Lessons Learned from Studies of CP Violation in the B-Meson System

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Outline

What is the mechanism of CP violation in Nature?

A status report.

- CP Violation in the SM

  $\Longrightarrow$ There is one CP-violating parameter in the CKM matrix.
- Why do we think there could be CP violation beyond the SM?

  The Case of the Missing Anti-Matter
- How can we test the CKM mechanism of CP violation?

  $\Longrightarrow$ Enter "the" Unitarity Triangle.
- How do we study CP violation in the B system?
- What do we now know about the mechanism of CP violation?
- How well can we test the CKM mechanism of CP violation?

The Cabibbo-Kobayashi-Maskawa (CKM) Matrix

The decay $K^- \to \mu^- \bar{\nu}_\mu$ occurs: the quark mass eigenstates *mix* under the weak interactions. By convention

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\rm weak} = V_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\rm mass} \quad ; \quad V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

In the Wolfenstein parametrization (1983)

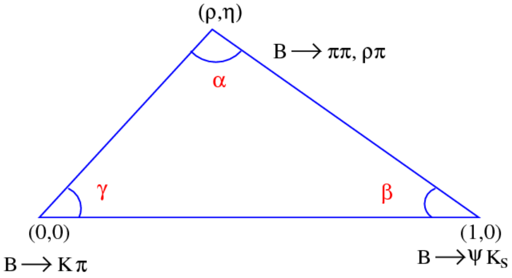
$$V_{\rm CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where $\lambda \equiv |V_{us}| \simeq 0.22$ and is thus "small". A, ρ, η are real.
All CP-violating phenomena are encoded in η.

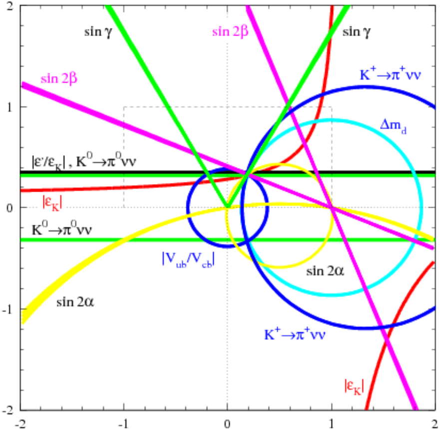
To test the SM picture of CP violation we must test the relationships it entails.

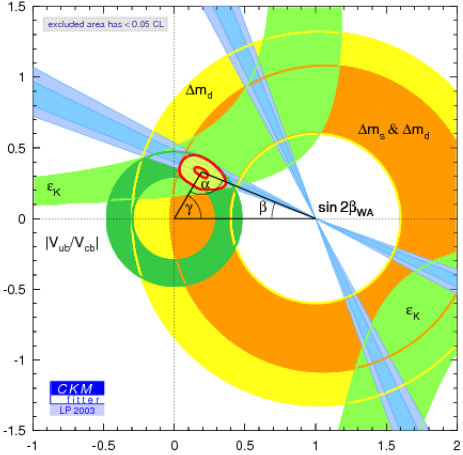
Why B-Meson Decay?

Studies of *b*-quark decay allows us to probe
$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0.$
— a relationship predicated by the unitarity of the CKM matrix.
All terms are $\mathcal{O}(\lambda^3)$. Enter "the" unitarity triangle...



Testing the Standard Model of CP Violation



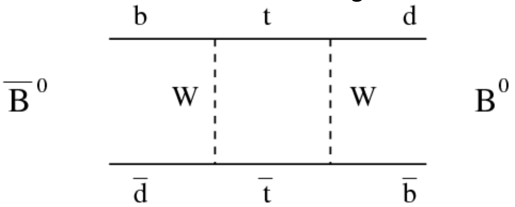


[CKMfitter: Höcker, Lacker, Laplace, Diberder, hep-ph/0104062 ; http://ckmfitter.in2p3.fr – August, 2003 update]

CP-Violation in B-Meson Decay

Different CP-violating phenomena exist (or are believed to exist) in the B meson system

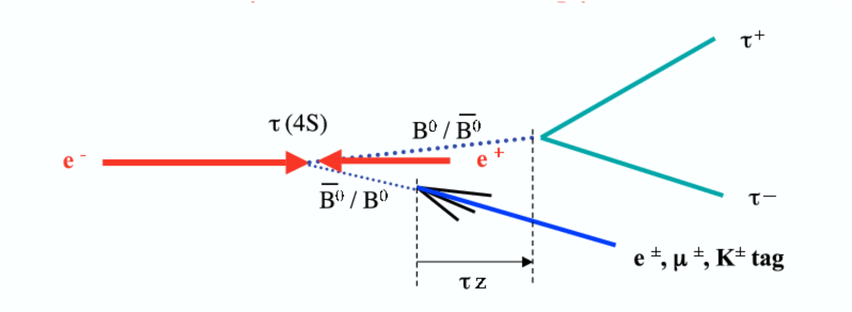
- CP violation in $B - \bar{B}$ mixing



- CP violation in the interference of $B - \bar{B}$ mixing and direct decay
- CP violation in direct decay

Note $|B^0(\tau)\rangle$... a state which is "tagged" as a B^0 meson at proper time $\tau = 0$ has a finite probability of being $\bar{B}$ at proper time τ.

Enter the asymmetric B-factory, to facilitate the study of the time-dependence of CP violation.
There are asymmetric B-factories at SLAC and KEK.



Strong Interaction Obfuscation

Want to learn about underlying CKM parameters, but strong-interaction dynamics can confound this goal. Consider

$$\mathcal{A}_{direct} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}$$

$A: \; M \to h_1 h_2$ and $\bar{A}: \; \bar{M} \to \bar{h}_1 \bar{h}_2$ An interference effect...

$$A = A_1 + A_2 \equiv A_1[1 + re^{i\delta}e^{i\phi}]$$

$$\bar{A} = \bar{A}_1 + \bar{A}_2 \equiv \bar{A}_1[1 + re^{i\delta}e^{-i\phi}]$$

$$\text{so that } \mathcal{A}_{direct} = \frac{-2r\sin\delta\sin\phi}{1 + 2r\cos\delta\cos\phi + r^2}$$

$\mathcal{A}_{direct}$ determines a combination of r, δ, ϕ . Note δ strong phase, ϕ weak phase.

Flavor symmetries (SU(2), SU(3)) can be used to relate r and δ of various decays in an approximate way. Precision studies ultimately demand better?

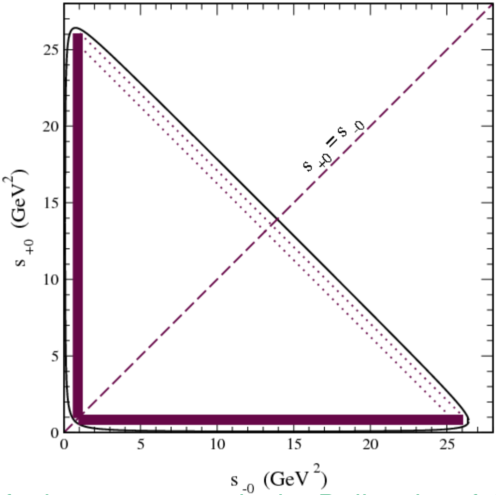
Studying direct CP violation in the B-meson system

Direct CP violation can be studied in a variety of ways:

- Partial rate asymmetry: $|A(B \to h_1 h_2)|^2 - |A(\bar{B} \to \bar{h}_1 \bar{h}_2)|^2 \neq 0$
- "ϵ' in the B system": cf. $B(t) \to \psi K_S$ and $B(t) \to \pi^+\pi^-$ [Wolfenstein, 1984]
  $\Gamma(B^0(t) \to f_{CP}) \propto$
  $$e^{-\Gamma t}\left[\frac{1+|\lambda_{f_{CP}}|^2}{2} + \frac{1-|\lambda_{f_{CP}}|^2}{2}\cos(\Delta m\, t) - \mathrm{Im}\lambda_{f_{CP}}\sin(\Delta m\, t)\right]$$
  where $\lambda_{f_{CP}} \equiv \eta_{f_{CP}}(q/p)(A(\bar{B} \to f_{CP})/A(B \to f_{CP}))$.
  Note $-\lambda_{\psi K_S} \neq \lambda_{\pi^+\pi^-}$ implicitly signals direct CP violation.
- Angular distribution in $B \to V_1 V_2$ [Sinha & Sinha, 1998]
- Population asymmetry in $|A(B \to f_{CP})|^2 + |A(\bar{B} \to f_{CP})|^2$ [SG, 2003; SG & Tandean, 2004]

Direct CP violation in the B-meson system established through the partial-rate asymmetry in the "self-tagged" modes $B(\bar{B}) \to K^{\pm}\pi^{\mp}$.

An Illustration: $B, \bar{B} \to \pi^+\pi^-\pi^0$ Decay



The failure of mirror symmetry in the Dalitz plot of the untagged decay rate signals the presence of direct CP violation.

Time-Dependent Studies to CP-Eigenstates

$\Gamma(B^0(t) \to f_{CP}) \propto$

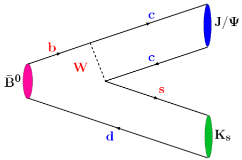
$$e^{-\Gamma t}\left[\frac{1+|\lambda_{f_{CP}}|^2}{2} + \frac{1-|\lambda_{f_{CP}}|^2}{2}\cos(\Delta m\, t) - \mathrm{Im}\lambda_{f_{CP}}\sin(\Delta m\, t)\right]$$

where $\lambda_{f_{CP}} \equiv \eta_{f_{CP}}(q/p)(A(\bar{B} \to \bar{f}_{CP})/A(B \to f_{CP}))$.

If the decay amplitude can be characterized by an unique weak phase, the strong dynamics cancels entirely!

Enter the "golden" mode $B \to \psi K_S$... $\mathrm{Im}\lambda_{\psi K_S}$ measures $\sin(2\beta)$.

Note $\sin(2\beta) = 0.675 \pm 0.026$ (WA) from ψK_S and related modes.



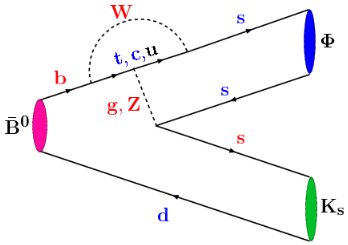
$\sin(2\beta)$ *from Penguin Modes*

The penguin modes $B \to \phi K_S$, $B \to \eta' K_S$, $B \to f_0 K_S$, etc. also measure $\sin(2\beta)$ in the SM. [Grossman, Worah (1996)]

Many possible modes exist.

N.B. the SM corrections to the $\sin(2\beta)$ measurement are not uniformly small.

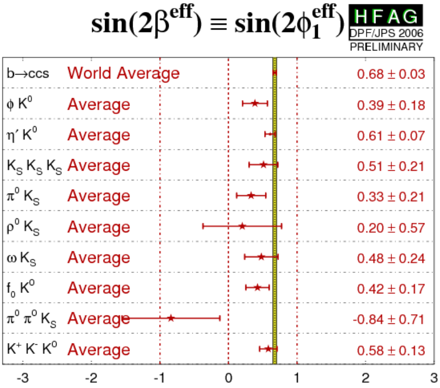
However, $S(\phi K_S) - S(\psi K_S) = 0.02 \pm 0.01$.



$\sin(2\beta)$ *from Penguin Modes*

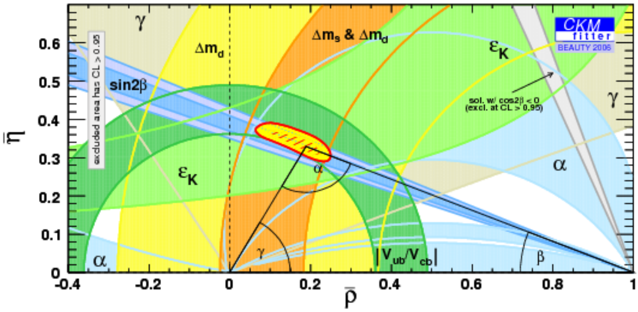
Naive average yields $\sin(2\beta) = 0.52 \pm 0.05$ (HFAG)– a deviation of 2.6σ! (cf. M. Neubert, Moriond-EW Mar 07, 0.50 ± 0.06)

Discounting differences as statistical fluctuations yields a “global” value of $\sin(2\beta) = 0.647 \pm 0.024$



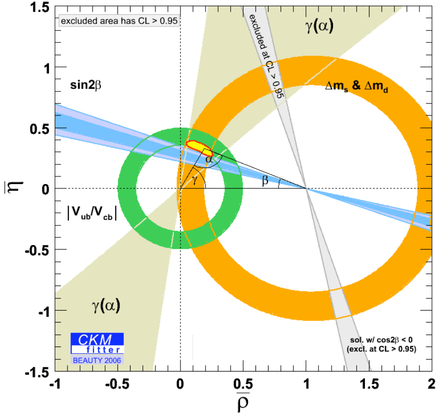
Testing the CKM paradigm, 2006

The possibility of non-SM CP violation is gradually being relegated to a smaller and smaller role.
Nevertheless, intriguing discrepanies remain, of which sin(2β) from tree and penguin modes is one.



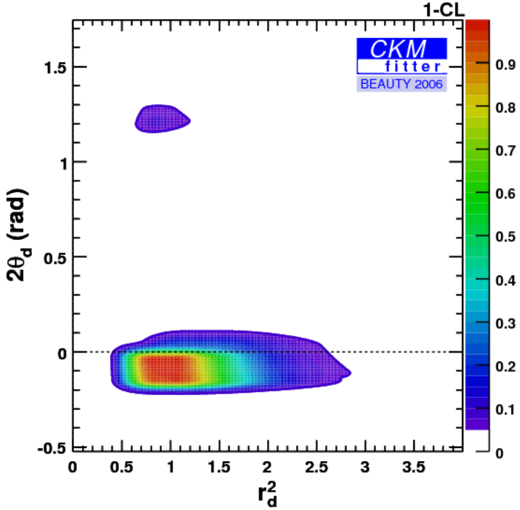
Testing the CKM paradigm, 2006

Can also compare combined average $\sin(2\beta) = 0.647 \pm 0.024$ with the value deduced from $|V_{ub}|$ and $|V_{td}|$ alone, to yield $\sin(2\beta) = 0.794 \pm 0.045$, for a deviation of 2.9σ. [M. Neubert, Moriond EW Mar 07]
Can be used to set limits on new physics in $B_d - \bar{B}_d$ mixing.



New Physics in $B_d - \bar{B}_d$ Mixing

$$\Delta m_d = \Delta m_d^{\rm SM} r_d^2 e^{i2\theta_d}$$



Can CP-Violating Observables in the B-Meson System Yield CKM parameters at the $\mathcal{O}(1\%)$ Level?

This is less daunting than it may seem.

Consider, e.g., $A_{\rm CP}(t)$ in $B(\overline{B}) \to J/\psi K_S$. The $b \to su\overline{u}$ "pollution" is suppressed by $\mathcal{O}(\lambda^2)$ and by loop effects.

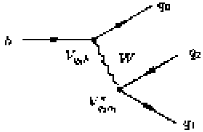
This yields $\sin(2\beta)$
up to an (estimated) correction of $-(2 \pm 2) \cdot 10^{-4}$, [Boos, Mannel, Reuter, 2004]
which can be tested with $B_s \to J/\psi K_S$ data. [Fleischer, 1999]

Flavor symmetries can also be used to probe CKM angles.

Here we consider the use of isospin symmetry to determine α from $B \to \pi\pi\,(n\pi)$ decay. Our goal is to assess all isospin-breaking effects.

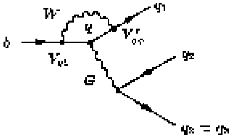
- $\Delta I = 3/2$

Tree Diagrams:



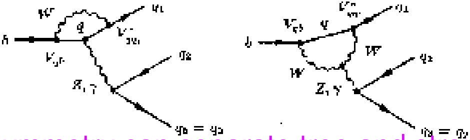
- $\Delta I = 1/2$

QCD Penguin Diagrams:



- $\Delta I = 1/2, 3/2$

EW Penguin Diagrams:



An assumption of isospin symmetry can separate tree and strong penguin contributions in $B \to \pi\pi,\ \rho\pi,\ \rho\rho$.

Isospin Analysis for α

The CKM angle α (or γ) can be determined under an assumption of isospin symmetry from the analysis of $B \to \pi\pi$ [Gronau, London, 1990], $B \to \rho\pi$ [Snyder, Quinn, 1993], and $B \to \rho\rho$ modes.

Here we focus on $B \to \pi\pi$.
$A_{\rm CP}(t)$ in $B(\overline{B}) \to \pi^-\pi^+$ decay yields $\sin(2\alpha_{\rm eff})$.

In the Standard Model $\alpha = \pi - \beta - \gamma$; $\gamma \leftrightarrow$ tree-level decay.
Penguins make $\Delta\alpha = \alpha_{\rm eff} - \alpha \neq 0$.
Under isospin, two pions have $I = 0, 2$ only; $B \to \pi\pi$ amplitude A_I.

$$A_{B^0\to\pi^+\pi^-} \equiv A_0 + \frac{1}{\sqrt{2}}A_2 \,, \quad A_{B^0\to\pi^0\pi^0} \equiv A_0 - \sqrt{2}A_2 \,, \quad A_{B^+\to\pi^+\pi^0} \equiv \frac{3}{2}A_2 \,,$$

QCD penguins yield $I = 0$ only $\Longrightarrow$ must separate out A_0/A_2 (& $\overline{A}_0/\overline{A}_2$).
Can do so with $\mathcal{B}(B(\overline{B}) \to \pi^i\pi^j)$ data.

$\pi^0 - \eta, \eta'$ *Mixing: Summary*

[SG, 2005]

$$\Delta\alpha = \frac{1}{2}(\bar{\phi}' - \phi') + \frac{1}{2}(\bar{\zeta} - \zeta) + \frac{1}{2}\left[(\bar{\phi} - \phi) - (\bar{\phi}' - \phi')\right] ,$$

Last term vanishes if ξ and $\bar{\xi}$ are real.

Up to $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$:

$$\delta(\Delta\alpha) = 1.2^\circ\,[\xi] + 1.5^\circ\,[P_{ew}] + 1.1^\circ\,[P_{\pi^0-\eta,\eta'}] + \cdots \approx 4^\circ ,$$

$$\sigma_\alpha^{\rm IB} = 0.4^\circ\,[\xi] + 0.3^\circ\,[P_{ew}] + 0.2^\circ\,[P_{\pi^0-\eta,\eta'}] + 1.1^\circ\,[\text{bound}] + \cdots \approx 2^\circ ,$$

There is no central limit theorem for theoretical error.

What has been omitted?!

$\Longrightarrow$ Long-distance electromagnetic effects.

$\pi^0 - \eta, \eta'$ *Mixing: Summary*

[SG, 2005]

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$\pi^0 - \eta, \eta'$ ***Mixing: Summary***

[SG, 2005]

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Last term vanishes if ξ and $\bar{\xi}$ are real.

Up to $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$:

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There is no central limit theorem for theoretical error.

What has been omitted?!

$\Longrightarrow$ Long-distance electromagnetic effects.

Isospin Breaking in $B \to \pi\pi$: Tests and Cross Checks

Detailed numbers can change as data is updated. Have used CP-averaged branching ratios throughout.

- How does the analysis rely on QCD factorization framework?
  Relies on factorization formula; also follows from SCET in leading power. Scalar penguins do not appear.
  $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ effects likely incur 10-20% corrections.
  Important to the extent that $X_{\eta^{(\prime)}}$, $\overline{X}_{\eta^{(\prime)}}$ are not real.
  $\Longrightarrow$ Signalled if $X_{\eta^{(\prime)}} \neq \overline{X}_{\eta^{(\prime)}}$.
- Does the use of the Feldmann-Kroll-Stech framework for η, η' matter?
  Have also employed two-angle formalism of Leutwyler. No difference incurred at current empirical precision. [Frère, Escribano, 2005]
- How can electromagnetic corrections be included?
  Recall $K \to \pi\pi$. Treat in simultaneous chiral and electromagnetic expansion.

Isospin Breaking in $B \to \rho\pi$, $B \to \rho\rho$

Isospin breaking effects will differ for different $n\pi$ modes.
Here other corrections can also appear; can mimic the violation of isospin.

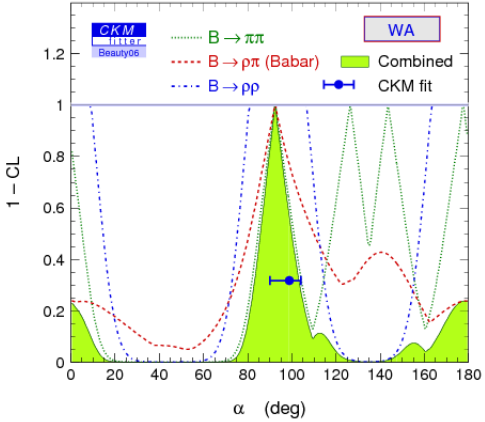
- $B \to \rho\pi$
  - Other resonances can populate $B \to 3\pi$ Dalitz plot.
    Non-ρ states yield small impact in neutral B modes.
    [SG, Meißner, 2002; Tandean and SG, 2002]
    Inclusion of ρ', ρ''? Analyzed assuming fixed P/T ratio.
  - Failure of 2-body unitarity in corners of Dalitz plot?
    Could impact empirical determination of strong phases.
  - $\rho^0 - \omega$ mixing
    $\rho^0 - \omega$ mixing can be removed via cuts in $M_{\pi\pi}$.
  - $\pi^0 - \eta, \eta'$ mixing
    α can be fixed through $B^0, \overline{B}^0$ data only. $\delta A_{5/2,2}$ always appears with $A_{3/2,2}$; no error accrues if $\delta A_{5/2,2}$ spawned from $\Delta I = 3/2$ operators in isospin-perfect limit. [Gardner, Meißner, 2002]

Isospin Breaking in $B \to \rho\pi$, $B \to \rho\rho$

$B \to \rho\rho$ decays analyzed in the manner of $B \to \pi\pi$.

- $B \to \rho\rho$
  - Other resonances can populate $B \to 4\pi$ Dalitz plot.
  - $\rho^0 - \omega$ mixing
    $\rho^0 - \omega$ mixing can be removed via cuts in $M_{\pi\pi}$.
  - $I = 1$ amplitude
    Emerges even if isospin is unbroken. Follows from finite ρ width.
    [Falk, Ligeti, Nir, Quinn, 2003]
    Current empirical assays assume it negligible.

Current Constraints on α



Decays are analyzed under an assumption of isospin symmetry to determine α.

Production Asymmetry in $e^+e^- \to B^+B^-, B^0\overline{B}^0$

Isospin Symmetry: $e^+e^- \to \Upsilon(4S)$ yields B^+B^- and $B^0\overline{B}^0$ pairs equally.

This can be tested. [Babar, hep-ex/0107025]

$$\frac{\mathcal{B}(B^+ \to (c\bar{c})K)}{\mathcal{B}(B^0 \to (c\bar{c})K)} = 1.17 \pm 0.07 \pm 0.04$$

Assuming isospin and using $\tau_{B^+}/\tau_{B^0} = 1.062 \pm 0.029$ yields

$$R^{+/0} \equiv \frac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.10 \pm 0.06 \pm 0.05$$

"compatible with unity at two standard deviations"

Theory yields $R^{+/0} - 1 \gtrsim 0.1$. [Kaiser, Manohar, Mehen, 2002]

Yield of $B^+B^-/B^0\overline{B}^0$ should also vary across $\Upsilon(4S)$. [Voloshin, 2003]

Production asymmetry is unlikely to be unity.

Summary and Outlook

The CKM mechanism of CP violation drives the pattern of results found in the B-meson system.
Non-SM sources of CP violation are not excluded, but merely relegated to a more minor role. Precision studies may yet reveal new physics!

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