Flavor Physics: Past, Present, Future

In celebration of Prof. G. Rajasekaran's 75th birthday

IMSc, Chennai
15 December 2012

Yossi Nir (*Weizmann Institute of Science*)

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

What is flavor?

- Flavors = Several copies of the same gauge quantum charges
- Quarks and leptons come in three flavors
  $(u, c, t),\ (d, s, b),\ (e, \mu, \tau),\ (\nu_1, \nu_2, \nu_3)$
- Flavor physics = Interactions that distinguish among flavors
- In the SM: only the Yukawa and weak (W) interactions
- Flavor parameters = Y_i (m_i), V_{ij} (W-couplings)
- Flavor changing processes: $B \to \psi K (b \to c\bar{c}s)$, $\mu \to e\ell\nu$...
- FCNC: $B^0 \leftrightarrow \bar{B}^0 (\bar{b}d \leftrightarrow b\bar{d})$, $\mu \to e\gamma$, $K \to \pi\nu\bar{\nu}$,...
- Flavor factories: BaBaR, Belle, MEG, LHCb, (CDF, D0)...

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

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
- CDF: $A_{\rm FB}^{t\bar t}(m_{t\bar t} > 450~{\rm GeV}) = +0.48 \pm 0.11$
  SM: $A_{\rm FB}^{t\bar t}(m_{t\bar t} > 450~{\rm GeV}) = +0.09 \pm 0.01$

A brief history of FCNC

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

Why is CPV interesting?

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

Why is CPV interesting?

- SM CPV cannot explain the baryon asymmetry – a puzzle:
  There must exist new sources of CPV
  Electroweak baryogenesis? (Testable at the LHC)
  Leptogenesis? (Window to $\Lambda_{\rm seesaw}$)
- 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
- D0: $A^b_{\rm SL} = (-7.9 \pm 1.7 \pm 0.9) \times 10^{-3}$
  SM: $A^b_{\rm SL} = (-0.23 \pm 0.06) \times 10^{-3}$
- LHCb: $\Delta A_{\rm CP} = (-0.82 \pm 0.21 \pm 0.11) \times 10^{-2}$
  SM: $\Delta A_{\rm CP} \lesssim 10^{-3}$

A brief history of CPV

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

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 – 2011
  - $S_{\psi K_S} = +0.67 \pm 0.02$
  - $S_{\phi K_S} = +0.56 \pm 0.18$, $S_{\eta' K_S} = +0.59 \pm 0.07$,
    $S_{\pi^0 K_S} = +0.57 \pm 0.17$, $S_{f_0 K_S} = +0.62 \pm 0.12$
  - $S_{K^+K^-K_S} = -0.82 \pm 0.07$, $S_{K_S K_S K_S} = +0.74 \pm 0.17$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.89 \pm 0.26$, $S_{D^*D^*} = -0.77 \pm 0.14$
  - $\mathcal{A}_{K^\mp\rho^0} = +0.37 \pm 0.11$, $\mathcal{A}_{\eta K^\mp} = -0.37 \pm 0.09$, $\mathcal{A}_{f_2 K^\mp} = -0.68 \pm 0.20$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $\mathcal{A}_{\eta K^{*0}} = +0.19 \pm 0.05$
  - ...

What have we learned?

Flavor Violation (FV)

- $\mathcal{L}_{\text{kinetic+gauge}}$ has a large global symmetry: $G_{\text{global}} = [U(3)]^5$
- $\mathcal{L}_{\text{Yukawa}} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj} + \overline{L_L}_i Y^e_{ij} \phi E_{Rj}$
  breaks $G_{\text{global}} \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Flavor physics:
  interactions that break the $[SU(3)]^5$ symmetry

$$\Downarrow$$

- $Q_L \to V_Q Q_L, \quad U_R \to V_U U_R, \quad D_R \to V_D D_R$
  $=$ Change of interaction basis
- Can be used to reduce the number of parameters in Y^u, Y^d

Kobayashi and Maskawa (I)

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 parameter in the CKM matrix:

- $\mathcal{L}_W \sim g V_{ij} \bar{u}_{Li} d_{Lj} W^-$

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

Kobayashi and Maskawa (II)

The achievements:

- Predicting the third generation
- Suggesting the correct mechanism of CP violation

$S_{\psi K_S}$

- Babar/Belle: $A_{\psi K_S}(t) = \frac{\frac{d\Gamma}{dt}[\overline{B^0_{\rm phys}}(t)\to\psi K_S]-\frac{d\Gamma}{dt}[B^0_{\rm phys}(t)\to\psi K_S]}{\frac{d\Gamma}{dt}[\overline{B^0_{\rm phys}}(t)\to\psi K_S]+\frac{d\Gamma}{dt}[B^0_{\rm phys}(t)\to\psi K_S]}$

- Theory: $A_{\psi K_S}(t) = S_{\psi K_S}\sin(\Delta m_B t)$

- SM: $\boxed{S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}}$

- The approximations involved are better than one percent!

- Experiments: $S_{\psi K_S} = 0.671 \pm 0.024$

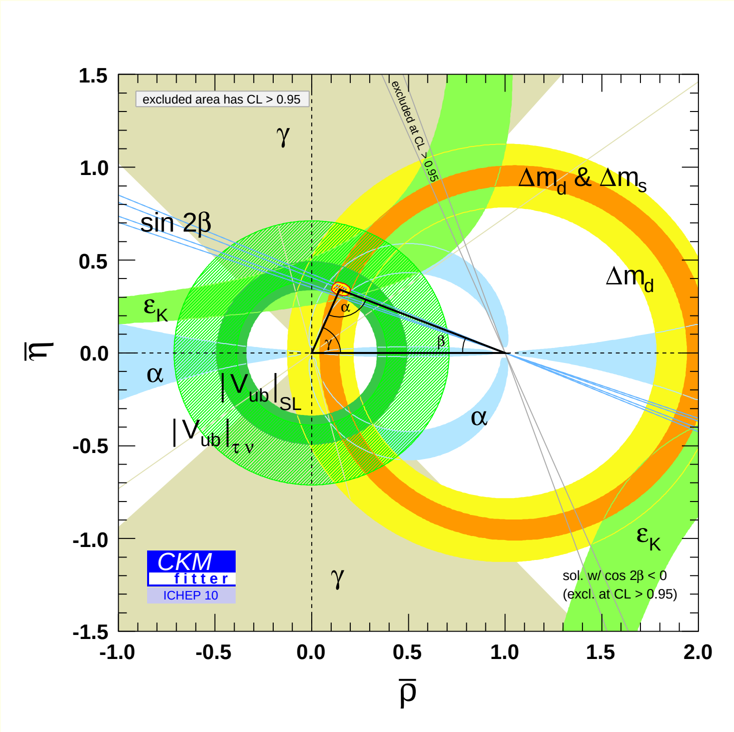
Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
  $\Longrightarrow$ Four CKM parameters: λ, A, ρ, η

- 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

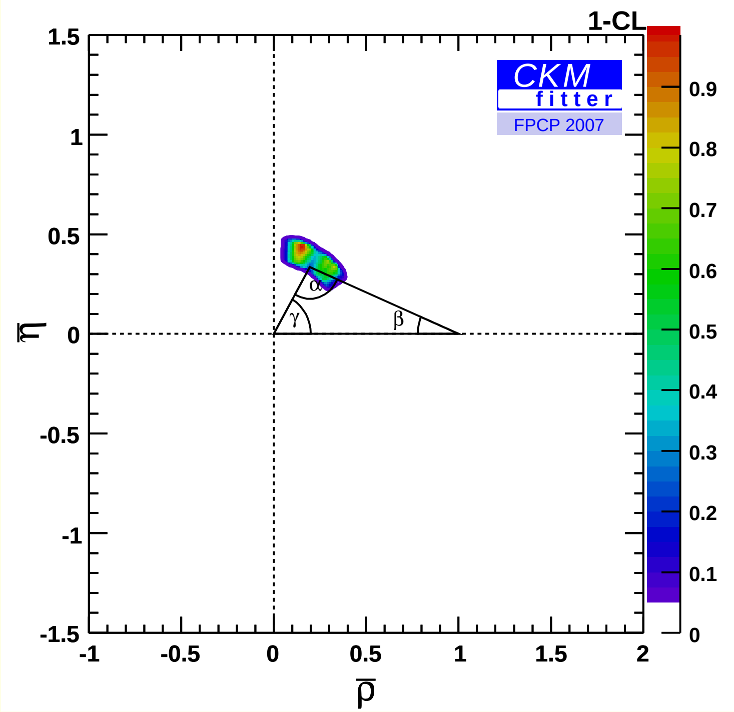
Very likely, the CKM mechanism dominates FV and CPV

Testing CKM - take II

- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Consider only tree decays and $B^0 - \overline{B}^0$ mixing
- Define $h_d e^{2i\sigma_d} = A^{\rm NP}(B^0 \to \overline{B})/A^{\rm SM}(B^0 \to \overline{B})$
  $\Longrightarrow$ Four parameters: ρ, η (CKM), h_d, σ_d (NP)
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}^d$
- Fit to η, ρ, 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

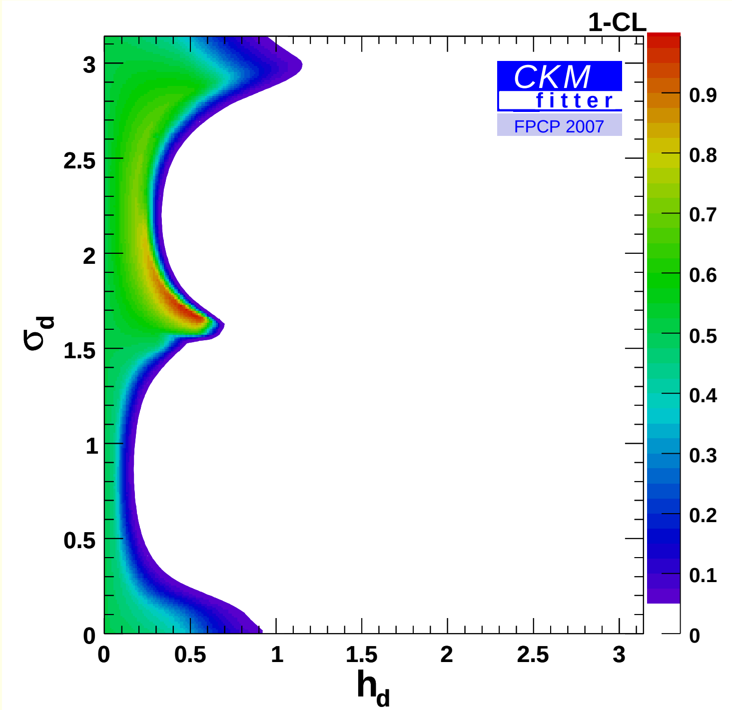
What have we learned?

$\eta \neq 0?$



- 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

Several $\sim 3\sigma$ tensions

- $S_{\psi K}$ vs. $\sin 2\beta$ from global fit
- $\mathrm{BR}(B \to \tau\nu)$ vs. prediction from global fit
- A^b_{SL} vs. (almost) null prediction of the SM
- ΔA_{CP} vs. (almost) null prediction of the SM

Intermediate summary I

- 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)
- CP violation in D, B_s may still hold surprises

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

$$\Downarrow$$

- The SM = Low energy effective theory
- Must write non-renormalizable terms suppressed by $\Lambda_{\rm NP}^{d-4}$
- $\mathcal{L}_{d=5} = \frac{y_{ij}^\nu}{\Lambda_{\rm seesaw}} L_i L_j \phi\phi$
- $\mathcal{L}_{d=6}$ 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, $\rm loop-factor$

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

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

- 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}

Small (hierachical?) flavor parameters?

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

Mixing	$\|z_{ij}\| \lesssim$	$\mathcal{I}m(z_{ij}) \lesssim$
$K-\overline{K}$	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}

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

- How? Why? = The NP flavor puzzle

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: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- SM flavor parameters have structure: smallness + hierarchy
- Why? = The SM flavor puzzle
  - Approximate symmetry? [Froggatt-Nielsen]
  - Strong dynamics? [Nelson-Strassler]
  - Location in extra dimension? [Arkani-Hamed-Schmaltz]
  - ?

Neutrino flavor parameters

- $\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2, \quad |\Delta m^2_{32}| = (2.4 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.02, \quad |U_{\mu 3}| = 0.68 \pm 0.06, \quad |U_{e3}| = 0.15 \pm 0.03$

Neutrino flavor parameters

- $\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2, \quad |\Delta m^2_{32}| = (2.4 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.02, \quad |U_{\mu 3}| = 0.68 \pm 0.06, \quad |U_{e3}| = 0.15 \pm 0.03$

- $|U_{23}| >$ any $|V_{ij}|$; $|U_{12}| >$ any $|V_{ij}| \quad (i \neq j)$
- $m_2/m_3 \gtrsim 1/6 >$ any m_i/m_j for charged fermions

- So far, neither smallness nor hierarchy
- Is neutrino flavor different from charged fermion flavor?

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:

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

Intermediate summary II

- Why is there smallness and hierarchy in the flavor parameters?

- Is there a relation Dirac/Majorana $\Leftrightarrow$ hierarchy/anarchy?
  Is there a relation Dirac/Majorana $\Leftrightarrow$ Abelian/non-Abelian?

- How does new physics at TeV suppress its flavor violation?
  Is the solution related to the previous ones?

What will we learn?

Exploring the unknown

Energy	$0.6 \to 4$ TeV
Distance	$10^{-19} \to 10^{-20}$ m
"Time"	$10^{-11} \to 10^{-13}$ s

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?

- What separates the electroweak scale from the Planck scale?

- What happened at the electroweak phase transition (10^{-11} second after the big bang)?

- What are the dark matter particles?

- How was the baryon asymmetry generated?

- What are the solutions of the flavor puzzles?

Experimentalists: Flavor at ATLAS/CMS???

- ATLAS/CMS are not optimized for flavor

Experimentalists: Flavor at ATLAS/CMS???

- ATLAS/CMS are not optimized for flavor

But...

- They can identify $e, \mu, (\tau)$
- They can tell 3rd generation quarks (b, t) from light quarks

Theorists: Flavor at ATLAS/CMS???

- The scale of flavor dynamics is unknown
- Very likely, it is well above the LHC direct reach

Theorists: Flavor at ATLAS/CMS???

- The scale of flavor dynamics is unknown
- Very likely, it is well above the LHC direct reach

But...

- If new particles that couple to the SM fermions are discovered – $\Longrightarrow$ New flavor parameters can be measured
  - Spectrum (degeneracies?)
  - Flavor decomposition (alignment?)
- 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

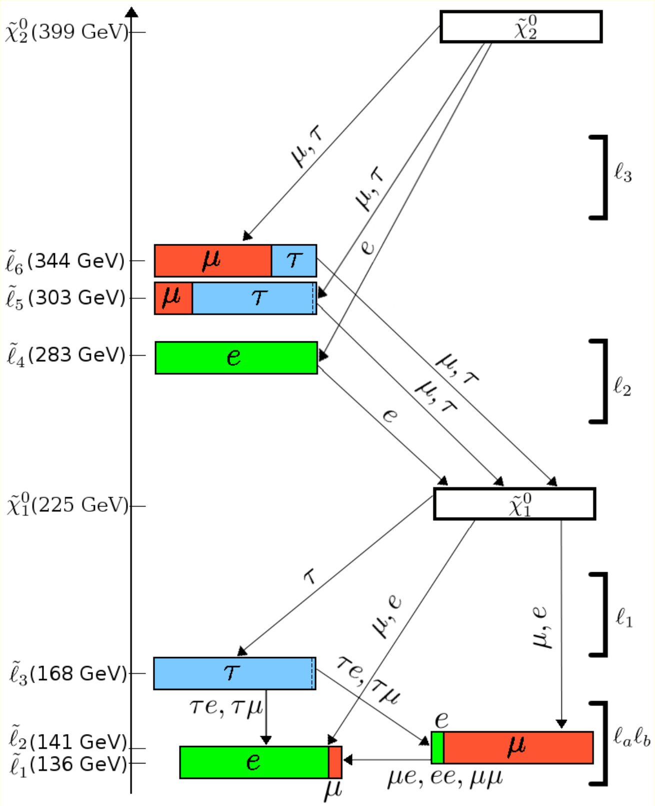
Gauge+Gravity Mediation

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

Assume: The flavor structure of X determined by FN:

- $X_{\tilde{E}_L} \sim \begin{pmatrix} 1 & U_{e2} & U_{e3} \\ \cdot & 1 & U_{\mu 3} \\ \cdot & \cdot & 1 \end{pmatrix}; \quad X_{\tilde{E}_R} \sim \begin{pmatrix} 1 & \frac{m_e/m_\mu}{U_{e2}} & \frac{m_e/m_\tau}{U_{e3}} \\ \cdot & 1 & \frac{m_\mu/m_\tau}{U_{\mu 3}} \\ \cdot & \cdot & 1 \end{pmatrix}$
- 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
$\lvert K_{e2}/K_{\mu 2}\rvert^2$	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
- Determine $|K_{e2}/K_{\mu 2}|$:
  Is the FN mechanism at work?
  How the SM flavor puzzle is solved

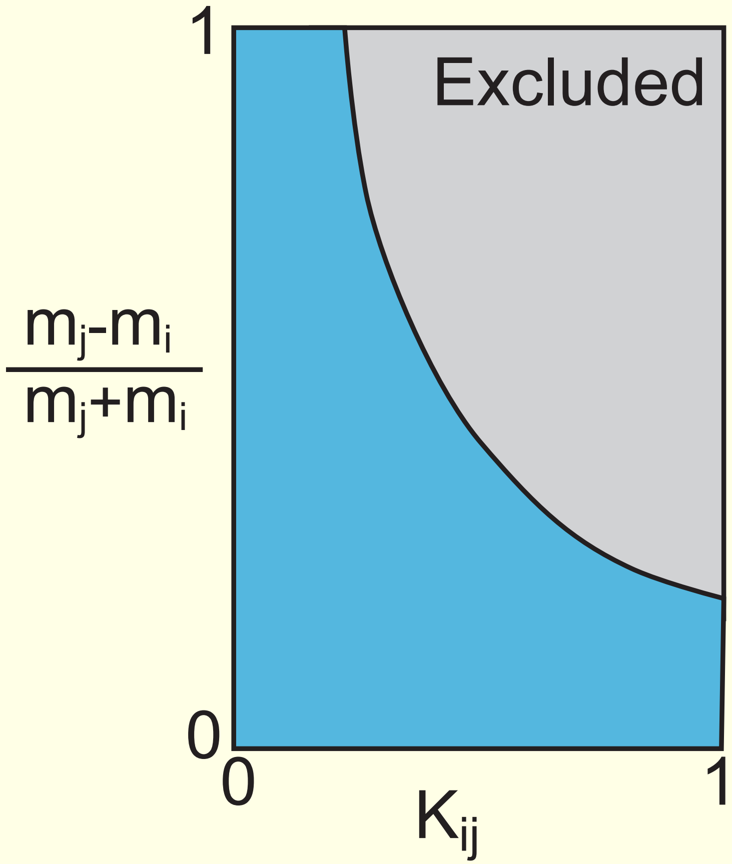
The role of flavor factories (FF)

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:
  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?

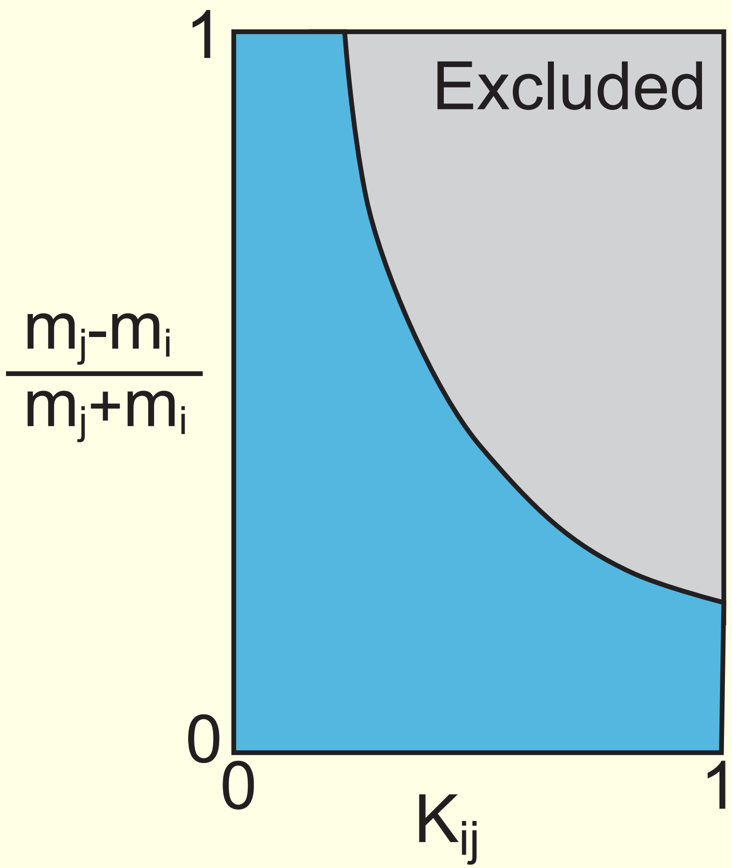
[Hiller, Hochberg, Nir, JHEP0903(09)115; JHEP1003(10)079]]

Summary

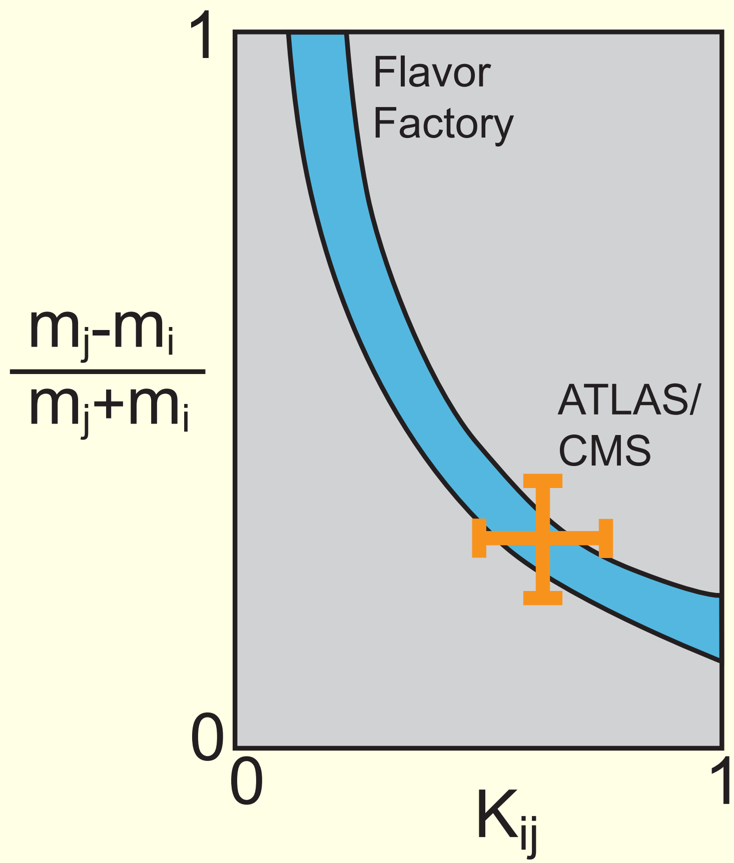


Flavor Factories

Summary



Flavor Factories



FF+ATLAS/CMS

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

Thanks to my flavor collaborators:

Kfir Blum, Jonathan Feng, Sky French, Oram Gedalia,
Eilam Gross, Daniel Grossman, Yuval Grossman,
Gudrun Hiller, Yonit Hochberg, Gino Isidori,
David Kirkby, Christopher Lester, Zoltan Ligeti,
Gilad Perez, Yael Shadmi, Jesse Thaler, Ofer Vitells,
Tomer Volansky, Jure Zupan

Backup Transparencies

$$\boxed{\Delta A_{CP}}$$

Hochberg, Nir, work in progress

Grossman, Kagan, Nir, Phys. Rev. D75 (2007) 036008 [hep-ph/0609178]

Evidence for New Physics

- $\Delta A_{CP} = A(K^+K^-) - A(\pi^+\pi^-)$

  $A_f = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$

- The Standard Model:

  $\Delta A_{CP} \sim \frac{4\alpha_s}{\pi} \mathcal{I}m \frac{V_{ub}^* V_{cb}}{V_{us}^* V_{cs}} \sim 3 \times 10^{-4}$

Evidence for New Physics

- $\Delta A_{CP} = A(K^+K^-) - A(\pi^+\pi^-)$

  $A_f = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$

- The Standard Model:

  $\Delta A_{CP} \sim \frac{4\alpha_s}{\pi} \mathcal{I}m \frac{V_{ub}^* V_{cb}}{V_{us}^* V_{cs}} \sim 3 \times 10^{-4}$

- LHCb:

  $$\boxed{\Delta A_{CP} = -(0.82 \pm 0.21 \pm 0.11) \times 10^{-2}}$$

  [LHCb, arXiv:1112.0938]

Direct CP Violation

- $\Delta A_{CP}(\mathrm{LHCb}) =$
  $a_{CP}^{\mathrm{dir}}(K^+K^-) - a_{CP}^{\mathrm{dir}}(\pi^+\pi^-) + (0.098 \pm 0.029)a^{\mathrm{ind}}$
- $a^{\mathrm{ind}} = (-0.03 \pm 0.23) \times 10^{-2}$

Direct CP Violation

- $\Delta A_{CP}(\text{LHCb}) =$
  $a_{CP}^{\text{dir}}(K^+K^-) - a_{CP}^{\text{dir}}(\pi^+\pi^-) + (0.098 \pm 0.029)a^{\text{ind}}$
- $a^{\text{ind}} = (-0.03 \pm 0.23) \times 10^{-2}$
- $\Longrightarrow$ Direct CP violation:
  $a^{\text{dir}}(f) = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$
- $A_f = A_T(1 + r_f e^{+i\phi_f} e^{+i\delta_f}), \quad \bar{A}_f = A_T(1 + r_f e^{-i\phi_f} e^{+i\delta_f})$
  $\Longrightarrow \ a^{dir}(f) \approx 2r_f \sin\phi_f \sin\delta_f$
- $r_f \sim 10^{-2}$ is required

  Grossman, Kagan, Nir, Phys. Rev. D75 (2007) 036008 [hep-ph/0609178]
- Often strong constraints from $D^0 - \overline{D}^0$ mixing or ϵ'/ϵ

$$\boxed{A^b_{\rm SL}}$$

Blum, Hochberg, Nir, JHEP 09 (2010) 035

Evidence for New Physics

- $A^b_{\rm SL} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$
- The Standard Model:

  $A^b_{\rm SL} = -(2.8 \pm 0.5) \times 10^{-4}$

  [Lenz and Niesrte, JHEP 0706, 072 (2007)]

Evidence for New Physics

- $A^b_{\mathrm{SL}} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$
- The Standard Model:

  $A^b_{\mathrm{SL}} = -(2.8 \pm 0.5) \times 10^{-4}$

  [Lenz and Niesrte, JHEP 0706, 072 (2007)]

- D0:

  $\boxed{A^b_{\mathrm{SL}} = -(7.9 \pm 1.7 \pm 0.9) \times 10^{-3}}$

  [D0, 1106.6308; PRD82,032001 (2010)]

Hints for New Physics?

	SM	Exp	
$A^b_{\rm SL}$	-0.00028 ± 0.00005	-0.008 ± 0.002	D0
$A^d_{\rm SL}$	-0.0006 ± 0.0002	-0.005 ± 0.005	HFAG
$\phi_s(B_s \to J/\psi\phi)$	-0.036 ± 0.002	$+0.13 \pm 0.18 \pm 0.07$	LHCb
$\phi_s(B_s \to J/\psi f^0)$	-0.036 ± 0.002	$-0.44 \pm 0.44 \pm 0.02$	LHCb

Four-quark operators

$$\mathcal{H}_{\rm eff}^{\Delta B=\Delta S=2} = \frac{1}{\Lambda^2}\left(\sum_{i=1}^{5} z_i Q_i + \sum_{i=1}^{3} \tilde{z}_i \widetilde{Q}_i\right)$$

$$\begin{aligned}
Q_1^{sb} &= \bar{b}_L^\alpha \gamma_\mu s_L^\alpha \bar{b}_L^\beta \gamma_\mu s_L^\beta, \quad \widetilde{Q}_1^{sb} = \bar{b}_R^\alpha \gamma_\mu s_R^\alpha \bar{b}_R^\beta \gamma_\mu s_R^\beta, \\
Q_2^{sb} &= \bar{b}_R^\alpha s_L^\alpha \bar{b}_R^\beta s_L^\beta, \quad \widetilde{Q}_2^{sb} = \bar{b}_L^\alpha s_R^\alpha \bar{b}_L^\beta s_R^\beta, \\
Q_3^{sb} &= \bar{b}_R^\alpha s_L^\beta \bar{b}_R^\beta s_L^\alpha, \quad \widetilde{Q}_3^{sb} = \bar{b}_L^\alpha s_R^\beta \bar{b}_L^\beta s_R^\alpha, \\
Q_4^{sb} &= \bar{b}_R^\alpha s_L^\alpha \bar{b}_L^\beta s_R^\beta, \quad Q_5^{sb} = \bar{b}_R^\alpha s_L^\beta \bar{b}_L^\beta s_R^\alpha
\end{aligned}$$

$$\boxed{A_{\rm SL}^b \implies \Lambda \lesssim 700 \text{ TeV}}$$

MFV

- $\tilde{z}_i$ highly suppressed;

$$\frac{z_1}{y_t^4(V_{ts}V_{tb}^*)^2} = r_1^+ - r_1^- y_b^2,$$
$$\frac{z_{2,3}}{y_t^4(V_{ts}V_{tb}^*)^2} = r_{2,3}(v^2/\Lambda^2)y_b^2,$$
$$\frac{z_{4,5}}{y_t^4(V_{ts}V_{tb}^*)^2} = r_{4,5}^+ y_b y_s - r_{4,5}^- y_b^3 y_s$$

- $r^+_{1,4,5}$ - real

- $\boxed{A^b_{\rm SL} \implies \Lambda_{\rm MFV} \lesssim 500\ {\rm GeV}\ \tan\beta}$

MFV + small tan β

- If $y_b \ll 1$: Only $Q_{2,3}$ can give large CPV in $B_s - \overline{B}_s$ mixing
- $\boxed{A_{\rm SL}^b \implies \Lambda_{Q_2} \lesssim 250 \text{ GeV} \sqrt{\tan\beta}}$
- Further predictions:
  $S_{\psi K} \approx S_{\psi K}^{\rm SM} - 0.15 \approx 0.65 \pm 0.05$
  $S_{\psi\phi} \approx S_{\psi\phi}^{\rm SM} + 0.25 \approx 0.25 \pm 0.06$
- Most likely, tree-level exchange of a scalar

CP violation as a probe of New Physics

The size of new MFV effects on CP violating observables:

	$y_b \sim 1$			$y_b \ll 1$		
i	$S_{\psi\phi}$	$S_{\psi K}$	ϵ_K	$S_{\psi\phi}$	$S_{\psi K}$	ϵ_K
1	small	small	large	small	small	large
2,3	large	large	small	large	large	small
4,5	large	small	large	small	small	large

- A-priori, seven different patterns
- Four would exclude MFV: SLL, SLS, LSS, LLL
- Within MFV:
  LLS $\Longrightarrow$ $Q_{2,3}$, LSL $\Longrightarrow$ $Q_{4,5}$+large $\tan\beta$, SSL $\Longrightarrow$ $Q_{1,4,5}$