Flavor Physics: Past, Present, Future

Nobel Symposium on LHC Results

Krusenberg herrgård
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Plan of Talk

1. Past: What have we learned?
   - Lessons from the B-factories

2. Present: Open questions
   - The NP flavor puzzle
   - The SM flavor puzzle

3. Future: What will we learn?
   - Collider $\Leftrightarrow$ Flavor interplay
   - The flavor of $h$
What have we learned?
What have we learned?

A brief history of CPV

• 1964 – 2000

• $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\Re(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3}$
What have we learned?

A brief history of CPV

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- 2000 – 2013, $5\sigma$
  - $S_{\psi K_S} = +0.68 \pm 0.02$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{f K_S} = +0.69 \pm 0.11$
  - $S_{K^+ K^- K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+ \pi^-} = -0.65 \pm 0.07$, $C_{\pi^+ \pi^-} = -0.36 \pm 0.06$
  - $S_{\psi \pi} = -0.93 \pm 0.15$, $S_{DD} = -0.98 \pm 0.17$, $S_{D^* D^*} = -0.77 \pm 0.10$
  - $A_{K^+ \pi^\pm} = -0.083 \pm 0.005$
  - $A_{D^+ K^\pm} = +0.19 \pm 0.03$
  - $A_{BS \rightarrow K^- \pi^+} = +0.27 \pm 0.04$
What have we learned?

Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
  - Four CKM parameters: $\lambda, A, \rho, \eta$
- $\lambda$ known from $K \rightarrow \pi \ell \nu$
  - $A$ known from $b \rightarrow c \ell \nu$
- Many observables are $f(\rho, \eta)$:
  - $b \rightarrow u \ell \nu \implies \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \implies \propto |V_{td}/V_{ts}|^2 \propto (1 - \rho)^2 + \eta^2$
  - $S_{\psi K_S} \implies \frac{2\eta(1-\rho)}{(1-\rho)^2 + \eta^2}$
  - $S_{\rho\rho}(\alpha)$
  - $A_{DK}(\gamma)$
  - $\epsilon_K$
What have we learned?

The B-factories Plot

Very likely, the CKM mechanism dominates FV and CPV
What have we learned?

**Testing CKM - take II**

- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Consider only tree decays and $B^0 - \bar{B}^0$ mixing
- Define $h_d e^{2i\sigma_d} = A^{NP}(B^0 \rightarrow \bar{B})/A^{SM}(B^0 \rightarrow \bar{B})$  
  $\implies$ Four parameters: $\rho, \eta$ (CKM), $h_d, \sigma_d$ (NP)
- Use $|V_{ub}/V_{cb}|, A_{DK}, S_{\psi K}, S_{\rho \rho}, \Delta m_{B_d}, A_{SL}^d$
- Fit to $\eta, \rho, h_d, \sigma_d$
- Find whether $\eta = 0$ is allowed
  If not $\implies$ The KM mechanism is at work
- Find whether $h_d \gg 1$ is allowed
  If not $\implies$ The KM mechanism is dominant
What have we learned?

$\eta \not= 0$?

- 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 NP flavor puzzle

The SM = Low energy effective theory

1. Gravity $\Rightarrow \Lambda_{\text{Planck}} \sim 10^{19}$ GeV

2. $m_\nu \neq 0 \Rightarrow \Lambda_{\text{Seesaw}} \leq 10^{15}$ GeV

3. $m_H^2$-fine tuning $\Rightarrow \Lambda_{\text{top-partners}} \sim$ TeV
   Dark matter $\Rightarrow \Lambda_{\text{wimp}} \sim$ 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
The NP flavor puzzle

New Physics

• The effects of new physics at a high energy scale $\Lambda_{NP}$ can be presented as higher dimension operators

• For example, we expect the following dimension-six operators:

$$\frac{z_{sd}}{\Lambda_{NP}^2} (\bar{d}_L \gamma_{\mu} s_L)^2 + \frac{z_{cu}}{\Lambda_{NP}^2} (\bar{c}_L \gamma_{\mu} u_L)^2 + \frac{z_{bd}}{\Lambda_{NP}^2} (\bar{d}_L \gamma_{\mu} b_L)^2 + \frac{z_{bs}}{\Lambda_{NP}^2} (\bar{s}_L \gamma_{\mu} b_L)^2$$

• New contribution to neutral meson mixing, e.g.

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

• Generic flavor structure $\equiv z_{ij} \sim 1$ or, perhaps, loop – factor
## Some data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_K/m_K$</td>
<td>$7.0 \times 10^{-15}$</td>
</tr>
<tr>
<td>$\Delta m_D/m_D$</td>
<td>$8.7 \times 10^{-15}$</td>
</tr>
<tr>
<td>$\Delta m_B/m_B$</td>
<td>$6.3 \times 10^{-14}$</td>
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### High Scale?

- For $z_{ij} \sim 1$ (and $\text{Im}(z_{ij}) \sim 1$):

<table>
<thead>
<tr>
<th>Mixing</th>
<th>$\Lambda_{NP}^{\text{CP}} \gtrsim$</th>
<th>$\Lambda_{NP}^{\text{CPV}} \gtrsim$</th>
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<tbody>
<tr>
<td>$K - \bar{K}$</td>
<td>1000 TeV</td>
<td>20000 TeV</td>
</tr>
<tr>
<td>$D - \bar{D}$</td>
<td>1000 TeV</td>
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• Did we misinterpret the Higgs fine tuning problem?
• Did we misinterpret the dark matter puzzle?
Small (hierarchical?) flavor parameters?

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

| Mixing | $|z_{ij}| \lesssim$ | $\text{Im}(z_{ij}) \lesssim$ |
|--------|---------------------|---------------------|
| $K - \bar{K}$ | $8 \times 10^{-7}$ | $6 \times 10^{-9}$ |
| $D - \bar{D}$ | $5 \times 10^{-7}$ | $1 \times 10^{-7}$ |
| $B - \bar{B}$ | $5 \times 10^{-6}$ | $1 \times 10^{-6}$ |
| $B_s - \bar{B}_s$ | $2 \times 10^{-4}$ | $2 \times 10^{-5}$ |
The NP flavor puzzle

Small (hierarchical?) flavor parameters?

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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

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

- 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
- Why? = The SM flavor puzzle
  - Approximate symmetry? [Froggatt-Nielsen]
  - Strong dynamics? [Nelson-Strassler]
  - Location in extra dimension? [Arkani-Hamed-Schmaltz]
  - ?
\( \nu \)-flavor parameters for anarchists

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

Gonzalez-Garcia et al., 1209.3023
**The flavor of \( \nu \)**

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Gonzalez-Garcia et al., 1209.3023

- \( |U_{\mu 3}| > \text{any } |V_{ij}| \)
- \( |U_{e2}| > \text{any } |V_{ij}| \)
- \( |U_{e3}| \ll |U_{e2}U_{\mu 3}| \)
- \( m_2/m_3 \gtrsim 1/6 > \text{any } m_i/m_j \) for charged fermions

- So far, neither smallness nor hierarchy
- Anarchy? (Consistent with FN)
The flavor of $\nu$

$\nu$-flavor parameters for tribimaximalists

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

- $\sqrt{1/3} = \text{trimaximal mixing: } |U_{e2}| = \sqrt{1/3} - 0.03$;
- $\sqrt{1/2} = \text{bimaximal mixing: } |U_{\mu3}| = \sqrt{1/2} - 0.06$;
- $0 = \text{bimaximal mixing: } |U_{e3}| = 0 + 0.15$

- 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:
  \[ |U|_{\text{TBM}} = \begin{pmatrix}
0.82 & 0.58 & 0 \\
0.41 & 0.58 & 0.71 \\
0.41 & 0.58 & 0.71
\end{pmatrix} \]

- Anarch-ists:
  \[ |U|_{\text{anarchy}} = \begin{pmatrix}
\mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\
\mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\
\mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6)
\end{pmatrix} \]
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?
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 $\Lambda_{NP}$

- Consistency between ATLAS/CMS and FF:
  necessary to understand the NP flavor puzzle

- NP in $c \rightarrow u$? $s \rightarrow d$? $b \rightarrow d$? $b \rightarrow s$? $t \rightarrow c$? $t \rightarrow u$?
  $\mu \rightarrow e$? $\tau \rightarrow \mu$? $\tau \rightarrow e$?

- $A_{FB}^{tt}$ - a wonderful example of collider-flavor interplay

  [Blum, Hochberg, Nir, JHEP 10 (2011) 124]

- $A_{FB}^{tt} \Leftrightarrow \Delta A_{CP}$? An intriguing possibility

  [Hochberg, Nir, PRL 108 (2012) 261601]
What will we learn?

Collider ⇔ Flavor

\[ \frac{m_j - m_i}{m_j + m_i} \]

Excluded

\[ K_{ij} \]

Flavor Factories
What will we learn?

Collider ⇔ Flavor

Flavor Factories

[Flavor Physics: Past, Present, Future] [Grossman, Ligeti, Nir, PTP122(09)125 [0904.4262]]
What will we learn?

Can we make progress?

- NP that couples to quarks/leptons $\implies$ 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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  Progress possible if structure not MFV but related to SM

- $h \implies$ The “NP” is already here!
  $Y_{\bar{f}_i f_j}$ are new flavor parameters that can be measured
What will we learn?

$h$ at present

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\gamma\gamma}$</td>
<td>$1.1 \pm 0.2$</td>
</tr>
<tr>
<td>$R_{ZZ^*}$</td>
<td>$1.1 \pm 0.2$</td>
</tr>
</tbody>
</table>

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

\(h \textbf{ in the future}\)

<table>
<thead>
<tr>
<th>Observable</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{\tau^+\tau^-})</td>
<td>1</td>
</tr>
<tr>
<td>(X_{\mu\mu} = \frac{\text{BR}(h \rightarrow \mu^+\mu^-)}{\text{BR}(h \rightarrow \tau^+\tau^-)})</td>
<td>((m_\mu/m_\tau)^2)</td>
</tr>
<tr>
<td>(X_{\mu\tau} = \frac{\text{BR}(h \rightarrow \mu^\pm\tau^\mp)}{\text{BR}(h \rightarrow \tau^+\tau^-)})</td>
<td>0</td>
</tr>
</tbody>
</table>

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

$h$ in the future

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<td>0</td>
</tr>
</tbody>
</table>

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

The flavorful $h$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\frac{\sigma_{\text{prod}}^{\text{SM}}}{\sigma_{\text{prod}}^{\text{tot}}} \Gamma_{\text{tot}}^{\text{SM}}$</th>
<th>$R_{\tau+\tau-}$</th>
<th>$X_{\mu+\mu-}/(m_\mu^2/m_\tau^2)$</th>
<th>$X_{\tau\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>NFC</td>
<td>$(V_{h\ell}v/\nu_\ell)^2$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>MSSM</td>
<td>$(\sin \alpha/\cos \beta)^2$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>MFV</td>
<td>$1 + 2av^2/\Lambda^2$</td>
<td>$1 - 4bm_\tau^2/\Lambda^2$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2HDM$^{\text{GMFV}}$</td>
<td>$\mathcal{O}(1)$</td>
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<td>$\mathcal{O}(X_{\mu+\mu-})$</td>
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<tr>
<td>FN</td>
<td>$1 + \mathcal{O}(v^2/\Lambda^2)$</td>
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<td>U_{23}</td>
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<tr>
<td>GL</td>
<td>9</td>
<td>25/9</td>
<td>$\mathcal{O}(X_{\mu+\mu-})$</td>
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Measurements of $Y_{ij}$ can exclude/support flavor models

Dery, Efrati, Hochberg, YN, 1302.3229; Dery, Efrati, Hiller, Hochberg, YN, 1304.6727
What will we learn?

**Intermediate summary III**

Measure new flavor parameters:

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

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
  \((10^{-11} \text{ second after the big bang})\)?

• What are the dark matter particles?

• How was the baryon asymmetry generated?

• What is the solution of the flavor puzzles?
Questions for the Symposium

- What will be the best experiments to make progress on flavor?

- What will be the best experiments to make progress on baryogenesis?

- Do we have a serious hint for new physics? $A_{FB}^{tt}$? $\Delta A_{CP}^D$? $A_{SL}^b$? $R(D(\ast))$?

- Is tribimaximal mixing viable/testable?