Measurement of $\sin (2 \alpha)$ at BABAR

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OUTLINE

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- Introduction
 - Experimental Techniques
 - Results and Prospects
-

Why measure $\sin(2\alpha)$

- Study fundamental question of CP violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

- Is everything limited to CKM matrix (Standard Model)?
 - see if triangle is closed ($\alpha + \beta + \gamma = \pi$)
 - $\sin(2\beta) = 0.78 \pm 0.08$

How to measure $\sin(2\alpha)$

- $\Upsilon(4S) \rightarrow B^0_{(t_1)} \bar{B}^0_{(t_1)}$ coherent P-wave
- Two paths: $B^0_{(t_1)} \rightarrow B^0_{(t_2)} \rightarrow f_{CP}$ Amplitude = $A_{f_{CP}}$
 $B^0_{(t_1)} \rightarrow \bar{B}^0_{(t_2)} \rightarrow f_{CP}$ Amplitude = $\bar{A}_{f_{CP}} \times (\frac{q}{p})_{\text{mix}}$
- Measure:

$$\Gamma(B^0 \rightarrow f, t_2) \propto e^{-|\Delta t|/\tau_B} (1 + C_{f_{CP}} \cos(\Delta m \Delta t) - S_{f_{CP}} \sin(\Delta m \Delta t))$$

$$\Gamma(\bar{B}^0 \rightarrow f, t_2) \propto e^{-|\Delta t|/\tau_B} (1 - C_{f_{CP}} \cos(\Delta m \Delta t) + S_{f_{CP}} \sin(\Delta m \Delta t))$$

$$S_{f_{CP}} = \frac{2\text{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$\lambda_{f_{CP}} = \left(\frac{q}{p}\right)_{\text{mix}} \times \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

- Have to look at $b \rightarrow u$ decays (V_{ub})

Pure tree: $\lambda_{\pi\pi} = \left(\frac{V_{td} V_{tb}^*}{V_{td}^* V_{tb}}\right) \left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right) = e^{2i\alpha}$ $S_{\pi\pi} = \sin(2\alpha)$

$B \rightarrow \pi^+ \pi^-, \pi^+ \pi^- \pi^0(\rho\pi), 4\pi(\rho\rho, a_1\pi), \dots$ $C_{\pi\pi} = 0$

Penguin “pollution” in $\sin(2\alpha)$

Mode	α_T	α_C	α_P	BABAR $\mathcal{B}(10^{-6})$
$\pi^- \pi^+$	$\sqrt{2}$	0	$\sqrt{2}$	$5.4 \pm 0.7 \pm 0.5$
$\pi^0 \pi^+$	1	1	0	$4.1^{+1.1}_{-1.0} \pm 0.8$
$\pi^0 \pi^0$	0	1	-1	< 3.4

- $C_{\pi\pi} \propto \sin(\delta_{\text{strong}})$ (direct- CP : $A \neq \bar{A}$)
- $S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2} \sin(2\alpha_{\text{eff}})$
- $2\alpha_{\text{eff}} = 2\alpha + \theta$
- θ from Isospin or Model

“Penguin Pollution” from $B \rightarrow K\pi$

- Large $B \rightarrow K\pi \Rightarrow$ cross-feed in $B \rightarrow \pi\pi$ reconstruction
- $B \rightarrow K\pi$ interesting by itself:
e.g. direct CP $\mathcal{A}_{CP} \sim 2(\frac{T'}{P'}) \sin(\gamma) \sin(\delta)$
- $SU(3) \Rightarrow |P/T|_{\pi\pi} \sim 0.28$ (e.g. Gronau/Rosner)

$$\alpha_P \cdot P' + \alpha_T \cdot T' + \alpha_C \cdot C'$$

Mode	α_P	α_T	α_C	BABAR $\mathcal{B}(10^{-6})$
$K^+\pi^-$	$\sqrt{2}$	$\sqrt{2}$	0	$17.8 \pm 1.1 \pm 0.8$
$K^0\pi^+$	$-\sqrt{2}$	0	0	$17.5^{+1.8}_{-1.7} \pm 1.3$
$K^+\pi^0$	-1	-1	1	$11.1^{+1.3}_{-1.2} \pm 1.0$
$K^0\pi^0$	-1	0	1	$8.2^{+3.1}_{-2.7} \pm 1.2$

Requirements on $\sin(2\alpha_{\text{eff}})$ Analysis

- Features common to $\sin(2\beta)$ and $\sin(2\alpha_{\text{eff}})$:
 - exclusive reconstruction of the signal B
 - flavor tagging of the other B
 - precise vertexing for time-dependence
- What is special about $\sin(2\alpha_{\text{eff}})$:
 - reconstruct rare decays ($\mathcal{B}_{\text{branching}} < 10^{-5}$)
 $\Rightarrow$ need high luminosity, many B 's
 - high combinatoric background
 $\Rightarrow$ sophisticated background suppression
 - potential $K\pi/\pi\pi$ cross-feed
 $\Rightarrow$ efficient particle identification, combined fit
 - “penguin pollution”
 $\Rightarrow$ fit for both cos and sin terms

BABAR Experiment

PEP-II

2002/06/14 06.45

BABAR

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

$$e^+e^- \rightarrow q\bar{q} \rightarrow \text{"jets"}$$

This analysis: through Dec.2001

$$N_{B\bar{B}} = (60.2 \pm 0.7) \times 10^6$$

- Silicon Vertex Tracker (SVT) ●
- Drift Chamber (DCH) ●
- Cherenkov Detector (DIRC) ●
- EM Calorimeter (EMC) ●
- Instr. Flux Return (IFR) ●

B -decay Analysis

Fully reconstruct $B \rightarrow \pi^+ \pi^-$ (or $K^+ \pi^-$)

- Vertex (SVT)
- Momentum (DCH+SVT)
- Energy (DCH+SVT)
- Particle ID (DIRC)

Constrain $\Upsilon(4S) \rightarrow BB$

- Beam momenta
- Beam spot

Look at the other B

- Vertex (SVT)
- Flavor tagging (full BABAR)
- Event shape (DCH+EMC)

Momentum Constraint

- Energy-substituted mass $(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B})$

$$m_{\text{ES}} = \sqrt{E_b^2 - \vec{p}_B^2}$$

- $E_b = (s/2 + \vec{p}_{ee} \cdot \vec{p}_B) / E_{ee}$
- $\sigma \sim 2.6$ MeV (E_{beam} dominated)
- B almost at rest (in $\Upsilon(4S)$ cm)

$$E_{\text{beam}}^{\text{cm}} = 5.29 \text{ GeV}$$

$$m_B = 5.28 \text{ GeV}$$

- Signal parameterization:

- from Monte Carlo
- and control samples

- Background parameterization

- from sidebands (float in the fit)

Energy Constraint

- Energy Constraint: $\Delta E = E_B^{\text{cm}} - E_{\text{beam}}^{\text{cm}}$
 - background suppression; $\sigma \sim 26$ MeV (mom resolution)
 - $K\pi/\pi\pi$ separation: include momentum correlation
 - boost $\Rightarrow$ broad momentum spectrum

Particle Identification

● Cherenkov angle θ_c from DIRC

- primary K/π separation
 $\cos(\theta_c) = 1/\beta n$, $\theta_c = f(p, \text{mass})$
- from 2.5 to $\sim 10\sigma$ separation
- boost $\Rightarrow$ momentum/angle correlation

Event Shape

- Suppress background:

$e^+e^- \rightarrow q\bar{q} \rightarrow \text{"jets"}$ (signal "spherical" $e^+e^- \rightarrow \gamma(4S) \rightarrow B\bar{B}$)

- Define in the $\gamma(4S)$ cm frame:

– sphericity axes $B/(\text{rest-of-event})$ angle θ_S
 $\cos(\theta_S) \leq 0.8$; reject $\sim 5/6$ background, $1/5$ signal

– CLEO $\mathcal{F}_{\text{Fisher}} = \sum_i \alpha_i p_i$

rest-of-event
momentum flow
in 9 cones

Fit for $\mathcal{B}$ Branching Fraction

- Unbinned Maximum Likelihood fit

$$\mathcal{L} = \exp \left(- \sum_{i=1}^8 n_i \right) \prod_{j=1}^N \left(\sum_{i=1}^8 n_i \mathcal{P}_i(\vec{x}_j; \vec{\alpha}) \right) \quad (1)$$

PDF: $\mathcal{P}_i(\vec{x}_j) = \mathcal{P}_{i1}(m_{\text{ES}}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{F}) \cdot \mathcal{P}_{i4}(\theta_c^+) \cdot \mathcal{P}_{i5}(\theta_c^-)$

- Fit 4 **signal** and 4 **background** yields (n_i):

$$\begin{aligned} & - n_{\pi^+\pi^-} \\ & - n_{K^+\pi^-} = n_{K\pi} \times (1 - \mathcal{A}_{CP})/2 \\ & - n_{K^-\pi^+} = n_{K\pi} \times (1 + \mathcal{A}_{CP})/2 \\ & - n_{K^+K^-} \end{aligned} \quad \left(\mathcal{A}_{CP} = \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}} \right)$$

- Float 8 **background** shape parameters

$$- m_{\text{ES}} \text{ (1), } \Delta E \text{ (2), } \mathcal{F} \text{ (5)}$$

- Reduce systematic uncertainty:

$$- \text{no vertexing } (\Delta t) \text{ or tagging in } \mathcal{B} \text{ Branching fit}$$

Branching Fraction Results

- Preliminary: ~ 60 million $\Upsilon(4S) \rightarrow B\bar{B}$, reconstruct $\sim 38\%$ eff

B Decay	Fit Events	$BABAR \mathcal{B}(10^{-6})$	Charge Asymmetry
$\pi^+\pi^-$	124^{+16+7}_{-15-9}	$5.4 \pm 0.7 \pm 0.4$	—
$K^\pm\pi^\mp$	$403 \pm 24 \pm 15$	$17.8 \pm 1.1 \pm 0.8$	$-0.05 \pm 0.06 \pm 0.01$
K^+K^-	$0.6^{+8.0}_{-7.4}$	< 1.1 (90% C.L.)	—

- Projection plots: $\frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{bkg}} + \mathcal{P}_{\text{sig}}} > \text{Cut}$ (“sphere” in 4D)
project PDF (total and bkg: $K\pi(\pi\pi)+q\bar{q}$)

$\mathcal{P}$ enhanced $B \rightarrow \pi^+\pi^-$

$\mathcal{P}$ enhanced $B \rightarrow K^\pm\pi^\mp$

Direct CP in πK and Related Modes

- Penguin+Tree $\Rightarrow$ direct- CP

– $\pi^+ K^0$, $\phi K^{(*)}$ - “pure” P
(New Physics in loops?)

– $\pi^+ \pi^0$ - pure T

$$\mathcal{A}_{CP} = \frac{2 |P| |T| \sin \Delta\phi \sin \Delta\delta}{|P|^2 + |T|^2 + 2 |P| |T| \cos \Delta\phi \cos \Delta\delta}$$

Preliminary with $60 \times 10^6 B\bar{B}$

B Decay	$\mathcal{A}_{CP}$
$\pi^\mp K^\pm$	$-0.05 \pm 0.06 \pm 0.01$
$\pi^0 K^\pm$	$0.00 \pm 0.11 \pm 0.02$
$\pi^\pm K^0$	$-0.17 \pm 0.10 \pm 0.02$
$\pi^\pm \pi^0$	$-0.05^{+0.27}_{-0.26} \pm 0.10$

Published with $23 \times 10^6 B\bar{B}$
Phys.Rev.D 65, 051101 (2002)

Vertexing (Δt)

- Vertex $B_{\pi\pi} \rightarrow \pi^+ \pi^-$

$$\Delta Z = Z_{\pi\pi} - Z_{\text{other}}$$

- Vertex other B :

$$\Delta t \approx \Delta Z / (\beta\gamma c)$$

(correct for direction)

- tracks not from $B_{\pi\pi}$
- $B_{\pi\pi}$ vertex and momentum
- $\Upsilon(4S)$ spot and momentum

$$\sigma_{\Delta Z} \sim 180 \mu\text{m}$$

$$\beta\gamma c\tau_B \sim 250 \mu\text{m}$$

Silicon Vertex Detector

Δt Parameterization

- $B \rightarrow \pi^+ \pi^-$ (tag other B : $Q_{\text{tag}} = \pm 1$ for $B^0/\bar{B}^0$)

$$f_{CP}(\Delta t) = \mathcal{R}_{\text{sig}}(\Delta t) \otimes [e^{-|\Delta t|/\tau_B} \times (1 \pm S_{\pi\pi}(1-2w) \sin(\Delta m_d \Delta t) \mp C_{\pi\pi}(1-2w) \cos(\Delta m_d \Delta t))]$$

- $B \rightarrow K^\pm \pi^\mp$ (kaon charge Q_K)

$$f_{\text{self}}(\Delta t) = \mathcal{R}_{\text{sig}}(\Delta t) \otimes [e^{-|\Delta t|/\tau_B} (1 \pm Q_K(1-2w) \cos(\Delta m_d \Delta t))]$$

- External info:

- resolution function $\mathcal{R}_{\text{sig}}$ (3 Gaussian)
- mistag fraction w (next slide)

- Background (empirical):

$$f_{\text{bkg}}(\Delta t) = \mathcal{G}_1(\Delta t) \otimes e^{-|\Delta t|/\tau_{\text{bkg}}} + \mathcal{G}_2(\Delta t) + \mathcal{G}_3(\Delta t) \quad (\text{Gaussian})$$

$$\tau_{\text{bkg}} = 0.56 \text{ ps} \quad (\tau_B = 1.54 \text{ ps})$$

B Flavor Tagging

- Tagging other *B*:

- Lepton charge ($b \rightarrow cl^- \nu$)
- Kaon charge ($b \rightarrow c \rightarrow s$)
- Neural Network (p , soft π ,...)
 - NT1 (more certain)
 - NT2 (less certain)
- Untagged

Tag	Mistag <i>w</i> (%)	Signal <i>ε</i> (%)	$\pi\pi$ bkg <i>ε</i>	$K\pi$ bkg <i>ε</i>
Lepton	8.6	11.1	0.9	1.0
Kaon	18.1	34.7	24.9	32.7
NT1	22.0	7.6	6.9	6.1
NT2	37.3	14.0	17.9	15.4
Notag	(50)	32.6	49.4	41.7

$$Q = \sum \epsilon_i (1 - 2w_i)^2 = 25.1 \pm 0.8\%$$

- Large sample of

$$B \rightarrow D^{(*)-} \pi^+ / \rho^+ / a_1^+ \\ J/\psi K^{*0} (K^+ \pi^-)$$

- determine mistag *w_i*, *ε_i*
- resolution function $\mathcal{R}_{\text{sig}}$
- validate vertexing/tagging

Time-dependent Fit

- Add Δt into ML fit:

$$\mathcal{P}_{i1}(m_{\text{ES}}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{F}) \cdot \mathcal{P}_{i4}(\theta_c^+) \cdot \mathcal{P}_{i5}(\theta_c^-) \cdot \mathcal{P}_{i6}(\Delta t)$$

– separate PDF, 5 tagging categories: $(n_i \epsilon_{i,c}), \mathcal{P}_{i,c}(\vec{x}_j)$

- Fit for: – “ $\sin(2\alpha_{\text{eff}})$ ”: $S_{\pi\pi}$ and $C_{\pi\pi}$
- Fix: – yields (n_i) from $\mathcal{B}$ branching fit
– τ_B and Δm_d
– signal resolution $\mathcal{R}_{\text{sig},c}$, mistag w_c , tag ϵ_{eff}
- Float 32 background shape parameters
 - m_{ES} (5)
 - ΔE (2)
 - $\mathcal{F}$ (5)
 - Δt resolution (8)
 - tagging $\epsilon_{\text{eff}} \pi\pi, K\pi, KK$ (12)

B Lifetime and Mixing with $B \rightarrow K\pi$

- Float Δm_d and τ_B in CP fit:

$$\Delta m_d = (0.517 \pm 0.062) \text{ ps}^{-1}$$

$$\tau_B = (1.66 \pm 0.09) \text{ ps}$$

- Projection in $B \rightarrow K^\pm \pi^\mp$:

$$\begin{aligned} \mathcal{A}_{\text{mix}} &= \frac{N_{\text{mix}} - N_{\text{unmix}}}{N_{\text{mix}} + N_{\text{unmix}}} \\ &= (1 - 2w) \cos(\Delta m_d \Delta t) \end{aligned}$$

- Validation of CP fit

Measurement of $\sin(2\alpha_{\text{eff}})$

	BABAR preliminary result	90% C.L.
$S_{\pi\pi}$	$-0.01 \pm 0.37 \pm 0.07$	$[-0.66, +0.62]$
$C_{\pi\pi}$	$-0.02 \pm 0.29 \pm 0.07$	$[-0.54, +0.48]$

• Check $A_{\pi\pi}(\Delta t) = \frac{n_{B^0} - n_{\bar{B}^0}}{n_{B^0} + n_{\bar{B}^0}}$

$\propto S_{\pi\pi} \sin(\Delta m_d \Delta t)$
 $- C_{\pi\pi} \cos(\Delta m_d \Delta t)$

- Systematics not dominant:

- θ_c param (0.04-0.06)
- $\mathcal{R}_{\text{sig}}$ (0.01-0.02) ...
- mistag w_c
- $\Delta m_d / \tau_B$
- $\Delta E / m_{\text{ES}} / \mathcal{F}$
- SVT alignment ...

always include **multiplicative** errors

Cross-Checks

- Parameterized and Simulated Monte Carlo fits:

- reproduce $\mathcal{L}$ ikelihood value

- reproduce errors ($\pm\sigma$):

$$\sigma_S = 0.37 - 0.48$$

$$\sigma_C = 0.28 - 0.34$$

- reproduce generated $S_{\pi\pi}$ and $C_{\pi\pi}$:

use **measured** central values
(e.g. plot: 1σ , 2σ , 3σ)

vary non-zero $S_{\pi\pi}$ and $C_{\pi\pi}$
consistent results

- $S_{\pi\pi}/C_{\pi\pi}$ correlation
(-13%) in nominal fit

More Cross-Checks

- Simplified analysis:

- select $\pi\pi$ sample (5D $\mathcal{P}$ -based-selection):

$$N_{\pi\pi} = 87.7$$

$$N_{K\pi} = 5.4$$

$$N_{bkg} = 52.1$$

- 2-parameter fit ($S_{\pi\pi}$ and $C_{\pi\pi}$)
results consistent
less accurate
(should be combined fit with $K\pi$)
- yield of $B^0 \rightarrow \pi\pi$ and $\bar{B}^0 \rightarrow \pi\pi$
no evidence for large $|C_{\pi\pi}|$

- Of course:

- tagging/vertexing/reconstruction
verified in $\sin(2\beta)$, mixing, $\mathcal{B}$ Branching analyses

Interpretation of Results

- Constrain α with $C_{\pi\pi}$ and $S_{\pi\pi}$ (α_{eff})

$$S_{\pi\pi} = \frac{2\text{Im}(\lambda_{\pi\pi})}{1+|\lambda_{\pi\pi}|^2}$$

$$S^2 + C^2 \leq 1$$

Gronau, Rosner

Phys.Rev.D 65, 093012 (2002)

$$C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}$$

$$\lambda_{\pi\pi} = e^{2i\alpha} \left(\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}} \right)$$

- External info:

$$|P/T| \sim 0.28$$

$$\beta = 26^\circ$$

$$-\pi < \delta < \pi$$

$$\alpha = (97^{+30}_{-21})^\circ$$

Summary

- First measurement of $\sin(2\alpha_{\text{eff}})$:

30 million $B\bar{B}$: summer 2001

BABAR Phys. Rev. D **65**, 051502 (2002)

$$(S_{\pi\pi} = 0.03_{-0.56}^{+0.53} \pm 0.11, C_{\pi\pi} = -0.25_{-0.47}^{+0.45} \pm 0.14)$$

60 million $B\bar{B}$: this measurement

$$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$$

$$C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$$

90 million $B\bar{B}$: expect this summer

$$\sigma(S_{\pi\pi}) \sim 0.31, \quad \sigma(C_{\pi\pi}) \sim 0.24$$

- Direct constraints on α

- Extensive *BABAR* program:

- Branchings and direct- CP in all $B \rightarrow \pi\pi/K\pi$ and other modes
- $\sin(2\alpha_{\text{eff}})$ in other modes