PROCEEDINGS OF SCIENCE

BSM from the top

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Due to its large mass and unique phenomenology the top quark is well suited for searches for new physics, both from and with the top quark. The existence of a light scalar, the Higgs boson, in the Standard Model motivates searches for light top partners. Supersymmetry and Composite Higgs Models are presented as two examples for BSM models in which light top partners naturally emerge. Furthermore, couplings of Axion-Like Particles (ALPs) to fermions are proportional to the fermion mass which motivates to single out the ALP-top coupling c_t. Constraints on c_t from direct and indirect collider searches are presented and compared. Finally, models for 4F operators in the Standard Model Effective Field Theory are discussed and the special features of top-quark operators are pointed out.

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1. Introduction

The top quark Yukawa coupling, y_t, of order one, leads to the top quark mass

$$m_t = \frac{v y_t}{\sqrt{2}} = 171 \text{ GeV}, \tag{1}$$

making it the heaviest quark in the Standard Model (SM). Due to its large mass it is strongly connected to the electroweak (EW) sector and affects the stability of the EW vacuum. Hence the top quark sector is especially suitable for EW precision tests and possible beyond the SM (BSM) corrections in the EW sector would lead to deviations that can be observed in top quark physics. Moreover, the top quark is the only quark that decays before it hadronises with the dominant decay channel being into b quarks and W bosons. This unique phenomenology is key to new physics searches from and with the top quark as presented in the following.

2. The Higgs hierarchy problem

One further motivation to search for new physics in the top sector is the Higgs hierarchy problem: The measured Higgs mass is $m_h = 125$ GeV, but the self-energy receives radiative corrections with the biggest effect coming from the top quark,

$$\Pi_{hh}^{(t)}(0) = -2y_t^2 \int \frac{d^4k}{(2\pi)^2}\left[\frac{1}{k^2 - m_t^2} + \frac{2m_t^2}{(k^2 - m_t^2)^2}\right]. \tag{2}$$

The first term is quadratically divergent and contributes to the Higgs mass via

$$\delta m_h^2 \propto -\left(\frac{m_t}{v^2}\right)^2 \Lambda^2. \tag{3}$$

At the Planck mass, $\Lambda = M_{Pl} = 10^{19}$ GeV, the correction is over 30 orders of magnitude larger than the physical Higgs mass and one might wonder why the latter is so fine-tuned. This motivates searches for a top partner to cancel the radiative effects. Two scenarios in which top partners emerge naturally are shortly discussed here: Supersymmetry and Composite Higgs Models (CHM).

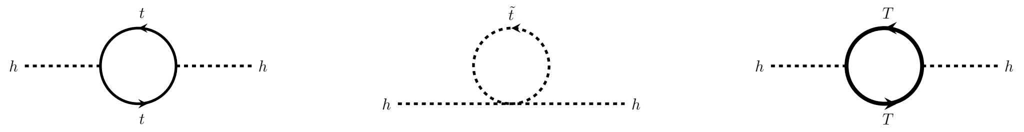
2.1 Supersymmetry

Supersymmetry (SUSY) introduces a spontaneously broken symmetry between fermions and bosons. The fermions and bosons have the same quantum numbers and, a priori, the same mass. The super-partner to the top, the stop $\tilde{t}$, contributes to the Higgs mass with the same Λ^2 dependence but opposite sign,

$$\Pi_{hh}(0)^{(\tilde{t})} = -2y_{\tilde{t}} \int \frac{d^4k}{(2\pi)^2}\frac{1}{k^2 - m_{\tilde{t}}^2}. \tag{4}$$

For $y_{\tilde{t}} = -y_t^2$ and $m_{\tilde{t}} = m_t$ the contributions from top and stop to m_h^2 cancel identically, and for a difference in the masses the divergence is proportional to $\Delta m = m_{\tilde{t}} - m_t$.

There are dedicated searches for SUSY particles at the LHC, in particular long standing and refined searches in multiple channels for the stop at ATLAS and CMS. Stop quarks decay dominantly into tops and neutralinos unless kinematically disfavoured by the stop and neutralino masses. One interesting channel are leptonic top decays which can be measured in a $2b + 2l$ + missing transverse energy (MET) final state.



(a) **(b)** **(c)**

Figure 1: Contributions to the Higgs mass from top quarks (a), top squarks in SUSY (b) and top partners that arise e.g. in Composite Higgs Models (c). See text for details.

2.2 Composite Higgs Models

In Composite Higgs Models, the Higgs boson is not a fundamental particle but instead appears as a composite bound state of heavy fermions, $\bar{F}F$. This bound state does not exist at high energies and hence there is no hierarchy problem in these models. Independently of the exact realisation, CHMs always contain a top partner with a mass close to the top quark to ensure the correct form of the Higgs potential and the right mechanism for electroweak symmetry breaking. This top partner $T = (T_L, T_R)$ mixes with the top quark through mass mixing

$$\mathcal{L} \supset (\bar{t}_L, \bar{T}_L) \begin{pmatrix} \frac{y_t v}{\sqrt{2}} & \Delta \\ 0 & M \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix} \tag{5}$$

and modifies its couplings to the Higgs boson. One possible realisation, cf. e.g. [1], is the Seesaw Composite Higgs Model which involves two successive symmetry breakings and the Higgs doublets mix pseudo Goldstone bosons arising from both symmetry breakings. It moreover predicts a pseudo-scalar Goldstone boson a associated with the heavy scale $f_a \sim \Lambda_{6\to 5}$ that could be an axion or axion-like particle (ALP) and couples to the top partner via derivative couplings

$$\mathcal{L} \supset -c_T \frac{\partial_\mu a}{\Lambda_{6\to 5}} (\bar{T}\gamma^\mu T). \tag{6}$$

The aforementioned $t - T$ mixing then introduces a top-ALP coupling c_t.

3. Axion-Like Particles

With Composite Higgs Models being one possible realisation, ALPs appear as pseudo Goldstone bosons in many SM extensions with a spontaneous breaking of a global symmetry. They are pseudo-scalars and obey a shift symmetry $a \to a + c$ which restricts the ALP couplings to SM particles and makes the couplings momentum-dependent. Accordingly, the energy scaling for processes involving ALPs differs from background processes which opens up many opportunities to probe ALPs. Traditional searches focus mainly on light ALPs and couplings to vector bosons. For searches in a larger mass range and with ALP-fermion couplings the top quark plays a crucial role.

The ALP is associated with a heavy scale f_a which is well above the electroweak scale, $f_a \gg v$. This observation allows us to take an EFT approach, $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_a$, where $\mathcal{L}_a$ is obtained up to next-to-leading order in the power expansion in a/f_a and parametrised by

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{1}{2} m_a^2 a^2 + c_{\tilde{W}} O_{\tilde{W}} + c_{\tilde{B}} O_{\tilde{B}} + c_{\tilde{G}} O_{\tilde{G}} + \sum_{f=u,d,e,Q,L} c_f O_f. \tag{7}$$

O_X for $X \in \{G, W, B\}$ contains the couplings of the ALPs to vector bosons and O_f the couplings to fermion pairs, which are proportional to the fermion mass. Accordingly, the ALP couples the strongest to the top quark:

$$\mathcal{L} \supset ic_t \frac{m_t a}{2f_a}(\bar{t}\gamma^5 t). \tag{8}$$

Observing this special role of the top quark motivates to switch on only c_t at tree-level, then the couplings to vector bosons are generated at 1-loop level via a top quark loop.
We can use high-energy LHC probes from processes that either involve or originate from the top quark and reinterpret them in terms of ALP searches to constrain the ALP-top coupling c_t [2]:

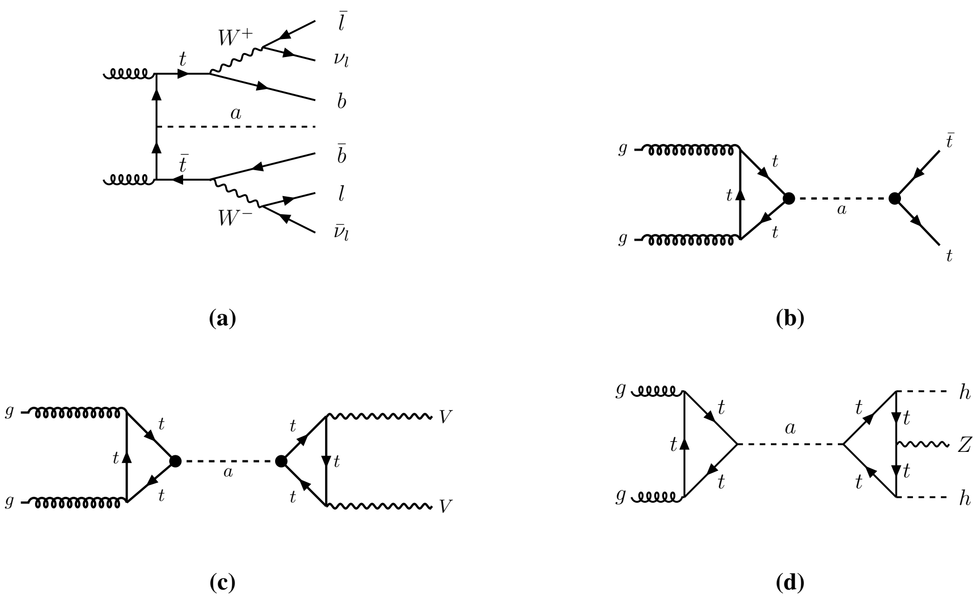


Figure 2: Diagrams for direct and indirect probes of the ALP-top coupling c_t, see text for details.

1. Direct limits on c_t can be obtained from associated production of the ALP with top quarks and leptonic top decays as the signal process, cf. Fig. 2 (a). Assuming the ALP collider stable, it escapes the detector as missing transverse energy (MET), leading to a 2b + 2l + MET final state. We can thus reinterpret a Run II ATLAS SUSY search for top squarks in that same final state.

2. Indirect constraints on c_t come from reinterpreting measurements of SM distributions in terms of signals mediated by an off-shell ALP, based on [3]. In particular they are non-resonant top-quark pair production, cf. Fig. 2 (b), final states with two on-shell gauge bosons, cf. Fig. 2 (c), and non-resonant Di-Higgs production in association with a Z boson [4], cf. Fig. 2 (d).

As summarised in [2], the bounds obtained from the reinterpretation of the direct searches are currently stronger than the indirect counterparts, but since the underlying processes scale differently with luminosity this hierarchy can change with higher luminosity.

4. SMEFT

The Standard Model Effective Field Theory (SMEFT) parametrises the effects of New Physics above the EW scale via a tower of higher-dimensional operators,

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + c_5 O_5 + \sum_i c_{6i} O_{6i} + \sum_i c_{7i} O_{7i} + \sum_i c_{8i} O_{8i} + \dots \tag{9}$$

The corresponding Wilson coefficients c_i are suppressed by powers of the heavy scale Λ. The SMEFT offers a framework to split the ubiquitous model-to-data analysis in particle physics, which consists in building BSM models to explain experimental data and constraining the model parameters by the data, into two steps: First, the Wilson coefficients can be constrained from precise low-energy measurements, using e.g. global SMEFT fits. This step is model-independent and needs to be done only once and for all. Then, BSM models are motivated to explain the SMEFT operators or specific sectors and the limits on the Wilson coefficients are translated into limits on the parameters of the model.

Operators involving four fermions (4F operators) arise at dimension-6, e.g. the operators containing 4 tops are given by

$$\begin{aligned}\mathcal{L}_{4t} = {} & \frac{c_{qq}^{(1)}}{\Lambda^2}(\bar{q}_3\gamma^\mu q_3)(\bar{q}_3\gamma_\mu q_3) + \frac{c_{qq}^{(3)}}{\Lambda^2}(\bar{q}_3\gamma^\mu\tau^I q_3)(\bar{q}_3\gamma_\mu\tau^I q_3) + \frac{c_{qu}^{(1)}}{\Lambda^2}(\bar{q}_3\gamma^\mu\tau^I q_3)(\bar{u}_R\gamma_\mu\tau^I u_R) \\ & + \frac{c_{qu}^{(8)}}{\Lambda^2}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{u}_R\gamma_\mu T^A u_R) + \frac{c_{uu}}{\Lambda^2}(\bar{u}_R\gamma^\mu\tau^I u_R)(\bar{u}_R\gamma_\mu\tau^I u_R).\end{aligned} \tag{10}$$

For the first and second fermion generation, the constraints from low-energy measurements are particularly strong and the new particles appearing in the model diagrams need to be heavy to fulfill these constraints. Nevertheless, 4F operators that are generated at 1-loop via box diagrams could contain lighter resonances than diagrams at tree-level. These resonances could be produced on-shell at the LHC and hence these models offer an interesting interplay between constraints from low-energy precision measurements and direct collider searches.

However, we need to avoid stable charged relics in the loops. One option which has been studied in [5] is requiring exit particles in the box diagram, which are particles that can linearly decay into SM particles. Models that contain DM candidates will automatically only generate contributions at 1-loop level and can be additionally constrained from the DM relic abundance [6].

For the the third fermion generation, the top partners need to be relatively light, leading to a completely different phenomenology. In [7] a benchmark model for a 4-top operator with a scalar top partner ϕ_T and a fermionic DM candidate χ and Langrangian

$$\mathcal{L}_{BSM} = \bar{\chi}\left(i\partial\!\!\!/ - \frac{1}{2}m_\chi\right)\chi + |D_\mu\phi_T|^2 - m_T^2|\phi_T|^2 - \left(y_{DM}\phi_T^\dagger\bar{\chi}t_R + h.c.\right) \tag{11}$$

is studied. An interesting channel for indirect searches is $t\bar{t}$ production from gluon fusion, $pp \to t\bar{t}$. For $\sqrt{s} \sim \sqrt{5}m_T$, the validity of the EFT is not guaranteed and the process has to be calculated in the full theory. The difference between the calculations in the EFT and the full theory lead to visible deviations in both the $m_{t\bar{t}}$ and p_T distribution of this process. The best channel for direct

PoS(LHCP2024)024

searches is the on-shell production of the top partner ϕ_T with a subsequent decay into $t + \chi$, leading to a $t\bar{t}$+ MET final state.
Higher-dimensional SMEFT operators become important for processes which can not be mediated at lower dimensions, e.g. Neutral Triple Gauge Couplings at dimension-8 [8].

5. Conclusion

Due to their heavy mass, top quarks are strongly connected to the electroweak sector and well suited for electroweak precision physics. The existence of a light scalar, the Higgs boson, motivates searches for light top-partners, which arise naturally in many BSM theories like e.g. Supersymmetry and Composite Higgs Models.
Additionally, it has been discussed that top quarks couple strongly to Axion-Like Particles and play a key role in both direct and indirect collider searches for ALPs. Furthermore, operators involving top quarks can be used in the SMEFT framework to classify and constrain new BSM models, including models with DM candidates. For light top partners the EFT validity is not guaranteed and a comparison with the calculations in the full BSM theory is crucial.

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PoS(LHCP2024)024