Composite Higgs from Strong Dynamics on the Lattice
Letter of Interest for EF02+EF08+EF09+TF08+TF05+CompF2

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With the discovery of the 125 GeV Higgs boson by Atlas and CMS [1–3] understanding the nature of the Higgs and explaining the origin of electro-weak symmetry breaking is one of the outstanding challenges for theoretical physics. However, so far experiments have not revealed any further guidance and, up to the range of a few TeV, no direct signs for new physics have been observed [4, 5]. For any theory aiming to describe the Higgs sector, this implies a large separation of scales is needed. A large separation of scales occurs, e.g., in near-conformal gauge theories which might be the essential building block to develop a theory describing physics beyond the Standard Model (BSM). The general idea is to extend the Standard Model (SM) by a new, strongly interacting, and near-conformal gauge-fermion system with massless fermions. The Higgs boson arises as a composite particle of this new strong sector [6–9] and two general scenarios can be considered. Either the Higgs boson is a dilaton-like particle (i.e. an iso-singlet scalar 0^{++} excitation) or a pseudo-Nambu–Goldstone boson (pNGB) of the new strongly interacting sector. The latter scenario is quite similar to the pion in quantum chromodynamics (QCD). In both cases quantum numbers and mass of the Higgs boson are expected to match experimental determinations once all interactions with the Standard Model (SM) are accounted for. Similarly the full theory has to pass electro-weak precision tests.

In the dilaton-like scenario, the new sector has ideally two massless flavors which give rise to three Goldstone bosons and, similar to the original idea of technicolor, these three Goldstone bosons become the longitudinal components of the electro-weak $W^\pm$ and Z^0 bosons. The scale of the new sector is fixed by relating the pseudoscalar decay constant of the new strong sector to the vacuum expectation value of the SM i.e. $F_{\text{ps}} \sim 246\text{GeV}$. The alternative pNGB scenario requires at least three massless flavors such that spontaneous breaking of the flavor symmetry creates pNGBs. Here the vacuum alignment is nontrivial and the alignment parameter χ introduces an additional degree of freedom. An example of a pNGB extension of the standard model is given by the two Higgs doublet model (2HDM) discussed e.g. in Refs. [10–12].

Expressing the general idea of composite Higgs models in terms of Lagrangian, we add to the Higgs-less SM $\mathcal{L}_{\text{SM0}}$ two terms. A Lagrangian of a new strong dynamics sector $\mathcal{L}_{\text{SD}}$ accompanied by a Lagrangian $\mathcal{L}_{\text{int}}$ to describes the interactions of SM particles with the new strong sector

$$\mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{SD}} + \mathcal{L}_{\text{int}} = \mathcal{L}_{\text{SM}} + \text{ new physics.}$$

The latter includes a mechanism to provide mass to SM fermions via four-fermion interactions (see [13] and references therein) or partial compositeness [14, 15]. All three terms together allow to deduce

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the SM, the Higgs boson, as well as "new physics" still to be experimentally discovered. To explore the viability of composite Higgs models, we start out by considering the new strong sector $\mathcal{L}_{\text{SD}}$ in isolation. The strongly coupled nature of the new sector warrants to study $\mathcal{L}_{\text{SD}}$ nonperturbatively using techniques of lattice field theory. Near-conformal models are candidates to describe large scale separation and have properties significantly different than QCD. Lattice calculations can identify the general and particular properties of possible systems [16].

A promising candidate for such a near-conformal gauge-fermion system is e.g. an SU(3) gauge theory with eight fundamental flavors [17–25]. Although a theory based on $N_f = 8$ flavors formally gives rise to a very large number of Goldstone bosons (many more than needed for the dilaton-like scenario), the thorough numerical investigations have triggered substantial attention. Most notably the system contains a light iso-singlet scalar (0^{++}) particle which is found to be as light as the pseudoscalar and much lighter than the vector resonance in the investigated parameter range [22–25]. An important step to extract firm conclusions from these findings for the $N_f = 8$ system is to identify the relevant effective field theory (EFT) which incorporates the light scalar. Several candidate EFTs have been proposed [26–30] but further numerical data are required to distinguish between candidate EFTs, refine, and improve their description. In the future we therefore aim to improve our understanding of the $N_f = 8$ system by pursuing high precision simulations using nHYP-smeared staggered fermions [31] with well-characterized uncertainties. In addition to performing larger-scale lattice calculations at smaller flavor masses in larger volumes, we will also calculate more observables in addition to the particle spectrum and decay constants, considering e.g. two-particle scattering processes [32]. Despite the large number of Goldstone bosons, the $N_f = 8$ theory has proved to be a simple test-bed to explore near-conformal TeV-scale strong dynamics. It has and will teach us how to find a better UV completion of the Higgs sector in the future.

Another particularly attractive alternative to identifying a near-conformal gauge theory is the construction of a mass-split model [33–35] which live in the basin of attraction of a conformal infrared fixed point (IRFP). Starting from a conformal system with N_f flavors, we choose four flavors to be light (massless) such that the light sector is chirally broken. The remaining heavy flavors are "active" and allow us to tune the system near the IRFP. Even though the low energy system is chirally broken, its properties are significantly different from a QCD-like system. Due to the proximity of a nearby IRFP, the system inherits conformal hyperscaling resulting in a highly predictive model [35]. Using a setup with improved Möbius domain-wall fermions as well as taking advantage of locating the IRFP for $N_f = 10$ [36], we presently explore a mass-split system with four light and six heavy flavors [37–39]. Our high-quality data enabled us to numerically test hyperscaling relations and, moreover, extend and demonstrate the validity of dilaton chiral perturbation theory (dChPT) [27–30, 40, 41] to the case of a mass-split system [39]. Since the mass of the heavy flavors is a continuously tuneable parameter (in contrast to the integer number of flavors), mass-split models provide a superb framework to explore near-conformal dynamics and determine phenomenologically relevant quantities like the S-parameter, the Higgs potential, or scattering amplitudes. In addition reliably establishing that near-conformal systems exhibit a light iso-singlet scalar is a top priority including a phase-shift calculation [42]. An interesting variation of the mass-split model we presently study is to consider a system with 2 light and eight or six heavy flavors which exhibits only three massless Goldstone bosons in the light sector.

Furthermore we are investigating the phase structure of the new strong sector in mass-split models. Specifically we would like to establish whether the mass-split SU(3) gauge theory with four light and six heavy flavors exhibits a first-order transition between its high-temperature plasma phase and its low-temperature confined phase. This property is a natural feature of the theory rather than being 'inserted' by hand. By performing numerical lattice calculations, we study this early-universe confinement transition in order to predict features of the stochastic background of gravitational waves it may have produced [43–45]. Our non-perturbative results will be needed to constrain (or discover) new strong BSM dynamics from searches for stochastic gravitational waves at future observatories.

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References

[1] ATLAS collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys.Lett. **B716** (2012) 1–29, [1207.7214].

[2] CMS collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys.Lett. **B716** (2012) 30–61, [1207.7235].

[3] ATLAS, CMS collaboration, G. Aad et al., *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, Phys. Rev. Lett. **114** (2015) 191803, [1503.07589].

[4] ATLAS collaboration, *Summary of new ATLAS results for ICHEP 2020*, 2020.

[5] CMS collaboration, R. Carlin, *CMS highlights ICHEP 2020*, 2020.

[6] O. Witzel, *Review on Composite Higgs Models*, PoS **LATTICE2018** (2019) 006, [1901.08216].

[7] USQCD collaboration, R. C. Brower, A. Hasenfratz, E. T. Neil, S. Catterall, G. Fleming, J. Giedt et al., *Lattice Gauge Theory for Physics Beyond the Standard Model*, Eur. Phys. J. **A55** (2019) 198, [1904.09964].

[8] V. Drach, *Composite electroweak sectors on the lattice*, 2005.01002.

[9] G. Cacciapaglia, C. Pica and F. Sannino, *Fundamental Composite Dynamics: A Review*, 2002.04914.

[10] T. Ma and G. Cacciapaglia, *Fundamental Composite 2HDM: SU(N) with 4 flavours*, JHEP **03** (2016) 211, [1508.07014].

[11] D. Buarque Franzosi, G. Cacciapaglia and A. Deandrea, *Sigma-assisted low scale composite Goldstone–Higgs*, Eur. Phys. J. C **80** (2020) 28, [1809.09146].

[12] D. Marzocca, *Addressing the B-physics anomalies in a fundamental Composite Higgs Model*, JHEP **07** (2018) 121, [1803.10972].

[13] LATTICE STRONG DYNAMICS collaboration, T. Appelquist, A. Avakian, R. Babich, R. C. Brower, M. Cheng, M. A. Clark et al., *Toward TeV Conformality*, Phys. Rev. Lett. **104** (2010) 071601, [0910.2224].

[14] D. B. Kaplan, *Flavor at SSC energies: A new mechanism for dynamically generated fermion masses*, Nucl. Phys. B **365** (1991) 259–278.

[15] L. Vecchi, *A dangerous irrelevant UV-completion of the composite Higgs*, JHEP **02** (2017) 094, [1506.00623].

[16] A. Hasenfratz, C. Rebbi and O. Witzel, *Snowmass Letter of Interest for TF03: CFT and formal QFT*, 2020.

[17] A. Deuzeman, M. P. Lombardo and E. Pallante, *The Physics of eight flavours*, Phys. Lett. **B670** (2008) 41–48, [0804.2905].

[18] X.-Y. Jin and R. D. Mawhinney, *Evidence for a First Order, Finite Temperature Phase Transition in 8 Flavor QCD*, PoS **LATTICE2010** (2010) 055, [1011.1511].

[19] A. Hasenfratz, D. Schaich and A. Veernala, *Nonperturbative β function of eight-flavor SU(3) gauge theory*, JHEP **06** (2015) 143, [1410.5886].

[20] Lattice Strong Dynamics collaboration, D. Schaich, A. Hasenfratz and E. Rinaldi, *Finite-temperature study of eight-flavor SU(3) gauge theory*, 1506.08791.

[21] Z. Fodor, K. Holland, J. Kuti, S. Mondal, D. Nogradi and C. H. Wong, *The running coupling of 8 flavors and 3 colors*, *JHEP* **06** (2015) 019, [1503.01132].

[22] LatKMI collaboration, Y. Aoki, T. Aoyama, M. Kurachi, T. Maskawa, K.-i. Nagai, H. Ohki et al., *Walking signals in $N_f = 8$ QCD on the lattice*, *Phys. Rev.* **D87** (2013) 094511, [1302.6859].

[23] LatKMI collaboration, Y. Aoki, T. Aoyama, E. Bennett, M. Kurachi, T. Maskawa, K. Miura et al., *Light flavor-singlet scalars and walking signals in $N_f = 8$ QCD on the lattice*, *Phys. Rev.* **D96** (2017) 014508, [1610.07011].

[24] Lattice Strong Dynamics collaboration, T. Appelquist, R. Brower, G. Fleming, A. Hasenfratz, X.-Y. Jin, J. Kiskis et al., *Strongly interacting dynamics and the search for new physics at the LHC*, *Phys. Rev.* **D93** (2016) 114514, [1601.04027].

[25] Lattice Strong Dynamics collaboration, T. Appelquist, R. Brower, G. Fleming, A. Gasbarro, A. Hasenfratz, X.-Y. Jin et al., *Nonperturbative investigations of SU(3) gauge theory with eight dynamical flavors*, *Phys. Rev.* **D99** (2019) 014509, [1807.08411].

[26] Lattice Strong Dynamics collaboration, T. Appelquist et al., *Linear Sigma EFT for Nearly Conformal Gauge Theories*, *Phys. Rev.* **D98** (2018) 114510, [1809.02624].

[27] T. Appelquist, J. Ingoldby and M. Piai, *Dilaton EFT Framework For Lattice Data*, *JHEP* **07** (2017) 035, [1702.04410].

[28] T. Appelquist, J. Ingoldby and M. Piai, *Analysis of a Dilaton EFT for Lattice Data*, *JHEP* **03** (2018) 039, [1711.00067].

[29] M. Golterman and Y. Shamir, *Low-energy effective action for pions and a dilatonic meson*, *Phys. Rev.* **D94** (2016) 054502, [1603.04575].

[30] M. Golterman and Y. Shamir, *Large-mass regime of the dilaton-pion low-energy effective theory*, *Phys. Rev.* **D98** (2018) 056025, [1805.00198].

[31] A. Hasenfratz, R. Hoffmann and S. Schaefer, *Hypercubic smeared links for dynamical fermions*, *JHEP* **0705** (2007) 029, [hep-lat/0702028].

[32] Lattice Strong Dynamics collaboration, T. Appelquist, R. C. Brower, G. T. Fleming, A. Gasbarro, A. Hasenfratz, J. Ingoldby et al., *Goldstone Scattering in the Presence of a Light Composite Scalar*, *in preparation* (2020) .

[33] R. C. Brower, A. Hasenfratz, C. Rebbi, E. Weinberg and O. Witzel, *A novel approach to the study of conformality in the SU(3) theory with multiple flavors*, *J. Exp. Theor. Phys.* **120** (2015) 423–427, [1410.4091].

[34] R. C. Brower, A. Hasenfratz, C. Rebbi, E. Weinberg and O. Witzel, *Composite Higgs model at a conformal fixed point*, *Phys. Rev.* **D93** (2016) 075028, [1512.02576].

[35] A. Hasenfratz, C. Rebbi and O. Witzel, *Large scale separation and hadronic resonances from a new strongly interacting sector*, *Phys. Lett.* **B773** (2017) 86–90, [1609.01401].

[36] A. Hasenfratz, C. Rebbi and O. Witzel, *Gradient flow step-scaling function for SU(3) with ten fundamental flavors*, *Phys. Rev. D* **101** (2020) 114508, [2004.00754].

[37] O. Witzel, A. Hasenfratz and C. Rebbi, *Composite Higgs from mass-split models*, 1810.01850.

[38] O. Witzel and A. Hasenfratz, *Constructing a composite Higgs model with built-in large separation of scales*, 1912.12255.

[39] Lattice Strong Dynamics collaboration, T. Appelquist, R. C. Brower, K. K. Cushman, G. T. Fleming, A. D. Gasbarro, A. Hasenfratz et al., *Near-conformal dynamics in a chirally broken system*, 2007.01810.

[40] T. Appelquist, J. Ingoldby and M. Piai, *Dilaton potential and lattice data*, *Phys. Rev. D* **101** (2020) 075025, [1908.00895].

[41] M. Golterman, E. T. Neil and Y. Shamir, *Application of dilaton chiral perturbation theory to $N_f = 8$,* SU(3) *spectral data*, 2003.00114.

[42] R. A. Briceno, J. J. Dudek, R. G. Edwards and D. J. Wilson, *Isoscalar $\pi\pi$ scattering and the σ meson resonance from QCD*, *Phys. Rev. Lett.* **118** (2017) 022002, [1607.05900].

[43] P. Schwaller, *Gravitational Waves from a Dark Phase Transition*, *Phys. Rev. Lett.* **115** (2015) 181101, [1504.07263].

[44] C. Caprini, M. Hindmarsh, S. Huber, T. Konstandin, J. Kozaczuk, G. Nardini et al., *Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions*, *JCAP* **1604** (2016) 001, [1512.06239].

[45] C. Caprini, M. Chala, G. C. Dorsch, M. Hindmarsh, S. J. Huber, T. Konstandin et al., *Detecting gravitational waves from cosmological phase transitions with LISA: an update*, *JCAP* **2003** (2020) 024, [1910.13125].