TeV Colored Higgsinos in Alternative Grand Unified Theories

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Recently, a type of GUT models with an extra dimension in AdS space can successfully solve the doublet-triplet problem, maintain proton stability, and allow the colored Higgs bosons and colored Higgsinos in the TeV mass region. We study the hadronic production and detection of these TeV colored Higgsinos and Higgs bosons. If the colored Higgsino is lighter than the colored Higgs boson, the colored Higgs boson will decay into a colored Higgsino and a gluino or a gravitino, and vice versa. The signatures would be stable massive charged particles with jets or missing energies.

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Introduction. Grand unified theories (GUT) were introduced in 70’s in an attempt to unify the electromagnetic, weak, and strong interactions into a single theory. The most well-known model is based on the SU(5) symmetry, which is the smallest single gauge group that can incorporate the SU(3) color, SU(2) weak, and the U(1) hypercharge interactions. In addition, the matter fermions are also grouped into representations of the SU(5), and thus achieving the quark-lepton unification to some extent. One of the most successful features of GUT is the electric charge quantization. The SU(5) symmetry is broken at some high scales to SU(3)\times SU(2)\times U(1)\times U(1)\times U(1), giving rise to heavy X, Y gauge bosons. The exchanges of the X, Y gauge bosons induce proton decay (e.g. $p \to e^+\pi^0$) via dimension-six operators $(QQ)(QL)$, which are suppressed by two powers of the GUT breaking scale: $g_{X,Y}^2/M_{\text{GUT}}^2$. Other dimension-six proton decay operators can also arise from exchanges of the Higgs color triplets. In the supersymmetric version of GUT, there are additional sources of proton decay. Exchanges of the colored Higgsinos, the supersymmetric partners of the Higgs color triplets, give rise to dimension-five operators $(QQ)(QL)$, which are only suppressed by one power of the GUT breaking scale.

Unobserved proton decay has pushed the mass of the colored Higgs bosons and Higgsinos to at least a few $10^{16}$ GeV. Compared to the mass of the weak doublet Higgs fields, which is fixed at around $O(100)$ GeV, the mass of the color triplet is $10^2$ orders of magnitude heavier. Such a large mass difference between the triplet and the doublet is a serious problem in supersymmetric GUT (SUSY-GUT), dubbed the doublet-triplet splitting problem. This problem arises because the weak-doublet Higgs fields, which are responsible for the electroweak symmetry breaking, and the color triplet belong to the same $\mathbf{5}$ and $\mathbf{5}$ representations of SU(5):

$$H(\mathbf{5}) = (H_C, H_u),$$
$$\tilde{H}(\mathbf{5}) = (\tilde{H}_C, H_d)$$

where the weak doublets $H_u$ and $H_d$ are responsible for the up- and the down-type quark (lepton) masses, respectively. Therefore, the color triplet and the weak doublet will naturally have the same Yukawa couplings to matter fermions. The color-triplet fields will cause the proton decay. That is the reason why the color triplet has to be very heavy (a few $10^{16}$ GeV) to avoid the proton decay constraint. The doublet-triplet problem is perhaps the most undesirable problem of the SUSY-GUT. Most attempts to the doublet-triplet problem in literature have been focused on how to naturally explain the hierarchy between the weak-doublet and the color-triplet masses after the GUT symmetry breaking.

An alternative approach to the doublet-triplet splitting problem is to suppress the Yukawa couplings of the color-triplet Higgs fields to matter fermions in order to preserve the proton longevity. Thus, no mass splitting between the weak-doublet and color-triplet Higgs fields is required. The color-triplet mass can be as low as $O(\text{TeV})$, and can be copiously produced at the upcoming LHC. The suppression of Yukawa couplings of the triplet can be achieved by some clever group structures or by extra dimension setups. A particularly interesting mechanism is by orbifolding. When one compactifies the extra dimensions, one can assign special boundary conditions to various components of a multiplet. After compactification, some components are automatically zero at the orbifold fixed point while other components are not, thus breaking the symmetry and naturally splitting the multiplet. If the multiplet consists of the Higgs color triplet and weak doublet, one can make the color triplet automatically zero on the fixed point, where matter fermions reside, to achieve proton stability and natural doublet-triplet splitting. In the model by Goldberger et al. (see also earlier works), they started from the Randall-Sundrum scenario: a slice of AdS space with two branes (the Planck brane and the TeV brane), one at each end. The hierarchy of scales is generated by the AdS warp factor $k$, which is of order of the five-dimensional Planck scale $M_5$. The fundamental scale on the Planck brane is $M_{\text{Pl}}$ while the fundamental scale on the TeV brane is rescaled to TeV by the warp factor: $T \equiv ke^{-\pi kR}$, where $R$ is the size of the extra dimension. The model is a 5D supersymmetric SU(5) gauge theory compactified on the orbifold $S^1/\mathbb{Z}_2$ in the AdS space. The boundary conditions break...
the SU(5) symmetry and provide a natural mechanism for the Higgs doublet-triplet splitting. The Planck brane respects the SM gauge symmetry while the TeV brane respects the SU(5) symmetry. By the boundary conditions the wave-function of the color-triplet Higgs fields is zero at the Planck brane, on which the matter fermions reside, while the doublet Higgs fields are nonzero at the Planck brane and give Yukawa couplings to the matter fermions. Thus, the excessive proton decay via the color-triplet Higgs fields is highly suppressed. The mass of the color-triplet fields is given by the warp factor to be in TeV scale.

In this Letter, we calculate the production and describe the detection of the TeV colored Higgs bosons and Higgsinos in hadron colliders. The colored Higgs bosons and Higgsinos will give rise to a novel signature like “heavy muons”. Depending on their masses, the colored Higgs boson will decay into the colored Higgsino and a gluino or a gravitino (in this kind of models the gravitino is very light $m_{\tilde{C}} < 10^{10}$), and vice versa. The present work has non-trivial improvements over our previous work $^{[12]}$: (i) we take into account production of both colored Higgs bosons and Higgsinos, (ii) the signature of colored Higgs boson decaying to colored Higgsino and gluino or gravitino gives rise to jets or missing energies, and (iii) increased event rates improve significantly the sensitivity at the LHC.

**Production of colored Higgsinos.** Let us denote the SUSY partner of $H_C$ by $\tilde{h}_C$ and that of $\tilde{H}_C$ by $\tilde{H}_C$ (anti-particles are denoted by $\tilde{H}_C^*$ and $\tilde{h}_C$, and $\tilde{H}_C$ and $\tilde{h}_C^*$, respectively.) As we already mentioned, the colored Higgs bosons and Higgsinos do not have sizable Yukawa couplings to the SM fermions in order to suppress the fast proton decay. Thus, the only allowed production channels of the colored Higgs bosons and Higgsinos in hadronic collisions are via the SU(3)$_C$ invariant interaction

$$
\mathcal{L} = -ig_sH_C^*\theta_\mu H_CT^aA^{a\mu} + g_s^2T^aT^bH_C^*H_CA^{a}_\mu A^{b}_{\mu} - g_sT^aA^{a}_\mu \tilde{h}_C\gamma^\mu \tilde{h}_C - \sqrt{2}g_s\left(H_C^*g^aT^a \tilde{h}_C + \tilde{H}_C^* T^a g^a H_C \right),
$$

where $T^a$ is the generator of SU(3), and $A^{a}_\mu \equiv A(\partial_\mu B) - (\partial_\mu A)B$. The last line is the matter-gaugino interaction with the gluino. The interactions for $\tilde{H}_C, \tilde{H}_C$ are the same as $H_C, \tilde{h}_C$, respectively. It is understood that $\tilde{h}_C$ is a left-handed field. The production of the colored Higgs bosons and Higgsinos in the lowest order is via the s-channel $q\bar{q}$ annihilation and the glue-gluon fusion. The production of the colored Higgs bosons has been calculated in Ref. $^{[7]}$. Here we present the formulas for the production of the colored Higgsinos:

$$
\frac{d\sigma}{d\cos\theta^*}(q\bar{q} \rightarrow \tilde{h}_C\tilde{h}_C) = \frac{\alpha_s^2}{9s} \beta \left(1 - \frac{2t_1\bar{u}_1}{s^2}\right)
$$

$$
\frac{d\sigma}{d\cos\theta^*}(gg \rightarrow \tilde{h}_C\tilde{h}_C) = \frac{\alpha_s^2}{96s} \beta \left[\frac{4s^2}{t_1\bar{u}_1} - 9\right]
$$

$$
\times \left[\frac{s^2}{t_1\bar{u}_1} - 2\right] \left(\frac{\bar{u}_1}{s^2} - \frac{m_{hh_C}^2}{s} + \frac{7m_{hh_C}^2}{s}\right)
$$

where $\beta = \sqrt{1 - 4m_{hh_C}^2/s}$, $t_1 = t - m_{hh_C}^2$, $\bar{u}_1 = \bar{u} - m_{hh_C}^2$, and $\theta^*$ is the scattering angle in the parton rest frame and is related to $\bar{t}_1$ by $\bar{t}_1 = -\frac{t^*}{s}(1 - \beta \cos \theta^*)$. Note that the expressions for the production cross section of the $\tilde{h}_C\tilde{h}_C$ pair are the same as the $\tilde{h}_C\tilde{h}_C$ pair. In the minimal SUSY SU(5), they have exactly the same mass. Even beyond the minimal model, since there is no particular reason why their masses should be very different, we simply take them to be equal and the results present in the following take into account both $\tilde{h}_C$ and $\tilde{h}_C$.

In the calculation, we employ the parton distribution function of CTEQ v.5 (set L) $^{[14]}$ and the one-loop renormalized running strong coupling constant with $\alpha_s(M_Z) = 0.119$. We show in Fig. 1 the production cross sections of colored Higgsinos and Higgs bosons vs the masses $m_{hh_C}$ and $m_{H_C}$ at the Tevatron (pp collisions), at the LHC (pp collisions), and in pp collisions at $\sqrt{s} = 50, 200$ TeV (the lower and upper energy range of the VLHC $^{[15]}$.)

**FIG. 1:** Total cross sections for the production of the colored Higgsino and Higgs boson pair at the Tevatron, LHC, and pp collisions at 50 and 200 TeV.

**Detection of colored Higgsinos.** Depending on their masses, the colored Higgs boson will decay into the colored Higgsino and a gluino or a gravitino, and vice versa.
We have the following scenarios

1. $m_{H_C} > m_{\tilde{h}_C}$ \quad $H_C \rightarrow \tilde{h}_C + \tilde{g}/\tilde{G}$
2. $m_{\tilde{h}_C} > m_{H_C}$ \quad $\tilde{h}_C \rightarrow H_C + \tilde{g}/\tilde{G}$.

The 95\% C.L. limit on the mass of the gluino is 195 GeV independent of the squark mass [10]. We use $m_{\tilde{g}} = 220$ GeV. In the case (i), if $m_{H_C} > m_{\tilde{h}_C} + m_{\tilde{g}}$, then the colored Higgs boson will decay into the colored Higgsino and the gluino, otherwise it will decay into the colored Higgsino and a gravitino. (Vice versa for the case (ii) $m_{\tilde{h}_C} > m_{H_C} + m_{\tilde{g}}$.)

In either case, the lighter of the colored Higgs boson and Higgsino will hadronize into a stable massive particle, which is electrically either neutral or charged. In the following discussion, let the colored Higgsino be the lighter one (the reverse is similar.) Both the neutral and charged states will undergo hadronic energy loss in the detector. Although it is strongly interacting, hadronic energy loss is negligible because of the small momentum transfer between the massive particle (TeV) and the nucleon. Thus, the energy loss via hadronic collisions does not lead to detection of the massive particle. On the other hand, the charged state will also undergo ionization energy loss $dE/dx$. In Ref. [6], we have shown that $dE/dx$ as a function of $\beta \gamma$ almost has no explicit dependence on the mass of the penetrating particle, especially in the range $0.1 < \beta \gamma < 1$. Therefore, when $dE/dx$ is measured in an experiment, the $\beta \gamma$ can be deduced, which then gives the mass of the particle if the momentum $p$ is simultaneously measured. Hence, $dE/dx$ is a good tool for particle identification for stable massive charged particles (MCP).

In fact, the CDF Collaboration did a few searches for stable MCPs [17]. The CDF analyses require that the particle produces a track in the central tracking system and penetrates to the outer muon chamber. (In the Run II analysis, the requirement of ionization in the outer muon chamber may not be necessary.) The CDF requirement on $\beta \gamma$ is

$$0.25 \lesssim \beta \gamma < 0.85.$$  

The lower limit is to make sure that the penetrating particle can make it to the outer muon chamber while the upper limit makes sure that the ionization loss in the tracking system is sufficient for a detection. We shall employ the same kinematical cut. We have verified in Ref. [7] that such a cut on $\beta \gamma$ is also valid for a 1 TeV particle. Since the lower cut on $\beta \gamma = p/M$ is 0.25, the momentum cut is 250 GeV for a 1 TeV particle. Such a cut on momentum already makes it background free from $\mu^\pm, \pi^\pm, K^\pm$. Another configuration cut due to the detector (both CMS and Atlas) is

$$|\eta| < 2.5.$$  

We also assume an efficiency of 80\% for each stable MCP to be detected by the central tracking system and the outer muon system. This efficiency is in addition to the cuts on $\eta$ and $\beta \gamma$.

We assume that the gluino decays into quarks and neutralino in the usual neutralino-LSP scenario. Thus, if gluinos appear in the decay of colored Higgs bosons, there will also be jets and missing energies in the final state. Therefore, one or two MCPs with or without jets can be seen in the final state. To definitely see a jet we impose

$$p_{T,j} > 50 \text{ GeV}, \quad |\eta_j| < 2.5.$$  

On the other hand, if the colored Higgs boson is not heavy enough to decay into the colored Higgsino and the gluino, it will decay into the colored Higgsino and the gravitino. In this type of models, the gravitino is often sub-eV [10 12]. In this case, there will be one or two MCPs with or without missing energies. However, since the MCP may not be fully ionized in the detector, it is rather difficult to determine the missing energy caused by the gravitino.

We estimate the number of observed events in the production of colored Higgsinos and Higgs bosons. Throughout, we use $m_{\tilde{g}} = 220$ GeV, $m_{\tilde{\chi}} = 120$ GeV, and $m_{H_C} = m_{\tilde{h}_C} + 100, 300, 500$ GeV for the case when the colored Higgs boson is heavier, and vice versa. We also employ the following factors in estimating the event rates:

(i) a probability of 1/2 that the colored particle will hadronize into an electrically charged particle,

(ii) an efficiency factor of 0.8 for each detected track, and

(iii) both channels of $H_C H_C^*$ and $\tilde{H}_C \tilde{H}_C^*$, and $\tilde{h}_C$ pair and $\tilde{h}_C$ pair production are added.

Since the search is background free, the discovery or evidence of existence for the colored Higgs bosons and Higgsinos depends crucially on the number of observed events, which we choose to be 10–20 events. We show the event rates for the LHC in Table [1] for both cases: $m_{H_C} > m_{\tilde{h}_C}$ and $m_{H_C} < m_{\tilde{h}_C}$.

Conclusions. The presence of light color-triplet Higgs fields in TeV mass scale is a novel feature for the alternative kind of GUT, instead of proton decay. This is made possible through some mechanisms to suppress the Yukawa couplings of the triplets to matter fermions; in particular the orbifolding in an AdS space naturally suppresses proton decay and gives TeV color triplet. The striking signature of these TeV colored Higgs bosons and Higgsinos would be stable massive charged particles, “heavy muons”, producing a track in the central tracking system and penetrating to the outer muon system. Such a signature is background free and gives a clean indication of massive charged particles (MCP). We have calculated the event rates for various final states (1 MCP; 2MCP, 1MCP+jets, and 2MCP+jets) at the LHC. The LHC with an accumulated luminosity of 100 fb$^{-1}$ is sensitive to almost 2 TeV colored Higgsinos and Higgs bosons.
We also note that the colored Higgs bosons and Higgsinos are SU(2)$_L$ singlets and thus do not contribute to the $S, T, U$ parameters \[18\]. In addition, since their Yukawa couplings to quarks and leptons are highly suppressed, they do not contribute to the $Z \to f \bar{f}$ processes or any other flavor processes. Therefore, there are no existing constraints on these particles, except for some direct search limits on stable massive charged particles. Observation of such color-triplet fields of TeV mass is definitely a signal for the alternative GUT.

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TABLE I: Event rates of massive charged particles (MCP) due to pair production of colored Higgs bosons $H_C H_C^*$ and $\tilde{H}_C \tilde{H}_C^*$ and colored Higgsinos $\tilde{h}_C h_C$ and $\tilde{h}_C h_C$ at the LHC with an integrated luminosity of 100 fb$^{-1}$.

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