Understanding Flavor and CP Violation

Stanford, October 27, 2008
B-Factory Symposium

Yossi Nir (*Weizmann Institute of Science*)

Plan of Talk

1. Introduction
2. What have we learned?
3. Open Questions
   - The SM flavor puzzle
   - The NP flavor puzzle
   - The baryon asymmetry
4. What will we learn?

Introduction

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 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]
- $\Delta m_B \implies m_t > m_W$ [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)]

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

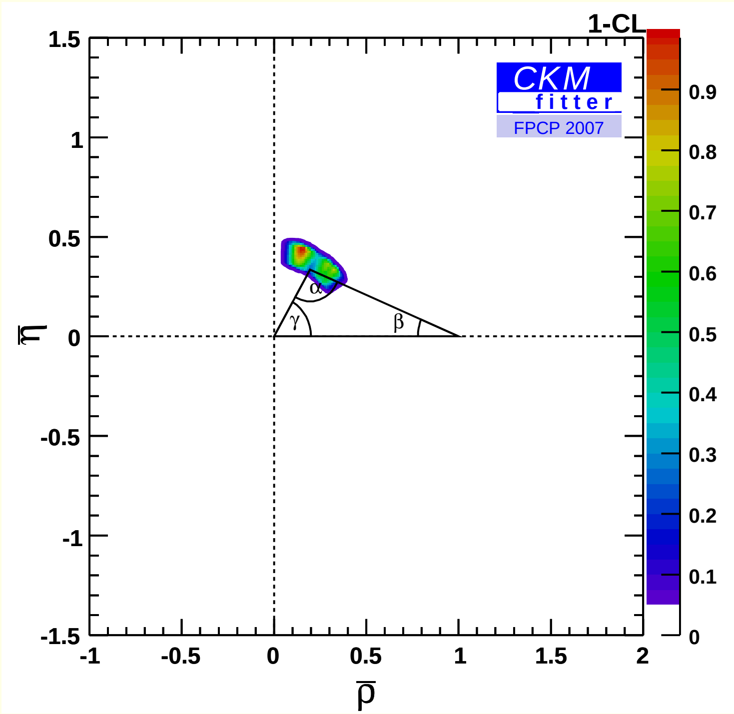
- 1964 – 2000
  - $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$; $\mathcal{R}e\ \varepsilon'/\varepsilon = (1.67 \pm 0.26) \times 10^{-3}$
- 2000 – 2008
  - $S_{\psi K_S} = +0.67 \pm 0.02$
  - $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{\pi^0 K_S} = +0.57 \pm 0.17$,
    $S_{\rho^0 K_S} = +0.63 \pm 0.17$, $S_{f_0 K_S} = +0.62 \pm 0.11$
  - $S_{K^+K^-K_S} = +0.82 \pm 0.07$, $S_{K_S K_S K_S} = +0.74 \pm 0.17$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{D^+D^-} = -0.89 \pm 0.26$
  - $\mathcal{A}_{K^\mp\rho^0} = +0.42 \pm 0.10$, $\mathcal{A}_{\eta K^\mp} = -0.27 \pm 0.09$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $\mathcal{A}_{\eta K^{*0}} = +0.19 \pm 0.05$
  - ...

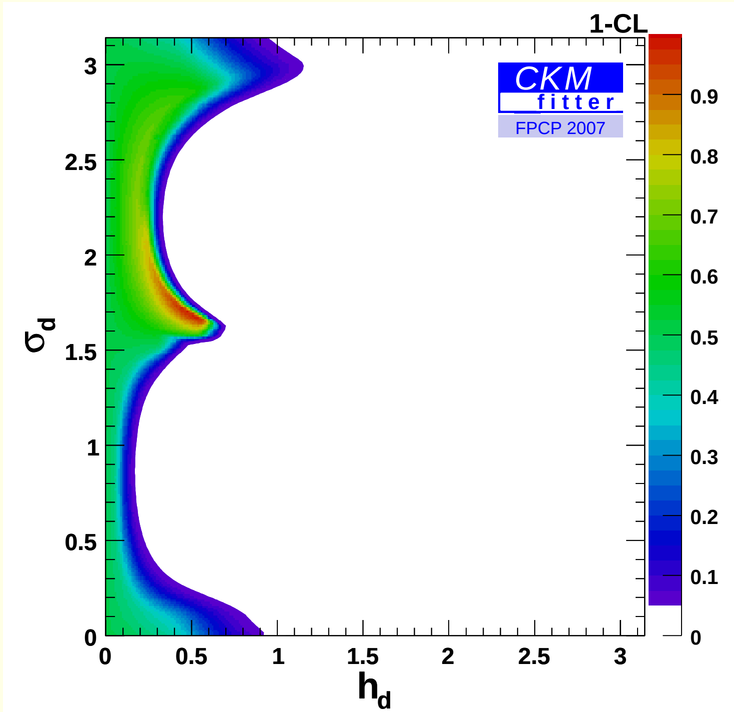
What Have We Learned?

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}, $\mathcal{A}_{\rm SL}^d$
- 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

Is CPV in $K \to \pi\pi$ small because of flavor?

SM:

- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

Is CPV in $K \to \pi\pi$ small because of flavor?

SM:

- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

B Physics: $S_{\psi K} \sim 0.7$

$\Longrightarrow$ Some CP violating phases are indeed $\mathcal{O}(1)$

Is CP violated in $\Delta B = 1$ processes?

SM:

- Indirect (M_{12}) and direct (A_f) CP violations are both large

Superweak:

- There is no direct (A_f) CP violation

K Physics: $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes ($s \to u\bar{u}d$)

Is CP violated in $\Delta B = 1$ processes?

SM:

- Indirect (M_{12}) and direct (A_f) CP violations are both large

Superweak:

- There is no direct (A_f) CP violation

K Physics: $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes ($s \to u\bar{u}d$)

B Physics: $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$,
$\mathcal{A}_{K^\mp\rho^0} = 0.42 \pm 0.10$

$\Longrightarrow$ CP is violated in $\Delta B = 1$ processes ($b \to u\bar{u}s$, $b \to u\bar{u}d$)

What have we learned?

- 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 $s \to d$, $c \to u$, $b \to d$, $b \to s$

Open Questions

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 mechanism

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

$$\Downarrow$$

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

$$+$$

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

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, $\mathrm{loop-factor}$

High Scale?

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

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

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

Small (hierachical?) flavor parameters?

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

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

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

How? Why? = The NP flavor puzzle

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2_{ij}}{\tilde{m}^2} \times K_{ij} \ll 1}$$

Why? = The SUSY flavor puzzle

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2_{ij}}{\tilde{m}^2} \times K_{ij} \ll 1}$$

Why? = The SUSY flavor puzzle

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

MSSM baryogenesis? Leptogenesis?

- MSSM baryogenesis
  - Light stop ($m_{\tilde{t}} < 125\ GeV$)
  - Light Higgs ($m_h < 125\ GeV$)
  - Non-negligible flavor-diagonal phases

$\Longrightarrow$ Testable at the LHC (+ EDMs)

- Leptogenesis
  - Heavy singlet neutrinos ($m_N \geq 10^9\ GeV$)
  - $10^{-3} \leq m_\nu \leq 10^{-1}\ eV$ - preferred
  - No constraint on low energy phases

$\Longrightarrow$ May remain forever an unproven plausible scenario

What will we learn?

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- and flavor factories observe no NP...

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- but flavor factories observe NP...
  - We may have misinterpreted the fine-tuning problem
  - We may have misinterpreted the dark matter puzzle

  - Flavor will provide the only clue for an accessible scale of NP

The NP Flavor Puzzle

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

In combination with flavor factories, we may...

- Understand how the NP flavor puzzle is (not) solved
  - Determine the sfermion mass scale ($\tilde{m}$)
  - Determine the sfermion mass splitting ($m_{\tilde{f}_j} - m_{\tilde{f}_i}$)
  - Determine the sfermion flavor decomposition (K_{ij})

Physics at $\Lambda_{\rm NP} \gg \Lambda_{\rm LHC}$

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

In combination with flavor factories, we may...

- Probe NP at $\Lambda_{\rm NP} \gg TeV$
  - Find the ratio between gravity- and gauge-mediated contributions ($r_{\rm gravity/gauge}$)
  - Determine the messenger scale of gauge mediation (M_m)
  - Find the hierarchy between the GMSB and see-saw scales

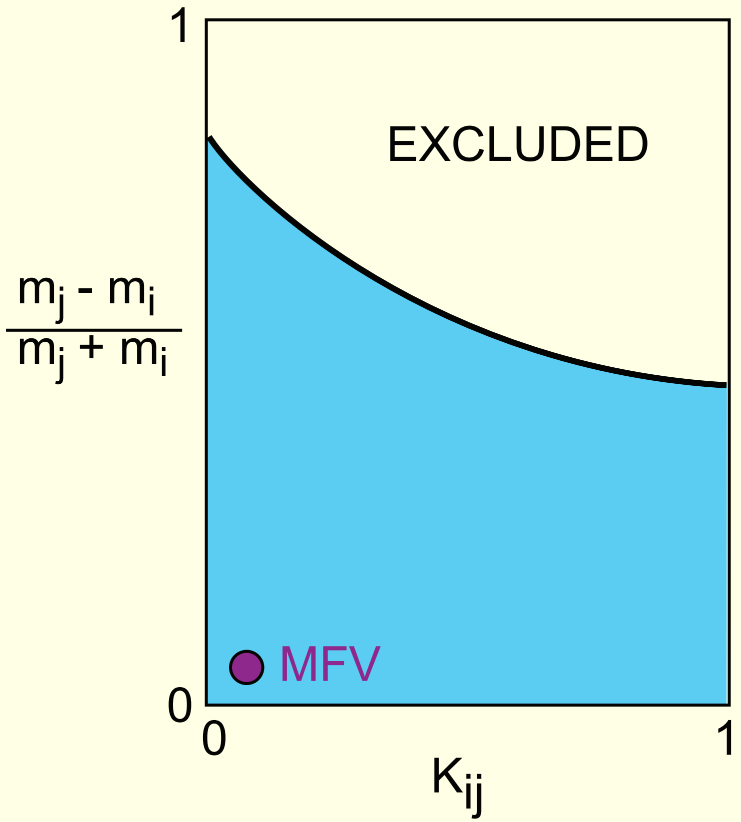
The SM Flavor Puzzle

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

In combination with flavor factories, we may...

- Get hints about the solution to the SM flavor puzzle
  - Assume $\tilde{M}^2 = \tilde{m}^2(\mathbf{1} + r_{\rm gravity/gauge} X)$
  - Mixing determined by X, no matter how small r is
  - It is plausible that X is determined by the FN mechanism
  - Measure mixing $\Longrightarrow$ $\boxed{\text{Test FN}}$

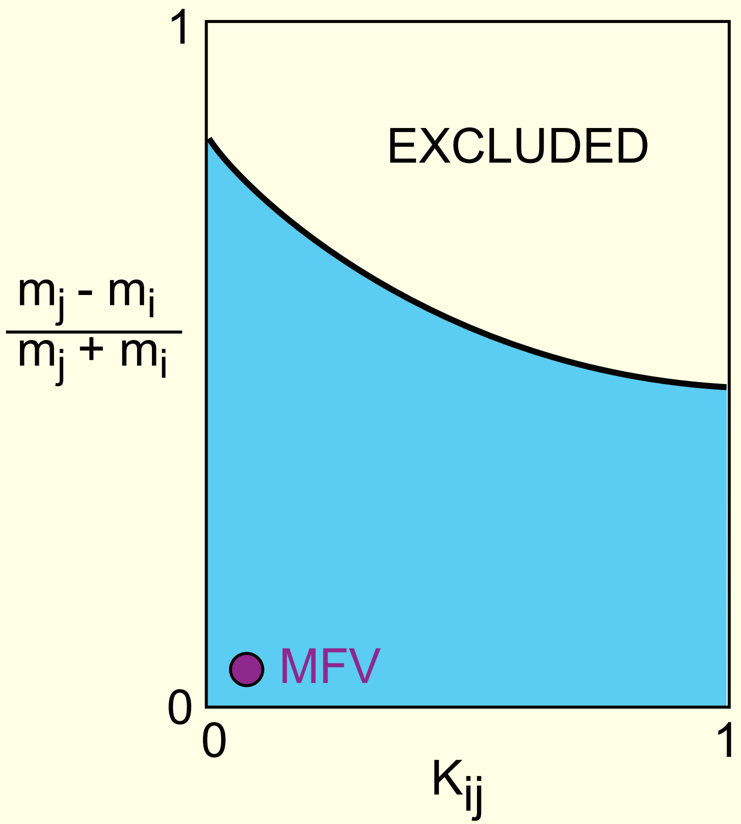
The SUSY flavor plane



Flavor Factories

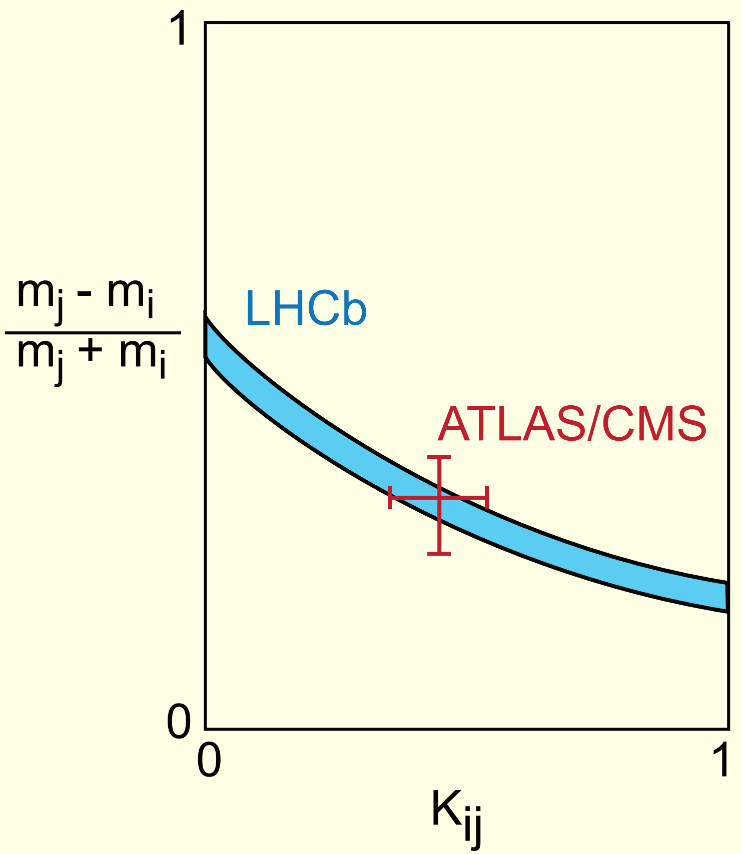
MFV

The SUSY flavor plane



Flavor Factories

MFV



FF+ATLAS/CMS

Non-MFV

What will we learn?

ATLAS/CMS and flavor factories give complementary information

- In the absence of NP at ATLAS/CMS, flavor factories will be crucial to find $\Lambda_{\rm NP}$
- The NP flavor puzzle is likely to be understood
- With supersymmetry: The SM flavor puzzle may be solved
- Flavor can probe physics at $\Lambda_{\rm NP} \gg \Lambda_{\rm LHC}$