Seeking a Needle in a Haystack

Recent Results from the B-Factory Experiments

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The Two Asymmetric Energy B Factories

**PEP-II at SLAC**

9 GeV (e⁻) × 3.1 GeV (e⁺)

peak luminosity:

\[1.2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\]

14 countries, 59 institutes, ~400 collaborators

**KEKB at KEK**

8 GeV (e⁻) × 3.5 GeV (e⁺)

peak luminosity:

\[1.7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\]

11 nations, 78 institutes, ~500 persons
Experimental Landscape (ca 2008)

Integrated Luminosity

- Belle: 720 fb$^{-1}$
- BaBar: 433 fb$^{-1}$

Million B Mesons

- CLEO II
- CLEO II.5

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Precision Physics and Rare Events

BaBar collected:

480 million \( \Upsilon(4S) \rightarrow B\bar{B} \)

630 million \( e^+ e^- \rightarrow c\bar{c} \)

460 million \( e^+ e^- \rightarrow \tau^+ \tau^- \)

??? New Physics
In the Standard model the weak eigenstates differ from the mass eigenstates.

The CKM Matrix:

\[ V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \approx \begin{pmatrix}
1 & \lambda & \lambda^3 \\
\lambda & 1 & \lambda^2 \\
\lambda^3 & \lambda^2 & 1
\end{pmatrix} \]
Experimental setting: $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$

- 20 MeV above BB threshold; no additional pions
- B mesons have small speed $\beta \sim 0.06$ in $Y(4S)$ frame
- Decay products of $B$ and $\bar{B}$ overlap in detector
- $e^+e^- \rightarrow qq$ continuum decays also produced
- At asymmetric B factories, B vertices differ by 260$\mu$m
Instrumented Flux Return for muon and neutral hadron identification

Electromagnetic calorimeter: ~6500 CsI crystals

Detector of interally reflected Cherenkov radiation

5-layer, double-sided silicon strip vertex tracker

Drift chamber

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Experimental Techniques: B meson reconstruction

Exploit kinematics of $e^+e^- \rightarrow \gamma(4S) \rightarrow B\bar{B}^0$ for signal selection

**Beam-energy substituted mass**

$$m_{ES} = \sqrt{E_{beam}^* - p_B^*}$$

**Energy difference**

$$\Delta E = E_B^* - E_{beam}^*$$

**Event topology**

(multivariate methods)

Correctly reconstructed BB events

$\sigma \sim 2.5$ MeV

Combinatorial background
Experimental Techniques: Single B Meson Beams

Lots of interesting modes include one or more neutrinos.

“Beams” with a single, monochromatic B and without c, QED etc would be very useful for: \( B \rightarrow \tau \nu, B \rightarrow \nu \nu, B \rightarrow K \nu \nu, \ldots \)

Fully reconstruct one of the Bs and study the remaining of the event \( \rightarrow \) closed kinematics, missing energy reconstruction

\[
\begin{align*}
\overline{B}^0 & \rightarrow D^{*+} \pi^- \\
B^0 & \rightarrow \psi(2S)K^0_s
\end{align*}
\]

Tag types

Semileptonic \( D(\ast) l(\nu \pi) \)
5K/fb\(^{-1}\)

Hadronic \( D(\ast) X \)
3K/fb\(^{-1}\)

\[ X=n\pi+m\pi^0+pK+qK_s \]

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Part 1: The Elements of the CKM Matrix
4 Fundamental parameters of the Standard Model
They cannot be predicted but can be measured

\[
\begin{align*}
V_{ud} & \quad n \rightarrow p \\
V_{us} & \quad K \rightarrow \pi \\
V_{ub} & \quad B \rightarrow \pi \\
V_{cd} & \quad D \rightarrow \pi \\
V_{cs} & \quad D \rightarrow K \\
V_{cb} & \quad B \rightarrow D \\
V_{td} & \quad B_d \rightarrow \bar{B}_d \\
V_{ts} & \quad B_s \rightarrow \bar{B}_s \\
V_{tb} & \quad t \rightarrow b 
\end{align*}
\]
The determination of the $|V_{ub}|$ and $|V_{cb}|$ relies on semileptonic decays $\rightarrow$ only one hadronic current

- Tree decays – insensitive to NP

Two complementary approaches:

- **Exclusive**: $X$ fully reconstructed
  - Need form factor normalization (non-perturbative)

- **Inclusive**: sum over many $X$ states, with at most partial reconstruction of the $X$ system
  - Use OPE in $(1/m_b)^n$

Form Factor

\[
\frac{d\Gamma(B \rightarrow \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2
\]

$X = \pi, \eta, \eta', \rho, \omega$

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**B → Dlν** in the recoil of fully reconstructed $B_{tag}$

- Fully reconstructed “tag” B meson.
  - Signal B 4-vector known.
  - Neutrino kinematics fully constrained.
  - Excellent $w$ resolution.
  - Very clean signal.
- Consistent with other methods
  - Larger stat uncertainty
  - Smaller systematic
- $>2\sigma |V_{cb}|$ exclusive vs inclusive discrepancy remains...

Fit results:

- Shape: $\rho^2 = 1.20 \pm 0.09 \pm 0.04$
- Intercept: $G(1)|V_{cb}| = (45.6 \pm 3.3 \pm 1.6) \times 10^{-3}$
- $|V_{cb}| = (39.8 \pm 1.8 \pm 1.3 \pm 0.9) \times 10^{-3}$

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$|V_{cb}|$: Global fit of $B \rightarrow D^{\ast}\emptyset\nu$

- Reconstruct $D^0$ and $D^+$ pairs (slow $\pi$ from $D^*$ not required).
- Binned 3D $\chi^2$ fit to $p_l$, $p_D$, and cosine of angle between $B$ and $D\emptyset$, all in CM frame.
- Fit for BFs and form factor slopes.

$G(1)|V_{cb}| = (44.1 \pm 0.8 \pm 2.2) \times 10^{-3}$

$F(1)|V_{cb}| = (35.6 \pm 0.2 \pm 1.2) \times 10^{-3}$

Lattice QCD: Form factor norm. at zero recoil.

$D^*\emptyset\nu$: $|V_{cb}| = (38.3 \pm 0.2 \pm 1.3 \pm 0.9) \times 10^{-3}$

$D\emptyset\nu$: $|V_{cb}| = (40.8 \pm 0.8 \pm 2.1 \pm 0.9) \times 10^{-3}$

G(1)$|V_{cb}|$ meas. twice as precise as world average!

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$|V_{cb}|$ from $B \to D^{(*)}\ell\nu_\ell$ Decays

- $B \to D\ell\nu$: [Graph showing data from various experiments]
  - BABAR global fit
  - CLEO
  - BELLE
  - BABAR tagged

$|V_{cb}| = (32.9 \pm 1.6) \times 10^{-3}$

- $B \to D^*\ell\nu$: [Graph showing data from various experiments]
  - CLEO
  - BELLE
  - OPAL
  - DELPHI

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

- $B \to D^{*0}$: [Graph showing data from various experiments]
  - BABAR D *
  - OPAL (excl.)

$|V_{cb}| = (38.7 \pm 1.4 \text{ exp} \pm 0.9 \text{ theo}) \times 10^{-3}$

For $F(1) = 0.924 \pm 0.012 \pm 0.019$

(J. Laiho) arXiv:0710.1111 [hep-lat]

(M. Okamoto et al NPPS 140, 461 (2005))

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$B \rightarrow \pi \ell \nu$ with semileptonic tag

- 383 million $B\bar{B}$ pairs
- Tag one $B$ in $D^{(*)}/\nu$.
- Require a $\pi/\ell$ pair in rest of event and nothing else.
- Fit $\cos^2 \phi_B$ in bins of $q^2$.

**Combined result**

\[ \mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu) = (1.54 \pm 0.17 \pm 0.09) \times 10^{-4} \]

- Consistent with world average.
- Inclusive vs exclusive $|V_{ub}|$ agreement acceptable.
$B \rightarrow \pi \ell \nu$ with semileptonic tag

Presented at ICHEP08

383 million $B\bar{B}$ pairs

Tag one $B$ in $D^{(*)}/\nu$.

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$|V_{ub}|$ from $B \rightarrow \pi \ell \nu$

Consistent with new LCSR result:
Duplancic, Khodjamirian, Mannel, Melic, Offen, 0801.1796 [hep-ph]

$|V_{ub}| = 3.44^{+0.22}_{-0.17} \times 10^{-3}$ (CKMfitter)

Theory lags behind experiments

$\delta |V_{ub}| / |V_{ub}|^{\exp} \sim 5\%$

$\delta |V_{ub}| / |V_{ub}|^{f^{(0)}} \sim 17\% \quad (e.g. \text{HPQCD} \& \text{FNAL})$

LCSR, unquenched and quenched LQCD give consistent results!

Experimental $q^2$ data are used to improve form factors (several methods)
Fit results, without constraint:

\[ |V_{ud}| = 0.97417(26) \]
\[ |V_{us}| = 0.2253(9) \]
\[ \chi^2/\text{ndf} = 0.65/1(42\%) \]
\[ |V_{ud}|^2 + |V_{us}|^2 = 0.9998(6) \]
(neglecting |V_{ub}|)

Fit results, unitarity constr.:

\[ |V_{us}| = 0.2255(7) \]
\[ \chi^2/\text{ndf} = 0.80/2 (67\%) \]
$|V_{us}|$ from $\tau$ decays

$|V_{us}|$ from the hadronic $\tau$ decays in final states with kaons

$$\frac{B(\tau^- \rightarrow K^- \nu_\tau)}{B(\tau^- \rightarrow \pi^- \nu_\tau)} = \frac{f_K^2 |V_{us}|^2}{f_\pi^2 |V_{ud}|^2} \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2$$

BaBar, Preliminary

$$\frac{B(\tau \rightarrow K^- \nu_\tau)}{B(\tau \rightarrow \pi^- \nu_\tau)} = 0.06531 \pm 0.00056 \pm 0.00093$$

Assume universal couplings

Using $f_K/f_\pi = 1.189 \pm 0.007$ from Lattice QCD

$|V_{us}| = 0.2255 \pm 0.0023$

Consistent with $|V_{us}|$ from $K_{\ell 3}, K_{\ell 2}$
|V_{us}| from the hadronic \( \tau \) decays in final states with kaons

\[
\frac{B(\tau^- \rightarrow K^- \nu_\tau)}{B(\tau^- \rightarrow \pi^- \nu_\tau)} = \frac{f_K^2 |V_{us}|^2}{f_\pi^2 |V_{ud}|^2} \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2
\]

Assume universal couplings

Using \( f_K/f_\pi = 1.189 \pm 0.007 \) from Lattice QCD


\[|V_{us}| = 0.2255 \pm 0.0023\]

Consistent with \( |V_{us}| \) from \( K_{\ell 3}, K_{\ell 2} \)
$|V_{td}/V_{ts}|$ from $b \to d \gamma$

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

- $S = 1$ for $\rho^+$, $1/2$ for $\rho^0$ or $\omega$.
- Form factor ratio
- Annihilation contribution

Branching ratios of order $10^{-6}$.

Very challenging!

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$|V_{td}/V_{ts}| : B \rightarrow \rho/\omega \gamma$

$B^+ \rightarrow \rho^+ \gamma$

Significance $B(\times10^{-6}) \pm $ stat $\pm $ sys

$3.2\sigma \quad 1.20^{+0.42}_{-0.37} \pm 0.20$

$B^0 \rightarrow \rho^0 \gamma$

$5.4\sigma \quad 0.97^{+0.24}_{-0.22} \pm 0.06$

Results Consistent with SM and previous measurements

$B^0 \rightarrow \omega^0 \gamma$

$2.2\sigma \quad < 0.9(90\% C.L.)$

or $0.50^{+0.27}_{-0.23} \pm 0.09$

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Comparison of $|V_{td}/V_{ts}|$ measurements

$$\frac{V_{td}}{V_{ts}} = 0.177 \pm 0.043(\text{exp.}) \pm 0.001(\text{th.})$$

(Ali, Asatrian & Greub, PLB 429, 87, 1998)

Theory error in BaBar $B \rightarrow X_d \gamma$ does not include error for using ~50% of states - i.e, does heavy quark duality still hold?

CDF B mixing (PRL 97, 242003)
$|V_{td}/V_{ts}| = 0.206 \pm 0.001 \pm 0.008$

BaBar exclusive
$|V_{td}/V_{ts}| = 0.233 \pm 0.025 \pm 0.022$

Belle exclusive (arXiv:0404.3770)
$|V_{td}/V_{ts}| = 0.195 \pm 0.020 \pm 0.015$

BaBar inclusive
$|V_{td}/V_{ts}| = 0.177 \pm 0.043 \pm 0.001$

(first error experiment, second theory)
Part 2: CP Violation in the Standard Model
CP Violation in the Standard Model

CP Operator:

\[ \text{CP}( \quad ) = \quad \]

To incorporate CP violation

\[ g \neq g^* \]

(coupling has to be complex)
CP Violation in the SM: The CKM Matrix

- The CKM matrix $V_{ij}$ is unitary with 4 independent fundamental parameters.

- Unitarity constraint from 1st and 3rd columns: $\sum_i V_{i3}^* V_{i1} = 0$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$\alpha = \pi - \gamma - \beta$$

$$\gamma \sim \arg[V_{ub}^*]$$

$$\beta \sim \arg[V_{td}^*]$$

$\gamma \sim \arg[V_{ub}^*]$
Interfering Amplitudes in $B^0 \rightarrow K\pi$ Decays

$A_1 = a_1 e^{i\phi_1} e^{i\delta_1}$
$A_2 = a_2 e^{i\phi_2} e^{i\delta_2}$

$\bar{A}_1 = a_1 e^{-i\phi_1} e^{i\delta_1}$
$\bar{A}_2 = a_2 e^{-i\phi_2} e^{i\delta_2}$

Interference $(A_1 + A_2)^2 \neq (\bar{A}_1 + \bar{A}_2)^2$

Asymmetry $= \frac{\Gamma(B) - \Gamma(B^*)}{\Gamma(B) + \Gamma(B^*)} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \approx 2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$
CP Violation in $B^0 \rightarrow K\pi$ Decays

467 x $10^6$ $B^0$ Mesons

Count $B^0 \rightarrow K^+\pi^-$ Decays

467 x $10^6$ $\bar{B}^0$ Mesons

Count $\bar{B}^0 \rightarrow K^-\pi^+$ Decays

Is $N(B^0 \rightarrow K^+\pi^-)$ equal to $N(\bar{B}^0 \rightarrow K^-\pi^+)$?
CP Violation in $B^0 \to K\pi$ Decays

467 x $10^6$ $B^0$ Mesons

Count $B^0 \to K^+\pi^-$ Decays

467 x $10^6$ $\bar{B}^0$ Mesons

Count $\bar{B}^0 \to K^-\pi^+$ Decays

Is $N(B^0 \to K^+\pi^-)$ equal to $N(\bar{B}^0 \to K^-\pi^+)$?

$$A_{CP} = \frac{Br(\bar{B} \to \bar{f}) - Br(B \to f)}{Br(\bar{B} \to \bar{f}) + Br(B \to f)}$$

$A_{cp}(K^+\pi^-) = \begin{cases} 
-0.107 \pm 0.016 & \text{BaBar} \\
-0.094 \pm 0.018 \pm 0.008 & \text{Belle} \\
-0.086 \pm 0.023 \pm 0.009 & \text{CDF} \\
-0.04 \pm 0.16 \pm 0.02 & \text{CLEO} \\
\Rightarrow -0.098 & \pm 0.012 & \text{@ 8.1}\sigma & \text{AVG} 
\end{cases}$

$A_{cp}(K^+\pi^0) = \begin{cases} 
+0.030 \pm 0.039 \pm 0.010 & \text{BaBar} \\
+0.07 \pm 0.03 \pm 0.01 & \text{Belle} \\
-0.29 \pm 0.23 \pm 0.02 & \text{CLEO} \\
\Rightarrow +0.050 \pm 0.025 & \text{@2.0}\sigma & \text{AVG} 
\end{cases}$

$\Delta A_{K\pi} = A_{cp}(K^+\pi^-) - A_{cp}(K^+\pi^0) = -0.147 \pm 0.028 \text{ @ 5.3}\sigma$

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Mixing Induced CP violation

Golden mode $B^0 \rightarrow J/\psi K_s$: CP eigenstate, high rate, theoretically clean

Two $V_{td}$ vertices $e^{-i2\beta}

Two Amplitudes $\rightarrow$ Interference $\rightarrow$ $A_{CP} \sim \sin 2\beta$
A Complication: Quantum Coherence

We need to know the flavor of the $B$ at a reference $t=0$ and measure the difference in decay time $\Delta t$.

We know this meson is $B^0$ at $t=0$.

$\beta_\gamma = 0.56$

The two mesons oscillate coherently: at any given time, if one is a $B^0$ the other is necessarily a $\bar{B}^0$.

$\Delta z = \Delta t \gamma \beta c$

In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson:

$l^- = \bar{B}^0 \quad l^+ = B^0$.

$\Delta t$ picoseconds later, the $B^0$ (or perhaps its now a $\bar{B}^0$) decays.

Time dependent asymmetry $A_{CP} = S_{CP}\sin(\Delta m \Delta t) - C_{CP}\cos(\Delta m \Delta t)$

$S_{CP} = -f_{CP}\sin2\beta$ ($f_{CP} = \pm 1$), $C_{CP}$ "direct" CP violation = 0 for $J/\psi K$.
$\sin 2 \beta$ from $B^0 \rightarrow J/\psi K^0$

**Final analysis: 465 M BB**

One dominant decay amplitude

$B^0 \rightarrow b d \rightarrow c \bar{c} J/\psi \rightarrow c \bar{s} d K^0$

No direct CPV expected

$$S_{J/\psi K^0_S} \approx \sin 2\beta, \quad C_{J/\psi K^0_S} \approx 0$$

Theoretical uncertainty in predictions ~1%

$$S_{(c\bar{c})K^0} = 0.691 \pm 0.029 \pm 0.014$$

$$C'_{(c\bar{c})K^0} = 0.027 \pm 0.020 \pm 0.016$$

Still statistics limited!

Consistent with Belle measurement

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\[ \sin(2\phi_1) = 0.642 \pm 0.031 \pm 0.017 \]

One dominant decay amplitude

No direct CPV expected

\[ S_{J/\psi K^0_S} \approx \sin 2\beta, \quad C_{J/\psi K^0_S} \approx 0 \]

Theoretical uncertainty in predictions \( \sim 1\% \)

Still statistics limited!

Consistent with Belle measurement

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Compilation of Results

\[ \sin(2\beta) \equiv \sin(2\phi_1) \]

\[
\begin{array}{l|l}
\text{BaBar} & 0.69 \pm 0.03 \pm 0.01 \\
\text{arXiv:0808.1903} & \\
\text{Belle } J/\psi K^0 & 0.64 \pm 0.03 \pm 0.02 \\
\text{PRL 98 (2007) 031802} & \\
\text{Belle } \psi(2S) K^+ & 0.72 \pm 0.09 \pm 0.03 \\
\text{PRD 77 (2008) 091103(R)} & \\
\text{ALEPH} & 0.84^{+0.82}_{-1.04} \pm 0.16 \\
\text{PLB 492, 259 (2000)} & \\
\text{OPAL} & 3.20^{+1.80}_{-2.00} \pm 0.50 \\
\text{EPJ C5, 379 (1998)} & \\
\text{CDF} & 0.79^{+0.41}_{-0.44} \\
\text{PRD 61, 072005 (2000)} & \\
\text{Average} & \\
\text{HFAG} & 0.672 \pm 0.024 \\
\end{array}
\]
Is sin(2\(\beta\)) universal?

- Decays mediated by several different quark-level transitions probe 2\(\beta\):
  - \(b \rightarrow c\bar{c}s\) (eg. J/\(\psi\) \(K_S\))
  - \(b \rightarrow c\bar{c}d\) (eg. J/\(\psi\) \(\pi^0\))
  - \(b \rightarrow c\bar{u}d\) (eg. \(D_{CP} \pi^0\))
  - \(b \rightarrow q\bar{q}s\) (eg. \(\phi K_S\))

- Consistency of measurements tests the Standard Model

- Today's situation: no smoking gun

NB. Dalitz plot analyses for \(\pi^+\pi^-K_S\) and \(K^+K^-K_S\)

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Let’s try this for the next angle: $\alpha$

- Access to $\alpha$ from the interference of a $b \rightarrow u$ decay ($\gamma$) with $B^0\overline{B}^0$ mixing ($\beta$)

$B^0\overline{B}^0$ mixing

$$\begin{align*}
B^0 & \rightarrow V^*_{ub} V_{td} d \\
\overline{B}^0 & \rightarrow \overline{V}_{td}^* V_{ub} \overline{d}
\end{align*}$$

$\frac{q}{p} \propto \frac{V^*_{ub} V_{td}}{V_{ub} V_{td}}$

Tree decay

$$\begin{align*}
\gamma & \rightarrow \overline{V}_{ub}^* d \overline{u} \\
\pi^- & \rightarrow \overline{u} \overline{c} \overline{t}
\end{align*}$$

$A \propto V^*_{ud} V_{ub}$

Penguin decay

$$\begin{align*}
\overline{B}^0 & \rightarrow \overline{V}_{td}^* V_{ub} \overline{d} \\
\pi^+ & \rightarrow \overline{u} \overline{c} \overline{t}
\end{align*}$$

$A \approx V^*_{td} V_{tb}$

$$\lambda = \frac{q}{p} \frac{A}{\overline{A}} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$\begin{align*}
\lambda &= e^{i2\alpha} \frac{T + P e^{i\gamma} e^{i\delta}}{T + P e^{-i\gamma} e^{i\delta}} \\
S &= \sin(2\alpha) \\
C &= 0
\end{align*}$$

Time-dep. asymmetry:

$$A_{\pi\pi}(\Delta t) = S_{\pi\pi} \sin(\Delta m_{\pi} \Delta t) - C_{\pi\pi} \cos(\Delta m_{\pi} \Delta t)$$

$\text{NB: } T = "tree" \text{ amplitude} \quad P = "penguin" \text{ amplitude}$

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How can we obtain $\alpha$ from $\alpha_{\text{eff}}$?
How to estimate $|\alpha - \alpha_{eff}|$: Isospin analysis

- Use SU(2) to relate decay rates of different $hh$ final states ($h \in \{\pi, \rho\}$).
- $B \to hh$ can have $I=0$ or $2$ but gluonic penguins only contribute to $I=0$ (by $\Delta I=1/2$ rule).
- Need to measure several related B.F.s.
- Works for $\pi\pi$, $\rho\rho$, $\rho\pi$ systems.

Limiting factor in analysis

- \( A^{+-} = A(B^0 \to \pi^+\pi^-) \)
- \( \tilde{A}^{+-} = A(\bar{B}^0 \to \pi^+\pi^-) \)
- \( A^{+0} = A(B^+ \to \pi^+\pi^0) \)
- \( \tilde{A}^{+0} = A(\bar{B}^0 \to \pi^0\pi^0) \)
- \( A^{00} = A(B^0 \to \pi^0\pi^0) \)
- \( \tilde{A}^{00} = A(\bar{B}^0 \to \pi^0\pi^0) \)


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Alpha: $B \rightarrow \pi \pi$ system

$B \rightarrow \pi^+\pi^-$

$\bar{B}^0$ tag

$B^0$ tag

Asym.

$B^0 \rightarrow \pi^0\pi^0$

Branching fraction and time-integrated CP asymmetry.

$\mathcal{B}^{00} = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$

$S^{00}$ not possible (no vertex)

$C^{00} = -0.43 \pm 0.26 \pm 0.05$

Final analysis: 465 M BB

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Alpha: $B \rightarrow \rho\rho$ system

**New from BaBar: $B^0 \rightarrow \rho^0\rho^0$ (arXiv:0807.4977)**

$B = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$

$f_L = 0.75^{+0.11}_{-0.14} \pm 0.04$

$S^{00} = +0.3 \pm 0.7 \pm 0.2$

$C^{00} = +0.2 \pm 0.8 \pm 0.3$

3.1σ evidence for $\rho^0\rho^0$

**New from Belle: $B^0 \rightarrow \rho^0\rho^0$: $B = (0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$**

**World averages:**

$B_{\rho^0\rho^0} = (0.72 \pm 0.28) \times 10^{-6}$

$B_{\rho^+\rho^-} = (24.2 \pm 3.2) \times 10^{-6}$

$B(\rho^0\rho^0) << B(\rho^+\rho^-)$

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Summary for $\alpha$

SM solution: $\alpha=(91\pm8)^\circ$

$\alpha \in [83.5; 94.0]^\circ$ @ 68% CL
\[ \gamma = \text{arg}[V_{ub}^*]: \text{CP violation in DK modes} \]

**E.g.** \[ B^+ \rightarrow D^0/D^0 K^+ \]

- \[ D \text{ decays do not involve } V_{ub} \text{ or } V_{td}; \text{ no contribution to phase} \]

- \[ D^0/D^0 \rightarrow \text{CP state (GLW)} \]
- \[ D^0/D^0 \rightarrow K^-\pi^+/K^+\pi^-, \text{CA/DCS (ADS)} \]
- \[ D^0/D^0 \rightarrow K_S\pi^+\pi^-, \text{Dalitz (GGSZ)} \]

**Relative phase** = \[ e^{-i\gamma} \]

**\( B^\pm \rightarrow DK \):** no time dependence; extract \( \gamma \) from rates and CP asymmetries but \( b \rightarrow u \) amplitude is small (for example \( r_B \) (DK\(^-\)) = 0.16 ± 0.05 ± 0.01 ± 0.05 Belle)
B\rightarrow D^{(*)}K^{(*)} with D\rightarrow K_S\pi^+\pi^- Dalitz Plot Analysis

Map out Dalitz plot from all D^0 \rightarrow K_S\pi^+\pi^- decays

γ = (76 ± 22 ± 5 ± 5)°

φ_3 = (76^{+12}_{-13} ± 4 ± 9)°

K. Honscheid, Ohio State University, San Carlos 2008
Summary for $\gamma$

$\gamma=(81\pm13)^\circ$

$\gamma=(71\pm20)^\circ$
The CKM Model has passed the experimental test

New Targets
- Effects of TeV new physics $\rightarrow$ deviations from SM
- LFV and new source of CPV
- Hidden flavor symmetry and its breaking

K. Honscheid, Ohio State University, San Carlos 2008
Quarks

\[
\begin{array}{cccc}
 u & c & t & f \\
 d & s & b & f \\
\end{array}
\]

Forces

\[
\begin{array}{cccc}
 Z & \gamma & W & g \\
 H & \text{Higgs boson} & & \\
\end{array}
\]

Leptons

\[
\begin{array}{cccc}
 e & \mu & \tau & v_e \\
 vl & v_\mu & v_\tau & f \\
\end{array}
\]

Visible Matter
Can we find evidence for New Physics in Heavy Flavor Decays?
Part 3: Where to look for New Physics?
Experimental Strategies

$b \to s \gamma$ penguins

$b \to s g$ penguins

$B, D \to l l, l \nu$

$B \to \tau \nu$

Surprises

LFV

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Inclusive $B \to X_s \gamma$ Branching Fraction

Belle update with $E_\gamma > 1.7$ GeV:

arXiv:0804.1580

SM NNLO calculation: $B \to X_s \gamma$

$\mathcal{B}(B \to X_s \gamma) |_{E_\gamma > 1.6 \text{ GeV}} = \left\{ \begin{array}{l}
(3.15 \pm 0.23) \times 10^{-4} \quad \text{Misiak et al.} \\
(2.98 \pm 0.26) \times 10^{-4} \quad \text{Becher Neubertv} \\
(3.47 \pm 0.49) \times 10^{-4} \quad \text{Anderson Gardi}
\end{array} \right.$

HFAG 2008:

$\mathcal{B}(B \to X_s \gamma) |_{E_\gamma > 1.6 \text{ GeV}} = (3.52 \pm 0.25) \times 10^{-4}$

K. Honscheid, Ohio State University, San Carlos 2008
The 95% lower bound of charged Higgs mass as a function of $\mathcal{B}(B \to X_s \gamma)$ and its error.

$M_{H^+} > 300 \text{ GeV/c}^2 @ 95\% \text{ C.L. for all } \tan\beta$
EW Penguins: $B \to Kl^+l^-$, $B \to K^*l^+l^-$, and $B \to X_s l^+l^-$

- With $l^+l^-$ pair, can produce both pseudoscalar and vector mesons
- SM: $\text{Br}(B \to Kl^+l^-) \sim 4 \times 10^{-7}$ ($\pm 30\%$ theory) $
\sim 3$ times that for $K^*$

Short-distance physics appears in the Wilson coefficients.
$C_7, C_9, C_{10}$ important for $b \to s l^+l^-$

Magnitude of $|C_7| \approx 0.33$ known from $B \to X_s \gamma$, but sign not constrained.
$|C_9|^2 + |C_{10}|^2$ constrained by $b \to s l^+l^-$ BF, but not relative sign.

New physics may modify the $C$'s or introduce additional terms (e.g., scalar, pseudoscalar)

$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} (V_{tb}V_{ts}^*) \sum_{i=1}^{10} C_i O_i$

New Physics affects Rates, Asymmetries (AFB, CP), $\mu\mu/ee$ ratio

K. Honscheid, Ohio State University, San Carlos 2008
$B \rightarrow K^{(*)} l^+ l^-$ Signals

$\Delta E$ cuts applied

K. Honscheid, Ohio State University, San Carlos 2008
Good agreement with SM BF

Obtain partial BF in 6 bins in $q^2$; extrapolate the total BF.

- $\text{BF}(B \to K^{*}\Pi) = (10.8\pm1.0\pm0.9) \times 10^{-7}$
- $\text{BF}(B \to K\Pi) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$

- $\text{BF}(B \to K^{*}\Pi) = (11.1\pm1.9\pm0.7) \times 10^{-7}$
- $\text{BF}(B \to K\Pi) = (3.9\pm0.7\pm0.2) \times 10^{-7}$

Veto events in the $J/\psi$ and $\psi'$ regions

- Belle, ICHEP 08
- BABAR, FPCP 08
- Melikhov et. al (quark model, PLB 410, 1997)
- Ali (PRD 66, 034002, 290, 2002)

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K* Longitudinal Polarization

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_K} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K)
\]
Unexpectedly Large Isospin Asymmetry?

\[ A_I \equiv \frac{B(B^0 \rightarrow K^{(*)0} \ell^+ \ell^-) - \left(\frac{\tau_0}{\tau_+}\right)B(B^+ \rightarrow K^{(*)+} \ell^+ \ell^-)}{B(B^0 \rightarrow K^{(*)0} \ell^+ \ell^-) + \left(\frac{\tau_0}{\tau_+}\right)B(B^+ \rightarrow K^{(*)+} \ell^+ \ell^-)} \]

Expected to be small in SM (Feldman and Matias, JHEP 0301, 074 (2003))
Anomalous $A_{FB}(q^2)$ in $B \rightarrow K^{(*)} \pi$? 

Data show positive $A_{FB}$ at low $q^2$, while the SM predicts negative $A_{FB}$.

At high $q^2$, data above the SM expectation.

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Search for $B \rightarrow \tau \nu$

- SM decay proceeds via W-annihilation diagram

$$B^{SM}(B^+ \rightarrow \tau^+ \nu_\tau) = 9.3 \times 10^{-5} \left[ \frac{f_{B^+}}{106 \text{ MeV}} \right]^2 \left[ \frac{|V_{ub}|}{0.00367} \right]^2$$

- $B(B \rightarrow \tau \nu) = (0.78^{+0.09}_{-0.13}) \times 10^{-4}$
  (CKM fitter 2008 prediction)

- Sensitive to new physics charged current

- Analysis:
  - Undetected neutrinos result in large missing energy and few kinematic constraints – high background.
  - Reduce the background by reconstructing the second B (“tag B”) in the event in the copious decay mode $B^- \rightarrow D^{*0} l^- \nu_l$
  - Reconstruct $B^+ \rightarrow \tau^+ \nu_\tau$ with $\tau^+ \rightarrow l^+ \nu \bar{\nu}$ or $\tau^+ \rightarrow h^+ \nu$, where $h = \pi$, $\rho$, or $a_1$
  - Require no additional charged tracks in the event
New Belle Result on $B^+ \rightarrow \tau^+ \nu$

Method: Tag B on one side (hadronic tag or $D(*) \ell \nu$ tag)

Look for $\tau$ signature with “extra” energy in the ECAL

Use 657 M BB with $D(*) \ell \nu$ tag

\[ N_{\text{sig}} = 154^{+36}_{-35} \text{ (stat)}^{+20}_{-22} \text{ (syst)} \]

$\Rightarrow B(B \rightarrow \tau \nu) = (1.65^{+0.38}_{-0.37} \pm 0.35 \pm 0.37) \times 10^{-4}$

2.1σ deviation

Note that interference is destructive in 2HDM (type II). $B > B_{\text{SM}}$ implies that $H^+$ contribution dominates

K. Honscheid, Ohio State University, San Carlos 2008
It doesn’t have to be a B meson decay
Can we find a light Higgs before the LHC is repaired?

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) adds a Higgs singlet [*] → extra Higgs boson, $A^0$, can be light.

\[ Y(3S) \rightarrow \gamma A^0; A^0 \rightarrow \chi \chi \text{ (invisible)} \]

Channel could dominate for a light component of the dark matter ($\chi$)

Parameter Scan
- blue points: $m_A < 2m_\tau$
- red points: $2m_\tau < m_A < 7.5$ GeV
- green points: $7.5$ GeV < $m_A < 8.8$ GeV
- black points: $8.8$ GeV < $m_A < 9.2$ GeV

Best limits come from recent CLEO search for $A^0 \rightarrow \mu\mu, \tau\tau$

[*] c.f. PRL 95:041801, 2005
and PRD 76:051105, 2007

hep/ex arXiv:0807.1427

K. Honscheid, Ohio State University, San Carlos 2008
Experimental Approach

Search for an invisibly-decaying particle recoiling against a single photon

Photon Selection:
- EMC shower shape, acceptance, etc.
- Veto events where there is activity in the muon system opposite the photon (veto $e^+ e^- \rightarrow \gamma\gamma$)
- Veto photons in regions where the muon system has gaps

Additional Constraints
- No activity in the tracking system (track veto)
- Maximum energy requirement on remaining photons ($<100$ MeV total energy)
A Y(3S) → γ + Invisible Candidate

We reject this background by vetoing correlations between our signal photon and activity in the muon system.

Total Signal Efficiency:

<table>
<thead>
<tr>
<th>Region</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy</td>
<td>10-11%</td>
</tr>
<tr>
<td>Low Energy</td>
<td>20%</td>
</tr>
</tbody>
</table>

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A Snapshot: Fits to the Photon Spectrum

$\chi^2/df = 22.5/42$

$e^+e^- \rightarrow \gamma\gamma$

Non-peaking background

Signal Model

K. Honscheid, Ohio State University, San Carlos 2008
Results for $Y(3S) \rightarrow \gamma + \text{Invisible}$

BaBar Preliminary Result:
arXiv:0808.0017 [hep-ex]

The fraction of the $A^0$ which is non-singlet

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Test CPT invariance of B-mixing (using dileptons) by studying the mixing asymmetry as a function of the sidereal day.

Measure $A_{\text{CP/CPT}}(\Delta t) =$

\[
\frac{\text{Prob}(B^0 \rightarrow \bar{B}^0)(|\Delta t|) - \text{Prob}(B^0 \rightarrow B^0)(|\Delta t|)}{\text{Prob}(B^0 \rightarrow \bar{B}^0)(|\Delta t|) + \text{Prob}(B^0 \rightarrow B^0)(|\Delta t|)}
\]

\[
\frac{N(\ell^+, \ell^-)(\Delta t < 0) - N(\ell^+, \ell^-)(\Delta t > 0)}{N(\ell^+, \ell^-)(\Delta t < 0) + N(\ell^+, \ell^-)(\Delta t > 0)}
\]

Based on PRL 80 (1998) 1818

Prob($B^0 \rightarrow B^0$)(|\Delta t|) = Prob($\bar{B}^0 \rightarrow \bar{B}^0$)(|\Delta t|)

Required by CPT Invariance
Results

\[ |B_L| = p\sqrt{1-z}|B^0| + q\sqrt{1+z}|\bar{B}^0| \]
\[ |B_H| = p\sqrt{1+z}|B^0| - q\sqrt{1-z}|\bar{B}^0| \]

**A\text{\textsubscript{CP/CPT}} Measures:**

Asymmetry vs. Sidereal time

1-D projection of 2-D \(|\Delta t|\) and sidereal time fit

Interpretation of measurement

\[ \Delta\Gamma \times \text{Re}(z) = \Delta\Gamma \times \text{Re}(z)_0 + \Delta\Gamma \times \text{Re}(z)_1 \cos(\Omega T + \varphi_i) \]
\[ \text{Im}(z) = \text{Im}(z)_0 + \text{Im}(z)_1 \cos(\Omega T + \varphi_i) \]

No Time Dependence

Significance is 2.8\sigma

PRL 100:131802, 2008.
Recent BaBar Searches for LFV: $\tau \rightarrow 3 \ell$ and $\tau \rightarrow l \omega$

Search for tri-lepton final states with 6 distinct combinations of electrons and muons

- $\tau \rightarrow \ell \ell \ell$
- $\tau \rightarrow l \omega$

<table>
<thead>
<tr>
<th>Model</th>
<th>$B(\tau \rightarrow \ell \ell \ell)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM+$\nu$-mixing (PRL95(2005)41602, EPJC9(1999)513)</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>SM+Heavy Majorana $\nu_R$ (PRD66(2002)034008)</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-Universal $Z'$ (PLD547(2002)252)</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>MSSM+seesaw (PRD66 (2002) 057301)</td>
<td>$B(\tau \rightarrow \mu \gamma) : B(\tau \rightarrow \mu \mu \mu) : B(\tau \rightarrow \mu \eta) = 1.5 : 1 : 8.4$</td>
</tr>
</tbody>
</table>

Search for $\tau^+ \rightarrow l^+ \omega$ (using electron and muon final states and $\omega \rightarrow \pi^+ \pi^- \pi^0$). Observation of either is an unambiguous sign of new physics.

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LFV Results

Event Selection: “1-prong” +

\[
\begin{align*}
(3\ell) & \quad (\ell\omega) \\
\Delta E &= E_{\text{Rec.}}^* - E_\tau^* \\
\Delta M &= M_{\text{rec.}} - m_\tau \\
\end{align*}
\]

\[m_{\text{EC}}: \tau \text{ mass with the}\]
\[\Delta E \text{ energy constrained to } E_{\text{beam}}/2\]

Expect \(\sim 1\) bkg. event per channel

Signal efficiency is 2-10\% per channel.

Results consistent with background

broad shaded area indicates regions containing 90\% of signal events

We find no evidence for these decays

90\% CL upper limits:

\( (4-8) \times 10^{-8} (3\ell) \)

and

\( 1 \times 10^{-7} (\ell\omega) \)

PRL 100:071802, 2008

PRL 99:251803, 2007

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Lepton Flavor Violation in $\tau$ Decay

- Forbidden in SM but various new physics models predict $B$ as high as $10^{-8}$

**SUSY**

$$\tau \rightarrow \tilde{\chi}^0 \rightarrow \gamma \mu$$

**SUSY Higgs**

$$\tau \rightarrow H^0, A^0 \rightarrow \mu$$

**MSSM**

$$\mu \tilde{s} \rightarrow \tau \tilde{\chi}^-$$

Current B Factory reach: $B \sim 10^{-8}$

One more magnitude lower
Part 4: Where do we go from here?
Where do we go from here?

- BaBar is complete
- Belle
  - Start Y(5S) run (+ some 2S)
  - Shutdown for upgrade
- CLEO-c is complete
- Tevatron
  - 8 fb\(^{-1}\) (2009)
- The near term future will be in Europe: LHCb
- Will there be a new accelerator dedicated to heavy flavor physics?

LHCb is waiting for data

- New Beam pipe
- More RF power
- Interaction Region
  - Crab crossing
  - \(\theta = 30\) mrad.
  - \(\beta y^* = 3\) mm
  - New QCS
- Damping ring
- Linac upgrade

\[ L = 4 \times 10^{35}/\text{cm}^2/\text{sec} \]

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Where do we go from here?

- BaBar is complete
- Belle
  - Start Y(5S) run (+ some 2S)
  - Shutdown for upgrade
- CLEO-c is complete
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  - 8 fb\(^{-1}\) (2009)
- The near term future will be in Europe: LHCb
- Will there be a new accelerator dedicated to heavy flavor physics?
If we had 50 times more data...

With 75 ab$^{-1}$ of data we could ask:

- Are there new $CP$-violating phases in $b,c$ or $\tau$ decay?
- Are there new right-handed currents?
- Are there new loop contributions to flavor-changing neutral currents?
- Are there new Higgs fields?
- Is there lepton flavor violation?
- Is there new flavor symmetry that elucidates the CKM hierarchy?
Site of the proposed Super-B Factory in Italy
Campus of Tor Vergata University in Rome
Site of the proposed Super-B Factory in Italy
Campus of Tor Vergata University in Rome

- Very high initial luminosity, $10^{36}$
- It is asymmetric: 4 on 7 GeV
- Ring magnets, RF, vacuum components can reused from PEP-II
- Reuse BaBar magnet, CsI as the basis for an upgraded detector
- Polarized beams possible
- Flexible design: $\Upsilon$ region, charm & tau threshold regions

**Time scales**
  INFN $\rightarrow$ Ministry
- Regione Lazio funded digging the SuperB tunnel!
- Luminosity in 2015
New Design for New Physics

Crab sextupoles OFF
waist line is orthogonal to the axis of bunch

Crab sextupoles ON
waist moves to the axis of other beam

IP beam distributions for KEKB

All particles from both beams collide in the minimum $\beta_y$ region, with a net luminosity gain

IP beam distributions for SuperB (without transparency conditions)

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Summary

- The 2 B-Factories continue to produce a wealth of new physics results
- CP Violation in the B sector is firmly established
- The CKM paradigm is established as the source of CP violation & flavor mixing in the SM
  
  **Wolfenstein parameterization:** \( \lambda \sim 0.23, A \sim 0.8, \rho \sim 0.2, \eta \sim 0.4 \)

- Precision measurements of the magnitudes of the CKM elements are now available (experimental uncertainties)
  
  - \( \sigma(|V_{cb}|) \sim 2-3\% \)
  - \( \sigma(|V_{ub}|) \sim 5\% \)
  - \( \sigma(|V_{td}|) \sim 1-2\% \)

- New upper limits for rare decays as low as \( 10^{-8} \)
- We are still looking for that needle in the haystack…

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