Search for vector-like light-flavor quark partners in proton-proton collisions at $\sqrt{s} = 8\,\mathbf{TeV}$

—Supplemental Material—

The CMS Collaboration
CERN

(Dated: December 27, 2017)

I. RESULTS USING AN ALTERNATIVE PARAMETRIZATION OF CHARGED AND NEUTRAL COUPLING STRENGTHS

In Section 8 in the main document results are presented for a scan over the branching fractions of the VLQ, while keeping the value of $\tilde{\kappa}_W$ fixed. As noted in Section 2.1, for non-zero $\tilde{\kappa}_W$ the exclusion limits on the VLQ mass cannot be evaluated for $\mathcal{B}_W = 0$, as Eq. (2) implies that the neutral-current single-production strength parameter $\tilde{\kappa}_Z$ diverges in this limit. This is indicated by the black shaded region below $\mathcal{B}_W \approx 0.1$ in Figs. 11 to 14.

However, from Ref. [1] a parametrization can be chosen that does not exhibit this divergent behavior. This involves fixing one generic single-production strength parameter κ_D and scanning over the branching fractions as before. The single parameter κ_D contains information from the charged-current, and Z and H neutral-current interactions, because it can be expressed as

$$\kappa_D^2 = \kappa_W^2 + \frac{\kappa_Z^2}{2} + \kappa_H^2 \left(\frac{1}{2} - \frac{m_H^2}{m_Q}\right) \tag{1}$$

with m_H the mass of the Higgs boson. Since κ is to be interpreted as a mixing angle, the range of κ_D is physically restricted between 0 and 1.

The following relations between the default and alternative parametrization can be deduced:

$$\tilde{\kappa}_W = \frac{\sqrt{2\mathcal{B}_W} m_Q}{v} \kappa_D, \tag{2}$$

$$\tilde{\kappa}_Z = \frac{2\sqrt{\mathcal{B}_Z} m_Q}{v} \kappa_D \tag{3}$$

From these relations it is seen that Eq. (2) still holds, but fixing κ_D in the scan instead of $\tilde{\kappa}_W$ provides a more consistent behavior throughout the scan. In particular, the combination $\kappa_D \neq 0$ and $\mathcal{B}_W = 0$ does not automatically lead to a divergence of $\tilde{\kappa}_Z$. Results derived in this parametrization are especially useful for scenarios where the VLQ only couples to Z or Higgs bosons; such scenarios have only been covered in the default results in Section 8 when considering VLQ pair production alone, but not including single production.

When fixing values of κ_D and scanning over the branching fractions, results are obtained for the combination of all channels in Tables I to XII. The scan in κ_D is performed from 0.05 to 1, initially in steps of 0.05, but in larger steps of 0.1 from $\kappa_D = 0.2$ onwards. Even for relatively small κ_D values, the mass limits become larger than 1800 GeV and cannot be evaluated with the produced VLQ signal MC samples. The reason for these high mass limits is that the single-production strengths governed by $\tilde{\kappa}_W$ and $\tilde{\kappa}_Z$ may become large even for relatively small κ_D values.

[1] Mathieu Buchkremer, Giacomo Cacciapaglia, Aldo Deandrea, and Luca Panizzi, "Model-independent framework for searches of top partners," Nucl. Phys. B **876**, 376 (2013).

TABLE I. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.05$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	635	690	[630,745]	[580,815]
0.0	0.8	0.2	610	660	[600,715]	[555,765]
0.0	0.6	0.4	585	625	[575,680]	[530,730]
0.0	0.4	0.6	555	585	[540,640]	[495,690]
0.0	0.2	0.8	500	535	[485,575]	[425,620]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	645	710	[650,775]	[590,850]
0.2	0.6	0.2	620	685	[610,740]	[565,785]
0.2	0.4	0.4	605	640	[575,705]	[530,755]
0.2	0.2	0.6	560	585	[535,655]	[475,715]
0.2	0.0	0.8	550	545	[480,605]	[400,685]
0.4	0.6	0.0	690	745	[685,810]	[610,880]
0.4	0.4	0.2	665	715	[645,780]	[580,835]
0.4	0.2	0.4	655	685	[590,750]	[530,800]
0.4	0.0	0.6	660	655	[565,725]	[500,770]
0.6	0.4	0.0	750	775	[715,845]	[645,895]
0.6	0.2	0.2	735	755	[695,820]	[600,875]
0.6	0.0	0.4	725	735	[665,790]	[580,850]
0.8	0.2	0.0	820	820	[750,880]	[685,945]
0.8	0.0	0.2	810	795	[730,860]	[660,915]
1.0	0.0	0.0	890	850	[785,925]	[725,1010]

TABLE II. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.1$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1140	1145	[775,1265]	[620,1385]
0.0	0.8	0.2	665	780	[645,1130]	[570,1215]
0.0	0.6	0.4	615	660	[580,750]	[535,960]
0.0	0.4	0.6	555	585	[540,655]	[495,710]
0.0	0.2	0.8	505	535	[485,575]	[425,615]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1160	1135	[785,1265]	[650,1385]
0.2	0.6	0.2	675	780	[655,1100]	[575,1195]
0.2	0.4	0.4	630	665	[580,755]	[525,875]
0.2	0.2	0.6	600	590	[530,670]	[470,735]
0.2	0.0	0.8	495	550	[470,600]	[400,690]
0.4	0.6	0.0	1290	1110	[790,1285]	[660,1400]
0.4	0.4	0.2	730	785	[685,1035]	[580,1215]
0.4	0.2	0.4	685	710	[600,795]	[535,895]
0.4	0.0	0.6	675	660	[570,740]	[495,795]
0.6	0.4	0.0	1420	1120	[810,1340]	[705,1540]
0.6	0.2	0.2	1360	835	[735,1130]	[625,1370]
0.6	0.0	0.4	805	770	[685,870]	[565,1090]
0.8	0.2	0.0	1620	1280	[870,1565]	[755,1750]
0.8	0.0	0.2	1555	1055	[800,1385]	[695,1685]
1.0	0.0	0.0	1765	1475	[1215,1730]	[835,1800*]

TABLE III. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.15$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1355	1420	[1300,1510]	[1165,1605]
0.0	0.8	0.2	1190	1275	[1125,1400]	[775,1490]
0.0	0.6	0.4	950	1070	[685,1190]	[550,1325]
0.0	0.4	0.6	575	610	[550,720]	[500,990]
0.0	0.2	0.8	505	535	[485,580]	[430,620]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1425	1425	[1310,1530]	[1150,1630]
0.2	0.6	0.2	1325	1250	[1115,1400]	[720,1495]
0.2	0.4	0.4	690	955	[625,1175]	[540,1300]
0.2	0.2	0.6	610	600	[540,710]	[470,820]
0.2	0.0	0.8	500	550	[485,610]	[400,685]
0.4	0.6	0.0	1575	1465	[1320,1635]	[1150,1765]
0.4	0.4	0.2	1495	1310	[1120,1495]	[730,1655]
0.4	0.2	0.4	1400	895	[685,1275]	[560,1505]
0.4	0.0	0.6	705	710	[585,825]	[495,1255]
0.6	0.4	0.0	1770	1630	[1385,1790]	[1200,1800*]
0.6	0.2	0.2	1735	1510	[1250,1715]	[810,1800*]
0.6	0.0	0.4	1675	1320	[805,1635]	[675,1775]
0.8	0.2	0.0	1800*	1785	[1615,1800*]	[1335,1800*]
0.8	0.0	0.2	1800*	1725	[1505,1800*]	[1205,1800*]
1.0	0.0	0.0	1800*	1800*	[1750,1800*]	[1560,1800*]

TABLE IV. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.2$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1500	1565	[1470,1710]	[1380,1785]
0.0	0.8	0.2	1380	1455	[1350,1555]	[1200,1660]
0.0	0.6	0.4	1210	1280	[1140,1410]	[780,1485]
0.0	0.4	0.6	655	900	[565,1130]	[495,1225]
0.0	0.2	0.8	505	540	[485,585]	[420,645]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1605	1590	[1480,1715]	[1370,1800*]
0.2	0.6	0.2	1495	1460	[1340,1590]	[1180,1710]
0.2	0.4	0.4	1350	1265	[1120,1410]	[595,1530]
0.2	0.2	0.6	665	695	[555,990]	[480,1210]
0.2	0.0	0.8	605	555	[480,625]	[400,710]
0.4	0.6	0.0	1800*	1725	[1555,1800*]	[1405,1800*]
0.4	0.4	0.2	1745	1585	[1400,1780]	[1230,1800*]
0.4	0.2	0.4	1635	1395	[1155,1640]	[740,1785]
0.4	0.0	0.6	1540	1035	[670,1385]	[525,1700]
0.6	0.4	0.0	1800*	1800*	[1720,1800*]	[1540,1800*]
0.6	0.2	0.2	1800*	1800*	[1615,1800*]	[1355,1800*]
0.6	0.0	0.4	1800*	1725	[1425,1800*]	[1170,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1720,1800*]
0.8	0.0	0.2	1800*	1800*	[1795,1800*]	[1620,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE V. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.3$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1760	1800*	[1720,1800*]	[1585,1800*]
0.0	0.8	0.2	1600	1700	[1565,1790]	[1465,1800*]
0.0	0.6	0.4	1455	1515	[1420,1615]	[1300,1730]
0.0	0.4	0.6	1205	1275	[1145,1405]	[550,1490]
0.0	0.2	0.8	490	555	[495,645]	[430,955]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1750,1800*]	[1615,1800*]
0.2	0.6	0.2	1785	1755	[1615,1800*]	[1485,1800*]
0.2	0.4	0.4	1655	1590	[1440,1730]	[1320,1800*]
0.2	0.2	0.6	1505	1300	[1065,1500]	[520,1665]
0.2	0.0	0.8	665	570	[495,735]	[n.a.,1255]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1750,1800*]
0.4	0.4	0.2	1800*	1800*	[1795,1800*]	[1650,1800*]
0.4	0.2	0.4	1800*	1800*	[1675,1800*]	[1495,1800*]
0.4	0.0	0.6	1800*	1720	[1470,1800*]	[1215,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1745,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE VI. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.4$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1775,1800*]
0.0	0.8	0.2	1770	1800*	[1750,1800*]	[1620,1800*]
0.0	0.6	0.4	1590	1695	[1560,1790]	[1470,1800*]
0.0	0.4	0.6	1405	1450	[1345,1545]	[1205,1645]
0.0	0.2	0.8	650	710	[505,1120]	[430,1225]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1715,1800*]
0.2	0.4	0.4	1800*	1800	[1660,1800*]	[1530,1800*]
0.2	0.2	0.6	1725	1610	[1400,1775]	[1275,1800*]
0.2	0.0	0.8	1520	1030	[530,1385]	[n.a.,1690]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1795,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1645,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE VII. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.5$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.8	0.2	1800*	1800*	[1800*,1800*]	[1770,1800*]
0.0	0.6	0.4	1735	1800*	[1720,1800*]	[1585,1800*]
0.0	0.4	0.6	1485	1570	[1470,1705]	[1370,1780]
0.0	0.2	0.8	1135	1150	[545,1295]	[435,1405]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.4	0.4	1800*	1800*	[1800*,1800*]	[1710,1800*]
0.2	0.2	0.6	1800*	1800*	[1640,1800*]	[1460,1800*]
0.2	0.0	0.8	1755	1530	[895,1730]	[n.a.,1800*]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE VIII. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.6$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.8	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.6	0.4	1800*	1800*	[1800*,1800*]	[1720,1800*]
0.0	0.4	0.6	1600	1700	[1560,1790]	[1475,1800*]
0.0	0.2	0.8	1205	1280	[1145,1405]	[450,1485]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.4	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.2	0.6	1800*	1800*	[1800,1800*]	[1650,1800*]
0.2	0.0	0.8	1800*	1720	[1510,1800*]	[890,1800*]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE IX. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.7$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.8	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.6	0.4	1800*	1800*	[1800*,1800*]	[1785,1800*]
0.0	0.4	0.6	1720	1785	[1680,1800*]	[1550,1800*]
0.0	0.2	0.8	1290	1390	[1240,1480]	[495,1560]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.4	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.2	0.6	1800*	1800*	[1800*,1800*]	[1770,1800*]
0.2	0.0	0.8	1800*	1800*	[1695,1800*]	[1415,1800*]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE X. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.8$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.8	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.6	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.4	0.6	1775	1800*	[1750,1800*]	[1635,1800*]
0.0	0.2	0.8	1390	1450	[1350,1545]	[1195,1670]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.4	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.2	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.0	0.8	1800*	1800*	[1795,1800*]	[1640,1800*]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE XI. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 0.9$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.8	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.6	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.4	0.6	1800*	1800*	[1800*,1800*]	[1720,1800*]
0.0	0.2	0.8	1450	1510	[1415,1620]	[1315,1730]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.4	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.2	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.0	0.8	1800*	1800*	[1800*,1800*]	[1750,1800*]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]

TABLE XII. Observed and median expected lower limits on the VLQ mass (in GeV) at 95% CL, or greater than 95% CL when indicated with $*$, for a range of different combinations of decay branching fractions. The ranges containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis, are also given. The cases where the limits could not be evaluated because simulated signal samples for VLQ masses below 400 GeV are not available, are indicated with 'n.a.'. The limits are determined assuming $\kappa_D = 1.0$.

$\mathcal{B}_W$	$\mathcal{B}_Z$	$\mathcal{B}_H$	Observed	Median expected	68% expected	95% expected
0.0	1.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.8	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.6	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.0	0.4	0.6	1800*	1800*	[1800*,1800*]	[1760,1800*]
0.0	0.2	0.8	1490	1565	[1475,1705]	[1380,1780]
0.0	0.0	1.0	430	n.a.	[n.a.,505]	[n.a.,535]
0.2	0.8	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.6	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.4	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.2	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.2	0.0	0.8	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.6	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.4	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.2	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.4	0.0	0.6	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.4	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.2	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.6	0.0	0.4	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.2	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]
0.8	0.0	0.2	1800*	1800*	[1800*,1800*]	[1800*,1800*]
1.0	0.0	0.0	1800*	1800*	[1800*,1800*]	[1800*,1800*]