Vector-like fermions: a review

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Outline

- Introduction: personal historical view
  - Grand Unified Theories, Majorana masses, Little Higgs models, SUSY
  - Extended spectrum
- Decoupling: well behaved (decoupling) but flavour violation, although model dependent predictions (**changing prejudices**)
  - Indirect effects
  - Direct effects
  - Fermion masses and mixings
- LHC searches (today's talks)

There is a large number of papers on the subject:

- H. Fritzsch, M. Gell-Mann and P. Minkowski, Phys. Lett. 59B (1975) 256 (SO(10) H. Georgi) Light (now, heavy then ~ 10's of GeV) **mirror**, anomaly free
- M.J. Bowick and P. Ramond, Phys. Lett. 103B (1981) 338 (E_6 F. Gursey, P. Ramond and P. Sikivie) Heavy (up to the GUT scale) **vector-like**
- F. del Aguila and M,J. Bowick, Phys. Lett. 119B (1982) 144 Phenomenology
- P. Candelas, G.T. Horowitz, A. Strominger and E. Witten, Nucl. Phys. B 258 (1985) 46 **SUSY** motivation (at the TeV scale in E_6 representations)
- G.C. Branco and L. Lavoura, Nucl. Phys. B 278 (1986) 738 Phenomenology
- F. del Aguila, L. Ametller, G.L. Kane and J. Vidal, Nucl. Phys. B 334 (1990) 1 Reach of hadron colliders
- F.J. Botella, G.C. Branco, M. Nebot, M.N. Rebelo and J.I. Silva-Marcos, arXiv: 1610.03018 [hep-ph] Model building
- J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer and M. Pérez-Victoria, [arXiv: 1306.0572 [hep-ph]] Review
- ATLAS and CMS limits. Specific talks this week, and especially today

Large μ

Heavy vector-like quark of charge 2/3

$$\mathcal{L}_{SM} + \mathcal{L}_T$$

$$\mathcal{L}_{SM} = \boxed{\overline{q_L} \mathrm{i} \not{D} q_L + \overline{t_R} \mathrm{i} \not{D} t_R - \lambda_t (\overline{q_L} \tilde{\phi} t_R + \overline{t_R} \tilde{\phi}^\dagger q_L)} + \ldots$$

$$\mathcal{L}_T = \boxed{\overline{T}(\mathrm{i} \not{D} - M) T} - \lambda_T (\overline{q_L} \tilde{\phi} T_R + \overline{T_R} \tilde{\phi}^\dagger q_L)$$

F. del Aguila, M. Perez-Victoria and J. Santiago [hep-ph/0007316]

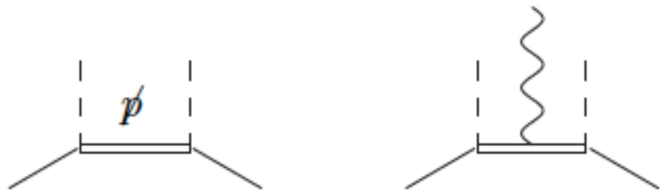
$$\mathcal{L}_{SM} + \mathcal{L}_6^{(0l)}$$

μ = M

$$\mathcal{L}_6^{(0l)} = \alpha_{\phi q}^{(1)} \mathcal{O}_{\phi q}^{(1)} + \alpha_{\phi q}^{(3)} \mathcal{O}_{\phi q}^{(3)} + \alpha_{u\phi} \mathcal{O}_{u\phi} + h.c.$$

$$\mathcal{O}_{\phi q}^{(1)} = \mathrm{i} \phi^\dagger D_\mu \phi \; \bar{q} \gamma^\mu q, \; \mathcal{O}_{\phi q}^{(3)} = \mathrm{i} \phi^\dagger \sigma^a D_\mu \phi \; \bar{q} \gamma^\mu \sigma^a q, \; \mathcal{O}_{u\phi} \underset{\bigstar}{=} \phi^\dagger \phi \bar{q} \tilde{\phi} t$$

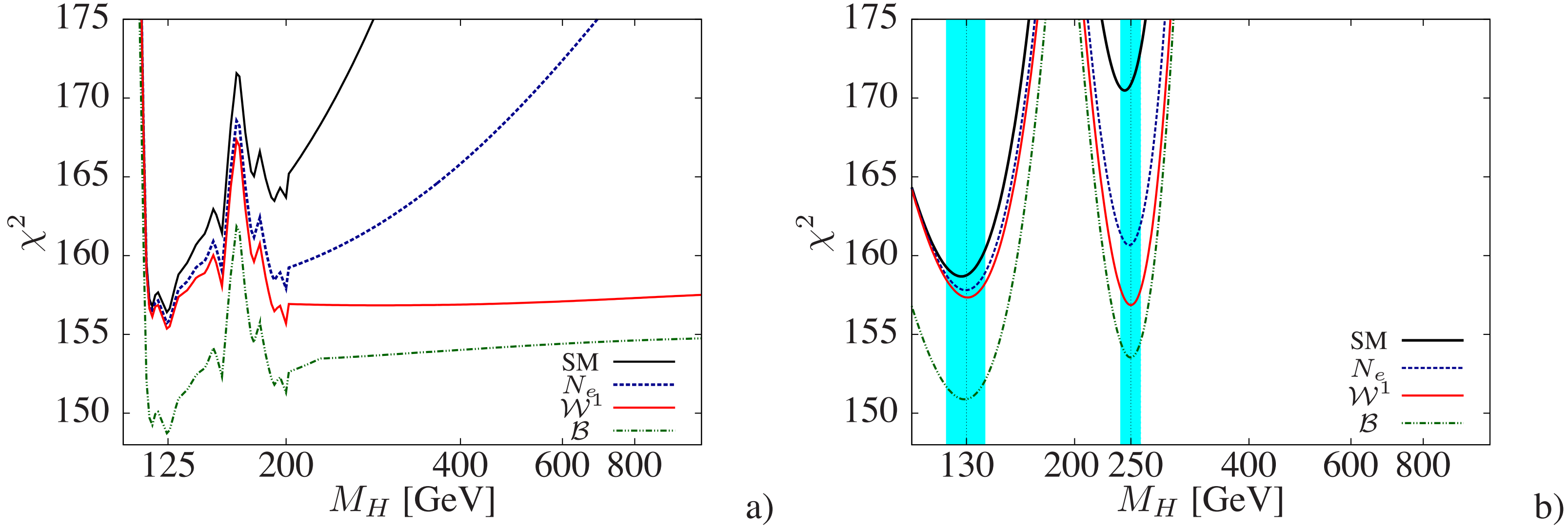
$$\alpha_{\phi q}^{(1)} = -\alpha_{\phi q}^{(3)} = \frac{|\lambda_T|^2}{4M^2}, \; \alpha_{u\phi} = 2 \lambda_t \alpha_{\phi q}^{(1)}$$



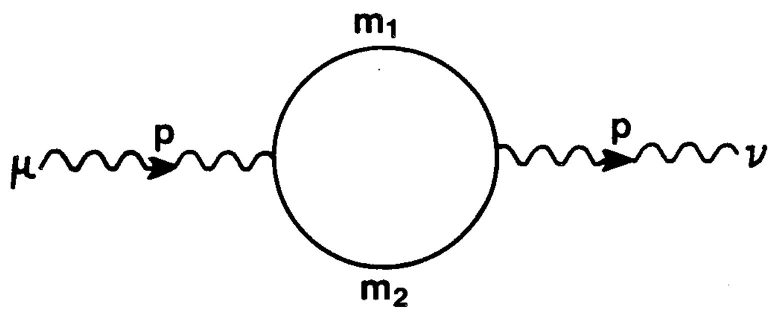
Small μ

EOM (no T_L interaction): $T_L = \frac{1}{M}(-\lambda_T \tilde{\phi}^\dagger q_L), \; T_R = \frac{\mathrm{i} \not{D}}{M^2}(-\lambda_T \tilde{\phi}^\dagger q_L)$

★ use t EOM to write the dimension 6 effective Lagrangian in the Warsaw basis



F. del Aguila and J. de Blas, [arXiv:1105.6103 [hep-ph]]



L. Lavoura and J.P Silva, Phys. Rev. D 47 (1993) 2046

	LH and RH parts	Masses (M large)	Gauge L	Gauge R	Higgs RL (q is a doublet)	Higgs LR (q is a singlet)	Lifetimes $M < M_{W,Z}$	Lifetimes $M_{W,Z} < M$	Usual SU(5) representations containing these $\Delta I=0$ quarks	Other characteristics
Singlets	U	No constraint	Q η q Z,W	η^2 mixing (no mixing if no other I=0 multi-plets)	Q q H	Q η q H			$10_F + \overline{10}_F$	
	D								$5_F + \overline{5}_F$ (Used in super-symmetry) and $45_F + \overline{45}_F$	
Doublets	U D	Particles in the same multiplet are nearly degenerate in mass	η^2 mixing (no mixing in NC if no other I=0 multiplets)	Q η q Z,W	Q η q H	Q q H	$\tau \lesssim \tau(Q\to q_b e\nu_e) \sim \left[\frac{G^2}{192\pi^3} m_b^2 M^3\right]^{-1} \sim 10^{-17}\left(\frac{50}{M \text{ in GeV}}\right)^3$ sec	$\tau \lesssim \tau(Q\to q_b Z) \sim \left[\frac{G}{8\sqrt{2}\pi} m_b^2 M\right]^{-1} \sim 10^{-21}\left(\frac{100}{M \text{ in GeV}}\right)$ sec	$10_F + \overline{10}_F$	
	. D U .		η^2 mixing						$45_F + \overline{45}_F$, 24_H	ratio of neutr to charged dec large
Triplets	U . D U . D	$\Delta M \sim m \frac{m}{M}$	Q η q Z,W	Negligible	Q q H	Q η q H			$45_F + \overline{45}_F$, other representations	imply exotics
	. D . . U .		Negligible		Negligible				other representations	
Other Multiplets			Negligible		Negligible		10^{-18} sec $< \tau <$ 1 sec		Difficult to embed	

F. del Aguila and M.J. Bowick, Nucl. Phys. B 224 (1983) 107

	LH and RH parts	Masses (M large)	Gauge L	Gauge R	Higgs RL (ℓ is a doublet)	Higgs LR (ℓ is a sing	Lifetimes $M < M_{W,Z}$	Lifetimes $M_{W,Z} < M$	Usual SU(5) representations containing these $\Delta I = 0$ leptons	Other characteristics
Singlets	N	No constraint	L —η— ℓ; Z,W	(N will be in general a self-conjugate Majorana spinor)	L —— ℓ; H	(N will be in general a self conjugate Majorana spinor)			1_F and 24_F	
	E		L —η— ℓ; Z,W	η^2 mixing (no mixing if no other $\Delta I=0$ multiplets)	L —— ℓ; H	L —η— ℓ; H	$\tau \le \tau(L \to \ell_\tau e \nu_e) \sim$	$\tau \le \tau(L \to \ell_\tau Z) \sim$	$10_F + \overline{10}_F$	
Doublets	N, E	Particles in the same multiplet are nearly degenerate in mass	η^2 mixing (no mixing in NC if no other $\Delta I=0$ multiplets)	L —η— ℓ; Z,W	L —η— ℓ; H	L —— ℓ; H	$\left[\frac{G^2}{192\pi^3} m_\tau^2 M^3\right]^{-1} \sim$ $10^{-15} \left(\frac{20}{M \text{ in GeV}}\right)^3$ sec	$\left[\frac{G}{8\sqrt{2}\pi} m_\tau^2 M\right]^{-1} \sim$ $10^{-20} \left(\frac{100}{M \text{ in GeV}}\right)$ sec	$5_F + \overline{5}_F$ (used in supersymmetry) and $45_F + \overline{45}_F$	No sequential character or associated nearl massless neutrin or conserved quantum number, ratio of neutral to charge decays large
	E .		η^2 mixing						other representations	
Triplets	E^c N E , N E .	$\Delta M \sim m \frac{m}{M}$	L —η— ℓ; Z,W	Negligible	L —— ℓ; H	L —η— ℓ; H			24_F, other representations	in general imply exotics
	E . .		Negligible		Negligible				other representations	
Other Multiplets			Negligible		Negligible		10^{-16} sec $< \tau <$ 1 sec		Difficult to embed	

Effective Lagrangian

accidental symmetries are not fulfiled by higher order operators **-lepton number, ...-**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{{\rm dim}\mathcal{O}_i > 4} \frac{c_i}{\Lambda^{{\rm dim}\mathcal{O}_i - 4}} \mathcal{O}_i$$

basis of local operators (no redundant) -systematic use of **equations of motion-**

$$\left(\frac{E}{\Lambda}\right)^{{\rm dim}\mathcal{O}_i - 4} \sim \epsilon$$

$\Rightarrow$

engineering dimension upper limit

$$\mathrm{dim}\mathcal{O}_i \sim 4 + \frac{\log\epsilon}{\log(E/\Lambda)} \qquad \left(2 = \frac{\log 0.01}{\log\frac{100\ \mathrm{GeV}}{1\ \mathrm{TeV}}}\right)$$

finite number of independent operators

F. del Aguila, M. Perez-Victoria and J. Santiago, [hep-ph/0007316]

	U_R^b	D_R^b	$\begin{pmatrix}X\\U\\D\end{pmatrix}_R^b$	$\begin{pmatrix}U\\D\\Y\end{pmatrix}_R^b$
$\overline{\begin{pmatrix}U\\D\end{pmatrix}_L}^a$	$\tilde{\phi}$	ϕ	$\frac{\sigma^I}{2}\tilde{\phi}$	$\frac{\sigma^I}{2}\phi$
$\overline{\begin{pmatrix}X\\U\end{pmatrix}_L}^a$	ϕ	—	$\frac{\sigma^I}{2}\phi$	—
$\overline{\begin{pmatrix}D\\Y\end{pmatrix}_L}^a$	—	$\tilde{\phi}$	—	$\frac{\sigma^I}{2}\tilde{\phi}$

$Q^{(m)}$	$-\mathcal{L}_{lh}$
U	$\lambda'^{(1)}_{aj} V_{ji} \bar{U}^a_R \tilde{\phi}^\dagger q^i_L$
D	$\lambda'^{(2)}_{ai} \bar{D}^a_R \phi^\dagger \, q^i_L$
$\begin{pmatrix}U\\D\end{pmatrix}$	$\boxed{\lambda'^{(3u)}_{ai} \overline{\begin{pmatrix}U\\D\end{pmatrix}_L}^a \tilde{\phi} u^i_R + \lambda'^{(3d)}_{ai} \overline{\begin{pmatrix}U\\D\end{pmatrix}_L}^a \phi d^i_R}$
$\begin{pmatrix}X\\U\end{pmatrix}$	$\lambda'^{(4)}_{ai} \overline{\begin{pmatrix}X\\U\end{pmatrix}_L}^a \phi u^i_R$
$\begin{pmatrix}D\\Y\end{pmatrix}$	$\lambda'^{(5)}_{ai} \overline{\begin{pmatrix}D\\Y\end{pmatrix}_L}^a \tilde{\phi} d^i_R$
$\begin{pmatrix}X\\U\\D\end{pmatrix}$	$\lambda'^{(6)}_{aj} V_{ji} \overline{\begin{pmatrix}X\\U\\D\end{pmatrix}_{R\,I}}^a \tilde{\phi}^\dagger \frac{\sigma^I}{2} q^i_L$
$\begin{pmatrix}U\\D\\Y\end{pmatrix}$	$\lambda'^{(7)}_{aj} V_{ji} \overline{\begin{pmatrix}U\\D\\Y\end{pmatrix}_{R\,I}}^a \phi^\dagger \frac{\sigma^I}{2} q^i_L$

Equations of motion and field redefinitions

Relevant (dimension < 4), marginal (dimension = 4) and irrelevant (dimension > 4) operators, which it is convenient to bring to a canonical form without redundancies:

- Necessary to make a meaningful comparison between different (phenomenological) analyses.
- Although there are subsets more suitable for given data subsets.

As in the case of lepton number violation, just discussed, new physics may originate at a rather large order but its effects in general do manifest at the lowest possible order after quantum corrections are taken into account.

$$\mathcal{L}_{SM} = \overline{q_L} \mathrm{i} \not{D} q_L + \overline{t_R} \mathrm{i} \not{D} t_R - \lambda_t (\overline{q_L} \tilde{\phi} t_R + \overline{t_R} \tilde{\phi}^\dagger q_L) + \ldots$$

$$\mathcal{O}_{\phi q}^{(1)} = \phi^\dagger \phi \, \overline{q_L} \, \mathrm{i} \, \not{D} \, q_L \quad \xrightarrow[\mathrm{i}\not{D} q_L - \lambda_t \tilde{\phi} t_R = 0]{q_L \text{ EOM:}} \quad \lambda_t \, (\mathcal{O}_{u\phi} = \phi^\dagger \phi \, \overline{q_L} \, \tilde{\phi} \, t_R)$$

$$\mathcal{Z}[J] = \int D\varphi \ \exp\left\{\mathrm{i}\int dx \ [\mathcal{L}(\varphi(x), \partial_\mu\varphi(x)) + J(x)\varphi(x)]\right\}$$

$$\mathcal{S}_{\text{eff}} = \int d^4x \ \mathcal{L}_{\text{eff}}$$

C. Arzt, hep-ph/9304230

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\dim\mathcal{O}_i > 4} \frac{c_i}{\Lambda^{\dim\mathcal{O}_i - 4}}\mathcal{O}_i = \sum_{n=0}^{\infty} \mathcal{L}_n$$

Any combination of terms which allows for the factorization of an equation of motion of a light field φ can be removed because it has no contribution to the S-matrix

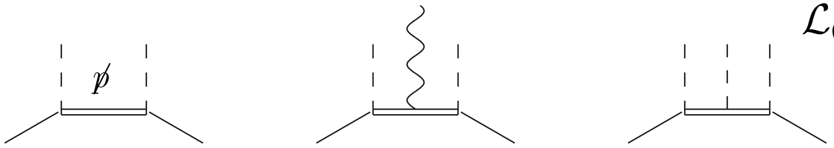
$$\mathcal{L}_m = \frac{1}{\Lambda^m}\left(\cdots + f(\varphi, \partial_\mu\varphi)\left(\frac{\delta\mathcal{L}_{\text{SM}}}{\delta\varphi^\dagger} - \partial_\mu\frac{\delta\mathcal{L}_{\text{SM}}}{\delta\partial_\mu\varphi^\dagger}\right)\right)$$

$$\frac{\delta\mathcal{L}_{\text{SM}}}{\delta\varphi^\dagger} - \partial_\mu\frac{\delta\mathcal{L}_{\text{SM}}}{\delta\partial_\mu\varphi^\dagger} = 0$$

This follows from the observation that the field redefinition $\varphi^\dagger \to \varphi^\dagger - \frac{1}{\Lambda^m} f(\varphi, \partial_\mu\varphi)$

cancels such a combination without modifying $\mathcal{L} = \sum_{n=0}^{m} \mathcal{L}_n$

$$\alpha^{(1)}_{\phi q}\left((\mathcal{O}^{(1)}_{\phi q} = \phi^\dagger\phi \ \overline{q_L} \ \mathrm{i}\not{D} \ q_L)\right) \longrightarrow \lambda_t \ \left((\mathcal{O}_{u\phi} = \phi^\dagger\phi \ \overline{q_L} \ \tilde{\phi} \ t_R)\right)$$



(a) (b) (c)

$$\begin{aligned}\mathcal{L}_6 = {} & (\alpha^{(1)}_{\phi q})_{ij}(\phi^\dagger iD_\mu\phi)(\bar{q}^i_L\gamma^\mu q^j_L) + (\alpha^{(3)}_{\phi q})_{ij}(\phi^\dagger\sigma^I iD_\mu\phi)(\bar{q}^i_L\gamma^\mu\sigma^I q^j_L)\\ & +(\alpha_{\phi u})_{ij}(\phi^\dagger iD_\mu\phi)(\bar{u}^i_R\gamma^\mu u^j_R) + (\alpha_{\phi d})_{ij}(\phi^\dagger iD_\mu\phi)(\bar{d}^i_R\gamma^\mu d^j_R)\\ & +(\alpha_{\phi\phi})_{ij}(\phi^T\epsilon iD_\mu\phi)(\bar{u}^i_R\gamma^\mu d^j_R) + (\alpha_{u\phi})_{ij}(\phi^\dagger\phi)(\bar{q}^i_L\tilde{\phi}u^j_R)\\ & +(\alpha_{d\phi})_{ij}(\phi^\dagger\phi)(\bar{q}^i_L\phi d^j_R) + \text{h.c.} \quad .\end{aligned}$$

$Q^{(m)}$	$\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	$\frac{(\alpha^{(3)}_{\phi q})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{\phi u})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{\phi d})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{\phi\phi})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{u\phi})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{d\phi})_{ij}}{\Lambda^2}$
U	$\frac{1}{4}V^\dagger_{ik}\frac{\lambda'^{(1)\dagger}_{ka}\lambda'^{(1)}_{al}}{M_a^2}V_{lj}$	$-\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	$2\frac{(\alpha^{(1)}_{\phi q})_{ik}}{\Lambda^2}V^\dagger_{kj}\lambda^u_j$	–
D	$-\frac{1}{4}\frac{\lambda'^{(2)\dagger}_{ia}\lambda'^{(2)}_{aj}}{M_a^2}$	$\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	–	$-2\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}\lambda^d_j$
$\begin{pmatrix}U\\D\end{pmatrix}$	–	–	$-\frac{1}{2}\frac{\lambda'^{(3u)\dagger}_{ia}\lambda'^{(3u)}_{aj}}{M_a^2}$	$\frac{1}{2}\frac{\lambda'^{(3d)\dagger}_{ia}\lambda'^{(3d)}_{aj}}{M_a^2}$	$-\frac{\lambda'^{(3u)\dagger}_{ia}\lambda'^{(3d)}_{aj}}{M_a^2}$	$-V^\dagger_{ik}\lambda^u_k\frac{(\alpha_{\phi u})_{kj}}{\Lambda^2}$	$\lambda^d_i\frac{(\alpha_{\phi d})_{ij}}{\Lambda^2}$
$\begin{pmatrix}X\\U\end{pmatrix}$	–	–	$\frac{1}{2}\frac{\lambda'^{(4)\dagger}_{ia}\lambda'^{(4)}_{aj}}{M_a^2}$	–	–	$V^\dagger_{ik}\lambda^u_k\frac{(\alpha_{\phi u})_{kj}}{\Lambda^2}$	–
$\begin{pmatrix}D\\Y\end{pmatrix}$	–	–	–	$-\frac{1}{2}\frac{\lambda'^{(5)\dagger}_{ia}\lambda'^{(5)}_{aj}}{M_a^2}$	–	–	$-\lambda^d_i\frac{(\alpha_{\phi d})_{ij}}{\Lambda^2}$
$\begin{pmatrix}X\\U\\D\end{pmatrix}$	$\frac{3}{16}V^\dagger_{ik}\frac{\lambda'^{(6)\dagger}_{ka}\lambda'^{(6)}_{al}}{M_a^2}V_{lj}$	$\frac{1}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	$\frac{2}{3}\frac{(\alpha^{(1)}_{\phi q})_{ik}}{\Lambda^2}V^\dagger_{kj}\lambda^u_j$	$\frac{4}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}\lambda^d_j$
$\begin{pmatrix}U\\D\\Y\end{pmatrix}$	$-\frac{3}{16}V^\dagger_{ik}\frac{\lambda'^{(7)\dagger}_{ka}\lambda'^{(7)}_{al}}{M_a^2}V_{lj}$	$-\frac{1}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	$-\frac{4}{3}\frac{(\alpha^{(1)}_{\phi q})_{ik}}{\Lambda^2}V^\dagger_{kj}\lambda^u_j$	$-\frac{2}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}\lambda^d_j$

$$
\begin{aligned}
\mathcal{L}^Z &= -\frac{g}{2\cos\theta_W}\Big(\bar{u}^i_L X^{uL}_{ij}\gamma^\mu u^j_L + \bar{u}^i_R X^{uR}_{ij}\gamma^\mu u^j_R \\
&\qquad - \bar{d}^i_L X^{dL}_{ij}\gamma^\mu d^j_L - \bar{d}^i_R X^{dR}_{ij}\gamma^\mu d^j_R - 2\sin^2\theta_W J^\mu_{EM}\Big) Z_\mu, \\
\mathcal{L}^W &= -\frac{g}{\sqrt{2}}(\bar{u}^i_L W^L_{ij}\gamma^\mu d^j_L + \bar{u}^i_R W^R_{ij}\gamma^\mu d^j_R) W^+_\mu + \text{h.c.}, \\
\mathcal{L}^H &= -\frac{1}{\sqrt{2}}(\bar{u}^i_L Y^u_{ij} u^j_R + \bar{d}^i_L Y^d_{ij} d^j_R) H + \text{h.c.}, \\
X^{uL}_{ij} &= \delta_{ij} - \frac{v^2}{\Lambda^2} V_{ik}(\alpha^{(1)}_{\phi q} - \alpha^{(3)}_{\phi q})_{kl} V^\dagger_{lj}, \\
&\boxed{X^{uR}_{ij} = -\frac{v^2}{\Lambda^2}(\alpha_{\phi u})_{ij},} \\
X^{dL}_{ij} &= \delta_{ij} + \frac{v^2}{\Lambda^2}(\alpha^{(1)}_{\phi q} + \alpha^{(3)}_{\phi q})_{ij}, \\
&\boxed{X^{dR}_{ij} = \frac{v^2}{\Lambda^2}(\alpha_{\phi d})_{ij},} \\
W^L_{ij} &= \tilde{V}_{ik}(\delta_{kj} + \frac{v^2}{\Lambda^2}(\alpha^{(3)}_{\phi q})_{kj}), \\
W^R_{ij} &= -\frac{1}{2}\frac{v^2}{\Lambda^2}(\alpha_{\phi\phi})_{ij}, \\
Y^u_{ij} &= \delta_{ij}\lambda^u_j - \frac{v^2}{\Lambda^2}\left(V_{ik}(\alpha_{u\phi})_{kj} + \frac{1}{4}\delta_{ij}[V_{ik}(\alpha_{u\phi})_{kj} + (\alpha_{u\phi})^\dagger_{ik} V^\dagger_{kj}]\right), \\
Y^d_{ij} &= \delta_{ij}\lambda^d_j - \frac{v^2}{\Lambda^2}\left((\alpha_{d\phi})_{ij} + \frac{1}{4}\delta_{ij}(\alpha_{d\phi} + \alpha^\dagger_{d\phi})_{ij}\right),
\end{aligned}
$$

A. Atre, M. Carena, T. Han and J. Santiago [arXiv:0806.3966 [hep-ph]]

$$\lambda_b \overline{\begin{pmatrix} T \\ B \end{pmatrix}}_L \phi b_R + \lambda_t \overline{\begin{pmatrix} T \\ B \end{pmatrix}}_L \tilde{\phi} t_R + \lambda_t' \overline{\begin{pmatrix} X \\ T' \end{pmatrix}}_L \phi t_R$$

$$\frac{\alpha_{\phi u}}{\Lambda^2} = -\frac{1}{2}\frac{\lambda_t^2}{M_{\frac{1}{6}}^2} + \frac{1}{2}\frac{\lambda_t'^2}{M_{\frac{7}{6}}^2} \rightarrow \boxed{Z_\mu \overline{t_R}\gamma^\mu t_R \rightarrow 0}$$

$$\frac{\alpha_{\phi d}}{\Lambda^2} = \frac{1}{2}\frac{\lambda_b^2}{M_{\frac{1}{6}}^2} \rightarrow Z_\mu \overline{b_R}\gamma^\mu b_R \rightarrow 0$$

$$\frac{\alpha_{\phi\phi}}{\Lambda^2} = -\frac{\lambda_t\lambda_b}{M_{\frac{1}{6}}^2} \rightarrow W_\mu \overline{t_R}\gamma^\mu b_R \rightarrow 0$$

$$\left\{ \begin{array}{l} \lambda_t = \lambda_t' \\ M_{\frac{1}{6}} = M_{\frac{7}{6}} \\ \lambda_b = 0 \end{array} \right.$$

$$[2_{\frac{1}{6}}, 2_{\frac{7}{6}}] = \left[\begin{pmatrix} T \\ B \end{pmatrix}, \begin{pmatrix} X \\ T' \end{pmatrix} \right]$$

$$SU(2)_L \times SU(2)^c$$

$$\left. \begin{array}{l} B_R, X_R \rightarrow W t_R \\ T_L + T_L' \rightarrow H t_R \\ T_R - T_R' \rightarrow Z t_R \end{array} \right\}$$

$Q^{(m)},\ Q^{(n)}$	$\frac{(\alpha_{u\phi}^{mn})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{d\phi}^{mn})_{ij}}{\Lambda^2}$
$U,\ \begin{pmatrix} U \\ D \end{pmatrix}$	$V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(1)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(3u)}}{M_a M_b}$	$-$
$U,\ \begin{pmatrix} X \\ U \end{pmatrix}$	$V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(1)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(4)}}{M_a M_b}$	$-$
$D,\ \begin{pmatrix} U \\ D \end{pmatrix}$	$-$	$\frac{\lambda_{ia}^{\prime(2)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(3d)}}{M_a M_b}$
$D,\ \begin{pmatrix} D \\ Y \end{pmatrix}$	$-$	$\frac{\lambda_{ia}^{\prime(2)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(5)}}{M_a M_b}$
$\begin{pmatrix} U \\ D \end{pmatrix},\ \begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\frac{1}{4}V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(6)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(3u)}}{M_a M_b}$	$\frac{1}{2}V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(6)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(3d)}}{M_a M_b}$
$\begin{pmatrix} U \\ D \end{pmatrix},\ \begin{pmatrix} U \\ D \\ Y \end{pmatrix}$	$\frac{1}{2}V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(7)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(3u)}}{M_a M_b}$	$\frac{1}{4}V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(7)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(3d)}}{M_a M_b}$
$\begin{pmatrix} X \\ U \end{pmatrix},\ \begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$-\frac{1}{4}V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(6)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(4)}}{M_a M_b}$	$-$
$\begin{pmatrix} D \\ Y \end{pmatrix},\ \begin{pmatrix} U \\ D \\ Y \end{pmatrix}$	$-$	$-\frac{1}{4}V_{ik}^{\dagger}\frac{\lambda_{ka}^{\prime(7)\dagger}\tilde{\lambda}_{ab}\lambda_{bj}^{\prime(5)}}{M_a M_b}$

Accidental symmetries

Lepton number is an accidental symmetry of the (minimal) Standard Model because all renormalizable couplings among the electroweak quark and lepton doublets and singlets and invariant under the gauge symmetry group SU(3)XSU(2)XU(1) do also preserve **baryon** and **lepton number**.

However, already at next order there exists **one dimension 5 operator with non-vanishing lepton number** equal to 2:

S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566
A. Santamaría's talk

$$\frac{C^{(5)}_{ee}}{\Lambda}\mathcal{O}^{(5)}_{ee} = \frac{C^{(5)}_{ee}}{\Lambda}\overline{\tilde{\ell}_{e\,L}}\phi\tilde{\phi}^{\dagger}\ell_{e\,L} \to -\frac{v^2 C^{(5)}_{ee}}{\Lambda}\overline{\nu^c_{e\,L}}\nu_{e\,L} + \cdots = -\frac{1}{2}(m_\nu)^*_{ee}\overline{\nu^c_{e\,L}}\nu_{e\,L} + \cdots$$

$$\tilde{\phi} = i\tau_2\phi^*,\ \tilde{\ell}_L = i\tau_2\ell^c_L$$

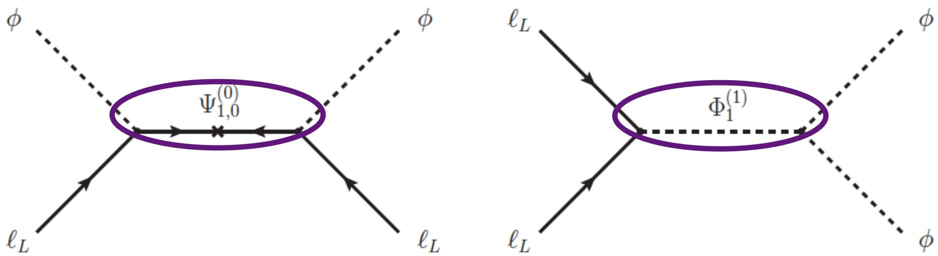
$$\langle\phi\rangle \equiv v \simeq 174\ \mathrm{GeV}$$

$$|(m_\nu)_{ee}| < 0.24 - 0.5\ \mathrm{eV}$$

$$|\Delta m^2_{31}| \cong 2.5\times 10^{-3}\ \ \mathrm{eV}^2$$

atmospheric neutrinos

$$\frac{\Lambda}{|C^{(5)}_{ee}|} > 10^{11}\ \mathrm{TeV}$$



see-saw I, III

see-saw II

P. Minkowski '77; M. Gell-Mann, P. Ramond and R. Slansky '79; T. Yanagida '79; R.N. Mohapatra and G. Senjanovic '80; J. Schechter and J.W.F. Valle '80

Coefficient	Type I	Type II	Type III
α_4	$-$	$2\frac{\lvert\mu_\Delta\rvert^2}{M_\Delta^2}$	$-$
$\frac{(\alpha_5)_{ij}}{\Lambda}$	$\frac{1}{2}\frac{(\lambda_N^T)_{ia}(\lambda_N)_{aj}}{M_{Na}}$	$-2\frac{\mu_\Delta(\lambda_\Delta)_{ij}}{M_\Delta^2}$	$\frac{1}{8}\frac{(\lambda_\Sigma^T)_{ia}(\lambda_\Sigma)_{aj}}{M_{\Sigma a}}$
$\frac{(\alpha_{\phi l}^{(1)})_{ij}}{\Lambda^2}$	$\frac{1}{4}\frac{(\lambda_N^\dagger)_{ia}(\lambda_N)_{aj}}{M_{Na}^2}$	$-$	$\frac{3}{16}\frac{(\lambda_\Sigma^\dagger)_{ia}(\lambda_\Sigma)_{aj}}{M_{\Sigma a}^2}$
$\frac{(\alpha_{\phi l}^{(3)})_{ij}}{\Lambda^2}$	$-\frac{(\alpha_{\phi l}^{(1)})_{ij}}{\Lambda^2}$	$-$	$\frac{1}{3}\frac{(\alpha_{\phi l}^{(1)})_{ij}}{\Lambda^2}$
$\frac{(\alpha_{ll}^{(1)})_{ijkl}}{\Lambda^2}$	$-$	$2\frac{(\lambda_\Delta)_{jl}(\lambda_\Delta^\dagger)_{ki}}{M_\Delta^2}$	$-$
$\frac{\alpha_\phi}{\Lambda^2}$	$-$	$-6(\lambda_3+\lambda_5)\frac{\lvert\mu_\Delta\rvert^2}{M_\Delta^4}$	$-$
$\frac{\alpha_\phi^{(1)}}{\Lambda^2}$	$-$	$4\frac{\lvert\mu_\Delta\rvert^2}{M_\Delta^4}$	$-$
$\frac{\alpha_\phi^{(3)}}{\Lambda^2}$	$-$	$4\frac{\lvert\mu_\Delta\rvert^2}{M_\Delta^4}$	$-$
$\frac{(\alpha_{e\phi})_{ij}}{\Lambda^2}$	$-$	$-$	$\frac{4}{3}\frac{(\alpha_{\phi l}^{(1)})_{ij}}{\Lambda^2}(\lambda_e)_{jj}$

The PMNS matrix is unitary to a very good approximation

$$\mathcal{L}_6 = \Big[(\alpha_{\phi l}^{(1)})_{ij}\boxed{\left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L^i}\gamma^\mu l_L^j\right)} + (\alpha_{\phi l}^{(3)})_{ij}\boxed{\left(\phi^\dagger i\sigma_a D_\mu \phi\right)\left(\overline{l_L^i}\sigma_a\gamma^\mu l_L^j\right)}$$
$$+ (\alpha_{e\phi})_{ij}\left(\phi^\dagger\phi\right)\left(\overline{l_L^i}\phi e_R^j\right) + (\alpha_{ll}^{(1)})_{ijkl}\frac{1}{2}\left(\overline{l_L^i}\gamma^\mu l_L^j\right)\left(\overline{l_L^k}\gamma_\mu l_L^l\right) + \text{h.c.}\Big]$$
$$+ \alpha_\phi^{(1)}\left(\phi^\dagger\phi\right)\left(\left(D_\mu\phi\right)^\dagger D^\mu\phi\right) + \alpha_\phi^{(3)}\left(\phi^\dagger D_\mu\phi\right)\left(\left(D^\mu\phi\right)^\dagger\phi\right) + \alpha_\phi\frac{1}{3}\left(\phi^\dagger\phi\right)^3$$

Modify the SM gauge couplings to neutrinos

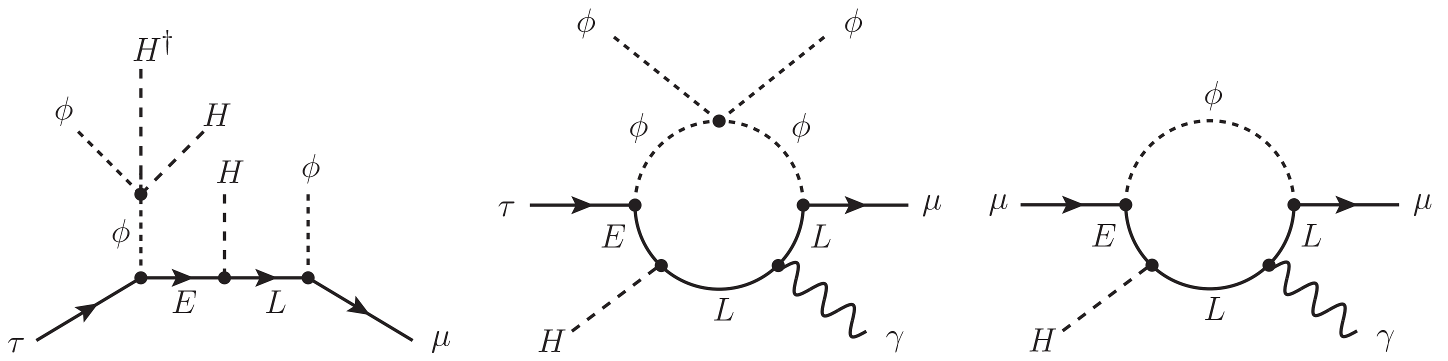
F. del Aguila, J.A. Aguilar-Saavedra, J. de Blas and M. Zralek, [arXiv:0710.2923 [hep-ph]]

$\boxed{h \to \tau\mu}$ $\qquad \tau \to \mu\gamma \qquad (g-2)_\mu$

$$\mathcal{L}_M = -M_L \bar{L}_L L_R - M_E \bar{E}_L E_R \;+\; \text{h.c.}$$

$$\mathcal{L}_Y = -Y_{LE} \bar{L}_L H E_R - Y_{EL} \bar{L}_R H E_L \;+\; \text{h.c.}$$

$$\begin{aligned} \mathcal{L}_\lambda \;=\; & -\lambda_{\mu L} \bar{\mu}_L L_R \phi^* - \lambda_{\tau L} \bar{\tau}_L L_R \phi \\ & -\lambda_{\mu E} \bar{\mu}_R E_L \phi^* - \lambda_{\tau E} \bar{\tau}_R E_L \phi \;+\; \text{h.c.} \end{aligned}$$



$L_\mu - L_\tau$

W. Altmannshofer, M. Carena and A. Crivellin, [arXiv:1604.08221 [hep-ph]]

Flavor changing top couplings

J.A. Aguilar-Saavedra, [arXiv:0904.2387 [hep-ph]]

$$\begin{aligned}\mathcal{L}_{Ztc} &= -\frac{g}{2c_W}\bar{c}\,\gamma^\mu\left(X_{ct}^L P_L + X_{ct}^R P_R\right) t\; Z_\mu \\ &\quad -\frac{g}{2c_W}\bar{c}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(\kappa_{ct}^L P_L + \kappa_{ct}^R P_R\right) t\; Z_\mu + \mathrm{H.c.}\end{aligned}$$

$$\delta X_{ct}^L = \frac{1}{2}\left[C_{\phi q}^{(3,2+3)} - C_{\phi q}^{(1,2+3)}\right]\frac{v^2}{\Lambda^2}\,,$$

$$\delta X_{ct}^R = -\frac{1}{2}C_{\phi u}^{2+3}\frac{v^2}{\Lambda^2}\,,$$

$$\delta\kappa_{ct}^L = \sqrt{2}\left[c_W C_{uW}^{32*} - s_W C_{uB\phi}^{32*}\right]\frac{v^2}{\Lambda^2}\,,$$

$$\delta\kappa_{ct}^R = \sqrt{2}\left[c_W C_{uW}^{23} - s_W C_{uB\phi}^{23}\right]\frac{v^2}{\Lambda^2}$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$

3 (2) stands for t (c)

$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}}\bar{c}\left(\eta_{ct}^L P_L + \eta_{ct}^R P_R\right) t\; H + \mathrm{H.c.}$$

$$\begin{aligned}\delta\eta_{ct}^L &= -\frac{3}{2}C_{u\phi}^{32*}\frac{v^2}{\Lambda^2} \\ \delta\eta_{ct}^R &= -\frac{3}{2}C_{u\phi}^{23}\frac{v^2}{\Lambda^2}\end{aligned}$$

Warsaw basis

W. Buchmüller and D. Wyler, Nucl. Phys. B268 (1986) 621

Gauge-invariant dimension 6 operators constructed with the Standard Model fields, up to redundancies which are taking care using equations of motion for fermions and gauge and Higgs bosons, integration by parts, Pauli (SU(2)) and Gell-Mann (SU(3)) matrix properties and Fierz transformations

B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, [arXiv:1008.4884 [hep-ph]]

J.A. Aguilar-Saavedra, [arXiv:1008.3562 [hep-ph]]

Ignoring flavor indices and assuming that there are not light right-handed neutrinos (and that baryon number is conserved)

Operator basis	*1986*	*2010*
No fermions	16	15
2 fermions	35	19
4 fermions	29	25
Dimension 6	**80**	**59**

J.A. Aguilar-Saavedra, [arXiv:1008.3562 [hep-ph]]

Three-body top decays and single and pair top production

Pauli (τ) and Gell-Mann (λ) matrices:

$$\sum_{I=1}^{3}(\tau^I)_{ij}(\tau^I)_{kl} = 2\left(\delta_{il}\delta_{kj} - \tfrac{1}{2}\delta_{ij}\delta_{kl}\right)$$

$$\sum_{a=1}^{8}(\lambda^a)_{ij}(\lambda^a)_{kl} = 2\left(\delta_{il}\delta_{kj} - \tfrac{1}{3}\delta_{ij}\delta_{kl}\right)$$

two orderings

Fierz rearrangements:

$$\begin{aligned}
(\bar{A}_L\gamma^\mu B_L)(\bar{C}_L\gamma_\mu D_L) &= (\bar{A}_L\gamma^\mu D_L)(\bar{C}_L\gamma_\mu B_L) \\
(\bar{A}_R\gamma^\mu B_R)(\bar{C}_R\gamma_\mu D_R) &= (\bar{A}_R\gamma^\mu D_R)(\bar{C}_R\gamma_\mu B_R) \\
(\bar{A}_R\gamma^\mu B_R)(\bar{C}_L\gamma_\mu D_L) &= -2(\bar{C}_L B_R)(\bar{A}_R D_L)
\end{aligned}$$

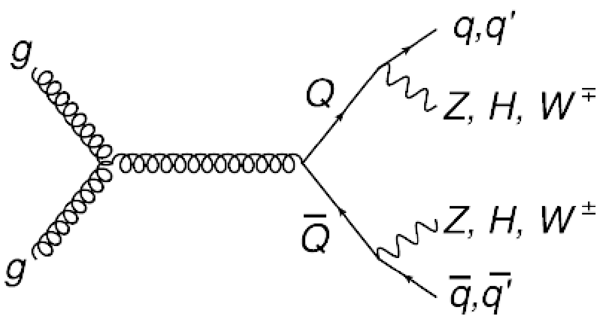
572 independent gauge-invariant four-fermion operators involving one or two top quarks (taking into account different fermion chiralities, colour contractions and flavour combinations) -out of the 25 different types of independent four-fermion operators-.

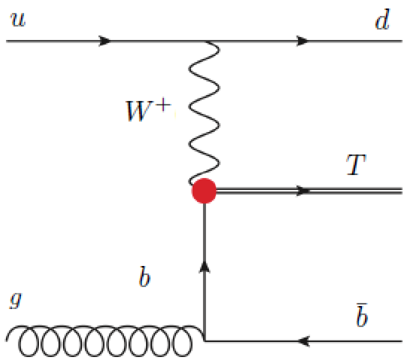
F. del Aguila, L. Ametller, G.L. Kane and J. Vidal, Nucl. Phys. B 334 (1990) 1

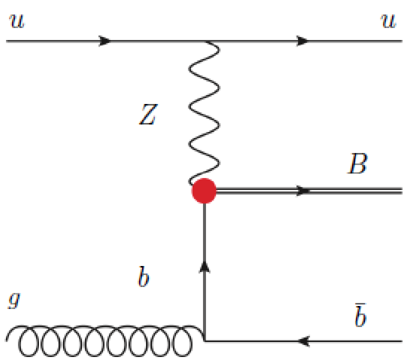
New vector-like fermion	Dominant production terms
D	$\mathscr{L}_{\text{QCD}} = -ig_s A_{a\mu} \bar{D} T^a \gamma^\mu D$
$\begin{pmatrix} \text{U} \\ \text{D} \end{pmatrix}$	$\mathscr{L}_{\text{QCD}} = -ig_s A_{a\mu} (\bar{U} T^a \gamma^\mu U + \bar{D} T^a \gamma^\mu D)$
U	$\mathscr{L}_{\text{QCD}} = -ig_s A_{a\mu} \bar{U} T^a \gamma^\mu U$
E	$\mathscr{L}_{\gamma+\text{Z}} = eA_\mu J^\mu_{\text{EM}} - \dfrac{es_{\text{W}}}{c_{\text{W}}} Z_\mu J^\mu_{\text{EM}};$
	$J^\mu_{\text{EM}} = -\bar{E}\gamma^\mu E$
$\begin{pmatrix} \text{N} \\ \text{E} \end{pmatrix}$	$\mathscr{L}_{\gamma+\text{W}^\pm+\text{Z}} = eA_\mu J^\mu_{\text{EM}}$
	$+ \dfrac{g_2}{2c_{\text{W}}} Z_\mu (\bar{N}\gamma^\mu N - \bar{E}\gamma^\mu E - 2s^2_{\text{W}} J^\mu_{\text{EM}})$
	$+ \dfrac{g_2}{\sqrt{2}} W^+_\mu \bar{N}\gamma^\mu E + \text{h.c.}; \quad J^\mu_{\text{EM}} = -\bar{E}\gamma^\mu E$

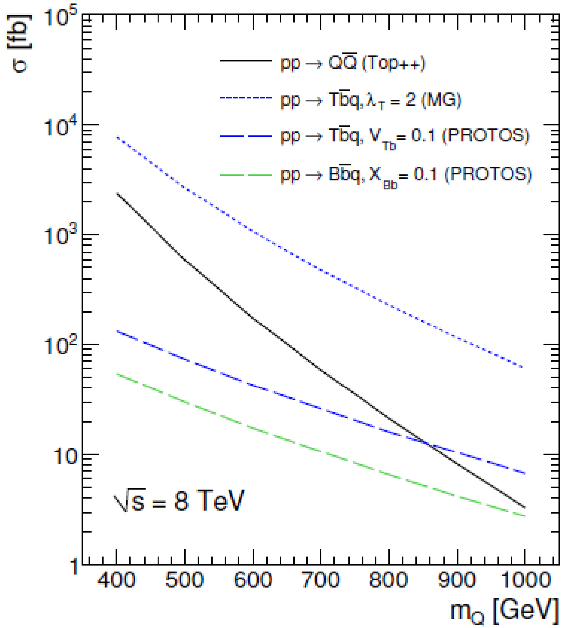
VLQs have a quite rich phenomenology

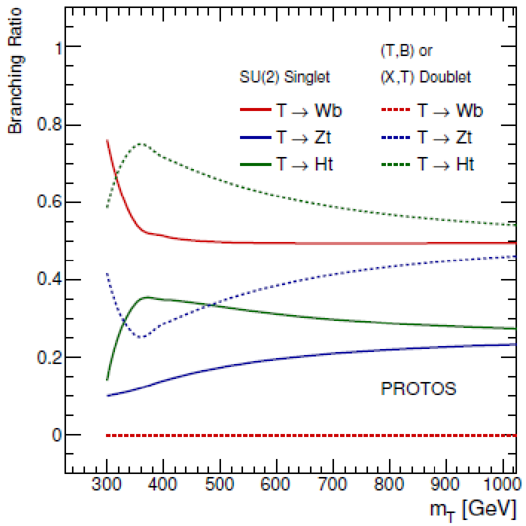
☞ pair and single production

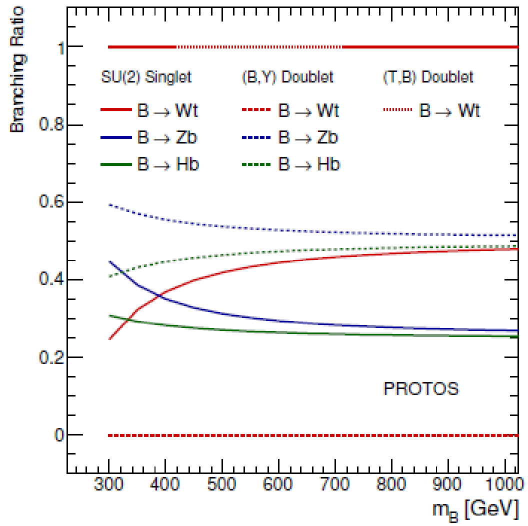






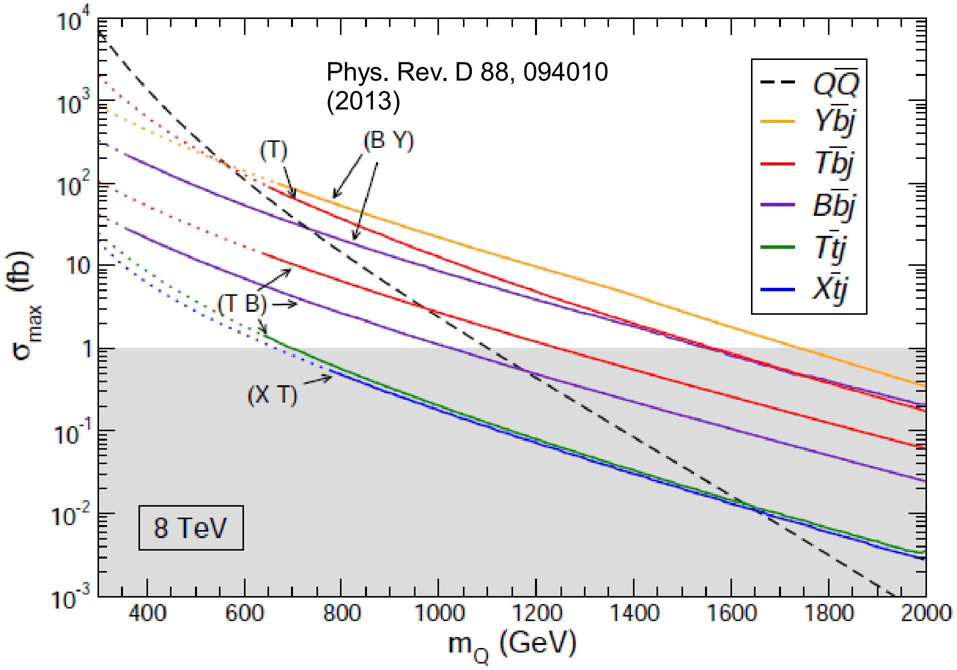


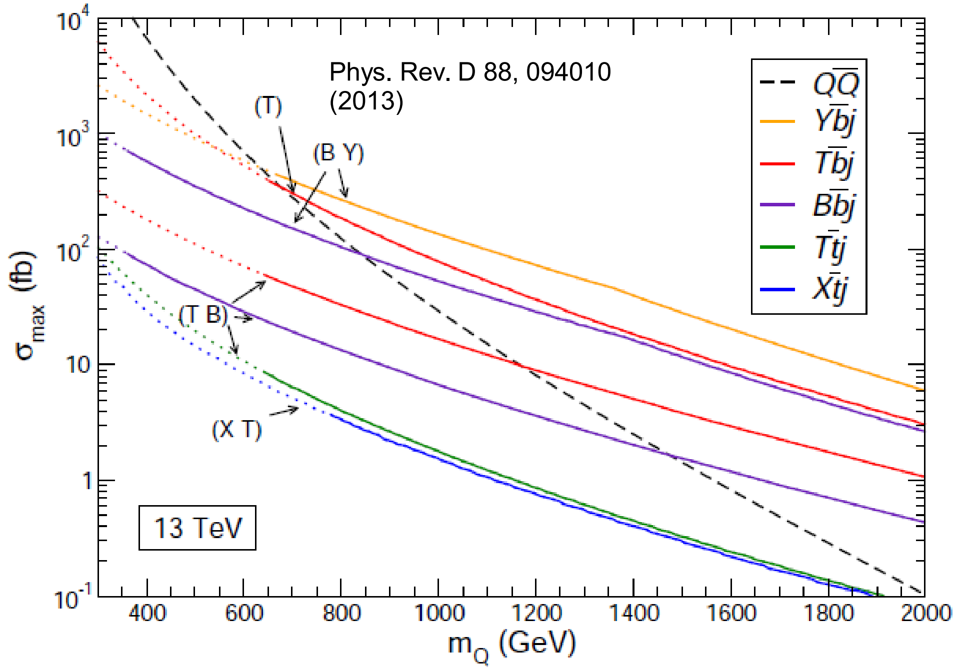




☞ FCNC present at tree level

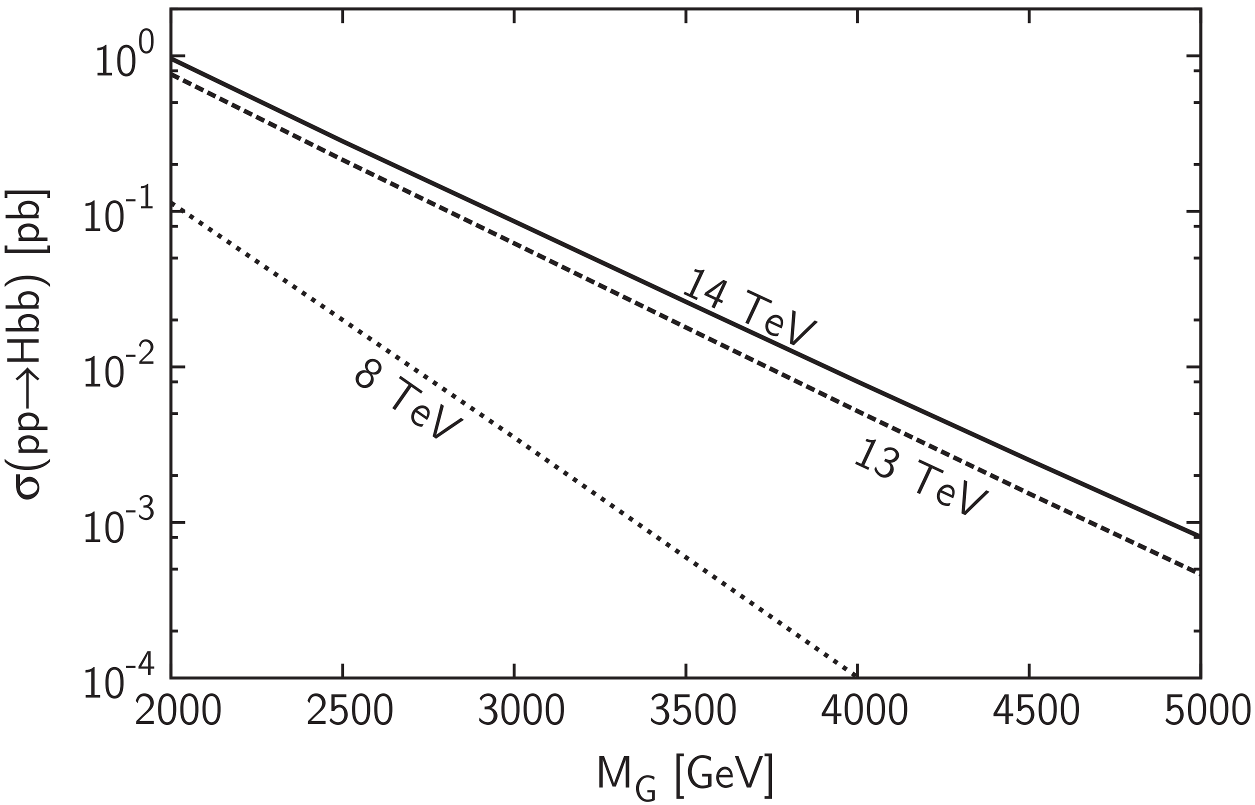
- Single production is more complicate (and interesting…) from the phenomenology point of view
  - Can dominate for high VLQ masses:





M. Chala and J. Santiago, [arXiv:1305.1940 [hep-ph]]

$$pp \longrightarrow G^* \longrightarrow B_H\bar{b} + \bar{B}_H b \longrightarrow Hb\bar{b} \longrightarrow 4b$$



Fraction of (vector-like) $Q\bar{Q}$ decays into final states with at most one neutrino. ℓ stands for e and μ. We take an average for the branching ratio into W, Z and H (see text) and assume that H always decays into $q\bar{q}$. For each mode we give in parentheses the fraction of events with at least one Higgs

Signal	Decay mode fraction	$D = U = \begin{pmatrix} U \\ D \end{pmatrix}$ (Fraction of events with a Higgs)
$q\bar{q}\ell\bar{\ell}\ell\bar{\ell}$	3×10^{-4}	(—)
$q\bar{q}\ell\bar{\ell}\ell\nu$	4×10^{-3}	(—)
$q\bar{q}q\bar{q}\ell\bar{\ell}$	0.03	(0.33)
$q\bar{q}q\bar{q}\ell\nu$	0.17	(0.33)
$q\bar{q}q\bar{q}q\bar{q}$	0.59	(0.55)

Total cross sections (in pb) for the signals with at least one lepton, and for different colliders and illustrative vector-like quark masses

	$q\bar{q}\ell\bar{\ell}\ell\bar{\ell}$ $D = U = \frac{1}{2}\begin{pmatrix} U \\ D \end{pmatrix}$	$q\bar{q}\ell\bar{\ell}\ell\nu$ $D = U = \frac{1}{2}\begin{pmatrix} U \\ D \end{pmatrix}$	$q\bar{q}q\bar{q}\ell\bar{\ell}$ $D = U = \frac{1}{2}\begin{pmatrix} U \\ D \end{pmatrix}$	$q\bar{q}q\bar{q}\ell\nu$ $D = U = \frac{1}{2}\begin{pmatrix} U \\ D \end{pmatrix}$
Tevatron $M_Q = 150$ GeV	2×10^{-3}	0.03	0.2	1.3
UNK $M_Q = 300$ GeV	2×10^{-3}	0.03	0.2	1.2
LHC $M_Q = 700$ GeV	3×10^{-4}	4×10^{-3}	0.03	0.2
SSC $M_Q = 700$ GeV	4×10^{-3}	0.05	0.4	2.4

Vector-like quarks: what next?

- With more data we will have new opportunities for discovery (or to improve on exclusion limits…):

	T_s	B_s	TB_{d_1}	TB_{d_2}	XT_d	BY_d
$\ell^+\ell^+\ell^-\ell^-$ (ZZ)	–	24 fb^{-1}	18 fb^{-1}	23 fb^{-1}	23 fb^{-1}	10 fb^{-1}
$\ell^+\ell^+\ell^-\ell^-$ (Z)	11 fb^{-1}	14 fb^{-1}	5.7 fb^{-1}	3.4 fb^{-1}	3.3 fb^{-1}	50 fb^{-1}
$\ell^+\ell^+\ell^-\ell^-$ (no Z)	35 fb^{-1}	25 fb^{-1}	11 fb^{-1}	3.3 fb^{-1}	3.5 fb^{-1}	–
$\ell^\pm\ell^\pm\ell^\mp$ (Z)	3.4 fb^{-1}	3.4 fb^{-1}	1.1 fb^{-1}	0.73 fb^{-1}	0.72 fb^{-1}	26 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$ (no Z)	11 fb^{-1}	3.5 fb^{-1}	1.1 fb^{-1}	0.25 fb^{-1}	0.25 fb^{-1}	–
$\ell^\pm\ell^\pm$	17 fb^{-1}	4.1 fb^{-1}	1.5 fb^{-1}	0.23 fb^{-1}	0.23 fb^{-1}	–
$\ell^+\ell^-$ (Z)	22 fb^{-1}	4.5 fb^{-1}	2.4 fb^{-1}	4.4 fb^{-1}	4.4 fb^{-1}	1.8 fb^{-1}
$\ell^+\ell^-$ $(Z, 4b)$	–	–	30 fb^{-1}	–	–	9.2 fb^{-1}
$\ell^+\ell^-$ (no Z)	2.7 fb^{-1}	9.3 fb^{-1}	0.83 fb^{-1}	1.1 fb^{-1}	1.1 fb^{-1}	0.87 fb^{-1}
$\ell^\pm$ $(2b)$	1.1 fb^{-1}	–	0.60 fb^{-1}	–	–	0.18 fb^{-1}
$\ell^\pm$ $(4b)$	0.70 fb^{-1}	1.9 fb^{-1}	0.25 fb^{-1}	0.16 fb^{-1}	0.16 fb^{-1}	6.2 fb^{-1}
$\ell^\pm$ $(6b)$	11 fb^{-1}	–	9.4 fb^{-1}	2.7 fb^{-1}	2.7 fb^{-1}	–

[arXiv:0907.3155]

Luminosity required to have a 5σ discovery in all final states studied.

This is an old study on the discovery reach of 500 GeV VLQs

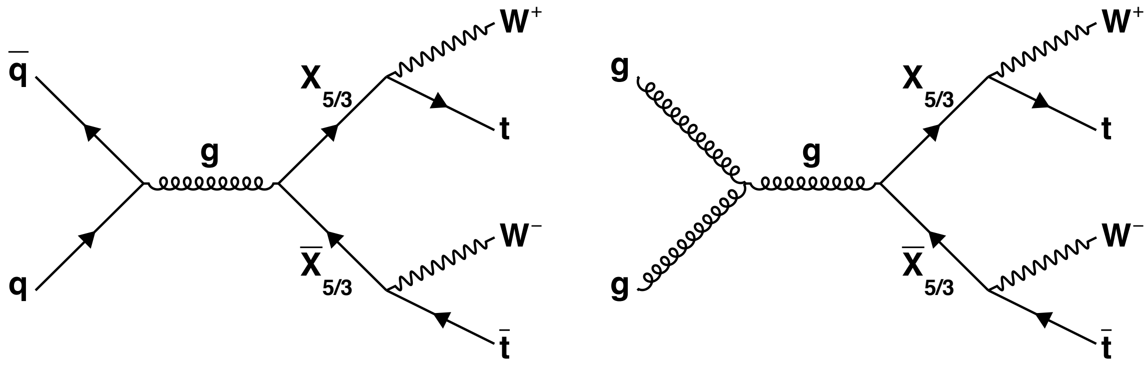
$\longrightarrow$ the message is still valid: different channels are required for a discovery (and to identify the nature of the discovered VLQ)

	Dominant decay terms
D	$\mathscr{L}=\left(\frac{g_2}{\sqrt{2}} W_\mu^+ \bar{u}_{\mathrm{L}i}\gamma^\mu C_{ij} \frac{m'_j}{M_\mathrm{Q}} D_\mathrm{L} - \frac{g_2}{2c_\mathrm{W}} Z_\mu \bar{d}_{\mathrm{L}i}\gamma^\mu \frac{m'_i}{M_\mathrm{Q}} D_\mathrm{L} - H \bar{d}_{\mathrm{L}i} \frac{m'_i}{v} D_\mathrm{R} \right) + \text{h.c.}$
$\begin{pmatrix} \mathrm{U} \\ \mathrm{D} \end{pmatrix}$	$\mathscr{L}=\left(-\frac{g_2}{\sqrt{2}} W_\mu^+ \left[\bar{U}_\mathrm{R} \gamma^\mu \frac{m_j}{M_\mathrm{Q}} d_{\mathrm{R}j} + \bar{u}_{\mathrm{R}j}\gamma^\mu C'_{ji} \frac{m_i^*}{M_\mathrm{Q}} D_\mathrm{R} \right] - \frac{g_2}{2c_\mathrm{W}} Z_\mu \left[\bar{U}_\mathrm{R}\gamma^\mu \frac{m_i}{M_\mathrm{Q}} C'^{\dagger}_{ik} u_{\mathrm{R}k} - \bar{d}_{\mathrm{R}j}\gamma^\mu \frac{m_j^*}{M_\mathrm{Q}} D_\mathrm{R} \right] - H[\bar{U}_\mathrm{L} \frac{m_i}{v} C'^{\dagger}_{ik} u_{\mathrm{R}k} + \bar{d}_{\mathrm{R}j} \frac{m_j^*}{v} D_\mathrm{L}] \right) + \text{h.c.}$
U	$\mathscr{L}=\left(\frac{g_2}{\sqrt{2}} W_\mu^+ \bar{U}_\mathrm{L}\gamma^\mu \frac{m'^*_j}{M_\mathrm{Q}} C_{ji} d_{\mathrm{L}i} + \frac{g_2}{2c_\mathrm{W}} Z_\mu \bar{U}_\mathrm{L}\gamma^\mu \frac{m'^*_i}{M_\mathrm{Q}} u_{\mathrm{L}i} - H\bar{U}_\mathrm{R} \frac{m'^*_i}{v} u_{\mathrm{L}i} \right) + \text{h.c.}$
E	$\mathscr{L}=\left(\frac{g_2}{\sqrt{2}} W_\mu^+ \bar{\nu}_{\mathrm{L}i}\gamma^\mu \frac{m'_i}{M_\mathrm{L}} E_\mathrm{L} - \frac{g_2}{2c_\mathrm{W}} Z_\mu \bar{e}_{\mathrm{L}i}\gamma^\mu \frac{m'_i}{M_\mathrm{L}} E_\mathrm{L} - H\bar{e}_{\mathrm{L}i}\frac{m'_i}{v} E_\mathrm{R} \right) + \text{h.c.}$
$\begin{pmatrix} \mathrm{N} \\ \mathrm{E} \end{pmatrix}$	$\mathscr{L}=\left(-\frac{g_2}{\sqrt{2}} W_\mu^+ \bar{N}_\mathrm{R}\gamma^\mu \frac{m_j}{M_\mathrm{L}} e_{\mathrm{R}j} + \frac{g_2}{2c_\mathrm{W}} Z_\mu \bar{E}_\mathrm{R}\gamma^\mu \frac{m_j}{M_\mathrm{L}} e_{\mathrm{R}j} - H\bar{E}_\mathrm{L} \frac{m_j}{v} e_{\mathrm{R}j} \right) + \text{h.c.}$

A. Atre, M. Carena, T. Han and J. Santiago
B. [arXiv:0806.3966 [hep-ph]]

$$[2_{\frac{1}{6}}, 2_{\frac{7}{6}}] = \left[\begin{pmatrix} T \\ B \end{pmatrix}, \begin{pmatrix} X \\ T' \end{pmatrix} \right]$$

$$\left. \begin{array}{l} B_R, X_R \to W t_R \\ T_L + T'_L \to H t_R \\ T_R - T'_R \to Z t_R \end{array} \right\} \left\{ \begin{array}{c} \lambda_t = \lambda'_t \\ M_{\frac{1}{6}} = M_{\frac{7}{6}} \\ \lambda_b = 0 \end{array} \right.$$



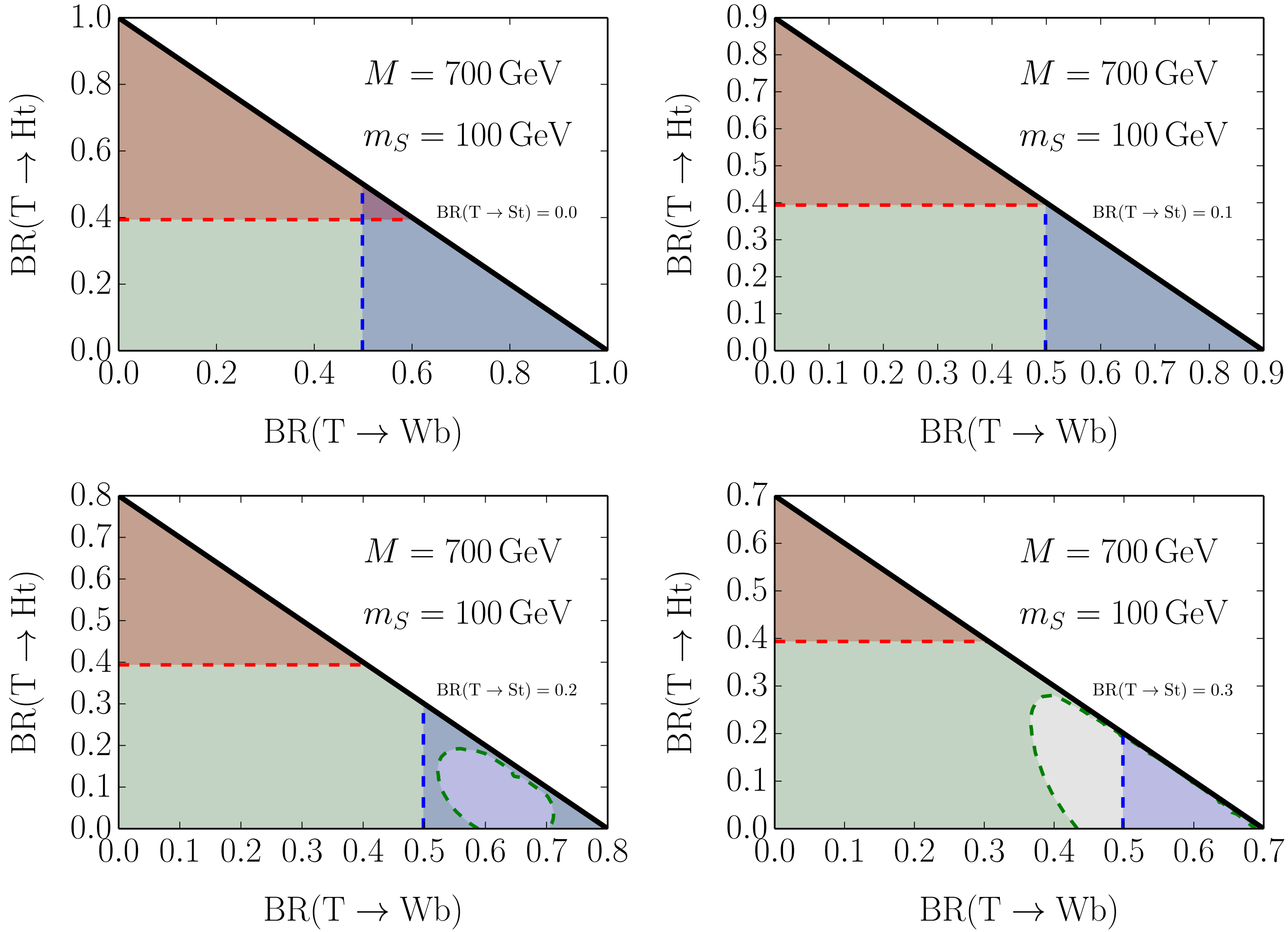
$X_{5/3}$ masses with right-handed (left-handed) couplings below 1.32 (1.30) TeV are excluded at 95% confidence level

CMS Collaboration, CMS PAS B2G-17-008

Under the assumption of strong pair production of vector-like quarks and 100% branching fractions to bW, an observed (expected) lower limit of 1295 (1275) GeV at 95% CL is set on the $T_{2/3}$($Y_{-4/3}$) quark mass

CMS Collaboration, CMS PAS B2G-17-003

M. Chala, [arXiv:1705.03013 [hep-ph]]



$$\mathrm{BR}(T \to Ht) + \mathrm{BR}(T \to Wb) + \mathrm{BR}(T \to Zt) + \boxed{\mathrm{BR}(T \to St)} = 1$$

Vector-like quarks: what next?

- But there is also a lot to do beyond that (and already with 100/fb):

  - More data will allow us to have more elaborate analysis
    - Advanced MVA techniques
    - Continue to explore (and improve) the use of boosted objects and top/W/Z/H tagging

  - And also to be more advanced in our assumptions
    (actually some of this work already started in run-1…)
    - Present limits relaxing the Σ BR(VLQ$\rightarrow$ SM) =1 assumption
    - Test the chirality of the VLQ couplings
    - Coupling to light generations
    - Alternative production mechanisms

Further conclusions

- Rare processes $\left(\sim \frac{m'}{M} \to \frac{m'^2}{M^2} \right)$
- Much richer phenomenology when lower is the new physics scale
- Complementary to production $\left(E \sim M \right)$

Thanks for your attention

CENTRO ANDALUZ DE FISICA
DE PARTICULAS ELEMENTALES

Universidad
de Granada