PROCEEDINGS OF SCIENCE

BSM theory perspectives for Run 3

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LHC Run 3 will approximately double the available LHC dataset. This wealth of data will be a huge push forward for the search for beyond the Standard Model (BSM) physics. In this contribution, I will discuss three physics targets for Run 3 from a theory perspective: (i) the search for uncovered BSM signatures, (ii) the search for rare decay processes of Standard Model particles, and the combination of LHC measurements with non-collider measurements. I will illustrate each of these topics by an explicit example: (i) the search for bosonic charged Higgs decays, (ii) the search for rare BSM top-quark decays, and (iii) the search for $\mathcal{CP}$ violation in the Higgs sector.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

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PoS(LHCP2023)213

1. Introduction

While the Standard Model (SM) of particle physics is remarkably successful in precisely describing a wide range of processes, there are several key observations that point towards the existence of physics beyond the SM (BSM). These include the existence of dark matter or the baryon asymmetry of the universe (BAU). The Large Hadron Collider (LHC) is a unique opportunity to reveal the nature of BSM physics.

While the first LHC runs were very successful in finding the Higgs boson, they have so far not revealed conclusive hints for BSM physics. The LHC physics program, however, is far from being completed. LHC Run 3 is expected to approximately double the available LHC data. This poses the question of how we should exploit this wealth of data.

A larger dataset leads to many opportunities. Focusing here on a theory perspective, a non-comprehensive list is given in the following:

- Increase sensitivity of existing searches for new particles.
- More precise measurements of the properties of the known particles.
- Search for BSM particles via so far uncovered experimental signatures.
- Search for rare BSM decay modes of the known particles.
- Expand the physics implications of LHC searches/measurements by leveraging the complementarity with non-collider measurements.

In this work, we will give illustrative examples for the last three points.

2. Uncovered BSM signatures

There are many proposals for new searches for so far uncovered signatures (see e.g. Refs. [1–4]). Here, we will focus on the search for bosonic charged Higgs decays which have recently received considerable attention in the literature [5–12]. The material presented here is based on the Ref. [5].

Charged Higgs bosons are present in doublet (and higher multiplet) extensions of the SM. Gauge invariance implies sum rules for the bosonic couplings of the charged Higgs bosons [13],

$$\sum_i |g(H_i^\pm W^\mp h_j)|^2 = \frac{g^2}{4}(1 - c(h_j WW)^2)\,, \quad \sum_i |g(H_i^\pm W^\mp a_j)|^2 = \frac{g^2}{4}\,, \tag{1}$$

where g is the $SU(2)_L$ gauge coupling and the sum runs over all charged Higgs bosons. h_j and a_j denote $\mathcal{CP}$-even and $\mathcal{CP}$-odd Higgs bosons, respectively. These sum rules implies that there is always a substantial coupling between a charged Higgs boson, a W boson, and a $\mathcal{CP}$-odd Higgs boson regardless of the BSM parameters. Moreover, also the couplings to a W boson and a $\mathcal{CP}$-even Higgs boson are large if the coupling of the scalar to W bosons is close to zero. If this scalar is the 125 GeV Higgs boson, experimental bounds implies that $c(h_j WW)^2 \sim 1$ — with $c(h_j WW)$ being the SM normalize Higgs–W-boson coupling — and, thereby, that the couplings to charged Higgs bosons are large. These sum rules make the decay channels $H_i^\pm \to W^\pm h_j$ — with h_j not being the

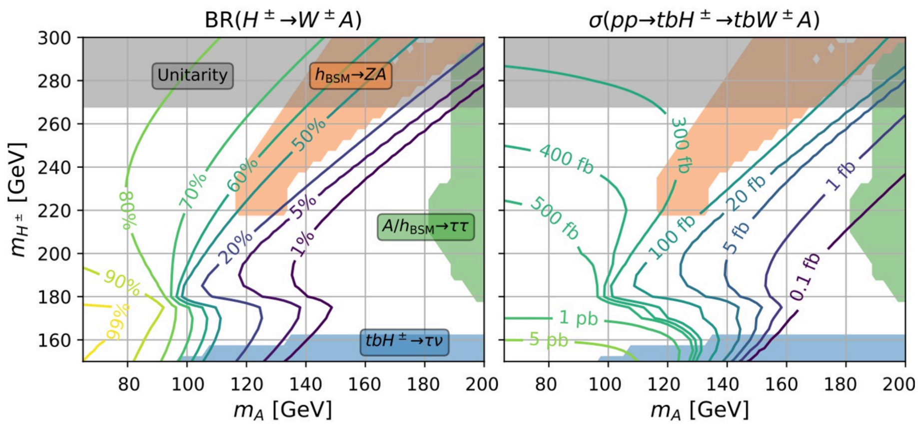

Figure 1: Left: Branching ratio of the charged Higgs boson into a W and an A boson in the $(m_A, m_{H^\pm})$ plane. Existing theoretical and experimental bounds are shown as coloured regions. Right: Same as left, but the cross section for the production of a charged Higgs boson in association with a top and a bottom quark and the subsequent decay into a W and an A boson is shown.

125 GeV Higgs boson — and $H^\pm \to W^\pm a_j$ natural candidates for charged Higgs searches (if these decay channels are kinematically allowed).

As a concrete example, we investigate the Two-Higgs-Doublet model of type-I in the alignment limit. The left panel of Fig. 1 shows the branching ratio for $H^\pm \to W^\pm A$, where $H^\pm$ is the 2HDM charged Higgs boson and A is the corresponding $\mathcal{CP}$-odd scalar, in the $(m_A, m_{H^\pm})$ plane (setting the mass of the BSM $\mathcal{CP}$-even scalar equal to $m_{H^\pm}$ and fixing the ratio of the vacuum expectation values to three). As soon as this decay mode is kinematically allowed, the branching ratio is large. This parameter region is hardly constrained by other constraints. Only perturbative unitarity and a few complementary searches exclude small areas of the parameter space. The large branching ratio results in a large cross section for the production of a charged Higgs boson in association with a top and a bottom quark and the subsequent decay into a W and an A boson. The resulting cross-section values are shown in the right panel of Fig. 1 and exceed 5 pb. Considering the various possible decay modes of the A boson (depending on the specific 2HDM scenario), this results in a large variety of testable final states.

Despite these potential large signals, so far only a limited amount of experimental searches targeting specific final states have been performed [14, 15]. Moreover, the existing searches are limited to specific mass configurations.

3. Search for rare BSM decay processes

The wealth of data collected during LHC Run 3 and also the upcoming High-Luminosity LHC (HL-LHC) offers a unique opportunity to search for rare BSM decay modes of SM particle. Here, we will focus on the search for rare top-quark decays [16]. Since top quarks are produced in vast quantities via di top-quark production, even decay channels with a very small branching ratio can be probed. The decay of the second top-quark in the event serves as a natural trigger.

Working in an effective-field theory framework, we consider a representative selection of operators inducing flavour-changing-neutral-current top-quark decays listed in Table 1. In addition

SM dim 6	
O^6_{quqd}	$(\bar{Q}_{Li} u_{Rj})\,(\bar{Q}_{Lk} d_{Rl})$
O^6_{qule}	$(\bar{Q}_{Li} u_{Rj})\,(\bar{L}_{Lk} e_{Rl})$
$O^6_{\Phi\Phi qu\Phi}$	$(\Phi^\dagger\Phi)(\bar{Q}_{Li} u_{Rj}\tilde{\Phi})$
$O^6_{\Phi D\Phi qq}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_{Li}\gamma^\mu Q_{Lj})$
$O^6_{qu\Phi G}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}\tau^A u_{Rj})\widetilde{\Phi}G^A_{\mu\nu}$
$O^6_{qu\Phi W}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\widetilde{\Phi}W^I_{\mu\nu}$
$O^6_{qu\Phi B}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}u_{Rj})\widetilde{\Phi}B_{\mu\nu}$

BSM dim 5	
O^5_{SqDq}	$S(\bar{Q}_{Li}\not{D}Q_{Lj})$
$O^5_{SQu\Phi}$	$S(\bar{Q}_{Li}u_{Rj}\widetilde{\Phi})$
BSM dim 6	
O^6_{qdlN}	$(\bar{Q}_{Li} d_{Rj})\,(\bar{L}_{Lk} N)$
O^6_{qulN}	$(\bar{Q}_{Li} u_{Rj})\,(\bar{N} L_{Lk})$
O^6_{dueN}	$\left(\bar{e}^c_{Rj} u_{Rj}\right)\,(\bar{d}_{Rk} N)$
O^6_{qqNN}	$(\bar{Q}_{Li}\gamma_\mu Q_{Lj})\,(\bar{N}\gamma^\mu N)$
O^6_{SSqDq}	$S^2(\bar{Q}_{Li}\not{D}Q_{Lj})$
$O^6_{SSqu\Phi}$	$S^2(\bar{Q}_{Li}u_{Rj}\widetilde{\Phi})$
$O^6_{qu\Phi Z'}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}u_{Rj})\widetilde{\Phi}F'_{\mu\nu}$

Table 1: Overview of operators inducing top-quark decays into SM particles (left) and BSM particles (right). Q_L is a Dirac spinor containing the left-handed quark doublet. The right-handed quarks are denoted by u_R and d_R, respectively. L_L and e_R are the left- and right-handed lepton doublets/singlets, respectively. i, j, k, and l are the quark and lepton generation indices. Other indices are suppressed. The Higgs doublet is called Φ. D denotes the SM covariant derivative, and $\not{D} \equiv \gamma^\mu D_\mu$. The SM vector-boson field strengths are called G, W, and B. The BSM singlets are called S (scalar) and N (Dirac fermion). The Z' field strength is denoted by F'. The superscript "c" denotes charge conjugation.

to dimension-six operators including only SM fields (left table), we also consider dimension-five and -six operators containing light SM singlets or a $U(1)$ gauge boson (right table). These include a scalar singlet S, a fermion singlet N, and the Z' boson.

Setting the new physics scale $\Lambda_{\text{NP}} = 1$ TeV, the BSM masses to 10 GeV, and all Wilson coefficients equal to one, we show the branching ratios and the expected number of events at HL-LHC for the various top-quark decay channels induced by operators listed in Table 1 in Fig. 2. For the decay modes with a SM final state (green bars), $O(0.1\%)$ branching ratios are easily reachable for operators involving gauge bosons and current-current operators. The branching ratios for the four-fermion operators are substantially smaller. Most of these SM final states are already probed experimentally as indicated by the dashed lines [17–20].

For the BSM final states, the branching ratios of the dimension-five operators are particularly large, while the decay channels induced by four-fermion operators are again suppressed. But even the suppressed decay modes result in $O(10^3)$ events at the HL-LHC. Despite the potentially large signal, most of these decay channels are not yet probed experimentally. The only exception is the $t \to Sj$ channel, for which the experimental search is, however, limited to the $S \to b\bar{b}$ decay channel [21]. Interestingly, the light singlets can, moreover, be long-lived (as can be demonstrated by a calculation of their minimal decay width). This opens up the possibility for displaced vertex searches which often profit from a low background. This clearly showcases the many opportunities for future experimental searches.

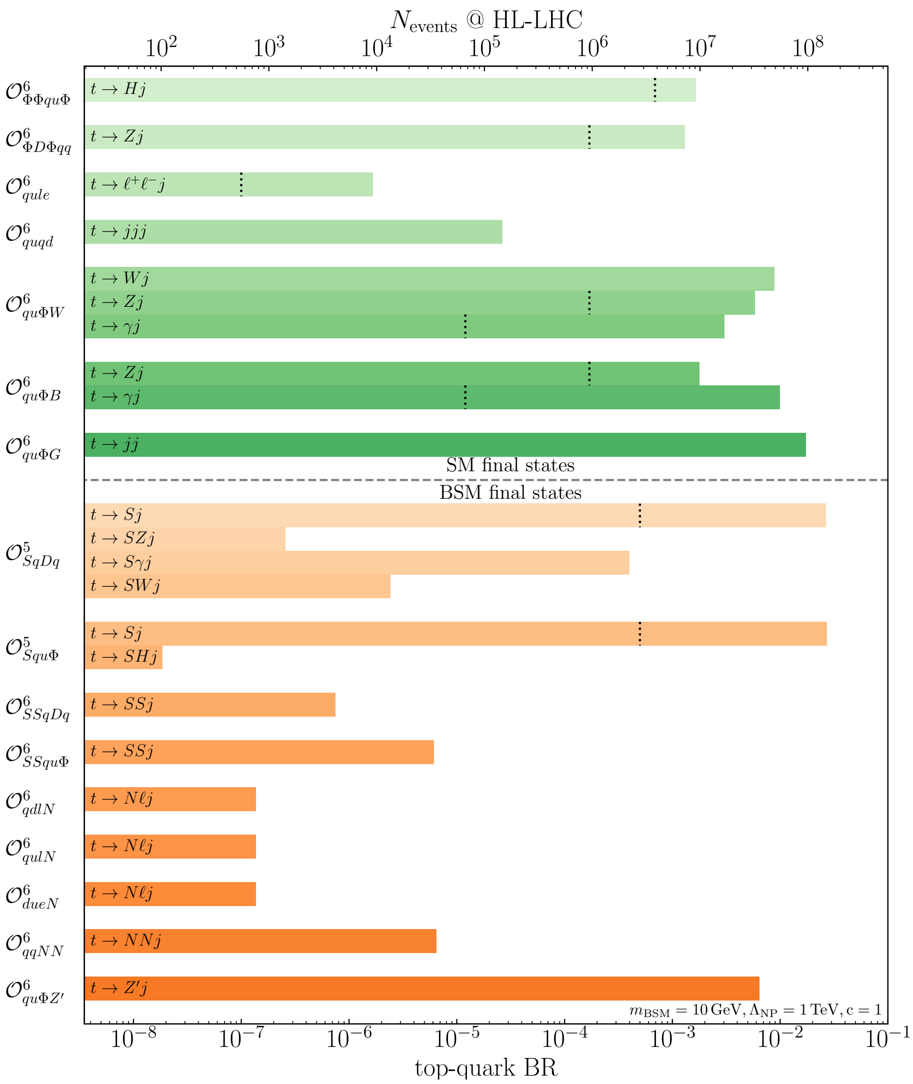

Figure 2: Branching ratios (lower axis) and expected number of events at HL-LHC (upper axis) for the various top-quark decay channels induced by operators listed on the left-hand side. The results for SM final states are shown in green colors at the upper side of the plot; the results for BSM final states, in orange colors at the bottom. The numerical results are obtained by setting $\Lambda_{\text{NP}} = 1$ TeV and all Wilson coefficients equal to one. Moreover, all masses of BSM particles have been set to 10 GeV. The black dotted lines indicate existing collider constraints.

4. Going global

As a third aspect, we discuss the combination of LHC measurements with non-collider measurements. Bringing together different types of data and leveraging their complementarity can provide new insights into the nature of BSM physics.

As an example, we discuss the search for $\mathcal{CP}$ violation in the Higgs section (using material from Ref. [22], see also Refs. [23–25] for related works). Exploiting the complementarity between LHC and electric dipole moment (EDM) measurements, we ask to which amount $\mathcal{CP}$ violation

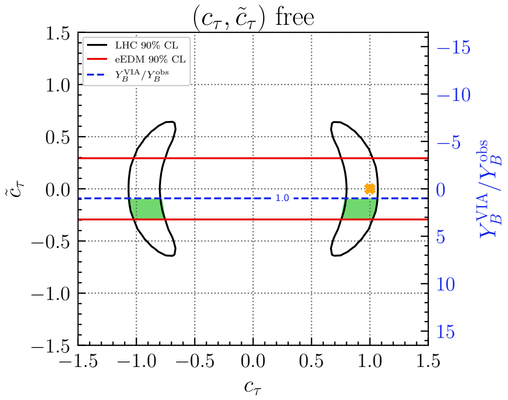

Figure 3: Constraints on c_τ and $\tilde{c}_\tau$ from LHC (black) and EDM measurements (red). The obtainable BAU is indicated by the blue dashed line. The green region is compatible with both LHC and EDM measurements as well as provides a sufficiently large contribution to the BAU.

in the Higgs sector can contribute to generating the baryon asymmetry of the Universe (BAU). In particular, we, here, focus on the $\mathcal{CP}$ structure of the tau-Yukawa coupling, which we parameterize in the following form,

$$\mathcal{L}_{\tau\text{-yuk}} = \frac{y_\tau^{\rm SM}}{\sqrt{2}}\bar{\tau}(c_\tau + i\gamma_5\tilde{c}_\tau)\tau H, \tag{2}$$

where here $y_\tau^{\rm SM}$ is the SM tau-Yukawa coupling. In the SM, $c_\tau = 1$ and $\tilde{c}_\tau = 0$.

At the LHC, this $\mathcal{CP}$ structure is constrained via the Higgs decay $H \to \tau^+\tau^-$ by measuring the angle between the tau decay planes [26, 27], which is a $\mathcal{CP}$-odd observables. The resulting 90% C.L. constraints in the $(c_\tau, \tilde{c}_\tau)$ parameter plane are shown in Fig. 3 as black contour. In this Figure, we also show the 90% C.L. constraints from measurements of the electron electric dipole moment (EDM) [28], where a $\mathcal{CP}$-odd tau-Yukawa coupling contributes via two-loop Barr-Zee diagrams, as red contour. In addition, we depict on the right axis the potential contribution of a $\mathcal{CP}$-odd tau-Yukawa coupling to the BAU (assuming optimal conditions for the electroweak phase transition). These BAU numbers should be considered as an optimistic upper bound. The region for which the BAU can be larger than the observed asymmetry and the LHC and EDM constraints are satisfied is indicated by the green region. This shows that $\mathcal{CP}$ violation in the tau-Yukawa coupling could potentially provide the missing $\mathcal{CP}$ violation needed to explain the BAU. It should, however, be noted that more recent EDM measurements [29] almost completely excluded this green region. The example, nevertheless, shows the important interplay of LHC and non-collider measurements which demonstrates how a global perspective can provide new insights into the nature of BSM physics.

5. Conclusions

LHC Run 3 and the HL-LHC will provide an unprecedented amount of data. This wealth of data will allow us to push the search for BSM physics to a new level. In this contribution, we showcased three aspects of how to harness this potential: (i) the search for uncovered BSM signatures, (ii) the search for rare BSM decay processes, and (iii) the combination of LHC measurements with non-collider measurements. We illustrated these aspects based on three examples. First, we showed that bosonic charged Higgs decays naturally have a large cross section but that so far only a very limited amount of experimental searches have been performed. Second, we highlighted that the large number of top quarks produced at the LHC allows us to search for rare BSM top-quark decays. Here, especially potentially long-lived decays into light singlets are a promising target. Third, we demonstrated how the combination of LHC and non-collider measurements to constrain the $\mathcal{CP}$ nature of the tau-Yukawa coupling allows us to test whether $\mathcal{CP}$ violation in the Higgs sector could contribute significantly to the baryon asymmetry of the Universe.

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PoS(LHCP2023)213