Constraining Minimal Flavor Violation at LHC

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LHC and the flavor puzzle

- working assumption: new states observed at LHC
  - motivation: hierarchy problem, dark matter
- then LHC also offers exploration of flavor puzzle
  - the spectrum of new particles
  - the couplings
- this talk: can LHC support/invalidate MFV?
Outline

- Flavor puzzle and MFV hypothesis
  - low energy constraints on NP from FCNCs
- MFV at LHC
  - focus on a particular set of models - vectorlike quarks
  - LHC phenomenology
- Outlook
NP flavor puzzle ($\Delta F = 2$ proc.)

- new physics $O(1)$ (maximally) flavor violating
  \[ \mathcal{H}_{\text{eff}} = \left( \frac{g^4}{16\pi^2 m_W^2} (V_{ti}^* V_{tj})^2 \frac{C_0}{4} + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \right) \left[ \bar{d}_i \gamma_\mu P_L d_j \right]^2 + \cdots \]

- measurements exclude $O(1)$ corrections to mixing

\[ h_q e^{i\sigma_q} = A_{Bq}^{NP} / A_{Bq}^{SM} \]
NP flavor puzzle ($\Delta F = 2$ proc.)

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$$\mathcal{H}_{\text{eff}} = \left( \frac{g^4}{16\pi^2 m_W^2} (V^*_{ti} V_{tj})^2 \frac{C_0}{4} + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \right) \left[ \bar{d}_i \gamma_\mu P_L d_j \right]^2 + \cdots$$

- measurements exclude $O(1)$ corrections to mixing

$K - \bar{K}$ mix.:

$$\left( V^*_{ts} V_{td} \right)^2 \frac{1}{4 \Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \Rightarrow \Lambda_{\text{NP}} \gtrsim 10^4 \text{ TeV}$$

$B_d - \bar{B}_d$ mix.:

$$\left( V^*_{tb} V_{td} \right)^2 \frac{1}{4 \Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \Rightarrow \Lambda_{\text{NP}} \gtrsim 500 \text{ TeV}$$

$B_s - \bar{B}_s$ mix.:

$$\left( V^*_{tb} V_{ts} \right)^2 \frac{1}{4 \Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \Rightarrow \Lambda_{\text{NP}} \gtrsim 100 \text{ TeV}$$

with $\Lambda_{\text{MFV}} = 4\pi m_W / g^2 \sim 2.4 \text{ TeV}$
Minimal Flavor Violation

- in SM flavor violation through Yukawas
  \[ \mathcal{L}_Y = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c \]

- for \( Y \to 0 \) global symmetry in quark sector
  \[ G_{\text{Flavor}} = SU(3)_Q \otimes SU(3)_D \otimes SU(3)_U \]

- Minimal Flavor Violation:
  - SM Yukawas the only source of FV

- Yukawas spurions under \( G_{\text{Flavor}} \)
  \[ Y_D \sim (3, \bar{3}, 1), \quad Y_U \sim (3, 1, \bar{3}) \]

- can be used to make EFT based analysis of low energy flavor data
Low energy operators

- 4 quark ops. constructed from flavor singlet bilinears
- for $\Delta F = 2$ the leading contrib comes from
  \[ \bar{Q}_L \Gamma Y_U Y_U^\dagger Q_L \]
- in basis where $Y_U \sim \text{diag}(0, 0, y_t) \Rightarrow D_L \rightarrow V_{CKM} D'_L$
- then same CKM factors as SM
  \[ \bar{Q}_L \Gamma Y_U Y_U^\dagger Q_L \rightarrow y_t^2 V_{ti}^* V_{tj} D_{Li}^\dagger D_{Lj} \]
Low energy constraints on MFV

cMFV - NP leads to same dim-6 ops. as in SM
- corresponds to small $\tan \beta$ in 2HDM
- all flavor violation proportional to $V_{CKM}$

$$\mathcal{H}_{\text{eff}} = (V_{ti}^* V_{tj})^2 \left( \frac{g^4}{16\pi^2 m_W^2} \frac{C_0}{4} + \frac{\tilde{C}_{NP}}{\Lambda_{NP}^2} \right) \left[ \bar{d}_i \gamma \mu P_L d_j \right]^2$$

- no new wek phases: $\tilde{C}_{NP}$ is real
- NP contributions also obey CKM hierarchy

for $K - \bar{K}$, $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing:

$$\frac{1}{4\Lambda_{MFV}^2} \gtrsim \frac{\tilde{C}_{NP}}{\Lambda_{NP}^2} \Rightarrow \Lambda_{NP} \gtrsim 2\Lambda_{MFV} \sim 5 \text{ TeV}$$

UTFit ’07: $\Lambda_{NP} > 7.8 \text{ TeV}$

- if NP in loops only, multiply bounds by $\sim \alpha_s$ or $\sim \alpha_W$

$$\Rightarrow m_{MFV} \gtrsim 1.5 \text{ TeV} \text{ or } \gtrsim 0.3 \text{ TeV}$$
Finding MFV

- from low energy flavor observables:
  - need to find a deviation from SM
  - look for correlations between obs. in $K, B, B_s$ decays
- if new states produced on shell: MFV @ LHC?
  - need to choose a specific example of new physics
Finding MFV

- from low energy flavor observables:
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- if new states produced on shell: MFV @ LHC?
  - need to choose a specific example of new physics

- we add to SM down-type, vector-like heavy quarks $B_L, B_R$, singlets of $SU(2)_L$
  - what are the possible spectra of the new quarks?
  - possible flavor structures of couplings to SM quarks?
  - can exclude MFV from $B_{L,R}$ decays/production?
  - if MFV not excluded, can LHC be used to support MFV?
Mass terms

- $B_L, B_R$: singlets of $SU(2)_L$, $Q = -1/3$
- the mass terms in Lagrangian

$$\mathcal{L}_Y + \frac{m_2}{v} Q_L Y_B B_R H + M_1 B_L X_{BD} D_R + M_2 B_L X_{BB} B_R$$

$m_2 \sim O(v)$, $M_1, 2 \gg v$

- impose MFV on $Y_B, X_{BD}, X_{BB}$
  - to have renorm. $B_{L,R}$ couplings to SM quarks $\Rightarrow$
  - $B_{L,R}$ are not singlets of $G_{Flavor}$

- MFV $\Rightarrow$ at least three gen. of extra quarks

- many $G_{Flavor}$ transform. assignments possible
- we choose the minimal: $B_{L,R}$ transform as $(3,1)$ or $(1,3)$ under $SU(3)_Q \times SU(3)_D \Rightarrow 4$ models
Spurion insertions

\[ \mathcal{L}_Y + \frac{m_2^2}{v} Q_L Y_B B_R H + M_1 \overline{B}_L X_{B_D} D_R + M_2 \overline{B}_L X_{B_B} B_R \]

- two relevant spurions
  \[ Y_D \sim (3, \bar{3}, 1), \quad Y_U Y_U^\dagger \sim (3 \times \bar{3}, 1, 1) \iff Y_U \sim (3, 1, \bar{3}) \]
- take basis with \( Y_U \) diagonal \( \Rightarrow Y_U Y_U^\dagger \sim \text{diag}(0, 0, 1) \)
  \((Y_U Y_U^\dagger)^n\) inserts break \( SU(3)_Q \rightarrow SU(2)_Q \times U(1)_Q \)
  \[ D_3 \equiv 1 + d_3 Y_U Y_U^\dagger \sim \text{diag}(1, 1, 1 + d_3), \quad d_3 \sim O(1) \]
  \((Y_D Y_D^\dagger)^n\) inserts can be neglected
The models

**model QQ:**
- $B_L \sim (3, 1)$, $B_R \sim (3, 1)$
- mass matrix
  
  \[
  \begin{pmatrix}
  \bar{Q}_L \{vY_D m_2D_3 \} \\
  \bar{B}_L \{M_1D_3Y_D \ M_2D_3 \} \\
  D_R \ B_R
  \end{pmatrix}
  \]

- 2 + 1 spectrum
- manifestation of $SU(3)_Q \rightarrow SU(2)_Q \times U(1)_Q$ breaking due to $y_t$
- the remaining split $O(m_{c}^2/v^2) \sim 10^{-4}$

**model DD:**
- $B_L \sim (1, 3)$, $B_R \sim (1, 3)$
- mass matrix
  
  \[
  \begin{pmatrix}
  \bar{Q}_L \{vY_D m_2D_3Y_D \} \\
  \bar{B}_L \{M_1 \ M_2 \} \\
  D_R \ B_R
  \end{pmatrix}
  \]

- degenerate spectrum
- the split of order $m_{b}/M^2 \Rightarrow$ negligible
The models II

**model QD:**

- $B_L \sim (3, 1)$, $B_R \sim (1, 3)$

- Mass matrix
  \[
  \overline{Q}_L \{ \begin{pmatrix} vY_D & m_2 D_3 Y_D \\ 0 & M_2 D_3 Y_D \end{pmatrix} \\
  \overline{B}_L \{ \begin{pmatrix} 0 \\ D_R \end{pmatrix} \}
  \]

- Hierarchical spectrum in ratios $m_d : m_s : O(m_b)$

- If relevant to LHC $\Rightarrow$ only the lightest heavy quark accessible

**model DQ:**

- $B_L \sim (1, 3)$, $B_R \sim (3, 1)$

- Mass matrix
  \[
  \overline{Q}_L \{ \begin{pmatrix} vY_D & m_2 D_3 \\ 0 & M_2 Y_D^\dagger D_3 \end{pmatrix} \\
  \overline{B}_L \{ \begin{pmatrix} 0 \\ D_R \end{pmatrix} \}
  \]

- In DQ need to choose either $m_2 = 0$ or $M_1 = 0$ to have hierarchical SM quarks
three diff. spectrums possible: 2+1, 3-fold degenerate, hierarchical
The couplings

- \( M \gg v \Rightarrow \Gamma(B' \to ZD'), \Gamma(B' \to WU') \) dominated by longitudinal \( Z, W \)
- Using Goldstone equivalence theorem these given by

\[
\overline{Q}L Y_B B_R H \xrightarrow{D_L \to D_L' V_{CKM}} \overline{D}'_L Y_{B'} B'_R \frac{h}{\sqrt{2}} + \overline{U}'_L V_{CKM} Y_{B'} B'_R h^+
\]

- Decay rates to \( W : Z : h \) in ratios 2 : 1 : 1

- The couplings \( Y_{B'} \) almost diag. for all 4 models

<table>
<thead>
<tr>
<th>Model</th>
<th>( Y_{B'} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>QQ</td>
<td>( \tilde{1} )</td>
</tr>
<tr>
<td>DD</td>
<td>( \tilde{1} \lambda )</td>
</tr>
<tr>
<td>QD</td>
<td>( \tilde{1} \lambda )</td>
</tr>
<tr>
<td>DQ</td>
<td>( \tilde{1} )</td>
</tr>
</tbody>
</table>

\[ \lambda = \text{diag}(y_d, y_s, y_b) \]
\[ \tilde{1} \equiv V_{CKM} D_3 V_{CKM} \sim \begin{pmatrix} 1 & 0 & \lambda^3 \\ 0 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & d_3 \end{pmatrix} \]

- The largest FV couplings
  - For \( Z \): \( (Y_{B'})_{23} \sim 0.04(Y_{B'})_{33} \)
  - For \( W \): \( (V_{CKM} Y_{B'})_{12} \sim 0.23(V_{CKM} Y_{B'})_{22} \)
LHC phenomenology
Observation

1st need to observe them: the mass reach?

- present exp. bound: $m_{B'} > 199$ GeV (assumed $Br(B' \rightarrow bZ) = 100\%$)  
  CDF, 2000

- Tevatron reach: $m_{B'} < 270(320)$ GeV discovery reach for $1(10)\text{ fb}^{-1}$  
  Andre, Rosner, 2003

- ATLAS reach study: general $B'$ from $2Z \rightarrow 4l \Rightarrow 5\sigma$  
  discovery reach with $300\text{ fb}^{-1}$ is $920$ GeV  
  Mehdiyev, Sultansoy, Unel, Yilmaz, 2006

- in several models with vectorlike up-type quarks  
  mass reach of $1 - 2.5$ TeV for $100 - 300\text{ fb}^{-1}$  
  Aguilar-Saavedra, 2005; Skiba, Tucker-Smith, 2007; Azuelos et al., 2004

- high end of disc. range from $qW \rightarrow B'$ fusion $\Rightarrow$ in $DQ$ and $QQ$ the $uW \rightarrow B'_1$ coupling unsuppressed
$pp \rightarrow B' \bar{B}'$ pair production (LO, using Pythia 6.4.10, CTEQ5L pdfs)

- even for $B' \bar{B}' \rightarrow Z j W j \rightarrow lljl$ about 2000 signal events at 100 fb$^{-1}$ for 3 gen. of $B'$ with $m_{B'} = 600$GeV and $O(1)$ S/B ratio
### Background estimates

<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}$</th>
<th>$t\bar{t} + j$</th>
<th>$t\bar{t} + 2j$</th>
<th>$W + 3j$</th>
<th>$W + 4j$</th>
<th>$Z + 3j$</th>
<th>$Z + 4j$</th>
<th>$WZ + 2j$</th>
<th>$WZ + 3j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>2.9 pb</td>
<td>9.1 pb</td>
<td>3.0 pb</td>
<td>(23.3 pb)</td>
<td>4.4 pb</td>
<td>(2.0 pb)</td>
<td>0.5 pb</td>
<td>0.020 pb</td>
<td>0.006 pb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$B'\bar{B}'$</th>
<th>$B'\bar{B}' \rightarrow ZX$</th>
<th>$B'\bar{B}' \rightarrow WZX$</th>
</tr>
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<tr>
<td>$\sigma$</td>
<td>2.7 pb</td>
<td>0.14 pb</td>
<td>0.022 pb</td>
</tr>
</tbody>
</table>

- LO calc using ALPGEN 2.11 with CTEQ5L pdfs
- 3 gen. with $m_{B'} = 600$ GeV
- jets: $p_T \geq 100$ GeV, $\Delta R \geq 1.0$
- decays to $W$s and $Z$s: sum over three lepton generations (excluding $Z \rightarrow \nu\nu$)
- center-of-mass energy of bckg events $> 2m_{B'}$
Testing MFV

- need to extract info on
  - spectrum of the heavy quarks
  - their partial and total decay widths

- tagging is important: the quark from $B'$ is classified as
  - light jet
  - heavy jet ($b$ or $c$)
  - or a $t$ quark

- if flavor violation small in the decays, understanding flavor tagging is crucial
  - mistag can hide FV
  - $t$ special since one can use $t \rightarrow Wj$ (under study)
From spectrum

- MFV predicts at TeV either
  - near degenerate $B'$ quarks (2+1 or 3)
  - or only one kinematically accessible flavor

- obs. of $n \geq 2$ nondeg. TeV quarks excludes MFV

- degeneracy of each state from production rate
  - always convoluted with decay $B r$'s ⇒ the $W/Z/H$ decays fixed using equivalence th.

- 3-fold degeneracy can get further support from flavor content of $B'$ events
  - MFV predicts that $1/3 B' \bar{B}'$ pairs decay to 3rd gen. quarks, $2/3$ to non-3rd gen. quarks
Single $B'$ production

- if $B'$ too heavy to be pair-produced, single $B'$ can still be significant
- especially true for models $DQ$, $QQ$ where $(Y_{B'})_{11} = O(1)$
- test of MFV: the singly produced $B'$ should not decay to 3rd gen. quarks
From flavor tagging

- MFV $\Rightarrow$ suppression of FV ($\propto V_{CKM}$)
- $B'$ decays to quarks of same generation
- if $B'$ pair produced, then LHC can test

\[
\frac{\Gamma(B'B' \rightarrow Xq_{1,2}q_3)}{\Gamma(B'B' \rightarrow Xq_{1,2}q_{1,2}) + \Gamma(B'B' \rightarrow Xq_{3}q_3)} \lesssim 10^{-3}
\]

(since the largest mixing with 3rd gen. is $\sim |V_{cb}| \sim 0.04$)
- this nontrivial check: in general $Y_{B'}$ still allowed to have large FV from low energy flavor exps.
if no degeneracy (only one state) ⇒ MFV predicts that the lightest $B'$ decays to $d, u$

for 2 + 1 case ⇒ MFV predicts the two degenerate $B'$'s decay to $q_{1,2}$ only, up to $\mathcal{O}(10^{-3})$ effects

further tests if charm tagging is also possible

consider a non-degenerate state that decays into light quarks (for example, model QD)

MFV implies $B'_1 \rightarrow q_1W/Z/h$ mostly, but also small charm branching ratio $\sim \lambda^2 \sim 5\%$.

larger amount of charm excludes MFV
Decay width

- In principle, decay widths of degenerate states are smoking guns.
  - In model $QQ$, $\Gamma$'s are equal, in $DD$ given by $m_d/m_s$.
  - But unlikely that they can be measured.
  - In models $QD$ and $DD$, the widths are suppressed below experimental resolution & still larger than needed for displaced vertices.
  - In models $DQ$ and $QQ$, the width $\sim$ experimental resolution (3%) ⇒ some hope that we may get info on the width.
Outlook

- other possibilities: down-type quarks in other reps of $G_{\text{Flavor}}$ (up-type $SU(2)_L$ singlet quarks, extra weak doublets, extra heavy leptons)

- 4 models considered span 4 representative cases:
  - spectrum degenerate or hierarchical
  - couplings to SM quarks universal or hierarchical

- general feature of MFV: NP flavor conserving to good extend
  - by roughly testing flavor structure of new quarks
    MFV can in principle be excluded/or probed
Open questions

- how well will the heavy-flavor tagging efficiency be known at high-$p_T$?
  - maybe better to have less efficient but better calibrated $b$-tagging methods
- What are the prospects for “$t$-tagging” in high multiplicity events?
  - interesting for $B' \rightarrow q_3$ decays
- how good is separation of SM bckg. from $B'$ signals using $B'$ mass recon.?
  - flavor studies are likely to be stats limited
  - can one use events with fewer leptons where $t\bar{t}$ and $W/Z+\text{jets}$ bckg. substantial?
Conclusions

- used models with extra vectorlike down-type quarks to discuss on-shell studies of MFV at LHC
- LHC can support or refute MFV hypothesis through determination of mass spectrum and production/decays
Hierarchy in CKM matrix

Wolfenstein parametrization:

- expand in $\lambda \sim 0.2$
- $A, \rho, \eta \sim O(1)$

$$V_{\text{CKM}} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}$$

- in the standard convention
- $3 \to 2$ transition CKM el. real
- $3 \to 1$ transition CKM el. complex
**MFV from low energy**

<table>
<thead>
<tr>
<th>MFV dim. 6 ops.</th>
<th>main observables</th>
<th>$\Lambda/\sqrt{2}$[TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{2}(\bar{Q}<em>L\lambda</em>{FC}\gamma_\mu Q_L)^2$</td>
<td>$\epsilon_K, \Delta m_{B_d}$</td>
<td>6.4 (5.0)</td>
</tr>
<tr>
<td>$H^\dagger (\bar{D}<em>R\lambda_d\lambda</em>{FC}\sigma_{\mu\nu}Q_L) F_{\mu\nu}$</td>
<td>$B \rightarrow X_s\gamma$</td>
<td>9.3 12.4</td>
</tr>
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<td>$H^\dagger (\bar{D}<em>R\lambda_d\lambda</em>{FC}\sigma_{\mu\nu}T^a Q_L) G^a_{\mu\nu}$</td>
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<td>2.6 3.5</td>
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<td>$(\bar{Q}<em>L\lambda</em>{FC}\gamma_\mu Q_L)(\bar{L}<em>L\gamma</em>\mu L_L)$</td>
<td>$B \rightarrow (X)\ell\bar{\ell}, K \rightarrow \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$</td>
<td>3.1 2.7</td>
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<td>$(\bar{Q}<em>L\lambda</em>{FC}\gamma_\mu T^a Q_L)(\bar{L}<em>L\gamma</em>\mu T^a L_L)$</td>
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<td>3.4 3.0</td>
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<tr>
<td>$(\bar{Q}<em>L\lambda</em>{FC}\gamma_\mu Q_L)(H^\dagger iD_\mu H)$</td>
<td>$B \rightarrow (X)\ell\bar{\ell}, K \rightarrow \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$</td>
<td>1.6 1.6</td>
</tr>
<tr>
<td>$(\bar{Q}<em>L\lambda</em>{FC}\gamma_\mu Q_L)(\bar{D}<em>R\gamma</em>\mu D_R)$</td>
<td>$B \rightarrow K\pi, \epsilon'/\epsilon, \ldots$</td>
<td>$\sim 1$</td>
</tr>
</tbody>
</table>

$\lambda_{FC} = V^*_{ti} V_{tj}$

- $B \rightarrow X_s\gamma$ very constraining
- constraints relevant also for LHC
- constraints on 4-quark ops. dominated by th. errors
- progress has been made since 2002
NP flavor puzzle ($\Delta F = 2$ proc.)

- new physics $O(1)$ (maximally) flavor violating

$$\mathcal{H}_{\text{eff}} = \left( \frac{g^4}{16\pi^2 m_W^2} (V_{ti}^* V_{tj})^2 \frac{C_0}{4} + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \right) \left[ \bar{d}_i \gamma_\mu P_L d_j \right]^2 + \cdots$$

- measurements exclude $O(1)$ corrections to mixing

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<th>Condition</th>
<th>Result</th>
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<tr>
<td>$K - \bar{K}$ mix.</td>
<td>$(V_{ts}^* V_{td})^2 \frac{1}{4\Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$</td>
<td>$\Lambda_{\text{NP}} \gtrsim 10^4 \text{ TeV}$ (1.5 $\cdot$ 10$^4$ TeV)</td>
<td></td>
</tr>
<tr>
<td>$B_d - \bar{B}_d$ mix.</td>
<td>$(V_{tb}^* V_{td})^2 \frac{1}{4\Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$</td>
<td>$\Lambda_{\text{NP}} \gtrsim 500 \text{ TeV}$ (210 TeV)</td>
<td></td>
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<tr>
<td>$B_s - \bar{B}_s$ mix.</td>
<td>$(V_{ts}^* V_{td})^2 \frac{1}{4\Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$</td>
<td>$\Lambda_{\text{NP}} \gtrsim 100 \text{ TeV}$ (32 TeV)</td>
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with $\Lambda_{\text{MFV}} = 4\pi m_W / g^2 \sim 2.4 \text{ TeV}$

\[ b \xrightarrow{t} \bar{d} \quad \bar{d} \xrightarrow{t} b \]