# Mysteries of Heavy Flavors

<table>
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<th>u</th>
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<tr>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
<td>$\nu_\tau$</td>
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</tbody>
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Patricia Burchat, Stanford University  
APS Meeting, Tampa, Florida, April 16-19, 2005
Notes for Printed Version of Presentation

- I delivered this presentation in the opening plenary session of the 2005 APS April Meeting in Tampa, Florida.

- My audience was a mix of particle, nuclear, astro, plasma and accelerator physicists.

- This talk is not intended to be a review of heavy-flavor physics.

- I deliberately do not put much distracting text on my presentation slides. Therefore, the logic of the presentation may not be clear from this printed version.

- For most decays, I include the minimum number of Standard-Model or New-Physics Feynman diagrams needed to make a pedagogical point. For many of the examples, other diagrams exist but, as Carl Wieman stressed in his talk in the same session, every additional detail imposed on a non-expert audience has its cost in terms of what they can absorb.

- This talk was prepared with Keynote and LaTeX Equation Editor (Mac OS X).
<table>
<thead>
<tr>
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</table>
$B(\mu \rightarrow \nu_\mu \nu_e e_e) \approx 100\%$

Suppressed by $\left( \frac{\Delta m^2_{\nu}}{M^2_W} \right)^2 \leq 10^{-50}!$

$B(\mu \rightarrow e \gamma) < 1.2 \times 10^{-11}$, $B(\mu \rightarrow e e e) < 1.0 \times 10^{-12}$
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Millions of $f \bar{f}$ pairs produced in $e^+e^-$ annihilations at the $B$ Factories [$\sim 40\%$ BABAR, $\sim 60\%$ Belle]
Millions of $f\bar{f}$ pairs produced in $e^+e^-$ annihilations at the $B$ Factories
[$\sim 40\%$ BABAR, $\sim 60\%$ Belle]
Experimental Results (BABAR and Belle):

\[ B(\tau \to \mu \gamma) < 0.9 \times 10^{-7} \]
\[ B(\tau \to e \gamma) < 3.9 \times 10^{-7} \]
\[ B(\tau \to eee, \mu \mu \mu, e \mu \mu, \mu ee) < (1 - 3) \times 10^{-7} \]

Non-observation of these decays further constrains new physics.
B Factories

\[ \begin{align*}
\bar{b}d &= B^0 \\
\bar{b}u &= B^- \\
\bar{b}s &= B_s \\
\bar{b}c &= B_c \\
\bar{b}ud &= \Lambda_b \\
\ldots
\end{align*} \]

Hadron machines (e.g., Tevatron)
\[ \overline{B}^0, \overline{B}^0_s \left\{ \begin{array}{c} b \\ \overline{d}, \overline{s} \end{array} \right\} \]

Standard Model: \( B(B_{d,s} \rightarrow \mu^+\mu^-) \approx (1 - 10) \times 10^{-10} \)
Upper Limits on Branching Fractions in Units of $10^{-7}$

$B^0 \rightarrow \mu^+ \mu^-$

$B_s \rightarrow \mu^+ \mu^-$

Upper Limits on Branching Fractions in Units of $10^{-7}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Limit</th>
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</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>0.00</td>
</tr>
<tr>
<td>Belle</td>
<td>0.01</td>
</tr>
<tr>
<td>CDF</td>
<td>0.02</td>
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</tbody>
</table>

$B_s \rightarrow \mu^+ \mu^-$

Upper Limits on Branching Fractions in Units of $10^{-7}$

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<tbody>
<tr>
<td>D0</td>
<td>0.03</td>
</tr>
<tr>
<td>CDF</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Sensitive searches for rare decays of $\mu$, $\tau$, $K$, $D$, $B^0$, $B^0_s$, ... through "loop" diagrams put strong constraints on new physics.

Mystery?
How does New Physics contrive to avoid detection in all these modes?

Further sensitivity to new physics through interference between amplitudes (CP violation).

A short tutorial...
Choose a phase convention such that $A_1$ is real.

$\delta$ is a phase that \textit{does not} change sign under $CP$.

$\phi$ is a phase that \textit{does} change sign under $CP$.

\[ P(i \to f) - P(\bar{i} \to \bar{f}) \propto 2|A_1 A_2| \sin \delta \sin \phi \]

$\Rightarrow$ Need to know $\delta$ in order to extract $\phi$. 
“Quark Mixing” provides a CP-violating phase in the Standard Model.

So does NEW PHYSICS.
\[
\overline{B}^0 \rightarrow \pi^+ K^-
\]

Two diagrams with different weak phases ... and different (uncalculable) strong phases...
CP Asymmetries Measured in Rare B Decays

\[
\frac{\Gamma(B) - \Gamma(B)}{\Gamma(B) + \Gamma(B)}
\]
Meson mixing: a source of a known non-CP-violating relative phase

No mixing:
\[ \cos(\Delta m t/2) \]

Mixing followed by decay:
\[ -i \sin(\Delta m t/2) \exp(2i\phi) \]

relative non-CP-violating phase

relative CP-violating phase
The “Golden Modes”

One dominant decay amplitude
⇒ theoretically clean!

Distinctive final state and “large” branching fraction \(10^{-4}\)
⇒ experimentally clean!

\[ b \xrightarrow{W} c_s \xrightarrow{d} K_{S,L}^0 \]
BABAR: $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$

Belle: $\sin 2\beta = 0.728 \pm 0.056 \pm 0.023$
The Quark Mixing Matrix and the Unitarity Triangle

apply unitarity constraint to these two columns
All Constraints from Direct and Indirect Measurements:

excluded area has CL > 0.95

CKM

fit
t
Moriond 05

Preliminary
Another mode sensitive to $\sin 2\beta$:

$$B \rightarrow \phi K^0_S$$

One dominant decay amplitude

$\Rightarrow$ theoretically clean

Loop $\Rightarrow$ sensitive to New Physics!

“Distinctive” final state but

“small” branching fraction ($10^{-6}$)

$\Rightarrow$ an experimental challenge!
Difference between asymmetry from tree and loop diagrams: 3.7 \sigma\text{(stat)}.
But each “loop” mode has (different) additional sub-dominant diagrams, which brings in theoretical uncertainties...

<table>
<thead>
<tr>
<th>System</th>
<th>BABAR 04</th>
<th>Belle 04</th>
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<tbody>
<tr>
<td>c\bar{c}K^0</td>
<td>0.722 ± 0.040 ± 0.023</td>
<td>0.728 ± 0.056 ± 0.023</td>
</tr>
<tr>
<td>Average (loop diagrams)</td>
<td>0.726 ± 0.037</td>
<td></td>
</tr>
<tr>
<td>\phi K^0</td>
<td>0.50 ± 0.25 ± 0.04</td>
<td>0.06 ± 0.33 ± 0.09</td>
</tr>
<tr>
<td>\eta K_S</td>
<td>0.30 ± 0.14 ± 0.02</td>
<td>0.65 ± 0.18 ± 0.04</td>
</tr>
<tr>
<td>f_0 K_S</td>
<td>0.85 ± 0.12 ± 0.10</td>
<td>-0.47 ± 0.41 ± 0.08</td>
</tr>
<tr>
<td>\rho K_S</td>
<td>0.35 ± 0.23 ± 0.04</td>
<td>0.30 ± 0.59 ± 0.11</td>
</tr>
<tr>
<td>\omega K_S</td>
<td>0.50 ± 0.34 ± 0.02</td>
<td>0.75 ± 0.64 ± 0.18</td>
</tr>
<tr>
<td>K K K^0</td>
<td>BABAR 04</td>
<td>Belle 04</td>
</tr>
<tr>
<td>K K K^0</td>
<td>0.55 ± 0.22 ± 0.12</td>
<td>0.49 ± 0.18 ± 0.04</td>
</tr>
<tr>
<td>Average (loop diagrams)</td>
<td>0.43 ± 0.07</td>
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Mysteries of Heavy Flavors?

- Mysteries of Standard Model FLAVOR physics remain.
- The B Factories and hadron machines are providing enormous data samples that allow us to explore the heavy-flavor sector with unprecedented precision.
- Many new analysis techniques have been developed to allow us to probe more and more decays that are potentially sensitive to new physics.
- If NEW PHYSICS is out there, then it must have a very special flavor and CP structure to evade all the existing searches.
- Will hints of discrepancies with the Standard Model survive? That depends on what more data reveal and on the ultimate precision of theoretical Standard-Model predictions.
Looking forward to more results in heavy flavor physics from BABAR, Belle, CDF, DO, LHCb (RSVP?)