PROCEEDINGS OF SCIENCE

Third-Family Lepton-Quark Fusion

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We analyze the signatures of new physics scenarios featuring third-family quark-lepton unification at the TeV scale in lepton-quark fusion at hadron colliders. Working with complete UV dynamics based on the SU(4) gauge symmetry in the third-family fermions, we simulate the resonant production of a vector leptoquark at the next-to-leading order, including its decay and matching to the parton showers. The precise theoretical control over this production channel allows us to set robust bounds on the vector leptoquark parameter space which are complementary to the other production channels at colliders. We emphasize the importance of the resonant channel in future searches and discuss the impact of variations in the model space depending on the flavor structure of the vector leptoquark couplings.

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1. Introduction

The experiments probing the Standard Model (SM) at different energies impose considerable constraints on new physics (NP) models addressing the Higgs hierarchy problem at the TeV scale. These bounds depend strongly on the flavor structure of NP states: universal couplings to SM fermions push their mass into the multi-TeV range, while third-family-specific couplings allow for significantly lower mass limits, often below 1 TeV [1]. This non-universal structure may suggest a connection to the SM flavor puzzle and provides a potential solution to the hierarchy problem.

Recent studies have explored NP models featuring third-family quark-lepton unification within a non-universal gauge framework [2, 3]. Consistency with finite naturalness and experimental data favors models embedding into the 4321 gauge group, $\mathcal{G}_{4321} = SU(4)_3 \times SU(3)_{12} \times SU(2)_L \times U(1)_X$, where would-be third-family fermions are charged under the $SU(4)_3$ gauge group, while lighter families interact via $SU(3)_{12}$ [4, 5]. This framework predicts a TeV-scale vector leptoquark U_1, offering a compelling explanation for observed anomalies in semileptonic B-meson decays and neutral current interactions [6].

Experimental searches for leptoquarks at the LHC rely on pair production, single production, and non-resonant t-channel exchange [7], with additional interest in resonant production via lepton-quark fusion. While an earlier LO study analyzed the resonant production of U_1 [8], we improve upon it by computing NLO QCD + QED corrections, matching to `Herwig` [9] for proper lepton showering, and incorporating recent CMS search results [10] to set exclusion limits on the U_1 parameter space.

2. Summary of the model

The model is based on the $\mathcal{G}_{4321}$ gauge group with gauge bosons H^A_μ, C^a_μ, W^I_μ, and X_μ. The breaking to the Standard Model (SM) group $SU(3) \times SU(2)_L \times U(1)_Y$ is achieved via vacuum expectation values (VEVs) of scalars Ω_3 and Ω_1. This results in massive gauge bosons: the coloron (G'), the vector leptoquark (U_1), and a neutral boson (Z').

The mass eigenstates are given by the linear combinations:

$$\begin{aligned} G'^a_\mu &= c_3 H^a_\mu - s_3 C^a_\mu\,, \\ Z'_\mu &= c_1 H^{15}_\mu - s_1 X_\mu\,, \\ U^{1,2,3}_\mu &= \frac{1}{\sqrt{2}}(H^{9,11,13}_\mu - iH^{10,12,14}_\mu)\,. \end{aligned} \tag{1}$$

where the mixing angles are $\theta_1 = \arctan(\sqrt{2/3}\, g_1/g_4)$ and $\theta_3 = \arctan(g_3/g_4)$, with $c_{1,3} \equiv \cos\theta_{1,3}$ and $s_{1,3} \equiv \sin\theta_{1,3}$. The masses of the new states are given by

$$m_U = \frac{1}{2} g_4 f_U\,, \quad m_{Z',G'} = \frac{m_U}{c_{1,3}} \frac{f_{Z',G'}}{f_U} \tag{2}$$

where $f_U^2 = \omega_1^2 + \omega_3^2$, $f_{Z'}^2 = \frac{3\omega_1^2}{2} + \frac{\omega_3^2}{2}$, $f_{G'}^2 = 2\omega_3^2$, and $\omega_{1,3}$ denote the VEVs of $\Omega_{1,3}$.

We focus on the production of the U_1 leptoquark via lepton-quark fusion at hadron colliders, including next-to-leading order (NLO) corrections from gluon and photon interactions. The relevant interactions are described by the Lagrangian

$$
\begin{aligned}
\mathcal{L}_{U_1} \supset \frac{g_4}{\sqrt{2}} U_\mu \left(\beta_L^{i\alpha} \bar{q}_L^i \gamma^\mu \ell_L^\alpha + \beta_R^{i\alpha} \bar{q}_R^i \gamma^\mu \ell_R^\alpha + \text{h.c.}\right) \\
- i g_s U_\mu^\dagger T^a U_\nu G^{a,\mu\nu} - \frac{2}{3} i e\, U_\mu^\dagger U_\nu F^{\mu\nu} ,
\end{aligned}
\tag{3}
$$

where $G^a_{\mu\nu}$ and $F_{\mu\nu}$ are the gluon and photon field strength tensors respectively, and e is the QED coupling. The couplings to left- and right-handed fermions, β_L and β_R, are 3×3 matrices encoding the flavor structure of the U_1 interactions.

In the minimal model, U_1 couples mainly to third-family fermions, maintaining an exact $U(2)^5$ flavor symmetry [11, 12]. Upon the flavor symmetry breaking, additional entries of $\beta_{L,R}$ are populated, which are constrained by low-energy phenomenology [12–14]. The dominant production mechanism for U_1 is through $b + \tau$ collisions due to the suppressed couplings to lighter quarks.

3. U$_1$ Leptoquark Resonant Production

To precisely characterize the production of the U_1 vector leptoquark in lepton-quark collisions, we compute the Born cross-section and determine the next-to-leading order (NLO) contributions. Using the results of the analytical calculations, we develop a Monte Carlo generator based on [15], which utilizes a `POWHEG-BOX-RES` [16] implementation for event generation, followed by matching to `Herwig`.

The partonic Born cross-section for the process $q^i + \ell^\alpha \to U_1$ is

$$\hat{\sigma}_{\text{LO}} = \frac{g_4^2}{4} \left(|\beta_L^{i\alpha}|^2 + |\beta_R^{i\alpha}|^2\right) m_U^2 \,. \tag{4}$$

NLO QCD corrections include gluon-initiated production, $g(p_1) + \ell(p_2) \to q(k) + U_1(q)$, and soft-gluon emission, $q(p_1) + \ell(p_2) \to g(k) + U_1(q)$, with the averaged matrix-squared elements

$$\overline{|\mathcal{M}|}^2_{g\ell} = -\frac{1}{2} g_s^2 g_4^2 \, \frac{s(s^2 + t^2 + 2um_U^2)}{t(s+t)^2} \,, \tag{5}$$

$$\overline{|\mathcal{M}|}^2_{q\ell} = \frac{4}{3} g_s^2 g_4^2 \, \frac{u(u^2 + t^2 + 2sm_U^2)}{t(u+t)^2} \,, \tag{6}$$

where s , t, and u are the partonic-level Mandelstam variables defined as $s = (p_1 + p_2)^2$, $t = (p_1 - k)^2$, $u = (p_1 - q)^2$, and we kept only the U_1 mass m_U.

Virtual QCD corrections are detailed in [17], and the finite part computed in dimensional regularization for `POWHEG` is

$$\mathcal{V}_{\text{fin}} = \frac{2}{3} g_4^2 s \left(\frac{13}{12} - \frac{4\pi}{\sqrt{3}} + \frac{\pi^2}{2} - \frac{5}{2} L_R - \frac{1}{2} L_R^2 \right) , \tag{7}$$

where $L_R = \log(\mu_R^2/s)$, and μ_R is the renormalization scale.

QED corrections from photon-initiated processes contribute at the same order as QCD corrections [18], with the matrix element for $\gamma q \to \ell U_1$ given by

$$\overline{|\mathcal{M}|}^2_{\gamma q} = -e^2 g_4^2 \left(\frac{Q_\ell s + Q_q t}{s+t} \right)^2 \frac{s^2 + t^2 + 2u\, m_U^2}{st} \,. \tag{8}$$

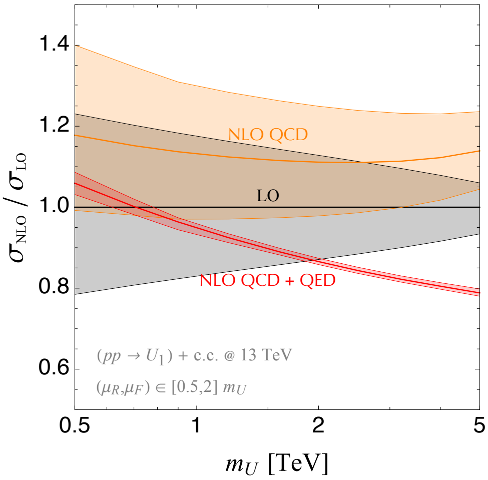

Figure 1: NLO K-factors for the resonant vector leptoquarks production at $\sqrt{s} = 13\,\text{TeV}$. The uncertainty bands were estimated using a seven-point scale variation of the factorization scale μ_F and the renormalization scale μ_R.

By integrating over the appropriate phase space and using the `LUXlep` PDF set [19], we can evaluate the K-factor, shown in Fig. 1. Additionally, implementing the results into a `POWHEG` model enables us to perform numerical estimates on the cross-section and derive relevant phenomenological bounds. Note, eqs. (5)–(8) should be multiplied by $(|\beta_L^{i\alpha}|^2 + |\beta_R^{i\alpha}|^2)/2$, and the sum over all quark and lepton flavor combinations participating in the production should be taken.

3.1 LHC Bounds

CMS search results targeting $b + \tau$ final states from a scalar leptoquark LQ$_s$ [10] allow us to constrain the coupling strength g_4 as a function of the leptoquark mass m_U. Using proton-proton collision data at $\sqrt{s} = 13$ TeV with an integrated luminosity of $\mathcal{L} = 138\,\text{fb}^{-1}$, we examine the efficiency of U_1 signal production compared to scalar leptoquarks. The efficiencies show minimal differences, expected from the experimental focus on resonance peaks.

Exclusion limits for the scalar leptoquark coupling λ are available on `HEPData` [10]. These limits can be translated to the vector leptoquark case, taking appropriately into account the relation between the couplings and the differences in the widths of the leptoquarks.

Figure 2 presents the exclusion bounds for the U_1 resonant production, comparing different production mechanisms. To this end, we employ `POWHEG` to compute the U_1 production cross section at NLO, assuming the leptoquark couples only to third-family fermions. We analyze two cases: $|\beta_L^{33}| = |\beta_R^{33}| = 1$ and $|\beta_L^{33}| = 1, |\beta_R^{33}| = 0$, resulting in fixed branching ratios of 68% and 50%, respectively. The exclusion bounds are competitive with other production mechanisms, especially for $g_4 \gtrsim 1$. The resonant production channel outperforms the single production mechanism, and the bounds improve differently with luminosity.

Finally, we observe that phenomenologically allowed deviations from the minimal model have a negligible effect on the derived bounds. For example, a fit to low-energy observables in [7] suggests a value of $\beta_L^{23} \simeq 0.2$, leading to an additional production channel for the U_1 leptoquark. We found that including this contribution from $s + \tau$ collisions results in a small improvement of

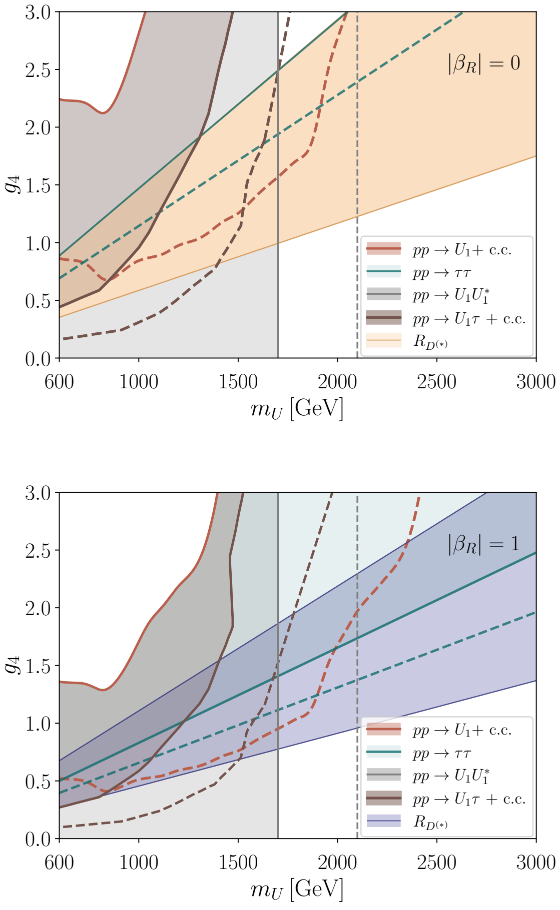

Figure 2: Excluded parameter space at 95% CL for the U_1 resonant production from the observed limits, indicated by the red shaded region, in comparison to other production mechanisms. The bounds from $pp \to \tau\tau$ at 137 fb^{-1} derived by CMS [20], are depicted by the solid green line. The brown area is the excluded parameter space from the single leptoquark production [21]. The gray line corresponds to the exclusion limits set by the leptoquark pair production $pp \to U_1 U_1^\dagger$ [20]. The dashed lines represent the expected bounds, projected to 3 ab^{-1} for the c.o.m. energy $\sqrt{s} = 14$ TeV and follow the same color coding. In the top (bottom) panel, $|\beta_R^{33}|$ is set to zero (one), whereas $|\beta_L^{33}|$ equals 1 in both cases.

about 2.5 % in the exclusion bounds. In the case of other couplings, the situation worsens, as the PDF enhancement for lighter quarks cannot offset the additional coupling suppression dictated by the model's $U(2)^5$ protection and strong constraints on light-family U_1 couplings. Therefore, the reported bounds are robust and applicable to a broad range of models based on the $\mathcal{G}_{4321}$ gauge group.

4. Conclusions

The main objective of this work is to give a precise analysis of a direct $b + \tau$ fusion producing a vector leptoquark at the LHC. Such a state is part of the spectrum of NP constructions that feature third-family quark-lepton unification.

After describing the gauge boson dynamics, we presented the results of NLO QCD + QED corrections for the partonic processes contained in $pp \to U_1$. Following the implementation of the NLO results into `POWHEG`, together with the utilization of the parton + lepton showering algorithm offered by `Herwig`, we have effectively constructed a Monte Carlo event generator for this production channel. It can be obtained from the following Github repository [22].

Based on our findings, we were able to translate the CMS exclusion bounds for the scalar leptoquarks to the case of the U_1. Despite the limiting exclusion power of the lepton-quark fusion channel at present, we have demonstrated that this channel will be prominent during the HL-LHC phase. Owing to the resonant enhancement, the limits on the U_1 leptoquark parameter space from the lepton-quark fusion are more sensitive to luminosity and the center-of-mass energy improvements than the limits from the other channels, resulting in their full complementarity in Fig. 2. Our work provides the necessary ingredients on the theoretical side to make the best use of this, opening the possibility of performing the first experimental search for the U_1 vector leptoquark in the lepton-quark fusion channel.

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