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Predicting $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ within the MFV-SMEFT using B, Top, Z and Drell-Yan data

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In high-energy physics, the Standard Model Effective Field Theory (SMEFT) serves as a framework for investigating new physics phenomena without relying on a specific model. In this study, we assess the potential of combining observables from different physics sectors in a unified SMEFT fit. Our analysis considers top-quark measurements, $b \to s$ flavor changing neutral current transitions, transitions like $Z \to b\bar{b}$ and $Z \to c\bar{c}$, alongside Drell-Yan data from the Large Hadron Collider (LHC). We explore the influence of Minimal Flavor Violation (MFV) when used as a flavor pattern in the global fit. By incorporating observables from different physics sectors, we can address flat directions in the parameter space and draw conclusions about the flavor structure based on the MFV parameterization. We demonstrate that the combination of measurements from different sectors yields stronger constraints on the SMEFT coefficients than the individual fits and emphasize how synergies in the global approach allow probing scales as high as 18 TeV. Based on the constraints on the Wilson coefficients obtained in our analysis, we predict $b \to s\nu\bar{\nu}$ branching ratios and and discuss how future measurements of these observables could provide new information in the search for physics beyond the Standard Model when being included in the global fit.

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PoS(EPS-HEP2023)298

1. Effective Field Theories

The Standard Model Effective Field Theory (SMEFT) serves as a common framework in the search for new physics (NP) phenomena beyond the electroweak scale. It allows a predominantly model-independent approach and enables connections between different sectors, especially beauty and top, via the $\mathrm{SU}(2)_L$ symmetry, as demonstrated in multiple studies [1–4]. The SMEFT Lagrangian is constructed by appending a series of higher-dimensional operators $O_i^{(d)}$ to the Standard Model (SM) Lagrangian. The additional operators are each multiplied by a corresponding Wilson coefficient, $C_i^{(d)}$, and are suppressed by a factor Λ^{d-4}, where Λ is the energy scale of the physics beyond the Standard Model (BSM), being well above the electroweak scale. The SMEFT Lagrangian is thus given as:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} \,. \tag{1}$$

For the scope of our research, we restrict our attention to dimension-six operators and work within the Warsaw basis [5]. We operate under the assumption that all Wilson coefficients are real-valued, upholding both lepton and baryon number conservation principles. It is worth noting that while SMEFT aptly describes collider observables, $b \to s$ observables are best interpreted within the context of the weak effective theory (WET). A connection between both theories is established through renormalization group equation (RGE) evolution and matching at the W-boson mass scale.

2. MFV expansion in SMEFT

In our analysis, we employ a flavor pattern which allows to reduce the number of degrees of freedom and to induce correlations among the different flavor constituents of the Wilson coefficients, thereby establishing connections across the physics sectors. We utilize the Minimal Flavor Violation (MFV) framework. Within this approach, the flavor architecture of the Wilson coefficients is articulated through insertions of the SM Yukawa matrix. This expansion is demonstrated for the example of an operator containing two left-handed quark doublets as:

$$\bar{q}_L q_L: \quad C_{ij} = \left(a_1 1 + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + a_4 \left(Y_u Y_u^\dagger\right)^2 + \dots\right)_{ij} \,. \tag{2}$$

Given its prominence as the largest of these couplings, our analysis is focusing only on the top-quark Yukawa coupling while the others are omitted in the subsequent discussions. Rotating the ansatz in Eq. (2) into the mass basis yields

$$\begin{aligned} C_{ij}\, \bar{q}_{L_i} q_{L_j} \supset \bar{u}'_{L_i} & \left[a_1 1 + a_2 \left[Y_u^{\text{diag}}\right]^2 + a_3\, V \left[Y_d^{\text{diag}}\right]^2 V^\dagger + a_4 \left[Y_u^{\text{diag}}\right]^4 + \dots\right]_{ij} u'_{L_j} \\ + \bar{d}'_{L_i} & \left[a_1 1 + a_2\, V^\dagger \left[Y_u^{\text{diag}}\right]^2 V + a_3 \left[Y_d^{\text{diag}}\right]^2 + a_4\, V^\dagger \left[Y_u^{\text{diag}}\right]^4 V + \dots\right]_{ij} d'_{L_j} \,, \end{aligned} \tag{3}$$

with the CKM matrix V. Powers of the top-quark Yukawa proportional to a_{2n} induce flavor changing neutral currents (FCNCs) in the down quark sector. In the lepton sector, this approach results in lepton flavor diagonal and universal Wilson coefficients. For our analysis we define

$$\tilde{C}_{q\bar{q}} = \frac{v^2}{\Lambda^2}\, a_1 \,, \quad \gamma_a = \sum_{n \geq 1} y_t^{2n}\, a_{2n}/a_1 \tag{4}$$

for left handed quark-doublets. With this, we absorb all higher orders of top-quark Yukawa insertions into the ratio γ_a as they lead to the same coupling pattern. Analogously, we define γ_b for right handed up-type quarks. See Ref. [6] for the definitions of the other quark bilinears.

3. Global SMEFT Fit

For our combined fit we include data from top-quark production and decay processes, Drell-Yan measurements, Z decays and $b \to s$ transitions. We aim to constrain 14 Wilson coefficients and the two MFV ratios γ_a and γ_b. The dependence of the considered observables on the Wilson coefficients is determined using Monte Carlo simulations and numerical predictions. Details on the simulations and the matching conditions for connecting SMEFT and WET coefficients can be found in Ref. [6]. Our analysis is performed using the EFT*fitter* package [7], relying on Bayesian inference facilitated by the the Bayesian Analysis Toolkit - BAT.jl [8]. We use a uniform prior distribution in the range $-1 \leq \tilde{C}_i \leq 1$ for the rescaled Wilson coefficients and a uniform prior distribution in $-10 \leq \gamma_{a/b} \leq 10$ for the two flavor parameters. Additionally, we also perform fits including only data from the individual physics sectors, assuming a benchmark value $\gamma_{a/b} = 1$. From the marginal posterior probability distributions we obtain 90% credible intervals for the Wilson coefficients. These intervals as well as the total width of these intervals are shown in Fig. 1.

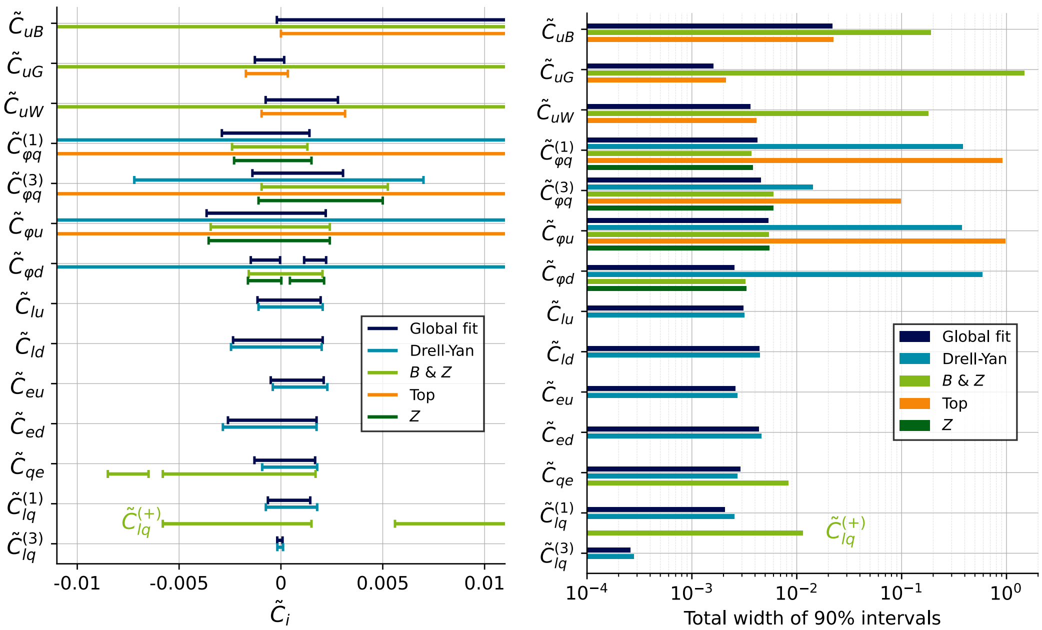

Figure 1: Resulting constraints on the SMEFT Wilson coefficients $\tilde{C}_i$ assuming Λ =10 TeV. Shown are the 90% credible intervals (left) and the total width of these intervals (right). We compare the result of the global fit to the fit results of the individual sectors. Plots taken from Ref. [6].

We observe that all constraints on the Wilson coefficients are compatible with the SM value $\tilde{C}_i = 0$. It is noticeable that synergies in the global fit lead to improved constraints compared to the bounds obtained by fits to the individual sectors. The marginalized posterior probability distribution

PoS(EPS-HEP2023)298

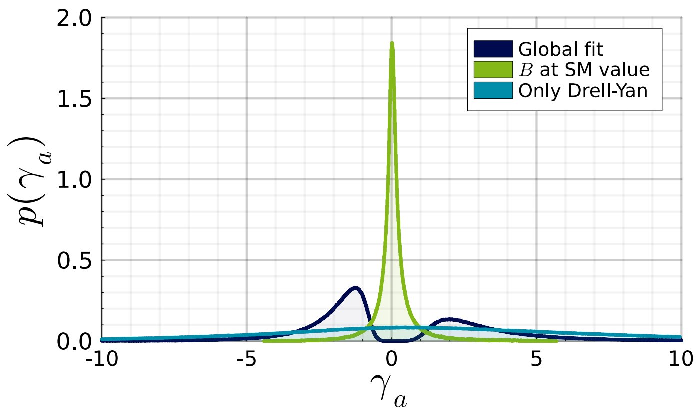

Figure 2: Marginalized posterior probability distribution of γ_a from the global fit (dark blue), from a scenario in which all $b \to s$ measurements are set to their SM prediction (green) and from a pure Drell-Yan fit (light blue). The plot is taken from Ref. [6].

of γ_a is shown in Fig. 2 in dark blue. This curve exhibits two peaks: a dominant one at $\gamma_a = -1.2$ and a subtler one at $\gamma_a = 1.9$. In contrast, the distribution for γ_b remains uniform, as can be seen in Ref. [6]. When repeating the fit but setting the $b \to s$ measurements to match the SM expectations only a single sharp peak around $\gamma_a = 0$ emerges, as shown by the green curve. These patterns suggest that deviations from the SM expectation in $b \to s$ measurements, currently observed at around 3σ, impact the shape of the posterior distribution of γ_a and indicate that higher-order corrections in the MFV expansion are favored by the data, as has also been observed before [3, 4]. This further emphasizes the potential of this parameter to probe the flavor structure of possible BSM phenomena.

4. Influence of dineutrino branching ratios

In SMEFT, b-hadron decays into charged leptons are directly connected to b-hadron decays into neutrinos via the $SU(2)_L$ symmetry. While $b \to s\ell^+\ell^-$ transitions probe the linear combination $C_{lq}^{(+)} = C_{lq}^{(1)} + C_{lq}^{(3)}$, dineutrino processes with $b \to s\nu\bar{\nu}$ transitions probe the orthogonal linear combination $C_{lq}^{(-)} = C_{lq}^{(1)} - C_{lq}^{(3)}$. Combining both types of processes would thus allow to improve the constraints on the individual coefficients $C_{lq}^{(1)}$ and $C_{lq}^{(3)}$.

So far, only experimental upper limits for $b \to s\nu\bar{\nu}$ transitions are available, which are not considered in our analysis. Using the results of our global fit, however, we can derive predictions for dineutrino branching ratios within our MFV-SMEFT assumptions. For this, the dependence of the branching ratios $\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$ and $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ on the SMEFT coefficients is determined and the samples of the posterior distribution visualized in Fig. 1 are inserted. The resulting posterior predictive distributions of the two branching ratios are shown in Fig. 3. It can be observed that the resulting 68% credible intervals are centered around the SM prediction and that they are below the experimental limits.

During the EPS-HEP2023 conference, first evidence for the observation of the $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ process was reported by the Belle II collaboration, with a significance of 3.6σ and a combined value of $(2.4 \pm 0.5) \times 10^{-5}$, showing a tension with the expected SM value of 2.8σ [9]. To investigate

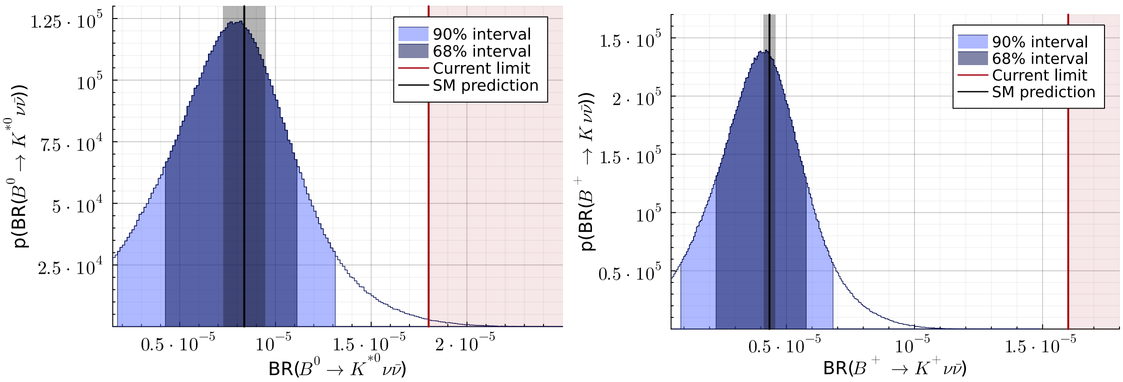

Figure 3: Posterior predictive distribution of the branching ratios $\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$ (left) and $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ (right). The 90% and 68% credible intervals are highlighted in blue. Also shown are the current 90% CL experimental limits in red as well as SM predictions with 1σ uncertainty in grey.

the impact of this observable, we include this value in our setup and repeat our global fit. We compare the results to three further benchmark scenarios where we include SM like (BM SM) as well as enhanced (BM $+2\sigma$) and suppressed (BM -2σ) branching ratios for both the decays $B^0 \to K^{*0}\nu\bar{\nu}$ and $B^+ \to K^+\nu\bar{\nu}$ assuming an integrated luminosity of $5\,\text{ab}^{-1}$. In the benchmark studies we observe that including dineutrino measurements has a significant impact on the resulting constraints, in particular regarding $\tilde{C}_{qe}$, $\tilde{C}_{lq}^{(1)}$ as well as the coefficients of the penguin operators. Even a SM-like measurement would lead to a non-zero value for $\tilde{C}_{qe}$ and $\tilde{C}_{\varphi d}$, as including the $b \to s\nu\bar{\nu}$ observables resolves the flat direction in the parameter space. Suppressed branching ratios would shift these coefficients to larger values, whereas enhanced branching ratios would result in a non-zero value for $\tilde{C}_{lq}^{(1)}$. In the fit where only the current evidence for $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ is included, similar effects as in the BM $+2\sigma$ scenario can be observed but being less pronounced as the experimental uncertainties are larger and only one additional observable is considered.

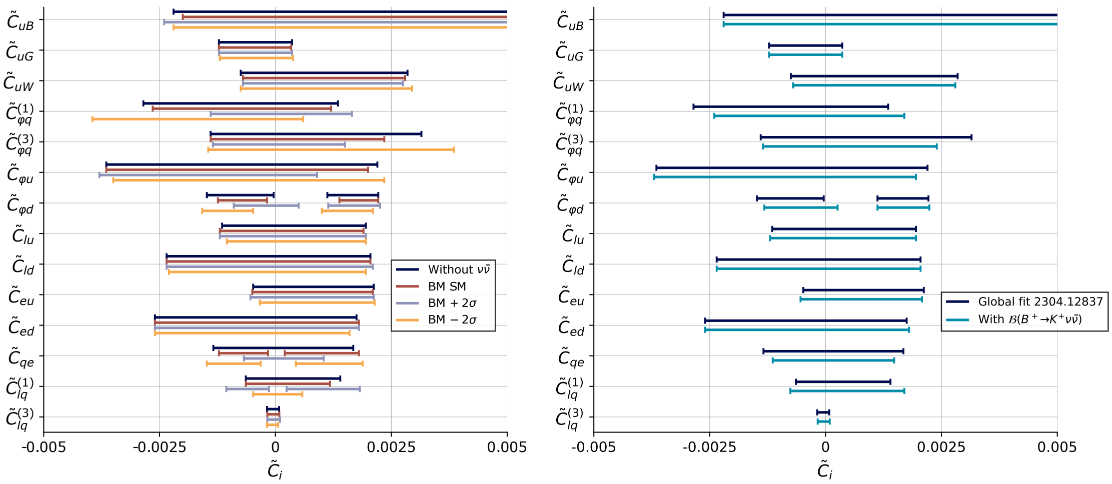

Figure 4: Resulting 90 % credible intervals of the global fit with dineutrino benchmark measurements as taken from Ref. [6] (left) and the 90 % credible intervals of the global fit including the new Belle II evidence value for $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ (right).

5. Conclusion

In our joint analysis of Beauty, Top, Z, and Drell-Yan measurements within SMEFT and MFV, we highlighted the inherent synergies of a global fit approach. Combining these measurements, constraints on the SMEFT Wilson coefficients have been derived that are stronger than those obtained from fits to the individual sectors. While the Wilson coefficients are all well constrained and in good agreement with the SM, we find that the MFV parameter γ_a is not compatible with zero, which is primarily attributed to the b anomalies. Strong bounds for specific operators like the semileptonic four-fermion triplet operator $\tilde{C}_{lq}^{(3)}$ translate into BSM scales of up to 18 TeV. Based on the constraints on the Wilson coefficients obtained in our global fit, we determine credible intervals for dineutrino branching ratios, which can play an important role in probing the semileptonic four-fermion operators. With the Belle II collaboration reporting first evidence for observing $b \to s\nu\bar{\nu}$ transitions, we demonstrate that future measurements of these processes can play an important role in unveiling new insights into potential new physics structures.

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