Searches for New Physics in Rare Leptonic and Electroweak Penguin Decays

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Outline

- Flavour physics, rare decays and New Physics
- The BABAR experiment
- Electroweak FCNC processes:
  \[ B^0 \rightarrow \ell^+ \ell^- \]
  \[ B \rightarrow X_{s/d} \gamma \]
  \[ B \rightarrow K(\ast) \ell^+ \ell^- \]
- Leptonic B decays:
  \[ B^+ \rightarrow \tau^+ \nu \]
  \[ B^+ \rightarrow \mu^+ \nu \text{ and } B^+ \rightarrow e^+ \nu \]
- Lepton flavour violating $\tau$ decays
- Summary/Outlook
Flavour physics defined by weak interaction couplings of quarks with universal coupling $g$, but modified by (non-diagonal) CKM matrix

- Parameterizes charged current couplings between three quark generations
- Weak eigenstates are essentially “rotated” in flavour space relative to mass eigenstates (i.e. physical quark states)

$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

- In the Standard Model, a single irreducible phase in CKM matrix is the only source of CP violation

Unitarity of $V$ implies relationships between various matrix elements:

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} \quad \iff \quad V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$
Primary objective of the **Asymmetric B Factories** is to determine the angles and sides of the $B_d$ Unitarity Triangle (UT)

- CKM mechanism for CP violation “confirmed” at ~5% level via measurements of $\sin2\beta$ in time-dependent CP studies of $B \to J/\psi K_s^0$ and related modes

- Seek New Physics via over-determination of UT parameters and “redundant” measurements in modes which have different non-SM sensitivities
Overall Unitarity Triangle determination from tree and $B_{d,s}^0$ and $K^0$ mixing ($\Delta F=2$) processes is consistent with Standard Model expectations

- implies that the scale associated with New Physics is $>>1$ TeV unless “phase” of New Physics is the same as the SM phase
**Why Rare Decays?**

**Minimal Flavour Violation (MFV)** – Postulate the existence of a large flavour symmetry which is broken at a very high mass scale

- Yukawa couplings (and hence CKM matrix) is only source of flavour mixing and CP violation
- Effective theory framework which is compatible with 2 Higgs doublet models, SUSY etc.

⇒ Potentially large non-SM effects in various rare meson decays even in the absence of evidence for New Physics in the (tree-level) UT determination

Rare Decays

High Energy Ring: 9.0 GeV electrons
Low Energy Ring: 3.1 GeV positrons
Peak luminosity: $1.21 \times 10^{34}$ cm$^{-2}$s$^{-1}$

(Run 5b, Nov 2006)

Boost $\beta\gamma=0.56$ yields typical separation of BB decay vertices of $<|\Delta z|> \sim 180\mu$m
The **BABAR** experiment

**B factory operations at SLAC since 1999:**

- Centre of mass energy of 10.58 GeV for $\Upsilon(4S) \rightarrow BB$
- **Asymmetric beam energies** produce a boost of $\beta\gamma=0.56$ in the lab frame

**DIIRC – RICH utilizing total internal reflection**

**EM calorimeter**
- 6580 CsI(Tl) crystals

**Magnet flux return instrumented with RPCs (→ LSTs)**
- 1.5 T solenoid

**5-layer silicon vertex detector**

**40 layer drift chamber (dE/dx)**
- $\sigma_{p_T}/p_T = (0.13 \cdot p_T /[GeV/c] + 0.45)\%$

**BABAR**
- $K-\pi$ separation

**DIRC – RICH utilizing total internal reflection**

**e^+ (3.1 GeV)**

**e^- (9.0 GeV)**

$\Upsilon$($4S$) → $BB$
Over 390 fb\(^{-1}\) of data recorded by BABAR since startup!

- ~390 million BB pairs plus an additional ~37 fb\(^{-1}\) of “off-resonance” data
- Luminosity in excess of 1.2x10\(^{34}\) cm\(^{-2}\)s\(^{-1}\) recorded at end of Run 5

Recent (several month) shutdown to permit substantial accelerator and detector upgrades

- Four sextants of barrel muon system replaced (two others replaced during earlier shutdown)

### Process effective \(\sigma\) (nb)

<table>
<thead>
<tr>
<th>Process</th>
<th>effective (\sigma) (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e^+e^- \to bb)</td>
<td>1.1</td>
</tr>
<tr>
<td>(e^+e^- \to cc)</td>
<td>1.3</td>
</tr>
<tr>
<td>(e^+e^- \to qq)</td>
<td>(q=u,d,s) ~2.1</td>
</tr>
<tr>
<td>(e^+e^- \to \tau^+\tau^-)</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Run 6 recently started Jan 2007

- Initially slow start due to bad background conditions

Nominal BABAR/PEP-II program scheduled to end summer 2008

- Anticipate total of ~900 fb\(^{-1}\) of data recorded

Target luminosity of \(2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\) expected to be achievable with no further upgrades required
Flavour changing neutral current (FCNC) processes do not occur in SM at tree level

- Loop-mediated processes can have large contributions from non-SM diagrams of same order as leading SM contributions:

\[ H^- \quad \chi^- \quad \tilde{g}, \chi^0 \]

Low-energy effective Hamiltonian for \( b \rightarrow s \) (or \( d \)) transitions:

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu) \]

- Products of field operators (nonperturbative hadronic matrix elements; HQE in inverse powers of \( m_b \))

- Wilson coefficients (calculated perturbatively; encode short-distance physics)

- New Physics can enter via non-SM values of Wilson coefficients
**Electroweak FCNCs**

\[ \mathbf{B} \rightarrow \mathbf{X}_{s/d} \gamma \]

\( C_7 \) (Photon penguin) only

Observables: branching fractions \( E_\gamma \) (or \( m_{\text{had}} \) spectrum), \( A_{\text{CP}} \)

\[ \mathbf{B} \rightarrow \mathbf{X}_{s/d} l^+ l^- \]

\( C_7, C_9 \) (Vector EW) and \( C_{10} \)

Observables: (partial) branching fractions, dilepton \( A_{\text{FB}}, A_{\text{CP}} \)

\[ \mathbf{B}^0_{s/d} \rightarrow l^+ l^- \]

\( C_{10} \) (Axial vector EW) only

Observables: branching fractions

New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes
**B_d^0 \rightarrow l^+ l^-**

Theoretically very clean:

- within SM only non-vanishing operator is $O_{10}$ and hadronic matrix element is $f_B$
  
- New Physics can enhance rate by factor $\sim 100$ or more

Experimentally very straightforward:

- Distinguish B decays from continuum using “event shape” variables
  
- Constrain kinematics of identified leptons to be consistent with a B meson parent...

SM predictions

- $\text{Br}(B^0 \rightarrow e^+e^-) \times 10^{-15}$
- $\text{Br}(B^0 \rightarrow \mu^+\mu^-) \times 10^{-10}$
- $\text{Br}(B^0 \rightarrow \tau^+\tau^-) \times 10^{-8}$
**B^0 → l^+ l^-**

**B^0 → μ^+μ^- simulation**

- Signal efficiencies obtained from MC (validated against data)
- Backgrounds estimated from data extrapolating sideband regions in data into signal region
- Limits obtained from **unblinded** signal yields in data using modified frequentist method

\[
m_{ES} \equiv \sqrt{E_{beam}^* + p_B^*}^2
\]

\[
\Delta E^* \equiv E_B^* - E_{beam}^*
\]

<table>
<thead>
<tr>
<th>channel</th>
<th>(N_{obs})</th>
<th>(N_{exp}^{bg})</th>
<th>(\varepsilon[%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^0 \rightarrow e^+ e^-)</td>
<td>0</td>
<td>0.71 ± 0.31</td>
<td>21.8 ± 1.2</td>
</tr>
<tr>
<td>(B^0 \rightarrow \mu^+ \mu^-)</td>
<td>0</td>
<td>0.72 ± 0.26</td>
<td>15.9 ± 1.1</td>
</tr>
<tr>
<td>(B^0 \rightarrow e^\pm \mu^\mp)</td>
<td>2</td>
<td>1.29 ± 0.44</td>
<td>18.1 ± 1.2</td>
</tr>
</tbody>
</table>

LFV
Recent results on rare decays $B_d^0 \rightarrow l^+ l^-$ from the BABAR experiment.

- Based on 111 fb$^{-1}$:
  - $B(B^0 \rightarrow e^+e^-) < 6.1 \times 10^{-8}$
  - $B(B^0 \rightarrow \mu^+\mu^-) < 8.3 \times 10^{-8}$
  - $B(B^0 \rightarrow e^\pm\mu^\mp) < 18 \times 10^{-8}$
  at 90% C.L


Soon to be updated to full BABAR statistics...

- Tevatron Run II limits on $B_s^0 \rightarrow l^+ l^-$ and $B_d^0 \rightarrow l^+ l^-$ have recently surpassed B factory sensitivity...

(Note that BABAR is not sensitive to $B_s^0 \rightarrow l^+ l^-$.)
**$B \rightarrow X_{s,d} \gamma$**

FCNC “penguin” first observed by CLEO in 1993:

![CLEO II](image)

**PRL 71, 674 (1993)**

Now a major industry at the asymmetric B factories!

- inclusive $b \rightarrow s \gamma$ determinations and extraction of HQET parameters:
  - Phys. Rev. D72:052004, 2005

- observations of CKM suppressed $b \rightarrow d \gamma$ decays in exclusive modes
Inclusive $B \rightarrow X_s \gamma$ measurement is one of the most sensitive indirect probes of New Physics

- Recent improvements to NNLO calculations resulted in a downward shift to the SM range for $B \rightarrow X_s \gamma$
- Experimental average now slightly high, effectively opening a window for New Physics!

![Graph showing $B \rightarrow X_s \gamma$ measurements](chart.png)

- CLEO: $[0.1 \text{ fb}^{-1}]$ (PRL87,251807(2001))
- BaBar: $[81.5 \text{ fb}^{-1}]$ (PRD72,052004(2005))
- BaBar: $[81.5 \text{ fb}^{-1}]$ (hep-ex/0507001)
- Belle: $[5.8 \text{ fb}^{-1}]$ (PLB511,151(2001))
- Belle: $[140 \text{ fb}^{-1}]$ (PRL93,061803(2004))
- Average: $[6.7 \text{ fb}^{-1}]$ (hep-ex/0503003)

(from Nakao, CKM Workshop, Dec2006)


(from Nakao, CKM Workshop, Dec2006)
CKM suppressed $b \to d\gamma$ modes have simple relation to $b \to s\gamma$ modes:

- Comparison of $b \to d\gamma$ and $b \to s\gamma$ can be used to extract CKM elements relating to top quark:

**Weak annihilation correction**

$$\Delta R = 0.1 \pm 0.1$$


$$\overline{B}[B \to (\rho/\omega)\gamma] = \frac{|V_{td}|^2}{|V_{ts}|^2} \left( \frac{1 - m_{\rho}/M_B^2}{1 - m_{K*}/M_B^2} \right)^3 \zeta^2 [1 + \Delta R]$$

**Flavour SU(3) breaking** (ratio of form factors)

$$\zeta = 1.17 \pm 0.09$$

Ball and Zwicky, JHEP 0604, 046 (2006); Ball and Zwicky, hep-ph/0603232

Experimentally challenging due to small signal branching fractions and high backgrounds

- substantial backgrounds due to photons arising from $\pi^0$, $\eta$ and $b \to s\gamma$ decays
Signal extracted from a maximum likelihood fit to signal + background

- $B \rightarrow \rho \gamma$: $m_{ES}$, $\Delta E$, NN, $\theta_{\text{helicity}}$ (4 parameters)
- $B \rightarrow \omega \gamma$: + Dalitz angle (5 parameters)
B→(ρ/ω)γ results

Belle PRL 96, 221601 (2006)

BABAR hep-ex/0612017 to appear in PRL (316fb⁻¹)

BABAR B→(ρ/ω)γ

<table>
<thead>
<tr>
<th>Mode</th>
<th>N_{signal}</th>
<th>Significance</th>
<th>BF(10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B⁺ → ρ⁺γ</td>
<td>42.0⁺₁⁺₁⁻₁₂.7</td>
<td>3.8σ</td>
<td>1.10⁺₀.₃₇⁻₀.₃₃ ± 0.09</td>
</tr>
<tr>
<td>B⁰ → ρ⁰γ</td>
<td>38.7⁺₁₀.₆⁻₉.₉</td>
<td>4.9σ</td>
<td>0.79⁺₀.₂₂⁻₀.₂₀ ± 0.06</td>
</tr>
<tr>
<td>B⁰ → ωγ</td>
<td>11.0⁺₆.₇⁻₅.₆</td>
<td>2.2σ</td>
<td>0.₄₀⁺₀.₂₄⁻₀.₂₀ ± 0.0₅</td>
</tr>
<tr>
<td>Combined BF</td>
<td>6.4σ</td>
<td></td>
<td>1.₂₅⁺₀.₂₅⁻₀.₂₄ ± 0.₀₉</td>
</tr>
</tbody>
</table>

Isospin test:

\[
\frac{\Gamma(B^+ \rightarrow \rho^+\gamma)}{2\Gamma(B^0 \rightarrow \rho^0\gamma)} - 1 = -0.₃₅ ± 0.₂₇
\]
Determination of $|V_{td}/V_{ts}|$

<table>
<thead>
<tr>
<th></th>
<th>$B(B \rightarrow (\rho/\omega)\gamma \ (10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>1.25  $^{+0.25}_{-0.24}$ $^{\pm 0.09}$</td>
</tr>
<tr>
<td>Belle</td>
<td>1.32  $^{+0.34+0.10}_{-0.31+0.09}$</td>
</tr>
<tr>
<td>Average</td>
<td>1.28  $^{+0.20}_{-0.20}$ $^{\pm 0.06}$</td>
</tr>
</tbody>
</table>

Use the combination of BABAR and Belle results for the extraction of ratio $|V_{td}/V_{ts}|$:

$$|V_{td}/V_{ts}|_{\rho/\omega\gamma} = 0.202^{+0.017}_{+0.016} \ (\text{exp}) \pm 0.015 \ (\text{th})$$

- Experimental uncertainties currently comparable to theory

Good agreement with results from $B$ mixing (combination of $B_d$ and $B_s$)

(See also Ball, Jones, Zwicky hep-ph/0612081)
**B → K(∗)ℓ+ℓ−**

\( B \rightarrow K^{(*)}\ell^+\ell^- \) receives contributions from \( C_7 \) (photon penguin), \( C_9 \) (vector EW) and \( C_{10} \) (axial-vector EW)

- Also substantial long-distance contributions (\( J/\Psi K \) and \( \Psi(2s)K \))

\[
B \rightarrow K^{(*)}\ell^+\ell^- \\
\text{Standard Model}
\]

\[
A_{FB} = C_7 \text{ (SM)} + C_9 \text{ (SM)} - C_7 \text{ (SM)} + C_9 \text{ (SM)}
\]

\[
C_7^{\text{eff}} = -C_7 \text{ (SM)}
\]

\[
C_9^{\text{eff}} = -C_9 \text{ (SM)}
\]

\[
C_{10}^{\text{eff}} = -C_{10} \text{ (SM)}
\]

\[
s_0 = (4.07^{+0.16}_{-0.13}) \text{ GeV}^2
\]

Interference between contributing amplitudes produces asymmetries in lepton angular distribution

- \( A_{FB} \) sensitive to non-SM values of Wilson coefficients
**B→K(∗)l⁺l⁻ Results**

Signals clearly visible for both B→Kl⁺l⁻ and B→K*l⁺l⁻ in current BABAR data:

- **Signal extracted from fit to**
  - $m_{ES}$ and $\Delta E$ for Kl⁺l⁻ (2D)
  - + $m_{K\pi}$ for K*l⁺l⁻ (3D)

![Graphs showing signal extraction](attachment:image.png)
$B \to K^*(\)l^+l^- \) Branching Fractions$

$B(B \to Kl^+l^-) = (0.34 \pm 0.07 \pm 0.02) \times 10^{-6} \ (6.6\sigma)$

$B(B \to K^*l^+l^-) = (0.78^{+0.19}_{-0.17} \pm 0.11) \times 10^{-6} \ (5.7\sigma)$
First determinations of $A_{FB}$ in bins of $q^2$ with sensitivity to Wilson coefficients:

- Belle and BABAR results both favour SM value for $C_{10}$ (high $q^2$) but less consistency with SM in low $q^2$ region
Leptonic B decays are helicity-suppressed EW tree processes in the SM:

\[ B^+( \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 |V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B}{8\pi} \left( 1 - \frac{m_\ell^2}{m_B^2} \right) \]

New physics contributions can arise from diagrams with internal lines containing non-SM particles:

Charged Higgs, R-parity violating SUSY scalar sparticles, Pati-Salam leptoquarks...
Large SM branching fraction, but experimentally challenging due to presence of several final states with multiple neutrinos

- few kinematic constraints which can be exploited for background suppression

Reconstruct the decay of the non-signal “tag” $B^-$ in $\Upsilon(4S) \rightarrow B^+B^-$ in one of a large number of exclusive decay modes, then

\[\Rightarrow \text{attribute all other particles to the decay of the “signal” } B^+ \text{ candidate}\]

- $B^- \rightarrow D^{(*)0} X^-$ Hadronic tags
  - yield ~$2700/fb^{-1}$
  \[m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}} \quad \Delta E = E_B - E_{CM}/2\]

- $B^- \rightarrow D^0 l \nu X^0$ Semileptonic tags
  - yield ~$6000/fb^{-1}$
  - presence of additional neutrino does not significantly impact analysis
Belle recently reported first evidence for $B^+ \rightarrow \tau^+ \nu$ based on 414 fb$^{-1}$ of data

- signal modes: $\tau^+ \rightarrow e^+ \nu \nu$, $\tau^+ \rightarrow \mu^+ \nu \nu$, $\tau^+ \rightarrow \pi^+ \nu$, $\tau^+ \rightarrow \rho^+ (\pi^+ \pi^0) \nu$, $\tau^+ \rightarrow a_1^+ (\pi^+ \pi^- \pi^+) \nu$

- signal extracted from a fit to the $E_{ECL}$ distribution

(sum of calorimeter energy not associated to either tag B or signal B candidates)

Observed an excess above expected background across all signal channels with $E_{ECL}$ shape compatible with signal:

$$B(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49} \text{(stat)}^{+0.46}_{-0.51} \text{(syst)}) \times 10^{-4}$$

(3.5$\sigma$ significance)

BABAR Semileptonic tag analysis based on $324 \times 10^6$ BB pairs

- Raw tag reconstruction efficiency $(6.77 \pm 0.05 \pm 0.10) \times 10^{-3}$
- signal modes: $\tau^+ \rightarrow e^+ \nu \nu$, $\tau^+ \rightarrow \mu^+ \nu \nu$, $\tau^+ \rightarrow \pi^+ \nu$, $\tau^+ \rightarrow \rho^+(\pi^+ \pi^0) \nu$

Overall signal yield obtained by likelihood-based combination of observed yields in individual channels (with uncertainties included)

- Use “double-tagged” $B^- \rightarrow D^0 \nu X^0$ events to validate $E_{\text{extra}}$ and other systematics

Slight excess observed across all signal channels:

$$B(B^+ \rightarrow \tau^+ \nu) = (0.88 \pm 0.70 \pm 0.11) \times 10^{-4}$$

(1.3$\sigma$ significance)

$$B(B^+ \rightarrow \tau^+ \nu) < 1.8 \times 10^{-4} \text{ @ 90\% CL}$$

- A previous BABAR analysis using a combination of hadronic and semileptonic tags on a smaller dataset reported

  $$B(B^+ \rightarrow \tau^+ \nu) < 2.6 \times 10^{-4} \text{ @ 90\% CL}$$

  (B. Aubert et al. PRD 73 057101 (2006))
**Combined $B^+ \rightarrow \tau^+ \nu$ results**

BABAR/Belle combination: $B(B^+ \rightarrow \tau^+ \nu) = (1.31 \pm 0.48) \times 10^{-4}$ (~2.5σ)

- Comparison with “SM” can be interpreted either as constraint on $|V_{ub}|$ (taking $f_B$ from lattice), or as a direct constraint on New Physics:

$$B(B^+ \rightarrow l^+ \nu)_{\text{MSSM}} = B(B^+ \rightarrow l^+ \nu)_{\text{SM}} \times \left[ 1 - \left( \frac{m_B^2}{m_{H^+}^2} \right) \tan^2 \beta \right]$$

No lepton flavour dependence!

- Using “SM” value from UTFit: $B(B^+ \rightarrow \tau^+ \nu) = (0.85 \pm 0.13) \times 10^{-4}$

![Graph and diagram showing Type II 2HDM and MSSM comparisons with experimental results.](image)
$B^+ \rightarrow l^+\nu$ ($l = e, \mu$)

Can use the same $B$ reconstruction method to search for other leptonic modes ($e$, $\mu$):

- only 1 neutrino, so reconstruction of tag $B$ completely constrains event kinematics:

- Signal $B$ rest frame estimated from tag $B$ 4-vector, permitting 2-body signal kinematics to be exploited:

**Standard Model Rates**

$B(B^+ \rightarrow \mu^+\nu) \sim 4 \times 10^{-7}$

$B(B^+ \rightarrow e^+\nu) \sim 10^{-12}$
\[ B^+ \rightarrow l^+ \nu \quad (l = e, \mu) \]

BABAR hadronic tagged analysis based on $229 \times 10^6$ BB pairs

- observed 0 events in each of $e$ and $\mu$ channels with expected backgrounds of 0.23 and 0.12 events respectively

- \[ B(B^+ \rightarrow e^+ \nu) < 7.9 \times 10^{-6} \]
- \[ B(B^+ \rightarrow \mu^+ \nu) < 6.2 \times 10^{-6} \]

at 90% CL

Method free from experimental issues relating to background modeling and estimation, but currently statistically limited

- complementary approach to, but not (yet) fully competitive with, “inclusive” analysis method...
Inclusive $\mathbf{B}^+ \rightarrow l^+\nu$ ($l = e, \mu$)

Reconstruct accompanying $B$ by 4-vector sum of particles recoiling against a high momentum lepton

- Recent Belle analysis based on $253 \text{ fb}^{-1}$:
  - Efficiencies much higher than exclusive method, but also higher backgrounds: $\epsilon_\mu = (2.18 \pm 0.06)\%$ $\epsilon_e = (2.39 \pm 0.06)\%$
  - Extract signal from fit to $M_{bc}$ distribution in region: $5.1 < M_{bc} < 5.29$; $-0.8 (-1.0) < \Delta E < 0.4$ GeV for $\mu(e)$

$$B(B^+ \rightarrow \mu^+\nu) < 1.7 \times 10^{-6}$$
$$B(B^+ \rightarrow e^+\nu) < 0.98 \times 10^{-6}$$

Experimental sensitivity within a factor of $\sim 2$ of SM rate for $\mathbf{B}^+ \rightarrow \mu^+\nu$!

- Similar method has been used in previous publications by BABAR, Belle and Cleo
Beyond Tree Level...

Tree-level charged Higgs (Type-II 2HDM or MSSM) contribution has the same effect on all leptonic modes:

\[
B(B^+ \rightarrow l^+ \nu)_{\text{MSSM}}^{\text{MSSM}} = B(B^+ \rightarrow l^+ \nu)_{\text{SM}}^{\text{SM}} \times \left[ 1 - \left( \frac{m^2_B}{m^2_{H^+}} \right) \tan^2 \beta / (1 + \epsilon_0 \tan^2 \beta) \right]^2
\]

- "Universality" preserved at tree level

At one-loop level, potentially large Lepton Flavour Violation (LFV) effects entering from e.g. SUSY in grand unification scenarios:

i.e. \(B^+ \rightarrow l^+ \nu_{l'}\) where \(l' \neq l\) via effective \(l \ H^+ \nu\) coupling

Observable effects in ratios, \(R_{b\tau}^{b\tau}\), of B leptonic branching ratios:

\[
\left( R_{B}^{\ell/\tau} \right)_{\text{MSSM}}^{\text{MSSM}} = \left( R_{B}^{\ell/\tau} \right)_{\text{SM}}^{\text{SM}} \left[ 1 + \frac{1}{R_{B\tau\nu}} \left( \frac{m^4_B}{M^4_{H^+}} \right) \left( \frac{m^2_{\tau}}{m^2_{\ell}} \right) |\Delta_{R}^{\ell}|^2 \tan^6 \beta / (1 + \epsilon_0 \tan \beta)^2 \right]
\]

- Uncertainties from \(V_{ub}\) and \(f_B\) cancel in ratio of modes!

\(\Rightarrow\) Can we get there???

In Standard Model, lepton flavour conservation is not associated with any underlying symmetry principle

- LFV generally permitted in New Physics models containing more than one Higgs doublet
  - In SUSY seesaw models, flavour changing insertions arise from Yukawa couplings in the slepton mass RGEs:

  ⇒ New Physics effects in $\tau \rightarrow l \gamma$ ($l = e, \mu$) can saturate experimental bounds in natural and well-motivated models
  - MSSM with heavy right-handed neutrinos and seesaw mechanism: $Br \sim 10^{-7}$
  - heavy Dirac neutrinos, RPV SUSY models, flavour changing $Z'$ models...
Higgs mediated LFV present in MSSM at loop level given that there is a source of LFV among sleptons:

- Predicts LFV effects in a variety of $\tau$ and B decay modes (with preference for 3rd generation couplings):

From A. Dedes, Super B Factory proceedings: hep-ph/0503261
**LFV $\tau$ decay searches**

$\tau^+\tau^-$ pairs copiously produced at B factories:

- $\sigma = 0.9$ nb $\Rightarrow$ ~350M $\tau^+\tau^-$ pairs in current BABAR dataset
- characteristic low-multiplicity signature with 1-1 or 1-3 charged track topologies
- At 10.51GeV CM energy, $\tau$ decay products produce somewhat collimated “jets”

Neutrinoless $\tau$ decays permit the use of kinematic variables similar to B decays

- exploit known CM energy and $\tau$ invariant mass:
  
  $$m_{EC} \text{ and } \Delta E = E_{e\gamma} - E_{CM}/2$$

- dominant backgrounds arise from Bhabha and leptonic $\tau$ decays
Two recent BABAR results based on $2.07 \times 10^8$ $e^+e^- \rightarrow \tau^+\tau^-$ events:

- $B(\tau \rightarrow e\gamma) < 1.1 \times 10^7$ at 90% CL
  PRL 96, 041801 (2006)

- $B(\tau \rightarrow \mu\gamma) < 6.8 \times 10^8$ at 90% CL
  PRL 95, 41802 (2005)

Interpreted as a bound on off-diagonal ($M_{L13}$) element of the left-handed slepton mass matrix (mSUGRA model*)

\[ \tau^+ \rightarrow l^+ l^- l^+ \quad \text{and} \quad \tau^+ \rightarrow l^+ h^- h^+ \]

**LFV results**

Based on 221.4 fb\(^{-1} \):
- \( B(\tau^+ \rightarrow e^- K^+ K^-) < 1.4 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow e^- K^+ \pi^-) < 1.7 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow e^- \pi^+ K^-) < 3.2 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow e^- \pi^+ \pi^-) < 1.2 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- K^+ K^-) < 2.5 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- K^+ \pi^-) < 3.2 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- \pi^+ K^-) < 2.6 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- \pi^+ \pi^-) < 2.9 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- K^+ K^-) < 1.5 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- K^+ \pi^-) < 1.8 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow e^- \pi^+ \pi^-) < 2.7 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- K^+ K^-) < 4.8 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- \pi^+ K^-) < 2.2 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- \pi^+ \pi^-) < 0.7 \times 10^{-7} \)

Based on 91.5 fb\(^{-1} \):
- \( B(\tau^+ \rightarrow e^- e^+ e^-) < 1.4 \times 10^{-7} \) at 90% C.L.
- \( B(\tau^+ \rightarrow \mu^+ e^- e^-) < 1.4 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- e^+ e^-) < 1.4 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^+ \mu^- e^-) < 1.4 \times 10^{-7} \)
- \( B(\tau^+ \rightarrow \mu^- \mu^+ e^-) < 1.4 \times 10^{-7} \)

**Based on 221.4 fb\(^{-1} \):**

New results on $\tau^+ \rightarrow l^+ h^0$ using essentially full BABAR data sample:

Based on 339 fb$^{-1}$:

- $B(\tau^+ \rightarrow e^+ \pi^0) < 1.3 \times 10^{-7}$
- $B(\tau^+ \rightarrow \mu^+ \pi^0) < 1.1 \times 10^{-7}$
- $B(\tau^+ \rightarrow e^+ \eta) < 1.6 \times 10^{-7}$
- $B(\tau^+ \rightarrow \mu^+ \eta) < 1.5 \times 10^{-7}$
- $B(\tau^+ \rightarrow e^+ \eta') < 2.4 \times 10^{-7}$
- $B(\tau^+ \rightarrow \mu^+ \eta') < 1.4 \times 10^{-7}$

at 90% C.L.

hep-ex/0610067
(submitted to PRL)

- New Physics sensitivity which is competitive and complementary to LEP and Tevatron limits from direct Higgs searches

Interpretation of $\tau^+ \rightarrow \mu^+ \eta$ in a SUSY seesaw model* (right-handed neutrino mass of $10^{14}$ GeV/c$^2$):

$H^0 \rightarrow \tau\tau, bb$

$M_{H^+}^2 = m_A^2 + m_W^2$

Rare decays can provide sensitivity to a variety of interesting New Physics scenarios at mass scales well beyond the B mass

- Indirect searches can provide information which is complementary or fully competitive with direct searches at energy frontier accelerators
- Presented here: $b \rightarrow d\gamma$, $b \rightarrow s\gamma$, $B^0_{d,s} \rightarrow l^+l^-$, $B \rightarrow K^{(*)}l^+l^-$, $B^+ \rightarrow \tau^+\nu$ and $B^+ \rightarrow \mu^+\nu$ and LFV $\tau$ decays...

Future prospects:

- **BABAR/Belle** to accumulate more than double their current total datasets by end of 2008 - total of 2 Billion BB pairs!
- **Hadron colliders** (Tevatron $\rightarrow$ LHC + LHCb) will greatly extend sensitivity of specific rare decays (e.g. $B \rightarrow K^{(*)}l^+l^-$ and $B^0_{s,d} \rightarrow l^+l^-$)

...and of course hopefully also SEE New Physics at the LHC

- Even AFTER New Physics is observed, the flavour sector can still provide important information

*High luminosity $e^+e^-$ Super Flavour Factory?*
SuperB?

Tor Vergata site on Roma II campus (near Frascati, Italy)
New Physics signatures

(2003 SLAC WS Proceedings)

<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 (large tan $\beta$)</td>
<td>$B_d$ mixing</td>
<td>-</td>
<td>$B \rightarrow (D)\tau\nu$</td>
<td>$B_s \rightarrow \mu\mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$b \rightarrow s\ell^+\ell^-$</td>
<td>$B_s$ mixing</td>
</tr>
<tr>
<td>SUSY GUT with $\nu_R$</td>
<td>-</td>
<td>$B \rightarrow \phi K_S$</td>
<td>-</td>
<td>$B_s$ mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$B \rightarrow K^+\gamma$</td>
<td></td>
<td>$\tau$ LFV, $\eta$ EDM</td>
</tr>
<tr>
<td>Effective SUSY</td>
<td>$B_d$ mixing</td>
<td>$B \rightarrow \phi K_S$</td>
<td>$A_{CP}^{b\rightarrow s\gamma}$, $b \rightarrow s\ell^+\ell^-$</td>
<td>$B_s$ mixing</td>
</tr>
<tr>
<td>KK graviton exchange</td>
<td>-</td>
<td>-</td>
<td>$b \rightarrow s\ell^+\ell^-$</td>
<td>-</td>
</tr>
<tr>
<td>Split fermions in large extra dimensions</td>
<td>$B_d$ mixing</td>
<td>-</td>
<td>$b \rightarrow s\ell^+\ell^-$</td>
<td>$K^0\bar{K}^0$ mixing</td>
</tr>
<tr>
<td>Bulk fermions in warped extra dimensions</td>
<td>$B_d$ mixing</td>
<td>$B \rightarrow \phi K_S$</td>
<td>$b \rightarrow s\ell^+\ell^-$</td>
<td>$D^0\bar{D}^0$ mixing</td>
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<tr>
<td>Universal extra dimensions</td>
<td>-</td>
<td>-</td>
<td>$b \rightarrow s\ell^+\ell^-$</td>
<td>$K \rightarrow \pi\nu\bar{\nu}$</td>
</tr>
</tbody>
</table>

Different pattern of the deviations from the SM prediction.
Correlation with other physics observables.
Elucidation of NP Scenario


SUSY Models

1. mSUGRA
   - $Q_{\text{soft}}$ is flavor blind
   - KM mixings
     - mixing in $\tilde{q}_L$

2. SUSY SU(5) w/ $V_R$
   - Large mixing in $V$
   - KM mixings
     - mixing in $\tilde{d}_R, \tilde{l}_L$
     - New CP phase
     - Mass of $V_R$

3. Degenerate
   - Non-degenerate

4. U(2) flavor symmetry
   - 1,2 gen. $(u,d,c,s,e,\mu)$
     - mixing in $\tilde{d}_R$
   - 3rd gen. $(t,b,\tau)$
     - mixing in $\tilde{l}_L$

Can we distinguish these 4 scenarios at Super-KEKB?
<table>
<thead>
<tr>
<th>Luminosity x 10^8</th>
<th>1</th>
<th>2.4</th>
<th>3.4</th>
</tr>
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<tbody>
<tr>
<td>Circumference (m)</td>
<td>2250</td>
<td>2250</td>
<td>2250</td>
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<tr>
<td>Revolution frequency (MHz)</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
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<tr>
<td>Eff. long. polarization (%)</td>
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<tr>
<td>RF frequency (MHz)</td>
<td>476</td>
<td>476</td>
<td>476</td>
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<tr>
<td>Harmonic number</td>
<td>3570</td>
<td>3570</td>
<td>3570</td>
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<tr>
<td>Momentum spread</td>
<td>8.4E-04</td>
<td>9.0E-04</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>1.8E-04</td>
<td>3.0E-04</td>
<td>1.8E-04</td>
</tr>
<tr>
<td>RF Voltage (MV)</td>
<td>6</td>
<td>18</td>
<td>6</td>
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<tr>
<td>Energy loss/turn (MeV)</td>
<td>1.9</td>
<td>3.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1733</td>
<td>1733</td>
<td>3466</td>
</tr>
<tr>
<td>Particles per bunch x 10^{10}</td>
<td>6.16</td>
<td>3.52</td>
<td>5.34</td>
</tr>
<tr>
<td>Beam current (A)</td>
<td>2.28</td>
<td>1.30</td>
<td>3.95</td>
</tr>
<tr>
<td>Beta y' (mm)</td>
<td>0.30</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>Beta x' (mm)</td>
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<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Emit y (pm)</td>
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<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Emit x (nm)</td>
<td>1.6</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Sigma y' (microns)</td>
<td>0.035</td>
<td>0.035</td>
<td>0.020</td>
</tr>
<tr>
<td>Sigma x' (microns)</td>
<td>5.657</td>
<td>5.657</td>
<td>4.000</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>6</td>
<td>6</td>
<td>6</td>
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<tr>
<td>Full Crossing angle (mrad)</td>
<td>34</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Wiggler (f)</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Damping time (trans/long)(ms)</td>
<td>32/16</td>
<td>32/16</td>
<td>25/12.5</td>
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<tr>
<td>Luminosity lifetime (min)</td>
<td>10.4</td>
<td>5.9</td>
<td>7.4</td>
</tr>
<tr>
<td>Touschek lifetime (min)</td>
<td>5.5</td>
<td>38</td>
<td>2.9</td>
</tr>
<tr>
<td>Effective beam lifetime (min)</td>
<td>3.6</td>
<td>5.1</td>
<td>2.1</td>
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<tr>
<td>Injection rate pps (100%)</td>
<td>4.9E+11</td>
<td>2.0E+11</td>
<td>1.5E+12</td>
</tr>
<tr>
<td>Tune shifts (x/y) (from formula)</td>
<td>0.004/0.17</td>
<td>0.004/0.17</td>
<td>0.007/0.16</td>
</tr>
<tr>
<td>RF Power (MW)</td>
<td>17</td>
<td>35</td>
<td>44</td>
</tr>
</tbody>
</table>
Sensitivity for Charged Higgs

Constraint from $B \rightarrow X_s \gamma$

$\Delta$ (form-factor) can be reduced with the present $B \rightarrow D \tau \nu$ data.
**Indirect limits**

Most restrictive limits on charged Higgs (in general 2HDM) are from indirect searches in tau and heavy flavour physics

- Leptonic decays of heavy pseudoscalar mesons:

\[ \mathcal{B}_r(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} |V_{ub}|^2 f_B^2 m_B m_\ell \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \]

- Charged Higgs (2HDM) modifies SM Br by a multiplicative factor:

\[ r_{H^+} = \left[1 - \tan^2 \beta \left(\frac{m_B^2}{m_{H^+}^2}\right)\right]^2 \]

- Leptonic tau decays:

\[ r_{H^+} \sim \left[1 - 2 \left(\frac{m_\tau^2}{m_{H^+}^2}\right) \tan^2 \beta \kappa(\frac{m_\tau^2}{m_\tau^2})\right] \]

- B meson radiative FCNC decays \((b \to s \gamma)\):
• LEP2 SM Higgs bound of $M_h > 114\text{GeV}$ was interpreted as a bound of $\tan\beta > 2.4$, but this was weakened by upward shift of top mass

• In 2HDM (and MSSM at tree level) Yukawa couplings to up and down -type fermions are given by

$$h_b = \sqrt{2} \frac{m_b}{\nu} \cos\beta,$$

$$h_t = \sqrt{2} \frac{m_t}{\nu} \sin\beta$$

hence $\tan\beta \sim 30$ would provide a "natural" explanation of the large top mass

Direct limits from Tevatron constrain only very large and small $\tan\beta$ values and moderate masses

Perturbative bounds at EW scale imply $0.3 < \tan\beta < 200$
Time dependent CP measurement

Exploit correlation between $B^0$ flavour and lepton charge, $K$ charge etc

Reconstruct decay vertex positions

\[ \Delta t \approx \frac{\Delta z}{\langle \beta \gamma \rangle c} \]
Rare Decays

Steven Robertson, Canadian Institute of Particle Physics
New Physics in $B_d \Delta F=2$ transitions

\[ C_{B_q} e^{2i\varphi_{B_q}} = \frac{A_q^{SM} e^{2i\beta} + A_q^{NP} e^{2i(\beta + \varphi_{q})^{NP}}}{A^{SM} e^{2i\beta}} \]
\[
\mathcal{B}(B_u \to \tau \nu) \bigg|_{\text{SM}}^{\tau_B \Delta M_{B_d}} = \frac{3\pi}{4\eta_B S_0 (m_t^2/M_W^2) \hat{B}_{B_d}} \frac{m_\tau^2}{M_W^2} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left|\frac{V_{ub}}{V_{td}}\right|^2
\]
Also published limits on $D^0 \rightarrow l^+l^-$

- sensitive to NP couplings to up-type quarks
- Veto $D^0$ produced in B decays $P_D > 2.4\text{GeV/c}$ and require $D^{*+} \rightarrow D^0 \pi^+$ to reduce combinatorial backgrounds

Based on 122 fb$^{-1}$ (incl. offpeak)

- $B(D^0 \rightarrow e^+e^-) < 1.2 \times 10^{-6}$ at 90% C.L.
- $B(D^0 \rightarrow \mu^+\mu^-) < 1.3 \times 10^{-6}$ PRL 93:191801, 2004
- $B(D^0 \rightarrow e^\pm\mu^{\mp}) < 0.81 \times 10^{-6}$ (hep-ex/0408023)
(for the constrained $m_h$-max scenario)

\[
M_{H^+}^2 = m_A^2 + m_W^2
\]

at tree level:

- MSSM courtesy of P. Bechtle
- LEP Exclusion
- $b \rightarrow s \gamma$ (HFAG, winter '06)
- $b \rightarrow s \gamma$ (800fb$^{-1}$)
- $b \rightarrow s \gamma$ (800fb$^{-1}$, half the theory error)
$B^+ \rightarrow l^+ \nu \gamma \ (l = e, \mu)$

Presence of photon removes helicity suppression and hence universality of leptonic branching fractions is recovered

$$\Gamma(B^+ \rightarrow l^+ \nu \gamma) = \alpha \frac{G_F^2 |V_{ub}|^2 m_B^5}{288 \pi^2} f_B^2 \left( \frac{Q_u}{\lambda_B} - \frac{Q_b}{m_b} \right)^2$$

- $\lambda_B$ related to B light cone distribution amplitude
- SM $\text{Br}(B \rightarrow l \nu \gamma) \sim (1-5) \times 10^{-6}$
  
  (Korchemsky, Pirjol and Yan, Phys Rev D61, 114510, 2000)

Recent BABAR analysis based on 232M BB pairs:

- $\text{Br}(B \rightarrow \mu \nu \gamma) < 5.2 \times 10^{-6}$
- $\text{Br}(B \rightarrow e \nu \gamma) < 5.9 \times 10^{-6}$
- $\text{Br}(B \rightarrow l \nu \gamma) < 5.0 \times 10^{-6}$ (combined)

- Experimental sensitivity approaching SM rate!
\[ B^+ \rightarrow K^+ \nu \nu \] (had+SL recoil)

Require only a single charged track \((K^\pm \text{ with } p_K > 1.25 \text{ GeV/c})\) and little or no additional calorimeter energy \(E_{\text{extra}} < 250 \text{ MeV}\).

<table>
<thead>
<tr>
<th>Tag</th>
<th>Hadronenic Efficiency (%)</th>
<th>Hadronenic Background</th>
<th>Observed events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.055 ± 0.005</td>
<td>3.9 ± 1.1</td>
<td>3</td>
</tr>
<tr>
<td>Semileptonic Efficiency (%)</td>
<td>0.115 ± 0.009</td>
<td>3.4 ± 1.2 *</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on 82 fb\(^{-1}\):

- \(B(B^+ \rightarrow K^+ \nu \nu) < 5.2 \times 10^{-5}\) at 90% C.L.
- \(B(B^+ \rightarrow \pi^+ \nu \nu) < 10 \times 10^{-5}\) at 90% C.L.

hep-ex/0411061 (accepted by PRL)
B mesons

B mesons are composed of a quark – antiquark pair, one of which is b-flavoured.

Neutral B mesons:

- $B^0 = d\bar{b}$
- $\bar{B}^0 = \bar{d}b$

Because $B^0$ and $\bar{B}^0$ mesons share common final states, they are able to MIX:

\[
\begin{pmatrix}
V_{td} & V_{*td} \\
V_{*tb} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
b \\
\bar{d}
\end{pmatrix}
\begin{pmatrix}
t \\
\bar{t}
\end{pmatrix}
\begin{pmatrix}
d \\
\bar{b}
\end{pmatrix}

\phi_M = \arg(V_{td}V_{*tb}^*) = \beta

\[
|B^0_{\text{phys}}(t)| \propto \cos(\Delta m_{B_d} t/2)|B^0 > + i e^{-2i\phi_M} \sin(\Delta m_{B_d} t/2)|\bar{B}^0 >
\]
Argus experiment (1987)

Demonstrated mixing of $B^0$ events using samples of double semileptonic events:

$$B^0 \rightarrow D^* \mu^+ \nu, \quad D^* \rightarrow D^0 \pi^-$$

$$B^0 \rightarrow D^* \mu^+ \nu , \quad D^* \rightarrow D^- \pi^0$$

- Large observed mixing suggested that it might be possible to observe large CP violating effects in B meson decays
  - Concept of an asymmetric B factory first proposed at Snowmass meeting in 1988
Measure CP violation in the interference between the decays of mixed and unmixed $B^0$ decays.

Combination of two decay amplitudes to the same final state manifests as an “interference pattern” in the measured decay rate as a function of decay time.

$$\lambda_{f_{CP}} \sim e^{-2i\beta} \left( A_{f_{CP}} / \overline{A}_{f_{CP}} \right)$$

$$A_{f_{CP}} = \frac{\Gamma(B^0_{phys}(t) \rightarrow f_{CP}) - \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}{\Gamma(B^0_{phys}(t) \rightarrow f_{CP}) + \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}$$

$$A_{f_{CP}} = C_{f_{CP}} \cos(\Delta m_d \Delta t) + S_{f_{CP}} \sin(\Delta m_d \Delta t)$$
Asymmetric B Factory concept

B mesons produced via $\Upsilon(4S) \rightarrow BB$ are nearly at rest the centre of mass frame (since very close to production threshold) and B meson lifetime is very short (~1.5ps)

- flight distance prior to decay is very small

- To get around this, electron and positron beams of unequal energies are collided so that the $\Upsilon(4S)$ is produced with a significant boost relative to the centre of mass frame

- The result is that the two B mesons end up with a measurable separation:

$$\Delta t \approx \frac{\Delta z}{\langle \beta \gamma \rangle c}$$

$$<|\Delta z|> \approx 200 \mu m$$

e.g. for a boost factor of $\beta \gamma \sim 0.6$
The $\Upsilon(4S)$ is a $b\bar{b}$ resonance which lies just above the mass threshold for production of $B\bar{B}$ meson pairs

- Cross section of $\sim 1.1\text{nb}$

$\Rightarrow$ $\sim 1.1$ million $B\bar{B}$ pairs produced per $\text{fb}^{-1}$

$B^0\bar{B}^0$ pair is produced in a coherent $L=1$ state

The two $B$ mesons evolve in phase until one decays (EPR situation)