DsixTools: The SMEFT Toolkit

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Motivation

DsixTools is a *Mathematica* package for the handling of the dimension six Standard Model Effective Field Theory (SMEFT).

The discovery of a SM-like Higgs boson together with the absence of new physics signals at the LHC seems to hint at the presence of a mass gap between the electroweak scale and the new dynamics. Departures from the SM at energies much smaller than the new physics scale are described in this case via the SMEFT.

The SMEFT Lagrangian is organized as an expansion in powers of $1/\Lambda$, where Λ represents the new physics scale and compensates the canonical dimension of the effective operators. The leading order of the SMEFT corresponds to the SM Lagrangian. Dominant new physics contributions to most processes of interest are expected to be encoded in effective operators of canonical dimension six.

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^{n_i-4}} \mathcal{O}_i \,,$$

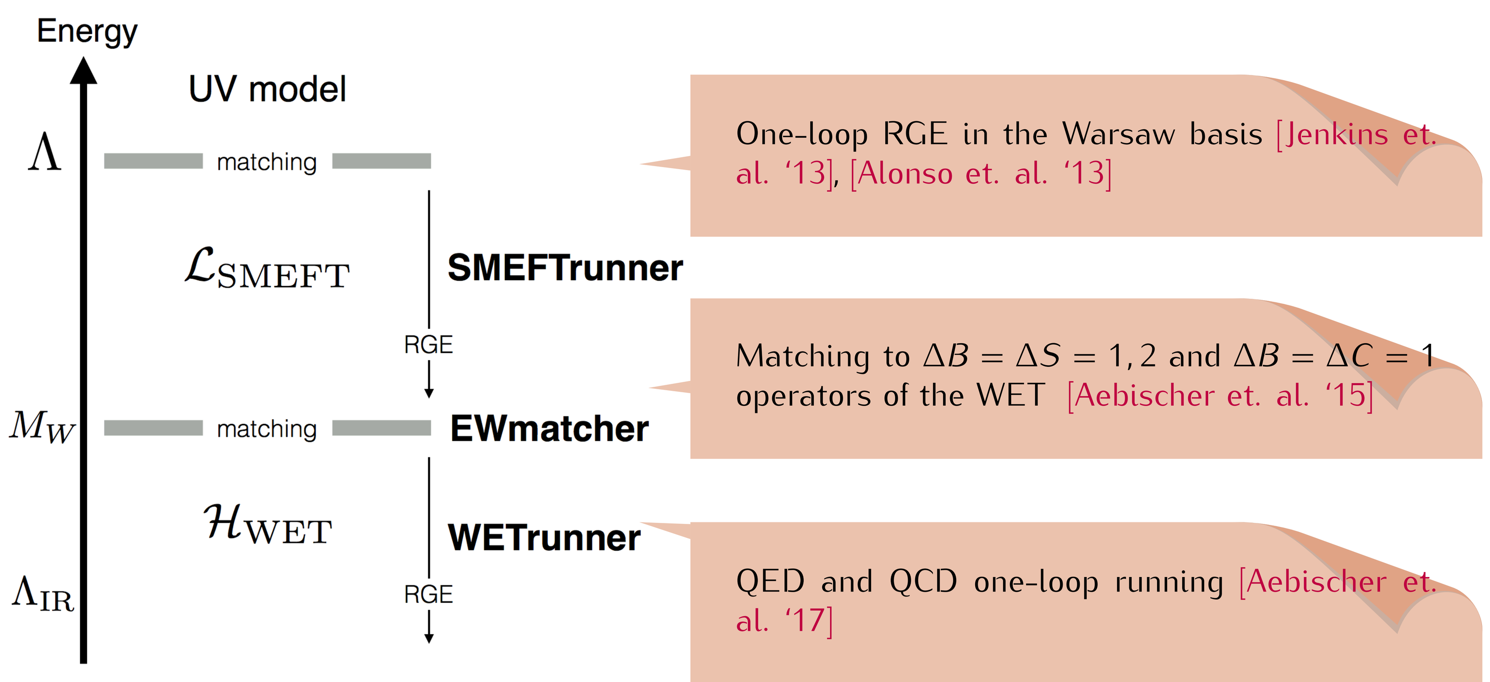
with n_i the canonical dimension of $\mathcal{O}_i$. A non-redundant basis of dim. 6 operators was defined in [Grzadkowski et. al. '10], known as the *Warsaw basis*.

The SMEFT allows to relate properties of the high energy dynamics at the scale Λ with measurements that take place at low energies while performing an expansion in $1/\Lambda$, keeping leading new physics effects in a consistent manner.

DsixTools in a Nutshell

Given some initial conditions for the Warsaw basis at the high scale, DsixTools allows the user to perform the full one-loop renormalization group evolution (RGE) down to the electroweak scale.

When the physics of interest lies well below the electroweak scale, it is useful to perform a matching of the dimension six basis to a low energy EFT in the broken electroweak phase. In the so-called Weak Effective Theory (WET), the SM heavy degrees of freedom (top quark, Higgs, $W^\pm$ and Z) have been integrated out. DsixTools implements the tree-level matching of the Warsaw basis to $\Delta B = \Delta S = 1, 2$ and $\Delta B = \Delta C = 1$ operators of the WET and includes the one-loop QCD and QED running from the electroweak scale down to the b-quark mass scale.



Running effects in phenomenology, an illustration

Extend the SM with a vector-like quark "Q_d" with $SU(2)_L \times U(1)_Y$ quantum numbers $(2, -5/6)$ and mass $M \gg M_W$. It has the following coupling to the SM:

$$\mathcal{L}_Y = - \bar{d}_R^i \lambda_i \tilde{H}^\dagger Q_{dL} + \text{h.c.}$$

Integrating out Q_d at tree-level generates the dim. 6 operator at $\mu = M$

$$\mathcal{L}_{\rm SMEFT} \supset \left(- \frac{1}{2} \frac{\lambda_i \lambda_j^*}{M^2} \right) (H^\dagger i \overleftrightarrow{D}_\mu H) [\bar{d}_R^i \gamma^\mu d_R^j] \,.$$

This operator generates through Yukawa RG effects a contribution to the left-right operator $O_{LR,1}^{ij} = [\bar{d}_i \gamma_\mu P_L d_j][\bar{d}_i \gamma^\mu P_R d_j]$ of the WET which has a numerically enhanced QCD running below the weak scale and chirally enhanced hadronic matrix elements for $\Delta F = 2$ transitions, especially in the Kaon sector [Bobeth et. al. '17].

Loading DsixTools

The code can be downloaded from the web page:

`https://dsixtools.github.io`

After placing the DsixTools folder in the *Applications* folder of the *Mathematica* base directory, the user can load DsixTools with the command

```
Needs["DsixTools`"]
```

Example: A DsixTools Program

This example illustrates the use of the SMEFTrunner, EWmatcher and WETrunner modules.

Examples are provided with the code in the form of *Mathematica* notebooks.

The objective will be to start with the dim. 6 operators at the high scale, implement the RGE down to the weak scale, carry out the matching to the WET, and perform the RGE down to the b-quark mass scale.

We start by specifying the initial conditions of the Warsaw basis and the SM parameters at the high scale with `ReadInputFiles["Options.dat", "WCsInput.dat", "SMInput.dat"]`. This reads the input cards: `WCsInput.dat` and `SMInput.dat`. The card `WCsInput.dat` looks like

```
Block WC1
1 0.000000      # G
2 0.000000      # G tilde
3 0.000000      # W
4 0.000000      # W tilde
Block WC2
1 0.000000      # phi
Block WC3
1 0.000000      # phiBox
2 0.000000      # phiD
Block WC4
1 0.000000      # phiG
...
8 0.000000      # phiWtildeB
Block WCUPHI
1 1 0.000000    # uphi(1,1)
1 2 0.000000    # uphi(1,2)
...
3 3 0.000000    # uphi(3,3)
...
```

We also set the options controlling the RGE from the high scale down to the weak scale by reading the card `Options.dat`. A typical card `Options.dat` will look as

```
Block SCALES
1 10000   # UV scale [GeV]
2 80.385  # EW scale [GeV]
Block OPTIONS
1 0      # CPV=0 : all parameters and WCs are assumed to be real
2 1      # ReadRGEs : 0 (RGEs reconstructed) or 1 (RGEs read ↪
   from a file)
3 1      # Method to solve RGEs : 1 (NDSolve) or 2 (leading log)
4 0      # Export RGEs
5 1      # Use SM RGEs to compute SM parameters at the ↪
   high-energy scale
6 0      # Export SMEFTrunner results
7 0      # Export EWmatcher results
8 0      # Export WETrunner results
9 1      # Type of input WCs: 1 (SMEFT) or 2 (WET)
```

We proceed to load the SMEFTrunner module with `LoadModule["SMEFTrunner"]`. The SMEFT β functions are constructed or read from a file (as specified in `Options.dat`) using the `LoadBetaFunctions` command. We can now perform the RGE from the high scale down to the weak scale with `RunRGEsSMEFT` and export the results to a file using `ExportSMEFTrunner`.

Now we match the SMEFT dim. 6 operators at the weak scale to the WET. This is done via the command `LoadModule["EWmatcher"]`. The input is automatically created in this case from the output of SMEFTrunner. Next, the EWmatcher module transforms the SMEFT WCs to the fermion mass basis by means of the `RotateToMassBasis` routine. Finally, `ApplyEWmatching` matches the SMEFT WCs onto the WET WCs. The output of the EWmatcher module can be exported to a file using `ExportEWmatcher`.

The QCD and QED one-loop running can be performed by loading the WETrunner module: `LoadModule["WETrunner"]`. Running and exporting the results is done with the commands `RunRGEsWET` and `ExportWETrunner`, respectively.

Summary

DsixTools is a *Mathematica* package aimed to facilitate the systematic use of EFT methods in the analysis of new physics models where the new dynamics appears at a scale much higher than the weak scale. One of the main features of the current version is the implementation of the full one-loop RGE of the SMEFT dimension six operators. The structure of DsixTools allows for an easy implementation of new modules. Therefore, the current content of the package is expected to grow substantially with future improvements, including additional tools and features.

DsixTools: The SMEFT Toolkit
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Manual: arXiv:1704.04504
Website: `https://dsixtools.github.io`

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