Future analyses of semileptonic decays with Hammer

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I. INTRODUCTION

Precision analyses of semileptonic b-hadron decays typically rely on detailed numerical Monte Carlo (MC) simulations. Implementing some underlying theoretical models, these simulations provide MC *templates* that may be used in fits, to interpret experimental yields in terms of theoretically well-defined parameters. In particular, all existing experimental measurements of $b \to c l \nu$ mediated semileptonic decays rely on large MC simulations to optimize selections, provide fit templates in discriminating kinematic observables, and to model resolution effects and acceptances. These observables include the ratio of semitauonic vs. semileptonic decays to light leptons,

$$R(H_c) = \frac{\Gamma(H_b \to H_c \tau \bar{\nu})}{\Gamma(H_b \to H_c l \bar{\nu})}\,, \qquad l = \mu,\, e\,, \qquad (1)$$

where $H_{b,c}$ denote b- and c-flavor hadrons. In addition, polarization fractions, asymmetries, and a variety of angular observables sensitive to new physics (NP) are also measured using the same set of tools. At present, the measurements of the $R(D^{(*)})$ ratios show about a 3σ tension with SM predictions, when the D and D^* modes are combined [1]. This is referred to as one of the lepton flavor universality (LFU) violation anomalies. In the future, much more precise results on semitauonic decays are expected, not only for various observables in the $B \to D^{(*)} \tau \bar{\nu}$ channels, but also for the not yet measured decay modes, $\Lambda_b \to \Lambda_c \tau \bar{\nu}$, $B_s \to D_s^{(*)} \tau \bar{\nu}$, as well as channels with excited charm hadrons in the final state.

II. BIASES IN NP INTERPRETATIONS

The measured ratios $R(D^{(*)})$ express tensions with respect to the SM simply in terms of the overall branching fractions. It has become frequent practice for phenomenological interpretations of these results to simply require that the postulated NP contributions account for the measured ratios (or other observables, such as the τ polarization fraction) within quoted uncertainties.

In the fits used to recover the values of $R(D^{(*)})$, the signal $B \to D^{(*)} l \nu$ decay distributions (as well as backgrounds) are assumed to have SM shapes, i.e., their reconstructed observables have an *SM template*, while their normalization is allowed to float independently. Introducing further NP contributions to explain the recovered values of $R(D^{(*)})$ generically also alters the $B \to D^{(*)} \tau \nu$ signal (and some background) decay distributions and acceptances. Therefore, these NP contributions lead to a mismatch between the theoretical assumptions: the SM used to generate the MC templates, and subsequent theoretical interpretations of the data. Put a different way, the introduction of NP modifies the signal (and possibly background) templates that should be used for the measurement, and thus may affect the extracted values of $R(D^{(*)})$ themselves.

Neglecting these effects may lead to the introduction of sizable biases in NP interpretations [2, 3]: Preferred regions and best-fit points for the Wilson coefficients can be incorrect. An example of the effect is shown in Fig. 1 [2]. A similar effect may also be important in the extraction of the CKM parameter $|V_{cb}|$, which is sensitive to the assumed form factor parametrizations used to generate the fit templates.

III. STRATEGIES FOR FUTURE MEASUREMENTS

To avoid these biases, either they need to be carefully controlled when experiments quote their results by reversing detector effects, or they can be avoided by using dedicated MC templates for each theoretical model the

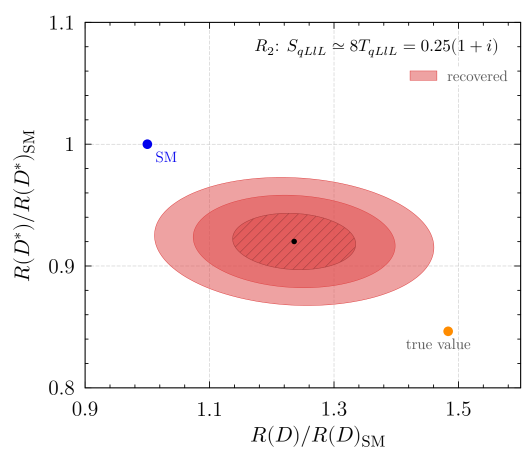

FIG. 1: An illustration of biases from fitting an SM template to a NP model (R_2 leptoquark). The orange dot corresponds to the predicted 'true value' of $R(D^{(*)})$ for the NP model, to be compared to the recovered 68%, 95% and 99% CLs of the SM template fit in shades of red, with uncertainties estimated to correspond to $5\,\text{ab}^{-1}$ of Belle II data. (From Ref [2].)

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measurement considers. The required MC sample for a single theoretical mode is already very large, to the extent that MC uncertainties sometimes dominate the systematic uncertainties in the measurements. Moreover, it is computationally infeasible to create dedicated MC templates for many possible theoretical models.

The recently developed tool, `Hammer` (*Helicity Amplitude Module for Matrix Element Reweighting*) [2, 4, 5], has been designed expressly to solve this problem: A fast and efficient means to reweight large MC samples to any desired NP, or to any description of the hadronic matrix elements. `Hammer` has been interfaced with existing experimental analysis frameworks at LHCb and Belle II. It is being used by several ongoing and forthcoming analyses, providing detailed control over which NP or hadronic descriptions should be considered

These problems — the biases in NP interpretations of semileptonic measurements, and infeasibility of direct production of sufficiently large MC samples to cover the theoretical space of models — and their available solutions are directly relevant to core questions considered by Rare and Precision Frontier working groups.

[1] Yasmine Sara Amhis *et al.* (HFLAV Collaboration), "Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018," (2019), arXiv:1909.12524 [hep-ex].

[2] Florian U. Bernlochner, Stephan Duell, Zoltan Ligeti, Michele Papucci, and Dean J. Robinson, "Das ist der HAMMER: Consistent new physics interpretations of semileptonic decays," (2020), (Accepted for publication in EPJC), arXiv:2002.00020 [hep-ph].

[3] Zoltan Ligeti, Michele Papucci, and Dean J. Robinson, "New Physics in the Visible Final States of $B \to D^{(*)}\tau\nu$," JHEP **01**, 083 (2017), arXiv:1610.02045 [hep-ph].

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[5] Stephan Duell, Florian Bernlochner, Zoltan Ligeti, Michele Papucci, and Dean Robinson, "HAMMER: Reweighting tool for simulated data samples," *Proceedings, 38th International Conference on High Energy Physics (ICHEP 2016): Chicago, IL, USA, August 3-10, 2016*, PoS **ICHEP2016**, 1074 (2017).