

MATCH2FIT v.1.8

User's Manual

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Contents

1	Introduction	3
2	Conceptual description	3
3	Prerequisites and installation.	4
4	Public commands	4
4.1	Reading matching results	4
4.2	Using <code>matchmakereft</code>	6
4.3	Generating the output for SMEFIT	6
4.4	Combining both steps	7
5	Limitations and outlook	7
A	Numerical parameters	8
B	Flavour symmetry in the SMEFIT global fit	8
C	Choices due to flavour symmetry	8
	References	9

1 Introduction

The epoch before HL-LHC in theoretical particle physics is marked by our efforts to extract every possible piece of information out of the combined LHC/HL-LHC experimental program. The absence of direct evidence for new fundamental particles calls for the use of Effective Field Theories (EFTs) as the ideal framework to parameterize any deviation from the Standard Model of particle physics.

The most used EFT for phenomenological analyses at LHC is the Standard Model Effective Field Theory (SMEFT). It is built upon the SM, preserves all the defining features of the SM and agrees with it when considering only operators of dimension up to 4 (see [1] for a recent review).

The use of EFTs allows us to separate the process of constraining a hypothetical UV model into mostly independent steps. The experimental observables have to be computed as a function of the EFT parameters, the so-called Wilson Coefficients (WCs) to the desired precision. Then, global fits accounting for hundreds of experimental measurements can be used to constrain the EFT parameters. Once one has selected a UV model to constrain, this can be matched to the EFT, resulting in relations between the EFT WCs and the parameters of the UV model. Experimental constraints on the latter can be derived from those relations and the aforementioned global fits, which might have to be performed again accounting for the constraints dictated by the UV model.

A plethora of tools have been developed to automate the different steps in the EFT programme (see [2] for a recent review). In particular, several groups have performed global fits of experimental data to SMEFT with varying datasets and degrees of precision in the theoretical predictions [3–9] and most of them have released public versions of their fitting codes. Some of them included results for pre-defined UV models matched to SMEFT. On the other hand, the matching process has been fully automated at tree-level and partially at 1-loop level, even with the use of 2 different techniques [10–13]. However, there is no automatic link between the fitting and matching codes that allows the user to define a UV model, match it and fit its parameters in a few commands. Tools with those features have been developed for scalar-extended BSM models, e.g. see [14], but not within the SMEFT community.

The MATCH2FIT package aims at bridging that remaining gap in the EFT programme by offering a first interface between matching and fitting tools. We chose `matchmakereft` [12] and `SMEFT` [9] as the matching and fitting codes respectively, with plans to extend the support to other software. The companion paper [15] explains how `SMEFT` has been updated to support fits on the space parameter of the UV models and shows the fit results for several UV models.

In this manual, we explain in detail how to use MATCH2FIT to produce the run cards needed by `SMEFT` to fit the UV models. The goal is that any user can install `matchmakereft`, `MATCH2FIT`, and `SMEFT` and then compute the bounds on the UV parameters of their UV model of interest.

2 Conceptual description

The basic goal of the package is to obtain the matching relations from a user-defined UV model onto SMEFT and express them in a language that can be understood by the global fit code. In this first implementation, the code only reads the matching relations for the WCs in the basis considered by the `SMEFT` collaboration. In addition to those specified in [6], this code also reads the matching result for $(c_{\ell\ell})_{1111}$ which has been included since

the implementation of the LEP and SLC EWPOs [15, 16]. We do not assume any relation between $(c_{\ell\ell})_{1111}$ and $(c_{\ell\ell})_{1221}$.


The package has 2 working modes. The first one simply reads the matching results in the output format used by `matchmakereft` and parses it to the format of run cards that can be fed into the SMEFIT fitting code. In this mode, the mandatory inputs to the package are the location of the file containing the matching results and a numerical value (in TeV) for the mass(es) of the heavy particle(s). Optionally, one can also specify a name for the UV model and a name for the “collection”, where a collection is a set of UV models with some common characteristics. The code will print the run card for a scan on the UV parameters with the accompanying file that defines the UV invariants, although the latter is not strictly required to perform the fit (see [15]). The computation of the UV invariants is, at the moment, limited to tree-level results. If 1-loop level matching results are fed, the 1-loop contributions will be ignored when computing the UV invariants.

The second working mode runs `matchmakereft` to perform the matching of a certain model to SMEFT and generates the same final output than the previous mode. It is also possible to just perform the matching without producing the run cards for SMEFIT. The input required in this mode is the one that `matchmakereft` needs to describe the heavy particles that will be integrated out. More precisely, it needs the `.fr`, `.red` and `.gauge` files, and optionally the `.red` file. The `.fr` file is just a Feynrules file that defines the heavy particle(s), its (their) free Lagrangian and its (their) interactions with the SM. The SM and SMEFT models are included in `matchmakereft` and we use them without modification. For more details on how to write the `.fr` file and what the other files must contain, see [12].

Finally, MATCH2FIT includes some accessory functions. These allow the user to check whether a given model satisfies the flavour assumptions of SMEFIT after matching at tree-level and, in case they are violated, to solve these conditions for the UV couplings of the model. MATCH2FIT will print the run cards for SMEFIT regardless of the fulfilment of the flavour symmetries. However, the user should be extremely careful when fitting a model that violates the flavour symmetries since this could lead to inconsistent results.

3 Prerequisites and installation.

This is a Wolfram Mathematica Package designed and tested in version 12.1 or later. To unlock its full functionality, this package requires a working installation of `matchmakereft`, see its installation instructions in the corresponding paper [12] or in its website. Besides the functions that use `matchmakereft`, the rest of the package works in any operative system.

To install this package, clone the Github repository  and paste the `match2fit.wl` file on `$BaseDirectory/Applications` or `$UserBaseDirectory/Applications` to be able to load it from any notebook. The accompanying Mathematica notebook shows how to load the package and execute the commands with the included sample models and matching results. It also shows how to use the options of each function.

4 Public commands

4.1 Reading matching results

- `parametersList[directory, model]`: Both arguments should be strings. This function

reads the file `model.fr` in `directory`, recognizes the masses and couplings of the heavy particles to be integrated out, and gives back an array with 2 elements. The first element is a list with the symbolical expression of the masses of the heavy particles. The second element is a list of the couplings defined for these heavy particles, excluding gauge couplings but not self-interactions.

- `parametersListFromMatchingResult[matchResFile, looplevel]`: Its first argument must be a string with the address of the file with the matching results. It recognizes the masses and couplings of the heavy particles from those results and gives an output in the same format as `parametersList`. This code assumes that any parameter with a name starting by m or M corresponds to masses and identifies any other parameter as a coupling. If the input of `parametersListFromMatchingResult` is the matching result obtained with the model fed into `parametersList`, any difference in their outputs should be only due to couplings (or whole particles) that do not affect the tree-level matching result. If the second argument, `looplevel`, is equal to 0, "tree", or "Tree", and the input file contains 1-loop matching results, the 1-loop contributions will be ignored. To use 1-loop results, `looplevel` must be set to 1, "loop", or "1loop". If the input file corresponds to tree-level matching results, there might be some spurious 1-loop pieces due to evanescent shifts (see here) and hence `looplevel` must be set to 0, "tree", or "Tree" to ensure their consistent removal.
- `flavourSymChecker[matchResFile, Options]`: It takes the file with matching results specified as input and checks if those results are compatible with the SMEF_{IT} flavour symmetry, $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_\ell \times U(1)_e)^3$ with some minor modifications as explained in App. B. If the constraints are satisfied, it returns YES. If not, it returns NO and it prints the first WC for which it found a symmetry violation. The option "UVFlavourAssumption" allows the user to specify a replacement list that can be used to apply flavour assumptions on the UV parameters. The left-hand side of the replacement rule should contain some of the UV parameters listed by `parametersListFromMatchingResult` or `parametersList` with or without numerical indices, according to how they appear in the matching results file. The code supports up to 4 numerical indices in a single group, i.e. couplings such as g_{UV} , $g_{UV}[1]$, $g_{UV}[1, 3]$ and $g_{UV}[1, 3, 2, 4]$ are supported, but $g_{UV}[1][3]$ or $g_{UV}[1][2, 3]$ are not. The default value of "UVFlavourAssumption" is an empty list. An example of how to set this option is,

```
1 {"UVFlavourAssumption" -> {gWtiQ[i, j] :> KroneckerDelta[i, j] * KroneckerDelta
   [i, 3] gWqf[3, 3] }}
```

This function is prepared to handle tree-level matching results only. If it detects 1-loop results in the input file, it warns the user of its limitations and proceeds to ignore the 1-loop contributions. Some models might produce tree-level matching results that contain spurious 1-loop pieces due to the evanescent shifts (see here) which are consistently ignored by this function. However, those pieces will trigger the warning for 1-loop results.

- `flavourSolver [matchResFile, Options]`: It takes the file with matching results specified as input and tries to solve the constraints imposed by the SMEF_{IT} flavour symmetry, $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_\ell \times U(1)_e)^3$ with some minor modifications as explained in App. B, for the UV couplings. In The running time, the number of solutions and their complexity depend on the model. It returns all found solutions. The only Option of this function is "UVFlavourAssumption", which follows the same description

given in the function `flavourSymChecker`. This function considers the SM Yukawa couplings as symbolical variables and they can be set to zero with the option "UVFlavourAssumption". This function is prepared to handle tree-level matching results only. If it detects 1-loop results in the input file, it warns the user of its limitations and proceeds to ignore the 1-loop contributions. Some models might produce tree-level matching results that contain spurious 1-loop pieces due to the evanescent shifts (see here) which are consistently ignored by this function. However, those pieces will trigger the warning for 1-loop results.

4.2 Using `matchmakereft`

- `matcher[directory, model, looplevel]`: it runs `matchmakereft` and performs the tree-level matching without printing any run card for SMEFIT. It takes two strings as arguments, *directory* and *model*, and a third argument, *looplevel*, that can be an integer or a string. The first one is the directory where the package will look for the files `model.fr`, `model.red` and `model.gauge`. If the code does not find one of those files, it will print a warning. It does not check for the existence of `model.herm`. The expected content of each of those files is specified in the documentation of `matchmakereft` [12]. The argument *looplevel* decides whether the matching will be performed at tree or 1-loop level. Setting *looplevel* equal to 0, "tree", or "Tree" will produce tree-level matching, while setting it to 1, "loop", or "1loop" will instruct `matchmakereft` to perform 1-loop level matching. `matchmakereft` will create the folder `directory/model_MM`, inside which the matching results will be stored as `MatchingResult.dat`. The code will check if `matchmakereft` reported any problem during the matching and will print a warning if so. After performing the matching, the package will remove most of the files and directories created by itself or `matchmakereft` for the sake of tidiness. It will only leave the directory `model_MM` and 2 files inside: `MatchingResult.dat` and `MatchingProblems.dat`.

4.3 Generating the output for SMEFIT

- `matchResToUVscanCard[matchResFile, mass, looplevel, Options]`: Function that reads the file with the tree-level matching results and prints the cards required for a UV scan. *matchResFile* must be a string with the exact address of the file that contains the matching results to be used. The format of that file should be exactly like the file `MatchingResult.dat` produced by `matchmakereft`. The argument *mass* should be the value in TeV that the mass(es) of the UV particle(s) will be set to. *mass* can be one numerical value or a list of them $\{m_1, \dots, m_N\}$, the latter being useful in the case of a multiparticle model. The order of the masses is the one returned by `parametersListFromMatchingResult`. If the user specifies only one numerical mass value for a multiparticle model, all the particles will be assigned the same mass. If `parametersListFromMatchingResult` identifies K masses and $N < K$, the code will assume $m_i = m_N$ for $N \leq i \leq K$. If $N > K$, the values m_i with $K < i \leq N$ will be ignored. The mass values are also printed on the card names and inside the cards. For multiple masses, the convention is to take the integer part of each value and stick them together in sequence. The third mandatory argument is *looplevel*, which indicates the loop order of the matching results to be read. The allowed values of this option are as for `parametersListFromMatchingResult`. `matchResToUVscanCard` has 3 options. The first one is "UVFlavourAssumption", which is identical to the one of the function `flavourSymChecker`, see its description for details on this option. The second option is "Collection", a string indicating the Collection to which the model

belongs. Its default value is "UserCollection". Finally, the option "Model" is a string that specifies the model name to be printed on the run cards, with default value "UserModel". An example of how to set these options is replacing the argument **Options** by:

```
1 {"UVFlavourAssumption" -> {"lambdaT1[a_] :> lambdaT1[3]}},
2 "Collection" -> "TestMatchingCollection", "Model" -> "TestModel" }
```

4.4 Combining both steps

Finally, the package includes a function that integrates the steps of matching and printing all the run cards according to the result of said matching.

- `modelToUVscanCard[directory,model,mass,looplevel, Options]`: Function that takes the files that define the UV model, performs the tree-level matching by running `matchmakereft`, and prints the run cards needed for a UV scan. The first two arguments are exactly like in `matcher`, i.e. the program will look for the files `model.fr`, `model.red`, and `model.gauge` in `directory` and will do the tree-level matching based on them. The argument `model` also defines the name of the model. `mass` should be the value(s) in TeV that the mass(es) of the UV particle(s) will be set to. The handling of several mass values is as in the function `matchResToUVscanCard`. The `looplevel` argument indicates whether the matching has to be performed at tree level (`looplevel` equal to 0, "tree" or "Tree") or 1-loop level (`looplevel` equal to 1, "loop", or "1loop"). The run card for SMEFiT will be printed using the results at the loop order indicated by `looplevel`. This function has 2 options. The first one is "UVFlavourAssumption", which is identical to the one of the function `flavourSymChecker`, see its description for details on this option. The second option is "Collection", a string indicating the Collection to which the model belongs. Its default value is "UserCollection". An example of how to set these options is replacing the argument **Options** by:

```
1 {"UVFlavourAssumption" -> {"lambdaT1[a_] :> lambdaT1[3]}},
2 "Collection" -> "TestMatchingCollection" }
```

5 Limitations and outlook

All SM couplings and masses are numerically evaluated when printing the run cards for the global fit. Their values are hard coded in the package and we summarise them in Appendix A. Future versions should allow the user to check and change easily these values.

The code does not check for the fulfilment of the SMEFiT flavour assumptions when printing the run cards for SMEFiT. This generates a degree of arbitrariness, e.g. the code uses the matching result for $(c_{\varphi q}^{(3)})_{22}$ as the result for $(c_{\varphi q}^{(3)})_{ii}$ without checking that $(c_{\varphi q}^{(3)})_{22} = (c_{\varphi q}^{(3)})_{11}$. We provide all these choices in Appendix C. The user should be aware of this and compensate for it with the required assumptions on the UV couplings. The support for different flavour symmetries on the WCs will be added in the future. This is key to ensure full compatibility with other fitting codes.

The code assumes that all UV couplings are real and applies this assumption when interpreting the matching results. The support for complex UV couplings and WCs will be added in future releases.

An important but more long-term upgrade is to read matching results in the xWCF format. This would allow for interfacing with other matching codes such as CoDEx and

Matchete. This would allow for additional interfacing with codes that implement the SMEFT RGE running.

This version, **v.1.8**, is the first one to fully automate the pipeline required to perform the fit of the UV model matched to the SMEFT at 1-loop level. However, accessory functions such as those dealing with flavour assumptions and the one that computes the UV invariants remain limited to tree-level results. Their extension to 1-loop results is a top priority to fully automate the analysis of the fit results with 1-loop matching.

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A Numerical parameters

The package uses numerical values for SM parameters in order to convert the matching expressions into functions of only the UV parameters to fit. The values are hard-coded inside the code. The default values are shown in Table 1. If the user wishes to change these values, they can do it by modifying the file `match2fit.wl`, section `SM numerical inputs`.

There is an internal switch to turn on and off certain masses and Yukawa couplings in the SM. The variable is called `flavourOption` and defined in section `SM numerical inputs`, subsection `Masses and Yukawas`, of the file `match2fit.wl`. The default value "SMEFiT3" enables all the 3rd-generation masses to be non-vanishing, with values shown in Table 1. If this switch is changed to "SMEFiTop", the top mass will be the only non-vanishing one. If the value of this variable is changed to "SMEFiTcharm", the non-vanishing masses will be the top, bottom, τ and charm masses, the latter with values $m_c = 1.25$ GeV.

B Flavour symmetry in the SMEFiT global fit

The default datasets in the SMEFiTglobal fit assume the flavour symmetry $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_\ell \times U(1)_e)^3$ plus some additional assumptions. First, it allows the symmetry-breaking Yukawa-like WCs $(c_{u\varphi})_{33}$, $(c_{u\varphi})_{22}$, $(c_{d\varphi})_{33}$, and $(c_{e\varphi})_{33}$, which correspond to deviations in the Yukawa coupling of the top, bottom and charm quarks and τ lepton [6]. All these differences with respect to $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_\ell \times U(1)_e)^3$ are also embedded in the conditions considered by the functions `flavourSymChecker` and `flavourSolver`.

C Choices due to flavour symmetry

The SMEFiT flavour symmetry forces certain WCs to be the same for certain values of their flavour indices. The code, when printing the run cards, reads the matching result

Parameter	Value
α_s	0.1179
$\sin^2 \theta_W$	0.23121
G_F	$1.1663787 \cdot 10^{-5} \text{ GeV}^{-2}$
g_3	$\sqrt{4\pi\alpha_s} = 1.2172$
g_2	$\sqrt{\frac{8}{\sqrt{2}}m_W^2 G_F} = 0.652905$
g_1	$g_2 \sqrt{\frac{\sin^2 \theta_W}{1-\sin^2 \theta_W}} = 0.358055$
m_W	80.379 GeV
m_Z	91.1876 GeV
m_h	125.25 GeV
v	246.22 GeV
λ_h	$\frac{1}{2} \left(\frac{m_h}{v} \right)^2$
m_t	172.76 GeV
m_b	4.18 GeV
m_τ	1.78 GeV
m_ψ	0 for any 1st or 2nd-gen. fermion.
$(y_\psi^{\text{SM}})_{ij}$	$\delta_{ij} \sqrt{2} \frac{m_\psi}{v}$

Table 1: Numerical parameters used by the package. Values extracted from [17]

for one particular value of those indices and assumes that all the other values give the same expression. This procedure leads to ambiguities if the model after matching does not follow the SMEFT flavour assumption on the WCs even after applying the UV flavour assumptions specified by the user. We provide in Table 2 a list of the flavour indices that the code uses to print the run card so the user can keep track of these possible ambiguities.

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SMEFiT WC	WC read by MATCH2FIT
$c_{\varphi q}^{(-)}$	$\left(c_{\varphi q}^{(1)}\right)_{22} - \left(c_{\varphi q}^{(3)}\right)_{22}$
$c_{\varphi q}^{(3)}$	$\left(c_{\varphi q}^{(3)}\right)_{22}$
$c_{\varphi u_i}$	$(c_{\varphi u})_{22}$
$c_{\varphi d_i}$	$(c_{\varphi d})_{22}$
$c_{Qq}^{1,8}$	$(c_{qq}^1)_{1331} + 3 (c_{qq}^3)_{1331}$
$c_{Qq}^{1,1}$	$(c_{qq}^1)_{1133} + \frac{1}{6} (c_{qq}^1)_{1331} + \frac{1}{2} (c_{qq}^3)_{1331}$
$c_{Qq}^{3,8}$	$(c_{qq}^1)_{1331} - (c_{qq}^3)_{1331}$
$c_{Qq}^{3,1}$	$(c_{qq}^3)_{1133} + \frac{1}{6} \left((c_{qq}^1)_{1331} - (c_{qq}^3)_{1331} \right)$
c_{tq}^8	$(c_{qu}^8)_{1133}$
c_{tq}^1	$(c_{qu}^1)_{1133}$
c_{tu}^8	$2 (c_{uu})_{1331}$
c_{tu}^1	$(c_{uu}^8)_{1133} + \frac{1}{3} (c_{uu}^8)_{1331}$
c_{Qu}^8	$(c_{qu}^8)_{3311}$
c_{Qu}^1	$(c_{qu}^1)_{3311}$
c_{td}^8	$(c_{ud})_{3333}$
c_{td}^1	$(c_{ud}^1)_{3333}$
c_{Qd}^8	$(c_{qd}^8)_{3333}$
c_{Qd}^1	$(c_{qd}^1)_{3333}$
$c_{\ell\ell}$	$(c_{\ell\ell})_{1221}$

Table 2: WCs in the Warsaw basis used by MATCH2FIT to determine the WCs in the SMEFiT basis. The definition of the latter ones can be found in [6].

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