Flavor Physics at the LHC

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LHC as a flavor factory

What are the unique capabilities of LHC for flavor studies? (energy, luminosity)

Which observables are most promising? (Higgs, top, CPV in charm & B_s, rare decays with di-leptons)

What have we learned already? (implications for SM hierarchy, flavor, DM puzzles, hints of NP?)

Disclaimer: personal selection of topics
Introduction

SM phenomenologically very successful theory

Strong theoretical arguments to consider it as effective theory

Unification of interactions

\[ \mathcal{L}_{\nu SM} = \mathcal{L}_{\text{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\text{eff}}(\phi, A_a, \psi_i) \]

\[ V_{\text{eff}} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + Y_{ij} \psi^i_L \psi^j_R \phi + \frac{y_{ij}}{\Lambda} \psi^i_L \psi^j_L \phi^T \phi + \ldots \]

EW scale stabilization

Origin of flavor

Need to understand/constrain size of additional terms in series
Introduction

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EW scale stabilization

\[ \Lambda [\text{GeV}] \]

\[ \mathcal{L}_{\text{BSM}} \rightarrow \mathcal{L}_{\text{SM}} + \sum_{i,(d>4)} \frac{Q_i^{(d)}}{\Lambda^{d-4}} \]

\[ 10^4 \quad 10^3 \quad 10^2 \]

\[ 10^11 \quad 10^{15} \quad 10^{19} \]

Origin of flavor

\[ ? \quad ? \quad ? \]
Introduction

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ΔF=1,2 FCNCs in K, D, B systems
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\[ \Lambda_{\text{GeV}} \approx 10^{2} \]

\[ 10^{3} \]

\[ 10^{4} \]

\[ 10^{5} \]

\[ 10^{6} \]

\[ K^{0} - K^{0} \]

\[ D^{0} - D^{0} \]

\[ B^{0} - \bar{B}^{0} \]

\[ B_{s} - \bar{B}_{s} \]

\[ Q_{AB}^{(6)} \sim z^{ij} [\bar{q}_{i} \Gamma^{A} q_{j}] \otimes [\bar{q}_{i} \Gamma^{B} q_{j}] \]

\[ \sum_{i, (d>4)} \frac{Q_{i}^{(d)}}{\Lambda^{d-4}} \]

FCNCs in K, D, B systems

QCD contributions to FCNCs

\[ \Delta F = 1, 2 \text{ FCNCs} \] in K, D, B systems

\[ \Lambda \text{ [GeV]} \]

\[ \Lambda_{\text{TeV}} \]
Unique LHC probes of flavor

**Top quark** - heaviest point-like particle known to exist

⇒ O(1) coupling to the Higgs \( y_t \equiv \sqrt{2m_t/v_{EW}} \approx 1 \)

⇒ Profound effects on EW and flavor physics

**Higgs boson** interactions with fermions of special interest

⇒ probe existence of new flavor dynamics not too far above the electroweak scale

⇒ suppressed contributions to low energy observables lead to weak indirect constraints
Testing flavor through Higgs observables
Testing flavor through Higgs observables

BSM modifications of Yukawa sector

\[ Q_Y^{(6)} \sim Y'_{ij} \psi^i_L \psi^j_R \phi(\phi^\dagger \phi) \]

In EW vacuum: \[ \mathcal{L}_Y = -m_i \psi^i_L \psi^i_R - \bar{Y}_{ij} (\psi^i_L \psi^j_R) h + \text{h.c.} + \ldots \]

Generally present if more than one source of fermion masses
Testing flavor through Higgs observables

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Simplest model examples:

(1) THDM III \[ \mathcal{L}_{\text{THDMIII}} \ni -Y_{ij}^{(1)} \psi_L^i \psi_R^j \phi^{(1)} - Y_{ij}^{(2)} \psi_L^i \psi_R^j \phi^{(2)} + \text{h.c.} \]
\[ \rightarrow \mathcal{L}_Y + \text{ couplings to heavier Higgs bosons} \]

c.f. Davidson & Greiner, 1001.0434

(2) Partial compositeness \[ \mathcal{L}_{\text{PC}} \ni -y_{ij} D_L^i S_R^j \phi - \bar{y}_{ij} D_R^i S_L^j \phi \]
\[ - M_D^i D_R^i D_L^i - M_S^i S_R^i S_L^i \]
\[ - m_D^{ij} D_R^i \psi_L^j - m_S^{ij} S_L^i \psi_R^j + \text{h.c.} \]
\[ \rightarrow \mathcal{L}_Y + \text{ couplings of heavier fermions} \]

c.f. Delaunay, Grojean & Perez, 1303.5701
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Stability of fermionic mass hierarchies: \[ |\bar{Y}_{ij} Y_{ji}| \lesssim \frac{m_i m_j}{v^2} \]


New neutral currents

• flavor diagonal (LHC) + EDMs if CPV
• flavor violating (flavor factories, LHC)

Brod, Haisch & Zupan, 1310.1385
Gorban & Haisch, 1404.4873
Giudice, Lebedev, 0804.1753
Agashe, Contino, 0906.1542
Goudelis, Lebedev, Park, 1111.1715
Arhrib, Cheng, Kong, 1208.4669
Alonso et al., 1212.3307
Dery et al., 1302.3229, 1304.6727
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Cheng & Sher,

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Are Higgs couplings to light flavors SM-like?

Current Higgs data exhibit poor sensitivity to first two
generation quark Yukawas

⇒ in production

1 loop contributions to $gg \to h$ suppressed by small loop function

$$A_{1/2} \sim r_q \log r_q, \quad r_q \equiv (m_q/m_h)^2 \ll 1$$

direct $qq \to h$ suppressed by small parton luminosity functions

$$\mathcal{L}_{u\bar{u}}(m_h)/\mathcal{L}_{gg}(m_h) \sim 4\%(2\%) @ 7\text{ TeV}(14\text{ TeV}) \text{ LHC}$$

⇒ in decay:

need to compete against dominant $h \to b\bar{b}$ mode

$$|\tilde{Y}_{qq}|^2 \sim 10^{-3} \frac{\Gamma_{h \to q\bar{q}}}{\Gamma_h}^{\text{SM}} \quad \tilde{Y}_{bb}^{\text{SM}} \equiv \frac{m_b}{v} \sim 0.02$$
Are Higgs couplings to light flavors SM-like?

Current Higgs data exhibit poor sensitivity to first two generation quark Yukawas

⇒ Global fit to LHC Higgs signal strengths

allowing modifications in $hgg (c_g), h\gamma\gamma (c_\gamma), hqq$

Fajfer, Greljo, J.F.K. & Mustac, 1304.4219
Delaunay, Golling, Perez & Soreq, 1310.7029

Admir Greljo
private communication
see also talk by Y. Soreq
Are Higgs couplings to light flavors SM-like?

Current Higgs data exhibit poor sensitivity to first two generation quark Yukawas

⇒ Global fit to LHC Higgs signal strengths allowing modifications in $hgg (c_g)$, $h\gamma\gamma (c_\gamma)$, $hqq$

Interesting connection to di-Higgs production

$$L_Y = -(\psi_L^i \psi_R^i) \left[ m_i \delta_{ij} + \bar{Y}_{ij} h + (\bar{Y}_{ij} - m_i/v \delta_{ij}) 3h^2/2v \right] + h.c.$$  

$$\sigma(hh)^{u\bar{u}} / \sigma(hh)^{SM} \sim 20(11) \times |\bar{Y}_{uu}/0.01|^2 \quad \text{at 8 TeV (14 TeV) LHC}$$
Testing flavor through Higgs observables

BSM modifications of Yukawa sector

\[ Q_Y^{(6)} \sim Y'_{ij} \psi_L^i \psi_R^j \phi(\phi^\dagger \phi) \]

In EW vacuum: \[ \mathcal{L}_Y = -m_i \psi_L^i \psi_R^i - \bar{Y}_{ij} (\psi_L^i \psi_R^j) h + \text{h.c.} + \ldots \]

Stability of fermionic mass hierarchies: \[ |\bar{Y}_{ij} \bar{Y}_{ji}| \lesssim \frac{m_i m_j}{v^2} \] (Cheng & Sher, Phys.Rev. D35, 3484 (1987))

New neutral currents

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Testing flavor through Higgs observables

Within SM effective $Y_{i\neq j}$ extremely suppressed (GIM+CKM/$m_v$ & chirality)

Constraints on first two generation $Y_{i\neq j}$ dominated by precision low energy observables

\[ e^- \rightarrow Y_{eP} + Y_{eP} \]

\[ \mu^- \rightarrow Y_{\muP} + Y_{\muP} \]

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

\[ g - 2, \text{ EDMs} \]

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

\[ M-M \text{ oscillations} \]

\[ \psi_i \quad \phi \quad \psi_j \]

\[ W \]

took from Joachim Kopp’s slides on LHC Results Forum (@UTexas)

Harnik, Kopp, Zupan, 1209.1397
McKeen, Pospelov, Ritz, 1208.4597
Blankenburg, Ellis, Isidori, 1202.5704
Probing Flavor Violation in Top - Higgs Sector

Top-Higgs FV interactions only enter low energy observables at loop level

⇒ EDMs still severely constrain CPV contributions

⇒ Sensitive only to certain products of couplings

Direct LHC probes

⇒ Higgs decays \[ BR(h \to t^*q) \simeq \frac{\Gamma(h \to t^*q)}{\Gamma_h} \simeq 0.12(0.27|y_{tq}|^2 + |y_{qt}|^2) \]

⇒ Top Decays \[ B(t \to hq) \simeq \frac{\Gamma(t \to hq)}{\Gamma(t \to W+b)} \simeq 0.29(|y_{tq}|^2 + |y_{qt}|^2) \]

⇒ Associated top-Higgs production (relevant for \( y_{tu}, y_{ut} \))

\[ \sigma(pp \to th) \simeq 74 \text{ (180) pb} \times (|y_{tu}|^2 + |y_{ut}|^2) \quad @ 8\text{TeV (14TeV) LHC} \]

+ several other, less sensitive signatures
Probing Flavor Violation in Top - Higgs Sector

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+ several other, less sensitive signatures

Gorban, Haisch, 1404.4873
Greljo, J.F.K. & Kopp, 1404.1278
Atwood, Gupta & Soni, 1305.2427
Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Two complementary production processes (in case of $thu$)

Can be disentangled using Higgs rapidity & total event charge
Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Several competitive signatures

**Multileptons**

\[ h \rightarrow WW^* \rightarrow \ell\ell\nu\nu, \ h \rightarrow \tau\tau, \]
\[ h \rightarrow ZZ^* \rightarrow \ell\ell jj, \ h \rightarrow ZZ^* \rightarrow \ell\ell\nu\nu, \]
\[ t \rightarrow b\ell^+\nu \]

- No Higgs/top reconstruction
- Many Higgs decay modes

**Lepton + di-photon**

\[ t \rightarrow b\ell^+\nu \quad h \rightarrow \gamma\gamma \]

- Low rate
- Exclusive Higgs reconstruction

**All hadronic (new)**

\[ h \rightarrow b\bar{b}, \ h \rightarrow gg, \ h \rightarrow \tau\bar{\tau}, \ h \rightarrow c\bar{c} \]
\[ t \rightarrow bud\bar{d} \]

- Horrendous backgrounds
- Largest rate

In the boosted regime, can employ jet substructure methods

Modified HEPTopTagger of Plehn et al., 0910.5472, 1006.2833

Higgs tagging: Butterworth et al., 0802.2470

Cacciari, Salam & Soyez, 1111.6097

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CMS-PAS-HIG-12-053 vector boson plus Higgs recast

CMS-PAS-HIG-13-025
(also ATLAS, arXiv:1403.6293)
Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Improving the LHC reach

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{y_{ut}^2 + y_{tu}^2}$</th>
<th>$\mathcal{B}(t \rightarrow hu)$</th>
<th>$\sqrt{y_{ct}^2 + y_{tc}^2}$</th>
<th>$\mathcal{B}(t \rightarrow hc)$</th>
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</thead>
<tbody>
<tr>
<td><strong>New limits from existing data</strong></td>
<td></td>
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</tr>
<tr>
<td>Sec. III A: Multilepton</td>
<td>$&lt; 0.19$</td>
<td>$&lt; 1.0%$</td>
<td>$&lt; 0.23$</td>
<td>$&lt; 1.5%$</td>
</tr>
<tr>
<td>Sec. III B: Diphoton plus lepton</td>
<td>$&lt; 0.12$</td>
<td>$&lt; 0.45%$</td>
<td>$&lt; 0.15$</td>
<td>$&lt; 0.66%$</td>
</tr>
<tr>
<td>Sec. III C: Vector boson plus Higgs</td>
<td>$&lt; 0.16$</td>
<td>$&lt; 0.70%$</td>
<td>$&lt; 0.21$</td>
<td>$&lt; 1.2%$</td>
</tr>
<tr>
<td><strong>Projected future limits (13 TeV, 100 fb$^{-1}$)</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Sec. III C: Vector boson plus Higgs</td>
<td>$&lt; 0.076$</td>
<td>$&lt; 0.15%$</td>
<td>$&lt; 0.084$</td>
<td>$&lt; 0.19%$</td>
</tr>
<tr>
<td>Sec. IV A: Multilepton</td>
<td>$&lt; 0.087$</td>
<td>$&lt; 0.22%$</td>
<td>$&lt; 0.11$</td>
<td>$&lt; 0.33%$</td>
</tr>
<tr>
<td>Sec. IV B: Fully hadronic</td>
<td>$&lt; 0.12$</td>
<td>$&lt; 0.36%$</td>
<td>$&lt; 0.13$</td>
<td>$&lt; 0.48%$</td>
</tr>
</tbody>
</table>

⇒ Limits on $\mathcal{B}(t \rightarrow hu) \times 1.5$ better than on $\mathcal{B}(t \rightarrow hc)$

⇒ Future LHC searches could test $|y_{tq}| \sim 0.1$
Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Greljo, J.F.K. & Kopp, 1404.1278

Discrimination between thc & thu couplings

Possible even without explicit Higgs reconstruction (like in multilepton searches)

In \( h \rightarrow WW^{*} \rightarrow l\overline{l} \nu \nu \) use leptons closest in rapidity as proxy for \( \eta_{h} \)

**Figure 5**

Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Projection of multilepton search sensitivity

(using a \( \eta_{ll} \) cut \( |\eta_{ll}| > 1 \))
Probing the invisible through flavor violation at LHC
Are there only SM particles at low-energy?

Experimentally:

- Even very light states could be missed if very weakly interacting,
- There is dark matter in the Universe; it could be relatively light.

Theoretically: Plenty of models predict new light particles

- Pseudo-Goldstone scalars (axion, familon,...),
- U(1) vectors (string, ED,...),
- Hidden sectors & messengers (SUSY, mirror worlds,...)
- Many others: millicharged fermions, dilaton, majoron, neutralino, sterile neutrino, gravitino,...
Invisibles Pair Production at Hadron Colliders

General discussion in terms of EFT

\[ \mathcal{L}_{\text{int}} = \sum_{a} \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a \]

- With B preservation, \( \mathcal{O}_a \) need to be bilinear in quark fields

\[
\begin{align*}
\mathcal{O}_{1a}^{ij} &= (\bar{Q}_L^i \gamma_\mu Q_L^j) \mathcal{J}_a^\mu, \\
\mathcal{O}_{2a}^{ij} &= (\bar{u}_R^i \gamma_\mu u_R^j) \mathcal{J}_a^\mu, \\
\mathcal{O}_{3a}^{ij} &= (\bar{d}_R^i \gamma_\mu d_R^j) \mathcal{J}_a^\mu, \\
\mathcal{O}_{4a}^{ij} &= (\bar{Q}_L^i H u_R^j) \mathcal{J}_a, \\
\mathcal{O}_{5a}^{ij} &= (\bar{Q}_L^i \tilde{H} d_R^j) \mathcal{J}_a,
\end{align*}
\]

- coupling to suitable dark sector currents, i.e.

\[
\mathcal{J}_{V,A}^\mu = \bar{\chi} \gamma_\mu \{1, \gamma_5\} \chi \\
\mathcal{J}_{S,P} = \bar{\chi} \{1, \gamma_5\} \chi \\
\mathcal{J} = \chi^\dagger \chi, \quad \mathcal{J}^\mu = \chi^\dagger \partial^\mu \chi
\]

\begin{align*}
\text{Fermionic} & \quad \text{Scalar}
\end{align*}
Flavor universal contributions \((C_{ij} \sim \delta_{ij})\)

\[ \Rightarrow \text{mono[jet, } \gamma, \ Z, \ W\] constraints using initial state radiation for tagging

Zhou, Berge & Whiteson, 1302.3619 (see also refs. therein)
Flavor Bounds

Can flavor violating interactions be competitive?

- Constraints from $\Delta F=2$ observables
  
  Example: 
  
  $$\frac{C_{1a}^{13}}{\Lambda} \lesssim \frac{1}{2 \text{ TeV}}, \quad \frac{C_{1a}^{23}}{\Lambda} \lesssim \frac{1}{0.3 \text{ TeV}},$$

  - effectively no bounds on $C_{2a,4a}^{13,23}$

- Large monotop ($t+E_{\text{miss}}$) signals possible due to chirality flipping operators
  
  (also $b+E_{\text{miss}}$, but can be due to flavor conserving ops.)

  - reconstruction using $j_{(b)}jj+E_{\text{miss}}$, or $j_{(b)}l+E_{\text{miss}}$

  ($\sim 1\%$ signal eff.)
Expectations in Models of Flavor

Minimal Flavor Violation

\[ C_{2a} = b_{1}^{(2a)} + b_{2}^{(2a)} Y_u^\dagger Y_u + b_{3}^{(2a)} Y_u^\dagger Y_d^\dagger Y_u + \cdots, \]
\[ C_{4a} = (b_{1}^{(4a)} + b_{2}^{(4a)} Y_d Y_u^\dagger + \cdots) Y_u. \]

- For \( b_1^a \sim b_2^a \sim b_3^a \) \( C_{2a} \) almost flavor diagonal and universal
- \( C_{4a} \) is highly hierarchical, can have large flavor violation if \( y_b \sim 1 \)

\[ \frac{\hat{\sigma}(ug \rightarrow t + 2\chi)}{\hat{\sigma}(ug \rightarrow u + 2\chi)} \sim \left( \frac{y_t |V_{ub}| y_b^2}{y_u} \right)^2 \sim 5 \cdot 10^5 \ y_b^4, \]
\[ \frac{\hat{\sigma}(cg \rightarrow t + 2\chi)}{\hat{\sigma}(cg \rightarrow c + 2\chi)} \sim \left( \frac{y_t |V_{cb}| y_b^2}{y_c} \right)^2 \sim 50 \ y_b^4. \]

Larger effects expected with horizontal symmetries


Single invisible + t Production

Corresponds to production of neutral mediators in DM models

• Example: Scalar DM (S) via (heavy \( h_2 \)) Higgs portal in THDMIII

\[
\mathcal{L}_{h_2} = \sum_{ij} \left( \tilde{y}_{ij}^u \bar{u}^i P_R u^j h_2 + \tilde{y}_{ij}^d \bar{d}^i P_R d^j h_2 \right) + \text{h.c.} + \lambda v_{EW} h_2 SS,
\]

• \( D-D \) mixing constraints

\[
|\tilde{y}_u^u \tilde{y}_u^c|, |\tilde{y}_u^t \tilde{y}_u^c| < 0.030 \times \left( \frac{m_{h_2}}{250\text{GeV}} \right)^2,
\]

\[
|\tilde{y}_u^u \tilde{y}_u^c|, |\tilde{y}_u^t \tilde{y}_u^c| < 0.0088 \times \left( \frac{m_{h_2}}{250\text{GeV}} \right)^2,
\]

\[
\sqrt{|\tilde{y}_u^u \tilde{y}_u^c \tilde{y}_u^t \tilde{y}_u^c|} < 0.0036 \times \left( \frac{m_{h_2}}{250\text{GeV}} \right)^2,
\]

Recently first experimental LHC search using hadronic final states by CMS (CMS-PAS-B2G-12-022)
Flavor probes of EW and Higgs sectors
$B_{s,d} \rightarrow \mu^+\mu^-$

Theoretically very clean (virtually no long-distance contributions)

$B_{d,SM} = (1.07 \pm 0.10) \times 10^{-10}$  \quad $\overline{B}_{s,SM} = (3.56 \pm 0.18) \times 10^{-9}$

Important effect due to $\Delta \Gamma_s \neq 0$

$\langle B(B_s \rightarrow f) \rangle[t] = \frac{1}{2} \int_0^t dt' \left[ \Gamma(B_s(t') \rightarrow f) + \Gamma(\overline{B}_s(t') \rightarrow f) \right]$  

de Bruyn et al., 1204.1735

Dominant parametric uncertainties

In good agreement with experiment

$\overline{B}_d^{(\text{exp})} = (3.6^{+1.9}_{-1.2}) \times 10^{-10}$  \quad $\overline{B}_s^{(\text{exp})} = (2.9^{+0.8}_{-0.6}) \times 10^{-9}$

Buras et al., 1208.0934, 1303.3820

LHCb, 1307.5024

CMS, 1307.5025
$B_{s,d} \rightarrow \mu^+\mu^-$

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector)

beyond tree level

Latest results beginning to test possible $B_d/B_s$ enhancement

Nontrivial test of MFV

Hurth et al., 0807.5039
Modified Z couplings

\[ \mathcal{L}_\text{eff}^Z = \frac{g}{c_W} Z_\mu \bar{d}^i \gamma^\mu \left[ (g_L^{ij} + \delta g_L^{ij}) P_L + (g_R^{ij} + \delta g_R^{ij}) P_R \right] d^j \]

Fixing flavor model one can compare:
flavor (non)universality (\(Z_{bb}/Z_{qq}\)) vs. flavor violation (\(Z_{bs}\))

**Example: MFV**

\[ Q_L^{(6)} \sim c_1 L (Y_u Y_u^\dagger)_i^j \bar{Q}_L^i \gamma^\mu Q_L^j \phi \hat{D}_\mu \phi \]
\[ Q_R^{(6)} \sim c_1 R Y_d^i (Y_u Y_u^\dagger)_i^j Y_d^j \bar{d}_R^i \gamma^\mu d_R^j \phi \hat{D}_\mu \phi \]

\[ \delta g_L^{bs} = \frac{V_{tb} V_{ts}^*}{|V_{tb}|^2} \delta g_L^b \quad \delta g_R^{bs} = \frac{m_s V_{tb} V_{ts}^*}{m_b |V_{tb}|^2} \delta g_R^b \]

(update using the latest exp. results)

Inclusion of other \(b \to s \mu^+ \mu^-\) modes could further improve these constraints
Deconstructing $b \to s (\gamma, \ell^+ \ell^-)$ transitions

Much more information available:

<table>
<thead>
<tr>
<th>$B \to (X_s, K^*) \gamma$</th>
<th>$C_7, C'_7$</th>
<th>$C_9, C'_9$</th>
<th>$C_{10}, C'_{10}$</th>
<th>$C_S, C'_S, C_P, C'_P$</th>
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<tr>
<td>$B \to (X_s, K, K^*) \ell^+ \ell^-$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>(★)</td>
</tr>
<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
<td></td>
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<td></td>
<td>★</td>
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adopted from Altmannshofer @ Snowmass Intensity Frontier Workshop 2013, Argonne
$B \rightarrow K^* \ell^+ \ell^-$ anomaly

Fit of angular observables ($A_{FB}, P_i$) binned in low $q^2$ region

- Mostly sensitive to $Q_7 \sim C_7 m_b [\bar{s} \sigma_{\mu \nu} (1 + \gamma_5) b] e F^{\mu \nu}$
  $Q_9 \sim C_9 [\bar{s} \gamma_\mu (1 - \gamma_5) b] [\bar{\ell} \gamma^\mu \ell]$ (chirally flipped ops.)

- In $\sim 3\sigma$ tension with SM estimates (dominated by $P_5'$, also $A_{FB}, P_2$)

- Can be reconciled by $\sim 40\%$ reduction of $\langle Q_9 \rangle$

A sign of NP? Recheck SM theory estimates

- Based on QCD factorization at large hadronic recoil
- Form factor reduction - broken by $\alpha_s$ (computed), $1/m_b$ (estimated) corrections
- Underestimated LD contributions? $\int d^4 x \, e^{-i q \cdot x} \langle \bar{K}^* | T \{ j^\text{em}_\mu (x), \mathcal{H}^{\text{had}, l_\mu} (0) \} | B \rangle$,
  Jager & Camalich, 1212.2263

First-principles QCD estimate possible?

Khodjamirian et al., 1006.4945
\[ B \to K^* \ell^+ \ell^- \text{ anomaly} \]

Possible experimental tests:

- More inclusive observables (integrated over \( q^2 = [1, 6] \text{ GeV}^2 \))
  - less sensitive to non-local (resonance) contributions
  - fine binning could enhance sensitivity to QCD effects

- Consider high \( q^2 \) (low hadronic recoil) region
  - different theory systematics (HQET OPE)

- Complementary observables in other modes
  \( (B_s \to \phi \ell^+ \ell^-, B \to K \ell^+ \ell^-, B \to X_s \ell^+ \ell^-, \ldots) \)
  - i.e. expect reduced rates compared to SM estimates
  - if due to QCD, don’t necessarily expect identical effects

- (Not too close to charm threshold!)
  
  - \( q^2 \) distribution
    - However, some indications that some of assumptions might be violated

- Recent indications?
  
  - Horgan et al., 1310.3722, 1310.3887
  
  - LHCb, 1307.7595

- Jager & Camalich, 1212.2263

- LHCb, 1403.8044
Conclusions

Success of SM (CKM paradigm) in describing (quark) flavor phenomena puzzling in light of EW hierarchy problem

Flavor physics intimately connected to Higgs phenomenology - directions just starting to be explored

Top-flavor processes ideal for LHC studies - interesting links to EW hierarchy, flavor, DM puzzles

Puzzling results in rare B decays due to be properly understood

see also Blanke et al., 1302.7232
Backup
Testing flavor through Higgs observables (at LHC)

Within SM effective $Y_{i\neq j}$ extremely suppressed (GIM+CKM/$m_\nu$ & chirality)

Constraints on first two generation $Y_{i\neq j}$ dominated by precision flavor observables (both lepton and quark)

Currently LHC already most constraining in $\tau$-$\mu$, $\tau$-$e$ sectors (recast of $h \rightarrow \tau \tau$)

Harnik, Kopp, Zupan, 1209.1397

McKeen, Pospelov, Ritz, 1208.4597
Blankenburg, Ellis, Isidori, 1202.5704
$B_{s,d} \rightarrow \mu^+\mu^-$

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector)

**Example**: general MSSM

\[
m_h \sim 125 \text{ GeV} \quad \downarrow \quad \text{large } A_{33}
\]

Measurement with $\sigma(BR) \sim 30\%$ provides relevant constraint on such couplings below stability bounds

\[
(|A_{23}A_{33}| < 3m_{\tilde{t}_L}^2) \text{ for } m_{\tilde{t}_L} < 1 \text{ TeV} , \ m_{\tilde{t}_R} < 0.5 \text{ TeV}
\]