with low $P_{T\text{min}}$. At higher values of $P_{T\text{min}}$ both the SM background and the signal are substantially reduced. For example, at 300 GeV they are reduced by a factor of $\sim 98\%$ and $\sim 42\%$ *w.r.t.* values at $P_{T\text{min}} = 50$ GeV, respectively. Thus the optimal signal-to-background ratio is obtained for $P_{T\text{min}} \lesssim 100$ GeV.

Figure 2 shows the visible energy (left panel) and the transverse momentum of hadrons + photons (right panel) for 10×10^6 string + SM and SM-only events. The visible energy and the transverse momentum are produced by the hard photons and the jets of the string decay. Their distributions are characterized by a long tail at high energy/momentum. The observation of events with visible energy (transverse momentum) greater than 6 (3) TeV would provide strong evidence of the formation of a string resonance.

Figure 3 shows histograms for different event-shape variables. String + SM interactions generally produce a distribution of high P_T jets at slightly higher values than

the SM background, i.e. string events tend to be more spherical than SM events. The jets originate from the decay of string resonances into photons and hadrons. The SM generates less heavier jets than string resonances. This is evident from the middle and right panels of Fig. 3.

In the analysis of dijets, the jets are selected according to the following criteria. The detector is assumed to have an absolute value of pseudorapidity $\eta = -\ln\{\tan(\frac{\theta}{2})\} = 2.6$. This ensures that the jets are originated in the hard 2×2 scattering rather than in multiple interactions or from the beam remnants. The contribution of jets which do not originate in the hard scattering are minimized by fixing the minimum transverse energy of all particles comprising the jet ($\sum_i E_{T_i}$) to 40 GeV [17]. The particles of the jet must be within a cone of $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ from the jet initiator, where θ and ϕ are the azimuthal and polar angles of the particle *w.r.t.* the beam axis, respectively.

The left panel of Fig. 4 shows the invariant mass plot of the two jets with highest P_T in each event. Because of the nature of the interaction, the bulk of the events (both string + SM and SM) are comprised of dijets. These were selected using the above cuts. The jet invariant mass is

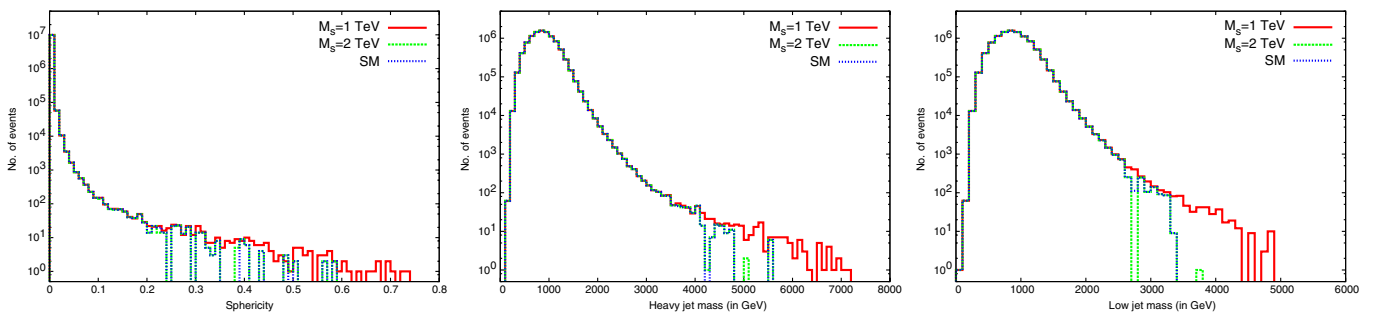


FIG. 3 (color online). Histograms of event-shape variables for 10×10^6 string + SM and SM-only events. String events are shown in solid red ($M_s = 1$ TeV) and dashed green ($M_s = 2$ TeV). SM events are shown in dotted blue. String events have on the average higher sphericity than SM events due to the slight increase in the number of jets (left panel). Similar conclusions are reached from the heavy and low jet mass distributions (middle and right panel, respectively).

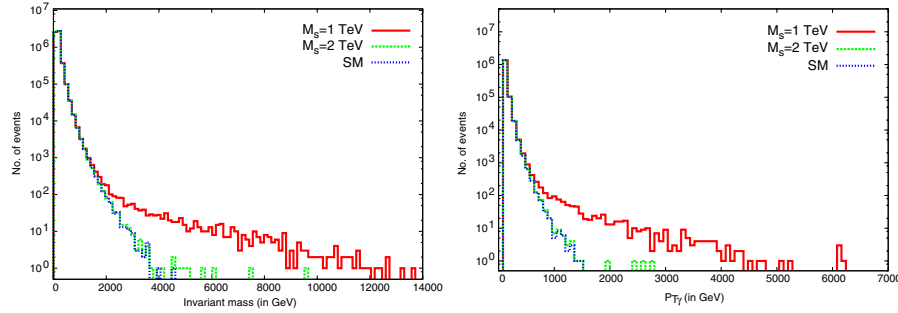


FIG. 4 (color online). Left Panel: Dijet invariant mass distribution. String decays may result in a large invariant mass. Right Panel: Distribution of the highest P_{T_γ} for 1.5×10^6 events. γ 's with high P_T created in the string decay are the source of the long tail.

$$M_{12} = \sqrt{m_1^2 + m_2^2 + 2(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)},$$

where $m_{1(2)}$, $E_{1(2)}$ and $\mathbf{p}_{1(2)}$ are the mass, energy and momenta of jet 1 (2), respectively. As expected, the SM invariant mass distribution is negligible beyond ~ 4 TeV. This is due to the production of direct soft photons and jets from the SM interaction. The string + SM distribution is characterized by a long tail up to energies of several TeV (3 times more than the SM). This tail is originated from the decay of string resonances into hard jets and photons. Therefore, the measure of a large invariant mass could provide strong evidence of a string-mediated interaction.

The right panel of Fig. 4 shows the distribution of the highest P_{T_γ} of isolated photons for string + SM and SM-only events. Following Ref. [17], the cuts on the photon are $P_{T_\gamma} \geq 80$ GeV, $\eta < 2.6$ and an isolation cut $\sum_n P_T < 7$ GeV in a cone of $R = 0.4$. The photons from string resonances are expected to have a higher P_{T_γ} than the SM photons because they are the direct products of the string decay. The main sources of background for direct photons are jet fluctuations and photons originating from the initial and final state radiation [17]. In the former case, a jet consists of a few particles including high- P_T mesons (generally π_0 [17]). The pions decay into a pair of photons with a $\sim 99\%$ branching ratio. Because of the high boost, the photons have a relatively small angular separation and therefore “fake” a single photon in the electromagnetic calorimeter. However, the rate of this process is 1 out of $\sim 10^3$ to 10^4 events [17]. Moreover, simulations show that the maximum P_T of isolated π_0 's is ~ 300 GeV. Therefore, photons from π_0 decay are excluded from the analysis by our choice of kinematical cuts. Other less significant sources of fake photons are $H \rightarrow \gamma\gamma$ [18] or processes from other exotic phenomena, e.g. SUSY [19] or large extra dimensions [3]. Isolation cuts on the photon can effectively reduce the number of these fake photons.

IV. CONCLUSIONS

We have investigated string resonances at the LHC and shown how to differentiate them from the SM background.

Our analysis has proven that string resonances could be detected when $M_s \sim 1$ TeV. With the LHC operating at a luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, a string scale of ~ 1 TeV could be detected within a year of the start of the LHC (assuming a signal-to-background ratio of 5). With the planned LHC luminosity upgrade to $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, a string scale of the order of ~ 2 TeV could be detected within two years of running the LHC. These results are in agreement with the results in Refs. [11,13].

String events show higher sphericity and higher visible energy than the SM background. These quantities allow discrimination of string events from SM background when combined with the measure of the P_T of isolated photons and the dijet invariant mass. Since the final products of the string resonances are directly produced from the string decay, the dijet invariant mass is characterized by a tail at high energies which is absent in the SM.

Other exotic phenomena could also be observed at the LHC near the TeV scale, such as the formation of BHs. A powerful way of discriminating between BH and string events would be searching for a Z_0 mass peak in the invariant mass of high- P_T leptons. Z_0 production is highly suppressed in case of string events [11]. On the contrary BH decay is characterized by the production of a variety of particles with high transverse momentum. A rough counting of the number of degrees of freedom of these particles shows that the estimated rate of hadron-to-lepton production is 5:1 and the rate of Z_0 and γ production is comparable ($\sim 2\%$ to 3%) with the Z_0 bosons decaying into opposite-sign leptons with a 3.4% branching ratio. Thus the invariant mass distribution of BH events peaks at ~ 92 GeV, confirming the production of a Z_0 boson [20]. The presence of a peak at ~ 92 GeV in the invariant mass of leptons would effectively rule out formation of string resonances.

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