Flavor Physics: Past, Present, Future

Workshop on Physics Opportunities with LHC at 7 TeV

KEK, Japan
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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?
   Flavor@LHC

Introduction

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

A brief history of FCNC

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

Why is CPV interesting?

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

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  In addition, QCD = CP invariant ($\theta_{\rm QCD}$ irrelevant)
  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector
- D0: $A^b_{\rm SL} = (-7.9 \pm 1.7 \pm 0.9) \times 10^{-3}$
  SM: $A^b_{\rm SL} = (-0.23 \pm 0.06) \times 10^{-3}$
- LHCb: $\Delta A_{\rm CP} = (-0.82 \pm 0.21 \pm 0.11) \times 10^{-2}$
  SM: $\Delta A_{\rm CP} \lesssim 10^{-3}$

A brief history of CPV

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

A brief history of CPV

- 1964 – 2000
  - $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.67 \pm 0.26) \times 10^{-3}$
- 2000 – 2011
  - $S_{\psi K_S} = +0.67 \pm 0.02$
  - $S_{\phi K_S} = +0.56 \pm 0.18$, $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{\pi^0 K_S} = +0.57 \pm 0.17$, $S_{f_0 K_S} = +0.62 \pm 0.12$
  - $S_{K^+K^-K_S} = -0.82 \pm 0.07$, $S_{K_S K_S K_S} = +0.74 \pm 0.17$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.89 \pm 0.26$, $S_{D^*D^*} = -0.77 \pm 0.14$
  - $\mathcal{A}_{K^\mp\rho^0} = +0.37 \pm 0.11$, $\mathcal{A}_{\eta K^\mp} = -0.37 \pm 0.09$, $\mathcal{A}_{f_2 K^\mp} = -0.68 \pm 0.20$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $\mathcal{A}_{\eta K^{*0}} = +0.19 \pm 0.05$
  - ...

What have we learned?

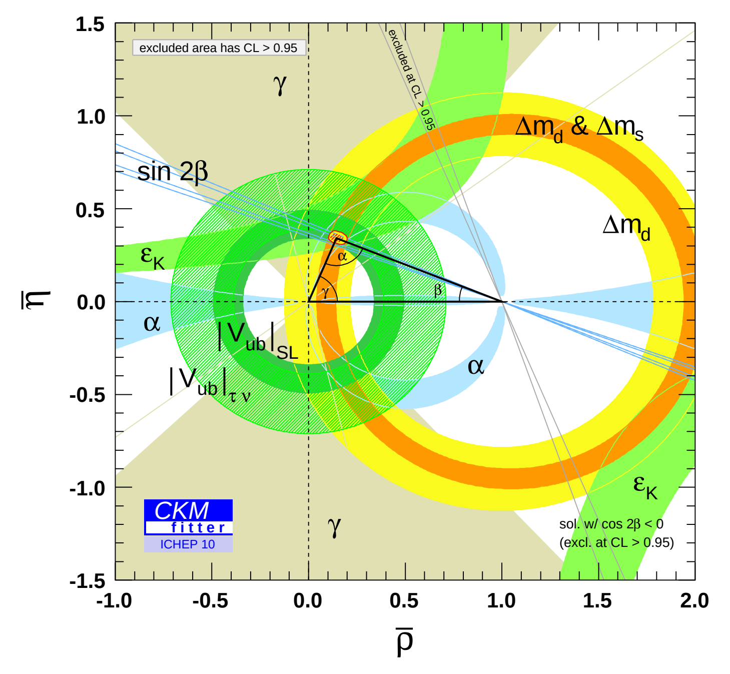
Testing CKM – Take I

- 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

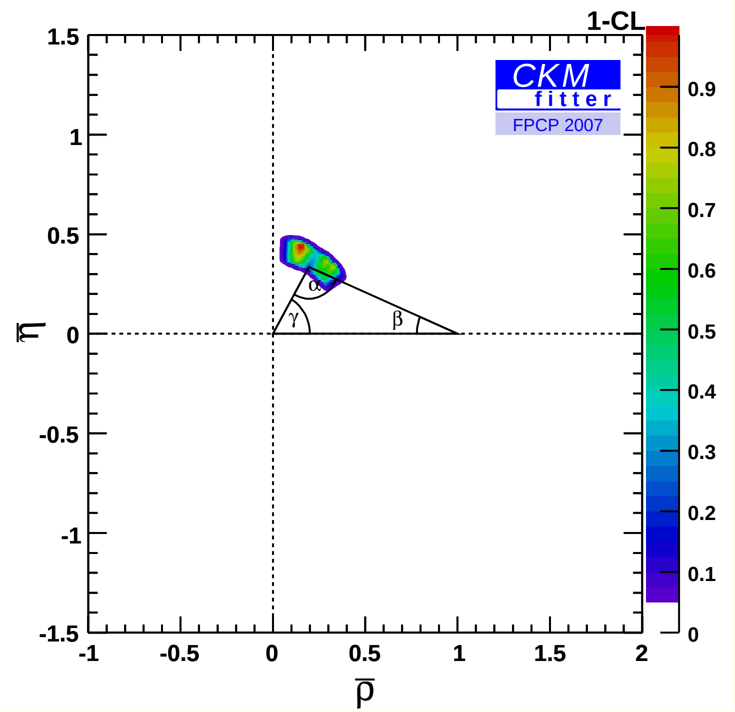
Very likely, the CKM mechanism dominates FV and CPV

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}, $\mathcal{A}^d_{\rm SL}$
- Fit to η, ρ, h_d, σ_d
- Find whether $\eta=0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d\gg 1$ is allowed
  If not $\Longrightarrow$ The KM mechanism is dominant

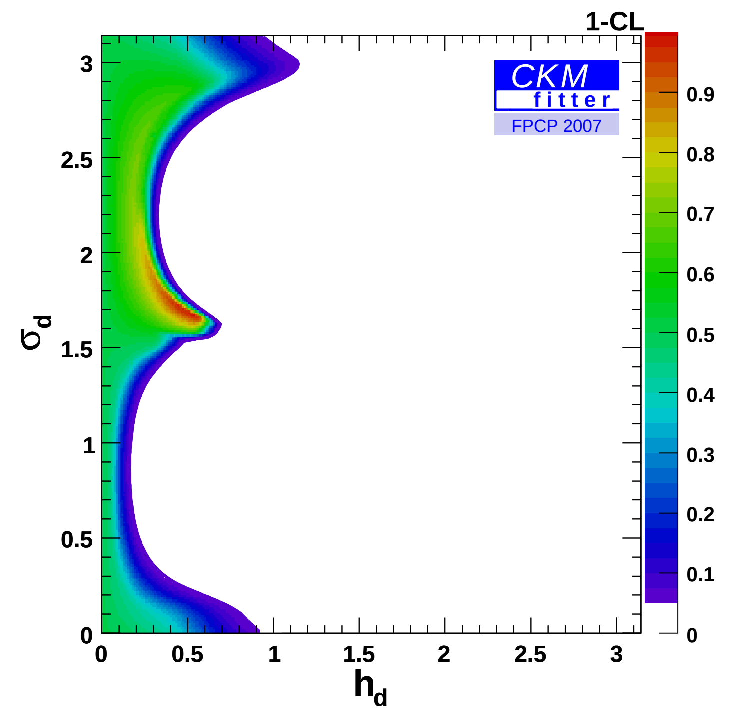
What have we learned?

$\eta \neq 0?$



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

$h_d \ll 1?$



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

Several $\sim 3\sigma$ tensions

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

Intermediate summary I

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

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

The NP Flavor Puzzle

The SM = Low energy effective theory

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

$$\Downarrow$$

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

Some data

$\Delta m_K/m_K$	7.0×10^{-15}
$\Delta m_D/m_D$	8.7×10^{-15}
$\Delta m_B/m_B$	6.3×10^{-14}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}
ϵ_K	2.3×10^{-3}
$A_\Gamma/y_{\rm CP}$	≤ 0.2
$S_{\psi K_S}$	0.67 ± 0.02
$S_{\psi\phi}$	≤ 1

High Scale?

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

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

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

Small (hierachical?) flavor parameters?

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

Mixing	$\lvert z_{ij}\rvert \lesssim$	$\mathcal{I}m(z_{ij}) \lesssim$
$K-\overline{K}$	8×10^{-7}	6×10^{-9}
$D-\overline{D}$	5×10^{-7}	1×10^{-7}
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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

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

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

Neutrino flavor parameters

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

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

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

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.0-0.2 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}$$

- Tribimaximal-ists:

$$|U|_{\rm TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- Anarch-ists:

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

Intermediate summary II

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

- Is there a relation Dirac/Majorana ⇔ hierarchy/anarchy?
  Is there a relation Dirac/Majorana ⇔ 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?

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?

Experimentalists: Flavor at ATLAS/CMS???

- ATLAS/CMS are not optimized for flavor

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But...

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

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But...

- If new particles that couple to the SM fermions are discovered –
  $\Longrightarrow$ New flavor parameters can be measured
  - Spectrum (degeneracies?)
  - Flavor decomposition (alignment?)
- In combination with flavor factories, we may...
  - Understand how the NP flavor puzzle is (not) solved
    $\Longrightarrow$ Probe NP at $\Lambda_{\rm NP} \gg TeV$
  - Get hints about the solution to the SM flavor puzzle

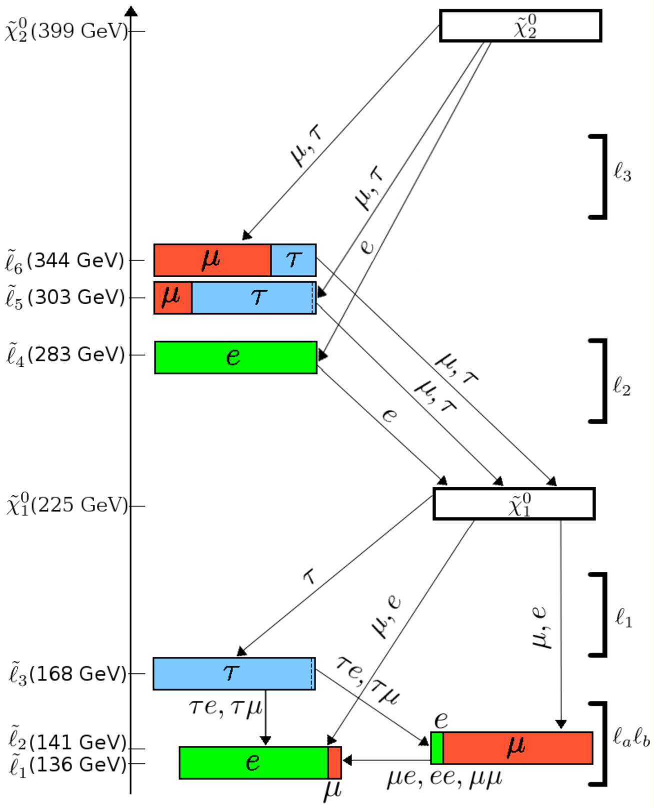
Gauge+Gravity Mediation

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

Assume: The flavor structure of X determined by FN:

- $X_{\tilde{E}_L} \sim \begin{pmatrix} 1 & U_{e2} & U_{e3} \\ \cdot & 1 & U_{\mu 3} \\ \cdot & \cdot & 1 \end{pmatrix}; \quad X_{\tilde{E}_R} \sim \begin{pmatrix} 1 & \frac{m_e/m_\mu}{U_{e2}} & \frac{m_e/m_\tau}{U_{e3}} \\ \cdot & 1 & \frac{m_\mu/m_\tau}{U_{\mu 3}} \\ \cdot & \cdot & 1 \end{pmatrix}$
- $\boxed{\text{Mixing depends only on } X \text{ which is related to the SM flavor}}$

SUSY flavor parameters from $\tilde{\ell}_1, e, \mu$



	True	Measured
$\tilde{\ell}_1$	135.83 GeV	135.9 ± 0.1 GeV
χ^0_1	224.83 GeV	225.10 ± 0.04 GeV
$\Delta m(\tilde{\ell}_{1,2})$	4.95 GeV	5.06 ± 0.06 GeV
$\tilde{\ell}_4$	282.86 GeV	283.1 ± 0.2 GeV
$\tilde{\ell}_5$	303.41 GeV	306 ± 1 GeV
$\tilde{\ell}_6$	343.53 GeV	341 ± 1 GeV
$\lvert K_{e2}/K_{\mu 2}\rvert^2$	0.069	0.054 ± 0.008

[Feng, Lester, Nir, Shadmi *et al.*, PRD77(2008)076002; PRD80(2009)114004; JHEP01(2010)047]

Lessons from $\tilde{\ell}_1, e, \mu$

- Determine Δm_{21} and $\sin\theta_{12}$:

  It is consistent with $\mu \to e\gamma$?

  How the SUSY flavor problem is solved

- Determine Δm_{21}, Δm_{54}, $\ldots$:

  What is messenger scale of gauge mediation (M_m)?

  Probe physics at $M_m \sim 10^{15}$ GeV

- Determine $|K_{e2}/K_{\mu 2}|$:

  Is the FN mechanism at work?

  How the SM flavor puzzle is solved

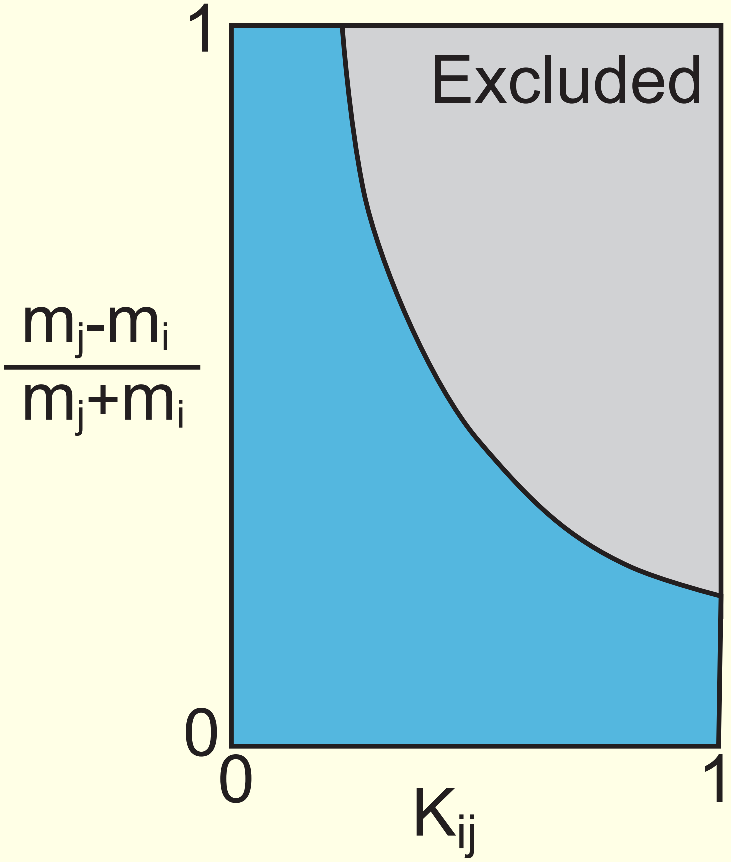
The role of flavor factories (FF)

ATLAS/CMS and flavor factories give complementary information

- In the absence of NP at ATLAS/CMS:
  flavor factories will be crucial to find $\Lambda_{\rm NP}$
- Consistency between ATLAS/CMS and FF:
  necessary to understand the NP flavor puzzle
- NP in $c\to u$? $s\to d$? $b\to d$? $b\to s$? $t\to c$? $t\to u$?
  $\mu\to e$? $\tau\to\mu$? $\tau\to e$?
  - MFV?
  - Structure related to SM?
  - Structure unrelated to SM?
  - Anarchy?

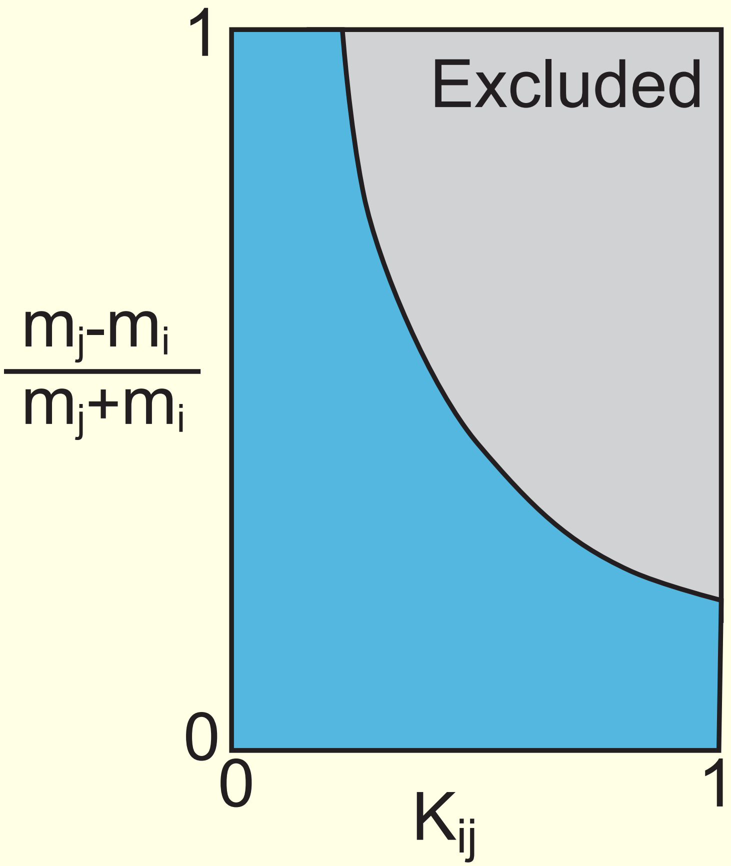
[Hiller, Hochberg, Nir, JHEP0903(09)115; JHEP1003(10)079]]

Summary



Flavor Factories

Summary



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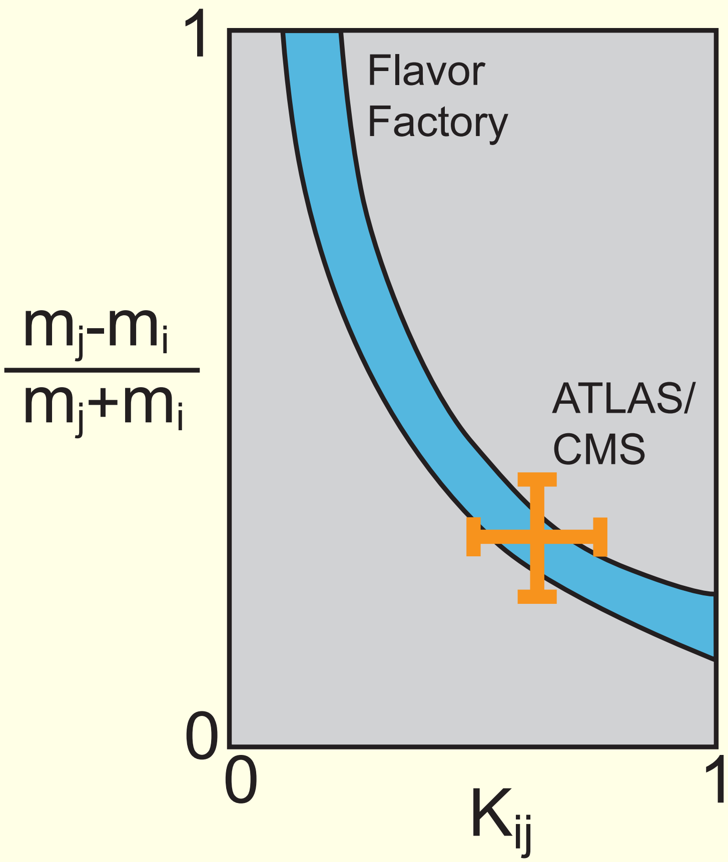

FF+ATLAS/CMS

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

Thanks to my flavor collaborators:

Kfir Blum, Jonathan Feng, Sky French, Oram Gedalia,
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David Kirkby, Christopher Lester, Zoltan Ligeti,
Gilad Perez, Yael Shadmi, Jesse Thaler, Ofer Vitells,
Tomer Volansky, Jure Zupan

Backup Transparencies

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

Hochberg, Nir, work in progress

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

Evidence for New Physics

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

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

- The Standard Model:

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

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- LHCb:

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

  [LHCb, arXiv:1112.0938]

Direct CP Violation

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

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

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

$$\boxed{A^{b}_{\rm SL}}$$

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

Evidence for New Physics

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

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

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

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

- D0:

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

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

Hints for New Physics?

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

Four-quark operators

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

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

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

MFV

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

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

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

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

MFV + small tan β

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

CP violation as a probe of New Physics

The size of new MFV effects on CP violating observables:

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

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

Flavor Violation (FV)

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

$$\Downarrow$$

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

Kobayashi and Maskawa (I)

The number of real and imaginary quark flavor parameters:

- With two generations:
  $2 \times (4_R + 4_I) - 3 \times (1_R + 3_I) + 1_I = 5_R + 0_I$
- With three generations:
  $2 \times (9_R + 9_I) - 3 \times (3_R + 6_I) + 1_I = 9_R + 1_I$
- The two generation SM is CP conserving
  The three generation SM is CP violating

CP violation = a single imaginary parameter in the CKM matrix:

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

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

Kobayashi and Maskawa (II)

The achievements:

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

$S_{\psi K_S}$

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

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

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

- The approximations involved are better than one percent!

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