Flavor Physics: Past, Present, Future

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Plan of Talk

1. Introduction
2. Past: What have we learned?
    - Lessons from the B-factories
3. Present: Open questions
    - The NP flavor puzzle
    - The SM flavor puzzle
4. Future: What will we learn?
    - Collider $\Leftrightarrow$ Flavor interplay
    - The flavor of h

Introduction

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 is flavor physics?

- Interactions that distinguish among the generations:
  - Neither strong nor electromagnetic interactions
  - Within the SM: Only weak and Yukawa interactions
- Flavor parameters:
  - Parameters with flavor index $(m_i,\ V_{ij})$
  - $V =$ the CKM matrix
    Within the SM: The only source of flavor changing processes
    Depends on four parameters: λ, A, ρ, η
  - $\eta =$ The KM phase
    Within the SM: The only source of CP violation

Flavor changing processes

- 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 (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 $\Lambda_{\rm NP} \gg E_{\rm experiment}$
  FCNC suppressed within the SM by $\alpha_W^n, |V_{ij}|, m_f$
- The Standard Model flavor puzzle:
  Why are the flavor parameters small and hierarchical?
  (Why) are the neutrino flavor parameters different?
- The New Physics flavor puzzle:
  If there is NP at the TeV scale, why are FCNC so small?
  The solution $\Longrightarrow$ Clues for the subtle structure of the NP

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  The solution $\Longrightarrow$ Clues for the subtle structure of the NP
- CDF: $A_{\rm FB}^{t\bar t}(m_{t\bar t} > 450~{\rm GeV}) = +0.28 \pm 0.06$
  SM: $A_{\rm FB}^{t\bar t}(m_{t\bar t} > 450~{\rm GeV}) = +0.09 \pm 0.01$

  [Kamenik, Shu, Zupan, EPJ C72, 2102]
- BaBar: $\mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu) >$ SM by 3.4σ

A brief history of FCNC

- $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu) \implies$ Charm [GIM, 1970]
- $\Delta m_K \implies m_c \sim 1.5\ GeV$ [Gaillard-Lee, 1974]
- $\varepsilon_K \neq 0 \implies$ Third generation [KM, 1973]
- $\Delta m_B \implies m_t \gg m_W$ [Various, 1986]

Flavor Experiments

- B-factories:
  - BaBar, Belle
  - LHCb
- Lepton-factories:
  - MEG
- High p_T:
  - CDF, D0
  - ATLAS, CMS

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: Weak interactions (η)
  - 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?

- SM CPV cannot explain the baryon asymmetry – a puzzle:
  There must exist new sources of CPV
  Electroweak baryogenesis? (Testable at the LHC)
  Leptogenesis? (Window to $\Lambda_{\rm seesaw}$)
- Within the SM, a single CP violating parameter η:
  In addition, QCD = CP invariant ($\theta_{\rm QCD}$ irrelevant)
  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector

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  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector
- D0: $A^b_{\rm SL}=(-7.9\pm1.7\pm0.9)\times10^{-3}$
  SM: $A^b_{\rm SL}=(-0.23\pm0.06)\times10^{-3}$
- LHCb+CDF+...: $\Delta A_{\rm CP}=(-0.33\pm0.12)\times10^{-2}$
  SM: $\Delta A_{\rm CP}\lesssim10^{-3}$

A brief history of CPV

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

A brief history of CPV

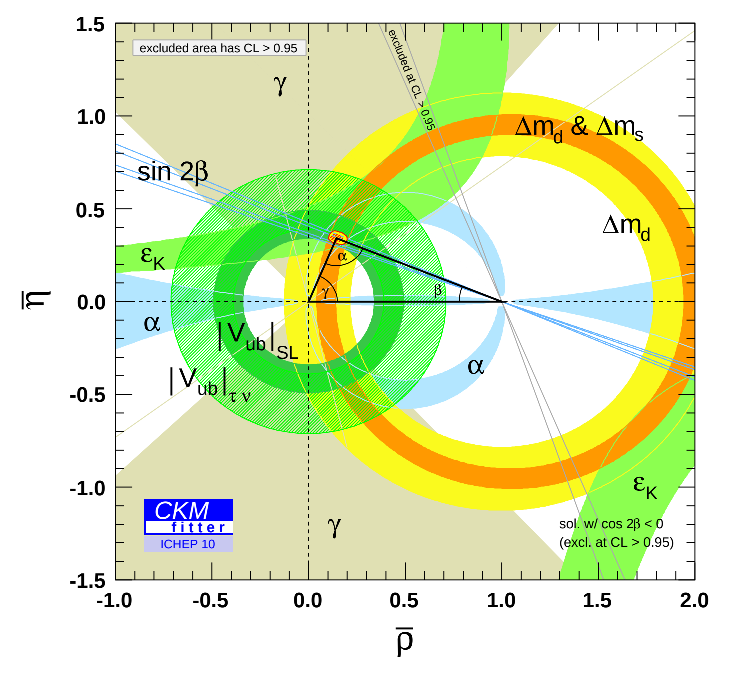
- 1964 – 2000
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- 2000 – 2013, 5σ
  - $S_{\psi K_S} = +0.68 \pm 0.02$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{f K_S} = +0.69 \pm 0.11$
  - $S_{K^+ K^- K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.36 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.98 \pm 0.17$, $S_{D^* D^*} = -0.77 \pm 0.10$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.083 \pm 0.005$
  - $\mathcal{A}_{D_+ K^\pm} = +0.19 \pm 0.03$
  - $\mathcal{A}_{B_s \to K^- \pi^+} = +0.27 \pm 0.04$

What have we learned?

Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
  $\Longrightarrow$ Four CKM parameters: λ, A, ρ, η
- λ known from $K \to \pi\ell\nu$
  A known from $b \to c\ell\nu$
- Many observables are $f(\rho, \eta)$:
  - $b \to u\ell\nu \implies \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \implies \propto |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - $S_{\psi K_S} \implies \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
  - $S_{\rho\rho}(\alpha)$
  - $\mathcal{A}_{DK}(\gamma)$
  - ϵ_K

The B-factories Plot



CKMFitter

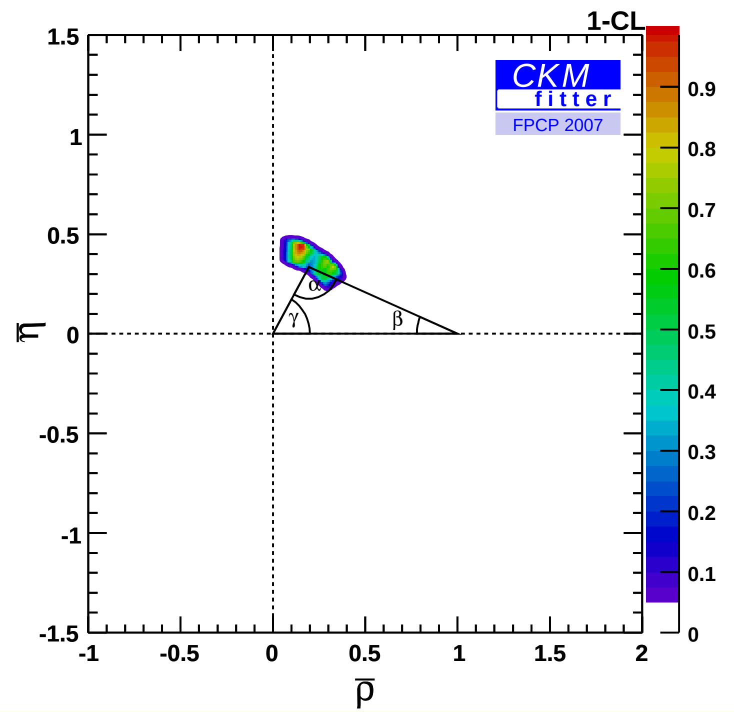
Very likely, the CKM mechanism dominates FV and CPV

Testing CKM - take II

- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Consider only tree decays and $B^0 - \overline{B}^0$ mixing
- Define $h_d e^{2i\sigma_d} = A^{\rm NP}(B^0 \to \overline{B})/A^{\rm SM}(B^0 \to \overline{B})$
  $\Longrightarrow$ Four parameters: ρ, η (CKM), h_d, σ_d (NP)
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}^d$
- Fit to η, ρ, h_d, σ_d
- Find whether $\eta = 0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d \gg 1$ is allowed
  If not $\Longrightarrow$ The KM mechanism is dominant

What have we learned?

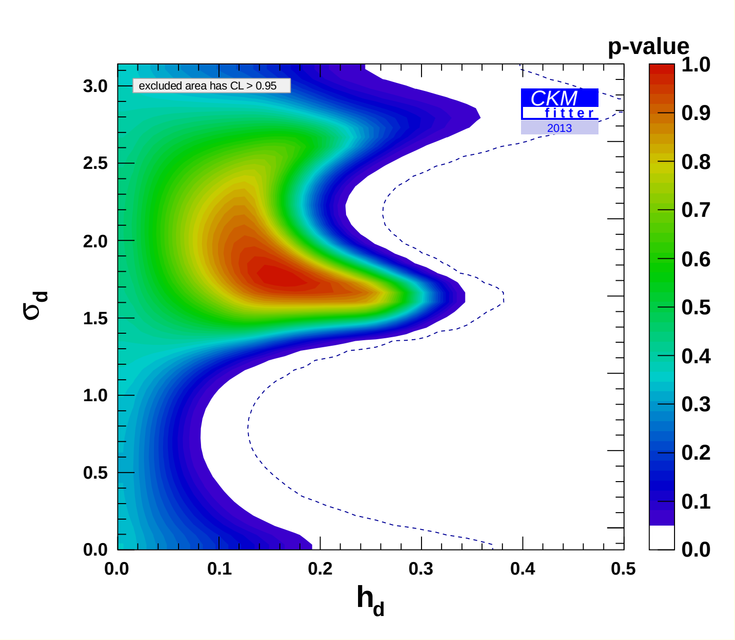
$\eta \neq 0$?



- $\boxed{\text{The KM mechanism is at work}}$

What have we learned?

$h_d \ll 1?$



- The KM mechanism dominates CP violation
- The CKM mechanism is a major player in flavor violation

Intermediate summary I

- The KM phase is different from zero (SM violates CP)
- The KM mechanism is the dominant source of the CP violation observed in meson decays
- Complete alternatives to the KM mechanism are excluded (Superweak, Approximate CP)
- CP violation in D, B_s may still hold surprises

- No evidence for corrections to CKM
- NP contributions to the observed FCNC are at most comparable to the CKM contributions ($s \leftrightarrow d$, $c \leftrightarrow u$, $b \leftrightarrow d$, $b \leftrightarrow s$)

The NP Flavor Puzzle

The SM = Low energy effective theory

1. Gravity $\Longrightarrow \Lambda_{\rm Planck} \sim 10^{19}$ GeV
2. $m_\nu \neq 0 \Longrightarrow \Lambda_{\rm Seesaw} \leq 10^{15}$ GeV
3. m_H^2-fine tuning $\Longrightarrow \Lambda_{\rm top-partners} \sim$ 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:

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

- 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}
$A_\Gamma/y_{\rm CP}$	≤ 0.2
$S_{\psi K_S}$	$+0.68\pm0.02$
$S_{\psi\phi}$	-0.04 ± 0.09

High Scale?

- For $z_{ij} \sim 1$ (and $\mathcal{I}m(z_{ij}) \sim 1$):

Mixing	$\Lambda_{\rm NP}^{\rm CPC} \gtrsim$	$\Lambda_{\rm NP}^{\rm CPV} \gtrsim$
$K-\overline{K}$	1000 TeV	20000 TeV
$D-\overline{D}$	1000 TeV	3000 TeV
$B-\overline{B}$	400 TeV	800 TeV
$B_s-\overline{B_s}$	70 TeV	200 TeV

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

Small (hierarchical?) flavor parameters?

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

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

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: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 0.1$
- SM flavor parameters have structure: smallness + hierarchy
- $\boxed{\text{Why? = The SM flavor puzzle}}$
    - Approximate symmetry? [Froggatt-Nielsen]
    - Strong dynamics? [Nelson-Strassler]
    - Location in extra dimension? [Arkani-Hamed-Schmaltz]
    - ?

ν-flavor parameters for anarchists

- $\Delta m^2_{21} = (7.5{\pm}0.2){\times}10^{-5}\ \mathrm{eV}^2, \quad |\Delta m^2_{32}| = (2.5{\pm}0.1){\times}10^{-3}\ \mathrm{eV}^2$
- $|U_{e2}| = 0.55 \pm 0.01, \quad |U_{\mu 3}| = 0.64 \pm 0.02, \quad |U_{e3}| = 0.15 \pm 0.01$

Gonzalez-Garcia et al., 1209.3023

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- $|U_{\mu3}| >$ any $|V_{ij}|$;
- $|U_{e2}| >$ any $|V_{ij}|$
- $|U_{e3}| \not\ll |U_{e2}U_{\mu3}|$
- $m_2/m_3 \gtrsim 1/6 >$ any m_i/m_j for charged fermions

- So far, neither smallness nor hierarchy
- Anarchy? (Consistent with FN)

ν-flavor parameters for tribimaximalists

- $\Delta m^2_{21} = (7.5{\pm}0.2){\times}10^{-5}\ \mathrm{eV}^2, \quad |\Delta m^2_{32}| = (2.5{\pm}0.1){\times}10^{-3}\ \mathrm{eV}^2$
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Gonzalez-Garcia et al., 1209.3023

- $\sqrt{1/3}$ = trimaximal mixing: $|U_{e2}| = \sqrt{1/3} - 0.03;$
- $\sqrt{1/2}$ = bimaximal mixing: $|U_{\mu 3}| = \sqrt{1/2} - 0.06;$
- 0 = bimaximal mixing: $\boxed{|U_{e3}| = 0 + 0.15}$

- Tribimaximal mixing?
- Non-Abelian flavor symmetry? A_4?

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.79-0.85 & 0.51-0.59 & 0.13-0.18 \\ 0.20-0.54 & 0.42-0.73 & 0.58-0.81 \\ 0.21-0.55 & 0.41-0.73 & 0.57-0.80 \end{pmatrix}$$

- 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:

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

Intermediate summary II

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

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

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

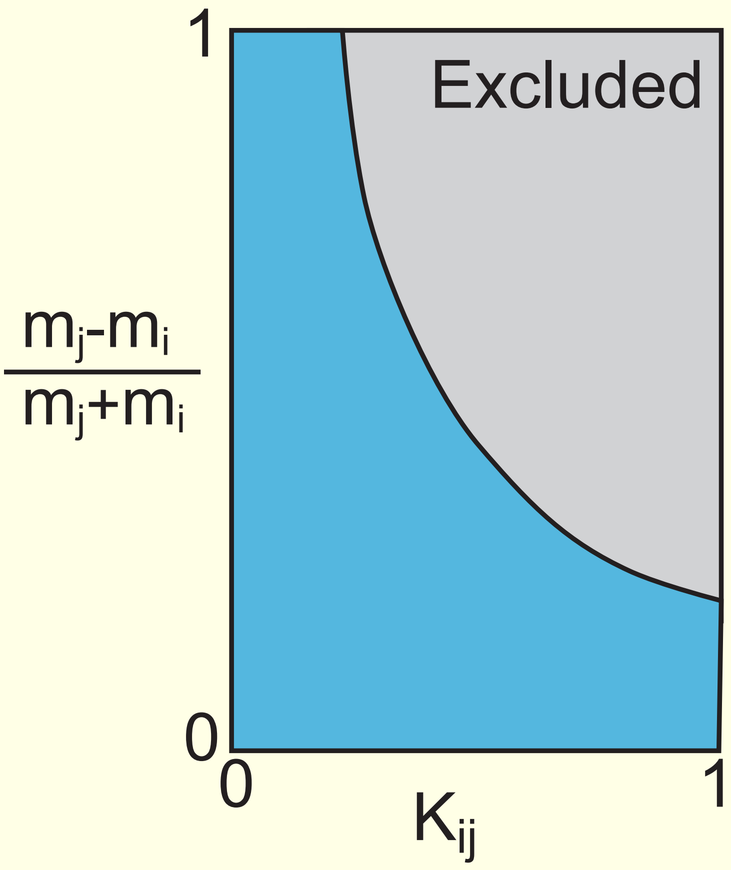
What will we learn?

Collider ⇔ Flavor

ATLAS/CMS and flavor factories give complementary information

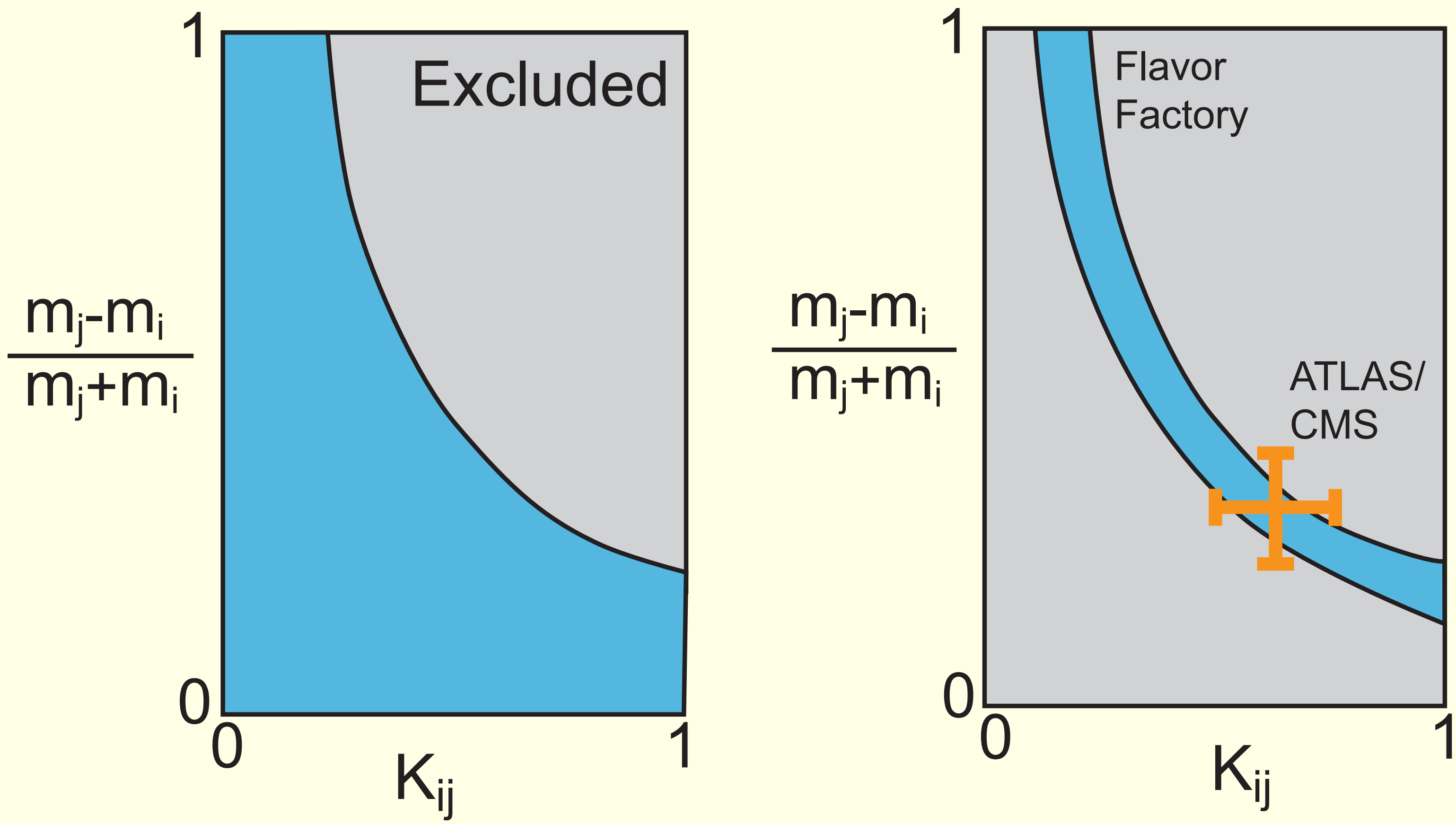
- In the absence of NP at ATLAS/CMS:
  flavor factories will be crucial to find $\Lambda_{\rm NP}$
- Consistency between ATLAS/CMS and FF:
  necessary to understand the NP flavor puzzle
- NP in $c \to u$? $s \to d$? $b \to d$? $b \to s$? $t \to c$? $t \to u$?
  $\mu \to e$? $\tau \to \mu$? $\tau \to e$?
- $A_{\rm FB}^{t\bar t}$ - a wonderful example of collider-flavor interplay
  [Blum, Hochberg, Nir, JHEP 10 (2011) 124]
- $A_{\rm FB}^{t\bar t} \Leftrightarrow \Delta A_{\rm CP}$? An intriguing possibility
  [Hochberg, Nir, PRL 108 (2012) 261601]

Collider ⇔ Flavor



Flavor Factories

Collider $\Leftrightarrow$ Flavor



Flavor Factories

FF+ATLAS/CMS

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

Can we make progress?

- NP that couples to quarks/leptons ⟹ 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 will surely understand how it is solved
- The SM flavor puzzle:
  Progress possible if structure not MFV but related to SM

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- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar f_i f_j}$ are new flavor parameters that can be measured

Intermediate summary III

Measure new flavor parameters:

- $Y_t,\ Y_b,\ Y_\tau$
- $\mathrm{BR}(h \to \mu\mu)/\mathrm{BR}(h \to \tau\tau)$
- $\mathrm{BR}(h \to \mu\tau)/\mathrm{BR}(h \to \tau\tau)$
- $\mathrm{BR}(t \to ch)$

Test solutions of NP/SM flavor puzzles:

- MFV
- FN
- NFC
- …

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 is the solution of the flavor puzzles?

Backup transparenices

h at present

Observable	Experiment
$R_{\gamma\gamma}$	1.1 ± 0.2
R_{ZZ^*}	1.1 ± 0.2

- $R_f = \frac{\sigma_{\rm prod}{\rm BR}(h\to f)}{[\sigma_{\rm prod}{\rm BR}(h\to f)]^{\rm SM}}$
- Indication that $Y_t = \mathcal{O}(1)$
- The beginning of Higgs flavor physics

h in the future

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

- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking

h in the future

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- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking
- ATLAS/CMS: $R_{\tau\tau} \sim 1.0 \pm 0.4, \quad R_{\mu\mu} < 9.8$

The flavorful h

Model	$\frac{\sigma_{\rm prod}^{\rm SM}}{\sigma_{\rm prod}}\frac{\Gamma_{\rm tot}}{\Gamma_{\rm tot}^{\rm SM}}\ R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$X_{\tau\mu}$
SM	1	1	0
NFC	$(V_{h\ell}v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
2HDM$^{\rm GMFV}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\frac{\lvert U_{23}\rvert m_\tau v}{\Lambda^2})$
GL	9	$25/9$	$\mathcal{O}(X_{\mu^+\mu^-})$

Measurements of Y_{ij} can exclude/support flavor models

Dery, Efrati, Hochberg, YN, 1302.3229; Dery, Efrati, Hiller, Hochberg, YN, 1304.6727