Flavor Physics: Past, Present, Future

Indirect Searches for NP at the Time of LHC
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Plan of Talk

1. Introduction
2. Past: What have we learned?
   Lessons from the B-factories
3. Present: Open questions
   - The NP flavor puzzle
   - The SM flavor puzzle
4. Future: What will we learn?
   Flavor@LHC

Introduction

Why is flavor physics interesting?

- Flavor physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiment}$
  FCNC suppressed within the SM by $\alpha_W^n, |V_{ij}|, m_f$
- 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 solution $\Longrightarrow$ Clues for the subtle structure of the NP

A brief history of FV

- $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu) \implies$ 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]

Flavor@GeV $\Longrightarrow$ NP@TeV

A recent example [Blum et al, PRL 102, 211802 (2009)]

- $\frac{\Delta m_K}{m_K} = (7.01 \pm 0.01) \times 10^{-15}; \quad \epsilon_K = (2.23 \pm 0.01) \times 10^{-3}$
- $\frac{\Delta m_D}{m_D} = (8.6 \pm 2.1) \times 10^{-15}; \quad A_\Gamma = (1.2 \pm 2.5) \times 10^{-3}$
- Consider $\frac{1}{\text{TeV}^2}\left[\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj}\right]^2$
- Take $Y_d = \lambda_d, \quad Y_u = V^\dagger \lambda_u, \quad X_Q = V_d^\dagger \text{diag}(\lambda_1, \lambda_2) V_d$
- $K + D \implies$ Degeneracy: $\lambda_2 - \lambda_1 \leq 0.004 - 0.0005$
  - Supersymmetry: $\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq 0.27 - 0.034$
  - RS-I: $\sqrt{\frac{\text{TeV}}{m_{\text{KK}}}} f_{Q_2} \lesssim 0.06 - 0.02.$

Why is CPV interesting?

- Within the SM, a single CP violating parameter η:
  In addition, QCD = CP invariant ($\theta_{\rm QCD}$ irrelevant)
  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector

- η cannot explain the baryon asymmetry – a puzzle:
  There must exist new sources of CPV
  Electroweak baryogenesis? (Testable at the LHC)
  Leptogenesis? (Window to $\Lambda_{\rm seesaw}$)

A brief history of CPV

- $1964-2000$
  - $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.67 \pm 0.26) \times 10^{-3}$

A brief history of CPV

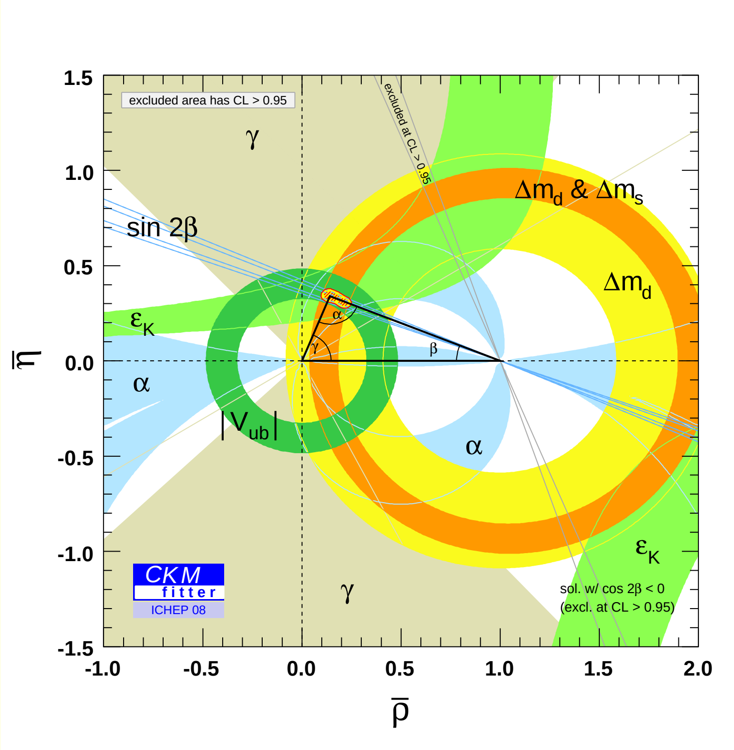
- 1964 – 2000
  - $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.67 \pm 0.26) \times 10^{-3}$
- 2000 – 2010
  - $S_{\psi K_S} = +0.67 \pm 0.02$
  - $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{\pi^0 K_S} = +0.57 \pm 0.17$, $S_{f_0 K_S} = +0.60 \pm 0.12$
  - $S_{K^+K^-K_S} = -0.82 \pm 0.07$, $S_{K_S K_S K_S} = +0.74 \pm 0.17$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.89 \pm 0.26$, $S_{D^*D^*} = -0.77 \pm 0.14$
  - $\mathcal{A}_{K^\mp\rho^0} = +0.37 \pm 0.11$, $\mathcal{A}_{\eta K^\mp} = -0.37 \pm 0.09$, $\mathcal{A}_{f_2 K^\mp} = -0.68 \pm 0.20$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $\mathcal{A}_{\eta K^{*0}} = +0.19 \pm 0.05$
  - ...

What have we learned?

Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
- λ known from $K \to \pi\ell\nu$
  A known from $b \to c\ell\nu$
- Many observables are $f(\rho, \eta)$:
  - $b \to u\ell\nu \implies \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \implies \propto |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - $S_{\psi K_S} \implies \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
  - $S_{\rho\rho}(\alpha)$
  - $\mathcal{A}_{DK}(\gamma)$
  - ϵ_K

The B-factories Plot



CKMFitter

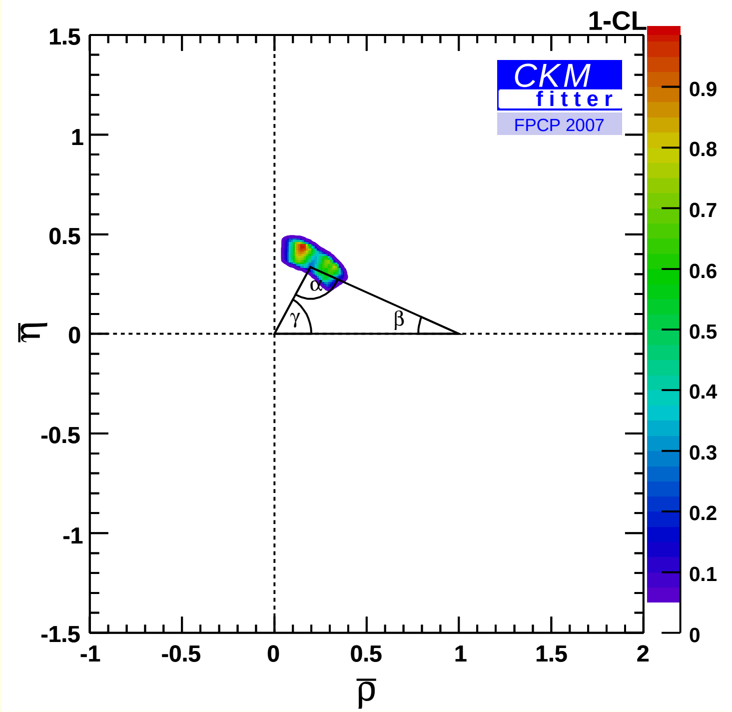
Very likely, the CKM mechanism dominates FV and CPV

Testing CKM - take II

- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Use only tree decays and $B^0 - \overline{B}^0$ mixing
- Define $h_d e^{2i\sigma_d} = \frac{A^{\rm NP}(B^0 \to \overline{B})}{A^{\rm SM}(B^0 \to \overline{B})}$
- 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

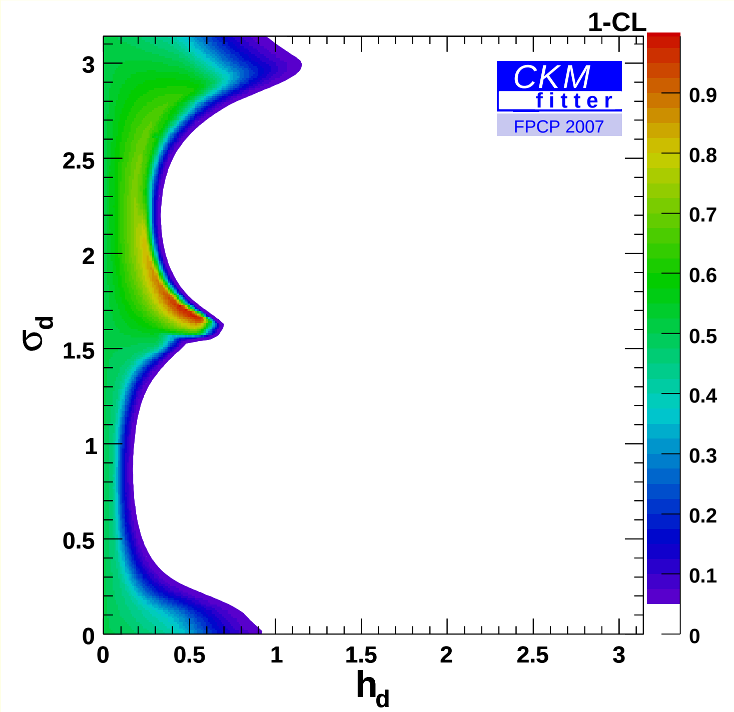
What have we learned?

$\eta \neq 0$?



- The KM mechanism is at work

$h_d \ll 1?$



- The KM mechanism dominates CP violation
- The CKM mechanism is a major player in flavor violation

Intermediate summary

- The KM phase is different from zero (SM violates CP)
- The KM mechanism is the dominant source of the CP violation observed in meson decays
- Complete alternatives to the KM mechanism are excluded (Superweak, Approximate CP)

- No evidence for corrections to CKM
- NP contributions to the observed FCNC are at most comparable to the CKM contributions
- NP contributions are very small in $s \to d$, $c \to u$, $b \to d$, $b \to s$

The NP Flavor Puzzle

The SM = Low energy effective theory

1. Gravity $\Longrightarrow \Lambda_{\text{Planck}} \sim 10^{19}\ GeV$
2. $m_\nu \neq 0 \Longrightarrow \Lambda_{\text{Seesaw}} \leq 10^{15}\ GeV$
3. m_H^2-fine tuning; Dark matter $\Longrightarrow \Lambda_{\text{NP}} \sim\ TeV$

$$\Downarrow$$

- The SM = Low energy effective theory
- Must write non-renormalizable terms suppressed by $\Lambda_{\text{NP}}^{d-4}$
- $\mathcal{L}_{d=5} = \frac{y_{ij}^\nu}{\Lambda_{\text{seesaw}}} L_i L_j \phi\phi$
- $\mathcal{L}_{d=6}$ contains many flavor changing operators

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:

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

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

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

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

Some data

$\Delta m_K/m_K$	7.0×10^{-15}
$\Delta m_D/m_D$	8.7×10^{-15}
$\Delta m_B/m_B$	6.3×10^{-14}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}
ϵ_K	2.3×10^{-3}
$A_\Gamma/y_{\rm CP}$	≤ 0.2
$S_{\psi K_S}$	0.67 ± 0.02
$S_{\psi\phi}$	≤ 1

High Scale?

- For $z_{ij} \sim 1$ (and $\mathcal{I}m(z_{ij}) \sim 1$), $\Lambda_{\rm NP} \gtrsim \frac{10^{-4}}{\sqrt{\Delta m/m}}\ TeV$

Mixing	$\Lambda_{\rm NP}^{\rm CPC} \gtrsim$	$\Lambda_{\rm NP}^{\rm CPV} \gtrsim$
$K-\overline{K}$	1000 TeV	20000 TeV
$D-\overline{D}$	1000 TeV	3000 TeV
$B-\overline{B}$	400 TeV	800 TeV
$B_s-\overline{B_s}$	70 TeV	70 TeV

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Did we misinterpret the Higgs fine tuning problem?

Did we misinterpret the dark matter puzzle?

Small (hierachical?) flavor parameters?

- For $\Lambda_{\rm NP} \sim 1\ TeV$, $z_{ij} \lesssim 10^8(\Delta m_{ij}/m)$

Mixing	$\lvert z_{ij}\rvert \lesssim$	$\mathcal{I}m(z_{ij}) \lesssim$
$K-\overline{K}$	8×10^{-7}	6×10^{-9}
$D-\overline{D}$	5×10^{-7}	1×10^{-7}
$B-\overline{B}$	5×10^{-6}	1×10^{-6}
$B_s-\overline{B_s}$	2×10^{-4}	2×10^{-4}

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The flavor structure of NP@TeV must be highly non-generic

How? Why? = The NP flavor puzzle

Minimal flavor violation (MFV)

- MFV = the only source of FV are the SM Yukawa matrices
- MFV $\Longrightarrow$ NP@TeV scale is consistent with FCNC constraints
- Most likely, an approximation
- Predictions:
  - Spectrum: often MFV implies degeneracies
  - Mixing: the third generation is approximately decoupled
- Example: Gauge mediated supersymmetry breaking
  - Squark spectrum: $2+1$
  - Squark decays: $\tilde{q}_{1,2} \to q_{1,2}, \quad \tilde{q}_3 \to q_3$
- In principle, testable in ATLAS/CMS

The SM Flavor Puzzle

Smallness and Hierarchy

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

- 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
- Why? = The SM flavor puzzle

The Froggatt-Nielsen (FN) mechanism

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

$$\Downarrow$$

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

$$+$$

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

Testing FN with Neutrinos

- The data:
  - $\Delta m^2_{21} = (7.9\pm0.3)\times10^{-5}\ eV^2, \quad |\Delta m^2_{32}| = (2.6\pm0.2)\times10^{-3}\ eV^2$
  - $\sin^2\theta_{12} = 0.31 \pm 0.02, \quad \sin^2\theta_{23} = 0.47 \pm 0.07, \quad \sin^2\theta_{13} = 0^{+0.08}_{-0.0}$
- The tests:
  - $s_{23} \sim 1, \quad m_2/m_3 \sim \epsilon^x$?
    Inconsistent with FN
  - $s_{23} \sim 1, \quad s_{12} \sim 1, \quad s_{13} \sim \epsilon^x$?
    Inconsistent with FN
  - $\sin^2 2\theta_{23} = 1 - \epsilon^x$?
    Inconsistent with FN

Neutrino Mass Anarchy

- Facts:
  - $\sin\theta_{23} \sim 0.70 >$ any $|V_{ij}|$
  - $\sin\theta_{12} \sim 0.56 >$ any $|V_{ij}|$
  - $m_2/m_3 \gtrsim 1/6 >$ any m_i/m_j for charged fermions
  - $\sin\theta_{13} \sim 0.1$ is still possible
- Possible interpretation:
  - Neutrino parameters are all of $O(1)$ (no structure):
    Neutrino mass anarchy
  - Consistent with FN
  - Close to GUT+FN predictions:
    $s_{23} \sim \frac{m_s/m_b}{|V_{cb}|} \sim 1; \quad s_{12} \sim \frac{m_d/m_s}{|V_{us}|} \sim 0.2; \quad s_{13} \sim \frac{m_d/m_b}{|V_{ub}|} \sim 0.5$

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.0-0.2 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}$$

- Tribimaximal-ists:

$$|U|_{\rm TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- Anarch-ists:

$$|U|_{\rm anarchy} = \begin{pmatrix} \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \end{pmatrix}$$

What will we learn?

Flavor Physics at the LHC era

ATLAS/CMS will, hopefully, observe NP;

In combination with flavor factories, we may...

- Understand how the NP flavor puzzle is (not) solved
  $\Longrightarrow$ Probe NP at $\Lambda_{\rm NP} \gg TeV$
- Get hints about the solution to the SM flavor puzzle

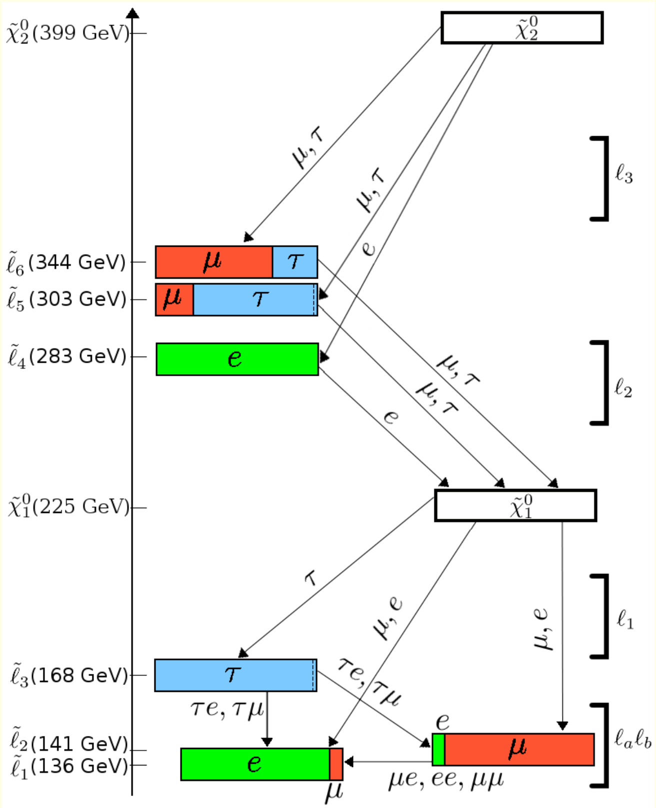
Gauge+Gravity Mediation

- Example: High (but not too high) scale gauge mediation
  - Gravity mediation sub-dominant but non-negligible
  - $r = \frac{\text{gravity}-\text{med}}{\text{gauge}-\text{med}} \sim \left(\frac{m_M}{m_P}\right)^2 \left(\frac{4\pi}{\alpha_3(m_M)}\right)^2 \frac{3}{8n_M}$
  - $\widetilde{M}^2_{\tilde{Q}_L}(m_M) = \tilde{m}^2_{\tilde{Q}_L}(\mathbf{1} + rX_{\tilde{Q}_L})$
  - Degeneracy depends on r

Assume: The flavor structure of X determined by FN:

- $X_{\tilde{Q}_L} \sim \begin{pmatrix} 1 & V_{us} & V_{ub} \\ \cdot & 1 & V_{cb} \\ \cdot & \cdot & 1 \end{pmatrix}; \quad X_{\tilde{D}_R} \sim \begin{pmatrix} 1 & \frac{m_d/m_s}{V_{us}} & \frac{m_d/m_b}{V_{ub}} \\ \cdot & 1 & \frac{m_s/m_b}{V_{cb}} \\ \cdot & \cdot & 1 \end{pmatrix}$
- Mixing depends only on X which is related to the SM flavor

SUSY flavor parameters from $\tilde{\ell}_1, e, \mu$



	True	Measured
$\tilde{\ell}_1$	135.83 GeV	135.9 ± 0.1 GeV
χ_1^0	224.83 GeV	225.10 ± 0.04 GeV
$\Delta m(\tilde{\ell}_{1,2})$	4.95 GeV	5.06 ± 0.06 GeV
$\tilde{\ell}_4$	282.86 GeV	283.1 ± 0.2 GeV
$\tilde{\ell}_5$	303.41 GeV	306 ± 1 GeV
$\tilde{\ell}_6$	343.53 GeV	341 ± 1 GeV
$\lvert U_{2e}/U_{2\mu}\rvert^2$	0.069	0.054 ± 0.008

[Feng, Lester, Nir, Shadmi *et al.*, PRD77(2008)076002; PRD80(2009)114004; JHEP01(2010)047]

Lessons from $\tilde{\ell}_1, e, \mu$

- Determine Δm_{21} and $\sin\theta_{12}$:
  It is consistent with $\mu \to e\gamma$?
  How the SUSY flavor problem is solved

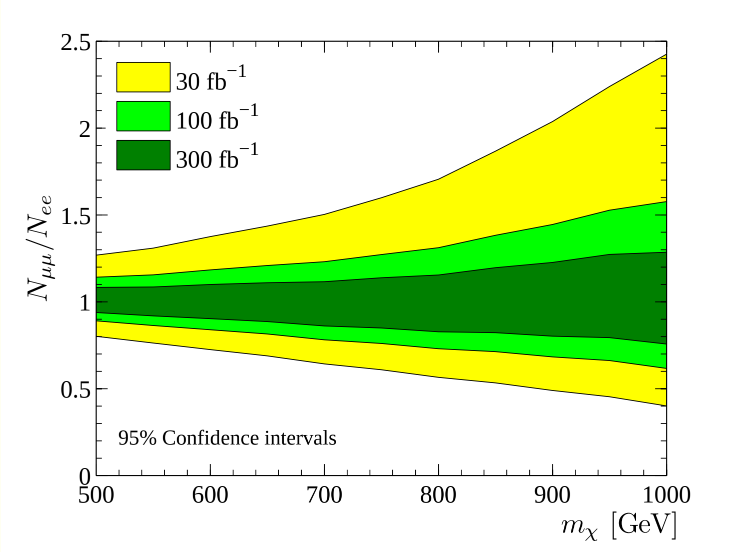
- Determine Δm_{21}, Δm_{54}, . . .:
  What is messenger scale of gauge mediation (M_m)?
  Probe physics at $M_m \sim 10^{15}$ GeV

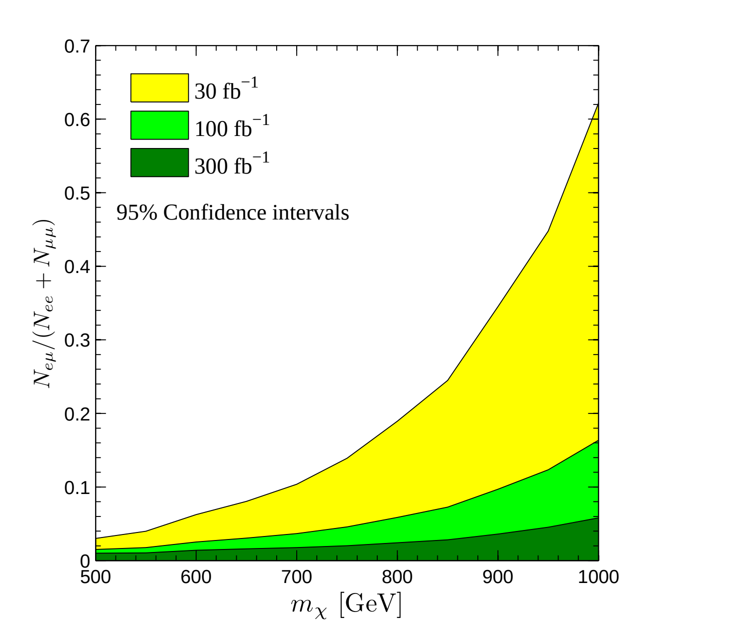
- Detremine $|U_{e2}/U_{\mu 2}|$:
  Is the FN mechanism at work?
  How the SM flavor puzzle is solved

Vector-like leptons and MLFV

- Imagine: Vector-like lepton doublets with $m \lesssim TeV$
  - Avoid large FCNC by MLFV
  - The only LFV comes from $Y^E = \text{diag}(y_e, y_\mu, y_\tau)$
    - The heavy mass spectrum:
      quasi-degeneracy or hierarchy $\propto Y^E$
    - The heavy-to-light couplings:
      universal or hierarchical (affects the lifetimes)
    - The heavy-to-light couplings:
      flavor-diagonal

Vector-like leptons and MLFV





- $N_{ee} \neq N_{\mu\mu}$ and/or $N_{e\mu} \neq 0$:
  Either MLFV with ν-related spurions or non-MLFV
- $N_{ee} = N_{\mu\mu}$ and $N_{e\mu} = 0$: Approximate $U(1)_e \times U(1)_\mu$
  Plus $m_{\chi_e} \approx m_{\chi_\mu}$: Approximate $U(2)_{e\mu}$

[Gross, Grossman, Nir, Vitells, PRD, in press [1001.2883]]

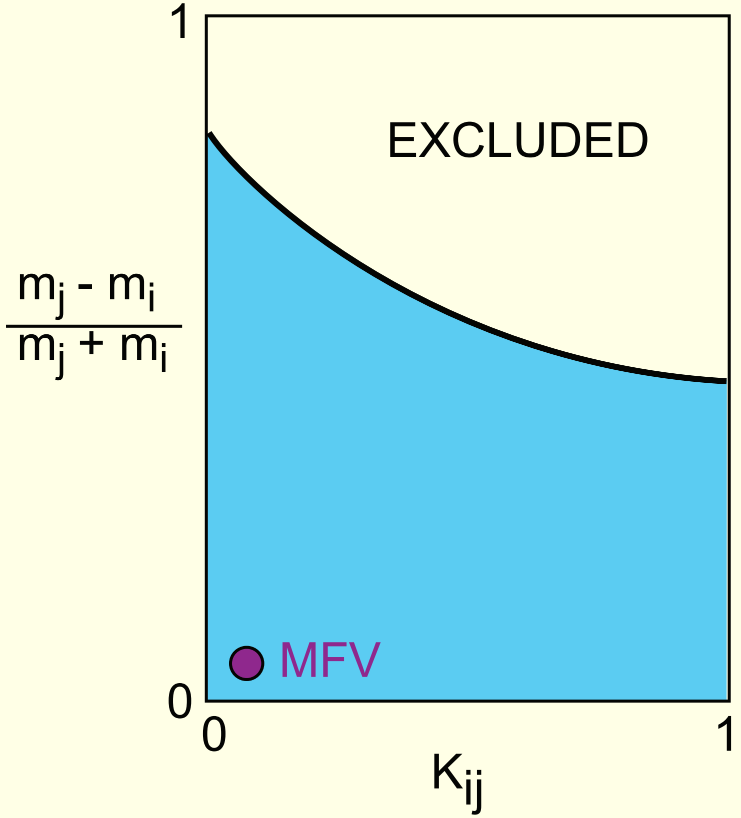
The role of flavor factories (FF)

ATLAS/CMS and flavor factories give complementary information

- In the absence of NP at ATLAS/CMS, flavor factories will be crucial to find $\Lambda_{\rm NP}$
- Consistency between ATLAS/CMS and FF is necessary to understand the NP flavor puzzle
- NP in $c \to u$? $s \to d$? $b \to d$? $b \to s$? $t \to c$? $t \to u$? $\mu \to e$? $\tau \to \mu$? $\tau \to e$?
  - MFV?
  - Structure related to SM?
  - Structure unrelated to SM?
  - Anarchy?

[Hiller, Hochberg, Nir, JHEP0903(09)115; JHEP, in press [1001.1513]]

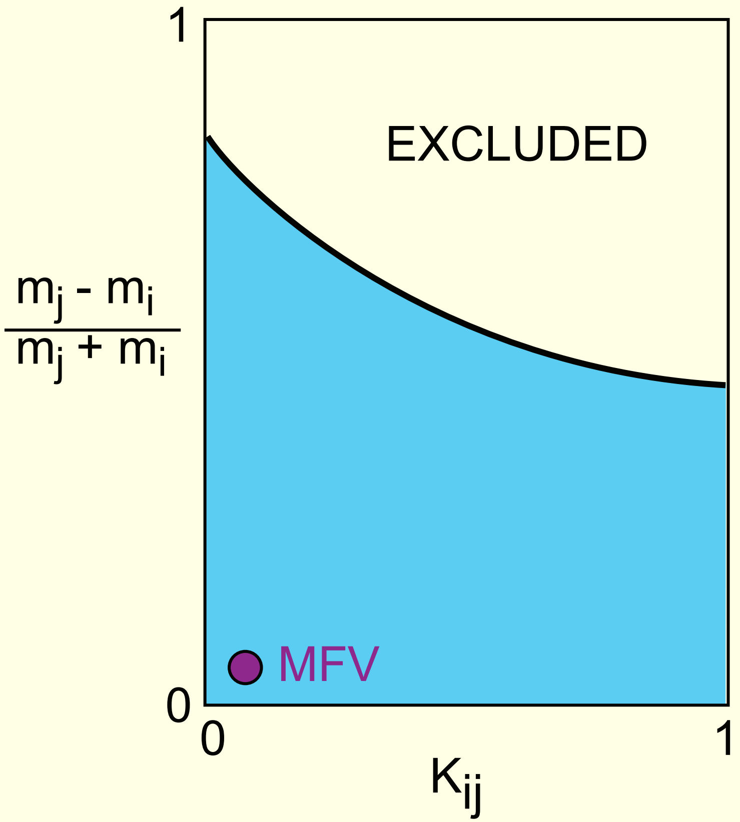
The NP flavor plane



Flavor Factories

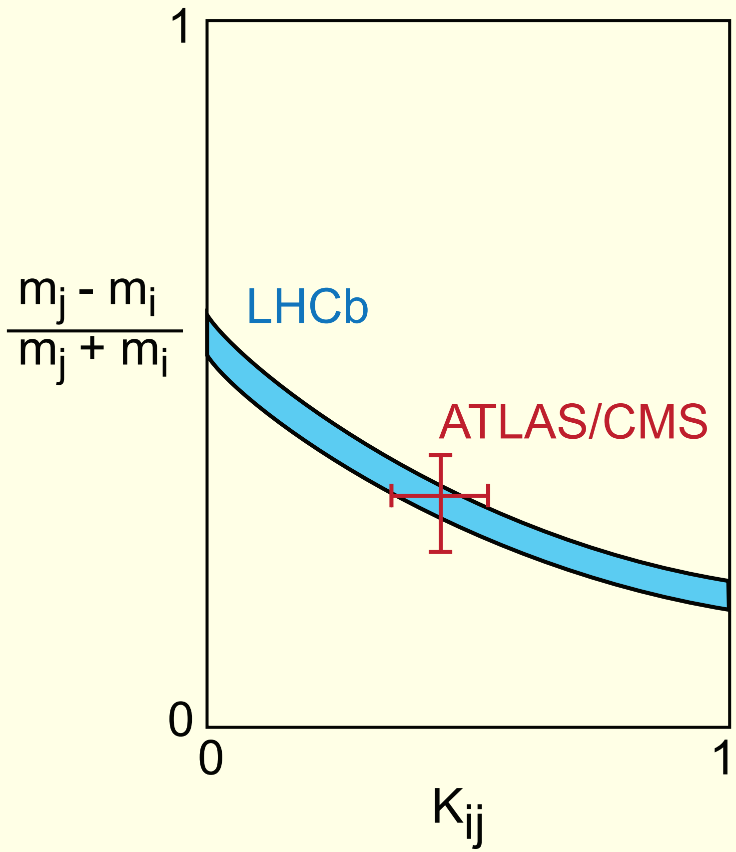
MFV

The NP flavor plane



Flavor Factories

MFV



FF+ATLAS/CMS

Non-MFV

[Grossman, Ligeti, Nir, PTP122(09)125 [0904.4262]]

Kobayashi and Maskawa

The number of real and imaginary quark flavor parameters:

- With two generations:
  $2 \times (4_R + 4_I) - 3 \times (1_R + 3_I) + 1_I = 5_R + 0_I$
- With three generations:
  $2 \times (9_R + 9_I) - 3 \times (3_R + 6_I) + 1_I = 9_R + 1_I$
- The two generation SM is CP conserving
  The three generation SM is CP violating

CP violation = a single imaginary parametr in the CKM matrix:

- V unitary with 3 real (λ, A, ρ) and 1 imaginary (η) parameters:

$$V \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho+i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The FN mechanism: Predictions (quarks)

- In the quark sector: 8 FN charges, 9 observables
- One prediction that is independent of charge assignments:
  $\boxed{|V_{ub}| \sim |V_{us}V_{cb}|}$
  Experimentally correct to within a factor of 2
- In addition, six inequalities:
  $|V_{us}| \gtrsim \frac{m_d}{m_s}, \frac{m_u}{m_c}; \quad |V_{ub}| \gtrsim \frac{m_d}{m_b}, \frac{m_u}{m_t}; \quad |V_{cb}| \gtrsim \frac{m_s}{m_b}, \frac{m_c}{m_t}$
  Experimentally fulfilled
- When ordering the quarks by mass:
  $V_{CKM} \sim \mathbf{1}$ (diagonal terms not suppressed parameterically)
  Experimentally fulfilled

The FN mechanism: Predictions (leptons)

- In the lepton sector: 5 FN charges, 9 observables
- Four predictions that are independent of charge assignments:
  $\boxed{m_{\nu_i}/m_{\nu_j} \sim |U_{ij}|^2}$
  $|U_{e3}| \sim |U_{e2}U_{\mu 3}|$
- In addition, three inequalities:
  $|U_{e2}| \gtrsim \frac{m_e}{m_\mu}; \quad |U_{e3}| \gtrsim \frac{m_e}{m_\tau}; \quad |U_{\mu 3}| \gtrsim \frac{m_\mu}{m_\tau}$
- When ordering the leptons by mass:
  $U \sim \mathbf{1}$

SUSY flavor parameters

	True	Measured	Observation
$\tilde{\ell}_1$	135.83 GeV	135.9 ± 0.1 GeV	direct observation of $\tilde{\ell}_1$ with $0.6 < \beta(\tilde{\ell}_1) < 0.8$
χ_1^0	224.83 GeV	225.10 ± 0.04 GeV	χ_1^0 peak in the $\tilde{\ell}_1^{\pm} e^{\mp}$ invariant mass distribution
$\Delta m(\tilde{\ell}_{1,2})$	4.95 GeV	5.06 ± 0.06 GeV	$\tilde{\ell}_1^{\pm} e^{\mp}$ minus $\tilde{\ell}_1^{\pm} \mu^{\pm}$ peak positions
$\tilde{\ell}_4$	282.86 GeV	283.1 ± 0.2 GeV	peak in $(\tilde{\ell}_1^{\mp} e^{\pm})e$ invariant mass distribution
$\tilde{\ell}_5$	303.41 GeV	306 ± 1 GeV	peak in $(\tilde{\ell}_1^{\mp} e^{\pm})\mu$ invariant mass distribution
$\tilde{\ell}_6$	343.53 GeV	341 ± 1 GeV	peak in $(\tilde{\ell}_1^{\mp} e^{\pm})\mu$ invariant mass distribution
$\lvert U_{2e}/U_{2\mu}\rvert^2$	0.069	0.054 ± 0.008	$N(\tilde{\ell}_1^{\pm} e^{\pm})/N(\tilde{\ell}_1^{\pm} \mu^{\pm})$