Searches with non-LFV channels

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- Charm mixing and correlations
- $B_s$ rare decays and mixing
1. Rare leptonic decays of charm

- These decays only proceed at one loop in the SM; GIM is very effective
  - SM rates are expected to be small

★ Rare decays $D \to M e^+e^-/\mu^+\mu^-$ and $D \to e^+e^-/\mu^+\mu^-$ are mediated by $c \to u \bar{u} l l$

$$L_{\text{eff}}^{\text{SD}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ub} \sum_{i=7,9,10} C_i Q_i,$$

$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{e} \gamma^\mu \gamma_5 l,$$

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu \gamma_\mu c_L \bar{e} \gamma_5 l,$$

- SM contribution is dominated by LD effects
- could be used to study NP effects

★ Example: R-parity-violating SUSY
  - operators with the same parameters contribute to D-mixing
  - feed results into rare decays

★ Easiest: $D \to e^+e^-/\mu^+\mu^-$
Standard Model contribution to $D \rightarrow \mu^+\mu^-$

★ Short distance analysis

\[ Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_{\mu} c_L \bar{\ell} \gamma_{\mu} \gamma_5 \ell, \]

- only $Q_{10}$ contribute, SD effects amount to $Br \sim 10^{-18}$
- single non-perturbative parameter (decay constant)

★ Long distance analysis

- LD effects amount to $Br \sim 10^{-13}$
- could be used to study NP effects in correlation with D-mixing

UKQCD, HPQCD; Jamin, Lange; Penin, Steinhauser; Khodjamirian

Burdman, Golowich, Hewett, Pakvasa; Fajfer, Prelovsek, Singer
Standard Model contribution to $D \rightarrow \mu^+\mu^-$

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Alexey A Petrov (WSU & MCTP)
What about D-mixing?

★ Let’s write the most general $\Delta C=2$ Hamiltonian

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} C_i(\mu) Q_i$$

... with the following set of 8 independent operators...

$$Q_1 = (\bar{u}_L \gamma_\mu c_L) (\bar{u}_L \gamma^\mu c_L), \quad Q_5 = (\bar{u}_R \sigma_{\mu\nu} c_L) (\bar{u}_R \sigma^{\mu\nu} c_L),$$
$$Q_2 = (\bar{u}_L \gamma_\mu c_L) (\bar{u}_R \gamma^\mu c_R), \quad Q_6 = (\bar{u}_R \gamma_\mu c_R) (\bar{u}_R \gamma^\mu c_R),$$
$$Q_3 = (\bar{u}_R c_L) (\bar{u}_R c_L), \quad Q_7 = (\bar{u}_L c_R) (\bar{u}_L c_R),$$
$$Q_4 = (\bar{u}_R c_L) (\bar{u}_R c_L), \quad Q_8 = (\bar{u}_L \sigma_{\mu\nu} c_R) (\bar{u}_L \sigma^{\mu\nu} c_R).$$

RG-running relate $C_i(m)$ at NP scale to the scale of $m \sim 1$ GeV, where ME are computed (on the lattice)

$$\frac{d}{d \log \mu} \bar{C}(\mu) = \gamma^T(\mu) \bar{C}(\mu)$$

Each model of New Physics provides unique matching condition for $C_i(\Lambda_{NP})$.
Generic restrictions on NP

★ Comparing to experimental value of $x$, obtain constraints on NP models
- assume $x$ is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

\[
\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q'_i 
\]

\[
\begin{align*}
Q_1^c &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\gamma \gamma_\mu c_L^\beta, \\
Q_2^c &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\alpha c_L^\beta, \\
Q_3^c &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha \\
Q_4^c &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\alpha c_R^\beta \\
Q_5^c &= \bar{u}_R^\beta c_L^\beta \bar{u}_L^\beta c_R^\alpha
\end{align*}
\]

★ ... which are

\[
|z_1| \lesssim 5.7 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
|z_2| \lesssim 1.6 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
|z_3| \lesssim 5.8 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
|z_4| \lesssim 5.6 \times 10^{-8} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
|z_5| \lesssim 1.6 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2.
\]

New Physics is either at a very high scales
- tree level: $\Lambda_{NP} \geq (4 - 10) \times 10^3$ TeV
- loop level: $\Lambda_{NP} \geq (1 - 3) \times 10^2$ TeV
or have highly suppressed couplings to charm!

★ Constraints on particular NP models available

Gedalia, Grossman, Nir, Perez

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Example of a model of New Physics

★ Consider an example: FCNC $Z^0$-boson

appears in models with
extra vector-like quarks
little Higgs models

1. Integrate out $Z$: for $\mu < M_Z$ get

$$\mathcal{H}_{2/3} = \frac{g^2}{8 \cos^2 \theta_W M_Z^2} (\lambda_{uc})^2 \bar{u}_L \gamma_\mu c_L \bar{u}_L \gamma^\mu c_L$$

2. Perform RG running to $\mu \sim m_c$ (in general: operator mixing)

$$\mathcal{H}_{2/3} = \frac{g^2}{8 \cos^2 \theta_W M_Z^2} (\lambda_{uc})^2 r_1(m_c, M_Z) Q_1$$

3. Compute relevant matrix elements and $x_D$

$$x_D^{(2/3)} = \frac{2 G_F f_D^2 M_D}{3 \sqrt{2} \Gamma_D} B_D (\lambda_{uc})^2 r_1(m_c, M_Z)$$

4. Assume no SM - get an upper bound on NP model parameters/correlate with rare decays!
Generic NP contribution to $D \rightarrow \mu^+\mu^-$

★ Most general effective Hamiltonian:

$$\langle f | \mathcal{H}_{NP} | i \rangle = G \sum_{i=1}^{G} C_i(\mu) \langle f | Q_i | i \rangle(\mu)$$

$$\tilde{Q}_1 = (\bar{\ell}_L \gamma_\mu \ell_L) \left( \bar{u}_L \gamma^\mu c_L \right),$$

$$\tilde{Q}_2 = (\bar{\ell}_L \gamma_\mu \ell_L) \left( \bar{u}_R \gamma^\mu c_R \right),$$

$$\tilde{Q}_3 = (\bar{\ell}_L \ell_R) \left( \bar{u}_R c_L \right),$$

$$\tilde{Q}_4 = (\ell_R \ell_L) \left( \bar{u}_R c_L \right),$$

$$\tilde{Q}_5 = (\ell_R \sigma_{\mu\nu} \ell_L) \left( \bar{u}_R \sigma^{\mu\nu} c_L \right),$$

plus $L \leftrightarrow R$

★ ... thus, the amplitude for $D \rightarrow e^+e^-/\mu^+\mu^-$ decay is

$$B_{D^0 \rightarrow e^+e^-} = \frac{M_D}{8\pi \Gamma_D} \left[ 1 - \frac{4m_e^2}{M_D^2} \left( 1 - \frac{4m_e^2}{M_D^2} \right) |A|^2 + |B|^2 \right] ,$$

$$B_{D^0 \rightarrow \mu^+\mu^-} = \frac{M_D}{8\pi \Gamma_D} \left( 1 - \frac{m_\mu^2}{M_D^2} \right)^2 \left[ |A|^2 + |B|^2 \right] ,$$

$$|A| = G \frac{f_D M_D^2}{4m_c} \left[ \tilde{C}_{3-8} + \tilde{C}_{4-9} \right] ,$$

$$|B| = G \frac{f_D}{4} \left[ 2m_\ell \left( \tilde{C}_{1-2} + \tilde{C}_{6-7} \right) + \frac{M_D^2}{m_c} \left( \tilde{C}_{4-3} + \tilde{C}_{9-8} \right) \right] ,$$

$$\tilde{C}_{i-k} \equiv \tilde{C}_i - \tilde{C}_k$$

Many NP models give contributions to both D-mixing and $D \rightarrow e^+e^-/\mu^+\mu^-$ decay: correlate!!!
Mixing vs rare decays: a particular model

★ Recent experimental constraints

★ Relating mixing and rare decay
  - consider an example: heavy vector-like quark (Q=+2/3)
  - appears in little Higgs models, etc.

Mixing:
\[
\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_{\text{w}} M_Z^2} \lambda_{uc} Q_1 = \frac{G_F \lambda_{uc}^2}{\sqrt{2}} Q_1
\]
\[
x_D^{(2/3)} = \frac{2 G_F \lambda_{uc}^2 f_D^2 M_D B_{Dr}(m_c, M_Z)}{3 \sqrt{2} \Gamma_D}
\]

Rare decay:
\[
A_{D^0 \to \ell^+ \ell^-} = 0 \quad B_{D^0 \to \ell^+ \ell^-} = \lambda_{uc} \frac{G_F f_D m_\mu}{2}
\]
\[
B_{D^0 \to \mu^+ \mu^-} = \frac{3 \sqrt{2}}{64 \pi} \frac{G_F m_\mu^2 x_D}{B_{Dr}(m_c, M_Z)} \left[1 - \frac{4 m_\mu^2}{M_D^2}\right]^{1/2}
\]
\[
\approx 4.3 \times 10^{-9} x_D \leq 4.3 \times 10^{-11}
\]

Note: a NP parameter-free relation!

E. Golowich, J. Hewett, S. Pakvasa and A.A.P. PRD79, 114030 (2009)

Alexey A Petrov (WSU & MCTP)

LHCb Theory Workshop, CERN, 2011
**Correlation between mixing/rare decays**
- possible for tree-level NP amplitudes

Spin-1 intermediate boson:

\[ \mathcal{H}^F_{V} = \mathcal{H}^{FCNC}_{V} + \mathcal{H}^{L}_{V} \]

\[
\mathcal{H}^{FCNC}_{V} = g_{V1} \bar{u}_L \gamma_{\mu} c_L V_{\mu} + g_{V2} \bar{u}_R \gamma_{\mu} c_R V_{\mu} \\
+ g_{V3} \bar{u}_L \sigma_{\mu\nu} c_R V_{\mu\nu} + g_{V4} \bar{u}_R \sigma_{\mu\nu} c_L V_{\mu\nu}
\]

Mixing:

\[
\chi_{D}^{(V)} = \frac{f_{D}^{2} M_{D} \bar{B}_{D}}{2 M_{V}^{2} \Gamma_{D}} \left[ \frac{2}{3} (C_{1}(m_{c}) + C_{6}(m_{c})) - \left[ \frac{1}{2} + \eta \frac{1}{3} \right] C_{2}(m_{c}) + \left[ \frac{1}{12} + \frac{\eta}{2} \right] C_{3}(m_{c}) \right] 
\]

\[
C_{1}(m_{c}) = r(m_{c}, M_{V}) g_{V1}^{2}, \\
C_{2}(m_{c}) = 2 r(m_{c}, M_{V})^{1/2} g_{V1} g_{V2}, \\
C_{3}(m_{c}) = \frac{2}{3} [r(m_{c}, M_{V})^{1/2} - r(m_{c}, M_{V})^{-4}] g_{V1} g_{V2}, \\
C_{6}(m_{c}) = r(m_{c}, M_{V}) g_{V2}^{2}
\]

Rare decay:

\[
\mathcal{B}_{D^{0} \rightarrow \ell^{+} \ell^{-}}^{(V)} = \frac{f_{D}^{2} m_{\ell}^{2} M_{D}}{32 \pi M_{V}^{4} \Gamma_{D}} \sqrt{1 - \frac{4 m_{\ell}^{2}}{M_{D}^{2}}} \\
\times (g_{V1} - g_{V2})^{2} (g_{V1}' - g_{V2}')^{2}.
\]

**NO contribution from vectors**
(vector current conservation)

\[
E. Golowich, J. Hewett, S. Pakvasa and A. A. P. \\
PRD79, 114030 (2009)
**Correlation between mixing/rare decays**
- possible for tree-level NP amplitudes

**Spin-0 intermediate boson:**
\[ \mathcal{H}_S = \mathcal{H}_{S_{FCNC}} + \mathcal{H}_{S}^L, \]
\[ \mathcal{H}_{S_{FCNC}} = g_{S_1} \bar{u}_L c_R S + g_{S_2} \bar{u}_R c_L S + g_{S_3} \bar{u}_L \gamma_\mu c_L \partial_\mu S + g_{S_4} \bar{u}_R \gamma_\mu c_R \partial_\mu S, \]
\[ \mathcal{H}_{S}^L = g'_{S_1} \bar{\ell}_L \ell_R S + g'_{S_2} \bar{\ell}_R \ell_L S + g'_{S_3} \bar{\ell}_L \gamma_\mu \ell_L \partial_\mu S + g'_{S_4} \bar{\ell}_R \gamma_\mu \ell_R \partial_\mu S. \]

**Mixing:**
\[ x_D^{(s)} = -\frac{f_D^2 M_D B_D}{2 \Gamma_D M_S^2} \left[ \left[ \frac{1}{12} + \frac{\eta}{2} \right] C_3(m_c) \right. \]
\[ \left. - \frac{5 \eta}{12} (C_4(m_c) + C_7(m_c)) + \eta (C_5(m_c) + C_8(m_c)) \right]. \]

**Rare decay:**
\[ \mathcal{B}_{D^0 \to \ell^+ \ell^-}^{(s)} = \frac{f_D^2 M_D^5}{128 \pi m_{c}^2 M_S^4 \Gamma_D} \sqrt{1 - \frac{4m_\ell^2}{M_D^2}} \left( g_{S_1} - g_{S_2} \right)^2 \]
\[ \times \left[ (g'_{S_1} + g'_{S_2})^2 \left( 1 - \frac{4m_\ell^2}{M_D^2} \right) + (g'_{S_1} - g'_{S_2})^2 \right]. \]

NO contribution from scalars
Mixing vs rare decays

★ Correlation between mixing/rare decays
- possible for tree-level NP amplitudes
- some relations possible for loop-dominated transitions

★ Consider several popular models

<table>
<thead>
<tr>
<th>Model</th>
<th>$B_{D^0 \rightarrow \mu^+ \mu^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model (SD)</td>
<td>$\sim 10^{-18}$</td>
</tr>
<tr>
<td>Standard Model (LD)</td>
<td>$\sim$ several $\times 10^{-13}$</td>
</tr>
<tr>
<td>$Q = +2/3$ Vectorlike Singlet</td>
<td>$4.3 \times 10^{-11}$</td>
</tr>
<tr>
<td>$Q = -1/3$ Vectorlike Singlet</td>
<td>$1 \times 10^{-11} (m_s/500 \text{ GeV})^2$</td>
</tr>
<tr>
<td>$Q = -1/3$ Fourth Family</td>
<td>$1 \times 10^{-11} (m_s/500 \text{ GeV})^2$</td>
</tr>
<tr>
<td>$Z'$ Standard Model (LD)</td>
<td>$2.4 \times 10^{-12}/(M_{Z'}(\text{TeV}))^2$</td>
</tr>
<tr>
<td>Family Symmetry</td>
<td>$0.7 \times 10^{-18}$ (Case A)</td>
</tr>
<tr>
<td>RPV-SUSY</td>
<td>$1.7 \times 10^{-9} (500 \text{ GeV}/m_{dk})^2$</td>
</tr>
</tbody>
</table>

Obtained upper limits on rare decay branching ratios.

Can we apply the same idea where better data exists?

Same idea can be employed to relate D-mixing to K-mixing

Blum, Grossman, Nir, Perez  
### 2. $D^0$-mixing vs $B_s$-mixing

<table>
<thead>
<tr>
<th>$D^0 - D^0$ mixing</th>
<th>$B^0 - B^0$ mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• intermediate down-type quarks</td>
<td>• intermediate up-type quarks</td>
</tr>
<tr>
<td>• SM: b-quark contribution is negligible due to $V_{cd}V_{ub}^*$</td>
<td>• SM: t-quark contribution is dominant</td>
</tr>
<tr>
<td>rate $\propto f(m_s) - f(m_d)$</td>
<td>rate $\propto m_t^2$</td>
</tr>
<tr>
<td>(zero in the SU(3) limit)</td>
<td>(expected to be large)</td>
</tr>
</tbody>
</table>

1. Sensitive to long distance QCD
2. Small in the SM: New Physics!
   (must know SM $\lambda$ and $\gamma$)

1. Computable in QCD (*)
2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators

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Falk, Grossman, Ligeti, and A.A.P.
Phys.Rev. D65, 054034, 2002
2nd order effect!!!
Available experimental data for $B_s$

- LHCb will probe $B_s \rightarrow \mu^+\mu^-$ at the SM level within a year

★ $B_s$ mixing data:

$$\Delta M_{B_s}^{(expt)} = (117.0 \pm 0.8) \times 10^{-13} \text{ GeV},$$

$$\Delta M_{B_s}^{(SM)} = \frac{(G_F M_W |V_{ts}^* V_{tb}|)^2}{6\pi^2} M_{B_s} f_{B_s}^2 \hat{B}_{B_s} \eta_{B_s} S_0(\bar{x}_t) = (125.2^{+13.8}_{-12.7}) \times 10^{-13} \text{ GeV}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_s(M_Z)$</td>
<td>$0.1184 \pm 0.0007$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ts}</td>
</tr>
<tr>
<td>$\Delta M_{B_s}$</td>
<td>$(117.0 \pm 0.8) \times 10^{-13}$ GeV</td>
</tr>
<tr>
<td>$\Delta \Gamma_{B_s}/\Gamma_{B_s}$</td>
<td>$0.092^{+0.051}_{-0.054}$</td>
</tr>
<tr>
<td>$\bar{m}_t(\bar{m}_t)$</td>
<td>$(163.4 \pm 1.2)$ GeV</td>
</tr>
<tr>
<td>$f_{B_s} \sqrt{\hat{B}_{B_s}}$</td>
<td>$275 \pm 13$ MeV</td>
</tr>
<tr>
<td>$f_{B_s}$</td>
<td>$0.2388 \pm 0.0095$ GeV</td>
</tr>
</tbody>
</table>

★ Rare decays

$$\mathcal{B}_{B_s \rightarrow \mu^+\mu^-}^{(PDG)} < 47 \times 10^{-9} \quad (\text{CL} = 90\%);$$

$$\mathcal{B}_{B_s \rightarrow \mu^+\mu^-}^{(CDF)} = (18^{+11}_{-9}) \times 10^{-9}$$

$$\mathcal{B}_{B_s \rightarrow \mu^+\mu^-}^{(LHC)} < 11 \times 10^{-9} \quad (\text{CL} = 95\%)$$

Buras, Carlucci, Gori, Isidori
New Physics in $B_s$-mixing

- Relate NP contributions in $B_s$ mixing and rare decays

★ $B_s$ mixing data:

$$\Delta M_{B_s} = \Delta M_{B_s}^{(SM)} + \Delta M_{B_s}^{(NP)} \cos \phi.$$  

$$\Delta M_{B_s}^{(Expt)} = \Delta M_{B_s}^{(SM)} + \Delta M_{B_s}^{(NP)}$$

$$\Delta M_{B_s}^{(NP)} = (-20.9 \rightarrow +5.6) \times 10^{-13} \text{ GeV}$$  

$$|\Delta M_{B_s}^{(NP)}| \leq 20.9 \times 10^{-13} \text{ GeV}$$

This characterizes the size of NP “window” still possible in $B_s$-mixing. This is what should be related to rare decays (same formulas...)

Mixing vs rare decays: some models

Consider RPV SUSY:

\[ \mathcal{W}_R = \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c. \]

Mixing:

\[ \mathcal{L}_R = - \lambda'_{i23} \bar{\nu}_i \tilde{b}_R s_L - \lambda'_{i32} \bar{\nu}_i \tilde{s}_R b_L + \text{H.c.}, \]

\[ \Delta M_{B_s}^{(R)} = \frac{5}{24} f_{B_s}^2 M_{B_s} F(C_3, B_3) \sum_i \frac{\lambda'_{i23} \lambda'_{i32}}{M_{\tilde{\nu}_i}^2}, \]

Rare decay:

\[ \mathcal{B}_{B_s \rightarrow \mu^+ \mu^-}^{(R)} = \frac{f_{B_s}^2 M_{B_s}^3}{64 \pi \Gamma_{B_s}} \left( \frac{M_{B_s}}{m_b} \right)^2 \left( 1 - \frac{4 m_{\mu}^2}{M_{B_s}^2} \right) \sqrt{1 - \frac{4 m_{\mu}^2}{M_{B_s}^2}}, \]

...assume that a single sneutrino dominates, neglect possible CP-violation...

\[ \mathcal{B}_{B_s \rightarrow \mu^+ \mu^-}^{(R)} = \frac{3}{20 \pi} \left( \frac{M_{B_s}^2}{m_b} \right) \left( \frac{M_{B_s}}{m_b} \right)^2 \left( 1 - \frac{2 m_{\mu}^2}{M_{B_s}^2} \right) \times \sqrt{1 - \frac{4 m_{\mu}^2}{M_{B_s}^2}}, \]

Mixing vs rare decays: some models

- FCNC pseudoscalars:

\[
\mathcal{B}_{B^0_d \to \ell^+ \ell^-}^{(a)} = \frac{3}{10\pi} \cdot \frac{M_{B_s}^2 \chi_s^{(a)}}{m_b f_a (\bar{C}_i, m_b)} \left( 1 - \frac{4m_{\ell}^2}{M_{B_s}^2} \right)^{1/2} \left( \frac{\lambda_{22}^E}{M_a} \right)^2,
\]

\( \lambda_{22}^E = 1, 0.5, 0.1 \)

\( E, \lambda \)

Mixing vs rare decays: some models

Sequential 4th generation of quarks:

\[ \mathcal{B}_{B_s \rightarrow \mu^+ \mu^-} = \frac{3\alpha^2 m_{\mu}^2 x_{B_s}}{8\pi B_{B_s} M_W^2} \sqrt{1 - \frac{4 m_{\mu}^2}{m_{B_s}^2} |C_{10}^{\text{tot}}|^2} |\Delta'|, \]

\[ \Delta' = \eta_t S_0(x_t) + \eta_{t'} R_{t't}^2 S_0(x_{t'}) + 2 \eta_{t'} R_{t't} S_0(x_{t'}, x_{t'}) \]

Soni et al

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Things to take home

- Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC in the future
  - a combination of bottom/charm sector studies
- Charm provides great opportunities for New Physics studies
  - unique access to up-type quark sector
  - large available statistics/in many cases small SM background
  - contributions from New Physics are still possible
- Can correlate mixing and rare decays with New Physics models
  - signals in D-mixing vs rare decays help differentiate among models
  - similar correlations in B_s studies restrict parameter space of several popular models