Probing Minimal Flavor Violation at LHC

Jure Zupan

CERN

based on *Y. Grossman, Y. Nir, J. Thaler, T. Volansky, J.Z.*, 0706.1845 [hep-ph],
Y. Grossman, Y. Hochberg, Y. Nir, J. Thaler, T. Volansky, J.Z., work in progress

Scope of this talk

- MFV a very natural way to solve NP flavor problem
  Chivukula, Georgi, 1987; Hall, Randall, 1990; Chiuchini, Degrassi, Gambino, Giudice, 1998; Buras, Gambino, Gorbahn, Jager, Silvestrini, 2000;D'Ambrosio, Giudice, Isidori, Strumia, 2002
  - SM Yukawas the only source of FV
  - spurions under $G_{\text{Flavor}} = SU(3)_Q \otimes SU(3)_D \otimes SU(3)_U$

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

- can high-p_T processes @LHC support/refute this hypothesis?
- Note: low energy exp. only partially constrain NP flavor sector $\Rightarrow$ LHC input can be nontrivial

Working assumptions

- new particles visible at LHC (hierarchy, dark matter...)
- NP obeys MFV hypothesis

Working assumptions

- new particles visible at LHC (hierarchy, dark matter...)
- NP obeys MFV hypothesis

to be specific:

- add to SM down-type, vector-like heavy quarks, singlets of $SU(2)_L$
- requirements:
  - MFV: B_L, B_R well defined transform. under $G_{\rm Flavor}$
  - visible at LHC: $m_{B_1} \lesssim 1\ {\rm TeV}$
  - $B_{L,R}$ decay to SM part. $\Rightarrow$ $B_{L,R}$ not singlets of $G_{\rm Flavor}$

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

Outline

- model with 3 gen. of extra vectorlike quarks
  - $O(1)$ FV possible in $B_{L,R}$ sector
- general consequences of MFV
- implications for LHC

General Model

- 3 generations of $B_{L,R}$
- mass terms

$$\begin{pmatrix} \overline{Q}_L \\ \overline{B}_L \end{pmatrix}^{\rm T} \begin{pmatrix} vY_D & m_2 Y_B \\ M_1 X_{BD} & M_2 X_{BB} \end{pmatrix} \begin{pmatrix} D_R \\ B_R \end{pmatrix}$$

- we take $v \sim m_2 \ll M_1 \sim M_2$
- Zq_iq_j couplings $\propto \delta_{ij} + U_{ij}$
  - expanding in v/M (taking $M_1 = 0$ for simplicity)

$$U_{ij} \sim \frac{m_2^2}{M_2^2}(Y_B X_{BB}^{-1})(Y_B X_{BB}^{-1})^\dagger$$

Low energy constraints

- from $Br(K_L \to \mu^+\mu^-)_{\text{SD}}$, ϵ'/ϵ, $B-\bar{B}$ mix., $B \to X_s l^+ l^-$

$$|U_{sd}| \lesssim 10^{-5}, \quad |U_{bd}| \lesssim 0.9 \times 10^{-3}, \quad |U_{bs}| \lesssim 1.1 \times 10^{-3}$$

- if $Y_B, X_{BB}^{-1} \sim O(1) \Rightarrow U_{ij} \sim \frac{m_2^2}{M_2^2}$
  - out of LHC reach, $M_{B_1} > 50 \text{ TeV}$

- if $Y_B \sim Y_D$, $X_{BB}^{-1} \sim O(1) \Rightarrow U_{ij} \sim \frac{m_{d_i} m_{d_j}}{M_2^2}$
  - all constraints automaticaly satisf. (even for $M_2 \sim v$)
  - lower bound on M_{B_1} from direct searches (also if MFV): $m_{B'} > 295 \text{ GeV}$ using 1.2fb^{-1} CDF, 2007
  - **$O(1)$ FV in $B_{L,R}$ sector possible**

Consequences of MFV

Symmetries of MFV

- in SM one large coupling: y_t
- MFV has app. symmetry

$$SU(2)_Q \otimes SU(2)_U \otimes SU(2 \text{ or } 3)_D$$

NP spectrum: either (at least) 2+1 degenerate or hierarchical

$$\begin{array}{lll} y_t \sim 1 & y_c \sim \lambda^3 & y_u \sim \lambda^7 \\ y_b \sim \lambda^2 & y_s \sim \lambda^4 & y_d \sim \lambda^6 \\ V_{us} \sim \lambda & V_{cb} \sim \lambda^2 & V_{ub} \sim \lambda^3 \end{array} \qquad \lambda = 0.22$$

Symmetries of MFV

- in SM the largest mixing: $V_{us} \simeq 0.22$
- MFV has app. $U(1)$ symmetry in mixing matrix

$$U(1)_d \otimes U(1)_s \otimes U(1)_b$$

NP does not mix $1^{\rm st}\&2^{\rm nd}$ with $3^{\rm rd}$ generation

$$\begin{array}{lll} y_t \sim 1 & y_c \sim \lambda^3 & y_u \sim \lambda^7 \\ y_b \sim \lambda^2 & y_s \sim \lambda^4 & y_d \sim \lambda^6 \\ V_{us} \sim \lambda & V_{cb} \sim \lambda^2 & V_{ub} \sim \lambda^3 \end{array} \qquad \lambda = 0.22$$

The models

- impose MFV
- choose G_{Flavor} assignments
  - take $B_{L,R}$ charged only under $SU(3)_Q \otimes SU(3)_D$
  - minimal assign.: $(3,1)$ or $(1,3)$ $\Rightarrow$ **4 models**
- two relevant spurions: Y_D, $Y_U Y_U^\dagger$
  - take basis with $Y_U \sim \text{diag}(0,0,1)$

    $D_3 \equiv \mathbf{1} + d_3 Y_U Y_U^\dagger \sim \text{diag}(1,1,1+d_3), \quad d_3 \sim O(1)$

Two nonchiral models

model QQ:

- $B_L \sim (3,1)$, $B_R \sim (3,1)$
- mass matrix
  $$X_{BB} = M_2 D_3$$
- $2+1$ spectrum
  - due to y_t breaking $SU(3)_Q \to SU(2)_Q \times U(1)_Q$
  - 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
  $$X_{BB} = M_2$$
- degenerate spectrum
  - the split of order $m_b^2/M^2 \Rightarrow$ negligible

Two chiral models

model **QD**:

- $B_L \sim (3,1)$, $B_R \sim (1,3)$
- mass matrix
  $X_{BB} = M_2 D_3 Y_D$

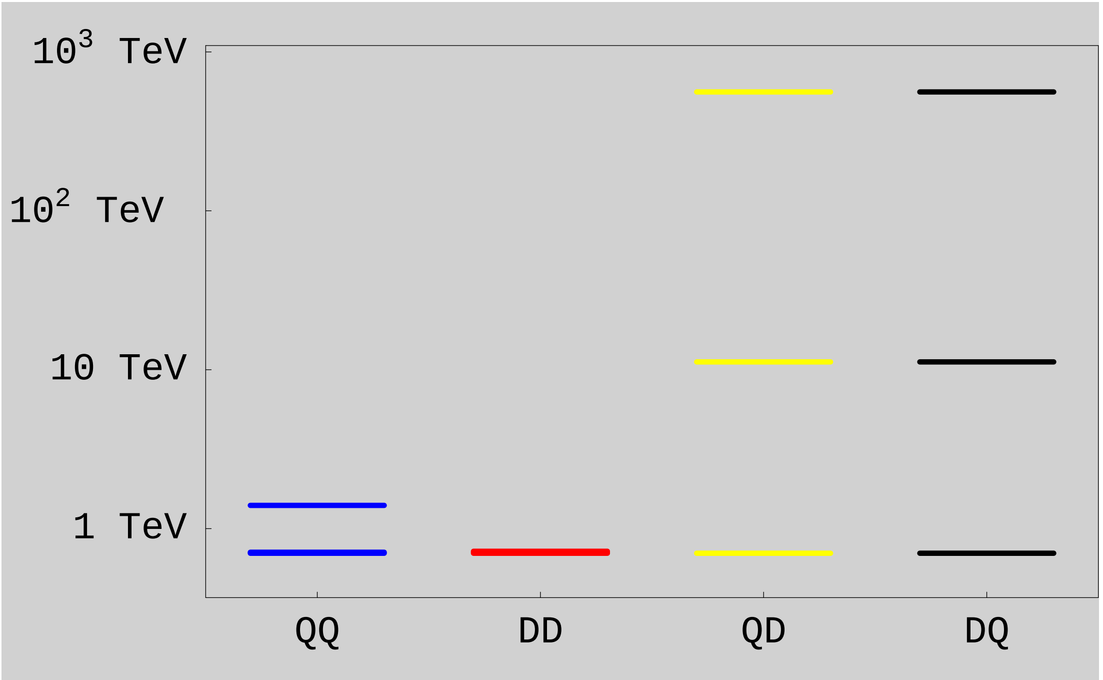
model **DQ**:

- $B_L \sim (1,3)$, $B_R \sim (3,1)$
- mass matrix
  $X_{BB} = M_2 Y_D^\dagger D_3$

- hierarchical spectrum in ratios $m_d : m_s : O(m_b)$
- if relevant to LHC $\Rightarrow$ only the lightest heavy quark accessible

Spectrum

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



The couplings

- $M \gg v \Rightarrow B' \to Zd', Wu'$ dominated by Z_L, W_L
- given by (Goldstone equivalence th.)
  - decay rates to $W : Z : h$ in ratios $2 : 1 : 1$

$$\overline{Q_L} Y_B B_R H \xrightarrow{D_L \to D'_L V_{CKM}} \overline{D'_L} Y_{B'} B'_R \frac{h}{\sqrt{2}} + \overline{U'_L} V_{\rm CKM} Y_{B'} B'_R h^+$$

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

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

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

- MFV: $Y_{B'}$ almost diag. for all 4 models
  - hierachical (**DD**, **QD**) or $O(1)$ (**QQ**, **DQ**)
  - FV supp. in $B' \to Zd'$ ($Y_{B'}$) and $B' \to Wu'$ ($V_{\rm CKM} Y_{B'}$)

Testing MFV

- from spectrum
  - need to be able to measure degeneracy
- from decays - tagging is important
  - need to distinguish b jet and t from light jets

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 disfavors MFV

caveat: several copies of B'_i could exist

- degeneracy of each state from production rate
  - always convoluted with decay $Br \Leftarrow$ the $W/Z/H$ decay Br fixed to $2:1:1$ (equivalence th.)
- 3-fold degeneracy: further support from flavor content of B' events
  - MFV $\Rightarrow 1/3\ B'\bar{B}'$ pairs decay to $3^{\rm rd}$ gen. quarks
    $2/3\ B'\bar{B}'$ pairs to $1^{\rm st}\&2^{\rm nd}$ gen. quarks

From flavor tagging

- MFV $\Rightarrow$ suppression of FV
  - 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 a nontrivial check
  - large FV in $Y_{B'}$ still allowed from low eng. flavor exps.
- 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

Other tests

- single B' production from quark-W/Z fusion
  - MFV test: singly produced B' should not decay to $3^{\rm rd}$ gen. quarks
- if charm tagging is possible
  - MFV test: $Br(B'_1 \to q_1 W) : Br(B'_1 \to cW)$ at most $1 : \lambda^2 \sim 5\%$
- using decay widths
  - in principle smoking guns for degenerate states
    - in model **QQ** Γ's are equal, in **DD** given by m_d/m_s
  - hard to measure, in **QQ**, **DQ**, the width $\sim$ exp. resolution (3%), otherwise below

Conclusions

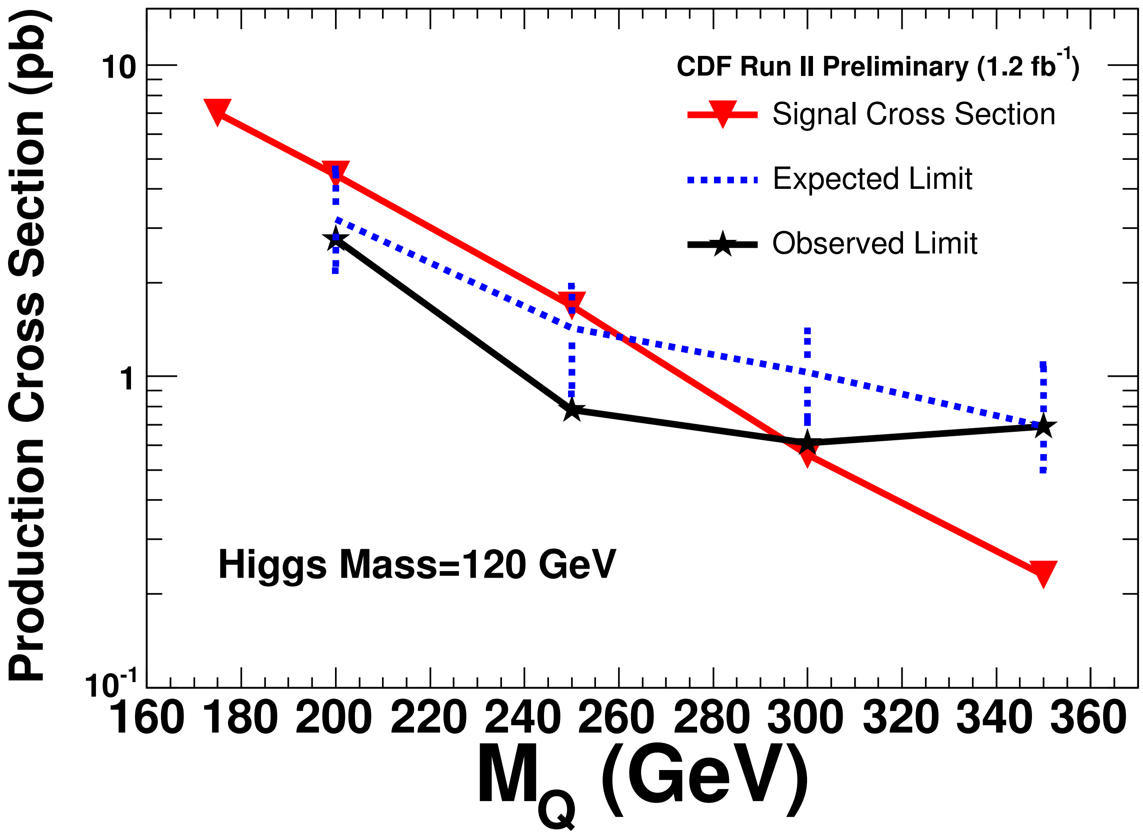
- probes of MFV at high p_T:
  - spectrum: degenerate or hierarchical
  - couplings to SM quarks flavor conserving to good extend

Backup slides

Direct searches

- present exp. bound: $m_{B'} > 295 \text{ GeV}$ using 1.2fb^{-1} assuming $m_H = 120 \text{ GeV}$

CDF, 2007

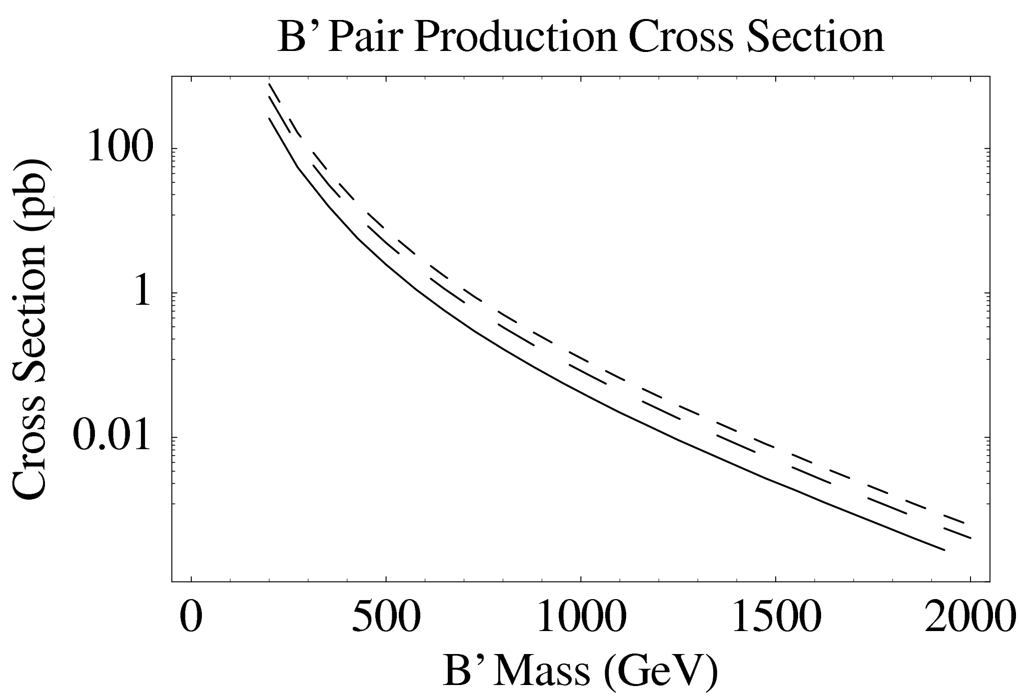


from pair prod. with

$B' \to Wj \to (l\nu)j$

Pair 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 $> 2m_{B'}$

Two chiral 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**
  - due to y_t breaking $SU(3)_Q \to SU(2)_Q \times U(1)_Q$
  - 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

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

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

The nonchiral models

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**:

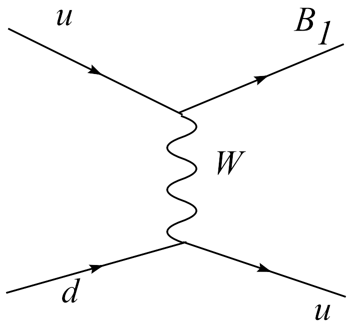
- $B_L \sim (1,3)$, $B_R \sim (3,1)$
- mass matrix

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

- 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

Single B' production

- from quark-W/Z fusion
- important if B' too heavy to be pair-produced
  - especially true for models $\mathbf{DQ}$, $\mathbf{QQ}$ where $(Y_{B'})_{11} = O(1)$
- test of MFV: singly produced B' should not decay to $3^{\rm rd}$ gen. quarks



- single B' production can be used to dist. $\mathbf{DQ}$, $\mathbf{QQ}$ from $\mathbf{QD}$, $\mathbf{DD}$

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

Testing MFV chart