Effective Field Theory Fits

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Menu of Flavors: Quarks, Charged Leptons & Neutrinos

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Outline of the Lectures

1. Theory of B Decays (yesterday)
   - Intro: Classification of B Decays
   - $B \to D^{(*)}\ell\nu$ and $R_{D^{(*)}}$
   - $B_s \to \mu^+\mu^-$
   - $B \to K^*\ell^+\ell^-$ and $R_{K^{(*)}}$
2. Effective Field Theory Fits (today)
   - B Decays as Probes of New Physics
   - The Flavor Anomalies
   - Fitting the $b \to c\ell\nu$ Anomalies
   - Fitting the $b \to s\ell\ell$ Anomalies

Direct and Indirect Searches for New Physics

We don't know how the new physics looks like and where it is.

$\rightarrow$ We have to search for it in all possible ways!

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1) Open the boxes!

Direct production of new particles

Direct and Indirect Searches for New Physics

We don't know how the new physics looks like and where it is.

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1) Open the boxes!

Direct production of new particles

2) Shake the boxes!

Look for virtual effects of new particles

The Standard Model as Effective Theory

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

The Standard Model as Effective Theory

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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

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

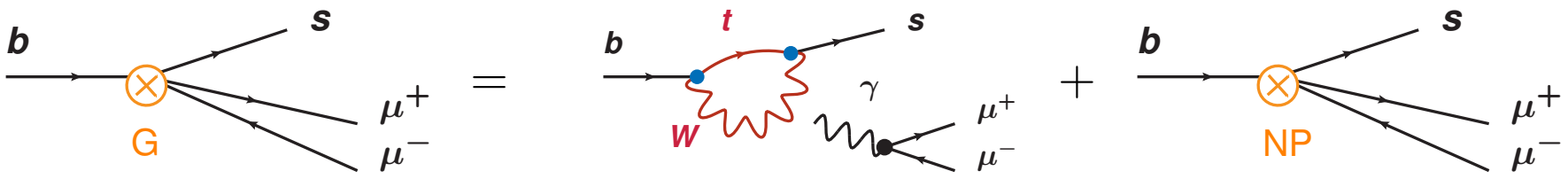
$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{O}_i^{\rm dim6}$$

SM flavor puzzle

Neutrino masses

NP flavor puzzle ...

New Physics in Rare B Decays



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

measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

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}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
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}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

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

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
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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}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
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Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
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$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
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SMEFT

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

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Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H} W_{\mu\nu}^I$
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$Q_{\ell d}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
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4 fermion interactions

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SMEFT

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}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
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}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

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

$7: \psi^2 H^2 D$	
$Q_{H l}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{H l}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
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$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
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}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
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$Q_{\ell q}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
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$Q_{\ell e}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\ell u}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
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$Q_{\ell equ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
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Higgs penguins

Higgs Penguin Operators

Higgs penguin operators

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

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

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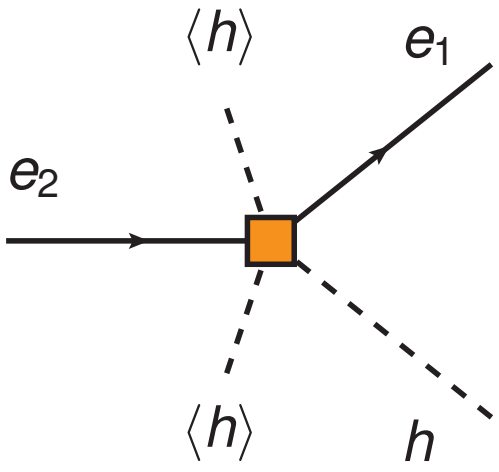

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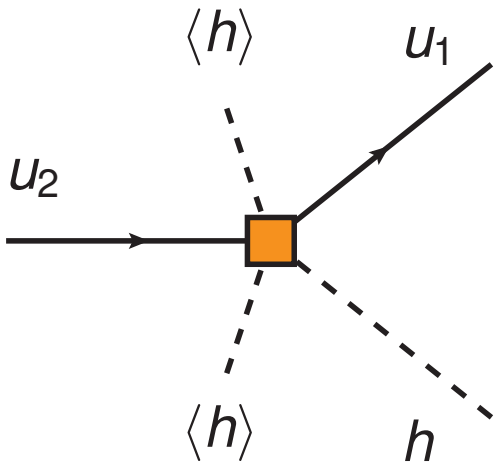

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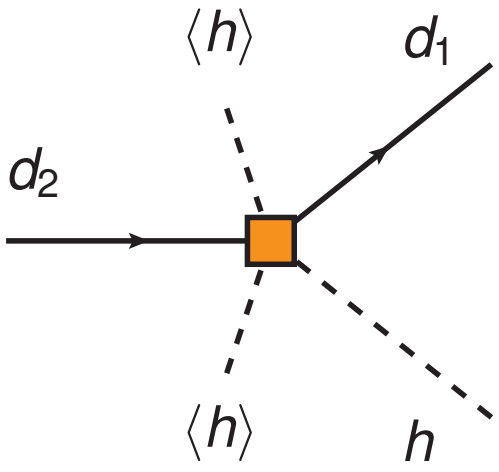

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Z Penguin Operators

Z-penguin operators

$$\mathcal{O}_{hl}^{(3)} = (H^\dagger i \overleftrightarrow{\mathrm{D}}_\mu^a H)(\bar{\ell}_1 \gamma^\mu \sigma_a P_L \ell_2)$$

$$\tilde{\mathcal{O}}_{hl}^{(1)} = (H^\dagger i \overleftrightarrow{\mathrm{D}}_\mu H)(\bar{\ell}_1 \gamma^\mu P_L \ell_2)$$

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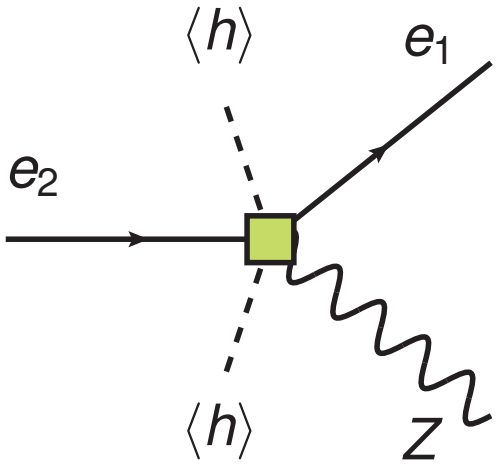

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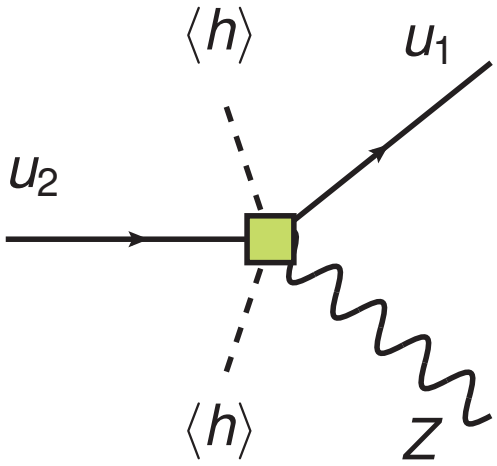

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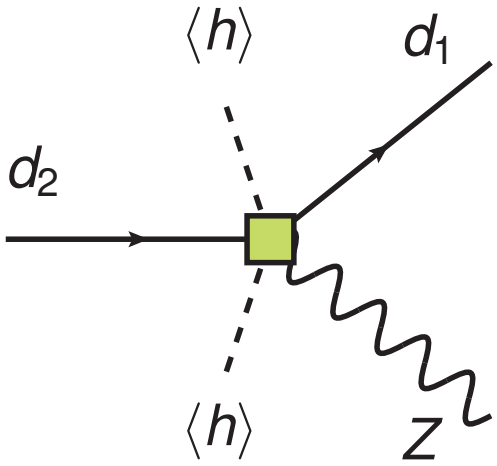

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dipole operators

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$$\mathcal{O}_{dW} = (\bar{q}_1 \sigma^{\mu\nu} P_R d_2) \sigma^a H \;\; W^a_{\mu\nu}$$

$$\mathcal{O}_{dB} = (\bar{q}_1 \sigma^{\mu\nu} P_R d_2) H \;\; B_{\mu\nu}$$

$$\ldots$$

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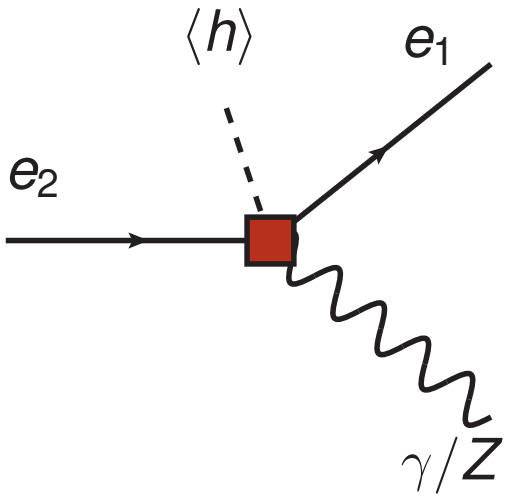

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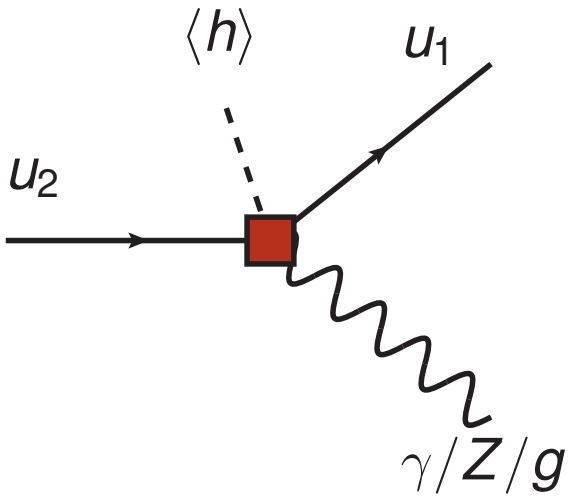

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$t \to u\gamma$, $t \to cZ$, $D^0 \to \rho\mu^+\mu^-$, ...

Dipole Operators

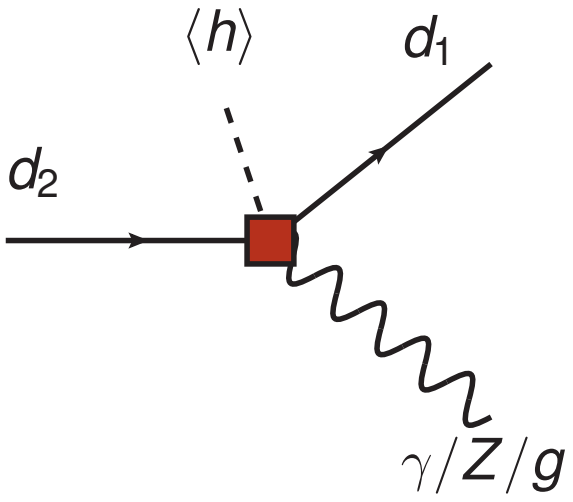
dipole operators

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

$$\mathcal{O}_{dW} = (\bar{q}_1 \sigma^{\mu\nu} P_R d_2) \sigma^a H \;\; W^a_{\mu\nu}$$

$$\mathcal{O}_{dB} = (\bar{q}_1 \sigma^{\mu\nu} P_R d_2) H \;\; B_{\mu\nu}$$

...



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$b \to s\gamma$, $B \to K^{(*)}\ell^+\ell^-$, ...

Four Fermion Contact Interactions

4 fermion interactions

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

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

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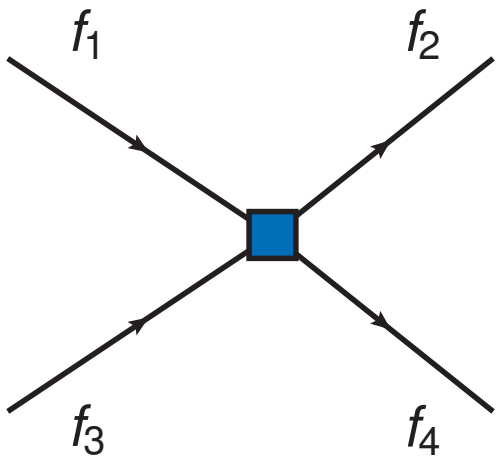

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Kaon mixing , D^0 mixing , B_d mixing , B_s mixing , ...

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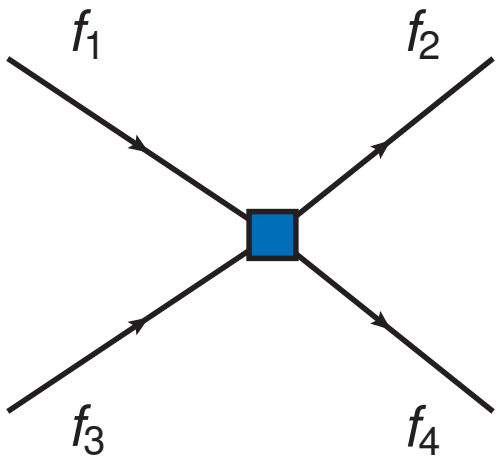

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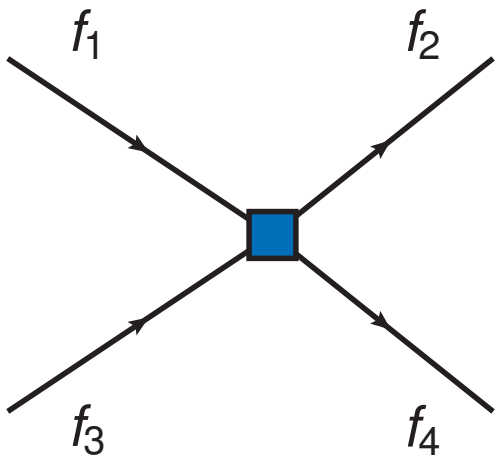

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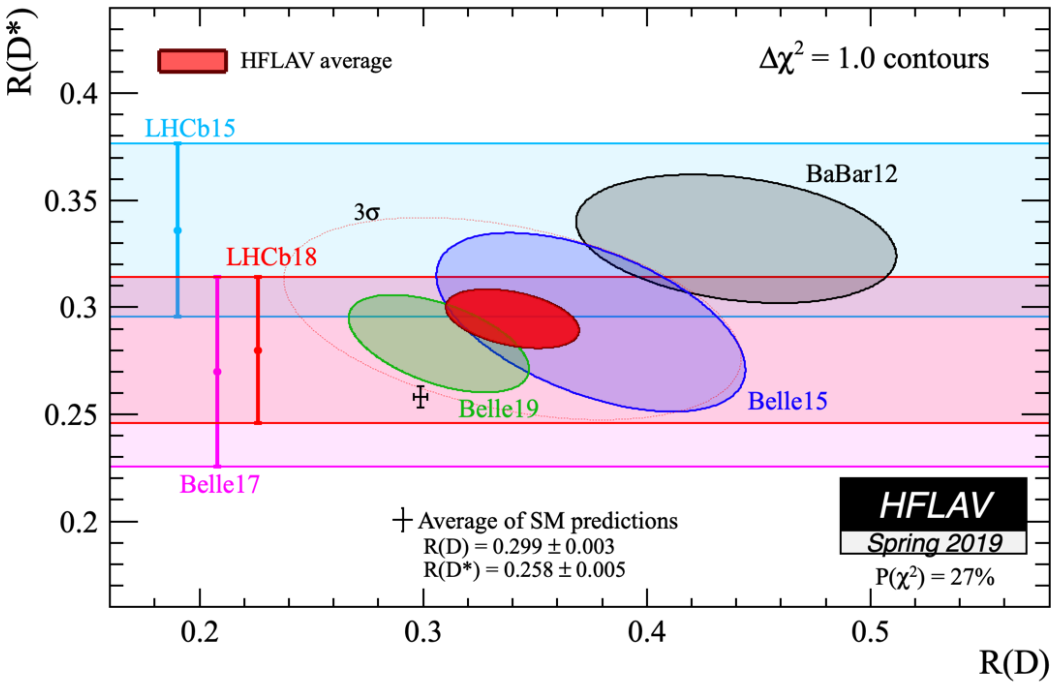
Flavor Anomalies

The $R_{D^{(*)}}$ Anomalies

world average from the heavy flavor averaging group



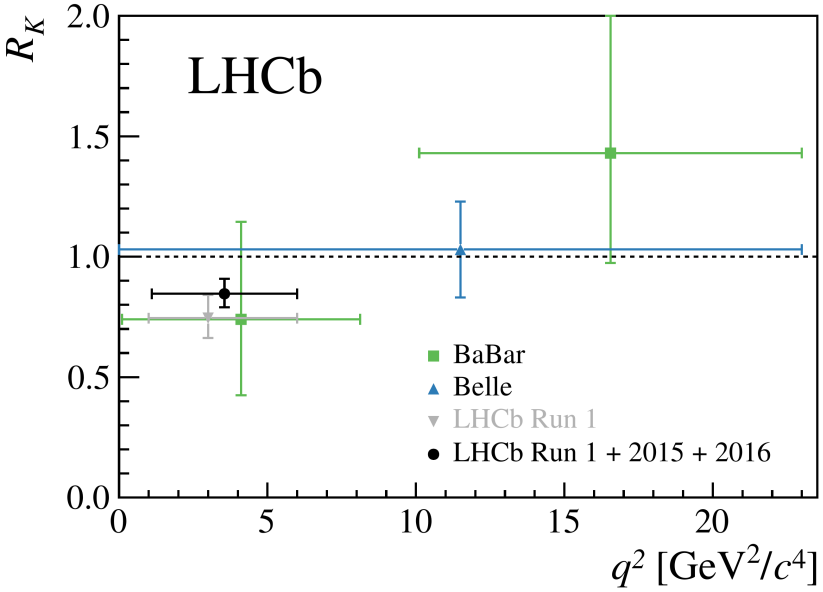
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

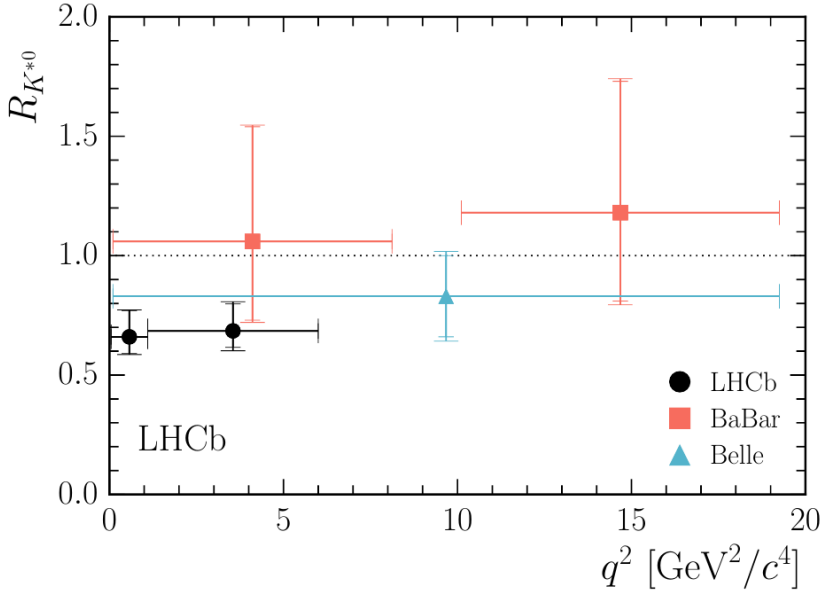
$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

$$R_D^{\text{exp}} = 0.340 \pm 0.027 \pm 0.013 \quad , \qquad R_{D^*}^{\text{exp}} = 0.295 \pm 0.011 \pm 0.008$$

combined discrepancy with the SM of 3.1σ

The $R_{K^{(*)}}$ Anomalies





$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

$$R_K^{[1,6]} = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

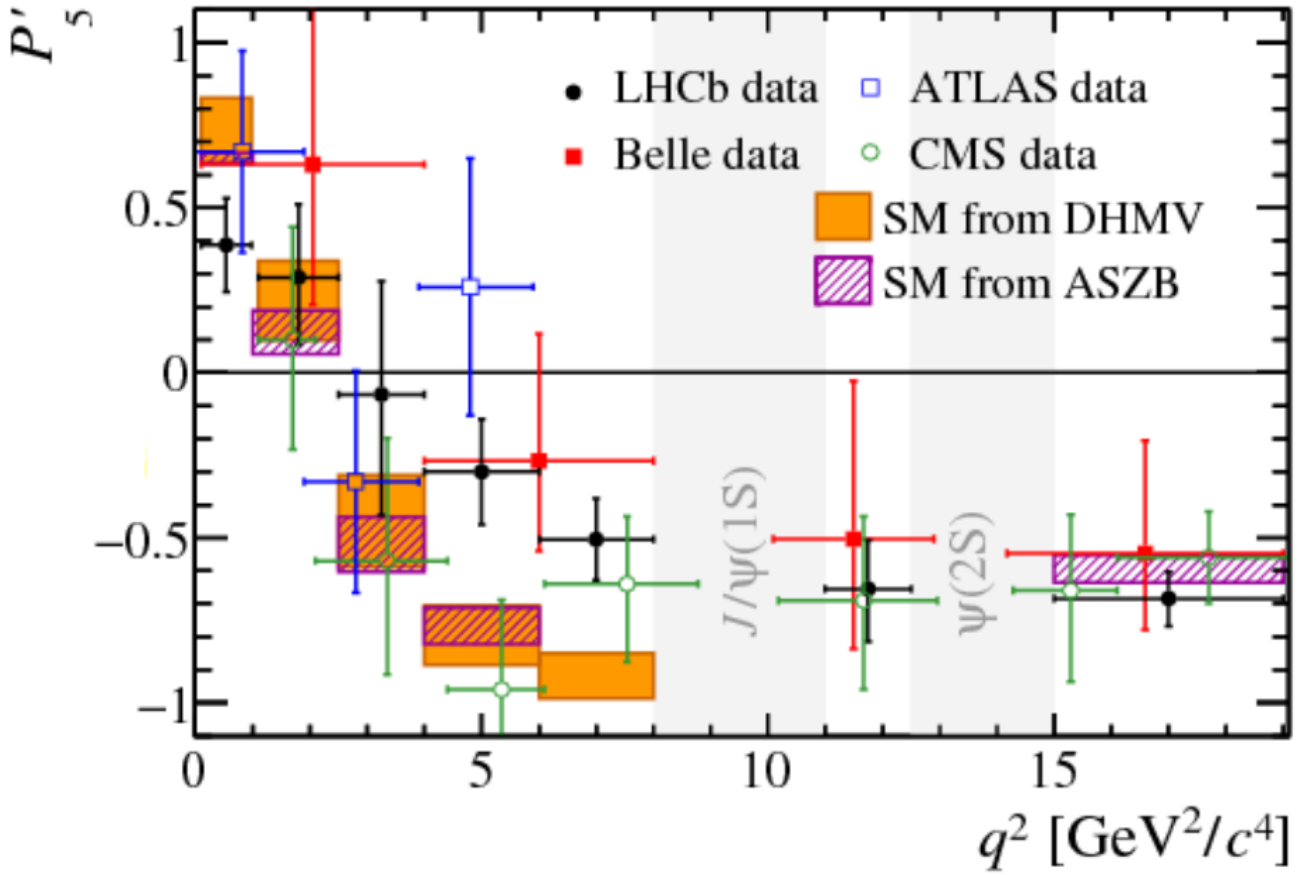
$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

3 observables
deviating by $\sim 2\sigma - 2.5\sigma$
from the SM predictions

In addition to the lepton flavor universality ratios
there are a handful other discrepancies
in the rare B decay data.

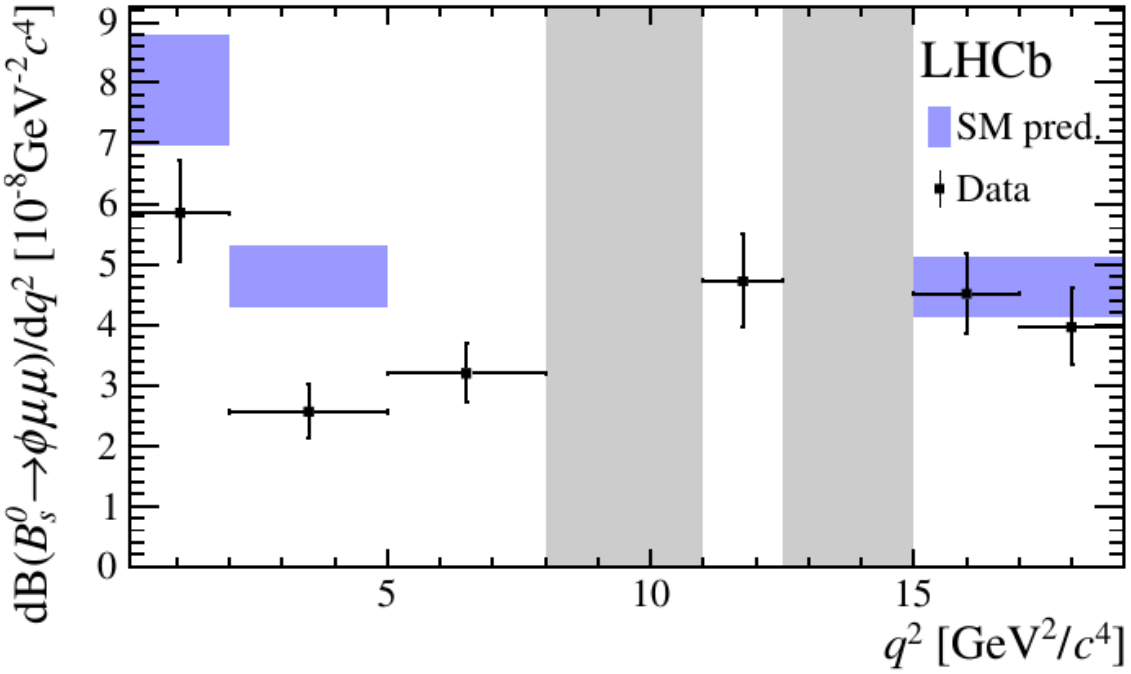
The P_5' Anomaly



ASZB = WA, Straub 1411.3161 + Bharucha, Straub, Zwicky 1503.05534

DHMV = Descotes-Genon, Hofer, Matias, Virto 1510.04239

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



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

What Could It Be?

	semileptonic rates	angular observables	LFU ratios

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experimental issues?	?	?	?
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

Can the flavor anomalies be explained
by some of the dimension 6 operators?

If yes, what is the associated
new physics scale?

Model Independent Global Fits

Lots of experimental data is available:

- multiple measurements of $R_{K^{(*)}}$, $R_{D^{(*)}}$ by several experiments
- measurement of absolute branching ratios
- measurements of angular distributions, polarization fractions, forward-backward asymmetries ...
- many observables are measured differential in q^2
- $O(100)$ measurements with characteristic sensitivity to new physics

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need to find new physics Wilson coefficient (or combination of Wilson coefficients) that agrees with all measurements simultaneously $\Rightarrow$ global fits

global fits are "serious business": need to read the fine print

- what is fitted? (single coefficient; all simultaneously, marginalized, profiled)
- which data is included?
- how are theoretical uncertainties treated?
- statistical approach? (χ^2, bayesian, frequentist)
- ...

R_D and R_{D^*}

New physics in tree level charged current decays?

$$b \to c\ell\nu$$

The effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \Delta C_i \, \mathcal{O}_i$$

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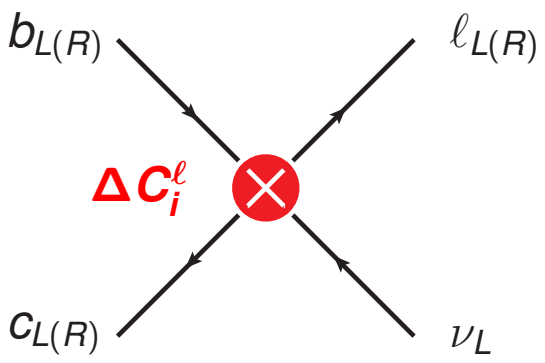
$$\Delta C_L^\ell (\bar{\ell}\gamma_\mu P_L \nu)(\bar{c}\gamma^\mu P_L b)$$

$$\Delta C_R^\ell (\bar{\ell}\gamma_\mu P_L \nu)(\bar{c}\gamma^\mu P_R b)$$

$$\Delta C_{S_L}^\ell (\bar{\ell} P_L \nu)(\bar{c} P_L b)$$

$$\Delta C_{S_R}^\ell (\bar{\ell} P_L \nu)(\bar{c} P_R b)$$

$$\Delta C_T^\ell (\bar{\ell}\sigma_{\mu\nu} P_L \nu)(\bar{c}\sigma^{\mu\nu} P_L b)$$



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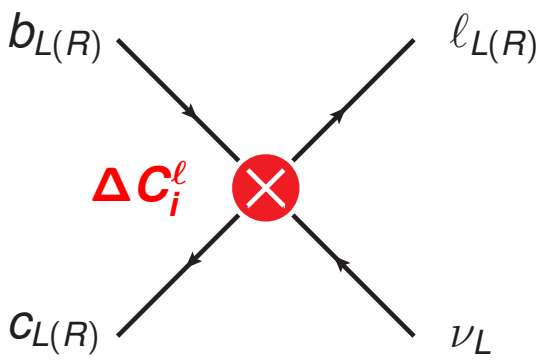
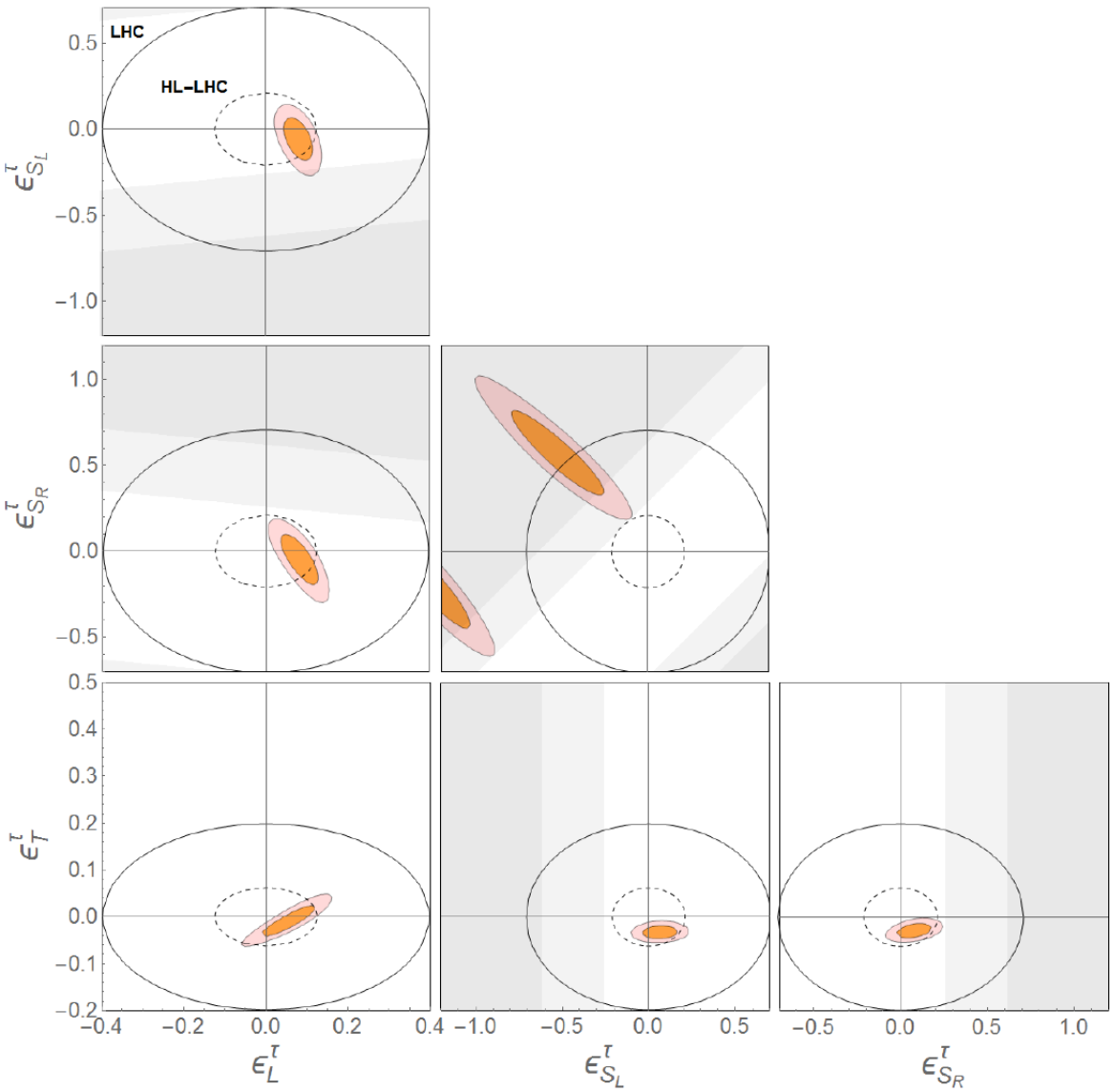


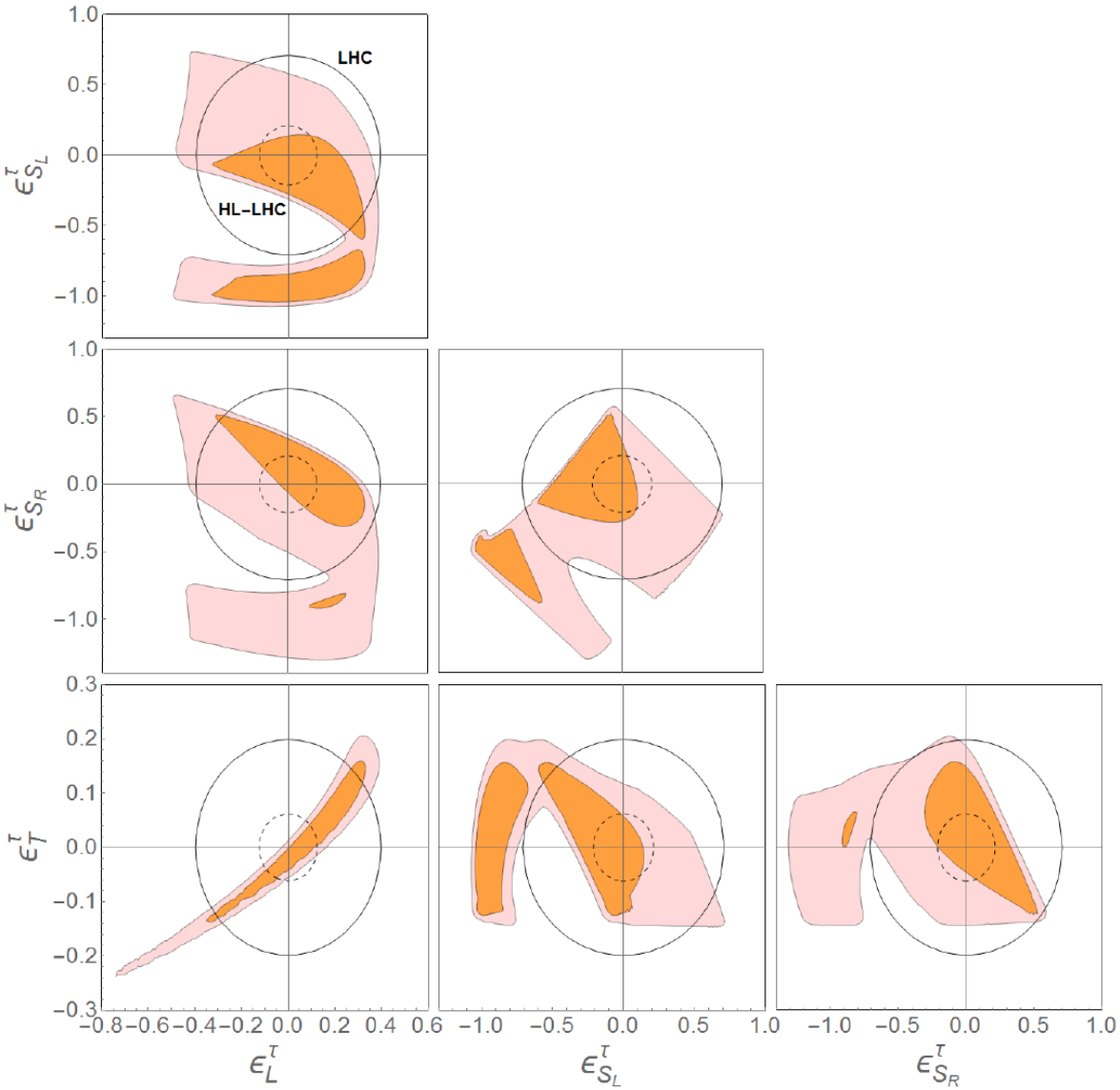
comments:
- ΔC_R^ℓ is lepton flavor universal at LO in the SMEFT
- $\Delta C_{S_L}^\ell$, $\Delta C_{S_R}^\ell$, and ΔC_T^ℓ depend on the renormalization scale

Wilson Coeffients Fits



Shi et al. 1905.08498

Wilson Coeffients Fits



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Implications for the New Physics Scale

Want to translate the results of the fits into a new physics scale Λ_{NP}

$\rightarrow$ reparameterize the effective Hamiltonian

$$\frac{4G_F}{\sqrt{2}} V_{cb} \Delta C \, \mathcal{O} = \frac{\#}{\Lambda_{\mathrm{NP}}^2} \mathcal{O}$$

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$$\frac{4G_F}{\sqrt{2}} V_{cb} \Delta C \, \mathcal{O} = \frac{\#}{\Lambda_{\text{NP}}^2} \mathcal{O}$$

What do you pick for # ?

$\# = 1 \;\rightarrow\;$ "generic" new physics

$\# = V_{cb} \;\rightarrow\;$ same CKM factors as in SM (minimal flavor violation)

$\# = \frac{1}{16\pi^2} \;\rightarrow\;$ loop suppressed new physics

$\# = 4\pi \;\rightarrow\;$ $\sim$scale where perturbative unitarity breaks down

Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$	$\Lambda_{\rm NP} \simeq 11.7$ TeV
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$	$\Lambda_{\rm NP} \simeq 3.3$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\ V_{cb}\ (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$	$\Lambda_{\rm NP} \simeq 0.7$ TeV

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Rather low scales. Model building is non-trivial!

R_K and R_{K^*}, P_5', $B_s \to \phi\mu\mu$

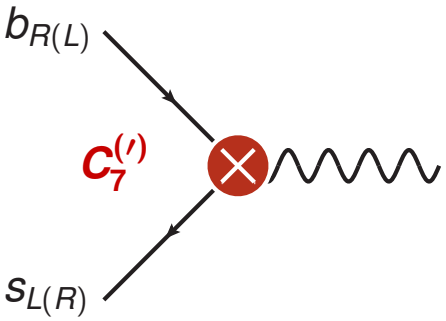
New physics in flavor changing neutral current decays?

$$b \to s\ell\ell$$

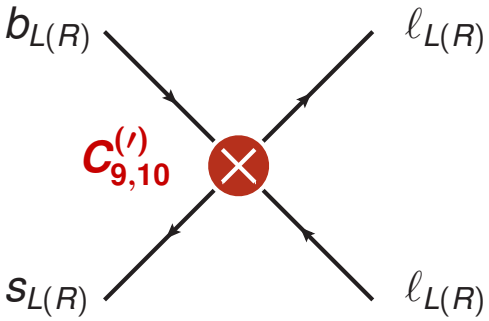
The effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(\Delta C_i \, \mathcal{O}_i + \Delta C_i' \, \mathcal{O}_i' \right)$$

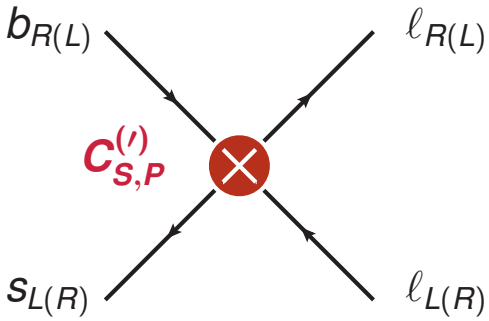
magnetic dipole operators



semileptonic operators



scalar operators



$$C_7^{(\prime)} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s} \gamma_\mu P_{L(R)} b)(\bar{\ell} \gamma^\mu \ell) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\ell} P_{L(R)} \ell)$$

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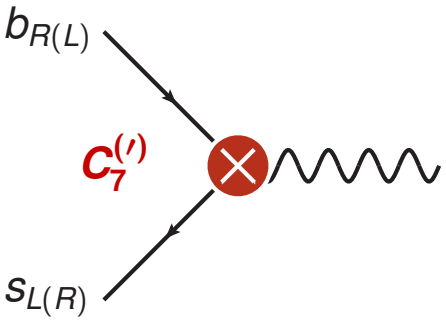

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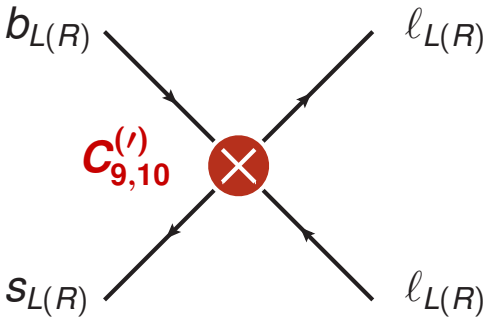

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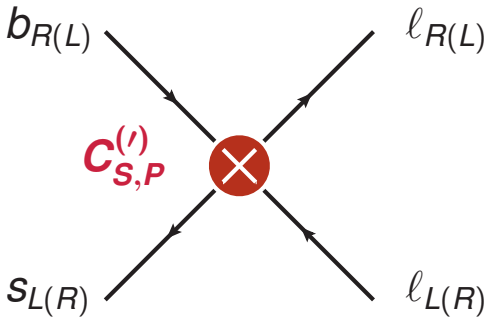

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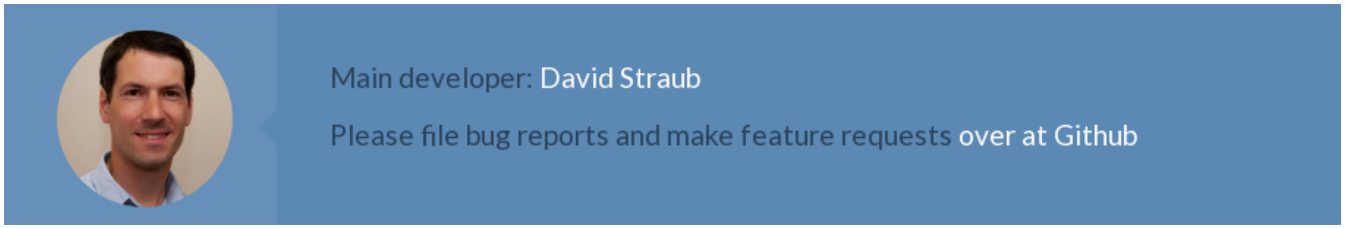
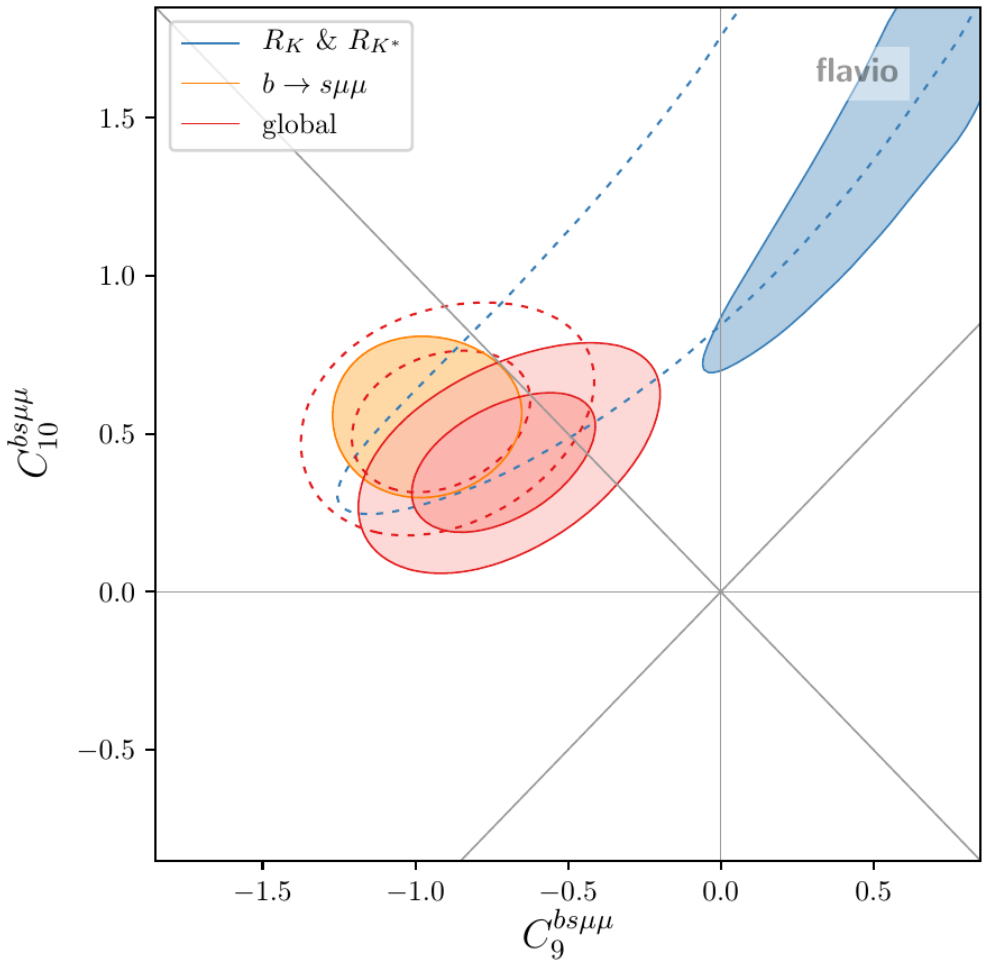
(tensor operators and other scalar operators are dim-8 in SMEFT)

flavio (advertisement)



https://flav-io.github.io/ 1810.08132

Fits to Wilson Coefficients



Aebischer, WA, Guadagnoli, Reboud, Stangl, Straub

1903.10434

global fit shows strong preference for new physics in C_9

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

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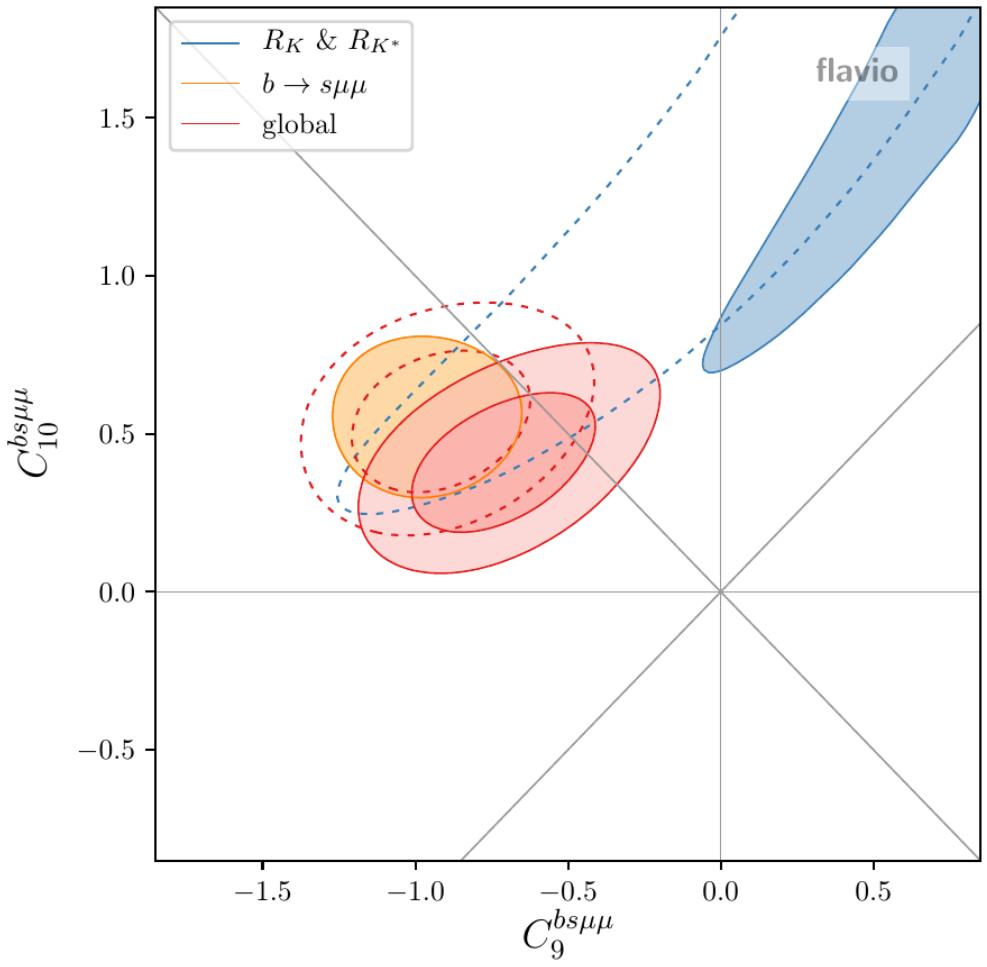

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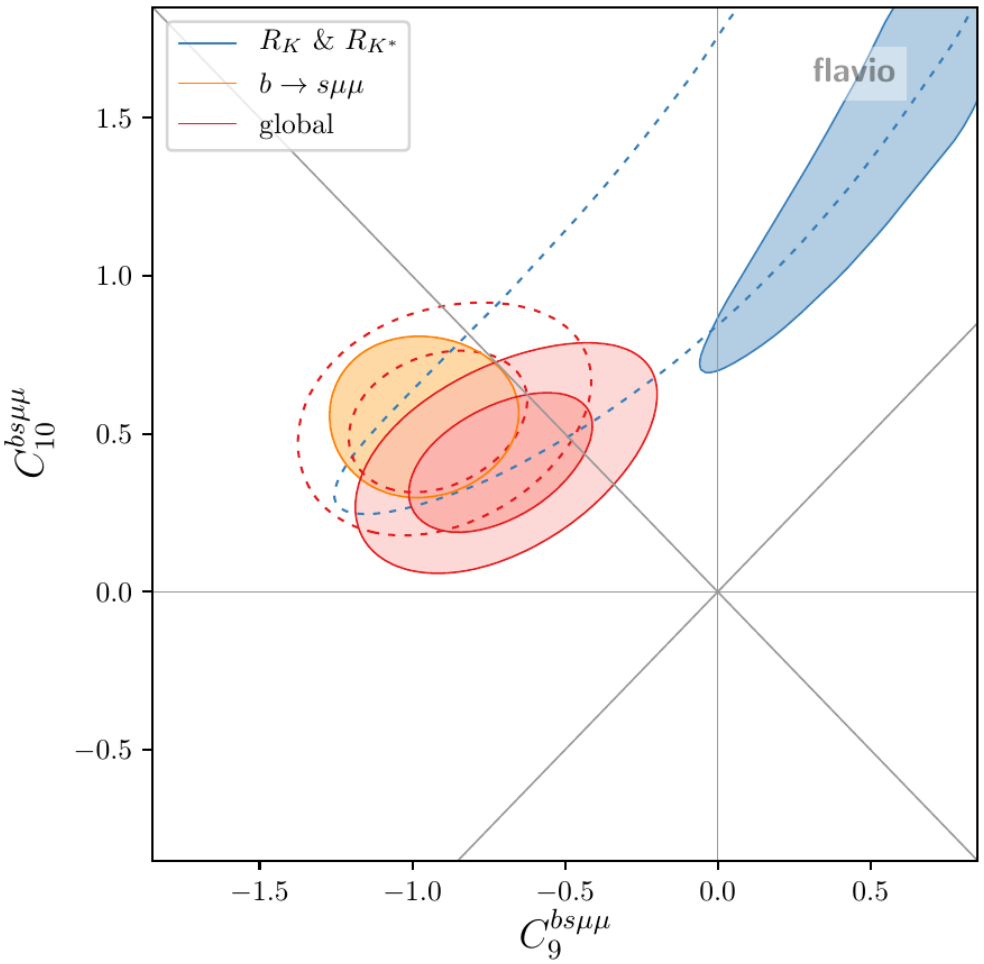
$> 5\sigma$ if you trust our theory errors (you probably shouldn't ...)

$\sim 4\sigma$ if you don't

Fits to Wilson Coefficients



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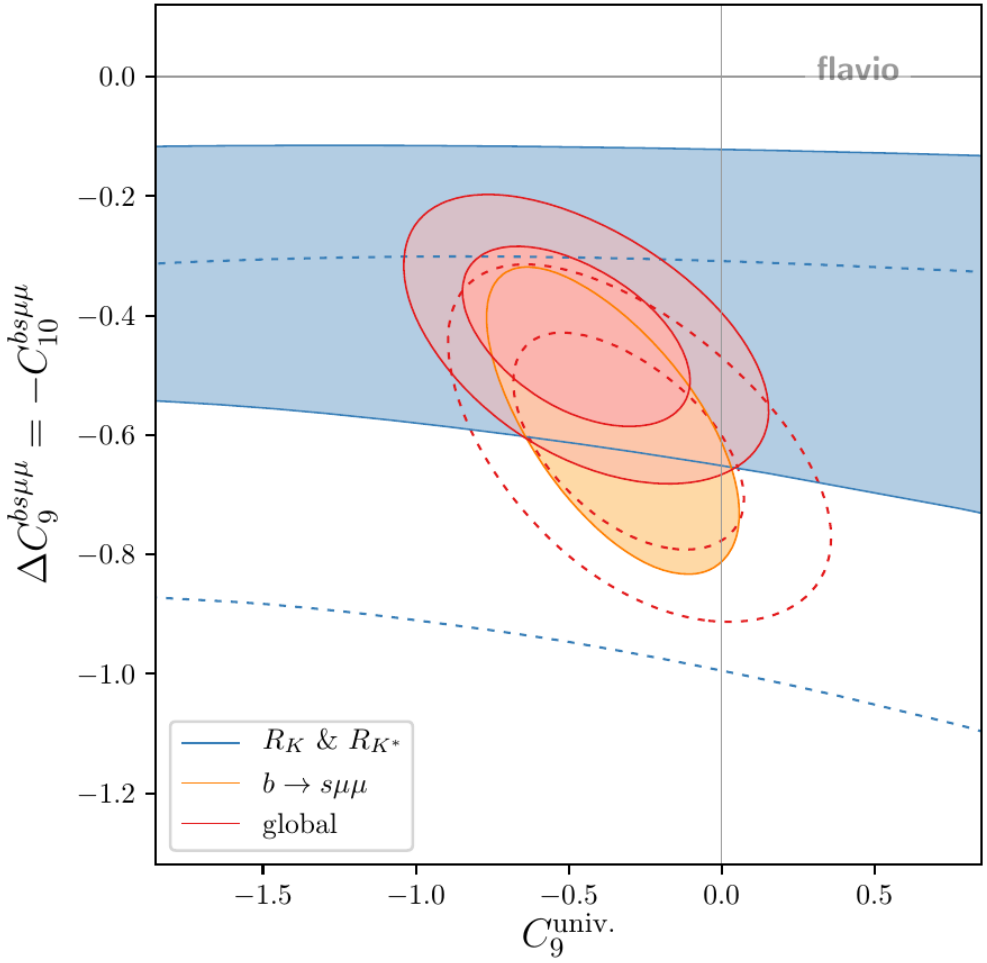
$\sim 4\sigma$ if you don't

after the latest exp updates: slight tension between $bs\mu\mu$ data and LFU ratios

Fits to Wilson Coefficients (2)



fit quality can be further improved by adding a small lepton universal NP contribution

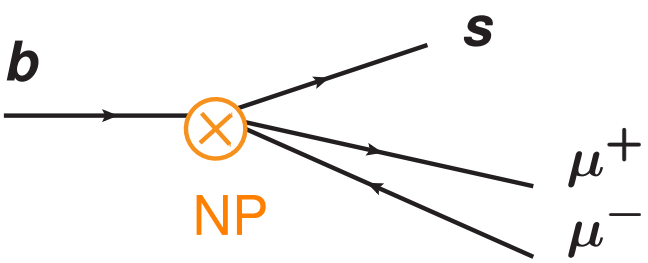
$$2\Delta C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha P_L \mu)$$

$$C_9^{\text{univ.}}(\bar{s}\gamma_\alpha P_L b)\sum_\ell(\bar{\ell}\gamma^\alpha \ell)$$

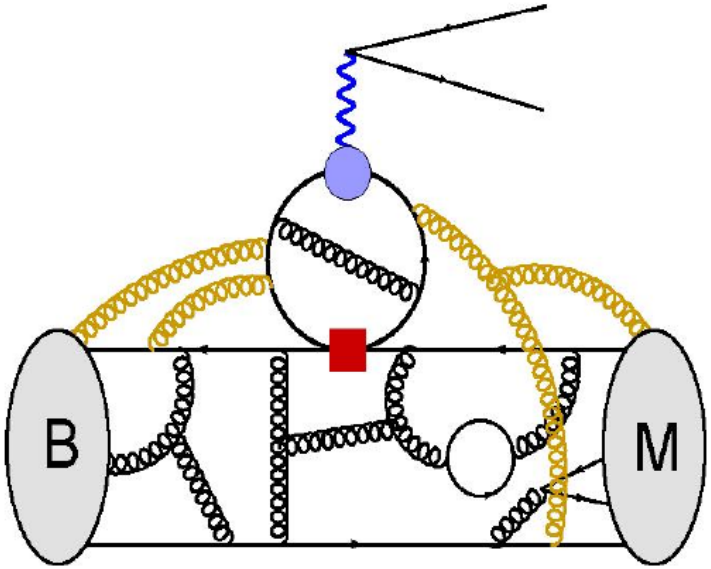
Aebischer, WA, Guadagnoli, Reboud, Stangl, Straub

1903.10434

New Physics or Hadronic Effects?



or



a flavor universal C_9 could be mimicked by hadronic effects

(same chirality structure!)

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics in C_9	Hadronic Contributions
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could violate lepton flavor universality	lepton flavor universal

Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 120\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\ V_{tb}V_{ts}^*\ (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\ V_{tb}V_{ts}^*\ (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$

Summary

- Current data on B decays shows discrepancies with SM expectations.
- Statistical fluctuations? Long distance QCD effects? New physics?
- Can be likely sorted out with more data.
- If it is new physics, model independent EFT fits indicate a new physics scale of O(1TeV) ($b \to c\ell\nu$) or O(10TeV) ($b \to s\ell\ell$)