Appendix A

Model Implementation

To obtain signal c.s., we have implemented various Lagrangian terms of warped model VLQs and Lagrangian for $e_s$ in FeynRules version 1.6.0 [132]. The user needs to provide FeynRules with the minimal information required to describe the new model. The FeynRules code then generates Universal FeynRules Output (UFO) [133] format model files suitable for Monte-Carlo generator MadGraph5 [134] that we have used to estimate the signal c.s. For SM background computations we have used model files which are already available with the MadGraph5 package.

A.1 DT model implementation in FeynRules

As an example, we show an implementation of the DT model in FeynRules. In the DT model we compute the numerical values of the terms appearing in the bottom mass matrix in Eq. (2.48). Using these values one can compute the mixing angles in Eq. (2.49) and hence all the couplings in the Lagrangian as shown in Eqs. (2.53)-(2.56). To implement the DT model we use existing SM FeynRules files where we add three bottom mass matrix elements $M_b$ (Mb), $M_{b'}$ (Mbp) and $M_{bb'}$ (Mbp) as external parameters (notations used in FeynRules are shown in braket). Next, we define internal parameters $\sin \theta_{L,R}$ (SL,SR) and $\cos \theta_{L,R}$ (CL,CR) as functions of $M_b$, $M_{b'}$ and $M_{bb'}$. We need to provide some information
of the $b'$ (bp) quark in FeynRules (we refer readers to FeynRules manual to know about the syntax) where we define a new fermion class as follows

$$F[5] \equiv \{
\begin{align*}
\text{ClassName} & \rightarrow \text{bp}, \\
\text{SelfConjugate} & \rightarrow \text{False}, \\
\text{Indices} & \rightarrow \text{Index}\{\text{Colour}\}, \\
\text{Mass} & \rightarrow \{\text{Mbp}, \ 1000\}, \\
\text{Width} & \rightarrow \{\text{Wbp}, \ 21.304\}, \\
\text{QuantumNumbers} & \rightarrow \{Q \rightarrow -1/3\}, \\
\text{PDG} & \rightarrow 7, \\
\text{PropagatorLabel} & \rightarrow \{"bp"\}, \\
\text{PropagatorType} & \rightarrow \text{Straight}, \\
\text{PropagatorArrow} & \rightarrow \text{Forward}, \\
\text{FullName} & \rightarrow \{"bp-quark"\},
\end{align*}
$$

We assign a new Monte-Carlo PDG code “7” for $b'$. FeynRules program cannot compute the total width of a particle using the masses and couplings information unless the analytical formula for the total width is defined explicitly in the code. We have computed the total width using analytical formula and used that value in the block above. We define interaction terms of the DT model (Eqs. (2.53)-(2.56)) following FeynRules syntax as

- **Kinetic term for $b'$**

  $$L_{bpKIN} := I \ bp\bar{b}.Ga[\mu].\Delta l[bp, \mu];$$

- **QCD and QED interactions**

  $$L_{bpQCD} := g_s \ bp\bar{b}.Ga[\mu].T[a].bp \ G[\mu,a];$$

  $$L_{bpQED} := -(ee/3) \ bp\bar{b}.Ga[\mu].bp \ A[\mu];$$

- **charged current interactions**
\[ L_{\text{bCC}} := (g \cdot W/\text{Sqrt}[2]) \cdot \bar{t}_{\text{bar}} \cdot \text{Proj}[\mu] \cdot b \cdot W[\mu]; \]

- Neutral current interactions

\[ L_{\text{bNC1}} := g \zeta ((-1/2 \cdot C_{L}^2 + 1/3 \cdot s_{\text{w}2}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot Z[\mu] + (1/3 \cdot s_{\text{w}2}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot Z[\mu] + (-1/2 \cdot s_{\text{L}^2} + 1/3 \cdot s_{\text{w}2}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot Z[\mu] + (1/3 \cdot s_{\text{w}2}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot Z[\mu]; \]

\[ L_{\text{bNC2}} := g \zeta (1/2 \cdot C_{L} \cdot C_{S}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot Z[\mu] \]

- Higgs interactions

\[ L_{\text{bH}} := -((M_{b} \cdot C_{L} \cdot C_{R} - M_{bbar} \cdot C_{L} \cdot S_{R}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot H + (M_{b} \cdot S_{L} \cdot S_{R} - M_{bbar} \cdot S_{L} \cdot C_{S}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot H + (-M_{b} \cdot C_{L} \cdot S_{R} + M_{bbar} \cdot C_{L} \cdot C_{S}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot H + (-M_{b} \cdot S_{L} \cdot C_{S} - M_{bbar} \cdot S_{L} \cdot S_{R}) \cdot \bar{b}_{\text{bbar}} \cdot \text{Proj}[\mu] \cdot b \cdot H)/\nu; \]

- Full Lagrangian for \( b' \) in the DT model

\[ L_{b} := L_{\text{bKIN}} + L_{\text{bQCD}} + L_{\text{bQED}} + (L_{\text{bCC}} + H_{C}[L_{\text{bCC}}]) + (L_{\text{bNC1}} + L_{\text{bNC2}} + H_{C}[L_{\text{bNC2}}]) + (L_{\text{bH}} + H_{C}[L_{\text{bH}}]); \]

In a similar way we have written FeynRules files for \( t', \psi \) and \( e_8 \) Lagrangian terms to generate MadGraph5 model files. In the future we plan to make these model files public.
Appendix B

Preparation of Matched Signal

While generating the combined signal for $e^8$ and inclusive $Z$ background, we sometime face double counting of an event. This can happen when a process after parton showering is actually the same process at the partonic level. Double counting can be avoided by considering a matching scale. This scale $Q_{cut}$ determines whether a jet has come from parton showering (if the jet-$p_T$ is below $Q_{cut}$) or originated at the partonic level (if the jet-$p_T$ is above $Q_{cut}$). We match the matrix element partons with the parton showers using the shower-$k_T$ scheme \cite{135} in MadGraph5 with the matching scale $Q_{cut} \sim 50$ GeV. We choose appropriate matching scale $Q_{cut}$ for signal and background by looking at the smoothness of their differential jet rate distributions as shown in Fig. B.1 and B.2 respectively. The smoothness of the transition region indicates how good the choice of $Q_{cut}$ is. After varying $Q_{cut}$ from 25 GeV to 100 GeV, we find $Q_{cut}$ about 50 GeV is a good choice of matching scale for both the signal and background. We generate the combined signal including the different production processes as discussed in section 5.4 as follows

\[
\begin{align*}
pp & \xrightarrow{e^8} ee + 0\text{-}j \text{ (includes } P_{md}) \\
pp & \xrightarrow{e^8} ee + 1\text{-}j \text{ (includes } P_{md} + 1\text{-}j, P_{2Bs}) \\
pp & \xrightarrow{e^8} ee + 2\text{-}j \text{ (includes } P_{md} + 2\text{-}j, P_{2Bs} + 1\text{-}j, P_{pair}, P_{3Bs}^3) \\
pp & \xrightarrow{e^8} ee + 3\text{-}j \text{ (includes } P_{md} + 3\text{-}j, P_{2Bs} + 2\text{-}j, P_{pair} + 1\text{-}j, P_{3Bs}^3 + 1\text{-}j) \quad \text{(B.1)}
\end{align*}
\]
where $P_{\text{pair}}$, $P_{2B_s}$, $P_{3B_s}^3$ and $P_{\text{ind}}$ are the pair, two body single, three body single of third type (as defined in 5.3.3) and indirect production channels respectively. An elaborate discussion on matching is beyond the scope of this thesis, and we refer the reader to Ref. [135] and the references therein for more details on the matching scheme and the procedure.

![Graphs](image)

Figure B.1: Differential jet rate distributions for the combined signal with $M_{c\bar{s}} = 2$ TeV and $\Lambda = 5$ TeV at the 14 TeV LHC. Here we choose $Q_{\text{cut}} = 50$ GeV.
Figure B.2: Differential jet rate distributions for the inclusive $Z$ (includes $Z + 0, 1, 2, 3$ jets) background at the 14 TeV LHC. Here we choose $Q_{\text{cut}} = 50$ GeV.