Constraining Minimal Flavor Violation at LHC

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based on Grossman, Nir, Thaler, Volansky, J.Z., 0706.1845 [hep-ph]

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

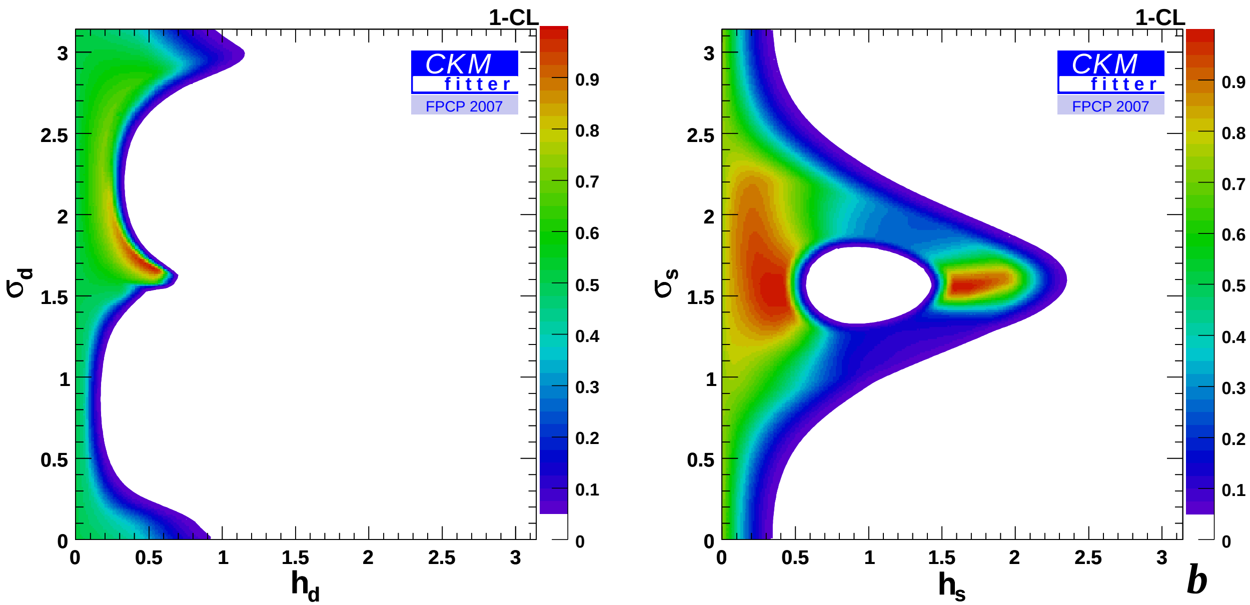
- Flavor puzzle and MFV hypothesis
  - low energy constraints on NP from FCNCs
- MFV at LHC
  - focus on a particular set of models -vectorlike quarks
  - LHC phenomenology
- Outlook

NP flavor puzzle ($\Delta F = 2$ proc.)

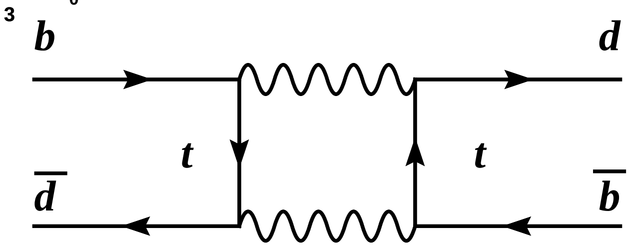
- new physics $O(1)$ (maximally) flavor violating

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

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



with $h_q e^{i2\sigma_q} = A^{NP}_{B_q}/A^{SM}_{B_q}$



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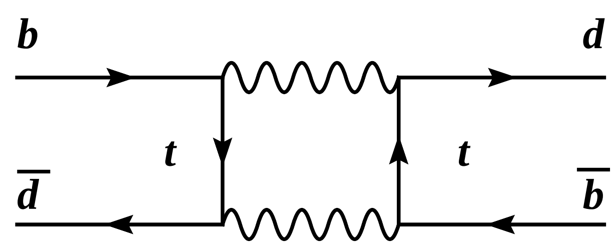
$K - \bar{K}$ mix.:	$(\underbrace{V_{ts}^*}_{\sim\lambda^2}\underbrace{V_{td}}_{\sim\lambda^3})^2 \frac{1}{4\Lambda_{\rm MFV}^2} \gtrsim \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \Rightarrow$	$\Lambda_{\rm NP} \gtrsim 10^4$ TeV
$B_d - \bar{B}_d$ mix.:	$(\underbrace{V_{tb}^*}_{\sim 1}\underbrace{V_{td}}_{\sim\lambda^3})^2 \frac{1}{4\Lambda_{\rm MFV}^2} \gtrsim \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \Rightarrow$	$\Lambda_{\rm NP} \gtrsim 500$ TeV
$B_s - \bar{B}_s$ mix.:	$(\underbrace{V_{tb}^*}_{\sim 1}\underbrace{V_{ts}}_{\sim\lambda^2})^2 \frac{1}{4\Lambda_{\rm MFV}^2} \gtrsim \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \Rightarrow$	$\Lambda_{\rm NP} \gtrsim 100$ TeV

with $\Lambda_{\rm MFV} = 4\pi m_W/g^2 \sim 2.4$ TeV



Minimal Flavor Violation

D'Ambrosio, Giudice, Isidori, Strumia, 2002

- in SM flavor violation through Yukawas

$$\mathcal{L}_Y = \overline{Q_L} Y_D D_R H + \overline{Q_L} Y_U U_R H_c$$

- for $Y \to 0$ global symmetry in quark sector

$$G_{\rm Flavor} = SU(3)_Q \otimes SU(3)_D \otimes SU(3)_U$$

- Minimal Flavor Violation:

SM Yukawas the only source of FV

- Yukawas spurions under $G_{\rm Flavor}$

$$Y_D \sim (3, \bar{3}, 1), \qquad Y_U \sim (3, 1, \bar{3})$$

- 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 $Y_U \sim \mathrm{diag}(0, 0, y_t) \Rightarrow D_L \to V_{CKM} D'_L$
- then same CKM factors as SM
$$\bar{Q}_L \Gamma Y_U Y_U^\dagger Q_L \to y_t^2 V_{ti}^* V_{tj} \bar{D}'_{Li} \Gamma D_{Lj}$$

Low energy constraints on MFV

Buras, Gambino, Gorbahn, Jager, Silvestrini, 2000
D'Ambrosio, Giudice, Isidori, Strumia, 2002

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

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

  - no new wek phases: $\tilde{C}_{\rm NP}$ is real
  - NP contributions also obey CKM hierarchy
- for $K-\bar{K}$, $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing:

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

UTFit '07: $\Lambda_{\rm NP} > 7.8\ {\rm TeV}$

  - if NP in loops only, multiply bounds by $\sim \alpha_s$ or $\sim \alpha_W$
    $\Rightarrow m_{\rm MFV} \gtrsim 1.5\ {\rm TeV}$ or $\gtrsim 0.3\ {\rm TeV}$

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

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  - 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

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

$m_2 \sim O(v)$, $M_{1,2} \gg v$

- 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} tranfsorm. 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

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

- two relevant spurions
  $Y_D \sim (3,\bar{3},1), \qquad Y_U Y_U^\dagger \sim (3\times\bar{3},1,1) \Leftarrow Y_U \sim (3,1,\bar{3})$
- take basis with Y_U diagonal $\Rightarrow Y_U Y_U^\dagger \sim \mathrm{diag}(0,0,1)$
  - $(Y_U Y_U^\dagger)^n$ inserts break $SU(3)_Q \to SU(2)_Q \times U(1)_Q$
    $D_3 \equiv \mathbf{1} + d_3 Y_U Y_U^\dagger \sim \mathrm{diag}(1,1,1+d_3), \qquad d_3 \sim O(1)$
  - $(Y_D Y_D^\dagger)^n$ inserts can be neglected

The models

model QQ:

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

$$\begin{matrix} \bar{Q}_L\{ \\ \bar{B}_L\{ \end{matrix} \begin{pmatrix} vY_D & m_2 D_3 \\ \underbrace{M_1 D_3 Y_D}_{D_R} & \underbrace{M_2 D_3}_{B_R} \end{pmatrix}$$

- $2+1$ spectrum
  - manifestation of $SU(3)_Q \to SU(2)_Q \times U(1)_Q$ 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

$$\begin{matrix} \bar{Q}_L\{ \\ \bar{B}_L\{ \end{matrix} \begin{pmatrix} vY_D & m_2 D_3 Y_D \\ \underbrace{M_1}_{D_R} & \underbrace{M_2}_{B_R} \end{pmatrix}$$

- degenerate spectrum
  - the split of order $m_b^2/M^2 \Rightarrow$ negligible

The models II

model **QD**:

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

$$\begin{matrix} \bar{Q}_L\{ \\ \bar{B}_L\{ \end{matrix} \begin{pmatrix} vY_D & m_2 D_3 Y_D \\ \underbrace{0}_{D_R} & \underbrace{M_2 D_3 Y_D}_{B_R} \end{pmatrix}$$

model **DQ**:

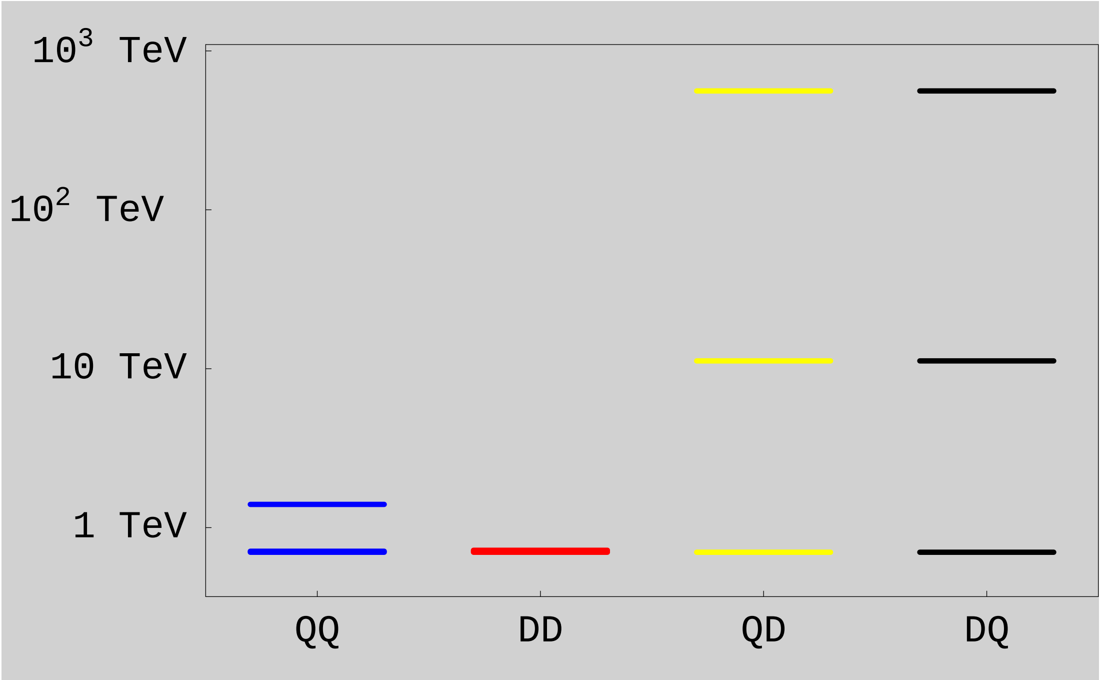
- $B_L \sim (1,3)$, $B_R \sim (3,1)$
- mass matrix

$$\begin{matrix} \bar{Q}_L\{ \\ \bar{B}_L\{ \end{matrix} \begin{pmatrix} vY_D & m_2 D_3 \\ \underbrace{(0)}_{D_R} & \underbrace{M_2 Y_D^\dagger D_3}_{B_R} \end{pmatrix}$$

- hierarchical spectrum in ratios $m_d : m_s : O(m_b)$
- if relevant to LHC $\Rightarrow$ only the lightest heavy quark accessible
- in **DQ** need to choose either $m_2 = 0$ or $M_1 = 0$ to have hierarchical SM quarks

Spectrum

- three diff. spectrums possible: 2+1, 3-fold degenerate, hierarchical



The couplings

- $M \gg v \Rightarrow \Gamma(B' \to Z D'), \Gamma(B' \to W U')$ 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

Model	QQ	DD	QD	DQ
$Y_{B'}$	$\tilde{1}$	$\tilde{1}\hat{\lambda}$	$\tilde{1}\hat{\lambda}$	$\tilde{1}$

$$\hat{\lambda} = \mathrm{diag}(y_d, y_s, y_b)$$

$$\tilde{1} \equiv V_{\mathrm{CKM}}^\dagger D_3 V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & 0 & \lambda^3 \\ 0 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & d_3 \end{pmatrix}$$

- the largest FV couplings
  - for Z: $(Y_{B'})_{23} \sim 0.04 (Y_{B'})_{33}$
  - for W : $(V_{\mathrm{CKM}} Y_{B'})_{12} \sim 0.23 (V_{\mathrm{CKM}} Y_{B'})_{22}$

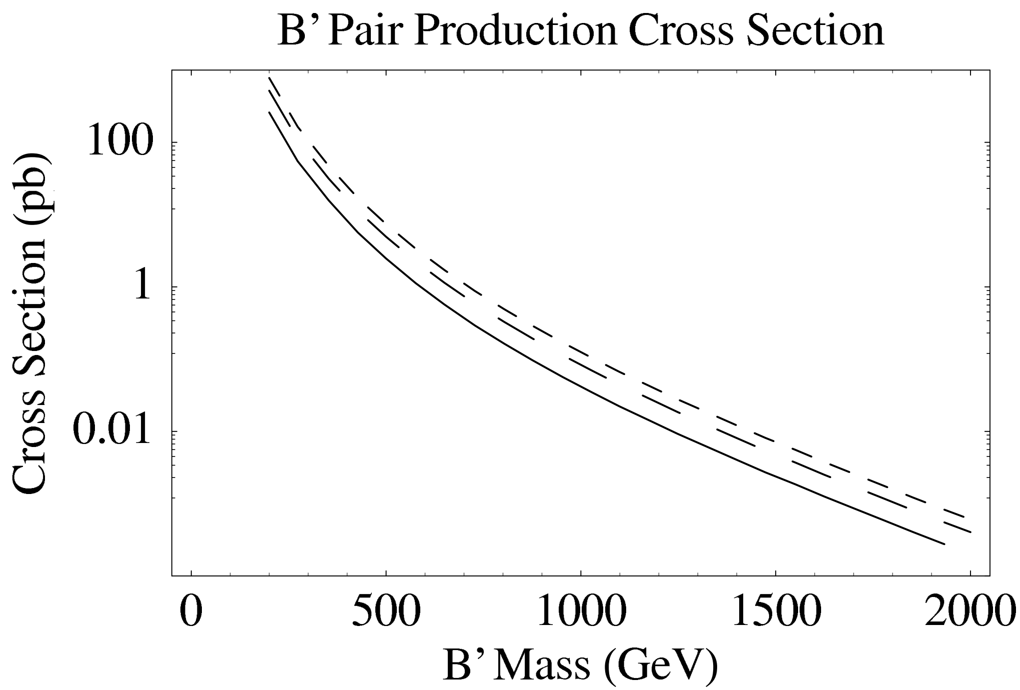
LHC phenomenology

Observation

- 1st need to observe them: the mass reach?
  - present exp. bound: $m_{B'} > 199\ \mathrm{GeV}$ (assumed $Br(B' \to bZ) = 100\ \%$) CDF, 2000
  - Tevatron reach: $m_{B'} < 270(320)\ \mathrm{GeV}$ discovery reach for $1(10)\ \mathrm{fb}^{-1}$ Andre, Rosner, 2003
  - ATLAS reach study: general B' from $2Z \to 4l \Rightarrow 5\sigma$ discovery reach with $300\ \mathrm{fb}^{-1}$ is $920\ \mathrm{GeV}$ Mehdiyev, Sultansoy, Unel, Yilmaz, 2006
  - in several models with vectorlike up-type quarks mass reach of $1 - 2.5\ \mathrm{TeV}$ for $100 - 300\ \mathrm{fb}^{-1}$ Aguilar-Saavedra, 2005; Skiba, Tucker-Smith, 2007; Azuelos *et al.*, 2004
  - high end of disc. range from $qW \to B'$ fusion $\Rightarrow$ in $\mathbf{DQ}$ and $\mathbf{QQ}$ the $uW \to B'_1$ coupling unsupressed

Production

- $pp \to B'\bar{B}'$ pair production (LO, using `Pythia 6.4.10`, CTEQ5L pdfs)



- even for $B'\bar{B}' \to ZjWj \to lljl$ about 2000 signal events at $100~\mathrm{fb}^{-1}$ for 3 gen. of B' with $m_{B'} = 600\mathrm{GeV}$ and $O(1)$ S/B ratio

Background estimates

	$t\bar{t}$	$t\bar{t}+j$	$t\bar{t}+2j$	$W+3j$	$W+4j$	$Z+3j$	$Z+4j$	$WZ+2j$	$WZ+3j$
σ	2.9 pb	9.1 pb	3.0 pb	(23.3 pb)	4.4 pb	(2.0 pb)	0.5 pb	0.020 pb	0.006 pb

	$B'\overline{B'}$	$B'\overline{B'} \to ZX$	$B'\overline{B'} \to WZX$
σ	2.7 pb	0.14 pb	0.022 pb

- LO calc using `ALPGEN 2.11` with CTEQ5L pdfs
- 3 gen. with $m_{B'} = 600 \text{ GeV}$
- jets: $p_T \geq 100 \text{ GeV}$, $\Delta R \geq 1.0$
- decays to Ws and Zs: sum over three lepton generations (excluding $Z \to \nu\nu$)
- 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 $t \to Wj$ (under study)

From spectrum

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

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

- degeneracy of each state from production rate
  - always convoluted with decay Br's $\Rightarrow$ 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 $\mathbf{DQ}$, $\mathbf{QQ}$ 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

$$\frac{\Gamma(B'\overline{B'} \to X q_{1,2} q_3)}{\Gamma(B'\overline{B'} \to X q_{1,2} q_{1,2}) + \Gamma(B'\overline{B'} \to X q_3 q_3)} \lesssim 10^{-3}$$

(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.

From flavor tagging II

- if no degeneracy (only one state) $\Rightarrow$ MFV predicts that the lightest B' decays to d, u
- for $2+1$ case $\Rightarrow$ 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 $B'_1 \to q_1 W/Z/h$ 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** Γ'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 exp. resolution & still larger than needed for displaced vertices
  - in models **DQ** and **QQ**, the width $\sim$ exp. resolution (3%) $\Rightarrow$ some hope that we may get info on the width

Outlook

- other possibilites: down-type quarks in other reps of G_{Flavor} (up-type $SU(2)_L$ singlet quarks, extra weak dublets, 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 $B' \to q_3$ 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 $W/Z+$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

Backup slides

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

D'Ambrosio, Giudice, Isidori, Strumia, 2002

MFV dim. 6 ops.	main observables	$\Lambda/\sqrt{2}$[TeV] $-$	$+$
$\frac{1}{2}(\bar{Q}_L\lambda_{\rm FC}\gamma_\mu Q_L)^2$	$\epsilon_K, \Delta m_{B_d}$	6.4	(5.0)
$H^\dagger\left(\bar{D}_R\lambda_d\lambda_{\rm FC}\sigma_{\mu\nu}Q_L\right)F_{\mu\nu}$	$B\to X_s\gamma$	9.3	12.4
$H^\dagger\left(\bar{D}_R\lambda_d\lambda_{\rm FC}\sigma_{\mu\nu}T^aQ_L\right)G^a_{\mu\nu}$	$B\to X_s\gamma$	2.6	3.5
$(\bar{Q}_L\lambda_{\rm FC}\gamma_\mu Q_L)(\bar{L}_L\gamma_\mu L_L)$	$B\to(X)\ell\bar{\ell}, K\to\pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$(\bar{Q}_L\lambda_{\rm FC}\gamma_\mu\tau^aQ_L)(\bar{L}_L\gamma_\mu\tau^aL_L)$	$B\to(X)\ell\bar{\ell}, K\to\pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$(\bar{Q}_L\lambda_{\rm FC}\gamma_\mu Q_L)(H^\dagger iD_\mu H)$	$B\to(X)\ell\bar{\ell}, K\to\pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$(\bar{Q}_L\lambda_{\rm FC}\gamma_\mu Q_L)(\bar{D}_R\gamma_\mu D_R)$	$B\to K\pi, \epsilon'/\epsilon, \ldots$	~ 1	

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

- $B\to X_s\gamma$ very constraining
  - constraints relevant also for LHC
- constraints on 4-quark ops. dominated by th. errors
  - progress has been made since 2002

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UTFit 0707.0636

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$B_d - \bar{B}_d$ mix.: $\big(\underbrace{V_{tb}^*}_{\sim 1} \underbrace{V_{td}}_{\sim\lambda^3}\big)^2 \frac{1}{4\Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \Rightarrow$ $\Lambda_{\text{NP}} \gtrsim 500$ TeV $(210\ \text{TeV})$

$B_s - \bar{B}_s$ mix.: $\big(\underbrace{V_{tb}^*}_{\sim 1} \underbrace{V_{ts}}_{\sim\lambda^2}\big)^2 \frac{1}{4\Lambda_{\text{MFV}}^2} \gtrsim \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \Rightarrow$ $\Lambda_{\text{NP}} \gtrsim 100$ TeV $(32\ \text{TeV})$

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