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.

Corfu Summer Institute 2021 "School and Workshops on Elementary Particle Physics and Gravity"  
29 August - 9 October 2021  
Corfu, Greece

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).
1. Introduction

The Standard Model (SM) is quite some success story which while been challenged in several experiments shows are 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 counterpart 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 an, 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 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 Sp(4) hyper-color gauge group with 5 Weyl fermions ψi in the anti-
symmetric and 6 Weyl fermions χj in the fundamental representation as underlying particles of the
composite sector. This fermion sector exhibits an SU(5) × SU(6) global symmetry. Its electroweak
sector has been investigated in [18, 28, 29]. The chiral condensates ⟨ψψ⟩ and ⟨χχ⟩ spontaneously
break the global symmetry to the stability group SO(5) × Sp(6). The SM color group SU(3)c is
realized as a gauged SU(3) subgroup of Sp(6), while the weak group SU(2)L is a gauged subgroup
of SO(5), which also contains a custodial subgroup SO(4) ∼ SU(2)L × SU(2)R. Moreover,
the U(1)Y hypercharge Y = T3R + X is a gauged linear combination of the diagonal generator of
SU(2)R ⊂ SO(5) and U(1)X ⊂ Sp(6). In addition, the model contains two global abelian symmetries
U(1)ψ and U(1)χ. One linear combination of these U(1) factors is Sp(4) anomaly free, and
the spontaneous breaking by the condensates yields a pNGB, while the would-be pNGB associated
to the orthogonal U(1) combination is expected to receive a mass through the Sp(4) anomaly.

This model contains three classes of pNGBs:

1. A SM singlet pNGB a from the Sp(4) anomaly-free spontaneously broken 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 SO(5), which decomposes into 31 + 30 +
   3−1 + 21/2 + 2−1/2 + 10 under SU(2)L × U(1)Y, with the 4 degrees of freedom in 21/2 + 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 31 + 30 + 3−1 of SU(2)L × SU(2)R decomposes into
   a singlet η1, a triplet η3 and a quintuplet η5 of the custodial diagonal SU(2).

3. 14 pNGBs in the color sector in the 14 of Sp(6), which decomposes into 80 + 32/3 + 3−2/3
   under SU(3)c × U(1)Y. In the following we will refer to π8 and π3 as octet and triplet pNGBs,
   respectively, and refer to [21] for technical details on the embedding of SU(3)c in Sp(6).
The π8 couples via the Wess-Zumino-Witten term to two gluons. Depending on the model
details it can also couple to an q̄q pair with a strength proportional m_q/f_x with f_x being
the decay constant related to this pNGB sector. Its phenomenology has been investigated in
ref. [32] where also mass bounds \( m_{\pi_3} \gtrsim 1.1 \text{ TeV} \) from LHC data have been obtained. We defer possible couplings of \( \pi_3 \) 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 \( \psi \) and two \( \chi \) 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

\[
14 \rightarrow 8_0 + 3_2/3 + \bar{3}_{-2/3}.
\]

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

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

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

\[
Q_3 = (X_{3/3}, X_{2/3}, T_L, B_L, i T_R)^T,
\]

\[
Q_3^c = (B_L^c, -T_L^c, -X_{2/3}^c, X_{3/3}^c, -i T_R^c)^T,
\]

\[
Q_8 = (\tilde{G}_u, \tilde{G}_u^0, \tilde{G}_d, \tilde{G}_d^0, i \tilde{g})^T.
\]

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

\[\frac{\bar{\xi}_L}{\Lambda_1^2} \psi \chi \chi q_{L,3} \text{ and } \frac{\bar{\xi}_R}{\Lambda_2^2} \psi \chi \chi t_R^c\]

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]:

\[
Q_1 = (\tilde{h}_u, \tilde{h}_u^0, \tilde{h}_d, \tilde{h}_d^0, i B)^T.
\]

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
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 \( \tilde{h}, \tilde{g} \) and \( \tilde{B} \) 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\cite{33,34}. This prescription needs to be adapted along the lines of \cite{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.\cite{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,

\[
B = 1/3 \quad \text{for} \quad Q_3, \pi_3; \quad B = 0 \quad \text{for} \quad Q_8, Q_1, \pi_8.
\]

The lightest state among the components of \( Q_8, Q_1 \) and \( \pi_3 \) 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 been estimated as \cite{21}

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

Here we have used \( r = 2\Delta m_{em}^2/(m_P + m_N) \approx 6 \cdot 10^{-4} \) with \( \Delta m_{em}^2 \approx 0.58 \text{ MeV} \) being the electromagnetic contribution to the proton neutron mass difference\cite{38,39}. This estimate confirms that the octet top partners are much more abundantly produced at the LHC compared to the usual
triplet top partners. Note that the mass difference between the octonitis and the gluoni is generated by EW corrections, which we estimate to be

$$\frac{2(m_G - m_G)}{m_G + m_G} \approx \frac{3}{4 \sin^2 \theta_W} r \sim 0.2\%,$$

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 octoniti to be slightly heavier than the neutral one due to electroweak symmetry breaking effects.

The decay patterns of the gluoni and the octoniti 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 $\tilde{B}, \tilde{h}^0, \pi_3$ 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 $\pi_3$. In case that $\pi_3$ is lightest among these particles, a stable $\pi_3$ is not viable, and new interactions must be present, which open baryon and/or lepton number violating $\pi_3$ 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, boni or higgonis, 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 $\tilde{h}^0, \tilde{h}^+ \tilde{h}^0$ and $\tilde{B}$ and the pNGB $\pi_3$ 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
interactions, one finds

$$m_{\tilde{h}^+} \geq m_{\tilde{h}^0} > m_{\tilde{B}},$$

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 bino and the higgsonis also receives a sizeable contribution from the SU(5)-breaking mass differences between the singlet and bi-doublet hyper-fermions $\psi$, 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 $\pi_3$ will decay into a SM-quark and either a bino or higgson as it carries baryon number:

$$\pi_3 \to t\tilde{B}, t\tilde{h}^0, b\tilde{h}^+.$$  \hspace{0.5cm} (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, $\pi_3$ 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 fore completeness, that in case of small mass difference between $\pi_3$ 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 $\tilde{G}^0, \tilde{g}$ lead to final states similar to those of gluinos in supersymmetric models. This applies in particular to the Majorana gluon $\tilde{g}$ that decays via the following channels

$$\tilde{g} \to \pi_3 \tilde{t}, \pi_3^* \tilde{t} \to t \bar{t} \tilde{B} / t \bar{t} \tilde{h}_0 / b \tilde{h}_0^+ + t \bar{b} \tilde{h}^+ \text{ and/or } \tilde{g} \to \pi_8 \tilde{B} \to t \bar{t} \tilde{B} / g \tilde{g} \tilde{B}, \quad (12)$$

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

$$\tilde{G}^0 \to \pi_3 \tilde{t} \to t \bar{t} \tilde{B} / t \bar{t} \tilde{h}_0 / b \tilde{h}_0^+ \text{ and/or } \tilde{G}^0 \to \pi_8 \tilde{h}_0 \to t \bar{t} \tilde{h}_0^0 / g \tilde{g} \tilde{h}_0^0; \quad (13a)$$

$$\tilde{G}^+ \to \pi_3 \tilde{b} \to t \bar{b} \tilde{B} / t \bar{b} \tilde{h}_0^0 / b \tilde{h}_0^+ \text{ and/or } \tilde{G}^+ \to \pi_8 \tilde{h}_0^+ \to t \bar{t} \tilde{h}_0^0 / g \tilde{g} \tilde{h}_0^+. \quad (13b)$$

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 fulfill the relation

$$\sigma(p p \to \tilde{G}^0 \overline{\tilde{G}^0}) = \sigma(p p \to \tilde{G}^+ \overline{\tilde{G}^+}) = 2 \sigma(p p \to \tilde{g} \overline{\tilde{g}}). \quad (14)$$

**Scenarios without a DM candidate:** If $\pi_3$ is lighter than $\tilde{B}$, lepton or baryon number violating interactions need to be included in order to avoid a stable $\pi_3$. The simplest possibilities are

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

or

$$\pi_3 \to u_i \nu \tilde{d}_j \quad \text{with } u_i = u, c, t \text{ and } l_j = e, \mu, \tau. \quad (16)$$

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 $\tilde{h}_0^0, \tilde{h}_0^+$ and $\tilde{B}$ can decay according to

$$\tilde{B} \to \pi_3 \tilde{t}, \quad \tilde{h}_0^0 \to \pi_3 \tilde{t}; \quad \text{and } \tilde{h}_0^+ \to \pi_3 \tilde{b}. \quad (17)$$

Moreover, there could be mixing of $\tilde{h}_0^0$ and $\tilde{h}_0^+$ 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

$$\tilde{h}_0^0 \to Z \nu, W^+ l^-, h \nu, \eta_{3,5}^- l^- \quad (18a)$$

$$\tilde{h}_0^+ \to W^+ \nu, Z l^+, h l^+, \eta_{3,5}^+ \nu \quad (18b)$$

$$\tilde{B} \to h \nu, \eta_{3,5}^\pm l^\mp. \quad (18c)$$
to name a few. Note that this possibility is only compatible with the $\pi_3$ decay in eq. (16), as it involves lepton number violation, and it also holds if $\pi_3$ 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 $\pi_3$ 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 $Q_8 = (\tilde{g}, \tilde{G}^+, \tilde{0})$ have the same mass. Furthermore, we assume the higgsino $\tilde{h}^{+,0}$ 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 $\pi_3$ decays dominantly into $t\bar{t}$ 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 gluon to the NNLOapprox+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 $C_L$ 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 gluino and octoni either decay exclusively via a $\pi_3$ or via $\pi_8$. 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 $m_{\pi_3}$ or $m_{\pi_8}$, 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 $\pi_8$ with $m_{\pi_8} = 1.1$ TeV which is at the level of current experimental constraints on $m_{\pi_3}$ [32]. In this setup we consider two limiting cases, namely that the $\pi_8$ 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 $Q_8 \rightarrow \pi_3 + t/\bar{b}$ (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 $\pi_3 + t/\bar{b}$ with $\pi_3 \rightarrow t \bar{B}$. We obtain a bound of about 2.65 TeV on the color octet top partner scale $m_{Q_8}$ for light $\bar{B}$. The lower row shows the case where $Q_8$ decays into $\pi_8 + p_T^{\text{miss}}$ and $\pi_8$ decays either into $gg$ (left plot) or $tt$ (right plot). For light $\bar{B}$ we obtain in case of $\pi_8 \rightarrow gg$ a bound on the octet fermion of about 2.75 TeV and in case of $\pi_8 \rightarrow tt$ of about 2.7 TeV. This clearly shows that decay products of the $\pi_8$ 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, $\pi_3$ and $\pi_8$, 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 $\pi_3$ with $m_{Q_8} - m_{\pi_3} = 200$ GeV; setup (ii) $Q_8$ subsequent decay to a SM third generation quark $t/b$ and $\pi_3$ with fixed $m_{\pi_3} = 1.4$ TeV; setup (iii) $Q_8$ decaying to $\pi_8$ 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.

Acknowledgements

This work has been supported by the “DAAD, Frankreich” PROCOPE 2021-2023, project number 57561441.

References

[1] G. Aad et al. [ATLAS], Phys. Lett. B 716 (2012), 1-29 [arXiv:1207.7214 [hep-ex]].
[2] S. Chatrchyan et al. [CMS], Phys. Lett. B 716 (2012), 30-61 [arXiv:1207.7235 [hep-ex]].
[3] D. B. Kaplan and H. Georgi, Phys. Lett. B 136 (1984), 183-186
[4] D. B. Kaplan, Nucl. Phys. B 365 (1991), 259-278
[5] R. Contino, Y. Nomura and A. Pomarol, Nucl. Phys. B 671 (2003), 148-174 [arXiv:hep-ph/0306259 [hep-ph]].

[6] K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B 719 (2005), 165-187 [arXiv:hep-ph/0412089 [hep-ph]].

[7] R. Contino, [arXiv:1005.4269 [hep-ph]].

[8] B. Bellazzini, C. Csáki and J. Serra, Eur. Phys. J. C 74 (2014) no.5, 2766 [arXiv:1401.2457 [hep-ph]].

[9] G. Panico and A. Wulzer, Lect. Notes Phys. 913 (2016), [arXiv:1506.01961 [hep-ph]].

[10] G. Cacciapaglia and F. Sannino, JHEP 04 (2014), 111 [arXiv:1402.0233 [hep-ph]].

[11] G. Cacciapaglia, C. Pica and F. Sannino, Phys. Rept. 877 (2020), 1-70 [arXiv:2002.04914 [hep-ph]].

[12] M. J. Dugan, H. Georgi and D. B. Kaplan, Nucl. Phys. B 254 (1985), 299-326

[13] J. Galloway et al., JHEP 10 (2010), 086 [arXiv:1001.1361 [hep-ph]].

[14] J. Barnard, T. Gherghetta and T. S. Ray, JHEP 02 (2014), 002 [arXiv:1311.6562 [hep-ph]].

[15] G. Ferretti and D. Karateev, JHEP 03 (2014), 077 [arXiv:1312.5330 [hep-ph]].

[16] L. Vecchi, JHEP 02 (2017), 094 [arXiv:1506.00623 [hep-ph]].

[17] G. Ferretti, JHEP 06 (2016), 107 [arXiv:1604.06467 [hep-ph]].

[18] A. Banerjee, et al. [arXiv:2203.07270 [hep-ph]].

[19] N. Bizot, G. Cacciapaglia and T. Flacke, JHEP 06 (2018), 065 [arXiv:1803.00021 [hep-ph]].

[20] A. Belyaev et al., JHEP 01 (2017), 094 [erratum: JHEP 12 (2017), 088] [arXiv:1610.06591 [hep-ph]].

[21] G. Cacciapaglia et al., JHEP 02 (2022), 208 [arXiv:2112.00019 [hep-ph]].

[22] Ed Bennett et al., JHEP 03 (2018), 185 [arXiv:1712.04220 [hep-lat]].

[23] Ed Bennett et al., JHEP 12 (2019), 053 [arXiv:1909.12662 [hep-lat]].

[24] Ed Bennett et al., Phys. Rev. D 101 (2020) no.7, 074516 [arXiv:1912.06505 [hep-lat]].

[25] N. Bizot et al., Phys. Rev. D 95 (2017) no.7, 075006 [arXiv:1610.09293 [hep-ph]].

[26] J. Erdmenger et al., JHEP 02 (2021), 058 [arXiv:2010.10279 [hep-ph]].

[27] J. Erdmenger et al., Phys. Rev. Lett. 126 (2021) no.7, 071602 [arXiv:2009.10737 [hep-ph]].

[28] A. Agugliaro et al., JHEP 02 (2019), 089 [arXiv:1808.10175 [hep-ph]].
29. A. Banerjee, D. B. Franzosi and G. Ferretti, JHEP 03 (2022), 200 [arXiv:2202.00037 [hep-ph]].

30. G. Cacciapaglia et al., Front. in Phys. 7 (2019), 22 [arXiv:1902.06890 [hep-ph]].

31. D. Buarque Franzosi et al., Eur. Phys. J. C 82 (2022) no.1, 3 [arXiv:2106.12615 [hep-ph]].

32. G. Cacciapaglia et al., JHEP 05 (2020), 027 [arXiv:2002.01474 [hep-ph]].

33. S. R. Coleman, J. Wess and B. Zumino, Phys. Rev. 177 (1969), 2239.

34. C. G. Callan, Jr. et al., Phys. Rev. 177 (1969), 2247.

35. D. Marzocca, M. Serone and J. Shu, JHEP 08 (2012), 013 [arXiv:1205.0770 [hep-ph]].

36. B. Fuks and H. S. Shao, Eur. Phys. J. C 77 (2017) no.2, 135 [arXiv:1610.04622 [hep-ph]].

37. W. Beenakker et al., JHEP 12 (2016), 133 [arXiv:1607.07741 [hep-ph]].

38. S. Borsanyi et al., Science 347 (2015), 1452-1455 [arXiv:1406.4088 [hep-lat]].

39. J. Gasser, H. Leutwyler and A. Rusetsky, Phys. Lett. B 814 (2021), 136087 [arXiv:2003.13612 [hep-ph]].

40. A. M. Sirunyan et al. [CMS], JHEP 10 (2019), 244 [arXiv:1908.04722 [hep-ex]].

41. G. Aad et al. [ATLAS], JHEP 04 (2021), 174 [arXiv:2012.03799 [hep-ex]].

42. A. Tumasyan et al. [CMS], Eur. Phys. J. C 81 (2021) no.11, 970 doi:10.1140/epjc/s10052-021-09721-5 [arXiv:2107.10892 [hep-ex]].

43. W. Porod and T. Wöhrmann, Phys. Rev. D 55 (1997), 2907-2917 [erratum: Phys. Rev. D 67 (2003), 059902] [arXiv:hep-ph/9608472 [hep-ph]].

44. W. Porod, Phys. Rev. D 59 (1999), 095009 [arXiv:hep-ph/9812230 [hep-ph]].

45. C. Boehm, A. Djouadi and Y. Mambrini, Phys. Rev. D 61 (2000), 095006 [arXiv:hep-ph/9907428 [hep-ph]].

46. S. Y. Choi et al., Phys. Rev. D 78 (2008), 095007 [arXiv:0808.2410 [hep-ph]].

47. K. Benakli et al., Phys. Rev. D 90 (2014) no.4, 045017 [arXiv:1403.5122 [hep-ph]].

48. A. Alloul et al., Comput. Phys. Commun. 185 (2014), 2250-2300 [arXiv:1310.1921 [hep-ph]].

49. N. D. Christensen et al., Eur. Phys. J. C 71 (2011), 1541 [arXiv:0906.2474 [hep-ph]].

50. C. Degrande et al., C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer and T. Reiter, Comput. Phys. Commun. 183 (2012), 1201-1214 [arXiv:1108.2040 [hep-ph]].

51. J. Alwall et al., JHEP 07 (2014), 079 [arXiv:1405.0301 [hep-ph]].
[52] R. D. Ball et al. [NNPDF], JHEP 04 (2015), 040 [arXiv:1410.8849 [hep-ph]].

[53] A. Buckley et al., Eur. Phys. J. C 75 (2015), 132 [arXiv:1412.7420 [hep-ph]].

[54] T. Sjöstrand et al., Comput. Phys. Commun. 191 (2015), 159-177 [arXiv:1410.3012 [hep-ph]].

[55] E. Conte, B. Fuks and G. Serret, Comput. Phys. Commun. 184 (2013), 222-256 [arXiv:1206.1599 [hep-ph]].

[56] E. Conte et al., Eur. Phys. J. C 74 (2014) no.10, 3103 [arXiv:1405.3982 [hep-ph]].

[57] B. Dumontet al., Eur. Phys. J. C 75 (2015) no.2, 56 [arXiv:1407.3278 [hep-ph]].

[58] E. Conte and B. Fuks, Int. J. Mod. Phys. A 33 (2018) no.28, 1830027 [arXiv:1808.00480 [hep-ph]].

[59] J. de Favereau et al. [DELPHES 3], JHEP 02 (2014), 057 [arXiv:1307.6346 [hep-ex]].

[60] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C 72 (2012), 1896 [arXiv:1111.6097 [hep-ph]].

[61] M. Cacciari, G. P. Salam and G. Soyez, JHEP 04 (2008), 063 [arXiv:0802.1189 [hep-ph]].

[62] ATLAS coll., ATLAS-CONF-2019-040.

[63] ATLAS coll., ATLAS-CONF-2018-041.