Results from the B-factories
(Lecture 2)

Adrian Bevan
$b \to c$ interfering with $b \to u$

$B \to D^{(*)}K^{(*)}$

$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)} \pi$

$B^0 \to D^{(*)} \rho$

+ charmless

$V_{ud} V_{ub}^* \over V_{cd} V_{cb}^*$

$\gamma$

$\alpha + \beta + \gamma - 180^\circ = (10 \pm 21)^\circ$

$(0,0)$

$b \to u\bar{u}d$

$B \to a_i \pi$

$B \to a_i \rho$

$B \to b_i \pi$

$B \to b_i \rho$

$B \to a_ia_i$

$b \to c\bar{c}s$

$B^0 \to J/\psi K_L^0$

$B^0 \to J/\psi K_S^0$

$B^0 \to \chi_{bc} K_S^0$

$B^0 \to \eta_c K_s^0$

$B^0 \to J/\psi K^{*0}$

$B \to J/\psi \pi^0$

$B \to D^{(*)+}D^{(*)-}$

$B \to \eta' K^0$

$B \to \rho K^0$

$B \to \omega K^0$

$B \to \pi^0 K^0$

$B \to \phi K^{(*)0}$

$B \to \bar{K} K K^0$

$B \to f^0(980)K^0$

$\cdots$
This lecture

• Direct CP violation

• Searching for New Physics
  – Alternate measurements of angles: $\Delta S$
  – Sides of the Unitarity Triangle: Over-constraining the SM

• CPT Tests

• $B \rightarrow VV$ decays (and related channels)
CP violation: Direct CP violation

• Recap from Lecture 1:
  – Number counting exercise: \( A_{CP} = \frac{N - \overline{N}}{N + \overline{N}} \)
  
  – Requires at least two amplitudes to interfere.
  – Amplitudes have to have different weak and strong phases.
  
\[
A_{CP} \propto a_1 a_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)
\]

  – We are comparing \( A_f \) with \( \overline{A}_f \).

  – Predictive power will be limited by our knowledge of weak phases and of the strong phase differences.
  
  • But there are many possible measurements that we can compare!
CP violation: Direct CP violation

- $B^0 \rightarrow K^\pm \pi^\mp$: Tree and gluonic penguin contributions

- Compute time integrated asymmetry

$$A_{K^\pm \pi^\mp} = \frac{N(B^0 \rightarrow K^- \pi^+) - N(B^0 \rightarrow K^+ \pi^-)}{N(B^0 \rightarrow K^- \pi^+) + N(B^0 \rightarrow K^+ \pi^-)} = -0.097 \pm 0.012$$

- Experimental results from Belle, BaBar, and CDF have significant weight in the world average of this CP violation parameter.

- Direct CP violation present in B decays.

- Unknown strong phase differences between amplitudes, means we can’t use this to measure weak phases!
CP violation: Direct CP violation

- $B^+ \to K^+ \pi^0$: Color suppressed tree and gluonic penguin contributions
  
  - Many theory calculations indicate that $A_{K^+\pi^-} \geq A_{K^+\pi^0}$.
  
  - Experimentally measure: $A_{K^+\pi^0} = 0.050 \pm 0.025$

- Difference between $B^+$ and $B^0$ asymmetries:
  
  $\Delta A_{K\pi} = 0.147 \pm 0.028$  ($>5\sigma$ from zero)

  - Difference could be an indication of new physics, however:
    
    - Theory calculations assume that only $T+P$ contribute to $K^+\pi^-$, and $C+P$ contribute to $K^+\pi^0$.
    
    - The $C$ contribution is larger than originally expected in $K^+\pi^0$.

For example, see G. Hou arXiv:0808.1932 and references therein.
Direct CP violation searches

\[ A_{CP} = \frac{N - \overline{N}}{\overline{N} + N} \]
\[ A_{CP} = 0 \]

= no CP violation

• This is a small sub-set of decays where we have searched for direct CP violation.

• 2 observed signals (> 5σ): \( K^+\pi^- \) and \( \pi^+\pi^- \); five possible effects (> 3σ): \( \rho^0K^+ \), \( \eta K^*0 \), \( \rho^+\pi^-D^*(0)K^* \), and \( D^0_{CPK} \).
CP violation: Searching for new physics

- $\sin 2\beta$ has been measured to $O(1^\circ)$ accuracy in $b \rightarrow c \bar{c} s$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to $\sin 2\beta$ (loop dominated process).
  - Measure S precisely in that mode ($S_{\text{eff}}$).
  - Control the theoretical uncertainty on the Standard Model ‘pollution’ ($\Delta S_{\text{SM}}$).
  - Compute $\Delta S_{\text{NP}} = S_{\text{eff}} - S_{c \bar{c} s} - \Delta S_{\text{SM}}$.
- In the presence of NP: $\Delta S_{\text{NP}} \neq 0$

Many tests have been performed in:
- $B \rightarrow d$ processes.
- $B \rightarrow s$ processes.

- Unknown heavy particles can introduce new amplitudes that can affect physical observables of loop dominated processes.
- Observables that might be affected include branching fractions, CP asymmetries, forward backward asymmetries … and so on.
- A successful search requires that we understand Standard Model contributions well!
SM uncertainties on $\Delta S$

- To find NP we need to understand the SM contributions to a process.
  - Leading order term is expected to be the same as a SM weak phase.
  - Higher order terms including re-scattering, suppressed amplitudes, final state radiation and so on can modify our expectations.

- Some channels are better understood than others.

- Sign of $\Delta S$ correction is mode dependent.

- Most precise $\Delta S$ correction is for $B^0 \rightarrow \eta' K^0$, where $\Delta S_{\text{theory}} \sim \pm 0.01$.

- Concentrate efforts on well understood channels.

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**Graph:**

Theory uncertainty on $\Delta S$

- $f_0^0(980) K^0$
- $\eta K^0$
- $\rho^0 K^0$
- $\omega K^0$
- $\pi^0 K_S^0$
- $\phi K^0$
- $\eta' K^0$

Not including LD amplitude

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**References:**

- SCET/QCDF, Williamson and Zupan, PRD74, 014003 (2006)
- QCDF Cheng, Chua and Soni, PRD72, 014006 (2005)
- SU(3) Gronau, Rosner and Zupan, PRD74, 093003 (2006)
B$\rightarrow$η$'$K$^0$

- Loop dominated $b\rightarrow s$ decay.

\[ S_{\eta'K^0} = 0.60 \pm 0.07 \]
\[ C_{\eta'K^0} = -0.04 \pm 0.05 \]

\[ \Delta S_{\eta'K^0} = 0.07 \pm 0.07_{\text{exp}} \pm 0.01_{\text{theory}} \]

- CP violation has been established in this decay channel by the B factories.
- Need at least 50 ab$^{-1}$ of data to do a precision search for NP at the level of current theoretical uncertainties.

- Possible to measure S and C for both $B^0 \rightarrow \eta'K_S^0$ (CP odd) and $B^0 \rightarrow \eta'K_L^0$ (CP even).

- These asymmetries can be compared with the Charmonium reference measurement to calculate $\Delta S$. 

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$B^0 \rightarrow J/\psi \pi^0$

- Tree and penguin contributions: can be sensitive to NP.
- Alternatively, can be used to constrain SM uncertainties in the Charmonium $\beta$ measurement. M. Ciuchini, M. Pierini, L. Silvestrini, 95, 221804 (2005).

- CP even final state:
  \[ S_{Tree}^{J/\psi \pi^0} = -S_{c\bar{c}s} \]

- CP violation observed in this decay.

  \[
  S_{J/\psi \pi^0} = -0.93 \pm 0.15 \\
  C_{J/\psi \pi^0} = -0.10 \pm 0.13 \\
  \Delta S_{J/\psi \pi^0} = 0.23 \pm 0.15_{\text{exp}}
  \]

- Require a dataset of $\sim 220\text{ab}^{-1}$ to make a $1\% \Delta S$ measurement in this channel.
Overview of $\Delta S$ measurements

- Comparing $\sin 2\beta$ in different physical processes, we see good agreement with the $b \rightarrow c c s$ reference point.

- Most of the $b \rightarrow s$ penguin channels have $\sin 2\beta_{\text{eff}} < \sin 2\beta$.
  - Could this be an indication of NP?
    - Insufficient statistics to tell.
  - Need to perform a mode-by-mode precision measurement in order to properly decouple Standard Model uncertainties from possible signals of NP.

- We need at least $50 \text{ab}^{-1}$ to start performing measurements that will have comparable experimental and theoretical uncertainties in $b \rightarrow s$ penguin processes.

- Need $\sim 220 \text{ab}^{-1}$ to do the same for $b \rightarrow d$.

- Can start to do the same with $\alpha$ and $\gamma$ once we have a precision measurement from one mode.
Summary of CP violation signals found

- We have discovered CP violation in the following channels:
  - $B^0 \rightarrow J/\psi K^0$ (S)
  - $B^0 \rightarrow J/\psi \pi^0$ (S)
  - $B^0 \rightarrow \psi(2S)K_S^0$ (S)
  - $B^0 \rightarrow \eta_1 c K^0_S$ (S)
  - $B^0 \rightarrow \eta' K^0$ (S)
  - $B^0 \rightarrow f_0^0(980)K_S^0$ (S)
  - $B^0 \rightarrow K^+K^-K^0$ (S)
  - $B^0 \rightarrow D^{*+}D^{*-}$ (S)
  - $B^0 \rightarrow \pi^+\pi^-$ (S and C)
  - $B^0 \rightarrow \eta K^{*0}$ ($A_{CP}$)
  - $B^0 \rightarrow \rho^\pm \pi^\mp$ ($A_{+-}$)
  - $B^0 \rightarrow K^{*\pm} \pi^\mp$ ($A_{CP}$)
  - $B^\pm \rightarrow \rho^0 K^\mp$ ($A_{CP}$)
  - $B \rightarrow D_{CP}^0 K$ ($A_{CP}$)
  - $B \rightarrow D^{(*)0} K^*$ ($A_{CP}$)

- Indirect CP violation measurement:
  - related to a weak phase in the Standard Model.
  - These modes measure either $\beta$ or $\alpha$.

- Direct CP violation measurement:
  - related to weak phase differences and strong phase differences in the Standard Model.
  - Can be used to constrain weak phases using model dependent analysis of charmless rare B meson decays.

- All of our measurements have been consistent with the SM (so far).
Sides of the Unitarity Triangle

\[ \frac{V_{ud}}{V_{cd}} \frac{V_{ub}^*}{V_{cb}^*} \]

\[ (0,0) \quad \alpha \quad \gamma \quad \beta \quad (1,0) \]
Sides of the Unitarity Triangle

- Use theory to relate partial branching fractions to $V_{ub}$ for a given region of phase space.
- Several theoretical schemes available.

\[ b \rightarrow ulv \]
\[ B \rightarrow \pi lv \]
\[ B \rightarrow X_u lv \]
\[ B \rightarrow \rho lv \]
\[ B \rightarrow \omega lv \]

\[
\begin{bmatrix}
V_{ud} & V_{ub}^* \\
V_{cd} & V_{cb}^*
\end{bmatrix}
\]

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

\[ V_{td} \quad V_{tb}^* \]
\[ V_{cd} \quad V_{cb}^* \]
Side measurements: $V_{ub}$

- $|V_{ub}| \propto B(B \rightarrow X_u \nu)$ in a limited region of phase space.
- Reconstruct both $B$ mesons in an event.
  - Study the $B_{\text{recoil}}$ to measure $V_{ub}$.
  - Measure $B$ as a function of $q_{\ell\nu}^2$, $m_X$, $m_{\text{MISS}}$ or $E_\ell$ and use theory to convert these results into $|V_{ub}|$.

- Can study modes exclusively or inclusively.

- Several models available to estimate $|V_{ub}|$
  - The resulting values of $V_{ub}$ have a significant model uncertainty.
Exclusively reconstructed $b \rightarrow ul\nu$

- If we fully reconstruct one $B$ meson in an event, then ...
  - ... with a single $\nu$ in the event, we can infer $P^\mu$ and 'reconstruct' the $\nu$.

- Clean signals!
- Low efficiency!

- Study $B$ decays to:
  
  - $B^0 \rightarrow \pi^- l^+ \nu$
  - $B^0 \rightarrow \rho^- l^+ \nu$
  - $B^+ \rightarrow \pi^0 l^+ \nu$
  - $B^+ \rightarrow \rho^0 l^+ \nu$
  - $B^+ \rightarrow \omega l^+ \nu$

- Fully reconstruct $B_{RECO}$
- Extract yields from $m_{MISS}^2$
  
  $$q^2 < 8(GeV)^2$$
  $$8 < q^2 < 16(GeV)^2$$
  $$q^2 > 16(GeV)^2$$

(reduces form factor dependence)

- Then compute $|V_{ub}|$.

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Belle: See W. Dungel, ICHEP 08 for more details
$V_{ub}$: Using $q^2$ distribution

- Use $B \to \pi l \nu$ decays

$$\mathcal{B}(B^0 \to \pi^+ l^- \nu) = (1.34 \pm 0.06 \pm 0.05) \times 10^{-4}$$

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_{\pi}^3 |f(q^2)|^2$$

- BABAR $B_{tag}$: $B^+ \to \pi^0 l^+ \nu \times 2 \tau_0/\tau_+$
  $1.82 \pm 0.28 \pm 0.13$

- BABAR $B_{rec}$ tag: $B^+ \to \pi^0 l^+ \nu \times 2 \tau_0/\tau_+$
  $1.54 \pm 0.41 \pm 0.21$

- BELLE $B_{tag}$: $B^+ \to \pi^0 l^+ \nu \times 2 \tau_0/\tau_+$
  $1.45 \pm 0.26 \pm 0.15$

- BELLE $B_{rec}$ tag: $B^+ \to \pi^0 l^+ \nu \times 2 \tau_0/\tau_+$
  $1.24 \pm 0.23 \pm 0.06$

- BABAR $B^0 \to \pi^0 l^+ \nu$
  $1.38 \pm 0.21 \pm 0.07$

- BELLE $B^0 \to \pi^- l^+ \nu$
  $1.38 \pm 0.19 \pm 0.14$

- BABAR untagged: $B^0 \to \pi^- l^+ \nu$
  $1.07 \pm 0.27 \pm 0.15$

- CLEO untagged: $B^+ \to \pi^- l^+ \nu$
  $1.37 \pm 0.15 \pm 0.11$

- BABAR untagged: $B^0 \to \pi^- l^+ \nu$
  $1.46 \pm 0.07 \pm 0.08$

- BELLE $B_{rec}$ tag: $B^0 \to \pi^- l^+ \nu$
  $1.12 \pm 0.18 \pm 0.05$

Average: $B^0 \to \pi^- l^+ \nu$
$1.34 \pm 0.06 \pm 0.05$

$\chi^2/\text{dof} = 3.5^\circ 9$ (CL = 94%)

Ball-Zwicky $q^2 < 16$
$3.34 \pm 0.12 + 0.55 - 0.37$


HPQCD $q^2 > 16$
$3.40 \pm 0.20 + 0.59 - 0.39$

Unquenched LQCD: PRD73, 074502 (2006)

FNAL $q^2 > 16$
$3.62 \pm 0.22 + 0.63 - 0.41$


APE $q^2 > 16$
$3.65 \pm 0.22 + 1.40 - 0.65$


Experiments have also studied higher mass meson $l \nu$ decays
$V_{ub}$: Using $M_X$ distribution

- High background from $c \rightarrow \ell \nu$ decays.
  - Kinematic cuts are used to suppress background.

- Use Operator Product Expansions to translate measured branching fractions to $V_{ub}$.

- Measure branching fraction in different kinematic regions.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Accepted region</th>
<th>$\Delta B [10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>$E_e &gt; 2.1 \text{ GeV}$</td>
<td>3.3 ± 0.2 ± 0.7</td>
</tr>
<tr>
<td>BABAR</td>
<td>$E_e &gt; 2.0 \text{ GeV}$</td>
<td>4.4 ± 0.4 ± 0.4</td>
</tr>
<tr>
<td>BABAR</td>
<td>$E_e &gt; 2.0 \text{ GeV}$</td>
<td>5.7 ± 0.4 ± 0.5</td>
</tr>
<tr>
<td>BELLE</td>
<td>$E_e &gt; 1.9 \text{ GeV}$</td>
<td>8.5 ± 0.4 ± 1.5</td>
</tr>
<tr>
<td>BABAR</td>
<td>$M_X &lt; 1.7 \text{ GeV}/c^2, q^2 &gt; 8 \text{ GeV}^2/c^2$</td>
<td>8.1 ± 0.8 ± 0.7</td>
</tr>
<tr>
<td>BELLE</td>
<td>$M_X &lt; 1.7 \text{ GeV}/c^2, q^2 &gt; 8 \text{ GeV}^2/c^2$</td>
<td>7.4 ± 0.9 ± 1.3</td>
</tr>
<tr>
<td>BELLE</td>
<td>$M_X &lt; 1.7 \text{ GeV}/c^2, q^2 &gt; 8 \text{ GeV}^2/c^2$</td>
<td>8.4 ± 0.8 ± 0.4</td>
</tr>
<tr>
<td>BABAR</td>
<td>$P_+ &lt; 0.66 \text{ GeV}$</td>
<td>9.4 ± 1.0 ± 0.8</td>
</tr>
<tr>
<td>BELLE</td>
<td>$P_+ &lt; 0.66 \text{ GeV}$</td>
<td>11.0 ± 1.0 ± 1.6</td>
</tr>
<tr>
<td>BABAR</td>
<td>$M_X &lt; 1.55 \text{ GeV}/c^2$</td>
<td>11.7 ± 0.9 ± 0.7</td>
</tr>
<tr>
<td>BELLE</td>
<td>$M_X &lt; 1.7 \text{ GeV}/c^2$</td>
<td>12.3 ± 1.1 ± 1.2</td>
</tr>
</tbody>
</table>

BLNP: PRD72, 073006 (2005)
ADFR: arXiv:0711.0860
BLL: PRD64, 113004 (2001)
Sides of the Unitarity Triangle

- Use theory to relate partial branching fractions to $V_{cb}$ for a given region of phase space.

$V_{ub}^* / V_{cd} V_{cb}$

$\beta$

$\gamma$

$(0,0)$

$(1,0)$

$V_{td} V_{tb}^*$

$b \rightarrow c l \nu$

$B \rightarrow D^{(*)} l \nu$

$B \rightarrow D^{**} l \nu$
Side measurements: $V_{cb}$

- Use the differential decay rates of $B \to D^* l \nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \to D^* l^- \bar{\nu})}{d \omega d \cos \theta_l d \cos \theta_V d \chi} \propto F^2(\omega, \theta_l, \theta_V, \chi) |V_{cb}|^2$$

- $F$ is a form factor.
- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

- Reconstruct $B^- \to D^{*0} e^- \bar{\nu}_e$ and $D \to K^+ \pi^-$

- Measurement is not statistically limited, so use clean signal mode for $D \to K\pi$ decay only.

- Extract signal yield, $F(1)|V_{cb}|$ and $\rho$ from 3D binned fit to data.
Side measurements: $V_{cb}$

- Use the differential decay rates of $B \to D^{*} l \nu$ to determine $|V_{cb}|$:

\[
\frac{d\Gamma(B \to D^{*} l^{-} \nu)}{d\omega d\cos\theta_{l} d\cos\theta_{V} d\chi} \propto F^{2}(\omega, \theta_{l}, \theta_{V}, \chi) |V_{cb}|^{2}
\]

- $F$ is a form factor.

- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

\[\mathcal{B}(B^{-} \to D^{*0} e^{-} \overline{\nu}) = (5.56 \pm 0.08 \pm 0.41)\%\]

\[F(1) |V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \times 10^{-3}\]

- Using $F(1)=0.919 \pm 0.033$ from Hashimoto et al., PRD66 014503 (2002).
Side measurements: $V_{cb}$

- Use the differential decay rates of $B \rightarrow Dl\nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \rightarrow Dl\nu)}{d\omega d\cos\theta_l d\cos\theta_\nu d\chi} \propto G^2(\omega) |V_{cb}|^2$$

- Use a sample of fully reconstructed tag $B$ mesons, then look for the signal.

- Improves background rejection, at the cost of signal efficiency.

- $G$ is a form factor.

- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

- Reconstruct the following $D$ decay channels:

  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^0$
  - $K^-\pi^+\pi^-$
  - $K_S^0\pi^+\pi^-\pi^0$
  - $K_S^0\pi^0$
  - $K^+K^-$
  - $\pi^+\pi^-$
  - $K_S^0K_S^0$

Use the beam energy to constrain $P^\mu$ to effectively ‘reconstruct’ $\nu$ from the missing energy-momentum: $m_{\text{MISS}} \approx m_{\nu} = 0$. 
Side measurements: $V_{cb}$

- Use the differential decay rates of $B \to Dl\nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \to Dl\bar{\nu})}{d\omega d\cos\theta_l d\cos\theta_\nu d\chi} \propto G^2(\omega) |V_{cb}|^2$$

- $G$ is a form factor.

- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

- $\omega$ is related to $q^2$ of the $B$ meson to the $D$
Side measurements: $V_{cb}$

- Use the differential decay rates of $B \to D l \nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(B \to D l \overline{\nu})}{d\omega d\cos\theta_l d\cos\theta_\nu d\chi} \propto G^2(\omega) |V_{cb}|^2$$

- $G$ is a form factor.

- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

- Results of a combined fit to $D^0$ and $D^\pm$ modes gives:

$$G(1) |V_{cb}| = (43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$$

$$|V_{cb}| = (39.8 \pm 1.8_{\text{stat}} \pm 1.3_{\text{syst}} \pm 0.9_{\text{FF}}) \times 10^{-3}$$

- Using $G(1)$ from Okamoto et al., NPPS 140 461 (2005) and correcting by 1.007 for QED effects.
\[ G(1) | V_{cb} | = (42 \pm 1.6) \times 10^{-3} \]

\[ | V_{cb} | = (39.7 \pm 1.4_{\text{exp}} \pm 0.9_{\text{theory}}) \times 10^{-3} \]

- Using \( G(1)=1.074 \pm 0.018\pm 0.016 \) from Okamoto et al., NPPS 140, 461 (2005).

\[ F(1) | V_{cb} | = (35.97 \pm 0.53) \times 10^{-3} \]

\[ | V_{cb} | = (38.7 \pm 0.6_{\text{exp}} \pm 0.9_{\text{theory}}) \times 10^{-3} \]

- Using \( F(1)=0.924 \pm 0.012\pm 0.019 \) from Laiho, arXiv:0710.1111 [hep-lat].
Sides of the Unitarity Triangle

- Use inclusive measurements of $b \rightarrow d \gamma$ and $b \rightarrow s \gamma$ to measure the ratio $|V_{td}| / |V_{ts}|$.

- Able to compare results with $B_s$ mixing results from the TeVatron.
• FCNC process (same topology as $B \to X_s \gamma$).
• Leading order contribution: electroweak penguin.
  - sensitive to NP

<table>
<thead>
<tr>
<th>$B \to X_d \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \pi^+ \pi^- \gamma$</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \pi^0 \gamma$</td>
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<tr>
<td>$B^+ \to \pi^+ \pi^- \pi^+ \gamma$</td>
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<tr>
<td>$B^0 \to \pi^+ \pi^- \pi^0 \gamma$</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \pi^- \pi^0 \gamma$</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \eta \gamma$</td>
</tr>
</tbody>
</table>

- Challenging analysis with large backgrounds at high $m_X$.
- Signal suppressed by $V_{td}$.
- Extract signal from a 2D Fit in $m_{ES}$ and $\Delta E$.

<table>
<thead>
<tr>
<th>$M(X) , [\text{GeV}/c^2]$</th>
<th>$N_S$</th>
<th>$\epsilon$</th>
<th>$B \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.6 &lt; M(X_d) &lt; 1.0$</td>
<td>66 + 26</td>
<td>7.0%</td>
<td>1.2 + 0.5 + 0.1</td>
</tr>
<tr>
<td>$1.0 &lt; M(X_d) &lt; 1.8$</td>
<td>107 + 47</td>
<td>5.2%</td>
<td>2.7 + 1.2 + 0.4</td>
</tr>
</tbody>
</table>

- Convert $B(d\gamma) / B(s\gamma)$ into a measurement of $|V_{td}| / |V_{ts}|$ using Ali, Asatrian, and Greub PLB 429 87 (1998)

$top: \quad 0.6 < m_{X_d} < 1.0 \text{GeV} / c^2$

$bottom: \quad 1.0 < m_{X_d} < 1.8 \text{GeV} / c^2$
• Exclusive analysis of $b \to d \gamma$ recently performed by Belle

\[
\frac{\mathcal{B}(B^0 \to \rho^0 \gamma)}{\mathcal{B}(B^0 \to K^{*0} \gamma)} = 0.0206^{+0.0045}_{-0.0043} \pm 0.0014,
\]

\[
\frac{\mathcal{B}(B \to \rho \gamma)}{\mathcal{B}(B \to K^{*} \gamma)} = 0.0302^{+0.0060}_{-0.0055} \pm 0.0026,
\]

\[
\frac{\mathcal{B}(B \to (\rho, \omega) \gamma)}{\mathcal{B}(B \to K^{*} \gamma)} = 0.0284 \pm 0.0050^{+0.0027}_{-0.0029}
\]

• Converting results to $|V_{td}| / |V_{ts}|$ obtain

\[
\frac{|V_{td}|}{|V_{ts}|} = 0.195^{+0.020}_{-0.019} \text{(exp)} \pm 0.015 \text{(th)} \quad [\text{Belle}]
\]

\[
= 0.177 \pm 0.043 \text{(exp)} \pm 0.001 \text{(th)} \quad [\text{BaBar}]
\]

Mainly from neglecting annihilation topologies.

N.B. Errors from fragmentation etc included in the quoted experimental error.
Tests of **CPT**
CPT

• Discrete symmetry conserved in Lorentz invariant local QFT.
  – i.e. the SM and popular extensions.

  – Expect **CPT** to be conserved based on prejudice that we have not seen it violated.
    • But we have seen that the same prejudice had to be given up for **P, C, and CP** symmetries in Weak decay.

  – Possible to construct a theory that violates **CPT**.

  – Don’t expect to see **CPT** violation, but we **must** look for it!

If **CPT** is conserved particles and antiparticles have:
• The same mass and lifetime.
• Symmetric electric charge.
• Opposite magnetic dipole moments (or gyro-magnetic ratios for point like leptons)
CPT

• Discrete symmetry conserved in Lorentz invariant local QFT.
  – i.e. the SM and popular extensions.
  
  – Expect CPT to be conserved based on prejudice that we have not seen it violated.
    • But we have seen that the same prejudice had to be given up for P, C, and CP symmetries in Weak decay.
  
  – Possible to construct a theory that violates CPT.
  
  – Don’t expect to see CPT violation, but we must look for it!

• Experimentally test CPT at the B factories via:
  – Measurements of the $\tau^+ / \tau^-$ lifetime.
  – Measuring ‘z’ in B decays (recall mass eigen-states):

$$|B_{L,H}\rangle = p\sqrt{1 + z}|B^0\rangle \pm q\sqrt{1 + z}|\bar{B}^0\rangle$$

$$z = \frac{(M_{11} - M_{22}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})}{\Delta m - \frac{i}{2} \Delta \Gamma}$$
CPT: Using hadronic B decays

- Similar selection of events as used for the $c\bar{c}s$ sin2$\beta$ analysis
  - $B_{\text{Flav}}$ decays: $B^0 \rightarrow D^{(*)-}\pi^+ (\rho^+, a_1^+), B^0 \rightarrow J/\psi K^{*0} (K^{*0} \rightarrow K^+ \pi^-)$
  - CP modes: $B^0 \rightarrow J/\psi K^0, \psi(2S)K_S^0, \chi_{1c} K_S^0$
  - Charged B control samples: $B^+ \rightarrow \overline{D}^{(*)0} \pi^+ , J/\psi K^{(*)+}, \psi(2S)K^+, \chi_{1c} K^+$

<table>
<thead>
<tr>
<th>$\frac{q}{p}$</th>
<th>$CP, T$</th>
<th>$CP, \mathcal{P}$</th>
<th>$CP, T$</th>
<th>$CP, \mathcal{P}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
<td>$= 1$</td>
<td>$\neq 1$</td>
</tr>
<tr>
<td>$z$</td>
<td>$= 0$</td>
<td>$\neq 0$</td>
<td>$= 0$</td>
<td>$\neq 0$</td>
</tr>
</tbody>
</table>

\[
\text{sgn}(\text{Re } \lambda_{CP}) \Delta \Gamma/\Gamma = -0.008 \pm 0.037 \text{(stat.)} \pm 0.018 \text{(syst.)} \left[ -0.084, 0.068 \right] ,
\]
\[
|q/p| = 1.029 \pm 0.013 \text{(stat.)} \pm 0.011 \text{(syst.)} \left[ 1.001, 1.057 \right] ,
\]
\[
(\text{Re } \lambda_{CP}/|\lambda_{CP}|) \text{ Re } z = 0.014 \pm 0.035 \text{(stat.)} \pm 0.034 \text{(syst.)} \left[ -0.072, 0.101 \right] ,
\]
\[
\text{Im } z = 0.038 \pm 0.029 \text{(stat.)} \pm 0.025 \text{(syst.)} \left[ -0.028, 0.104 \right] .
\]

- compatible with CPT, CP and T conservation.
CPT: Using di-lepton events

- Reconstruct $B\bar{B}$ pairs where both $B$ mesons decay via $b \rightarrow Xl\nu$
  - Sample includes direct $b \rightarrow l$ events: lepton charge tags the $B$ flavor.
  - As $B^0$ mesons mix we can have $++$, $−−$, and $+−$ charge combinations for the two leptons: measure $N^{++}$, $N^{−−}$, and $N^{+−}$.
  - We can measure two asymmetries:

$$A_{T/CP}(|\Delta t|) = \frac{P(B^0 \rightarrow B^0) - P(\bar{B}^0 \rightarrow \bar{B}^0)}{P(B^0 \rightarrow B^0) + P(\bar{B}^0 \rightarrow \bar{B}^0)}$$

$$= \frac{N^{++} - N^{−−}}{N^{++} + N^{−−}} = \frac{1 - |q/p|^4}{1 + |q/p|^4},$$

$$A_{CPT/CP}(\Delta t) \approx 2 \frac{\text{Im} z \sin(\Delta m\Delta t) - \text{Re} z \sinh(\frac{\Delta m\Delta t}{2})}{\cosh(\frac{\Delta m\Delta t}{2}) + \cos(\Delta m\Delta t)}$$

$$\Delta t = t_1 - t_2$$

$\Delta t$ = proper time difference between the decays of the two $B$ mesons.

$$N^{++} \propto \frac{e^{-\Gamma|\Delta t|}}{2} |p|^2 \left\{ \cosh \left( \frac{\Delta \Gamma \Delta t}{2} \right) - \cos(\Delta m\Delta t) \right\},$$

$$N^{−−} \propto \frac{e^{-\Gamma|\Delta t|}}{2} |q|^2 \left\{ \cosh \left( \frac{\Delta \Gamma \Delta t}{2} \right) - \cos(\Delta m\Delta t) \right\},$$

$$N^{+−} \propto \frac{e^{-\Gamma|\Delta t|}}{2} \left\{ \cosh \left( \frac{\Delta \Gamma \Delta t}{2} \right) - 2 \text{Re} z \sinh \left( \frac{\Delta \Gamma \Delta t}{2} \right) + \cos(\Delta m\Delta t) + 2 \text{Im} z \sin(\Delta m\Delta t) \right\}.$$

$$A_{T/CP}^{SM} \sim 10^{-3}$$

$A_{CPT/CP}$ sensitive to $\Delta \Gamma \times \text{Re}(z)$

CPT: Using di-lepton events

- Can also study variations as a function of sidereal time.
  \[ 1 \, d_{\text{sidereal}} \approx 0.99727 \, d_{\text{solar}} \]
- \( z \) depends on the 4-momentum of the B candidate:
  \[ z \approx \frac{\beta^\mu \Delta a_\mu}{\Delta m - i \Delta \Gamma/2} \]

Results shown are compatible with CPT conservation.


\[
|q/p| - 1 = (-0.8 \pm 2.7\,\text{(stat.)} \pm 1.9\,\text{(syst.)}) \times 10^{-3},
\]

\[
\text{Im } z = (-13.9 \pm 7.3\,\text{(stat.)} \pm 3.2\,\text{(syst.)}) \times 10^{-3},
\]

\[
\Delta \Gamma \times \text{Re } z = (-7.1 \pm 3.9\,\text{(stat.)} \pm 2.0\,\text{(syst.)}) \times 10^{-3} \, \text{ps}^{-1}.
\]
$B \rightarrow VV$ decays
(and related channels)
Angular analysis

• With sufficient statistics one can perform a full angular analysis:

\[ B \rightarrow V_1 V_2 \]

\[ J^P: \quad 0^- \rightarrow 1^- \]

\[ \theta_1, \theta_2 \] are the helicity angles: angles between the \( \pi^0 \) momentum and the direction opposite to that of the \( B^0 \) in the vector rest frame.

\[ \phi \] is the angle between the vector meson decay planes.

• We define the fraction of longitudinally polarised events as:

\[ \frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}, \]

where the \( H_m \) are helicity amplitudes.
Angular analysis

- Consider the tree contribution for $B \rightarrow \rho^+ \rho^-$

- In the transversity basis we have three CP eigen-states:

\[
A_0 = H_0 \\
A_\parallel = \frac{1}{\sqrt{2}}(H_{+1} + H_{-1}) \\
A_\perp = \frac{1}{\sqrt{2}}(H_{+1} - H_{-1})
\]

- Spin flip’s are helicity suppressed:

\[
A_0 : A_\parallel : A_\perp \sim O(1) : O\left(\frac{m_V}{m_B}\right) : O\left(\frac{m_V}{m_B}\right)^2
\]

- With sufficient statistics we can measure $S$ and $C$ for each of these three components.

- If $f_L \sim 1$ we just measure $S$ and $C$ for the longitudinal polarisation.

- Neglecting motion within the mesons only $H_0$ is allowed.

- Relative quark motion in the mesons gives rise to the $H_{+1}$ and $H_{-1}$ contributions.

- $H_{+1/-1}$ require 1 and 2 spin flips, respectively.
**B→VV decays**

- B→ρρ decays fit the pattern:
  \[ f_L = 1 - \frac{m_V^2}{m_B^2} \]

- \( f_L \) is large for:
  - \( K^{*0} \bar{K}^{*0} \)
  - \( \omega \rho^+ \)
  - \( \phi K_2^{*0} \)
  - \( \rho^0 K^{*+} \)

- \( f_L \approx 0.5 \) for some penguin dominated modes: notably \( \phi K^* \).

- What mechanism(s) result in the observed behaviour?
• Able to simultaneously measure $f_L$, $f_\parallel$ (and $f_\perp$).

<table>
<thead>
<tr>
<th>parameter</th>
<th>$\phi K^*(892)$</th>
<th>$\phi K_2^*(1430)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B J \times 10^{-6}$</td>
<td>$9.7 \pm 0.5 \pm 0.5$</td>
<td>$7.5 \pm 0.9 \pm 0.4$</td>
</tr>
<tr>
<td>$f_{LJ}$</td>
<td>$0.494 \pm 0.034 \pm 0.013$</td>
<td>$0.901^{+0.046}_{-0.058} \pm 0.037$</td>
</tr>
<tr>
<td>$f_{\perp J}$</td>
<td>$0.212 \pm 0.032 \pm 0.013$</td>
<td>$0.002^{+0.018}_{-0.002} \pm 0.031$</td>
</tr>
</tbody>
</table>

• VV $\phi K^*$ has $f_L \sim 0.5$ and $f_\perp \sim 0.2$.
  – Doesn’t fit naïve picture very well.

• VT $\phi K^*$ has $f_L \sim 0.9$ and $f_\perp \sim 0.0$.
  – Fits naïve picture.

• $f_\perp << f_\parallel$ in the SM.
  – This ratio could be inverted in the presence of right handed currents.

• Important to study other similar decays!
• When we don’t have a large signal, it is not possible to do a full angular analysis.
  – Fit for the fraction of longitudinally polarised events (as with the $\rho \rho \alpha$ analysis from Lecture 1).

$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4} \left[ f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4} (1 - f_L) \sin^2\theta_1 \sin^2\theta_2 \right]$$

• Signal yield is extracted from a fit to $m_{ES}$, $\Delta E$, $m_{K\pi}$, and $m_{3\pi}$ in bins of helicity angle.

• Perform a $\chi^2$ fit only varying $f_L$ to extract polarisation information.

• Signal significance: 3.0 \sigma

$$\mathcal{B} = \left(1.8 \pm 0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$$
• When we don’t have a large signal, it is not possible to do a full angular analysis.
  – Fit for the fraction of longitudinally polarised events (as with the $\rho \rho \alpha$ analysis from Lecture 1).

\[
\frac{d^2 \Gamma}{\Gamma d \cos \theta_1 d \cos \theta_2} = \frac{9}{4} \left[ f_L \cos^2 \theta_1 \cos^2 \theta_2 + \frac{1}{4} (1 - f_L) \sin^2 \theta_1 \sin^2 \theta_2 \right]
\]

\[ f_L = 0.56 \pm 0.26^{+0.18}_{-0.08} \]
B → ϕρ, ϕφ

- Rare decays:
  - ϕϕ OZI suppressed.
  - ϕρ±, 0 Electroweak penguin processes.

- Could be sensitive to new physics.
  - Different enhancements for different scenarios: RPV SUSY/2HDM/MSUGRA

- BR ~ 10⁻⁹.

- ϕρ⁺ could be enhanced by ϕ-ω mixing up to O(10⁻⁷); what about ϕρ⁰?

**Note:** ε = ε(f_L); Fit for f_L eff with a known R = ε_L/ε_T

So:

\[ f_L = \frac{f_L^{\text{eff}}}{R + f_L^{\text{eff}} (1 - R)}, \]

**What do we use for f_L when fitting the data if there is insufficient signal?**

i) Use prejudice from a theory calculation [OK if they agree].

ii) Scan for signal for different f_L and take the largest upper limit/most significant result.

For each value of f_L compute the value of Nsig and its error, as well as the significance of the result, branching fraction and 90% CL upper limit.
• Rare decays:
  - $\phi\phi$ OZI suppressed.
  - $\phi\rho^{\pm,0}$ Electroweak penguin processes.

• Could be sensitive to new physics.
  - Different enhancements for different scenarios: RPV SUSY/2HDM/MSUGRA

• $BR \sim 10^{-9}$.

• $\phi\rho^+$ could be enhanced by $\phi\omega$ mixing up to $O(10^{-7})$; what about $\phi\rho^0$?

<table>
<thead>
<tr>
<th>$N$</th>
<th>Mode</th>
<th>$Y_S$</th>
<th>Bias</th>
<th>$\epsilon(%)$</th>
<th>$\prod B_i(%)$</th>
<th>$\sigma$</th>
<th>$B(\times 10^{-7})$</th>
<th>$UL(\times 10^{-7})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>209</td>
<td>$\phi\phi^0$</td>
<td>$-1.5^{+3.7}_{-2.9}$</td>
<td>$-0.4 \pm 0.2$</td>
<td>40.4 [28.7]</td>
<td>24.3 $\pm$ 1.2</td>
<td>0.0</td>
<td>$-0.4^{+1.2}_{-0.5} \pm 0.3$</td>
<td>$&lt;2.0$</td>
</tr>
<tr>
<td>3175</td>
<td>$\phi\rho^+$</td>
<td>$22.5^{+11.3}_{-9.7}$</td>
<td>$+2.3 \pm 1.1$</td>
<td>5.7 [9.8]</td>
<td>49.3 $\pm$ 0.6</td>
<td>2.2</td>
<td>$15^{+7}_{-6} \pm 9$</td>
<td>$&lt;30$</td>
</tr>
<tr>
<td>3949</td>
<td>$\phi\rho^0$</td>
<td>$3.9^{+6.3}_{-4.4}$</td>
<td>$+0.8 \pm 0.4$</td>
<td>24.1 [26.5]</td>
<td>49.3 $\pm$ 0.6</td>
<td>1.0</td>
<td>$0.9^{+1.3}_{-0.9} \pm 0.9$</td>
<td>$&lt;3.3$</td>
</tr>
<tr>
<td></td>
<td>$\phi f_0$</td>
<td>$0.8^{+2.4}_{-1.4}$</td>
<td>$-1.7 \pm 0.5$</td>
<td>22.1</td>
<td>...</td>
<td>0.0</td>
<td>$0.2^{+0.6}_{-0.3} \pm 0.3$</td>
<td>$&lt;3.8$</td>
</tr>
<tr>
<td></td>
<td>$f_0 f_0$</td>
<td>$-13.6^{+4.8}_{-3.5}$</td>
<td>$-1.8 \pm 0.5$</td>
<td>25.5</td>
<td>...</td>
<td>0.0</td>
<td>$-1.4^{+0.5}_{-0.4} \pm 1.5$</td>
<td>$&lt;2.3$</td>
</tr>
</tbody>
</table>

• No signal observed.

August 2008

Adrian Bevan
• Have searched for a number of rare $B \to VV$ decays.

• Many rare penguin processes are suppressed to $\mathcal{B} \sim O(10^{-9})$.
  • These could be sensitive probes of NP!

• Also searched for $B \to AV$:
  • $a_1^+ \rho$ \[<61 \times 10^{-6}\]
  • $b_1^{+/-} \rho^{-/+}$ \[<1.7 \times 10^{-6}\]

• Recent theory prediction gave $\mathcal{B}(b_1^{+/-} \rho^{-/+}) \sim 15$ to $48 \times 10^{-6}$


• We have a lot to learn from VV & AV decays!
Summary

• The B-factories have tested the CKM mechanism to an unprecedented level:
  \[ \sigma(\bar{\rho}) \sim 16\% , \quad \sigma(\bar{\eta}) \sim 4.7\% \]

• CKM works at this level.
  – Still not enough CP violation to explain the universal matter-antimatter asymmetry!
  – Is there NP in weak interactions with (s)quarks to make up the shortfall?

• CPT has been experimentally tested by the B-factories.

• Need more precise searches for new physics and possible deviations from CKM.

• Rare B decays to final states with V and A are not fully understood (from experimental or theoretical perspectives).

• Next generations of B factories will start to build on the knowledge of BaBar and Belle soon.
Outlook

- BaBar has finished taking data:
  - 467 million B pairs recorded at the Y(4S)
  - Recorded 30 fb$^{-1}$ at the Y(3S) and 14.5 fb$^{-1}$ at the Y(2S)
  - Performed an energy scan above the Y(4S)

- Belle
  - Will record 1 ab$^{-1}$ at the Y(4S)
  - Has data at the Y(1S), Y(5S) and above the Y(5S)
  - Will be upgraded to $\sim 10^{35}$ (SuperKEKB)

- LHC-b
  - Should start taking data in September 2008.
    - We can look forward to results soon after!

- SuperB
  - Could start taking data as early as 2015. Would aim to record 75 ab$^{-1}$ in the first 6 years of data taking.
Experimental References

- **Alternate $\beta$ and CPT**
  
  
  
  
  
  
  
  
  
  
  
  

- **Direct CP Asymmetries**
  
  $B \rightarrow K\pi$
  
  
  
  $B \rightarrow \rho\pi$
  
  

- **Sides** (Also see the HFAG web site: Semi-leptonic group page for older publications)
  
  $V_{ub}$
  
  
  
  
  
  
  

  $b \rightarrow d\gamma$
  
  

  $V_{cb}$
  
  
  

- **$B \rightarrow VV$ decays**
  
  (Also see $\alpha$: $\rho\rho$ Refs. for Lecture 1)
  
  
  
  
  BaBar Collaboration (B. Aubert et al.), arXiv:0708.1630 (contributed to LepPh07).
  
  
  
  