Effective Field Theory Fits

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UC SANTA CRUZ

SLAC Summer Institute 2019,
Menu of Flavors: Quarks, Charged Leptons & Neutrinos
August 15, 2019
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
We don’t know how the new physics looks like and where it is.

→ We have to search for it in all possible ways!
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1) **Open the boxes!**

Direct production of new particles
We don’t know how the new physics looks like and where it is.

→ We have to search for it in all possible ways!

1) **Open the boxes!**

Direct production of new particles

2) **Shake the boxes!**

Look for virtual effects of new particles
\[ \mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 \]
\[ + \bar{\Psi} \Phi \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu} \]
\[ + Y H\bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}} \]
The Standard Model as Effective Theory

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

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

$$+ Y H \bar{\psi} \psi + \frac{1}{\Lambda} (L H)^2 + \frac{1}{\Lambda^2} \sum_i O_{i}^{\text{dim}6}$$

CC problem
Hierarchy problem
Vacuum stability?
Strong CP problem

SM flavor puzzle
Neutrino masses
NP flavor puzzle ...
New Physics in Rare B Decays

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

- measure precisely
- calculate precisely the SM contribution
- get information on NP coupling and scale
Many Flavor Violating Dimension Six Operators

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

<table>
<thead>
<tr>
<th>1: $X^3$</th>
<th>2: $H^6$</th>
<th>3: $H^4D^2$</th>
<th>5: $\psi^2H^3 + \text{h.c.}$</th>
</tr>
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<tbody>
<tr>
<td>$Q_G$</td>
<td>$f^{ABC} e^A e^B e^C$</td>
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4 fermion interactions

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<tr>
<th>4: $X^3H^3$</th>
<th>6: $\psi^2XH + \text{h.c.}$</th>
<th>7: $\psi^2H^2D$</th>
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<td>$Q_{HC}$</td>
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Grzadkowski et al. 1008.4884, Alonso et al 1312.2014

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2499 baryon number conserving dim. 6 operators in total

SMEFT

4 fermion interactions
Many Flavor Violating Dimension Six Operators

4 fermion interactions

dipole transitions

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| $Q_{GG}$ | $f^{ABC}G_{\mu
u}G_{\rho\sigma}G_{\mu
u}G_{\rho\sigma}$ | $Q_{HH}$ | $(H^\dagger H)^3$ |
| $Q_{GQ}$ | $f^{ABC}G_{\mu
u}G_{\rho\sigma}G_{\mu
u}G_{\rho\sigma}$ | $Q_{HH}$ | $(H^\dagger H)(H^\dagger H)$ |
| $Q_{QQ}$ | $e^{JK}W_{\mu
u}W_{\rho\sigma}W_{\mu
u}W_{\rho\sigma}$ | $Q_{HH}$ | $(H^\dagger D_{\rho\sigma}H)(H D_{\rho\sigma}H)$ |
| $Q_{GQ}$ | $e^{JK}W_{\mu
u}W_{\rho\sigma}W_{\mu
u}W_{\rho\sigma}$ | $Q_{HH}$ | $(H^\dagger H)(\bar{q}_d, q_d)(H^\dagger H)(\bar{q}_u, q_u)$ |

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EFT Fits

SSI 2019 6 / 33
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4 fermion interactions
dipole transitions
Z-penguins

SMEFT

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<td>(f^{ABC}G_{\mu}^{AB}G_{\mu}^{BC}G_{\mu}^{CA})</td>
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<td>(Q_{\tilde{G}})</td>
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<td>(Q_{\eta H, T} (\bar{H}^T H)^{\dagger} (\bar{H}^T D_{\mu} H))</td>
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<td>L))</td>
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**dipole transitions**

**Z-penguins**

**Higgs penguins**
Higgs Penguin Operators

Higgs penguin operators

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

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

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

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

\[ h \rightarrow \tau \mu , \quad \tau \rightarrow \mu \gamma , \quad \tau \rightarrow 3\mu , \ldots \]
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\[ t \rightarrow hu , \quad D^0 - \bar{D}^0 \text{ mixing} , \quad D^0 \rightarrow \mu^+ \mu^- , \ldots \]
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[Exercise: show that these interactions lead indeed to flavor violating Higgs couplings]

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, \( B_s \to \mu^+\mu^- \), ...

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Z-penguin operators

\[ O^{(3)}_{hl} = (H^\dagger i \mathcal{D}_\mu^a H)(\ell_1 \gamma^\mu \sigma_a P_L \ell_2) \]

\[ \tilde{O}^{(1)}_{hl} = (H^\dagger i \mathcal{D}_\mu H)(\ell_1 \gamma^\mu P_L \ell_2) \]

\[ O_{he} = (H^\dagger i \mathcal{D}_\mu H)(\bar{e}_1 \gamma^\mu P_R e_2) \]

...
Z Penguin Operators

Z-penguin operators

\[ O_{hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}_1 \gamma^\mu \sigma_a P_L \ell_2) \]

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

\[ O_{he} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_1 \gamma^\mu P_R e_2) \]

\[ \langle h \rangle \]

\[ e_2 \rightarrow e_1 \]

\[ Z \langle h \rangle \]

induced processes:

\[ Z \rightarrow \tau \mu , \quad \tau \rightarrow 3 \mu , \quad \mu \rightarrow e \text{ conversion} \]
Z-penguin operators

\[ O_{h l}^{(3)} = (H^\dagger i \overset{\leftrightarrow}{D}_{\mu}^a H)(\ell_1 \gamma^\mu \sigma a P_L \ell_2) \]

\[ \tilde{O}_{h l}^{(1)} = (H^\dagger i \overset{\leftrightarrow}{D}_{\mu} H)(\ell_1 \gamma^\mu P_L \ell_2) \]

\[ O_{he} = (H^\dagger i \overset{\leftrightarrow}{D}_{\mu} H)(\bar{e}_1 \gamma^\mu P_R e_2) \]

... 

induced processes:

\[ Z \rightarrow \tau \mu \ , \ \tau \rightarrow 3 \mu \ , \ \mu \rightarrow e \text{ conversion} \ , \ ... \]

\[ t \rightarrow Zu \ , \ D^0 - \bar{D}^0 \text{ mixing} \ , \ D^0 \rightarrow \mu^+ \mu^- \ , \ ... \]
Z Penguin Operators

Z-penguin operators

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\[ t \rightarrow Zu , \quad D^0 - \bar{D}^0 \text{ mixing} , \quad D^0 \rightarrow \mu^+ \mu^- , \quad ... \]
\[ Z \rightarrow bs , \quad B \text{ meson mixing} , \quad \text{Kaon mixing} , \quad B \rightarrow K\ell^+ \ell^- , \quad ... \]
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

**dipole operators**

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

**induced processes:**

\[
\mu \rightarrow e\gamma, \ \tau \rightarrow 3\mu, \ \mu \rightarrow e \text{ conversion}
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induced processes:

\[ \mu \rightarrow e\gamma \ , \ \tau \rightarrow 3\mu \ , \ \mu \rightarrow e \ \text{conversion} \ , \ ... \]
\[ t \rightarrow u\gamma \ , \ t \rightarrow cZ \ , \ D^0 \rightarrow \rho\mu^+\mu^- \ , \ ... \]
**Dipole Operators**

**dipole operators**

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

induced processes:

\[
\mu \rightarrow e \gamma, \ \tau \rightarrow 3\mu, \ \mu \rightarrow e \text{ conversion}, \ ...
\]

\[
t \rightarrow u\gamma, \ t \rightarrow cZ, \ D^0 \rightarrow \rho \mu^+ \mu^- \ , ...
\]

\[
b \rightarrow s\gamma, \ B \rightarrow K^{(*)} \ell^+ \ell^- \ , ...
\]
4 fermion interactions

\[ O_{dd} = (\bar{d}_1 \gamma_{\mu} P_R d_2) (\bar{d}_3 \gamma^\mu P_R d_4) \]

\[ O_{\ell u} = (\bar{\ell}_1 \gamma_{\mu} P_L \ell_2) (\bar{u}_1 \gamma^\mu P_R u_2) \]

\[ + \] many other Dirac and flavor structures
4 fermion interactions

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+ many other Dirac and flavor structures

induced processes:

Kaon mixing, \( D^0 \) mixing, \( B_d \) mixing, \( B_s \) mixing, ...
Four Fermion Contact Interactions

4 fermion interactions

\[ O_{dd} = (\bar{d}_1 \gamma_\mu P_R d_2)(\bar{d}_3 \gamma^{\mu} P_R d_4) \]

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+ many other Dirac and flavor structures

induced processes:

Kaon mixing , \( D^0 \) mixing , \( B_d \) mixing , \( B_s \) mixing , ...

\( t \to u\mu\mu \) , \( D^0 \to \rho\mu^+\mu^- \) , \( B_d \to \mu^+\mu^- \) , \( B \to K^{(*)}\ell^+\ell^- \) , ...
Four Fermion Contact Interactions

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\[ O_{dd} = (\bar{d}_1 \gamma_\mu P_R d_2)(\bar{d}_3 \gamma^\mu P_R d_4) \]
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+ many other Dirac and flavor structures

induced processes:

Kaon mixing, \( D^0 \) mixing, \( B_d \) mixing, \( B_s \) mixing, ...
\( t \rightarrow u \mu \mu \), \( D^0 \rightarrow \rho \mu^+ \mu^- \), \( B_d \rightarrow \mu^+ \mu^- \), \( B \rightarrow K(\ast) \ell^+ \ell^- \), ...
\( \tau \rightarrow e \mu \mu \), \( \mu \rightarrow 3e \), \( \mu \rightarrow e \) conversion, ...

Flavor Anomalies
The $R_D(\ast)$ Anomalies

world average from the heavy flavor averaging group

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

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

$\ell = \mu$ (LHCb)

$$R_D^{\text{exp}} = 0.340 \pm 0.027 \pm 0.013 \quad , \quad R_D^{\text{exp}}(\ast) = 0.295 \pm 0.011 \pm 0.008$$

combined discrepancy with the SM of 3.1$\sigma$
The $R_{K(*)}$ Anomalies

\[ R_{K(*)} = \frac{BR(B \rightarrow K^{(*)}\mu\mu)}{BR(B \rightarrow K^{(*)}ee)} \]

\[ R_{K}^{[1,6]} = 0.846^{+0.060+0.016}_{-0.054-0.014} \]

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

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

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

\[ \text{ASZB} = \text{WA, Straub 1411.3161} + \text{Bharucha, Straub, Zwicky 1503.05534} \]

\[ \text{DHMV} = \text{Descotes-Genon, Hofer, Matias, Virto 1510.04239} \]
The $B_s \rightarrow \phi \mu^+ \mu^-$ Anomaly

branching ratio is $3.5\sigma$ below SM prediction for $1 \text{GeV}^2 < q^2 < 6 \text{GeV}^2$
### What Could It Be?

<table>
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<tr>
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- Issues?
- Statistical fluctuations?
- Parametric uncertainties?
- Hadronic effects?
- New Physics?

Wolfgang Altmannshofer

EFT Fits

SSI 2019
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Can the flavor anomalies be explained by some of the dimension 6 operators?

If yes, what is the associated new physics scale?
Lots of experimental data is available:

- multiple measurements of $R_K(\ast)$, $R_D(\ast)$ 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
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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? ($\chi^2$, Bayesian, frequentist)
- ...
$R_D$ and $R_{D^*}$

New physics in tree level charged current decays?

$b \rightarrow c\ell\nu$
The effective Hamiltonian

\[ H_{\text{eff}} = H_{\text{eff}}^{\text{SM}} + \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \Delta C_i \mathcal{O}_i \]
The effective Hamiltonian

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

\[ \Delta C_\ell^L (\bar{\ell} \gamma_\mu P_L \nu)(\bar{c} \gamma^\mu P_L b) \]
\[ \Delta C_\ell^R (\bar{\ell} \gamma_\mu P_L \nu)(\bar{c} \gamma^\mu P_R b) \]
\[ \Delta C_\ell^{SL} (\bar{\ell} P_L \nu)(\bar{c} P_L b) \]
\[ \Delta C_\ell^{SR} (\bar{\ell} P_L \nu)(\bar{c} P_R b) \]
\[ \Delta C_\ell^T (\bar{\ell} \sigma_{\mu \nu} P_L \nu)(\bar{c} \sigma^{\mu \nu} P_L b) \]
The effective Hamiltonian

\[ H_{\text{eff}} = H_{\text{eff}}^{\text{SM}} + \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \Delta C_i \mathcal{O}_i \]

\[ \Delta C_L^\ell (\bar{\ell} \gamma_\mu P_L \nu)(\bar{c} \gamma^\mu P_L b) \]
\[ \Delta C_R^\ell (\bar{\ell} \gamma_\mu P_L \nu)(\bar{c} \gamma^\mu P_R b) \]
\[ \Delta C_{SL}^\ell (\bar{\ell} P_L \nu)(\bar{c} P_L b) \]
\[ \Delta C_{SR}^\ell (\bar{\ell} P_L \nu)(\bar{c} P_R b) \]
\[ \Delta C_T^\ell (\bar{\ell} \sigma_{\mu\nu} P_L \nu)(\bar{c} \sigma^{\mu\nu} P_L b) \]

comments: • \( \Delta C_R^\ell \) is lepton flavor universal at LO in the SMEFT

• \( \Delta C_{SL}^\ell \), \( \Delta C_{SR}^\ell \), and \( \Delta C_T^\ell \) depend on the renormalization scale
Wilson Coefficients Fits

Shi et al. 1905.08498
Wilson Coefficients Fits

Shi et al. 1905.08498
Want to translate the results of the fits into a new physics scale $\Lambda_{\text{NP}}$

$\rightarrow$ reparameterize the effective Hamiltonian

$$\frac{4G_F}{\sqrt{2}} V_{cb} \Delta C \mathcal{O} = \frac{\#}{\Lambda_{\text{NP}}^2} \mathcal{O}$$
Want to translate the results of the fits into a new physics scale $\Lambda_{\text{NP}}$

→ reparameterize the effective Hamiltonian

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

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
unitarity bound \[ \frac{4\pi}{\Lambda_{NP}^2} (\bar{c}\gamma_{\mu} P_L b)(\bar{\tau}\gamma^{\mu} P_L \nu) \]
\[ \Lambda_{NP} \simeq 11.7 \text{ TeV} \]

generic tree \[ \frac{1}{\Lambda_{NP}^2} (\bar{c}\gamma_{\mu} P_L b)(\bar{\tau}\gamma^{\mu} P_L \nu) \]
\[ \Lambda_{NP} \simeq 3.3 \text{ TeV} \]

MFV tree \[ \frac{1}{\Lambda_{NP}^2} V_{cb} (\bar{c}\gamma_{\mu} P_L b)(\bar{\tau}\gamma^{\mu} P_L \nu) \]
\[ \Lambda_{NP} \simeq 0.7 \text{ TeV} \]
Implications for the New Physics Scale

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Rather low scales. Model building is non-trivial!
New physics in flavor changing neutral current decays?

\[ b \rightarrow s \ell \ell \]
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

\[ C_7^{(i)} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F_{\mu\nu} \]

semileptonic operators

\[ C_9^{(i)} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \ell) \]

\[ C_{10}^{(i)} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \gamma_5 \ell) \]

scalar operators

\[ C_{S,P}^{(i)} (\bar{s} P_{R(L)} b) (\bar{\ell} P_{L(R)} \ell) \]
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

\[ C_7^{(i)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \text{, } C_9^{(i)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma_\mu \ell) \text{, } C_S^{(i)} (\bar{s} P_{R(L)} b)(\bar{\ell} P_{L(R)} \ell) \text{, } C_{10}^{(i)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \]

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

A Python package for flavour physics phenomenology in the Standard Model and beyond

View on GitHub

Main developer: David Straub
Please file bug reports and make feature requests over at Github

https://flav-io.github.io/ 1810.08132
global fit shows strong preference for new physics in $C_9$

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

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\gamma_5\mu)$$

Aebischer, WA, Guadagnoli, Reboud, Stangl, Straub

1903.10434
global fit shows strong preference for new physics in $C_9$

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

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

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

$\sim 4\sigma$ if you don’t
global fit shows strong preference for new physics in $C_9$

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

$\sim 4\sigma$ if you don’t

after the latest exp updates: slight tension between $bs\mu\mu$ data and LFU ratios
fit quality can be further improved by adding a small lepton universal NP contribution

\[2\Delta C_{9}^{bs\mu\mu} (\bar{s}\gamma_{\alpha} P_{L} b)(\bar{\mu}\gamma^{\alpha} P_{L}\mu)\]

\[C_{9}^{\text{univ.}} (\bar{s}\gamma_{\alpha} P_{L} b) \sum_{\ell} (\bar{\ell}\gamma^{\alpha}\ell)\]
New Physics or Hadronic Effects?

or

a flavor universal $C_9$ could be mimicked by hadronic effects

(same chirality structure!)
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Implications for the New Physics Scale

unitarity bound
\[
\frac{4\pi}{\Lambda_{\text{NP}}^2} (\bar{s}_\nu P_L b)(\bar{\mu}_\nu' \mu) \quad \Lambda_{\text{NP}} \approx 120 \text{ TeV} \times (C_{9}^{\text{NP}})^{-1/2}
\]

generic tree
\[
\frac{1}{\Lambda_{\text{NP}}^2} (\bar{s}_\nu P_L b)(\bar{\mu}_\nu' \mu) \quad \Lambda_{\text{NP}} \approx 35 \text{ TeV} \times (C_{9}^{\text{NP}})^{-1/2}
\]

MFV tree
\[
\frac{1}{\Lambda_{\text{NP}}^2} V_{tb} V_{ts}^* (\bar{s}_\nu P_L b)(\bar{\mu}_\nu' \mu) \quad \Lambda_{\text{NP}} \approx 7 \text{ TeV} \times (C_{9}^{\text{NP}})^{-1/2}
\]

generic loop
\[
\frac{1}{\Lambda_{\text{NP}}^2} \frac{1}{16\pi^2} (\bar{s}_\nu P_L b)(\bar{\mu}_\nu' \mu) \quad \Lambda_{\text{NP}} \approx 3 \text{ TeV} \times (C_{9}^{\text{NP}})^{-1/2}
\]

MFV loop
\[
\frac{1}{\Lambda_{\text{NP}}^2} \frac{1}{16\pi^2} V_{tb} V_{ts}^* (\bar{s}_\nu P_L b)(\bar{\mu}_\nu' \mu) \quad \Lambda_{\text{NP}} \approx 0.6 \text{ TeV} \times (C_{9}^{\text{NP}})^{-1/2}
\]
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 $O(1\text{TeV})$ ($b \rightarrow c \ell \nu$) or $O(10\text{TeV})$ ($b \rightarrow s \ell \ell$)