Models of Flavor Physics

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Plan of Lectures

1. Lecture1
   (a) What is flavor physics?
   (b) Why is it interesting?
   (c) Flavor in the Standard Model
   (d) The SM flavor puzzle
   (e) Lessons from the B-factories
2. Lecture2
   (a) The NP flavor puzzle
   (b) Minimal Flavor Violation
   (c) Flavor models
   (d) Flavor@LHC

What is Flavor Physics?

What are flavors?

Copies of the same gauge representation:
$SU(3)_{\rm C} \times U(1)_{\rm EM}$

Up-type quarks	$(3)_{+2/3}$	u, c, t
Down-type quarks	$(3)_{-1/3}$	d, s, b
Charged leptons	$(1)_{-1}$	e, μ, τ
Neutrinos	$(1)_0$	ν_1, ν_2, ν_3

What are flavors?

In the interaction basis:

$SU(3)_\mathrm{C} \times SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$

Quark doublets	$(3,2)_{+1/6}$	Q_{Li}
Up-type quark singlets	$(3,1)_{+2/3}$	U_{Ri}
Down-type quark singlets	$(3,1)_{-1/3}$	D_{Ri}
Lepton doublets	$(1,2)_{-1/2}$	L_{Li}
Charged lepton singlets	$(1,1)_{-1}$	E_{Ri}

In QCD:

$SU(3)_\mathrm{C}$

Quarks	(3)	u, d, s, c, b, t

What is flavor physics?

- Interactions that distinguish among the generations:
  - Neither strong nor electromagnetic interactions
  - Within the SM: Only weak and Yukawa interactions
- In the interaction basis:
  - The weak interactions are also flavor-universal
  - The source of all SM flavor physics: Yukawa interactions among the gauge interaction eigenstates
- Flavor parameters:
  - Parameters with flavor index (m_i, V_{ij})

More flavor dictionary

- Flavor universal:
  - Coupling/paremeters $\propto \mathbf{1}_{ij}$ in flavor space
  - Example: strong interactions
    $\overline{U_R} G^{\mu a} \lambda^a \gamma_\mu \mathbf{1} U_R$
- Flavor diagonal:
  - Coupling/paremeters that are diagonal in flavor space
  - Example: Yukawa interactions in mass basis
    $\overline{U_L} \lambda_u U_R H, \quad \lambda_u = \mathrm{diag}(y_u, y_c, y_t)$

And more flavor dictionary

- Flavor changing:
  - Initial flavor number $\neq$ final flavor number
  - Flavor number = # particles – # antiparticles
  - $B \to \psi K \quad (\bar{b} \to \bar{c} c \bar{s})$; $K^- \to \mu^- \overline{\nu_2} \quad (s\bar{u} \to \mu^- \overline{\nu_2})$
- Flavor changing neutral current processes:
  - Flavor changing processes that involve either U or D but not both and/or either ℓ^- or ν but not both
  - $\mu \to e\gamma$; $K \to \pi\nu\bar{\nu}$ $(s \to d\nu\bar{\nu})$; $D^0 - \overline{D}^0$ mixing $(c\bar{u} \to u\bar{c})$...
  - FCNC are highly suppressed in the SM

The Flavor Factories

- B-factories: Belle and BaBar
  Asymmetric $e^+ - e^-$ colliders producing $\Upsilon(4S) \to B\bar{B}$

- Tevatron: CDF and D0
  $p - \bar{p}$ colliders at 2 TeV (B_s...)

- MEG: $\mu \to e\gamma$

- LHC: LHCb, ATLAS, CMS

- Future: NA62, Super-B, LHCb-upgrade...

Why is Flavor Physics Interesting?

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?

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]

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

- $\Delta m_D + \Delta m_K \implies \Delta m_{\tilde{q}}/m_{\tilde{q}} \lesssim 0.04 - 0.1$

  [Ciuchini et al, PLB 655, 162 (2007); Nir, JHEP 0705, 102 (2007); Blum et al, PRL 102, 211802 (2009)]

What is CP violation?

- Interactions that distinguish between particles and antiparticles ($e.g.$ $e_L^- \leftrightarrow e_R^+$)
  - Neither strong nor electromagnetic interactions
    (Comment: $\theta_{\rm QCD}$ is irrelevant to our discussion)
  - Within the SM: Charged current weak interactions ($\delta_{\rm KM}$)
  - With NP: many new sources of CPV
  - Manifestations of CP violation:
    - $\Gamma(B^0 \to \psi K_S) \neq \Gamma(\overline{B^0} \to \psi K_S)$
    - $K_S, K_L \neq K_+, K_-$

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

- $1964 - 2000$
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$

A brief history of CPV

- 1964 – 2000
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- 2000 – 2012
  - $S_{\psi K_S} = +0.68 \pm 0.02$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{f_0 K_S} = +0.69 \pm 0.11$
  - $S_{K^+K^-K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.36 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{D^+D^-} = -0.98 \pm 0.17$, $S_{D^{*+}D^{*-}} = -0.77 \pm 0.10$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.087 \pm 0.008$
  - $\mathcal{A}_{D_+K^\pm} = +0.19 \pm 0.03$

The Standard Model

The Standard Model

- $G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- $\langle\phi(1,2)_{+1/2}\rangle \neq 0$ breaks $G_{\rm SM} \to SU(3)_C \times U(1)_{EM}$
- Quarks: $3 \times \left\{Q_L(3,2)_{+1/6} + U_R(3,1)_{+2/3} + D_R(3,1)_{-1/3}\right\}$
  Leptons: $3 \times \left\{L_L(1,2)_{-1/2} + E_R(1,1)_{-1}\right\}$

$$\Downarrow$$

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kinetic+gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

- $\mathcal{L}_{\rm SM}$ depends on 18 parameters
- All have been measured

Flavor Symmetry

- $\mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}}$ has a large global symmetry: $G_{\text{global}} = [U(3)]^5$
- $Q_L \to V_Q Q_L, \quad U_R \to V_U U_R, \quad D_R \to V_D D_R,$ $L_L \to V_L L_L, \quad E_R \to V_E E_R$
- Take, for example $\mathcal{L}_{\text{kinetic+gauge}}$ for $Q_L(3,2)_{+1/6}$: $i\overline{Q_L}_i(\partial_\mu + \frac{i}{2}g_s G_\mu^a \lambda^a + \frac{i}{2}g_s W_\mu^b \tau^b + \frac{i}{6}g' B_\mu)\gamma^\mu \delta_{ij} Q_{Lj}$
- $\overline{Q_L}\mathbf{1}Q_L \ \to \ \overline{Q_L}V_Q^\dagger \mathbf{1} V_Q Q_L = \overline{Q_L}\mathbf{1}Q_L$
- Take, for example $\mathcal{L}_{\text{kinetic+gauge}}$ for $E_R(1,1)_{-1}$: $i\overline{E_R}_i(\partial_\mu - ig' B_\mu)\gamma^\mu \delta_{ij} E_{Rj}$
- $\overline{E_R}\mathbf{1}E_R \ \to \ \overline{E_R}V_E^\dagger \mathbf{1} V_E E_R = \overline{E_R}\mathbf{1}E_R$

Quark Flavor Violation

- $\mathcal{L}^q_{\rm Yukawa} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj}$
  breaks $U(3)_Q \times U(3)_U \times U(3)_D \to U(1)_B$
- 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
- $Y^d \to V_Q Y^d V_D^\dagger, \quad Y^u \to V_Q Y^u V_U^\dagger$
- Can be used to reduce the number of parameters in Y^u, Y^d

Kobayashi and Maskawa (I)

CP violation $\leftrightarrow$ Complex couplings:

- Hermiticity: $\mathcal{L} \sim g_{ijk}\phi_i\phi_j\phi_k + g^*_{ijk}\phi^\dagger_i\phi^\dagger_j\phi^\dagger_k$
- CP transformation: $\phi_i\phi_j\phi_k \leftrightarrow \phi^\dagger_i\phi^\dagger_j\phi^\dagger_k$
- CP is a good symmetry if $g_{ijk} = g^*_{ijk}$

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

The quark flavor parameters

- Convenient (but not unique) interaction basis:
  $Y^d \to V_Q Y^d V_D^\dagger = \lambda^d, \quad Y^u \to V_Q Y^u V_U^\dagger = V^\dagger \lambda^u$
- λ^d, λ^u diagonal and real:
  $$\lambda^d = \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix}; \quad \lambda^u = \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix}$$
- V unitary with 3 real (λ, A, ρ) and 1 imaginary (η) parameters:
  $$V \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho+i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$
- Another convenient basis: $Y^d \to V\lambda^d, \quad Y^u \to \lambda^u$

The mass basis

- To transform to the mass basis: $D_L \to D_L, \;\; U_L \to V U_L$
- $m_q = y_q \langle \phi \rangle$
- V = The CKM matrix

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U_L} V \gamma^\mu D_L W^+_\mu + \text{h.c.}$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- η - the only source of CP violation

Kobayashi and Maskawa (II)

The achievements:

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

Lepton Flavor Violation

- $\mathcal{L}^{\ell}_{\text{Yukawa}} = \overline{L_L}_i Y^e_{ij} \phi E_{Rj}$
  breaks $U(3)_L \times U(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Flavor physics:
  interactions that break the $[SU(3)]^5$ symmetry

$$\Downarrow$$

- $L_L \to V_L L_L, \quad E_R \to V_E E_R$
  = Change of interaction basis
- $Y^e \to V_L Y^e V_E^\dagger$
- Can be used to make $Y^e \to \lambda_e = \text{diag}(Y_e, Y_\mu, Y_\tau)$
  No lepton flavor changing interactions within the SM

Intermediate Summary I

- Within the Standard Model
  - The W-mediated quark interactions – the only source of FC and CPV physics: $\mathcal{L}_W = \frac{g}{\sqrt{2}}\overline{U_L}V\gamma^\mu D_L W_\mu^+ + \text{h.c.}$
  - All flavor changing processes depend on 4 CKM parameters: λ, A, ρ, η
  - All CP violating processes depend on the single KM phase: η

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
  - Approximate symmetry? [Froggatt-Nielsen]
  - Strong dynamics? [Nelson-Strassler]
  - Location in extra dimension? [Arkani-Hamed-Schmaltz]
  - ?

Neutrino flavor parameters

- $\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\ \text{eV}^2, \quad |\Delta m^2_{32}| = (2.5 \pm 0.1) \times 10^{-3}\ \text{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.01, \quad |U_{\mu 3}| = 0.70 \pm 0.04, \quad |U_{e3}| = 0.16 \pm 0.01$

Neutrino flavor parameters

- $\Delta m^2_{21} = (7.6\pm0.2)\times10^{-5}\ \mathrm{eV}^2$, $|\Delta m^2_{32}| = (2.5\pm0.1)\times10^{-3}\ \mathrm{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.01$, $|U_{\mu3}| = 0.70 \pm 0.04$, $|U_{e3}| = 0.16 \pm 0.01$

- Note:
  - $|U_{\mu3}| >$ any $|V_{ij}|$; $|U_{e2}| >$ any $|V_{ij}|$ $(i \neq j)$
  - $m_2/m_3 >$ any m_i/m_j for charged fermions
  - $|U_{e3}| \not\ll 1$
  - So far, neither smallness nor hierarchy
  - Is neutrino flavor different from charged fermion flavor?

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.79 - 0.86 & 0.50 - 0.61 & 0.1 - 0.2 \\ 0.25 - 0.53 & 0.47 - 0.73 & 0.56 - 0.79 \\ 0.21 - 0.51 & 0.42 - 0.69 & 0.61 - 0.83 \end{pmatrix}$$

- 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:

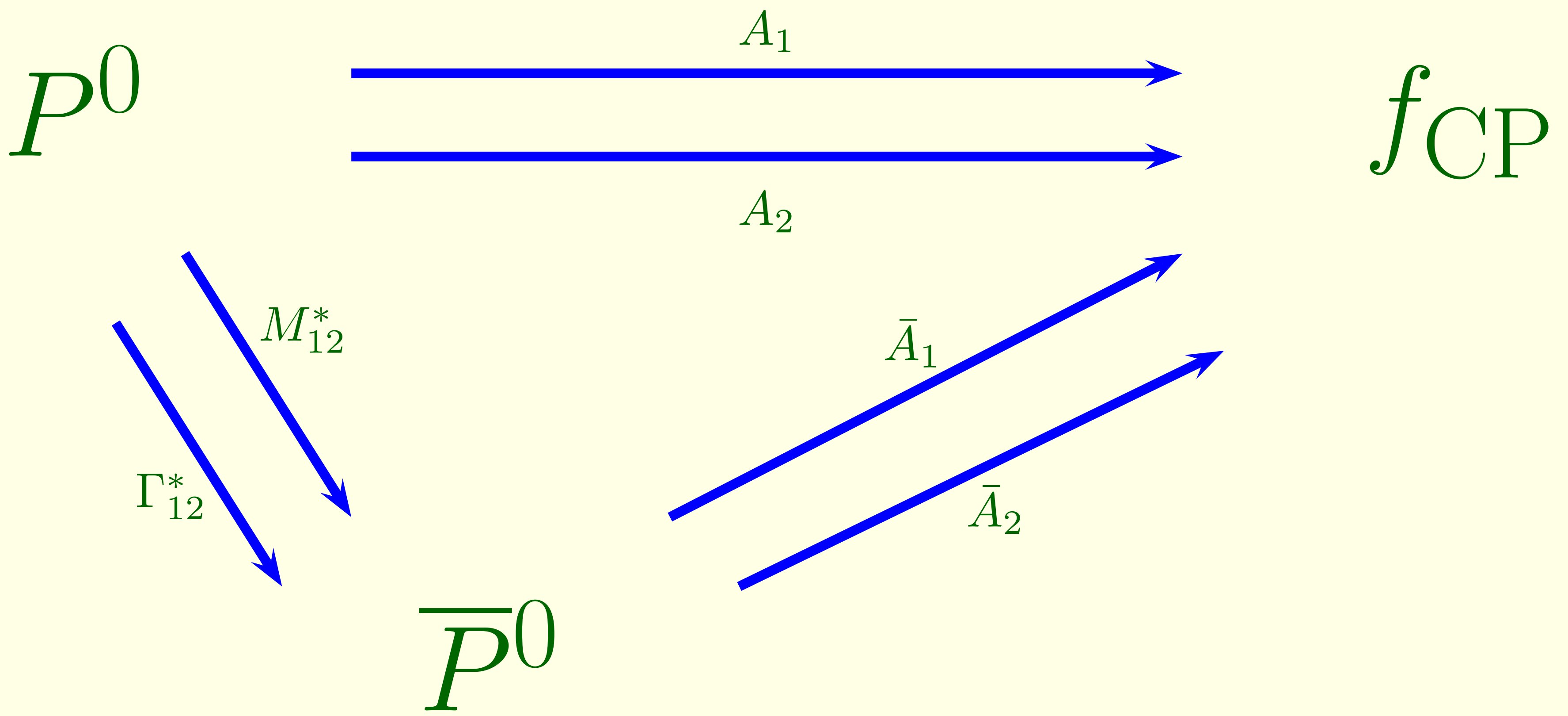
$$|U|_{\rm anarchy} = \begin{pmatrix} \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \end{pmatrix}$$

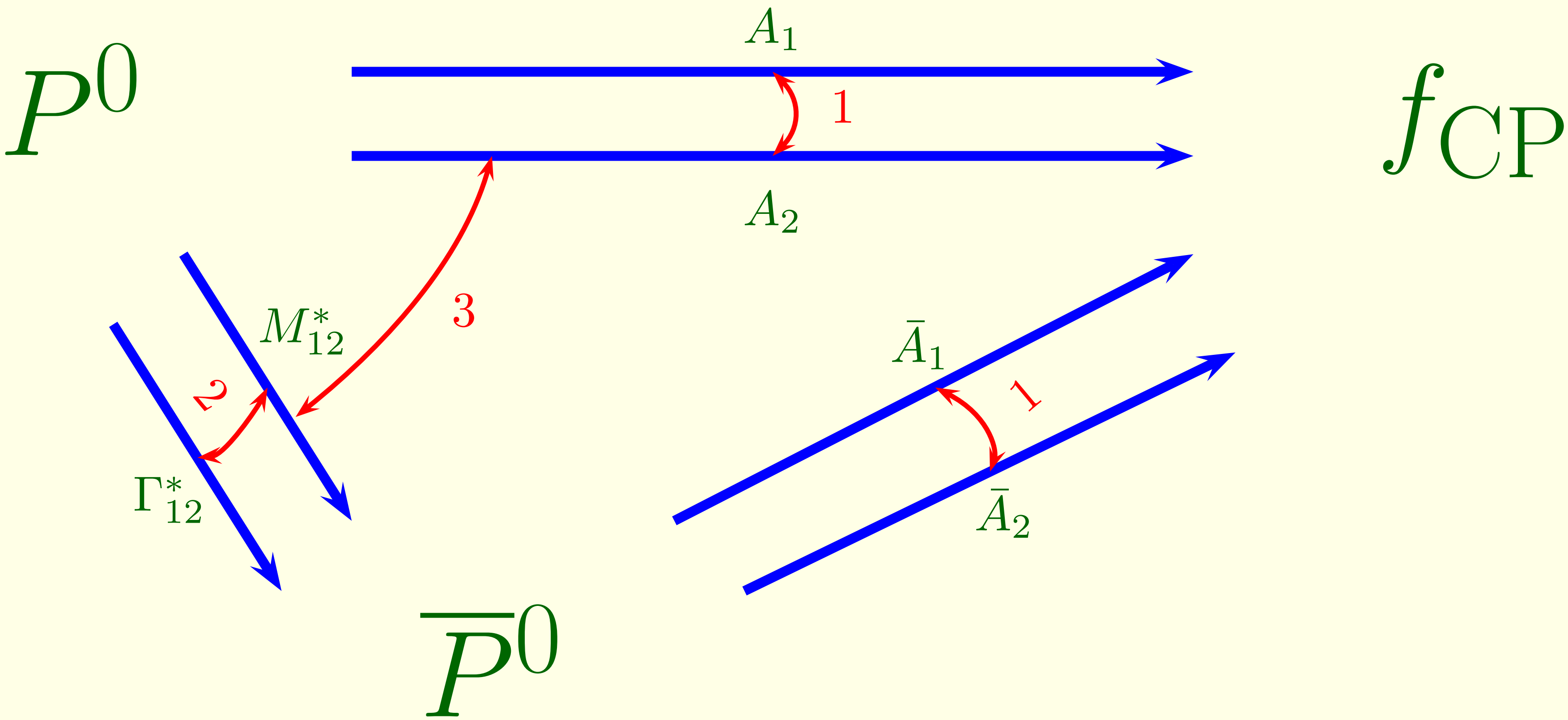
Intermediate Summary II

- 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?

What have we learned?

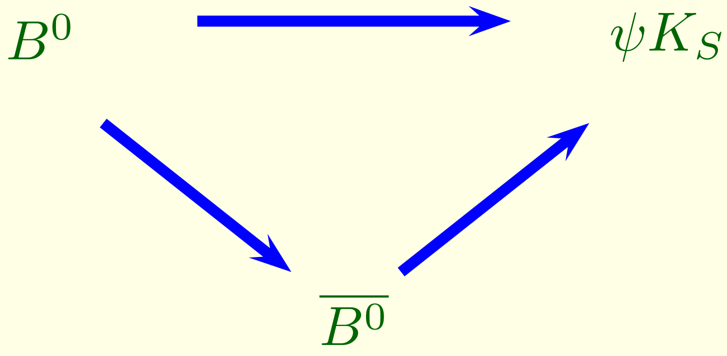

P^0
A_1
A_2
$f_{\rm CP}$
M_{12}^*
Γ_{12}^*
$\bar{A}_1$
$\bar{A}_2$
$\overline{P}^0$



1	Decay	$\lvert\bar{A}/A\rvert \neq 1$	$\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}$	$\mathcal{A}_{K^\mp\pi^\pm}$	$P^\pm \to f^\pm$
2	Mixing	$\lvert q/p\rvert \neq 1$	$\frac{q}{p} = \frac{2M_{12}^*-i\Gamma_{12}^*}{\Delta M-i\Delta\Gamma}$	$\mathcal{R}e\ \varepsilon$	$P^0, \overline{P}^0 \to \ell^\pm X$
3	Interference	$\mathcal{I}m\lambda \neq 0$	$\lambda = \frac{M_{12}^*}{\lvert M_{12}\rvert}\frac{\bar{A}}{A}$	$S_{\psi K_S}$	$P^0, \overline{P}^0 \to f_{CP}$

What have we learned?

$S_{\psi K_S}$



- 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: $A_{\psi K_S}(t)$ dominated by interference between $A(B^0 \to \psi K_S)$ and $A(B^0 \to \overline{B^0} \to \psi K_S)$
- $\Longrightarrow A_{\psi K_S}(t) = S_{\psi K_S} \sin(\Delta m_B t)$
  $\Longrightarrow \; S_{\psi K_S} = \mathcal{I}m \left[\frac{A(B^0\to\overline{B^0})}{|A(B^0\to\overline{B^0})|} \frac{A(\overline{B^0}\to\psi K_S)}{A(B^0\to\psi K_S)} \right]$

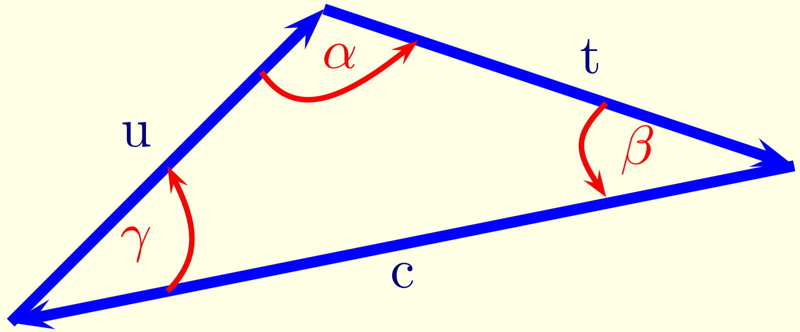
$S_{\psi K_S}$ in the SM

- $$S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}$$
- In the language of the unitarity triangle:
  $S_{\psi K_S} = \sin 2\beta$
- The approximations involved are better than one percent!
- Experiments: $S_{\psi K_S} = 0.68 \pm 0.02$

The Unitarity Triangle

- A geometrical presentation of $\boxed{V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0}$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



The Unitarity Triangle

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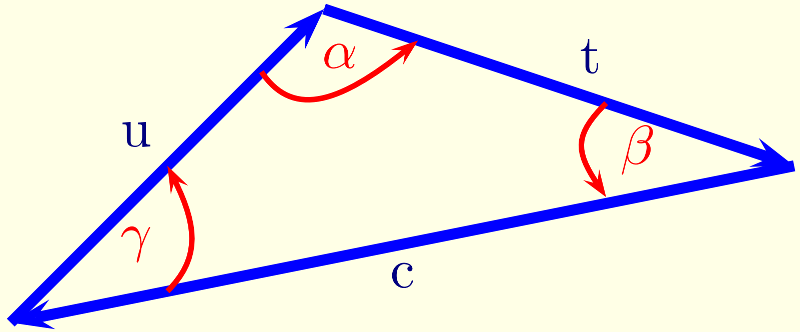
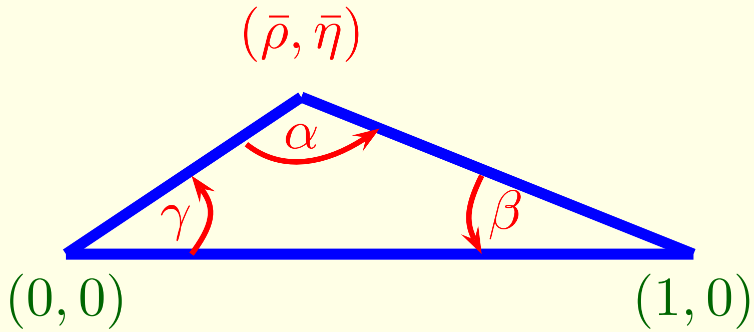


- Rescale and rotate: $\boxed{A\lambda^3 \left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)\right] = 0}$

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



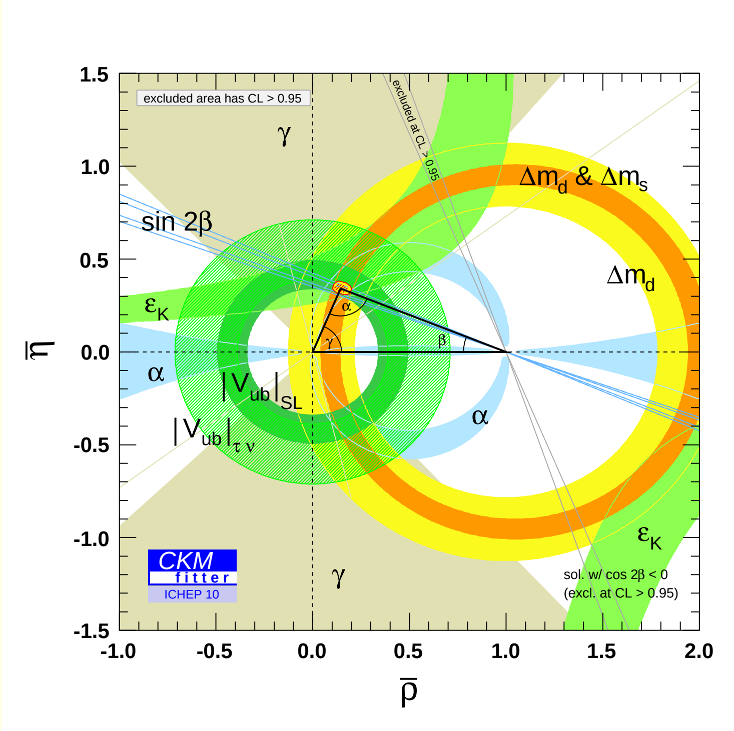
Wolfenstein (83); Buras *et al.* (94)

$\alpha \equiv \phi_2; \quad \beta \equiv \phi_1; \quad \gamma \equiv \phi_3$

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

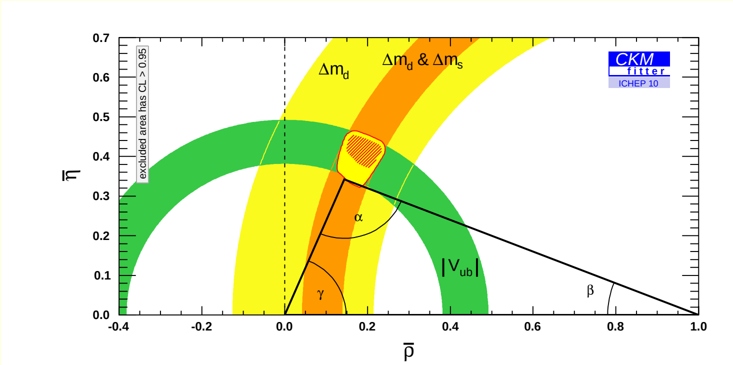
The B-factories Plot

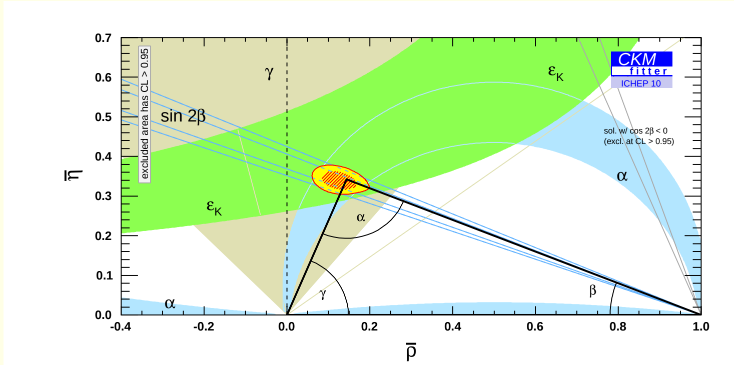


CKMFitter

Very likely, the CKM mechanism dominates FV and CPV

CPC vs. CPV





Very likely, the KM mechanism dominates CP violation

$S_{\psi K_S}$ with NP

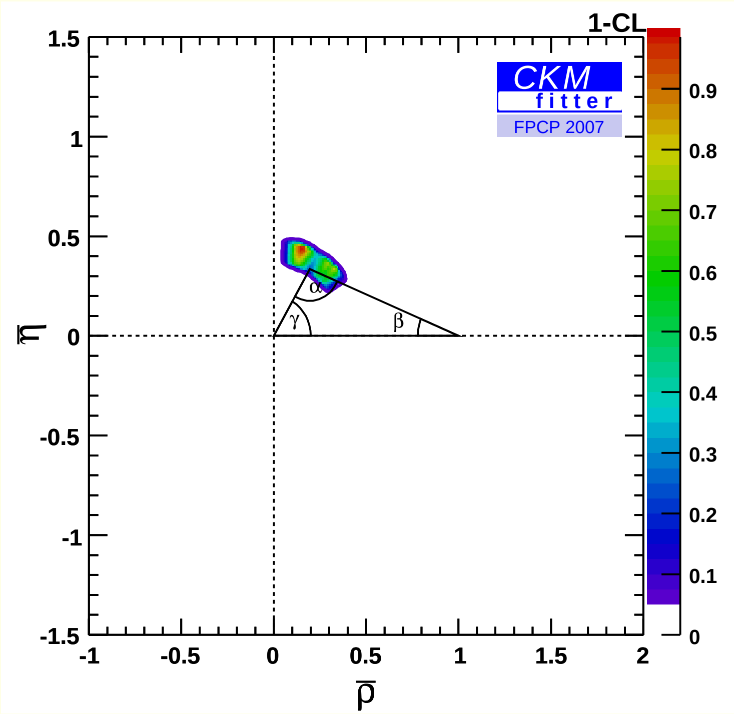
- Reminder: $S_{\psi K_S} = \mathcal{I}m\left[\frac{A(B^0\to\overline{B^0})}{|A(B^0\to\overline{B^0})|}\frac{A(\overline{B^0}\to\psi K_S)}{A(B^0\to\psi K_S)}\right]$
- New physics contributions to the tree level decay amplitude - negligible
- New physics contributions to the loop + CKM suppressed mixing amplitude could be large
- Define $h_d e^{2i\sigma_d} = \frac{A^{\rm NP}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$

  $r_d e^{2i\theta_d} = 1 + h_d e^{2i\sigma_d} = \frac{A^{\rm full}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$
- $\boxed{S_{\psi K_S} = \sin[2(\beta+\theta_d)] = f(\rho,\eta,h_d,\sigma_d)}$

Testing CKM - take II

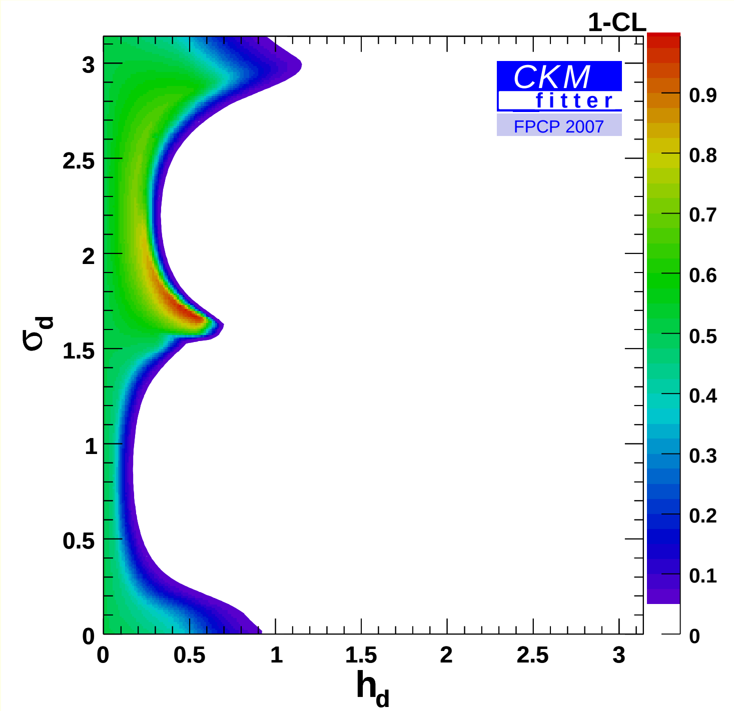
- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Use only tree decays and $B^0 - \overline{B}^0$ mixing
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}^d_{\rm SL}$
- Fit to η, ρ, h_d, σ_d
- Find 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

$\eta \neq 0?$



- 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

Hints of new physics?

- LHCb+CDF+...: $\Delta A_{\rm CP}^c = (-0.66 \pm 0.15) \times 10^{-2}$
  SM(?): $\Delta A_{\rm CP}^c \lesssim 10^{-3}$

- D0: $A_{\rm SL}^b = (-7.9 \pm 1.7 \pm 0.9) \times 10^{-3}$
  SM: $A_{\rm SL}^b = (-0.23 \pm 0.06) \times 10^{-3}$

- CDF+D0: Forward-backward asymmetry in $t\bar{t}$ production

Observable	Experiment	SM
$A_{\rm FB}^t$	0.18 ± 0.04	~ 0.08
$A_{\rm FB}^\ell$	0.15 ± 0.04	~ 0.02
$A_{\rm FB}^t(m_{t\bar{t}} > 450)$	0.28 ± 0.06	$0.10 - 0.15$

Intermediate summary III

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

Plan of Lectures

1. Lecture1
   (a) What is flavor physics?
   (b) Why is it interesting?
   (c) Flavor in the Standard Model
   (d) The SM flavor puzzle
   (e) Lessons from the B-factories
2. Lecture2
   (a) The NP flavor puzzle
   (b) Minimal Flavor Violation
   (c) Models of Flavor Physics
   (d) Flavor@LHC

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 $\Lambda_{\rm NP}^{d-4}$
- $\mathcal{L}_{d=5} = \frac{y^\nu_{ij}}{\Lambda_{\rm seesaw}} L_i L_j \phi\phi$
- $\mathcal{L}_{d=6}$ 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, $\mathrm{loop-factor}$

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_Γ	≤ 0.2
$S_{\psi K_S}$	0.68 ± 0.02
$S_{\psi\phi}$	≤ 1

High Scale?

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

		$\Lambda_{\rm NP} \gtrsim$
$\Delta m_K/m_K$	7.0×10^{-15}	1000 TeV
$\Delta m_D/m_D$	8.7×10^{-15}	1000 TeV
$\Delta m_B/m_B$	6.3×10^{-14}	400 TeV
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	70 TeV
ϵ_K	2.3×10^{-3}	20000 TeV
A_Γ	≤ 0.004	3000 TeV
$S_{\psi K_S}$	0.67 ± 0.02	800 TeV
$S_{\psi\phi}$	≤ 1	70 TeV

High Scale

- For $z_{ij} \sim 1$, $\Lambda_{\rm NP} \gg 1000\ TeV$

- For $z_{ij} \sim \alpha_2^2$, $\Lambda_{\rm NP} \gg 100\ TeV$

High Scale

- For $z_{ij} \sim 1$, $\Lambda_{\rm NP} \gg 1000\ TeV$

- For $z_{ij} \sim \alpha_2^2$, $\Lambda_{\rm NP} \gg 100\ TeV$

$$\Downarrow$$

- Did we misinterpret the Higgs fine tuning problem?

- Did we misinterpret the dark matter puzzle?

Small (hierachical?) flavor parameters?

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

		$z_{ij} \lesssim$
$\Delta m_K/m_K$	7.0×10^{-15}	9×10^{-7}
$\Delta m_D/m_D$	8.7×10^{-15}	6×10^{-7}
$\Delta m_B/m_B$	6.3×10^{-14}	5×10^{-6}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-4}
		$\mathcal{I}m(z_{ij}) \lesssim$
ϵ_K	2.3×10^{-3}	4×10^{-9}
A_Γ	≤ 0.004	1×10^{-7}
$S_{\psi K_S}$	0.67 ± 0.02	1×10^{-6}
$S_{\psi\phi}$	≤ 1	2×10^{-4}

Small (hierachical?) flavor parameters

- For $\Lambda_{\rm NP} \sim TeV$, $\mathcal{I}m(z_{sd}) < 6 \times 10^{-9}$

- For $\Lambda_{\rm NP} \sim TeV$, $|z_{bs}| < 2 \times 10^{-4}$

Small (hierachical?) flavor parameters

- For $\Lambda_{\rm NP} \sim \ TeV$, $\mathcal{I}m(z_{sd}) < 6 \times 10^{-9}$

- For $\Lambda_{\rm NP} \sim \ TeV$, $|z_{bs}| < 2 \times 10^{-4}$

$$\Downarrow$$

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

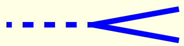
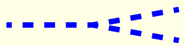
- How? Why? = The NP flavor puzzle

How does the SM ($\Lambda_{\rm SM} \sim m_W$) do it?

		$z_{ij} \sim$	$z_{ij}^{\rm SM}$
$\Delta m_K/m_K$	7.0×10^{-15}	5×10^{-9}	$\alpha_2^2 y_c^2 \vert V_{cd}V_{cs}\vert^2$
$\Delta m_D/m_D$	8.7×10^{-15}	5×10^{-9}	Long Distance
$\Delta m_B/m_B$	6.3×10^{-14}	7×10^{-8}	$\alpha_2^2 y_t^2 \vert V_{td}V_{tb}\vert^2$
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-6}	$\alpha_2^2 y_t^2 \vert V_{ts}V_{tb}\vert^2$
		$\frac{\mathcal{I}m(z_{ij})}{\vert z_{ij}\vert} \sim$	$\frac{\mathcal{I}m(z_{ij}^{\rm SM})}{\vert z_{ij}^{\rm SM}\vert}$
ϵ_K	2.3×10^{-3}	$\mathcal{O}(0.01)$	$\mathcal{I}m\frac{y_t^2(V_{td}^*V_{ts})^2}{y_c^2(V_{cd}^*V_{cs})^2} \sim 0.01$
A_Γ	≤ 0.004	≤ 0.2	0
$S_{\psi K_S}$	0.67 ± 0.02	$\mathcal{O}(1)$	$\mathcal{I}m\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}\frac{V_{cb}^*V_{cd}}{V_{cb}V_{cd}^*} \sim 0.7$
$S_{\psi\phi}$	≤ 1	≤ 1	$\mathcal{I}m\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\frac{V_{cb}^*V_{cs}}{V_{cb}V_{cs}^*} \sim 0.02$

- Does the new physics know the SM Yukawa structure? (MFV)

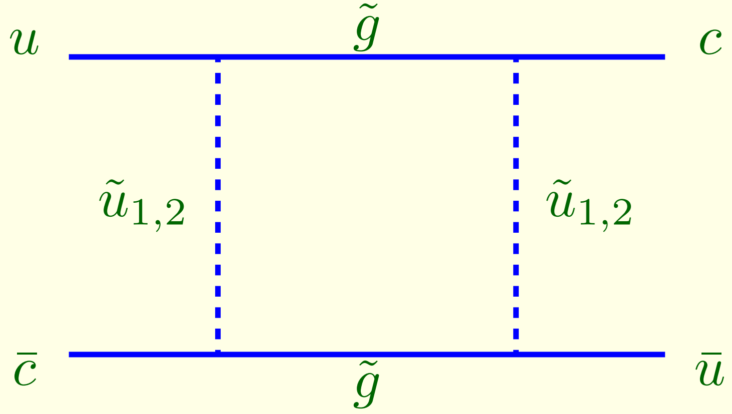
Supersymmetry for Phenomenologists

		FV	CPV
	Y	$+$	$+$
	μ	$-$	$+$
	A	$+$	$+$
	$m_{\tilde{g}}$	$-$	$+$
	$m^2_{\tilde{f}}$	$+$	$+$
	B	$-$	$+$

80 real + 44 imaginary parameters

The $D^0 - \overline{D^0}$ mixing challenge

Take, for example, the contribution from the first two generations of squark doublets to $D - \bar{D}$ mixing:



$\Lambda_{\rm NP} = m_{\tilde{Q}}$

$z_{cu} \sim 3.8 \times 10^{-5} \frac{(\Delta m^2_{\tilde{Q}})^2}{m^4_{\tilde{Q}}} (K^{u_L}_{21} K^{u_L *}_{11})^2$

$$\Longrightarrow \; \frac{TeV}{m_{\tilde{Q}}} \times \frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}} \times \sin 2\theta_u \leq 0.05 - 0.10$$

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

Gauge Mediated Supersymmetry Breaking

Gauge interactions generate universal soft squark and slepton masses:

- $\widetilde{M}^2_{\tilde{q}_L} = \tilde{m}^2\mathbf{1} + D_{q_L}\mathbf{1} + v_q^2 Y_q Y_q^\dagger$
- RGE: $\tilde{m}^2_{\tilde{Q}_L}(m_Z) = \tilde{m}^2(r_3\mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger)$
- Strong $[\mathcal{O}(10^{-4})]$ degeneracy between $\tilde{Q}_{L1} - \tilde{Q}_{L2}$; CKM-size alignment
- The only source of flavor violation = The SM Yukawa couplings
- An example of minimal flavor violation (MFV)
- MFV solves all SUSY flavor problems

Intermediate Summary IV

- How does new physics at TeV suppress its flavor violation?
- Degeneracy? Alignment?
- Is the flavor structure of the NP related to the SM Yukawa structure?
- Are the solutions of the NP and SM flavor puzzles related?

Minimal Flavor Violation

Spurions

- $\mathcal{L}^{\rm SM}_{\rm gauge}$ has a global symmetry, $G^q_{\rm flavor} = SU(3)_Q \times SU(3)_U \times SU(3)_D$, under which $Q_L(3,1,1),\ U_R(1,3,1),\ D_R(1,1,3)$
- $\mathcal{L}^q_{\rm Yukawa} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj}$ breaks $G^q_{\rm flavor}$
- $G^q_{\rm flavor}$ would be a good symmetry if Y^q were fields transforming as $Y^u(3,\bar{3},1),\ Y^d(3,1,\bar{3})$
- We say that Y^u, Y^d are spurions that break $G^q_{\rm flavor}$

MFV: Definition

A class of models that obey the following principle:

- The only breaking of flavor universality comes from Y_u, Y_d $(\lambda_d, \lambda_u, V)$
- The only spurions that break $SU(3)_Q \times SU(3)_U \times SU(3)_D$ are $Y_u(3, \bar{3}, 1)$ and $Y_d(3, 1, \bar{3})$

In MFV models, the NP flavor puzzle is solved

Operationally...

1. SM = Low energy effective theory:
   All higher dimensional operators, constructed from SM fields and the Y_q-spurions are formally invariant under $[SU(3)]^3$
2. A new high energy physics theory:
   All operators, constructed from SM and NP fields and the Y_q-spurions are formally invariant under $[SU(3)]^3$
   Example: Gauge mediated supersymmetry breaking (GMSB)

Example (1)

- Consider $\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu d_L)^2$
- $\overline{s_L} \in (\bar{3},1,1), \quad d_L \in (3,1,1) \quad \Longrightarrow \quad (\overline{s_L}\gamma_\mu d_L) \in (8,1,1)$
- $Y_d Y_d^\dagger = (3,1,\bar{3}) \times (\bar{3},1,3) \supset (8,1,1)$
  $Y_u Y_u^\dagger = (3,\bar{3},1) \times (\bar{3},3,1) \supset (8,1,1)$
- But we are in the down mass basis: $Y_d = \lambda_d \Longrightarrow (Y_d Y_d^\dagger)_{12} = 0$
- Must be $(Y_u Y_u^\dagger)_{12} = (V^\dagger \lambda_u^2 V)_{12} \approx y_t^2 V_{td}^* V_{ts}$
- $z_{sd} \propto y_t^4 (V_{td}^* V_{ts})^2$
- $z_{cu} \propto y_b^4 (V_{ub} V_{cb}^*)^2$
  $z_{bd} \propto y_t^4 (V_{td}^* V_{tb})^2$
  $z_{bs} \propto y_t^4 (V_{ts}^* V_{tb})^2$
- With the help of a loop factor, phenomenologically OK!

Example (2)

- $\tilde{Q}_L^\dagger \tilde{Q}_L = (\bar{3},1,1) \times (3,1,1) = (1+8,1,1)$
- $\Longrightarrow\ m^2_{\tilde{Q}_L} = \mathbf{1} + a_u Y_u Y_u^\dagger + a_d Y_d Y_d^\dagger$
  $Y_d Y_d^\dagger$ – FC in u-basis; $Y_u Y_u^\dagger$ – FC in d-basis
- $\tilde{U}_R^\dagger \tilde{U}_R = (1,\bar{3},1) \times (1,3,1) = (1,1+8,1)$
- $\Longrightarrow\ m^2_{\tilde{U}_R} = \mathbf{1} + b_u Y_u^\dagger Y_u$ – no FC!
- $\tilde{D}_R^\dagger \tilde{D}_R = (1,1,\bar{3}) \times (1,1,3) = (1,1,1+8)$
- $\Longrightarrow\ m^2_{\tilde{D}_R} = \mathbf{1} + b_d Y_d^\dagger Y_d$ – no FC!

Example $(2 \to 1)$

GMSB, two generations:

- $\frac{\Delta m^2_{\tilde{d}_L}}{m^2_{\tilde{d}_L}} \sim y_c^2, \quad K^{d_L^*}_{21} K^{d_L}_{11} = V^*_{cd} V_{cs}$
  $\Longrightarrow \ z_{sd}^{\rm GMSB} \sim y_c^4 (V^*_{cd} V_{cs})^2$
- $\frac{\Delta m^2_{\tilde{u}_L}}{m^2_{\tilde{u}_L}} \sim y_c^2, \quad K^{u_L^*}_{21} K^{u_L}_{11} = \frac{y_s^2}{y_c^2} V_{us} V^*_{cs}$
  $\Longrightarrow \ z_{cu}^{\rm GMSB} \sim y_s^4 (V^*_{us} V_{cs})^2$

MFV contributions to CPV

- Deviations from SM:

	$y_b \sim 1$			$y_b \ll 1$		
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

- MFV will be excluded if
  - $S_{\psi K}$-large and $S_{\psi\phi}$-small
  - $S_{\psi K}, S_{\psi\phi}, \epsilon_K$ all large

$V_{\rm CKM}$, with apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

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

$V_{\rm CKM}$, with apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

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

- The CKM matrix a-la ATLAS/CMS:

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

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 ${\rm Br}(q_3) \sim {\rm Br}(q_{1,2})$
- Examples of new particles: Vector-like quarks; squarks...

MFV + SUSY

- Squarks:
  - Spectrum: $2+1$
  - Decays: $2 \to u, d, s, c, \quad 1 \to t, b$
- Sleptons, $\Lambda_{\rm seesaw} > \Lambda_{\rm mediation}$:
  - spectrum: 3
  - Decays: flavor diagonal
- Sleptons, $\Lambda_{\rm seesaw} < \Lambda_{\rm mediation}$:
  - $Y_N,\ M_R$ may leave a footprint on the slepton spectrum and flavor decomposition

Intermediate summary V: MFV

A class of NP models where...

- The only violation of the global $[SU(3)]_q^3$ 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 susy breaking
- Probably, only an approximation
- The NP is subject to an approximate $[SU(2)]^3$ symmetry
- All FC processes $\propto V_{\rm CKM}$
- Testable at flavor factories (LHCb) and at ATLAS/CMS
- Has nothing to say about the SM flavor puzzle

Flavor Models

Reminder: The SM flavor puzzle

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

- 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
  - Approximate symmetry? [Froggatt-Nielsen]

The Froggatt-Nielsen (FN) mechanism

- Approximate "horizontal" symmetry (e.g. $U(1)_H$)
- Small breaking parameter $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\epsilon(-1)$ is a spurion that breaks $U(1)_H$
- Selection rules:
  - $Y^d_{ij} \sim \epsilon^{H(Q_i)+H(\bar{d}_j)+H(\phi_d)}$
  - $Y^u_{ij} \sim \epsilon^{H(Q_i)+H(\bar{u}_j)+H(\phi_u)}$
  - $Y^\ell_{ij} \sim \epsilon^{H(L_i)+H(\bar{\ell}_j)+H(\phi_d)}$
  - $Y^\nu_{ij} \sim \epsilon^{H(L_i)+H(L_j)+2H(\phi_u)}$

The FN mechanism: An example

- $H(Q_i) = 3, 2, 0, \quad H(\bar{u}_j) = 4, 1, 0, \quad H(\phi_u) = 0$

$$\Downarrow$$

$$Y^u \sim \begin{pmatrix} \epsilon^7 & \epsilon^4 & \epsilon^3 \\ \epsilon^6 & \epsilon^3 & \epsilon^2 \\ \epsilon^4 & \epsilon & 1 \end{pmatrix}$$

- $Y_t : Y_c : Y_u \sim 1 : \epsilon^3 : \epsilon^7$
- $(V_L^u)_{12} \sim \epsilon, \quad (V_L^u)_{23} \sim \epsilon^2, \quad (V_L^u)_{13} \sim \epsilon^3$
- A good fit with $|\epsilon| \sim 0.2$

The FN mechanism: another example

- $U(1)_H$ broken by $\epsilon(-1) \sim 0.05$
- $\mathbf{10}(2,1,0), \quad \bar{\mathbf{5}}(0,0,0)$

$$\Downarrow$$

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

$$+$$

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

The 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:
  $U \sim \mathbf{1}$

Testing FN with Neutrinos

- $\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2$, $|\Delta m^2_{32}| = (2.5 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.01$, $|U_{\mu 3}| = 0.70 \pm 0.04$, $|U_{e3}| = 0.16 \pm 0.01$

- Attempting a FN explanation:
  - $s_{23} \sim 1$, $m_2/m_3 \sim \epsilon^x$?
    Inconsistent with FN
  - $s_{23} \sim 1$, $s_{12} \sim 1$, $s_{13} \sim \epsilon^x$?
    Inconsistent with FN
  - $\sin^2 2\theta_{23} = 1 - \epsilon^x$?
    Inconsistent with FN

Neutrino Mass Anarchy

- $\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\ \text{eV}^2, \quad |\Delta m^2_{32}| = (2.5 \pm 0.1) \times 10^{-3}\ \text{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.01, \quad |U_{\mu 3}| = 0.70 \pm 0.04, \quad |U_{e3}| = 0.16 \pm 0.01$

- Possible interpretation:
  - Neutrino parameters are all of $O(1)$ (no structure):
    Neutrino mass anarchy
  - Consistent with FN
  - Close to GUT+FN predictions:
    $s_{23} \sim \frac{m_s/m_b}{|V_{cb}|} \sim 1; \quad s_{12} \sim \frac{m_d/m_s}{|V_{us}|} \sim 0.2; \quad s_{13} \sim \frac{m_d/m_b}{|V_{ub}|} \sim 0.5$

The FN mechanism and supersymmetry

- Assume: SUSY breaking terms subject to FN selection rules
  - Sfermion masses are non-degenerate
    (except for RGE effects if mediation scale is high)
  - Alignment: gluino-quark-squark mixing angles are small
- Example:
  - $H(Q_i) = 3, 2, 0, \quad H(\bar{u}_i) = 4, 1, 0, \quad H(\phi_u) = 0$
  - $m_{\tilde{Q}_1}, m_{\tilde{Q}_2}, m_{\tilde{Q}_3} = \mathcal{O}(1) \times \tilde{m}$ (anarchy)
  - $\theta^L_{12} \sim \epsilon, \quad \theta^L_{23} \sim \epsilon^2, \quad \theta^L_{13} \sim \epsilon^3$
    $\theta^R_{12} \sim \epsilon^3, \quad \theta^R_{23} \sim \epsilon, \quad \theta^R_{13} \sim \epsilon^4$
- General prediction: $\theta^L_{ij} \sim |V_{ij}|, \quad \theta^R_{ij} \sim \frac{m_i/m_j}{|V_{ij}|}$
- Structure of susy flavor:
  related to, but not the same as, SM Yukawa

Intermediate Summary VI: FN

- The SM flavor puzzle can be explained by an approximate Abelian symmetry
- The NP flavor puzzle can be solved by the same mechanism (with a little help from RGE)
- The NP flavor parameters are related to, but not the same as, the SM flavor parameters
- If we discover new particles, and measure their spectrum and flavor decomposition, we can test various solutions to the flavor puzzles

Flavor@ATLAS/CMS

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

Solving the SUSY Flavor Puzzle

If ATLAS/CMS observe squarks and sleptons...

- 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})

$$\Downarrow$$

Learn how the SUSY flavor suppression is obtained

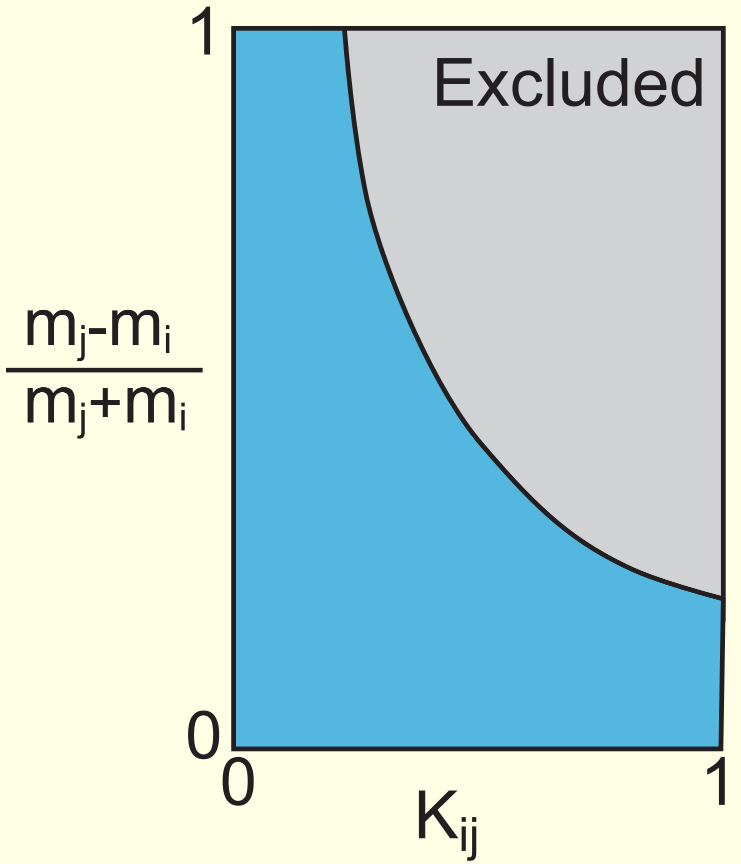
The role of flavor factories (FF)

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?

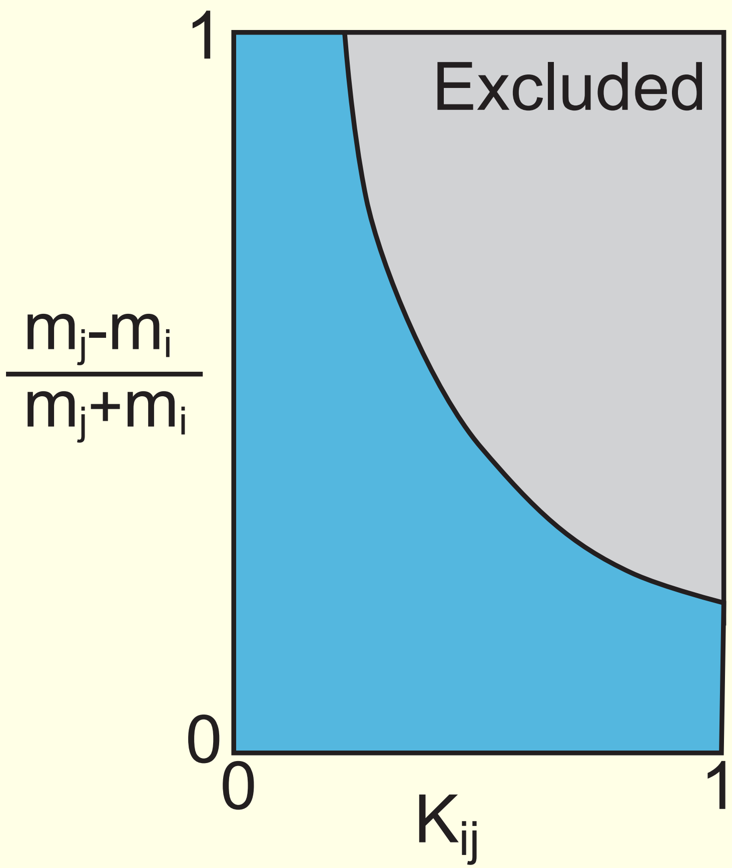
[Hiller, Hochberg, Nir, JHEP0903(09)115; JHEP1003(10)079]]

Intermediate summary VII

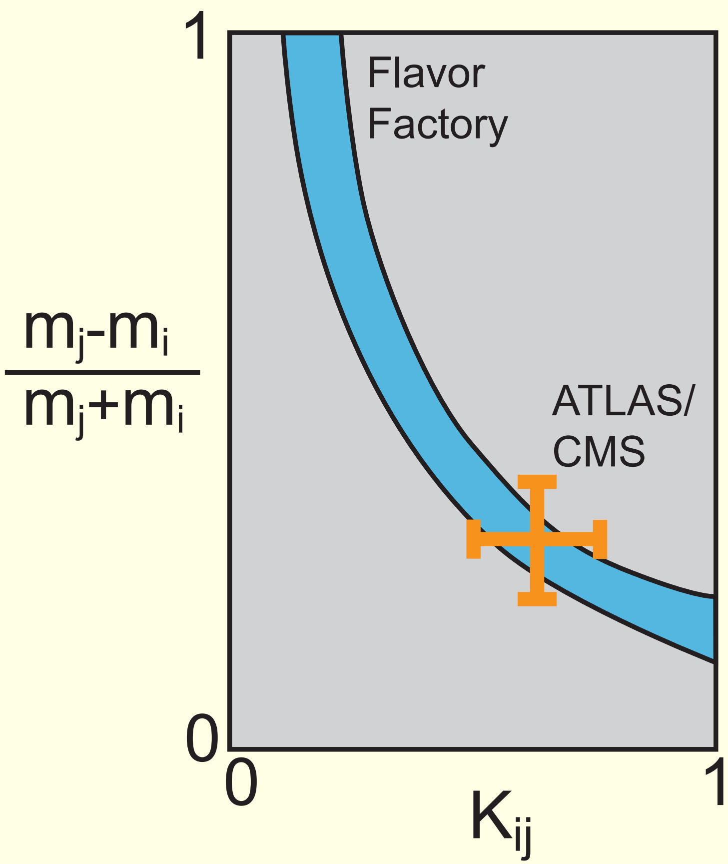


Flavor Factories

Intermediate summary VII



Flavor Factories



FF+ATLAS/CMS

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

Summary

- Past:
  - The CKM mechanism of flavor violation has passed successfully numerous experimental tests
  - The KM mechanism was proven to dominate the observed CP violation
- Present:
  - The SM flavor puzzle: Why smallness and hierarchy?
  - The NP flavor puzzle: Why degeneracy and/or alignment?
- Future:
  - Progress on NP flavor puzzle guaranteed
  - Progress on SM flavor puzzle possible if there is accessible new physics with flavor structure related to the SM

The SM flavor puzzle with strong dynamics

- At high scale $\mu > M_>$, anarchy: $Y(M_>) = \mathcal{O}(1)$
- A range of scales, $M_> > \mu > M_<$, where first two generations couple to a conformal sector:
  $Y(M <) = Y(M_>) \left(\frac{M_<}{M_>}\right)^{\frac{1}{2}(\gamma_{Li}+\gamma_{Rj})}$
  γ_{Mi} = the anomalous dimension of the field Φ_{Mi}
- Generates a small parameter $\epsilon \equiv (M_</M_>)^{1/2}$
- $m_i/m_j \sim \epsilon^{\gamma_{Li}+\gamma_{Ri}-\gamma_{Lj}-\gamma_{Rj}}$
  $|V_{ij}| \sim \epsilon^{\gamma_{Li}-\gamma_{Lj}}$
- For SM flavor parameters, predictions similar to FN

The NP flavor puzzle with strong dynamics

For the SUSY flavor problems, various options:

- Supersymmetry broken by the conformal sector
  - $\tilde{m}_{1,2}$ directly from conformal sector
  - $\tilde{m}_3$ from gauge mediation
  - $\Longrightarrow$ Heavy first two sfermion generations: $\tilde{m}_{1,2} \gg \tilde{m}_3$
- Supersymmetry breaking at scale higher than $M_>$
  - $\tilde{m}_{1,2} \to 0$ at $M_<$
  - $\tilde{m}_{1,2}$ from RGE between $M_< \to m_Z$
  - $\Longrightarrow$ Degenerate first two sfermion generations: $\tilde{m}_1 \simeq \tilde{m}_2$

The SM flavor puzzle with extra dimension

- Anarchical 5d Yukawa couplings: $Y_{ij}^{5d} = \mathcal{O}(1)$
- Higgs field located near the IR brane
- Wave functions of light fermions located near the UV brane
- Wave functions of heavy fermions located near the IR brane
- 4d Yukawa couplings proportional to overlap of Higgs and fermion wave functions: $Y_{ij}^{4d} \propto f_{Li} f_{Rj}$
  f_{Mi} = wave function of ψ_{Mi} at the IR brane
- $m_i/m_j \sim \frac{f_{Li} f_{Ri}}{f_{Lj} f_{Rj}}$
  $|V_{ij}| \sim f_{Li}/f_{Lj}$
- For SM flavor parameters, predictions similar to FN

The NP flavor puzzle with extra dimension

- Main problem: Flavor changing couplings of the first KK level gluon
- However, its wave function located at the IR brane, similar to the Higgs field
- FC operators involving first two generations suppressed; *e.g.* $(\overline{s_L}d_R)(\overline{s_R}d_L) \propto \frac{m_s m_d}{M_{KK}^2}$
- FC operators involving the top not strongly suppressed; *e.g.* $\Gamma(t \to cZ)$ orders of magnitude above the SM prediction