PREFIT School '20: Problem Sheet

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I. DAY 1

Simplified model — Consider enlarging the SM with a gauge singlet real vector Z'_μ,

$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{M_{Z'}^2}{2} Z'_\mu Z'^\mu + Z'_\mu J^\mu \,, \tag{1}$$

where J^μ is the current built from SM fermion fields

$$J^\mu = \kappa_q \, \bar{q}_L \gamma^\mu q_L + \kappa_u \, \bar{u}_R \gamma^\mu u_R + \kappa_d \, \bar{d}_R \gamma^\mu d_R + \kappa_l \, \bar{l}_L \gamma^\mu l_L + \kappa_e \, \bar{e}_R \gamma^\mu e_R \,. \tag{2}$$

Here, $q_L = (u_L, V d_L)^T$ and $l_L = (\nu_L, e_L)^T$ are the left-handed quark and lepton doublets, while u_R, d_R, and e_R are the right-handed singlets. V is the CKM matrix such that all fermions are already rotated to the mass eigenstate basis. We assume an exact $U(3)^5$ flavour symmetry which forces all Z' interactions to be flavour universal, i.e. proportional to the identity matrix in flavour space. (Convince yourself that this also holds for $\bar{d}_L \gamma^\mu d_L$.) Therefore, instead of being a 3×3 matrix, κ_f is a real parameter. In this simplified model we do not specify the origin of the vector mass $M_{Z'}$ and treat it as an input parameter. There are in total six input parameters, one mass and five coupling constants ($f = q, u, d, l, e$).

Matching to the SM effective field theory — Let us now integrate out this field and match to the SMEFT. Solving the equation of motion for Z' and inserting the solution to Eq. (1), we find (do it please!)

$$\mathcal{L}_{EFT} = -\frac{1}{2M_{Z'}^2} J_\mu J^\mu \,, \tag{3}$$

which contains all operators of canonical dimension six. Expanding this expression, we get operators

$$\begin{aligned}
\mathcal{O}_{ll} &= (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)\,, & \mathcal{O}_{qq}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)\,, & \mathcal{O}_{ql}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{l}\gamma^\mu l)\,,\\
\mathcal{O}_{uu} &= (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)\,, & \mathcal{O}_{dd} &= (\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)\,, & \mathcal{O}_{ee} &= (\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)\,,\\
\mathcal{O}_{qu}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)\,, & \mathcal{O}_{qd}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)\,, & \mathcal{O}_{qe} &= (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)\,,\\
\mathcal{O}_{lu} &= (\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)\,, & \mathcal{O}_{ld} &= (\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)\,, & \mathcal{O}_{le} &= (\bar{l}\gamma_\mu l)(\bar{e}\gamma^\mu e)\,,\\
\mathcal{O}_{eu} &= (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)\,, & \mathcal{O}_{ed} &= (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)\,, & \mathcal{O}_{ud}^{(1)} &= (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)\,,
\end{aligned} \tag{4}$$

in the *Warsaw basis* [1]. The matched Willson coefficients, defined by

$$\mathcal{L}_{\rm SMEFT} = \sum_{f,f'} \mathcal{C}_{ff'} \, \mathcal{O}_{ff'} \,, \tag{5}$$

are (please check it!)

$$\mathcal{C}_{ff'} = -\frac{2-\delta_{ff'}}{2M_{Z'}^2} \kappa_f \kappa_{f'} \,. \tag{6}$$

where $f, f' = q, u, d, l, e$ and $\delta_{ff'}$ is the Kronecker delta.

Task — Implement the Z' model and the EFT model in the `UFO` using `FeynRules` [2].

II. DAY 2

Use the UFO models with MadGraph5_aMC@NLO [3] to study at tree-level $pp \to \ell^+\ell^-$ (where $\ell = e, \mu$) at 13 TeV c.o.m. energy. As a signal benchmark point, set

$$M_{Z'} = 2\ \text{TeV}\,, \quad \kappa_q = \kappa_l = 0\,, \quad \kappa_u = \kappa_d = 0.2\,, \quad \kappa_e = 0.6\,. \tag{7}$$

Task 1
Perform five different simulations:

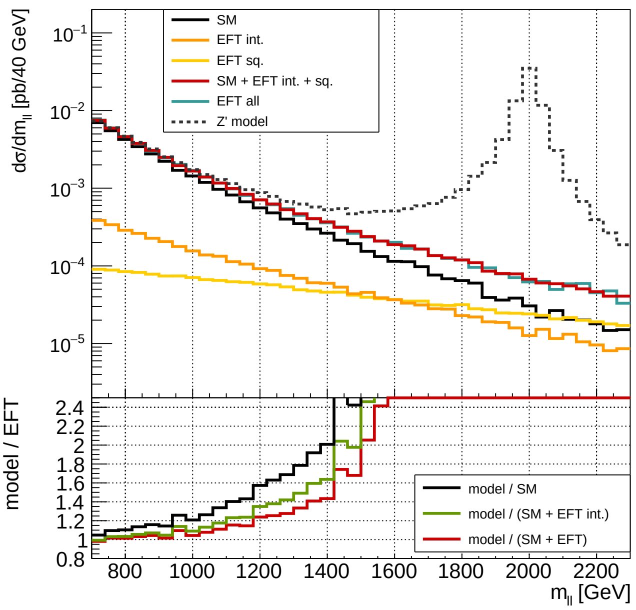
1. in the Z' model,
2. in the SM,
3. the SM – EFT interference only,
4. the EFT squared only,
5. the total EFT (to match the sum of 2. + 3. + 4. as a cross check).

Check that the automatically generated total Z' decay width in the simulation agrees with the formula

$$\Gamma_{Z'} = \frac{M_{Z'}}{24\pi} \sum_f N_C^f \left[(\kappa_{f_L}^2 + \kappa_{f_R}^2) \left(1 - \frac{m_f^2}{M_{Z'}^2} \right) + 6\kappa_{f_L}\kappa_{f_R} \frac{m_f^2}{M_{Z'}^2} \right] \sqrt{1 - \frac{4m_f^2}{M_{Z'}^2}}\,, \tag{8}$$

where $f = u, c, t, d, s, b, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$. Also, m_f is the fermion mass and N_C^f its color factor.

Task 2
Plot the dilepton invariant mass distribution for five different simulations in the range 0.7 TeV – 2.3 TeV. You should get



Discussion: In which energy range does the EFT represent the full model well? Where and why it breaks down? Where and why does the SM – EFT interference dominates over the EFT squared contributions (and vice versa)? (Tip: Use the EFT power counting.)

Task 3
Use PYTHIA [4] to shower and hadronise the events in the Z' model. Use MadAnalysis [5] to plot the dilepton invariant mass distribution before and after. What are the main differences?

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[2] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, Comput. Phys. Commun. **185**, 2250 (2014), 1310.1921.
[3] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, JHEP **07**, 079 (2014), 1405.0301.
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[5] E. Conte, B. Fuks, and G. Serret, Comput. Phys. Commun. **184**, 222 (2013), 1206.1599.