Understanding Flavor at the LHC

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arXiv:0706.1845 [Phys. Rev. D76 (2007) 096006] with:

Yuval Grossman, Jesse Thaler, Tomer Volansky, Jure Zupan

arXiv:0712.0674 [Phys. Rev. D77 (2008) 076002] with:

Jonathan Feng, Christopher Lester, Yael Shadmi

arXiv:0802.0916 [JHEP 0803 (2008) 046] with:

Gudrun Hiller

Plan of Talk

1. Introduction
2. The SM flavor puzzle
3. The NP flavor puzzle
4. SUSY flavor: degeneracy and alignment
5. SUSY flavor @ LHC
6. Testing MFV @ LHC

Introduction

What is flavor physics?

- Interactions that distinguish among the generations:
  - Neither gauge nor Higgs self-ineteractions
  - Within the SM: Only Yukawa interactions
- The experimentalist's view:
  - Spectrum, BR, $A_{\rm CP}$
  - Quark and lepton masses, mixing angles and phases
- The theorist's view:
  - In the absence of Yukawa couplings: $SU(3)_{Q_L}\times SU(3)_{U_R}\times SU(3)_{D_R}\times SU(3)_{L_L}\times SU(3)_{E_R}$
  - Interactions that break the global $[SU(3)]^5$ symmetry

Why is flavor physics interesting?

- Flavor physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiment}$
- The Standard Model flavor puzzle:
  Why are the flavor parameters small and hierarchical?
  (Why) are the neutrino flavor parameters different?
- The New Physics flavor puzzle:
  If there is NP at the TeV scale, why are FCNC so small?
- The puzzle of the baryon asymmetry:
  Flavor suppression kills KM baryogenesis
  Flavor matters in leptogenesis

A brief history

- $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu) \implies$ Charm [GIM, 1970]
- $\Delta m_K \implies m_c \sim 1.5\ GeV$ [Gaillard-Lee, 1974]
- $\varepsilon_K \neq 0 \implies$ Third generation [KM, 1973]
- $\Delta m_B \implies m_t \gg m_W$ [Various, 1986]

A recent example of flavor@GeV $\implies$ SUSY@TeV:

- $\Delta m_D + \Delta m_K \implies \Delta m_{\tilde{q}}/m_{\tilde{q}} \lesssim 0.2$

  [Ciuchini et al, PLB 655, 162 (2007); Nir, JHEP 0705, 102 (2007)]

From BABAR/BELLE to ATLAS/CMS

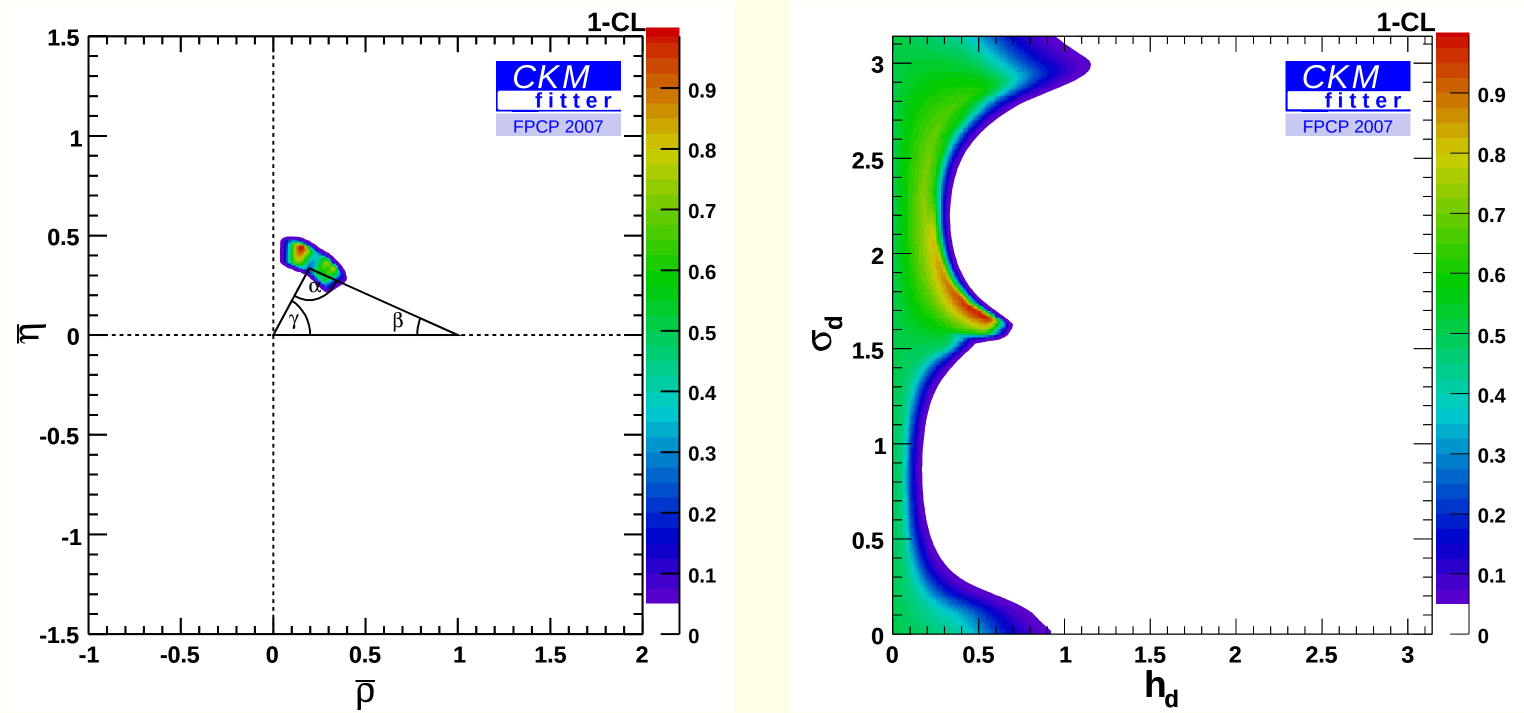
The B-factories...

- Clarified the picture of CP violation
  $\Longrightarrow$ The KM mechanism dominates CPV in meson decays
- Constrained extensions of the Standard Model
  $\Longrightarrow$ Challenges for model builders
- Deepened the NP flavor puzzle
  $\Longrightarrow$ FCNC are small in $s \to d$, $c \to u$, $b \to d$ and $b \to s$

Is the KM mechanism at work? dominant?

- Assume: New Physics in tree decays - negligible
- Define $1 + h_d e^{2i\sigma_d} = \frac{\langle B^0|\mathcal{H}^{\rm full}|\overline{B}^0\rangle}{\langle B^0|\mathcal{H}^{\rm SM}|\overline{B}^0\rangle}$
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}^d_{\rm SL}$
- Fit to $\boxed{\eta}$, ρ, $\boxed{h_d}$, σ_d
- Find whether $\eta = 0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d \gg 1$ is allowed
  If not $\Longrightarrow$ The KM mechanism is dominant

The KM mechanism dominates



CKMFitter

From BABAR/BELLE to ATLAS/CMS

ATLAS/CMS will, hopefully, observe NP at $\Lambda_{\rm NP} \lesssim TeV$ and...

- Measure new flavor parameters
- Teach us about how the NP flavor puzzle is (not) solved
- Probe NP at $\Lambda_{\rm NP} \gg TeV$
- Provide hints about the solution to the SM flavor puzzle

The SM Flavor Puzzle

Smallness and Hierarchy

$$
\begin{gathered}
Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5} \\
Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4} \\
Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6} \\
|V_{us}| \sim 0.2, \;\; |V_{cb}| \sim 0.04, \;\; |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1
\end{gathered}
$$

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- The SM flavor parameters have structure: smallness and hierarchy
- $\boxed{\text{Why?} \; = \text{The SM flavor puzzle}}$

The Froggatt-Nielsen mechanism

- Approximate “horizontal” symmetry (e.g. $U(1)_H$)
- Small breaking parameter $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\mathbf{10}(2,1,0), \quad \bar{\mathbf{5}}(0,0,0)$

$$\Downarrow$$

$$Y_t : Y_c : Y_u \sim 1 : \epsilon^2 : \epsilon^4$$
$$Y_b : Y_s : Y_d \sim 1 : \epsilon : \epsilon^2$$
$$Y_\tau : Y_\mu : Y_e \sim 1 : \epsilon : \epsilon^2$$
$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\rm KM} \sim 1$$

$$+$$

$$m_3 : m_2 : m_1 \sim 1 : 1 : 1$$
$$|U_{e2}| \sim 1, \quad |U_{\mu 3}| \sim 1, \quad |U_{e3}| \sim 1$$

The NP Flavor Puzzle

New Physics

- The effects of new physics at a high energy scale $\Lambda_{\rm NP}$ can be presented as higher dimension operators

- For example, we expect the following dimension-six operators:

$$\frac{z_{sd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu s_L)^2+\frac{z_{cu}}{\Lambda^2_{\rm NP}}(\overline{c_L}\gamma_\mu u_L)^2+\frac{z_{bd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu b_L)^2+\frac{z_{bs}}{\Lambda^2_{\rm NP}}(\overline{s_L}\gamma_\mu b_L)^2$$

- New contribution to neutral meson mixing, *e.g.*

$$\frac{\Delta m_B}{m_B}\sim\frac{f_B^2}{3}\times\frac{z_{bd}}{\Lambda^2_{\rm NP}}$$

- Generic flavor structure $\equiv z_{ij}\sim 1$ or, perhaps, $\rm loop-factor$

High Scale?

- For $z_{ij} \sim 1$,

$$\Lambda_{\rm NP} \gtrsim \begin{cases} 1 \times 10^4\ TeV & \epsilon_K \\ 1 \times 10^3\ TeV & \Delta m_K \\ 9 \times 10^2\ TeV & \Delta m_D \\ 4 \times 10^2\ TeV & \Delta m_B \\ 7 \times 10^1\ TeV & \Delta m_{B_s} \end{cases}$$

Did we misinterpret the fine tuning problem and the dark matter puzzle?

Small (hierachical?) flavor parameters?

- For $\Lambda_{\rm NP} \sim 1\ TeV$,

$$\begin{aligned}
\mathcal{I}m(z_{sd}) &\lesssim 6\times10^{-9} \\
z_{sd} &\lesssim 8\times10^{-7} \\
z_{cu} &\lesssim 1\times10^{-6} \\
z_{bd} &\lesssim 6\times10^{-6} \\
z_{bs} &\lesssim 2\times10^{-4}
\end{aligned}$$

$\Longrightarrow$ $\boxed{\text{The flavor structure of NP@TeV must be highly non-generic}}$

How? Why? = The NP flavor puzzle

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2}{\tilde{m}^2} \times \sin\tilde{\theta} \ll 1}$$

Why? = The SUSY flavor puzzle

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2}{\tilde{m}^2} \times \sin\tilde{\theta} \ll 1}$$

Why? = The SUSY flavor puzzle

- Solutions:
  - Heaviness: $\tilde{m} \gg 1\ TeV$
  - Degeneracy: $\Delta\tilde{m}^2 \ll \tilde{m}^2$
  - Alignment: $\sin\tilde{\theta} \ll 1$
  - Split Supersymmetry
  - Gauge-mediation
  - Horizontal symmetries

Degeneracy and Alignment

Feng, Lester, Nir, Shadmi, arXiv:0712.0674

CMSSM, mSUGRA...

CMSSM:

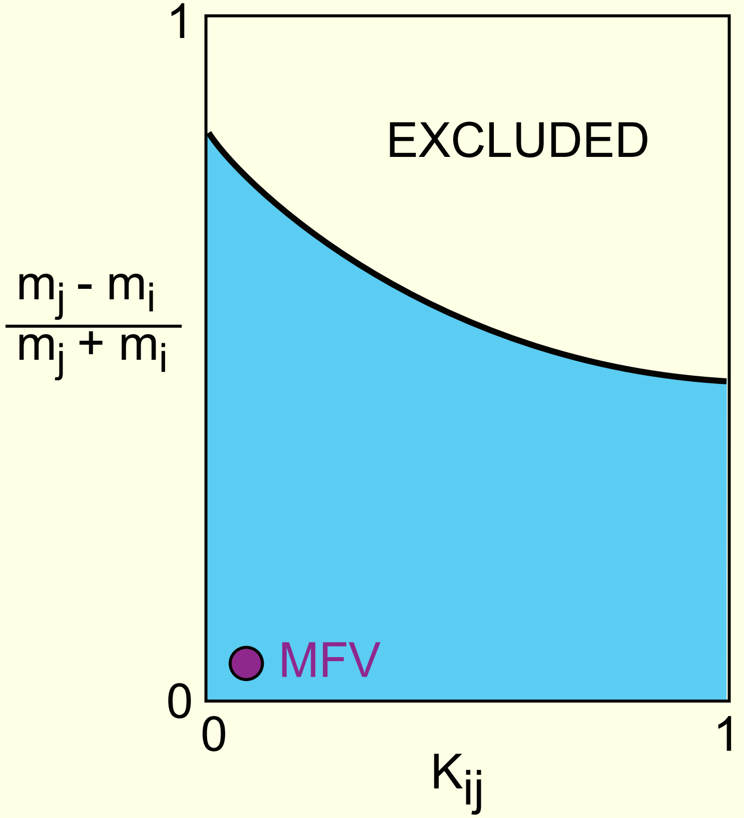
- Most LHC studies employ the CMSSM/mSUGRA ansatz
- A reasonable starting point to understand discovery potential, dark matter constraints, etc.
- To my opinion, not a good starting point to study flavor

Beyond CMSSM:

- FCNC imply $(\Delta\tilde{m}_{ij}^2/\tilde{m}^2)K_{ij} \leq \ldots$
- Natural and well-motivated SUSY models span the entire allowed $(\Delta\tilde{m}_{ij}^2/\tilde{m}^2) - K_{ij}$ plane

SUSY flavor can be rich and informative

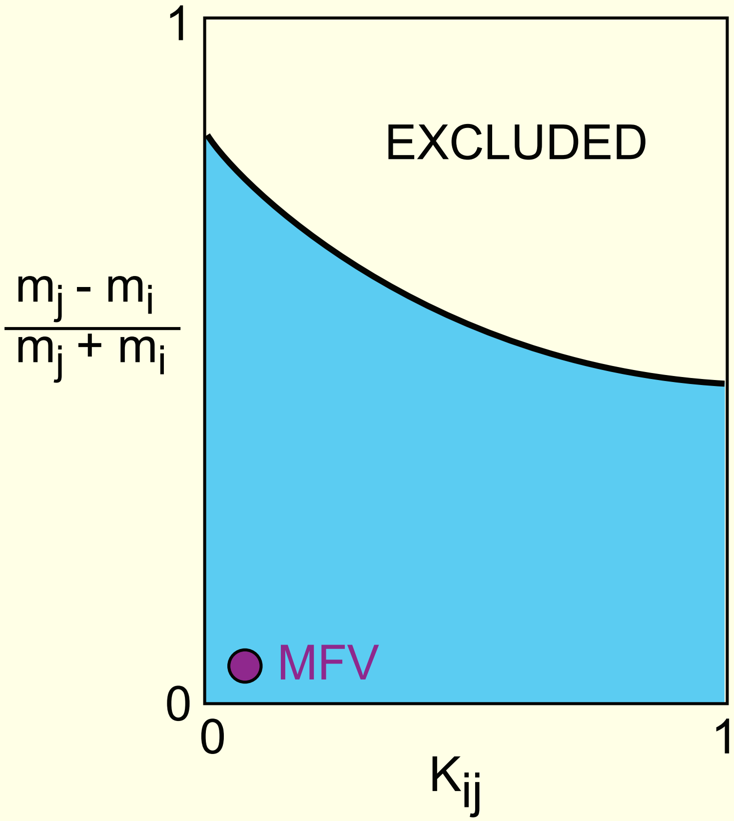
The SUSY flavor plane



Flavor factories

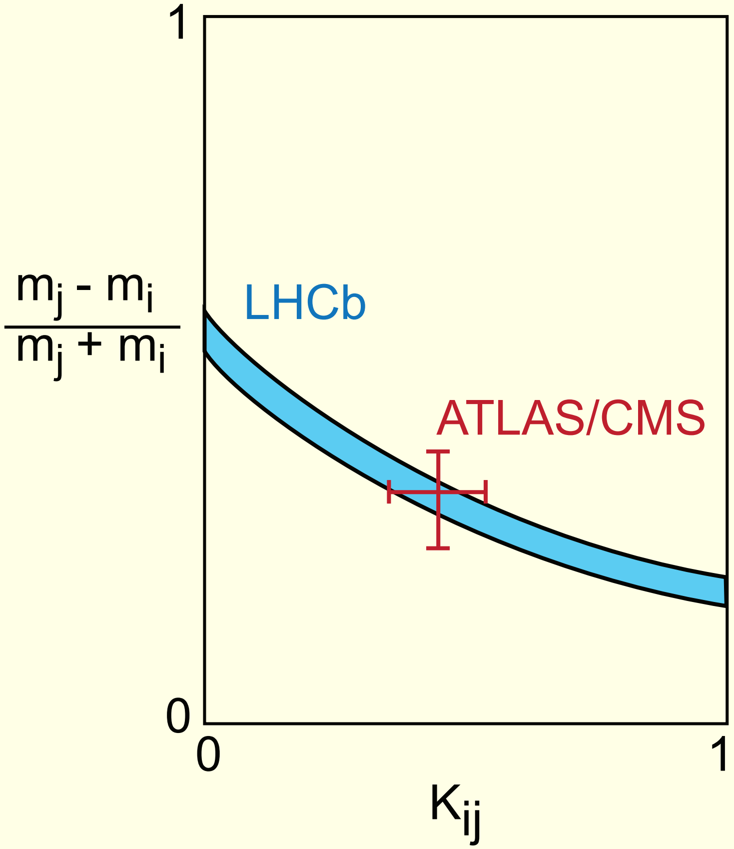
MFV

The SUSY flavor plane



Flavor factories

MFV



+ATLAS/CMS

Non-MFV

Gauge-gravity hybrid models

1. Gauge-mediated contributions are universal:
   $(\tilde{m}_L^2)_{ij}^{\rm gauge} \sim N_m(\alpha_2/\pi)^2(F/M_m)^2\delta_{ij}$
2. In general, gravity-mediated contributions are not:
   $(\tilde{m}_L^2)_{ij}^{\rm gravity} \sim (F/M_{\rm Pl})^2 X_{ij}^L$

$$\Longrightarrow \frac{\Delta m_{\tilde{L}}^2}{m_{\tilde{L}}^2} \sim N_m^{-1}\left(\frac{\alpha_2}{\pi}\right)^{-2}\left(\frac{M_m}{M_{\rm Pl}}\right)^2$$

The slepton mass splitting can be anywhere between $m_\ell^2/m_{\tilde{\ell}}^2$ and 1

Super-FN models

- The mechanism that generates the structure in the SM Yukawas is likely to affect the structure of the gravity mediated soft terms
- With the Froggatt-Nielsen mechanism:

1. $(Y_E)_{ij} \propto \epsilon^{H(L_i)+H(\bar{E}_j)}$
2. $(X_E)_{ii} \sim 1$, $(X_E)_{ij} \sim \epsilon^{H(\bar{E}_i)-H(\bar{E}_j)}$

$$\Longrightarrow K^{\tilde{\gamma}}_{ij} \sim \begin{cases} \epsilon^{H(\bar{E}_i)-H(\bar{E}_j)} & \text{gravity/gauge} > m_\ell^2/m_{\text{susy}}^2 \\ 0 & \text{gravity/gauge} < m_\ell^2/m_{\text{susy}}^2 \end{cases}$$

$\tilde{E}_L$ mixing – anywhere between 0 and $\sim U_{ij}$
$\tilde{E}_R$ mixing – anywhere between 0 and $\sim \frac{m_i/m_j}{U_{ij}}$

SUSY Flavor @ LHC

Feng, Lester, Nir, Shadmi, arXiv:0712.0674

Unusual SUSY collider phenomenology

In our framework:

- LSP = gravitino (for $x < 1$)
- NLSP = charged slepton (for $N_m \gtrsim 2$)
- NLSP long lived: $\tau \simeq 16 \text{ hours } \left(\frac{m_{\tilde{G}}}{GeV}\right)^2 \left(\frac{100\ GeV}{m_{\tilde{E}_R}}\right)^5$

$$\Downarrow$$

- Fully reconstructible events (no missing energy!)
- Slepton traps $\Longrightarrow$ new opportunities
- Slepton mass and lifetime $\Longrightarrow m_{\tilde{G}},\ F$

Measuring slepton mass splittings

$$\frac{\Delta m^2_{\tilde{L}}}{m^2_{\tilde{L}}} \sim N_m^{-1} \left(\frac{\alpha_2}{\pi}\right)^{-2} \left(\frac{M_m}{M_{\rm Pl}}\right)^2$$

If ATLAS/CMS measure the level of degeneracy,
we will learn about...

- The gravity ↔ gauge balance
- $\Delta m^2_{\tilde{L}}/m^2_{\tilde{L}} \implies M_m$
- How is the supersymmetric flavor problem solved?

Measuring slepton mixings

$$K_{ij}^{\tilde{\gamma}} \sim \text{or} \ll (m_i/m_j)/U_{ij}?$$

If ATLAS/CMS measure the flavor decomposition,
we will learn about...

- The seesaw scale vs the supersymmetry breaking scale
- $K_{ij} \implies H(E_i) - H(E_j)$
- How is the SM flavor problem solved?

Minimal Flavor Violation

Grossman, Nir, Thaler, Volansky, Zupan, arXiv:0706.1845

Hiller, Nir, arXiv:0802.0916

MFV

A class of NP models where...

- The only violation of the global $[SU(3)]^3_q$ symmetry $=$ The Yukawa-spurions: $Y_U(3,\bar{3},1), \quad Y_D(3,1,\bar{3})$
- 'Solution' to the NP flavor puzzle
- Examples: gauge-, anomaly-, gaugino-mediated supersymmetry breaking
- The NP is subject to an approximate $[SU(2)]^3$ symmetry
- All FC processes $\propto \; V_{\mathrm{CKM}}$

Apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

$V_{\rm CKM} =$

$$\begin{pmatrix} 0.97383 \pm 0.00024 & 0.2272 \pm 0.0010 & (3.96 \pm 0.09) \times 10^{-3} \\ 0.2271 \pm 0.0010 & 0.97296 \pm 0.00024 & (4.221^{+0.010}_{-0.080}) \times 10^{-2} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (4.161^{+0.012}_{-0.078}) \times 10^{-2} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

Apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

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- The CKM matrix a-la ATLAS/CMS:

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

MFV predictions: Mixing

- The only source of mixing – the CKM matrix:

$$V_{\rm CKM}^{\rm LHC} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

New particles will decay to either 3rd generation or non-3rd generation quarks but not to both

- ATLAS/CMS can exclude MFV by observing $\mathrm{Br}(q_3) \sim \mathrm{Br}(q_{1,2})$
- Examples of new particles: vector-like quarks; squarks...

Conclusions

- Consistency of flavor precision measurements at $E_{\rm exp} \sim GeV$ with SM poses a problem to NP at $\Lambda_{\rm NP} \sim TeV$
- If new particles are discovered –
  New flavor parameters will be measured
- The parameters of interest: M, BR$(\to f_3, f_l)$, $\sigma_{\rm prod}$
- Rare decays constrain $(\Delta m_{ij}/m) \times K_{ij}$;
  ATLAS/CMS can measure Δm_{ij} and K_{ij} separately
- The NP flavor puzzle may be understood
- MFV can, in principle, be excluded
- With supersymmetry: The SM flavor puzzle may be solved