Production and decay of vector-like fermions at LHC

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Standard Model

- Relativistic QFT describing electromagnetic, weak and strong interactions of the elementary particles

- Excellent consistent explanation compatible with the experimental data

However…

- Does not include gravitational interaction

- Does not explain dark matter and dark energy

- Neutrino masses

- Anomalies in the experimental data

B-Physics anomalies

Recent data on B meson decays shows a violation of a key SM prediction: Lepton Flavour Universality:

$$R_{K^{(*)}} = \frac{\mathscr{B}\left(B \to \bar{K}^{(*)}\mu^+\mu^-\right)}{\mathscr{B}\left(B \to \bar{K}^{(*)}e^+e^-\right)}$$

$$R_{D^{(*)}} \equiv \frac{\mathscr{B}\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}\right)}{\mathscr{B}\left(B \to D^{(*)}\ell^-\bar{\nu}\right)}$$

3.1σ deviation from SM!

Indication on Physics Beyond SM: EFT approach singles out a TeV scale leptoquark mediator to explain the anomaly

Among other leptoquark solutions the most successful mediator able to explain both the anomalies at the same time is a $U_1 = (\mathbf{3}, \mathbf{1}, +2/3)$.

UV model: 4321 model

- Gauge group: $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_X$
- Non-universal gauge couplings: U_μ, Z'_μ, G'_μ couple mostly to the third family

$$\psi_L = \begin{pmatrix} q_L'^3 \\ l_L'^3 \end{pmatrix}, \ \psi_R^+ = \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix}, \ \psi_R^- = \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix}$$

Vector like fermions:

$$\chi_L = \begin{pmatrix} Q_L' \\ L_L' \end{pmatrix}, \ \chi_R = \begin{pmatrix} Q_R \\ L_R \end{pmatrix}$$

RH neutrino ν_R^3 as a part of the $SU(4)$ multiplet

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
ψ_L	**4**	**1**	**2**	0
ψ_R^+	**4**	**1**	**1**	1/2
ψ_R^-	**4**	**1**	**1**	−1/2
$q_L'^i$	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
$\ell_L'^i$	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1
χ_L	**4**	**1**	**2**	0
χ_R	**4**	**1**	**2**	0
H	**1**	**1**	**2**	1/2
Ω_3	$\overline{\mathbf{4}}$	**3**	**0**	1/6
Ω_1	$\overline{\mathbf{4}}$	**1**	**0**	−1/2

Matter content

Vector-like fermions

After the 4321 -> SM symmetry breaking:

- generate interaction of light fermion families with the leptoquark
- generate the correct structure for the SM fermion masses and quark mixings

After the EW symmetry the new SU(4) charged fields modify the LH and RH EW current, e.g.:

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \begin{pmatrix} \bar{b}_R & \bar{B}_R \end{pmatrix} (\gamma^\mu W_\mu^-) \begin{pmatrix} o(\frac{v^2}{M_Q^2}) & -\frac{Y_-^q v}{\sqrt{2} M_Q} \\ -\frac{Y_+^q v}{\sqrt{2} M_Q} & 1 \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix} + g \begin{pmatrix} \bar{t}_R & \bar{T}_R \end{pmatrix} (\gamma^\mu Z_\mu) \begin{pmatrix} o(\frac{v^2}{M_Q^2}) & -\frac{Y_+^q v}{\sqrt{2} M_Q} \\ -\frac{Y_+^q v}{\sqrt{2} M_Q} & 1 \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix}$$

$$Y_-^q \sim Y_b \sim Y_\tau \sim O(10^{-2})$$

$$Y_+^q \sim Y_t \sim Y_\nu \sim O(1)$$

Phenomenology of VL fermions

- Interesting phenomenology since the VL lepton mass is constrained by the anomaly to be around 1 TeV

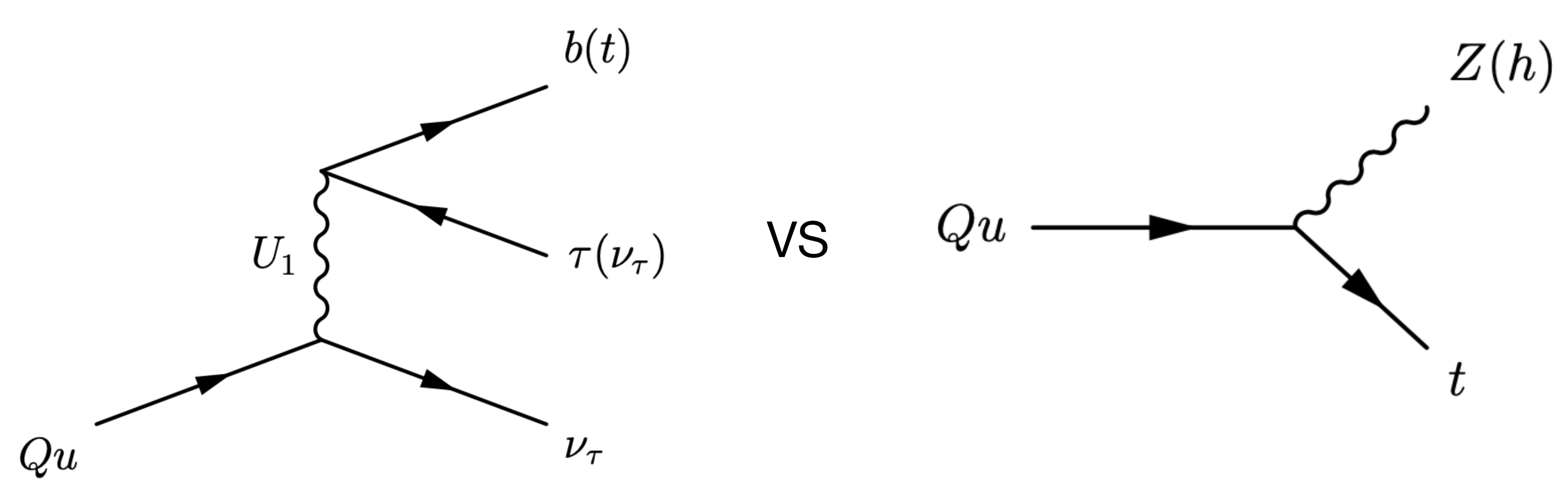
- VL quarks could be very heavy, but this scenario is unfavourable from the viewpoint of quark lepton unification

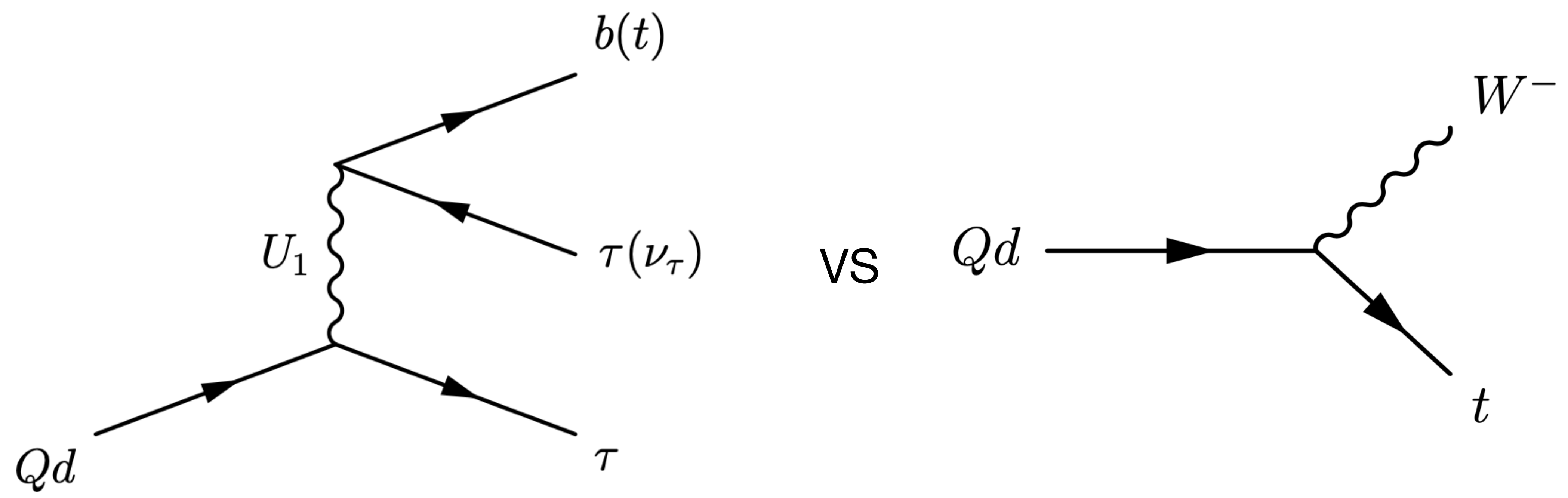
  Until now it has been assumed in the literature:

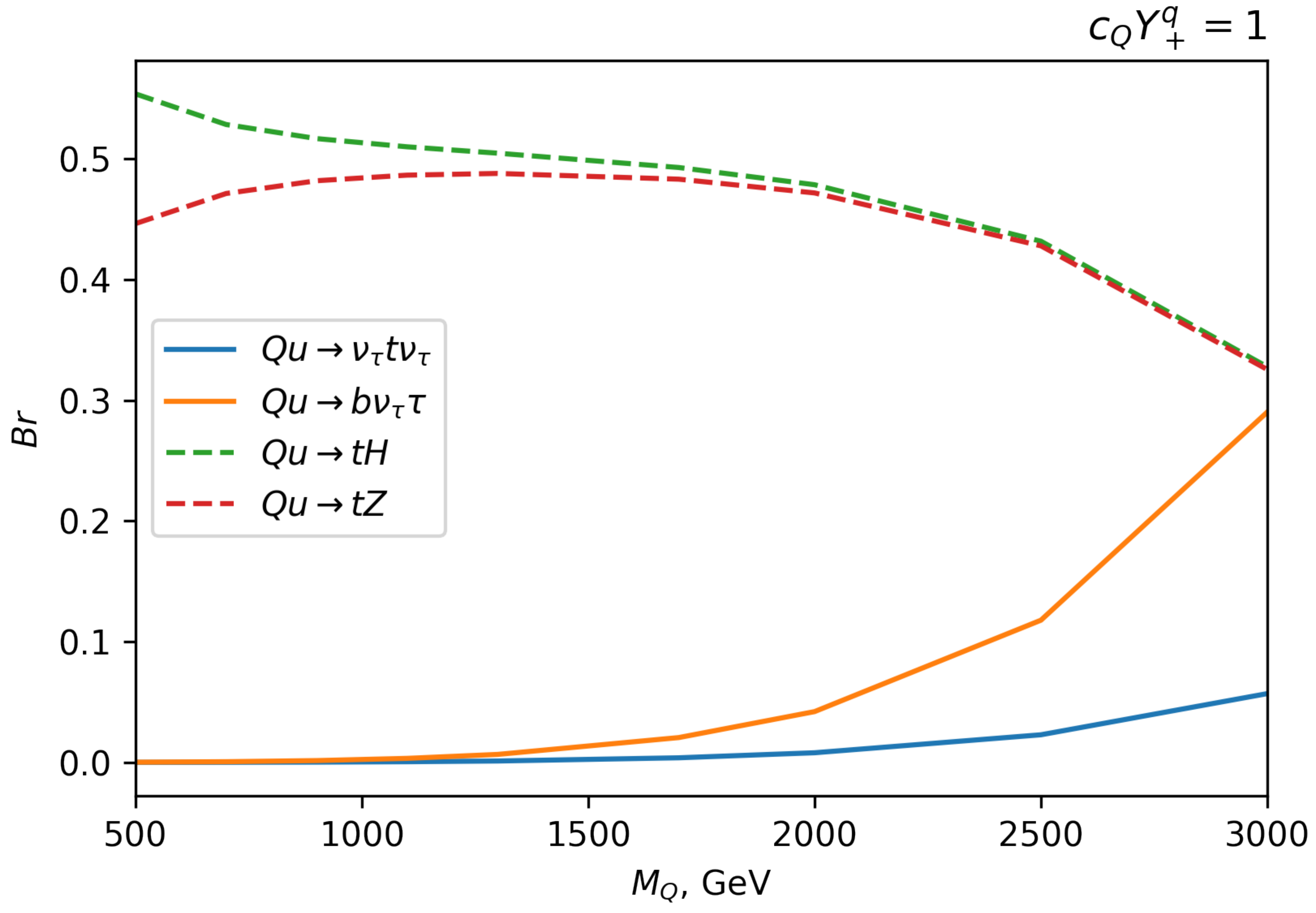
- Main decay channel is a 3 body decay via new heavy mediators

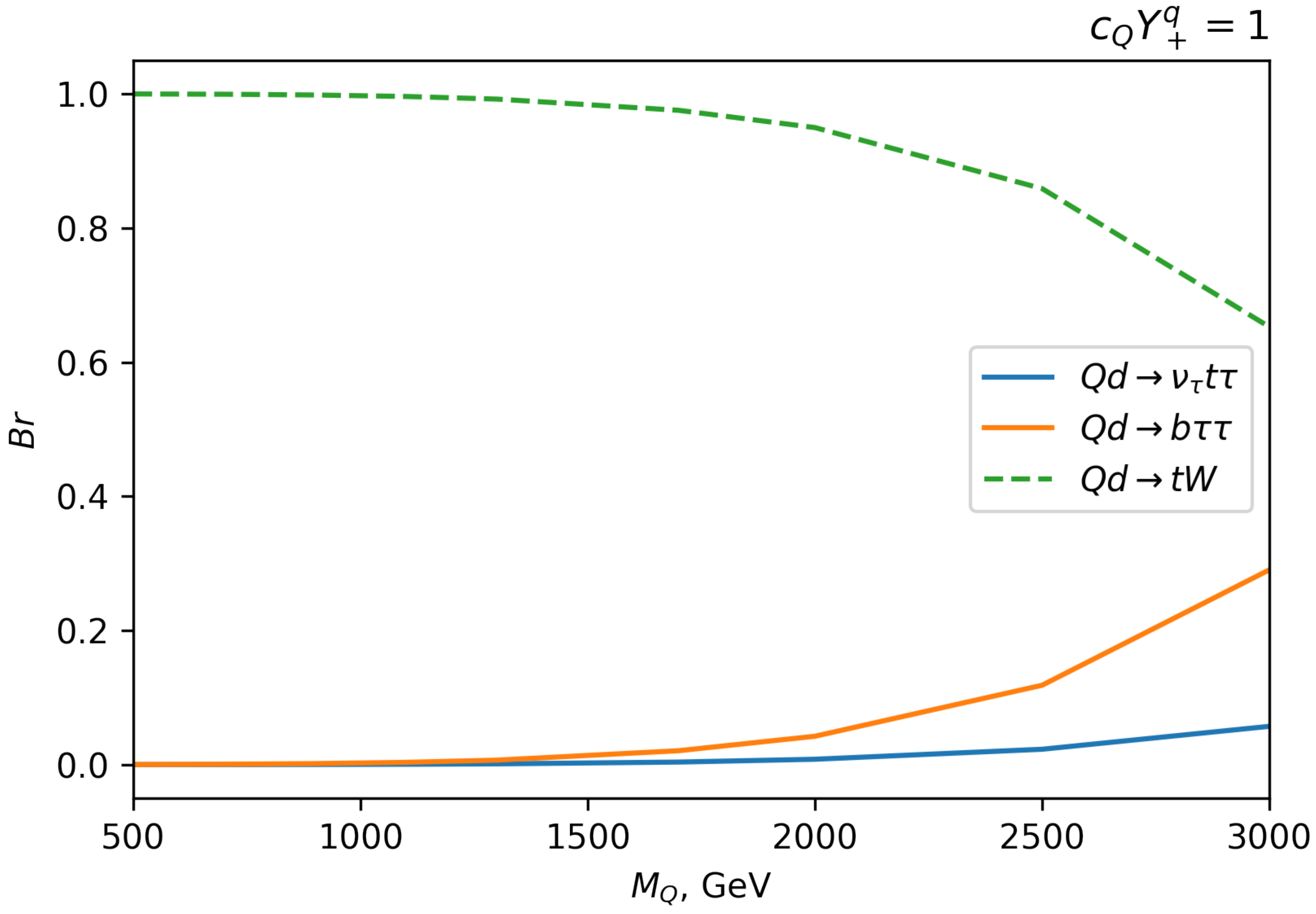
- Main production channel: pair production via new heavy mediator

Decay channels of the vector-like quarks









Decay channels of the vector-like leptons

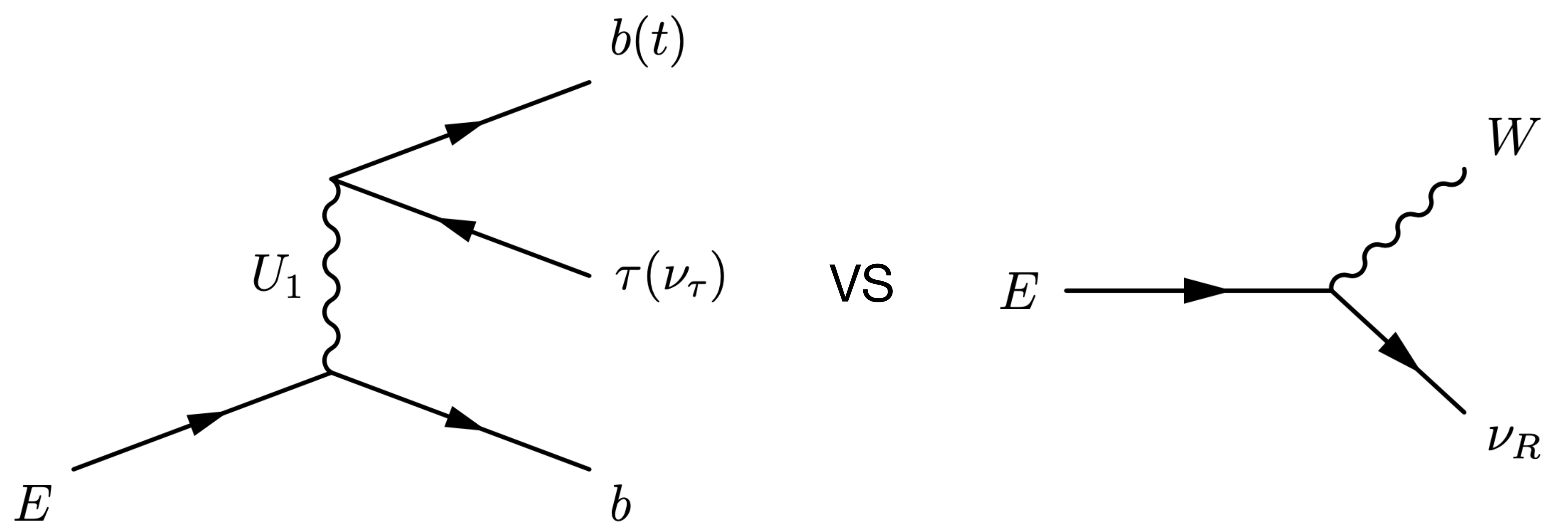
More involved because RH neutrino enter the game

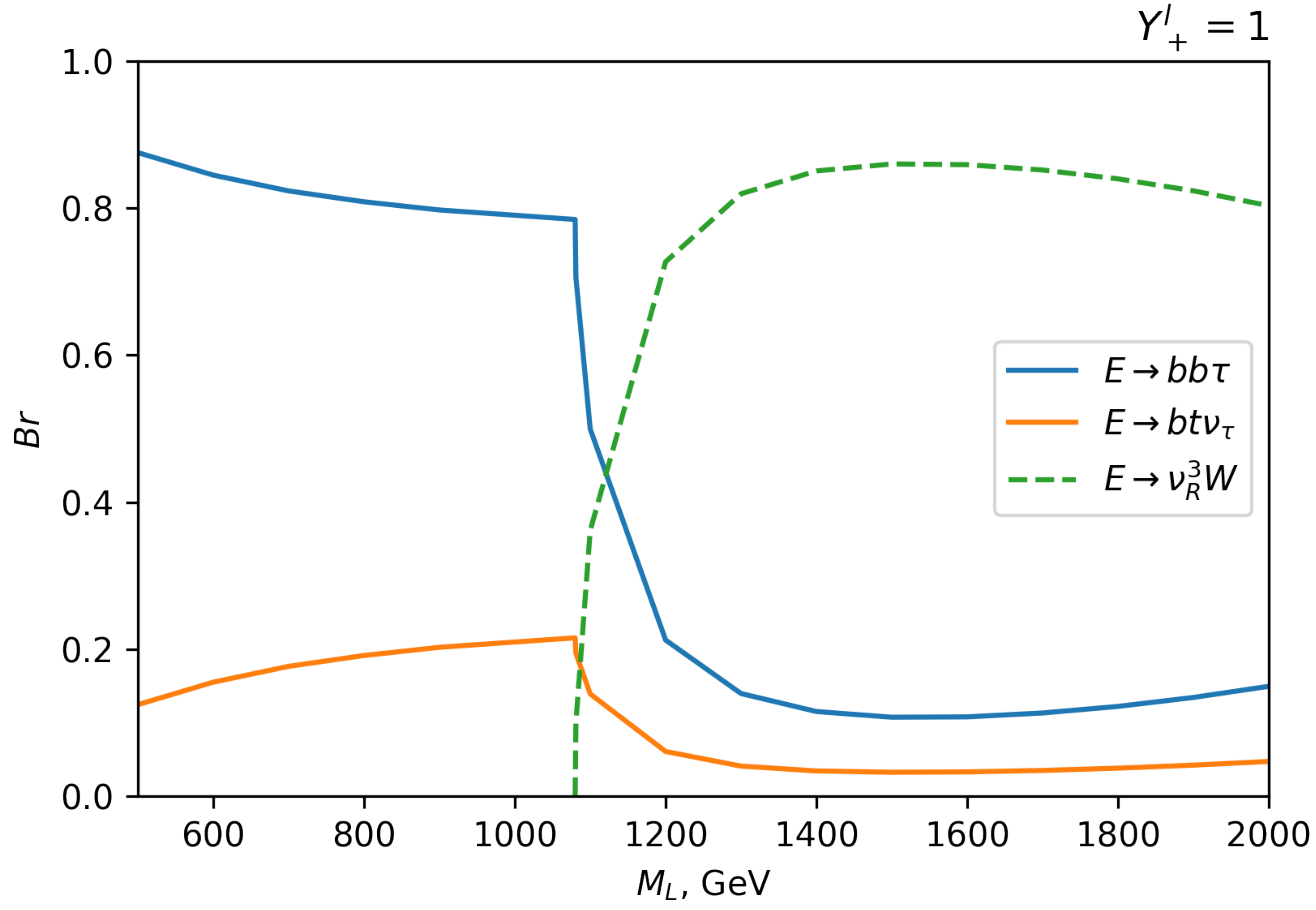
RH neutrino cannot have a Majorana mass in this model since they are a part of $SU(4)$ multiplet with the top quark
$\Rightarrow$ seesaw mechanism is not allowed

Solution: Inverse seesaw $\Rightarrow$ TeV scale RH neutrino masses

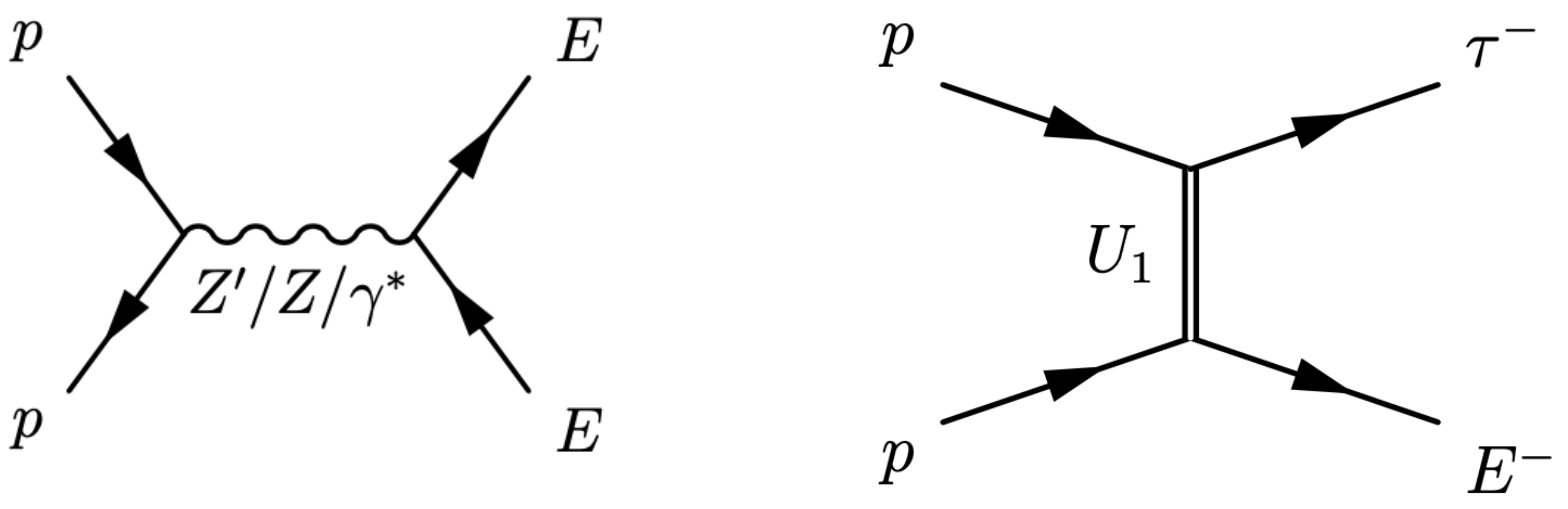
In the case of $m_R > M_L$:

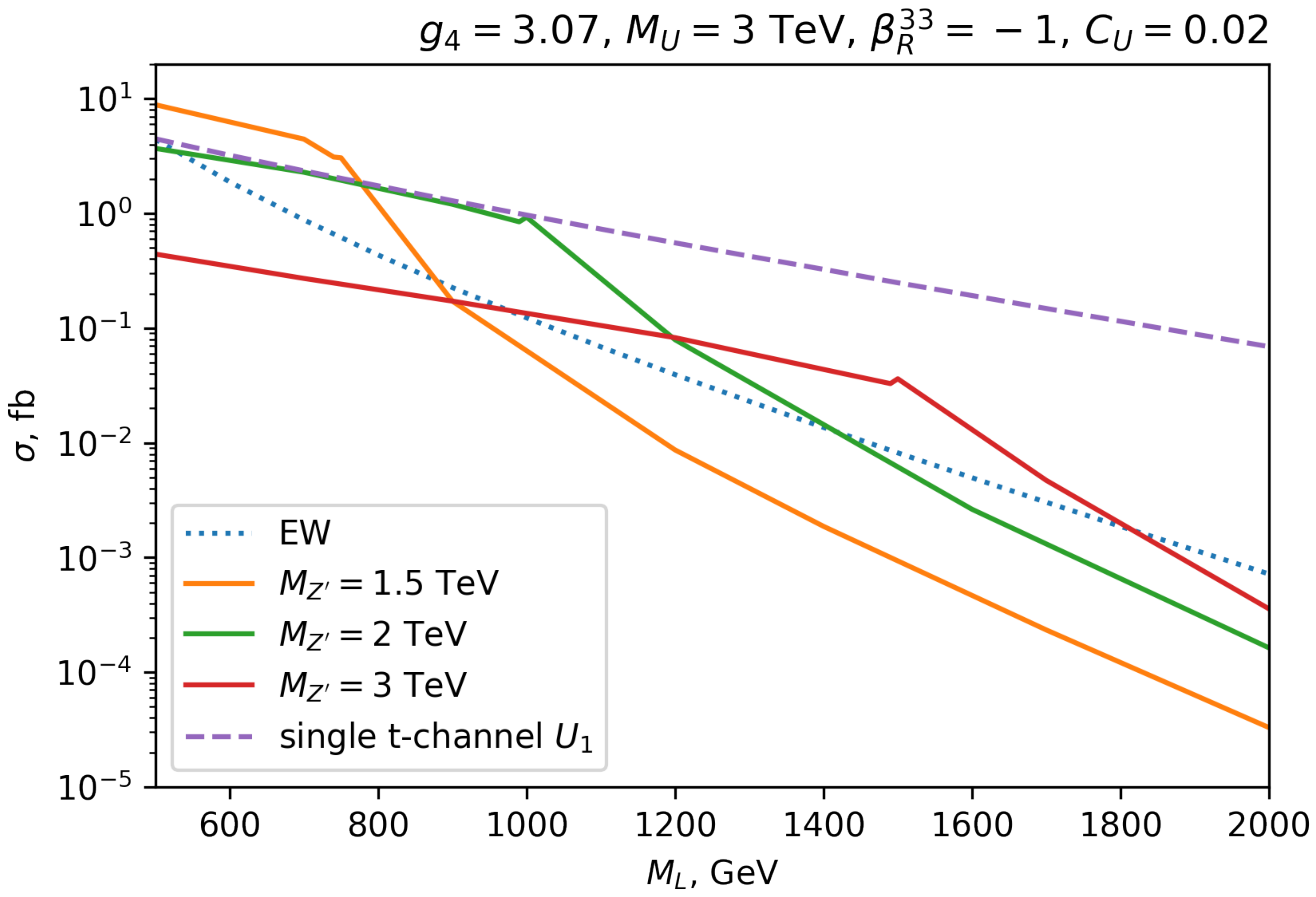
$$Br(E \to bb\tau) \approx 0.8, \;\; Br(E \to bt\nu_\tau) \approx 0.2$$





VL lepton production

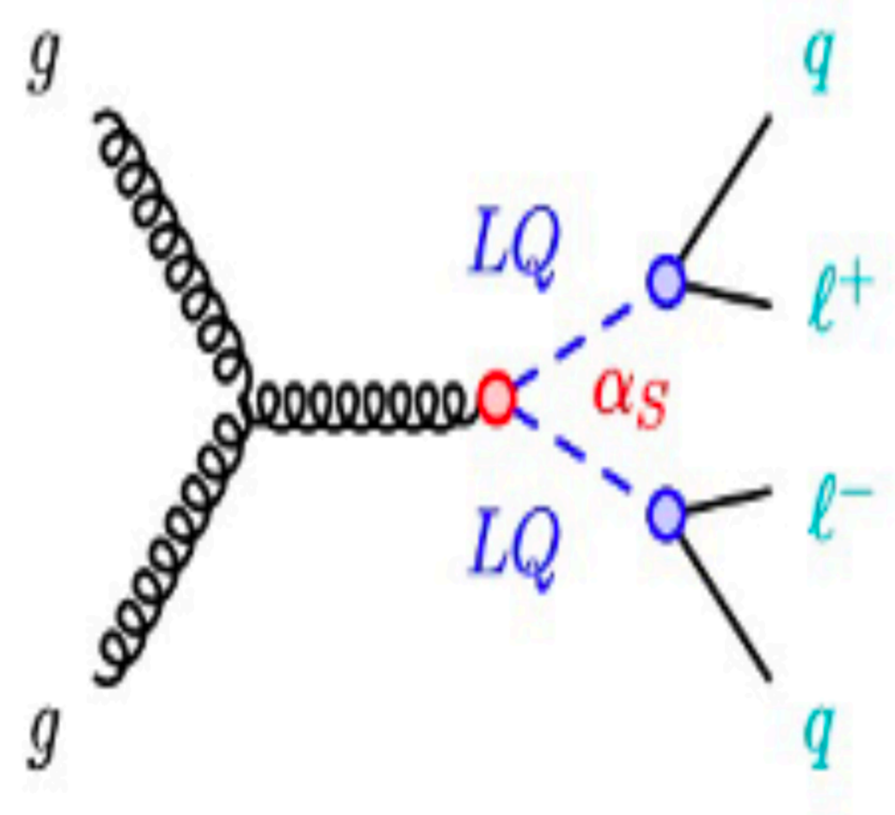




- singly produced VL leptons have a significant cross-section
- dominant for larger VL lepton masses

Collider signature

- dominant decay channel: $E \to bb\tau$
- dominant production channel: $pp \to E\tau$ via t-channel LQ
- collider signature: $pp \to bb\tau\tau$
- possible to use current searches for LQ pair production to recast the data
- propose a new search



Conclusion

- 2 body decay channel dominates for in the case of VL quarks
- RH neutrinos are important in the phenomenology of the VL quarks
- singly produced VL leptons have a significant signature
- more efficient searches should be made

SM-like mixing

Yukawa interactions for heavy vector-like fermions with SM Higgs:

$$\mathscr{L}_Y = \bar{\chi}'_L Y_+ \Phi_c \psi_+^R + \bar{\psi}'_L Y_u \Phi_c \psi_+^R + \bar{\chi}'_L Y_- \psi_-^R \Phi + \bar{\psi}'_L Y_d \psi_-^R \Phi, \qquad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ h + v \end{pmatrix}$$

Mass matrix for the up-type quarks:

$$\begin{pmatrix} \bar{c}_L & \bar{t}_L & \bar{T}_L \end{pmatrix}_u \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y_t \frac{v}{\sqrt{2}} & 0 \\ 0 & Y_+^q \frac{v}{\sqrt{2}} & M_T \end{pmatrix} \begin{pmatrix} c_R \\ t_R \\ T_R \end{pmatrix} = (\bar{\tilde{\Psi}}_L^u) \left(V_L^u\right)^\dagger M_u^{diag} \left(V_R^u \tilde{\Psi}_R^u\right),$$

$$Y_+^q = -s_W^q Y_u + c_W^q Y_+$$
$$Y_t = c_W^q Y_u + s_W^q Y_+$$

$$V_L^u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\frac{Y_+^q Y_t v^2}{2M_Q^2} \\ 0 & \frac{Y_+^q Y_t v^2}{2M_Q^2} & 1 \end{pmatrix}, \qquad V_R^u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\frac{Y_+^q v}{\sqrt{2}M_Q} \\ 0 & \frac{Y_+^q v}{\sqrt{2}M_Q} & 1 \end{pmatrix}$$

The non-diagonal entries are suppressed by a factor of v/M_Q

Yukawa couplings

$$Y_\tau = c_\chi Y_b + s_\chi Y^q_-$$

$$Y_\nu = c_\chi Y_t + s_\chi Y^q_+$$

without the mixing between the VL fermions and 3rd family fermions $Y_\tau = Y_b$

$$Y^q_- \sim Y_b \sim Y_\tau \sim O(10^{-2})$$

$$Y^q_+ \sim Y_t \sim Y_\nu \sim O(1)$$

Impact on gauge sector

Like in SM mixing effect can be moved to the gauge sector. It impacts CC and NC interactions and mixes heavy fermions with SM fermions in interactions with SM mediators.

$O\left(\frac{v^2}{M_Q^2}\right)$

$$\mathcal{L}_L^{CC} = \frac{g}{\sqrt{2}}\bar{\Psi}_L^u V^\dagger \gamma^\mu \Psi_L^d W_\mu^+ + h.c., \ V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\frac{v^2}{2M_Q^2}\left(Y_-^q Y_b - Y_+^q Y_t\right) \\ 0 & \frac{v^2}{2M_Q^2}\left(Y_-^q Y_b - Y_+^q Y_t\right) & 1 \end{pmatrix}$$

The heavy right-handed fermions are also charged under $SU(2)$. This results in the new type of interaction with $SU(2)$ bosons

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} W_\mu^+ \bar{\Psi}_R^u V_R^u P_3 (V_R^d)^\dagger \gamma^\mu \Psi_R^d + h.c. + g W_\mu^3 \bar{\Psi}_R^u V_R^u P_3 (V_R^u)^\dagger \gamma^\mu \Psi_R^u + (u \Longleftrightarrow d)$$

$O\left(\frac{v}{M_Q}\right)$

$$= \frac{g}{\sqrt{2}}\left(\bar{b}_R \quad \bar{B}_R\right)(\gamma^\mu W_\mu^-)\begin{pmatrix} o(\frac{v^2}{M_Q^2}) & -\frac{Y_-^q v}{\sqrt{2}M_Q} \\ -\frac{Y_+^q v}{\sqrt{2}M_Q} & 1 \end{pmatrix}\begin{pmatrix} t_R \\ T_R \end{pmatrix} + g\left(\bar{t}_R \quad \bar{T}_R\right)(\gamma^\mu Z_\mu)\begin{pmatrix} o(\frac{v^2}{M_Q^2}) & -\frac{Y_+^q v}{\sqrt{2}M_Q} \\ -\frac{Y_+^q v}{\sqrt{2}M_Q} & 1 \end{pmatrix}\begin{pmatrix} t_R \\ T_R \end{pmatrix}$$

mixing in the NC interactions