FlavorKit: a brief overview

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Abstract

We give a brief overview of FlavorKit, a kit for the study of flavor observables beyond the standard model. In contrast to previous flavor codes, FlavorKit is not restricted to a single model, but can be used to obtain predictions for flavor observables in a wide range of models. FlavorKit can be used in two different ways. The basic usage of FlavorKit allows for the computation of a large number of lepton and quark flavor observables, using generic analytical expressions for the Wilson coefficients of the relevant operators. The setup is based on the public codes SARAH and SPheno, and thus allows for the analytical and numerical computation of the observables in the model defined by the user. If necessary, the user can also go beyond the basic usage and define his own operators and/or observables. For this purpose, a Mathematica package called PreSARAH has been developed. This tool uses FeynArts and FormCalc to compute generic expressions for the required Wilson coefficients at the tree- and 1-loop levels. Similarly, the user can easily implement new observables. With all these tools properly combined, the user can obtain analytical and numerical results for the observables of his interest in the model of his choice.

Keywords: beyond the Standard Model, flavor physics, rare processes, computer codes

1. Introduction

The recent discovery of the Higgs boson at the LHC [1, 2] and the measurement of its properties and couplings to fermions and gauge bosons [3] have led to a global picture in very good agreement with the Standard Model (SM) predictions. Although there is still room for deviations from the SM expectations, these are now quite constrained.

At this point, we should not forget that, besides theoretical considerations such as the hierarchy problem, there are good phenomenological reasons to go beyond the SM (BSM). Among others, these include dark matter, non-zero neutrino masses and mixings and the baryon asymmetry of the universe. These fundamental problems of current particle physics and cosmology do not have an explanation within the SM, and thus motivate the search for new physics.

The unknown origin of the flavor sector of the SM is another good reason to consider extended BSM scenarios. This program has been extensively followed in the quark sector and, more recently, in the lepton sector after the discovery of neutrino flavor oscillations. Low energy experiments focused on flavor observables can play a major role in the search of new physics, since new particles leave their traces via quantum effects in flavor violating processes such as $b \to s \gamma$, $B_s \to \mu^+\mu^-$ or $\mu \to e\gamma$. Therefore, low energy experiments devoted to observables from the Kaon- and B-meson sectors, rare lepton decays and electric dipole moments turn out to be complementary to the direct searches at high energy colliders, opening a window to new physics in the high intensity frontier.

Here we present a general overview of FlavorKit [4], a computer tool for the computation of flavor observables. There are already several public tools for this purpose: SuperIso [5], SUSY_Flavor [6], NMSSM-Tools [7], MicrOmegas [8], SuperBSG [9], SuperLFV [10], SuseFlav [11]. IsaJet with
2. Computation of flavor observables

Once we have chosen a BSM model, the strategy for the computation of a flavor observable follows three steps:

- **Step 1:** First, one considers an effective Lagrangian that includes the operators that contribute to the flavor observable of our interest,

  \[ \mathcal{L}_{\text{eff}} = \sum_i C_i O_i. \] (1)

  This Lagrangian consists of a list of operators, \( O_i \), with Wilson coefficients \( C_i \). These can be induced either at tree or at higher loop levels and include both the SM and the BSM contributions (\( C_i = C_i^{\text{SM}} + C_i^{\text{BSM}} \)).

- **Step 2:** The Wilson coefficients are computed taking into account all possible tree-level and 1-loop topologies leading to the \( O_i \) operators.

- **Step 3:** The results for the Wilson coefficients are plugged in a general expression for the observable and a final result is obtained.

This general strategy can be easily shown with an example. Let us consider the computation of \( \text{BR}(\mu \to e\gamma) \) in the Standard Model extended by right-handed neutrinos and Dirac neutrino masses. The first step is, as explained above, to choose the relevant operators. In this case, at leading order the radiative decays \( \mu \to l_\mu \gamma \) only receive contributions from dipole operators. Therefore, the relevant effective Lagrangian is given by

\[ \mathcal{L}_{\mu e \gamma}^{\text{dipole}} = i e m_\mu \bar{e} \sigma^{\mu\nu} q_\nu \left( K_L^2 P_L + K_R^2 P_R \right) \mu A_\mu + \text{h.c.} \] (2)

Here \( e \) is the electric charge, \( q \) the photon momentum and \( P_{LR} = \frac{1}{2} (1 \mp Y) \) are the usual chirality projectors. This concludes step 1.

In the next step, one must compute the Wilson coefficients \( K_L^{LR} \) in the model under consideration. In the SM extended with right-handed neutrinos, the radiative process \( \mu \to e\gamma \) is induced by 1-loop diagrams with W-bosons and neutrinos running in the loop, as shown in Fig. 1. One finds \cite{16}

\[ K_L^1 = \frac{G_F}{2 \sqrt{2} \pi} m_\mu \sum_i U_{l\mu} U_{e\mu}^* (F_1 + F_2) \] (3)

\[ K_L^2 = \frac{G_F}{2 \sqrt{2} \pi} m_e \sum_i U_{l\mu} U_{e\mu}^* (F_1 - F_2) \] (4)

Here, \( U_{ij} \) denote the entries of the so-called PMNS matrix and \( F_1 \) and \( F_2 \) are loop functions. Approximately, one has \( F_1 = -\frac{1}{4} \left( m_\mu \right)^2 \) and \( F_2 = 0 \). Finally, we are just left with the final step, the computation of the observable. The relation between the Wilson coefficients \( K_L^{LR} \) and \( \text{BR}(\mu \to e\gamma) \) is found to be \cite{17}

\[ \text{BR}(\mu \to e\gamma) = \frac{a m_\mu}{4 \Gamma_\mu} \left( |K_L^1|^2 + |K_L^2|^2 \right), \] (5)

where \( \Gamma_\mu \) is the muon total decay width. This general expression holds for all models. With this final step, the computation concludes.

As we have seen, the main task to get a result for a flavor observable in a new model is to derive analytical expressions for the relevant Wilson coefficients. This is the most complicated and model dependent part of the calculation, and it might be a very demanding task in some cases. First, all masses and vertices involved in the computation must be known analytically. Furthermore, in some models the number of Feynman diagrams that

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forms the necessary input files for the Wilson coefficients we present. In order to solve these practical problems, we use numerical evaluations of the results, which shows a schematic description of FlavorKit: the user can define new operators in PreSARAH, which then calculates generic expressions for the Wilson coefficients using FeynArts and FormCalc and creates the necessary input files for SARAH. In addition, Fortran code is provided to relate the Wilson coefficients to specific flavor observables. This information is finally used by SARAH to generate SPheno code for the numerical calculation of the observables.

This can contribute to a specific Wilson coefficient could be very high, thus leading to lengthy (and prone to error) computations, and renormalization group equations (RGEs) are sometimes required to evaluate the Wilson coefficients at a given energy scale. Finally, a proper numerical evaluation of the results is usually welcome, as some numerical difficulties may appear in particular limits of complicated loop functions. In order to solve these practical problems we present FlavorKit, a tool that allows for a fully automatized calculation of a wide range of flavor observables for several classes of models.

3. FlavorKit

In this Section we give a general overview of the FlavorKit tool. For more details we refer to the manual [14]. The code is public and can be downloaded from the website [http://sarah.hepforge.org/FlavorKit.html](http://sarah.hepforge.org/FlavorKit.html) where additional information and regular updates are published.

FlavorKit is a combination of several public codes. The main ingredients are SARAH [18] and SPheno [14, 15]. The former is a Mathematica package for building and analyzing BSM models. SARAH can compute all vertices, mass matrices, tadpoles equations, 1-loop corrections for tadpoles and self-energies, as well as 2-loop RGEs in a given model. This analytical information can then be transferred to SPheno, a Fortran code for the numerical evaluation of the particle spectrum as well as several observables. Furthermore, FlavorKit also makes use of FeynArts/FormCalc [19, 20] to compute generic expressions for the required Wilson coefficients at the tree- and 1-loop levels.

As previously discussed, the critical step in the computation of a flavor observable is the diagrammatic computation of the Wilson coefficients of the involved operators. For this purpose, we have created a new Mathematica package called PreSARAH. This package uses FeynArts and FormCalc to calculate generic 1-loop amplitudes, to extract the coefficients of the demanded operators, to translate them into the syntax needed for SARAH and to write the necessary wrapper code. Currently, PreSARAH works for any 4-fermion or 2-fermion-1-boson operators and will be extended in the future to include other kinds of operators. The current version contains a long list of fully implemented operators, ready to be used in the evaluation of flavor observables. The results obtained with PreSARAH are then interpreted by SARAH, which adapts the generic expressions to the specific details of the model chosen by the user and uses snippets of Fortran code to calculate flavor observables from the resulting Wilson coefficients. Finally, SARAH can be used to obtain analytical output in ISiTExX format or to create Fortran modules for SPheno, in case the user is interested in performing numerical studies. The approach is described in Fig. 2 which shows a schematic description of FlavorKit. FlavorKit can be used in two ways:

- **Basic usage:** This is the approach to be followed by the user who does not need any operator nor observable beyond what is already implemented in FlavorKit. In this case, FlavorKit reduces to the standard SARAH package.

- **Advanced usage:** This is the approach to be followed by the user who needs an operator or an observable not included in FlavorKit. The user can define his own operators and get analytical results for their coefficients using PreSARAH. The resulting output can be passed to SARAH and then continue with the basic usage. In case the user is interested in a new observable, not implemented in FlavorKit, he can also add it easily. The only requirement is the addition of a few lines of Fortran code with the relation between the new observable and the Wilson coefficients of the operators that contribute (these can be implemented by default or added by the user). Then one can continue with the basic usage.

Let us give some more details about these two ways to use FlavorKit.
### 3.1. Basic usage

In the basic usage of \texttt{FlavorKit} the user simply uses \texttt{SARAH}. More information about installation and usage of \texttt{SARAH} can be found in the manual \cite{18}. For the list of observables already implemented in \texttt{FlavorKit} see Table \ref{tab:observables}.

The most recent versions of \texttt{SARAH} (after version 4.2.0) include \texttt{FlavorKit} routines that allow one to obtain $\texttt{LaTeX}$ files with the analytical expressions for the Wilson coefficients. These are given individually for each Feynman diagram contributing to the coefficients, what helps identifying the individual weights of the different physical contributions. The resulting \texttt{LaTeX} files are saved in the folder

\texttt{[SARAH]/FlavorKit/[Type]/Processes/}

Finally, in case the user is interested in the numerical evaluation of the flavor observables, a \texttt{SPheno} module can be created. This follows again the usual steps in \texttt{SARAH}. The generated \texttt{Fortran} code can be used to run fast and reliable numerical studies of the parameter space of the model.

### 3.2. Advanced usage

In some cases the user might be interested in new contributions to a flavor observables induced by operators not considered in the \texttt{FlavorKit} implementation. Similarly, the user might also be interested in new observables, not included in the current version of the tool. In both cases, \texttt{FlavorKit} can be easily extended to satisfy all the user’s requirements.

In order to introduce new observables in \texttt{FlavorKit}, the user must create two new files: a steering file with the extension .m, and a \texttt{Fortran} body with the extension .f90. These have to be placed in the folder

\texttt{[SARAH]/Output/[MODEL]/EWSB/TeX/FlavorKit/}

where [\texttt{Type}] is either LFV for lepton flavor violating or QFV for quark flavor violating observables. The steering file provides basic information about the process. For instance, the steering file to calculate the rate for $\ell_a \to \ell \gamma$ reads

\begin{verbatim}
NameProcess = "LLpGamma";
NameObservables = [(muEgamma, 701, "BR(mu->e gamma)");
                    (tauEgamma, 702, "BR(tau->e gamma)");
                    (tauMuGamma, 703, "BR(tau->mu gamma)");];
NeededOperators = [K2L, K2R];
Body = "LLpGamma.f90";
\end{verbatim}

The three observables will be saved in the variables \texttt{muEgamma}, \texttt{tauEgamma} and \texttt{tauMuGamma} and will show up in the output file written by \texttt{SPheno} in the block \texttt{FlavorKitLFV}, with numbers 701 to 703. Moreover, the steering file also refers to the body file, in this case \texttt{LLpGamma.f90}. This reads

\begin{verbatim}
Real(dp) :: width
Integer :: i1, gt1, gt2
Do i1=1,3
  If (i1.eq.1) Then ! mu -> e gamma
    gt1 = 2
    gt2 = 1
  Elseif (i1.eq.2) Then ! tau -> e gamma
    gt1 = 3
    gt2 = 1
  Else ! tau -> mu gamma
    gt1 = 3
    gt2 = 2
  End if

  width = 0.25*dp+nfj(gt1)*5+(Abs(K2L(gt1,gt2))*2 &
                        +Abs(K2R(gt1,gt2))*2)+Alpha

  If (i1.eq.1) Then
    muEgamma = width/(width+GammaMu)
  Elseif (i1.eq.2) Then
    tauEgamma = width/(width+GammaTau)
  Else
    tauMuGamma = width/(width+GammaTau)
  End if
End do
\end{verbatim}

Here \texttt{Real(dp)} is the \texttt{SPheno} internal definition of double precision variables. If necessary, the user can also use complex numbers with \texttt{Complex(dp)}. This file contains standard \texttt{Fortran90} code relating the observables (previously declared in the steering file) with the Wilson coefficients computed by \texttt{FlavorKit} ($K^L_2$ and $K^R_2$ in this example). The relation can make use of SM parameters, such as the fine structure constant, $\alpha$.

\begin{table}[h]
\centering
\begin{tabular}{cl}
\hline
Lepton flavor & Quark flavor \\
$\ell_a \to \ell \gamma$ & $\mathcal{B}\ell_\ell \to \ell' \ell$ \\
$\ell_a \to 3 \ell$ & $\mathcal{B} \ell \to X \ell \ell$ \\
$\ell_a \to \ell \ell', \ell$ & $\mathcal{B} \ell \to X \ell \ell'$ \\
$\mu - e$ conversion in nuclei & $\mathcal{B} \to X_{e,\ell} \ell$ \\
$\tau \to P \ell$ & $B \to K^+ \ell \ell$ \\
$h \to \ell_a \ell_b$ & $K \to \pi \ell \ell$ \\
$Z \to \ell_a \ell_b$ & $\Delta M_{\ell\ell}$ \\
& $\Delta M_K$ and $\epsilon_K$ \\
\hline
\end{tabular}
\caption{List of flavor violating processes and observables which have already been implemented in \texttt{FlavorKit} (version 1.0.1). To the left, observables related to lepton flavor, whereas to the right observables associated to quark flavor.}
\end{table}
These are internally defined in \textit{FlavorKit}, but can also be changed by the user.

With this feature, the user can easily add new observables or modify the implementation of the ones already present in the tool (see Table\[1\] for the list of observables already implemented in \textit{FlavorKit}). For example, the user can change the values of some parameters (like hadronic form factors or decay constants) and adapt the calculation to his own needs. All it takes is to write a few lines of Fortran code with the definition of the observable in terms of the Wilson coefficients that give a contribution.

The user can also implement new operators and obtain analytical expressions for their Wilson coefficients. In this case, he will need to use \textit{PreSARAH}, which provides generic expressions for the coefficients, later to be adapted to specific models with \textit{SARAH}. In order to do so, the user must extend the content of the folder

\begin{verbatim}
[$SARAH$]/FlavorKit/[$Type$]/Operators/
\end{verbatim}

where \textit{[$Type$]} is again either LFV for operators leading to lepton flavor violating processes or QFV for operators that induce quark flavor violation. The extension only involves one input file. This file must contain the definition of the operator and some basic details about its computation. For instance, the \textit{PreSARAH} input file to calculate the Wilson coefficients of the $(\bar{\ell}T)\bar{d}Td$ operators reads

\begin{verbatim}
NameProcess="2L2d";
ConsideredProcess = "4Fermion";
ExternalFields=[[ ChargedLepton, bar[ChargedLepton],
DownQuark, bar[DownQuark]]];

FermionOrderExternal=[2,1,4,3];
NeglectMasses=[1,2,3,4];

AllOperators={
  (+ scalar operators)
  [OldddLL, Op[7].Op[7]],
  [OldddRR, Op[6].Op[6]],
  [OldddRL, Op[6].Op[7]],
  [OldddLR, Op[7].Op[6]],

  (+ vector operators)
  [OlddddVV, Op[7].Lor[1].Op[7].Lor[1]],
  [OlddddVV, Op[6].Lor[1].Op[6].Lor[1]],
  [OlddddVL, Op[7].Lor[1].Op[6].Lor[1]],
  [OlddddV, Op[6].Lor[1].Op[7].Lor[1]],

  (+ tensor operators)
  [OlddddTT, Op[7].Lor[1].Lor[2].Op[7].Lor[1].Lor[2]],
  [OlddddTR, Op[7].Lor[1].Lor[2].Op[6].Lor[1].Lor[2]],
  [OlddddRT, Op[6].Lor[1].Lor[2].Op[7].Lor[1].Lor[2]],
  [OlddddRR, Op[6].Lor[1].Lor[2].Op[6].Lor[1].Lor[2]]
};
\end{verbatim}

We neglect all external masses in the operators (using \textit{NeglectMasses}=[1,2,3,4]), and the different coefficients of the scalar operators $(\bar{\ell}P_{\gamma\rho})\bar{d}P_{\gamma\rho}d$ are denoted as 01lddSXY, the ones for the vector operators $(\bar{\ell}P_{X\gamma\rho})\bar{d}P_{Y\gamma\rho}d$ as 01lddVXY and the ones for the tensor operators $(\bar{\ell}P_{X\sigma\mu\nu})\bar{d}(\sigma^\mu\nu)P_{Y\rho}d$ as 01lddTYX, with $X, Y = L, R$. To make the definitions of the operators more readable, we have simplified the syntax of the \textit{DiracChain} object in \textit{FeynArts/FormCalc}. \textit{PreSARAH} puts everything with the head $\bar{\ell}d$ into a Dirac chain, using the defined fermion order. For 4-fermion operators the combination of both operators is written as dot product. For example, $\bar{\ell}d$.$\bar{\ell}d$ is internally translated into

\begin{verbatim}
DiracChain[Spinor[k[1], MassEx1, -1], 6, Spinor[k[2], MassEx2, 1]] →
DiracChain[Spinor[k[3], MassEx3, -1], 6, Spinor[k[4], MassEx4, 1]]
\end{verbatim}

For more details see the \textit{FlavorKit} manual\(^2\). Finally, we explicitly choose not to calculate all possible combinations of external states, but only some specific cases of interest: $\muedd, \muedd, \tauedd, \muedd, \muedd, \muedd$.

These two possibilities, extending the list of observables and extending the list of operators, makes \textit{FlavorKit} an adaptable code, that can be used for the calculation of observables not considered by the authors of the tool\(^1\).

Before concluding, let us briefly comment on the validation of \textit{FlavorKit}. This involves three steps:

1. **Agreement with SM results**: we have explicitly checked that \textit{FlavorKit} reproduces correctly the SM predictions for the flavor observables in the literature.

2. **Independence of scale in loop function**: the loop integrals for 2- and 3-point functions ($B$, $C$) depend on the renormalization scale $Q$. However, we checked numerically that the sum of all diagrams is indeed independent of the choice of $Q$. In some cases the check was also done analytically, confirming the consistency of our results.

3. **Comparison with other tools**: we also did a detailed numerical comparison with other flavor tools using the \textit{SPheno} code produced by \textit{SARAH}\(^3\).

\(^2\)\textit{FlavorKit} was used in \cite{20} to perform the first complete study of lepton flavor violation in models with a low-scale seesaw. This paper represents a perfect example of what \textit{FlavorKit} can offer.

\(^3\)\textit{SARAH}
for the Minimal Supersymmetric Standard Model (MSSM). We find that FlavorKit agrees with the codes specialized for the MSSM to the same level as those codes agree among each other. The small numerical differences are caused by the treatment of the resummation of the bottom Yukawa couplings, the different order at which SM and supersymmetric contributions are implemented, the different handling of the Weinberg angle, and the different level at which the RGE running is taken into account by the tools.

In conclusion, the validation of FlavorKit is successful. The results are in good agreement with those obtained with other flavor tools and the required consistency checks are passed.

4. Summary

FlavorKit is a combination of computer tools that allows the user to get predictions for his favourite flavor observables in the model of his choice. It combines the analytical power of SARAH with the numerical routines of SPheno, leading to the perfect tool for phenomenological studies. Furthermore, it is easily extendable: new observables and operators can be added (thanks to FeynArts and FormCalc). This results in a user friendly computer tool, ready for the study of flavor physics beyond the Standard Model.

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