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Interplay Between LHC and Flavor Physics

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The discovery of the Higgs boson and subsequent measurements of its properties at the LHC have spectacularly confirmed key standard model (SM) predictions concerning electroweak symmetry breaking. At the same time, flavor physics, also intimately tied to Higgs interactions, remains among the least understood sectors of the SM. On the one hand, the peculiar pattern of quark and lepton masses, and their mixing angles, may be the clue to some new dynamics beyond SM. Experimental studies of the Higgs boson are finally starting to probe this aspect of flavor physics directly. On the other hand, the generally excellent agreement between SM predictions and existing experimental measurements of the multitude of flavor physics observables at lower energies represents a serious challenge to SM extensions predicting new particles in direct reach of the LHC. Fortunately, several recent experimental hints of possible deviations from SM predictions in rare semileptonic B meson decays do have interesting implications for direct searches performed at high energies.

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PoS(KMI2017)032

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1. Introduction

After the discovery of the Higgs boson as the last missing elementary particle predicted by the standard model (SM) the main focus of high energy physics has shifted towards elucidating the possible solutions to unresolved puzzles within the SM, such as the electroweak-Planck scale hierarchy, the patterns of quark and lepton flavor parameters or the origin of neutrino masses. In addition several open questions arise when applying SM dynamics to the very early Universe concerning the origin of the cosmological baryon asymmetry, dark matter (DM) and dark energy. Searches for related effects of physics beyond SM – also called new physics (NP) – are conducted across multiple venues. Both flavor and high p_T measurements are among the most promising ones and provide complementary probes of possible NP models. The interdependence can however also be more involved: on the one hand, a nontrivial flavor structure of NP modifies the associated signatures at the LHC; on the other hand possible non-standard observations in flavor changing processes can motivate NP searches at high p_T. In this contribution we examine some illustrative examples.

2. New Physics Reach of Flavor and LHC

In absence of NP degrees of freedom at energies below or at the electroweak (EW) scale $v_{\rm EW} \simeq 246\,$GeV, one can treat the SM as an effective field theory (EFT) valid below a cut-off NP mass scale $\Lambda > v_{\rm EW}$. One can thus consider additional terms in the theory Lagrangian consisting of SM field operators ($\mathscr{O}_n^{(d)}$) with canonical dimensions $d > 4$:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_{d>4}\sum_n \frac{c_n^{(d)}}{\Lambda^{d-4}}\mathscr{O}_n^{(d)}\,. \tag{2.1}$$

Direct searches for production of new particles at the LHC are starting to push the NP scale Λ into the TeV region (see e.g. Ref. [1]). This should be compared to indirect constraints on NP sources of flavor violation coming for example from precise determination of neutral meson mixing and CP violation parameters. If parametrized in terms of $\mathscr{O}_{AB}^{(6)} \equiv z^{ij}\left[\bar q_i \Gamma^A q_j\right] \otimes \left[\bar q_i \Gamma^B q_j\right]$, where $\Gamma^{A,B}$ are the usual elements of the Clifford algebra and $i \neq j$ quark flavor indices, current measurements are probing scales up to $\Lambda \sim 10^{6(4)}\,$TeV assuming $z^{ij} \sim i(1)$, i.e. well beyond the LHC energy threshold (see e.g. Ref. [2] and recent updates in Refs. [3, 4]).

An illustrative and explicit example is that of the minimal supersymmetric standard model (MSSM) with a split spectrum of super-partners, where the gauginos and higgsinos remain close to the EW scale in order to preserve unification of gauge couplings, while all the sfermions have masses of the order tens to thousands of TeV [5]. In particular, PeV scale stop (and sbottom) masses are required to accommodate the correct Higgs boson mass in absence of large trilinear supersymmetry breaking couplings and at moderate ratios of the two Higgs doublet vevs ($\tan\beta$) within the MSSM. At one-loop level one has namely

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3m_t^2}{4\pi^2 v_{\rm EW}^2}\log\frac{m_{\tilde t}^2}{m_t^2}\,. \tag{2.2}$$

Allowing for generic supersymmetry breaking soft sfermion masses $\tilde m \sim m_{\tilde q} \sim m_{\tilde l}$ with $\mathscr{O}(1)$ flavor misalignment with respect to the SM Yukawas and $\mathscr{O}(1)$ mass splittings among the different

PoS(KMI2017)032

sfermion mass eigenstates, existing flavor measurements are already sensitive to $\tilde m \gtrsim$ PeV, well above the direct mass reach of any currently foreseen high-energy particle collider experiment. The most senstive flavor and CP probes include CP violation in the neutral kaon and charmed meson systems, the neutron and electron electric dipole moments (EDMs), as well as probes of charged lepton flavor violation in the $\mu - e$ sector ($\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion in nuclei). Interestingly several of these probes are expected to be further significantly improved in the coming decade [5].

In light of these severe indirect constraints, a pressing question is whether realistic NP models can be constructed with new degrees of freedom in direct reach of the LHC. While the introduction of generic $\mathscr{O}(1)$ flavor violation is not necessary, the fact that SM Higgs interactions themselves already break the flavor symmetry of the SM gauge sector imposes an effective lower bound on the amount of flavor violation expected in NP models addressing the SM EW hierarchy or flavor puzzles. In particular considering for illustration only NP Lorentz scalar or vector operators (which we here commonly denote as X) coupled linearly to SM field currents involving down-type quarks, the relevant lowest dimensional effective operator structures are of the form [6]

$$\mathscr{H}_{\rm eff} \ni \frac{c^{IJ}_{RL}}{\Lambda^n} H^\dagger \bar D^I Q^J \otimes X + \frac{c^{IJ}_{LR}}{\Lambda^n}\bar Q^I D^J H \otimes X + \frac{c^{IJ}_{LL}}{\Lambda^n}\bar Q^I Q^J \otimes X + \frac{c^{IJ}_{RR}}{\Lambda^n}\bar D^I D^J \otimes X\,, \tag{2.3}$$

where I,J are quark generation indices and we have suppressed all spin and Lorentz contractions. It is easy to realize that as with the SM Higgs, any additional scalar coupled to SM fermions will necessarily induce flavor breaking (the direction of which can be at most aligned with the corresponding Higgs Yukawas). On the other hand, new massive vectors coupling to SM conserved fermionic currents (like B-L), can preserve flavor – at least at the tree-level. In both these minimal cases, the appearance of flavor changing neutral currents (FCNCs) is deferred to the one-loop order including possible GIM suppression as in the SM, i.e. $c^{IJ} \sim (g/4\pi)^2 V^*_{tI} V_{tJ} \times c^{33}$. Such NP is also called minimal flavor violating (MFV) (see Ref. [7] for a more formal definition). For MFV NP with weak loop suppressed FCNCs, the most precise neutral kaon and B-meson mixing observables exhibit comparable sensitivity currently approaching the interesting TeV mass reach [2].

As another explicit example consider a simplified model of thermal relic particle DM, where the DM is a massive fermion (χ) coupled to the SM through a (pseudo)scalar portal (field A). The relevant interactions can effectively be written as

$$\mathscr{L}_{\rm int} = i g_\chi A \bar\chi \gamma_5 \chi + \sum_{f=q,\ell,\nu} i g_f A \bar f \gamma_5 f\,. \tag{2.4}$$

This form of DM-SM interactions is mostly transparent to existing direct DM detection experiments since the relevant processes of DM scattering on nuclei are severely suppressed [8]. The model can be made consistent with MFV by assuming SM Yukawa-like structure of g_f, i.e. $g_f = \sqrt{2} g_0 m_f / v_{\rm EW}$ with g_0 being flavor universal. Finally, direct production of χ pairs at the LHC is suppressed in the part of parameter space where $2m_\chi > m_A$ such that on-shell $A \to \chi\bar\chi$ decays are kinematically forbidden and resonantly produced A's predominantly decay back to SM final states. Experimentally, this challenging scenario is best probed through mediator (A) effects on processes involving SM particles. In particular, at low enough mass A can be produced in hadron decays and probed in final states involving charged leptons, such as $K_L \to \pi_0(A \to \ell^+\ell^-)$ or $B \to K(A \to \mu^+\mu^-)$ [9]. Above

PoS(KMI2017)032

the hadronic resonance region, A can be efficiently resonantly produced at the LHC through heavy quark loop induced gluon fusion and can be searched for in the form of a narrow di-muon [10] or di-photon [11] resonance. Finally, for $m_A > 2m_t$, resonant top pair production becomes the dominant search venue [11]. We observe in this particular example, that flavor and high-p_T searches are not competing but complementary probes of NP, sensitive to different parameter (in this case mass of A) ranges.

3. Flavor Probes of Higgs Sector

In the SM all elementary particles obtain their mass through couplings to the Higgs field. In the case of charged fermions, their hierarchical mass spectra thus imply correspondingly hierarchical fermionic couplings (Yukawas y_f) of the Higgs boson:

$$y_f^{\rm SM} = \sqrt{2}\frac{m_f}{v_{\rm EW}}\,. \tag{3.1}$$

Several key predictions following from the above relation have only become experimentally accessible with the discovery of the Higgs boson [12]

- proportionality: $y_{ii} \propto m_i\,,$
- factor of proportionality: $y_{ii}/m_i = \sqrt{2}/v_{\rm EW}\,,$
- diagonality: $y_{i\neq j} = 0\,.$

There have been many recent proposals on how to probe these three sets of predictions, both directly at the LHC in Higgs boson production and decays [13, 14, 15, 16, 17, 18], as well as indirectly, e.g. through virtual Higgs boson effects in rare FCNC and CP violating processes at lower energies [19, 20, 21]. Especially challenging to probe are of course the tiny SM predicted couplings of the Higgs boson to the lighter fermions. It is important to stress, that these relations represent genuinely new probes of the elementary flavor dynamics, complementary to existing flavor programme testing the structure of the CKM.

It is thus not surprising that the slight hint of an excess in the $h\to\tau\mu$ channel as reported by the CMS collaboration in their 8 TeV LHC data [22] caught the attention of the community. The excess has been neither confirmed nor excluded in subsequent analyses by ATLAS at 8 TeV [23] and CMS using their early data taken at 13 TeV pp collisions [24]. The size of the effect, $\mathscr{B}(h\to\tau\mu)\sim 0.8\%$, is marginally consistent with theoretical constraints on radiative stability of the Yukawas $|y_{\tau\mu}y_{\mu\tau}| \lesssim m_\tau m_\mu/v_{\rm EW}^2$ [25]. More challenging to accommodate are the existing experimental bounds on lepton flavor violating radiative tau decays $\tau\to\mu\gamma$. One can namely show that in the NP decoupling (SM EFT) limit, the leading effective operators sourcing $h\to\tau\mu$ and $\tau\to\mu\gamma$ have exactly the same flavor structure and thus the later cannot be suppressed using flavor symmetries without also reducing the former. Furthermore, non-vanishing $h\tau\mu$ couplings $y_{\tau\mu,\mu\tau}$ induce a finite shift to $\tau\to\mu\gamma$ at one-loop through virtual Higgs exchange [20]. Taking only this single contribution into account, values of $y_{\tau\mu,\mu\tau}$ accommodating the CMS hint lead to values of $\mathscr{B}(\tau\to\mu\gamma)$ close to current experimental bounds. In explicit NP models, where $y_{\tau\mu,\mu\tau}$ are generated dynamically, there are typically comparable or larger effects due to virtual exchanges of

PoS(KMI2017)032

NP degrees of freedom. In particular, such effects generically rule out models where non-vanishing $y_{\tau\mu,\mu\tau}$ is only generated at loop-level. Tree-level generation of $y_{\tau\mu,\mu\tau}$ through mixing of SM leptons with vector-like fermions is also ruled out [26]. The only remaining alternative (tree-level generation of $y_{\tau\mu,\mu\tau}$) appears in presence of multiple sources of EW symmetry breaking (as in multiple Higgs doublet models, or models with sources of strong EW symmetry breaking) [25, 27]. Even in this case, generically, predicted rates of $\tau \to \mu\gamma$ are within reach of the upcoming Belle II experiment. Another generic implication of percent level $h \to \tau\mu$ is the presence of new degrees of freedom within the kinematical reach of the LHC. Finally, a combination of existing $\mu \to e\gamma$ and $\mu \to e$ nuclear conversion experimental constraints already model-independently excludes simultaneously observable rates for both $h \to \tau\mu$ and $h \to \tau e$ [25].

Before closing this section we note that a nontrivial NP flavor structure can have important implications for on-shell searches at the LHC. For example, within two Higgs doublet models accommodating percent level $\mathscr{B}(h \to \tau\mu)$, both additional neutral as well as charged scalars can predominantly decay into leptons [28]. In particular $R^{H^+/A}_{hW^+Z} \simeq R^{H^+/A}_{t\bar{b}\bar{t}} = R^{H^+/A}_{\tau^+\nu\mu^-} + R^{H^+/A}_{\mu^+\nu\tau^-} = 1$ where $R^{H^+/A}_{XYZ} \equiv \Gamma(H^+ \to XY)/\Gamma(A \to XZ)$ and assuming $m_{H^+} \sim m_A$.

4. Flavor Anomalies versus High-p_T Searches

In the recent years curious discrepancies have arisen between SM expectations and experimental measurements of charged current mediated semitauonic B meson decays. In particular, while the $B \to D^{(*)}\ell\nu$ modes with $\ell = e,\mu$ are important observables in the determination of the CKM modulus $|V_{cb}|$, the corresponding semitauonic $B \to D^{(*)}\tau\nu$ decay rates can be very precisely predicted within the SM, if they are normalized to the electron or muon modes [29, 30]:

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)} . \tag{4.1}$$

A recent experimental average by HFAG [31] exhibits a 3.9σ tension when both $R(D)$ and $R(D^*)$ measurements are combined and compared to the corresponding SM predictions. At the current level of the excesses ($R(D^{(*)})_{\rm exp}/R(D^{(*)})_{\rm SM} \simeq 1.25$), the dominant theoretical uncertainties due to subleading hadronic effects, which do not cancel in the lepton flavor ratios, and are at the level of few percent, are completely negligible. At the same time, the size of the observed effect in processes, which in the SM are tree-level charged current dominated, calls for tree-level NP contributions [32]. Furthermore, if weakly coupled, new dynamics needs to involve EM charged (mediator) particles with masses at or below $M \lesssim \mathscr{O}(\text{TeV})$. This makes them susceptible to direct searches at high energy particle colliders. Experiments at LEP have put robust bounds on new charged particles which thus need to be heavier than approximately $M \gtrsim 100$ GeV . In addition, FCNC constraints as well as existing precise tests of lepton flavor universality with pion, kaon, charm and tau decays require an approximate flavor alignment such that NP significantly affecting $R(D^{(*)})$ should necessarily couple most strongly to the third generation of SM fermions. Consequently $SU(2)_L$ invariance predicts non-vanishing correlated effects in top quark decays. For mediator masses below $M < m_t - m_b \simeq 170\,\text{GeV}$ existing LHC measurements of leptonic top quark branching fractions are already severely constraining the relevant parameter space [33] (see Fig. 1). On the other hand, off-shell NP effects relevant for heavier mediator masses will be much more challenging to

PoS(KMI2017)032

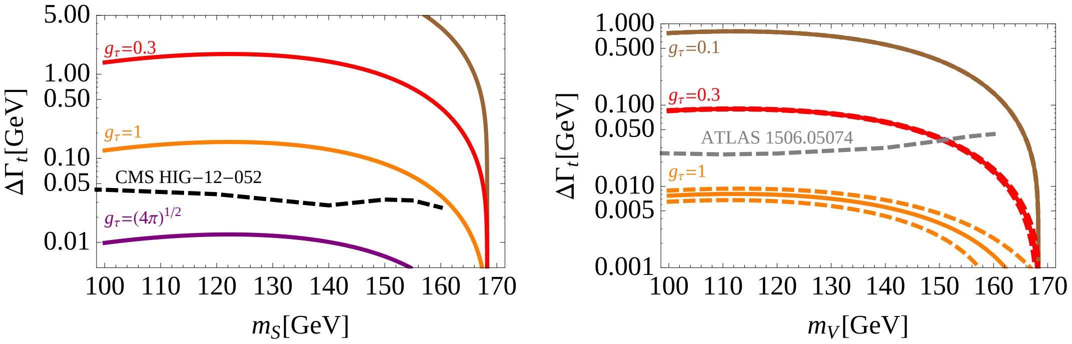

Figure 1: Current experimental constraints on simplified model parameters coming from LHC top decay measurements for the case of a charged scalar (left) [34] or vector (right) [35] boson coupled predominantly to the third generation of SM quarks and leptons and accommodating the $R(D^{(*)})$ anomaly [33]. Here $\Delta\Gamma_t = \Gamma_t - \Gamma_t^{\rm SM}$ equaling $\Gamma(t \to b(S \to \tau\nu))$ for the scalar and $\Gamma(t \to b(V \to \tau\nu))$ for the vector mediator model, while g_τ denotes the mediator coupling to $\tau\nu$. See Ref. [33] for details.

probe in the interesting range of parameters since they need to compete with the large two-body $\Gamma(t \to bW^+) \sim 1.5$ GeV SM rate.

Most of the NP models proposed to address the $R(D^{(*)})$ anomaly in addition predict sizable tau lepton production at high p_T and are thus subject to severe constraints coming from LHC searches for $\tau^+\tau^-$ production at high invariant mass [36]. For example, the simplest $SU(2)_L$ triplet spin-1 mediator model [37] can only accommodate the experimental $R(D^{(*)})$ values provided the new neutral resonances have $M < 500$ GeV and/or $\Gamma/M > 30\%$. Future LHC di-tau production measurements are expected to further severely constrain all such scenarios.

5. Conclusions

Flavor is a powerful guide for high-p_T searches at the LHC. On the one hand it helps to ensure that no stones are left unturned (and that the most interesting stones are turned over first). On the other hand, should significant signals of NP appear in flavor observables, one can readily identify prospective LHC experimental targets.

In the eventual case that new phenomena are discovered at the LHC, flavor physics will allow to disentangle different possible interpretations and discriminate between different proposals and scenarios. Two recent examples of such guidance are the 125 GeV Higgs boson were low energy flavor observables already tightly constrain the possible departures of its coupings to SM fermions from SM predictions (see e.g. [20]); as well as the now defunct 750 GeV di-photon resonance apparent in the early 13TeV LHC data, where similar considerations could immediately be used to constrain the number of interesting prospective final states involving SM fermions [38, 39].

Finally, as long as no new degrees of freedom are seen at the LHC, precision tests of flavor, CP, baryon and lepton numbers are possibly the best probes to keep pushing the NP reach to higher scales/smaller couplings. In fact, the sensitivity of these indirect probes in many cases already (far) exceeds energies and scales attainable in present and planned collider as well as cosmic ray experiments.

PoS(KMI2017)032

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PoS(KMI2017)032

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PoS(KMI2017)032