Summary

[Diagram of a plot showing various parameters and exclusion regions with labels such as $\sin 2\beta$, $\Delta m_d$, $\Delta m_s$, $\varepsilon_K$, $|V_{ub}|$, $\alpha$, and $\beta$. The plot includes exclusion areas marked with CL > 0.95.]
Content

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- CP violation: phenomenology
- Unitarity triangle and CKM fits

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- B factories and detectors
- Measurement of $\beta$

Lecture 3
- Measurement of $\alpha$
- Measurement of $\gamma$
- $V_{ub}$, $V_{cd}$, $V_{td}$
- Other B-physics topics: $b \rightarrow s \gamma$, rare decays, $B_s$ mixing, etc…
- CKM fit results

Lecture 4
- Charm physics: $D^0$ mixing, …
- Other topics: spectroscopy, $\tau$ physics, LFV
- Future projects: LHCb, Belle-2 ad Super-B
- Summary and conclusion
B Factories: Accelerators and Detectors
B Factory: requirements

• Primary goal: measure “sin2β” in $B^0$ decays to $J/ψK^0_s$

• Needed:
  - high-statistics sample of $B^0$ mesons
  - full kinematical reconstruction of the signal events…
    … + efficient background rejection
  - accurate lifetime measurement of the $B^0$ candidates
  - efficient B-flavor tagging
B Factory: requirements

• Primary goal: measure “\(\sin 2\beta\)” in \(B^0\) decays to \(J/\psi K^0_s\)

• Needed:
  
  - high-statistics sample of \(B^0\) mesons
    => high-luminosity \(e^+e^-\) collider at the \(Y(4S)\) resonance
  
  - full kinematical reconstruction of the signal events…
    … + efficient background rejection
    => \(4\pi\) detector: tracking + calorimetry + particle ID
  
  - accurate lifetime measurement of the \(B^0\) candidates
    => boosted \(Y(4S)\) center-of-mass frame + excellent vertexing
  
  - efficient \(B\)-flavor tagging
    => excellent lepton and kaon identification capabilities
$B^0$ measurement principle at a B factory

$e^- - e^+ + \Upsilon(4S)$

$B_1 \rightarrow B^0 \rightarrow B_2$

$\Delta z \approx 260 \mu m$

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

Used for "flavor tagging"
PEP-II at SLAC

- PEP-II $e^+e^-$ collider at Stanford Linear Accelerator Center
- 2.2km ring, 1658 bunches
- 9.0GeV electrons on 3.1GeV positrons
  => boost $\beta\gamma=0.56$
- Peak luminosity: $12 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
- Integrated luminosity: 553 fb$^{-1}$
- Operated until 2008
KEK-B at KEK

• KEK-B $e^+e^-$ collider at KEK (Japan)
• 3km ring, 5120 bunches
• 8.0GeV electrons on 3.5GeV positrons
  => boost $\beta\gamma=0.43$
• Peak luminosity: $21\times10^{33}\text{cm}^{-2}\text{s}^{-1}$
• Integrated luminosity: $1040\text{fb}^{-1}$
• Still in operation
Luminosity at B factories

(fb⁻¹)

KEKB  World  PEP-II

> 1 ab⁻¹
On resonance:
Y(5S): 121 fb⁻¹
Y(4S): 711 fb⁻¹
Y(3S): 3 fb⁻¹
Y(2S): 24 fb⁻¹
Y(1S): 6 fb⁻¹
Off reson./scan:
~ 100 fb⁻¹

~ 550 fb⁻¹
On resonance:
Y(4S): 433 fb⁻¹
Y(3S): 30 fb⁻¹
Y(2S): 14 fb⁻¹
Off resonance:
~ 54 fb⁻¹
Detector: requirements

• Mutipurpose detector
  => several analyses are possible

• Exclusive reconstruction of decay products
  => full signal reconstruction and good background rejection

• Hermetic detector to reconstruct all generated particles
  => high efficiency

• This is obtained with:

  1. reconstruction of charged particles trajectories
     => vertexing + tracking detectors

  2. measurement of neutral particles energy
     => calorimeters

  3. identification of photons, electrons, muon, kaons, K_S and K_L
     => Cerenkov and time-of-flight (TOF) detectors
     (+calorimeters)
The BABAR Detector

- **Tracking:** \( \sigma(p_T)/p_T = 0.13\% \ p_T \oplus 0.45\% \)
- **DIRC:** \( \frac{K}{\pi} \) separation >3.5\( \sigma \) for p<3.5 GeV/c
- **EMC:** \( \sigma_E/E = 2.3\% \ E^{-1/4} \oplus 1.9\% \)

**Components:**
- **Silicon Vertex Tracker:** 5 double-sided layers
- **Drift Chamber:** 40 layers
- **DIRC (PID):** 144 quartz bars
- **Electro-Magnetic Calorimeter:** 6580 CsI(Tl) crystals
- **1.5T Solenoid** (superconducting)
- **Instrumented Flux Return**
In 2001, Belle discovered CP violation in the B meson system, in 2002, it announced a precise measurement of the CP violating parameter, \( \sin^2 \theta = 0.719 \pm 0.074 \pm 0.035 \). This result is in agreement with the other experiments, and provides a confirmation of the Kobayashi-Maskawa model for CP violation. An updated result will be announced at this conference. (Tom Browder’s talk at Session 5)

KEKB consists of a linear injector and two 3km-circumference storage rings. KEKb components of KEKB

Superconducting RF cavity EPICS based control

RF cavity with a large energy storage
cavity

IR with a finite crossing angle

Horizontal Emittance 18 24

LER (e^+e^-) 1.14 2.4 8.0 -0.0249

HER (e^-) 0.85 13.0 -0.0207

1061 1410 1284 1.14 2.30 0.097/0.066 0.067/0.050

247@1061 45.506/43.545 44.513/41.586

59/0.58 58/0.7 2.30 2.30

Beam Energy 3.5 8 GeV

mA mA

MV cm

10^{-33} /cm^2/sec

10^5@1410

10.308 514/3096/11433

Beam current

Number of bunches

Bunch current

Bunch spacing

Bunch trains

Tot

al RF volatage Vc

Sy

chrotron tune

i

Betatron tune

i

Beta’s at IP

Estimated vertical beam size at IP

Beam-beam parameters

Beam lifetime

Lu

minosity (Belle Csl)

Lum

inosity records

per day /7days/month

KEKB is first to achieve luminosity above 10^{34}!!

The peak luminosity of the KEKB asymmetric B factory exceeded 10^{34}/cm^2/s: this enables Belle to accumulate more than a half million B-anti B pairs per day. http://kcgsrv1.kek.jp/
BELLE detector: asymmetric layout
Analysis techniques: generalities

• Analysis tools use at the B factories:
  - identify the signal B meson ($B_{\text{sig}}$) and suppress backgrounds
  - flavor tagging of the $B_{\text{sig}}$ companion ($B_{\text{tag}}$)
  - vertexing $\Rightarrow$ proper-time information
  - charged-particle identification

  and...

  - “recoil” analysis technique
Backgrounds at the Y(4S)

• For B physics analyses, the dominant backgrounds are:
  1. continuum background
     - $e^+e^- \rightarrow qq$, $q=u,d,s,c$
     - $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$
  2. combinatorial background
     - other decays of the Y(4S) resonance
     - BB events (not signal), reconstructed as signal
       - e.g. $B \rightarrow \rho\pi$ reconstructed as $B \rightarrow \pi\pi$ ("feed down")
         or the opposite ("feed up")
       - e.g. $B_1 \rightarrow D\pi$ and $B_2 \rightarrow D(\rightarrow K\pi)l\nu$ reconstructed as $B \rightarrow DK$
Background: example for $b \rightarrow s \gamma$

- In inclusive $b \rightarrow s \gamma$ analysis:
  - measure the photon energy spectrum $E_\gamma$
  - dominant backgrounds:
    - continuum
    - $B$ decays to charm ($b \rightarrow c$)

Illustrative plot from CLEO
Variables for reconstruction of B mesons

A. Kinematic
- B mass
- B energy
- mass of daughter particles
- decay angle of daughter particles (when applicable)

B. Particle identification
- Cherenkov angle from ring-imaging Cherenkov detector
- Time-of-flight

C. Time
- decay time information from production and decay vertices

D. Event shape
- variables characterizing how jetty the event is
  (continuum is jetty, while Y(4S)→BB events are isotropic)
B mass and energy

- B mass and energy
  - center of mass (CM) energy: $\sqrt{s}=10.58\text{GeV}$
  - $E^*$ and $p^*$ = B energy and momentum in CM

Define: B mass calculated with energy fixed at the beam energy

$$m_{ES} = \sqrt{\frac{1}{4} s - p_B^*}$$

Define: Energy difference between the B and the beam energy

$$\Delta E = E_B^* - \frac{1}{2} \sqrt{s},$$

- Names for the B mass:
  - beam energy constrained mass $m_{bc}$ (at Belle)
  - energy-substituted mass $m_{ES}$ (at BABAR)
B mass and energy: properties

- B mass properties
  - maximum at the beam energy $\sqrt{s}/2$
  - signal B peaking at the B mass (5.279GeV) with a resolution of order a few MeV
  - continuum: phase-space distribution with endpoint at $\sqrt{s}/2$

- Energy difference $\Delta E$
  - signal peaking at $\Delta E=0$, with resolution 20-60MeV (depends strongly on neutrals)
  - B backgrounds generally populate low of high $\Delta E$ regions
  - continuum: linear with slope

- $m_{ES}$ and $\Delta E$ are essentially uncorrelated!
B mass and energy: generalization

• $m_{ES}$ and $\Delta E$ can be written in an Lorentz invariant form:

$$m_{ES} = \sqrt{\left(\frac{1/2}{E_0} s + \frac{p_0 \cdot p_B}{E_0}\right)^2} - p_B^2$$

$$\Delta E = (2 q_0 q_B - s)/2\sqrt{s},$$

where

- $q_B = (E_B, p_B)$ is the B 4-momentum vector
- $q_0 = (E_0, p_0)$ is the 4-momentum vector of the $e^+e^-$ system

• Setting $p_0=0$, we retrieve

$$m_{ES} = \sqrt{\frac{1}{4}s - p_B^*^2}$$

$$\Delta E = E_B^* - \frac{1}{2} \sqrt{s},$$
B mass and energy: example $B^- \rightarrow D^0\pi^-$

FIG. 7. Distributions of (a) $m_{ES}$ and (b) $\Delta E$ from the $B^- \rightarrow \pi^- D^0$ data sample used to determine the small corrections to signal Monte Carlo PDF shapes.
Daughter resonance mass

• mass distributions modeled with:
  - gaussians for signal resonance with width smaller than the resolution
  - Breit-Wigner for signal resonance with width larger than the resolution
  - linear or quadratic shape for background

• resolution depends strongly on the neutral (see e.g. $\eta \rightarrow \pi^+ \pi \pi^0$ and $\eta \rightarrow \gamma \gamma$)
Event shape

- B mesons are produced (almost) at rest in Y(4S) CM => decay products are isotropic in CM frame
- the light quarks (u,d,s,c) in continuum events have high momentum => decay products are emitted along a main direction
- define the thrust axis as the axis that maximizes the sum of momenta projected on this axis
- the cosine of the angle $\theta_T$ of the thrust axis of the B candidate with respect to the thrust axis of the rest of the event is flat for signal, and sharply peaked at 1.0 for continuum
Event shape variables

- Variables:
  - Angle $\not\rightarrow (B$ momentum, beam axis)
  - Angle $\not\rightarrow (B$ thrust axis, beam axis)
  - Legendre moments of the energy flow about the $B$ thrust axis
  - etc...
- Combine these variables into a single Fisher discriminant (to avoid correlated variables in ML fit)
- Achieve $\sim 1.2 \sigma$ separation

Fisher discriminant = linear combination, maximizing the signal-background separation
Decay time difference

- $\sigma(\Delta z) \approx 180 \mu m$
- $\sigma(\Delta t) \approx 1.1 \text{ps (BABAR)} \& 1.4 \text{ps (Belle)}$

F.Blanc, Heavy Flavor Physics
Flavor tagging

• Various tagging algorithms based on:
  - leptons
  - kaons ($b \to c \to s$)
  - other global event properties

• Combined in a neural network (BABAR) or likelihood (Belle)

• Mistag from effects such as opposite lepton sign in $b$ or $c$ quark decay
Tagging performance

- Tagging efficiency depends on
  - fraction of events for which tagging can be obtained: $\varepsilon$
  - probability to make wrong B flavor identification: $p_w$

- $D = 1 - 2p_w$ is the dilution (1=perfect identification; 0=no flavor identification)

$\Rightarrow$ effective tagging power: $\varepsilon D^2 = \varepsilon(1 - 2p_w)^2$

<table>
<thead>
<tr>
<th>Category</th>
<th>Eff. dilution ($D$) (%)</th>
<th>Tagging Power $\varepsilon D^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BaBar</td>
<td>Belle</td>
</tr>
<tr>
<td>Lepton</td>
<td>0.875–1</td>
<td>8.96 ± 0.07</td>
</tr>
<tr>
<td>Kaon I</td>
<td>0.75–0.875</td>
<td>10.82 ± 0.07</td>
</tr>
<tr>
<td>Kaon II</td>
<td>0.625–0.75</td>
<td>17.19 ± 0.09</td>
</tr>
<tr>
<td>Kaon-Pion</td>
<td>0.5–0.625</td>
<td>13.67 ± 0.08</td>
</tr>
<tr>
<td>Pion</td>
<td>0.25–0.5</td>
<td>14.18 ± 0.08</td>
</tr>
<tr>
<td>Other</td>
<td>0–0.25</td>
<td>9.54 ± 0.07</td>
</tr>
<tr>
<td>Total tagging power</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F.Blanc, Heavy Flavor Physics
Extraction of physics quantities

- Discriminating variables are generally combined in a maximum likelihood (ML) fit

  - use uncorrelated variables

  - correlated variables are combined into a single NN or Fisher discriminant

- extended ML fits are used for branching fraction measurements ($N$ events, $Y_j$=yields, $P^i_j$=probability for event $i$ and event category $j$)

\[ \mathcal{L} = \frac{\exp(- \sum_j Y_j)}{N!} \prod_i \sum_j Y_j P^i_j \]

- time-dependent fits are extensions of the above function

- PDF parameters are determined from control samples, or left floating in the ML fit

- up to $O(100)$ free parameters in some ML fits!
Testing the ML fit

• The ML fits are tested on MC
• Create samples of same size as the real data sample, with
  - fully generated signal and B-background events (contain correlations)
  - continuum events generated from the PDFs (no correlations)
• Fit these “toy” MC samples to study biases in the fit procedure
  - can be used to correct for the bias in the real data fit
  - used to determine systematic uncertainties

<table>
<thead>
<tr>
<th>htemp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries: 1000</td>
</tr>
<tr>
<td>Mean: 0.4041</td>
</tr>
<tr>
<td>RMS: 0.9969</td>
</tr>
<tr>
<td>Underflow: 0</td>
</tr>
<tr>
<td>Overflow: 0</td>
</tr>
<tr>
<td>Integral: 1000</td>
</tr>
<tr>
<td>$\chi^2$/ndf: 72.2/71</td>
</tr>
<tr>
<td>Prob: 0.4381</td>
</tr>
<tr>
<td>Constant: 1.2 ± 31.2</td>
</tr>
<tr>
<td>Mean: 0.0316 ± 0.4052</td>
</tr>
<tr>
<td>Sigma: 0.0224 ± 0.9975</td>
</tr>
</tbody>
</table>

Figure 12: Pull distribution for a fitted parameter in 1000 “toy” experiments.
Recoil technique

• Y(4S) → BB => we can reconstruct one B meson (B_{reco}), and we know the momentum and direction of the other B (B_{sig})
  - this method gives a very clean sample of B_{sig} decays recoiling against the reconstructed B_{reco}
  - but the overall statistics is low

• Very useful to look for relatively abundant B decays, but which are subject to sizable backgrounds

• For example:
  - inclusive semileptonic B decays
  - B^0 → υυ (“invisible” decay)
  - inclusive charmless b → sg
A word about blind analysis

E. Blind analysis

A blind analysis technique was adopted for the extraction of $\sin 2\beta$ and $\Delta m_d$ in order to eliminate possible experimenter's bias. We used a method that hides not only the central value for these parameters from the unbinned maximum-likelihood fit, but also the visual $CP$ asymmetry in the $\Delta t$ distribution. The error on both the asymmetry and $\Delta m_d$ is not hidden.

The amplitude of the asymmetry $A_{CP}(\Delta t)$ from the fit was hidden by a one-time choice of sign flip and arbitrary offset based on a user-specified key word. The sign flip hides whether a change in the analysis increases or decreases the resulting asymmetry. However, the magnitude of the change is not hidden. The visual $CP$ asymmetry in the $\Delta t$ distribution is hidden by multiplying $\Delta t$ by the sign of the tag and adding an arbitrary offset.

With these techniques, systematic studies can be performed while keeping the numerical value of $\sin 2\beta$ or $\Delta m_d$ hidden. In particular, we can check that the hidden $\Delta t$ distributions are consistent for $B^0$ and $\bar{B}^0$ tagged events. The same is true for all the other checks concerning tagging, vertex resolution and the correlations between them. For instance, fit results in the different tagging categories can be compared to each other, since each fit is hidden in the same way. The analysis procedure for extracting $\sin 2\beta$ and $\Delta m_d$ were frozen prior to unblinding.
Analysis technique: summary

- Use **Maximum Likelihood (ML) fit** technique
- Use **kinematic**, **event shape** and **decay time** variables
- Apply loose cuts ⇒ keep side-bands for background fitting
- Main background: \( e^+e^- \rightarrow q\bar{q} \) continuum \((q=u,d,s,c)\)
  - Rejected with preliminary cut on thrust angle
- Extract from ML fit:
  - **signal yields**
  - **charge asymmetries**
  - **time dependent asymmetries**
  - + several parameters (PDFs, efficiencies, etc...)
- Several crosschecks:
  - "toy MC"
  - control samples
  - etc...

\[ |\cos\Theta_{\text{thrust}}| \]
Comparison between Belle & BABAR

• Luminosity:
  - excellent KEK-B performance => factor ~2 better statistics than PEP-II

• Detector performance:
  - somewhat better resolutions at BABAR

• Physics parameter extraction:
  - Belle uses simple and robust fits
  - BABAR uses complicated multi-dimensional fits

• Overall comparison:
  - similar performance, but sometimes different systematics

=> excellent competition and crosschecks of results
Measurement of the angle $\beta$
Time-dependent asymmetry

• The asymmetry $A_f(t)$ can be written (assuming $\Delta \Gamma = 0$ and $|q/p|=1$)

$$A_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

where

$$S_f \equiv \frac{2\Im \lambda_f}{1 + |\lambda_f|^2} \quad C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

$$\lambda_f = e^{-i\phi_M} \left( \frac{\bar{A}_f}{A_f} \right)$$
Feynman diagrams for $b \rightarrow q\bar{q}q'$

(a) $t_f$

Tree

(b) $p_f q_u$

Penguin

Figure 12.2: Feynman diagrams for (a) tree and (b) penguin amplitudes contributing to $B^0 \rightarrow f$ or $B_s \rightarrow f$ via a $b \rightarrow q\bar{q}q$ quark-level process.

Since the amplitude $A_f$ involves two different weak phases, the corresponding decays can exhibit both CP violation in the interference of decays with and without mixing, $S_f \neq 0$, and CP violation in decays, $C_f \neq 0$. (At the present level of experimental precision, the contribution to $C_f$ from CP violation in mixing is negligible, see Eq. (12.70).) If the contribution from a second weak phase is suppressed, then the interpretation of $S_f$ in terms of Lagrangian CP-violating parameters is clean, while $C_f$ is small. If such a second contribution is not suppressed, $S_f$ depends on hadronic parameters and, if the relevant strong phase is large, $C_f$ is large.

As summary of $b \rightarrow q\bar{q}q$ modes with $q' = s$ or $d$ is given in Table 12.1. The $b \rightarrow ddq$ July 30, 2010 14:36
The Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2] is a 3\times3 unitary matrix that describes the mixing between quark flavors. It is parameterized by

\[
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

This matrix is phase-independent and is used to describe the transitions between quark flavors in the Standard Model (SM). The CKM matrix is written in terms of

\[
\begin{pmatrix}
  1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
  -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
  A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

where \(\lambda\), \(\rho\), and \(\eta\) are parameters. The real and imaginary parts of the CKM matrix are given by

\[
\text{Re}(V_{\text{CKM}}) \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}, \quad \text{Im}(V_{\text{CKM}}) \approx \begin{pmatrix} 0 & 0 & \lambda^3 \\ \lambda^5 & 0 & 0 \\ \lambda^3 & \lambda^4 & 0 \end{pmatrix}
\]
Decay amplitudes

• For B→J/ψK_S decays, the ratio $\bar{A}/A$ is

$$\frac{\bar{A}_{\psi K_S}}{A_{\psi K_S}} = \frac{(V_{cb} V^*_{cs}) T_{\psi K}}{(V_{cb} V^*_{cs}) T_{\psi K}} + \frac{(V_{ub} V^*_{us}) P^u_{\psi K}}{(V_{ub} V^*_{us}) P^u_{\psi K}} \times \frac{V^*_{cd} V_{cs}}{V_{cd} V^*_{cs}}$$

Tree Penguin $K^0$ mixing

• For several B decays, determine the dominant phase in the decay amplitude, and the size of the next contribution

<table>
<thead>
<tr>
<th>$b \to \bar{q}q\bar{q}'$</th>
<th>$B^0 \to f$</th>
<th>$B_s \to f$</th>
<th>CKM dependence of $A_f$</th>
<th>Suppression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{b} \to \bar{c}c\bar{s}$</td>
<td>$\psi K_S$</td>
<td>$\psi$</td>
<td>$(V^<em><em>{cb} V</em>{cs}) T + (V^</em><em>{ub} V</em>{us}) P^u$</td>
<td>loop $\times \lambda^2$</td>
</tr>
<tr>
<td>$\bar{b} \to \bar{s}s\bar{s}$</td>
<td>$\phi K_S$</td>
<td>$\phi$</td>
<td>$(V^<em><em>{cb} V</em>{cs}) P^c + (V^</em><em>{ub} V</em>{us}) P^u$</td>
<td>$\lambda^2$</td>
</tr>
<tr>
<td>$\bar{b} \to \bar{u}u\bar{s}$</td>
<td>$\pi^0 K_S$</td>
<td>$K^+ K^-$</td>
<td>$(V^<em><em>{cb} V</em>{cs}) P^c + (V^</em><em>{ub} V</em>{us}) T$</td>
<td>$\lambda^2$/loop</td>
</tr>
<tr>
<td>$\bar{b} \to \bar{c}c\bar{d}$</td>
<td>$D^+ D^-$</td>
<td>$\psi K_S$</td>
<td>$(V^<em><em>{cb} V</em>{cd}) T + (V^</em><em>{tb} V</em>{td}) P^t$</td>
<td>loop</td>
</tr>
<tr>
<td>$\bar{b} \to \bar{s}s\bar{d}$</td>
<td>$\phi\pi$</td>
<td>$\phi K_S$</td>
<td>$(V^<em><em>{tb} V</em>{td}) P^t + (V^</em><em>{ub} V</em>{cd}) P^c$</td>
<td>$\approx 1$</td>
</tr>
<tr>
<td>$\bar{b} \to \bar{u}u\bar{d}$</td>
<td>$\pi^+ \pi^-$</td>
<td>$\pi^0 K_S$</td>
<td>$(V^<em><em>{ub} V</em>{ud}) T + (V^</em><em>{tb} V</em>{td}) P^t$</td>
<td>loop</td>
</tr>
</tbody>
</table>
Measurement of $\beta$ in $B^0$ decays

• For $B \rightarrow J/\psi K_S$ and other $b \rightarrow ccs$ processes:

$$\lambda_{\psi K_S} = e^{-2i\beta} \Rightarrow S_{\psi K_S} = \sin 2\beta \quad \text{and} \quad C_{\psi K_S} = 0$$

- correct to better than 1%

• For $B \rightarrow \phi K_S$ and other $b \rightarrow sss$ processes:

$$\lambda_{\phi K_S} = e^{-2i\beta} \Rightarrow S_{\phi K_S} = \sin 2\beta \quad \text{and} \quad C_{\phi K_S} = 0$$

- correct to better than a few percents

• For $B \rightarrow \pi^+ \pi^-$ and other $b \rightarrow uud$ processes:

- the dominant decay amplitude contains the phase $\gamma$, and are therefore measuring $\sin(2\beta + 2\gamma) = \sin(2\alpha)$
B → J/ψ K_S

BABAR, PRD 79 (2009) 072009

BELLE, PRL 98 (2007) 031802

(a) J/ψ K_S

(d) B^0 → J/ψ K^0

F.Blanc, Heavy Flavor Physics
b→ccs modes: m_{ES} distributions (BABAR)

**Figure Description:**

- **Figure a)** shows the m_{ES} distribution for the decay $B^0 \rightarrow J/\psi K^0_S$, $B^0 \rightarrow \psi(2S)K^0_S$, $B^0 \rightarrow \chi_{c1} K^0_S$, and $B^0 \rightarrow \eta_c K^0_S$.
- **Figure b)** represents the $B^0 \rightarrow J/\psi K^0_L$ decay.
- **Figure c)** illustrates the $B^0 \rightarrow J/\psi K^{*0}$ decay.
- **Figure d)** displays the $B_{flav}$ modes.

**Equations:**

- Eq. (7)
- Eq. (8)

**Parameters:**

- $m_{ES}$ (GeV/c^2)
- $\Delta E$ (MeV)
- Events / 2 MeV/c^2
- Events / 2 MeV

**Additional Information:**

- The $B$ meson decays are modeled by convolving distributions of the core and tail components, which can include two flavors, $c$ and $b$.
- Events are measured within a large region and assigned the shift of the measured $m_{ES}$.

**Note:** The figures are from the BABAR experiment, PRD 79 (2009) 072009.
b→ccs modes: asymmetries (BABAR)
\[ \sin(2\beta) \equiv \sin(2\phi_1) \]

- **BaBar**
  - \( \chi_{s0} K_s \)
  - PRD 80 (2009) 112001
  - \( \sin(2\beta) = 0.690 \pm 0.520 \pm 0.040 \pm 0.070 \)

- **BaBar**
  - \( J/\psi \) (hadronic) \( K_s \)
  - PRD 69 (2004) 052001
  - \( \sin(2\beta) = 1.560 \pm 0.420 \pm 0.210 \)

- **Belle**
  - \( J/\psi K^0 \)
  - PRL 98 (2007) 031802
  - \( \sin(2\beta) = 0.642 \pm 0.031 \pm 0.017 \)

- **Belle**
  - \( \psi(2S) K_S \)
  - PRD 77 (2008) 091103(R)
  - \( \sin(2\beta) = 0.718 \pm 0.090 \pm 0.031 \)

- **Average HFAG**
  - \( \sin(2\beta) = 0.672 \pm 0.023 \)
\cos 2\beta

- Time-dependent angular analysis of $B^0 \rightarrow J/\psi K^{*0}$
- interference between CP=+1 and CP=-1 amplitude => \cos 2\beta

- Results favor one of the solutions for the angle $\beta$

=> \cos 2\beta > 0
sin2β in b→ccs modes

\[ \beta \equiv \phi_1 \]

\[ \beta = (21.1 \pm 0.9)° \]

DISFAVoured by J/ψK*, D*D*Ks & Dχc0
**sin2β in charmless penguin B⁰ decays**

- Weak phase in the decay amplitudes can modify the measured asymmetry

=> \[ S = \sin^2 \beta \]

- Estimation of the value for \( \Delta S = -\eta S_f - S_{ccs} \) from QCD

- Table: prediction for \( \sin^2 \beta^{\text{eff}} \) for several modes:

<table>
<thead>
<tr>
<th>(-\eta_f S_f)</th>
<th>QCDF(^a)</th>
<th>pQCD(^b)</th>
<th>SCET(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\phi K_S)</td>
<td>0.75(^{+0.00}_{-0.04})</td>
<td>0.71 (\pm) 0.01</td>
<td>0.69</td>
</tr>
<tr>
<td>(\omega K_S)</td>
<td>0.85(^{+0.03}_{-0.06})</td>
<td>0.84(^{+0.03}_{-0.07})</td>
<td>0.50(^{+0.05}_{-0.06})</td>
</tr>
<tr>
<td>(\rho^0 K_S)</td>
<td>0.64(^{+0.03}_{-0.07})</td>
<td>0.50(^{+0.10}_{-0.06})</td>
<td>0.85(^{+0.04}_{-0.05})</td>
</tr>
<tr>
<td>(\eta' K_S)</td>
<td>0.74(^{+0.00}_{-0.04})</td>
<td>–</td>
<td>0.706 (\pm) 0.008</td>
</tr>
<tr>
<td>(\eta K_S)</td>
<td>0.79(^{+0.02}_{-0.04})</td>
<td>–</td>
<td>0.69 (\pm) 0.16</td>
</tr>
<tr>
<td>(\pi^0 K_S)</td>
<td>0.79(^{+0.02}_{-0.04})</td>
<td>0.74(^{+0.02}_{-0.03})</td>
<td>0.80 (\pm) 0.03</td>
</tr>
<tr>
<td>(f_0(980)K_S)</td>
<td>0.731(^{+0.001}_{-0.001})</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(K^+ K^- K_S^c)</td>
<td>0.728(^{+0.009}_{-0.020})</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(K_S K_S K_S)</td>
<td>0.719(^{+0.009}_{-0.020})</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(K_S \pi^0 \pi^0)</td>
<td>0.729(^{+0.009}_{-0.020})</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
$m_{bc}$ in $b \rightarrow s$ penguin decays (BELLE)
\textbf{sin2β in b→s penguin decays (BELLE)}

\begin{table}[h]
\centering
\begin{tabular}{lccc}
\hline
Mode & sin2\(\phi_1^{\text{eff}}\) & \(\mathcal{A}_f\) \\
\hline
\(\phi K^0\) & +0.50 ± 0.21 ± 0.06 & +0.07 ± 0.15 ± 0.05 \\
\(\eta'/K^0\) & +0.64 ± 0.10 ± 0.04 & -0.01 ± 0.07 ± 0.05 \\
\(K_S^0 K_S^0 K_S^0\) & +0.30 ± 0.32 ± 0.08 & +0.31 ± 0.20 ± 0.07 \\
\(J/\psi K^0\) & +0.642 ± 0.031 ± 0.017 & +0.018 ± 0.021 ± 0.014 \\
\hline
\end{tabular}
\end{table}

BELLE, PRL 98 (2007) 031802
$\sin 2\beta^{\text{eff}}$ in $b \rightarrow s$ penguin decays: summary

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$

<table>
<thead>
<tr>
<th>$b \rightarrow c\bar{c}s$</th>
<th>World Average</th>
<th>$0.67 \pm 0.02$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$0.26 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.90 \pm 0.09$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.56 \pm 0.18$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.57 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.64 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.59 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.90 \pm 0.03$</td>
<td></td>
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<tr>
<td>Belle</td>
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<td></td>
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<tr>
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<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.55 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.67 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.57 \pm 0.17$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.35 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.64 \pm 0.10$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.54 \pm 0.21$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.55 \pm 0.02$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.11 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.45 \pm 0.24$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.48 \pm 0.10$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.48 \pm 0.53$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.20 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.20 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.97 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.01 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.01 \pm 0.33$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$0.86 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>$0.68 \pm 0.15$</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>$0.82 \pm 0.07$</td>
<td></td>
</tr>
</tbody>
</table>
**sin2β_{\text{eff}} in b\rightarrow s penguin decays: summary**

\[
\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1\text{eff}})
\]

<table>
<thead>
<tr>
<th>Decay</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b\rightarrow ccs World Average</td>
<td>0.67 ± 0.02</td>
</tr>
<tr>
<td>(\phi K^0) Average</td>
<td>0.56 ± 0.16</td>
</tr>
<tr>
<td>(\eta' K^0) Average</td>
<td>0.59 ± 0.07</td>
</tr>
<tr>
<td>(K_S K_S K_S) Average</td>
<td>0.74 ± 0.17</td>
</tr>
<tr>
<td>(\pi^0 K^0) Average</td>
<td>0.57 ± 0.17</td>
</tr>
<tr>
<td>(\rho^0 K_S) Average</td>
<td>0.54 ± 0.18</td>
</tr>
<tr>
<td>(\omega K_S) Average</td>
<td>0.45 ± 0.24</td>
</tr>
<tr>
<td>(f_0 K_S) Average</td>
<td>0.62 ± 0.11</td>
</tr>
<tr>
<td>(f_2 K_S) Average</td>
<td>0.48 ± 0.53</td>
</tr>
<tr>
<td>(f_3 K_S) Average</td>
<td>0.20 ± 0.53</td>
</tr>
<tr>
<td>(\pi^0 \pi^0 K_S) Average</td>
<td>-0.72 ± 0.71</td>
</tr>
<tr>
<td>(\phi \pi^0 K_S) Average</td>
<td>0.97 ± 0.03</td>
</tr>
<tr>
<td>(\pi^+ \pi^- K_S) Average</td>
<td>0.01 ± 0.33</td>
</tr>
<tr>
<td>(K^+ K^- K^0) Average</td>
<td>0.82 ± 0.07</td>
</tr>
</tbody>
</table>
$\sin2\beta_{\text{eff}}$ in $b\to s$ penguin decays: C vs S

$\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1\text{eff}}) \ vs \ C_{\text{CP}} \equiv -A_{\text{CP}}$

Contours give $-2\Delta (\ln L) = \Delta \chi^2 = 1$, corresponding to 60.7% CL for 2 dof
ΔS and the 2σ discrepancy

• Since around ~2005, the naïve average of sin2β_{eff} in b→s penguin decays has been ≈2σ low relative to sin2β measured in charmonium modes

• The average has slowly moved towards sin2β with more data and more decay modes (regression to the mean?)

• QCD uncertainties are large, and no new physics can be invoked at this point

• More data, and more modes (B_s decays?) should help clarify the situation

<table>
<thead>
<tr>
<th>Year</th>
<th>sin2β_{eff} naïve average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.50±0.06</td>
</tr>
<tr>
<td>2006</td>
<td>0.53±0.05</td>
</tr>
<tr>
<td>2007</td>
<td>0.56±0.05</td>
</tr>
<tr>
<td>2008</td>
<td>0.64±0.04</td>
</tr>
<tr>
<td>2009</td>
<td>0.62±0.04</td>
</tr>
<tr>
<td>2010</td>
<td>0.64±0.04</td>
</tr>
</tbody>
</table>
\[ \sin(2\beta + \gamma) \]

- \( B^0 \) decays to open charm are sensitive to \( \sin(2\beta + \gamma) \)
  - interference between
    - CKM-favored \( b \to c \) decay amplitude \( A_{\text{fav}} \) (no weak phase)
      and
    - CKM-suppressed \( b \to u \) decay amplitude \( A_{\text{supp}} \) (weak phase \( \gamma \))
  - with and without mixing (phase \( 2\beta \))
  => overall phase difference \( 2\beta + \gamma \)

- Final states are not CP eigenstates. For example:
  - \( B^0 \to D^-\pi^+ \) (CKM-favored)
  - \( B^0 \to D^+\pi^- \) (CKM-suppressed)
\( \sin(2\beta + \gamma) \)

- Coefficient of the sine term in time-dependent asymmetry

\[
S_f = -2r_f \sin(2\beta + \gamma - \delta_f) \\
S_f = -2r_f \sin(2\beta + \gamma + \delta_f)
\]

where

\[
r_f = \left| \frac{A_{\text{CKM-suppressed}}}{A_{\text{CKM-favored}}} \right| \quad (\approx 0.01)
\]

\( \delta_f \) = strong phase

- Measure \( r_f \) in charged B decays, and use isospin relations

- Measure \( S_f \) and \( S_f \implies \) clean extraction of \((2\beta + \gamma)\) and \(\delta_f\)
\[ \sin(2\beta + \gamma) \]

- The uncertainty on \( r_f \) is large
- In practice, we plot \( \sin(2\beta + \gamma) \) as a function of \( r_f \)
Summary on angle $\beta$

- $\beta$ is the most accurately measured CKM triangle property
- Several modes contribute to the measurement of $\beta$
  - $B \to (c c)K_S$ decays:
    - all consistent
    - with small theoretical uncertainties
  - $b \to s$ penguin decays:
    - inconsistencies at the level of 1-2$\sigma$
    - but large theoretical uncertainties