CP Violation at BaBar: sin2β

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CP Violation until 2000

- First observation of CPV in kaon decays by Cronin, Fitch et al. (1964)
- Kobayashi and Maskawa provide mechanism for CPV (1973)
- Large CP asymmetries in B decays predicted by Bigi and Sanda (1980)
- Indirect $\sin^2 \beta$ measurements from unitarity constraints and direct measurements had poor precision
- Large CLEO sample of 10M $B\bar{B}$
  - CLEO had measured many B BRs, but no CPV measurements

$\sin^2 \beta$ was BaBar’s opportunity to provide an important new measurement with early data
Sensitivity to $\sin 2\beta$
The sin2β Measurement

$\Upsilon(4S)$ produces coherent $B\bar{B}$ pair:
$\Delta t = \Delta z / \beta \gamma c$

$\beta \gamma_{\Upsilon(4S)} = 0.56$

- Many novel techniques were necessary to measure sin2β
  - $K_L$ reconstruction, $\Delta t$ measurement, flavor tagging, multi-parameter likelihood fits, blind analysis method
The Golden sin2β Modes

- **Theoretically clean** in the Standard Model
  - $S_{J/ψK} \sim \sin 2β \sim O(10^{-3})$
  
  [Boos, Reuter, Mannel, PRD 70, 036006 (2004)]
  [Ciuchini, Pierini, Silvestrini, PRL 95, 221804 (2005)]
  [Li, Mishima, JHEP 0703, 009 (2007)]

- **Relatively large branching ratios** and **clean experimental signature**
  - Small background levels
  - Now ~25 reconstructed and flavor-tagged $B \to (c\bar{c})K$ CP decays per $10^6$ $BB$ events

\[ \eta_{CP} \text{ even} \]
\[ \eta_{CP} \text{ odd} \]
Δt Measurement and Resolution Function

- New proper time measurement technique
  - B production point (in z) is unknown at BaBar
  - We don’t measure t, but Δt (which is distributed as a “two-sided exponential”)
  - Need to disentangle resolution function from Δt distribution

- Δt resolution much more important for B lifetime measurement than for sin2β
  - Δt measurement dominated by z resolution of B_{tag} decay vertex (σ_{Δt} ~ 1.1 ps)
  - τ_B ~ 1.5 ps, λ_{B-mixing} = 2π / Δm ~ 12 ps
  - Sin2β only loosely correlated with resolution function

- Demonstrate understanding of resolution function with precision measurement of B lifetimes (2% error)
  - Use much larger sample of fully-reco’ed B decays to flavor final states (B_{flav})
  - Most precise B^+/B^0 lifetime ratio measurement at that time

BaBar, PRL 87, 201803 (2001)

$$\tau_{B^0} = 1.546 \pm 0.032 \pm 0.022 \text{ ps},$$
$$\tau_{B^*} = 1.673 \pm 0.032 \pm 0.023 \text{ ps},$$
$$\tau_{B^*/B^0} = 1.082 \pm 0.026 \pm 0.012$$
B Flavor Tagging from $B\bar{B}$ Mixing

- Flavor of $B_{\text{tag}}$ unambiguously defines flavor of $B_{CP}$ at production
  - Determine flavor of $B_{\text{tag}}$ from its charged decay products ($l, K, \text{high-}p \text{ tracks and soft } \pi$)
  - Started out with conservative cut-based approach and slowly moved toward multivariate estimators
  - Effective tagging efficiency $\sum \varepsilon (1-2w)^2 \sim 30\%$

- Measure mis-tag rates $w$ with $B_{\text{flav}}$ sample
  - Mistag rates cannot be determined from $B_{CP}$ sample, but did not want to rely on MC
  - Mistag rates in $B_{\text{flav}}$ sample same as in $B_{CP}$ sample, with known mixing amplitude ($=1$)

- Demonstrate tagging performance with precision measurement of $B\bar{B}$ mixing frequency (3.7%)
  - Together with BaBar’s $\Delta m$ from di-lepton analysis best measurement of $\Delta m$ at that time

$\Delta m_{B^0} = 0.516 \pm 0.016 \pm 0.010 \text{ ps}^{-1}$

BaBar, PRL 88, 221802 (2001)
The Likelihood Fit

"I remember my friend Johnny von Neumann used to say, with four parameters I can fit an elephant, and with five I can make him wiggle his trunk." Enrico Fermi (1953)

- Extract \( \sin^2 \beta \) with simultaneous unbinned likelihood fit to \( \Delta t \) spectra of \( B_{CP} \) and \( B_{flav} \) samples
  - 35 fit parameters for first paper
    - Determination of common parameters (mistag rates, \( \Delta t \) resolution) dominated by much larger \( B_{flav} \) sample
    - Only \( \sin^2 \beta \) dominated by \( B_{CP} \) sample

- Very small total correlation between \( \sin^2 \beta \) and other parameters (<10%)

Need at least 30 parameters to fit something that resembles an elephant!
Blind Analysis

- Avoid possible experimenter’s bias
  - e.g. towards the standard model prediction

- Sin2β measurement well suited for blind analysis
  - Value and sign of sin2β in fit are hidden
  - Apparent asymmetry in Δt distribution for B⁰ and B⁰-tagged events are hidden
  - Systematic uncertainties are estimated before unblinding

- BaBar established a culture of removing experimenter’s bias whenever possible
  - BaBar’s CP asymmetry, mixing and lifetime analyses have been blinded in a similar way
  - Branching ratio measurements use “hidden signal box”, etc.

The first look at blinded sin2β data (July 10, 2000)

\[
\sin 2\beta (\text{blind}) = 1.22 \pm 0.37
\]
Towards the First Result

- First public $\sin^2 \beta$ result targeted for ICHEP 2000 conference in Osaka (July 27- Aug 2)

- **Elba BaBar meeting** (May 28-31)
  - Defined the Elba flavor tagger
    - Hybrid tagger with 4 categories (lepton, kaon + 2 NN)
  - First measurement of mistag rates with $B_{\text{flav}}$ sample presented on 3.7/fb

- **SLAC BaBar meeting** (July 10-13)
  - Tagging performance measured in data, $\Delta m$ competitive with world’s best measurement
  - First blinded CP fit on 8/fb (statistical error larger than expected, 5% probability)

- **Last 2 weeks**
  - Last 1/fb added on July 15
  - Unblinding of $\sin^2 \beta$ on July 17
  - Final Osaka paper (BAD 44) on July 25

- **$\sin^2 \beta$ result presented at ICHEP on July 31**

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**Time** | **Activity** | **datasample**
---|---|---
Elba | Extract collections of charged $B'$s/ fully exclusive $B_0$ | 2.8 fb-1
Elba to June 13th | Setup hbooks/comis for all charged $B$'s and exclusive $B_0$ | “
“ | Extract CP events (3 modes) | “
“ | Reconcile differences between TagMix analyses | “
“ | Understand data/MC differences in tagging | “
“ | Choose 2 taggers and agree on TagMix strategy | “
“ | Agree upon $D^*\ell\nu$ selection | “
June 13th | Tag $\ell\ell$, Vertexing studies on Charged $B$'s | “
June 13th | Freeze and QA data sample for the 27th | ~6 fb-1
June 13th to 27th | Extract $D^*\ell\nu$ collections | ~6 fb-1
June 27th | New ntuple production | “
June 27th | CP fitting on non CP modes | “
June 27th | Blind $\sin^2 \beta$ fit on data | “
June 27th | Freeze and QA data sample for Osaka | “
June 27th to CollMtg | CP fitting on $\Upsilon\ell\nu$ | “
CollMtg | Detailed $\sin^2 \beta$ systematics | ~8 fb-1
27th June-CollMtg | Finalize TagMix Paper | ~8 fb-1
CollMtg (10-13 Jul) | Finalize $\sin^2 \beta$ Paper | ~8 fb-1
CollMtg (10-13 Jul) | Show complete blind analysis | ~8 fb-1
CollMtg (10-13 Jul) | Freeze analysis | “
CollMtg (10-13 Jul) | [stop db sweeps/outages?] | “
During Coll Mtg | Unblind analysis | “
July 25th | Practice talk for Osaka and go on VACATION! | “
Validations, Validations, Validations, …

- **Monte Carlo Studies**
  - Parametrized MC and full simulation with various $\sin^2\beta$ values

- **Null-tests** for CP asymmetries in $B_{\text{flav}}$ and $B^+$ control samples

- 10 alternative B vertex fit configurations

- 3 independent fitting packages

- Alternative extraction of mistag rates
  - time-integrated method in optimized $\Delta t$ interval (*Single-Bin method*)

- Alternative extraction of $\sin^2\beta$ with Kin
  \[ K \sim -\eta_{CP} \sin(\Delta m \Delta t) \]

- Full measurements of $\tau_B$ and $\Delta m$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Apparent CP-asymmetry</th>
</tr>
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<tbody>
<tr>
<td>Hadronic charged $B$ decays</td>
<td>$0.03 \pm 0.07$</td>
</tr>
<tr>
<td>Hadronic neutral $B$ decays</td>
<td>$-0.01 \pm 0.08$</td>
</tr>
<tr>
<td>$J/\psi K^+$</td>
<td>$0.13 \pm 0.14$</td>
</tr>
<tr>
<td>$J/\psi K^{*0}$ ($K^{*0} \rightarrow K^{+}\pi^-$)</td>
<td>$0.49 \pm 0.26$</td>
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</tbody>
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First Physics Results from BABAR

David Hitlin
Caltech
for the BABAR Collaboration

XXXth International Conference
on High Energy Physics
Osaka
July 31, 2000

October 27, 2008

BaBar, hep-ex/0008048
BaBar’s First Paper

Measurement of CP-Violating Asymmetries in $B^0$ Decays to CP Eigenstates

- BaBar’s $\sin 2\beta$ result published on March 19, 2001 in PRL 86, 2518 (2001)
  - Back-to-back with Belle’s $\sin 2\beta$ paper

- Improvements to analysis since ICHEP
  - Reblinded after ICHEP
  - Doubled the data sample to 23M $B\bar{B}$s
  - Added $B \rightarrow J/\psi K^0_L$ mode
  - Combined likelihood fit to $B_{CP}$ and $B_{flav}$ samples with 35 free parameters

- $\sin 2\beta$ is slowly going up…
  \[ \sin 2\beta = 0.34 \pm 0.20 \pm 0.05 \]
  \[ |\lambda| \text{ consistent with 1} \]
Observation of $CP$ Violation in the $B^0$ Meson System

- Submitted to PRL on July 5, 2001
  - Belle submitted 14 days later, published back-to-back

- Analysis improvements **doubled sensitivity**
  - 40% more data added
  - Improved track and $K^0_S$ reconstruction
  - Added $B \rightarrow J/#psi \, K^0_*$ and $B \rightarrow \chi_{c1} \, K^0_S$ modes
  - Better SVT alignment and vertex reconstruction

- 2nd most cited BaBar physics paper

$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05 \ (4.1\sigma)$$
$$|\lambda| = 0.93 \pm 0.09 \pm 0.03$$

BaBar, PRL 87, 091801 (2001)
Towards a precision measurement

- 3 more BaBar $\sin 2\beta$ PRLs and 2 PRDs
  - “The” $\sin 2\beta$ PRD [PRD 66, 032003('01)]
    - Longest BaBar paper with 54 pages
  - Run 1+2 paper [PRL 89, 201802 ('02)]
    - 3rd most cited BaBar paper
  - Run 1-4 paper [PRL 94, 161803 ('05)]
  - Run 1-5 paper [PRL 99, 171803 ('07)]
  - Final $\sin 2\beta$ result on full data set [arXiv:0808.1903, to be subm. to PRD]

- BaBar’s $\sin 2\beta$ measurement benefited from continuously improving the analysis for each publication
  - Tagging, samples, systematics,….

- After some up’s and down’s BaBar and Belle have converged on $\sin 2\beta$

\[
\sin 2\beta = 0.671 \pm 0.024 \\
C = 0.005 \pm 0.020
\]

$\sin 2\beta$ HFAG
World Average

\[
\sin 2\beta = 0.691 \pm 0.029 \pm 0.014 \\
C = 0.026 \pm 0.020 \pm 0.016
\]
Removing the $90^\circ-\beta$ Ambiguity

- The sign of $\cos^2\beta$ resolves the $90^\circ-\beta$ ambiguity in $\sin^2\beta$

- Interference terms between CP-odd and CP-even amplitudes in B decays to three-body or VV final states are sensitive to $\cos^2\beta$

$B^0 \rightarrow J/\psi K^{*0}$ [BABAR, PRD 71, 032005 (2005)]: $\cos 2\beta > 0 @ 89\%$ C.L.
$B^0 \rightarrow D^{(*)0} K^{0}_{S}\pi^{+}$ [BABAR, PRL 99, 231802 (2007)]: $\cos 2\beta > 0 @ 86\%$ C.L.
$B^0 \rightarrow D^{+} D^{-} K^{0}_{S}$ [BABAR, PRD 74, 091101 (2006)]: $\cos 2\beta > 0 @ 94\%$ C.L.
$B^0 \rightarrow K^{+} K^{-} K^{0}_{S}$ [BABAR, arXiv:0808.0700 (2008)]: $\cos 2\beta > 0 @ 4.8\sigma$

$\cos 2\beta < 0$ solutions excluded: $\beta = (21.1 \pm 0.9)^\circ$
Impact on the Standard Model

- Sin2β is now the most precise constraint on the apex of the Unitarity Triangle
  - Contrary to the sides sin2β is still limited by statistics

- Sin2β serves as a benchmark for other “β” measurements from decays sensitive to New Physics (e.g. hadronic-penguins) and the sides and other angle measurements
Searching for New Physics:
Sin2β in Cabibbo-suppressed Tree Decays

Large discrepancies from S = -sin2β in these modes could indicate evidence for new physics

All CP measurements are consistent with the Standard Model prediction

BaBar, arXiv 0808.1866, submitted to PRD

\[ S_{D^*D^-} = -0.70 \pm 0.16 \pm 0.03 \]
\[ C_{D^*D^-} = +0.05 \pm 0.09 \pm 0.02 \]
\[ S_{D^+D^-} = -0.63 \pm 0.36 \pm 0.05 \]
\[ C_{D^+D^-} = +0.07 \pm 0.23 \pm 0.03 \]

BaBar, PRL 99, 081801 (2007)

\[ S_{D^{(*)0}h^0} = -0.56 \pm 0.23 \pm 0.05 \]
\[ C_{D^{(*)0}h^0} = -0.23 \pm 0.16 \pm 0.04 \]

BaBar, PRL 101, 021801 (2008)

\[ S_{J/ψ\pi^0} = -1.23 \pm 0.21 \pm 0.04 \]
\[ C_{J/ψ\pi^0} = -0.20 \pm 0.19 \pm 0.03 \]
Rare decays mediated by heavy virtual particles can receive contributions from New Physics.

CP violating amplitudes of such decays predicted by the Standard Model could differ from actual observations.
CP Asymmetries in Penguin Decays

- Measured $S_{CP}$ in many penguin-dominated modes and compared to $\sin^2 \beta$ measured in $B^0 \rightarrow (c\bar{c})K$

- Most significant difference in “naïve” penguin average reached in 2004

- More precise measurements have decreased the significance of $\delta S$ below 1σ
  - Some measurements come now from complicated 3-body time-dependent Dalitz analyses
  - $S_{CP}$ in charmless penguin modes is still a good place to look for new physics, but no evidence with BaBar statistics

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

• $\sin^2 \beta$ measurements by the B-factories established CP violation in the B system
  – Confirmed CKM mechanism as dominant source for CP violation in quark mixing

• $\sin^2 \beta$ analysis had a large impact on the whole BaBar physics analysis program
  – Pioneered the time-dependent analysis techniques
    • Flavor tagging, vertex and $\Delta t$ reconstruction
    • Many-parameter likelihood fits, blind analysis techniques

• High standards imposed on $\sin^2 \beta$ measurement laid the foundation for the quality, thoroughness and conservatism that is maintained until today in BaBar’s analysis program and review process