The Relevance of Flavour Physics in the LHC Era

David Hitlin
Workshop on Flavour in the Era of the LHC
CERN
November 10, 2005
“The aim of physics is to find new terms in the Hamiltonian of the universe. Everything else is chemistry.”

M. Schwartz

By this stringent yardstick, most of us, while we strive to do physics, wind up doing chemistry.

Nonetheless, flavour physics has historically been a rich source of physics, even by Mel’s criterion.

Does flavour physics in the LHC era meet this rigorous criterion?

What are the crucial experiments in the search for new terms in the flavour Hamiltonian (New Physics)?
Where is flavour physics now?

- The PEP-II/\textit{BABAR} and KEKB/Belle \textit{B} Factories, together with CLEO\textit{c} and modern \textit{K} decay experiments, have brought us to the precision measurement regime for many heavy quark and heavy lepton measurements.

- CDF and DØ at Tevatron Run II are now producing physics and have unique capabilities in $B_s$ mixing, rare decays and $b$ baryon studies.

- Bottom line: the CKM phase is consistent with being the source for all observed \textit{CP}-violating phenomena.
  - There must, however, be additional sources of \textit{CP} violation.

- Over the next few years, \textit{CP} violation and rare decays in the flavour sector will be pursued with improved precision, and, equally important, with improved sophistication.
  - e.g., the best current methods for measurement of $\alpha (\phi_2)$ and $\gamma (\phi_1)$ were not those put forward in the initial phase.
The Unitarity Triangle summarizes the salient features of Standard Model heavy flavour physics

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^2(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^2(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} \]

Unitarity: \[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

\[ (\bar{\rho}, \bar{\eta}) \]

\[ V_{ud}V_{ub}^* \quad \alpha(\phi_2) \quad V_{td}V_{tb}^* \]

\[ V_{cd}V_{cb}^* \quad \gamma(\phi_3) \quad -V_{cd}V_{cb}^* \]

\[ (0,0) \quad (1,0) \quad \bar{\rho} \]

CP violation \( \propto J = \text{Im} \left[ V_{ud}V_{cs}^*V_{us}V_{cd}^* \right] \approx A^2\lambda^6\eta \sim 10^{-5} \), the Jarlskog invariant:
Let me count the ways

- There are many ways to overconstrain the Unitarity Triangle
- Useful constraints from $B$ and $K$ decays
Overconstraining the Unitarity Triangle

\[ B \rightarrow X_u \ell \bar{\nu} \]
\[ B \rightarrow \pi \ell \bar{\nu} \]
\[ V_{ud} V_{ub}^* \]
\[ \alpha(\phi_2) \]
\[ \gamma(\phi_3) \]
\[ \beta(\phi_1) \]
\[ -V_{cd} V_{cb}^* \]

\[ B^\pm \rightarrow (\bar{D}^0/D^0) K^\pm \]
\[ \rightarrow (\bar{D}^0/D^0)_{CP} K^\pm \] (GLW)
\[ \rightarrow K^+ K^- \pi^\pm \] (ADS)
\[ \rightarrow (K_S^0 \pi^+ \pi^-) K^\pm \] (Dalitz plot)

\[ B \rightarrow X_c \ell \bar{\nu} \]
\[ B \rightarrow D^*_c \ell \bar{\nu} \]
\[ \tau_B \]

\[ B^0(\bar{B}^0) \rightarrow \rho^+ \rho^- \]
\[ B^0(\bar{B}^0) \rightarrow \rho^0 \gamma \]
\[ B^0 \bar{B}^0 \text{ oscillation rate} \]
\[ B^0 \bar{B}^0 \text{ oscillation rate} \]

\[ B^0(\bar{B}^0) \rightarrow (c\bar{c}) K_S^0 \]
\[ B^0(\bar{B}^0) \rightarrow (s\bar{s}) K_S^0 \]
\[ B^0(\bar{B}^0) \rightarrow (c\bar{c}d\bar{d}) \]
\[ A_{f_{CP}}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} \]

\[ A_{f_{CP}}(t) = S \cdot \sin(\Delta m \cdot t) - C \cdot \cos(\Delta m \cdot t) \]

\[ S = \frac{2 \cdot \text{Im}(\lambda)}{1 + |\lambda|^2} \quad C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \]

\[ \lambda = \sqrt{M_{12}^* - \frac{i}{2} \Gamma_{12}^*} \cdot \frac{\langle f_{CP} | H | \overline{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle} = \frac{q}{p} \cdot \overline{A_f} \]

If there is New Physics it could be in the decay amplitude or the mixing amplitude.

For a single decay amplitude: |\(q/p| = 1\)

\[ |\lambda| = 1 \quad \Rightarrow \quad S = \text{Im}(\lambda), \quad C = 0 \]

\[ A_{f_{CP}}(t) = \text{Im}(\lambda) \cdot \sin(\Delta m \cdot t) \]
sin2$\beta$ is now a precision measurement

\[
\sin^2 \beta = +0.722 \pm 0.040 \pm 0.023
\]

\[
\sin 2\phi_i = +0.652 \pm 0.039 \pm 0.020
\]
Unitary Triangle 2005

\[ |V_{td}/V_{ts}| \text{ from } B \to \rho \gamma \text{ vs. } B \to K^* \gamma \]
Is there New Physics in $B^0\overline{B}^0$ mixing?

- Assume: New Physics in tree decays - negligible
- Define $r_d^2 \exp(2i\theta_d) = 1 + h e^{i\sigma} = \langle B^0 | H_{\text{full}} | \overline{B}^0 \rangle / \langle B^0 | H_{\text{SM}} | B^0 \rangle$
- Use $|V_{ub}/V_{cb}|$, $A_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, $\Delta m_{B_d}$, $A_{SL}$
- Fit to $\eta$, $\rho$, $|r_d|$, $\theta_d$ (or $|h|$, $\sigma$)
- Find whether $h \neq 0$ ($r_d \neq 1$) is allowed

For arbitrary phase, $h = |A_{NP}/A_{SM}| \sim 0.2 \pm 0.2$
$B_s$ mixing limits

- New CDF/DØ results

Limit $14.5 \rightarrow 16.6 \text{ ps}^{-1}$
sensitivity $18.3 \rightarrow 20.0 \text{ ps}^{-1}$
LHCb sensitivity to $B_s^0 \overline{B_s}^0$ mixing

In 1 year, $\geq 5\sigma$ observation of $B_s^0$ oscillations up to $\Delta M_s = 68$ ps$^{-1}$
Is there New Physics in $B_s^0 \overline{B_s^0}$ mixing?

Current

If $\Delta m_s = (18.3 \pm 0.3) \text{ps}^{-1}$

Agashe, Papucci, Perez, Pirjol
Mixing-induced CP violation: phase mismatch $\phi_s - 2\phi_D \approx \phi_s \neq 0, \pi$

“first mix, then decay”

- $\phi_s^{SM} \equiv 2 \arg [V_{ts}^* V_{tb}] \approx -2\beta_s = \mathcal{O}(-0.04) \text{ rad}$

$\overline{B}_s^0 \rightarrow W^- \rightarrow V_{ts}^* \rightarrow t \rightarrow V_{tb} b$

$B_s^0 \rightarrow W^+ \rightarrow V_{cs} \rightarrow s \rightarrow \phi, \eta'$

$\overline{B}_s^0 \rightarrow V_{cb}^* \rightarrow c \rightarrow J/\psi, \eta_c$

$\rightarrow \text{CP-asymmetry directly measures } \phi_s = \mathcal{O}(-0.04) \text{ rad (for given } \eta_{f_{CP}})$

$$A_{CP}(t) = \frac{-\eta_{f_{CB}} \sin(\phi_s) \sin(\Delta M_s t)}{\cosh(\frac{\Delta \Gamma_s}{2}) - \eta_{f_{CP}} \cos(\phi_s) \sinh(\frac{\Delta \Gamma_s}{2})}$$

<table>
<thead>
<tr>
<th>Channels</th>
<th>$\sigma(\phi_s)$ [rad]</th>
<th>Weight $(\sigma/\sigma_i)^2$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow J/\psi \eta(\gamma \gamma)$</td>
<td>0.112</td>
<td>6.4</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi \eta(\pi^+ \pi^- \pi^0)$</td>
<td>0.148</td>
<td>3.6</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \eta_c \phi$</td>
<td>0.106</td>
<td>7.1</td>
</tr>
<tr>
<td>Combined three pure CP eigenstates channels</td>
<td>0.068</td>
<td>17.1</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi \phi$</td>
<td>0.031</td>
<td>82.9</td>
</tr>
<tr>
<td>Combined all four CP eigenstates channels</td>
<td>0.028</td>
<td>100.0</td>
</tr>
</tbody>
</table>

With $10 \text{ fb}^{-1}$ (5 years): $\sigma(\phi_s) \sim 0.013 \text{ rad} \rightarrow \sim 3\sigma$ for $\phi_s = -0.04 \text{ rad (SM)}$
Constraints on New Physics

- Even at current precision, the *grosso modo* agreement of flavour physics experimental results with Standard Model predictions places very meaningful limits on physics beyond the Standard Model.
- In the presence of New Physics, many of these simple relations can be modified.
- This has spawned a minor phenomenological industry that has provided guidance for the current experiments and a roadmap for future investigations.

- Where to look for New Physics?
  - FCNC processes
  - $b \rightarrow s$ vertices: $\Delta F=1$, $\Delta F=2$
    - CP violation, mixing, rare $b$ and $\tau$ decays
  - Precision measurements in $K$, $D$ and $B$ decays
The LHC era begins

- What will remain to be done in flavour physics when the current programs at BABAR, Belle, CDF and DØ are over?
  - Overconstrained tests of the CKM matrix to the level of precision warranted by theoretical uncertainties
  - Searches, and, quite likely, measurements of deviations from the Standard Model that will be crucial to an understanding of New Physics uncovered at the LHC

- What facilities will we have?
  - LHC: ATLAS, CMS, LHCb
  - Linear collider (ILC/CLIC)?
  - A Super B Factory?
  - Rare kaon experiments?
  - $\tau$/charm collider
  - Fixed target charm experiment?

- Which facilities beyond the LHC are most crucial to flavour studies?
An Endangered Species Act for heavy quarks in the US?

<table>
<thead>
<tr>
<th>Year</th>
<th>u</th>
<th>c</th>
<th>t</th>
<th>d</th>
<th>s</th>
<th>b</th>
</tr>
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<tbody>
<tr>
<td>2003</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2005</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2006-2008</td>
<td></td>
<td></td>
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</tbody>
</table>

2006-2008

**Babar**

**SuperBabar**

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Data samples \((b)\) at the start* of the LHC era

- **\(B_{ABAR}\)** and Belle will each have collected a total data sample of approximately 1 \(ab^{-1}\) by \(~2008\)
  - \(2 \text{ ab}^{-1} = 2 \times 10^9\) produced \(B\bar{B}\) pairs

- The Tevatron Run II experiments CDF and DØ will each have collected 4-8 \(fb^{-1}\) by \(~2009\)
  - Premier objective is a measurement of \(B^0_s \bar{B}^0_s\) mixing
How can flavour physics complement the LHC program?

- The Higgs will likely come first
- The search for evidence of physics beyond the Standard Model will then take center stage
  - There have been many exercises showing how, with sufficiently large data samples and concomitant improved precision, heavy quark and $\tau$ measurements can uniquely discriminate between SUSY breaking models, extra dimension scenarios, etc.
  - These need sharpening, on both sides: high $p_t$ and flavour physics
- It is possible that the LHC will find the Standard Model Higgs and nothing else
  - In this situation, precision flavour physics may be the best way we have to search for physics beyond the Standard Model
Strategies

- Improve measurements of CKM unitarity triangle measurements to the precision warranted by theory
  - $CP$ asymmetries in tree-dominated processes
  - Differences in $CP$ asymmetries between tree and penguin-dominated processes

- Search for/measure FCNC processes, highly suppressed in the Standard Model, in which New Physics may show up
  - Generation 3 to generation 2 ($b \rightarrow s$, $\tau \rightarrow \mu$) transitions are especially promising
  - $B_s$ oscillations
  - $b \rightarrow s \gamma$ branching fraction, $A_{CP}$
  - $A_{FB}(b \rightarrow s \ell^+ \ell^-)$
  - $B_s \rightarrow \mu^+ \mu^-$
Precision of $\alpha$, $\sin 2\beta$, $\gamma$ in this decade

- Through $\sim 2008$ (and beyond), precision of UT angle measurements will continue to be statistics limited

- $\alpha$, $\gamma$ methods shown run into model problems at 2 ab$^{-1}$ level

  - With higher statistics, other methods may be better
    - e.g. for $\alpha$, use $B \to \pi\pi$ + isospin analysis instead of $B \to \rho\rho$

LHCb (1 year @ $2 \times 10^{32}$) (Schneider)

$$\sigma(\alpha) = 10^0$$

$$\sigma(\gamma) = 5^0(B^\pm \to D^0 K^\pm)$$

$$\sigma(\sin 2\beta) = 0.02$$
Global CKM fit: 2008

\[
\sigma(V_{ub}) = 6.5\% \quad \sigma(\Delta m_s) = 5\% \quad \sigma(\sin 2\beta) = 0.019 \quad \sigma(\alpha) = 8^\circ \quad \sigma(\gamma) = 10^\circ
\]
What is the ultimate possible UT precision?

- Theoretical limits (continuum methods)
  - Many measurements will not be theory-limited for quite some time

<table>
<thead>
<tr>
<th>Ligeti:</th>
<th>Measurement (in SM)</th>
<th>Theoretical limit</th>
<th>Present error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B \to \psi K_S$ ($\beta$)</td>
<td>$\sim 0.2^\circ$</td>
<td>$1.6^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B \to \phi K_S$, $\eta^{(')} K_S$, ... ($\beta$)</td>
<td>$\sim 2^\circ$</td>
<td>$\sim 10^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B \to \pi \pi$, $\rho \rho$, $\rho \pi$ ($\alpha$)</td>
<td>$\sim 1^\circ$</td>
<td>$\sim 15^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B \to DK$ ($\gamma$)</td>
<td>$\ll 1^\circ$</td>
<td>$\sim 25^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B_s \to \psi \phi$ ($\beta_s$)</td>
<td>$\sim 0.2^\circ$</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$B_s \to D_s K$ ($\gamma - 2\beta_s$)</td>
<td>$\ll 1^\circ$</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$B \to X \ell^+ \ell^-$</td>
<td>$\sim 5%$</td>
<td>$\sim 20%$</td>
</tr>
<tr>
<td></td>
<td>$B \to K^{(*)} \nu \bar{\nu}$</td>
<td>$\sim 5%$</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$K^+ \to \pi^+ \nu \bar{\nu}$</td>
<td>$\sim 5%$</td>
<td>$\sim 70%$</td>
</tr>
<tr>
<td></td>
<td>$K_L \to \pi^0 \nu \bar{\nu}$</td>
<td>$&lt; 1%$</td>
<td>—</td>
</tr>
</tbody>
</table>
Ultimate UT precision - II

- Unitarity triangle using unquenched lattice results

Current precision

"Ultimate" precision

Okamoto

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Ultimate UT precision - III

- Prediction for SuperKEKB at 50 ab$^{-1}$ (~2020)

- LHCb measurements will also be pertinent (or, they may be the only measurements)

- Rare $K$ decay constraints

<table>
<thead>
<tr>
<th>Reaction</th>
<th>short-distance (e.w.) contrib. to the total rate $\left(\Gamma - \Gamma_{\text{no s.d.}}\right) / \Gamma$</th>
<th>present irreducible th. error on the s.d. amplitude extracted from BR only</th>
<th>total BR within SM (central value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \pi^0 \nu \bar{\nu}$</td>
<td>&gt; 99%</td>
<td>1%</td>
<td>$8 \times 10^{-11}$</td>
</tr>
<tr>
<td>$K^- \to \pi^+ \nu \bar{\nu}$</td>
<td>88%</td>
<td>3%</td>
<td>$3 \times 10^{-11}$</td>
</tr>
<tr>
<td>$K_L \to \pi^0 e^+ e^-$</td>
<td>38%</td>
<td>15% Dalitz $\sim 10%$</td>
<td>$3.5 \times 10^{-11}$</td>
</tr>
<tr>
<td>$K_L \to \pi^0 \mu^+ \mu^-$</td>
<td>28%</td>
<td>30% Dalitz $\sim 15%$</td>
<td>$1.5 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
The real motivation for precision measurements of rare $K$ decay branching fractions is the sensitivity to New Physics.

The same is true for high precision $B$ and $\tau$ decay studies.
After the LHC finds New Physics

- LHC, by the mass difference and threshold methods, will measure SUSY masses to a precision of 5 to 10 GeV
- ILC or CLIC, a decade later, will dramatically improve errors, by, e.g., measuring slepton masses with a threshold scan to a precision ~100 MeV with 10 fb-1 per point

<table>
<thead>
<tr>
<th>LHC</th>
<th>LHC+ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m_{\tilde{\chi}^0_1} )</td>
<td>4.8</td>
</tr>
<tr>
<td>(\Delta m_{\tilde{t}_R} )</td>
<td>4.8</td>
</tr>
<tr>
<td>(\Delta m_{\tilde{\chi}^0_2} )</td>
<td>4.7</td>
</tr>
<tr>
<td>(\Delta m_{\tilde{q}_L} )</td>
<td>8.7</td>
</tr>
<tr>
<td>(\Delta m_{\tilde{b}_L} )</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Correlations allow model discrimination (without ILC)

- In the meantime it is important to clarify the flavour structure of New Physics discoveries with high statistics \(K, B\) and \(\tau\) experiments
- These studies can uniquely discriminate between SUSY models
Many SM extensions yield measurable effects in $B$ physics

- **Little Higgs w MFV UV fix**
- **Extra dim w SM on brane**
- **Supersoft SUSY breaking Dirac gauginos**
- **MSSM MFV small $\tan\beta$**
- **MSSM MFV large $\tan\beta$**
- **SUSY GUTs**
- **Effective SUSY**

**SM-like $B$ physics**

**New Physics in $B$ data**

after G. Hiller
Heavy flavour studies complement LHC direct searches
Experimental signatures of extended flavour structure

- FCNC processes, LFV processes and CPV in loop decays

- There are many clean measurements that are diagnostic of models
  - New CP violating phase in $b \to sqq$: CPV($t$) in $B^0 \to \phi K_{s'} \eta' K_s K_s K_s$
  - Right-handed current in $b \to s\gamma$: CPV($t$) in $B^0 \to K_s \pi^0 \gamma$
  - Lepton flavour violation in $\tau$ decays: $B(\tau \to \mu \gamma)$
  - Charged Higgs in tree diagram: $B(B \to D\tau\nu)/B(B \to D\mu\nu)$
  - $b \to d\gamma$, $A_{FB}$ in $b \to s\ell^+\ell^-, B \to K^*\nu\nu, B \to \ell\nu, \ldots$
  - $B_s$ mixing

- Some measurements are unique to hadron experiments, some to $e^+e^-$, and some can be done in both environments
Many rare processes are sensitive to New Physics

<table>
<thead>
<tr>
<th>Mode</th>
<th>Standard Model Branching Fraction $\mathcal{B}$</th>
<th>New Physics Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow s\gamma$</td>
<td>$\sim 3 \times 10^{-4}$</td>
<td>$\mathcal{B}, A_{CP}, A_{FB}$</td>
</tr>
<tr>
<td>$b \rightarrow sg$</td>
<td>$\sim 10^{-5}$ per mode</td>
<td>$A_{CP}$</td>
</tr>
<tr>
<td>$B \rightarrow X\ell\ell$</td>
<td>$\sim 10^{-6}$ per mode</td>
<td>$\mathcal{B}, A_{CP}, A_{FB}$</td>
</tr>
<tr>
<td>$B \rightarrow X\nu\nu$</td>
<td>$\sim 10^{-6}$ per mode</td>
<td>$\mathcal{B}$ up to $10^{-5}$/mode</td>
</tr>
<tr>
<td>$D \rightarrow X\ell\ell$</td>
<td>$\sim 10^{-6}$ per mode</td>
<td>$\mathcal{B}$ up to $10^{-5}$/mode</td>
</tr>
<tr>
<td>$B \rightarrow \tau\nu$</td>
<td>$\sim 10^{-4}$</td>
<td>Close to SM sensitivity</td>
</tr>
<tr>
<td>$\tau \rightarrow l\gamma$</td>
<td>$\sim 10^{-40}$</td>
<td>$\mathcal{B}$ up to $10^{-8}$</td>
</tr>
<tr>
<td>$B \rightarrow ll$</td>
<td>$&lt; 10^{-11}$</td>
<td>$\mathcal{B}$ up to $10^{-5}$</td>
</tr>
<tr>
<td>$D \rightarrow ll$</td>
<td>$&lt; 10^{-9}$</td>
<td>$\mathcal{B}$ up to $10^{-6}$</td>
</tr>
</tbody>
</table>

The observed pattern of effects is diagnostic of the mechanism of SUSY breaking or the type of extra dimension model.
Flavour physics provides a roadmap

- **New $CPV$ or flavour violation?**
  - No
  - Yes
    - **Only in LH currents?**
    - Yes
      - **MFV**
    - No
      - **SM**
    - **Deviations from SM?**
      - Yes
        - **NMFV**
      - No
        - **Only in 3rd generation?**
          - Yes
            - **$\Delta F=1,2$ correlations?**
            - **Perez**
          - No
            - **Flavour physics already strongly restricts SUSY**
              - $K$ physics $\varepsilon'/\varepsilon$, $K^0\bar{K}^0$
              - Hg EDM
              - $B$ physics $B(b \rightarrow s\gamma)$, $\Delta m_{B_s}$,......

- **Standard Model flavour structure:**
  - No right-handed couplings
  - One $CP$-violating phase
  - Small quark mixing
What can a Super $B$ Factory bring to the party?

- Flavour physics, whether $b$, $c$ or $\tau$ decays, provides
  - Sensitivity to New Physics (SUSY, extra dimensions, .....)
  - New $CP$ phases, non-Standard Wilson coefficients, ..... 
  - Strong and unique constraints on models of SUSY breaking
    - $B(b\to s\gamma)$ has already ruled out a host of New Physics models

- Super $B$ specific measurements
  - $CPV$ in $b\to s$
  - FCNC ($K\ell\ell$, $K\nu\nu$ .....)
  - LFV ($\tau$ decays)
  - Higgs mediation ($B\to \tau\nu$, $B\to D\tau\nu$, etc.)
  - Precision CKM Unitarity Triangle parameters
    - Measure $\alpha, \beta, \gamma, V_{ub}, V_{cb}, \Delta m_d$ to the limit of theoretical precision (see above)

- There is, of course, some overlap with LHC$b$
Probes of new physics

- In the Standard Model we expect the same value for “$\sin 2\beta$” in $b \to c\bar{c}s$, $b \to c\bar{c}d$, $b \to s\bar{s}s$, $b \to d\bar{d}s$ modes, but different SUSY models can produce different asymmetries.

- Since the penguin modes have branching fractions one or two orders of magnitude less than tree modes, great deal of luminosity is required to make these measurements to meaningful precision.

\[
\lambda_{\text{tree}} = \frac{q}{p} \frac{A}{A} = \eta \frac{V_{tb} V_{td}^*}{V_{tb} V_{td}^*} V_{cb} V_{cs}^* = (-1)e^{-2i\beta}
\]

\[
\lambda_{\text{penguin}} = \frac{q}{p} \frac{A}{A} = \eta \frac{V_{tb} V_{td}^*}{V_{tb} V_{td}^*} V_{tb} V_{ts}^* = (-1)e^{-2i\beta}
\]

In general $S_{J/\psi K_S} \neq S_{\phi K_S}$; $C_{J/\psi K_S} \neq C_{\phi K_S}$.
There are penguin and tree corrections to $b \rightarrow ss\bar{s}$, $s\bar{d}d$ modes.

<table>
<thead>
<tr>
<th>$b \rightarrow ss\bar{s}$, $s\bar{d}d$ mode</th>
<th>$B$</th>
<th>$x10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \phi K^0_S$</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta' K^0_S$</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^0 K^0_S$</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^0_S$</td>
<td>440</td>
<td>1</td>
</tr>
</tbody>
</table>

Issues: triggering, charged/neutral vertexing, ...
There is as yet no evidence for New Physics from $CP$ asymmetry measurements in $b \to s$ transitions

As we press the search, we must understand
- The required and achievable experimental precision
- The reliability of theoretical calculations

Kirkby and Nir, PDG
How good are the SM predictions?

Two body:
Beneke, PLB 620 (2005) 143

\[ \Delta = S_{\text{penguin}} - \sin 2\beta \]

Calculations within framework of QCD factorization
squark mass matrix ($d$ sector)

\[
\begin{pmatrix}
    m^2_{d_L} & m_d (A_d - \mu \tan \beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\
    m_d (A_d - \mu \tan \beta) & m^2_{d_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\
    (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{RL} & m_s (A_s - \mu \tan \beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} & (\Delta^d_{23})_{RR} \\
    (\Delta^d_{13})_{LR} & (\Delta^d_{13})_{RL} & (\Delta^d_{23})_{RL} & m_{b_L} (A_b - \mu \tan \beta) \\
    (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{RR} & (\Delta^d_{23})_{LR} & m_{b_R} (A_b - \mu \tan \beta) \\
\end{pmatrix}
\]

Mass spectrum: LHC, LC

Assuming all $\Delta$'s small and squarks nearly degenerate, we can use mass insertion approximation (MIA):

\[
\left( \delta^d_{ij} \right)_{AB} = \frac{\left( \Delta^d_{ij} \right)_{AB}}{m^2}
\]

Flavour mixing parametrization

$b \to s$ (23), $b \to d$ (13)

Off diagonal terms can provide unique information on $CP$ phases
The scale of New Physics

- Mass insertion approximation: model-independent ($\delta_{LL,RR}$)

$\phi_{13}$ mass insertion  $\phi_{23}$ mass insertion

$\Delta A_{CP} (J/\psi K_S - \pi^0 K_S)$  $\Delta A_{CP} (J/\psi K_S - \phi K_S)$

after Ciuchini, Franco, Martinelli, Masiero, & Silvestrini
How much integrated luminosity?

- 50 ab\(^{-1}\) is required for \(CP\) asymmetry measurements in rare penguin modes and for rare branching fractions
New Physics effects in the MMSM/THDM

- $b \rightarrow s g$ penguins

- $b \rightarrow s \gamma$ penguins

- $B, D \rightarrow \ell\ell, \nu\nu$

- $B \rightarrow \tau\nu$

- $\tau \rightarrow \ell\gamma$

- LFV

David Hitlin  Flavour in the Era of the LHC  CERN  November 10, 2005
Theoretically clean, but $A_{CP}$ is very small in the Standard Model, since the photon is polarized, and the final state is almost flavor specific

⇒ Helicity suppression:

$\sim m_s/m_b$

Requires vertex reconstruction with $K_S$ alone

SuperKEKB study:

$\sigma(A_{CP}^{\text{mix}}(B\to K^*\gamma, K^*\to K_S\pi^0)) = 0.04$

$\sigma(A_{CP}^{\text{dir}}(B\to X_s\gamma)) = 0.005$

for 50 ab$^{-1}$
Asymmetric $B$ factories provide a uniquely clean environment

- High (30%) and well-measured flavour-tagging efficiency

- $B$ decays with neutrinos
  \[ B \rightarrow D_{\tau\nu}, \tau\nu, u\ell\nu, \ldots \]

- $B$ decays with $\gamma, \pi^0$
  \[ B \rightarrow X_s\gamma, \pi^0\pi^0, \ldots \]

- $B$ vertex reconstruction with $K_S^0$ alone
  \[ B \rightarrow K_S^0\pi^0, K_S^0\pi^0\gamma, \ldots \]

Coherent production: reconstructing one $B$ meson yields the four-momentum of the recoiling $B$ – a “$B$ beam”
$A_{\text{CP}}^{\text{mix}}$ in four SUSY models

Direct $CPV$

- $m_{\tilde{g}}(GeV)$
- $50ab^{-1}$
- Goto, Okada, Shimizu, Shindou, Tanaka

Mixing $CPV$

- $m_{\tilde{g}}(GeV)$
- $m_{\tilde{g}}(GeV)$

David Hitlin   Flavour in the Era of the LHC   CERN   November 10, 2005
$b \to s \ell^+ \ell^-$, $B \to K \ell^+ \ell^-$, $B \to K^* \ell^+ \ell^-$

- Uniquely sensitive tests of Wilson coefficients
\[ b \rightarrow s \ell^+ \ell^-, \; B \rightarrow K \ell^+ \ell^-, \; B \rightarrow K^* \ell^+ \ell^- \]

- Exclusive decays affected by larger uncertainties
- Inclusive decays are better: only in \( e^+ e^- \)
- Use of ratios: AFB, ACP, \( e^+ e^-/\mu^+ \mu^- \)
\[ b \to s\ell^+\ell^-, \; B \to K\ell^+\ell^-, \; B \to K^*\ell^+\ell^- \]

Precision

- SuperB factory with 50 ab\(^{-1}\)
  - \(-A_{FB} vs q^2\)

LHC

- \(B(B \to X_{sll})\) with 140 fb\(^{-1}\)
  - 2 fb\(^{-1}\): (4.0 ± 1.2) GeV\(^2\) with
  - 10 fb\(^{-1}\): (4.0 ± 0.5) GeV\(^2\)

\[ \Rightarrow 13\% \text{ error on } C_{7}^{\text{Eff}}/C_{9}^{\text{Eff}} \]
Extra dimension models
- Randall-Sundrum example (Rizzo)
- Zero crossing moves with mass of lightest KK graviton

\[ b \rightarrow s \ell^+ \ell^-, \ B \rightarrow K \ell^+ \ell^-, \ B \rightarrow K^* \ell^+ \ell^- \]
(More) model-independent analysis of NP couplings

New Physics scalar and pseudoscalar couplings can result in a difference in
\[
R_{K,K^*,xs} = \frac{\mathcal{B}(B \to (K, K^*, xs) e^+ e^-)}{\mathcal{B}(B \to (K, K^*, xs) \mu^+ \mu^-)}
\]
from unity
\[
R_{K,K^*,xs}
\]
is correlated with the (unobserved) rate \(\mathcal{B}(B_s \to \mu^+ \mu^-)\)

Hiller and Krüger

David Hitlin  Flavour in the Era of the LHC  CERN  November 10, 2005
(More) model-independent analysis of NP couplings

New Physics scalar and pseudoscalar couplings can result in a difference in

\[ R_{K,K^*,x_s} = \frac{\mathcal{B}(B \to (K, K^*, x_s)e^+e^-)}{\mathcal{B}(B \to (K, K^*, x_s)\mu^+\mu^-)} \]

from unity

\[ R_{K,K^*,x_s} \]

is correlated with the (unobserved) rate \( \mathcal{B}(B_s \to \mu^+\mu^-) \)

Hiller and Krüger

Koppenburg
Prospects

- $R_K$ can be measured very well at a Super $B$ factory.
- It would appear to be difficult at LHCb due to difficulty with triggering on electrons, but a new study indicates that if the trigger can be modified, there is good sensitivity.
- A 10% measurement of $R_K$ is possible with 2.5 ab$^{-1}$ at a Super $B$ factory or with 2 fb$^{-1}$ at LHCb with an electron trigger.
Rare $B$ decays: $B^0_s \rightarrow \mu^+ \mu^-$

- **Standard Model** $B \sim 3.5 \times 10^{-9}$
  - Current limit (CDF+DØ) $< 1.5 \times 10^{-7}$ @ 95% CL
- **Should be observed at LHC**

<table>
<thead>
<tr>
<th></th>
<th>1 year</th>
<th>$B^0_s \rightarrow \mu^+ \mu^-$ signal (SM)</th>
<th>$b \rightarrow \mu$, $b \rightarrow \mu$ background</th>
<th>Inclusive $bb$ background</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>2 fb$^{-1}$</td>
<td>17</td>
<td>$&lt; 100$</td>
<td>$&lt; 7500$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>10 fb$^{-1}$</td>
<td>7</td>
<td>$&lt; 20$</td>
<td></td>
</tr>
<tr>
<td>CMS (1999)</td>
<td>10 fb$^{-1}$</td>
<td>7</td>
<td>$&lt; 1$</td>
<td></td>
</tr>
</tbody>
</table>

Excluded!
$B \rightarrow \tau \nu$

Standard Model prediction:

$$BF(B^+ \rightarrow \tau^+ \nu_\tau) = 1.2 \times 10^{-4} \left( \frac{f_B}{200 \text{MeV}} \right)^2 \left( \frac{V_{ub}}{0.004} \right)^2$$

can be modified by an $H^+$ at large $\tan \beta$

$$BF(B^+ \rightarrow \tau^+ \nu_\tau) = 1.3^{+1.0}_{-0.9} \times 10^{-4}$$

(< 2.6 \times 10^{-4} at 90\% C.L.)
$B \to \tau \nu$ limit on $H^+$ mass

$$B(B \to \tau \nu) = B(B \to \tau \nu)_{\text{SM}} \times r_H,$$

$$r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)^2$$

95% CL excluded region at 5ab$^{-1}$ (if $B_{\text{obs}} = B_{\text{SM}}$)

Iijima
$B^+ \rightarrow \bar{D}^0 \tau \nu_\tau$

- **Standard Model:** $\mathcal{B} = 8 \times 10^{-3}$

- For 50 ab$^{-1}$: $\sigma \mathcal{B} / \mathcal{B} = 2.5\%$

\[m_b \tan \beta + m_c \cot \beta\]

\[H^+/W^+ \quad m_c \tan \beta \quad \tau^+ \quad \nu_\tau\]

\[\frac{\Gamma(B \rightarrow D\tau\nu_{\tau})}{\Gamma(B \rightarrow D\mu\nu_{\mu})} = B\]

\[B = \frac{\Gamma(B \rightarrow D\tau\nu_{\tau})}{\Gamma(B \rightarrow D\mu\nu_{\mu})}\]

SuperKEKB
$\tau \rightarrow \ell \gamma$ and mSUGRA

- $\tan \beta = 55$
- Inverted hierarchy
- $\tau$ is LSP
- $\text{Br}(\tau \rightarrow e\gamma) < 1 \times 10^{-8}$
- $\text{Br}(\tau \rightarrow e\gamma) < 2 \times 10^{-8}$
- $\text{Br}(\tau \rightarrow e\gamma) < 5 \times 10^{-8}$
- $\text{Br}(\tau \rightarrow e\gamma) < 11 \times 10^{-8}$

Current BABAR limit
The pattern of deviation from the SM values is diagnostic

<table>
<thead>
<tr>
<th>Model</th>
<th>$B_d$ Unitarity</th>
<th>Time-dep. CPV</th>
<th>Rare $B$ decay</th>
<th>Other signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSUGRA (moderate tan $\beta$)</td>
<td>$B_d$ mixing</td>
<td></td>
<td>$B \to (D)^*\tau\nu$</td>
<td>$B_s \to \mu\mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$b \to s\ell^+\ell^-$</td>
<td>$B_s$ mixing</td>
</tr>
<tr>
<td>mSUGRA (large tan $\beta$)</td>
<td></td>
<td>$B_d$ mixing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUSY GUT with $\nu_R$</td>
<td></td>
<td>$B \to \phi K_S$</td>
<td>$B \to K^*\gamma$</td>
<td>$B_s$ mixing, $\tau$ LFV, $n$ EDM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective SUSY</td>
<td>$B_d$ mixing</td>
<td>$B \to \phi K_S$</td>
<td>$A_{CP} (b \to s\gamma)$</td>
<td>$B_s$ mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$b \to s\ell^+\ell^-$</td>
<td></td>
</tr>
<tr>
<td>KK graviton exchange</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Split fermions in large extra</td>
<td>$B_d$ mixing</td>
<td></td>
<td>$b \to s\ell^+\ell^-$</td>
<td>$K^0\bar{K}^0$ mixing</td>
</tr>
<tr>
<td>extra dimensions</td>
<td></td>
<td></td>
<td></td>
<td>$D^0\bar{D}^0$ mixing</td>
</tr>
<tr>
<td>Bulk fermions in warped extra</td>
<td>$B_d$ mixing</td>
<td>$B \to \phi K_S$</td>
<td>$b \to s\ell^+\ell^-$</td>
<td>$B_s$ mixing mixing</td>
</tr>
<tr>
<td>extra dimensions</td>
<td></td>
<td></td>
<td></td>
<td>$D^0\bar{D}^0$ mixing</td>
</tr>
<tr>
<td>Universal extra dimensions</td>
<td></td>
<td>$b \to s\ell^+\ell^-$</td>
<td></td>
<td>$K \to \pi\nu\nu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$b \to s\gamma$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Flavour physics is a DNA chip for New Physics

- mSUGRA (moderate tanβ)
- mSUGRA (large tanβ)
- mSUGRA SUSY GUT with $\nu_R$
- Effective SUSY
- SU(5) SUSY GUT with $\nu_R$
- KK graviton exchange
- Split fermions in large extra dimensions
- Bulk fermions in warped extra dimensions
- Universal extra dimensions
- $B_d$ unitarity
- Time-dependent CP violation
- Rare $B$ decays
- Other signals
The role of hadronic experiments

- Measure $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ and $\mathcal{B}(K_L^0 \to \pi^0 \nu \bar{\nu})$
- Search for LFV in $\mu$ to $e$ conversion, $\mu \to e\gamma$

- Measure $B_s$ mixing
- Measure CPV in $J/\psi\phi$
- Measure $\mathcal{B}(B_s \to \mu\mu)$ at SM level or above
- Measure $A_{FB}$ in exclusive $b \to s\ell\ell$
- Measure $\mathcal{B}(B \to Kee)/\mathcal{B}(B \to K\mu\mu)$?
- Improve measurements of $\alpha$, $\beta$, $\gamma$
The role of a Super $B$ Factory (if one exists)

- Measure $\alpha, \beta, \gamma, V_{ub}, V_{cb}, \Delta m_d$ to the limit of theoretical precision
- Measure $CPV$ in $b \to sss$ decays to sufficient precision to ascertain a pattern
- Measure $A_{FB}$ in inclusive and exclusive $b \to s\ell\ell$ decays
- Measure $B(B \to Kee)/B(B \to K\mu\mu)$
- Measure $B \to \tau\nu$
- Search for right handed couplings in $b \to s\gamma$
- Search for NP effects in $B \to VV$ decay
- Search for $CPV$ in $b \to s\gamma$ and $b \to s\ell\ell$ decays
- Search for LFV: $\tau \to \mu\gamma$ decay
- Search for charged Higgs in $B \to D\tau\nu$ decay
Will there be a Super $B$ Factory?

- Potential upgrades of PEP-II, KEKB
  - SuperPEP-II design aimed at $\mathcal{L}=7 \times 10^{35}$
  - SLAC is now out of the local HEP accelerator business
  - SuperKEKB design has $\mathcal{L}=4 \times 10^{35}$ with 50 ab$^{-1}$ by 2020
  - Proposed to ministry; awaits a decision

- Another approach is being considered
  - Raimondi has suggested revisiting the recirculating linear collider scheme proposed in the ’80’s by Amaldi and Coignet, in the light of modern accelerator physics techniques
  - The luminosity goal is $\mathcal{L} \sim 10^{36}$
  - The idea appears quite promising
  - Linear collider-related R&D over the past two decades has addressed many of the technical issues
  - INFN is actively considering an LCSuper$B$ based on an international collaborative effort
  - A workshop will be held on Nov 11/12 at Frascati

http://www.lnf.infn.it/conference/superbf05/
One and one half Super B Factory concepts

Conceptual design
(Raimondi, Biagini, Seeman, ...)

Final damping
~7 GeV

Predamping
~4 GeV

Final damping

Final Focus

e^+
target

e^−
Conclusions

- Heavy flavour physics, in all its guises, can play a significant role in deepening our understanding of the Standard Model, and, should New Physics be found at LHC, it provides unique tools for probing the flavour structure of the new particles (squarks?)

- If the scale of New Physics is < 1 TeV, as motivated by our current understanding of the Higgs mechanism, there will be measurable effects in the heavy quark/heavy lepton sector
  - LHC will yield information on masses and couplings of new particles by direct production
  - Information on squark off-diagonal couplings requires detailed studies of heavy quark decays at Super B Factories or dedicated hadronic experiments

- The effects of new physics loops can be seen in rare decay branching fractions and kinematic distributions and in $CP$-violating asymmetries in channels with very small branching fractions
Conclusions - II

- The new generation of experiments at hadronic accelerators will doubtless extend the fruitful programs of the current $B$ Factories.

- It is important that other approaches be followed as well:
  - A Super $B$ Factory can, in the next decade, provide unique high precision measurements as well as results complementary to those of hadronic experiments.
  - Rare $K$ decay experiments.
  - Searches for lepton flavor violation.

- Flavour physics has a glorious history and remains relevant as a tool for understanding New Physics at the LHC.

- This timely series of workshops can sharpen our understanding of what is needed at LHC and at other facilities to deeply probe the structure of New Physics, in particular the flavour structure.