CP violation in the quark sector: What have we learned?

Patricia Burchat, Stanford University
World Summit on Physics Beyond the Standard Model
Galapagos Islands, June 22-25, 2006
Notes for Printed Version of Presentation

• I delivered this presentation on June 22, 2006, at the World Summit on Physics Beyond the Standard Model in San Cristobal Island, Galapagos.

• I deliberately do not put much distracting text on my presentation slides. Therefore, the logic of the presentation may not be clear from this printed version.

• This talk is not intended to be a review of heavy-flavor physics or CP violation.

• For summarizing our current knowledge of results, I have relied heavily on the invaluable compilations by the Heavy Flavor Averaging Group, the CKMfitter Group, and the UTfit Group.

• For most decays, I include the minimum number of Standard-Model or New-Physics Feynman diagrams needed to make a pedagogical point, rather than all possible diagrams.

• This talk was prepared with Keynote and LaTeX Equation Editor (Mac OS X).
Galapagos World Summit on “Physics Beyond the Standard Model”

The success of the Galapagos World Summit on Physics Beyond the Standard Model will be judged by the QUALITY OF ORIGINAL IDEAS coming from this meeting.

www.usfq.edu.ec/phy/summit.pdf

2nd World Summit

2nd World Summit Physics Beyond the Standard Model Galapagos Islands, Ecuador June 22-25, 2006 ... 1st World Summit: “Evolution”. Contact: monam@usfq.edu.ec.

www.usfq.edu.ec/phy/ - 20k - Cached - Similar pages

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ANNOUNCING THE 2ND WORLD SUMMIT GALAPAGOS ISLANDS, ECUADOR Physics Beyond the Standard Model June 22-25, 2006 Universidad San Francisco de Quito ...


Science & Technology at Scientific American.com: The Woodstock of ...

The World Summit on Evolution, held in the Galapagos Islands, revealed a science rich in history and tradition, data and theory, as well as controversy and ...

www.sciam.com/article.cfm?articleID=00020722-64FD-12BC-A0E483414B7FFE87 - 58k - Jun 16, 2006 - Cached - Similar pages

CERN Document Server: CERN & HEP Events

Miscellaneous, 22 - 25 Jun 2006, 2nd World Summit: Physics Beyond the Standard Model Physics Beyond the Standard Model, Galapagos, Islands, Ecuador ...

cdsweb.cern.ch/events/events.py/?date=future&categ=All&order=date&jrec=26 - 24k - Jun 17, 2006 - Cached - Similar pages

Upcoming HEP Conferences


www.hep.net/conferences/conf.html - 20k - Cached - Similar pages
Last year’s World Summit on Evolution was a natural for the Galapagos. How can we compete??

- Evidence for CP Violation: difference in the time evolution of matter and anti-matter.
- Evidence for Neutrino Mass: evolution of neutrino flavor in space and time.
- Evidence for Dark Energy: unexpected evolution of the expansion rate of the universe.
Some people believe that skepticism is the rejection of new ideas, or worse, they confuse “skeptic” with “cynic” and think that skeptics are a bunch of grumpy curmudgeons unwilling to accept any claim that challenges the status quo. This is wrong. **Skepticism is a provisional approach to claims. It is the application of reason to any and all ideas — no sacred cows allowed.** In other words, skepticism is a method, not a position. Ideally, skeptics do not go into an investigation closed to the possibility that a phenomenon might be real or that a claim might be true. When we say we are “skeptical,” we mean that we must see compelling evidence before we believe.
Ideas to treat with healthy skepticism...

• Supersymmetry: solution to the large quantum corrections to the Higgs mass.

• $R$-parity conservation in SUSY: prevents proton decay -- and provides attractive Dark Matter candidate.

• Cosmological Constant: solution to Dark Energy mystery?

Motivation for best possible experimental investigation...
B Factories

\[
\begin{align*}
    b\bar{d} &= B^0 \\
    b\bar{u} &= B^- \\
    b\bar{s} &= B_s \\
    b\bar{c} &= B_c \\
    b\bar{ud} &= \Lambda_b \\
    \ldots
\end{align*}
\]

Hadron machines (Tevatron, LHC)
≈ 1,000,000,000 $B\bar{B}$ pairs served...

... plus ≈ 1,000,000,000 $c\bar{c}$ pairs and ≈ 1,000,000,000 $\tau^+\tau^-$ pairs
Outline

• Radiative decays
• Direct $CP$ violation
• The angles $\alpha$, $\beta$, $\gamma$
• $CP$ violation in $b \rightarrow s\bar{s}s$ decays with loops
• $B_{(s)} \rightarrow \mu^+\mu^-$
• Two recent results:
  1. Observation of $B_s$ mixing
  2. Observation of $B \rightarrow \tau\nu$
• Putting it all together.
B(µ → eee) could be of order $10^{-13}$ with “New Physics” (e.g., MSSM).

Experimental Results: $B(µ → eγ) < 1.2×10^{-11}$, $B(µ → eee) < 1.0×10^{-12}$
Experimental Results (BABAR and Belle):

\[ \mathcal{B}(\tau \to \mu\gamma) < 0.7 \times 10^{-7} \]

\[ \mathcal{B}(\tau \to e\gamma) < 1.1 \times 10^{-7} \]

\[ \mathcal{B}(\tau \to eee, \mu\mu\mu, e\mu\mu, \mu ee) < (1 - 3) \times 10^{-7} \]
Keeping track of it all...

- Review of Particle Physics
- Heavy Flavor Averaging Group
- CKMfitter Group (primarily frequentist)
- UTfit Group (primarily Bayesian)
$\mathcal{B}(B \to X_{s d} \gamma)$

$\mathcal{B}(B \to X_s \ell^+ \ell^-)$

Branching Ratio x $10^6$

Branching Ratio x $10^6$
**Top Panel:**

$b \rightarrow s\gamma$

- **BaBar '05**
- **Cleo '01**
- **Belle '04**
- **Neubert '04**
- **Buras et al. '02**

**Bottom Panel:**

1. \( B \rightarrow K^*\ell^+\ell^- \)
2. \( B \rightarrow K\ell^+\ell^- \)

**Graph Details:**

- The top graph shows the branching fraction for \( b \rightarrow s\gamma \), with data points from various experiments (BaBar '05, Cleo '01, Belle '04, Neubert '04, Buras et al. '02).
- The bottom graph displays branching fractions for two different decay modes: \( B \rightarrow K^*\ell^+\ell^- \) and \( B \rightarrow K\ell^+\ell^- \), with data points from Ali '02 and Zhong '02.

**Notation:**

- \( B \rightarrow K^*\ell^+\ell^- \): Branching fraction data for this decay mode.
- \( B \rightarrow K\ell^+\ell^- \): Branching fraction data for this decay mode.
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\[ \overline{B}^0 \rightarrow \pi^+ K^- \]

Is \( P(\overline{B}^0 \rightarrow \pi^+ K^-) = P(B^0 \rightarrow \pi^- K^+) \)?

\[ V_{ub} \]
\[ V_{us}^* \]
\[ W \]
\[ V_{tb} \]
\[ V_{ts}^* \]
\[ B^0 \rightarrow \pi^+ K^- \]

Two diagrams with different weak phases ...

\[ B^0 \]
\[ b \]
\[ V_{ub} \]
\[ W \]
\[ V_{us}^* \]
\[ u \]
\[ s \]
\[ K^- \]

\[ B^0 \]
\[ V_{tb} \]
\[ V_{ts}^* \]
\[ b \]
\[ t \]
\[ s \]
\[ K^- \]
\[ \pi^+ \]
\[ \overline{B}^0 \rightarrow \pi^+ K^- \]

and different (uncalculable) strong phases.
Direct CP Violation

\[ \Gamma(B^0 \rightarrow \pi^+ K^-) - \Gamma(B^0 \rightarrow \pi^- K^+) \]
\[ \frac{\Gamma(B^0 \rightarrow \pi^+ K^-) - \Gamma(B^0 \rightarrow \pi^- K^+)}{\Gamma(B^0 \rightarrow \pi^+ K^-) + \Gamma(B^0 \rightarrow \pi^- K^+)} \]
\[ = -0.108 \pm 0.017 \]
CP Asymmetries Measured in Rare B Decays

\[
\frac{\Gamma(B) - \Gamma(\bar{B})}{\Gamma(B) + \Gamma(\bar{B})}
\]
CP Asymmetries Measured in Rare B Decays

\[ \frac{\Gamma(B) - \Gamma(\bar{B})}{\Gamma(B) + \Gamma(\bar{B})} \]

Chart showing CP asymmetries measured in rare B decays with data points from different experiments, including CLEO, Belle, BABAR, CDF, and PDG2004, with new average indicated.
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The Quark Mixing Matrix and the Unitarity Triangle

apply unitarity constraint to these two columns
CP Violation observed in interference between decays with and without mixing.

World Average:

$$\sin 2\beta = 0.69 \pm 0.03$$
History of Statistical Uncertainty on $\sin^2\beta$ in BABAR

Expected reduction in statistical error due to increase in data sample size:

$$\frac{1}{\sqrt{N(B\bar{B})}}$$
History of Statistical Uncertainty on \(\sin 2\beta\) in BABAR
The angle $\alpha$:

$B \to \pi\pi$: large penguin contributions; many ambiguities.

$B \to \rho\pi$: use interference in Dalitz plot.

$B \to \rho\rho$: small penguin contributions; longitudinal polarization dominates.

$\alpha = (97^{+5}_{-16})^\circ$

$\alpha = (100^{+15}_{-9})^\circ$
The angle $\gamma$ from $B^+ \to D^*(*)K^*(*)+$:
Depends on $r_B \equiv \left| \frac{A(B^+\to D^0(*)K^+)}{A(B^+\to \overline{D}^0(*)K^+)} \right|$.

GLW: $B \to D_{CP}K$
ADS: $B \to D_{K^\pm\pi^\pm}K$

GGSZ: $B \to D_{K^0_s\pi^+\pi^-}K$;
Dalitz analysis $\Rightarrow$ measure $\gamma$ and $r_B$. 
CKM Fit: Angles Only

$\sin 2\beta$

$\eta$

$\rho$

sol. w/ $\cos 2\beta < 0$
(excl. at CL > 0.95)

Note: The diagram illustrates the constraints on the CKM angles $\alpha$, $\beta$, and $\gamma$ in the context of a fit with CL > 0.95. The plot shows excluded areas based on the fit results.
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Modes that are sensitive to new physics through loops:

\[ \overline{B}^0 \rightarrow \eta'K_s \]

\[ \overline{B}^0 \rightarrow \eta'K^0 \]

Belle

Entries / 1.5 ps

-0.5
0
0.5
-7.5 -5 -2.5 0 2.5 5 7.5

Asymmetry

\[ B^0 \rightarrow \eta'K^0 \]

\[ B^0 \rightarrow \eta'K_0 \]

\[ \phi, \eta', \ldots \]

\[ K^0_{S,L} \]
Difference between asymmetry from tree and loop diagrams: 2.5 $\sigma$(stat). But each “loop” mode has (different) additional sub-dominant diagrams, which brings in theoretical uncertainties...

Average (loop diagrams) $0.50 \pm 0.06$
Theoretical Predictions -- QCD Factorization

\[ \sin 2\beta_{\text{eff}} - \sin 2\beta \]

\( \phi K_S \)
\( \eta' K_S \)
\( \pi^0 K_S \)
\( \omega K_S \)
\( \text{KK} K_S \)
\( 3K_S \)
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Standard Model prediction: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$
Upper Limits on Branching Fractions in Units of $10^{-7}$

$B^0 \rightarrow \mu^+ \mu^-$

\[ \begin{array}{ccc}
5 & & \\
4 & & \\
3 & & \\
2 & & \\
1 & & \\
0 & & \\
\end{array} \]

BABAR | Belle | CDF

$B_s \rightarrow \mu^+ \mu^-$

\[ \begin{array}{ccc}
5 & & \\
4 & & \\
3 & & \\
2 & & \\
1 & & \\
0 & & \\
\end{array} \]

D0 | CDF

LHCb: $\approx 30 \ B_s \rightarrow \mu^+ \mu^-$ events per year for expected SM branching fraction of $\approx 4 \times 10^{-9}$. 
Outline

- Radiative decays
- Direct \( CP \) violation
- The angles \( \alpha, \beta, \gamma \)
- \( CP \) violation in \( b \to s\bar{s}s \) decays with loops
- \( B_{(s)} \to \mu^+\mu^- \)
- Two recent results:
  1. Observation of \( B_s \) mixing
  2. Observation of \( B \to \tau\nu \)
- Putting it all together.
CDF: $\Delta m_s = (17.33^{+0.42}_{-0.21} \pm 0.07) \text{ ps}^{-1}$

$\Delta m_s$ measured to $\approx 2\%$ precision ($\Delta m_s/\Gamma \approx 25$).

_c.f._, $\Delta m_d$ measured to $1\%$ precision ($\Delta m_d/\Gamma \approx 0.8$).
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- Putting it all together.
$B^- \rightarrow \tau^- \bar{\nu}_\tau$ now observed

World average: $\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (10.4^{+3.0}_{-2.7}) \times 10^{-5}$

CKM fit + LQCD: $\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (9.6 \pm 1.5) \times 10^{-5}$
Theoretical Input

- Uncertainties on all non-angle CKM measurements now dominated by theoretical uncertainties from non-perturbative parameters (e.g., decay constants and bag parameters).

Lattice QCD

- “Staggered fermion” technique plus “4th-root of determinant” technique looks promising for reducing light quark masses to their physical values.

- Two new related methods, “domain wall fermions” and “overlap fermions”, promising but in infancy.
$B^- \to \tau^- \bar{\nu}_\tau$ and $\Delta m_d$ both depend on $f_B$. Therefore, constraints are correlated.
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- $B(s) \rightarrow \mu^+\mu^-$
- Two recent results:
  1. Observation of $B_s$ mixing
  2. Observation of $B \rightarrow \tau\nu$
- Putting it all together.
Tree-dominated

versus

Loop-dominated
CP-Violating
versus
CP-Conserving
“Theory-free” (only angles) vs. QCD-based (no angles)
The Future

1. B Factories:
   - 1 billion $B\bar{B}$ pairs recorded now (not all analyzed yet).
   - 4 billion $B\bar{B}$ pairs expected by end of 2008.
   - $\geq$ factor of 2 improvement in statistical uncertainties + new analyses.
   - Belle recorded $\approx 2 \text{ fb}^{-1}$ in a three-day engineering run at the $\Upsilon(5S)$ and may return to this energy in the future.
   - [Sample result: $\mathcal{B}(B_s \rightarrow \gamma\gamma) < 0.56 \times 10^{-4}.$]

2. Hadron machines: Tevatron, LHCb, ATLAS, CMS
   - $B_s$ mixing ($\Delta m_s$, $\Delta \Gamma_s$, $\beta_s$),
   - radiative decays and leptonic decays of $B$ and $B_s$,
   - CKM angle $\gamma$ from $B$ and $B_s$ decays, ...
Now

Expected in 2010
CP violation in the quark sector: What have we learned?
Bayesian Reality, by the UTfit group

Frequentist Reality by the CKMfitter Group

Polar Coordinates VIII
by Frank Stella

Sinjerli Variation
by Frank Stella

Frequentist Reality by the CKMfitter Group
What have we really learned?

• The B Factories and hadron machines are providing enormous data samples that allow us to explore the heavy-flavor sector with unprecedented precision.

• Many new analysis techniques have been developed to allow us to probe more and more decays that are potentially sensitive to new physics.

• If NEW PHYSICS is out there, then it must have a very special flavor and CP structure to evade all the existing searches.

• Continue to confront new theoretical ideas and hints of discrepancies in experimental results with healthy skepticism.