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Search strategies for heavy quark partners at LHC run-II

Thomas Flacke*
Department of Physics, Korea Advanced Institute of Science and Technology,
335 Gwahak-ro, Yuseong-gu, Daejeon 305-701, Korea
and
Department of Physics, Korea University, Seoul 136-713, Korea
E-mail: flacke@korea.ac.kr

We present results on several new search strategies for heavy vector-like quark partners at the early stages of the LHC run-II. Run-II will have sensitivity to single- and pair-produced quark partners with masses beyond 1 TeV. Decays of such heavy particles yield highly boosted tops, Higgses, and weak gauge bosons, all of which decay dominantly hadronically. At low boost, hadronic final states suffer from large Standard Model backgrounds, such that leptonic or semi-leptonic decay channels yielded better discovery potential at run-I. At high boost, the SM background of hadronic final states can be substantially suppressed when applying jet-substructure techniques. We present several case studies where the identification of hadronically decaying tops, Higgses, and/or electroweak gauge bosons allow to make new search channels competitive at run-II.

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1. Introduction and Overview

The discovery of a Higgs-like resonance by ATLAS [1] and CMS [2] represents a big success for particle physics and completes the Standard Model elementary particle spectrum. Nevertheless, an $m_h \approx 125$ GeV elementary Higgs neither provides a solution to the hierarchy problem nor does it provide a dynamical mechanism for electroweak symmetry breaking (*i.e.* a dynamical generation of the Higgs potential). Many Standard Model extensions which address the hierarchy problem predict QCD charged partner states to the top quark (and other quarks) with masses at the TeV scale which cancel the quadratically divergent loop contribution to the Higgs mass.[1] In supersymmetry the partner state is a boson (the stop), while *e.g.* little Higgs models or composite Higgs models (CHM) predict vector-like fermionic partners ("heavy quark partners") which are the topic of this presentation.

We discuss several new search strategies for heavy quark partners. For concreteness, we use an effective field theory description of the minimal composite Higgs model [5, 6] in our simulations which we review in the following, but we present our results in a model independent fashion such that they can be applied to other realizations of vector-like quark partner models.

2. A sample model: the minimal composite Higgs model

In composite Higgs models, the Higgs multiplet is realized as a Goldstone boson multiplet which arises from the spontaneous breaking a global symmetry which occurs through dimensional transmutation at a scale $\Lambda \sim 4\pi f \sim$ few TeV of a new strongly coupled gauge group. The vector-like quark partners are bound states of the strongly coupled theory, which are assumed to couple linearly to elementary quarks. These couplings (as well as weakly gauging the $SU(2)_L \times U(1)$ in the surviving global subgroup) explicitly break the global symmetry and induce a Higgs potential, making the Higgs a pseudo-Goldstone boson. In this way, a scale hierarchy $M_{pl} >> \Lambda \sim m_T > f > m_h, v$ is naturally generated. In the minimal composite Higgs model, the global symmetry breaking pattern is $SO(5) \times U(1)_X \to SO(4) \times U(1)_X \simeq SU(2)_L \times SU(2)_R \times U(1)_X$, which allows to gauge the electroweak SM subgroup to obtain the correct quantum numbers for the Higgs. It at the same time incorporates a custodial symmetry which helps to avoid large corrections to the electroweak T parameter. As of now, no full UV completions of composite Higgs models are known. For recent progress on non-supersymmetric UV completions *c.f.* Refs.[7, 8, 9]. Also generically, a strongly coupled sector will induce large FCNCs, which however can be controlled in various constructions (*c.f. e.g.* Refs.[10, 11, 12]). Inspite of these open questions, composite Higgs models represent an attractive approach to the hierarchy problem, and their phenomenology can be studied in terms of an effective field theory framework.

The linear couplings between the elementary quarks and their partners (which come in multiplets of the global symmetry) induce mass-mixing between them such that the lightest mass eigenstates (which are to be identified with the SM quarks) are a linear combination of the elementary quarks and strongly coupled states and are thus termed "partially composite". The mass-mixing also induces couplings between (SM) quarks, their heavy quark partners, and the electroweak bosons W, Z, h, which are relevant for the production of heavy quark partners at the LHC and the

[1] Two notable potential exceptions are Twin-Higgs models [3] and recently proposed relaxion models [4].

partners' decays and branching ratios. The typical strength of these couplings is the corresponding EW (or Yukawa) coupling times a mixing angle. In these proceedings we refrain from giving the full Lagrangian and interactions used for our simulations and model implementations (they can be found in Refs.[13, 14]) and instead summarize the qualitative features relevant for LHC searches:

- Quark partners come in multiplets of the global symmetry group in which the the EW group is embedded. For example a top-partner multiplet embedded into the **5** of $SO(5)$ contains one charge 5/3 partner, three charge 2/3 partners and one charge -1/3 partner.
- Quark partners are charged under $SU(3)$ and can be QCD-pair produced. This production mechanism is rather model-independent as the coupling strength is fixed, and the production cross section only depends on the mass of the quark partner.
- Quark partners can be single-produced from SM quarks and EW gauge bosons. The couplings relevant for this production mechanism are generically of electroweak strength or below, but model-dependent.
- The branching ratios of quark partners are generically model-dependent. Again taking quark partners in the **5** of $SO(5)$ as an example: the charge 5/3 state $X_{5/3}$ can only decay into W^+t due to charge conservation while the three charge 2/3 states (which we collectively denote by T) can decay into W^-b, Zt or ht, and the respective branching ratios are model- and parameter dependent.

3. Heavy quark searches at the LHC

3.1 A brief summary of the LHC run-I results

Both ATLAS and CMS performed numerous dedicated searches for 3rd family quark partners at the LHC run-I. The searches focus on QCD pair production of charge 5/3, 2/3, and -1/3 partners and their decay into 3rd family quarks and $W/Z/h$.[2] Searches are performed in various final states, including all-hadronic searches (using jet-substructure techniques), single- or multi-lepton final state searches, and – for charge 5/3 partner searches – also same-sign dilepton final states. The mass bounds on 3rd family partners are $m_{X53} > 840$ GeV, $m_T > 700-950$ GeV, and $m_B > 600-800$ GeV where the latter two bounds have a range because they depend on the T and B branching fractions into different final states.

Most ATLAS and CMS searches focussed on QCD pair produced top partners while for singly produced top partners bounds were obtained in a recast of other experimental searches in Ref.[17], which show that for typical couplings (in composite Higgs models), single-production channels yield at most comparable and mostly weaker bounds on the quark partner masses than the pair-production channels.

Bounds for vector-like quark partners of light quarks have been obtained in a recast from several experimental searches in Ref. [13]. The bounds from QCD pair production are generically weaker than for 3rd family quark partners. In particular a bound on the charge 5/3 partner is obtained at $m_{X53} > 530$ GeV. Notably, the bound on the charge 2/3 partner can be even weaker

[2] *C.f.* [15] and [16] for a detailed list of searches and results.

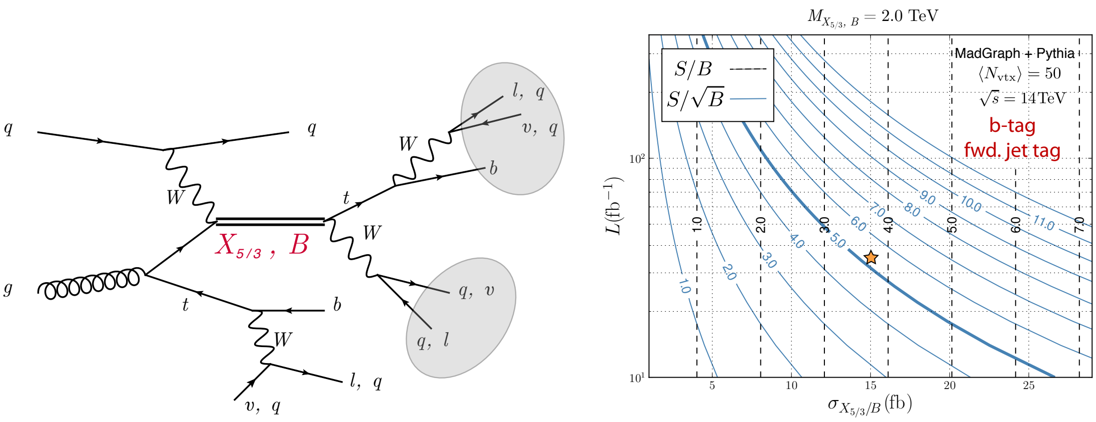

Figure 1: Left: Single-production of a $X_{5/3}$ or B vector-like top quark partner with subsequent semi-leptonic decay. Right: Simulated signal (S) over background (B) ratio and $S\sqrt{B}$ for a 2 TeV quark partner in the luminosity vs. single-production cross section plane, obtained in Ref.[14].

($M_Q > 410$ GeV) if it dominantly decays into hj [18].[3] Bounds on singly-produced 1st or 2nd family quark partners can be stronger, but are model-dependent.

3.2 Alternative search channels and strategies for heavy quark searches at run-II

Two main points make it necessary to re-evaluate the prospects for the various heavy quark search channels when moving up in energy from run-I to run-II. First, the higher energy results in sensitivity to higher quark partner masses, but for TeV scale particles, their decay products have very high p_T. For vector-like heavy quarks, this leads to highly "boosted" tops, W, Z, and Higgs bosons which can decay hadronically into collimated jets whose analysis requires improved (jet-substructure) techniques. Therefore, in particular hadronic decays will have altered detection efficiencies at run-II as compared to methods adopted in run-I searches. Second, as compared to QCD pair production, single-production channels generically have smaller (and model dependent) couplings, but they are less phase-space suppressed as only one heavy BSM state has to be produced. Therefore, single production channels become more promising for higher quark partner masses searches, and with the increase of energy, the mass sensitivity of run-II is pushed into the regime where single production channels typically dominate.

As a first example, we present prospects for searches of single-produced $X_{5/3}$ or B in the semi-leptonic decay channel of $X_{5/3}/B \to tW$[14]. The process is shown in Fig. 1 (left). The "canonical" search for $X_{5/3}$ would be a same-sign dilepton search which has a very low background. The semi-leptonic channel we consider has a larger signal cross section due to the larger branching ratio of W and t into hadrons, but also has larger backgrounds. Although the final state we consider might appear complex, it contains several distinctive features which allow efficient suppression of SM backgrounds (which are dominated by SM $t\bar{t}$ and W+jets final states). The signal is characterized by a high energy forward jet (which can be tagged), two b quarks, and a highly boosted tW system with one hard lepton, missing energy and a "fat jet", *i.e.* a jet with substructure arising from the hadronically decaying W or t, which we reconstruct, using the Template Overlap Method [20].

[3] The sensitivity on this di-Higgs, di-jet channel can be substantially improved at LHC run-II [19].

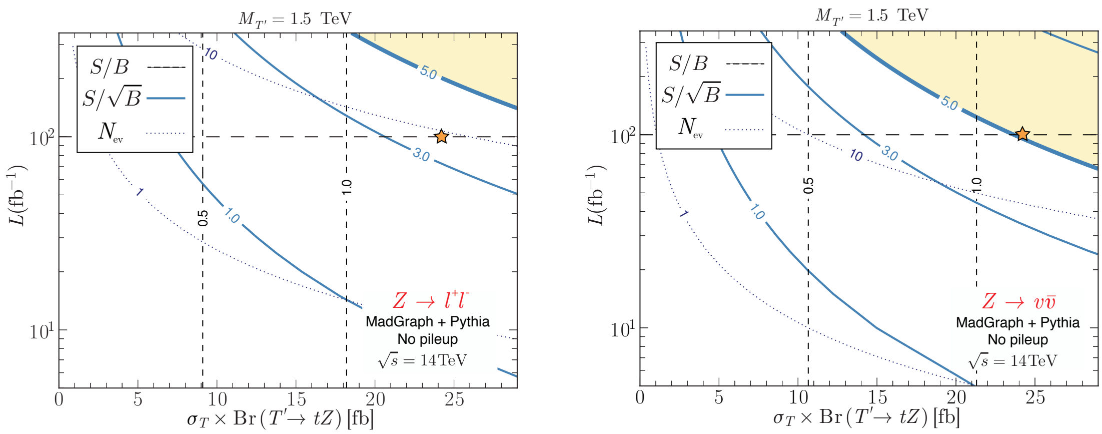

Figure 2: Simulated signal (S) over background (B) ratio, $S\sqrt{B}$, and number of events $N_{\rm ev}$ for a 1.5 TeV quark partner with charge 2/3 decaying into tZ in the luminosity vs. single-production cross section times plane, obtained in Ref.[21]. Left: leptonic decay channel of the Z. Right: Invisible decay $Z \to \nu\bar{\nu}$.

The details of signal and background simulations as well as detailed cut-flow tables for several quark partner sample masses can be found in Ref. [14]. One of our results is shown in Fig.1 (right). In order to present results in a model-independent way we show the signal-to-background ratio (S/B) and $S/\sqrt{B}$ in the luminosity vs. single-production cross section plane. As shown in Fig.1 (right, marked by a star), a 2 TeV top partner can be detected with a significance $S/\sqrt{B} > 5$ at a luminosity of 35 fb^{-1} if it has a production cross section of 15 fb, even in the presence of (on average) 50 pile-up events. This sensitivity is comparable (and even exceeds) the expected sensitivity of the same-sign dilepton channel at the same production rate, making the semi-leptonic channel an attractive search channel for $X_{5/3}$ at LHC run-II which also has potential advantages in the mass reconstruction of the resonance if an excess is found.

As a second example, we present a comparison of the charge 2/3 top partner search in the tZ decay channel [21] with the t decaying hadronically and the Z decaying either into dileptons or invisibly into neutrinos (analogously to Fig.1 (left), the top partner is produced in conjunction with a forward jet and a third family anti quark, this time a $\bar{b}$). The "canonically considered" di-lepton channel allows for a Z reconstruction with low SM backgrounds (dominated by $Z+X$), but suffers from a low branching ratio of $Z \to ll$. The invisible Z decay comes with a higher branching ratio but does not allow to reconstruct the Z which only yields high missing energy in the final state. To provide a "fair" comparison, we use the same cuts for the high energy forward jet and the hadronic top identification and only alter the cuts for the Z decay where we use standard techniques for Z reconstruction from dileptons on the one hand and a very hard missing E_T cut for the invisible Z decay search (*c.f.* Ref. [21] for details). We studied two sample masses for the top partner of 1 TeV and 1.5 TeV. For 1 TeV, we find comparable performance for both search channels while for a mass of 1.5 TeV, the invisible channel outperforms as is shown in Fig.2, where we again present results in terms of S/B and $S/\sqrt{B}$ in the luminosity vs. production cross section (times branching fraction of $T \to tZ$) plane.

This latter study has been the starting point of a larger, comprehensive overview on charge

2/3 top partner single production channel searches, their various final states and their discovery and exclusion potential at run-II. The work was still in progress whilst this talk was given but it completed now, and results are available in Ref. [22].

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