Flavor and CP violation

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Plan of lectures

- Introduction
- The SM: from definition to Lagrangian
- The SM: from Lagrangian to phenomenology
- The CKM matrix: parametrization and UT’s
- FCNC: SM suppression factors
- CP violation
- Baryogenesis
- Testing CKM
- The New Physics flavor puzzle
- The Standard Model flavor puzzle
- The flavor of Higgs
- Flavor anomalies?

Introduction

Dictionary and motivation

What is Flavor?

- Flavors = several particles (mass eigenstates) with the same quantum charges
- Within the Standard Model:

Type	$SU(3)_C \times U(1)_{EM}$	Flavors
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

Flavored Dictionary

Term	Definition	SM
Flavor Physics	Int's that distinguish among flavors	Weak, Yukawa
Flavor parameters	Parameters that carry flavor index	m_f, V_{ij}
Flavor universal	Int's with couplings $\propto \mathbf{1}$	Strong, EM
Flavor diagonal	Int's with only diagonal couplings	Yukawa
Flavor changing	Processes where $F_{\text{initial}} \neq F_{\text{final}}$	

F = number of particles minus number of anti-particles of a certain flavor

Flavor Changing Processes

Flavor Changing Charged Current (FCCC)

- Both up-type and down-type quarks, and/or both charged leptons and neutrinos take part
  - $\mu \to e\,\overline{\nu_e}\nu_\mu$
  - $K^- \to \mu^-\overline{\nu_\mu}\quad (s\bar{u} \to \mu^-\overline{\nu_\mu})$
  - $B \to \psi K\ (b \to c\bar{c}s)$

Flavor Changing Neutral Current (FCNC)

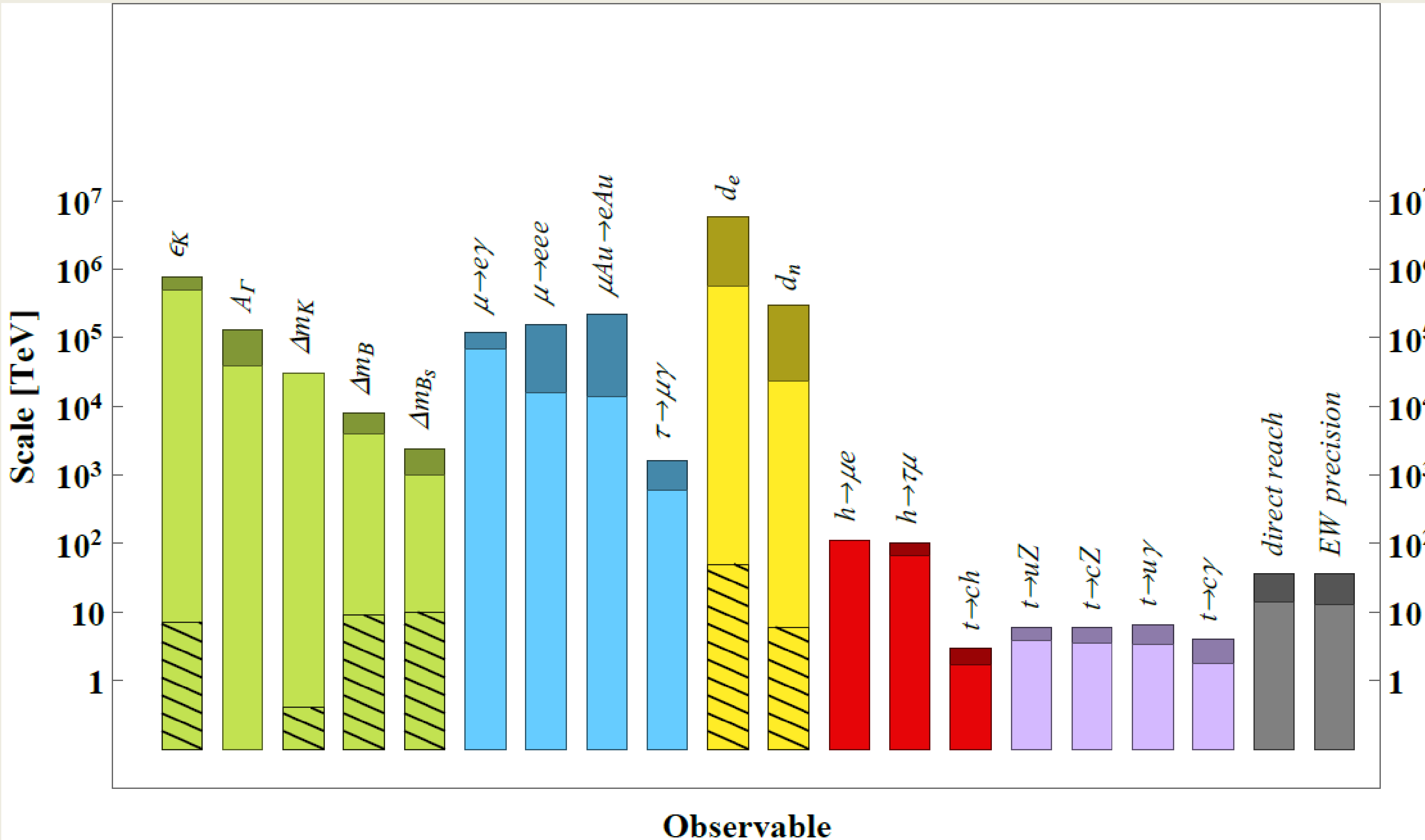
- Either up-type or down-type quarks, but not both, and/or either charged leptons or neutrinos, but not both, take part
  - $\mu \to e\gamma$
  - $K_L \to \mu^+\mu^-\quad (s\bar{d} \to \mu^+\mu^-)$
  - $B \to \phi K\ (b \to s\bar{s}s)$

Why is Flavor Interesting?

- Flavor physics can discover new physics or probe it before it is directly observed in experiments

- The NP flavor puzzle
  - If there is NP at the TeV scale, why doesn't it modify FCNC?
- The SM flavor puzzle
  - Why is there structure in the SM flavor parameters?
- The ν flavor puzzle
  - Why are neutrino-related flavor parameters different?

Why is Flavor Interesting?



Examples of Flavored Discoveries

- The smallness of $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K^+ \to \mu^+\nu)$
  $\Longrightarrow$ Predicting the charm quark
- The size of Δm_K
  $\Longrightarrow m_c$
- The size of Δm_B
  $\Longrightarrow m_t$
- The measurement of ϵ_K
  $\Longrightarrow$ Third generation
- The measurement of ν flavor transitions
- $\Longrightarrow m_\nu \neq 0$

The SM:
From definition to Lagrangian

Constructing a model

- The symmetry
- Pattern of spontaneous symmetry breaking
- Representations of fermions and scalars

$$\Longrightarrow \mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{\psi} + \mathcal{L}_{Y} + \mathcal{L}_{\phi}$$

- Spectrum
- Interactions
- Accidental symmetries
- Parameters

SM: Definition

- The symmetry is a local
$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Spontaneously broken by the VEV of
$$\phi(1,2)_{+1/2}, \quad \langle \phi^0 \rangle = \frac{v}{\sqrt{2}}$$
$$G_{SM} \to SU(3)_C \times U(1)_{EM}, \quad Q_{EM} = T_3 + Y$$

- Three fermion generations ($i = 1,2,3$)
$$Q_{Li}(3,2)_{+1/6}, U_{Ri}(3,1)_{+2/3}, D_{Ri}(3,1)_{-1/3},$$
$$L_{Li}(1,2)_{-1/2}, E_{Ri}(1,1)_{-1}$$

Local $SU(3)_C \times SU(2)_L \times U(1)_Y$

- Requires the following gauge boson DoF:
  - $G_a^\mu(8,1)_0, W_a^\mu(1,3)_0, B^\mu(1,1)_0$
- Field strengths
  - $G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f_{abc} G_b^\mu G_c^\nu$
  - $W_a^{\mu\nu} = \partial^\mu W_a^\nu - \partial^\nu W_a^\mu - g \epsilon_{abc} W_b^\mu W_c^\nu$
  - $B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$
- Covariant derivative
  - $D^\mu = \partial^\mu + i g_s G_a^\mu L_a + i g W_b^\mu T_b + i g' B^\mu Y$
    - L_a are $SU(3)$ generators: $\frac{1}{2}\lambda_a$ for (3), 0 for (1)
    - T_b are $SU(2)$ generators: $\frac{1}{2}\tau_b$ for (2), 0 for (1)

Covariant derivatives

- $D^\mu Q_{Li} = \left(\partial^\mu + \frac{i}{2} g_s G_a^\mu \lambda_a + \frac{i}{2} g W_b^\mu \tau_b + \frac{i}{6} g' B^\mu\right) Q_{Li}$
- $D^\mu U_{Ri} = \left(\partial^\mu + \frac{i}{2} g_s G_a^\mu \lambda_a + \frac{2i}{3} g' B^\mu\right) U_{Ri}$
- $D^\mu D_{Ri} = \left(\partial^\mu + \frac{i}{2} g_s G_a^\mu \lambda_a - \frac{i}{3} g' B^\mu\right) D_{Ri}$
- $D^\mu L_{Li} = \left(\partial^\mu + \frac{i}{2} g W_b^\mu \tau_b - \frac{i}{2} g' B^\mu\right) L_{Li}$
- $D^\mu E_{Ri} = (\partial^\mu - i g' B^\mu) E_{Ri}$
- $D^\mu \phi = \left(\partial^\mu + \frac{i}{2} g W_b^\mu \tau_b + \frac{i}{2} g' B^\mu\right) \phi$

$\mathcal{L}_{kin}$

$$\mathcal{L}_{kin}^{SM} = -¼G_a^{\mu\nu}G_{a\mu\nu} - ¼W_b^{\mu\nu}W_{b\mu\nu} - ¼B^{\mu\nu}B_{\mu\nu}$$
$$-i\overline{Q_{Li}}\gamma_\mu D^\mu Q_{Li} - i\overline{U_{Ri}}\gamma_\mu D^\mu U_{Ri} - i\overline{D_{Ri}}\gamma_\mu D^\mu D_{Ri}$$
$$- i\overline{L_{Li}}\gamma_\mu D^\mu L_{Li} - i\overline{E_{Ri}}\gamma_\mu D^\mu E_{Ri} - (D^\mu\phi)^\dagger(D_\mu\phi)$$

$\mathcal{L}_\psi$

- The SM fermions are in chiral rep's of G_{SM}

$$\Longrightarrow m_{\mathrm{Dirac}} = 0$$

- The SM fermions have $Y \neq 0$

$$\Longrightarrow m_{\mathrm{Majorana}} = 0$$

$$\mathcal{L}_\psi^{SM} = 0$$

$\mathcal{L}_Y$

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{Li}} \phi D_{Rj} + Y_{ij}^u \overline{Q_{Li}} \tilde{\phi} U_{Rj} + Y_{ij}^e \overline{L_{Li}} \phi E_{Rj} + h.c.$$

- W/o loss of generality, we can change to a basis

$$Y^e \to \hat{Y}_e = U_{eL} Y^e U_{eR}^\dagger$$

such that

$$\hat{Y}_e = \mathrm{diag}\left(y_e, y_\mu, y_\tau\right)$$

- In this basis:

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}; \quad e_R, \mu_R, \tau_R$$

$\mathcal{L}_Y$

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{Li}} \phi D_{Rj} + Y_{ij}^u \overline{Q_{Li}} \tilde{\phi} U_{Rj} + Y_{ij}^e \overline{L_{Li}} \phi E_{Rj} + h.c.$$

- W/o loss of generality, we can change to a basis

$$Y^u \to \hat{Y}_u = V_{uL} Y^u V_{uR}^\dagger$$

such that

$$\hat{Y}_u = \mathrm{diag}(y_u, y_c, y_t)$$

- In this basis:

$$\begin{pmatrix} u_L \\ d_{uL} \end{pmatrix}, \begin{pmatrix} c_L \\ d_{cL} \end{pmatrix}, \begin{pmatrix} t_L \\ d_{tL} \end{pmatrix}; \;\; u_R, c_R, t_R$$

$\mathcal{L}_Y$

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{Li}} \phi D_{Rj} + Y_{ij}^u \overline{Q_{Li}} \tilde{\phi} U_{Rj} + Y_{ij}^e \overline{L_{Li}} \phi E_{Rj} + h.c.$$

- W/o loss of generality, we can change to a basis

$$Y^d \to \hat{Y}_d = V_{dL} Y^d V_{dR}^\dagger$$

such that

$$\hat{Y}_d = \mathrm{diag}(y_d, y_s, y_b)$$

- In this basis:

$$\begin{pmatrix} u_{dL} \\ d_L \end{pmatrix}, \begin{pmatrix} u_{sL} \\ s_L \end{pmatrix}, \begin{pmatrix} u_{bL} \\ b_L \end{pmatrix}; \quad d_R, s_R, b_R$$

$\mathcal{L}_Y$

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{Li}} \phi D_{Rj} + Y_{ij}^u \overline{Q_{Li}} \tilde{\phi} U_{Rj} + Y_{ij}^e \overline{L_{Li}} \phi E_{Rj} + h.c.$$

- In general, $V_{uL} \neq V_{dL}$

$$\Longrightarrow \text{The } \hat{Y}_u \text{ basis} \neq \text{The } \hat{Y}_d \text{ basis}$$

- In the $\hat{Y}_u$ basis

$$Y^d = V \hat{Y}_d$$

- In the $\hat{Y}_d$ basis

$$Y^u = V^\dagger \hat{Y}_u$$

- In either case

$$V = V_{uL} V_{dL}^\dagger$$

- $V_{uL}, V_{uR}, V_{dL}, V_{dR}$ depend on the basis from which we start
- V does not. It is physical

$\mathcal{L}_\phi$

$$\mathcal{L}_\phi^{SM} = -\mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2$$

- $\lambda > 0$ to have the potential bounded from below
- $\mu^2 < 0$ to have $\langle\phi\rangle \neq 0$
- In unitary gauge $\phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$

$\mathcal{L}^{SM}$

$$\mathcal{L}^{SM} = -¼G_a^{\mu\nu}G_{a\mu\nu} - ¼W_b^{\mu\nu}W_{b\mu\nu} - ¼B^{\mu\nu}B_{\mu\nu}$$
$$-i\overline{Q_{Li}}\gamma_\mu D^\mu Q_{Li} - i\overline{U_{Ri}}\gamma_\mu D^\mu U_{Ri} - i\overline{D_{Ri}}\gamma_\mu D^\mu D_{Ri}$$
$$- i\overline{L_{Li}}\gamma_\mu D^\mu L_{Li} - i\overline{E_{Ri}}\gamma_\mu D^\mu E_{Ri} - (D^\mu\phi)^\dagger(D_\mu\phi)$$
$$+(Y_{ij}^d\overline{Q_{Li}}\phi D_{Rj} + Y_{ij}^u\overline{Q_{Li}}\tilde{\phi}U_{Rj} + Y_{ij}^e\overline{L_{Li}}\phi E_{Rj} + h.c.)$$
$$-\mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2$$

The SM: From $\mathcal{L}^{SM}$ to phenomenology

The SM: from $\mathcal{L}^{SM}$ to phenomenology

- Spectrum
- Interactions
- Accidental symmetries
- Flavor parameters

The SM spectrum

particle	spin	color	Q_{EM}	mass [v]
$W^{\pm}$	1	(1)	± 1	$g/2$
Z^0	1	(1)	0	$\sqrt{g^2+g'^2}/2$
A^0	1	(1)	0	0
G	1	(8)	0	0
h	0	(1)	0	$\sqrt{2\lambda}$
e,μ,τ	½	(1)	-1	$y_{e,\mu,\tau}/\sqrt{2}$
ν_e,ν_μ,ν_τ	½	(1)	0	0
u,c,t	½	(3)	$+2/3$	$y_{u,c,t}/\sqrt{2}$
d,s,b	½	(3)	$-1/3$	$y_{d,s,b}/\sqrt{2}$

EM interactions

$$\mathcal{L}_{\mathrm{QED},\psi} = -\frac{2e}{3}\overline{u}_i \gamma_\mu A^\mu u_i + \frac{e}{3}\overline{d}_i \gamma_\mu A^\mu d_i + e\overline{\ell}_i \gamma_\mu A^\mu \ell_i$$

- Vector-like, P conserving
- Diagonal
- Universal

Strong interactions

$$\mathcal{L}_{\mathrm{QCD},\psi} = -\frac{g_s}{2}\overline{q_i}\lambda_a\gamma_\mu G_a^\mu q_i$$

- Vector-like, P conserving
- Diagonal
- Universal

NC weak interactions

$$\mathcal{L}_{Z,\psi} = \frac{e}{s_W c_W}[\frac{1}{2}\overline{\nu_{L\alpha}}\gamma_\mu Z^\mu \nu_{L\alpha} - \left(\frac{1}{2} - s_W^2\right)\overline{e_{Li}}\gamma_\mu Z^\mu e_{Li} + s_W^2 \overline{e_{Ri}}\gamma_\mu Z^\mu e_{Ri}$$
$$+\left(\frac{1}{2} - \frac{2}{3}s_W^2\right)\overline{u_{Li}}\gamma_\mu Z^\mu u_{Li} - \frac{2}{3}s_W^2 \overline{u_{Ri}}\gamma_\mu Z^\mu u_{Ri}$$
$$-\left(\frac{1}{2} - \frac{1}{3}s_W^2\right)\overline{d_{Li}}\gamma_\mu Z^\mu d_{Li} + \frac{1}{3}s_W^2 \overline{d_{Ri}}\gamma_\mu Z^\mu d_{Ri}]$$

- Chiral, P violating
- Diagonal
  - $BR(Z \to e^+\mu^-) < 7.5 \times 10^{-7}$
- Universal
  - $\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.001 \pm 0.003$

CC weak interactions - leptons

$$\mathcal{L}_{W,\ell} = -\frac{g}{\sqrt{2}}(\overline{\nu_{eL}}\gamma_\mu W^{+\mu} e_L^- + \overline{\nu_{\mu L}}\gamma_\mu W^{+\mu} \mu_L^- + \overline{\nu_{\tau L}}\gamma_\mu W^{+\mu} \tau_L^- + h.c.)$$

- Only left-handed, P violating
- Diagonal
- Universal
  - $\Gamma(\mu^+\nu_\mu)/\Gamma(e^+\nu_e) = 0.99 \pm 0.02$

CC weak interactions - quarks

$$\mathcal{L}_{W,q} = -\frac{g}{\sqrt{2}}(\overline{u_L}\ \overline{c_L}\ \overline{t_L})\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\gamma_\mu W^{+\mu}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

$V = V_{uL} V_{dL}^{\dagger}$ = the CKM matrix

- Only left-handed, P violating
- Neither universal nor diagonal
- Universality of gauge interactions is hidden in unitarity of V
  - $3(\sum_j |V_{uj}|^2 + \sum_j |V_{cj}|^2) = 6 \Longrightarrow \Gamma(\text{hadrons})/\Gamma(\text{leptons}) = 2$
  - Experiment: 2.09 ± 0.01
  - $\sum_j |V_{uj}|^2 = \sum_j |V_{cj}|^2 \Longrightarrow \Gamma(W \to cX)/\Gamma(W \to uX) = 1$
  - Experiment: 0.98 ± 0.02

Yukawa interactions

$$\mathcal{L}_Y = -\frac{h}{v}\Sigma_f m_f \overline{f_L} f_R + h.c.$$

- Diagonal
- Non-universal
- Proportional: $Y_f/m_f = \sqrt{2}/v$

Higgs decays

mode	BR_{SM}	$\mu_{experiment}$	Comments
$b\bar{b}$	0.58	0.98 ± 0.20	
WW^*	0.21	0.99 ± 0.15	3-body
gg	0.09		loop
$\tau^+\tau^-$	0.06	1.09 ± 0.23	
ZZ^*	0.03	1.17 ± 0.23	3-body
$c\bar{c}$	0.03		
$\gamma\gamma$	0.002	1.14 ± 0.14	loop

Higgs decays

Theory at tree level: $BR_{bb}: BR_{\tau\tau}: BR_{cc} = 3m_b^2: m_\tau^2: 3m_c^2$

WW^*, ZZ^*: three body decays (*e.g.* $Z\mu^+\mu^-$)

No tree level hgg coupling $(h(1)_0; m_g = 0)$

- Loop - t dominated

No tree level $h\gamma\gamma$ coupling $(h(1)_0; m_\gamma = 0)$

- Loop - W, t dominated
- $BR_{\gamma\gamma} \sim 0.002$- discovery mode!

$ZZ^*, WW^*, \gamma\gamma, \tau\tau, b\bar{b}$ experimentally established

The SM interactions

interaction	fermions	force carrier	coupling	flavor
EM	u, d, ℓ	A^0	eQ	universal
Strong	u, d	G	g_s	universal
NC weak	all	Z^0	$g(T_3 - s_W^2 Q)/c_W$	universal
CC weak	$\bar{u}d / \bar{\nu}\ell$	$W^\pm$	$gV / g\mathbf{1}$	non-universal/ universal
Yukawa	u, d, ℓ	h	y_f	Diagonal

Accidental Symmetries

- The SM has an accidental global symmetry:
  - $G_{\text{global}}^{SM} = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
- The proton must not decay
  - $e.g.\ p \to e^+\pi^0$ forbidden
- FCNC decays of charged leptons forbidden
  - $e.g.\ \mu \to e\gamma$ forbidden
- Neutrinos are massless
  - Neutrino flavor transitions observed!
  - The SM is, at best, a good low-energy EFT

Breaking accidental symmetries

- Accidental symmetries are broken by higher-dimensional (non-renormalizable) terms
- At dimension five:

  $-\frac{z_{ij}}{\Lambda} L_i L_j \phi\phi$ breaks $U(1)_e \times U(1)_\mu \times U(1)_\tau$
- At dimension six:

  $-\frac{y_{ijkl}}{\Lambda^2} Q_i Q_j Q_k L_l$ breaks $U(1)_B$

Global Symmetries

- $\mathcal{L}_{kin}$ has a global symmetry:

$$U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

- The following transformations change basis:

$$Q_L \to V_Q Q_L, U_R \to V_U U_R,\ D_R \to V_D D_R, L_L \to V_L L_L, E_R \to V_E E_R$$

$$5 \times (3_R + 6_I) = 15_R + 30_I \text{ parameters}$$

- $\mathcal{L}_Y$ breaks this symmetry into

$$G_{\text{global}}^{SM} = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

$$4_I \text{ parameters}$$

- Can remove $15_R + 26_I$ parameters

Counting flavor parameters

- $Y^e \Longrightarrow 9_R + 9_I$ parameters
- $[U(3)]^2 \to [U(1)]^3 \Longrightarrow 6_R + 9_I$ parameters
- Thus, $3_R(m_\ell) + 0_I$ physical parameters

- $Y^{u,d} \Longrightarrow 18_R + 18_I$ parameters
- $[U(3)]^3 \to U(1) \Longrightarrow 9_R + 17_I$ parameters
- Thus, $9_R\left(m_q, \theta_{ij}\right) + 1_I(\delta_{KM})$ physical parameters

The CKM Matrix
Parametrization, UT's

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- The Standard Model flavor puzzle
- The flavor of Higgs
- Flavor anomalies?

The Wolfenstein parametrization

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

$$\lambda = 0.2251 \pm 0.0005$$
$$A = 0.81 \pm 0.03$$
$$\rho = +0.160 \pm 0.007$$
$$\eta = +0.350 \pm 0.006$$

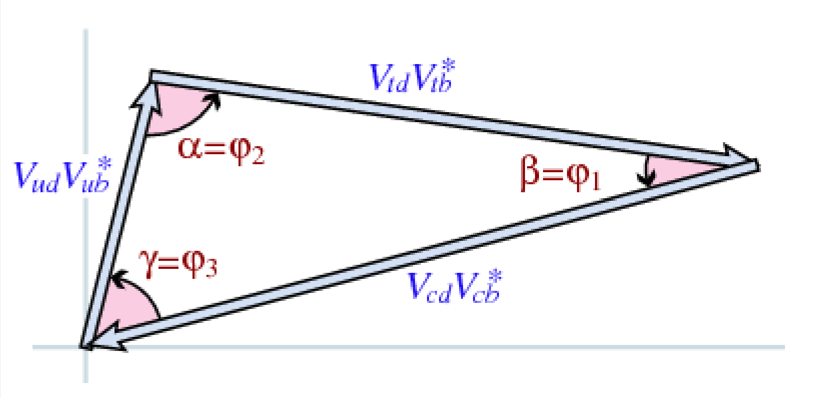
The standard parametrization

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$
$$\approx \begin{pmatrix} 1 & s_{12} & s_{13}e^{-i\delta} \\ -s_{12} & 1 & s_{23} \\ s_{12}s_{23} - s_{13}e^{i\delta} & -s_{23} & 1 \end{pmatrix}$$

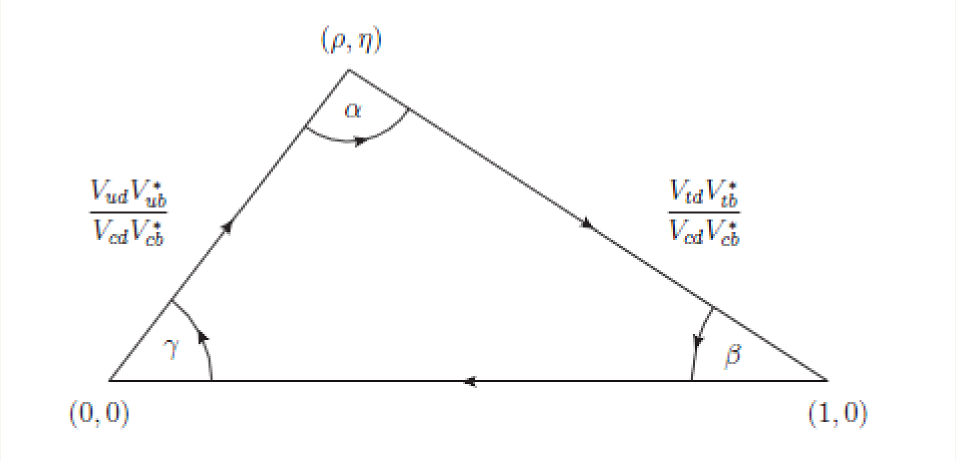
$$s_{12} \approx 0.225$$
$$s_{23} \approx 0.042$$
$$s_{13} \approx 0.0037$$
$$\delta \approx 74^{o}$$

The Unitarity Triangle (UT)

- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



- Rescaled UT: Divide all sides by $V_{cd}V_{cb}^*$



FCCC processes

Process	CKM
$u \to d\ell^+\nu$	$\|V_{ud}\| = 0.97417 \pm 0.00021$
$s \to u\ell^-\bar{\nu}$	$\|V_{us}\| = 0.2248 \pm 0.0006$
$c \to d\ell^+\nu$ or $\nu_\mu + d \to c + \mu^-$	$\|V_{cd}\| = 0.220 \pm 0.005$
$c \to s\ell^+\nu$ or $c\bar{s} \to \ell^+\nu$	$\|V_{cs}\| = 0.995 \pm 0.016$
$b \to c\ell^-\bar{\nu}$	$\|V_{cb}\| = 0.0405 \pm 0.0015$
$b \to u\ell^-\bar{\nu}$	$\|V_{ub}\| = 0.0041 \pm 0.0004$
$pp \to tX$	$\|V_{tb}\| = 1.01 \pm 0.03$
$b \to sc\bar{u}$ and $b \to su\bar{c}$	$\gamma = (73 \pm 5)^o$

FCNC

SM suppression factors

Loop suppression

The W-boson cannot mediate FCNC at tree level

Only neutral bosons can a-priori mediate FCNC at tree level: g, γ, Z, h ?

The couplings of massless gauge bosons are universal (gauge invariance)

g, γ cannot mediate FCNC at tree level;

Z? h?

Z-mediated FCNC?

Class I

- All mass e.s. of given spin, color, charge in the same $SU(2)_L \times U(1)_Y$ rep
- Z-couplings universal
- **SM**
- Example: all $u_L(3)_{+2/3}$ come from $(3,2)_{+1/6}$

Class II

- Mass e.s. of given spin, color, charge carry different T_3
- Z-couplings neither universal nor diagonal
- Vector-like fermions
- Example: $u_{4L}(3)_{+2/3}$ from $(3,1)_{+2/3}$

h-mediated FCNC?

Class I

1. Chiral fermions
2. Single Higgs doublet couples to each sector

- h-couplings diagonal

- **SM**
- NFC-2HDM
- MSSM

Class II

1. Vector fermions
2. 2+ Higgs doublets

- Off-diagonal h-couplings

- Vector-like fermions
- MHDM

CKM suppression

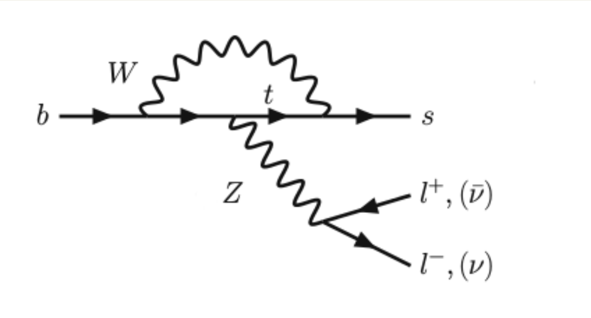
- All FCNC processes $\propto V_{ij}, i \neq j$
- $V_{us}, V_{cd} \sim \lambda,;\ V_{cb}, V_{ts} \sim \lambda^2;\ \ V_{ub}, V_{td} \sim \lambda^3$
  - $(\lambda \sim 0.2)$
- $\Delta F = 1$ example:
  - $A(b \to s\gamma) \propto V_{tb}V_{ts}^* \sim \lambda^2$
- $\Delta F = 2$ example:
  - $A\left(B^0 \to \overline{B^0}\right) \propto (V_{tb}V_{td}^*)^2 \sim \lambda^6$

GIM suppression

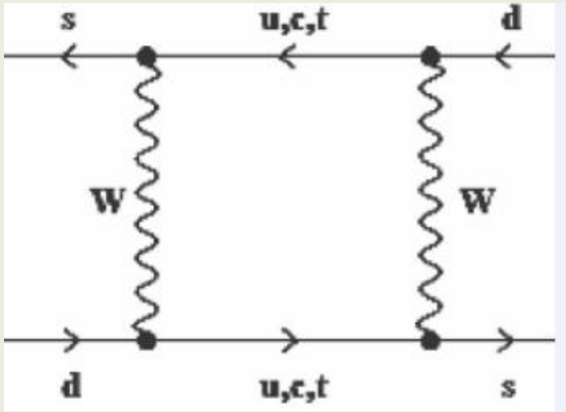
- If all quarks in a given sector were degenerate, there would be no FC W-couplings
- FCNC in the d (u) sector $\propto \Delta m_{ij}^2$ in the u (d) sector
- Processes involving b-quark - no suppression
  - $A(b \to s\gamma) \propto m_t^2/m_W^2$
- Processes involving only first 2 generations – suppressed
  - $A\left(K^0 \to \overline{K^0}\right) \propto m_c^2/m_W^2$

FCNC examples

- $\Delta F = 1$: $b \to s\ell^+\ell^-$
- $A_{b\to s\ell\ell} \propto \frac{g^4}{16\pi^2}(V_{tb}V_{ts}^*)\frac{m_t^2}{m_W^2}$



- $\Delta F = 2$: $K^0 - \overline{K^0}$ mixing
- $M_{K\bar{K}} \propto \frac{g^4}{16\pi^2}(V_{cs}V_{cd}^*)^2\frac{m_c^2}{m_W^2}$



FCNC in and beyond the SM

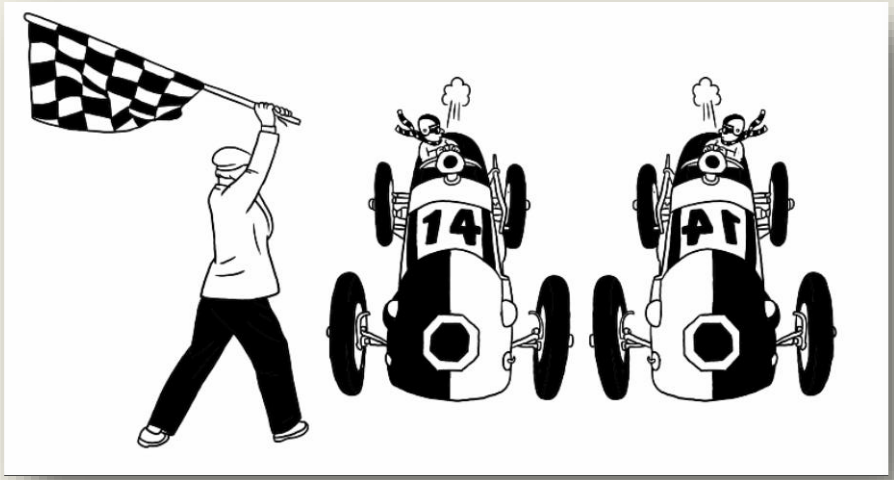
- Within SM - highly suppressed
  - Loop suppression
  - CKM suppression
  - GIM suppression (if dominated by light gen's)
- Beyond SM – in general, suppressed only by high scale
  - New physics can contribute to FCNC comparably to the SM even if it takes place at a scale orders of magnitude higher than the electroweak scale

CP Violation

- Introduction
- The SM: from definition to Lagrangian
- The SM: from Lagrangian to phenomenology
- The CKM matrix: parametrization and UT’s
- FCNC: SM suppression factors
- CP violation
- Baryogenesis
- Testing CKM
- The New Physics flavor puzzle
- The Standard Model flavor puzzle
- The flavor of Higgs
- Flavor anomalies?

What is CP Violation?

- Interactions that distinguish between particles and antiparticles (e.g. $e_L^- \leftrightarrow e_R^+$)



- 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?

CP asymmetries provide some of the cleanest probes of flavor physics

- Reason: CP is a good symmetry of the strong int's

η_B (a CPV observable) is many orders of magnitude larger than the SM prediction

- Conclusion: There must exist BSM sources of CPV

CPV $\Leftrightarrow$ Complex couplings

- Under CP:
  - $\psi \leftrightarrow \bar{\psi}, \;\; \phi \leftrightarrow \phi^\dagger$
- Hermiticity of the Lagrangian:
  - $\mathcal{L}_Y = Y_{ij}\overline{\psi_i}\phi\psi_j + Y_{ij}^*\overline{\psi_j}\phi^\dagger\psi_i$
- Under CP:
  - $\mathcal{L}_Y \to Y_{ij}\overline{\psi_j}\phi^\dagger\psi_i + Y_{ij}^*\overline{\psi_i}\phi\psi_j$
- $\mathcal{L}_Y$ is CPV if $Y_{ij} \neq Y_{ij}^*$
  - More accurately, CP is violated if, using all freedom to redefine the phases of the fields, there is no basis where all couplings are real

SM2: CP conserving

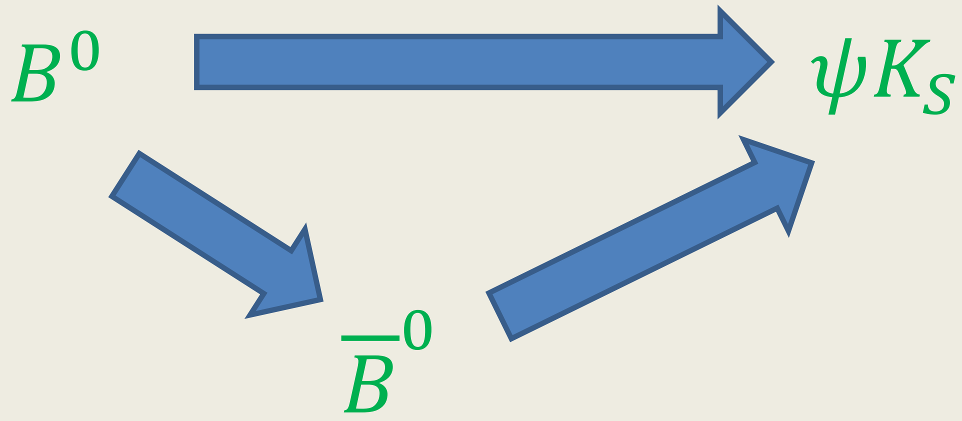
- $Y^e \Longrightarrow 4_R + 4_I$ parameters
- $[U(2)]^2 \to [U(1)]^2 \Longrightarrow 2_R + 4_I$ parameters
- Thus, $2_R(m_\ell) + 0_I$ physical parameters

- $Y^{u,d} \Longrightarrow 8_R + 8_I$ parameters
- $[U(2)]^3 \to U(1) \Longrightarrow 3_R + 8_I$ parameters
- Thus, $5_R\left(m_q, \theta_{12}\right) + 0_I$ physical parameters

SM3: not necessarily CPV

- J = Phase-convention independent CPV
  - $Im\left[V_{ij}V_{kl}V_{il}^*V_{kj}^*\right] = J\sum_{m,n=1}^{3}\epsilon_{ikm}\epsilon_{jln}$
- CPV requires $J \neq 0$
  - $J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}s_{\delta} \approx \lambda^6 A^2 \eta$
- Necessary & sufficient condition for CPV in SM
  - $X_{CP} = \Delta m_{tc}^2 \Delta m_{tu}^2 \Delta m_{cu}^2 \Delta m_{bs}^2 \Delta m_{bd}^2 \Delta m_{sd}^2\, J \neq 0$
- An equivalent formulation in interaction basis:
  - $X_{CP} \equiv Im\left\{\det\left[M_d M_d^{\dagger}, M_u M_u^{\dagger}\right]\right\} \neq 0$

$S_{\psi K_S}$



- BaBar/Belle: $A_{\psi K_S}(t) = \dfrac{d\Gamma/dt\left[\overline{B}^0_{\text{phys}}(t) \to \psi K_S\right] - d\Gamma/dt\left[B^0_{\text{phys}}(t) \to \psi K_S\right]}{d\Gamma/dt\left[\overline{B}^0_{\text{phys}}(t) \to \psi K_S\right] + d\Gamma/dt\left[B^0_{\text{phys}}(t) \to \psi K_S\right]}$
- Theory: $A_{\psi K_S}(t)$ dominated by interference between

  $A(B^0 \to \psi K_S)$ and $A(B^0 \to \overline{B}^0 \to \psi K_S)$

$\Longrightarrow A_{\psi K_S}(t) = S_{\psi K_S} \sin(\Delta m_B t)$

- BaBar/Belle: $S_{\psi K_S} = 0.69 \pm 0.02$

$S_{\psi K_S}$ in the SM

- Model independently, $S_{\psi K_S} = Im[\frac{M^*_{B\bar{B}}}{|M_{B\bar{B}}|}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}]$

$$\boxed{S^{SM}_{\psi K_S} = Im\left[\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\frac{V_{cb}V^*_{cd}}{V^*_{cb}V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}}$$

- All hadronic parameters cancel in $A_{\psi K_S}(t)$ (and $S_{\psi K_S}$) as a result of the CP invariance of QCD
- The approximations involved are better than one percent!
- Similar theoretical cleanliness in CPV observables:
  $K \to \pi\bar{\nu}\nu, \qquad B \to DK$

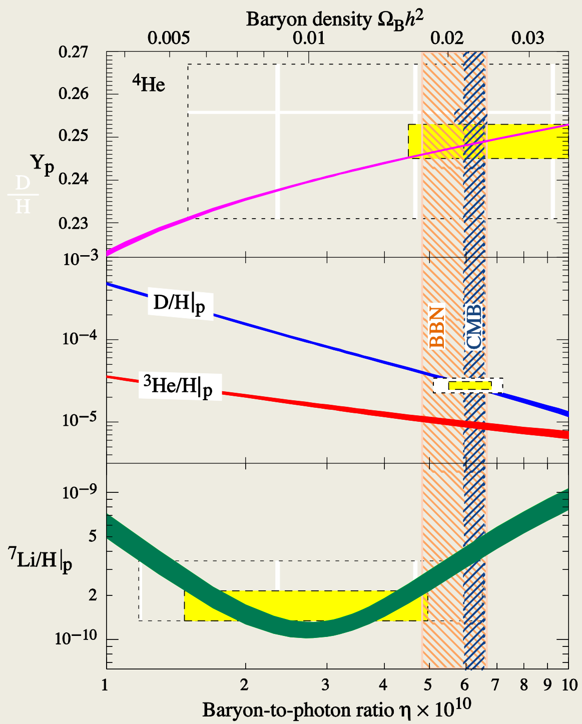
Baryogenesis

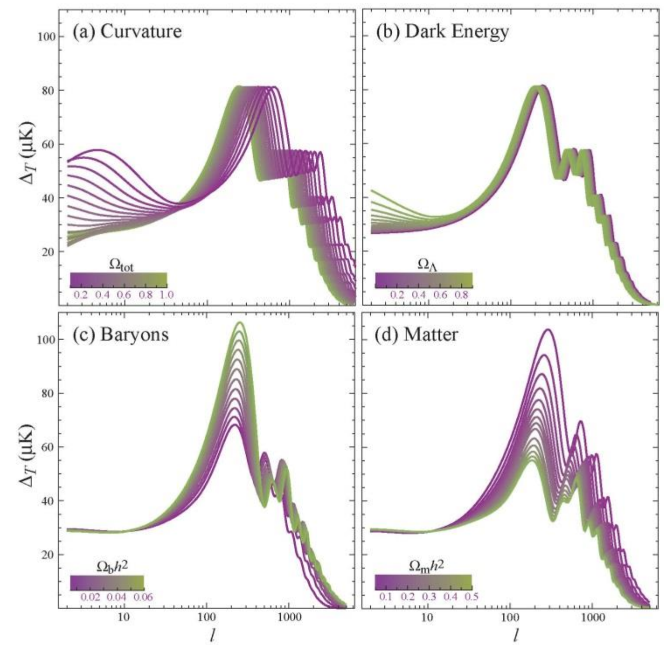
The Baryon Asymmetry

- $\eta_b \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$
  - $b = p, n$
  - $\bar{b} = \bar{p}, \bar{n}$
  - $n_e = n_p$

- Antimatter disappeared from the Universe:
  - $n_{\bar{b}}/n_\gamma \approx 0$
- Matter has survived:
  - $n_b/n_\gamma \approx 10^{-9}$

How do we know?





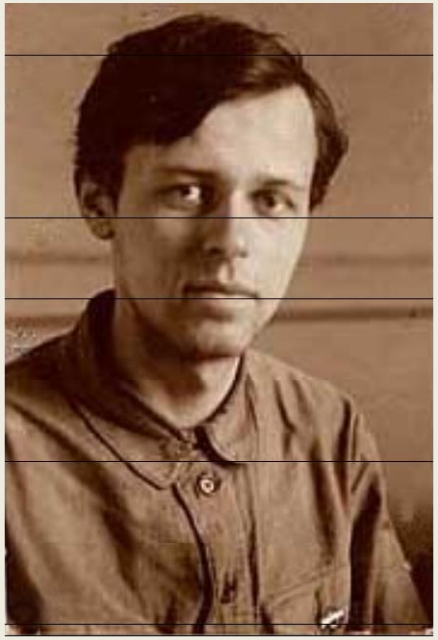
Nucleosynthesis

$\eta_{10} = 5.6 \pm 0.9$

CMB

$\eta_{10} = 6.2 \pm 0.2$

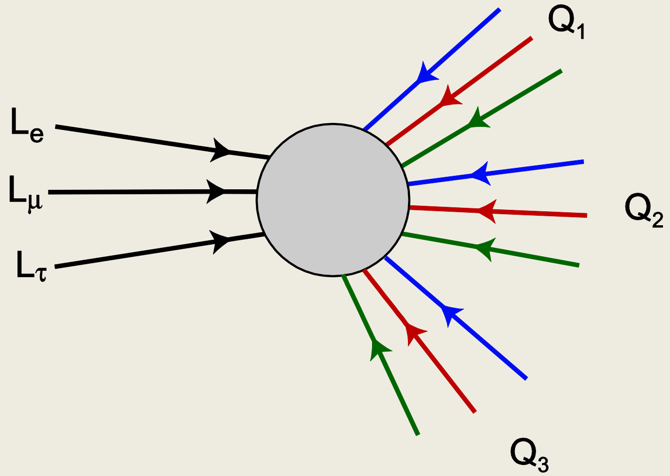
Sakharov Conditions



- The baryon asymmetry can be dynamically generated (baryogenesis) provided that
  1. Baryon number is violated
  2. CP and C are violated
  3. Departure from thermal equilibrium

If CP were not violated, neither matter nor antimatter would have survived

SM $B + L$ violation



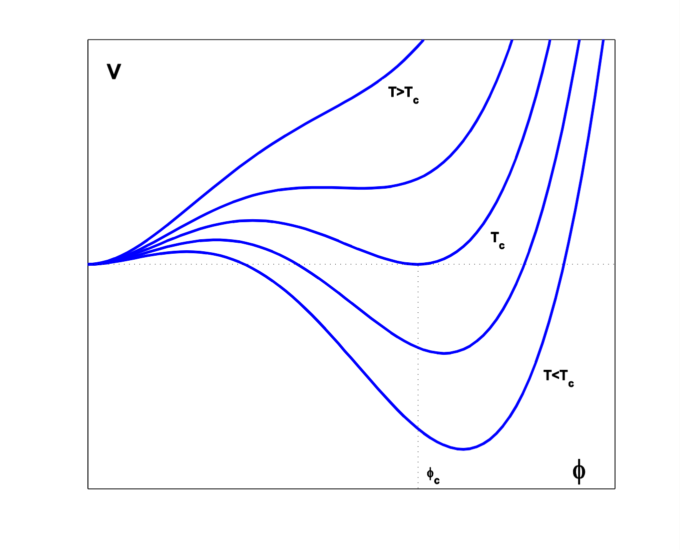
- $T = 0$: $\Gamma \propto e^{-2\pi/\alpha_w}$
- $T \gg T_{\text{EWPT}}$: $\Gamma \propto 250\alpha_w^5 T$

- $\Gamma_{B+L\text{ violation}} > H$ for $T_{\text{EWPT}} < T < 10^{12}\ GeV$
- Baryon number is no longer violated after $t \sim 10^{-11}\ seconds$

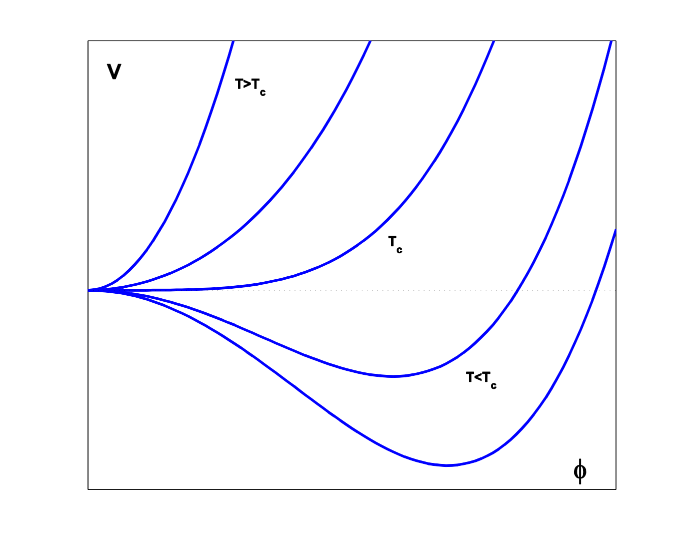
- Electroweak baryogenesis: $t \sim 10^{-11}\ seconds$
- Leptogenesis: $t < 10^{-27}\ seconds$

SM EWPT

- Need a strongly 1st order PT



- $m_h \sim 126\ GeV$



- $\langle\phi\rangle: 0 \rightarrow v$ continuously and uniformly in space
- The $B + L$ violating processes switch off slowly
- The baryon asymmetry is erased

The SM EWPT is not of the right kind

SM CP violation

$$\eta_b \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}\Big|_0 \sim 10^{-9} \;\Leftrightarrow\; \eta_b^{\mathrm{SM}} \propto \frac{X_{CP}}{T_c^{12}} \sim 10^{-20}$$

The KM mechanism cannot produce large enough baryon asymmetry

There must exist new sources of CPV beyond δ_{KM}

Testing CKM

Testing CKM

Is CKM self-consistent?

Does $\eta \neq 0$?

How much room for NP in FCNC?

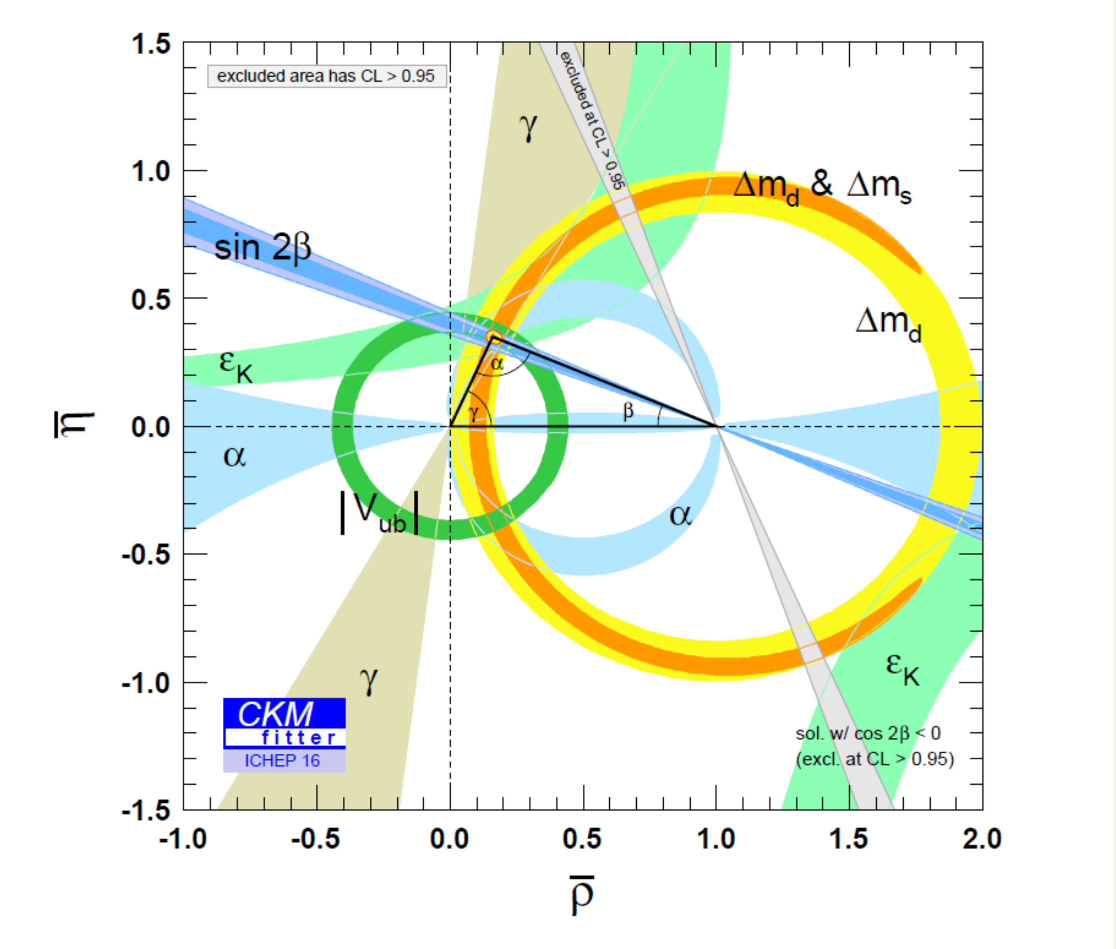
Self-consistency?

- 4 parameters (λ, A, ρ, η),
  $\gg$ 4 observables:
  test self-consistency
- $K \to \pi\ell\nu \xRightarrow{|V_{us}|=\lambda} \lambda = 0.2251 \pm 0.0005$
- $B \to D^{(*)}\ell\nu \xRightarrow{|V_{cb}|=A\lambda^2} A = 0.81 \pm 0.03$
- Left with 2 parameters (ρ, η),
  $\gg$ 2 observables

ρ, η-dependent observables

observable	CKM dependence	ρ, η dependence
$\Gamma(b \to u\ell\nu)$	$\|V_{ub}\|^2$	$\rho^2 + \eta^2$
Various $\Gamma(B \to DK)$	$Im\,\frac{V_{cb}V_{cs}^*}{V_{ub}V_{us}^*}$	$\gamma = \arg\frac{\rho + i\eta}{\sqrt{\rho^2+\eta^2}}$
CPV in $B \to \psi K_S$	$Im\,\frac{V_{tb}^*V_{td}V_{cb}V_{cd}^*}{V_{tb}V_{td}^*V_{cb}^*V_{cd}}$	$\sin 2\beta = \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
CPV in $B \to \pi\pi, \rho\pi, \rho\rho$	$Im\,\frac{V_{tb}^*V_{td}V_{ub}V_{ud}^*}{V_{tb}V_{td}^*V_{ub}^*V_{ud}}$	$\alpha = \pi - \beta - \gamma$
$\Delta m_B/\Delta m_{B_s}$	$\|V_{td}/V_{ts}\|^2$	$(1-\rho)^2 + \eta^2$
ϵ_K	$Im\,\frac{(V_{ts}V_{td}^*)^2}{(V_{us}V_{ud}^*)^2}$	$\frac{\eta(1-\rho)}{(1-\rho)^2-\eta^2}$

Self-consistency test



$$\rho = +0.160 \pm 0.07$$
$$\eta = +0.350 \pm 0.006$$

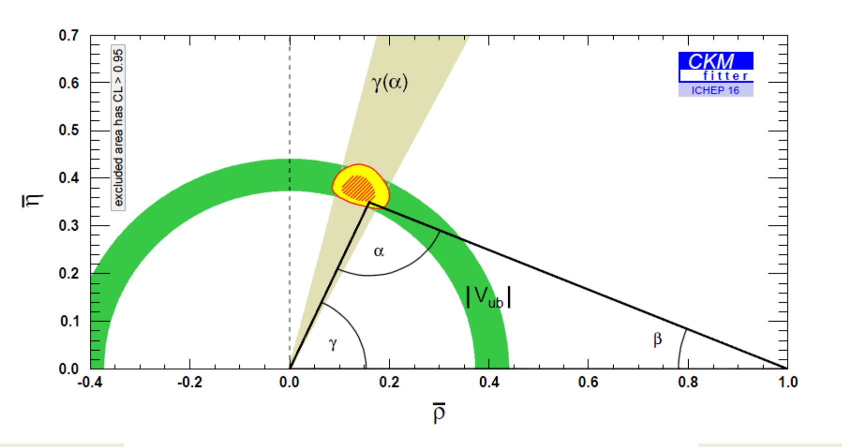
Allowing for NP

- Assuming that all FC and CPV processes are dominated by CKM is self-consistent $\Longrightarrow$
  - Very likely, FC processes are dominated by the CKM mechanism, and CPV in FC processes is dominated by the KM phase
- We can do better: Assume that tree level processes are CKM dominated, but allow NP of arbitrary size and phase in FCNC processes $\Longrightarrow$
  - Is the KM mechanism at work?
  - How much room for NP is there in FCNC?

$$M_{B\bar{B}} = M_{B\bar{B}}^{SM}(\rho,\eta) \times \Delta_d$$

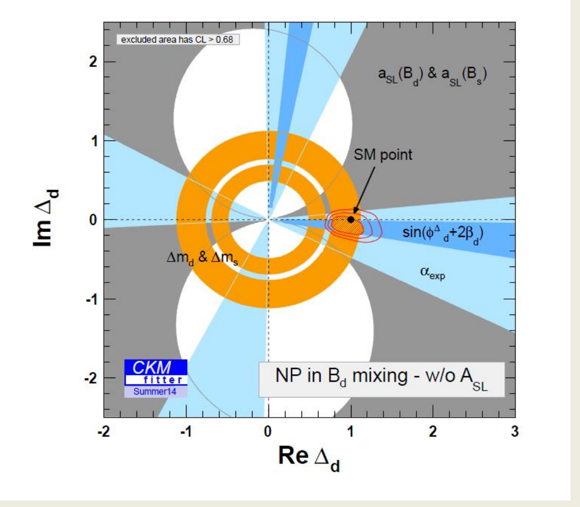
- Tree level:

$b \to u\ell\nu$	$\rho^2 + \eta^2$
$B \to DK$	γ
$B \to \rho\rho$, isospin, $S_{\psi K_S}$	γ



- FCNC

$S_{\psi K_S}$	$\sin[2\beta + \arg(\Delta_d)]$
Δm_B	$\lvert\Delta_d\rvert$
A_{SL}	$\sin[\arg(\Delta_d)]/\lvert\Delta_d\rvert$



Conclusions

1. The Kobayashi-Maskawa mechanism of CPV is at work ($\eta = 0.38 \pm 0.02$)
2. A NP contribution to $B^0 - \overline{B^0}$ mixing amplitude that carries a phase very different from the KM phase is constrained to lie below the 10% level
3. A NP contribution to $B^0 - \overline{B^0}$ mixing amplitude which is aligned with the KM phase is constrained to lie below the 20% level

The NP flavor puzzle

The NP flavor puzzle

- SM = EFT
- Flavor constraints
- The NP flavor puzzle
- Minimal flavor violation (MFV)

SM = Low energy EFT

- SM = low energy effective theory, valid below a scale $\Lambda \gg m_Z$:

Gravity

- $\Lambda_{\text{Planck}} \sim 10^{19}\ GeV$

Neutrino masses

- $\Lambda_{\text{Seesaw}} \lesssim 10^{15}\ GeV$

Dark Matter

- $\Lambda_{\text{WIMP}} \sim TeV$

The fine-tuning problem

- $\Lambda_{\tilde{t}} \sim TeV$

- Must consider non-renormalizable terms suppressed by powers of Λ

Non-renormalizable terms

Example: $\mathcal{L}^{NP}_{\Delta F=2} = \sum_{i\neq j} \frac{z_{ij}}{\Lambda^2}\left(\overline{Q_{Li}}\gamma_\mu Q_{Lj}\right)^2$

In particular: $\mathcal{L}^{NP}_{\Delta B=2} = \sum_{i\neq j} \frac{z_{db}}{\Lambda^2}\left(\overline{Q_{Ld}}\gamma_\mu Q_{Lb}\right)^2$

$$M^{NP}_{B\bar{B}} \sim \frac{1}{6}\frac{z_{db}}{\Lambda^2} m_B f_B^2 B_B$$

$$|M^{NP}_{B\bar{B}}/M^{SM}_{B\bar{B}}| < 0.2; Im(M^{NP}_{B\bar{B}}/M^{SM}_{B\bar{B}}) < 0.1$$

$$\frac{|z_{db}|}{\Lambda^2} < \frac{2.3\times 10^{-6}}{TeV^2}, \qquad \frac{Im(z_{db})}{\Lambda^2} < \frac{1.1\times 10^{-6}}{TeV^2}$$

Probing NP with FCNC

- Lower bounds on Λ for $z_{ij} = 1$
- Upper bounds on z_{ij} for $\Lambda = 1$ TeV

Operator	Λ[TeV] CPC	Λ[TeV] CPV	$\lvert z_{ij}\rvert$	$Im(z_{ij})$	Observables
$(\bar{s}_L\gamma_\mu d_L)^2$	9.8×10^{2}	1.6×10^{4}	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\epsilon_K$
$(\overline{s_R}d_L)(\overline{s_L}d_R)$	1.8×10^{4}	3.2×10^{5}	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\epsilon_K$
$(\bar{c}_L\gamma_\mu u_L)^2$	1.2×10^{3}	2.9×10^{3}	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;A_\Gamma$
$(\overline{c_R}u_L)(\overline{c_L}u_R)$	6.2×10^{3}	1.5×10^{4}	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;A_\Gamma$
$(\overline{b_L}\gamma_\mu d_L)^2$	6.6×10^{2}	9.3×10^{2}	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_B;S_{\psi K}$
$(\overline{b_R}d_L)(\overline{b_L}d_R)$	2.5×10^{3}	3.6×10^{3}	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_B;S_{\psi K}$
$(\overline{b_L}\gamma_\mu s_L)^2$	1.4×10^{2}	2.5×10^{2}	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};S_{\psi\phi}$
$(\overline{b_R}s_L)(\overline{b_L}s_R)$	4.8×10^{2}	8.3×10^{2}	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};S_{\psi\phi}$

Conclusions

- NP can contribute to FCNC at a level comparable to the SM even if it takes place at a scale that is six orders of magnitude above the electroweak scale
- If $z_{ij} = O(1)$, then $\Lambda > 10^4 - 10^5$ TeV
  - We misinterpreted the hints from the dark matter puzzle
  - We misinterpreted the hints from the fine tuning problem
- If $\Lambda_{\rm NP} = O(\text{TeV})$, then the NP flavor structure is far from generic
  - Degeneracy
  - Alignment
- The NP flavor puzzle: If there is NP at $\Lambda \sim$ TeV, why doesn’t it modify FCNC?

Minimal Flavor Violation (MFV)

- For $Y^{u,d,e} = 0$, the SM has an $[SU(3)]^5$ symmety
  - Y^u breaks $SU(3)_Q \times SU(3)_U$
  - Y^d breaks $SU(3)_Q \times SU(3)_D$
  - Y^e breaks $SU(3)_L \times SU(3)_E$
- MFV: $Y^{u,d,e}$ are the only source of $[SU(3)]^5$ breaking
- $Y^{u,d,e}$ = spurions: $[SU(3)]^5$ would have been respected if
  - $Y^u(3, \bar{3}, 1,1,1)$
  - $Y^d(3,1, \bar{3}, 1,1)$
  - $Y^e(1,1,1,3, \bar{3})$
- MFV: All higher dimension operators, constructed from SM-fields and Y^f-spurions, are formally invariant under $[SU(3)]^5$
- Example: Gauge mediated supersymmetry breaking

MFV at work

- Apply MFV to z_{ij} of the dimension-six terms:

Operator	$z_{ij} \propto$	CKM+GIM	$\lvert z_{ij}\rvert < (\Lambda/TeV)^2 \times$
$(\bar{s}_L\gamma_\mu d_L)^2$	$y_t^4(V_{ts}V_{td}^*)^2$	10^{-7}	9.0×10^{-7}
$(\overline{s_L}d_R)(\overline{s_R}d_L)$	$y_t^4 y_s y_d(V_{ts}V_{td}^*)^2$	10^{-14}	6.9×10^{-9}
$(\bar{c}_L\gamma_\mu u_L)^2$	$y_b^4(V_{cb}V_{ub}^*)^2$	10^{-14}	5.6×10^{-7}
$(\overline{c_L}u_R)(\overline{c_R}u_L)$	$y_b^4 y_c y_u(V_{cb}V_{ub}^*)^2$	10^{-20}	5.7×10^{-8}
$(\overline{b_L}\gamma_\mu d_L)^2$	$y_t^4(V_{tb}V_{td}^*)^2$	10^{-4}	2.3×10^{-6}
$(\overline{b_L}d_R)(\overline{b_R}d_L)$	$y_t^4 y_b y_d(V_{tb}V_{td}^*)^2$	10^{-9}	3.9×10^{-7}
$(\overline{b_L}\gamma_\mu s_L)^2$	$y_t^4(V_{tb}V_{ts}^*)^2$	10^{-3}	5.0×10^{-5}
$(\overline{b_L}s_R)(\overline{b_R}s_L)$	$y_t^4 y_b y_s(V_{tb}V_{ts}^*)^2$	10^{-6}	8.8×10^{-6}

- MFV allows NP at $\Lambda \sim$ TeV

The SM Flavor Puzzle

- Introduction
- The SM: from definition to Lagrangian
- The SM: from Lagrangian to phenomenology
- The CKM matrix: parametrization and UT's
- FCNC: SM suppression factors
- CP violation
- Baryogenesis
- Testing CKM
- The New Physics flavor puzzle
- **The Standard Model flavor puzzle**
- The flavor of Higgs
- Flavor anomalies?

The SM Flavor Puzzle

- The SM flavor puzzle
- The FN mechanism
- The flavor of neutrinos

Smallness and Hierarchy

$y_t \sim 1$	$y_c \sim 10^{-2}$	$y_u \sim 10^{-5}$
$y_b \sim 10^{-2}$	$y_s \sim 10^{-3}$	$y_d \sim 10^{-4}$
$y_\tau \sim 10^{-2}$	$y_\mu \sim 10^{-3}$	$y_e \sim 10^{-6}$
$\|V_{us}\| \sim 0.2$	$\|V_{cb}\| \sim 0.04$	$\|V_{ub}\| \sim 0.004$
$\delta_{KM} \sim 1$		

- Only two parameters are $O(1)$:
  - y_t and δ_{KM}
- The other flavor parameters exhibit smallness and hierarchy
  - $y_e/y_t \sim 10^{-6}$
- Accidental or for a reason?
- Compare to the other SM parameters:
  - $g_s \sim 1, g \sim 0.6, e \sim 0.3, \lambda \sim 0.12$

Proposed solutions

- Approximate Abelian symmetry (FN)
- Approximate non-Abelian symmetry (DLK)
- Conformal dynamics (NS)
- Location in extra dimension (A-HS)
- Loop corrections
- Non-renormalizable terms (GL)

The Froggatt-Nielsen (FN) mechanism

- $U(1)_H$ symmetry
- Broken by a small parameter ϵ; $H(\epsilon) = -1$
- In general, different fermion generations carry different H-charges
- $y_f \propto \epsilon^{H(\overline{f_L})+H(f_R)+H(\phi)}$
- $|V_{ij}| \propto \epsilon^{H(Q_{Li})-H(Q_{Lj})}$

FN - example

- $H(\bar{Q}_i) = H(U_i) = H(E_i) = (2,1,0)$
- $H(\bar{L}_i) = H(D_i) = (2,2,2), H(\phi) = 0$
- $Y^u \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$; $Y^d \sim (Y^e)^T \sim \begin{pmatrix} \epsilon^4 & \epsilon^4 & \epsilon^4 \\ \epsilon^3 & \epsilon^3 & \epsilon^3 \\ \epsilon^2 & \epsilon^2 & \epsilon^2 \end{pmatrix}$

$y_t \sim 1$	$y_c \sim \epsilon^2$	$y_u \sim \epsilon^4$
$y_b \sim \epsilon^2$	$y_s \sim \epsilon^3$	$y_d \sim \epsilon^4$
$y_\tau \sim \epsilon^2$	$y_\mu \sim \epsilon^3$	$y_e \sim \epsilon^4$
$\lvert V_{us}\rvert \sim \epsilon$	$\lvert V_{cb}\rvert \sim \epsilon$	$\lvert V_{ub}\rvert \sim \epsilon^2$

- For $\epsilon \sim 0.05$ – roughly consistent with the observed hierarchy

The flavor of neutrinos

- $\Delta m^2_{21} = (7.5 \pm 0.2) \times 10^{-5}\ eV^2, \left|\Delta m^2_{32}\right| = (2.5 \pm 0.1) \times 10^{-3}\ eV$^2
- $|U_{e2}| = 0.55 \pm 0.01, \left|U_{\mu 3}\right| = 0.67 \pm 0.03, |U_{e3}| = 0.148 \pm 0.003$

- $\left|U_{\mu 3}\right| >$ any $|V_{ij}|$
- $|U_{e2}| >$ any $\left|V_{ij}\right|$
- $|U_{e3}|$ is not particularly small $(|U_{e3}| \sim 0.4|U_{e2}U_{\mu 3}|)$
- $m_2/m_3 > 1/6 >$ any m_i/m_j for charged fermions

- Neither smallness nor hierarchy have been observed so far in the neutrino related flavor parameters

Anarchy *vs.* TBM

- Anarchy:
  - $M_\nu \sim \frac{v^2}{\Lambda_{\text{Seesaw}}} \begin{pmatrix} 0.6 & 0.6 & 0.6 \\ 0.6 & 0.6 & 0.6 \\ 0.6 & 0.6 & 0.6 \end{pmatrix}$
  - Consistent with FN with $H(L_1) = H(L_2) = H(L_3)$

- Tribimaximal mixing:
  - $|U|_{TBM} = \begin{pmatrix} 2/\sqrt{6} & 1/\sqrt{3} & 0 \\ 1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$
  - Requires non-Abelian symmetry (A_4) and special pattern of symmetry breaking

The flavor of Higgs

The Flavor of Higgs

Testing the SM predictions

Testing flavor models

SM: $Y^F = (\sqrt{2}/v)M_F$

- Proportional
  - ${}^{y_i}/_{y_j} = {}^{m_i}/_{m_j} \quad (y_i \equiv Y_{ii})$

- Factor of proportionality
  - ${}^{y_i}/_{m_i} = {}^{\sqrt{2}}/_{v}$

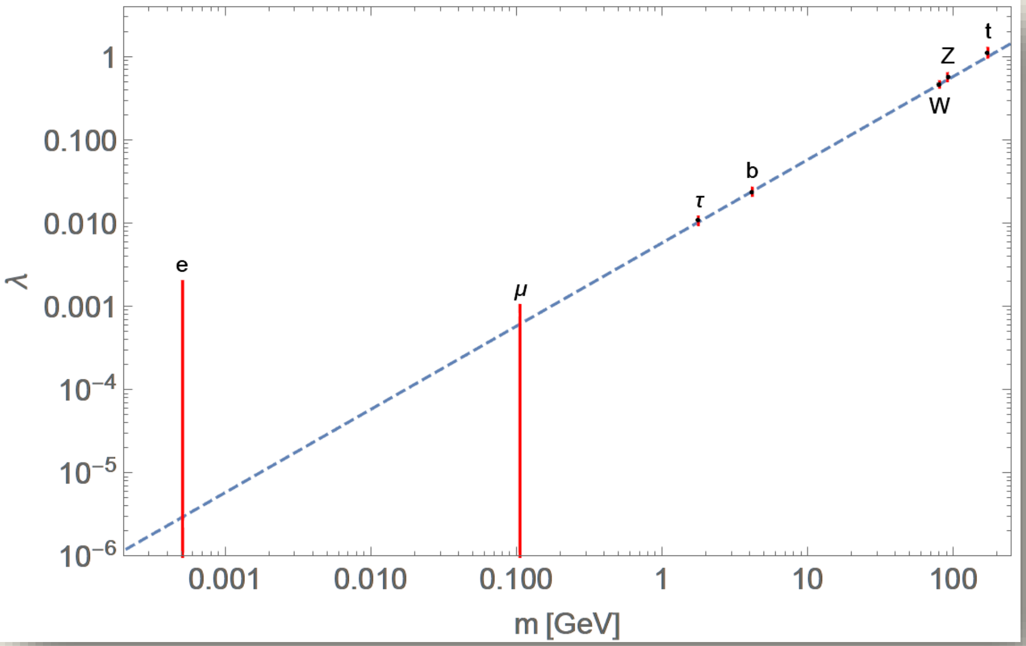
- Diagonal
  - $Y_{ij} = 0$ for $i \neq j$

- Real
  - $Im(y_i/m_i) = 0$

Proportionality?

$$\mu_f \equiv \frac{\sigma(pp \to h)BR(h \to f)}{[\sigma(pp \to h)BR(h \to f)]_{SM}}$$

μ_f	**Experiment**
$\mu_{t\bar{t}h}$	1.29 ± 0.18
μ_{ZZ^*}	1.17 ± 0.23
μ_{WW^*}	0.99 ± 0.15
$\mu_{b\bar{b}}$	0.98 ± 0.20
$\mu_{\tau\tau}$	1.09 ± 0.23
$\mu_{\mu\mu}$	< 1.7
μ_{ee}	$< 4 \times 10^5$



Diagonality?

Observable	Experiment	$Y_{ij} \leq$
$\mathrm{BR}(t \to ch)$	$\leq 2.2 \times 10^{-3}$	9.0×10^{-2}
$\mathrm{BR}(t \to uh)$	$\leq 2.4 \times 10^{-3}$	9.4×10^{-2}
$\mathrm{BR}(h \to \tau\mu)$	$\leq 2.5 \times 10^{-3}$	1.4×10^{-3}
$\mathrm{BR}(h \to \tau e)$	$\leq 6.1 \times 10^{-3}$	2.3×10^{-3}
$\mathrm{BR}(h \to \mu e)$	$\leq 3.4 \times 10^{-4}$	6.0×10^{-4}

Conclusions

- $y_e, y_\mu < y_\tau$ in support of proportionality
- y_t, y_b, y_τ obey $y_{3rd}/m_{3rd} \approx \sqrt{2}/v$ in agreement with the SM factor
- Strong upper bounds on violation of diagonality, $Y_{tq}/Y_{tt} < 0.1,\ Y_{\tau\ell}/Y_{\tau\tau} < 0.1$

- The beginning of Higgs flavor physics

SM EFT

$$\mathcal{L}_Y^{d=4} = \lambda_{ij}\overline{f_L^i} f_R^j \phi + h.c.$$

$$\mathcal{L}_Y^{d=6} = \frac{\lambda'_{ij}}{\Lambda^2}\overline{f_L^i} f_R^j \phi\left(\phi^\dagger \phi\right) + h.c.$$

$$\sqrt{2}m = V_L\left(\lambda + \frac{v^2}{2\Lambda^2}\lambda'\right)V_R^\dagger v$$

where $m = diag(m_e, m_\mu, m_\tau)$

$$Y_{ij} = \frac{\sqrt{2}m_i}{v}\delta_{ij} + \frac{v^2}{\Lambda^2}\hat{\lambda}_{ij}$$

where $\hat{\lambda} = V_L \lambda' V_R^\dagger$

MFV

- $\lambda'_\ell = a\lambda_\ell + b\lambda_\ell\lambda_\ell^\dagger\lambda_\ell + O\left(\lambda_\ell^5\right)$
- $Y_{ij}^e = \frac{\sqrt{2}m_i}{v}\delta_{ij}\left(1 + \frac{av^2}{\Lambda^2} + \frac{2bm_i^2}{\Lambda^2}\right)$

- Diagonality: $Y_{\mu\tau}, Y_{\tau\mu} = 0$
- Factor: $\mathrm{y}_\tau = \frac{\sqrt{2}m_\tau}{v}\ (1 + \frac{av^2}{\Lambda^2})$
- Proportionality: $\frac{y_\mu}{y_\tau} = \frac{m_\mu}{m_\tau}[1 - \frac{2b\left(m_\tau^2 - m_\mu^2\right)}{\Lambda^2}]$

FN

- $\lambda'_{ij} = O(1)\lambda_{ij}$
- $Y^e_{ij} = \frac{\sqrt{2}m_i}{v}\delta_{ij} + \frac{a_{ij}v^2}{\Lambda^2} \times \begin{cases} U_{ij}\,(m_j\,/v) & (i \leq j) \\ (m_j/v)/U_{ji} & (i > j) \end{cases}$

- Diagonality: $Y_{\mu\tau} = O(\frac{U_{23}vm_\tau}{\Lambda^2}), Y_{\tau\mu} = O(\frac{vm_\mu}{U_{23}\Lambda^2})$
- Factor: $y_\tau = \frac{\sqrt{2}m_\tau}{v}\ [1 + \frac{a_\tau v^2}{\Lambda^2}]$
- Proportionality: $\frac{y_\mu}{y_\tau} = \frac{m_\mu}{m_\tau}[1 + \frac{(a_\mu - a_\tau)v^2}{\Lambda^2}]$

h-testing flavor models

- Measure $h \to \tau\tau, \tau\mu, \mu\mu$
- Test MFV, FN, NFC, GL…

Model	$\frac{Y_\tau^2}{2m_\tau^2/v^2}$	$\frac{Y_\mu^2/Y_\tau^2}{m_\mu^2/m_\tau^2}$	$\frac{Y_{\mu\tau}^2}{Y_\tau^2}$
SM	1	1	0
MFV*	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(m_\tau^2/\Lambda^2)$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{\mu3}\|^2 v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(10^{-2})$

Flavor Anomalies?

$$R_{K^{(*)}}, R_{D^{(*)}}, \Delta A_{CP}, K_L \to \pi\nu\nu$$

$B \to K^{(*)}\mu^+\mu^-$

$$R_{K^{(*)},[a,b]} = \frac{\int_a^b dq^2\,[d\Gamma(B \to K^{(*)}\mu^+\mu^-)/dq^2}{\int_a^b dq^2\,[d\Gamma(B \to K^{(*)}e^+e^-)/dq^2}$$

Observable	SM	Experiment
$R_{K,[1,6]GeV^2}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*,[1.1,6]GeV^2}$	1.00 ± 0.01	$0.69^{+0.11}_{-0.07} \pm 0.05$
		$0.846^{+0.060\,+0.016}_{-0.054\,-0.014}$
$R_{K^*,[0.045,1.1]GeV^2}$	0.91 ± 0.03	$0.66^{+0.11}_{-0.07} \pm 0.03$

- LHCb, 1903.09252

$R_{K^{(*)}}$ from NP

- Given other measurements, it is plausible that (if indeed NP) the modification is in $b \to s\mu\mu$
- Destructive interference is needed
- Assume $\Lambda_{NP} \gg m_W \Longrightarrow$ SM-EFT
- Only two dimension-six operators
- $\mathcal{L}_{d=6} \sim \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [C_{LL} O_{LL} + C_{RL} O_{RL}]$

  $O_{AB} = (\bar{s}\gamma^{\mu} P_A b)(\bar{\mu}\gamma_{\mu} P_B \mu)$

$R_{K^{(*)}}$ from SM-EFT

$$R_{K,[1,6]GeV^2} = 1 + 2Re\left(\frac{C_{LL}^{NP} + C_{RL}^{NP}}{C_{LL}^{SM}}\right)$$

$$R_{K^*,[1,6]GeV^2} \approx 1 + 2Re\left(\frac{C_{LL}^{NP} - C_{RL}^{NP}}{C_{LL}^{SM}}\right)$$

$\Longrightarrow C_{LL}^{NP}/C_{LL}^{SM} \sim -0.15$ is singled out as the prime candidate to explain the anomalies

$R_{K^{(*)}}$ from leptoquarks

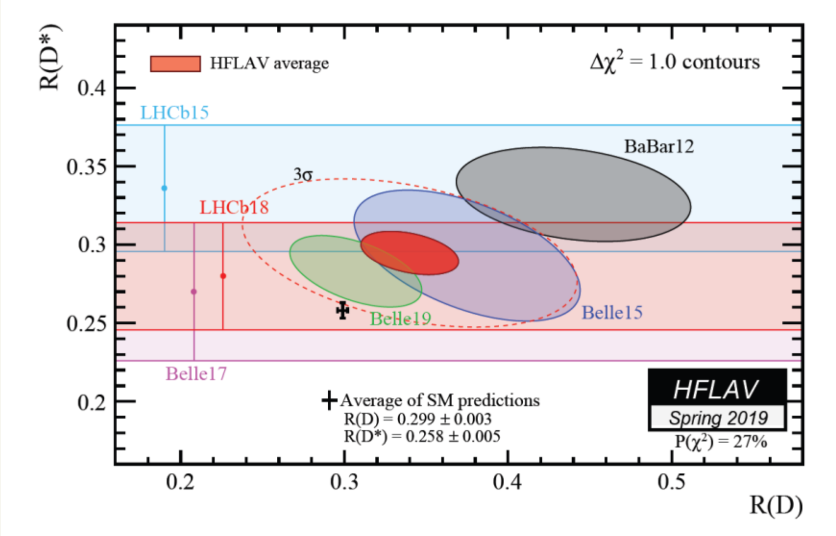
Representation	Couples to	Generates
$(3,1)_{-4/3}$	$\bar{D}\bar{E}$	C_{RR}
$(3,2)_{+1/6}$	$\bar{D}L$	C_{RL}
$(3,2)_{+7/6}$	$\bar{Q}E$	C_{LR}
$(3,3)_{-1/3}$	$\bar{Q}\bar{L}$	C_{LL}

- Only $T(3,3)_{-1/3}$ can account for both R_K and R_{K^*}
- To generate $C_{LL}^{NP}/C_{LL}^{SM} \sim -0.15$, we must have $\frac{Re(Y_{\mu s}^{T} Y_{\mu b}^{T*})}{m_T^2} \sim -\frac{0.004}{TeV^2}$
- Predictions: $\frac{BR(B_s \to \mu^+\mu^-)}{BR(B_s \to \mu^+\mu^-)_{SM}} = \frac{BR(B_s \to \phi\mu^+\mu^-)}{BR(B_s \to \phi\mu^+\mu^-)_{SM}} = R_K = R_{K^*}$
- If Y_{ij}^T obey MFV, then $\frac{Y_{\tau s}^T Y_{\tau b}^{T*}}{Y_{\mu s}^T Y_{\mu b}^{T*}} = \frac{y_\tau^2}{y_\mu^2}$
- In this case, the combination of $R_K, BR(B \to K\tau\tau), \Delta m_{B_s}$ and the LHC lower bound on m_T cannot be satisfied simultaneously $\Longrightarrow$MFV will be excluded

$B \to D^{(*)}\tau\nu$

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

Observable	SM	Experiment	EXP/SM
R_D	0.299 ± 0.003	0.340 ± 0.030	1.14 ± 0.10
R_{D^*}	0.258 ± 0.005	0.295 ± 0.014	1.14 ± 0.05



$R_{D^{(*)}}$ from NP

- Assume $\Lambda_{NP} \gg m_W \Longrightarrow$ SM-EFT
- 3 combinations of 2 lepton and 2 quark fields can give the required $b \to c$ transition: $\bar{L}L\bar{Q}Q, \bar{E}L\bar{u}Q, \bar{e}L\bar{Q}d$
- Given the presence of L and Q, many related FCNC processes

$R_{D^{(*)}}$ in simplified models

Representation	Couples to	Generates
scalar $(3,1)_{-1/3}$	$\bar{L}Q^c, \bar{E}U^c$	$C_{QQLL}^{3333}, C_{QuLe}^{3233}$
vector $(1,3)_0$	$\bar{Q}Q, \bar{L}L$	C_{QQLL}^{3333}
vector $(3,1)_{+2/3}$	$\bar{Q}L, \bar{D}E$	$C_{QQLL}^{3333}, C_{QdLe}^{3333}$
scalar $(3,2)_{+7/6}$	$\bar{U}L, \bar{Q}E$	C_{QuLe}^{3233}
Vector $(3,2)_{-5/6}$	$\bar{Q}E^c, \bar{L}D^c$	C_{QdLe}^{3333}

- The flavor indices correspond to models of horizontal $[SU(2)]^3$ models
- Can work for $m_X <$ a few TeV
- Many constraints from other measurements, e.g. $b\bar{b} \to \tau\tau$

ΔA_{CP}

- CP violation in charm decays:
  - $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$
  - $A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}$
- SM:
  - $$\Delta A_{CP} = 4Im\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) Im\left(\frac{A_{\Delta U=0}}{A_{\Delta U=1}}\right)$$
    $$\approx -2.8 \times 10^{-3} \times Im\left(\frac{A_{\Delta U=0}}{A_{\Delta U=1}}\right)$$
- 2019 measurement (LHCb, 1903.08726):
  - $\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$

ΔA_{CP} - Theory

- SM:
  - $\Delta A_{CP}^{SM} \approx -2.8 \times 10^{-3} \times \left(\frac{\alpha_s}{\pi}\right) \times r_{QCD}$
  - $r_{QCD} \sim 10$? Grossman+Schacht, 1903.10952
- NP: Dery+Nir, in progress
  - EFT $\Longrightarrow \Lambda_{NP} < 40\ TeV$
  - 2HDM
  - SUSY
  - Vector-like up quarks

$K_L \to \pi^0 \nu \bar{\nu}$

- KOTO experiment at J-PARC:
  - S.E.S: 6.9×10^{-10}
  - BG estimation: 0.05 ± 0.02
  - Shinohara@KAON2019: 4 candidate events
- SM:
  - $\mathrm{BR} \sim 3.0 \times 10^{-11}$
  - Grossman-Nir bound: $\mathrm{BR} < 1.5 \times 10^{-9}$
  - ?

Flavored Conclusions

FCNC: Loop x CKM x GIM suppression

$\Longrightarrow$ Excellent probe of NP at very high energy scales

Quarks: smallness, hierarchy

$\Longrightarrow$ Approximate symmetry?

Squarks: degeneracy, alignment

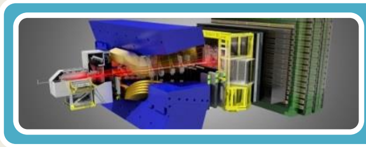
$\Longrightarrow$ Flavor paradise, but where are they?

Neutrinos: anarchy $\Longrightarrow$ Knowing more

does not necessarily mean understanding better

Higgs: diagonality? proportionality?

$\Longrightarrow$ A new opportunity for flavor



R_K, R_D: Statistical fluctuations or New Physics?

$\Longrightarrow$ Stay tuned for LHCb and Belle II