Thomas Flacke [IBS CTPU, Daejeon](http://ctpu.ibs.re.kr/html/ctpu_en/home/home_0101.html) **Exotic top partner decays: search gaps and opportunities**

Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, H. Serodio, A. Parolini [\[JHEP 1701, 094\]](http://inspirehep.net/record/1493857) G. Cacciapaglia, G. Ferretti,T. Flacke, H. Serodio [\[EPJC 78 \(2018\) no.9, 724](http://inspirehep.net/record/1633600)] G. Cacciapaglia, G. Ferretti,T. Flacke, H. Serodio [\[arXiv:1902.06890](http://inspirehep.net/record/1720828)] N. Bizot, G. Cacciapaglia, T. Flacke [[JHEP 1806, 065](http://inspirehep.net/record/1658051)] Ke-Pan Xi, G. Cacciapaglia, T. Flacke [\[arXiv:1907.05894](http://inspirehep.net/record/1744126)] G. Cacciapaglia, T. Flacke, Myeonghun Park, Mengchao Zhang [\[arXiv:1908.07524](https://arxiv.org/abs/1908.07524)]

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asia pacific center for theoretical physics

Outline typically dominates. Note that below the *W* mass, the decays into a virtual *W* boson \blacksquare $\mathbf v$ we will note that, which here. It should also be noted that, which has not consider that, which has no team $\mathbf v$

Below the *t*¯*b* threshold, ⁺ mostly decays into *W*+: this is due both to the suppression

• Vector-like quarks (VLQs): 1. Singlet pseudo-scalar, *T* ! *t a* and *B* ! *b a*. The presence of a light CP-odd

that can strongly a \sim

fermion–scalar bound states $\frac{2}{4}$

• A theory motivation for VLQs: (Underlying models of) a composite Higgs

models where the fermions are present, as described in Refs α

 \mathcal{A} and the classes of models in the literature, we identified 4 types of situations of

- VLQ decays into BSM scalars are common
- Exotic charge $2/3$ VLQ decays: $T \rightarrow t \ a, \ a \rightarrow gg \text{ or } bb$ *(substantially) reduced bounds from existing* searches. The searches but exclusively into \mathbf{r} and \mathbf{r} and \mathbf{r}
- Exotic charge 5/3 VLQ decays: $X_{5/3} \rightarrow \bar{b} \pi_6$, $X_{5/3} \rightarrow t \phi^+, X_{5/3} \rightarrow b \phi^{++}$ bounds from reinterpreting SSL searches and possible improvements. *bounds from reinterpreting SSL searches and* $t_n = t_n$ $\mathcal{L}_{\mathcal{L}}$, let us remark that the charged parameter $\mathcal{L}_{\mathcal{L}}$ that the other top the other top the other top the other top that the other top the other to

5*/*3 top partner *X*5*/*3. Note that coloured pNGB can also modify the production rates

*iD/ MX*5*/*³

for the VLQ *X*5*/*³ and the charged scalar couplings, respectively read

⌘

*X*5*/*³ +

^X

g

*^X*5*/*3*W/* ⁺*PL^t* (2.12)

• Conclusions Sec. 3.4), where it is accompanied by a double-charged scalar. The e \sim partners. The resulting new decay modes are discussed in more details in Sec. 3.4. One interesting final state that we want to mention is due to decays of a charge 2*/*3 partner in

of the VLQs, especially if \mathcal{S} is the VLQs, especially if \mathcal{S}

= *X*5*/*³

⇣

L

Vector-like quarks (top- partners or quark partners) with charge $5/3$, $2/3$, $-1/3$, $-4/3$ T_{max} correspond to T_{max} and T_{max} around the thin reduced the thin reduced limit. The t with charge 5/3, 2/3, -1/3, -4/3

 $X_{\frac{5}{3}}$ (with $X_{\frac{5}{3}}$ → tW ⁺): $M_X \ge 1.3$ TeV, [\[CMS PAS B2G-16-019,](http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-16-019/index.html) [ATLAS: 1806.01762\]](http://inspirehep.net/record/1676481) *T* & *B*: Combined bounds on pair-produced top partners

CMS bounds on pair production

Vector-like quark pair production

[[][CMS B2G Summary Plots\]](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G#B2G_Summary_Plots)

CMS bounds on single production

Vector-like quark single production

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Composite Higgs Models: Towards underlying models

A wish list to construct and classify candidate models: Underlying models of a composite Higgs should

[Gherghetta etal](http://inspirehep.net/record/1266277) (2015), [Ferretti etal](http://inspirehep.net/record/1272866) (2014), PRD 94 (2016) [no 1, 015004](http://inspirehep.net/record/1411113), [JHEP 1701, 094](http://inspirehep.net/record/1493857)

- contain no elementary scalars (to not re-introduce a hierarchy problem),
- have a simple hyper-color group,
- have a Higgs candidate amongst the pNGBs of the bound states,
- have a top-partner amongst its bound states (for top mass via partial compositeness),
- satisfy further "standard" consistency conditions (asymptotic freedom, no gauge anomalies).

The resulting models all have:

- two species of underlying fermions: ψ for EW embedding, χ for SU(3) embedding,
- several top partner multiplets $\psi \psi \chi$ or $\psi \chi \chi$ bound states,
- Several pNGBs beyond the Higgs multiplet, $\psi \psi$ and $\chi \chi$ bound states.

New PNGBs in composite Higgs models from underlying gauge-fermion theories

1. ALL models:

weak direct

 \geq O(200) GeV

≳ 1 TeV

a and *η '*:(one HC anomaly free, one anomalous pseudo-scalar) which couple to SM gauge bosons through WZW couplings and to fermions with *mf /f.* [\[PRD 94 \(2016\) no 1, 015004,](http://inspirehep.net/record/1411113) [JHEP1701,094,](http://inspirehep.net/record/1493857) [EPJC 78 \(2018\) no.9, 724](http://inspirehep.net/record/1633600), [arXiv:1902.06890\]](http://inspirehep.net/record/1720828) bounds

- 2. ALL models:
- \gtrsim 1 TeV π_8 : Color octet pseudo-scalar pNGB which couples to *gg, gy, gZ, tt* [HEP1701,094]
	- 3. Depending on the embedding model: Additional colored and uncolored pNGBs

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Top partners in CH UV embeddings $[JHEP 1806, 065]$ salt, point the *ward of the bounds addults* below the bounds show the shock and show the shock bounds show that σ **partners in CHUV embeddings**

dedicated searches are not available, collider bounds on direct production of the charged

- UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top / bottom and a pNGB are kinematically possible. \overline{U} application we chose scatter \overline{U} and above scenes with additional The material or the material problems of the subject of the charge of the charge parties of the charge of the *•* **For** *top* / bottom and a pNGB are kinematically possible. • UV embeddings of composite Higgs models come with additiona pNGBs, which are naturally lighter than the
- With an underlying model specified, relations for branching ratios of top partners to h/W/Z vs new pNGBs can be determined.
	- Scanning through the different underlying models we looked for Examing though the unicient underlying models we fooked for the exercise.
"common exotic" top partner decays and found several scenarios: ²² common exotic" top partner decays and found several scenarios
	- 1. decays of *T* (and *B)* to the singlet pseudo-scalar singlet *a,* \overline{X} ¹¹ ys on the two *b* while singlet pseudo-scalar singlet *d*, \bigcap decays of T (and R) to the singlet pseudo-scalar singlet σ
		- 2. decays of *T* to the "exclusive pseudo-scalar" η ,

of PC with a gauge-fermion underlying description \mathcal{C}

3. $X_{5/3} \rightarrow b \pi_6$ (with subsequent $\pi_6 \rightarrow t \ t$), $X_{5/3} \to t \phi^+, \quad X_{5/3} \to b \phi^+.$ $\Rightarrow \bar{h} \pi_c$ (with $\phi_{5/3} \to t \phi^+$, $X_{5/3} \to b \phi^{++}$ *^X*5*/*³ ! *tW* (with subsequent top decay to *bW*+), but with di↵erent kinematics. 3. $X_{5/3} \rightarrow \overline{b} \pi_6$ (with subsequent $\pi_6 \rightarrow t \bar{t}$), X_{σ} is X_{σ} to the coloured potential coloured points to the theory coloured points to the theory coupling to the theory coloured points to the coloured points to the coloured points to the coloured points to the c VLQs imply additional decay channels beyond the standard ones. As an example, we

As a second example for exotic decays of a charge 5*/*3 top partner, we consider a model

 $S_{\rm eff}$, where it is accompanied by a double-charged scalar. The e \sim

for the VLQ *X*5*/*³ and the charged scalar couplings, respectively read

of the VLQs, especially if heavier than them [33].

• Decays of the pNGBs yield manifold novel multi-body decay modes and **LHC** signatures. s of the pivols yield manhold hover multi-body decay modes and participation of the resulting new decay modes are discussed in S . consider a pNGB transforming as a sextet of QCD colour and with charge 4*/*3. This states in the predis yield manhold hover multi-body decay models with the exotic charge. 211 C signatures.

Common exotic VLQ decays: $T \rightarrow t a$ a lighter pseudo-scalar *a*. Such a light pseudo-scalar *a* is genuinely present in models of in Eq. (2.1) parameterises the coupling of *T* to the pseudo-scalar *a*. This term does not els common exotic VLQ decar \mathcal{P} the TCP candidate \mathcal{P}

Candidate 1: decays to the singlet pseudo-scalar singlet *a* Effective Lagrangian(s): {JHEP 1806, 065} P_{c} with a gauge-fermion is description $\frac{1}{2}$ and $\frac{1}{2}$ associated with $\frac{1}{2}$ the parameters of a global of a vector of the single potential subsettions of a vector- $S_n = \frac{1}{2} \int_0^1 \frac{1}{2} \, dx = \$ or through single-production dictated by the first three terms (*Cf. e.g.* Refs [18, 19] for complete landscape of possibilities. We show that \sim 1.1 \pm 1.1 \pm 1.1 \pm Candidate 1. decays to the singlet pseudo-scala $Effective$ Lagrangian(s) *THEP* 1806, 065 \mathcal{C} be point out that searches for di-tau resonances (which is a resonance of \mathcal{C} [[JHEP 1806, 065](http://inspirehep.net/record/1658051)]

completion, as defined in Ref. [12]. All the possible models in Ref. [12]. All the possible models in possible

$$
\mathcal{L}_{T} = \overline{T} (i\rlap{\,/}D - M_{T}) T + \left(\kappa_{W,L}^{T} \frac{g}{\sqrt{2}} \overline{T} W^{+} P_{L} b + \kappa_{Z,L}^{T} \frac{g}{2c_{W}} \overline{T} \not{\&} P_{L} t \n- \kappa_{h,L}^{T} \frac{M_{T}}{v} \overline{T} h P_{L} t + i \kappa_{a,L}^{T} \overline{T} a P_{L} t + L \leftrightarrow R + \text{ h.c.}\right),
$$
\n
$$
\mathcal{L}_{B} = \overline{B} (i\rlap{\,/}D - M_{B}) B + \left(\kappa_{W,L}^{B} \frac{g}{\sqrt{2}} \overline{B} W^{-} P_{L} t + \kappa_{Z,L}^{B} \frac{g}{2c_{W}} \overline{B} \not{\&}^{+} P_{L} b \n- \kappa_{h,L}^{B} \frac{M_{B}}{v} \overline{B} h P_{L} b + i \kappa_{a,L}^{B} \overline{B} a P_{L} b + L \leftrightarrow R + \text{ h.c.}\right).
$$

 α and the mixing angles of the mixing angles of the elementary top. If only decays into S

To illustrate the relevance of the new decay channels, we consider two benchmark

^W*,*^R ⁼ 0*.*⁰⁸ *,* ^B

^a*,*^L = 0*.*25 *,* (2.3)

$$
\mathcal{L} = \frac{1}{2} (\partial_{\mu} a)(\partial^{\mu} a) - \frac{1}{2} m_{a}^{2} a^{2} - \sum_{f} \frac{i C_{f} m_{f}}{f_{a}} a \bar{\psi}_{f} \gamma^{5} \psi_{f} \qquad (1)
$$

$$
+ \frac{g_{s}^{2} K_{g} a}{16 \pi^{2} f_{a}} G_{\mu \nu}^{a} \tilde{G}^{a \mu \nu} + \frac{g^{2} K_{W} a}{16 \pi^{2} f_{a}} W_{\mu \nu}^{i} \tilde{W}^{i \mu \nu} + \frac{g^{\prime 2} K_{B} a}{16 \pi^{2} f_{a}} B_{\mu \nu} \tilde{B}^{\mu \nu}
$$

^W*,*^L = 0*.*02 *,* ^B

the above parametrisation, the coecients *^T*

Bm1 : *M^T* = 1 TeV *,* ^T

resonance [3, 4], mostly motivated by models that fea-

 $\frac{1}{\sqrt{2}}$

 $\frac{1}{\sqrt{2}}$

In this letter, we focus on the LHC phenomenology

of a light new scalar with a mass between 10 and 100

GeV which can resonantly decay into a pair of SM par-

 $\frac{1}{\sqrt{2}}$

strained from electroweak precision measurements (indi-

rectly) and from direct searches at LEP and Tevatron. At

the LHC, besides the above mentioned di-photon chan-

nel, light (pseudo)scalars are usually searched for in the

decays of the 125 GeV Higgs boson. This search strat-

 $\frac{1}{\sqrt{2}}$

tivated by supersymmetry or 2HDMs. Below roughly

 $\frac{1}{2}$

mesons, or in experiments looking for light axion-like

particles (ALPs) [7–10]. Thus, the common lore is that

a new scalar, in order to escape detection, needs to be

Note, however, that it is enough to have small cou-

plings to electrons and to the electroweak gauge bosons

in order to escape direct LEP searches and electroweak

precision bounds, as well as small couplings to the Higgs

 $t_{\rm eff}$

ons (and heavy quarks) are less constrained, leading to

Bm2 : *M^B* = 1*.*38 TeV *,* ^B

Common exotic VLQ decays: *T*→*t a*

Examples of diagrams:

- T (and B) can be produced like "standard" top partners: QCD pair production or single production.
- New final states: MANY, depending on ma and single- or pair-production.
- For light $m_a < m_t$, gg and bb decays dominate.

For light *a*: Bounds on $pp \rightarrow TT \rightarrow t \, a \, t \, a$, with $a \rightarrow gg$ or $a \rightarrow bb$

Red: RPV-SUSY (hadronic) [CERN-EP-2015-020 \(ATLAS\)](https://cds.cern.ch/record/1993236?ln=sk) [CERN-EP-2017-298 \(ATLAS\)](https://cds.cern.ch/record/2312375?ln=en)

Recast searches Blue: VLQ search [CERN-EP-2018-031 \(ATLAS\)](https://cds.cern.ch/record/2310460?ln=en)

Gray: Excited top search [CERN-EP-2017-272 \(CMS\)](http://cds.cern.ch/record/2294721?ln=en)

 $[1908.07524]$ $[1908.07524]$ $[1908.07524]$ 11/20 The bounds on VLQ top partner masses are substantially lower when *T* decays into *t a* dominate. In particular $T \rightarrow t$ *a* $\rightarrow t$ *g g* is weakly constrained.

For light *a*: Bounds on $pp \rightarrow TT \rightarrow t \, a \, t \, h$, with $a \rightarrow gg$ or $a \rightarrow bb$

If decays into both standard and exotic channels occur, and searches are not explicitly sensitive to *T→ta,* naive bounds can be estimated.

Inclusive pair production search bounds on σ_{TT} are reduced by $\sim (1 - BR_a)$, Exclusive pair production search bounds on σ_{TT} are reduced by $(I - BR_a)^2$.

T→t h searches potentially have explicit *T→t a* sensitivity, so an explicit recast is required

[[1908.07524](https://arxiv.org/abs/1908.07524)]

CP-odd singlet ⌘ present in the *SU*(4)*/Sp*(4) ' *SO*(6)*/SO*(5) coset [31]. The charge **2011 TOP PARTIC VELY SOCCO SPACES** $Common exotic VLQ decays: $X_{5/3}$$ assumed to decrease the two $\frac{1}{\sqrt{2}}$ which yields a same signature (SSL) s Common exotic VLQ decays: *X5/3*

the decays of a charge 5*/*3 top partner *X*5*/*3. The latter is a commonly considered state

from leptonic *W* decays [96], with low SM background and thus very high sensitivity.

*X*5*/*³ is therefore an ideal target for searches at hadron colliders. Semi-leptonic decays

of *t W*⁺ have higher background but also a higher branching ratio and provide another

scalars that couple exclusively with one specific top partner, *T*e. This is the case for a

charge-4 colour sextet v � main reason behind the main reason behind the main reason behind the modify of the modifying

particles but exclusively into *t* ⌘, and it cannot be singly- but only pair-produced at

state is present in some underlying models $\{32\}$, and it can couple to the exotic charge to the exotic charge

Candidate 3: $X_{5/3} \rightarrow \overline{b} \pi_6$ (with subsequent $\pi_6 \rightarrow t t$) In models with $\frac{\Gamma(\zeta)}{\Gamma(\zeta)}$ $\Gamma(\zeta)$ heading in the solar sector. Γ and ditional decay channels between σ and the stational ones. consider a particular and with consider a sextet of α colour and with charge 4*/3.* This colour and with charge 4*/3.* This colour and with charge 4*/3. This colour and with charge 4/3. This colour and with charge 4/3.* In models with SU(6)/SO(6) breaking in the color sector. Effective Lagrangian: attractive channel. For pair-produced *X*5*/*3, the current bound on its mass is *MX*5*/*³ *>* 1*.*3 In models with $SU(0)/SU(0)$ breaking in the color sector. T_{eff} and 1.1 , $\text{CIT}(\triangle/\text{C}\triangle/\text{C})$ is possible, but 1 ³/3 is possible, but model-produced \triangle dependent in the absence of $\mathcal{O}(0)$ of $\mathcal{O}(0)$ becausing in the color sector.

$$
\mathcal{L}_{X_{5/3}}^{\pi_6} = \overline{X}_{5/3} \left(i\rlap{\,/}D - M_{X_{5/3}} \right) X_{5/3} \n+ \left(\kappa_{W,L}^X \frac{g}{\sqrt{2}} \overline{X}_{5/3} W^+ P_L t + i \kappa_{\pi_6,L}^X \overline{X}_{5/3} \pi_6 P_L b^c + L \leftrightarrow R + \text{ h.c.} \right)
$$

The sextence arises, for example, as p and p example, as part of the pNGB spectrum in U embeddings of the pNGB spectrum in U

$$
\mathcal{L}_{\pi_6} = |D_{\mu}\pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \left(i\kappa_{tt,R}^{\pi_6} \bar{t}\pi_6 (P_R t)^c + L \leftrightarrow R + \text{ h.c.} \right)
$$

that, in the model we consider, ⇡⁶ is a singlet of *SU*(2)*L*. The coupling ⇡⁶

while the one associated to the one associated to the δ couplings to S couplings to S

tops are thus suppressed by *m*²

where *b^c* and *t*

L⇡6

Common exotic VLQ decays: $X_{\frac{5}{3}}$ through ⁺ and one standard) or *tt*¯*b*¯*bWW* (for one decay through ⁺ and one

Candidate 4:
$$
X_{5/3} \rightarrow t \phi^+
$$
 and $X_{5/3} \rightarrow b \phi^{++}$

for the VLQ *X*5*/*³ and the charged scalar couplings, respectively read

In models with SU(5)/SO(5) breaking in the EW sector, we have charged (and doubly charged) pNGBs. In models with $SU(5)/SO(5)$ breaking in the EW sector, we have characterized scalar the latter arises for $\frac{1}{100}$ $\frac{v}{\sqrt{2}}$ and $\frac{v}{\sqrt{2}}$. The latter arises for example as particular to the latter of the products with $SO(3)/SO(5)$ breaking in the L w sector, we have enarged *X*⁵/ $\frac{1}{2}$ *N Y SO*(5) breaking in the EW sector, we have charged \mathcal{L}

 $S_{\rm eff}$, where it is accompanied by a doubly-charged scalar. The e 4 ective Lagrangians calar. The e 4 ective Lagrangians calar. The e 4

Effective Lagrangian: particulars. The resulting new decay modes are discussed in modes are discussed in S

$$
\mathcal{L}_{X_{5/3}}^{\phi} = \overline{X}_{5/3} \left(i\rlap{\,/}D - M_{X_{5/3}} \right) X_{5/3} + \left(\kappa_{W,L}^{X} \frac{g}{\sqrt{2}} \overline{X}_{5/3} \psi^{+} P_{L} t + i \kappa_{\phi^{+},L}^{X} \overline{X}_{5/3} \phi^{+} P_{L} t + i \kappa_{\phi^{+},L}^{X} \overline{X}_{5/3} \phi^{++} P_{L} b + L \leftrightarrow R + \text{h.c.} \right)
$$
\n
$$
\mathcal{L}_{\phi} = \sum_{\phi = \phi^{+}, \phi^{++}} \left(|D_{\mu}\phi|^{2} - m_{\phi}^{2} |\phi|^{2} \right) + \left(\frac{eg K_{W\gamma}^{\phi}}{8\pi^{2} f_{\phi}} \phi^{+} W_{\mu\nu}^{-} \tilde{B}^{\mu\nu} + \frac{g^{2} c_{w} K_{WZ}^{\phi}}{8\pi^{2} f_{\phi}} \phi^{+} W_{\mu\nu}^{-} \tilde{B}^{\mu\nu} + \frac{g^{2} K_{W}^{\phi}}{8\pi^{2} f_{\phi}} \phi^{++} W_{\mu\nu}^{-} \tilde{W}^{\mu\nu,-} + i \kappa_{tb,L}^{\phi} \frac{m_{t}}{f_{\phi}} \bar{t}_{\phi}^{+} P_{L} b + L \leftrightarrow R + \text{h.c.} \right). \tag{2.13}
$$

tb,L

f

^t+*PL^b* ⁺ *^L* \$ *^R* + h.c.◆

when *X*5*/*³ is pair-produced and both decay into this exotic channel. Di↵erent decays

interesting final state that we want to mention is due to decays of a charge 2*/*3 partner in

. (2.13)

ि संस्कृत का क्**रिकेट संस्कृत करने के संस्कृत कर**
संस्कृत

++*W*

^µ⌫*W*˜ *^µ*⌫*,* ⁺ *ⁱ*

Examples of processes:

Full list of final states from *X5/3* pair-production:

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2

Recasting the most recent CMS $X_{5/3}$ same-sign lepton search *JHEP* 1903, 082 we obtain bounds on *X5/3* pair-production with exotic *X5/3* decays:

 $[1907.05894]$ $[1907.05894]$ $[1907.05894]$

 $\boldsymbol{\phi}^{++}$

 $[1907.05894]$ $[1907.05894]$ $[1907.05894]$

Bonus Plots

The recast can also be used to constrain several exotic $T_{2/3}$ decays. (c.f. [Shu etal \(2018\)](http://inspirehep.net/record/1711794), [Benbrik etal \(2019\)](http://inspirehep.net/record/1744131) for studies of other exotic channels)

[[1907.05894](http://inspirehep.net/record/1744126)]

Some exotic decay channels provide opportunities to substantially increase sensitivity. E.g.: $X_{\frac{5}{3}} \rightarrow t\phi^+ \rightarrow tW^+ \gamma$ with a hard photon in the FS.

Conclusions

- `Exotic'' decays of top partners to $t/b + pNGBs$ rather than to $t/b + W/Z/h$ occur commonly, for example, in CH UV embeddings. These decays lead to many final states which are not explicitly targeted by current LHC searches.
- Charge 5/3 resonances: $X_{5/3}$ same-sign dilepton searches can be reinterpreted to obtain constraints on exotic *X5/3* decays. Signal efficiencies of existing searches for exotic decays are modified, but of the same order. For some of the exotic channels, substantial improvements are possible.
- Charge 2/3 resonances: We investigate the decays *T→t a* with *a → gg* or $a \rightarrow bb$. For these decays (especially for $T \rightarrow t$ $a \rightarrow t$ g g), bounds from existing searches on m_T are substantially weaker than for standard VLQ decays.

There is a lot to do!

Backup

Motivation for Vector-like quarks: a composite Higgs

An alternative solution to the hierarchy problem:

- Generate a scale $A_{HC} < < M_{pl}$ through a new confining gauge group.
- Interpret the Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector.

[[Georgi, Kaplan](http://inspirehep.net/record/193935) (1984)]

The price to pay:

- additional resonances around *ΛHC* (vectors, vector-like fermions, scalars),
- additional light pNGBs an extended sector (?).
- deviations of the Higgs couplings from their SM values of $O(v/f)$.

Example: $SU(4)/Sp(4)$ coset based on $GHC = Sp(2Nc)$ \mathscr{S} and property fundamental theory and property transformation \mathscr{S} Universe stude students and *Sp(4)* coset has under the global symmetries $\mathcal{O}(1)$.

top partners: (3*,* 2*,* 2)²*/*³ states (for *tL*) in ⁵

(3*,* 1*,* 1)²*/*³ or (3*,* 1*,* 3)²*/*³ (for *tR*) in ¹

One example: SU(4)/Sp(4) coset based on *G*HC = Sp(2*Nc*)

Underlying field content

Bound states of the model

1*,*2*,* ⁵

⁴*,* ¹⁰ and

1*,*2*,* ⁵

This is the BSM + Higgs sector which interacts with SM gauge bosons and matter through:

1*,*2*,* ³*,* ⁵

4*,* ¹⁰

fermions: *tR*-partners

 2Δ

List of "minimal" CHM UV embeddings

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[[JHEP1701,094](http://inspirehep.net/record/1493857)]

Chiral Lagrangian for the pNGBs provision for rangian for the pixcibs $\overline{\mathbf{a}}$ ngian for 1 and **...**
1 HEP1701,094 Initial Lagrangian for the pincips

 $R_{\rm eff}$ including the singlet associated with the singlet associated with the non-anomalous U(1). Here, $R_{\rm eff}$

irrep. To allow us to write a common expression for all cases, we introduce the quantity

The pseudo-Goldstones are parameterized by the Goldstone boson matrices $[JHEP1701,094]$ $[JHEP1701,094]$ $[JHEP1701,094]$ perturbation the parameterized by the condition boson

A. Chiral Lagrangian

$$
\Sigma_r = e^{i2\sqrt{2}c_5\pi_r^a T_r^a/f_r} \cdot \Sigma_{0,r} , \quad \Phi_r = e^{ic_5a_r/f_{a_r}},
$$

where $r = \psi, \chi$, π^a are the non-abelian Goldstones, T^a are the corresponding broken *^r T^b* generators, $\mathcal{L}_{0,f}$ is the E *iv* preserving vacuum, and *a* are the $\mathcal{C}(1)$ donastones where $r = \psi, \chi$, π^a are the non-abelian Goldstones, T^a are the corresponding broken generators, $\Sigma_{0,r}$ is the EW preserving vacuum, and a are the U(1) Goldstones parameterized via the Goldstone boson matrices. (c₅ is √2 for real reps and 1 otherwise). where $r = w$, χ , π^a are the non-abelian Goldstones. T^a are the corresponding broken α , π are the non-abenatic conditiones, that the corresponding broken $\sum_{i=1}^{\infty}$ is the L α preserving vacuum, and a are the $O(1)$ denotednes λ 's contain the pNGBs from the pNGBs from the non-abelian cosets, while λ

, (4)

singlets respectively. The matrix ⌃0*,r* is the EW-preserving vacuum. The lowest order chiral Lagrangian is $\mathbf{F}_{\text{max}} = \mathbf{F}_{\text{max}} + \mathbf{F}_{\text{max}}$ t order chiral Lagrangian is *f* α decay constants *f* α ^{*r*} in such a way constant of the decay constants *f* light. All mesons can therefore be described by a single meson matrix ²

of QCD where both singlets can be light, so that we introduce the parameters

Tr[*T^a*

$$
\mathcal{L}_{\chi pt} = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2} \operatorname{Tr}[(D_\mu \Sigma_r)^\dagger (D^\mu \Sigma_r)] + \frac{f_{a_r}^2}{2c_5^2} (\partial_\mu \Phi_r)^\dagger (\partial^\mu \Phi_r).
$$

where we chose the normalization such that $m_W = \frac{g}{2} f_{a\mu} \sin \theta$ where θ is the vacuum

L L^p *C Chose* **the** *n***</u>** misalignment angle. rma
C $\frac{1}{2}$ *zation* such $\frac{1}{2}f_{\psi}$ θ where θ is the vacuum N_{max} and N_{max} we chose the nature of the irrep) for N_{max} for both irrep) for both irrep) for both in both in both in the intervals of the $\frac{1}{2}$ $\int \psi$ on ψ where ψ is the raction is the large N limit, expect $f_{ax} = \sqrt{N_r} f_r$. where we chose the normalization such that $m_W = \frac{9}{2} f_\psi \sin \theta$ where θ is the vacuum *g* 2 f_{ψ} sin θ where θ is the vacuum In the large N limit, expect $f_{a_r} = \sqrt{N_r} f_r$. L ^{ptor} *r*= *,* e cl

cosets, included to the cost to the non-military significant respectively. (ratios can be estimated, but in the end only calculated
on the Lattice. simply gives a kinetic term which does not depend on *f^a^r* . However, the couplings of *a^r* will \blacksquare - The different pNGBs can have different decay constants depends on an arbitrary parameter, i.e. the charge *Q^r* of the fermions under the global **Example 10** Upshot: - The pNGBs are described in a non-linear sigma model. **(ratios can be estimated, but in the end only calculated on the Lattice.** *on the Lattice*.

f 2 ÷

Sources of masses and couplings of the pseudo Goldstone bosons: [[JHEP1701,094\]](http://inspirehep.net/record/1493857)

- 1. The SM gauge group is weakly gauged, which explicitly breaks the global symmetry. This yields mass contributions for SM charged pNGBs. As the underlying fermions are SM charged, it also yields anomaly couplings of pNGBs to SM gauge bosons.
- 2. The elementary quarks (in particular tops) need to obtain masses. This can be achieved through linear mixing with composite fermionic operators ("top partners"), which explicitly break the global symmetries.
- 3. Mass terms for the underlying fermions explicitly break the global symmetries and give (correlated) mass contributions to all pseudo Goldstones.

Weak gauging and partial compositeness is commonly used in composite Higgs models to explain the generation of a potential for the Higgs (aka EW pNGBs). On the level of the underlying fermions, such mixing requires 4-fermion operators.

What are the implications of the above points for the SM singlet, and the coloroctet pNGB?

Couplings of pNGBs to SM gauge bosons: generators depends on the global group the global group the gauge interactions are embedded in an interactions the same as for the same as for the same as for the same.

The underlying fermions are charged under the SM gauge fields, and thus ABJ anomalies induce couplings of the Goldstone bosons to the SM fields which are fully determined by the underlying quantum numbers. The underlying fermions are charged under the SM gauge fields, and thus <u>ARI</u> determined by the underlying quantum numbers.
 $\frac{1}{1}$ the underlying fem [[JHEP1701,094](http://inspirehep.net/record/1493857)]

Singlets:
$$
\mathcal{L}_{\text{WZW}} \supset \frac{\alpha_A}{8\pi} c_5 \frac{C_A^r}{f_{a_r}} \delta^{ab} a_r \ \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A^b_{\alpha\beta}
$$
,

Tr[*S^aS^b*

] = *ab*

Non-abelian pNGBs: $\mathcal{L}_{WZW} \supset \frac{\sqrt{U_A U_A}}{T} c_5 \frac{U_{AA'}}{T} c^{abc} \pi^a_{\zeta} \varepsilon^{\mu\nu\alpha\beta} A^a_{\cdots} A'$ L_{WZW} $\sqrt{\alpha_A \alpha_{A'}}$ $\frac{C_{A}C_{A}}{4\sqrt{2}\pi}c_{5}$ $C^r_{AA'}$ *fr* c^{abc} π_r^a $\varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A'^b_{\alpha\beta}$,

Cr

where where

1. Singlets

where

1. Singlets

E. West-Zumino-Witten terms and with the second with the secon

where
$$
C_{AA'}^r c^{abc} = d_r \text{Tr}[T_{\pi}^a \{S^b, S^c\}]
$$

*AA*0*cabc*

for complex *r*, and there is an additional factor of 1*/*2 for real/pseudo-real representations.

Upshot: - The couplings C^rA of pNGBs to gauge bosons are fully **Example 18 Similar 19 Set 10 Se** ⇡ *{S^b }*] (37)

- **that, in the case of interest of the cases of Branching ratios.**
	- **Only unknown parameters are decay constants fr.**

= *dr*Tr[*T^a*

, S^c

, for SU(5) () and SU(6) () ;

Couplings to tops and top mass: [JHEP1701,09 for the top, where the mass is proportional to two linear mixings of the elementary fermions of the elementary fe be realised in the class of models under consideration. If both pre-Yukawas involve the same [[JHEP1701,094](http://inspirehep.net/record/1493857)]

We want to realize top masses through partial compositeness, i.e. We want to realize top masses through partial compositeness i.e

 $\mathcal{L}_{mix} \supseteq y_L \bar{q}_L \Psi_{q_L} + y_R \bar{\Psi}_{t_R} t_R + h.c.$ $\mathcal{L}_{mix} \supseteq y_L q_L \Psi_{q_L} + y_R \Psi_{t_R} t_R + h.c.$

bound states The spurions v_L athus carry charges under the $U(1)$ where ψ are the composite top partners, depending on the model either $\psi \psi \chi$ or $\psi \chi \chi$ bound states. The spurions $y_{L,R}$ thus carry charges under the $U(1)_{\chi,\psi}$.

The top mass in partial compositeness is proportional to $y_L * y_R$ fand thus also has definite $U(1)_{\chi,\psi}$ charges $n_{\psi,\chi}$. For $\psi\psi\chi$: $U(1)_{\chi,\psi}$ charges $n_{\psi,\chi}$. For $\psi\psi\chi$: although not all the possible compositeness is proportional to $y_L^T y_R$ tand thus also has definite

couplings of the pions can then be recovered by assigning a charge to the pre-Yukawas *yL/R* y_L *,* $y_R \sim (\pm 2, 1)$ *,* $(0, -1)$ *,* $\Rightarrow m_{top} \sim (\pm 4, 2)$ *,* $(0, \pm 2)$ *,* $(\pm 2, 0)$ *,* u_r u_r $u_p \sim (+2, 1)$ $(0, -1)$ \Rightarrow $m_{\text{tan}} \sim (+4, 2)$ $(0, +2)$ $(+2, 0)$

although not all the possible cases are generated in all the models. For \sim The singlet-to-top coupling Lagrangian can be written as f_{in} airealet to top coupling I concretion can be written as

$$
\mathcal{L}_{top}=m_{\mathrm{top}}\Phi_{\psi}^{n_{\psi}}\Phi_{\chi}^{n_{\chi}}\ \bar{t}_L t_R+h.c.=m_{\mathrm{top}}\ \bar{t}t+i c_5\left(n_{\psi}\frac{a_{\psi}}{f_{a_{\psi}}}+n_{\chi}\frac{a_{\chi}}{f_{a_{\chi}}}\right)m_{\mathrm{top}}\ \bar{t}\gamma^5 t+\ldots
$$

NOTE:

- for both singlets. The couplings of the singlets tops can the singlets tops can therefore be written as α • The term that generates the top mass also generates couplings of the pNGBs to tops.
- *x* In ass also generates couplings of the pixities to tops.
 Ne n discrete set and top partner embedding, with a discrete set *ne* possible top couplings depend on the model as
noices. າd *n a* + *n* embe *f*_a
complished to the *the model* and top partner embedding, with a discrete set • The possible top couplings depend on the model and top partner embedding, with a discrete set of choices.

accommodate enough partners to realize partners to realize partners for all fermions: the Yukawa was partners for all fermions: the Yukawa

◆

◆

- For the singlet pNGBs, the coupling never vanishes as in no case $n_{\psi} = 0 = n_{\chi}$. *F_a <i>faf***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f*_{*f*}*<i>f***_{***f***}***f***_{***f***</sup>***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}***f***_{***f***}**}</sub> f_n • For the singlet pNGBs, the coupling never vanishes as in no case $n_{\psi} = 0 = n_{\chi}$.
- the analogous argument yields zero coupling of n_0 to tops if n_χ situation can nevertheless in never n_χ ², The encloseus exampt violds zero coupling. • The analogous argument yields zero coupling of π_8 to tops if $n_{\chi} = 0$.

✓

SE $\overline{\text{sh}}$ *m*top *fa xGBs couple to top-pair f^a f^a f^a f^a t ,* (19) where we recognise that the couplings of the pNGB α is proportional to the pNGB α the non-anomalous U(1). Upsnot: - pinGBs couple to top-pairs.

- there is a discrete set of possible couplings per model. **Upshot: - pNGBs couple to top-pairs.**

✓

Underlying fermion mass terms: te ImTr[*X† ^r*⌃*r*] Ė *.* (10) [[JHEP1701,094](http://inspirehep.net/record/1493857)]

f^a^r

. (10)

The SM singlet pNGBs cannot obtain mass through the weak gauging. To make them massive, we add mass terms for χ (and in principle ψ) which break the chiral symmetry. They yield mass terms

$$
\mathcal{L}_m = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2} \Phi_r^2 \text{Tr}[X_r^{\dagger} \Sigma_r] + h.c. = \sum_{r=\psi,\chi} \frac{f_r^2}{4c_5^2} \left[\cos \left(2c_5 \frac{a_r}{f_{a_r}} \right) \text{ReTr}[X_r^{\dagger} \Sigma_r] - \sin \left(2c_5 \frac{a_r}{f_{a_r}} \right) \text{ImTr}[X_r^{\dagger} \Sigma_r] \right].
$$

4*c*² 5

The spurions X_r are related to the the fermion masses linearly *r*_{*f*} α the the fermion masses linearly α

^L^m ⁼ ^X

8*c*² 5

$$
X_r = 2B_r m_r \qquad r = \psi, \chi \, ,
$$

 β is a dimensional constant β is a dimensional constant β is a dimensional constant β Note that, without loss of generality, *m^r* is a real matrix in the non-abelian flavour space of If m_r is a common mass for all underlying fermions of species r, we get corresponds to the EW preserving vacuum and where *µ^r* is a common mass for all underlying fermion mass for an

$$
m_{\pi_r}^2 = 2B_r\mu_r \,, \quad m_{a_r}^2 = 2N_r \frac{f_r^2}{f_{a_r}^2} B_r\mu_r = \xi_r \ m_{\pi_r}^2
$$

*a*_r = *masses*
a^{*r*} = *ratios* - ratios can be estimated, but calculating them needs the *f* 2 **a**^{*r*} *af a*^{*f*} *af af* *****af*** ***af*** ***af*** ***a* Upshot: - masses of singlet and non-abelian pNGBs are related.

We also note that Eq. (10) contains linear contains linear contains to the singlets to the singlets to the non-

Singlets: masses and mixing UHEP1701, \overline{C} singlets we introduce the 2 singlets we introduced, one remains a pNGB because it is associated, one remains a pNGB because it is associated, one remains a pNGB because it is associated with it is associated with to singlets in the sets of non abelian pions, specifically from the EW coset, can also be Singlets: masses and mixing $[JHEP1701,$ would require that the contribution of the fermion mass were small, i.e. *m*⇡ ⌧ *f* . This [[JHEP1701,094](http://inspirehep.net/record/1493857)]

. (8)

The states $a_{\psi, \chi}$ mix due to an anomaly w.r.t. the hyper color group which breaks $U(1)_{\psi}$ x $U(1)_{\chi}$ to $U(1)_a$. $10 U(1)$ _a.
The examply free and anomalous combinations are τ α and α and the anomalous α and the anomalous α and the anomalous α and α and α states $a_{\psi,\chi}$ mix due to an anomaly w.r.t. the hyper color group which breaks U(1) $_{\psi}$ x $_{\phi}$ t_a . the strong constraint interesting from search search with the constraint $\frac{\partial \psi}{\partial t}$ and $\frac{\partial \psi}{\partial t}$ a.
omaly free and anomalous combinations are

The anomaly free and anomalous combinations are α *f* α *d* α *f* α *d* α *f* α

$$
\tilde{a} = \frac{q_{\psi}f_{a_{\psi}}a_{\psi} + q_{\chi}f_{a_{\chi}}a_{\chi}}{\sqrt{q_{\psi}^2f_{a_{\psi}}^2 + q_{\chi}^2f_{a_{\chi}}^2}}, \quad \tilde{\eta}' = \frac{q_{\psi}f_{a_{\psi}}a_{\chi} - q_{\chi}f_{a_{\chi}}a_{\psi}}{\sqrt{q_{\psi}^2f_{a_{\psi}}^2 + q_{\chi}^2f_{a_{\chi}}^2}}.
$$

File singlet mass terms (meruding contributions from underlying termion masses) is t The singlet mass terms (including contributions from underlying fermion masses) is thus The singlet mass terms (including contributions from underlying fermion ma singlet mass terms (including contributions from underly)

$$
\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{a_{\chi}}^2 a_{\chi}^2 + \frac{1}{2} m_{a_{\psi}}^2 a_{\psi}^2 + \frac{1}{2} M_A^2 (\cos \zeta a_{\chi} - \sin \zeta a_{\psi})^2
$$

 $f_{a_{\nu}}$, \ldots *d* M _{*f*} *q f^a , f^a* = $S \, C$ *q*2 *f* ² *^a* + *q*² *f* ² *^a .* (9) where *M*² *^A* is the mass generated by instanton e↵ects, proportional to the topological susceptiwhere $\tan \zeta = \frac{4\chi J a_{\chi}}{c}$, and M_A is a mass contribution generated by instanton effects. $q_\chi f_{a_\chi}$ $q_\psi f_{a_\psi}$ $,$ and N $\ddot{}$ \bar{x} a mass contribution generated by instants \overline{I} ass contribu *a* tal

The masses of the pNGBs are the pN
1 1 ⇣ α are

of the masses, as *m*²

+ *q*²

B. Couplings

listed in Table I.

be generated by loop corrections in the chiral Lagrangian (29, 30).

The masses of the pivots are
\n
$$
m_{a/\eta'}^2 = \frac{1}{2} \left(M_A^2 + m_{a_\chi}^2 + m_{a_\psi}^2 \mp \sqrt{M_A^4 + \Delta m_{a_\chi}^4 + 2M_A^2 \Delta m_{a_\chi}^2 \cos 2\zeta} \right)
$$

chose *q*² + *q*² = 1 without loss of generality. The values of *q/q* for the various models are $\frac{1}{2}$ hogic with and the interactions in the mass eigenbasis are obtained by rotating from the $a_{\psi, \chi}$ basis into the a, η' DASIS WILLET $\left(\frac{\Delta m^2 + \Delta m^2}{\sqrt{m^2 + \Delta m^2 - \Delta m^2}}\right)^{1/2}$ with $\sqrt{2}$ as $\sqrt{2}$ as $\sqrt{2}$ as $\sqrt{2}$ as $\sqrt{2}$ basis with \setminus

2*m*²

. Note that for *m^a* ⌧ *m*⌘⁰ (*m^a* ⌧ *MA*), then

$$
\tan \alpha = \tan \zeta \left(1 - \frac{\Delta m_{\eta'}^2 + \Delta m_a^2 - \sqrt{(\Delta m_{\eta'}^2 - \Delta m_a^2)^2 - 4\Delta m_{\eta'}^2 \Delta m_a^2 \tan^{-2} \zeta}}{2\Delta m_{\eta'}^2} \right)
$$

The coupling of the singlets can only be generated by terms explicitly be generated by terms and through their mass terms. of colours is large and/or the representation of the underlying fermions is large. Another ⌘0 example of the contract of the **Upshot: - The** $\langle \chi \chi \rangle$ **and** $\langle \psi \psi \rangle$ **pNGBs mix through an anomaly** \blacksquare . Note that for *m^a* ⌧ *m*⌘⁰ (*m^a* ⌧ *MA*), then

a

↵ ⇠ ⇣ and the mass eigenstates coincide with the pNGB and the anomalous combination,

symmetries. The partial gauging of the non-abelian global symmetries cannot do the job, as

a/⌘⁰ *m*²

symmetries. The partial gauging of the non-abelian global symmetries cannot do the job, as

a/⌘⁰ = *m*²

in the EW sector, due to the EW sector, due to the condensation of the mass of

Singlet pNGB summary and phenomenology $\overline{\mathcal{O}}$ once this is fixed, all the couplings of the pseudo-scalars to SM states are fixed in terms of the pseudo-scalars to SM states are fixed in terms of the pseudo-scalars to SM states are fixed in terms of the ps properties of the unit of the unit of the unit show and

can fix it by applying the Maximal Attractive Channel (MAC) hypothesis [57], see Tab. III. see T

a and *η* ': Arise from the SSB of $U(1)_\chi \times U(1)_\psi$. One linear combination has a G_{HC} anomaly (η') and is expected heavier. The orthogonal linear combination (*a*) is a pNGB. $\phi = \{a, \eta'\}$ *a* and *n*³; Arise from the SSR of U(1) \times U(1) One linear combination has a Guo anomal parameterised as L_{eff} \supset 1 2 $\frac{1}{(\partial_{\mu}\phi)(\partial^{\mu}\phi)-\frac{1}{2}}$ 2 $m_\phi^2 \phi^2$ $+\frac{\phi}{10}$ $16\pi^2 f_\psi$ \overline{a} $g_s^2 K_g^{\phi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + g^2 K_W^{\phi} W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + g'^2 K_B^{\phi} B_{\mu\nu} \tilde{B}^{\mu\nu}$ \setminus [[arXiv:1902.06890](http://inspirehep.net/record/1720828)]

$$
-i\sum_{f} \frac{C_{f}^{\phi} m_{f}}{f_{\psi}} \phi \bar{\psi}_{f} \gamma^{5} \psi_{f}
$$

+ $\frac{2v}{f_{\psi}^{2}} K_{\phi h}^{\text{eff}} (\partial_{\mu} \phi) (\partial^{\mu} \phi) h + \frac{2m_{Z}}{f_{\psi}} K_{hZ}^{\text{eff}} (\partial_{\mu} \phi) Z^{\mu} h$

- *ma* must result from *explicit* breaking of the U(1)s*. m^η* also obtains mass from instantons.
- f_{ψ} (decay constant of the EW sector) results from chiral symmetry breaking. \mathbf{F} (decay constant of the FW sector) results from chiral symmetry breaking $J\psi$ (accay constant of the EW sector) results from enhal symmetry oreaking.
- The WZW coefficients $K\phi$ are determined by the quantum numbers of χ , ψ (and (m_a, m_η)).
	- The coefficients $C\phi_f$ are also fixed (depending on dominantly mixing top-partner).

The Lagrangian in Eq. (2) matches with a generic Axion-Like Particle (ALP) Lagrangian (ALP) Lagrangian (SI) La

- *h* $\phi\phi$ and *h* ϕ *Z* couplings are induced at 1-loop order. *induced at 1-loop order.*
- *a* and *η'* are produced in gluon fusion.
- The resonances are narrow.

with *F*˜*µ*⌫

constant

Production cross section for a pseudo-scalar

from gluon fusion as a function of its mass *^M* at LHC with ^p*^s* = 13 TeV [STILL

FIG. 1: Production cross section of a pseudo scalar with coupling *g/f* = 1 TeV¹ **TCP**

TABLE III. Couplings of a and η' to gauge bosons for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). The last two rows shows the numerical value of the decay constant ratios used in this work **TCP**

C_t^a	M1	M2	M3	$\overline{\mathrm{M}}4$	M5	M6	$\rm M7$	M8	M ₉	M10	M11	M12
$(\pm 2, 0)$	± 1.1	± 1.1	$\pm .79$	$\pm .73$	± 1.1	± 1.0	± 1.1	$\pm .68$	$\pm .58$	$\pm .46$	$\pm .54$	$\pm .70$
	± 1.2	± 1.2	± 1.1	± 1.1	± 1.2	± 1.2	± 1.2	$\pm .92$	$\pm .89$	$\pm .85$	$\pm .88$	$\pm .92$
$(0, \pm 2)$	$\mp .88$	$\mp .45$	$\mp .66$	∓ 1.2	∓ 1.8	∓ 1.7	$\mp .46$	$\mp .23$	∓ 1.5	∓ 1.2	$\mp .36$	$\mp .31$
	$\mp .46$	$\mp .23$	$\mp .37$	$\mp .69$	$\mp .92$	$\mp .91$	$\mp .24$	$\mp .12$	$\mp .86$	$\mp .72$	$\mp .20$	$\mp .17$
(4, 2)	$-.71$.18	.92	.24	-2.5	-2.4	.18	1.1	$-.38$	$-.31$.72	1.1
	.29	.75	1.9	1.6	$-.63$	$-.62$.75	1.7	.91	.99	1.5	1.7
$(-4, 2)$	2.8	2.0	-2.2	-2.7	4.6	4.5	2.0	-1.6	-2.7	-2.2	-1.4	-1.7
	2.1	1.7	-2.6	-2.9	3.1	3.0	1.7	-2.0	-2.6	-2.4	-2.0	-2.0
$C_t^{\eta'}$	M1	$\rm M2$	M3	$\rm M4$	M5	M6	M7	M8	M9	M10	M11	M12
	$\pm .69$	$\pm .66$	$\pm .99$	± 1.0	$\pm .69$	$\pm .71$	$\pm .62$	$\pm .73$	$\pm .82$	$\pm .89$	$\pm .84$	$\pm .71$
$(\pm 2, 0)$	$\pm .36$	$\pm .34$	$\pm .55$	$\pm .58$	$\pm .36$	$\pm .37$	$\pm .32$	$\pm .40$	$\pm .46$	$\pm .52$	$\pm .48$	$\pm .39$
	± 1.4	$\pm .74$	$\pm .53$	$\pm .87$	± 2.7	± 2.6	$\pm .83$	$\pm .21$	± 1.1	$\pm .64$	$\pm .23$	$\pm .31$
$(0, \pm 2)$	± 1.5	$\pm .83$	$\pm .76$	± 1.3	± 3.1	± 3.0	$\pm .92$	$\pm .28$	± 1.7	± 1.2	$\pm .37$	$\pm .40$
	3.4	2.1	2.5	2.9	6.1	5.8	2.3	1.7	2.7	2.4	1.9	1.7
(4,2)	\parallel 3.5 \parallel 2.0 \parallel 1.9			2.5	$6.6\,$	6.3	2.2 1.1		2.6	2.2	1.3	1.2
$\left (-4,2) \right \begin{array}{c} -2.0 \ -3.7 \end{array} \begin{array}{c} \end{array} \begin{array}{c} -8.2 \ -1.3 \end{array} \begin{array}{c} \end{array} \begin{array}{c} -1.5 \ -3.3 \end{array} \begin{array}{c} \end{array} \begin{array}{c} -1.2 \ -5.8 \end{array} \begin{array}{c} \end{array} \begin{array}{c} -4.4 \ -5.6 \end{array} \begin{array}{c} \end{array} \begin{array}{c} -1.3 \ -5.5 \end{array} \begin{array}{c} \end{array} \begin{array}{c} -5.5$												

TABLE IV. Coupling of a and η' to the top, C_t , for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). For models with top partners in the form $\psi \chi \chi$ (see Table I), the two last rows should be intended (2, 4) and (2, -4).

FIG. 1. Leading contributions to the de- FIC 1 Leading contributions to the decay $\phi \rightarrow Zh$

$$
K_{hZ}^{\phi \text{eff}} = \frac{3m_t^2}{32\pi^2 v m_Z} C_t^{\phi} \left[2(\kappa_t - \kappa_Z) \mathcal{B}_0(\tau_{\phi/t}) - \kappa_t \left(\mathcal{B}_0(\tau_{h/t}) - \mathcal{B}_0(\tau_{\phi/t}) \right) \right. \\ \left. + (4 - \tau_{Z/t}) \mathcal{C}_0(\tau_{\phi/t}, \tau_{h/t}, \tau_{Z/t}; 1) + (\tau_{\phi/t} + \tau_{h/t} - \tau_{Z/t}) \mathcal{C}_1(\tau_{\phi/t}, \tau_{h/t}, \tau_{Z/t}; 1) \right) \right]
$$

with (*x, y, z*) the K¨all´en function. For very light pseudo-scalars the decay *h* ! *Z* is allowed,

*^B*0(⌧*/t*)+2 *^C*0(⌧*/t,* ⌧*h/t,* ⌧*/t*; 1) + ¹

K^e↵

^h ⁼ ³*^t*

shown in Fig. 2, gives

$$
K_{\phi h}^{\text{eff}} = \frac{3\kappa_t}{8\pi^2} \left(\frac{C_t^{\phi} m_t}{v} \right)^2 \left[\mathcal{B}_0(\tau_{\phi/t}) + 2\mathcal{C}_0(\tau_{\phi/t}, \tau_{h/t}, \tau_{\phi/t}; 1) + \frac{1}{1 - 2\tau_{a/h}} \left(\mathcal{B}_0(\tau_{h/t}) - \mathcal{B}_0(\tau_{a/t}) \right) \right]
$$

1 2⌧*a/h*

*B*0(⌧*h/t*) *B*0(⌧*a/t*)

.

SM singlet branching ratios $C\mathbf{M}$ ginglet huanghing uetice e en pressed in terms of the Branching Ratio formulasing Ratio for the Branching Ratio for the Branching Ratio ated at loop at loop at loop level. In our models, the contributions to the e \mathbf{N} the singlet pseudo-scalars, *Z* and Higgs bosons are given by the diagrams in Fig. 1 [31]. Explicit

3*m*²

shown in Fig. 2, gives

$$
\Gamma(\phi \to had) = \frac{\alpha_s^2(m_\phi) m_\phi^3}{8\pi^3 f_\psi^2} \left[1 + \frac{83}{4} \alpha_s(m_\phi) \right] \left| K_{gg}^{\phi} + C_t^{\phi} C_0 (0, \tau_{\phi/t}, 0; 1) \right|^2
$$
\n
$$
\Gamma(\phi \to \gamma \gamma) = \frac{\alpha^2 m_\phi^3}{64\pi^3 f_\psi^2} \left| K_{\gamma \gamma}^{\phi} + \frac{8}{3} C_t^{\phi} C_0 (0, \tau_{\phi/t}, 0; 1) \right|^2
$$
\n
$$
\Gamma(\phi \to WW) = \frac{\alpha^2 m_\phi^3 (1 - 4\tau_{W/\phi})^{3/2}}{32\pi^3 f_\phi^2 s_W^4} \left| K_{WW}^{\phi} - \frac{3}{2} C_t^{\phi} C_{1+2} (\tau_{W/t}, \tau_{\phi/t}, \tau_{W/t} \cdot \tau_{\phi/t}) \right|^2
$$
\n
$$
\Gamma(\phi \to WW) = \frac{\alpha^2 m_\phi^3 (1 - 4\tau_{W/\phi})^{3/2}}{32\pi^3 f_\phi^2 s_W^2 c_W^2} \left| K_{ZW}^{\phi} \right| C_t^{\phi} \left(\sum_{l=3}^8 s_W^{2l} \right) C_0 (R_{Z/L} \tau_{\phi/L} \cdot \Sigma_{L}) \left| t - \frac{\phi}{2} C_t^{\phi} C_{1} \right|
$$
\n
$$
- \frac{\alpha^2 m_\phi^3 (1 - \frac{1}{2} \tau_{Z/\phi})^{3/2}}{64\pi^3 f_\psi^2 s_W^4 c_W^4} \left| K_{ZZ}^{\phi} + C_t^{\phi} \left[s_W^2 \left(\frac{\delta}{3} s_W^2 - 2 \right) C_0 (\tau_{Z/t}, \tau_{\phi/t}, \tau_{Z/t}^2; 1) - \frac{3}{4} C_{1+2} (\tau_{Z/t}, \tau_{\phi/t}, \tau_{Z/t}; 1) \right|^2 \right]
$$
\n
$$
\Gamma(\phi \to hZ) = \frac{m_\phi^3}{16\pi f_\psi^2} \left| K_{hZ}^{\phi \text{eff}} \right|^2 \lambda (1, \tau_{Z/\phi}, \tau_{h/\phi})^{3/2}
$$
\n
$$
\Gamma(h \to \phi \phi)
$$

 $t_{\rm c}$

Models with a pseudo-scalar state generically contain a coupling to *Zh* [61], which is gener-

At loop level, a coupling *h*² is also generated. This is relevant for *M < mh/*2, for which

IV. LHC BOUNDS AND HIGH-LUMINOSITY PROJECTIONS AND HIGH-LUMINOSITY PROJECTIONS AND HIGH-LUMINOSITY PROJECTIONS

The presence of the light composite pseudo-scalars can be tested at the LHC via the single

 \mathcal{H}_{H} decays decays into two pseudo-scalars are open. Explicit calculation of the leading diagrams, \mathcal{H}_{H}

FIG. 7. Representative Branching Ratios of a in the decoupling limit for all models and for the six choices of top partner charges. We only show gg (light and dark green), $\gamma\gamma$ (brown and red) and $\tau\tau$ (purple and lilac).

a and *η':* For a given model, we can combine bounds and sensitivities from resonance searches to get a bound on the compositeness scale f .

Projected reach at HL-LHC

NOTE: Low mass region has a "gap" between 15 - 65 GeV.

Soft τ_{lep} or τ_{had} cannot be used to trigger on, but initial state radiation can boost the gg \rightarrow a $\rightarrow \tau \tau$ system (at the cost of production cross section, but we have enough).

As a very naive proof of principle analysis we look for a $j \tau_{\mu} \tau_{e}$ final state (jet + opposite sign, opposite flavor leptons) with cuts:

- $p_{T_{\mu}} > 42$ GeV (for triggering)
- $\cdot p_{Te} > 10 \text{ GeV}$
- $\Delta R_{\mu} > 0.5$, $\Delta R_{ej} > 0.5$,
- $\Delta R_{\mu e}$ < 1.0
- no lower cut on $\Delta R_{\mu e}$!
- $m_{\mu e} > 100 \text{ GeV}$

Main background: Z/γ^* +jets: 35 fb, tt+jets: 70 fb, Wt+jets: 7.4 fb, VV+jets: 13 fb.

TABLE II: The values of $\sigma_{\text{prod}} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1 \text{ TeV}$ and $m_a = 10 \cdots 100$ GeV for each of the models defined in Table I.

Note: This first proof of principle study is highly nonoptimized.

- Cutting harder on $\Delta R_{\mu e}$ can substantially increase background suppression for the lighter mass range.
- We did not use any τ ID or triggers.

• We only used the OSOF lepton channel. $\tau_{\mu} \tau_{\mu}$, $\tau_{\mu} \tau_{had}$, $\tau_{had} \tau_{had}$ have larger branching ratios but require a more careful background analysis.

[And needs tagging efficiencies for boosted $\tau_{\mu} \tau_{had}$, $\tau_{had} \tau_{had}$ systems which are beyond our capabilities, but possible for experimentalists.]

Soft τ_{lep} or τ_{had} cannot be used to trigger on, but initial state radiation can boost the gg \rightarrow a $\rightarrow \tau \tau$ system (at the cost of production cross section, but we have enough).

As a very naive proof of principle analysis we look for a $j \tau_{\mu} \tau_{e}$ final state (jet + opposite sign, opposite flavor leptons) with cuts:

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Main background: Z/γ^* +jets: 35 fb, tt+jets: 70 fb, Wt+jets:

TABLE II: The values of $\sigma_{\text{prod}} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1 \text{ TeV}$ and $m_a = 10 \cdots 100$ GeV for each of the models defined in 7.4 fb, VV+jets: 13 fb. $Table I.$ [EPJC 78 (2018) [no.9, 724](http://inspirehep.net/record/1633600)]

…are there other "common" top partner decays? [HEP 1806, 065]

- UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top / bottom and a pNGB are kinematically possible.
- With an underlying model specified, we can relate top partner branching ratios to h/W/Z vs new pNGBs, as all relevant couplings arise from the Goldstone boson matrix.
- Scanning through the different underlying models we looked for "common" exotic" top partner decays and found several scenarios.

Example: [JHEP 1806, 065] Relating top partner couplings to Higgs and other pNGBs The various top partners are labelled as follows: *T B <u>IHEP 1806, 065]</u>* 2*/*3, is trivially identified with the singlet *S* that couples linearly to the right-handed top. The various top partner couplings to 11 *X*5*/*³ [**JHEP** 1806, 065] Relating top partner couplings to Higgs and other pNGBs

For models with EW breaking pattern SU(4)/Sp(4), top-partners come in $Sp(4)$ representations, e.g. 5 (for the t_L partner) and 1 (for the t_R partner). Γ Ω an Ω of Ω of Ω of Eq. (3.1). The spatial singlet representation, Ω Ω ⁽⁴⁾. Ω _{Ω}(4). the *spatial* singlet representation, Ω $\frac{2}{\pi}$ /3, is the singlet with the singlet with the singlet $\frac{2}{\pi}$ /3, is that $\frac{2}{\pi}$ /3, is the right-handed top. The right $\mathcal{L}(\mathbf{v})$ representations, \mathbf{v} , \mathbf{s} . \mathbf{v} (for the \mathbf{u} $\mathcal{S}_{n}(A)$ representations e σ 5 (for the tr partner) and 1 \mathbf{r} in the \mathbf{r} -plen and of the sources of the with E *X*2*/*³ *, B* $SU(4)/Sp(4)$, top-partners come in W_{V} is the definitions, σ_{S} . σ (for the d_r parameter down both parameter).

and such a top partner easily arises as a "chimera baryon" 7 in underlying models with two stress with two models

the *SU*(2)*^L* doublet *Q* of Eq. (3.1). The *Sp*(4) singlet representation, having hypercharge

$$
5\text{-plet} \rightarrow \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix} , \begin{pmatrix} T \\ B \end{pmatrix} , \tilde{T}_5 ; \qquad \text{singlet} \rightarrow \tilde{T}_1
$$

The "mass matrix" (pNGB interactions, expanded to leading order in contained in the $\frac{1}{2}$ the singlet and of the singlet \tilde{t} are the sources of the source of the source of the sources of the source of the sources of the \mathcal{P}_{θ} (a) and the easily $\psi_t = \{0, 1, 42/3, 11, 15\}$ s_{θ}=v/f) reads in the basis $\psi_t = \{t, T, X_{2/3}, \widetilde{T}_1, \widetilde{T}_5\}$ the mass matrix (pNGB interactions, expanded to The "mass matrix" (pNGR interactions expanded to leading order in the couplings to the pNGBs other than the Higgs doublet, we will keep them explicitly in $\varphi_t = \frac{1}{2}$, $\frac{1}{2}$

 \mathcal{I} this work, we will follow the same procedure and notations as in Ref. \mathcal{I} to obtain the same procedure and notations as in Ref. \mathcal{I}

$$
\bar{\psi}_{tR} \begin{pmatrix}\n0 & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5 \frac{a}{f_a}} f s_{\theta} & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5 \frac{a}{f_a}} f s_{\theta} & y_{1R} e^{i\xi_1 \frac{a}{f_a}} f c_{\theta} & iy_{5R} c_{\theta} \eta \\
y_{5L} e^{i\xi_5 \frac{a}{f_a}} f c_{\theta/2}^2 & M_5 & 0 & 0 & 0 \\
-y_{5L} e^{i\xi_5 \frac{a}{f_a}} f s_{\theta/2}^2 & 0 & M_5 & 0 & 0 \\
-\frac{y_{1L}}{\sqrt{2}} e^{i\xi_1 \frac{a}{f_a}} f s_{\theta} & 0 & 0 & M_1 & 0 \\
-i \frac{y_{5L}}{\sqrt{2}} s_{\theta} \eta & 0 & 0 & 0 & M_5\n\end{pmatrix} \psi_{tL}
$$

² *s*✓⌘ 0 00 *M*⁵

ⁱ ^y

*X*5*/*³

*X*2*/*³

5*R* 2 *e*

 $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ *y*5*Le <i>/*² *M*₅ *b*iagonalizing the mass matrix (and expanding in *a* and *n*) yields coupling \int *top* and *f* to the process to the process in terms of the pre-reel
W **The Diagonalizing the Diagonalizing the** Diagonalizing the mass matrix (and expanding in a and η) yields couplings of top and top partners to the pNGB in terms of the pre-Yukawas *y*1,5 . EVLQ

Common exotic VLQ decays a lighter pseudo-scalar *a*. Such a light pseudo-scalar *a* is genuinely present in models of in Eq. (2.1) parameterises the coupling of *T* to the pseudo-scalar *a*. This term does not

Candidate 1: decays to the singlet pseudo-scalar singlet *a* Effective Lagrangian(s): [JHEP 1806, 065] P_{c} with a gauge-fermion is description $\frac{1}{2}$ and $\frac{1}{2}$ associated with $\frac{1}{2}$ the parameters of a global of a vector of the single potential subsettions of a vector- $S_n = \frac{1}{2} \int_0^1 \frac{1}{2} \, dx = \$ or through single-production dictated by the first three terms (*Cf. e.g.* Refs [18, 19] for complete landscape of possibilities. We show that \sim 1.1 \pm 1.1 \pm 1.1 \pm Candidate 1. decays to the singlet pseudo-scala $Effective$ Lagrangian(s) *[JHEP 1806, 065]* \mathcal{C} be that searches for di-tau resonances (which see resonanc [[JHEP 1806, 065](http://inspirehep.net/record/1658051)]

completion, as defined in Ref. [12]. All the possible models in Ref. [12]. All the possible models in possible

$$
\mathcal{L}_{T} = \overline{T} (i\rlap{\,/}D - M_{T}) T + \left(\kappa_{W,L}^{T} \frac{g}{\sqrt{2}} \overline{T} W^{+} P_{L} b + \kappa_{Z,L}^{T} \frac{g}{2c_{W}} \overline{T} \not{\&} P_{L} t \n- \kappa_{h,L}^{T} \frac{M_{T}}{v} \overline{T} h P_{L} t + i \kappa_{a,L}^{T} \overline{T} a P_{L} t + L \leftrightarrow R + \text{ h.c.}\right),
$$
\n
$$
\mathcal{L}_{B} = \overline{B} (i\rlap{\,/}D - M_{B}) B + \left(\kappa_{W,L}^{B} \frac{g}{\sqrt{2}} \overline{B} W^{-} P_{L} t + \kappa_{Z,L}^{B} \frac{g}{2c_{W}} \overline{B} \not{\&}^{+} P_{L} b \n- \kappa_{h,L}^{B} \frac{M_{B}}{v} \overline{B} h P_{L} b + i \kappa_{a,L}^{B} \overline{B} a P_{L} b + L \leftrightarrow R + \text{ h.c.}\right).
$$

 α and the mixing angles of the mixing angles of the elementary top. If only decays into S

To illustrate the relevance of the new decay channels, we consider two benchmark

^W*,*^R ⁼ 0*.*⁰⁸ *,* ^B

^a*,*^L = 0*.*25 *,* (2.3)

$$
\mathcal{L} = \frac{1}{2} (\partial_{\mu} a)(\partial^{\mu} a) - \frac{1}{2} m_{a}^{2} a^{2} - \sum_{f} \frac{i C_{f} m_{f}}{f_{a}} a \bar{\psi}_{f} \gamma^{5} \psi_{f} \qquad (1)
$$

$$
+ \frac{g_{s}^{2} K_{g} a}{16 \pi^{2} f_{a}} G_{\mu \nu}^{a} \tilde{G}^{a \mu \nu} + \frac{g^{2} K_{W} a}{16 \pi^{2} f_{a}} W_{\mu \nu}^{i} \tilde{W}^{i \mu \nu} + \frac{g^{\prime 2} K_{B} a}{16 \pi^{2} f_{a}} B_{\mu \nu} \tilde{B}^{\mu \nu}
$$

^W*,*^L = 0*.*02 *,* ^B

the above parametrisation, the coecients *^T*

Bm1 : *M^T* = 1 TeV *,* ^T

resonance [3, 4], mostly motivated by models that fea-

 $\frac{1}{\sqrt{2}}$

 $\frac{1}{\sqrt{2}}$

In this letter, we focus on the LHC phenomenology

of a light new scalar with a mass between 10 and 100

GeV which can resonantly decay into a pair of SM par-

 $\frac{1}{\sqrt{2}}$

strained from electroweak precision measurements (indi-

rectly) and from direct searches at LEP and Tevatron. At

the LHC, besides the above mentioned di-photon chan-

nel, light (pseudo)scalars are usually searched for in the

decays of the 125 GeV Higgs boson. This search strat-

 $\frac{1}{\sqrt{2}}$

tivated by supersymmetry or 2HDMs. Below roughly

 $\frac{1}{2}$

mesons, or in experiments looking for light axion-like

particles (ALPs) [7–10]. Thus, the common lore is that

a new scalar, in order to escape detection, needs to be

Note, however, that it is enough to have small cou-

plings to electrons and to the electroweak gauge bosons

in order to escape direct LEP searches and electroweak

precision bounds, as well as small couplings to the Higgs

 $t_{\rm eff}$

ons (and heavy quarks) are less constrained, leading to

Bm2 : *M^B* = 1*.*38 TeV *,* ^B

we show the branching ratios in the two benchmarks as a function of the anti-two benchmarks as \mathcal{R} mass. Each

Benchmark parameters (obtained as eff. parameters from UV model): respectively characterised by the following couplings: $\text{Bm1}: \quad M_T = 1 \text{ TeV} \; , \quad \kappa_{\rm Z,R}^{\rm T} = -0.03 \; , \; \; \kappa_{\rm h,R}^{\rm T} = 0.06 \; , \; \; \kappa_{\rm a,R}^{\rm T} = -0.24 \; , \; \; \kappa_{\rm a,L}^{\rm T} = -0.07 \; ;$ $Bm2: M_B = 1.38 \text{ TeV}, \quad \kappa_{W,L}^B = 0.02, \quad \kappa_{W,R}^B = -0.08, \quad \kappa_{a,L}^B = -0.25,$ (2.3)

ratios of *T* ! *t a* and *B* ! *b a* are model dependent. However, the benchmarks we Branching ratios of quark partners to *a* in these benchmarks:

BSM couplings.

on 100% branching ratio *T* ! *tZ* or *T* ! *th* are around 1 TeV. Bounds on *M^T* from electroweak singleproduction \mathcal{H} EVLQ

Examples of diagrams:

- T and B can be produced like "standard" top partners: QCD pair production or single production.
- New final states: MANY, depending on ma and single- or pair-production

or *tZZ* resonances. In our benchmark model(s), these *a* decays do not have large common cabile villy decays realised, for example, which II adapted Sommon shows regarded y Common exotic VLQ decays

2*/*3 that does not mix with the SM top, and a lighter pseudo-scalar ⌘. This situation is

• Decays of *a* to vector bosons (if kinematically allowed) can yield *t*, *tZ*, *tWW*,

and a di-boson resonance) o \mathcal{A} and \mathcal{A} many handles for excellent SM background rejection.

 \mathbf{A} is the additional singlet and the top partner couplings respect a partner coupling \mathbf{A}

are generated at leading order \mathbb{P}^4 . The coupling to light fermions are model dependent, and \mathbb{P}^4

they are absent at the leading order \mathbb{S} . Thus, to keep the scenario minimal, we will only only only only only only \mathbb{S}

^B ⁼ *K*⌘

sK⌘

Candidate 2: Decays of a top partner to the "exclusive pseudo-scalar" η . In models with SU(4)/Sp(4) breaking, one specific top partner couples only to the CP-odd SM singlet pNGB η . Both are odd under η -parity. η parity is broken by EW anomaly couplings, and η decays to WW, ZZ, Z γ . 2.2 III *H*odels with St only to the CI-oud Sivi singlet pix D η . Both are oud under η -partly. η realised, for example, in composite Higgs models based on *SU*(4)*/Sp*(4) breaking, where tehihae^r Lth $SU(4)/Sp(4)$ breal $\frac{1}{2}$ *k* $\frac{1}{2}$ are specific top partner couples similar to Eq.(2.4). However, in this specific case, not all couplings arise on the same

Effective Lagrangian: \mathbf{b}

Lagrangian

$$
\mathcal{L}_{\widetilde{T}} = \overline{\widetilde{T}} \left(i \not{D} - M_{\widetilde{T}} \right) \widetilde{T} - \left(i \kappa_{\eta, L}^{\widetilde{T}} \overline{\widetilde{T}} \eta P_L t + L \leftrightarrow R + \text{ h.c.} \right)
$$
\n
$$
\mathcal{L}_{\eta} = \frac{1}{2} (\partial_{\mu} \eta)(\partial^{\mu} \eta) - \frac{1}{2} m_{\eta}^2 \eta^2 + \frac{g_s^2 K_g^{\eta}}{16 \pi^2 f_{\eta}} \eta G_{\mu\nu}^a \widetilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8 \pi^2 f_{\eta}} \eta W_{\mu\nu}^+ \widetilde{W}^{-,\mu\nu}
$$
\n
$$
+ \frac{e^2 K_\gamma^{\eta}}{16 \pi^2 f_{\eta}} \eta A_{\mu\nu} \widetilde{A}^{\mu\nu} + \frac{g^2 c_W^2 K_Z^{\eta}}{16 \pi^2 f_{\eta}} \eta Z_{\mu\nu} \widetilde{Z}^{\mu\nu} + \frac{eg c_W K_{Z\gamma}^{\eta}}{8 \pi^2 f_{\eta}} \eta A_{\mu\nu} \widetilde{Z}^{\mu\nu}
$$

^W . Thus, the coupling to photons vanishes, and the

- The η -parity top partner is only QCD-pair produced.
- It decays 100% to tn.
- η dominantly decays to W⁺ W⁻ or Z γ (depending on its mass).

Candidate 3: $X_{5/3} \rightarrow \bar{b} \pi_6$ (with subsequent $\pi_6 \rightarrow t \ t$) In models with $\frac{\Gamma(\theta)}{\Gamma(\theta)}$ known in the color sector VLQs imply additional decay channels beyond the standard ones. As an example, we consider a particular and with consider a sextet of α colour and with charge 4*/3.* This colour and with charge 4*/3.* This colour and with charge 4*/3.* This colour and with charge 4*/3. This colour and with charge 4/3* In models with SU(6)/SO(6) breaking in the color sector. Effective Lagrangian: $\frac{1}{k}$ $\frac{1}{k}$ **Candidate** 3. $\Delta 5/3 \rightarrow 0.66$ (with subsequent $\mu_0 \rightarrow \mu_1$) fortive Lagrangian: $Common$ original sensitivity A $multicial
 $\overline{b} \pi_a$ (with subsequent π_b x[†]$ </u> **Candidate** 5: $\Lambda_{5/3} \rightarrow 0$ π_6 (with subsequent $\pi_6 \rightarrow 0$) E *ffectiv* $:$ Lagrangia $\ddot{}$ *X*5*/*³ Common exotic VLQ decays *L*⇡⁶ = *|Dµ*⇡6*|* ⇡⁶ *|*⇡6*| tt,R t*⇡6(*PRt*) → *L* U) where *b^c* and *t ^c* denote the charge conjugate of the bottom and the top quark fields. Note the curve Lagrangian.

pa
p22 p22 p22

collider and the

L⇡6

*X*5*/*³

$$
\mathcal{L}_{X_{5/3}}^{\pi_6} = \overline{X}_{5/3} \left(i\rlap{\,/}D - M_{X_{5/3}} \right) X_{5/3} + \left(\kappa_{W,L}^X \frac{g}{\sqrt{2}} \overline{X}_{5/3} W^+ P_L t + i \kappa_{\pi_6,L}^X \overline{X}_{5/3} \pi_6 P_L b^c + L \leftrightarrow R + \text{ h.c.} \right)
$$

of *t W*⁺ have higher background but also a higher branching ratio and provide another

attractive channel. For pair-produced *X*5*/*3, the current bound on its mass is *MX*5*/*³ *>* 1*.*3

$$
\mathcal{L}_{\pi_6} = |D_{\mu}\pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \left(i\kappa_{tt,R}^{\pi_6} \bar{t}\pi_6 (P_R t)^c + L \leftrightarrow R + \text{ h.c.} \right)
$$

Benchmark parameters (obtained as eff. parameters from UV model):

Examples of diagrams:

• $X_{5/3}$ and B can be produced in QCD pair production or single production.

EVLQ

• π_6 decays to t t.

when *X*5*/*³ is pair-produced and both decay into this exotic channel. Di↵erent decays Common exotic VLQ decays

Candidate 4:
$$
X_{5/3} \rightarrow t \phi^+
$$
 and $X_{5/3} \rightarrow b \phi^{++}$

for the VLQ *X*5*/*³ and the charged scalar couplings, respectively read

In models with SU(5)/SO(5) breaking in the EW sector, we have charged (and doubly charged) pNGBs. In models with $SU(5)/SO(5)$ breaking in the EW sector, we have characterized scalar the latter arises for $\frac{1}{100}$ $\frac{v}{\sqrt{2}}$ and $\frac{v}{\sqrt{2}}$. The latter arises for example as particular to the latter of the products with $SO(3)/SO(5)$ breaking in the L w sector, we have enarged *X*⁵/ $\frac{1}{2}$ *N Y SO*(5) breaking in the EW sector, we have charged \mathcal{L}

 $S_{\rm eff}$, where it is accompanied by a doubly-charged scalar. The e 4 ective Lagrangians calar. The e 4 ective Lagrangians calar. The e 4

Effective Lagrangian: particulars. The resulting new decay modes are discussed in modes are discussed in S

$$
\mathcal{L}_{X_{5/3}}^{\phi} = \overline{X}_{5/3} \left(i\rlap{\,/}D - M_{X_{5/3}} \right) X_{5/3} + \left(\kappa_{W,L}^{X} \frac{g}{\sqrt{2}} \overline{X}_{5/3} \psi^{+} P_{L} t + i \kappa_{\phi^{+},L}^{X} \overline{X}_{5/3} \phi^{+} P_{L} t + i \kappa_{\phi^{+},L}^{X} \overline{X}_{5/3} \phi^{++} P_{L} b + L \leftrightarrow R + \text{h.c.} \right)
$$
\n
$$
\mathcal{L}_{\phi} = \sum_{\phi = \phi^{+}, \phi^{++}} \left(|D_{\mu}\phi|^{2} - m_{\phi}^{2} |\phi|^{2} \right) + \left(\frac{eg K_{W\gamma}^{\phi}}{8\pi^{2} f_{\phi}} \phi^{+} W_{\mu\nu}^{-} \tilde{B}^{\mu\nu} + \frac{g^{2} c_{w} K_{WZ}^{\phi}}{8\pi^{2} f_{\phi}} \phi^{+} W_{\mu\nu}^{-} \tilde{B}^{\mu\nu} + \frac{g^{2} K_{W}^{\phi}}{8\pi^{2} f_{\phi}} \phi^{++} W_{\mu\nu}^{-} \tilde{W}^{\mu\nu,-} + i \kappa_{tb,L}^{\phi} \frac{m_{t}}{f_{\phi}} \bar{t}_{\phi}^{+} P_{L} b + L \leftrightarrow R + \text{h.c.} \right). \tag{2.13}
$$

tb,L

f

^t+*PL^b* ⁺ *^L* \$ *^R* + h.c.◆

through ⁺ and one standard) or *tt*¯*b*¯*bWW* (for one decay through ⁺ and one

interesting final state that we want to mention is due to decays of a charge 2*/*3 partner in

. (2.13)

[[JHEP 1806, 065](http://inspirehep.net/record/1658051)] EVLQ usually originate from the same coset. In models based on the *SU*(5)*/SO*(5) breaking pattern (minimal coset with charged pNGBs), the charged scalar *[±]* belongs to *SU*(2)*L*-

ि संस्कृत का क्**रिकेट संस्कृत करने के संस्कृत कर**
संस्कृत

++*W*

^µ⌫*W*˜ *^µ*⌫*,* ⁺ *ⁱ*

m++ for the benchmark model Bm4 introduced in Sec. 3.4. Common exotic VLQ decays

Benchmark parameters (obtained as eff. parameters from UV model): $\text{Bm4}: \;\; M_{X_{5/3}} = 1.3 \; \text{TeV} \; , \quad \kappa_{\text{W,L}}^{\text{X}} = 0.03 \; , \;\; \kappa_{\text{W,R}}^{\text{X}} = 0.13 \; , \;\; \kappa_{\phi^+, \text{L}}^{\text{X}} = 0.49 \; , \;\; \kappa_{\phi^+, \text{R}}^{\text{X}} = 0.12 \; ,$ $\kappa_{\phi^{++},L}^X = -0.69$, $\kappa_{tb,L}^{\phi} = 0.53$, (2.14)

Figure 5. Branching ratios of *X*5*/*³ as a function of the mass of the charged pNGBs *m* = *m*⁺ =

Production of $X_{5/3}$: Single- or pair-production. Decays of the pNGBs: $\phi^{++} \rightarrow W^+ W^+$, $W^+ \phi^+$ $\phi^+ \rightarrow t\mathbf{b}, \, \mathbf{W}^+ \mathbf{Z}, \, \mathbf{W}^+ \gamma$

EVLQ

Examples of processes:

EVLQ