Flavor Physics
Part 2

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Summer School on Symmetries, Fundamental Interactions and Cosmology 2016,

Abtei Frauenwörth, September 20, 2016

Summary of the First Lecture

- 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

1. 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
2. Flavor 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

$$
\begin{aligned}
\mathcal{L}_{\text{SM}} \quad \sim \quad & \Lambda^4 \; + \; \Lambda^2 H^2 \; + \; \lambda H^4 \\
& + \bar{\Psi} \not{D} \Psi \; + \; (D_\mu H)^2 \; + \; (F_{\mu\nu})^2 \; + \; F_{\mu\nu} \tilde{F}^{\mu\nu} \\
& + Y H \bar{\Psi} \Psi \; + \; \frac{1}{\Lambda} (LH)^2 \; + \; \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}
\end{aligned}
$$

The Standard Model as Effective Theory

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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

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

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

SM flavor puzzle

Neutrino masses

NP flavor puzzle
...

The Hierarchy Problem

What gives mass to the Higgs itself?

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

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

1) can be added by hand

2) not protected from
quantum corrections

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

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

$$\Delta m^2 \sim \frac{1}{16\pi^2} M^2_{\text{Planck}} \simeq 10^{36}\text{GeV}^2$$

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

The Hierarchy Problem

—

Canada		United States		
9,984,670 km^2	$-$	9,826,675 km^2	$=$	157,995 km^2

The Hierarchy Problem

$-$

$= \quad 1\ \text{Å}^2$

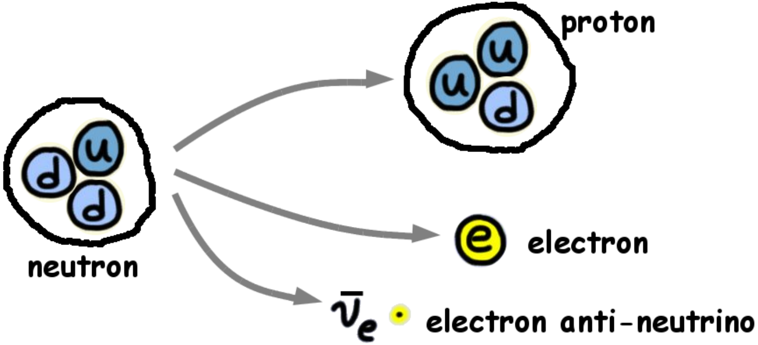
Canada
9,984,670 km^2 $\quad - \quad$ United States
9,826,675 km^2 $\quad = \quad$ 157,995 km^2

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!

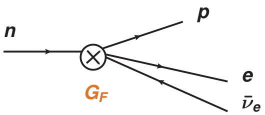
In order to protect the Higgs mass
from huge quantum corrections and to avoid finetuning,
we expect New Physics at the TeV scale

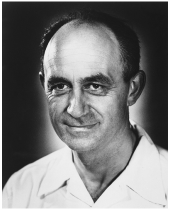
How can we get information on New Physics at high scales from low energy experiments?

Beta Decay



Beta Decay





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

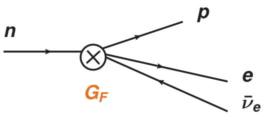
the interaction strength is given by
the Fermi constant

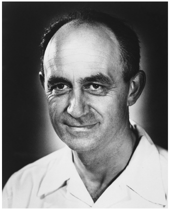
$$G_F \simeq 1.17 \times 10^{-5}\ \text{GeV}^{-2}$$

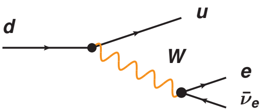
this defines an energy scale

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

Beta Decay







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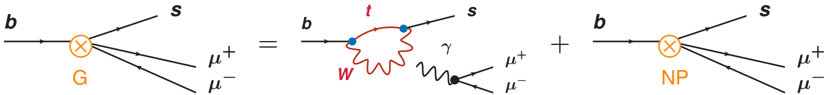
in the Standard Model
we understand beta decay
as consequence of
the exchange of virtual
weak gauge bosons

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

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

New Physics in Flavor Changing Neutral Currents



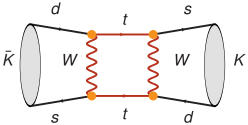
$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

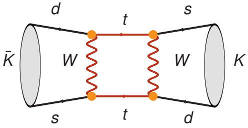
- Standard Model amplitude is loop suppressed and CKM suppressed



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

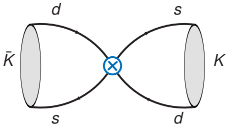
Example: CP Violation in Kaon mixing

- Standard Model amplitude is loop suppressed and CKM suppressed



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

- Generic New Physics amplitude only suppressed by New Physics scale



$$\propto \frac{1}{\Lambda_{\rm NP}^2}$$

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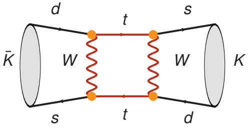

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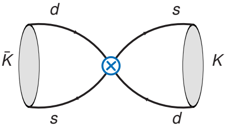

$$\propto \frac{1}{\Lambda_{\rm NP}^2}$$

- CP Violation in Kaon Mixing can probe extremely high scales

$$\Lambda_{\rm NP} \sim \frac{M_W^2}{m_t} \frac{4\pi}{g^2} \frac{1}{|V_{td} V_{ts}^*|} \sim 10^4 \text{ TeV}$$

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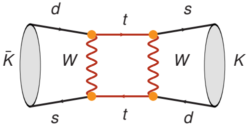

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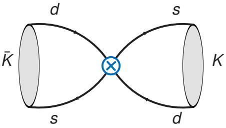

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- CP Violation in Kaon Mixing can probe extremely high scales

$$\Lambda_{\rm NP} \sim \frac{M_W^2}{m_t} \frac{4\pi}{g^2} \frac{1}{|V_{td} V_{ts}^*|} \sim 10^4 \text{ TeV}$$

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

Many Flavor Violating Dimension Six Operators

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

Many Flavor Violating Dimension Six Operators

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			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	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
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$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{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}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	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}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
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				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
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4 fermion interactions

Many Flavor Violating Dimension Six Operators

$1: X^3$		$2: H^6$		$3: H^4 D^2$		$5: \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

$4: X^2 H^2$		$6: \psi^2 X H + \text{h.c.}$		$7: \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
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}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	$Q_{Hud} + \text{h.c.}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$		$8: (\bar R R)(\bar R R)$		$8: (\bar L L)(\bar R R)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	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}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	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}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$		$8: (\bar L R)(\bar L R) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

4 fermion interactions

dipole transitions

Many Flavor Violating Dimension Six Operators

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
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Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
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Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
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$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
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Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
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$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q^{(1)}_{qd}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\epsilon_{jk}(\bar{q}^k_s T^A d_t)$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

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dipole transitions

Z-penguins

Higgs penguins

Higgs Penguin Operators

Higgs penguin operators

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

$$\mathcal{O}_{uh} = (H^\dagger H)(\bar{q}_1 P_R u_2)H^c$$

$$\mathcal{O}_{dh} = (H^\dagger H)(\bar{q}_1 P_R d_2)H$$

Higgs Penguin Operators

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

Higgs penguin operators

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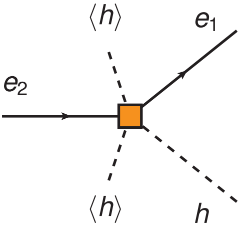

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induced processes:

$h \to \tau\mu$, $\tau \to \mu\gamma$, $\tau \to 3\mu$, ...

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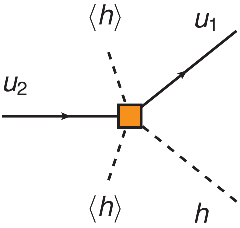

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$t \to hu$, $D^0 - \bar{D}^0$ mixing , $D^0 \to \mu^+\mu^-$, ...

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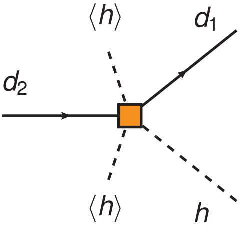

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induced processes:

$h \to \tau\mu$, $\tau \to \mu\gamma$, $\tau \to 3\mu$, ...
$t \to hu$, $D^0 - \bar{D}^0$ mixing , $D^0 \to \mu^+\mu^-$, ...
$h \to bs$, B meson mixing , Kaon mixing , $B_s \to \mu^+\mu^-$, ...

Z-penguin operators

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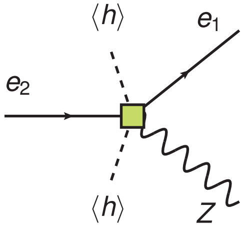

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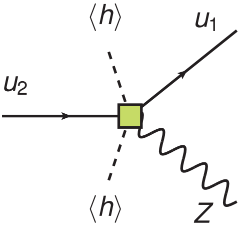

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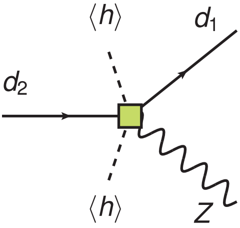

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dipole operators

$$\mathcal{O}_{dG} = (\bar{q}_1 \sigma^{\mu\nu} T^A P_R d_2) H \;\; G^A_{\mu\nu}$$

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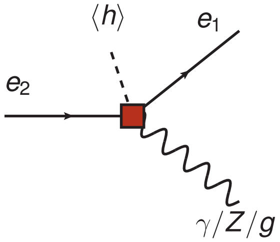

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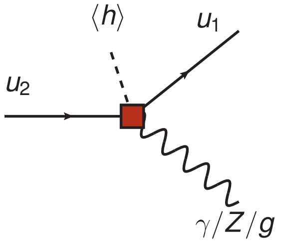

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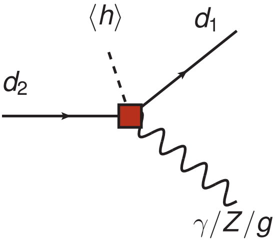

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Four Fermion Contact Interactions

4 fermion interactions

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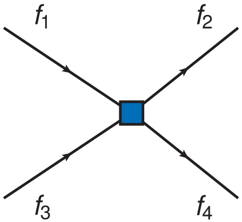

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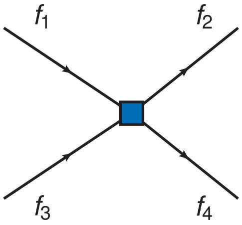

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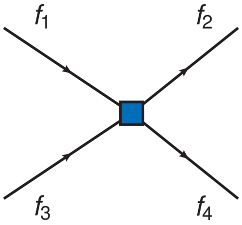

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(analogous for other meson systems)

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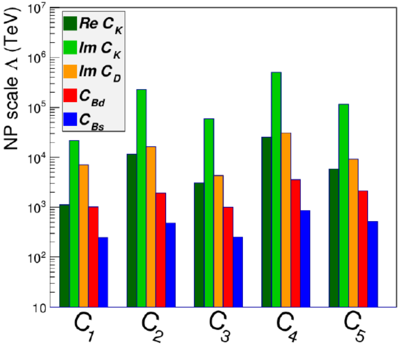

Lower bounds on NP scale (in TeV at 95% prob.)

(bounds on Λ assuming $|C_i| = 1$)

The New Physics Flavor Puzzle

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

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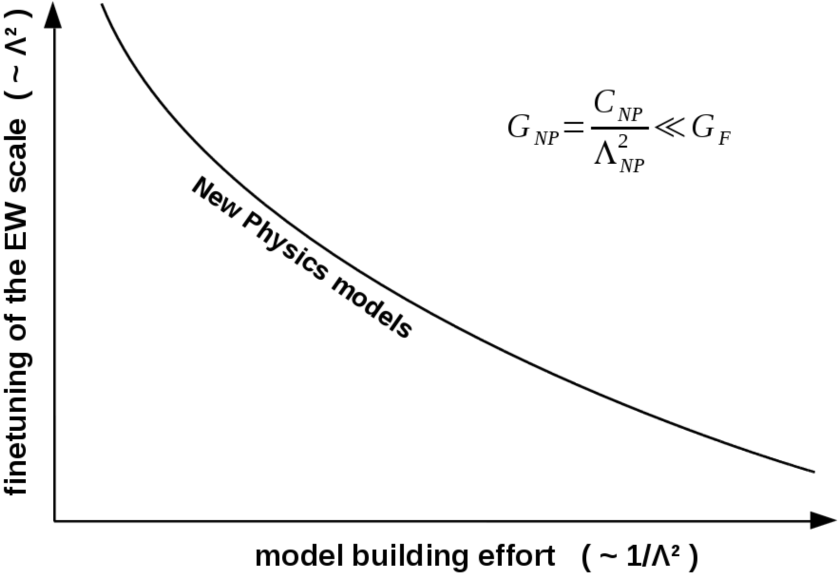
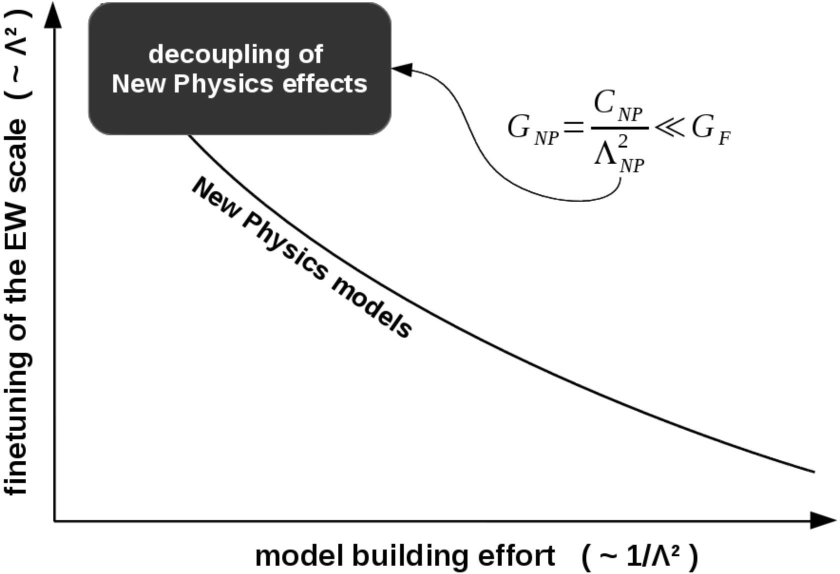
If there is New Physics at or below the TeV scale, why have we not seen it yet in flavor observables?

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

Reactions to the New Physics Flavor Puzzle

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New Physics effects
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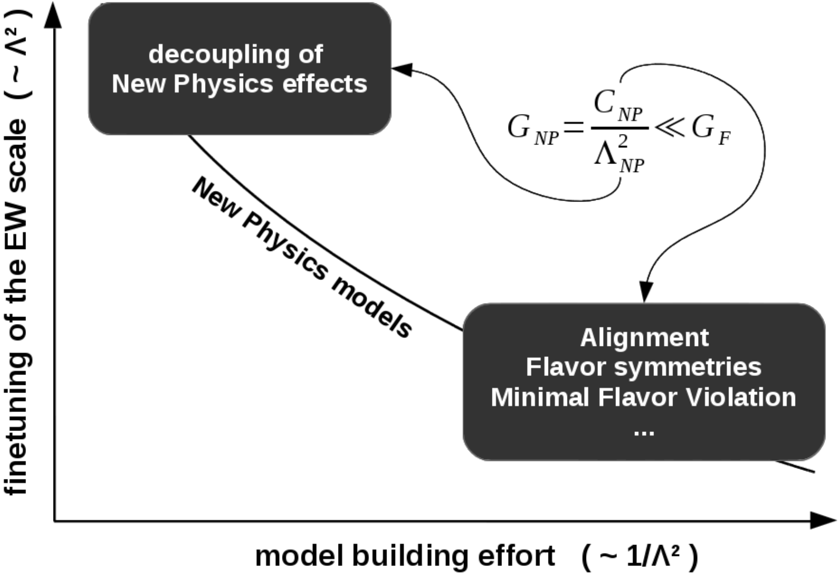
New Physics models
finetuning of the EW scale (~ Λ²)
model building effort (~ 1/Λ²)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New Physics models
Alignment
Flavor symmetries
Minimal Flavor Violation
...
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Minimal Flavor Violation

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

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the Yukawa interactions are now formally flavor invariant

$$\mathcal{L} \supset H^c(\bar{Q} Y_u U) \ + \ H^c(\bar{Q} Y_d D) \ + \ H(\bar{L} Y_\ell E)$$

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?

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

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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

$$H_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v s_\beta + h_2 + i a_2) \end{pmatrix} \quad , \quad H_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v c_\beta + h_1 + i a_1) \\ H_1^- \end{pmatrix}$$

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- 5 physical degrees of freedom: h and H, A, and $H^\pm$

  assuming CP conservation:

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} H_2^\pm \\ H_1^\pm \end{pmatrix}$$

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FCNCs at Tree Level

both Higgs doublets can couple to the SM fermions

$$\begin{aligned} \mathcal{L} \supset \quad & (y_u)_{ik}\, H_2 \bar{Q}_i U_k + (\tilde{y}_u)_{ik}\, H_1^\dagger \bar{Q}_i U_k \\ & +(y_d)_{ik}\, H_1 \bar{Q}_i D_k + (\tilde{y}_d)_{ik}\, H_2^\dagger \bar{Q}_i D_k \\ & +(y_\ell)_{ik}\, H_1 \bar{L}_i E_k + (\tilde{y}_\ell)_{ik}\, H_2^\dagger \bar{L}_i E_k \quad + \text{h.c.} \end{aligned}$$

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$$+(y_d)_{ik}\ H_1 \bar{Q}_i D_k + (\tilde{y}_d)_{ik}\ H_2^\dagger \bar{Q}_i D_k$$
$$+(y_\ell)_{ik}\ H_1 \bar{L}_i E_k + (\tilde{y}_\ell)_{ik}\ H_2^\dagger \bar{L}_i E_k \quad + \text{h.c.}$$

- for generic couplings y and $\tilde{y}$,
  quark masses and Higgs couplings are not aligned, e.g.

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

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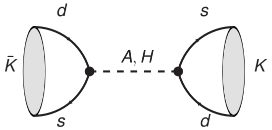
→ tree level FCNCs

→ incredible strong constraints
from meson mixing



2HDMs with Natural Flavor Conservation

- 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 (Z_2)
- 4 possibilities: $(y_u)_{ik}\ H_2 \bar{Q}_i U_k + (\tilde{y}_d)_{ik}\ H_2^\dagger \bar{Q}_i D_k + (\tilde{y}_\ell)_{ik}\ H_2^\dagger \bar{L}_i E_k$

	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

$$\begin{aligned}\tilde{y}_u &= \epsilon_u y_u + \epsilon'_u y_u y_u^\dagger y_u + \epsilon''_u y_d y_d^\dagger y_u + \dots \\ \tilde{y}_d &= \epsilon_d y_d + \epsilon'_d y_d y_d^\dagger y_d + \epsilon''_d y_u y_u^\dagger y_d + \dots \\ \tilde{y}_\ell &= \epsilon_\ell y_\ell + \epsilon'_\ell y_\ell y_\ell^\dagger y_\ell + \dots\end{aligned}$$

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

2HDMs with Minimal Flavor Violation

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\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 + \ldots \\
\tilde{y}_\ell &= \epsilon_\ell y_\ell + \epsilon'_\ell y_\ell y_\ell^\dagger y_\ell + \ldots
\end{aligned}$$

Exercise part 1:
demonstrate that these terms are formally invariant under the flavor group

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

2HDMs with Minimal Flavor Violation

- expansion of the “wrong” Higgs couplings

$$\tilde{y}_u = \epsilon_u y_u + \epsilon'_u y_u y_u^\dagger y_u + \epsilon''_u y_d y_d^\dagger y_u + \ldots$$
$$\tilde{y}_d = \epsilon_d y_d + \epsilon'_d y_d y_d^\dagger y_d + \epsilon''_d y_u y_u^\dagger y_d + \ldots$$
$$\tilde{y}_\ell = \epsilon_\ell y_\ell + \epsilon'_\ell y_\ell y_\ell^\dagger y_\ell + \ldots$$

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

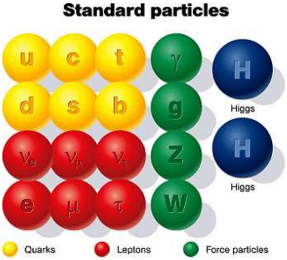
The Minimal Supersymmetric Standard Model

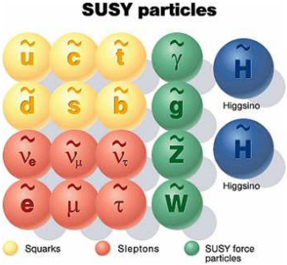
Supersymmetry (SUSY) implies:
every fermion has a bosonic partner
and vice versa

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

$$\tan\beta = \langle H_u \rangle / \langle H_d \rangle$$

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





Flavor and CP Violation in the MSSM

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

Flavor and CP Violation in the MSSM

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

Higgsino and Higgs masses
$\rightarrow$ 2 phases

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

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squark and slepton masses
$\rightarrow$ 15 angles + 15 phases

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

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gaugino masses
$\rightarrow$ 3 phases

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

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

trilinear couplings
$\rightarrow$ 18 angles + 27 phases

$$A_u\, H_u \tilde{Q}_L^\dagger \tilde{U}_R + A_d\, H_d \tilde{Q}_L^\dagger \tilde{D}_R + A_\ell\, H_d \tilde{L}_L^\dagger \tilde{E}_R$$

Flavor and CP Violation in the MSSM

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Higgsino and Higgs masses
$\rightarrow$ 2 phases

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

squark and slepton masses
$\rightarrow$ 15 angles + 15 phases

$$m^2_Q \tilde{Q}^\dagger_L \tilde{Q}_L + m^2_U \tilde{U}^\dagger_R \tilde{U}_R + m^2_D \tilde{D}^\dagger_R \tilde{D}_R$$
$$+ m^2_L \tilde{L}^\dagger_L \tilde{L}_L + m^2_E \tilde{E}^\dagger_R \tilde{E}_R$$

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

Flavor and CP Violation in the MSSM

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

Higgsino and Higgs masses
$\to$ 2 phases

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

squark and slepton masses
$\to$ 15 angles + 15 phases

$$m_Q^2 \tilde{Q}_L^\dagger \tilde{Q}_L + m_U^2 \tilde{U}_R^\dagger \tilde{U}_R + m_D^2 \tilde{D}_R^\dagger \tilde{D}_R$$
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not all phases are physical! (like in the case of the CKM matrix)

2 phases can be rotated away...

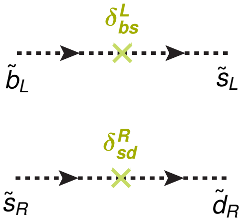
squark flavor mixing can lead to large FCNCs at the 1-loop level

most transparent parametrization in terms of “mass insertions”

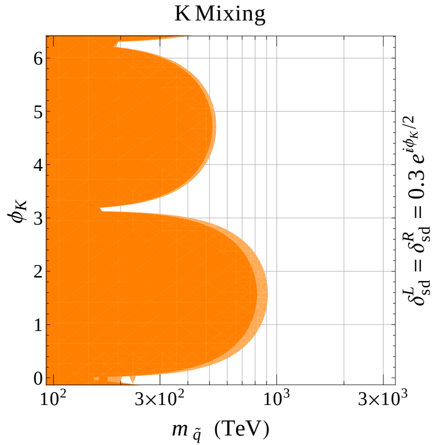
$$m_Q^2 = \tilde{m}_Q^2(\mathbb{1} + \delta_q)$$

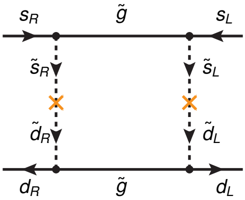
$$m_U^2 = \tilde{m}_U^2(\mathbb{1} + \delta_u)$$

$$m_D^2 = \tilde{m}_D^2(\mathbb{1} + \delta_d)$$



Probing PeV Scale Squarks





$$M_{12}^K \propto \frac{\alpha_s^2}{m_{\tilde{q}}^2} \left(\delta^L_{sd}\delta^R_{sd}\right)$$

- 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

$$m_Q^2 = \tilde{m}_Q^2 \Big(1\!\!1 + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger +$$

$$+ b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + ... \Big)$$

$$m_U^2 = \tilde{m}_U^2 \Big(1\!\!1 + b_4 Y_u^\dagger Y_u + ... \Big)$$

$$m_D^2 = \tilde{m}_D^2 \Big(1\!\!1 + b_5 Y_d^\dagger Y_d + ... \Big)$$

Minimal Flavor Violation in the MSSM

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$$+ b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + ... \Big)$$
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$$m_D^2 = \tilde{m}_D^2 \Big(1\!\!1 + b_5 Y_d^\dagger Y_d + ... \Big)$$

trilinear couplings

$$A_u = \tilde{A}_u \Big(1\!\!1 + b_6 Y_d Y_d^\dagger + b_7 Y_u Y_u^\dagger + ... \Big) Y_u$$
$$A_d = \tilde{A}_d \Big(1\!\!1 + b_8 Y_u Y_u^\dagger + b_9 Y_d Y_d^\dagger + ... \Big) Y_d$$

Minimal Flavor Violation in the MSSM

soft masses
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$$\left. + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + ... \right)$$

$$m_U^2 = \tilde{m}_U^2 \left(1\!\!1 + b_4 Y_u^\dagger Y_u + ... \right)$$

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$$A_d = \tilde{A}_d \left(1\!\!1 + b_8 Y_u Y_u^\dagger + b_9 Y_d Y_d^\dagger + ... \right) Y_d$$

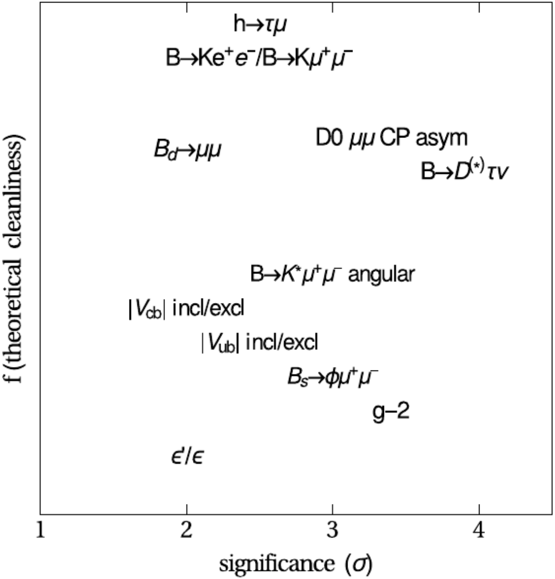
gaugino/higgsino/higgs
masses

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

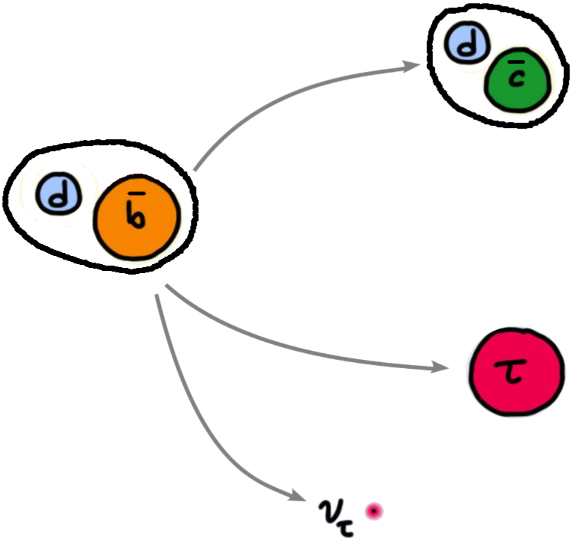
- flavor violation controlled by small CKM elements
- sources of CP violation beyond the CKM are allowed in MFV

Flavor Anomalies

Overview of Current Flavor Anomalies



Z. Ligeti


d
$\bar{b}$
d
$\bar{c}$
τ
ν_τ

“The R_D and R_{D^*} Anomalies”

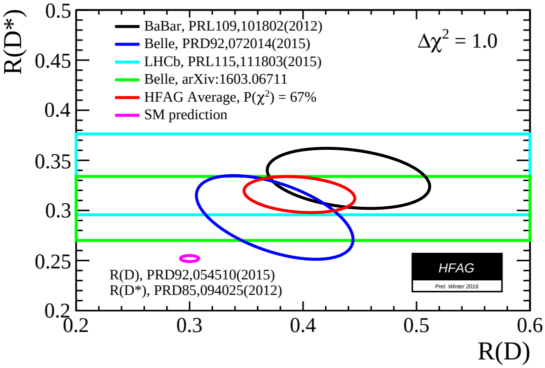
$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

SM predictions very well under control

Fajfer, Kamenik, Nisandzic ’12

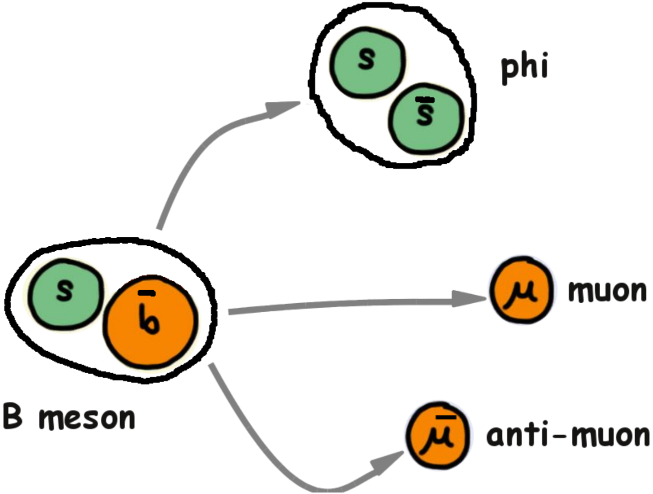
HPQCD collaboration ’15



Belle, BaBar and LHCb results are all high

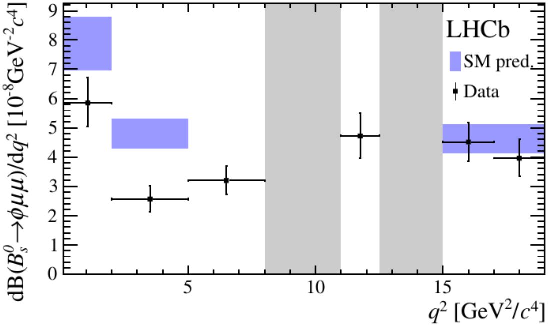
combined significance $\sim 4\sigma$

The $B_s \to \phi\mu^+\mu^-$ Decay



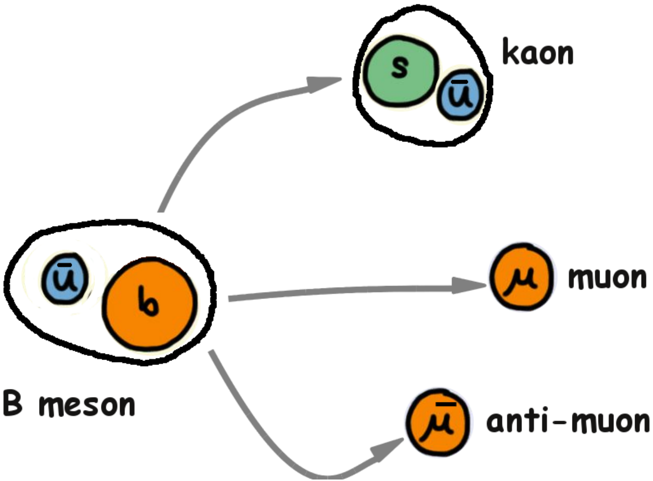
“The $B_s \to \phi\mu^+\mu^-$ Anomaly”

LHCb 1506.08777

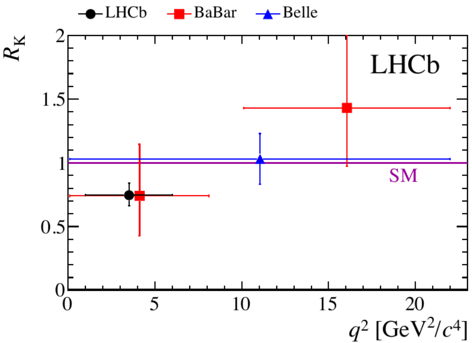


branching ratio is 3.5σ below SM prediction for $1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$

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



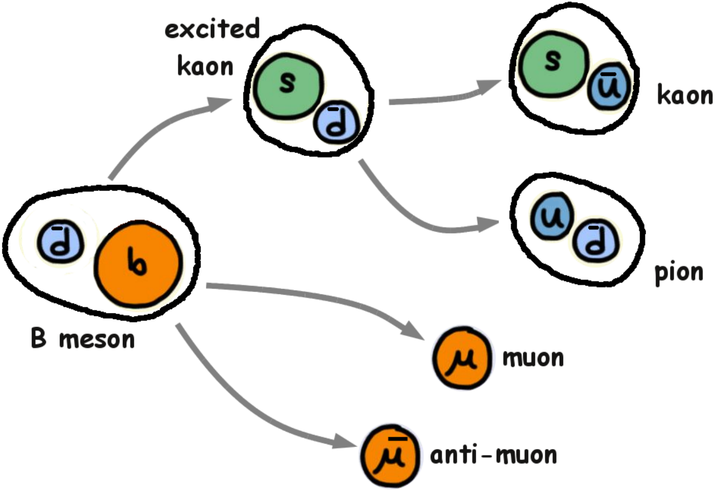
LHCb 1406.6482

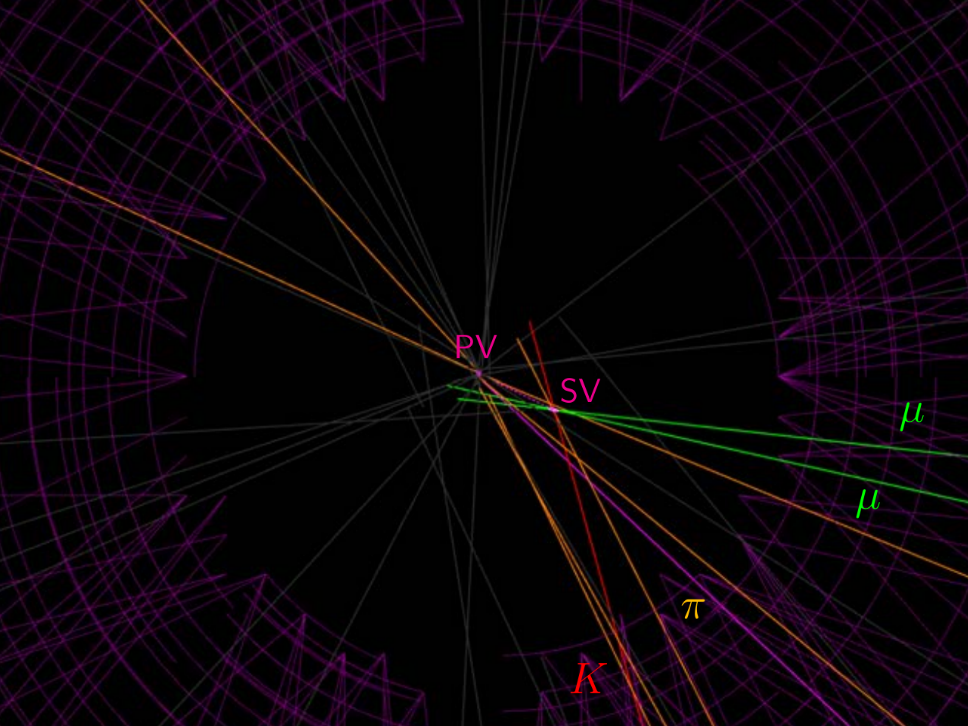


2.6σ hint for violation of lepton flavor universality (LFU)

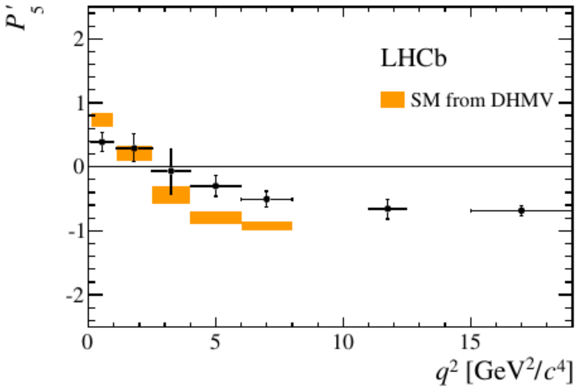
$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

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




PV
SV
μ
μ
π
K

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

...

2.8σ deviation in [4,6] GeV^2 bin
($+$3.0σ in [6,8] GeV^2 bin)

What Could It Be?

	branching ratios	angular observables	LFU ratios

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

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?