Flavor Physics

Invisibles15 School
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Plan of Lectures

1. Questions for the LHC
2. Introduction to Flavor
   - Definitions and Motivation
   - Flavor in the Standard Model
3. Past: What have we learned?
   - Lessons from the B-factories
4. Present: The open questions
   - The flavor puzzles
   - Flavor models
5. Future: What will we learn?
   - Flavor@LHC
   - The flavor of h

Questions for the LHC

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- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What happened at the electroweak phase transition?
- How was the baryon asymmetry generated?
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

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- What is the solution of the flavor puzzles?
  The topic of these lectures

Introduction to Flavor

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:

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

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:

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

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:
  - Couplings/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:
  - Couplings/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
  - $B \to \psi K \quad (\bar{b} \to \bar{c} c \bar{s}) : \quad \Delta b = -\Delta s = 1;\ \Delta c = 0$
- Flavor changing neutral current (FCNC) 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

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]

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 experimental 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 experimental CPV

- $1964 - 2000$
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- $2000 - 2015,\ 5\sigma$
  - $S_{\psi K_S} = +0.68 \pm 0.02$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.63 \pm 0.06$, $S_{f K_S} = +0.69 \pm 0.11$
  - $S_{K^+ K^- K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+\pi^-} = -0.66 \pm 0.06$, $C_{\pi^+\pi^-} = -0.31 \pm 0.05$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.98 \pm 0.17$, $S_{D^* D^*} = -0.71 \pm 0.09$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.082 \pm 0.006$
  - $\mathcal{A}_{D_+ K^\pm} = +0.19 \pm 0.03$
  - $\mathcal{A}_{B_s \to K^-\pi^+} = +0.26 \pm 0.04$

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: Belle-II, LHCb-upgrade...

The Standard Model

The Standard Model

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

$$\Downarrow$$

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yuk}}$$

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

A comment on $\mathcal{L}_\psi$

$$\boxed{\mathcal{L}_\psi = 0}$$

- Quarks:
  - $Q_L(3,2)_{+1/6},\ U_R(3,1)_{+2/3},\ D_R(3,1)_{-1/3}$ = chiral rep
    No Dirac mass
  - $Q_L(3,2)_{+1/6},\ U_R(3,1)_{+2/3},\ D_R(3,1)_{-1/3} = U(1)_Y$-charged
    No Majorana mass
- Leptons:
  - $L_L(1,2)_{-1/2},\ E_R(1,1)_{-1}$ = chiral representation
    No Dirac mass
  - $L_L(1,2)_{-1/2},\ E_R(1,1)_{-1}$ = charged under $U(1)_Y$
    No Majorana mass

$\mathcal{L}_{\rm SM}$

$$
\begin{aligned}
\mathcal{L}_{\rm kin} &= -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\
&\quad +i\overline{Q_{Li}}\not{D}Q_{Li} + i\overline{U_{Ri}}\not{D}U_{Ri} + i\overline{D_{Ri}}\not{D}D_{Ri} \\
&\quad +i\overline{L_{Li}}\not{D}L_{Li} + i\overline{E_{Ri}}\not{D}E_{Ri} \\
&\quad +(D^\mu\phi)^\dagger(D_\mu\phi) \\
\mathcal{L}_{\rm Higgs} &= -\mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 \quad (\mu^2<0,\ \lambda>0) \\
\mathcal{L}_{\rm Yuk} &= \overline{Q_{L}}_iY^u_{ij}\tilde{\phi}U_{Rj} + \overline{Q_{L}}_iY^d_{ij}\phi D_{Rj} + \overline{L_{L}}_iY^e_{ij}\phi E_{Rj} + {\rm h.c.}
\end{aligned}
$$

Flavor Symmetry

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

Flavor Violation

- $\mathcal{L}_{\text{Yuk}} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj} + \overline{L_L}_i Y^e_{ij} \phi E_{Rj}$
  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
- $Y^d \to V_Q Y^d V_D^\dagger, \quad Y^u \to V_Q Y^u V_U^\dagger$
- Can be used to reduce the number of parameters in Y^u, Y^d

Counting flavor parameters

- Quark sector:
  - $Y_u, Y_d \implies 2 \times [9_R + 9_I]$
  - $[SU(3)]^3_q \to U(1)_B \implies -3 \times [3_R + 6_I] + 1_I$
  - Physical parameters: $9_R + 1_I$

- Lepton sector:
  - $Y_e \implies 9_R + 9_I$
  - $[SU(3)]^2_\ell \to [U(1)]^3 \implies -2 \times [3_R + 6_I] + 3_I$
  - Physical parameters: 3_R

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: $Y^d \to V\lambda^d, \quad Y^u \to \lambda^u$

Kobayashi and Maskawa

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 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

FCNC

- FCNC $\equiv$ FC processes involving only down-type or only up-type quarks
- Example: Neutral meson mixing:
  $K^0 - \overline{K}^0$, $B^0 - \overline{B}^0$, $B_s^0 - \overline{B}_s^0$, $D^0 - \overline{D}^0$

Sector	CP-conserving	CP-violating
sd	$\Delta m_K/m_K = 7.0 \times 10^{-15}$	$\epsilon_K = 2.3 \times 10^{-3}$
cu	$\Delta m_D/m_D = 8.7 \times 10^{-15}$	$A_\Gamma/y_{\rm CP} \lesssim 0.2$
bd	$\Delta m_B/m_B = 6.3 \times 10^{-14}$	$S_{\psi K} = +0.67 \pm 0.02$
bs	$\Delta m_{B_s}/m_{B_s} = 2.1 \times 10^{-12}$	$S_{\psi\phi} = -0.04 \pm 0.09$

FCNC: Loop suppression I

- The $W-$boson cannot mediate FCNC process at tree level since it couples to up-down pairs;
  Only neutral bosons can potentially mediate FCNC at tree level

- Massless gauge bosons have flavor-universal and, in particular, flavor diagonal couplings;
  The gluons and the photon do not mediate FCNC at tree level

What about Z? h?

FCNC: Loop suppression II

- Within the SM, the $Z-$boson does not mediate FCNC at tree level because all fermions with the same color and charge originate in the same $SU(2)_L \times U(1)_Y$ representation

- Within the SM, the $h-$boson does not mediate FCNC at tree level because
  - All SM fermions are chiral $\Longrightarrow$ no bare mass terms
  - The scalar sector has a single Higgs doublet

Within the SM, all FCNC processes are loop suppressed

FCNC: CKM- and GIM-suppression

- All FC processes $\propto$ off-diagonal entries in the CKM matrix
  $|V_{us}|, |V_{cd}| \sim \lambda; \quad |V_{cb}|, |V_{ts}| \sim \lambda^2; \quad |V_{ub}|, |V_{td}| \sim \lambda^3$
  - $\Gamma(b \to s\gamma) \propto |V_{tb}V_{ts}|^2 \sim \lambda^4$
  - $\Delta m_B \propto |V_{tb}V_{td}|^2 \sim \lambda^6$
- If all quarks in a given sector were degenerate
  $\Longrightarrow$ No FC W-couplings
- FCNC in the down (up) sector
  $\propto$ Δm^2 between the quarks of the up (down) sector
- The GIM-suppression effective for processes involving the first two generations
  - $\Delta m_K \propto (m_c^2 - m_u^2)/m_W^2$
  - $\Delta m_D^{\text{s.d.}} \propto (m_s^2 - m_d^2)/m_W^2$

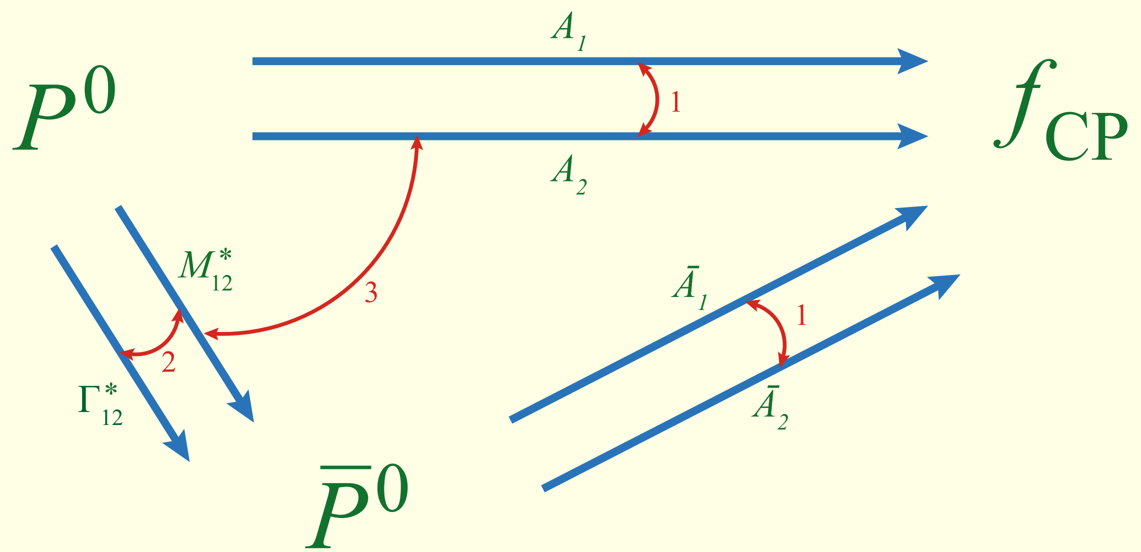
Intermediate summary I

- Flavor violation: m_q, $V_{\rm CKM}$
- Flavor changing processes: $V_{\rm CKM}$
- CP violation: η

- FCCC: tree level
- FCNC: loop- (α_2^2), CKM- (V_{ij}), GIM- ($\frac{m_2^2-m_1^2}{m_W^2}$) suppressed

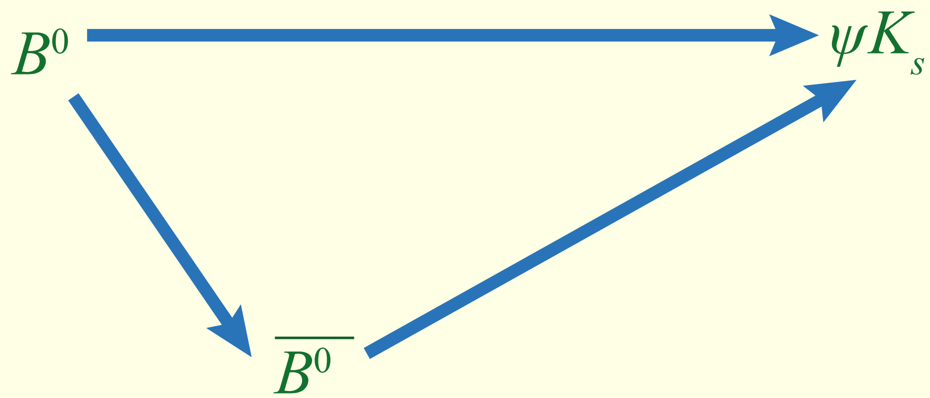
What have we learned?

The three types of CPV



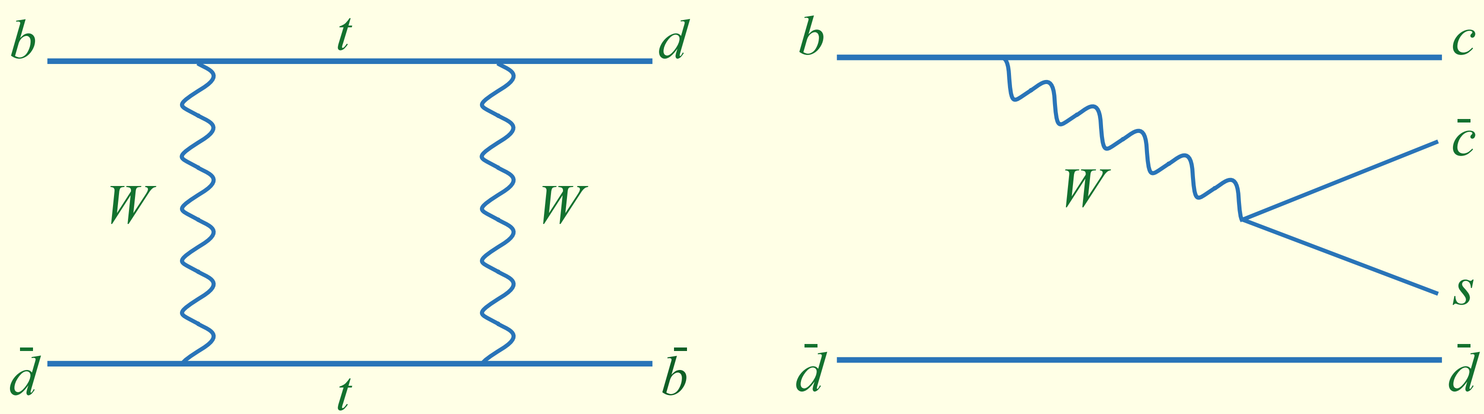
1	Decay	$\vert\bar{A}/A\vert \neq 1$	$\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}$	$\mathcal{A}_{K^\mp\pi^\pm}$	$P^\pm \to f^\pm$
2	Mixing	$\vert q/p\vert \neq 1$	$\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta M - i\Delta\Gamma}$	$\mathcal{R}e\ \varepsilon$	$P^0, \overline{P}^0 \to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

$S_{\psi K_S}$



- 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



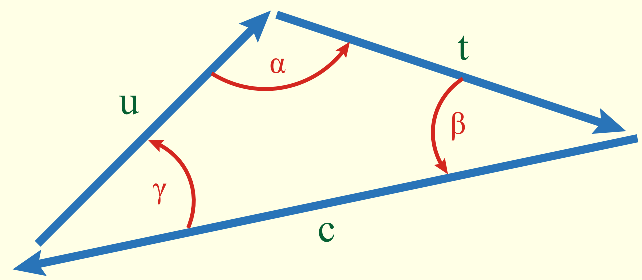
M_{12} $\bar{A}_{\psi K}$

- $$S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}$$
- 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 $\boxed{V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0}$

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



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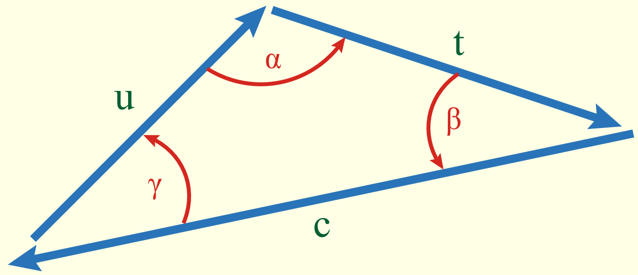
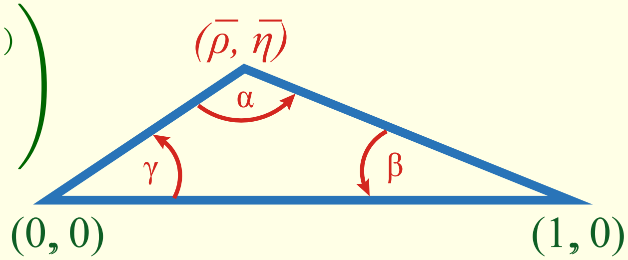


- Rescale and rotate: $\boxed{A\lambda^3\left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)\right] = 0}$

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



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

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

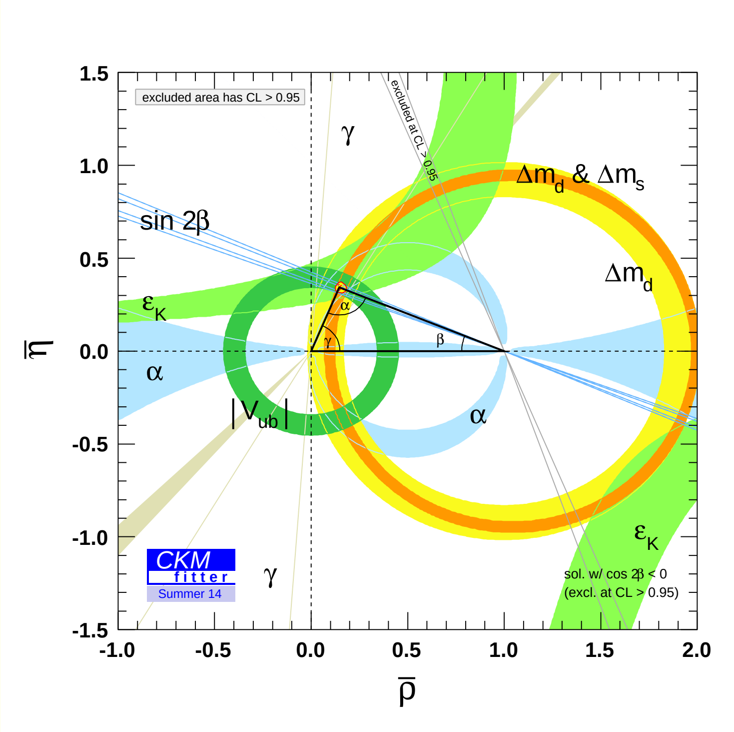
Testing CKM – Take I

- 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 $f(\rho, \eta)$:
  - $b \to u\ell\nu \ \Longrightarrow \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \ \Longrightarrow \propto |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - $S_{\psi K_S} \ \Longrightarrow \ \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
  - $S_{\rho\rho}(\alpha)$
  - $\mathcal{A}_{DK}(\gamma)$
  - ϵ_K

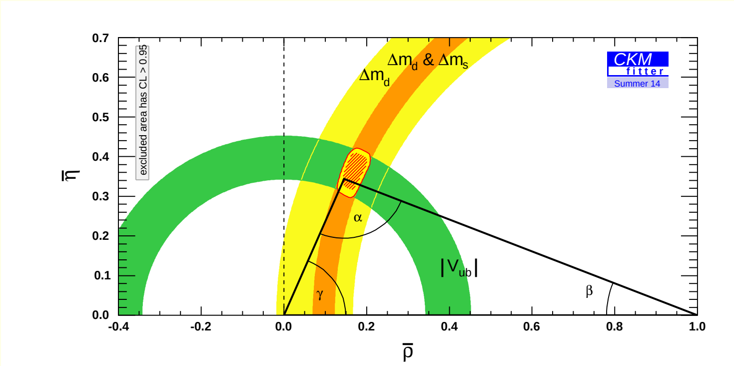
The B-factories Plot

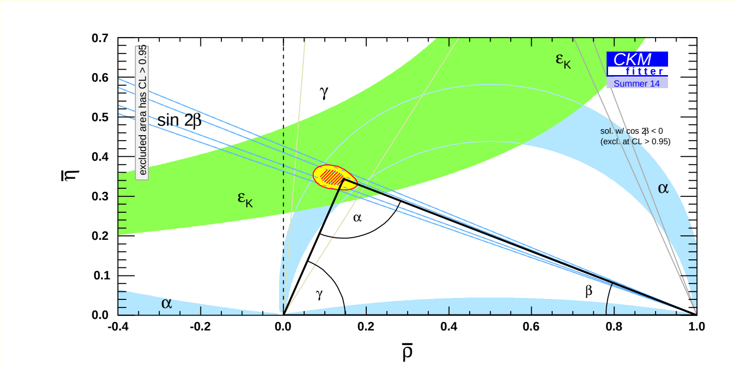


CKMFitter

Very likely, the CKM mechanism dominates FV and CPV

CPC vs. CPV

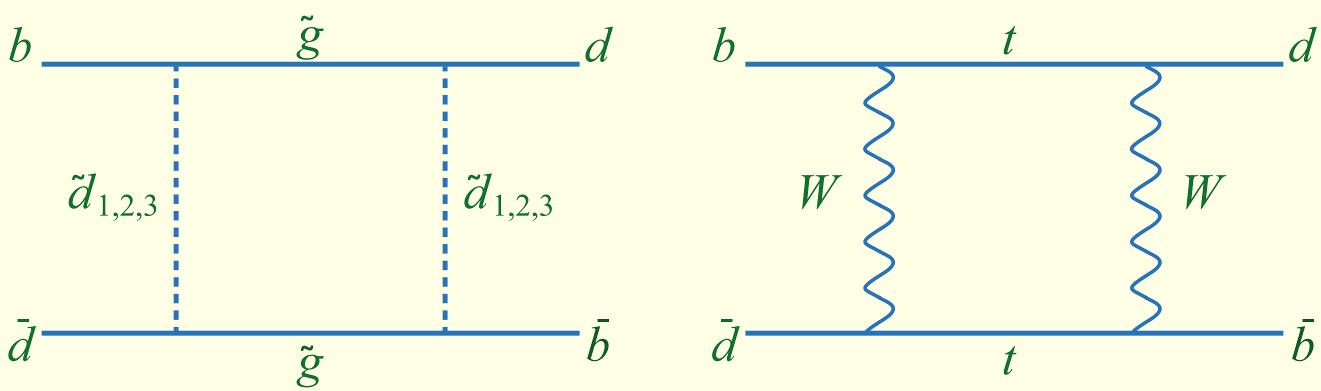




Very likely, the KM mechanism dominates CP violation

$S_{\psi K_S}$ with NP

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



$r_d e^{2i\theta_d} = 1 + h_d e^{2i\sigma_d} = \frac{A^{\rm full}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$

- $\boxed{S_{\psi K_S} = \sin[2(\beta+\theta_d)] = f(\rho,\eta,h_d,\sigma_d)}$

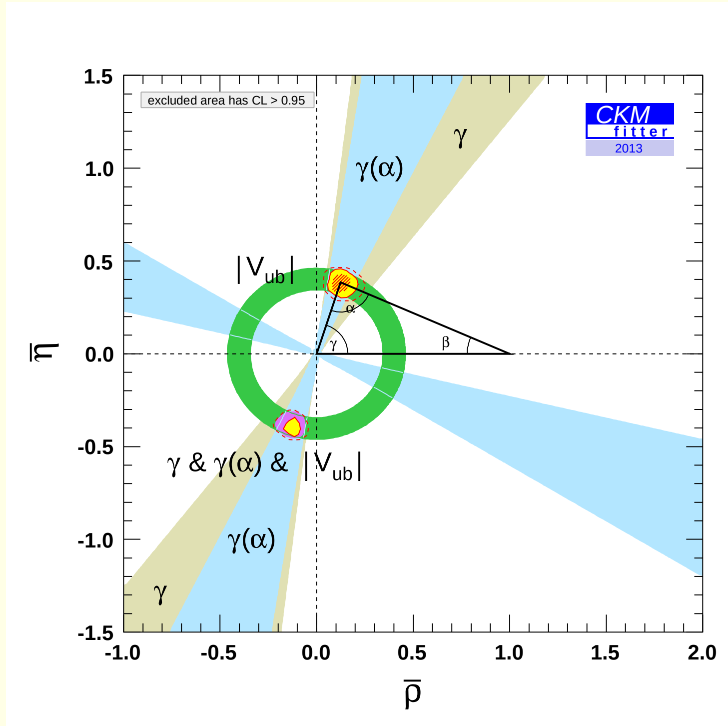
Testing CKM - take II

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

- Find whether $\eta = 0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d \gtrsim 1$ is allowed
  If not $\Longrightarrow$ The CKM mechanism is dominant

What have we learned?

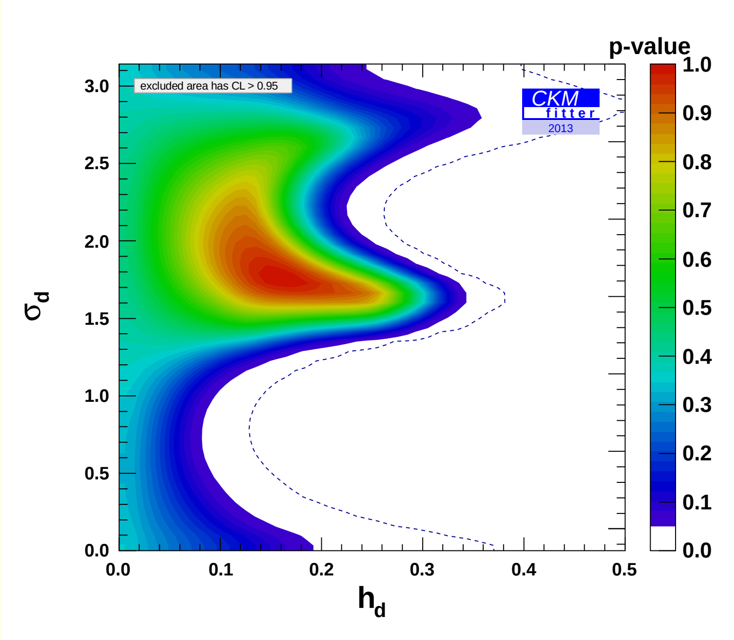
$$\eta \neq 0?$$



- The KM mechanism is at work

What have we learned?

$h_d \ll 1$?



- The KM mechanism dominates CP violation
- The CKM mechanism dominates flavor violation

NP in flavor?

• Most tensions either disappeared or below 3σ or involve large hadronic uncertainties:

- Lepton universality in $B \to D^{(*)}\tau\nu$
- Lepton universality in $B \to K\ell^+\ell^-$
- Angular distribution in $B \to K^*\ell^+\ell^-$
- CP violation in $D \to K^+K^-, \pi^+\pi^-$
- CP violation in $B_{d,s} \to \ell\nu X$

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

- BaBar: 3.4σ deviation from SM in $R(D^{(*)}) = \frac{\Gamma(B\to D^{(*)}\tau\nu)}{\Gamma(B\to D^{(*)}\ell\nu)}$

	BaBar	Belle	LHCb	SM
$R(D)$	0.44 ± 0.07	0.37 ± 0.07		0.30 ± 0.02
$R(D^*)$	0.33 ± 0.03	0.29 ± 0.04	0.34 ± 0.04	0.252 ± 0.003

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

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- Naively: $R(D) = 0.41 \pm 0.05 = 3.1\sigma$,
  $R(D^*) = 0.32 \pm 0.02 = 3.4\sigma$, $R(D^{(*)}) = 4.6\sigma$
- τ's difficult for B-factories
- SM predictions fairly robust: HQS + lattice QCD

Z. Ligeti in Naturalness 2014 (WIS)

Intermediate summary II

- 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
- The CKM mechanism is the dominant source of the flavor violation observed in meson decays
- NP contributions to the observed FCNC are small ($s \leftrightarrow d$, $c \leftrightarrow u$, $b \leftrightarrow d$, $b \leftrightarrow s$)
- So what remains to be understood?

The Flavor Puzzles

Smallness and Hierarchy

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

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 0.1$

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- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 0.1$
- SM flavor parameters have structure: smallness + hierarchy
- Why? = The SM flavor puzzle

Neither Smallness Nor Hierarchy

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

Gonzalez-Garcia et al., 1409.5439

Neither Smallness Nor Hierarchy

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Gonzalez-Garcia et al., 1409.5439

- $|U_{\mu 3}| >$ any $|V_{ij}|$;
- $|U_{e2}| >$ any $|V_{ij}|$
- $|U_{e3}| \not\ll |U_{e2} U_{\mu 3}|$
- $m_2/m_3 \gtrsim 1/6 >$ any m_i/m_j for charged fermions
- So far, neither smallness nor hierarchy
- Why is the ν flavor structure different?
  = The ν flavor puzzle

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.80-0.85 & 0.51-0.58 & 0.14-0.16 \\ 0.22-0.52 & 0.44-0.70 & 0.61-0.79 \\ 0.25-0.53 & 0.46-0.71 & 0.59-0.78 \end{pmatrix}$$

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- Tribimaximal-ists:

$$|U|_{\rm TBM} = \begin{pmatrix} 0.82 & 0.58 & 0 \\ 0.41 & 0.58 & 0.71 \\ 0.41 & 0.58 & 0.71 \end{pmatrix}$$

- Anarch-ists:

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

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 $\Longrightarrow \Lambda_{\rm top-partners} \sim\ TeV$
   Dark matter $\Longrightarrow \Lambda_{\rm wimp} \sim\ TeV$

$$\Downarrow$$

- 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:

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

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

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

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

Some data

Sector	CP-conserving	CP-violating
sd	$\Delta m_K/m_K = 7.0 \times 10^{-15}$	$\epsilon_K = 2.3 \times 10^{-3}$
cu	$\Delta m_D/m_D = 8.7 \times 10^{-15}$	$A_\Gamma/y_{\rm CP} \lesssim 0.2$
bd	$\Delta m_B/m_B = 6.3 \times 10^{-14}$	$S_{\psi K} = +0.67 \pm 0.02$
bs	$\Delta m_{B_s}/m_{B_s} = 2.1 \times 10^{-12}$	$S_{\psi\phi} = -0.04 \pm 0.09$

High Scale?

- $\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2$
- For $|z_{ij}| \sim 1, \quad \mathcal{I}m(z_{ij}) \sim 1$:

Mixing	$\Lambda_{\rm NP}^{CPC} \gtrsim$	$\Lambda_{\rm NP}^{CPV} \gtrsim$	Mixing	$\Lambda_{\rm NP}^{CPC} \gtrsim$	$\Lambda_{\rm NP}^{CPV} \gtrsim$
$K-\overline{K}$	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	200 TeV

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- Did we misinterpret the Higgs fine-tuning problem?
- Did we misinterpret the dark matter puzzle?

Degeneracy and Alignment?

- $\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2$
- For $\Lambda_{\rm NP} \sim 1\ TeV$:

Mixing	$\lvert z_{ij}\rvert \lesssim$	$\mathcal{I}m(z_{ij}) \lesssim$	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^{-5}

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- 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}	$\alpha_2^2 y_c^2 \lvert V_{cd}V_{cs}\rvert^2$
$\Delta m_D/m_D$	8.7×10^{-15}	5×10^{-9}	Long Distance
$\Delta m_B/m_B$	6.3×10^{-14}	7×10^{-8}	$\alpha_2^2 y_t^2 \lvert V_{td}V_{tb}\rvert^2$
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-6}	$\alpha_2^2 y_t^2 \lvert V_{ts}V_{tb}\rvert^2$
		$\frac{\mathcal{I}m(z_{ij})}{\lvert z_{ij}\rvert} \sim$	$\frac{\mathcal{I}m(z_{ij}^{\rm SM})}{\lvert z_{ij}^{\rm SM}\rvert}$
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	$\mathcal{O}(1)$	$\mathcal{I}m \frac{V_{tb}V_{td}^*}{V_{tb}^* V_{td}} \frac{V_{cb}^* V_{cd}}{V_{cb} V_{cd}^*} \sim 0.7$
$S_{\psi\phi}$	≤ 0.1	≤ 0.1	$\mathcal{I}m \frac{V_{tb}V_{ts}^*}{V_{tb}^* V_{ts}} \frac{V_{cb}^* V_{cs}}{V_{cb} V_{cs}^*} \sim 0.02$

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

Two Higgs Doublets Models (2HDM)

- $\mathcal{L}_{\rm Yukawa} = -\sum_{i=1,2}\left(\overline{Q}\tilde{\phi}_i Y_i^U U + \overline{Q}\phi_i Y_i^D D + \overline{L}\phi_i Y_i^E E + {\rm h.c.}\right)$
- Without loss of generality, choose a basis
  $\langle\phi_M\rangle = v/\sqrt{2}, \quad \langle\phi_A\rangle = 0$
  $$\begin{pmatrix}\phi_M \\ \phi_A\end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta\end{pmatrix}\begin{pmatrix}\phi_1 \\ \phi_2\end{pmatrix}$$
- In this basis: $\boxed{Y_M^F = \sqrt{2}M^F/v, \quad Y_A^F = {\rm arbitrary}}$
- Five scalar mass eigenstates: $h, H, A, H^\pm$
  $$\begin{pmatrix}\phi_H \\ \phi_h\end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha\end{pmatrix}\begin{pmatrix}\phi_1 \\ \phi_2\end{pmatrix}$$

The 2HDM flavor puzzle

- $Y_h^F = c_{\alpha-\beta} Y_A^F - s_{\alpha-\beta} Y_M^F$
  $Y_H^F = s_{\alpha-\beta} Y_A^F + c_{\alpha-\beta} Y_M^F$
- Proportionality is lost: $Y^F_{h,H,A} \not\propto Y^F_M$
- Diagonality is lost: $(Y^F_{h,H,A})_{ij} \neq 0$ for $i \neq j$
- FCNC at tree level
- For example, $z^h_{sd} \sim c^2_{\alpha-\beta} (Y^D_A)_{sd} (Y^D_A)_{ds} / m_h^2$
  $\Longrightarrow \quad c^2_{\alpha-\beta} (Y^D_A)_{sd} (Y^D_A)_{ds} \lesssim 10^{-10}$

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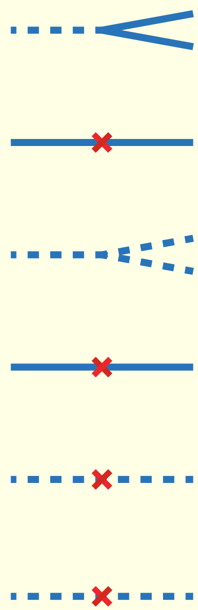
  $\Longrightarrow \quad c^2_{\alpha-\beta} (Y_A^D)_{sd} (Y_A^D)_{ds} \lesssim 10^{-10}$

Why? = The 2HDM flavor puzzle

Supersymmetry (for Phenomenologists)

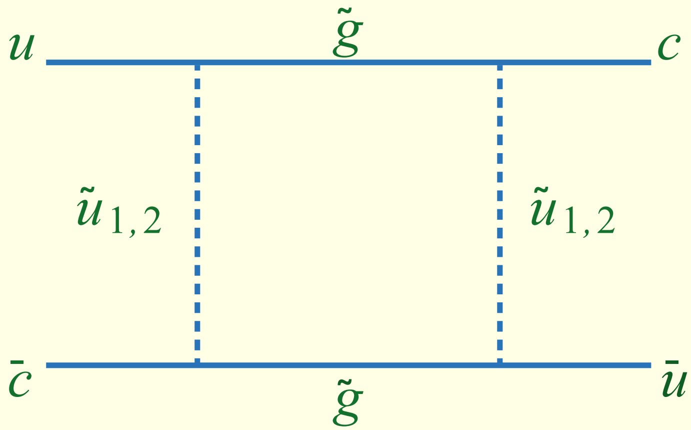


	FV	CPV
Y	+	+
μ	−	+
A	+	+
$m_{\tilde{g}}$	−	+
$m^2_{\tilde{f}}$	+	+
B	−	+

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:



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

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

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

The SUSY flavor puzzle

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

Why? = The SUSY flavor puzzle

The SUSY flavor puzzle

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

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

Intermediate summary III

- The SM flavor puzzle:
  Why is there smallness and hierarchy in the SM flavor parameters?
- The ν flavor puzzle:
  Why is there neither smallness nor hierarchy in the neutrino flavor parameters?
- The NP flavor puzzle:
  Why is there alignment and/or degeneracy in NP@TeV flavor parameters?

Flavor Models

Natural Flavor Conservation (NFC)

- A solution to the 2HDM flavor puzzle
- NFC $\equiv$ Each fermion sector (U, D, E) couples to a single Higgs doublet
- Type II: $\overline{Q}Y^U U\phi_2 + \overline{Q}Y^D D\phi_1 + \overline{L}Y^E E\phi_1$
  $\Longrightarrow \quad Y_A^U = \cot\beta\, Y_M^U, \;\; Y_A^{D,E} = \tan\beta\, Y_M^{D,E}$
- In all NFC models, $Y_A \propto Y_M$:
  - Proportionality is restored $Y^F_{h,H,A} \propto Y^F_M$
  - Diagonality is restored $(Y^F_{h,H,A})_{ij} = 0$ for $i \neq j$
- No Higgs-mediated FCNC at tree level

Minimal Flavor Violation (MFV)

- A solution to the NP flavor puzzle
- SM: When $Y^F = 0 \Longrightarrow$ A large global symmetry
  $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$
- MFV $\equiv$ The only NP breaking of the $SU(3)^5$ symmetry:
  $Y^U(3,\bar{3},0,0,0),\ Y^D(3,0,\bar{3},0,0),\ Y^E(0,0,0,3,\bar{3})$
  $(\lambda_u, \lambda_d, V, \lambda_e)$
- Example: Gauge mediated supersymmetry breaking
- FV suppressed by small fermion masses and CKM angles

MFV, 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)

MFV-EFT Example

- Consider $\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu d_L)^2$
- $\overline{s_L} \in (\bar{3},1,1), \quad d_L \in (3,1,1) \quad \Longrightarrow \quad (\overline{s_L}\gamma_\mu d_L) \in (8,1,1)$
- $Y_d Y_d^\dagger = (\bar{3},1,3) \times (3,1,\bar{3}) \supset (8,1,1)$
  $Y_u Y_u^\dagger = (\bar{3},3,1) \times (3,\bar{3},1) \supset (8,1,1)$
- 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!

The Froggatt-Nielsen mechanism (FN)

- A solution to both the SM and the NP flavor puzzles
- Can solve also the ν flavor puzzle
- Approximate "horizontal" symmetry (e.g. $U(1)_H$)
- Small breaking parameter $\epsilon_H = \langle S_{-1}\rangle/\Lambda \ll 1$
- $\Longrightarrow$ Selection rules:
  - $Y^d_{ij} \sim \epsilon^{H(Q_i)+H(\bar{d}_j)+H(\phi_d)}$
  - $Y^u_{ij} \sim \epsilon^{H(Q_i)+H(\bar{u}_j)+H(\phi_u)}$
  - $Y^\ell_{ij} \sim \epsilon^{H(L_i)+H(\bar{\ell}_j)+H(\phi_d)}$
  - $Y^\nu_{ij} \sim \epsilon^{H(L_i)+H(L_j)+2H(\phi_u)}$
- Can generate hierarchy and alignment, but not degeneracy

The FN mechanism: An example

- $H(Q_i) = 2, 1, 0, \quad H(\bar{d}_j) = 2, 1, 0, \quad H(\phi_d) = 0$

$$\Downarrow$$

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

- $Y_b : Y_s : Y_d \sim 1 : \epsilon^2 : \epsilon^4$
- $(V_L^d)_{12} \sim \epsilon, \quad (V_L^d)_{23} \sim \epsilon, \quad (V_L^d)_{13} \sim \epsilon^2$

The FN mechanism: a viable model

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

$$\Downarrow$$

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

$$+$$

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

Intermediate summary IV

- Various solutions to the SM flavor puzzle
  - Approximate Abelian symmetry
  - Approximate non-Abelian symmetry ($[SU(2)]^3, \ldots$)
  - Strong dynamics
  - Location in extra dimension
- Various solutions to the NP flavor puzzle
  - Approximate Abelian symmetry
  - Approximate non-Abelian symmetry ($[SU(2)]^3, \ldots$)
  - Strong dynamics
  - MFV
  - NFC (2HDM)

The flavor of h

Dery, Efrati, Hochberg, YN, JHEP1305,039 [arXiv:1302.3229]

Dery, Efrati, Hiller, Hochberg, YN, JHEP1308,006 [arXiv:1304.6727]

Dery, Efrati, YN, Soreq, Susič, PRD90, 115022 [arXiv:1408.1371]

Can we make progress?

- NP that couples to quarks/leptons $\Longrightarrow$ New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure could be:
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:
  With ATLAS/CMS we are likely to understand how it is solved
- The SM flavor puzzle:
  Progress possible if structure not MFV but related to SM

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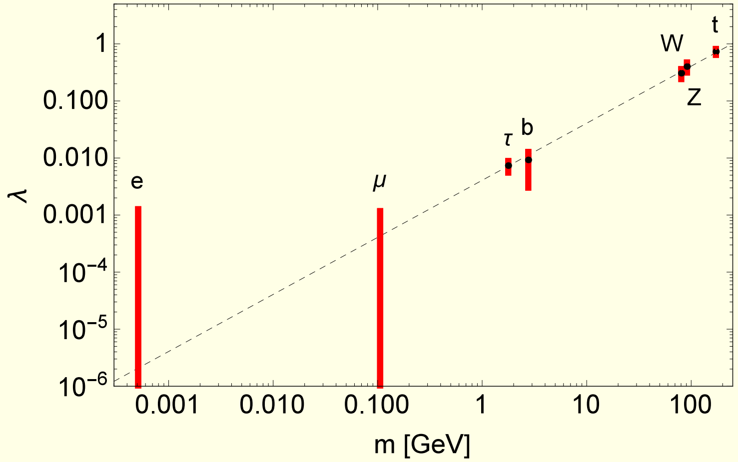
- The SM flavor puzzle:
  Progress possible if structure not MFV but related to SM
- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar f_i f_j}$ are new flavor parameters that can be measured

Relevant data

Observable	Experiment
$R_{\gamma\gamma}$	1.15 ± 0.18
R_{ZZ^*}	1.2 ± 0.2
R_{WW^*}	0.9 ± 0.2
$R_{b\bar{b}}$	0.7 ± 0.3
$R_{\tau\tau}$	1.04 ± 0.23
$R_{\mu\mu}$	< 7
R_{ee}	$< 4 \times 10^5$

- $R_f = \frac{\sigma_{\rm prod} {\rm BR}(h \to f)}{[\sigma_{\rm prod} {\rm BR}(h \to f)]^{\rm SM}}$

$Y_f \propto m_f$?



A. Efrati

- Indication that Y_t, Y_b, Y_τ not far from SM
- The beginning of Higgs flavor physics

Leptonic observables

Observable ($\ell = e, \mu$)	SM
$R_{\tau^+\tau^-}$	1
$X_{\ell\ell} = \frac{\mathrm{BR}(h\to\ell^+\ell^-)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	$(m_\ell/m_\tau)^2$
$X_{\ell\tau} = \frac{\mathrm{BR}(h\to\ell^\pm\tau^\mp)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	0

- What can we learn from $R_{\tau\tau}$, $X_{\ell\ell}$, $X_{\ell\tau}$?

Leptonic observables

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- What can we learn from $R_{\tau\tau},\ X_{\ell\ell},\ X_{\ell\tau}$?
- ATLAS/CMS:
  - $R_{\tau\tau} = 1.04 \pm 0.23$
  - $X_{\mu\mu} < 15(m_\mu/m_\tau)^2 \sim 0.05, \quad X_{ee} < 8\times 10^5 (m_e/m_\tau)^2 \sim 0.07$
  - $\text{BR}_{\mu\tau} = 0.009 \pm 0.004 \implies X_{\mu\tau} = 0.14 \pm 0.06 < 0.3$

Natural Flavor Conservation (NFC)

- A solution to the 2HDM flavor puzzle
- NFC $\equiv$ Each fermion sector (U, D, E) couples to a single Higgs doublet
- Type II: $\overline{Q}Y^U U\phi_2 + \overline{Q}Y^D D\phi_1 + \overline{L}Y^E E\phi_1$
- $\boxed{Y_h^E = (\sin\alpha/\cos\beta)(\sqrt{2}M_E/v)}$

$h \to \mu\tau$ in EFT

- SM: Forbidden by the accidental $U(1)_\mu \times U(1)_\tau$
- $d=5$ terms $\frac{(Y^N)_{ij}}{\Lambda} L_i L_j \phi\phi$: Allowed, but FCNC $\Longrightarrow$
  - Loop suppression $\sim \alpha_2^2$
  - Mixing suppression $\sim |U_{\mu 3} U_{\tau 3}|^2$
  - GIM suppression $\sim (\Delta m_{23}^2 / m_W^2)^2$
- $d=6$ terms $\frac{1}{\Lambda^2} (\phi^\dagger \phi) \phi \overline{\mu_L} Z^e_{\mu\tau} \tau_R$:
  The leading contribution –
  $M_E = \frac{v}{\sqrt{2}} \left(Y^e + \frac{v^2}{2\Lambda^2} Z^e \right), \quad Y_h^E = Y^e + 3 \frac{v^2}{2\Lambda^2} Z^e$
  $\Longrightarrow \; Y_h^E = (\sqrt{2} M_E / v) + \frac{v^2}{2\Lambda^2} Z^e$
- Note: $\frac{1}{\Lambda^2} \phi \overline{\mu_L} X^e_{\mu\tau} \sigma_{\mu\nu} \tau_R F^{\mu\nu} \;\; \Longrightarrow \;\; \tau \to \mu\gamma$

Minimal Flavor Violation (MFV)

- A solution to the NP flavor puzzle
- SM: When $Y^F = 0 \Longrightarrow$ A large global symmetry
  $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$
- MFV $\equiv$ The only NP breaking of the $SU(3)^5$ symmetry:
  $Y^U(3,\bar{3},0,0,0),\ Y^D(3,0,\bar{3},0,0),\ Y^E(0,0,0,3,\bar{3})$
- Example: $\frac{1}{\Lambda^2}(\phi^\dagger\phi)\overline{L_{Li}}Z^e_{ij}\phi E_{Rj}$
- $\boxed{Z^e = (a + bY^{E\dagger}Y^E)Y^E}$

The Froggatt-Nielsen mechanism (FN)

- A solution to both the SM and the NP flavor puzzles
- A $U(1)_H$ symmetry broken by a small spurion $\epsilon_H(-1) \ll 1$

- Example: $\frac{1}{\Lambda^2}(\phi^\dagger\phi)\overline{L_{Li}}Z^e_{ij}\phi E_{Rj}$
- $\boxed{Z^e_{ij} = \mathcal{O}(y_j|U_{ij}|)}$

Flavor models

- 2HDM with Type II NFC
  - Universal correction to the diagonal couplings
- SM-EFT with MFV
  - Non-universal correction to the diagonal couplings
- SM-EFT with FN
  - Non-universal correction to the diagonal couplings + Off-diagonal couplings

Higgs Physics = new flavor arena

Model	$Y_\tau^2/(2m_\tau^2/v^2)$	$(Y_\mu^2/Y_\tau^2)/(m_\mu^2/m_\tau^2)$	$Y_{\mu\tau}^2/Y_\tau^2$
SM	1	1	0
NFC-II	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|^2v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(10^{-2})$

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Measuring Y_{ij} can probe flavor models

Model building: The question

- Experimentally, the best direct probes of FC Higgs couplings:
  - $t \to hq \ (q = c, u)$
  - $h \to \tau\ell \ (\ell = \mu, e)$
- Are there viable and natural flavor models that have
  - $Y_{qt} \sim 0.17$ but $Y_{uc} \lesssim 10^{-4}$?
  - $Y_{\ell\tau} \sim 0.02$ but $Y_{e\mu} \lesssim 10^{-6}$?
- Naively
  - $Y_{uc}/Y_{ct} \sim |V_{us}/V_{cb}|(m_c/m_t) \sim 10^{-2} \Longrightarrow$ too large
  - $Y_{e\mu}/Y_{\mu\tau} \sim |U_{e2}/U_{\mu 3}|(m_\mu/m_\tau) \sim 0.05 \Longrightarrow$ too large

Model building: The answer

- NFC
  - Impossible ($Y_{qt} = Y_{\ell\tau} = 0$)
- MFV
  - Impossible* ($Y_{ct} \lesssim V_{cb} \sim 0.04$, $Y_{\mu\tau} = 0$)
- FN:
  - Possible only with supersymmetry and holomorphic zeros

Model building: The answer

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  - Impossible ($Y_{qt} = Y_{\ell\tau} = 0$)
- MFV
  - Impossible* ($Y_{ct} \lesssim V_{cb} \sim 0.04$, $Y_{\mu\tau} = 0$)
- FN:
  - Possible only with supersymmetry and holomorphic zeros
- The upper bounds on Y_{ct} and $Y_{\mu\tau}$ can be saturated within viable and natural flavor models
- The models are not generic and need to be carefully selected
- If $t \to hq$ or $h \to \tau\ell$ is observed in experiments, it will challenge present explanations of the flavor puzzles

Intermediate summary V

Measure:

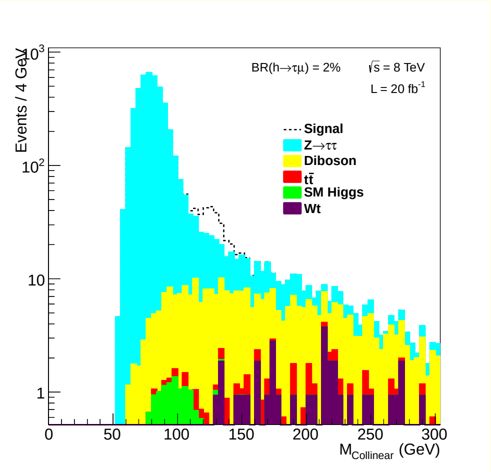
- Third generation couplings: $Y_t,\ Y_b,\ Y_\tau$
- Second generation couplings: $Y_c,\ Y_s,\ Y_\mu$
- Flavor violating couplings: $Y_{\mu\tau},\ Y_{e\tau},\ Y_{ct},\ Y_{ut}$

Test:

- NFC
- MFV
- FN
- ...

$Y_{\tau\ell}$: Experiment

Shikma Bressler, Avital Dery, Aielet Efrati, PRD 90 (2014) 015025 [1405.3229]



On the blackboard

if time allows...

Concluding Comments

Flavor Physics at the LHC era

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

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- but flavor factories observe NP...
  - We may have misinterpreted the fine-tuning problem
  - We may have misinterpreted the dark matter puzzle
  - Flavor will provide the only clue for an accessible scale of NP

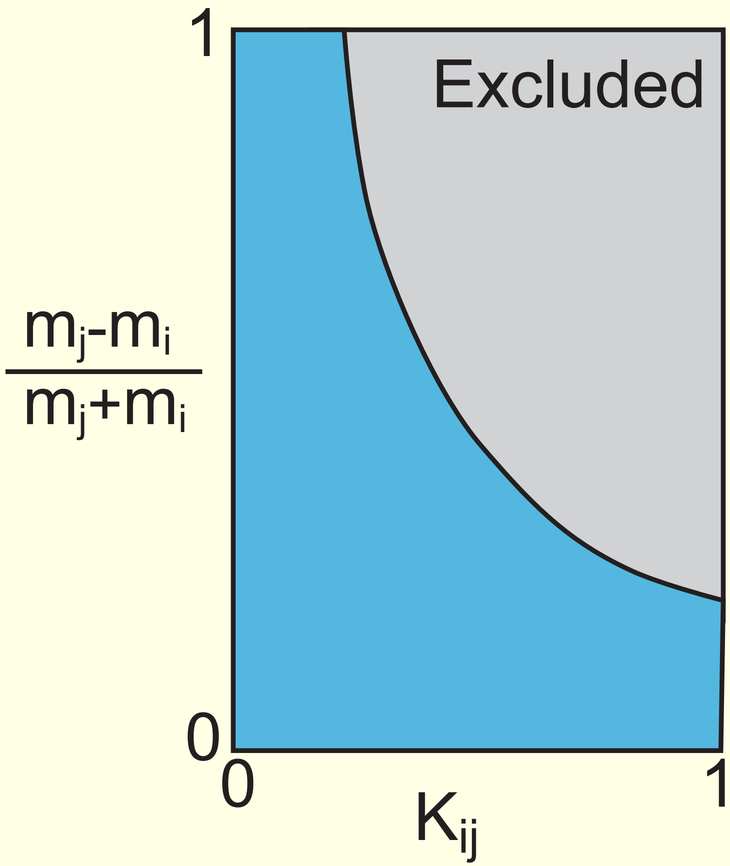
Flavor Physics at the LHC era

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

In combination with flavor factories, we may...

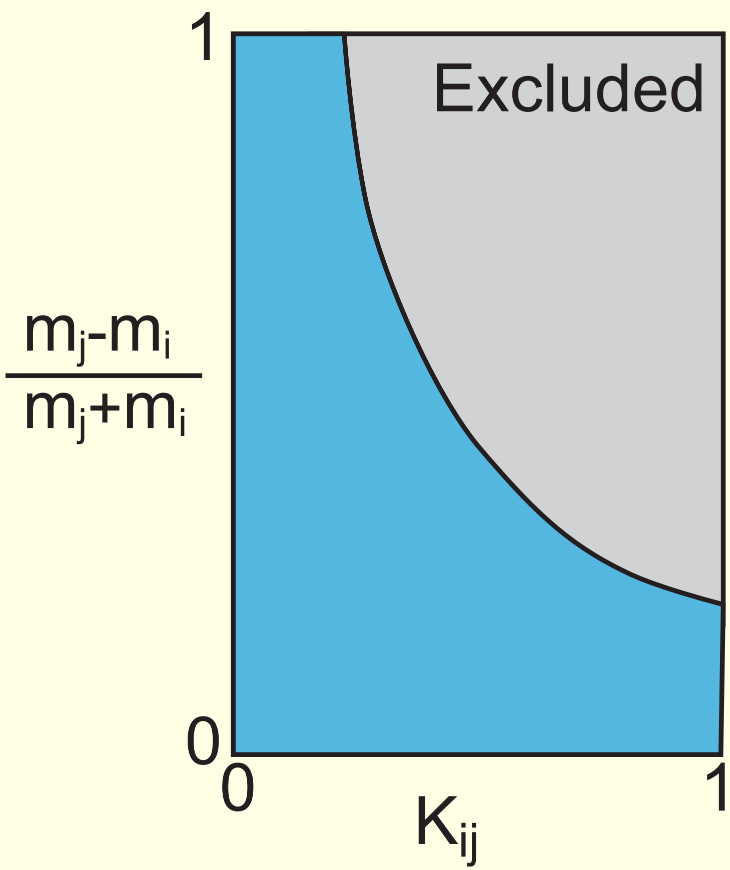
- Understand how the NP flavor puzzle is (not) solved
- Probe NP at $\Lambda_{\rm NP} \gg TeV$
- Get hints about the solution to the SM flavor puzzle

Degeneracy *vs.* Alignment

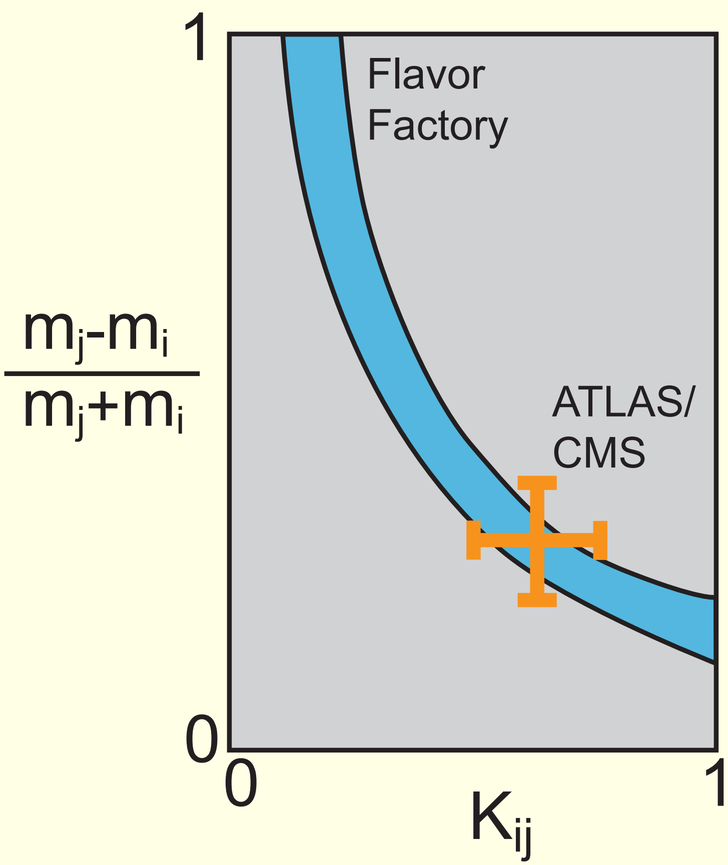


Flavor Factories

Degeneracy *vs.* Alignment



Flavor Factories



FF+ATLAS/CMS

Conclusions

- In the absence of NP at ATLAS/CMS, flavor factories will be crucial to find $\Lambda_{\rm NP}$
- The NP flavor puzzle is likely to be understood
- Understanding the NP flavor puzzle $\Longrightarrow$
  Probe physics at $\Lambda_{\rm NP} \gg \Lambda_{\rm LHC}$
- With NP that is affected by the mechanism that determines the Yukawa structure: The SM flavor puzzle may be solved
- The Yukawa couplings of h: A new arena for flavor physics

Conclusions

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- With NP that is affected by the mechanism that determines the Yukawa structure: The SM flavor puzzle may be solved
- The Yukawa couplings of h: A new arena for flavor physics
- My modest request from Nature (and from ATLAS/CMS):
  ${\rm BR}(h \to \mu\tau) \sim 0.01$ at $\gtrsim 5\sigma$