

LHC phenomenology of unusual top partners in composite Higgs models

Werner Porod*

Institut für Theoretische Physik und Astrophysik, Uni Würzburg, Emil-Hilb-Weg 22, D-97074 Würzburg, Germany

E-mail: porod@physik.uni-wuerzburg.de

Composite Higgs models with a fermionic UV completion can contain additional colored states beside the usual top-partners. We focus here on a model which contains in addition SU(3) color octet top partners as well as color singlet ones. The latter can in principle serve as a dark matter candidate. We consider a particular composite Higgs model which contains SU(3) color octet top partners besides the usually considered triplet representations. Moreover, color singlet top partners are present as well which can in principle serve as dark matter candidates. We investigate the LHC phenomenology of these unusual top partners. Some of these states could at first glance be confused with gluinos predicted in supersymmetric models.

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1. Introduction

The Standard Model (SM) is quite some success story which while been challenged in several experiments shows a remarkable agreement between theory and experiment. The discovery of a Higgs-like scalar resonance at the LHC [1, 2] has completed this framework particle-wise. However, the lightness of the observed boson, whose properties agree with the SM prediction, has materialized long-standing questions on the SM as the ultimate theory of particle interactions. Why is the Higgs boson mass insensitive to the scale of new physics (Planck mass)? Is there a dynamical origin for the spontaneous breaking of the electroweak (EW) symmetry? Is it indeed an elementary scalar particle?

These questions can be addressed by tying the properties of the Higgs-like scalar to those of fundamental fermionic states, which do not suffer from quantum sensitivity to large scales. The two time-honoured avenues realizing this idea are supersymmetry (SUSY) and compositeness. In SUSY scalars are associated with fermions via a new symmetry extending Poincaré invariance of particle interactions. In compositeness models scalars emerge as resonances of underlying bound fermions. In this contribution we follow the composite avenue. The basic idea is inspired by QCD but realized with an extended symmetry of the condensing theory to allow for a misaligned vacuum [3]. The large top Yukawa coupling can be explained via the mechanism of partial compositeness [4]. At the price of a moderate tuning, this class of models features a limit where a light Higgs-like state emerges as a pseudo-Nambu-Goldstone boson (pNGB). This idea got boosted in the early 2000s thanks to the holographic principle [5] linking near-conformal theories in 4 dimensions to gauge/gravity theories in 5 dimensions on a warped background. Based on the symmetry breaking pattern $SO(5)/SO(4)$ a ‘minimal’ model was proposed [6], where the number of pNGBs matches the 4 degrees of freedom of the SM Higgs field. The phenomenology of this model has been widely explored, see e.g. the reviews [7–9].

The minimal model and variations thereof are a useful templates to understand the phenomenology of a composite pNGB Higgs. However, from the point of view of an underlying gauge-fermion theory à la QCD the symmetry breaking pattern $SO(5)/SO(4)$ cannot be obtained as the global symmetry group of the underlying fermions is unitary [10, 11]. The minimal breaking patterns for a composite Higgs which arises from models with underlying fermions are $SU(4)/Sp(4)$, $SU(5)/SO(5)$ or $SU(4) \times SU(4)/SU(4)$ [10, 12, 13]. These models predict additional pNGBs besides the usual Higgs doublet. Moreover, models featuring top partial compositeness [14–16] require additional QCD-charged underlying fermions in order to allow for fermionic bound states with the same quantum numbers as the SM top quark. The underlying colored fermions condense like their electroweak counter parts yielding additional colored pNGBs in the low energy effective theory [17].

The presence of the additional pNGBs generates new decay channels for the top partners [19] besides the ones usually considered in direct searches at the LHC. These can substantially shift the mass bounds for these states for which we refer to [18] for a summary. These models do not only have an extended pNGB sector but usually contain also additional baryonic states which do not transform as $SU(3)_c$ triplets. We will demonstrate some generic features focusing on one specific model, first proposed in ref. [15] and dubbed M5 in ref. [20]. It belongs to a class of models, comprising 12 candidates, where the top partners arise as chimera baryons made of two different

species of confining fermions. A peculiar feature of the model M5 compared to the others is that the baryon spectrum contains color-octet fermionic states. They are predicted to be among the lightest top partners and, thus, play the leading role in the LHC phenomenology of this model [21]. Moreover, the pNGB sector contains a color-triplet with the charge of a right-handed stop as well as a color octet. In addition color-neutral baryons are predicted. We will see that the spectrum and phenomenology of the model M5 shows surprising similarities to supersymmetric models. Finally, the properties of the confining gauge dynamics, based on $\text{Sp}(4)$, is being studied on the Lattice with promising results [22–24]. Complementary information on the mass spectrum and decay constants of the composite states can also be obtained using Nambu-Jona-Lasinio models [25] or holographic techniques [26, 27].

2. Model aspects

The M5 model has an $\text{Sp}(4)$ hyper-color gauge group with 5 Weyl fermions ψ_i in the anti-symmetric and 6 Weyl fermions χ_j in the fundamental representation as underlying particles of the composite sector. This fermion sector exhibits an $\text{SU}(5) \times \text{SU}(6)$ global symmetry. Its electroweak sector has been investigated in [18, 28, 29]. The chiral condensates $\langle \psi\psi \rangle$ and $\langle \chi\chi \rangle$ spontaneously break the global symmetry to the stability group $\text{SO}(5) \times \text{Sp}(6)$. The SM color group $\text{SU}(3)_c$ is realized as a gauged $\text{SU}(3)$ subgroup of $\text{Sp}(6)$, while the weak group $\text{SU}(2)_L$ is a gauged subgroup of $\text{SO}(5)$, which also contains a custodial subgroup $\text{SO}(4) \sim \text{SU}(2)_L \times \text{SU}(2)_R$. Moreover, the $\text{U}(1)_Y$ hypercharge $Y = T_R^3 + X$ is a gauged linear combination of the diagonal generator of $\text{SU}(2)_R \subset \text{SO}(5)$ and $\text{U}(1)_X \subset \text{Sp}(6)$. In addition, the model contains two global abelian symmetries $\text{U}(1)_\chi$ and $\text{U}(1)_\psi$. One linear combination of these $\text{U}(1)$ factors is $\text{Sp}(4)$ anomaly free, and the spontaneous breaking by the condensates yields a pNGB, while the would-be pNGB associated to the orthogonal $\text{U}(1)$ combination is expected to receive a mass through the $\text{Sp}(4)$ anomaly.

This model contains three classes of pNGBs:

1. A SM singlet pNGB a from the $\text{Sp}(4)$ anomaly-free spontaneously broken $\text{U}(1)$ which is expected to be light. It couples axion-like to SM particles and we refer to [20, 30, 31] for studies of collider bounds.
2. 14 pNGBs in the electroweak sector in the **14** of $\text{SO}(5)$, which decomposes into $\mathbf{3}_1 + \mathbf{3}_0 + \mathbf{3}_{-1} + \mathbf{2}_{1/2} + \mathbf{2}_{-1/2} + \mathbf{1}_0$ under $\text{SU}(2)_L \times \text{U}(1)_Y$, with the 4 degrees of freedom in $\mathbf{2}_{1/2} + \mathbf{2}_{-1/2}$ identified as the composite Higgs doublet. This sector has been studied in [18, 28], to which we refer for further details. The main aspect relevant for the discussion below is that, after the EW symmetry breaking, the bi-triplet $\mathbf{3}_1 + \mathbf{3}_0 + \mathbf{3}_{-1}$ of $\text{SU}(2)_L \times \text{SU}(2)_R$ decomposes into a singlet η_1 , a triplet η_3 and a quintuplet η_5 of the custodial diagonal $\text{SU}(2)$.
3. 14 pNGBs in the color sector in the **14** of $\text{Sp}(6)$, which decomposes into $\mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}$ under $\text{SU}(3)_c \times \text{U}(1)_Y$. In the following we will refer to π_8 and π_3 as octet and triplet pNGBs, respectively, and refer to [21] for technical details on the embedding of $\text{SU}(3)_c$ in $\text{Sp}(6)$. The π_8 couples via the Wess-Zumino-Witten term to two gluons. Depending on the model details it can also couple to an $q\bar{q}$ pair with a strength proportional m_q/f_χ with f_χ being the decay constant related to this pNGB sector. Its phenomenology has been investigated in

ref. [32] where also mass bounds $m_{\pi_8} \gtrsim 1.1$ TeV from LHC data have been obtained. We defer possible couplings of π_3 after the presentation of the chimera hyper-baryons.

The model contains fermionic resonances (chimera hyper-baryons) in the confined phase corresponding to composite operators made of one ψ and two χ hyper-fermions. They can be classified in terms of their transformation properties under the stability group $\text{SO}(5) \times \text{Sp}(6)$, see ref. [21] for further details. We focus here on hyper-baryons transforming as **14** of $\text{Sp}(6)$ which decomposes under $\text{SU}(3)_c \times \text{U}(1)_X$ as

$$\mathbf{14} \rightarrow \mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}. \quad (1)$$

Here we have fixed $\text{U}(1)_X$ charge such that the color-triplets can mix with the SM elementary top fields to generate partial compositeness for the top quark mass origin. The components of the **14** are embedded in the anti-symmetric matrix

$$\Psi_{\mathbf{14}} = \begin{pmatrix} -Q_3^c & -\frac{1}{2\sqrt{2}}Q_8^a \lambda^a \\ \frac{1}{2\sqrt{2}}Q_8^a (\lambda^a)^T & -Q_3 \end{pmatrix}, \quad (2)$$

where $Q_{3,ij}^{(c)} = \frac{1}{2}\epsilon_{ijk}Q_{3,k}^{(c)}$ gives correct transformations for the $\text{SU}(3)_c$ generator embedding (i.e. the diagonals transform like $\mathbf{3} \times \mathbf{3} \supset \bar{\mathbf{3}}$ and $\bar{\mathbf{3}} \times \bar{\mathbf{3}} \supset \mathbf{3}$ while the off-diagonals transform like octets). Each component Q_3 and Q_8 also transform as a fundamental of $\text{SO}(5)$:

$$Q_3 = (X_{5/3}, X_{2/3}, T_L, B_L, iT_R)^T, \quad (3a)$$

$$Q_3^c = (B_L^c, -T_L^c, -X_{2/3}^c, X_{5/3}^c, -iT_R^c)^T, \quad (3b)$$

$$Q_8 = (\tilde{G}_u^+, \tilde{G}_u^0, \tilde{G}_d^0, \tilde{G}_d^-, i\tilde{g})^T. \quad (3c)$$

The first four components transform as two doublets of $\text{SU}(2)_L$ (and a bi-doublet of $\text{SU}(2)_L \times \text{SU}(2)_R$), while the fifth is a singlet.

The couplings of the top fields to the hyper-baryons depend on the choice of three-hyper-fermion operator. More specifically, the partial compositeness couplings for the left-handed top (in the doublet $q_{L,3}$) and right-handed top t_R^c are assumed to originate from a four-fermion interaction such as

$$\frac{\xi_L}{\Lambda_t^2} \psi \chi \chi q_{L,3} \quad \text{and} \quad \frac{\xi_R}{\Lambda_t^2} \psi \chi \chi t_R^c \quad (4)$$

with the appropriate components of the hyper-fermions. Here we have chosen to couple them to the operator $\psi \chi \chi$ in the channel **(5, 15)** of $\text{SU}(5) \times \text{SU}(6)$. This choice implies the presence of the singlet baryons as well [21]:

$$Q_1 = (\tilde{h}_u^+, \tilde{h}_u^0, \tilde{h}_d^0, \tilde{h}_d^-, i\tilde{B})^T. \quad (5)$$

We note for completeness that all the hyper-baryon fields introduced so-far are 2-component Weyl spinors. Henceforth, the top partners in this model include all the components of the **14** and the singlet, as all their components couple with the top.

We see that the low energy spectrum of this model contains unusual top partners, transforming as color octets and color singlets, besides the usual top partners in eqs. (3a) and (3b). They

correspond to the following states, written in terms of 4-components spinors:

$$\text{Octoni (Dirac): } \tilde{G}^+ = \begin{pmatrix} \tilde{G}_u^+ \\ \tilde{G}_d^- \end{pmatrix}, \quad \tilde{G}^0 = \begin{pmatrix} \tilde{G}_u^0 \\ \tilde{G}_d^0 \end{pmatrix}, \quad \text{Gluoni (Majorana): } \tilde{g} = \begin{pmatrix} \tilde{g} \\ \tilde{g} \end{pmatrix}; \quad (6a)$$

$$\text{Higgsoni (Dirac): } \tilde{h}^+ = \begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_d^- \end{pmatrix}, \quad \tilde{h}^0 = \begin{pmatrix} \tilde{h}_u^0 \\ \tilde{h}_d^0 \end{pmatrix}, \quad \text{Boni (Majorana): } \tilde{B} = \begin{pmatrix} \tilde{B} \\ \tilde{B} \end{pmatrix}. \quad (6b)$$

The indices u and d indicate that the corresponding $SU(2)_L$ doublets have isospin $1/2$ and $-1/2$, respectively. The choice of the names is motivated by the fact that the states \tilde{h} , \tilde{B} and \tilde{g} have the same quantum numbers as the higgsino, bino, and gluino in supersymmetric extensions of the SM.

The low energy Lagrangian for the hyper-baryons can be worked out following the Coleman-Callan-Wess-Zumino prescription [33, 34]. This prescription needs to be adapted along the lines of [35] to include couplings to SM fermions which are implemented in incomplete representation of the $SU(5) \times SU(6)$. The details as well as the resulting Lagrangian are given in ref. [21]. It turns out that all the couplings of this Lagrangian allow to assign SM baryon number charges B to all the top partners, so that B is still preserved in the presence of top partial compositeness. This results in all the color triplets to carry $B = 1/3$, like quarks, while color octets and singlets remain neutral. Hence,

$$B = 1/3 \text{ for } Q_3, \pi_3; \quad B = 0 \text{ for } Q_8, Q_1, \pi_8. \quad (7)$$

The lightest state among the components of Q_8 , Q_1 and π_3 must be stable in absence of either baryon or lepton number violation as a consequence, as there is no matching SM final state.

3. LHC phenomenology

The LHC phenomenology of this model depends crucially on the mass hierarchy among the QCD-colored baryons, which have the largest production cross sections. They have a common mass M_{14} as they all belong to the same baryon multiplet – the **14** of $Sp(6)$ – and the mass differences are only due to the SM gauge interactions and the top couplings. The octet top partners, however, enjoy the largest pair production cross section thanks to their QCD quantum numbers, as shown in fig. 1 which is particularly important if the baryons have approximately the same mass.

A typical spectrum for the colored top partners is illustrated in Fig. 2 (left). The triplets that have charges matching the top and bottom quarks, i.e. $2/3$ and $-1/3$, receive large positive corrections due to the mixing with the top fields, which makes them heavier than the octets and the $X_{5/3}$. The mass difference between the octets and $X_{5/3}$ is due to QCD corrections and can be estimated as [21]

$$\frac{2(m_{\tilde{g}} - m_{X_{5/3}})}{m_{\tilde{g}} + m_{X_{5/3}}} \approx \frac{\alpha_S(\text{TeV})}{\alpha_{em}(\text{GeV})} \left(3 - \frac{4}{3}\right) r \sim 1.4\%. \quad (8)$$

Here we have used $r = 2\Delta m^{\text{em}}/(m_P + m_N) \simeq 6 \cdot 10^{-4}$ with $\Delta m^{\text{em}} \simeq 0.58$ MeV being the electromagnetic contribution to the proton neutron mass difference [38, 39]. This estimate confirms that the octet top partners are much more abundantly produced at the LHC compared to the usual

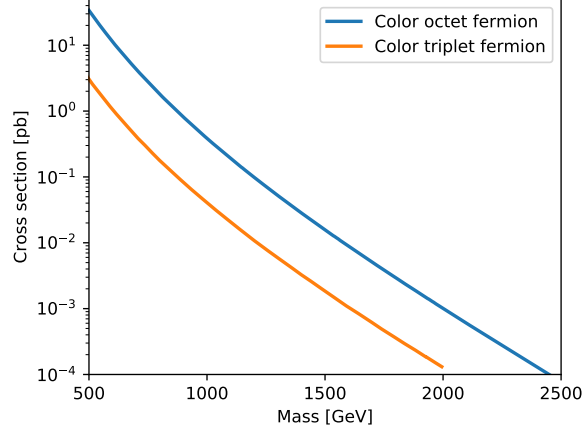


Figure 1: Comparison of the production cross sections of a color triplet top partner (at QCD NLO, from [36]) and a color octet Majorana top partner (at NNLO_{approx}+NNLL from [37]).

triplet top partners. Note that the mass difference between the octonions and the gluoninos is generated by EW corrections, which we estimate to be

$$\frac{2(m_{\tilde{G}} - m_{\tilde{g}})}{m_{\tilde{G}} + m_{\tilde{g}}} \approx \frac{3}{4} \frac{1}{\sin^2 \theta_W} r \sim 0.2\%, \quad (9)$$

where we included the dominant contribution of SU(2)_L. We note for completeness that a contribution to this mass difference is also generated by SU(5)-breaking mass differences in the ψ sector, which could go in either direction. Finally, we expect the charged octonions to be slightly heavier than the neutral one due to electroweak symmetry breaking effects.

The decay patterns of the gluoninos and the octonions depend on the mass hierarchy with the singlet top partners and the QCD-colored pNGBs. We expect the pNGBs to be lighter than the colored hyper-baryons. However, the singlet top partners receive a mass $M_1 \neq M_{14}$ from the confining strong dynamics, and the precise values can only be obtained from lattice studies. We will explore two different scenarios for M_1 . As discussed above, the lightest state among $\tilde{B}, \tilde{h}^{0,\pm}, \pi_3$ is stable unless additional baryon or lepton number violating interactions are added to the model. A stable \tilde{B}/\tilde{h}^0 provides a potential dark matter (DM) candidate if either \tilde{B} and/or \tilde{h}^0 are lighter than π_3 . In case that π_3 is lightest among these particles, a stable π_3 is not viable, and new interactions must be present, which open baryon and/or lepton number violating π_3 decay channels. Note that this could also occur if the singlet top partners are the lightest. Both cases carry resemblance with supersymmetric signatures: gluinos decaying into tops plus missing transverse energy in the first case and R-parity violating decays in the second one.

Scenarios with a DM candidate: In this scenario the singlet top partners, bionions or higgsinos, are lighter than the colored pNGBs, and cannot decay into any SM final state being the lightest hyper-baryons. We note, that the top partners \tilde{h}^0, \tilde{h}^+ and \tilde{B} and the pNGB π_3 have quantum numbers resembling the higgsino-bino and right-handed stop sectors of supersymmetric models. Their phenomenology depends on the mass hierarchy among them and, considering only electroweak

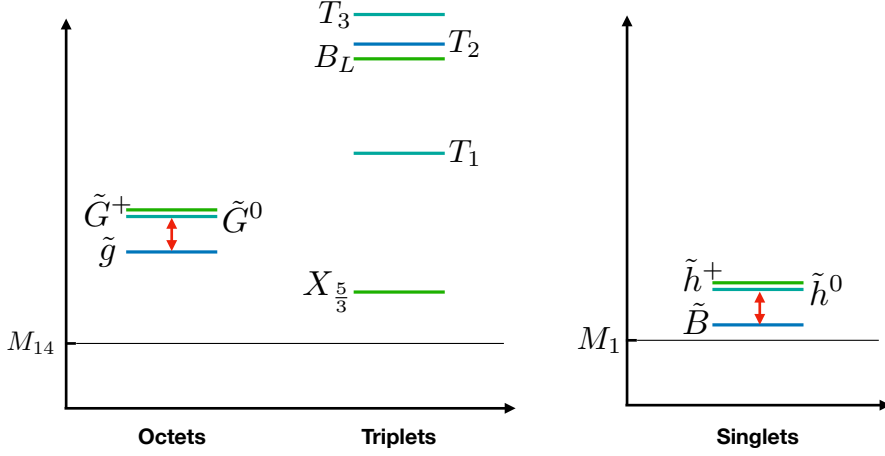


Figure 2: Template spectrum of the chimeria baryon states, where $T_{1,2,3}$ (B_L) are the mass eigenstates with the same charge as the top (bottom) quark. They receive a positive mass shift due to the mixing with the top quark. The mass splitting highlighted by the red arrow can also receive significant contribution from the different masses in the ψ sector.

interactions, one finds

$$m_{\tilde{h}^+} \gtrsim m_{\tilde{h}^0} > m_{\tilde{B}}, \quad (10)$$

as shown in fig. 2 (right) with a mass splitting estimated to range around $2 \cdot 10^{-4} M_1$, see eq. (9). A small mixing is also generated by electroweak symmetry breaking. However, the mass difference between the boni and the higgsoni also receives a sizeable contribution from the SU(5)-breaking mass differences between the singlet and bi-doublet hyper-fermions ψ , which could go in either direction. The most natural expectation is that the spectrum remains fairly compressed, hence we would expect \tilde{h}^+ and \tilde{h}^0 to decay into soft leptons and mesons plus \tilde{B} . Thus, all three particles would effectively contribute to the missing transverse momentum at the LHC as the soft decay products are hardly registered in the detectors. Consequently, such a scenario might be easily confused with a supersymmetric model at first glance.

The QCD-colored pNGB π_3 will decay into a SM-quark and either a boni or higgsoni as it carries baryon number:

$$\pi_3 \rightarrow t\tilde{B}, t\tilde{h}^0, b\tilde{h}^+. \quad (11)$$

This resembles the decays of stops in supersymmetric models. In principle, decays into lighter families, like $c\tilde{B}$ and $u\tilde{B}$, are also possible, but in the spirit of composite Higgs models we expect those to be strongly suppressed. In the following we assume that the decay into $\tilde{B}t$ dominates. In other words, π_3 behaves exactly like a right-handed stop in supersymmetry, and LHC bounds from stop searches can be directly applied [40–42]. For large mass differences this gives a bound of about 1.3 TeV. We note for completeness, that in case of small mass difference between π_3 and \tilde{B}

three-body decays via an off-shell top-quark would become important similar to supersymmetric models [43–45].

In the scenario considered here, the decays of octet top partners $\tilde{G}^{0,+}$ and \tilde{g} lead to final states similar to those of gluinos in supersymmetric models. This applies in particular to the Majorana gluoni \tilde{g} that decays via the following channels

$$\tilde{g} \rightarrow \pi_3 \bar{t}, \pi_3^* t \rightarrow t \bar{t} \tilde{B} / t \bar{t} \tilde{h}^0 + t \bar{t} \tilde{h}^0 / b \bar{t} \tilde{h}^+ + t \bar{b} \tilde{h}^- \quad \text{and/or} \quad \tilde{g} \rightarrow \pi_8 \tilde{B} \rightarrow t \bar{t} \tilde{B} / g g \tilde{B}, \quad (12)$$

depending on the mass spectrum. In all cases the final states contain large missing transverse momentum caused by the assumed stability of \tilde{B} . Consequently, gluino searches at the LHC can be used to constrain these scenarios. A similar comment applies in case of the Dirac states \tilde{G}^0 and \tilde{G}^+ , which can decay into the following channels

$$\tilde{G}^0 \rightarrow \pi_3 \bar{t} \rightarrow t \bar{t} \tilde{B} / t \bar{t} \tilde{h}^0 / b \bar{t} \tilde{h}^+ \quad \text{and/or} \quad \tilde{G}^0 \rightarrow \pi_8 \tilde{h}^0 \rightarrow t \bar{t} \tilde{h}^0 / g g \tilde{h}^0; \quad (13a)$$

$$\tilde{G}^+ \rightarrow \pi_3 \bar{b} \rightarrow t \bar{b} \tilde{B} / t \bar{b} \tilde{h}^0 / b \bar{b} \tilde{h}^+ \quad \text{and/or} \quad \tilde{G}^+ \rightarrow \pi_8 \tilde{h}^+ \rightarrow t \bar{t} \tilde{h}^+ / g g \tilde{h}^+. \quad (13b)$$

We note for completeness, that \tilde{G}^0 resembles a Dirac gluino in extended SUSY models [46, 47], while the charged octoni \tilde{G}^+ is a novel state from composite models without a supersymmetric analogue. Moreover, we note that for a fixed mass the QCD production cross sections fulfil the relation

$$\sigma(pp \rightarrow \tilde{G}^0 \tilde{G}^0) = \sigma(pp \rightarrow \tilde{G}^+ \tilde{G}^-) = 2\sigma(pp \rightarrow \tilde{g} \tilde{g}). \quad (14)$$

Scenarios without a DM candidate: If π_3 is lighter than \tilde{B} , lepton or baryon number violating interactions need to be included in order to avoid a stable π_3 . The simplest possibilities are

$$\pi_3 \rightarrow \bar{d}_i \bar{d}_j \quad \text{with } d_i = d, s, b \text{ and } i \neq j \quad (15)$$

or

$$\pi_3 \rightarrow u_i \nu_{l_j}, d_i l_j \quad \text{with } u_i = u, c, t \text{ and } l_j = e, \mu, \tau. \quad (16)$$

The former violates baryon number whereas the latter violates lepton number. Note, that only one of the two interaction types can be present as otherwise the proton could decay at a rate incompatible with experiment. This scenario corresponds to typical R-parity violating supersymmetric models for stop decays. However, we stress that the origin of these couplings is very different from the supersymmetric case and no R-parity analogue exists in composite models.

The QCD-singlet top partners \tilde{h}^0 , \tilde{h}^+ and \tilde{B} can decay according to

$$\tilde{B} \rightarrow \pi_3^* t, \pi_3 \bar{t}; \quad \tilde{h}^0 \rightarrow \pi_3 \bar{t}; \quad \text{and} \quad \tilde{h}^+ \rightarrow \pi_3 \bar{b}. \quad (17)$$

Moreover, there could be mixing of \tilde{h}^0 and \tilde{h}^- with the left-handed leptons, extending the spirit of partial compositeness to the lepton sector. Additional decay channels into electroweak gauge bosons and pNGBs would be present, such as

$$\tilde{h}^0 \rightarrow Z \nu, W^+ l^-, h \nu, \eta_{3,5}^+ l^- \quad (18a)$$

$$\tilde{h}^+ \rightarrow W^+ \nu, Z l^+, h l^+, \eta_{3,5}^+ \nu \quad (18b)$$

$$\tilde{B} \rightarrow h \nu, \eta_{3,5}^\pm l^\mp, \quad (18c)$$

to name a few. Note that this possibility is only compatible with the π_3 decay in eq. (16), as it involves lepton number violation, and it also holds if π_3 is heavier than these states. As a consequence, final states from the decays of the color-octet baryon will contain additional jets and leptons from the new decays of π_3 and the singlet baryons, and reduced missing transverse momentum.

3.1 LHC bounds on color octet hyper-baryons

We concentrate here on the case with a stable \tilde{B} as in this case one can re-interpret gluino searches in the present context. We have seen above, that the color-octets are among the lightest color-charged hyper-baryons. Their cross-section is significantly larger compared to those of the color triplets, see fig. 1. We assume that all octet top partners $Q_8 = (\tilde{g}, \tilde{G}^{+,0})$ have the same mass. Furthermore, we assume the higgsinos $\tilde{h}^{+,0}$ to be nearly mass degenerate with the boni \tilde{B} and that they decay promptly to \tilde{B} plus soft leptons and mesons. Therefore all (color) singlet top partners $Q_1 = (\tilde{B}, \tilde{h}^{+,0})$ have a common mass scale. Moreover, we assume that π_3 decays dominantly into $t\tilde{B}$ for simplicity.

We have implemented the relevant parts of the M5 model FEYNRULES [48–50] to generate a leading-order LO UFO model as detailed in [21]. We have used MADGRAPH5_AMC@NLO [51] with the LO set of NNPDF 3.0 of parton densities [52, 53] in conjunction with PYTHIA 8 [54] to produce hadron-level events of pair-produced octet top partners with various decay modes. We have simulated events at LO and we have rescaled production cross sections for the Majorana gluoni to the NNLO_{approx}+NNLL result for gluinos with the corresponding mass of Ref.[37]. For octonis we have rescale to twice the gluino cross section, correspondingly.

We have passed the generated signal events to MADANALYSIS 5 version 1.8.44 [55–58] for detector simulation, event reconstruction based on DELPHES 3 [59] and the FASTJET [60] implementation of the anti- k_T algorithm [61], and the extractions of CL_s exclusions relative to the ATLAS and CMS searches at the LHC with $\sqrt{s} = 13$ TeV which are publicly available in the MADANALYSIS 5 PAD. The most sensitive available searches for the final states under consideration are ATLAS and CMS searches for stops and gluinos [40, 62, 63].

We will focus here on the two limiting cases where the gluoni and octoni either decay exclusively via a π_3 or via π_8 . We will also comment on the combination of both decay possibilities below. The Feynman diagrams for the dominant production cross section combined with the corresponding decays are displayed in fig. 3. The signatures are either $4t + p_T^{\text{miss}}$, $2t + 2j + p_T^{\text{miss}}$ or $4j + p_T^{\text{miss}}$ which in case of octoni production can also be accompanied by soft jets or soft leptons.

The cross section for pair production is solely a function of the octet top partner mass m_{Q_8} , but the kinematics of the processes depend in addition on the boni mass m_{Q_1} and the mass of the involved color pNGB, either m_{π_3} or m_{π_8} , leaving us with 4 relevant mass parameters. To present results, we chose three kinematically different setups: For setup (i) the mass difference $m_{Q_8} - m_{\pi_3} = 200$ GeV is fixed. In this case the t/b of the Q_8 decay has little momentum in the Q_8 rest-frame. For setup (ii) we fix $m_{\pi_3} = 1.4$ TeV such that present bounds from stop searches are satisfied [40–42]. In setup (iii) we consider decays into π_8 with $m_{\pi_8} = 1.1$ TeV which is at the level of current experimental constraints on m_{π_8} [32]. In this setup we consider two limiting cases, namely that the π_8 decays either solely into gg or solely into $t\bar{t}$. We scan in all setups over m_{Q_8} and m_{Q_1} .

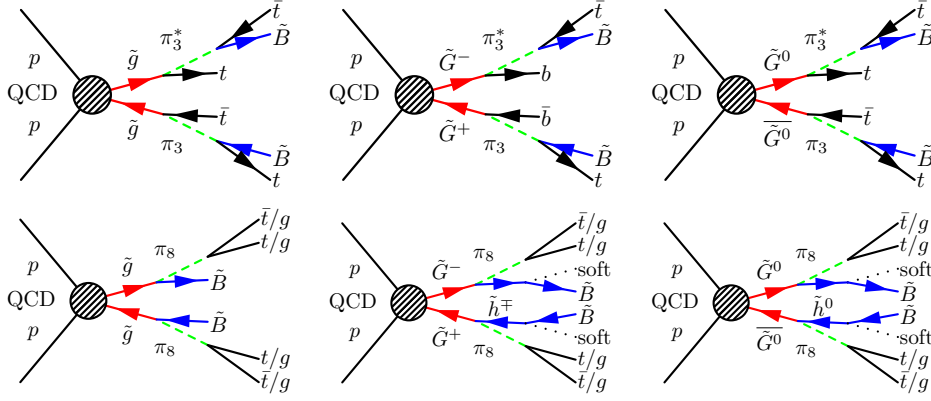


Figure 3: Feynman diagrams of QCD pair production of octet top partners $Q_8 = (\tilde{g}, \tilde{G}^+, \tilde{G}^0)$ with dominant decays $Q_8 \rightarrow \pi_3 + t/b$ (upper row) or with dominant decays $Q_8 \rightarrow Q_1\pi_8$ (lower row).

Figure 4 shows the resulting bounds for the different cases. For each scan point, we have generated 10^5 events which were analysed with LHC searches available in MADANALYSIS 5. In most of the parameter space, the leading bounds arise from the CMS search focusing on multi jets plus missing transverse momentum [40]. The black and grey lines show the obtained 95% and 68% CL exclusion boundaries, below which singlet and octet fermion masses are excluded. The upper row of this figure shows the case where the octet fermions decay into $\pi_3 + t/b$ with $\pi_3 \rightarrow t\tilde{B}$. We obtain a bound of about 2.65 TeV on the color octet top partner scale m_{Q_8} for light \tilde{B} . The lower row shows the case where Q_8 decays into $\pi_8 + p_T^{\text{miss}}$ and π_8 decays either into gg (left plot) or $t\bar{t}$ (right plot). For light \tilde{B} we obtain in case of $\pi_8 \rightarrow gg$ a bound on the octet fermion of about 2.75 TeV and in case of $\pi_8 \rightarrow t\bar{t}$ of about 2.7 TeV. This clearly shows that decay products of the π_8 are of lesser importance for this kinematical configuration. However, the plots of the lower row show clear the impact of the kinematics in case that the octet and singlet hyper-baryons have close masses. We also note that depend only weakly on the decays of the Q_8 and, thus, one obtains similar bounds in case that both decay channels, π_3 and π_8 , are of equal importance, see ref. [21] for further details. This finding is non-trivial as the kinematics of the decays are very different.

4. Conclusions

We have explored the collider phenomenology of composite Higgs models with a fermionic UV completion. As a particular example we have focused on the so-called M5 model class. A peculiar feature of this model is that the hyper-baryon spectrum contains color-octet fermionic states. They are predicted to be among the lightest top partners and, thus, play the leading role in the LHC phenomenology of this model. We have presented the generic phenomenological features of this model. We have seen that, in scenarios where both lepton and baryon number are conserved, the color singlet top partners can be potentially dark matter candidates. As a consequence the color octet top partners share several features of gluinos in SUSY models with conserved R-parity. This has allowed us to use existing recast tools to obtain mass bounds of up to about 2.7 TeV on these fermions due to existing LHC analyses. The usual color triplet top partners are expected to be in

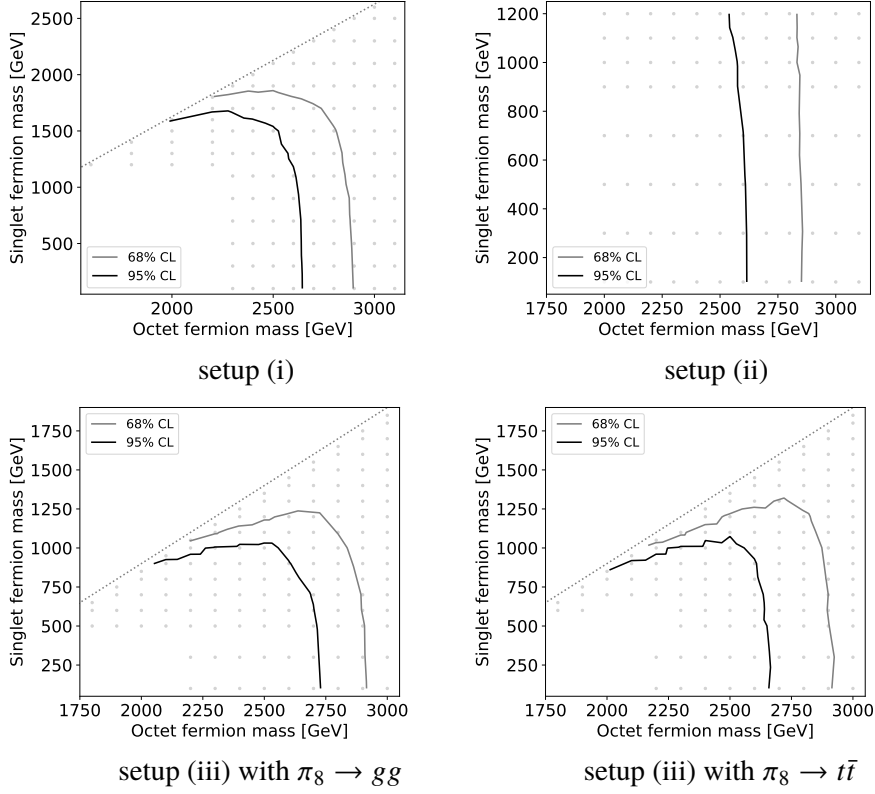


Figure 4: Bounds on the fermion masses for QCD pair production of an octet fermion Q_8 in the m_{Q_8} - m_{Q_1} plane for different setups: setup (i) Q_8 subsequent decay to a SM third generation quark t/b and π_3 with $m_{Q_8} - m_{\pi_3} = 200$ GeV; setup (ii) Q_8 subsequent decay to a SM third generation quark t/b and π_3 with fixed $m_{\pi_3} = 1.4$ TeV; setup (iii) Q_8 decaying to π_8 with either $\pi_8 \rightarrow gg$ (left) or $\pi_8 \rightarrow t\bar{t}$ (right) and fixed $m_{\pi_8} = 1.1$ TeV. Plots are taken from ref. [21].

the same mass range or even heavier than the octet baryons, which would be an explanation of the null results in the direct LHC searches for these states.

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