

Squarkonium, diquarkonium, and octetonium at the LHC and their diphoton decays

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Motivated by the recent diphoton excess by both ATLAS and CMS collaborations at the LHC, we systematically investigate the production and diphoton decay of onia formed by pair of all possible color exotic scalars in minimal extension. When such scalar massive metastable colored and charged (MMCC) particles are produced in pair near threshold, η onium can be formed and decay into diphoton through annihilation as $pp \rightarrow \eta \rightarrow \gamma\gamma$. Squarkonium is formed by metastable squarks in supersymmetric models such as stoponium. Diquarkonium is formed by metastable color sextet diquarks which may be realized in the Pati-Salam model. Octetonium is formed by color octet scalars bosons as in the Manohar-Wise model. Stoponium prediction is much smaller than the required signal to account for the diphoton excess. Due to the enhancement factor from color and electric charge, predictions of diquarkonium and octetonium are of $\mathcal{O}(10 \text{ fb})$ which are significantly greater than the stoponium prediction. Since the color enhancement also results in large production at the colliders, such light color exotic states of $\mathcal{O}(375 \text{ GeV})$ suffer from severe direct search constraints. On the other hand, if their dominant decay mode involve top quark, they may be buried in the $t\bar{t}$ plus jets samples and can potentially be searched via $t + j$ resonance.

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I. INTRODUCTION

Recently both the ATLAS and the CMS collaborations have reported an excess of $\gamma\gamma$ events at the LHC Run-2 with a center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ [1,2]. This excess emerges with a bump in the diphoton invariant mass spectrum around 750 GeV over the predicted continuous falling background. The ATLAS collaboration used 3.2 fb^{-1} of data and the local (global) significance is $3.6(2.0)\sigma$. The CMS collaboration observed a local (global) significance as $2.6(\text{less than } 1.2)\sigma$ with 2.6 fb^{-1} of data. The observed events have quite similar kinematic properties with the background events in this spectrum region. Even though a clearer picture requires more data, it is still worth studying the possible hint from this excess. Considering the current volume of data sample, a rough estimation of the cross-section $\sigma(pp \rightarrow X \rightarrow \gamma\gamma)$ is of a few fb.

Landau-Yang theorem excludes the diphoton resonance from being vector boson and only spin-0 or spin-2 resonance can be viable candidate. KK -graviton predicts similar order of dilepton decay which may suffer from direct constrain [3]. If the excess arises from a spin-0 resonance, candidate can be realized among fundamental scalar, a pion-like π^0 or an η -like resonance. Direct searches

via W^+W^- or ZZ put stringent bound over the heavy Higgs-like scalar [4] and a CP -odd Higgs A is then more plausible. Minimal model with CP -odd Higgs suffers from huge suppression of decay branching fraction because of decrease in $\gamma\gamma$ partial width due to lack of W -loop contribution and enhancement of total width from on-shell $t\bar{t}$ decay. Many papers have been published to discuss the implications of the diphoton resonance [5,6] which cover proposals as CP -odd Higgs with exotic quark, sneutrino with R -parity violation, pseudoscalar from chiral symmetry breaking of new strong dynamics.

A proton-proton collider like LHC is typically a quantum chromodynamics (QCD) machine where new physics in the strong interaction sector will appear in the early stages of operation even with limited luminosity. The recent diphoton anomaly can well be a signal as onia formed by massive metastable colored and charged (MMCC) states. For a MMCC state Q , if the total width $\Gamma_Q < \Lambda_{\text{QCD}}$, the particle Q could form a hadronic bound state long before it decays. Since Q is colored, it can be produced in pair as $Q\bar{Q}$ at the LHC and they will form hadronic states as for instance $Q\bar{q}$ with light quarks from vacuum. In addition, near the threshold, they can form hadronic bound state $\eta(Q\bar{Q})$ as scalar onium. The onium η_Q is produced through gluon fusion and decay into photon pair,

$$pp \rightarrow \eta_Q \rightarrow \gamma\gamma. \quad (1)$$

On the other hand, if Q is fermionic, the hadronic bound states include both scalar and vector states in analogy to η_c

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and J/ψ case [6]. The vector state will not decay into diphoton but decay into di-lepton which suffers from severe constraint of direct searches at LHC. However the η -like state can be produced via gluon fusion $gg \rightarrow \eta$ while the J/ψ -like state can only be produced through $q\bar{q}$ annihilation, therefore the production of the vector state is significantly lower than that of the scalar state at the LHC. Taking this into account, it requires more study on the LHC constraints on vector bound state of $Q\bar{Q}$ for fermionic Q . In the following we discuss only scalar MMCC cases.

We investigate three categories of such scalar MMCC to illustrate the feature. The next section, we focus on stoponium resonance from light stop of compressed supersymmetry. Then we discuss the other two color exotics, color sextet scalar as diquark and the color octet scalars and their constraints. We then discuss the diphoton production of diquarkonium formed by long-lived diquark/anti-diquark pair and the octetonium formed by color-octet scalars. We then conclude in the final section.

II. STOPONIUM

A first well-known example of such scalar MMCC state is a stop in the minimal supersymmetric standard model (MSSM). When metastable stops are produced in pair at colliders, stoponium can be formed near threshold [7–9] and stoponium can decay into gg , ZZ , $\gamma\gamma$ etc. through annihilation. Here we briefly summarize the diphoton signal from stoponium at the LHC which was studied in [8,9].

As a consequence of large top Yukawa, third generation squarks are typically the lightest among the sfermion spectrum and can even be the next lightest supersymmetric particle (NLSP). In compressed SUSY model, the mass difference between stop and lightest neutralino, $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$, can be of a few GeV. Therefore, stop can only decay through loop or four-body

$$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0, \quad \tilde{t}_1 \rightarrow b\ell\nu\tilde{\chi}_1^0. \quad (2)$$

The total width of stop is only of $\mathcal{O}(\text{KeV})$ which is less than Λ_{QCD} . When being produced, such stop will form hadronic state as R -hadron, which is the composite colorless state of colored metastable superparticles with light quarks. However, if stop decay within the tracking system, most of the R -hadron searches do not apply. In addition, the stop decay is largely into neutralino with extremely soft objects like D -meson. The pair production signal is mostly large missing transverse energy \cancel{E}_T . The only bound then comes from $pp \rightarrow j + \tilde{t}_1\tilde{t}_1^*$ and the signal is the monojet plus \cancel{E}_T . Without any kinematic handle, bound on such final state is rather weak. Dark matter annihilation is mainly through $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow t\bar{t}$ but may also have $\tilde{\chi}_1^0\tilde{t}_1$ co-annihilation and it is not difficult to obtain the viable parameter region with correct relic density [8].

On the other hand, pair production of stop does not necessarily lead to large \cancel{E}_T which is common signature for all R -parity conserving MSSM. Stop production near threshold can also form hadronic bound state as stoponium $\eta_{\tilde{t}}$ as a typical example of squarkonium [8]. The stoponium can decay into gg , $\gamma\gamma$, W^+W^- , ZZ , hh , $t\bar{t}$, $b\bar{b}$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0$ by annihilation. The stoponium production rate can be estimated from Higgs production from gluon fusion by scaling from ratio of partial width $\Gamma(\eta \rightarrow gg)/\Gamma(H \rightarrow gg)$. A comprehensive phenomenology study has been performed by [8]. However, at 14 TeV LHC, the predicted $\sigma(pp \rightarrow \eta_{\tilde{t}} \rightarrow \gamma\gamma)$ is about 0.05 fb for $m_{\eta} = 750$ GeV which is much less than the required rate to account for the current diphoton excess. Detailed calculations for stoponium production and decays to $\gamma\gamma$ or ZZ are also presented in [9]. A recent lattice study on the origin of the stoponium wave function [10] indicates that the stoponium production rate may be about 3.5 times larger than the potential model calculation [11] adopted in [8], which is still far too small to accommodate the LHC diphoton excess.

III. SCALAR COLOR EXOTICS

Since the stoponium prediction is much lower to account for the excess, one would need large enhancement in production or diphoton decay. In this session, we discuss the scalar color exotics. In minimal extension, scalar exotics decay into fermionic quark pairs. Under $SU(3)_C$,

$$\begin{aligned} 3 \otimes 3 &= 6 \oplus \bar{3} \\ 3 \otimes \bar{3} &= 8 \oplus 1. \end{aligned} \quad (3)$$

Therefore, the scalar color exotics can only be sextet, antitriplet and octet under $SU(3)_C$. The above color structure corresponds to the following Lorentz structure respectively as

$$\bar{\psi}^c\psi\Phi + \bar{\psi}\psi\phi \quad (4)$$

where ψ is a Dirac spinor. The first term violate the global fermion number $B + L$ while the second term corresponds to fermion number conservation. The Φ field can be identified as sextet or antitriplet scalar while the ϕ field can be identified as singlet or octet. Sextet and antitriplet scalar both couple to quark pairs and hence are called diquark. Taking $\psi = P_L\psi + P_R\psi$, it is straightforward to conclude that diquark Φ couples to the same chiral field while the field ϕ couples to spinor with different chirality. Under $SU(2)_L$, diquark Φ can be either triplet or singlet while ϕ can only be doublet.

The antitriplet diquark sometimes can be identified as scalar quark in supersymmetric theory. If R -parity is violated, squark can decay into quark pair through superpotential $\epsilon_{\alpha\beta\gamma}u_\alpha^c d_\beta^c d_\gamma^c$ coupling. On the other hand,

stoponium in the previous session already gives the maximal prediction among squarkonia states.

As we argued, color octet scalars must be $\phi_8(8, 2, 1/2)$ under the SM gauge symmetry with Yukawa coupling

$$y\bar{Q}_L u_R \phi_8 + \text{H.c.} \quad (5)$$

The octet scalars has been partially studied in Manohar-Wise model [12].

The color sextet scalar is a symmetric 2nd rank tensor of $SU(3)_C$. Diquarks couple to SM quarks as Fermion number violation $\psi^T C^{-1} \psi \phi$, where ψ is a Dirac spinor and ϕ is the scalar diquark. In $SU(3)_C \times SU(2)_L \times U(1)_Y$, the sextet diquark can be Δ_6 , a $SU(2)_L$ adjoint $(6, 3, 1/3)$ and $SU(2)_L$ singlets

$$\begin{aligned} \Phi_6^{+4/3} &: (6, 1, 4/3); \\ \Phi_6^{-2/3} &: (6, 1, -2/3); \\ \Phi_6^{+1/3} &: (6, 1, +1/3). \end{aligned} \quad (6)$$

Sextet diquark can be identified as a color sextet scalar in Pati-Salam model $SU(4)_C \times SU(2)_R \times SU(2)_L$. During the symmetry breaking of

$$\begin{aligned} SU(4)_C \times SU(2)_R \times SU(2)_L &\rightarrow SU(3)_C \times SU(2)_R \\ &\times SU(2)_L \times U(1)_{B-L}, \end{aligned} \quad (7)$$

a **10**-dimensional symmetric second rank tensor under $SU(4)$ can be decompose as

$$\begin{aligned} (10, 1, 3) &= (6, 3, 1, 2/3) + (3, 3, 1, -2/3) + (1, 3, 1, -2) \\ (10, 3, 1) &= (6, 1, 3, 2/3) + (3, 1, 3, -2/3) + (1, 1, 3, -2) \end{aligned} \quad (8)$$

Even though the scale of $SU(2)_R \times SU(4)_C$ symmetry breaking is around 10^{10} GeV, in a supersymmetric Pati-Salam model [13,14], light color sextet scalar (diquark) can be realized as a result of existence of accidental symmetries where the masses of color sextet scalar only arises through high dimension operators. All the diquark states are charged under electromagnetic interaction and hence, non-zero vacuum expectation value is strictly forbidden for diquarks. Diquark carries nonzero $U(1)_B$ Baryon number while the $SU(2)$ triplet state in Eq. (8) carries nonzero $U(1)_L$ lepton number. When $SU(2)$ triplet acquire vacuum expectation value during symmetry breaking, Majorana neutrino mass naturally arises and Lepton number is violated by two units. Due to $U(1)_{B-L}$ gauge symmetry, the lepton number violation can also be converted into baryon number violation

$$\Delta L = 2 \rightarrow \Delta B = 2. \quad (9)$$

However, such B/L violation does not lead to proton decay which is $\Delta B = 1$ and $\Delta L = 1$ effect, $\Delta B = 2$ violation only leads to neutron-antineutron ($n - \bar{n}$) oscillation and the electroweak scale diquark is fully compatible with present limits [13]. In addition, such diquark also helps in post-sphaleron baryogenesis [15].

The diquark decay through Yukawa coupling

$$f_\Phi u_R^T C^{-1} u_R \Phi_6^\dagger \quad (10)$$

with the width as [14]

$$\Gamma_{ij} = \frac{3}{8\pi(1 + \delta_{ij})} |f_{ij}|^2 M_{\Phi_6} \lambda^{1/2}(1, r_i^2, r_j^2) (1 - r_i^2 - r_j^2) \quad (11)$$

where $\lambda(x, y, z) = (x - y - z)^2 - 4yz$ and $r_i = m_i/M_{\Phi_6}$. The Yukawa couplings are typically constrained by flavor physics. For instance, for the $SU(2)_L$ singlet with only coupling to the up-type quarks as $\Phi_6(6, 1, 4/3)$, the most stringent bounds on the couplings f_{ij} come from $D^0 - \bar{D}^0$ mixing, to which Φ_6 would make a tree level contribution proportional to $f_{11} f_{22} / M_{\Phi_6}^2$. The off-diagonal coupling f_{ij} will contribute to flavor violation processes, for instance $D \rightarrow \pi\pi$ which is proportional to $f_{12} f_{11} / M_{\Phi_6}^2$. The current bounds require that

$$f_{11} f_{22} \lesssim 10^{-6}; \quad f_{11} f_{12} \lesssim 10^{-2}, \quad (12)$$

for M_{Φ_6} of a few hundred GeV to TeV mass range [16]. Less stringent constraint comes from one loop process as $c \rightarrow u\gamma$. To escape from the bound, the charm-related couplings should be negligible. In the region of $f \lesssim 10^{-3}$, Φ_6 decay width is less than Λ_{QCD} [14] and Φ_6 becomes metastable.

IV. DIQUARKONIUM AND OCTETONIUM

We first use the $\Phi_6^{+4/3}$ to illustrate the feature then scale down to other sextet diquarkonia. Near threshold, $\Phi_6 \Phi_6^\dagger$ can form diquarkonium η_Φ which would decay dominantly into the gg channel. Since $\Phi_6^{+4/3}$ is a $SU(2)_L$ singlet, η_Φ decays also into $\gamma\gamma$, $Z\gamma$ and ZZ , with the latter two channels suppressed by $\tan^2 \theta_W$ and $\tan^4 \theta_W$ in comparison to the diphoton channel. Therefore $\text{Br}(\eta_\Phi \rightarrow \gamma\gamma) \approx \Gamma(\eta_\Phi \rightarrow \gamma\gamma) / \Gamma(\eta_\Phi \rightarrow gg)$.

Since the gluon fusion production of such diquarkonium is proportional to the partial width $\Gamma(\eta_\Phi \rightarrow gg)$, at leading order, the production rate is

$$\frac{\sigma(pp \rightarrow \eta_\Phi)}{\sigma(pp \rightarrow H)} = \frac{\Gamma(\eta_\Phi \rightarrow gg)}{\Gamma(H \rightarrow gg)}. \quad (13)$$

We find the partial decay width of $\eta_\Phi \rightarrow gg$ at leading order as

$$\Gamma(\eta_\Phi \rightarrow gg) = \frac{50\alpha_S^2 |R(0)|^2}{3 m_{\eta_\Phi}^2}, \quad (14)$$

in which the numerical factor is 25/2 times larger than that of $\Gamma(\eta_{\bar{t}} \rightarrow gg)$. Here $R(0)$ is the radial wave function at the origin. The large color-factor enhancement in the above digluon decay comes from the relation $Tr(T^A T^B) = \delta^{AB}/2$ in the fundamental representation while $Tr(T^A T^B) = 5\delta^{AB}/2$ in the sextet representation of $SU(3)_C$. The factor 1/2 arises from the normalization of the wave function at color space, which is $1/\sqrt{6}$ for diquarkonium and $1/\sqrt{3}$ for stoponium.

Similarly, the diphoton decay width at leading order is

$$\Gamma(\eta_\Phi \rightarrow \gamma\gamma) = \frac{1024\alpha^2 |R(0)|^2}{27 m_{\eta_\Phi}^2}, \quad (15)$$

in which the numerical factor is 32 times larger than that of $\Gamma(\eta_{\bar{t}} \rightarrow \gamma\gamma)$. Here part of the enhancement (factor of 16) comes from the diquark electric charge which is twice larger than that of stop, another factor of 2 enhancement is due to the fact that there are six colors for diquarks instead of three colors for stops. It is expected that $R(0)$ of diquarkonium should be larger than that of stoponium because of the stronger perturbative color interactions between diquarks. Intuitively, for such a heavy onium, the potentials of both stoponium and diquarkonium should be essentially coulombic and therefore calculable in a model-independent way. However both the potential model estimation [11] and the recent lattice study [10] on the stoponium wave function exhibit substantial departure from coulombic limit. For the case of diquarkonium, only potential model estimation is available [11]: it was estimated as $|R(0)|^2/m_{\eta_\Phi}^2 \simeq 1.5$ GeV for a 750 GeV diquarkonium.

Using the potential model estimation of the wave function at the origin, we then find $\sigma(pp \rightarrow \eta_{\Phi+4/3} \rightarrow \gamma\gamma)$ to be about 12 fb for $m_{\eta_\Phi} = 750$ GeV at 13 TeV LHC, which may be slightly larger to account for the LHC diphoton excess. Correspondingly, $\sigma(pp \rightarrow \eta_\Phi \rightarrow gg)$ is predicted to be about 1.6 pb and is within the experimental bounds [17].

Scaling by fourth power of electric charge, one can also obtain

$$\begin{aligned} \sigma(pp \rightarrow \eta_{\Phi-2/3} \rightarrow \gamma\gamma) &= \frac{1}{16} \sigma(pp \rightarrow \eta_{\Phi+4/3} \rightarrow \gamma\gamma) \\ \sigma(pp \rightarrow \eta_{\Phi+1/3} \rightarrow \gamma\gamma) &= \frac{1}{256} \sigma(pp \rightarrow \eta_{\Phi+4/3} \rightarrow \gamma\gamma). \end{aligned} \quad (16)$$

The prediction of $\eta_{\Phi-2/3}$ is then too small to account for the LHC diphoton excess.¹

Another example of exotic onium is color-singlet octetonia formed by a pair of color-octet scalars ϕ_8 with the quantum numbers (8, 2, 1/2) [12]. Such octetonia state has been carefully studied in [18–20]. The diphoton and digluon decay widths of this octetonia at the leading order can be found as

$$\Gamma(\eta_8 \rightarrow \gamma\gamma) = 16\alpha^2 \frac{|R(0)|^2}{m_{\eta_8}^2}, \quad (17)$$

$$\Gamma(\eta_8 \rightarrow gg) = 18\alpha_S^2 \frac{|R(0)|^2}{m_{\eta_8}^2}, \quad (18)$$

with $|R(0)|^2/m_{\eta_8}^2 \simeq 1.2$ GeV [11] for a 750 GeV octetonia. In addition, total decay width of octetonia also depends on the Yukawa coupling η_U due to new decay channel [18–20] such as top quark pairs and $\sigma(pp \rightarrow \eta_8 \rightarrow \gamma\gamma)$ can well be of the right magnitude to explain the LHC diphoton excess as in [18–20] for some choice of η_U .

V. LHC BOUNDS ON COLOR EXOTICS WITHOUT PARITY

As a QCD machine, the large production rates of color exotics enable the possibility of early discovery or put stringent bounds on such color exotics based on existing data from LHC or Tevatron.

In the case of supersymmetric theory, if R -parity is not broken, the final state of the cascade decay is always a stable particle with odd R -parity. Constrained by astrophysics and cosmology, such stable particle must be electric neutral and the color singlet thus can be identified as the dark matter candidate. Such final state then appears as missing transverse energy \cancel{E}_T . As we discussed, the pair production of stop in compressed supersymmetry leads to monojet plus \cancel{E}_T which does not have much kinematic handle.

On the other hand, without such parity, color exotics as diquark or color octet scalars will then decay into quark pairs. If the exotics decay into light jets, pair production of such exotics then leads to four jets final states with two dijet resonance and the production rate with 375 GeV resonance is about 36 pb [14] for color sextet diquark and slightly high for octet states. Since all four jets arise from heavy resonance decay, the four jets are all of high p_T which can

¹There is no lattice study on the diquarkonium system yet, as far as we know. If future lattice study also found the production rate of η_Φ to be 3–4 times larger than the potential model estimation, just like the case of stoponium reported in [10], the diquarkonium formed by another color-sextet $SU(2)_L$ singlet Higgs $\Phi_6(6, 1, -2/3)$ could be a candidate to interpret the LHC diphoton excess with $\sigma(pp \rightarrow \eta_\Phi \rightarrow \gamma\gamma)$ predicted to be around 3–4 fb.

significantly reduce the SM four jets background. LHC run-I has excluded coloron octet up to 800 GeV and antitriplet diquark up to 350 GeV [21]. The sextet diquark production rate is slightly lower than the octet and the 375 GeV diquark decaying into dijet must be excluded already. The diquark with electric charge $-2/3$ that only couples to the down-type quarks and other diquark states that only couple to first two generations fall into this category and have been completely excluded. The diquark with electric charge $+4/3$ can also decay into same-sign top quark pair as $\Phi_6 \rightarrow tt$. The pair production of diquark then leads to four top final state, in particular, with same-sign dilepton plus jets and E_T which fall into the regular supersymmetric Majorana gluino search or sgluon search and such light diquark states suffer from severe constraint of gluino bound [14]. The sgluon pair with decay into four-top final state has completely excluded such possibility [22].

On the other hand, if the decay final state consists of one top quark, the pair production will then fall into $t\bar{t}$ plus jets. For instance, f_{13} dominates the $\Phi_6^{+4/3}$ or f_{33} dominates the $\Phi_6^{+1/3}$ couplings or charged color octet scalars ϕ_8^+ with large top coupling. Then these exotics decay into top plus light jet as

$$\Phi_6^{+4/3} \rightarrow t + u; \quad \Phi_6^{+1/3} \rightarrow t + b; \quad \phi_8^+ \rightarrow t + \bar{b}. \quad (19)$$

We plot the normalized invariant mass distribution $M_{t\bar{t}}$ of SM $pp \rightarrow t\bar{t}$ and $pp \rightarrow \Phi\Phi^* \rightarrow t\bar{t}jj$ in Fig. 1. It is clear that the $t\bar{t}$ invariant mass of 375 GeV resonance decay has an almost identical feature as the SM.

First of all, the diquark production rates of $M_\Phi = 375$ GeV are listed as the following

$$\begin{aligned} \sigma(pp \rightarrow \Phi_6\Phi_6^*)_{\sqrt{s}=1.96 \text{ TeV}, M_\Phi=375 \text{ GeV}} &\simeq 0.01 \text{ pb} \\ \sigma(pp \rightarrow \Phi_6\Phi_6^*)_{\sqrt{s}=7 \text{ TeV}, M_\Phi=375 \text{ GeV}} &\simeq 3.3 \text{ pb} \\ \sigma(pp \rightarrow \Phi_6\Phi_6^*)_{\sqrt{s}=14 \text{ TeV}, M_\Phi=375 \text{ GeV}} &\simeq 36 \text{ pb}. \end{aligned} \quad (20)$$

In comparison with the $t\bar{t}$ production rates are measured at Tevatron and 7 TeV LHC [23,24]

$$\begin{aligned} \sigma(pp \rightarrow t\bar{t})_{\sqrt{s}=1.96 \text{ TeV}}^{\text{exp}} &= 7.60 \pm 0.41(\text{stat}) \pm 0.20(\text{syst}) \\ &\pm 0.36(\text{lumi}) \text{ pb} \\ \sigma(pp \rightarrow t\bar{t})_{\sqrt{s}=7 \text{ TeV}}^{\text{exp}} &= 158 \pm 2(\text{stat}) \pm 10(\text{syst}) \\ &\pm 4(\text{lumi}) \text{ pb} \end{aligned} \quad (21)$$

For the exiting data with lower central mass energy collisions, the production rate of diquark is significantly lower than the systematic errors. Even for 14 TeV LHC, the production is less than 5% of the SM prediction of $t\bar{t}$ with invariant mass peak at the SM $t\bar{t}$ threshold. Therefore, we argue the color exotics with decay into one top quark plus a light jet may completely be buried in the SM $t\bar{t}$ samples.

Such resonance with $t+q$ decay requires $t+j$ reconstruction which has been carried in [25,26]. The resonant $t+j$ reconstruction was designed to search for W'_R with $gd \rightarrow tW'$ production and $W'_R \rightarrow \bar{t}b$. For $t+j$ invariant mass $M_{tj} \sim 375$ GeV, the exclusion limit is over 10 pb for 7 TeV LHC by ATLAS. Due to phase-space suppression, both Φ_6 and ϕ_8 with resonant mass of 375 GeV are significantly less than that exclusion. The CMS has also excluded spin-1/2 excited quark $t' \rightarrow t+g$ in a window between 465 and 512 GeV [26]. The production rate for the spin-1/2 exotic quark is about 3 pb for $m_{t'} = 375$ GeV at 7 TeV and very close to the production rate of sextet diquark. We then argue the exclusion can be directly applied here and the light diquark decay into top plus jet can evade the CMS search in [26].

However, color octet scalars $\phi_8: (8, 2, 1/2)$ form a $SU(2)$ doublet with two physical states. In addition to the ϕ_8^+ which can dominantly decay into $t\bar{b}$, there always exists an electric neutral state with degenerate mass. The neutral state $\phi_8^0 \rightarrow t\bar{t}$ has been excluded by the four-top sgluon search [22] and $\phi_8^0 \rightarrow b\bar{b}$ has been excluded by the four light jets search [21].

On the other hand, the above constraints are all due to the case with prompt decay. Long-lived particle (LLP) searches on the LHC are very dependent on the estimated proper decay length, electric charge, and LLP masses. Both the ATLAS and CMS collaborations have published constrains on LLPs with various strategies, including specific energy loss [27,28], time of flight [29,30], displaced vertex [31,32], HCal detection [33], and stopped decay [34,35]. The very features of LLPs are large ionization energy loss rate $\frac{dE}{dx}$ and long time of flight. Heavy exotics Φ_6 and ϕ_8 are produced with small velocities, some even reaching a

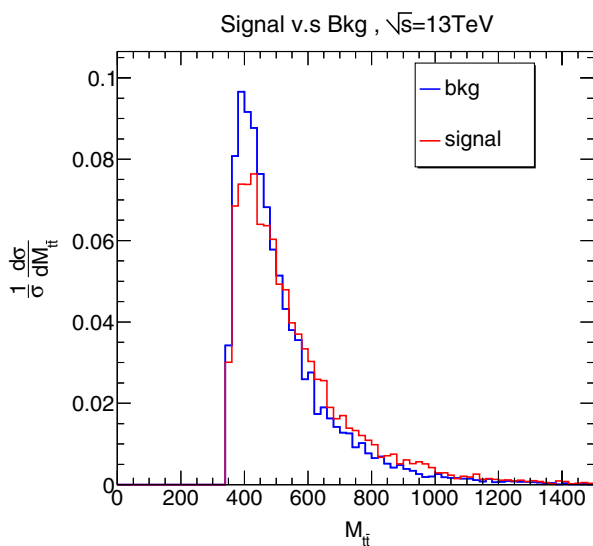


FIG. 1. Normalized $t\bar{t}$ invariant mass of SM $pp \rightarrow t\bar{t}$ and $pp \rightarrow \Phi\Phi^* \rightarrow t\bar{t}jj$.

nonrelativistic region. They hadronize immediately into colorless bound states with different electric charges. The small $\beta\gamma$ values of charged states lead to an anomalously large energy loss rate measured in the tracker. In the meantime, if they have a lifetime greater than $\mathcal{O}(\text{ns})$, they could traverse the whole detector and leave a signal with large time of flight measured in the muon detector. These events are generally selected out with either a muon trigger or a calorimeter-based E_T trigger. In the muon trigger case, the charged colorless bound states would fake heavy muonlike signals in the muon system. Further analysis could incorporate their distinctive energy loss rate for the particle identification. Even if they decay before hitting on the outmost layer, the decay products should not include top quarks as the muon leptons from top decays may still trigger the event selection algorithm. So ϕ_8 which decays to $t\bar{t}$ or $b\bar{b}$ can hardly escape the full-detector search strategy. However, the charged bound states could interact with the detector material and eventually arrive as a neutral state. Then E_T trigger works as a compensation in this case. For example, in the ATLAS R -hadron search, gluino mass is excluded to 1270 GeV with the full-detector information and 1260 GeV with the muon-agnostic information [29].

We assume the $\Phi_6^{+4/3}$ is metastable and focus on its searches in the following. Metastable sextet diquarks form neutral, singly and doubly charged hadrons like $\Phi_6\bar{u}\bar{u}$, Φ_6d , and Φ_6u soon after their production and decay as, for instance,

$$X^{++}(\Phi_6u) \rightarrow p^+ + \pi^+. \quad (22)$$

Displaced decay searches are sensitive to multijet signals in the tracker volume. The CMS tracker is able to detect a long-lived neutral particle X in a mass range of 50 GeV to 350 GeV decaying to $q\bar{q}$ pair [32]. The production cross-section limit depends on the mean proper decay length of X , but always below that of Φ_6 pair production. As the upper exclusion mass limit is very close to 375 GeV, we assume technically it can be extended to probe such mass region. In the scenario where the LLPs could traverse the tracker and then decay into light jet pairs in the calorimeters, more calorimeter-based strategies are effective. Though the previous jet pair resonance search does not apply here because of the strict reconstructed primary vertex requirement for a four jets event [21], such high p_T jet events are recorded and it is easy to check whether a resonance could be reconstructed. Moreover, the ATLAS calorimeter signal searches covers a radius from the outer ECal to the HCal and looks for metastable neutral particles that decay in this region [33]. The production cross section limit covers a mass region up to 150 GeV for a pair of such

neutral states decaying from a heavy hidden scalar. The CMS displaced decay and ATLAS HCal decay searches are designed for neutral LLPs, but we expect the charged hadronic states that would inevitably leave significant charged tracks are detectable within these methods which has never been reported. At last, there is a scenario where bound states with small β values may stop in the detectable region due to the energy loss when interacting with detector material. Then there should be an upper lifetime limit set by the out-of-time decay searches where no active event is expected in the detector [34,35]. In general, one expects much more severe bounds over the charged LLP in comparison with neutral LLP which is already excluded up to 1.2 TeV for octet [29].

VI. CONCLUSIONS

In summary, we discuss the interpretation of the recent diphoton excess as onia of massive metastable colored and charged particles. To escape from the stringent bound on dilepton final states from vector onia decays, the onia should be formed by scalar particles. One example is stoponium which has been discussed in details in [8,9], however the predicted diphoton signal is significantly smaller than the required rate to explain the LHC diphoton excess. We then consider various color exotics as sextet diquark or color octet scalar. Diphoton from octetonium can well be of the right magnitude to explain the LHC diphoton excess as in [18–20] for some parameter choice. Diquarkonium formed by color sextet diquark with electric charge to be 4/3 also predicts the diphoton signal as 12 fb at 13 TeV LHC with the enhancement from color factor and electric charge. On the other hand, light color exotics suffer from severe constraints of direct searches at the hadron colliders. Color sextet or octet scalars with decay into light jets or top pairs have been excluded at this mass range. We find the only viable channel is when $\Phi^{+4/3} \rightarrow u + t$ dominates the diquark decay which predicts resonance with top plus jet and is still below the current bound.

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