Hints for Flavorful New Physics?

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The Standard Model as Effective Theory

$$\mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}$$

The Standard Model as Effective Theory



What is the New Physics scale Λ ?

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Indirect Tests of New Physics



	$1: X^{3}$	2:	H^{6}	$3: H^4D^2$				$5: \psi^2 H^3 + h.c.$		
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_H ($H^{\dagger}H)^{3}$	$Q_{H\square}$	(H^{\dagger})	$H)\square(H^{\dagger}h)$	I)	Q_{eH}	$(H^{\dagger}H)(\bar{l}_{p}e_{r}H)$	
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$			Q_{HD}	$(H^{\dagger}D_{\mu})$	H) [*] ($H^{\dagger}I$	$D_{\mu}H$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$							Q_{dH}	$(H^{\dagger}H)(\bar{q}_{p}d_{r}H)$	
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$									
	$4:X^2H^2$	($b : \psi^2 X H$	+ h.c.			7	$: \psi^2 H^2$	D	
Q_{HG}	$H^{\dagger}H G^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu})$	$e_r)\tau^I HW$	1 μν	$Q_{Hl}^{(1)}$		$(H^{\dagger}i\dot{1}$	$\vec{D}_{\mu}H)(\bar{l}_{p}\gamma^{\mu}l_{r})$	
$Q_{H\tilde{G}}$	$H^{\dagger}H \widetilde{G}^{A}_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^\mu$	$\nu e_r)HB_p$	Ψ	$Q_{Hl}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$	
Q_{HW}	$H^{\dagger}H W^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu})$	$T^A u_r) \tilde{H}$	$G^A_{\mu\nu}$	Q_{He}		$(H^{\dagger}i\overleftarrow{I}$	$\vec{\partial}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$	
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu})$	$u_r)\tau^I \tilde{H} V$	$V^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$		$(H^{\dagger}i\overleftarrow{I}$	$\vec{D}_{\mu}H)(\bar{q}_p\gamma^{\mu}q_r)$	
Q_{HB}	$H^{\dagger}H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^\mu$	$\nu u_r)\tilde{H}B_i$	uν	$Q_{Hq}^{(3)}$		$(H^\dagger i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r})$	
$Q_{H\widetilde{B}}$	$H^{\dagger}H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu})$	$T^A d_r)H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftarrow{L})$	$\vec{D}_{\mu}H)(\bar{u}_p\gamma^{\mu}u_r)$	
Q_{HWB}	$H^{\dagger}\tau^{I}HW^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu})$	$(d_r)\tau^I H V$	$V^{I}_{\mu\nu}$	Q_{Hd}		$(H^{\dagger}i\overleftarrow{I}$	$\vec{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$	
$Q_{H \widetilde{W} B}$	$H^\dagger \tau^I H \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu}$	$\nu d_r H B_p$	w	Q_{Hud} +	h.c.	$i(\widetilde{H}^{\dagger}L$	$(\bar{u}_p \gamma^{\mu} d_r)$	
	$8:(\bar{L}L)(\bar{L}L)$		8:(.	$\bar{R}R)(\bar{R}R)$)		8:	$(\bar{L}L)(\bar{R}F)$?)	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	(\bar{e}_i)	$_{p}\gamma_{\mu}e_{r})(\bar{e}_{s}$	$\gamma^{\mu}e_t$)	Q_{le}	($\bar{l}_p \gamma_\mu l_r)(\bar{e}$	$i_s \gamma^{\mu} e_t$)	
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_j$	$\gamma_{\mu}u_{r})(\bar{u},$	$\gamma^{\mu}u_t$)	$Q_{\rm fu}$	- ($(\bar{u}_p \gamma_\mu l_r)(\bar{u}_p)$	$_{s}\gamma^{\mu}u_{t})$	
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_{j}$	$_{p}\gamma_{\mu}d_{r})(\bar{d}_{s}$	$\gamma^{\mu}d_t)$	Q_{ld}	($\bar{l}_p \gamma_\mu l_r)(\bar{d}$	$(\bar{l}_s \gamma^{\mu} d_t)$	
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	(\bar{e}_{I})	$\gamma_{\mu}e_{r})(\bar{u}_{s}$	$\gamma^{\mu}u_t$)	Q_{qe}	($\bar{q}_p \gamma_\mu q_r)(\bar{\epsilon}$	$\bar{e}_s \gamma^{\mu} e_t$)	
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	(ē,	$_{p}\gamma_{\mu}e_{r})(\bar{d}_{s}$	$\gamma^{\mu}d_t$)	$Q_{qu}^{(1)}$	(ġ	$\bar{q}_p \gamma_\mu q_r)(\bar{u}$	$i_s \gamma^{\mu} u_t$)	
		$Q_{ud}^{(1)}$	(<i>ū</i> _j	$_{p}\gamma_{\mu}u_{r})(\bar{d}_{t}$	$\gamma^{\mu}d_{t})$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_p)$	$(T^A q_r)(i$	$i_s \gamma^{\mu} T^A u_t$)	
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu)$	$T^A u_r)(\bar{d}_i$	$\gamma^{\mu}T^{A}d_{t})$	$-Q_{qd}^{(1)}$	(ē	$\bar{q}_p \gamma_\mu q_r)(\dot{a}$	$\bar{l}_s \gamma^{\mu} d_t$)	
						$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_p)$	$_{x}T^{A}q_{r})(c$	$\bar{l}_s \gamma^{\mu} T^A d_t$)	
	8 : (<i>LR</i>)(<i>L</i>	RL) + h	.c.	8:()	$(\bar{L}R)(\bar{L}R)$	+ h.c.				
	Q _{teda} (Ē	$(\bar{d}_s q)$	(ii) G	2(1)	$(\bar{q}_n^j u_r)\epsilon_i$	$_{ik}(\bar{q}_{s}^{k}d_{t})$	_			
	areat [()	, . , (2 ⁽⁸⁾	$\bar{e}^{j}T^{A}u_{x})e_{i}$	$u(\bar{a}^kT^Ad)$)			

 $Q_{lequ}^{(1)}$

 $(\bar{l}_{p}^{j}e_{r})\epsilon_{jk}(\bar{q}_{s}^{k}u_{t})$ $Q_{lemu}^{(3)}$ $(\bar{l}_{p}^{j}\sigma_{\mu\nu}e_{r})\epsilon_{jk}(\bar{q}_{s}^{k}\sigma^{\mu\nu}u_{t})$

2499 baryon and lepton number conserving dim. 6 operators

Grzadkowski et al. 1008.4884,

Alonso et al 1312 2014

	$1:X^3$	$2:H^6$		$3 : H^4D^2$				$5:\psi^2H^3+{\rm h.c.}$	
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_H (E	$(H^{\dagger}H)^{3}$	$Q_{H\square}$	$(H^{\dagger}$	$H)\Box(H^{\dagger}H)$	()	Q_{eH}	$(H^{\dagger}H)(\bar{l}_{p}e,H)$
$Q_{\tilde{G}}$	$f^{ABC} {\tilde G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$			Q_{HD}	$(H^{\dagger}D_{\mu}$	H) [*] ($H^{-}I$	$D_{\mu}H)$	Q_{uH}	$(H^{+}H)(\bar{q}_{p}u_{r}\tilde{H})$
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}=$							Q_{dH}	$(H^{\dagger}H)(\bar{q}_{p}d_{r}H)$
$Q_{\tilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$								
	$4:X^2H^2$	6	$\psi^2 X H$	+ h.c.			1	$7: \psi^2 H^2$	D
Q_{HG}	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e$	$_{\tau})\tau^{I}H$	$W^{I}_{\mu\nu}$	$Q_{H!}^{(1)}$		$(\Pi^{\dagger}i^{\dagger}I$	$\vec{\mathcal{D}}_{\mu} II (\bar{l}_{p} \gamma^{\mu} l_{\tau})$
$Q_{H\bar{G}}$	$H^{\dagger}H {\widetilde G}^A_{\mu\nu}G^{A\mu\nu}$	Q_{zB}	$(\bar{l}_p \sigma^{\mu\nu}$	$e_{\tau})HE$	ε _{μ.ν} .	$Q_{H!}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p} au^{I}\gamma^{\mu}l_{r})$
Q_{HW}	$H^{\dagger}HW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_{\rho}\sigma^{\mu\nu}T)$	$(A_{v_r})\tilde{H}$	$G^A_{\mu\nu}$	Q_{He}		$(H^{\dagger}i\dot{L}$	$\vec{P}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_{\rm F}\sigma^{\mu\nu}u$	$_{r})\tau^{I}\tilde{H}$	$W^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$		$(H^{\dagger}i\overset{\leftarrow}{I}$	$\vec{D}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$
Q_{HB}	$H^*H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu})$	$u_r)HI$	3,10	$Q_{Hq}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{q}_{\rho}\tau^{I}\gamma^{\mu}q_{r})$
$Q_{H\widetilde{B}}$	$H^*H \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T$	$(^{A}d_{r})H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftarrow{D}$	$\dot{D}_{\mu}H)(\bar{u}_p\gamma^{\mu}u_r)$
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d$	$(\tau)\tau^{I}H$	$W^{I}_{\mu\nu}$	Q_{Hd}		$(H^{\dagger}i\overline{L})$	$\vec{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$
$Q_{H\widetilde{W}B}$	$H^{\dagger}\tau^{I}H \widetilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	Q_{AB}	$(\bar{q}_p \sigma^{\mu\nu})$	$d_r)HI$	$\beta_{\mu\nu}$	Q_{Hud} +	h.c.	$i(\widetilde{H}^*L$	$(\bar{v}_{p}\gamma^{\mu}d_{r})$
	8 : $(\bar{L}L)(\bar{L}L)$		8 : (İ	$(R)(\bar{R})$	Z)		8:	$(\bar{L}L)(\bar{R}F)$	2)
2:1	$(\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p$	$\gamma_\mu e_r)(i$	$\epsilon_s \gamma^{\mu} e_t$)	Q_{lv}	($\bar{l}_p \gamma_\mu l_\tau)(\bar{e}$	$(_{s}\gamma^{\mu}e_{t})$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	(\bar{u}_p)	$\gamma_{\mu}u_r)(i$	$i_s \gamma^{\mu} u_i$)	Q_{lu}	($\bar{l}_p \gamma_\mu i_r)(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^J q_r)(\bar{q}_s \gamma^\mu \tau^J q_t)$	Q_{dd}	(\bar{d}_p)	$\gamma_{\mu}d_r)(a$	$\bar{i}_s \gamma^{\mu} d_t$)	Q_{ld}	($\bar{l}_p \gamma_\mu l_\tau)(\bar{d}$	$(\gamma^{\mu}d_{t})$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_{eu}	(\bar{e}_p)	$\gamma_{\mu}e_{\tau})(i$	$i_s \gamma^{\mu} u_t$)	Q_{qe}	($\bar{q}_p \gamma_\mu q_r)(\bar{\epsilon}$	$\bar{\epsilon}_s \gamma^{\mu} v_t$)
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau' l_r)(\bar{q}_s \gamma^\mu \tau^I q_i)$	Q_{cd}	(\bar{e}_p)	$\gamma_{\mu}e_{r})(\dot{e}$	$\bar{l}_o \gamma^{\mu} d_t$)	$Q_{q_2}^{(1)}$	6	$\bar{l}_p \gamma_\mu q_r)(\bar{u}$	$i_a \gamma^{\mu} u_t$)
		$Q_{nd}^{(1)}$	(\bar{u}_p)	$\gamma_{\mu}u_r)(e$	$\bar{l}_s \gamma^{\mu} d_t$)	$Q_{q_{2}}^{(8)}$	$(\bar{q}_p\gamma)$	$_{a}T^{A}q_{r})(\bar{u}$	$i_a \gamma^\mu T^A v_i$)
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T)$	$^{\circ A}u_{r})(e$	$\bar{l}_s \gamma^{\mu} T^A d_i$)	$Q_{qd}^{(1)}$	()	$\bar{q}_p \gamma_\mu q_r)(\dot{a}$	$\bar{l}_s \gamma^{\mu} d_t$)
						$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_l$	$_{\mu}T^{A}q_{r})(\dot{a}$	$\bar{l}_s \gamma^{\mu} T^A d_t$
	$8 : (\bar{L}R)(\bar{I}$	$\bar{R}L$) + h.c		8:	$(\bar{L}R)(\bar{L}R)$	+ h.c.			
	$Q_{ledg} = (\bar{l}_j^2)$	$(\bar{d}_s q_t)$) Q	(1) gugd	$(\bar{q}_p^j u_r)e$	$_{jk}(\bar{q}_{s}^{k}d_{t})$	_		
			Q	(8) gugd	$(\bar{q}_p^j T^A u_r) \epsilon$	$_{jk}(\bar{q}_{s}^{k}T^{A}d_{t}$)		
			Q	(1) lega	$(\bar{l}_{p}^{j}\epsilon_{r})\epsilon_{j}$	$_{k}(\bar{q}_{s}^{k}u_{1})$			
			0	(3)	$(\overline{P}, \sigma_{m}, c_{n})c_{n}$	$\sqrt{a^k}\sigma^{\mu\nu}\mu$	a –		

2499 baryon and lepton number conserving dim. 6 operators

Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

flavor violation from

4 fermion interactions

	$1: X^3$	$2:H^6$			$3 : H^4 D^2$				$5: \psi^2 H^3 + h.c.$		
Q_G	$\int^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	Q_H (3	$H^{\dagger}H)^{3}$	$Q_{H\square}$	(H	$^{\dagger}H)\Box(H^{\dagger}H)$		Q_{eH}	$(H^{\dagger}H)(\bar{l}_{p}e, H)$	Ŧ)	
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$			Q_{HD}	$(H^{\dagger}D$	$_{\mu}H)^{*}(H^{*}H)$	$D_{\mu}H)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \hat{I}$	\tilde{H})	
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$							Q_{dH}	$(H^{\dagger}H)(\bar{q}_{p}d_{r}H)$	H)	
$Q_{\tilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$										
	$4:X^2H^2$	6	$: \psi^2 X H$	+ h.c.			1	$7: \psi^2 H^2$	D		
Q_{HG}	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e$	$e_r)\tau^I H$	$W^{I}_{\mu\nu}$	$Q_{H_{2}}^{(1)}$		$(\Pi^{\dagger}i^{\dagger})$	$\vec{\mathcal{D}}_{\mu} II) (\bar{l}_p \gamma^{\mu} l_r)$	_	
$Q_{H\bar{G}}$	$H^{\dagger}H \tilde{G}^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{zB}	$(\bar{l}_p \sigma^{\mu})$	$\nu e_{\tau})HE$	l _{μ.} ,	$Q_{H^{1}}^{(3)}$		$(H^{\dagger}i\overleftarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$		
Q_{HW}	$H^{\dagger}HW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_{p}\sigma^{\mu\nu})$	$({}^{A}u_{r})\tilde{H}$	$G^A_{\mu\nu}$	Q_{Hs}		$(H^{\dagger}i\dot{T}$	$\overrightarrow{\mathcal{O}}_{\mu}H)(\overrightarrow{e}_{p}\gamma^{\mu}e_{r})$		
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{wW}	$(\bar{q}_{\rm F}\sigma^{\mu\nu} v$	$u_r)\tau^I \hat{H}$	$W^{I}_{\mu\nu}$	$Q_{H_{q}}^{(1)}$		$(H^{\dagger}i\overleftarrow{I}$	$\overrightarrow{\partial}_{\mu}H)(\overline{q}_{p}\gamma^{\mu}q_{r})$		
Q_{HB}	$H^{*}H B_{\mu\nu}B^{\mu\nu}$	Q_{nB}	$(\bar{q}_p \sigma^{\mu i}$	$v u_r) \tilde{H} I$	3 ₁₀ ,	$Q_{H_{q}}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r})$)	
$Q_{H\widetilde{B}}$	$H^{*}H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu})$	$\Gamma^A d_\tau H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftarrow{L}$	$\dot{D}_{\mu}H)(\bar{u}_p\gamma^{\mu}u_{\tau})$		
Q_{HWB}	$H^{\dagger} \tau^{I} H W^{I}_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu \nu} \sigma^{\mu} \sigma^{\mu$	$(l_r)\tau^l H$	$W^{I}_{\mu\nu}$	Q_{Ha}		$(H^{\dagger}i\dot{I}$	$\vec{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$		
$Q_{H\widetilde{W}B}$	$H^{\dagger}\tau^{I}H \widetilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	Q_{AB}	$(\bar{q}_{\nu}\sigma^{\mu\nu}$	$(d_r)HI$	3μυ	Q_{ilud} +	h.c.	$i(\widetilde{H}^*L$	$(\bar{u}_p \gamma^\mu d_r)$		
	$8: (\bar{L}L)(\bar{L}L)$	_	8:(1	$\bar{R}R)(\bar{R}I$	2)		8:	$(\bar{L}L)(\bar{R}I)$	R)		
Q_{11}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_{p}$	$\gamma_{\mu}e_{r})(i$	$\bar{e}_s \gamma^{\mu} e_t$)	Q_{lv}	($\bar{l}_p \gamma_\mu l_\tau)(\bar{e}$	$_{s}\gamma^{\mu}e_{i})$		
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p$	$\gamma_{\mu}u_{r})(i$	$i_s \gamma^{\mu} u_t$)	Q_{lu}	($\bar{l}_{\mu}\gamma_{\mu}l_{\tau})(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$		
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^J q_r)(\bar{q}_s \gamma^\mu \tau^J q_t)$	Q_{dd}	(\vec{d}_p)	$(\gamma_{\mu}d_{r})(a)$	$\tilde{t}_s \gamma^{\mu} d_t$)	Q_{ld}	($\bar{l}_p \gamma_\mu l_\tau)(\bar{d}$	$(\gamma^{\mu}d_{t})$		
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_{eu}	$(\bar{e}_p$	$\gamma_{\mu}e_{\tau})(i$	$i_s \gamma^{\mu} u_l$)	Q_{qe}	($\bar{q}_{p}\gamma_{\mu}q_{r})(\dot{a}$	$\tilde{e}_s \gamma^{\mu} e_t$)		
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau' l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{cd}	$(\bar{e}_p$	$\gamma_{\mu}e_{r})(\dot{e}$	$\bar{l}_o \gamma^\mu d_t$)	$Q_{qx}^{(1)}$	- (($\bar{l}_{p}\gamma_{\mu}q_{r})(i$	$i_s \gamma^{\mu} u_t$)		
		$Q_{nd}^{(1)}$	$(\bar{u}_p$	$\gamma_{\mu}u_{r})(e$	$\bar{l}_s \gamma^{\mu} d_t$)	$Q_{q_{2}}^{(8)}$	$(\bar{q}_p\gamma)$	$T^A q_r)(i$	$i_s \gamma^\mu T^A u_i)$		
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu)$	$T^A u_r)(e$	$\bar{l}_s \gamma^{\mu} T^A d_i$	$Q_{qd}^{(1)}$	()	$\bar{q}_p \gamma_\mu q_r)(\bar{c}$	$\bar{l}_s \gamma^{\mu} d_t$)		
						$Q_{qd}^{(8)}$	$(\bar{q}_{p}\gamma$	$T^A q_r)(a$	$\bar{l}_s \gamma^{\mu} T^A d_t$)		
	$8 : (\bar{L}R)($	$\bar{R}L$) + h.	c.	8:	$(\bar{L}R)(\bar{L}R)$	+ h.c.					
	Q_{ledy} (1	$(\bar{d}_s q_t)$	i) Q	$q_{uqd}^{(1)}$	$(\bar{q}_p^j u_r)$	$v_{jk}(\bar{q}_s^k d_t)$					
			Ģ	(8) gugd	$(\bar{q}_p^j T^A u_r)$	$\epsilon_{jk}(\bar{q}_s^k T^A d_l)$)				
			Ģ	$2_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)e$	$j_k(\bar{q}_s^k u_t)$					
			Ģ	$2_{legu}^{(3)}$	$(\tilde{l}_{p}^{j}\sigma_{\mu\nu}c_{r})e$	$_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u$	0				

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flavor violation from

4 fermion interactions

dipole transitions

	$1: X^3$	2 : H	6	$3 : H^{i}$	$^{4}D^{2}$	$5: \psi^2 H^3 + h.c.$
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_H (H	$(^{\dagger}H)^3 = Q_{H_{c}}$	$(H^{\dagger}I)$	$H)\Box(H^{\dagger}H)$	I) $Q_{eH} = (H^{\dagger}H)(\bar{l}_{\mu}e_{\nu}H)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$		Q_{HI}	$(H^{\dagger}D_{\mu})$	$H)^* (H^*)$	$D_{\mu}H$ = $Q_{uH} = (H^{\dagger}H)(\bar{q}_{p}u_{r}\tilde{H})$ =
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho} =$					$Q_{dH} = (H^{\dagger}H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\mu}_{\nu} W^{K\mu}_{\rho}$					
	$4:X^2H^2$	6 :	$\psi^2 X H$ + h.c.			$7: \psi^2 H^2 D$
Q_{HG}	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H$	$W^I_{\mu\nu}$	$Q_{H_{2}}^{(1)}$	$(\Pi^{\dagger}i\overleftrightarrow{D}_{\mu}\Pi)(\overline{l}_{p}\gamma^{\mu}l_{\tau})$
$Q_{H\widetilde{G}}$	$H^{\dagger}H {\widetilde{G}}^A_{\mu\nu}G^{A\mu\nu}$	Q_{vB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H$	$B_{\mu\nu}$	$Q_{H^{1}}^{(3)}$	$(H^{\dagger}i\overleftrightarrow{D}^{I}_{\mu}H)(\overline{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$
Q_{HW}	$H^{\dagger}HW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A v_r) \hat{I}$	$\tilde{A} G^A_{\mu\nu}$	Q_{He}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_F \sigma^{\mu\nu} u_r) \tau^I \tilde{H}$	$W^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$
Q_{HB}	$H^{-}H B_{\mu\nu}B^{\mu\nu}$	Q_{nB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H}$	$B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^{\dagger}i\overleftrightarrow{D}^{I}_{\mu}H)(\bar{q}_{\rho}\tau^{I}\gamma^{\mu}q_{\nu})$
$Q_{H\widetilde{B}}$	$H^{*}H \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) I$	$I G^A_{\mu\nu}$	Q_{Hu}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{u}_{p}\gamma^{\mu}u_{r})$
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H$	$W^{I}_{\mu\nu}$	Q_{Hd}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$
$Q_{H\widetilde{W}B}$	$H^{\dagger}\tau^{I}H\widetilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_{\nu}\sigma^{\mu\nu}d_{\tau})H$	$B_{\mu\nu}$	Qilud +	h.c. $i(\tilde{H}^{*}D_{\mu}H)(\bar{u}_{p}\gamma^{\mu}d_{r})$
	$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}$	R)	\sim	$8:(\bar{L}L)(\bar{R}R)$
Q_{1l}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)($	$\bar{e}_s \gamma^{\mu} e_t$)	Q_{lv}	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)($	$\bar{u}_s \gamma^{\mu} u_l$)	Q_{lu}	$(\bar{l}_p \gamma_\mu i_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^J q_r)(\bar{q}_s \gamma^\mu \tau^j q_l)$	Q_{dd}	$(d_p \gamma_\mu d_r)($	$(\bar{d}_s \gamma^{\mu} d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)($	$\bar{u}_s \gamma^{\mu} u_t$)	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau' l_r)(\bar{q}_s \gamma^\mu \tau^I q_i)$	Q_{cd}	$(\bar{e}_p \gamma_\mu e_r)($	$\bar{d}_o \gamma^{\mu} d_t$)	$Q_{q_2}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{nd}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)$	$(\bar{d}_s \gamma^{\mu} d_t)$	$Q_{q_{\mathcal{H}}}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_i)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)$	$(\bar{d}_s \gamma^{\mu} T^A d_i)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$
					$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
	$8 : (\bar{L}R)(\bar{c})$	$\bar{R}L$) + h.c	. 8:	$(\bar{L}R)(\bar{L}R)$ +	⊦h.c.	
	Q_{leda} (\overline{l}	$(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)e_j$	$_{k}(\bar{q}_{s}^{k}d_{t})$	_
	****** 1 ()					
	1		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_j$	$_{k}(\bar{q}_{s}^{k}T^{A}d_{i}$.)
			$Q_{quqd}^{(8)}$ $Q_{lequ}^{(1)}$	$(\bar{q}_p^j T^A u_r) \epsilon_j$ $(\bar{l}_p^j e_r) \epsilon_j \mu$	$_{k}(\bar{q}_{s}^{k}T^{A}d_{t})$ $_{k}(\bar{q}_{s}^{k}u_{t})$.)

2499 baryon and lepton number conserving dim. 6 operators

Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

flavor violation from

4 fermion interactions

dipole transitions

Z-penguins

	$1 : X^{3}$	2 : .	H^6	$3: H^4D^2$			5 :	$\psi^2 H^3 + h.c.$	
Q_G	$\int^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_H (.	$H^{\dagger}H)^{3}$	$Q_{H\square}$	(H^{\dagger})	$H)\Box(H^{\dagger}H)$	I)	Q_{eH}	$(H^{\dagger}H)(\bar{l}_{\mu}e,H)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$			Q_{HD}	$(H^{\dagger}D_{\mu}$	$H)^{*}(H^{*})$	$D_{\mu}H)$	Q_{uH}	$(H^{+}H)(\bar{q}_{p}u_{r}\tilde{H})$
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}=$				•			Q_{dH}	$(H^{\dagger}H)(\bar{q}_{p}d_{r}H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$								
	$4:X^2H^2$	6	$: \psi^2 X H$	+ h.c.			7	$: \psi^2 H^2$	D
Q_{HG}	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e$	$(\tau)\tau^{I}III$	$V^{I}_{\mu\nu}$	$Q_{H_{1}}^{(1)}$		(∏†iŤ	$\vec{\mathcal{D}}_{\mu} II (\bar{l}_{p} \gamma^{\mu} l_{\tau})$
$Q_{H\widetilde{G}}$	$H^{\dagger}H {\widetilde G}^A_{\mu\nu}G^{A\mu\nu}$	Q_{zB}	$(\bar{l}_p \sigma^{\mu})$	$(e_r)HB$	4.00	$Q_{H_{1}}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$
Q_{HW}	$H^{\dagger}H W^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T$	$(A_v)\tilde{H}$	$G^A_{\mu\nu}$	Q_{He}		$(H^{\dagger}i\overleftarrow{L}$	$\vec{P}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{\tau})$
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_{\rm F}\sigma^{\mu\nu} v$	$\iota_r)\tau^I \tilde{H}$	$W^{I}_{\mu\nu}$	$Q_{Hg}^{(1)}$		$(H^{\dagger}i\overleftarrow{L}$	$\vec{\partial}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$
Q_{HB}	$H^*H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu i}$	$(u_r)\tilde{H}I$	$\beta_{\mu\nu}$	$Q_{Hq}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r})$
$Q_{H\widetilde{B}}$	$H^*H \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu})$	$\Gamma^A d_r)H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftarrow{D}$	$\dot{D}_{\mu}H)(\bar{u}_p\gamma^{\mu}u_r)$
Q_{HWB}	$H^{\dagger}\tau^{I}H W^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu \nu} a)$	$(l_{\tau})\tau^{I}H$	$W^{I}_{\mu\nu}$	Q_{Hd}		$(H^{\dagger}i\overleftarrow{L}$	$\vec{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$
$Q_{H\widetilde{W}E}$	$H^{\dagger}\tau^{I}H \widetilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_{\nu}\sigma^{\mu\nu}$	$(d_r)HE$	$\beta_{\mu\nu}$	Q_{Hud} +	h.c.	$i(\widetilde{H}^*L$	$(\bar{u}_p \gamma^\mu d_r)$
	$8:(\bar{L}L)(\bar{L}L)$		8:(1	$\bar{R}R)(\bar{R}I$	2)		8:($(\bar{L}L)(\bar{R}F)$	3)
$Q_{!1}$	$= (\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_j$	$\gamma_\mu e_r)(\bar{e}$	$s\gamma^{\mu}e_t)$	Q_{lv}	()	$(\bar{e}\gamma_{\mu}l_{\tau})(\bar{e}$	$_{s}\gamma^{\mu}e_{t})$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p$	$\gamma_{\mu}u_r)(i$	$i_s \gamma^{\mu} u_t$)	Q_{lu}	(\bar{l})	$_{p}\gamma_{\mu}i_{\tau})(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^J q_r)(\bar{q}_s \gamma^\mu \tau^J q_t)$	Q_{dd}	(\bar{d}_p)	$\gamma_{\mu}d_r)(c$	$i_s \gamma^{\mu} d_t$	Q_{Id}	(1	$(p_p \gamma_\mu l_r)(d$	$(_{s}\gamma^{\mu}d_{t})$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_{eu}	$(\bar{e}_p$	$\gamma_{\mu}e_{\tau})(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$	Q_{qe}	$(\bar{q}$	$(\rho \gamma_{\mu} q_{r})(i$	$\bar{e}_s \gamma^{\mu} e_t$)
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau' l_r)(\bar{q}_s \gamma^\mu \tau^I q_i)$	Q_{cd}	$(\bar{e}_p$	$\gamma_{\mu}e_{r})(\dot{a}$	$(_{o}\gamma^{r}d_{t})$	$Q_{q_{2}}^{(1)}$	$(\bar{q}$	$_{p}\gamma_{\mu}q_{r})(\bar{u}$	$i_s \gamma^{\mu} u_t$)
		$Q_{nd}^{(1)}$	$(\bar{u}_p$	$\gamma_{\mu}u_r)(\dot{\epsilon}$	$l_s \gamma^{\mu} d_t)$	$Q_{q_{2}}^{(8)}$	$(\bar{q}_p \gamma_\mu$	$T^A q_r)(\bar{u}$	$i_s \gamma^{\mu} T^A u_i$)
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu)$	$l^A u_r)(\dot{c}$	$\bar{l}_s \gamma^{\mu} T^A d_i)$	$Q_{qd}^{(1)}$	$(\bar{q}$	$i_p \gamma_\mu q_r)(\dot{a}$	$\bar{l}_s \gamma^{\mu} d_t$)
						$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_p$	$T^A q_r)(\dot{a}$	$\bar{l}_s \gamma^{\mu} T^A d_t$)
	$8:(\bar{L}R)(\bar{I}$	$\overline{R}L$) + h.	c.	8:	$(\bar{L}R)(\bar{L}R)$	+ h.c.			
	$Q_{ledg} = \langle \bar{l}_{j}^{2} \rangle$	$(\bar{d}_s q)$	(j) - Ç	(1) gugd	$(\bar{q}_p^j u_r) \epsilon_j$	$_{ik}(\bar{q}_{s}^{k}d_{t})$			
			Q	(8) g.ugd	$(\bar{q}_p^j T^A u_r) \epsilon_j$	$_{ik}(\bar{q}_{s}^{k}T^{A}d_{t})$)		
			G	(1) lega	$(\bar{l}_{p}^{j}e_{r})\epsilon_{j}$	$k(\bar{q}_{s}^{k}u_{1})$			
			Ģ	(3) Jean	$(\bar{l}_n^j \sigma_{\mu\nu} e_r) \epsilon_i$	$_{k}(\bar{q}_{s}^{k}\sigma^{\mu\nu}u$	ð		

2499 baryon and lepton number conserving dim. 6 operators

Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

flavor violation from

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Higgs penguins

Hints For Flavorful New Physics?



Hints For Flavorful New Physics?



Hints For Flavorful New Physics?





New Physics in Rare B Decays

Global Fits of Rare *B* Decay Data



add new physics in form of 4 fermion contact interactions

 $O_9 \propto (\bar{s}\gamma_{\mu}P_{\mu}b)(\bar{\mu}\gamma^{\mu}\mu)$

 $O_{\rm o}' \propto (\bar{s}\gamma_{\mu}P_{\rm B}b)(\bar{\mu}\gamma^{\mu}\mu)$

muonic vector current

(global fit taking into account all relevant data on radiative. semi-leptonic and leptonic B decays)

WA. Straub 1411.3161/1503.06199 (also Descotes-Genon et al. 1510.04239; Hurth et al. 1603.00865)

Implications for the New Physics Scale

generic tree
$$\frac{1}{\Lambda_{NP}^2} (\bar{s}\gamma_{\nu}P_Lb)(\bar{\mu}\gamma^{\nu}\mu)$$
 $\Lambda_{NP} \simeq 35 \text{ TeV} \times (C_9^{NP})^{-1/2}$ MFV tree $\frac{1}{\Lambda_{NP}^2} V_{tb} V_{ts}^* (\bar{s}\gamma_{\nu}P_Lb)(\bar{\mu}\gamma^{\nu}\mu)$ $\Lambda_{NP} \simeq 7 \text{ TeV} \times (C_9^{NP})^{-1/2}$ generic loop $\frac{1}{\Lambda_{NP}^2} \frac{1}{16\pi^2} (\bar{s}\gamma_{\nu}P_Lb)(\bar{\mu}\gamma^{\nu}\mu)$ $\Lambda_{NP} \simeq 3 \text{ TeV} \times (C_9^{NP})^{-1/2}$ MFV loop $\frac{1}{\Lambda_{NP}^2} \frac{1}{16\pi^2} V_{tb} V_{ts}^* (\bar{s}\gamma_{\nu}P_Lb)(\bar{\mu}\gamma^{\nu}\mu)$ $\Lambda_{NP} \simeq 0.6 \text{ TeV} \times (C_9^{NP})^{-1/2}$

(MFV = Minimal Flavor Violation)

My Favorite Model

Z' based on gauging $L_{\mu} - L_{\tau}$ with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269



Q: heavy vector-like fermions ϕ : scalar that breaks $L_{\mu} - L_{\tau}$

$L_{\mu} - L_{\tau}$ and Lepton Flavor Universality



the Z' model based on gauged $L_{\mu} - L_{\tau}$ predicts:

1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state 2) no effect in the e^+e^- final state

Predictions for LFU Ratios

WA, Yavin 1508.07009



WA, Gori, Pospelov, Yavin, 1406.2332



Wolfgang Altmannshofer

WA, Gori, Pospelov, Yavin, 1406.2332

 $(g-2)_{\mu} > 5\sigma$ LHC muon g-2 $Z \rightarrow 4\mu$ branching ratio 0.1 g 0.01 can explain **B** anomalies 10^{-3} $(g-2)_{\mu} \pm 2\sigma$ 10^{2} 10^{3} 0.01 0.1 10 $m_{Z'}$ (GeV)

WA, Gori, Pospelov, Yavin, 1406.2332



WA, Gori, Pospelov, Yavin, 1406.2332



WA, Gori, Pospelov, Yavin, 1406.2332



Flavor Violating Higgs Decays

Flavor Violating Higgs in the EFT

$$\mathcal{L} = \mathbf{Y} \ ar{\Psi} \Psi \ H + rac{ar{\mathbf{Y}}}{\Lambda^2} \ ar{\Psi} \Psi H^3$$

flavor violating higgs couplings if Y and \tilde{Y} are not aligned

Flavor Violating Higgs in the EFT

$$\mathcal{L} = \mathbf{Y} \, \bar{\Psi} \Psi \, H + \frac{\mathbf{Y}}{\Lambda^2} \, \bar{\Psi} \Psi H^3 + \frac{c}{\Lambda^2} \, \bar{\Psi} \sigma_{\mu\nu} \Psi \, H \, F^{\mu\nu}$$

flavor violating higgs couplings if Y and \tilde{Y} are not aligned generically one also expects flavor violating dipoles at dim. 6 level



Contributions to lepton Yukawa couplings (a), electromagnetic dipole (b)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

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Hints for Flavorful New Physics?

Flavor Violating Higgs in the EFT

$$\mathcal{L} = \mathbf{Y} \, \bar{\Psi} \Psi \, H + \frac{\bar{\Upsilon}}{\Lambda^2} \, \bar{\Psi} \Psi H^3 + \frac{c}{\Lambda^2} \, \bar{\Psi} \sigma_{\mu\nu} \Psi \, H \, F^{\mu\nu}$$

flavor violating higgs couplings if Y and \tilde{Y} are not aligned generically one also expects flavor violating dipoles at dim. 6 level



Contributions to lepton Yukawa couplings (a), electromagnetic dipole (b)

Example for a realization:



WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

"Bound" on $h \rightarrow \tau \mu$

$$\mathcal{L} = Y \,\bar{\Psi}\Psi \,H + \frac{\tilde{Y}}{\Lambda^2} \,\bar{\Psi}\Psi H^3 + \frac{c}{\Lambda^2} \,\bar{\Psi}\sigma_{\mu\nu}\Psi \,H \,F^{\mu\nu}$$
generically we expect $c \sim \tilde{Y} \frac{e}{16\pi^2}$

can derive a "generic upper bound"

$$\mathsf{BR}(\pmb{h}
ightarrow au \mu \gamma) \sim \mathsf{26} imes \mathsf{BR}(au
ightarrow \mu \gamma) \lesssim \mathsf{10^{-6}}$$

(orders of magnitude below current and future sensitivities)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Wolfgang Altmannshofer

Avoiding the Bound



Avoiding the Bound



$$\mathcal{L} = Y \, \bar{\Psi} \Psi \, H$$

 $+ rac{ ilde{Y}}{\Lambda_1^2} \, \bar{\Psi} \Psi H^3 + rac{c}{\Lambda_2^2} \, \bar{\Psi} \sigma_{\mu
u} \Psi \, H \, F^{\mu
u}$

arrange the new physics sector such that $\Lambda_1 \ll \Lambda_2$

WA, Carena, Crivellin 1604.08221

Avoiding the Bound



$$\mathcal{L} = Y \,\bar{\Psi}\Psi \,H$$
$$+ \frac{\tilde{Y}}{\Lambda_1^2} \,\bar{\Psi}\Psi H^3 + \frac{c}{\Lambda_2^2} \,\bar{\Psi}\sigma_{\mu\nu}\Psi \,H \,F^{\mu\nu}$$

$$\mathcal{L} = Y \, \bar{\Psi} \Psi \, H$$

+ $\tilde{Y} \, \bar{\Psi} \Psi \langle X \rangle + rac{c}{\Lambda^2} \, \bar{\Psi} \sigma_{\mu\nu} \Psi \, H \, F^{\mu\nu}$

arrange the new physics sector such that $\Lambda_1 \ll \Lambda_2$

WA, Carena, Crivellin 1604.08221

can decouple the dipole

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Wolfgang Altmannshofer

"Sequestered" Fermion Masses

let's entertain the idea of a second source of fermion masses

$\mathcal{M} = \mathcal{M}_0 + \Delta \mathcal{M}$

- ► M₀: due to the (main component of the) 125 GeV Higgs provides the bulk of the 3rd generation masses
- ► ΔM: due to some other source mainly responsible for the 1st and 2nd generation masses

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501; Botella et al. 1602.08011

"Sequestered" Fermion Masses

let's entertain the idea of a second source of fermion masses

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► M₀: due to the (main component of the) 125 GeV Higgs provides the bulk of the 3rd generation masses

► ΔM: due to some other source mainly responsible for the 1st and 2nd generation masses

is easily realized in a 2HDM, if one Higgs has a rank 1 Yukawa coupling

$$\mathcal{M}_{0} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_{\tau} \end{pmatrix}, \quad \Delta \mathcal{M} \simeq \begin{pmatrix} m_{e} & O(m_{e}) & O(m_{e}) \\ O(m_{e}) & m_{\mu} & O(m_{\mu}) \\ O(m_{e}) & O(m_{\mu}) & O(m_{\mu}) \end{pmatrix}$$

(similar in the quark sector)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501; Botella et al. 1602.08011

Flavor Violating Couplings of the Higgs

in general the fermion masses and the *h* couplings cannot be diagonalized simultaneously

e.g.
$$\frac{y_{\mu\tau}}{y_{\mu}^{\rm SM}} = -\frac{\Delta \mathcal{M}_{\mu\tau}}{m_{\mu}} \frac{\cos(eta - lpha)}{\sineta\coseta}$$

Flavor Violating Couplings of the Higgs

in general the fermion masses and the *h* couplings cannot be diagonalized simultaneously

e.g.
$$\frac{y_{\mu\tau}}{y_{\mu}^{SM}} = -\frac{\Delta \mathcal{M}_{\mu\tau}}{m_{\mu}} \frac{\cos(\beta - \alpha)}{\sin\beta\cos\beta}$$

generic expectations for lepton flavor violating Higgs decays

$$\begin{array}{ll} \mathsf{BR}(h \to \tau \mu) & \sim & \displaystyle \frac{m_{\mu}^2}{3m_b^2} \sim 10^{-3} \\ \mathsf{BR}(h \to \tau e) & \sim & \displaystyle \frac{m_e^2}{3m_b^2} \sim 10^{-7} \\ \mathsf{BR}(h \to \mu e) & \sim & \displaystyle \frac{m_e^2 m_{\mu}^2}{3m_{\tau}^2 m_b^2} \sim 10^{-10} \end{array}$$

Additional Flavor Violating Signatures

flavor violating rare top decays with branching ratios as large as

 $\mathsf{BR}(t o ch) \sim |V_{cb}|^2 \sim 10^{-3}$ $\mathsf{BR}(t o uh) \sim |V_{ub}|^2 \sim 10^{-5}$

might be in reach of the high luminosity LHC

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927 + in preparation

Wolfgang Altmannshofer

Hints for Flavorful New Physics?

Additional Flavor Violating Signatures

flavor violating rare top decays with branching ratios as large as

 $\mathsf{BR}(t o ch) \sim |V_{cb}|^2 \sim 10^{-3}$ $\mathsf{BR}(t o uh) \sim |V_{ub}|^2 \sim 10^{-5}$ lepton flavor violating rare B meson decays with sizable branching ratios

 $\begin{aligned} \mathsf{BR}(B_s \to \tau \mu) &\sim \mathsf{few} \times 10^{-7} \\ \mathsf{BR}(B \to K \tau \mu) &\sim \mathsf{few} \times 10^{-7} \\ \mathsf{BR}(B \to K^* \tau \mu) &\sim \mathsf{few} \times 10^{-7} \end{aligned}$

might be in reach of the high luminosity LHC

LHCb might be sensitive to the K^* and K rates

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927 + in preparation

Heavy Higgs Production and Decays

most important production and decay modes involve 2nd gen. fermions



WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Interesting Collider Signatures



current most stringent constraint: di-muon resonance searches (gray shaded region)

Interesting signatures include:

same sign tops $pp \rightarrow tH/A \rightarrow tt\bar{c}$

di-jet resonances that are produced in association with a top $pp \rightarrow tH/A \rightarrow tc\bar{c}$ $pp \rightarrow tH^{\pm} \rightarrow tcs$

flavor violating heavy Higgses $pp \rightarrow H/A \rightarrow \tau \mu$

WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Conclusions



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Several anomalies exist in flavor observables Statistical fluctuations? Hadronic uncertainties? New Physics?

Anomalies in rare B decays can be consistently described by New Physics in form of a four fermion contact interaction C₉(s̄γ_αP_Lb)(μ̄γ^αμ) at a scale as high as 35 TeV

 \rightarrow could originate from a LFU violating Z' (or lepto-quarks ...)

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 Flavor violating Higgs decays at an observable level point to a second source of electro-weak symmetry breaking

 \rightarrow a flavorful 2HDM with non-standard collider signatures