UFO and MG Hands-On lectures: projects

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I. UFO

1. **Restriction cards in Feynrules.** After importing the `Zprime.fr` and `SM.fr` models in Mathematica, load the restriction file given in the materials with

   ```
   LoadRestriction[masslessFermions.rst]
   ```

   Printout the Feynman rules from the `LYukawa` Lagrangian. What changed? Expand the flavors in these rules using the option `FlavorExpand -> True` inside `FeynmanRules` to check the flavor dependence. Also check the mass spectrum of `LYukawa` to look at fermion masses.

2. **Flavor indices.** Introduce flavor dependence in the $\kappa_u Z'_\mu \bar{u}_R \gamma^\mu u_R$ interaction: define the κ_u parameter with Generation indices, set all the off-diagonal entries to 0 and the diagonal ones to arbitrary numbers [tip: use the Yukawa coupling definitions in `SM.fr` as an example].

   Import the model in Mathematica and output the Feynman rules for `LZprime`, with and without flavor expansion. Can you see what changed? [tip: after the `FeynmanRules` command you can use `./kd|kq|kl|ke -> 0` in order to remove the other interactions].

   Re-define again κ_u using the `Definitions` option everywhere instead of `Value` and check again the Yukawa Feynman rules. What changed?

3. **Internal parameters in FeynRules.** Modify the EFT Feynrules model as follows: introduce κ_u, κ_d, κ_e, $M_{Z'}$ as in the Z' model and define `ceu`, `ced` as internal parameters. Assign them the `Value` given by the explicit matching formula

   $$C_{ij} = -\frac{2-\delta_{ij}}{2M_{Z'}^2}\kappa_i\kappa_j\,. \qquad (1)$$

   Check the Feynman rules in Mathematica.

   Optionally [after MG lecture!]: export this new model to UFO, set the values of $M_{Z'}$, κ_i to the benchmark we used in the lecture, and generate events for $pp \to l^+l^-$ with the full EFT, pure interference and pure quadratic contributions. Verify that you get results consistent with those from the `Zprime_EFT_UFO`.

4. Given the quantum numbers of the Z' introduced in the simplified model, the interaction term

   $$\kappa_H Z'_\mu (iH^\dagger \overleftrightarrow{D}^\mu H) \qquad (2)$$

   is also allowed in general, with

   $$(iH^\dagger \overleftrightarrow{D}^\mu H) = i(D^\mu H^\dagger)H - iH^\dagger(D^\mu H). \qquad (3)$$

   What other operators of the Warsaw basis (`1008.4884`) would be induced when the Z' is integrated out, if this interaction is included in addition to the fermionic ones? [tip: add this interaction to the expression of J_μ and use the general matching formula]

   What is the physical interpretation of this interaction?

   Hint: expand $(iH^\dagger \overleftrightarrow{D}^\mu H)$ in unitary gauge. To do it in FeynRules, define it directly in the notebook as

   ```
   Block[{ii,jj},
     ExpandIndices[
            I Phibar[ii] DC[Phi[ii],mu] - I DC[Phibar[jj],mu] Phi[jj],
     FlavorExpand->{SU2D,SU2W}]/.feynmangaugerules
   ]
   ```

5. Imagine integrating out the Z' model and matching to operators with dimension higher than 6. What kind of higher-dimensional operators would contribute to $pp \to l^+l^-$ (at tree level)?

II. MG/PS

1. **Interaction orders**. Import the EFT UFO in MadGraph and generate diagrams for the $pp \to l^+l^-$ process in different ways, playing with interaction orders. For instance, try:

```
generate p p > l+ l-  EFT == 1
generate p p > l+ l-  EFTceu = 1
generate p p > l+ l-  EFTceu == 1
generate p p > l+ l-  EFT^2 == 1 EFTceu^2 == 1
generate p p > l+ l-  EFT^2 == 2 EFTceu^2 == 1
```

   or other combinations you can think of. Output each try to a different directory, and compare the diagrams produced.

   Writing the contributions to the cross section as

$$\sigma_{tot} = \sigma_{SM} + C_{eu}\sigma^{(1)}_{eu} + C_{ed}\sigma^{(1)}_{ed} + C^2_{eu}\sigma^{(2)}_{eu} + C^2_{ed}\sigma^{(2)}_{ed} + C_{eu}C_{ed}\sigma^{(2)}_{eu,ed} \tag{4}$$

   indicate with a ✗ which terms are included in the result obtained with each syntax. The first line is already filled as an example. [tip: remember that = is the same as <= and that the `^2` notation refers to the orders in the squared amplitude]

syntax	σ_{SM}	$\sigma^{(1)}_{eu}$	$\sigma^{(1)}_{ed}$	$\sigma^{(2)}_{eu}$	$\sigma^{(2)}_{ed}$	$\sigma^{(2)}_{eu,ed}$
`EFT=1`	✗	✗	✗	✗	✗	✗
`EFTceu=1`						
`EFTceu==1`						
`EFT^2==1 EFTceu^2==1`						
`EFT^2==2 EFTceu^2==1`						

   Optionally: for each try, copy the benchmark `run_card.dat` and `param_card_EFT.dat` into the `Cards` directory and compute the cross section. This can be done quickly without generating events running eg.:

```
./pp_ll_EFT_1/bin/madevent survey
```

2. **Restriction cards in MadGraph.** Make a copy of the `param_card_Zprime.dat` and rename it into `restrict_massless.dat`. Place it in `SM_Zprime_UFO/Cards`.

   Start MadGraph and import the model with

```
import model SM_Zprime_UFO-massless
```

   generate $pp \to l^+l^-$ (with or without Z', it's indifferent) and output it to `pp_ll_restricted`. Open the `index.html` file in this folder and check the Feynman diagrams. Do you notice any difference wrt. those obtained during the lecture?

   Open `pp_ll_restricted/Cards/param_card.dat`. Is this the same as the card found eg. in `pp_ll_SM`? What parameters are missing?

   Modify the `restriction_massless.dat` card replacing `0.000000e+00` $\to$ `1.e-99` in the values of the κ_i parameters and repeat the operation above. Did anything change in the `param_card.dat` generated?

3. **Negative interference.** Flip the sign of the κ_e parameter both in the Z' and the EFT UFOs, repeat the event generation we did in the lecture (all processes apart from the SM. for the Z' generation, copy a new `param_card` in the folder, so that the width is re-computed) and re-do the plot of the m_{ll} spectrum with the new results.

   Compare to the result obtained in the lecture. What changed in the overall behavior?