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BSM tools for High-p_T Tutorial

Task 1. SMEFT

1) Write down in `FeynRules` the SMEFT Lagrangian for the semi-leptonic $d = 6$ operators:

$$\mathcal{O}^{(1)}_{\ell q} = (\ell_L \gamma^\mu \ell_L)(q_L \gamma^\mu q_L)$$
$$\mathcal{O}^{(3)}_{\ell q} = (\ell_L \gamma^\mu \tau^I \ell_L)(q_L \gamma^\mu \tau^I q_L).$$

Recall that the Wilson coefficients (WC) are Hermitian 4-tensors: $[\mathcal{C}^1_{\ell q}]_{\alpha\beta ij}$ with $\alpha, \beta = 1, 2, 3$ lepton-flavor indices and $i, j = 1, 2, 3$ quark-flavor indices (omitted above). In order to simplify the task fix the lepton flavor indices to the second generation (we will later be interested in muons) and the quark indices to be flavor-diagonal.

Tip: *The* `SM.fr` *is always the first place too look for inspiration (the second place is the online repo for the simplified models). Take a look at how the CKM is implemented in* `SM.fr` *as inspiration for the WC parameters.*

2) Use `FeynRules` to inspect the Feynman rules of the model with and without expanded flavor indices. Which combination of WCs enter into the Drell-Yan scattering processes $\bar{u}_i u_j \to \mu^+\mu^-$, $\bar{d}_i d_j \to \mu^+\mu^-$? Use this to parameterize the scattering cross-sections as a second order polynomial in the WCs.

3) In order to xcheck the models, produce the `UFO` model and export it to `MadGraph`. Look at the various diagrams by running:

```
MG5_aMC> import model <your_UFO_model>
MG5_aMC> generate p p > mu+ mu- NP=1
MG5_aMC> output <PROC_Name>
MG5_aMC> open index.html
```

Task 2. Mediators

1) Write down the `FeynRules` models for the following simplified Lagrangians: i) a vector singlet $Z' \sim (\mathbf{1}, 0)$ where the representations refer to the SM group in the broken phase $\mathrm{SU}(3)_c \times U(1)_{\mathrm{EM}}$ and, ii) a vector leptoquark $U \sim (\mathbf{3}, \mathbf{1}, -2/3)$ where the reps refer to the SM group $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$:

$$\mathcal{L}_{Z'} = g^u_{ij}\, Z'_\mu(\bar{u}^i \gamma^\mu \mathbb{P}_L u^j) + g^d_{ij}\, Z'_\mu(\bar{d}^i \gamma^\mu \mathbb{P}_L d^j) + g^e_{\alpha\beta}\, Z'_\mu(\bar{e}^\alpha \gamma^\mu \mathbb{P}_L e^\beta)$$
$$\mathcal{L}_U = \frac{1}{\sqrt{2}}\, x_{i\alpha}\, U^c_\mu(\bar{q}^{c,\,i}_L \gamma^\mu \ell^\alpha_L) + h.c.$$

where c is a color index.

2) Now assume that each of these new states are much heavier than the EW scale. Match these models (at tree level) to the low energy EFTs using `Matchete`. The installation of `Matchete` can be done from within a `Mathematica` notebook via:

```
Import["https://gitlab.com/matchete/matchete/-/raw/master/install.m"]
```

Tip: *For the leptoquark you can directly import the SM in* `Matchete`*, but for the Z' model you need to define the broken phase group $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{EM}}$ and the corresponding quark/lepton fields. See the full SM implementation in the appendix of* [1] *for inspiration.*

References

[1] Javier Fuentes-Martín, Matthias König, Julie Pagès, Anders Eller Thomsen, and Felix Wilsch. A proof of concept for matchete: an automated tool for matching effective theories. *Eur. Phys. J. C*, 83(7):662, 2023.

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