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- ▶ In the SM, all flavor violation is due to the Higgs
- At tree level there are no FCNCs; flavor violation occurs only in charged currents, parametrized by the CKM matrix
- FCNCs arise at the 1-loop level. Example: meson mixing; gives access to CKM elements V_{td} and V_{ts} and their phases
- Where do the hierarchies in the CKM elements and the fermion masses come from?

Outline of the Lectures

- Isoto Flavor Physics in the Standard Model
 - Flavor Symmetry and Flavor Symmetry Breaking
 - The CKM Matrix
 - Meson Mixing and CP Asymmetries
 - The Standard Model Flavor Puzzle
- Plavor Physics Beyond the Standard Model
 - The New Physics Flavor Puzzle
 - Flavor in BSM Models
 - Flavor Anomalies

Part 2

Flavor Physics Beyond the Standard Model

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



The Hierarchy Problem

What gives mass to the Higgs itself?

The Higgs mass parameter is not forbidden by any symmetry of the Standard Model

- 1) can be added by hand
- 2) not protected from quantum corrections

$$m^2 = m^2_{(0)} + \Delta m^2 \sim (125 {
m GeV})^2$$

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$$m^2 = m^2_{(0)} + \Delta m^2 \sim (125 {
m GeV})^2$$

quantum corrections to the Higgs mass are sensitive to the largest scales

$$\Delta m^2 \sim rac{1}{16\pi^2} M_{ extsf{Planck}}^2 \simeq 10^{36} extsf{GeV}^2$$

fine tuned cancellation between the quantum corrections and the "bare mass" is required

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The Hierarchy Problem



Canada 9,984,670 km²

United States - 9,826,675 km² = 157,995 km²

The Hierarchy Problem



Canada 9,984,670 km² United States $9,826,675 \text{ km}^2 = 157,995 \text{ km}^2$

tuning of the Higgs mass would correspond to the surface area of Canada and the United States differing by approximately the size of an atom!

In order to protect the Higgs mass from huge quantum corrections and to avoid finetuning, we expect New Physics at the TeV scale How can we get information on New Physics at high scales from low energy experiments?



Beta Decay





effective low energy description of nuclear beta decay by a 4 fermion contact interaction

the interaction strength is given by the Fermi constant

 $G_F\simeq 1.17\times 10^{-5}~GeV^{-2}$

this defines an energy scale

$$\Lambda = (G_F \sqrt{2})^{-1/2} \simeq 246 \; {
m GeV}$$

Beta Decay







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$$\Lambda = (\textit{G}_{\textit{F}}\sqrt{2})^{-1/2} \simeq 246 \; \text{GeV}$$

in the Standard Model we understand beta decay as consequence of the exchange of virtual weak gauge bosons

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8m_W^2}$$

$$m_W \simeq 80 {
m GeV}$$

New Physics in Flavor Changing Neutral Currents



Standard Model amplitude is loop suppressed and CKM suppressed





Standard Model amplitude is loop suppressed and CKM suppressed



$$\propto rac{g^4}{16\pi^2} rac{m_t^2}{M_W^4} (V_{td} V_{ts}^*)^2$$

 Generic New Physics amplitude only suppressed by New Physics scale



Standard Model amplitude is loop suppressed and CKM suppressed



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► CP Violation in Kaon Mixing can probe extremely high scales

$$\Lambda_{
m NP}\sim rac{M_W^2}{m_t}rac{4\pi}{g^2}rac{1}{|V_{td}V_{ts}^*|}\sim 10^4~{
m TeV}$$

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► CP Violation in Kaon Mixing can probe extremely high scales

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[Exercise: estimate the scale that can be probed with rare B decays]

Wolfgang Altmannshofer

	$1: X^{3}$	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 ($H^{\dagger}H)^{3}$	$Q_{H\square}$	$(H^{\dagger}$	$H)\Box(H^{\dagger}H)$	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}	$(H^{\dagger}D_{\mu})$	$(H^{\dagger})^{*}(H^{\dagger})$	$D_{\mu}H$	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}	$(H^{\dagger}H)(\bar{q}_{p}d_{r}H)$		
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$										
	$4:X^2H^2$	6		$7: \psi^2 H^2 D$							
Q_{HG}	$H^{\dagger}H G^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu})$	$e_r)\tau^I H V$	$V^{I}_{\mu\nu}$	$Q_{Hl}^{(1)}$		$(H^{\dagger}i\overleftarrow{1}$	$\vec{D}_{\mu}H)(\bar{l}_{p}\gamma^{\mu}l_{r})$		
$Q_{H\tilde{G}}$	$H^{\dagger}H \tilde{G}^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^\mu)$	$\nu e_r)HB$	μν	$Q_{Hl}^{(3)}$		$(H^{\dagger}i\overleftarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$		
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}		$(H^{\dagger}i\overleftarrow{L}$	$\vec{D}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$		
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu})$	$u_r)\tau^I \tilde{H}$	$W^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$		$(H^{\dagger}i\overleftarrow{I}$	$\vec{D}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$		
Q_{HB}	$H^{\dagger}H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^\mu$	$v u_r) \tilde{H} E$	$\mu\nu$	$Q_{Hq}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r})$			
$Q_{H\widetilde{B}}$	$H^{\dagger}H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu})$	$T^A d_r)H$	$G^{A}_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{u}_{p}\gamma^{\mu}u_{r})$			
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}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$			Q_{Hud} +	h.c.	$i(\tilde{H}^{\dagger}L$	$(\bar{u}_p \gamma^\mu d_r)$		
	$8:(\bar{L}L)(\bar{L}L)$	$8:(\bar{R}R)(\bar{R}R)$)	$8 : (\bar{L}L)(\bar{R}R)$					
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	(ē	$\gamma_{\mu}e_{r})(\bar{e}$	$s\gamma^{\mu}e_t$)	Q_{le}	($(\bar{l}_p \gamma_\mu l_r)(\bar{e}$	$_{s}\gamma^{\mu}e_{t})$		
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_j$	$\gamma_{\mu}u_{r})(\bar{v}$	$_{s}\gamma^{\mu}u_{t})$	Q_{lu}	($\bar{l}_p \gamma_\mu l_r)(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$		
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}$	$\gamma_{\mu}d_{r})(\dot{d}$	$s\gamma^{\mu}d_{t})$	Q_{td}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$				
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_j$	$\gamma_{\mu}e_{r})(\bar{u}$	$s\gamma^{\mu}u_t$)	Q_{qe}	($i_s \gamma^{\mu} e_t$)			
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r) (\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	(\bar{e}_i)	$\gamma_{\mu}e_{r})(d$	$_{s}\gamma^{\mu}d_{t})$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}$		$i_s \gamma^{\mu} u_t$)		
		$Q_{ud}^{(1)}$	(ū	$\gamma_{\mu}u_{r})(\dot{a}$	$(\bar{d}_{s}\gamma^{\mu}d_{t}) = Q_{qu}^{(8)} (\bar{q}_{p})$		$(\bar{q}_p \gamma$	$\gamma_{\mu}T^{A}q_{r})(\bar{u}_{s}\gamma^{\mu}T^{A}u_{t})$			
		$Q_{ud}^{(8)}$	$\bar{d}_{d}^{(j)} = (\bar{u}_{p}\gamma_{\mu}T^{A}u_{r})(\bar{d}_{s}\gamma^{\mu}T^{A}d)$			$Q_{qd}^{(1)}$	$Q_{qd}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$				
						$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma$	$\mu T^A q_r)(a$	$\bar{l}_s \gamma^{\mu} T^A d_t$)		
	$8 : (\bar{L}R)(\bar{L}R)$	$\bar{R}L$) + h	.c.	$. 8 : (\bar{L}R)(\bar{L}R) + h.c.$							
	$Q_{ledq} = (\bar{l}_j)$	$(\bar{d}_s q)$	(j)	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon$	$_{jk}(\bar{q}_s^k d_t)$					
			0	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon$	$_{jk}(\bar{q}_s^kT^Ad_t$)				
			$Q_{lequ}^{(1)} = (\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$								
			(2(3)	$\bar{l}_{n}^{j}\sigma_{\mu\nu}e_{r})\epsilon$	$_{ik}(\bar{q}^k_s\sigma^{\mu\nu}u)$.)				

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

	$1 : X^3$	2:I	I^{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 (1	$T^{\dagger}H)^{3}$	$Q_{H\square}$	$(H^{\dagger}$	$H)\Box(H^{\dagger}H)$)	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}	$_{HD} = (H^{\dagger}D_{\mu}H)^{*}(H^{*}D_{\mu}H)$			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}	$(H^\dagger H)(\bar{q}_p d_r H)$		
$Q_{\tilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$										
	$4:X^2H^2$	$6:\psi^2 XH + \mathrm{h.c}$						$7 : \psi^2 H^2 D$			
Q_{HG}	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu \nu} e$	$_{\tau})\tau^{I}IIV$	$V^{I}_{\mu\nu}$	$Q_{H!}^{(1)}$		$(\Pi^{\dagger}i\overleftarrow{I}$	$\vec{D}_{\mu}II)(\bar{l}_{p}\gamma^{\mu}l_{\tau})$		
$Q_{H\bar{G}}$	$H^{\dagger}H {\widetilde G}^{A}_{\mu \nu}G^{A \mu \nu}$	Q_{zB}	$(\bar{l}_p \sigma^{\mu\nu}$	$e_\tau HB$	ur.	$Q_{H!}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$		
Q_{HW}	$H^{\dagger}H W^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_{p}\sigma^{\mu\nu}I$	$(A_{v_r})\tilde{H}$	$G^A_{\mu\nu}$	Q_{He}		$(H^{\dagger}iL$	$(\bar{e}_p \gamma^{\mu} e_r)$		
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_{\rm F}\sigma^{\mu\nu}u$	$_{r})\tau^{I}\tilde{H}$	$W^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$		$(H^{\dagger}i\overleftarrow{L}$	$\partial_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$		
Q_{HB}	$H^{*}H B_{\mu\nu}B^{\mu\nu}$	Q_{nB}	$(\bar{q}_p \sigma^{\mu\nu})$	$u_r)\tilde{H}B$	μıν	$Q_{Hq}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D})$	${}^{l}_{\mu}H)(\bar{q}_{\rho}\tau^{I}\gamma^{\mu}q_{\tau})$		
$Q_{H\widetilde{B}}$	$H^*H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T$	$^{A}d_{r})H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{u}_{p}\gamma^{\mu}u_{r})$			
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d$	$(\tau)\tau^{\prime}H$	$V^{I}_{\mu\nu}$	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}	$Q_{AB} = (\bar{q}_{\nu}\sigma^{\mu\nu}d_{\tau})H B_{\mu\nu}$			Q_{Hud} + h.c.			$_{\mu}H)(\bar{u}_{\rho}\gamma^{\mu}d_{r})$		
	$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{h}$	$(\bar{R}R)(\bar{R}R)$)		8 : (.	$\bar{L}L)(\bar{R}\bar{R}$	0		
24	8 : $(\overline{L}L)(\overline{L}L)$ $(\overline{l}_p \gamma_\mu l_r)(\overline{l}_s \gamma^\mu l_t)$	Qee	8 : (Ā	$(\bar{R}R)(\bar{R}R)$ $(\bar{r}R)(\bar{r}R)$	$\gamma^{\mu}e_t$)	Q_{lv}	8 : (, (ī,	$\bar{L}L)(\bar{R}\bar{R})$ $_{p}\gamma_{\mu}l_{\tau})(\bar{e})$	$(\gamma^{\mu}e_{i})$		
29 Q.(1) Q.(2)	8 : $(\overline{L}L)(\overline{L}L)$ $(\overline{l}_{p}\gamma_{\mu}l_{\tau})(\overline{l}_{s}\gamma^{\mu}l_{t})$ $(\overline{q}_{p}\gamma_{\mu}q_{\tau})(\overline{q}_{s}\gamma^{\mu}q_{t})$	Q_{ee} Q_{uu}	8 : $(\bar{B}_{p'})$ $(\bar{u}_{p'})$	$(\bar{R}R)(\bar{R}R)$ $\gamma_{\mu}e_{r})(\bar{e}$ $\gamma_{\mu}u_{r})(\bar{u}$	$_{s\gamma^{\mu}e_{t}})$ $_{s\gamma^{\mu}u_{t}})$	Q_{lv} Q_{lu}	8 : (, (ī ₁ (ī ₂	$\bar{L}L)(\bar{R}\bar{R}$ $_{p}\gamma_{\mu}l_{\tau})(\bar{e}$ $_{s}\gamma_{\mu}i_{\tau})(\bar{u}$	$(\gamma^{\mu}e_{i})$ $_{s}\gamma^{\mu}u_{t})$		
$Q_{qq}^{(1)} = Q_{qq}^{(1)} = Q_{qq}^{(3)}$	$\begin{split} &8:(\bar{L}L)(\bar{L}L)\\ &(\bar{l}_{g}\gamma_{\mu}l_{r})(\bar{l}_{s}\gamma^{\mu}l_{t})\\ &(\bar{q}_{p}\gamma_{\mu}q_{r})(\bar{q}_{s}\gamma^{\mu}q_{t})\\ &(\bar{q}_{p}\gamma_{\mu}\tau^{\dagger}q_{r})(\bar{q}_{s}\gamma^{\mu}\tau^{i}q_{t}) \end{split}$	Q _{ee} Q _{uu} Q _{dd}	$8 : (\bar{B})$ (\bar{v}_p) $(\bar{u}_{p'})$ $(\bar{d}_{p'})$	$(\bar{R}R)(\bar{R}R)$ $\gamma_{\mu}e_{r})(\bar{e}$ $\gamma_{\mu}u_{r})(\bar{u}$ $\gamma_{\mu}d_{r})(\bar{d}$	$s\gamma^{\mu}e_t$) $s\gamma^{\mu}u_t$) $s\gamma^{\mu}d_t$)	Q_{le} Q_{lu} Q_{ld}	8 : (, (ī ₁ (ī ₁	$\frac{\overline{L}L(\overline{R}B)}{\rho\gamma_{\mu}l_{\tau}}(\overline{e}, \gamma_{\mu}l_{\tau})(\overline{e}, \gamma_{\mu}l_{\tau})(\overline{u}, \gamma_{\mu}l_{\tau})(\overline{u}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau}))(\overline{d}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau}))(\overline{d}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau}))(\overline{d}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau}))(\overline{d}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}l_{\tau}))(\overline{d}, \gamma_{\mu}l_{\tau}))($	$(\gamma^{\mu}e_{t})$ $(\gamma^{\mu}u_{t})$ $(\gamma^{\mu}d_{t})$		
$Q_{qq}^{(1)} = Q_{qq}^{(1)} Q_{qq}^{(3)} = Q_{tq}^{(3)} = Q_{tq}^{(1)}$	$\begin{split} &8:(\bar{L}L)(\bar{L}L)\\ &(\bar{l}_{g}\gamma_{\mu}l_{\tau})(\bar{l}_{s}\gamma^{\mu}l_{t})\\ &(\bar{q}_{p}\gamma_{\mu}q_{\tau})(\bar{q}_{s}\gamma^{\rho}q_{t})\\ &(\bar{q}_{p}\gamma_{\mu}\tau^{-1}q_{\tau})(\bar{q}_{s}\gamma^{\rho}\tau^{-1}q_{t})\\ &(\bar{l}_{p}\gamma_{\mu}l_{\tau})(\bar{q}_{s}\gamma^{\mu}q_{t}) \end{split}$	Q _{ee} Q _{uu} Q _{dd} Q _{eu}	8 : $(\bar{B}_{p'})$ $(\bar{u}_{p'})$ $(\bar{d}_{p'})$ $(\bar{e}_{p'})$	$\overline{(R)}(\overline{RR})$ $\gamma_{\mu}e_{r})(\overline{e}$ $\gamma_{\mu}u_{r})(\overline{u}$ $\gamma_{\mu}d_{r})(\overline{d}$ $\gamma_{\mu}e_{r})(\overline{u}$	$s\gamma^{\mu}e_{l})$ $s\gamma^{\mu}e_{l})$ $s\gamma^{\mu}u_{l})$ $s\gamma^{\mu}d_{l})$ $s\gamma^{\mu}u_{l})$	Q_{lv} Q_{lu} Q_{ld} Q_{qe}	8 : (, (l ₁ (l ₁ (l ₁ (q ₁	$\overline{L}L)(\overline{R}\overline{R}$ $_{\nu}\gamma_{\mu}l_{\tau})(\overline{e}, \gamma_{\mu}l_{\tau})(\overline{a}, \gamma_{\mu}l_{\tau})(\overline{a}, \gamma_{\mu}l_{\tau})(\overline{d}, \gamma_{\mu}q_{\tau})(\overline{e})$	$\left(\begin{array}{c} \left(\right) & \\ s\gamma^{\mu}e_{t} \right) & \\ s\gamma^{\mu}u_{t} \end{array} ight) & \\ s\gamma^{\mu}d_{t} ight) & \\ s\gamma^{\mu}e_{t} ight) & \end{array}$		
$egin{array}{c} Q^{(1)}_{qq} & Q^{(1)}_{qq} & Q^{(3)}_{lq} & Q^{(1)}_{lq} & Q^{(3)}_{lq} & Q^{$	$\begin{split} & 8: (\bar{L}L)(\bar{L}L) \\ & (\bar{l}_{g}\gamma_{\mu}l_{r})(\bar{l}_{s}\gamma^{\mu}l_{\ell}) \\ & (\bar{q}_{g}\gamma_{\mu}q_{r})(\bar{q}_{s}\gamma^{\mu}q_{\ell}) \\ & (\bar{q}_{g}\gamma_{\mu}\tau^{1}q_{r})(\bar{q}_{s}\gamma^{\mu}\tau^{i}q_{\ell}) \\ & (\bar{l}_{g}\gamma_{\mu}t_{r})(\bar{q}_{s}\gamma^{ii}q_{\ell}) \\ & (\bar{l}_{g}\gamma_{\mu}\tau^{i}l_{r})(\bar{q}_{s}\gamma^{ii}\tau^{i}q_{\ell}) \end{split}$	Qee Quu Qdd Qeu Qod	8 : $(\bar{B}_{p'})$ $(\bar{u}_{p'})$ $(\bar{d}_{p'})$ $(\bar{e}_{p'})$	$(\overline{R}R)(\overline{R}R)$ $\gamma_{\mu}e_{r})(\overline{e}$ $\gamma_{\mu}u_{r})(\overline{u}$ $\gamma_{\mu}d_{r})(\overline{d}$ $\gamma_{\mu}e_{r})(\overline{d}$ $\gamma_{\mu}e_{r})(\overline{d}$	$s\gamma^{\mu} e_{t}$) $s\gamma^{\mu} u_{t}$) $s\gamma^{\mu} d_{t}$) $s\gamma^{\mu} u_{t}$) $s\gamma^{\mu} d_{t}$)	Q_{le} Q_{lu} Q_{ld} Q_{qe} $Q_{qu}^{(1)}$	8 : $(\bar{l}_{p}$ $(\bar{l}_{p}$ $(\bar{l}_{p}$ $(\bar{q}_{p}$ $(\bar{q}_{p}$	$\frac{\bar{L}L(\bar{R}B}{\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau}))(\bar{a}, \gamma_{\mu}q_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau})))$	$\left(\begin{array}{c} \left(\gamma^{\mu}e_{t}\right) \\ s\gamma^{\mu}u_{t} \right) \\ s\gamma^{\mu}u_{t} \right) \\ s\gamma^{\mu}e_{t} \right) \\ s\gamma^{\mu}v_{t} \right) \\ s\gamma^{\mu}u_{t} \right)$		
$Q_{qq}^{(1)}$ $Q_{qq}^{(3)}$ $Q_{qq}^{(3)}$ $Q_{lq}^{(1)}$ $Q_{lq}^{(3)}$	$\begin{split} & 8: (\bar{L}L)(\bar{L}L) \\ & (\bar{l}_{2} \gamma_{ij} l_{\tau})(\bar{l}_{1} \gamma^{ii} l_{i}) \\ & (\bar{q}_{p} \gamma_{\mu} q_{\tau})(\bar{q}_{1} \gamma^{\mu} q_{i}) \\ & (\bar{q}_{p} \gamma_{\mu} \tau^{\prime} q_{r}) (\bar{q}_{1} \gamma^{\mu} \tau^{\prime} q_{r}) \\ & (\bar{l}_{p} \gamma_{\mu} t_{\tau})(\bar{q}_{1} \gamma^{\mu} q_{i}) \\ & (\bar{l}_{p} \gamma_{\mu} \tau^{\prime} l_{\tau})(\bar{q}_{n} \gamma^{ii} \tau^{\prime} q_{i}) \\ & (\bar{l}_{p} \gamma_{\mu} \tau^{\prime} l_{\tau})(\bar{q}_{n} \gamma^{ii} \tau^{\prime} q_{i}) \end{split}$	Q_{ee} Q_{uu} Q_{dd} Q_{eu} Q_{od} $Q_{ud}^{(1)}$	8 : $(\bar{B}_{p'})$ $(\bar{u}_{p'})$ $(\bar{d}_{p'})$ $(\bar{e}_{p'})$ $(\bar{e}_{p'})$ $(\bar{u}_{p'})$	$(R)(\bar{R}R)$ $\gamma_{\mu}e_{r})(\bar{e}$ $\gamma_{\mu}u_{r})(\bar{u}$ $\gamma_{\mu}d_{r})(\bar{d}$ $\gamma_{\mu}e_{r})(\bar{u}$ $\gamma_{\mu}e_{r})(\bar{d}$ $\gamma_{\mu}u_{r})(\bar{d}$	$s\gamma^{\mu}e_{t})$ $s\gamma^{\mu}u_{t})$ $s\gamma^{\mu}u_{t})$ $s\gamma^{\mu}u_{t})$ $s\gamma^{\mu}u_{t})$ $s\gamma^{\mu}u_{t})$ $s\gamma^{\mu}d_{t})$	Q_{lx} Q_{ly} Q_{ld} Q_{qx} $Q_{qx}^{(1)}$ $Q_{qx}^{(8)}$	$8 : (, \bar{l}_{p}$ $(\bar{l}_{p}$ (\bar{l}_{q}) (\bar{q}_{p}) $(\bar{q}_{p}\gamma_{p})'$	$\frac{\bar{L}L)(\bar{R}B}{r_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{u}, T^{A}q_{\tau})(\bar{u})$	$\left(\gamma^{\mu}e_{i}\right)$ $\left(\gamma^{\mu}a_{i}\right)$ $\left(\gamma^{\mu}d_{i}\right)$ $\left(\gamma^{\mu}d_{i}\right)$ $\left(\gamma^{\mu}v_{i}\right)$ $\left(\gamma^{\mu}v_{i}\right)$ $\left(\gamma^{\mu}T^{A}v_{i}\right)$		
$\begin{array}{c} Q_{qq}^{(1)} \\ Q_{qq}^{(3)} \\ Q_{qq}^{(3)} \\ Q_{qq}^{(1)} \\ Q_{lq}^{(1)} \\ Q_{lq}^{(3)} \end{array}$	$\begin{split} & 8: (\tilde{L}L)(\tilde{L}L) \\ & (\tilde{l}_{\gamma} \gamma_{\mu} l_{\tau}) (\tilde{l}_{\gamma} \gamma^{\mu} l_{c}) \\ & (\tilde{d}_{p} \gamma_{\mu} a_{\tau}) (\tilde{d}_{\gamma} \gamma^{\mu} q_{c}) \\ & (\tilde{a}_{p} \gamma_{\mu} a_{\tau}) (\tilde{a}_{\gamma} \gamma^{\mu} \gamma q_{c}) \\ & (\tilde{a}_{p} \gamma_{\mu} \tau) (\tilde{a}_{\gamma} \gamma^{\mu} \gamma q_{c}) \\ & (\tilde{b}_{p} \gamma_{\mu} t_{\gamma}) (\tilde{q}_{z} \gamma^{\mu} \tau^{I} q_{c}) \\ & (\tilde{b}_{p} \gamma_{\mu} \tau^{I} l_{\tau}) (\tilde{q}_{z} \gamma^{\mu} \tau^{I} q_{c}) \end{split}$	Q_{ee} Q_{uu} Q_{dd} Q_{cu} Q_{cd} $Q_{nd}^{(1)}$ $Q_{ud}^{(8)}$	$\begin{array}{c c} & & & & \\ & & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ &$	$\bar{k}R)(\bar{R}R)$ $\gamma_{\mu}e_{r})(\bar{e}$ $\gamma_{\mu}u_{r})(\bar{u}$ $\gamma_{\mu}u_{r})(\bar{u}$ $\gamma_{\mu}e_{r})(\bar{u}$ $\gamma_{\mu}e_{r})(\bar{d}$ $\gamma_{\mu}u_{r})(\bar{d}$	$s\gamma^{\mu}e_{\ell})$ $s\gamma^{\mu}u_{\ell})$ $s\gamma^{\mu}u_{\ell})$ $s\gamma^{\mu}u_{\ell})$ $s\gamma^{\mu}u_{\ell})$ $s\gamma^{\mu}d_{\ell})$ $s\gamma^{\mu}d_{\ell})$ $s\gamma^{\mu}d_{\ell})$	Q_{le} Q_{lu} Q_{ld} Q_{qe} $Q_{qg}^{(1)}$ $Q_{qg}^{(8)}$ $Q_{qd}^{(2)}$	$8 : (, \bar{l}_{p} \\ (\bar{l}_{p} \\ (\bar{l}_{p} \\ (\bar{q}_{p} \\ (\bar{q}_{p} \gamma_{\mu}' \\ (\bar{q}_{p} \gamma_{\mu}' \\ (\bar{q}_{p} \gamma_{\mu}' \\ (\bar{q}_{p} \gamma_{\mu}') $	$\frac{\bar{L}L)(\bar{R}B}{\rho\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau}))$	$\begin{array}{l} \left(\begin{array}{c} & \\ _{x}\gamma^{\mu}e_{t} \end{array} \right) \\ _{x}\gamma^{\mu}u_{t} \end{array} \\ _{x}\gamma^{\mu}u_{t} \end{array} \\ _{x}\gamma^{\mu}v_{t} \end{array} \\ _{y}\gamma^{\mu}v_{t} \end{array} \\ _{y}\gamma^{\mu}r_{t} \\ _{y}\gamma^{\mu}T^{A}u_{t} \end{array} $		
$2^{(1)}_{q_{q_{q_{q_{q_{q_{q_{q_{q_{q_{q_{q_{q_$	$\begin{split} & 8: (\tilde{L}L)(\tilde{L}L) \\ & (\tilde{l}_{\gamma} \gamma_{\mu} l_{\tau}) (\tilde{l}_{\gamma} \gamma^{\mu} l_{c}) \\ & (\tilde{d}_{p} \gamma_{\mu} a_{r}) (\tilde{d}_{\gamma} \gamma^{\mu} q_{c}) \\ & (\tilde{d}_{p} \gamma_{\mu} a_{r}) (\tilde{d}_{\gamma} \gamma^{\mu} \tau^{r} q_{c}) \\ & (\tilde{d}_{p} \gamma_{\mu} \tau^{l}) (\tilde{d}_{p} \gamma^{\mu} \tau^{r} q_{c}) \\ & (\tilde{l}_{p} \gamma_{\mu} l_{\tau}) (\tilde{q}_{z} \gamma^{\mu} \tau^{r} q_{c}) \\ \end{split}$	Q_{ec} Q_{uu} Q_{dd} Q_{cu} Q_{cd} $Q_{nd}^{(1)}$ $Q_{ud}^{(8)}$	8 : (\bar{h}) (\bar{e}_p) $(\bar{d}_{p'})$ $(\bar{e}_{p'})$ $(\bar{e}_{p'})$ $(\bar{u}_p\gamma_{\mu}T)$	$\overline{kR}(\overline{RR})(\overline{RR})(\overline{q}, R)(\overline{q}, R)$) $s\gamma^{\mu}e_{t}$) $s\gamma^{\mu}u_{t}$) $s\gamma^{\mu}d_{t}$) $s\gamma^{\mu}u_{t}$) $s\gamma^{\mu}u_{t}$) $s\gamma^{\mu}d_{t}$) $(s\gamma^{\mu}d_{t})$ $(s\gamma^{\mu}T^{A}d_{t})$	$egin{aligned} Q_{lz} & Q_{ly} & Q_{ly} & Q_{ld} & Q_{qx} & Q_{qx} & Q_{qx} & Q_{qx} & Q_{qy} & Q_{qy} & Q_{qd} & Q_{Q$	$8 : (, \overline{l}_p \\ (\overline{l}_p \\ (\overline{l}_p \\ (\overline{q}_p \\ (\overline{q}_p \gamma_p)' \\ (\overline{q}_p \gamma_p)' \\ (\overline{q}_p \gamma_p)' \end{cases}$	$\frac{\bar{L}L)(\bar{R}\bar{R}}{\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{u}, \gamma_{\mu}q_{\tau})(\bar{u}, \gamma_{\mu}q_{\tau})(\bar{u}, \gamma_{\mu}q_{\tau})(\bar{u}, \gamma_{\mu}q_{\tau})(\bar{u}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau}))(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau}))(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau}))(\bar{d}, \gamma_{\mu}q_{\tau})(\bar{d}, \gamma_{\mu}q_{\tau}))(\bar{d}, \gamma_{\mu}q_{\tau}))$	$\begin{array}{l} & & \\ & & \\ & & & \\$		
$Q_{qq}^{(1)}$ $Q_{qq}^{(3)}$ $Q_{tq}^{(3)}$ $Q_{tq}^{(3)}$	8 : $(\overline{L}L)(\overline{L},L)$ $(f_{p}\gamma_{\mu}l_{\tau})(f_{\gamma}\gamma^{\mu}l_{\ell})$ $(\overline{q}_{p}\gamma_{\mu}q_{\tau})(\overline{q}_{\gamma}\gamma^{\mu}q_{\ell})$ $(\overline{q}_{p}\gamma_{\mu}\tau^{\dagger}q_{r})(\overline{q}_{\gamma}\gamma^{\mu}\tau^{\dagger}q_{\ell})$ $(\overline{l}_{p}\gamma_{\mu}r_{\ell})(\overline{q}_{\gamma}\gamma^{\mu}\tau^{\dagger}q_{\ell})$ $(\overline{l}_{p}\gamma_{\mu}\tau^{\dagger}l_{\tau})(\overline{q}_{\mu}\gamma^{\mu}\tau^{\dagger}q_{\ell})$ $S : (\overline{L}R)(l$	Q_{ee} Q_{uu} Q_{dd} Q_{eu} Q_{od} $Q_{ud}^{(1)}$ $Q_{ud}^{(k)}$ $Q_{ud}^{(k)}$	8 : $(\bar{B}$ $(\bar{e}_{p'})^{(\bar{e}_{p'})}$ $(\bar{d}_{p'})^{(\bar{e}_{p'})}$ $(\bar{e}_{p'})^{(\bar{e}_{p'})}$ $(\bar{u}_{p}\gamma_{\mu}T)^{(\bar{e}_{p'})}$ c.	$(R)(\bar{R}R)$ $\gamma_{\mu}e_{r})(\bar{e}$ $\gamma_{\mu}u_{r})(\bar{u}$ $\gamma_{\mu}d_{r})(\bar{d}$ $\gamma_{\mu}e_{r})(\bar{d}$ $\gamma_{\mu}e_{r})(\bar{d}$ $\gamma_{\mu}u_{r})(\bar{d}$ $(A_{\mu}u_{r})(\bar{d}$ $(A_{\mu}u_{r})(\bar{d})$ $(A_{\mu}u_{r})(\bar{d})$	$\gamma^{\mu}e_{l}$ $\gamma^{\mu}e_{l}$ $\gamma^{\mu}u_{l}$ $\gamma^{\mu}u_{l}$ $\gamma^{\mu}u_{l}$ $\gamma^{\mu}u_{l}$ $\gamma^{\mu}d_{l}$ $\gamma^{\mu}d_{l}$ $\gamma^{\mu}d_{l}$ $\bar{r}\gamma^{\mu}T^{A}d_{l}$ $\bar{L}R)(\bar{L}R)$	Q_{lv} Q_{lu} Q_{qu} Q_{qe} $Q_{qx}^{(1)}$ $Q_{qd}^{(2)}$ $Q_{qd}^{(3)}$ $Q_{qd}^{(8)}$ + h.c.	8 : (, , , , , , , , , , , , , , , , , ,	$\frac{\bar{L}L)(\bar{R}\bar{K}}{\bar{q}\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{e}, \gamma_{\mu}q_{\tau})(\bar{a}, \gamma_{\mu}q_{\tau}))$	$\begin{array}{l} & & \\ &$		
$2_{ii}^{(1)}$ $Q_{q_i}^{(2)}$ $Q_{q_i}^{(1)}$ $Q_{lq}^{(2)}$ $Q_{lq}^{(2)}$	$\frac{8:(\tilde{L}L)(\tilde{L}L)}{([g\gamma_0, t_r)([\tilde{q}, \gamma_0, \tau_r])(\tilde{q}, \gamma_0, \tau_r])}$ $(\tilde{q}_{g\gamma_0, q_r})(\tilde{q}_{g\gamma}\gamma_0, \tau_r](\tilde{q}_{g\gamma}\gamma_0, \tau_r])$ $(\tilde{q}_{g\gamma_0, q_r}, \tau_{g\gamma})(\tilde{q}_{g\gamma}\gamma_0, \tau_r]$ $(\tilde{q}_{g\gamma_0, q_r}, \tau_{g\gamma})(\tilde{q}_{g\gamma}\gamma_0, \tau_r])$ $\frac{8:(LR)(t)}{Q_{tody}}(\tilde{q}_{g\gamma}\gamma_0, \tau_r])$	Q_{ee} Q_{uu} Q_{dd} Q_{eu} Q_{od} $Q_{nd}^{(1)}$ $Q_{ud}^{(2)}$ $\overline{R}L) + h$ $\overline{J}e_{e}()(\overline{d}_{s}q_{t})$	8 : (\bar{B}) $(\bar{a}_{p'})$ $(\bar{a}_{p'})$ $(\bar{a}_{p'})$ $(\bar{c}_{p'})$ $(\bar{a}$	$\frac{\partial R}{\partial r} (\bar{R}R) (\bar{R}R) (\bar{q}r) $	$(\bar{q}_{2}^{\mu}e_{t})$ $s\gamma^{\mu}e_{t})$ $s\gamma^{\mu}d_{t})$ $s\gamma^{\mu}d_{t})$ $s\gamma^{\mu}d_{t})$ $(s\gamma^{\mu}d_{t})$ $(\bar{s}\gamma^{\mu}T^{A}d_{t})$ $(\bar{L}R)(\bar{L}R)$ $(\bar{q}_{2}^{\mu}u_{r})e$	$\begin{array}{c} Q_{lv} \\ Q_{ly} \\ Q_{dy} \\ Q_{qe} \\ Q_{qx}^{(1)} \\ Q_{qy}^{(2)} \\ Q_{qd}^{(3)} \\ Q_{qd}^{(8)} \\ Q_{qd}^{(8)} \\ + h.c. \\ _{jk}(\bar{q}_{k}^{d}d_{t}) \end{array}$	8 : (.) $(\bar{l}_p$ (\bar{l}_p) $(\bar{q}_p)^{-1}$ $(\bar{q}_p)^{-1}$ $(\bar{q}_p)^{-1}$ $(\bar{q}_p)^{-1}$	$\frac{\bar{L}L)(\bar{R}B}{q_{r}\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}q_{r})(\bar{e}, \gamma_{\mu}q_{r})(\bar{e}, \gamma_{\mu}q_{r})(\bar{e}, \gamma_{\mu}q_{r})(\bar{e}, \gamma_{\mu}q_{r})(\bar{e}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))$	$\begin{array}{l} & & \\ &$		
$\begin{array}{c} z_{11} \\ Q_{qq}^{(1)} \\ Q_{qq}^{(3)} \\ Q_{qq}^{(3)} \\ Q_{lq}^{(3)} \\ Q_{lq}^{(3)} \end{array}$	$\begin{split} & \frac{8:(\tilde{L}L)(\tilde{L}L)}{(l_{g}\gamma_{0}l_{r})(l_{g}\gamma^{e}l_{\ell})} \\ & \frac{(l_{g}\gamma_{0}d_{r})(l_{g}\gamma^{e}l_{\ell})}{(l_{g}\gamma_{0}a_{r})(l_{g}\gamma^{e}a_{r})} \\ & \frac{(l_{g}\gamma_{0}a_{r})(l_{g}\gamma^{e}a_{r})}{(l_{g}\gamma_{0}a_{r})(l_{g}\gamma^{e}a_{r})} \\ & \frac{(l_{g}\gamma_{0}a_{r})(l_{g}\gamma^{e}a_{r})}{(l_{g}\gamma_{0}a_{r}^{e}l_{r})} \\ & \frac{8:(\tilde{L}R)(l_{g}\gamma^{e}a_{r})}{Q_{told}} \left[\tilde{Q}_{t} \right] \end{split}$	Q_{ee} Q_{uu} Q_{dd} Q_{cu} Q_{od} $Q_{ad}^{(1)}$ $Q_{ad}^{(1)}$ $Q_{ad}^{(1)}$ RL) + h.s	$\begin{array}{c c} 8: (\bar{B}) \\ \hline & (\bar{a}_{p'} \\ (\bar{a}_$	\overline{R})($\overline{R}R$ $\gamma_{\mu}e_{r}$)(\overline{e} $\gamma_{\mu}u_{r}$)(\overline{u} $\gamma_{\mu}u_{r}$)(\overline{u} $\gamma_{\mu}e_{r}$)(\overline{d} $\gamma_{\mu}e_{r}$)(\overline{d} $\gamma_{\mu}u_{r}$)(\overline{d} 8 : ((1) $\gamma_{\mu}u_{\mu}$)(\overline{d} 8 : () $\gamma^{\mu}e_{\ell})_{s}\gamma^{\mu}u_{\ell})_{s}\gamma^{\mu}u_{\ell})_{s}\gamma^{\mu}u_{\ell})_{s}\gamma^{\mu}u_{\ell})_{s}\gamma^{\mu}u_{\ell})_{s}\gamma^{\mu}u_{\ell})_{s}\gamma^{\mu}d_{\ell})_{s}\gamma^{\mu}d_{\ell})_{s}\gamma^{\mu}d_{\ell})_{s}\gamma^{\mu}T^{A}d_{\ell})$ $\overline{L}R)(\overline{L}R)_{s}(\overline{q}_{p}^{\mu}T^{A}u_{r})e^{i\frac{\pi}{2}T^{A}}u_{r}}e^{i\frac{\pi}{2}T^{A}}u_{r}}}e^{i\frac{\pi}{2}T$	$\begin{array}{ c c c }\hline Q_{te} \\ Q_{tu} \\ Q_{tu} \\ Q_{qe} \\ Q_{qx}^{(z)} \\ Q_{qd}^{(z)} \\ Q_{qd}^{(z)} \\ Q_{qd}^{(s)} \\ + h.c. \\ _{jk}(\bar{q}_{s}^{k}d_{t}) \\ _{jk}(\bar{q}_{s}^{k}T^{A}d_{t}) \end{array}$	8: (. $(\bar{l}_{j}$ $(\bar{l}_{p})_{ij}$ $(\bar{q}_{p})_{ij}$ $(\bar{q}_{p})_{ij}$ $(\bar{q}_{p})_{ij}$	$\frac{\bar{L}L)(\bar{R}\bar{K}}{\bar{q}\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q))(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r}))(a$	$\begin{array}{l} \left(\begin{array}{c} \left(\begin{array}{c} \left(\right) \\ r_{\gamma}^{\alpha} u_{\ell} \right) \\ r_{\gamma}^{\alpha} u_{\ell} \right) \\ r_{\gamma}^{\alpha} d_{\ell} \\ r_{\gamma}^{\alpha} r_{\ell} \\ r_{\gamma}^{\alpha} r_{\ell} \\ r_{\ell} \\ r_{\ell}^{\alpha} r_{\ell} \\ r_{\ell} \\ r_{\ell}^{\alpha} r_{\ell} \\ r_{\ell} \\ r_{\ell} \\ r_{\ell} \\ r_{\ell} \\$		
${f Q}_{11}^{(2)} = {f Q}_{qq}^{(3)} = {f Q}_{tq}^{(3)} = {f $	$\frac{8 : (\tilde{L}L)(\tilde{L}L)}{(l_{g}\gamma_{0}l_{f})(l_{g}\gamma_{g}r_{d})(l_{g}\gamma_{g}r_{d})}$ $\frac{(l_{g}\gamma_{0}r_{g})(l_{g}\gamma^{g}r_{d})}{(l_{g}\gamma_{0}r_{g})(l_{g}\gamma^{g}r_{d})}$ $\frac{(l_{g}\gamma_{0}r_{f})(l_{g}\gamma^{g}r_{f}r_{d})}{(l_{g}\gamma_{0}r_{f})l_{g}(l_{g}\gamma^{g}r_{f}r_{d})}$ $\frac{8 : (LR)(l_{g}r_{d}r_{d})}{Q_{tedg}} \left(\tilde{l}_{g}r_{d}r_{d}r_{d}r_{d}r_{d}r_{d}r_{d}r_{d$	Q_{ec} Q_{uu} Q_{dd} Q_{cu} Q_{cd} $Q_{ad}^{(1)}$ $Q_{ad}^{(8)}$ $\bar{R}L) + h$ $\bar{f}_{er}.)(\bar{d}_{s}q_{t}$	8 : $(\bar{h}$ $(\bar{e}_{p'})^{i}$ $(\bar{u}_{p'})^{i}$ $(\bar{e}_{p'})^{i}$ $(\bar{e}_{p'})^{i}$ $(\bar{u}_{p}\gamma_{\mu}T)^{i}$ $(\bar{u}_{p}\gamma_{\mu}T)^{i}$ $(\bar{u}_{p})^{i}$	$\frac{\bar{R}R(\bar{R}R)}{\gamma_{\mu}e_{r}(\bar{e})(\bar{e}}$ $\gamma_{\mu}e_{r})(\bar{e}$ $\gamma_{\mu}u_{r})(\bar{u}$ $\gamma_{\mu}e_{r})(\bar{d}$ $\gamma_{\mu}e_{r})(\bar{d}$ $\gamma_{\mu}u_{r})(\bar{d}$ $\frac{R}{\tau_{\mu}u_{r}}(\bar{d})$ $\frac{R}{\tau_{\mu}u_{r}}(\bar{d})$ $\frac{R}{\tau_{\mu}u_{r}}$ $\frac{R}{\tau_{\mu}u_{r}}$) $\gamma^{\mu}e_l$) $\gamma^{\mu}a_l$) $\gamma^{\mu}a_l$) $\gamma^{\mu}a_l$) $\gamma^{\mu}a_l$) $\gamma^{\mu}a_l$) $(\gamma^{\mu}a_l)$ $(\bar{\gamma}^{\mu}d_l)$ $(\bar{x}\gamma^{\mu}T^Ad_l)$ $(\bar{t}_{I}^{\mu}a_{r})e$ $(\bar{t}_{I}^{\mu}c_{r})e$	$\begin{array}{c} \hline \\ \hline \\ Q_{te} \\ Q_{tu} \\ Q_{qe} \\ Q_{qx}^{(2)} \\ Q_{qg}^{(3)} \\ Q_{qd}^{(3)} \\ Q_{qd}^{(4)} \\ + \text{h.e.} \\ \\ \downarrow_k(\bar{q}_s^k d_t) \\ _{jk}(\bar{q}_s^k T^A d_t) \\ _{ik}(\bar{q}_s^k u_t) \end{array}$	8 : (, $(\bar{l}_j)_{\bar{l}_j}$ $(\bar{l}_{\mu})_{\bar{l}_j}$ $(\bar{q}_{\mu})_{\bar{l}_j}$ $(\bar{q}_{\mu})_{\bar{l}_j}$ $(\bar{q}_{\mu})_{\bar{l}_j}$ $(\bar{q}_{\mu})_{\bar{l}_j}$	$\frac{\bar{L}L)(\bar{R}\bar{K}}{\gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{e}, \gamma_{\mu}l_{\tau})(\bar{a}, \gamma_{\mu}l_{\tau})(\bar{d}, \gamma_{\mu}q_{r})(\bar{d}, \gamma_{\mu}q_{r})(\bar{d}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r})(\bar{a}, \gamma_{\mu}q_{r}))(\bar{a}, \gamma_{\mu}q_{r}))))$	$\begin{array}{l} \left(\begin{array}{c} \left(\right) \\ r_{\gamma}^{\alpha} e_{i} \right) \\ r_{\gamma}^{\alpha} u_{\ell} \right) \\ r_{\gamma}^{\alpha} d_{\ell} \\ s_{\gamma}^{\mu} e_{\ell} \right) \\ s_{\gamma}^{\mu} r_{\ell} u_{i} \\ s_{\gamma}^{\mu} r_{\ell} u_{i} \right) \\ s_{\gamma}^{\mu} r_{\ell} d_{\ell} \right) \\ s_{\gamma}^{\mu} r^{A} d_{\ell} \right) \end{array}$		

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

4 fermion interactions

	$1: X^{3}$	$2:H^6$			$3 : H^4 D^2$			$5:\psi^2H^3+{\rm h.c.}$	
Q_G	$\int ABC G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	$Q_H = (H^{\dagger}H)^3 = Q_{H\Box}$			(H	$(H^{\dagger}H)\Box(H^{\dagger}H)$			$(H^{\dagger}H)(\bar{l}_{p}e,H)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	Q_{HD}			$(H^{\dagger}D$	$(H^{\dagger}D_{\mu}H)^{*}(H^{\dagger}D_{\mu}H)$			$(H^{\dagger}H)(\bar{q}_{p}u_{r}\widetilde{H})$
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$							Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$								
	$4: X^2 H^2$	6	$: \psi^2 X H$	f + 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_{τ}) $\tau^{I} IIV$	$V^{I}_{\mu\nu}$	$Q_{H1}^{(1)}$		$(\Pi^{\dagger}i^{\dagger}I$	$\vec{D}_{\mu}II)(\bar{l}_{p}\gamma^{\mu}l_{\tau})$
$Q_{H\bar{G}}$	$H^{\dagger}H \tilde{G}^{A}_{\mu\nu} G^{A\mu\nu}$	Q_{zB}	$(\bar{l}_p \sigma^\mu$	$\nu e_{\tau})HB$	har.	$Q_{H^{1}}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r}) =$
Q_{HW}	$H^{\dagger}HW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu})$	$U^A u_r) \tilde{H}$	$G^A_{\mu\nu}$	Q_{Hs}		$(H^{\dagger}i\dot{L}$	$\vec{p}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$
$Q_{H\widetilde{V}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	$Q_{\pi W}$	$(\bar{q}_{\rm F}\sigma^{\mu u})$	$u_r)\tau^I \tilde{H}$	$W^{I}_{\mu\nu}$	$Q_{H_{q}}^{(1)}$		$(H^{\dagger}i\overleftarrow{I}$	$\overrightarrow{\partial}_{\mu}H)(\overline{q}_{p}\gamma^{\mu}q_{r})$
Q_{HB}	$H^{-}H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu})$	$v u_r) \tilde{H} E$	$\beta_{\mu\nu}$	$Q_{H_{q}}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r})$
$Q_{H\widetilde{B}}$	$H^*H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu})$	$T^A d_r)H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftarrow{D}$	$(\bar{u}_p \gamma^{\mu} u_r)$
Q_{HWB}	$H^{\dagger}\tau^{I}HW^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu \nu} e$	$(d_\tau)\tau^I H$	$W^{I}_{\mu\nu}$	Q_{Hd}		$(H^{\dagger}i\overleftarrow{L})$	$(\bar{d}_p \gamma^{\mu} d_r)$
$Q_{H\widetilde{W}B}$	$H^{\dagger} \tau^{I} H \widetilde{W}^{I}_{\mu\nu} B^{\mu\nu}$	Q_{AB}	$(\bar{q}_{\nu}\sigma^{\mu}$	$\nu d_{\tau})HE$	3μυ	Q_{Hud} +	h.c.	$i(\widetilde{H}^*L$	$(\bar{u}_{\rho}\gamma^{\mu}d_{r})$
	$8: (\overline{L}L)(\overline{L}L)$	_	8:(.	$\bar{R}R)(\bar{R}h$	2)		8:	$(\bar{L}L)(\bar{R}F)$	l)
Q_{11}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	(ē _j	$_{p}\gamma_{\mu}e_{r})(\bar{e}$	$s\gamma^{\mu}e_t)$	Q_{lv}	($\bar{l}_p \gamma_\mu l_\tau)(\bar{e}$	$_{s}\gamma^{\mu}e_{i})$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_j$	$\gamma_{\mu}u_{r})(\bar{u}$	$i_s \gamma^{\mu} u_t$)	Q_{lu}	(1	$(\bar{u}_p \gamma_\mu l_r)(\bar{u}_p \gamma_\mu l_r)$	$_{s}\gamma^{\mu}u_{t})$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^J q_r)(\bar{q}_s \gamma^\mu \tau^J q_t)$) Q _{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s$		$i_s \gamma^{\mu} d_t$	$Q_{ld} = (l$		$\bar{l}_p \gamma_\mu l_r)(\bar{d}$	$_{s}\gamma^{\mu}d_{t})$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_{eu}	$Q_{eu} = (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s)$			Q_{qe}	(ē	$\bar{i}_{P}\gamma_{\mu}q_{r})(\bar{c}$	$_{s}\gamma^{\mu}v_{t})$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^J l_r)(\bar{q}_s \gamma^\mu \tau^J q_t)$	$Q_{ed} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_p)$			$(\gamma^{\mu}d_t)$	$Q_{qx}^{(1)}$	- ()	$\bar{q}_p \gamma_\mu q_r)(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$
		$Q_{nd}^{(1)}$	$Q_{nd}^{(1)} = (\bar{u}_p \gamma_\mu u_r)(\dot{a}$		$\bar{l}_s \gamma^{\mu} d_t$)	$\gamma^{\mu}d_i$ = $Q_{q_{\mathcal{R}}}^{(8)}$ $(\bar{q}_p\gamma)$		$(\bar{u}_s \gamma^\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_i)$	
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu)$	$T^A u_r)(\vec{a}$	$\bar{l}_s \gamma^{\mu} T^A d_t$	$Q_{qd}^{(1)}$	(¢	$\bar{q}_p \gamma_\mu q_r)(\dot{a}$	$\bar{l}_s \gamma^{\mu} d_t$)
						$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_l$	$T^A q_r)(\dot{a}$	$\bar{l}_s \gamma^{\mu} T^A d_t$
	$8 : (\bar{L}R)($	$\bar{R}L$) + h	с.	8:($(\bar{L}R)(\bar{L}R)$	+ h.c.			
	Q_{ledy} (1	$(\bar{d}_{p}e_{r})(\bar{d}_{s}q)$	_g) ζ) $Q_{guad}^{(1)} = (\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_l)$					
			4	$Q_{guast}^{(8)} = (\bar{q}_{\nu}^{i}T^{A}u_{r})\epsilon_{jk}(\bar{q}_{s}^{k}T^{A}d_{t})$					
			6	$Q_{lequ}^{(1)}$	$(\bar{l}_{p}^{j}e_{r})e$	$j_k(\bar{q}_s^k u_t)$			
			Ģ	$2_{legs}^{(3)}$ ($(\tilde{l}_{p}^{j}\sigma_{\mu\nu}c_{\tau})e$	$_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u$	ð		

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

4 fermion interactions

dipole transitions

	$1 : X^{3}$	2 : I	I^6	3 : E	$I^{4}D^{2}$	$5: \psi^2 H^3$.	+ h.c.	
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_H (1	$(H^{\dagger}H)^{3}$ 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_{i}	$HD = (H^{\dagger}D)$	$(H)^* (H^* D_\mu I$	$(H^{\dagger}H) = Q_{uH} = (H^{\dagger}H)$	$(\bar{q}_p u_r \tilde{H})$	
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$					$Q_{dH} = (H^{\dagger}H)$	$(\bar{q}_p d_r H)$	
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$							
	$4 : X^2 H^2$	6	$\psi^2 X H + h$.c.		$7: \psi^2 H^2 D$		2499 baryon number conserving
Q_{HG}	$\Pi^+\Pi^- G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu}$	Q_{eW}	$(l_p \sigma^{\mu\nu} e_r) \tau^{\mu}$	$HW^{I}_{\mu\nu}$	$Q_{H_1}^{(i)}$	$(II^{i}ID_{\mu}II)(I_{i}$	$\gamma^{\mu}t_{\tau}$)	dim. 6 operators in total
$Q_{H\overline{G}}$	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{vB}	$(l_p \sigma^{\mu\nu} e_r).$	$HB_{\mu\nu}$	Q_{H}^{oo}	$(H^{\dagger}i D_{\mu}^{I}H)(l_{p})$	$r^{z} \gamma^{\mu} l_{r}$	
Q_{HW}	$H^{\dagger}HW^{I}_{\mu\nu}W^{I}u\nu$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A v_i$	$()H G^{A}_{\mu\nu}$	Q_{He}	$(H^{\dagger}i D_{\mu}H)(\tilde{e}_{j})$	$\gamma^{\mu}e_{\tau})$	Grzadkowski et al. 1008.4884,
$Q_{H\widetilde{W}}$	$H^{\dagger}HW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{wW}	$(\bar{q}_F \sigma^{\mu\nu} u_r) \tau^{\mu\nu}$	$H W^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^{\dagger}i D_{\mu}H)(\bar{q})$	$\gamma^{\mu}q_{r})$	Alonso et al 1312.2014
Q_{HB}	$H^*H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)$.	$\bar{H} B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^{\dagger}i D^{I}_{\mu}H)(\bar{q}_{p})$	$r^{I}\gamma^{\mu}q_{r})$	
$Q_{H\widetilde{B}}$	$H^{-}H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r$	$H G^A_{\mu\nu}$	Q_{Hu}	$(H^{\dagger}i\overleftarrow{D}_{\mu}H)(\overline{u}_{\mu})$	$\gamma^{\mu}u_{\tau}$)	
Q_{HWB}	$H^{\dagger}\tau^{I}HW^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu \nu} d_r) \tau^{\mu}$	$H W^{I}_{\mu\nu}$	Q_{Hd}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\overline{d}_{\mu})$	$\gamma^{\mu}d_{r})$	
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_{\nu}\sigma^{\mu\nu}d_{\tau}).$	$H B_{\mu\nu}$	$Q_{Hud} + h.c$:. $i(\tilde{H}^*D_{\mu}H)(\bar{v}_j$	$\gamma^{\mu}d_r)$	A formation interactions
	$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)$	$(\bar{R}R)$	_	$8 : (\overline{L}L)(\overline{R}R)$		4 lermion interactions
Q_{11}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_l)$	$(\bar{e}_s \gamma^{\mu} e_t)$	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}	$(\bar{u}_p \gamma_\mu u_l)$	$(\bar{u}_s \gamma^{\mu} u_t)$	Q_{lu}	$(\bar{l}_{\rm F}\gamma_\mu i_{\rm F})(\bar{u}_s\gamma^\mu u_t)$		dipole transitions
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^j q_r)(\bar{q}_s \gamma^\mu \tau^j q_l)$	$) = Q_{dd}$	$(\bar{d}_p \gamma_\mu d)$	$(d_s \gamma^{\mu} d_t)$	Q_{LI}	$(\bar{l}_p \gamma_\mu l_r) (\bar{d}_s \gamma^\mu d_t)$		
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e,$	$(\bar{u}_s \gamma^{\mu} u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$		
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau' l_r)(\bar{q}_s \gamma^\mu \tau^I q_i)$	$) = Q_{cd}$	$(\bar{e}_p \gamma_\mu e_i$	$(\bar{d}_o \gamma^{\mu} d_t)$	$Q_{q_{2}}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$		7-penquine
		$Q_{nd}^{(1)}$	$(\bar{u}_p \gamma_\mu u$	$_{r})(\bar{d}_{s}\gamma^{\mu}d_{t})$	$Q_{qu}^{(8)} = (\hat{q}$	$(\bar{u}_s \gamma_\mu T^A q_r) (\bar{u}_s \gamma^\mu T^A)$	(i)	2-periguins
		$Q_{nd}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u$	$(\bar{d}_s \gamma^{\mu} T^A d_i)$	$Q_{ad}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$		
					$Q_{qd}^{(8)}$ (4	$(\bar{d}_s \gamma_\mu T^A q_r) (\bar{d}_s \gamma^\mu T^A q_r)$	h)	
	$8 \cdot (\bar{L}R)$	$(\bar{R}L) + h$	c 3	$8 \cdot (\bar{L}R)(\bar{L}R)$	+ h c			
	0	Ūv)(ā n	A 0 ⁽¹⁾	(7/14)	$a(\bar{a}^k d_i)$			
	Gleda (*p**)(asqi	(8)	$(q_p u_r) \in (\pi i \pi A_{ir})$	us (aktrisau)			
			Q_{quiqd} $O^{(1)}$	$(I_p f^{(i)} u_r) e$ $(\overline{I} f_r) e$	$(=k_m)$			
			$Q_{lequ}^{(3)}$	$(l_p^2 e_r) \epsilon$	$j_k(q_s u_i)$			
			Qiegu	$(l_p \sigma_{\mu\nu} e_r) \epsilon$	$_{jk}(q_s^*\sigma^{\mu\nu}u_t)$			

	$1 : X^3$	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}	$(H^{\dagger}H)(\bar{l}_{p}e,H)$	
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$			Q_{HD}	$(H^{\dagger}D_{\mu}H)^{*}(H^{\dagger}D_{\mu}H)$			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}	$(H^{\dagger}H)(\bar{q}_p d_r H)$	
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$									
$4: X^2 H^2$		$6:\psi^2 XH+{\rm h.c.}$					7	$: \psi^{2}H^{2}D$		
Q_{HG}	$H^{\dagger}HG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu}$	$e_r \tau^I HW$	$V^{I}_{\mu\nu}$	$Q_{H!}^{(1)}$		$(\Pi^{\dagger}i^{\dagger})$	$\vec{\mathcal{D}}_{\mu} II (\bar{l}_p \gamma^{\mu} l_{\tau})$	
$Q_{H\widetilde{G}}$	$H^{\dagger}H\widetilde{G}^{A}_{\mu u}G^{A\mu u}$	Q_{zB}	$(\bar{l}_p \sigma^{\mu})$	$\nu e_r)HB_p$	ar.	$Q_{H^{\dagger}}^{(3)}$		$(H^{\dagger}i\overleftarrow{D}$	${}^{I}_{\mu}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$	
Q_{HW}	$H^{\dagger}HW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu})$	$\Gamma^A v_r) \tilde{H}$	$G^A_{\mu\nu}$	Q_{He}		$(H^{\dagger}i\dot{I}$	$\vec{D}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$	
$Q_{H\widetilde{W}}$	$H^{\dagger}H \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_F \sigma^{\mu\nu})$	$u_r)\tau^I \tilde{H} V$	$V^{I}_{\mu\nu}$	$Q_{Hq}^{(1)}$		$(H^{\dagger}i\overleftarrow{I}$	$\vec{D}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$	
Q_{HB}	$H^{-}H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu}$	$\nu u_r)\tilde{H}B$	ja.	$Q_{Hq}^{(3)}$		$(H^{\dagger}i\overleftrightarrow{D}$	${}^{I}_{\mu}H)(\bar{q}_{\rho}\tau^{I}\gamma^{\mu}q_{r})$	
$Q_{H\widetilde{B}}$	$H^*H \tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_{p}\sigma^{\mu\nu}$	$T^A d_r)H$	$G^A_{\mu\nu}$	Q_{Hu}		$(H^{\dagger}i\overleftarrow{L}$	$\dot{D}_{\mu}H)(\bar{u}_p\gamma^{\mu}u_{\tau})$	
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}		$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$		
$Q_{H\widetilde{W}B}$	$H^{\dagger}\tau^{I}H\widetilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_{\nu}\sigma^{\mu}$	$\nu d_{\tau})HB$	μυ	Q_{Hud} +	h.c.	$i(\widetilde{H}^*L$	$(\bar{v}_p \gamma^\mu d_r)$	
	$8:(\bar{L}L)(\bar{L}L)$		8:($\bar{R}R)(\bar{R}R$	$(\bar{R}R)$			$\bar{L}L)(\bar{R}I$	3)	
$Q_{!1}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_i	:e (ē	$_{p}\gamma_{\mu}e_{r})(\bar{e}_{i}$	$\gamma^{\mu}e_t$)	Q_{lv}	(\bar{l}_j)	$_{p}\gamma_{\mu}l_{\tau})(\bar{e}$	$_{s}\gamma^{\mu}e_{t})$	
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{i}	uu (ü.	$_{p}\gamma_{\mu}u_{r})(\bar{u}$	$s\gamma^{\mu}u_{t})$	Q_{lu}	(\bar{l}_{p})	$\gamma_{\mu} i_{\tau})(\bar{u}$	$_{s}\gamma^{\mu}u_{t})$	
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^J q_r)(\bar{q}_s \gamma^\mu \tau^J q_l)$	Q_i	11 (d	$_{p}\gamma_{\mu}d_{r})(\bar{d}$	$\gamma^{\mu}d_{t})$	$Q_{Li} = (l$		$\gamma_{\mu}l_{\tau})(d$	$(_{s}\gamma^{\mu}d_{t})$	
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_i)$	Q_i	:u (ē	$_{p}\gamma_{\mu}e_{\tau})(\bar{u}_{z}$	$_{\mu}e_{\tau})(\bar{u}_{s}\gamma^{\mu}u_{t})$		$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$		$\bar{\epsilon}_s \gamma^{\mu} e_t$)	
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau' l_r)(\bar{q}_s \gamma^\mu \tau^I q_i)$	Q_i	$d = (\bar{e}$	$_p \gamma_\mu e_r)(\bar{d}_i$	$\gamma^{\mu}d_{t})$	$Q_{q_2}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)$		$i_a \gamma^{\mu} u_t$)	
		$Q_{nd}^{(1)}$		$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$		$Q_{q_{2}}^{(8)}$	$(\bar{q}_p \gamma_\mu)$	$T^A q_r)(i$	$i_s \gamma^{\mu} T^A u_i)$	
		Q_i^0	$(\bar{u}_p \gamma_\mu)$	$T^A u_r)(\bar{d}$	$\gamma^{\mu}T^{A}d_{i})$	$Q_{qd}^{(1)}$	$(\bar{q}_l$	$\gamma_{\mu}q_{r})(\dot{a}$	$\bar{l}_s \gamma^{\mu} d_t$)	
					$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu$	$T^A q_r)(\dot{c}$	$\bar{l}_s \gamma^{\mu} T^A d_t$		
	$8 : (\bar{L}R)($	$\bar{R}L) +$	h.c.	8:($\bar{L}R)(\bar{L}R)$	+ h.c.				
	Q_{ledq} (\bar{l}	$(\bar{d}_{p}^{j}e_{\tau})(\bar{d}$	q_{tj} ($Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_j$	$_{ik}(\bar{q}_{s}^{k}d_{t})$				
			0	$Q_{quqd}^{(8)} = (\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$						
			($Q_{lequ}^{(1)} = (\bar{l}_{p}^{j}e_{r})\epsilon_{jk}(\bar{q}_{s}^{k}u_{t})$						
		($2^{(3)}_{eee}$ ($(\overline{l}_{n}^{j}\sigma_{\mu\nu}e_{r})\epsilon_{ik}(\overline{q}_{s}^{k}\sigma^{\mu\nu}u_{t})$						

2499 baryon number conserving dim. 6 operators in total

> Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

4 fermion interactions

dipole transitions

Z-penguins

Higgs penguins

Higgs penguin operators

 $\mathcal{O}_{eh} = (H^{\dagger}H)(\bar{\ell}_1 P_R e_2)H$

 $\mathcal{O}_{uh} = (H^{\dagger}H)(\bar{q}_1P_Ru_2)H^c$ $\mathcal{O}_{dh} = (H^{\dagger}H)(\bar{q}_1P_Rd_2)H$

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[Exercise: show that these interactions lead indeed to flavor violating Higgs couplings]

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[Exercise: show that these interactions lead indeed to flavor violating Higgs couplings]

induced processes:

 $h
ightarrow au \mu$, $au
ightarrow \mu \gamma$, $au
ightarrow {f 3} \mu$, ...



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[Exercise: show that these interactions lead indeed to flavor violating Higgs couplings]

induced processes:

$$\begin{array}{l} h \to \tau \mu \ , \quad \tau \to \mu \gamma \ , \quad \tau \to 3 \mu \ , \ ... \\ t \to h u \ , \quad D^0 - \bar{D}^0 \ \text{mixing} \ , \quad D^0 \to \mu^+ \mu^- \ , \ ... \end{array}$$



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induced processes:

$$\begin{array}{ll} h \rightarrow \tau \mu \,, & \tau \rightarrow \mu \gamma \,, & \tau \rightarrow 3 \mu \,, \, ... \\ t \rightarrow h u \,, & D^0 - \bar{D}^0 \text{ mixing }, & D^0 \rightarrow \mu^+ \mu^- \,, ... \\ h \rightarrow b s \,, & \text{B meson mixing }, & \text{Kaon mixing }, & B_s \rightarrow \mu^+ \mu^- \,, ... \end{array}$$



Z-penguin operators

$$\mathcal{O}_{hl}^{(3)} = (H^{\dagger}i\overleftrightarrow{\mathbf{D}}_{\mu}^{a}H)(\bar{\ell}_{1}\gamma^{\mu}\sigma_{a}P_{L}\ell_{2})$$
$$\tilde{\mathcal{O}}_{hl}^{(1)} = (H^{\dagger}i\overleftrightarrow{\mathbf{D}}_{\mu}H)(\bar{\ell}_{1}\gamma^{\mu}P_{L}\ell_{2})$$
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. . .

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ightarrow au \mu$, $\ au
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Z-penguin operators

$$\begin{aligned} \mathcal{O}_{hl}^{(3)} &= (H^{\dagger}i\overleftrightarrow{\mathbf{D}_{\mu}^{a}}H)(\bar{\ell}_{1}\gamma^{\mu}\sigma_{a}P_{L}\ell_{2})\\ \tilde{\mathcal{O}}_{hl}^{(1)} &= (H^{\dagger}i\overleftrightarrow{\mathbf{D}_{\mu}}H)(\bar{\ell}_{1}\gamma^{\mu}P_{L}\ell_{2})\\ \mathcal{O}_{he} &= (H^{\dagger}i\overleftrightarrow{\mathbf{D}_{\mu}}H)(\bar{e}_{1}\gamma^{\mu}P_{R}e_{2}) \end{aligned}$$



induced processes:

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induced processes:

$$\begin{array}{ll} Z o au \mu \ , & au o 3\mu \ , & \mu o e \ {
m conversion} \ , & ... \\ t o Zu \ , & D^0 - \bar{D}^0 \ {
m mixing} \ , & D^0 o \mu^+ \mu^- \ , ... \\ Z o bs \ , & {
m B} \ {
m meson} \ {
m mixing} \ , & {
m Kaon} \ {
m mixing} \ , & B o K \ell^+ \ell^- \ , ... \end{array}$$

Dipole Operators

dipole operators

$$\mathcal{O}_{dG} = (\bar{q}_1 \sigma^{\mu\nu} T^A P_R d_2) H \ G^A_{\mu\nu}$$
$$\mathcal{O}_{dW} = (\bar{q}_1 \sigma^{\mu\nu} P_R d_2) \sigma^a H \ W^a_{\mu\nu}$$
$$\mathcal{O}_{dB} = (\bar{q}_1 \sigma^{\mu\nu} P_R d_2) H \ B_{\mu\nu}$$

Dipole Operators



...



induced processes:

 $\mu
ightarrow {m e} \gamma \;, \;\; au
ightarrow {m 3} \mu \;\;, \;\; \mu
ightarrow {m e}$ conversion $\;, \;\; \dots \;$

Dipole Operators



...



induced processes:

 $\mu \rightarrow e\gamma$, $\tau \rightarrow 3\mu$, $\mu \rightarrow e$ conversion, ... $t \rightarrow u\gamma$, $t \rightarrow cZ$, $D^0 \rightarrow \rho \mu^+ \mu^-$,...
Dipole Operators



...



induced processes:

 $\begin{array}{l} \mu \rightarrow {\boldsymbol e} \gamma \;, \;\; \tau \rightarrow 3 \mu \;, \;\; \mu \rightarrow {\boldsymbol e} \; {\rm conversion} \;, \;\; ... \\ t \rightarrow u \gamma \;, \;\; t \rightarrow {\boldsymbol c} {\boldsymbol Z} \;, \;\; {\boldsymbol D}^0 \rightarrow \rho \mu^+ \mu^- \;, ... \\ \boldsymbol{b} \rightarrow {\boldsymbol s} \gamma \;, \;\; {\boldsymbol B} \rightarrow {\boldsymbol K}^{(*)} \ell^+ \ell^- \;, \, ... \end{array}$

4 fermion interactions

$$\mathcal{O}_{dd} = (\bar{d}_1 \gamma_\mu P_R d_2) (\bar{d}_3 \gamma^\mu P_R d_4)$$
$$\mathcal{O}_{\ell u} = (\bar{\ell}_1 \gamma_\mu P_L \ell_2) (\bar{u}_1 \gamma^\mu P_R u_2)$$

+ many other Dirac and flavor structures

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Kaon mixing , D^0 mixing , B_d mixing , B_s mixing , ...

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Bounds From Meson Mixing

4 fermion contact interactions leading to Kaon mixing

$$\frac{C_{1}}{\Lambda^{2}}(\bar{d}\gamma_{\mu}P_{L}s)(\bar{d}\gamma^{\mu}P_{L}s)$$

$$\frac{C_{2}}{\Lambda^{2}}(\bar{d}P_{L}s)(\bar{d}P_{L}s)$$

$$\frac{C_{3}}{\Lambda^{2}}(\bar{d}_{\alpha}P_{L}s_{\beta})(\bar{d}_{\beta}P_{L}s_{\alpha})$$

$$\frac{C_{4}}{\Lambda^{2}}(\bar{d}P_{L}s)(\bar{d}P_{R}s)$$

$$\frac{C_{5}}{\Lambda^{2}}(\bar{d}_{\alpha}P_{L}s_{\beta})(\bar{d}_{\beta}P_{R}s_{\alpha})$$

(analogous for other meson systems)

need hadronic matrix elements from lattice to translate measurements into NP bounds

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(bounds on Λ assuming $|C_i| = 1$)

Low energy flavor observables are sensitive to New Physics far beyond the TeV scale



Low energy flavor observables are sensitive to New Physics far beyond the TeV scale



solutions of the hierarchy problem require New Physics at or below the TeV scale

Wolfgang Altmannshofer

Flavor Physics 2

Low energy flavor observables are sensitive to New Physics far beyond the TeV scale

currently no convincing evidence for deviations from Standard Model predictions in flavor experiments



solutions of the hierarchy problem require New Physics at or below the TeV scale

Low energy flavor observables are sensitive to New Physics far beyond the TeV scale



currently no convincing evidence for deviations from Standard Model predictions in flavor experiments

> If there is New Physics at or below the TeV scale, why have we not seen it yet in flavor observables?

solutions of the hierarchy problem require New Physics at or below the TeV scale

Flavor Physics 2

Reactions to the New Physics Flavor Puzzle



Reactions to the New Physics Flavor Puzzle





model building effort (~ $1/\Lambda^2$)

Reactions to the New Physics Flavor Puzzle





model building effort (~ $1/\Lambda^2$)

recall from the first lecture that without the Yukawa couplings, the SM has a large global flavor symmetry

 $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E \times U(1)^5$

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The $SU(3)^5$ symmetry can be formally restored if one promotes the Yukawa couplings to "spurions" that transform in the following way

$$Y_{u} = \mathbf{3}_{Q} \times \overline{\mathbf{3}}_{U}, \quad Y_{d} = \mathbf{3}_{Q} \times \overline{\mathbf{3}}_{D}, \quad Y_{\ell} = \mathbf{3}_{L} \times \overline{\mathbf{3}}_{E}$$

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, $Y_d = \mathbf{3}_Q \times \overline{\mathbf{3}}_D$, $Y_\ell = \mathbf{3}_L \times \overline{\mathbf{3}}_E$

the Yukawa interactions are now formally flavor invariant

$$\mathcal{L} \supset H^{c}(\overline{Q}Y_{u}U) + H^{c}(\overline{Q}Y_{d}D) + H(\overline{L}Y_{\ell}E)$$

Minimal Flavor Violation

the SM Yukawas remain the only sources of flavor breaking also in theories beyond the SM

Chivukula, Georgi '87; D'Ambrosio et al. '02

What happens to flavor changing interactions among down quarks?

$$d^L = \mathbf{3}_Q, \ d^R = \mathbf{3}_D, \ Y_u = \mathbf{3}_Q \times \overline{\mathbf{3}}_U, \ Y_d = \mathbf{3}_Q \times \overline{\mathbf{3}}_D$$

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no flavor change

$$(ar{d}^L Y_d Y_d^\dagger \gamma^\mu d^L) \hspace{0.2cm}
ightarrow \hspace{0.2cm} (ar{d}^L (Y_d^{diag})^2 \gamma^\mu d^L) \hspace{0.2cm}
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$$(ar{d}^L\gamma^\mu d^L) \ o \ (ar{d}^L\gamma^\mu d^L) \ o \$$
no flavor change

$$egin{array}{lll} (ar{d}^L Y_d Y_d^\dagger \gamma^\mu d^L) &
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$$(\bar{d}^L Y_d Y_d^{\dagger} \gamma^{\mu} d^L) \rightarrow (\bar{d}^L (Y_d^{diag})^2 \gamma^{\mu} d^L) \rightarrow \text{no flavor change}$$

 $(\bar{d}^L Y_u Y_u^{\dagger} \gamma^{\mu} d^L) \rightarrow (\bar{d}_i^L V_{ti}^* V_{tk} y_t^2 \gamma^{\mu} d_k^L) \rightarrow \text{flavor change!}$

flavor changing transitions are proportional to small CKM elements (same as in the SM)

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flavor changing transitions are proportional to small CKM elements (same as in the SM)

transitions involving right handed quarks are further suppressed by small Yukawa couplings

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Meson mixing constraints are strongly relaxed in the MFV framework

The couplings C_i are now suppressed

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new physics can be at the TeV scale without violating the bounds

Flavor Violation in Models of New Physics

Two Higgs Doublet Models

one of the simplest extensions of the SM Higgs sector

▶ two Higgs doublets H_1 and H_2 with hypercharges -1/2 and +1/2

$$H_{2} = \begin{pmatrix} H_{2}^{+} \\ \frac{1}{\sqrt{2}}(vs_{\beta} + h_{2} + ia_{2}) \end{pmatrix} , \quad H_{1} = \begin{pmatrix} \frac{1}{\sqrt{2}}(vc_{\beta} + h_{1} + ia_{1}) \\ H_{1}^{-} \end{pmatrix}$$

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► 5 physical degrees of freedom: *h* and *H*, *A*, and *H*[±] assuming CP conservation:

$$\begin{pmatrix} G^{\pm} \\ H^{\pm} \end{pmatrix} = \begin{pmatrix} s_{\beta} & -c_{\beta} \\ c_{\beta} & s_{\beta} \end{pmatrix} \begin{pmatrix} H_{2}^{\pm} \\ H_{1}^{\pm} \end{pmatrix}$$
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_{\alpha} & -s_{\alpha} \\ s_{\alpha} & c_{\alpha} \end{pmatrix} \begin{pmatrix} h_{2} \\ h_{1} \end{pmatrix} , \quad \begin{pmatrix} G \\ A \end{pmatrix} = \begin{pmatrix} s_{\beta} & -c_{\beta} \\ c_{\beta} & s_{\beta} \end{pmatrix} \begin{pmatrix} a_{2} \\ a_{1} \end{pmatrix}$$

FCNCs at Tree Level

both Higgs doublets can couple to the SM fermions

$$\mathcal{L} \supset (y_u)_{ik} H_2 \bar{Q}_i U_k + (\tilde{y}_u)_{ik} H_1^{\dagger} \bar{Q}_i U_k + (y_d)_{ik} H_1 \bar{Q}_i D_k + (\tilde{y}_d)_{ik} H_2^{\dagger} \bar{Q}_i D_k + (y_\ell)_{ik} H_1 \bar{L}_i E_k + (\tilde{y}_\ell)_{ik} H_2^{\dagger} \bar{L}_i E_k + \text{h.c.}$$
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▶ for generic couplings y and ỹ, quark masses and Higgs couplings are not aligned, e.g.

$$(m_d)_{ik} = \frac{v}{\sqrt{2}} \left(c_\beta(y_d)_{ik} + s_\beta(\tilde{y}_d)_{ik} \right), \quad (g_d^A)_{ik} = \frac{1}{\sqrt{2}} \left(s_\beta(y_d)_{ik} - c_\beta(\tilde{y}_d)_{ik} \right)$$

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- \rightarrow tree level FCNCs



- Natural Flavor Conservation: no tree level FCNCs if all types of fermions couple only to one Higgs doublet (Glashow, Weinberg '77)
- Can be enforced by: (softly broken) continuous symmetries (Peccei-Quinn) or discrete symmetries (Z₂)
- ► 4 possibilities: $(y_u)_{ik} H_2 \overline{Q}_i U_k + (\tilde{y}_d)_{ik} H_2^{\dagger} \overline{Q}_i D_k + (\tilde{y}_\ell)_{ik} H_2^{\dagger} \overline{L}_i E_k$

	type I
up quarks	H ₂
down quarks	H ₂
leptons	H ₂

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	type I	type II	
up quarks	H ₂	H ₂	
down quarks	H_2	H_1	
leptons	H_2	H_1	

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	type I	type II	type III	
up quarks	H ₂	H ₂	H ₂	
down quarks	H_2	H_1	H ₂	
leptons	H_2	H_1	H_1	

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	type I	type II	type III	type IV
up quarks	H ₂	H ₂	H ₂	H ₂
down quarks	H_2	H_1	H ₂	H ₁
leptons	H_2	H_1	H_1	H ₂

2HDMs with Minimal Flavor Violation

expansion of the "wrong" Higgs couplings

$$\begin{split} \tilde{y}_{u} &= \epsilon_{u} y_{u} + \epsilon'_{u} y_{u} y_{u}^{\dagger} y_{u} + \epsilon''_{u} y_{d} y_{d}^{\dagger} y_{u} + \dots \\ \tilde{y}_{d} &= \epsilon_{d} y_{d} + \epsilon'_{d} y_{d} y_{d}^{\dagger} y_{d} + \epsilon''_{d} y_{u} y_{u}^{\dagger} y_{d} + \dots \\ \tilde{y}_{\ell} &= \epsilon_{\ell} y_{\ell} + \epsilon'_{\ell} y_{\ell} y_{\ell}^{\dagger} y_{\ell} + \dots \end{split}$$

 still Flavor Changing Neutral Currents at tree level, but controlled by small Yukawas and CKM elements

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Exercise part 1:

demonstrate that these terms are formally invariant under the flavor group

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Exercise part 1:

demonstrate that these terms are formally invariant under the flavor group

Exercise part 2: rotate into the quark mass eigenstate basis and show that off-diagonal entries in \tilde{y}_u and \tilde{y}_d are suppressed by small CKM elements

 still Flavor Changing Neutral Currents at tree level, but controlled by small Yukawas and CKM elements

The Minimal Supersymmetric Standard Model

Supersymmetry (SUSY) implies: every fermion has a bosonic partner and vice versa

requires 2 Higgs doublets to give mass to up-type and down-type fermions (2HDM type II)

 $\tan\beta = \langle H_{\rm u} \rangle / \langle H_{\rm d} \rangle$

expect at least some SUSY particles (Higgsinos, stops, gluinos) at or below O(TeV) for a *natural* electro-weak scale

Standard particles



SUSY particles



The MSSM can contain many new sources of flavor and CP violation

The MSSM can contain many new sources of flavor and CP violation

Higgsino and Higgs masses \rightarrow 2 phases

 $\mu \tilde{H}_u \tilde{H}_d + \frac{B\mu}{H_u} H_u H_d + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2$

The MSSM can contain many new sources of flavor and CP violation

Higgsino and Higgs masses \rightarrow 2 phases

squark and slepton masses \rightarrow 15 angles + 15 phases

 $\mu \tilde{H}_{u} \tilde{H}_{d} + \frac{B \mu H_{u} H_{d}}{H_{d}} + \frac{m_{H_{u}}^{2} |H_{u}|^{2}}{H_{d}} + \frac{m_{H_{d}}^{2} |H_{d}|^{2}}{H_{d}}$

$$\begin{split} m_Q^2 \tilde{Q}_L^{\dagger} \tilde{Q}_L + m_U^2 \tilde{U}_R^{\dagger} \tilde{U}_R + m_D^2 \tilde{D}_R^{\dagger} \tilde{D}_R \\ + m_L^2 \tilde{L}_L^{\dagger} \tilde{L}_L + m_E^2 \tilde{E}_R^{\dagger} \tilde{E}_R \end{split}$$

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 $m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$

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 $\textbf{\textit{A}}_{u} ~ \textbf{\textit{H}}_{u} \tilde{\textbf{\textit{Q}}}_{L}^{\dagger} \tilde{\textbf{\textit{U}}}_{R} + \textbf{\textit{A}}_{d} ~ \textbf{\textit{H}}_{d} \tilde{\textbf{\textit{Q}}}_{L}^{\dagger} \tilde{\textbf{\textit{D}}}_{R} + \textbf{\textit{A}}_{\ell} ~ \textbf{\textit{H}}_{d} \tilde{\textbf{\textit{L}}}_{L}^{\dagger} \tilde{\textbf{\textit{E}}}_{R}$

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not all phases are physical! (like in the case of the CKM matrix)

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not all phases are physical! (like in the case of the CKM matrix)

2 phases can be rotated away...

Wolfgang Altmannshofer

Flavor Physics 2

squark flavor mixing can lead to large FCNCs at the 1-loop level

most transparent parametrization in terms of "mass insertions"

$$m_Q^2 = \tilde{m}_Q^2 (\mathbf{1} + \delta_q)$$
$$m_U^2 = \tilde{m}_U^2 (\mathbf{1} + \delta_u)$$
$$m_D^2 = \tilde{m}_D^2 (\mathbf{1} + \delta_d)$$



Probing PeV Scale Squarks





$$M_{12}^{K} \propto rac{lpha_{s}^{2}}{m_{ ilde{q}}^{2}} \left(\delta_{sd}^{L} \delta_{sd}^{R}
ight)$$

 squarks of several 100 - 1000 TeV can be probed if relevant phases are not suppressed

Minimal Flavor Violation in the MSSM

soft masses of squarks and sleptons

$$\begin{split} m_{Q}^{2} &= \tilde{m}_{Q}^{2} \left(1\!\!1 + b_{1} Y_{u} Y_{u}^{\dagger} + b_{2} Y_{d} Y_{d}^{\dagger} + \right. \\ &+ b_{3} Y_{d} Y_{d}^{\dagger} Y_{u} Y_{u}^{\dagger} + b_{3}^{*} Y_{u} Y_{u}^{\dagger} Y_{d} Y_{d}^{\dagger} + ... \right) \\ m_{U}^{2} &= \tilde{m}_{U}^{2} \left(1\!\!1 + b_{4} Y_{u}^{\dagger} Y_{u} + ... \right) \\ m_{D}^{2} &= \tilde{m}_{D}^{2} \left(1\!\!1 + b_{5} Y_{d}^{\dagger} Y_{d} + ... \right) \end{split}$$

Minimal Flavor Violation in the MSSM

soft masses of squarks and sleptons

trilinear couplings

$$m_{Q}^{2} = \tilde{m}_{Q}^{2} \left(\mathbf{1} + b_{1} Y_{u} Y_{u}^{\dagger} + b_{2} Y_{d} Y_{d}^{\dagger} + b_{3} Y_{d} Y_{d}^{\dagger} Y_{u} Y_{u}^{\dagger} + b_{3}^{*} Y_{u} Y_{u}^{\dagger} Y_{d} Y_{d}^{\dagger} + \dots \right)$$

$$m_{U}^{2} = \tilde{m}_{U}^{2} \left(\mathbf{1} + b_{4} Y_{u}^{\dagger} Y_{u} + \dots \right)$$

$$m_{D}^{2} = \tilde{m}_{D}^{2} \left(\mathbf{1} + b_{5} Y_{d}^{\dagger} Y_{d} + \dots \right)$$

$$A_{u} = \tilde{A}_{u} \left(11 + b_{6} Y_{d} Y_{d}^{\dagger} + b_{7} Y_{u} Y_{u}^{\dagger} + ... \right) Y_{u}$$
$$A_{d} = \tilde{A}_{d} \left(11 + b_{8} Y_{u} Y_{u}^{\dagger} + b_{9} Y_{d} Y_{d}^{\dagger} + ... \right) Y_{d}$$

Minimal Flavor Violation in the MSSM

soft masses of squarks and sleptons

trilinear couplings

$$m_{Q}^{2} = \tilde{m}_{Q}^{2} \left(11 + b_{1} Y_{u} Y_{u}^{\dagger} + b_{2} Y_{d} Y_{d}^{\dagger} + b_{3} Y_{d} Y_{d}^{\dagger} Y_{u} Y_{u}^{\dagger} + b_{3}^{*} Y_{u} Y_{u}^{\dagger} Y_{d} Y_{d}^{\dagger} + ... \right)$$
$$m_{U}^{2} = \tilde{m}_{U}^{2} \left(11 + b_{4} Y_{u}^{\dagger} Y_{u} + ... \right)$$
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gaugino/higgsino/higgs masses

 $m_1, m_2, m_3, \mu, B\mu$

- flavor violation controlled by small CKM elements
- sources of CP violation beyond the CKM are allowed in MFV

Wolfgang Altmannshofer

Flavor Physics 2

Flavor Anomalies

Overview of Current Flavor Anomalies



Z. Ligeti

The $B \rightarrow D^{(*)} \tau \nu$ Decays



"The R_D and R_{D^*} Anomalies"

$$egin{aligned} R_D &= rac{{
m BR}(B o D au
u)}{{
m BR}(B o D\ell
u)} \ R_{D^*} &= rac{{
m BR}(B o D^* au
u)}{{
m BR}(B o D^* au
u)} \end{aligned}$$

SM predictions very well under control

Fajfer, Kamenik, Nisandzic '12 HPQCD collaboration '15



Belle, BaBar and LHCb results are all high combined significance $\sim 4\sigma$

The $B_{s} ightarrow \phi \mu^{+}\mu^{-}$ Decay



"The $B_s \rightarrow \phi \mu^+ \mu^-$ Anomaly"



branching ratio is 3.5σ below SM prediction for $1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$

The $B \rightarrow K \mu^+ \mu^-$ Decay



"The R_K Anomaly"



2.6 σ hint for violation of lepton flavor universality (LFU)

$$R_{K} = rac{\mathsf{BR}(B o K\mu^{+}\mu^{-})_{[1,6]}}{\mathsf{BR}(B o Ke^{+}e^{-})_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

The $B ightarrow K^* (ightarrow K\pi) \mu^+ \mu^-$ Decay





"The $B ightarrow K^* \mu^+ \mu^-$ Anomaly"

LHCb 1512.04442



 P'_5 characterizes the angular distribution of the decay products

WA, Ball, Bharucha, Buras, Straub, Wick 0811.1214

Bobeth et al. 1212.2321

Descotes-Genon et al. 1207.2753, 1303.5794

2.8 σ deviation in [4,6] GeV² bin (+3.0 σ in [6,8] GeV² bin)

What Could It Be?

branching ratios	angular observables	LFU ratios

What Could It Be?

	branching	angular	LFU
	ratios	observables	ratios
statistical fluctuations?	\checkmark	\checkmark	\checkmark

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	\checkmark	\checkmark	\checkmark
parametric uncertainties?	\checkmark	×	×
What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	\checkmark	\checkmark	\checkmark
parametric uncertainties?	\checkmark	×	×
underestimated hadronic effects?	\checkmark	\checkmark	×

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	\checkmark	\checkmark	\checkmark
parametric uncertainties?	\checkmark	×	×
underestimated hadronic effects?	\checkmark	\checkmark	×
New Physics?	\checkmark	\checkmark	\checkmark

Summary of the Second Lecture

- Low energy flavor observables have indirect sensitivity to very high scales
- If there is new physics at the TeV scale, why have we not seen it yet in flavor observables?
- The idea of Minimal Flavor Violation can tame flavor violation in new physics models
- ► Few anomalies exist in flavor measurements. Are they first hints for new physics?