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New signature for color octet pseudoscalars at the CERN LHC

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Color octet (pseudo)scalars, if they exist, will be copiously produced at the CERN Large Hadron Collider (LHC). However, their detection can become a very challenging task. In particular, if their decay into a pair of top quarks is kinematically forbidden, the main decay channel would be into two jets, with a very large background. In this brief report we explore the possibility of using anomaly-induced decays of the color octet pseudoscalars into gauge bosons to find them at the LHC.

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I. INTRODUCTION

In spite of its great experimental successes [1], the standard model (SM) of the electroweak interactions is still widely regarded as an incomplete theory. The reasons are manifold, including the existence of nonbaryonic dark matter and nonzero neutrino masses in addition to the theoretical problems of triviality and naturalness related to the scalar Higgs sector responsible for the mechanism of electroweak symmetry breaking.

There are many extensions of the SM that require the existence of color octet scalar particles, such as the extra component of the gluon field in models with extra dimensions [2], supersymmetric models with an adjoint chiral supermultiplet [3], or models with an extended color symmetry [4]. The existence of color octet scalars has also been used to explain the accelerated expansion of the Universe [5]. Extended scalar sectors of the SM with color octet scalars that respect the principle of minimal flavor violation were also recently considered [6,7]. Color octet scalars may also have important effects in the Higgs boson production via gluon fusion [8].

Early studies on the existence of color octet scalars were done in the context of one-family technicolor models [9]. Both electroweak triplets ($P_8^{\pm,0}$) and singlets ($P_8^{0\prime}$, sometimes denoted also as technieta η_{T8}, a notation which we will adopt in this paper) are present in the spectrum of the pseudo-Nambu-Goldstone boson (PNGB) arising from the global $SU(8)_L \times SU(8)_R \to SU(8)_V$ spontaneous symmetry breaking [10]. The masses of the color octet PNGB arise mainly from QCD contributions and are expected to be of the order of 300 GeV [11].

The cross section for pair production of the color octet scalars is dominated by gluon fusion, which in turn is determined by gauge invariance [12] and consequently, except for the gluon parton densities, is mostly model independent, being fixed by the masses of the particles. There could also be a model dependent enhancement due to the coupling of the scalars to color octet vector resonances such as a technirho ρ_{T8} [13], which in turn couples to quarks and gluons. However, as shown by two of the present authors [12], a proper gauge invariant treatment of the ρ_{T8} results in a vanishing ρ_{T8}- g- g coupling [14]. Hence, only the quark initial state can cause this enhancement.

While models of a strongly interacting sector responsible for electroweak symmetry breaking fell in disfavor in the mid-1990's due to tight bounds from electroweak precision measurements, they have experienced a recent resurrection due to the correspondence with weakly interacting models in extra dimensions [15]. In this case, the ρ_{T8} could be interpreted as the Kaluza-Klein excitation of the gluon. Tevatron searches have excluded the existence of a ρ_{T8} in the mass range $260 < M_{\rho_{T8}} < 480$ GeV decaying primarily into two jets [16]. However, this limit should be used with caution since it was obtained from a naive vector meson dominance estimate and model uncertainties can suppress the production cross section [17–19]. Also, in our case the main decay mode of ρ_{T8} is into a pair of color octet pseudoscalars.

Pair production of color octet scalars at the LHC has recently been analyzed [6,7,20,21]. Their detection was discussed using the $b\bar{b}b\bar{b}$, $b\bar{b}t\bar{t}$, and $t\bar{t}t\bar{t}$ channels [20–22] for a scalar mass of the order of a TeV. However, the low mass values suggested by technicolor models, typically below the $t\bar{t}$ threshold, can be more challenging to observe. One may think that the Tevatron limits on the ρ_{T8} from

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dijets can also be applied to the color octet scalars. However, since the single color octet scalar production cross section is much smaller (in the model discussed below it goes through the anomaly only), the limit is not applicable [23].

We find it timely to extend the work done previously in [12], where rarer decay modes of the color octet (pseudo) scalar are used, namely, decays induced by the chiral anomaly into massless gauge bosons (photons and gluons), to investigate the possibility of detecting these new states at the LHC.

In Sec. II we describe the details of our model, in particular, the description of η_{T8} pair production and decay. In Sec. III we present the details and results of our simulations of η_{T8} pairs, produced in $p-p$ collisions at LHC energies and detected as $\gamma+3$ jet events; we include a study of the background and the cuts required for a statistically significant signal. Finally, in Sec. IV we draw our conclusions.

II. MODEL

When introducing massive vector bosons in a theory that contains gauge fields, care must be taken not to spoil the gauge symmetry. In our case, we need to describe QCD with the addition of color octet vector bosons. Following the prescription of Ref. [12], we introduce two massive vector fields, $\tilde{G}^\mu$ and $\tilde{\rho}^\mu$, each transforming as an octet under their respective $SU(3)_G$ and $SU(3)_\rho$ symmetry groups, with a mixing term which is fixed in such a way that the resulting mass matrix has a zero eigenvalue. The corresponding eigenvector is identified with the physical gluon field. The orthogonal combination is identified with the physical color octet vector resonance ρ_{T8}. The physical $SU(3)_{\rm QCD}$ gauge symmetry is the linear combination of the generators of $SU(3)_G$ and $SU(3)_\rho$ corresponding to the massless gluon. The color octet pseudoscalar η_{T8} is introduced as a matter field that transforms purely under gauged $SU(3)_\rho$. In contrast, quarks are introduced in the fundamental representation of the gauged-$SU(3)_G$ symmetry. Hence, in the mass eigenbasis there is a direct coupling of quarks to the physical color octet resonance ρ_{T8}.

At this point the free parameters of the model can be taken as the masses of the color octet vector and scalar particles, $M_{\rho_{T8}}$ and $M_{\eta_{T8}}$, and a coupling constant g_ρ that controls the strong interaction decay of the technirho into technietas, $\rho_{T_8} \to \eta_{T_8}\eta_{T_8}$.

One extra parameter, the PNGB decay constant F_Q, is necessary to describe the possible η_{T8} decays. The amplitude for $\eta_{T8} \to q\bar{q}$ decay is given by

$$\mathcal{M}(\eta^a_{T8} \to q\bar{q}) = \frac{m_q}{F_Q}\bar{q}\gamma_5\frac{\lambda^a}{2}q \tag{1}$$

where λ^a are the Gell-Mann $SU(3)$ matrices. The color octet technieta couples to gauge bosons through the Adler-Bell-Jackiw anomaly with an amplitude given by [24]

$$\mathcal{M}(\eta_{T8} \to B_1B_2) = \frac{S_{\eta_{T8}B_1B_2}}{4\sqrt{2}\pi^2F_Q}\epsilon_{\mu\nu\alpha\beta}\varepsilon_1^\mu\varepsilon_2^\nu k_1^\alpha k_2^\beta \tag{2}$$

where ε_i and k_i denote the polarization vector and momentum of the vector boson i. For the cases in which we are interested, one has

$$S_{\eta^a_{T8}g^bg^c} = g_s^2 d_{abc}N_{\rm TC} \tag{3}$$

and

$$S_{\eta^a_{T8}g^b\gamma} = \frac{g_se}{3}\delta_{ab}N_{\rm TC} \tag{4}$$

where $N_{\rm TC}$ is the number of technicolors, which we take as $N_{\rm TC}=2$ for definiteness.

Hence, our model is completely determined by $M_{\rho_{T8}}$, $M_{\eta_{T8}}$, g_ρ, and F_Q. However, we should stress that our results are very insensitive to $M_{\rho_{T8}}$, g_ρ, and F_Q, since the pure QCD process dominates over the resonance contribution and the decay branching ratios of the η_{T8} are independent of F_Q. In the next section we perform a realistic simulation of the possibility to detect a pair of color octet technietas produced in the process $pp \to \eta_{T8}\eta_{T8} \to \gamma ggg$ at the LHC.

III. SIMULATION

The model was implemented in COMPHEP [25] using LANHEP [26]. We used COMPHEP for generating events for the double technieta production. Subsequently, they were processed by a FORTRAN code we wrote in order to generate the η_{T8} decay products. All the simulations were done for $M_{\eta_{T8}} = 320$ GeV. For definiteness we fixed $M_{\rho_{T8}} = 640$ GeV and $F_Q = 80$ GeV (as mentioned before, our results are insensitive to these values). We restricted ourselves to consider only $M_{\eta_{T8}}$ below the top quark threshold because above that point the technieta width is strongly dependent on the existence of a topcolor interaction.

We considered two sources of standard model background: the production of a photon and three jets and the production of four jets with the possibility that a jet can be misinterpreted as a photon. We assume that the probability that such misidentification occurs is about 10^{-3}. The background was generated using MADGRAPH/MADEVENT with CTEQ5L as a parton distribution function. We considered gluons and all the (anti)quarks of the first two generations in the initial state and as sources of jets. All the possible tree-level partonic subprocesses were taken into account in the calculation of $pp \to \gamma jjj$ and $pp \to jjjj$.

In order to introduce some degree of realism in our calculations, we took into account the smearing of the final momenta. We used the following parametrization for the detector resolution:

$$\frac{\sigma(E)}{E} = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \quad \text{for photons,} \tag{5}$$

$$\frac{\sigma(E)}{E} = \frac{0.80}{\sqrt{E(\mathrm{GeV})}} \quad \text{for jets.} \tag{6}$$

In fact, the resolution at ATLAS is expected to be better than what we have used here, so in that sense our estimate is on the conservative side.

The reconstruction of the technieta was done by studying the photon-jet invariant mass ($M_{\gamma j}$) and the two-jet invariant mass (M_{jj}). We addressed the combinatorics problem by taking the $M_{\gamma j}$ closer to $M_{\eta_{T_8}}$ as a "technieta candidate."

The background was reduced imposing the following set of kinematical cuts:

$$P_{T\gamma} > 80\ \mathrm{GeV}, \tag{7}$$

$$P_{Tj} > 80\ \mathrm{GeV}, \tag{8}$$

$$|M_{\gamma j} - M_{jj}| < 0.15 M_{\eta}, \tag{9}$$

$$|M_{\gamma j} - M_{\eta_{T_8}}| < 20\ \mathrm{GeV}. \tag{10}$$

In Fig. 1, we show the reconstructed technieta mass obtained by summing up the $M_{\gamma j}$ and M_{jj} distributions after the cuts were applied. The dashed line represents the direct background, while the double-dotted-dashed line is the result obtained when a jet is misidentified as a photon. Our signal is shown by the dotted-dashed line.

Assuming an integrated luminosity of $\mathcal{L} = 10\ \mathrm{fb}^{-1}$, we expect to observe about 21 400 events with 4200 of them corresponding to our signal. That would correspond to a deviation from the SM with a statistical significance of 32σ.

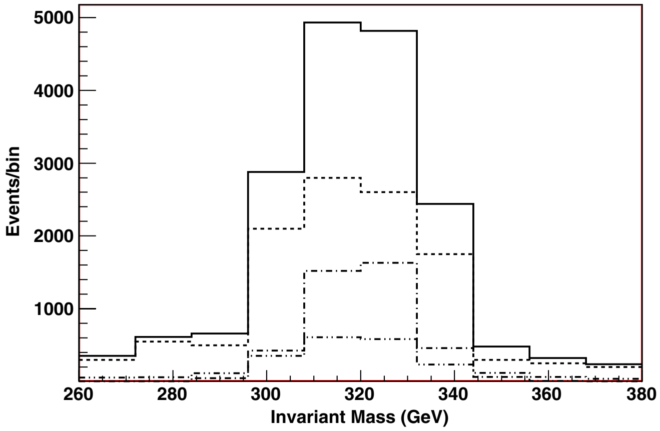

FIG. 1 (color online). Reconstructed technieta invariant mass distribution The dashed line represents the direct background, while the double-dotted-dashed line is the result obtained when a jet is misidentified as a photon. Our signal is shown by the dotted-dashed line.

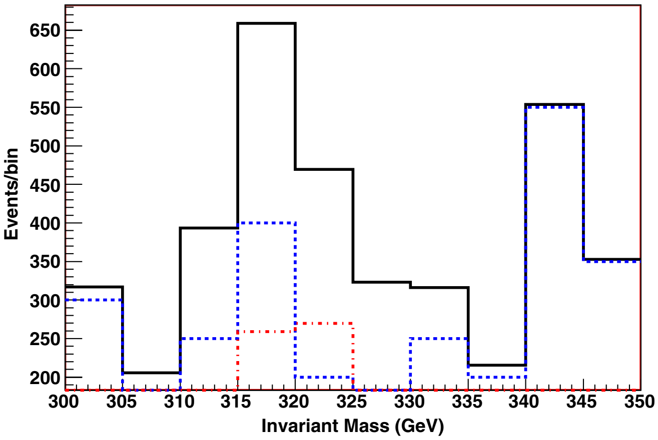

FIG. 2 (color online). Reconstructed technieta invariant mass distribution using a set of cuts independent of the technieta mass. The dashed line represents the direct background (we neglect the small indirect background due to misidentification). Our signal is shown by the dotted-dashed line.

In this analysis, we have used some cuts that depend on the technieta mass. This procedure may be uncomfortable from the experimental point of view since the mass of the searched particle is not known *a priori* and the whole possible range must be scanned. Fortunately, in our case the mass interval is limited because, due to QCD contributions, the technieta cannot be lighter than 300 GeV and we do not expect the channel considered in this work to be useful for discovery if the technieta is heavier than 350 GeV.

However, it is possible to devise a search strategy which is independent of the technieta mass. Consider the following set of cuts:

$$P_{T\gamma} > 80\ \mathrm{GeV}, \tag{11}$$

$$P_{Tj} > 80\ \mathrm{GeV}, \tag{12}$$

$$|M_{\gamma j} - M_{jj}| < 10\ \mathrm{GeV}, \tag{13}$$

$$|\min(\cos\theta_{\gamma j})| < 0.6, \tag{14}$$

where $\theta_{\gamma j}$ is the angle formed by a photon and a jet. The last cut comes from the fact that the technieta is a spin 0 particle and its decay is isotropic in its rest system, while the background tends to have peaks at $\cos\theta_{\gamma j} = \pm 1$.

Figure 2 shows the invariant mass distribution obtained with the new set of cuts. We expect to observe, integrating over the whole mass range, 12 600 background events and 1100 events coming from the technietas with $\mathcal{L} = 10\ \mathrm{fb}^{-1}$, corresponding to a 10σ signal.

IV. CONCLUSIONS

We studied the pair production and detection of color octet pseudoscalar bosons at the LHC, which could be present in models of electroweak symmetry breaking induced by new strong interactions. We restricted our analysis to $m_{\eta_{T8}}$ (the color octet pseudoscalar mass) below $2m_t$, in which case the decay into t- $\bar{t}$ is forbidden and consequently the detection is more challenging. In such cases, the color octet pseudoscalar decays mainly into two gluons, induced by the anomaly, while the direct decay into b-$\bar{b}$ has a fraction less than 20%. We perform simulations for the production and decay of pseudoscalar pairs, including background. We did not look for the dominant 4-jet mode, but for the suppressed 3-jet + photon mode, which has a much lower background. We used two different methods of analysis. In one method we assume $m_{\eta_{T8}}$ to be known in our cuts, and obtain a number of events 32σ above the expected background, for an integrated luminosity of 10 fb^{-1}. In our second method, we did not include any value of $m_{\eta_{T8}}$ in our cuts, but relied only on the invariant mass reconstruction of the two decaying pseudoscalars, in which case the number of events resulted in a statistical significance of 10σ above the expected background. These results show that the LHC has the potential to detect or exclude the existence of such pseudoscalar colored bosons.

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