ToolQit: Leptoquark Models and Limits

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We introduce the leptoquark (LQ) toolkit, TooLQit, which includes leading-order (LO) FeynRules models for all types of LQs and CaLQ, a Python-based calculator designed to estimate indirect limits on LQ parameters using high-energy dilepton data from the LHC. CaLQ can calculate the LHC limits on LQ couplings (even multiple couplings at once) for any mass values using a χ^2 method. The tool has a command-line interface and works in two modes: interactive and non-interactive. The interactive mode is useful for testing a few coupling values at specific masses, while the non-interactive mode can process a list of points. This allows users to scan parameter spaces or check if a given LQ parameter region meets experimental constraints. The non-interactive mode is especially helpful for confirming whether a parameter space allowed by other experiments also agrees with the LHC data. We demonstrate this with example scans for one- or two-coupling scenarios for the U_1 LQ. Our code is available at...

I. INTRODUCTION

Many beyond-the-Standard Model (BSM) scenarios (e.g., Pati-Salam model [1, 2], grand unified theories [3–5], quark-lepton compositeness [6, 7], coloured Zee-Babu models [8], technicolor models [9, 10] and R-parity-violating supersymmetric models [11], etc.) contain coloured scalar or vector bosons with nonzero lepton numbers in the TeV range. Depending on their weak representations, there are several possibilities for these scalar or vector particles, commonly called leptoquarks (LQs) [12–15]. All these are generally well-studied in the literature. Recently, LQs attracted significant attention mainly in the context of various experimental anomalies like the one observed in the ratios of B-meson semileptonic decays ($R_{D^{(*)}}$, which still exhibit a combined 3.3σ deviation from theoretical predictions [16]) or the anomalous magnetic moment of the muon $(g-2)_\mu$ [17], etc. There are other theoretical/phenomenological motivations for TeV-scale LQs as well. For example, they can explain baryon asymmetry via leptogenesis [18], enhance the production of uncoloured particles [19–21], play roles in Higgs physics [22–24], can act as a portal to dark matter [25, 26], can stabilise the electroweak vacuum [27], and have the potential to produce gravitational waves by inducing first-order electroweak phase transition [28], etc.

On the experimental side, these particles are well-explored. Since LQs simultaneously decay to quarks and leptons, their signatures are unique and, mainly because of the presence of leptons in the final states, the LHC experiments show good sensitivity towards most LQ models. Both CMS [29] and ATLAS [30] collaborations have dedicated search programs for LQs. They have extensively looked for signatures of LQ productions in various final states (like dilepton-dijet final states from LQ pair productions) and, so far, have put strong bounds on LQ parameters. The current mass exclusion bounds on scalar LQs from the pair production searches are within 1-2 TeV; for vectors, the limits are stronger by a few hundred GeVs.

Since, at the LHC, LQs are produced in pairs mainly via QCD interactions, these can be interpreted as model-independent lower bounds on LQ masses, assuming the unknown Yukawa couplings (LQ-quark-lepton) responsible for LQ decays are small enough not to affect their production cross section [31]. However, these new couplings are not small in various BSM scenarios. Hence, the new couplings may also contribute to the production processes [32]: large new couplings will contribute to the pair productions and open up new processes like single and indirect or non-resonant (i.e., t-channel LQ exchange and their

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interference with the SM background) productions [33–35]. The presence of LQs can also be inferred from other processes. For example, with order-one new coupling(s), TeV-range LQs will lead to observable shifts in the high-p_T tails of the dilepton or lepton+$\not{E}_T$ distributions. Hence, depending on the sizes of the new couplings, the LQ models can have better prospects and stricter limits [35–45]. The HL-LHC prospects for the LQ searches can be improved using boosted top signatures [46–48].

As the LHC records more and more data, its sensitivity towards BSM processes with small cross sections increases with improving statistics. Many processes that were difficult (or impossible) to probe with the data collected in the earlier runs will come within its reach. Hence, with the ongoing Run III, we need to ensure that the BSM signal simulations are not (unnecessarily) neglecting contributions that could be within the reach of the LHC at high luminosity. One way to do that will be to simulate signals at higher orders. For example, currently, various BSM processes can be simulated at the next-to-leading order (NLO) in QCD [49–51] (see Refs. [52–54] for LQ processes in particular). However, there is another possible direction for improvement. Some electroweak contributions, which can lead to observable effects, are ignored in current simulations. For example, in Ref. [44], we showed how the oft-ignored photon/Z-mediated LQ productions lead to noticeable shifts in the (model-independent) exclusion limits.

In this paper, we introduce TooLQit—a toolkit with FeynRules [55] models of all possible LQs for Monte Carlo simulations and an automatic calculator for the indirect limits on the Yukawa couplings of (some, at present) LQs from the current dilepton data. While the models are leading order (LO) at present, they include the electroweak vertices, including the photon/Z-gluon-LQ-LQ vertex (since LQs carry electric charges and are colour triplets, such a vertex is possible). For ease of use, we introduce a set of intuitive notations for the LQs and the new couplings. The calculator (CaLQ) is a Python code to calculate the indirect limits on the LQ-q-ℓ Yukawa couplings. Similar Mathematica-based LQ and SMEFT limit calculator HighPT utilizes the high-p_T dilepton and monolepton plus missing energy tails [56, 57]. Using this package, limits can be calculated only for the LQ mediator masses 1, 2 and 3 TeV. Currently, CaLQ contains the data for the two simplest LQ candidates. For two weak-singlet LQs—the charge-$1/3$ scalar S_1 and the charge-$2/3$ vector U_1—CaLQ can tell us if a parameter point (i.e., the mass of the LQ and a set of nonzero LQ-q-ℓ couplings) is excluded by the current dilepton data or not. It works on a χ^2 minimization—the method we developed in Ref. [35] (also [40]) and generalised in Ref. [42, 58].

In Section II, we explain our notations and describe the FeynRules models and in Section III, we describe the calculator.

II. LEPTOQUARK MODELS

As listed in Ref. [15], there are twelve possible renormalizable LQ models: six scalars (commonly referred to as $S_1, \widetilde{S}_1, \overline{S}_1, R_2, \widetilde{R}_2, S_3$) and six vectors ($U_1, \widetilde{U}_1, \overline{U}_1, V_2, \widetilde{V}_2, U_3$). Their $SU(2)_L$ structures are (in the EM charge basis) shown below (the superscripts show the electric charges).

$$
\begin{aligned}
&S_1 \equiv \left(S_1^{\frac{1}{3}}\right), \widetilde{S}_1 \equiv \left(\widetilde{S}_1^{\frac{4}{3}}\right), \overline{S}_1 \equiv \left(\overline{S}_1^{\frac{4}{3}}\right) \qquad R_2 \equiv \begin{pmatrix} R_2^{\frac{5}{3}} \\ R_2^{\frac{2}{3}} \end{pmatrix}, \widetilde{R}_2 \equiv \begin{pmatrix} \widetilde{R}_2^{\frac{2}{3}} \\ \widetilde{R}_2^{-\frac{1}{3}} \end{pmatrix} \qquad S_3 \equiv \begin{pmatrix} S_3^{4/3} \\ S_3^{1/3} \\ S_3^{-2/3} \end{pmatrix} \\
&U_1 \equiv \left(U_1^{\frac{2}{3}}\right), \widetilde{U}_1 \equiv \left(\widetilde{U}_1^{\frac{5}{3}}\right), \overline{U}_1 \equiv \left(\overline{U}_1^{-\frac{1}{3}}\right) \qquad V_2 \equiv \begin{pmatrix} V_2^{\frac{5}{3}} \\ V_2^{\frac{2}{3}} \end{pmatrix}, \widetilde{V}_2 \equiv \begin{pmatrix} \widetilde{V}_2^{\frac{2}{3}} \\ \widetilde{V}_2^{-\frac{1}{3}} \end{pmatrix} \qquad U_3 \equiv \begin{pmatrix} U_3^{5/3} \\ U_3^{2/3} \\ U_3^{-1/3} \end{pmatrix}
\end{aligned} \tag{1}
$$

The hypercharges are obtained by the Gell-Mann-Nishijima formula: $Q = T^3 + Y$ where T^3 is the third component of the weak-isospin.

Scalar Lagrangian: The kinetic Lagrangian of a generic scalar LQ Φ can be expressed as,

$$
\mathscr{L}_\Phi^{kin} = \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - M_\Phi^2 \Phi^\dagger \Phi, \tag{2}
$$

TABLE I. Yukawa interactions in up- and down-aligned scenarios for scalar and vector LQs excluding diquark interactions. Throughout the paper, a slightly modified yet more explicit notation for the Yukawa couplings is adopted.

LQ Model	Down-aligned Yukawa Interactions	Up-aligned Yukawa Interactions
S_1	$-y^{LL}_{1ij}\, \overline{d^C_L}^i \nu^j_L S_1 + (V^* y^{LL}_1)_{ij}\, \overline{u^C_L}^i e^j_L S_1 + y^{RR}_{1ij}\, \overline{u^C_R}^i e^j_R S_1$	$-(V^T y^{LL}_1)_{ij}\, \overline{d^C_L}^i \nu^j_L S_1 + y^{LL}_{1ij}\, \overline{u^C_L}^i e^j_L S_1 + y^{RR}_{1ij}\, \overline{u^C_R}^i e^j_R S_1$
$\widetilde{S}_1$	$\widetilde{y}^{RR}_{1ij}\, \overline{d^C_R}^i e^j_R \widetilde{S}_1$	
R_2	$-y^{RL}_{2ij}\, (\overline{u}^i_R e^j_L R_2^{5/3} - \overline{u}^i_R \nu^j_L R_2^{2/3})$ $+(V y^{LR}_2)_{ij}\, \overline{u}^i_L e^j_R R_2^{5/3} + y^{LR}_{2ij}\, \overline{d}^i_L e^j_R R_2^{2/3}$	$-y^{RL}_{2ij}\, (\overline{u}^i_R e^j_L R_2^{5/3} - \overline{u}^i_R \nu^j_L R_2^{2/3})$ $+y^{LR}_{2ij}\, \overline{u}^i_L e^j_R R_2^{5/3} + (V^\dagger y^{LR}_2)_{ij}\, \overline{d}^i_L e^j_R R_2^{2/3}$
$\widetilde{R}_2$	$-\widetilde{y}^{RL}_{2ij}\, (\overline{d}^i_R e^j_L \widetilde{R}_2^{2/3} - \overline{d}^i_R \nu^j_L \widetilde{R}_2^{-1/3})$	
S_3	$-y^{LL}_{3ij}\, \overline{d^C_L}^i \nu^j_L S_3^{1/3} - (V^* y^{LL}_3)_{ij}\, \overline{u^C_L}^i e^j_L S_3^{1/3}$ $-\sqrt{2} y^{LL}_{3ij}\, \overline{d^C_L}^i e^j_L S_3^{4/3} + \sqrt{2}(V^* y^{LL}_3)_{ij}\, \overline{u^C_L}^i \nu^j_L S_3^{-2/3}$	$-(V^T y^{LL}_3)_{ij}\, \overline{d^C_L}^i \nu^j_L S_3^{1/3} - y^{LL}_{3ij}\, \overline{u^C_L}^i e^j_L S_3^{1/3}$ $-\sqrt{2}(V^T y^{LL}_3)_{ij}\, \overline{d^C_L}^i e^j_L S_3^{4/3} + \sqrt{2} y^{LL}_{3ij}\, \overline{u^C_L}^i \nu^j_L S_3^{-2/3}$
U_1	$(V x^{LL}_1)_{1ij}\, \overline{u}^i_L \gamma^\mu \nu^j_L U_{1,\mu} + x^{LL}_{1ij} \overline{d}^i_L \gamma^\mu e^j_L U_{1,\mu}$ $+x^{RR}_{1ij}\, \overline{d}^i_R \gamma^\mu e^j_R U_{1,\mu} + x^{\overline{RR}}_{1ij}\, \overline{u}^i_R \gamma^\mu \nu^j_R U_{1,\mu}$	$x^{LL}_{1ij}\, \overline{u}^i_L \gamma^\mu \nu^j_L U_{1,\mu} + (V^\dagger x^{LL}_1)_{ij} \overline{d}^i_L \gamma_\mu e^j_L U_{1,\mu}$ $+x^{RR}_{1ij}\, \overline{d}^i_R \gamma^\mu e^j_R U_{1,\mu} + x^{\overline{RR}}_{1ij}\, \overline{u}^i_R \gamma^\mu \nu^j_R U_{1,\mu}$
$\widetilde{U}_1$	$\widetilde{x}^{RR}_{1ij}\, \overline{u_R}^i \gamma^\mu e^j_R \widetilde{U}_1$	
V_2	$-x^{RL}_{2ij}\, (\overline{d^C_R}^i \gamma^\mu \nu^j_L V^{1/3}_{2,\mu} - \overline{d^C_R}^i \gamma^\mu e^j_L V^{4/3}_{2,\mu})$ $+(V^* x^{LR}_2)_{ij}\, \overline{u^C_L}^i \gamma^\mu e^j_R V^{1/3}_{2,\mu} - x^{LR}_{2ij}\, \overline{d^C_L}^i \gamma^\mu e^j_R V^{4/3}_{2,\mu}$	$-x^{RL}_{2ij}\, (\overline{d^C_R}^i \gamma^\mu \nu^j_L V^{1/3}_{2,\mu} - \overline{d^C_R}^i \gamma^\mu e^j_L V^{4/3}_{2,\mu})$ $+x^{LR}_{2ij}\, \overline{u^C_L}^i \gamma^\mu e^j_R V^{1/3}_{2,\mu} - (V^\dagger x^{LR}_2)_{ij}\, \overline{d^C_L}^i \gamma^\mu e^j_R V^{4/3}_{2,\mu}$
$\widetilde{V}_2$	$-\widetilde{x}^{RL}_{2ij}\, (\overline{u^C_R}^i \gamma^\mu e^j_L \widetilde{V}_2^{1/3} - \overline{u^C_R}^i \gamma^\mu \nu^j_L \widetilde{V}_2^{-2/3})$	
U_3	$-x^{LL}_{3ij}\, \overline{d_L}^i \gamma^\mu e^j_L U^{2/3}_\mu + \sqrt{2} x^{LL}_{3ij}\, \overline{d_L}^i \gamma^\mu \nu^j_L U_3^{-1/3}$ $+(V x^{LL}_3)_{ij}\, \overline{u_L}^i \gamma^\mu \nu^j_L U^{2/3}_\mu + \sqrt{2}(V x^{LL}_3)_{ij}\, \overline{u_L}^i \gamma^\mu e^j_L U^{5/3}_\mu$	$x^{LL}_{3ij}\, \overline{u_L}^i \gamma^\mu \nu^j_L U^{2/3}_\mu + \sqrt{2} x^{LL}_{3ij}\, \overline{u_L}^i \gamma^\mu e^j_L U^{5/3}_\mu$ $+\sqrt{2}(V^\dagger x^{LL}_{3ij})\, \overline{d_L}^i \gamma^\mu \nu^j_L U_\mu^{-1/3} - (V^\dagger x^{LL}_3)_{ij}\, \overline{d_L}^i \gamma^\mu e^j_L U^{2/3}_\mu$

where

$$D_\mu = \partial_\mu - i g_s \frac{\lambda^a}{2} G^a_\mu - i g \frac{\sigma^k}{2} W^k_\mu - i g' Y B_\mu .$$

Here, g_s is the strong coupling constant, g and g' are the electroweak couplings, Y is the hypercharge (expanding the covariant derivative gives the $(\gamma/Z) g \Phi\Phi$ terms). The interaction Lagrangian for Φ can be written as,

$$\mathscr{L}^{int}_\Phi = y^L_{\Phi,ij} \left[\bar{q}^{i,a}_R \ell^j_L + \xi_\Phi \bar{q}'^{\,i,a}_R \nu^j_L \right] \Phi^a + y^R_{\Phi,ij}\, \bar{q}^{i,a}_L \ell^j_R \Phi^a + h.c., \tag{3}$$

where we do not consider the diquark interaction terms. Here, i and $j = \{1,\ 2,\ 3\}$ are the quark and lepton generation indices, respectively, a is the colour index, ξ_ϕ is either zero or ± 1, and, depending on the charge of LQ, q and q' is either a quark or a charge-conjugated quark.

Vector Lagrangian: We can write the kinetic Lagrangian for a generic vector LQ χ as,

$$\mathscr{L}^{kin}_\chi = -\frac{1}{2} \left(D_\mu \chi_\nu - D_\nu \chi_\mu \right)^\dagger \left(D^\mu \chi^\nu - D^\nu \chi^\mu \right) + M^2_\chi \chi^\dagger_\mu \chi^\mu + i g_s (1-\kappa) \chi^\dagger_\mu T^a \chi^\nu G^{\mu\nu a}, \tag{4}$$

where κ is the additional $g\chi\chi$ coupling. The interaction term for the vLQ χ is given as,

$$\mathscr{L}_\chi = x^L_{\chi,ij} \left[\bar{q}^{i,a}_L \gamma^\mu \ell^j_L + \xi_\chi\, \bar{q}'^{\,i,a}_L \gamma^\mu \nu^j_L \right] \chi^a_\mu + x^R_{\chi,ij}\, \bar{q}^{i,a}_R \gamma^\mu \ell^j_R\, \chi^a_\mu + \text{h.c.}, \tag{5}$$

where ξ_χ is either zero or ± 1.

Up/down-aligned Yukawa interactions: We show the LQ interactions in Table. I. Since one can assume the mixing among the left-handed quarks in the SM to be either in the up or down sectors, we consider two types of LQ Yukawa interactions where the LQ couples to the left-handed quarks: up-aligned, where LQ interactions are aligned with the up-type quarks (i.e., the mixing is among the down-type quarks) and

TABLE II. LQ notations and Monte Carlo codes in the `.fr` model files.

LQ types	FR notation	Monte Carlo codes
$S_1(\mathbf{3},\mathbf{1},\frac{1}{3})$	`s101`	4200011
$\widetilde{S}_1(\overline{\mathbf{3}},\mathbf{1},\frac{4}{3})$	`s114`	4200114
$S_3(\overline{\mathbf{3}},\mathbf{3},\frac{1}{3})$	`s304, s301, s302`	4200034, 4200031, 4200032
$R_2(\mathbf{3},\mathbf{2},\frac{7}{6})$	`r205, r202`	4200025, 4200022
$\widetilde{R}_2(\mathbf{3},\mathbf{2},\frac{1}{6})$	`r212, r211`	4200122, 4200121
$\overline{S}_1(\mathbf{3},\mathbf{1},-\frac{2}{3})$	`s122`	4210212
$U_1(\mathbf{3},\mathbf{1},\frac{2}{3})$	`u102`	4210012
$\widetilde{U}_1(\mathbf{3},\mathbf{1},\frac{5}{3})$	`u115`	4210015
$U_3(\mathbf{3},\mathbf{3},\frac{2}{3})$	`u305, u302, u301`	4210035, 4210032, 4210031
$V_2(\overline{\mathbf{3}},\mathbf{2},\frac{5}{6})$	`v201, v204`	4210021, 4210024
$\widetilde{V}_2(\overline{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	`v212, v211`	4210122, 4210121
$\overline{U}_1(\mathbf{3},\mathbf{1},-\frac{1}{3})$	`u121`	4210211

down-aligned, where LQ interactions are aligned with the down-type quarks (mixing is among the up-type quarks). For clarity, we show how the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements enter the Lagrangians through quark fields (in the mass basis):

$$\begin{aligned}
d'^{\,i}_L &= V_{ij} d_L{}^j, & u'^{\,i}_L &= V^\dagger_{ij} u^j_L, \\
\overline{d'_L}^{\,i} &= V^*_{ij} \overline{d_L}^{\,j}, & \overline{u'_L}^{\,i} &= V^T_{ij} \overline{u_L}^{\,j}, \\
d'^{Ci}_L &= V^*_{ij} d^{Cj}_L, & u'^{Ci}_L &= V^T_{ij} u^{Cj}_L, \\
\overline{d'^{C}_L}^{\,i} &= V_{ij} \overline{d'^{C}_L}^{\,j}, & \overline{u'^{C}_L}^{\,i} &= V^\dagger_{ij} \overline{u^{C}_L}^{\,j},
\end{aligned} \tag{6}$$

where V is the CKM matrix and the primed fields are in the interaction basis.

A. FeynRules models: notations and conventions

Naming convention: In the `.fr` (FeynRules [55]) files, the LQs are named according to the following convention (see Table II):

- First character is a letter. For scalar LQs, it is either a lowercase `s` (for $S_1, S_3, \widetilde{S}_1$, and $\overline{S}_1$) or an `r` (for R_2 and $\widetilde{R}_1$). Similarly, for vector LQs, the letter is either a lowercase `u` (for $U_1, U_3, \widetilde{U}_1$, and $\overline{U}_1$) or a `v` (for V_2 and $\widetilde{V}_2$).
- The next three characters are numbers. The first digit indicates whether the LQ is a singlet (1), doublet (2) or triplet (3) under $SU(2)_L$.
- The second digit is 1 if there is a tilde on top of the LQ symbol, 2 if there is a bar, and 0 if neither.
- The last digit is set equal to to $|3Q|$, where Q is the electric charge of the LQ.

Monte Carlo codes: We use a similar scheme for assigning Monte Carlo codes to the LQs.

- For all LQs, the first two digits are set to 42.
- The third digit is 0 if the LQ is a scalar and 1 if it is a vector.
- The fourth digit is kept free and set to 0.
- The fifth digit is 1 if there is a tilde on top of the LQ symbol, 2 if there is a bar, and 0 if neither.

- The sixth digit indicates the weak representation of the LQ species, i.e., it is 1 for a singlet, 2 for a doublet, and 3 for a triplet.

- The last digit is set equal to $|3Q|$.

In the `.fr` files, the particles are defined in the `M$ClassesDescription` block. We can consider the example of U_1:

```
M$ClassesDescription = {
V[100] == {
    ClassName        -> u102,
    SelfConjugate    -> False,
    Indices          -> {Index[Colour]},
    Mass             -> {Mu102, 1000},
    Width            -> {Wu102, 10},
    QuantumNumbers   -> {Q -> 2/3, LeptonNumber -> -1},
    PropagatorLabel  -> "u102",
    PropagatorType   -> Sine,
    PropagatorArrow  -> Forward,
    PDG              -> 4210012,
    ParticleName     -> "u102",
    AntiParticleName -> "u102~",
    FullName         -> "up-type vector LQ"
    },
V[110] == {
    ClassName      -> u10,
    Unphysical     -> True,
    Indices        -> {Index[SU2S], Index[Colour]},
    FlavorIndex    -> SU2S,
    SelfConjugate  -> False,
    QuantumNumbers -> {Y -> 2/3},
    Definitions    -> {u10[mu_,1,cc_] :> u102[mu,cc]}
  }
};
```

The default values of the mass and decay width of `V[100]` (i.e., U_1) are set to 1000 and 10 GeV, respectively. `V[110]` is a weak-singlet (set via a user-defined index `SU2S`) unphysical field defined to include the interactions of U_1 with the SM gauge bosons without explicitly writing them out in the Lagrangian.

LQ Yukawa couplings: We write a generic LQ Yukawa coupling in the following form,

$$y^{cd}_{ab,ij}/x^{cd}_{ab,ij},$$

where

- The symbol y denotes a scalar LQ and x, a vector.

- The superscripts $c,d = \{L,R\}$ denote the quark and lepton chiralities, respectively.

- The subscript a is 1 for a weak-singlet LQ, 2 for a doublet and 3 for a triplet.

- The next subscript b is 1 if there is a tilde symbol on top of the LQ symbol, 2 if there is a bar symbol and 0 otherwise.

- The subscripts i and j show the quark and lepton generations, respectively.

We can consider the example of U_1, for which the Yukawa coupling matrices take the form:

$$x_1^{LL} = \begin{bmatrix} x_{10,11}^{LL} & x_{10,12}^{LL} & x_{10,13}^{LL} \\ x_{10,21}^{LL} & x_{10,22}^{LL} & x_{10,23}^{LL} \\ x_{10,31}^{LL} & x_{10,32}^{LL} & x_{10,33}^{LL} \end{bmatrix}, \qquad x_1^{RR} = \begin{bmatrix} x_{10,11}^{RR} & x_{10,12}^{RR} & x_{10,13}^{RR} \\ x_{10,21}^{RR} & x_{10,22}^{RR} & x_{10,23}^{RR} \\ x_{10,31}^{RR} & x_{10,32}^{RR} & x_{10,33}^{RR} \end{bmatrix}. \tag{7}$$

The coupling, $x_{10,21}^{LL}$, couples the U_1 LQ with a second-generation quark and a first-generation lepton, and so on. In general, these Yukawa coupling matrices are complex. In the model files, the $x_{ab,ij}^{cd}/y_{ab,ij}^{cd}$ couplings are written as `XABCD[I,J]/YABCD[I,J]` in the `M$Parameters` block. For example, real + complex couplings models, one cross section plot?

```
M$Parameters = {
X10LL == {
        ParameterType    -> External,
        ComplexParameter -> False,
        Indices          -> {Index[Generation], Index[Generation]},
        BlockName        -> YUKU1LL,
        Value            -> {X10LL[1,1] -> 0.0, X10LL[1,2] -> 0.0, X10LL[1,3] -> 0.0,
                             X10LL[2,1] -> 0.0, X10LL[2,2] -> 0.0, X10LL[2,3] -> 0.0,
                             X10LL[3,1] -> 0.0, X10LL[3,2] -> 0.0, X10LL[3,3] -> 0.0},
        TeX              -> Superscript[Subscript[x,10],LL],
        InteractionOrder -> {QLD, 1},
        Description      -> "U1 leptoquark LL Yukawa coupling matrix"
}
};
```

The model files have the following interaction hierarchy:

```
M$InteractionOrderHierarchy = {
                               {QCD, 1},
                               {QED, 2},
                               {QLD, 3}
                              };
```

where `QLD` is for the LQ Yukawa (i.e., new-physics) couplings. The interaction and kinetic terms are included in the Lagrangian in the following manner (considering the example of the up-aligned U_1 model) [55]:

```
Lu1Kin := Block[{mu,nu,a,aa},
          ExpandIndices[-(1/2)(DC[u10bar[nu,a,aa],mu] - DC[u10bar[mu,a,aa],nu]).
          (DC[u10[nu,a,aa],mu] - DC[u10[mu,a,aa],nu])]];

Lu1int := X10LL[i,j] u102[mu,a] (CKM[i,k].dqbar[p,k,a].Ga[mu,p,q].
          ProjM[q,r].l[r,j] + uqbar[p,i,a].Ga[mu,p,q].ProjM[q,r].vl[r,j]) +
          X10RR[i,j] u102[mu,a] dqbar[p,i,a].Ga[mu,p,q].ProjP[q,r].l[r,j];

LBSM := Lu1Kin + Lu1int + HC[Lu1int];
```

The model files [in `.fr` and Universal Feynman Output (UFO) [59, 60] formats] are available from GitHub at https://github.com/rsrchtsm/LQ_Models. all authors

B. Producing U_1 at the LHC: Demonstration with MadGraph

For an illustration, we import the U_1 model UFO file [59, 60] into MadGraph5 [61] and generate the pair production process for U_1 at the LHC through the following command:

```
generate p p > u102 u102~ QCD=2 QED=0 QLD=2
```

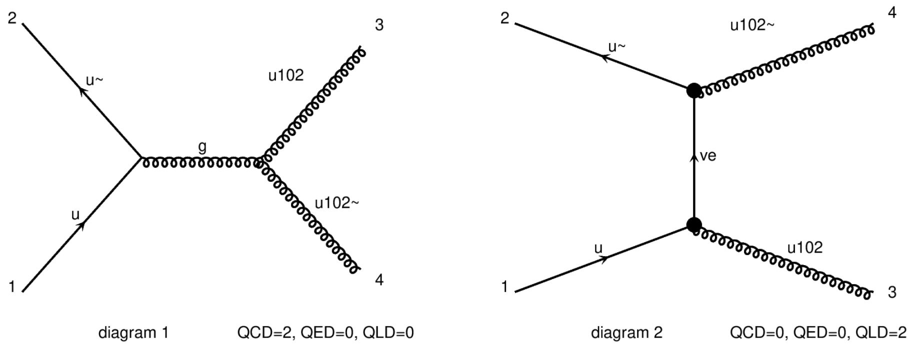


FIG. 1. U_1 pair production at the LHC: Examples of Feynman diagrams generated by MadGraph.

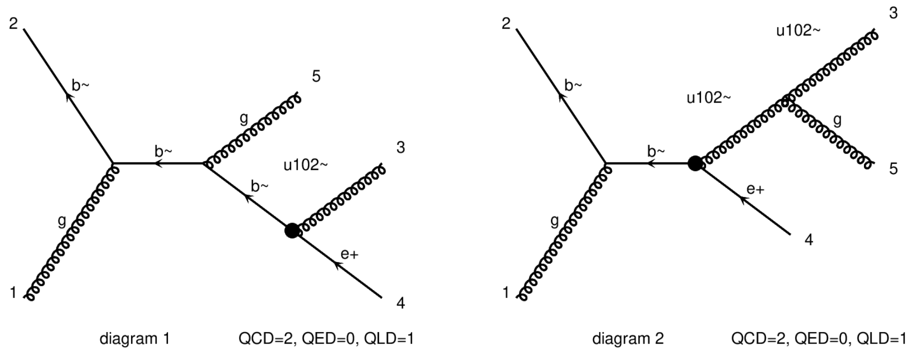


FIG. 2. Three-body single production of U_1 at the LHC: Examples of Feynman diagrams generated by MadGraph.

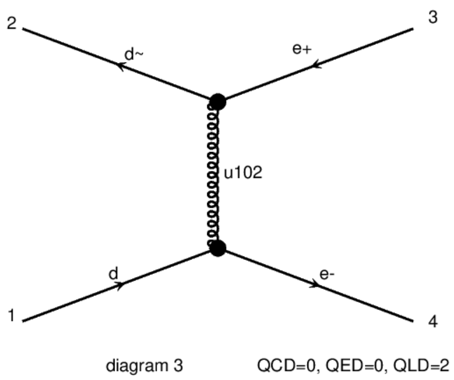


FIG. 3. Drell-Yan via U_1: Examples of Feynman diagrams generated by MadGraph.

which involves the QCD and LQ Yukawa couplings (see Fig. 1). The U_1 pair can be further decayed to symmetric and asymmetric final states:

$$U_1 U_1 \to \left\{ \begin{array}{lcl} & \text{Symmetric final states} & \\ (\ell j)(\ell j)/(\ell b)(\ell b) & \equiv & \ell\ell + 2j/2j_b \\ (j\nu)(j\nu)/(t\nu)(t\nu) & \equiv & 2j/2j_t + \not{E}_T \\ & \text{Asymmetric final states} & \\ (\ell b)\,(\ell j) & \equiv & \ell\ell + j_b + j \\ (\ell j/\ell b)\,(j\nu/t\nu) & \equiv & \ell + (jj)/(jj_b)/(j_t j)/(j_t j_b) + \not{E}_T \\ (t\nu)\,(j\nu) & \equiv & j_t + j + \not{E}_T \end{array} \right\}, \tag{8}$$

where $\ell = e, \mu, \tau$ and $j_b,\ j_t$ denote b and t jets, respectively. Similarly, we can generate the U_1 single production processes and the U_1-mediated dilepton processes including its interference with the Z/γ mediated Drell-Yan process in MadGraph5 at the LO.

III. CaLQ: CALCULATOR FOR (INDIRECT) LHC LIMITS

There are two main sources of LHC limits on LQ parameters [44]: direct searches and the high-P_T tails of the dilepton $\ell\ell$ data. `CaLQ` is a Python code that estimates whether the indirect LHC limits (i.e., from the high-P_T tails) from the dilepton data [62, 63] allow/exclude a point on the LQ parameter space. It is currently at the alpha stage. While the code is generic, it has only two models: the singlet scalar and vector LQ, namely, S_1 and U_1, and has no mixed-generation dilepton data. In the coming versions, We plan to introduce other common LQ models and the limits from mixed generation dilepton data and direct searches (see, e.g., Refs. [42, 44]). As mentioned in the Introduction, `CaLQ` follows the χ^2 minimisation and parameter limit estimation method described in Ref. [42] to obtain the indirect limits—it is essentially an automation of that technique.

The $\chi^2 = \chi^2(M_{LQ}, \vec{\lambda})$ function is estimated as,

$$\chi^2(M_{LQ},\vec{\lambda}) = \sum_{\ell\ell=ee,\mu\mu,\tau\tau} \chi^2_{\ell}(M_{LQ},\vec{\lambda}) = \sum_{\ell\ell}\sum_{b\in \text{bins}} \left(\frac{\mathcal{N}^b_{\text{Theory}}(M_{LQ},\vec{\lambda}) - \mathcal{N}^b_{\text{Data}}}{\Delta\mathcal{N}^b}\right)^2\Bigg|_{\ell\ell}, \tag{9}$$

where $\vec{\lambda} = \{x_i \text{ or } y_i\}$ denotes the set of nonzero LQ Yukawa couplings, and $\Delta\mathcal{N} = \sqrt{(\Delta\mathcal{N}_{stat})^2 + (\Delta\mathcal{N}_{syst})^2}$ is the error with the statistical error set as $\Delta\mathcal{N}^b_{stat} = \sqrt{\mathcal{N}^b_{\text{Data}}}$ as a first approximation and an overall systematic error, i.e., $\Delta\mathcal{N}^b_{syst} = \delta \times \mathcal{N}^b_{\text{Data}}$ with $\delta = 0.1$ (default value). The code uses the binned data from the HepData repository. For the $\tau\tau$ mode, it uses the transverse mass distributions from Ref. [62]. For the other leptons, it uses the dilepton invariant-mass distributions [63]. In the above relation, the expected number of events is estimated as

$$\mathcal{N}^b_{\text{Theory}}(M_{LQ},\vec{\lambda}) = \mathcal{N}^b_{\text{LQ}}(M_{LQ},\vec{\lambda}) + \mathcal{N}^b_{\text{SM}} = \left[\mathcal{N}^{pp}(M_{LQ},\vec{\lambda}) + \mathcal{N}^{sp}(M_{LQ},\vec{\lambda}) + \mathcal{N}^{ip}(M_{LQ},\vec{\lambda})\right]^b + \mathcal{N}^b_{\text{SM}}. \tag{10}$$

Here, $\mathcal{N}^{pp}(M_{LQ},\vec{\lambda})$, $\mathcal{N}^{sp}(M_{LQ},\vec{\lambda})$, and $\mathcal{N}^{ip}(M_{LQ},\vec{\lambda})$ are the numbers of events from LQ pair production (PP), single production (SP), and indirect production (IP; Drell-Yan, i.e., $qq \to \ell\ell$ via a t-channel LQ exchange and its interference with the SM $qq \to \ell\ell$ process) channels, respectively. For the calculator, we simulated these processes in MadGraph5 at the LO[1] with NNPDF2.3LO parton distributions [69] and the *dynamic renormalization and factorization scales* choice to estimate their contributions. The simulated events were passed through Pythia8 [70] for showering and hadronisation and were matched up to two jets using the `MLM` matching scheme [71, 72]. Then they were passed through Delphes [73] for detector effects. We used the anti-k_T [74] jet algorithm in FastJet [75] for forming the jets. We mimicked the selection criteria and cuts used in Refs. [62, 63] to analyse the `.root` files and obtain the resulting binwise efficiencies.

As shown in Appendix A of Ref. [42], the $\vec{\lambda}$-dependence of the BSM contributions can be parametrised simply. For example, $\mathcal{N}^{nr,\,b}(M_{LQ},\vec{\lambda})$ can be written as

$$\mathcal{N}^{ip,\,b}(M_{LQ},\vec{\lambda}) = \left\{\sum_i^n \lambda_i^2 \sigma_i^{ip_2}(M_{LQ}) \times \varepsilon_i^{ip_2,\,b}(M_{LQ}) + \sum_{i\geq j}^n \lambda_i^2\lambda_j^2 \sigma_{ij}^{ip_4}(M_{LQ}) \times \varepsilon_{ij}^{ip_4,\,b}(M_{LQ})\right\} \times \mathscr{L}, \tag{11}$$

where $\sigma_{ij}^{ip_4}(M_{LQ})$ is the t-channel LQ exchange contribution to the dilepton cross section calculated by setting $\lambda_i = \lambda_j = 1$ and $\lambda_{k\neq\{i,j\}} = 0$, $\sigma_i^{ip_2}(M_{LQ})$ is the interference contribution obtained by setting $\lambda_i = 1$ and $\lambda_{k\neq i} = 0$, the ε's are the corresponding signal efficiencies (the signal fractions surviving the cuts and the detector effects in bin b), and $\mathscr{L}$ is the luminosity. Here, we have assumed all couplings to be real for simplicity (the LHC data is largely insensitive to the complex nature of the couplings, anyway). For a particular value of M_{LQ}, the χ^2 is minimised in a n-dimensional space (where n is the number of nonzero new Yukawa couplings). From the minimum χ^2 value, the 1σ and 2σ parameter limits are estimated by calculating $\Delta\chi^2$. `CaLQ` uses interpolated cross sections and efficiencies from stored data files.

[1] For S_1, the QCD NLO corrections are known for the pair production process [52, 64–68]. To account for that, an average $k^{\text{NLO}}_{\text{QCD}}$ factor of 1.5 is included for this process. This value is editable. Also, for U_1, we have assumed zero contribution from the additional $g\chi\chi$ coupling, κ [see Eq. (4)].

A. Setting up the calculator

To get CaLQ, we can either

1. clone the repository **YC:** *"Upload repository on rsrchrtsm's github and update here"*

```
$ cd folder/to/clone/into/ # Go to folder location to download CaLQ
$ git clone https://github.com/atirek-ak/iCaLQ
$ cd CaLQ
```

   or

2. download the zip file from https://github.com/atirek-ak/iCaLQ/archive/refs/tags/1.0.0.zip and unzip it. **YC:** *"Upload repository on rsrchrtsm's github and update here"*

CaLQ is a PYTHON3 code. It is possible to use it in a virtual environment or directly. It depends on four packages: NUMPY, SCIPY, SYMPY, and PANDAS. The command

```
$ pip install numpy sympy scipy pandas
```

installs the required packages without a virtual environment. Otherwise, we can create a virtual environment:

```
$ python3 -m venv venv
$ source venv/bin/activate
$ pip install -r requirements.txt
```

CaLQ is now ready for use.

B. Running the calculator

There are two ways to use CaLQ: interactive and non-interactive.

Interactive mode: The interactive mode is useful for testing a few parameter points. Entering the following command takes us to the interactive mode.

```
$ python3 calq.py
```

The CaLQ logo appears (see Fig. 4). It is followed by a list of available input commands, the supported LQ models and some illustrative Yukawa couplings to show the format.

- ❑ `Couplings available`: The format of the coupling(s) are mentioned in Section. II A. The calculator-specific U_1 and S_1 couplings are listed below as matrices:

$$x_1^{LL} = \begin{bmatrix} \texttt{X10LL[1,1]} & \texttt{X10LL[1,2]} & \texttt{X10LL[1,3]} \\ \texttt{X10LL[2,1]} & \texttt{X10LL[2,2]} & \texttt{X10LL[2,3]} \\ \texttt{X10LL[3,1]} & \texttt{X10LL[3,2]} & \texttt{X10LL[3,3]} \end{bmatrix}, \tag{12}$$

$$x_1^{RR} = \begin{bmatrix} \texttt{X10RR[1,1]} & \texttt{X10RR[1,2]} & \texttt{X10RR[1,3]} \\ \texttt{X10RR[2,1]} & \texttt{X10RR[2,2]} & \texttt{X10RR[2,3]} \\ \texttt{X10RR[3,1]} & \texttt{X10RR[3,2]} & \texttt{X10RR[3,3]} \end{bmatrix}, \tag{13}$$

$$y_1^{LL} = \begin{bmatrix} \texttt{Y10LL[1,1]} & \texttt{Y10LL[1,2]} & \texttt{Y10LL[1,3]} \\ \texttt{Y10LL[2,1]} & \texttt{Y10LL[2,2]} & \texttt{Y10LL[2,3]} \\ - & - & - \end{bmatrix}, \tag{14}$$

$$y_1^{RR} = \begin{bmatrix} \texttt{Y10RR[1,1]} & \texttt{Y10RR[1,2]} & \texttt{Y10RR[1,3]} \\ \texttt{Y10RR[2,1]} & \texttt{Y10RR[2,2]} & \texttt{Y10RR[2,3]} \\ - & - & - \end{bmatrix}. \tag{15}$$

  The S_1 couples to a charged lepton along with an up-type quark. The current CaLQ does not put limits on the top-quark couplings (`Y10XX[3,J]`) as the top quark is essentially absent in the initial states.


```
File Edit View Search Terminal Help
$ python3 calq.py

            Calculator for LHC limits
                on leptoquarks

              * Version 1.0.0 *
Authors: (alphabetically) Arvind Bhaskar, Arijit Das,
         Atirek Kumar, Rachit Sharma, Subhadip Mitra,
         Tanumoy Mandal, and Yash Chaurasia

========================================================
Commands available:
 import_model:, mass=, couplings: , extra_width=,
 ignore_single_pair: (yes/no), significance=(1/2),
 systematic_error=, status, initiate, help
Couplings available:
 Examples for S1: Y10LL[1,1] Y10RR[2,3] [...]
 Examples for U1: X10LL[3,2] X10RR[1,1] [...]
Default values:
 import_model: U1
 mass = 1000
 couplings: X10LL[3,3]
 extra_width = 0
 ignore_single_pair: no
 significance = 2
 systematic_error = 0.1
========================================================
calq > import_model: S1
calq > mass= 1792.4
calq > couplings: Y10LL[2,2]
calq > status
 Leptoquark model: S1
 Leptoquark mass = 1792.4
 Couplings: Y10LL[2,2]
 Extra width = 0
 Ignore single & pair processes: no
 Significance = 2
 Systematic error = 0.1
calq > initiate
Y10LL[2,2] contributions calculated!!
Finding chi-square minima...
Minimum chi-square at values:
Y10LL[2,2] : 0.23307028263126972
Input coupling values in the following order:   Y10LL[2,2]
 > 0.3
Delta chi-square: 0.001431573461404767
Allowed: Yes

 > 3.0
Delta chi-square: 1100.8600175189251
Allowed: No

 > done
calq > exit
```

FIG. 4. Screenshot of `CaLQ` running in the interactive mode.

- `ignore_single_pair`: This command allows the user to ignore the resonant pair and single production contributions. For heavy LQs, the contribution from the resonant modes is small. Inputting '*yes*' or '*y*' will make `CaLQ` ignore the resonant contribution to evaluate the limits. This helps in speeding up the calculations. The default input is set to *no*.

- `significance`: Input 1 and 2, for 1σ and 2σ limits, respectively.

- `systematic_error`: the fractional systematic error, $\delta = \delta^b$ appearing in $\Delta\mathcal{N}^b_{syst}$ [Eq. (9)]. The default value is 0.1.

- `extra_width`: The indirect limits are largely independent of branching ratios (BRs). However, for a light LQ, the single and pair production processes contribute to the dilepton final states, which depend on the BRs. `CaLQ` estimates the relevant BRs automatically from the choice of Yukawa couplings and a hardcoded (approximate, LO) decay width expression. If, however, there is an additional decay mode, the user can add the extra width in GeV. The default value is 0 GeV.

The list is followed by a prompt, ‘`CaLQ >`’. Then the following inputs initialise the calculator.

- ❑ ‘`CaLQ > import_model=`’: the choice of LQ, ‘`S1`’ or ‘`U1`’.
- ❑ ‘`CaLQ > mass=`’: the mass of the LQ in GeV. Currently, the calculator computes the LHC bounds for LQs in the mass range 1000–5000 GeV.
- ❑ ‘`CaLQ > couplings=`’: the nonzero Yukawa couplings, each separated from the previous one by a space.
- ❑ ‘`CaLQ > initiate`’: initiates the calculator and computes the χ^2 and its minimum(minima) corresponding to the input values and coupling(s).

For instance, the inputs below will select a 1000 GeV U_1 in a two-coupling scenario.

```
CaLQ > import_model=U1
CaLQ > mass=1000.0
CaLQ > couplings=X10LL[1,1] X10LL[3,2]
CaLQ > initiate
```

Once initiated, the `CaLQ` prompt changes from ‘`CaLQ >` ’ to ‘`>` ’. We can now enter the values of the Yukawa couplings to be tested. The prompt accepts inputs in the form ‘`<f1> <f2>` ⋯ `<fn>`’ (`<f1>` to `<fn>` are floating point numbers, i.e., real and n is the number of Yukawa couplings, see Fig. 4). The couplings can be entered in the manner shown below:

```
> 0.1 0
> 0.37 0.0001
> 0.5 0.7
```

If there are multiple couplings, we can enter the couplings separated by a space. We enter the values of the couplings in the same order as the input couplings. Based on the $\delta\chi^2$, the allowed (disallowed) input Yukawa couplings within the 1σ or 2σ exclusion limits are displayed with a yes or no. Entering

```
> done
```

(or ‘`d`’, ‘`q`’, ‘`quit`’, ‘`exit`’) exits the query mode. The prompt then returns to the input mode, and input parameters show the previous values, which can be updated.

`CaLQ` also supports the following two commands:

- ❑ ‘`status`’: the user can see the current values entered as inputs.
- ❑ ‘`help`’: displays the list of commands available.

Finally, the command

```
CaLQ > exit
```

(or ‘`q`’, ‘`quit`’, ‘`.exit`’, ‘`exit()`’) stops the calculator.

Non-interactive mode: To use the calculator in the non-interactive mode, we use the tag `-ni` or `--non-interactive`:

```
$ python3 CaLQ.py -ni [options]
```

The `options` field takes the following inputs:

- ❑ `--help`: Display the help message (see Fig. 5).
- ❑ `--input-card=[filename]`: Takes a file with `.card` extension where we can specify the input parameters as follows:

  Line 1: Model name (e.g. `S1` or `U1`)

```
File  Edit  View  Search  Terminal  Help
$ python3 calq.py -ni --help
usage: calq.py [-h] [--non-interactive] [--no-banner]
               [--input-card INPUT_CARD] [--input-values INPUT_VALUES]
               [--output-yes OUTPUT_YES] [--output-no OUTPUT_NO]
               [--output-common OUTPUT_COMMON]

CaLQ Usage:

optional arguments:
  -h, --help            show this help message and exit
  --non-interactive, -ni
                        Run in non-interactive mode. This requires input-card
                        and input-values to be specified.
  --no-banner, -nb      CaLQ banner is not printed.
  --input-card INPUT_CARD
                        [filename]: Input card file. Format is explained in
                        README.md
  --input-values INPUT_VALUES
                        [filename]: Input values to check from the given file.
                        Format is explained in README.md
  --output-yes OUTPUT_YES
                        [filename]: Specify the name of output file (allowed
                        values) (overwrites the existing file). Default:
                        calq_yes.csv
  --output-no OUTPUT_NO
                        [filename]: Specify the name of output file
                        (disallowed values) (overwrites the existing file).
                        Default: calq_no.csv
  --output-common OUTPUT_COMMON
                        [filename]: Specify the name of output file
                        (overwrites the existing file). Default:
                        calq_common.csv
```

FIG. 5. The `CaLQ` help menu in the non-interactive mode.

Line 2: LQ mass in GeV
Line 3: Yukawa couplings (e.g., `X10LL[1,2] X10LL[2,2]`)
Line 4: `ignore_single_pair` (`yes` or `no`)
Line 5: `significance` (1σ or 2σ)
Line 6: `systematic_error`
Line 7: `extra_width`
Line 8: `random_points` [If `random_points` is set to zero, the user has to enter the Yukawa coupling values in a separate text file with the extension `--input-values=[filename]`. If one set `random points` as, say, "1000", the calculator generates 1000 random points between -3.5 and 3.5 as inputs to the Yukawa couplings. An example input card and an example `.vals` file are found in the `sample` directory, see Fig. 6]

- ❑ `--no-banner` or `-nb`: The `CaLQ` banner is not printed.

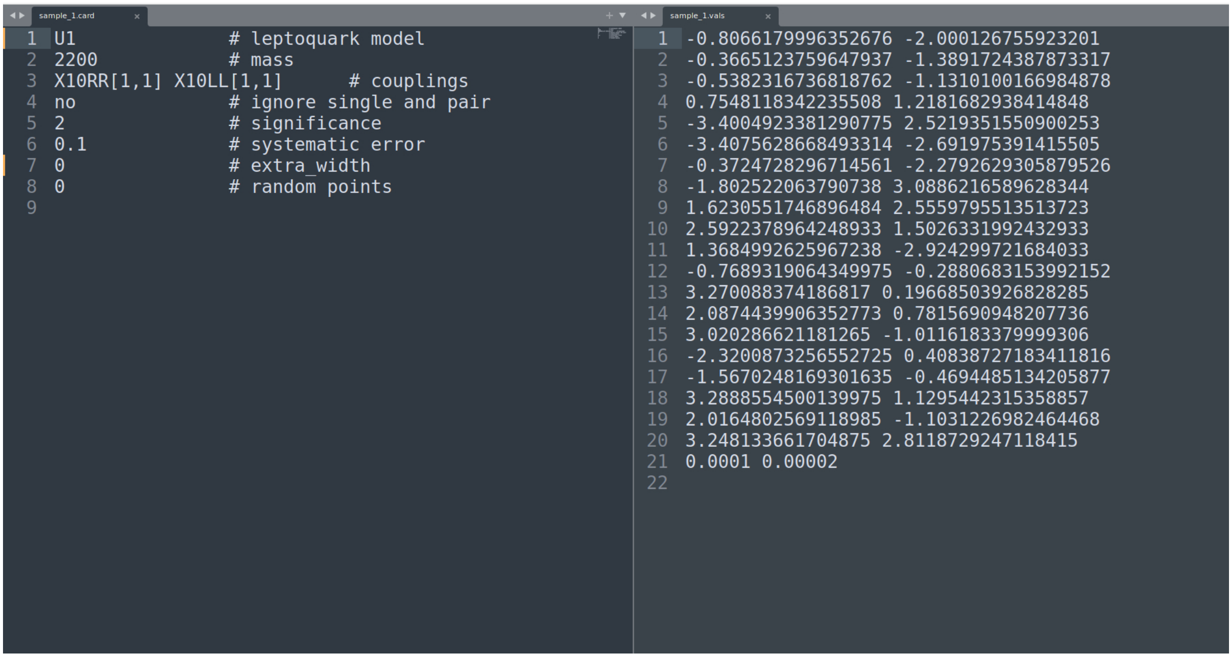
- ❑ `--output-yes=[filename]`: We specify the name of the output file containing allowed parameter points (overwrites any existing file). The default name of this output file is set as `calq_yes.csv`. Otherwise, in the field `filename` we can specify the path of the output file with a different name.

- ❑ `--output-no=[filename]`: Specify the name of the output file containing the disallowed parameter points (overwrites the existing file). The default name of this output file is set as `calq_no.csv`. Otherwise, in the field `filename` we can specify the path of the output file with a different name.

A sample bash script (`sample_1.sh`) is available in the calq folder. After suitably modifying the input parameters in the `.card` file, one can enter the desired couplings in the `.vals` file and run the bash file to obtain the output. The non-interactive mode relies on the input card and the query values. The output files are generated in the comma-separated-values (`.csv`) format in the order of the given couplings. The last number in a row shows the $\Delta\chi^2$ value for the particular parameter set. The `calq_yes.csv` and `calq_no.csv` files can be used for further analysis.

C. CaLQ workflow

Once the user provides the inputs, all fields are type-checked and confirmed to be valid/within the allowed ranges. If any of the fields are invalid, an error message is displayed. For instance:



```
sample_1.card
U1                # leptoquark model
2200              # mass
X10RR[1,1] X10LL[1,1]      # couplings
no                # ignore single and pair
2                 # significance
0.1               # systematic error
0                 # extra_width
0                 # random points
```

```
sample_1.vals
-0.8066179996352676 -2.000126755923201
-0.3665123759647937 -1.3891724387873317
-0.5382316736818762 -1.1310100166984878
0.7548118342235508 1.2181682938414848
-3.4004923381290775 2.5219351550900253
-3.4075628668493314 -2.691975391415505
-0.3724728296714561 -2.2792629305879526
-1.802522063790738 3.0886216589628344
1.6230551746896484 2.5559795513513723
2.5922378964248933 1.5026331992432933
1.3684992625967238 -2.924299721684033
-0.7689319064349975 -0.2880683153992152
3.270088374186817 0.19668503926828285
2.0874439906352773 0.7815690948207736
3.020286621181265 -1.0116183379999306
-2.3200873256552725 0.40838727183411816
-1.5670248169301635 -0.4694485134205877
3.2888554500139975 1.1295442315358857
2.0164802569118985 -1.1031226982464468
3.248133661704875 2.811872924711841 5
0.0001 0.00002
```

FIG. 6. Non-interactive inputs.

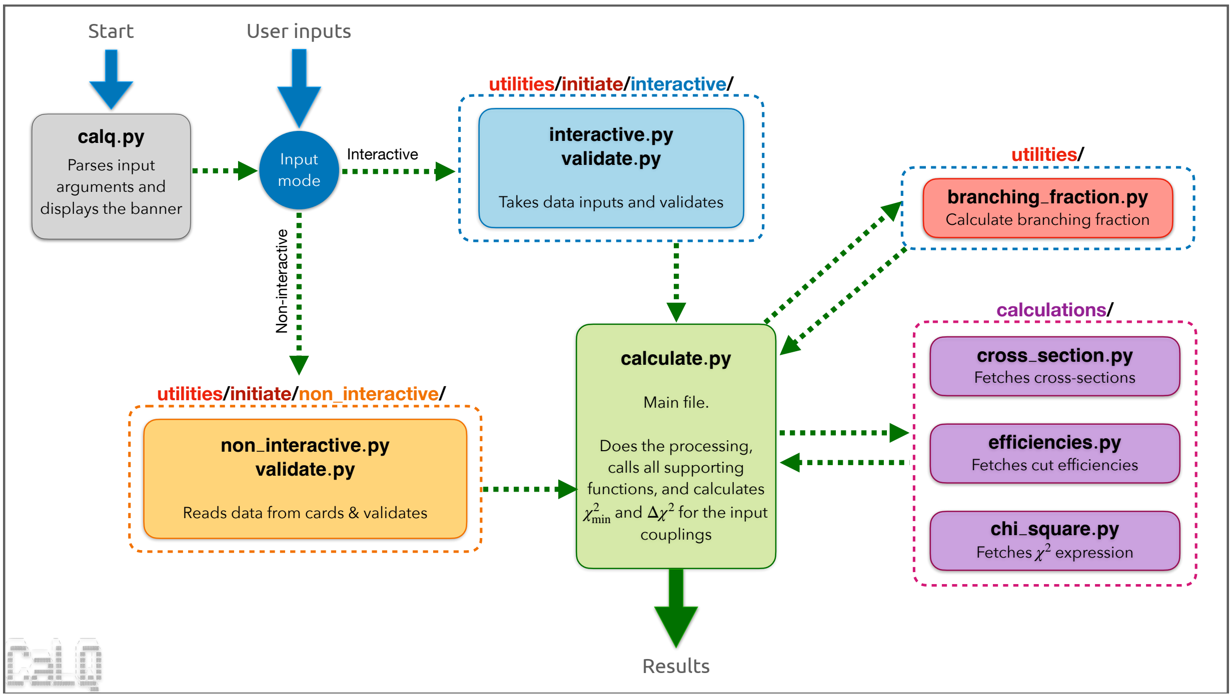


FIG. 7. The CaLQ codeflow.

```
$ [Model error]: Not a valid leptoquark model. Allowed models: ['S1', 'U1'].
```

or

```
$ [Mass error]: Leptoquark mass should be a valid number between 1000 and 5000.
```

or

```
$ [Coupling error]: The first letter should be Y for scalar leptoquarks and X, for
   vector leptoquarks. For valid format, please refer to README.md.
```

CaLQ processes the data after validating the inputs. It

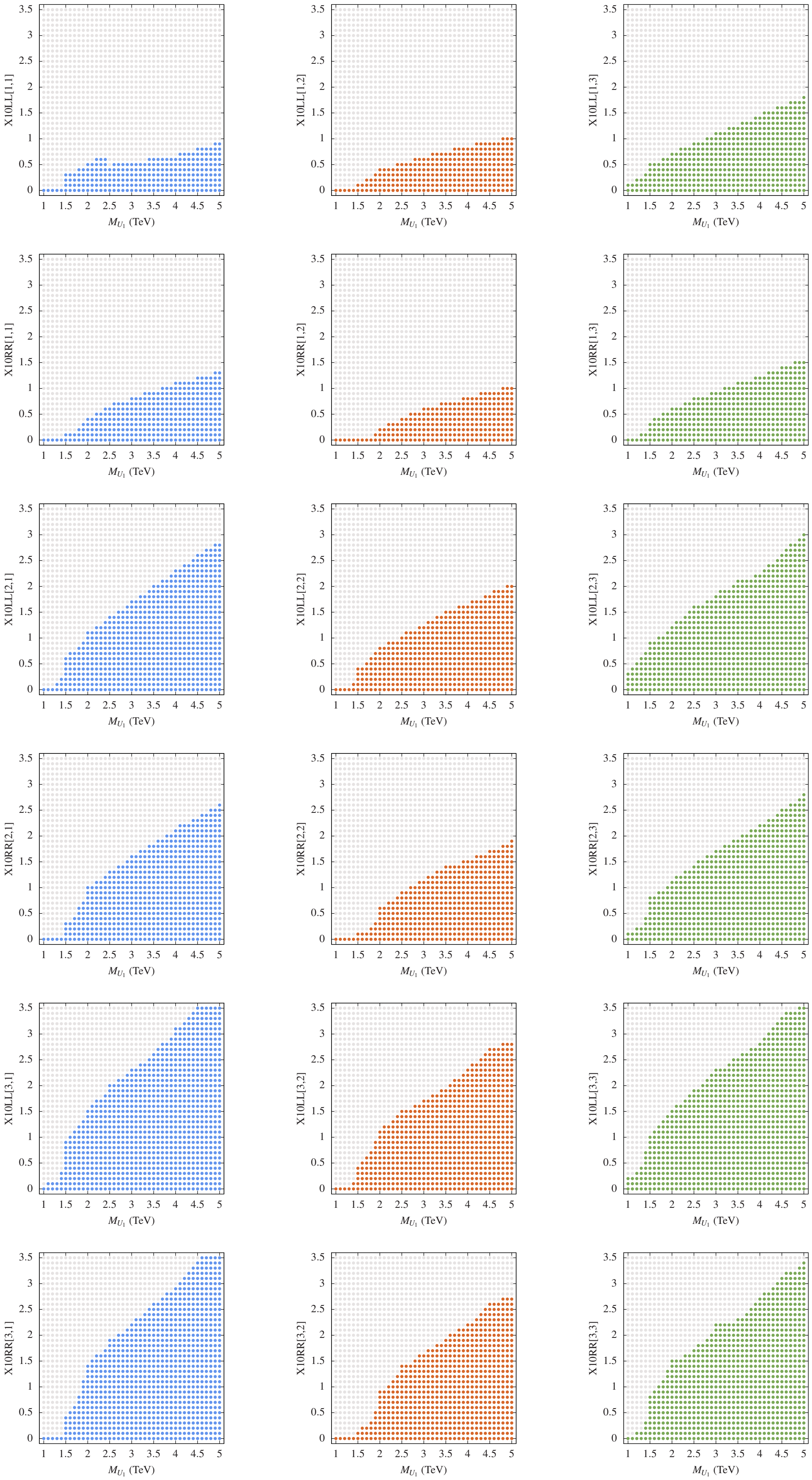


FIG. 8. Illustrative one-coupling scans for the U_1. The grey regions are ruled out at the 2σ level.

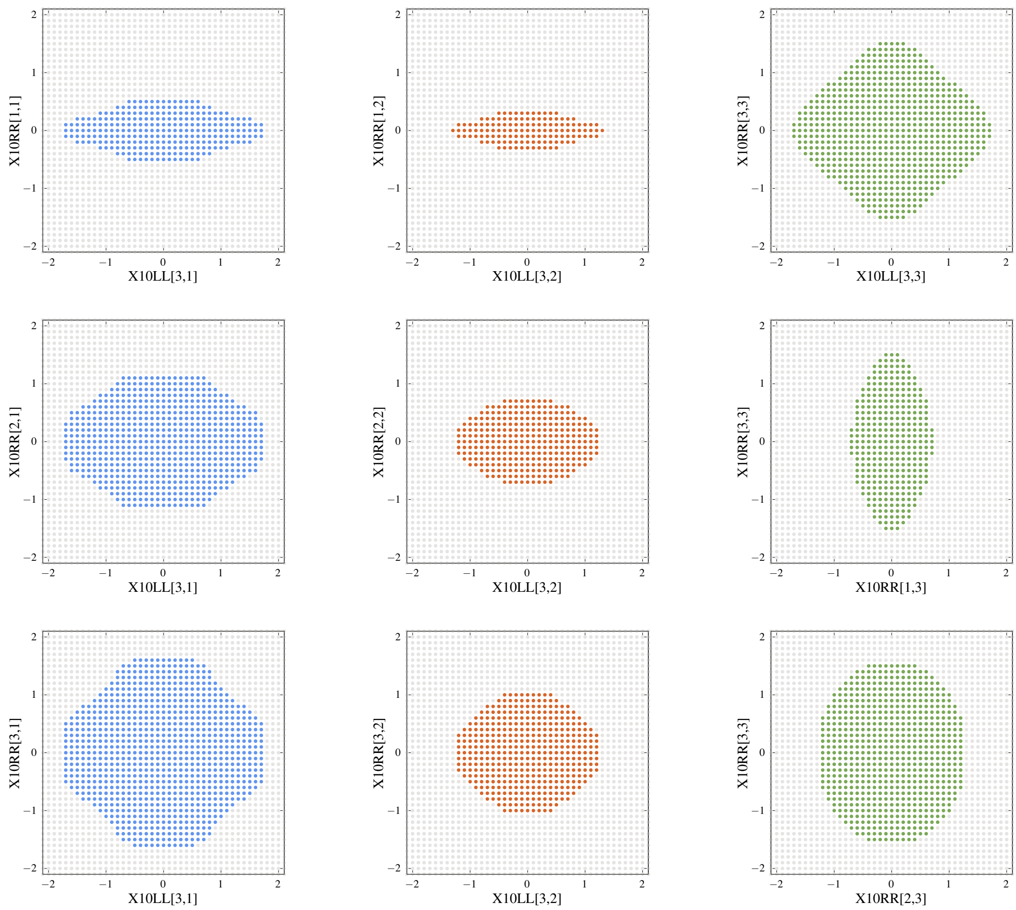


FIG. 9. Illustrative two-coupling scans for a 2250 GeV U_1. The grey regions are ruled out at the 2σ level.

sorts the Yukawa coupling values for reading multi-coupling data,

$\downarrow$

extracts the chirality and the lepton & quark generation information from the couplings,

$\downarrow$

and loads the production cross sections, binwise efficiencies and the observed dilepton data.

(cross sections and efficiencies are stored in steps of 250 GeV for $1 \leq$ LQ mass ≤ 5 TeV.)

After data validation, the code interpolates and calculates the cross sections and efficiencies for the entered LQ mass to form the χ^2 polynomial. It computes the ee, $\mu\mu$, and $\tau\tau$ contributions separately and adds them. It then looks for the global minimum using the `scipy.optimize()` function. The function is called with multiple starting points to prevent it from running into a local minimum. Once the minimum χ^2 is calculated, `CaLQ` calculates the χ^2 for the input couplings and estimates the corresponding $\Delta\chi^2$ to check whether the parameter point is within the allowed range (1σ or 2σ). If it is, the calculator outputs "`yes`", otherwise, it outputs "`no`". We show the codeflow in Fig. 7.

D. Demonstration: Limits on U_1 parameters

To demonstrate the outputs of `CaLQ`, we show the results of one-coupling scans with U_1 in Fig. 8. For these, we passed a coupling-mass grid (with step size $\{\Delta\lambda, \Delta M_{U_1}\} = \{0.1,\ 100\ \text{GeV}\}$) to `CaLQ` for each coupling and marked the allowed/not allowed points with different colours. In Fig. 9, we show some two-coupling scans. For these, we set the mass of U_1 at a random value, 2250 GeV and perform a two-coupling grid scan.

IV. CONCLUSION: SUMMARY, LIMITATIONS, AND OUTLOOKS

We introduce the LQ toolkit, `TooLQit`, which includes LO `FeynRules` models of all possible LQs and `CaLQ`, a calculator designed to estimate indirect limits from dilepton data. This comprehensive set of models and the accompanying calculator offer valuable resources for BSM phenomenology studies and future experimental searches at the LHC. LQs, being integral components of a wide range of BSM scenarios, are actively searched for in LHC experiments. `TooLQit` represents a foundational step towards consolidating various LQ-related computational tools onto a unified platform. This toolkit enables users to evaluate constraints on LQ models and explore their discovery potential at the LHC or other collider experiments. While the current version has certain limitations (detailed below), the fully open-source nature of the code provides users with flexibility and insights, allowing them to adapt and extend the tools for new/custom cases.

`TooLQit/FeynRules models:`

– The set contains all LQs listed in Refs. [12, 15]. The models follow a set of systematic and easy-to-follow notations/naming conversions (explained in Section II A). Apart from the `.fr` files and the Mathematica codes, we also provide the Universal FeynRules Output files suitable for MadGraph5.

– Currently, the models provided are at LO. While NLO QCD LQ models are already available in the literature (e.g., see Ref. [52]), the `TooLQit` LO models include interactions of LQs with electroweak gauge bosons, such as the mixed QCD-QED γ/Z-g-LQ-LQ vertex. These interactions can be significant in some scenarios (e.g., see Ref.[44]), especially when the EM charge of LQ is high.

– We are working on the NLO models, which we plan to include in the future. We also plan to cover new LQ states that interact with exotic fermions.

`TooLQit/CaLQ:`

– It is a Python package that automatically estimates the indirect LHC limits on the LQ-q-ℓ Yukawa couplings by a χ^2 estimation. It is based on the method we developed in Ref. [35] (applied in Ref. [40]) and generalised in Ref. [42].

– Currently, it is at the alpha stage: it contains the data for just the two LQ models. For two weak-singlet LQs (the charge-$1/3$ scalar S_1 and the charge-$2/3$ vector U_1), CaLQ can check whether a parameter point (i.e., the mass of the LQ—between 1 and 5 TeV—and a set of nonzero LQ-q-ℓ couplings) is allowed by the current dilepton (ee, $\mu\mu$, $\tau\tau$) data [62, 63].

– It has a command-line interface and works in two modes: interactive and non-interactive. The interactive mode is suitable for testing a few coupling points at specific mass values. The non-interactive mode is designed to handle a list of points, enabling users to run a scan or check whether a given LQ parameter region satisfies experimental constraints. The non-interactive mode is handy for evaluating whether a parameter space allowed by other experimental bounds is consistent with the LHC data.

– We plan to include support for all other single LQ models available in the literature in `CaLQ` as well as popular multi-LQ models such as $\tilde{R}_2 + S_1/S_3$ [76–78], $S_1 + S_3$ [79], etc. Since the code is modular and the χ^2 technique is generic, we also plan to enable custom model support where a user generates some specific processes to produce `.root` files, run some codes (which we supply) on these files and import the output in `CaLQ`.

– We plan to include the LHC data on monolepton plus missing energy (e.g., Refs. [80, 81]) and mixed-flavours dilepton searches (e.g., Ref. [82]). In addition to this, we plan to include the limits from the latest direct searches (e.g., as listed in Ref. [44]).

Compare with HighPT. licence

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