CP Violation for the Heaven and the Earth — Sighting the 4th Generation?

George W.S. Hou (侯維恕)
National Taiwan University
February 2, 2009, Seminar @ Virginia
Can *all this* be understood from my vantage?

**Story of a star-gazing ant**
I. Intro: the Heavenly Attraction

II. $\Delta A_{K\pi}$ Problem — Z Penguin and t' Loop

III. $\Delta m_{B_s}$ Measurement $\Rightarrow$ Prediction for $\sin2\Phi_{B_s}$

IV. Soaring to the Heavens: Enough CPV for BAU?

V. Direct Sighting @ Tevatron vs LHC

VI. Conclusion: Know in 3-5 Years
I. Intro: the Heavenly Attraction
In the beginning God created the heaven and the earth. 

— Genesis 1:1 (KJV)
CPV & BAU (& U): The Sakharov View

- Baryon Number Violation
- CP Violation
- Deviation from Equilibrium

(1967)

Equal Matter - Antimatter  
Pair Annihilation

Bang

Matter left!  
$10^{-9}$  
13Byr

Us
EVIDENCE FOR THE $2\pi$ DECAY OF THE $K_2^0$ MESON*†

Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the $2\pi$ decay of the $K_2^0$ meson. Several previous experiments have served to set an upper limit of 1/300 for the fraction of $K_2^0$'s which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, $K_2^0$ mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a 1.5-in. × 1.5-in. × 48-in. collimator at an average distance of 14.5 ft. from

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, $m^*$, assuming each charged particle had the mass of the charged pion. In this detector the $K_{e3}$ decay leads to a distribution in $m^*$ ranging from 280 MeV to ~536 MeV; the $K_{\mu3}$, from 280 to ~518; and the $K_{e3}$, from 280 to 363 MeV. We emphasize that $m^*$ equal to the $K^0$ mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, $\theta$, between it and the direction of the $K_2^0$ beam were determined. This

$$2\times1 \begin{array}{cc} -3 & T \\ S \end{array} : f S$$
**CP-Violation in the Renormalizable Theory of Weak Interaction**

Makoto KOBAYASHI and Toshihide MASKAWA

*Department of Physics, Kyoto University, Kyoto*

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

... field corresponding to $U(1)$ which is irrelevant to our discussion. With an appropriate phase convention of the quartet field we can take $U$ as

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. \quad (6)$$

Therefore, if $\mathcal{L}' = 0$, no CP-violations occur in this case. It should be noted, however, that this argument does not hold when we introduce one more fermi doublet with the same charge assignment. This is because all phases of elements of a $3 \times 3$ unitary matrix cannot be absorbed into the phase convention of some fields. This possibility of CP-violation will be discussed later on.
components, respectively. Just as the case of \((A, C)\), we have a similar expression for the charged weak current with a 3\(\times\)3 instead of 2\(\times\)2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

\[
\begin{pmatrix}
\cos \theta_1 & -\sin \theta_1 \cos \theta_3 & -\sin \theta_1 \sin \theta_3 \\
\sin \theta_1 \cos \theta_3 & \cos \theta_1 \cos \theta_3 \cos \theta_2 - \sin \theta_1 \sin \theta_3 e^{i\beta} & \cos \theta_1 \cos \theta_3 \sin \theta_2 + \sin \theta_1 \cos \theta_2 e^{i\beta} \\
\sin \theta_1 \sin \theta_3 & \cos \theta_1 \sin \theta_3 \cos \theta_2 + \cos \theta_2 \sin \theta_3 e^{i\beta} & \cos \theta_1 \sin \theta_3 \sin \theta_2 - \cos \theta_2 \sin \theta_1 e^{i\beta}
\end{pmatrix}
\]

(13)

Then, we have \(CP\)-violating effects through the interference among these different current components. An interesting feature of this model is that the \(CP\)-violating effects of lowest order appear only in \(\Delta S \neq 0\) non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, \(\Delta S = 0\) non-leptonic and pure-leptonic processes.
Complex Dynamics: KM Sector of SM

only charged current interactions change flavor

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\approx \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho + i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

3x3 “Rotation”

Unitary

Need presence of all 3 generations to exhibit CPV in Standard Model
KM CPV Confirmed ~ 2001

The MOMA plot

Nontrivial

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]
"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Yoichiro Nambu  
1/2 of the prize  
USA

Enrico Fermi Institute,  
University of Chicago
Chicago, IL, USA

b. 1921  
(in Tokyo, Japan)

Makoto Kobayashi  
1/4 of the prize  
Japan

High Energy Accelerator Research Organization (KEK)  
Tsukuba, Japan

b. 1944

Toshihide Maskawa  
1/4 of the prize  
Japan

Kyoto Sangyo University;  
Yukawa Institute for Theoretical Physics (YITP),  
Kyoto University  
Kyoto, Japan

b. 1940
$V_{\nu 2}$

\[
\begin{pmatrix}
1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 & \lambda \\
-\lambda + A^2 \lambda^5 \left( \frac{1}{2} - \rho - i \bar{\eta} \right) & 1 - \frac{1}{2} \lambda^2 - \left( \frac{1}{8} + \frac{1}{2} A^2 \right) \lambda^4 \\
\end{pmatrix}
\]

**Unique CPV Phase:** Common Area of Triangle

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

$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$

N.B. geometric picture
CPV so far only observed in KM ...

- Nontrivial CPV Phase: $A$

Nontrivial \[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

- All like-charge quark pairs nondegenerate,

Otherwise $\to$ Back to 2-gen. and CPV vanish

\[ J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) A \]

Jarlskog Invariant (1985) for CPV

\[ \text{Im det} \left[ m_u m_u^*, \quad m_d m_d^* \right] \]
b → d transitions consistent with SM

b → s: the Current Frontier

Nontrivial

V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
A Real Hint, ... or Not !?
\[\Delta A_{K\pi} = A_{K^+\pi^0} - A_{K^+\pi^-} = +0.164 \pm 0.037 \quad 4.4\sigma\]

\[+0.07 \pm 0.03 \quad \text{vs} \quad -0.094 \pm 0.020\]

**b \rightarrow s CPV**

**Difference is Large!**

And Established

Belle + BaBar (+ CDF)
Difference in direct charge-parity violation between charged and neutral $B$ meson decays

Equal amounts of matter and antimatter are predicted to have been produced in the Big Bang, but our observable Universe is clearly matter-dominated. One of the prerequisites for understanding this elimination of antimatter is the nonconservation of charge-parity (CP) symmetry. So far, two types of CP violation have been observed in the neutral $K$ meson ($K^0$) and $B$ meson ($B^0$) systems. CP violation involving the mixing between $K^0$ and its antiparticle $\bar{K}^0$ (and likewise $B^0$ and $B^\ast_0$), and direct CP violation in the decay of each meson, is a substantial larger for the $B^0$ meson system. However, they are still consistent with the standard model of particle physics, which has a unique source of CP violation that is known to be too small to account for the matter-dominated Universe. Here we report that the direct CP violation in charged $B^\pm \to K^\pm \pi^0$ decay is different from that in the neutral $B^0$ counterpart. The direct CP-violating decay rate asymmetry, $A_{K^\pm \pi^0}$ (that is, the difference between the number of observed $B^- \to K^- \pi^0$ events versus $B^+ \to K^+ \pi^0$ events, normalized to the sum of these events) is measured to be about $+7\%$, with an uncertainty that is reduced by a factor of 1.7 from a previous measurement. However, the asymmetry $A_{K^\pm \pi^0}$ for $B^0 \to K^- \pi^+$ versus $B^0 \to K^+ \pi^-$ is at the $-10\%$ level. Although it is susceptible to strong interaction effects that need further clarification, this large deviation in direct CP violation between charged and neutral $B$ meson decays could be an indication of new sources of CP violation—which would help to explain the dominance of matter in the Universe.
It would seem that we are well on the way to understanding the basis of particle–antiparticle asymmetry in the early Universe.

In fact, we are not. The KM predictions depend crucially on the masses of the intermediate-mass s and c quarks. But the high temperature of the Universe just after the Big Bang makes these masses irrelevant in calculations of the cosmic-matter excess. The degree of asymmetry predicted by the KM model is ten orders of magnitude too small.
The Lore/Lure that Despairs the Experimenter
The Abyss: CPV in KM and B.A.U.

**The Lore**

\[ \frac{n_{\bar{B}}}{n_{\gamma}} \equiv 0 \]

\[ \frac{n_{\bar{B}}}{n_{\gamma}} = (6.2 \pm 0.2) \times 10^{-10} \]  

**WMAP**

\[ \text{KM} \sim 10^{-20} \]

**Too Small in SM**

Jarlskog Invariant in SM3

(need 3 generation in KM)

\[ J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) A \]

Normalize by \( T \sim 100 \text{ GeV} \)

EW Phase Transition Temperature

\( \sim \text{v.e.v.} \)

\[ \frac{J}{T^{12}} \sim 10^{-20} \]

**Masses too Small!**

\[ A \sim 3 \times 10^{-5} \]  

in SM

is common (unique) area of triangle

**CPV Phase**

Small, but *not Too small*
(u, d,) s, c, b quarks too light
b quark or its antiparticle. The lighter d or \( \bar{d} \) does not participate. Given this fact, one would expect that replacing the d or \( \bar{d} \) in the B meson by the similarly light u or \( \bar{u} \) would produce the same asymmetry. But Belle observes that the equivalent decays of the mesons corresponding to those quark compositions, \( B^+ \rightarrow K^+\pi^0 \) and \( \bar{B}^- \rightarrow K^-\pi^0 \), have an asymmetry of the opposite sign. Together with the same asymmetries recently announced by BaBar\(^{2,3} \), the effect has a statistical significance greater than five standard deviations — the ‘gold standard’ of particle physicists for proof that an effect is real.

Unlike the decays of the neutral B mesons \( B^0 \) and \( \bar{B}^0 \), the decays of the charged B mesons \( B^+ \) and \( \bar{B}^- \) produce two u quarks or antiquarks. This means that other processes that preferentially produce u quarks rather than d quarks might affect the asymmetry. The electroweak penguin is just such an effect — but to alter the asymmetry, this process must differ from the standard electroweak penguin which affects the decay rates symmetrically. A contribution from an exotic loop is required. There are admittedly other possibilities that might explain the anomaly in the asymmetry: a direct weak-interaction decay process, the so-called colour-suppressed contribution, also has the required properties. The size of this contribution depends on the quarks involved. In decays of mesons containing the c quark, it is substantial. For the heavier B mesons, however, it is indeed expected to be suppressed.

The new results\(^1\) are not conclusive, but they are tantalizing. They might be due to properties of standard b quark weak interactions that we cannot quite yet estimate precisely, but it is equally possible that this is the first hint of an entirely new mechanism for particle–antiparticle asymmetry. In the next few years, these ideas will be tested, both through the analysis of the huge Belle and BaBar data set, and from the hunt for exotic particles at the LHC. We do not yet know whether it is penguins or even more unusual creatures that produce our Universe made of matter and not antimatter.

Michael E. Peskin is in the Theoretical Physics Group, Particle Physics and Astrophysics, SLAC.
“I must say that I am very skeptical that the new Belle result is new physics -- a larger than expected color suppressed amplitude is an explanation that is ready at hand. On the other hand, I felt that it was necessary to push the new physics interpretation when writing for the Nature audience, people outside of high energy physics, because this is why the result is potentially newsworthy.”
Mixing-dep. CPV in \( B_d \) and \( B_s \) in SM

\[
\sin^2 \phi_1 = \sin^2 \beta
\]

Measured by Belle/BaBar in \( B_d \rightarrow J/\psi K_s \)

\[
\sin^2 \Phi_{B_s} \approx -0.04 \quad \text{in SM3}
\]

Measure in \( B_s \rightarrow J/\psi \phi \)

“possible only at LHCb”

- Recent Hint @ Tevatron
  \[
  \sin^2 \Phi_{B_s} < 0 \quad (\leq 3\sigma)
  \]

- Consistent with 4th generation Prediction from \( \Delta A_{K\pi} \)

- BSM w/o hadronic uncertainty \( \text{iff true.} \)

- So what!? The \( 10^{-10} \) Abyss ...

George W.S. Hou (NTU)   UVa, Feb 2, 2009   25
II. $\Delta A_{K\pi}$ Problem — Z Penguin and $t'$ Loop

the Experimentalist

Just when $\Delta S_{\phi K}$ “disappeared”...
$A_{CP}(B \rightarrow K^+\pi^0)$

$K^\pm\pi^0$: 728 ± 53

$A_{CP}(K^\pm\pi^0) = 0.04 \pm 0.05 \pm 0.02$

hint that $A_{CP}(K^+\pi^-) \neq A_{CP}(K^\pm\pi^0)$? (2.4σ)

[also seen by BaBar]

Large EW penguin ($Z^0$)?

New Physics?

ICHEP 2004, Beijing
The partial rate asymmetry $\mathcal{A}_{CP}(K^+\pi^-)$ is found to be $-0.101 \pm 0.025 \pm 0.005$, which is $3.9\sigma$ from zero. The significance calculation includes the effects of systematic uncertainties. Our result is consistent with the value reported by BABAR, $\mathcal{A}_{CP}(K^+\pi^-) = -0.133 \pm 0.030 \pm 0.009$ [7]. The combined experimental result has a significance greater than $5\sigma$, indicating that direct CP violation in the $B$ meson system is established. Our measurement of $\mathcal{A}_{CP}(K^+\pi^0)$ is consistent with no asymmetry; the central value is $2.4\sigma$ away from $\mathcal{A}_{CP}(K^+\pi^-)$. If this result is confirmed with higher statistics, the difference may be due to the contribution of the electroweak penguin diagram or other mechanisms [16]. No evidence of

The Crawlin’ of one Ant

Going Up a Hill ...
an by Inami and Lim,\textsuperscript{9} and we follow their notation. The effective Lagrangean arising from Fig. 1 is

\begin{equation}
\mathcal{L}_{\text{eff}}^{\ell^+\rightarrow \ell^-} = 2\sqrt{2} G_F \chi_{\ell}\left[ \bar{C}_i (s_{\gamma} L b) (\bar{1}_Y L) - s_W F_1^i (2\bar{C}_i^l) (\bar{s}_{\gamma} L b) (\bar{1}_Y L) \right. \\
- \left. s_W F_2^i [s_i \sigma_{\mu}(q^2)(m_L + m_b R) b] (\bar{1}_Y L) \right],
\end{equation}

(1)

\begin{equation}
\mathcal{L}_{\text{eff}}^{\ell^+\rightarrow \nu} = - 2\sqrt{2} G_F \chi_{\ell} \bar{D}_i (s_{\gamma} L b) (\bar{\nu}_{\gamma} L \nu),
\end{equation}

(2)

where \( \chi = g^2/16 \pi^2 \), \( \nu_i \equiv V^{*}_{ib} V_{ib} \), \( i \) is summed from 2 to \( n \) (where \( n \) is the number of generations),\textsuperscript{10} \( s_W \) is the sine of the Weinberg angle, and we exhibit\textsuperscript{11}

\begin{equation}
\bar{C}_i \equiv \bar{C}_i^l + \bar{C}_i^\text{box} = \frac{1}{4} x_i + \frac{3}{4} \left[ - \frac{x_i}{x_i - 1} \right]^2 \ln x_i - \frac{3}{4} \frac{x_i}{x_i - 1},
\end{equation}

(3)

\begin{equation}
\bar{D}_i \equiv \bar{D}_i^l + \bar{D}_i^\text{box} = \frac{1}{4} x_i + \frac{3}{4} \frac{x_i(x_i - 2)}{(x_i - 1)^2} \ln x_i + \frac{3}{4} \frac{x_i}{x_i - 1},
\end{equation}

(4)

where \( x_i = m_i^2/M_W^2 \), and \( m_i \) is the internal quark mass. The important feature of Eqs. (3) and (4) is the term \( x_i/4 \),\textsuperscript{8}

\begin{table}[h]
\centering
\begin{tabular}{ |c|c| }
\hline
\( \gamma \) & \( Z \) \\
\hline
\end{tabular}
\end{table}

\[ \alpha G_F < \frac{G_F m_t^2}{2} \]

\[ \text{nondecoupling} \]
Decoupling Thm: Heavy **Masses** are decoupled in QED/QCD
∴ **Appear in Propagator**

**Nondecoupling:** **Yukawa Couplings** $\lambda_Q$ **Appear in Numerator**

Subtlety of Spont. Broken Gauge Theory
Going Up a Hill ...

The Crawlin’ of one Ant
Implications of a Heavy Top Quark and a Fourth Generation on the Decays $B \to Kl^+l^-, \ K\nu\nu$

Wei-Shu Hou and R. S. Willey

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

and

A. Soni

Department of Physics, University of California, Los Angeles, Los Angeles, California 90024

(Received 12 November 1986)

We point out the importance of the $Z$ and box diagram to the decays $B \to Kl^+l^-, \ K\nu\nu$. The rate for $B \to Kl^+l^-$ grows rapidly for internal quark masses $\geq 100 \ GeV$. With three generations and 25 GeV $\lesssim m_t \lesssim 200 \ GeV$ the branching ratio ranges roughly from $10^{-6}$ to $10^{-5}$. With four generations, this rate could go up another order of magnitude. The mode $B \to K\nu\nu$ typically has a higher branching ratio, but is harder to detect experimentally. The rare $B$ decays combined with information from $K \to \pi\nu\bar{\nu}$ studies may provide a test of the symmetry-breaking mechanism of the standard model and/or evidence for a fourth generation.
- $N_{\nu}$ counting? 4th “neutrino” heavy
  Massive neutrinos call for new Physics

- Disfavored by EW Precision  
  (see e.g. J. Erler hep-ph/0604035; PDG06)

An extra generation of ordinary fermions is excluded at the 99.999% CL on the basis of the $T$ parameter alone, corresponding to $N_F = 2.81 \pm 0.21$ for the number of families. This assumes that there are no new contributions to $T$ or $U$ and therefore that the families are degenerate. In principle this restriction can be relaxed by allowing $T > 0$ as well, since $T > 0$ is expected from a non-degenerate extra family. However, recent analyses favor $T < 0$, thus strengthening the exclusion limits. A more detailed analysis is required if the extra neutrino (or the extra down-type quark) is close to the pseudo-Goldstone mass limit [208]. This can drive $S$ to small or even negative values but at the expense of too-large contributions to $T$. These results are in agreement with a fit to the number of light neutrinos, $\nu_r = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1231 \pm 0.0020$ mainly from $R_L$ and $\tau_\tau$). However, the $S$ parameter fits are valid even for a very heavy fourth family neutrino.

• 4th generation not in such great conflict with EWPrT

Kribs, Plehn, Spannowsky, Tait, PRD’07

George W.S. Hou (NTU)
This is Still the Standard Model
\[ \lambda_{t'} \equiv V_{t's}^* V_{t'b} \equiv r_{sb} e^{i \phi_{sb}} \]

\[ t \Leftrightarrow t', t' \]

\[ \lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0 \]

\[ \lambda_t \equiv -\lambda_c - \lambda_{t'} \]

Nondecoupling of \( t' \)

GIM Respecting

\[
\lambda_u (C_1 O_1 + C_2 O_2) + \sum_{i=3}^{10} (\lambda_c C_i^t - \lambda_{t'} (C_i^{t'} - C_i^t)) O_i
\]

\[
H_{\text{eff}}^4 = \frac{G_F}{\sqrt{2}} \left[ \lambda_u (C_1 O_1 + C_2 O_2) + \sum_{i=3}^{10} (\lambda_c C_i^t - \lambda_{t'} (C_i^{t'} - C_i^t)) O_i \right]
\]
\[ C_9^t - C_9^{t'} \propto x_t - x_{t'} \]

**nondecoupling**

\[ \Delta S_0^{(1)} = S_0(t, t') - S_0(t, t) \]
\[ \Delta S_0^{(2)} = S_0(t', t') + S_0(t, t) - 2S_0(t, t') \]
\[ \Delta A = A_{K^+\pi^0} - A_{K^+\pi^-} \approx 15\% \] and \[ P_{\text{EW}}^{b\rightarrow s} \]

\[ \Delta A \approx 12\% \text{ vs } 15\% \text{ (data)} \]

\[ m_{t'} = 300 \text{ GeV} \]

(illustration)

WSH, Nagashima, Soddu, PRL'05

\[ B^- \rightarrow t, t' \]

\[ \bar{u} \rightarrow s \]

\[ d \rightarrow \pi^0 \]

\[ K^- \]
\[
\lambda_{t'} \equiv V_{t's}^* V_{t'b} \equiv r_{sb} e^{i \phi_{sb}}
\]

\[
\lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0
\]

\[
\begin{array}{c}
\text{Nondecoupling of } t' \\
\text{CPV Phase}
\end{array}
\]

\[
M_{12} \propto f_{B_s}^2 B_{B_s} \lambda_{t'}^2 S_0(t,t) + 2 \lambda_c \lambda_{t'} [S_0(t,t) - S_0(t,t')] + \lambda_{t'}^2 [S_0(t,t) - 2 S_0(t,t') + S_0(t',t')] 
\]

\[
H_{\text{eff}}^4 = \frac{G_F}{\sqrt{2}} \left[ \lambda_u (C_1 O_1 + C_2 O_2) + \sum_{i=3}^{10} (\lambda_c C_i^t - \lambda_{t'} (C_i^{t'} - C_i^t)) O_i \right]
\]
Difference in $B^+$ and $B^0$ Direct CP Asymmetry as an Effect of a Fourth Generation

Wei-Shu Hou, Makiko Nagashima, and Andrea Soddu

Department of Physics, National Taiwan University, Taipei, Taiwan 106, Republic of China
(Received 8 March 2005; revised manuscript received 20 June 2005; published 30 September 2005)

Direct CP violation in $B^0 \rightarrow K^+ \pi^-$ decay has emerged at the $-10\%$ level, but the asymmetry in $B^+ \rightarrow K^+ \pi^0$ mode is consistent with zero. This difference points towards possible new physics in the electroweak penguin operator. We point out that a sequential fourth generation, with sizable $V_{t's}^* V_{t'b}$ and near maximal phase, could be a natural cause. We use the perturbative QCD factorization approach for $B \rightarrow K \pi$ amplitudes. While the $B^0 \rightarrow K^+ \pi^-$ mode is insensitive to $t'$, we critically compare $t'$ effects on direct CP violation in $R^+ \rightarrow K^+ \pi^0$ with $h \rightarrow s \ell^+ \ell^-$ and $B_s$ mixing. If the $K^+ \pi^0 - K^+ \pi^-$ asymmetry difference persists, we predict $\sin 2\Phi_{B_s}$ to be negative.

As prediction, we find $\sin 2\Phi_{B_s} < 0$ for CPV in $B_s$ mixing, which is plotted versus $\phi_s$ in Fig. 3(d). We find $\sin 2\Phi_{B_s}$ in the range of $-0.2$ to $-0.7$ and correlating with $A_{K^+\pi} - A_{K^-\pi}$. Three generation SM predicts zero. Note that refined measurements of $B(h \rightarrow s \ell \ell)$ and future measurements of $\Delta m_{B_s}$ and $\sin 2\Phi_{B_s}$, together with theory improvements, can pinpoint $m_{t'}$, $r_s$, and $\phi_s$. We note further that [6] $14.4 \text{ ps}^{-1} < \Delta m_{B_s} < 21.8 \text{ ps}^{-1}$ cannot yet be excluded because data are compatible with a signal in this region. We eagerly await $B_s$ mixing and associated CPV measurement in the near future.
\[ \Delta A = A_{K^+\pi^0} - A_{K^+\pi^-} \sim 15\% \quad \text{and} \quad P_{b \to s}^{\text{EW}} \]

\[ \Delta A \approx 12\% \quad \text{vs} \quad 15\% \quad \text{(data)} \]

\[ m_{t'} = 300 \text{ GeV} \]

(illustration)

\[ \phi_{sb} \]

Can Account for Belle/BaBar Direct CPV Difference

Both \( \Delta A \) and \( \Delta S \) in Right Direction!

SM3 input
$V_{CKM}^4$ =

```
\begin{pmatrix}
0.9745 & 0.2225 & 0.0038 e^{-i \theta_1} & 0.0038 e^{-i \theta_2} \\
-0.044 e^{-i \theta_3} & -0.1136 e^{-i \theta_4} & 0.9746 & 0.2168 e^{-i \theta_5} \\
0.0055 e^{-i \theta_6} & 0.9746 & 0.2168 e^{-i \theta_7} & 0.9688 \\
0.0038 e^{-i \theta_8} & -0.0555 e^{-i \theta_9} & -0.2200 & 0.9688
\end{pmatrix}
```

"Typical" CKM Matrix  
$m_{t'} = 300 \text{ GeV}

**Extract Information from Constraints**

$b \rightarrow s$

$b \rightarrow d$

Nontrivial

Satisfy $b \rightarrow d$: $\checkmark$

Cannot tell triangle from quadrangle

$V_{us}^* V_{ub}$

$V_{cs}^* V_{cb}$

$V_{td}^* V_{tb}$

$x \sim 0.22$
$A_{FB}(B \rightarrow K^*l^+l^-)$ and Other Predictions
Implication for $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$

Nontrivial (phase) $V_{td}^* V_{ts}$

Current E391A U.L.  
$2.86 \times 10^{-7}$ (90% c.l.)  
Very hard to measure

$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \simeq 3 \times 10^{-11}$

Rate could be enhanced by up to almost two orders!!

$K_L \to \pi^0 \nu \bar{\nu}$ enhanced to $5 \times 10^{-10}$ or even higher!!

In general larger than $K^+ \to \pi^+ \nu \bar{\nu}$ ($2-3 \times 10^{-10}$)

:: Large CPV Phase
III. $\Delta m_{B_s}$ Measurement $\rightarrow$ Prediction for $\sin2\Phi_{B_s}$
Mixing-dep. CPV in $B_d$ and $B_s$ in SM

$\sin 2\phi \approx \sin 2\beta$

Measured by Belle/BaBar

$\sin^2 \Phi_{B_s} = -0.04$ in SM3

Measure in $B_s \rightarrow J/\psi \phi$
Prediction: Large CPV in $B_s$ Mixing

$V_{ud} V_{ub}^*$
$b \rightarrow d$

$-V_{cd} V_{cb}^*$

$V_{cs} V_{cb}^*$

$V_{ts} V_{tb}^*$

$b \rightarrow s$

No Hadronic Uncertainty ...

Strength and Size of $\sin 2\Phi_{B_s}$

$\sin 2\Phi_{B_s} \sim -0.5$ to $-0.7$

Despite $\Delta m_{B_s}$, $\overline{B}(b \rightarrow s/l)$ SM-like

WSH, Nagashima, Soddu, PRD’07

UVa, Feb 2, 2009
B_s Mixing vs B \rightarrow X_s \ell^+\ell^-

different nondecoupl. functions

Large CPV in B_s Mixing
Use nominal $m_{t'} = 300$ GeV
Change $m_{t'}$, Change parameter range
Effect the Same.

(Similar)
\[
\lambda_{t'} \equiv V_{t's}^* V_{t'b} \equiv r_{sb} e^{i\phi_{sb}}
\]

\[f_{B_s} \sqrt{B_{B_s}} = 295 \pm 32 \text{ MeV}\]

- Fixed \( r_{sb} \) ⇒ Narrow \( \phi_{sb} \) Range destructive with top
- For \( r_{sb} \sim 0.02 - 0.03, \quad [V_{cb} \sim 0.04 \phi_{sb} \text{ Range } \sim 60^\circ - 70^\circ\]

Finite CPV Phase

Consistent w/ \( B(b \rightarrow s\ell\bar{\ell})\)

SM-like!

Large CPV Possible!

Despite \( \Delta m_{B_s}, B(b \rightarrow s\ell\bar{\ell}) \) SM-like
Large CPV in $B_s$ Mixing

Can Large CPV in $B_s$ Mixing Be Measured @ Tevatron?

Sign Predicted!

$\sin 2\Phi_{B_s} \sim \pm 0.5 - \pm 0.7$

Despite $\Delta m_{B_s}$, $B(b \rightarrow s l)$ SM-like

Large CPV in $b \rightarrow s$ George W.S. Hou (NTU) CDF/D0 4/12/07 51
Prediction: Large CPV in $B_s$ Mixing

$$f_B \sqrt{B_B} = 295 \pm 32 \text{ MeV}$$

$B_s$ Mixing Measured @ Tevatron in 4/2006

- For $r_{sb} \sim 0.02 - 0.03$, $|V_{cb} \sim 0.04$
- $\phi_{sb}$ Range $\sim 60^\circ - 70^\circ$

Finite CPV Phase

$$\sin 2\Phi_{B_s} \sim -0.5 - -0.7$$

Despite $\Delta m_{B_s}$, $B(b \to s\ell\nu)$ SM-like

WSH, Nagashima, Soddu, PRL'05

George W.S. Hou (NTU)

UVa, Feb 2, 2009 52
Prediction: Large CPV in $B_s$ Mixing

Can Large CPV in $B_s$ Mixing Be Measured @ Tevatron?

Sign Predicted!

$\sin 2\phi_{B_s} \sim -0.5 - 0.7$

Despite $\Delta m_{B_s}$, $B(b \rightarrow s\ell\bar{\ell})$ SM-like

Sure thing by LHCb ca. 2010 (?)
\[ \sin 2\Phi_{B_S} \sim -0.5 - -0.7 \]

Further ICHEP'08 Updates (CDF/DØ/fitters): Strengthen!

<table>
<thead>
<tr>
<th>Observable</th>
<th>68% Prob.</th>
<th>95% Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_{B_S} [^\circ] )</td>
<td>-19.9 ± 5.6</td>
<td>[13.45, 9.25]</td>
</tr>
<tr>
<td>( \Delta \Gamma [\text{ps}^{-1}] )</td>
<td>-68.2 ± 4.9</td>
<td>[-78.45, -58.2]</td>
</tr>
</tbody>
</table>

\( \sin 2\Phi_{B_S} = -0.64 \pm ? \)

Incredible !!!
An Updated Measurement of the CP Violating Phase $\beta^{J/\psi\phi}_{s}$

The CDF Collaboration

It is interesting to note that the Belle and BABAR collaborations have observed an asymmetry between direct CP asymmetries of charged and neutral $B \rightarrow K \pi$ decays with 5$\sigma$ significance [5, 6]. In the absence of an under-estimation of the contribution from color-suppressed tree decays, it is difficult to explain this discrepancy without some source of new physics contributing to the electroweak penguin which governs the $b \rightarrow s$ transition. In the standard model, this isospin-violating diagram should be highly suppressed, but if a new source of physics is indeed present in these transitions it may be enough to cause the different CP asymmetries that have been observed. In the $B^{0}_{s} \rightarrow J/\psi \phi$ decay, the $b \rightarrow s$ transition occurs through the mixing box diagram shown in Fig. 1. It is possible that new particles could enter this transition through the $b \rightarrow s$ quark transition. While there are surely a number of possible sources of new physics that might give rise to such discrepancies, George Hou predicted the presence of a $t'$ quark with mass between $\sim 300$ and $1000$ GeV/$c^2$ in order to explain the Belle result and predicted a future observation of a large CP-violating phase in $B^{0}_{s} \rightarrow J/\psi \phi$ decays [7, 8]. Another result of interest in the context of these measurements is the excess observed at $\sim 350$ GeV/$c^2$ in the recent $t'$ search at CDF using 2.3 fb$^{-1}$ of data [9]. In this direct search for a fourth generation up-type quark, a significance of less than 2$\sigma$ is obtained for the discrepancy between the data and the predicted backgrounds, so that the effect, while intriguing, is presently consistent with a statistical fluctuation. A updated search with more data would also clearly be of interest, particularly if a large value of $\beta^{J/\psi\phi}_{s}$ persists with the addition of more data.
(Conservative) outlook

% of CDF ‘clones’ that would observe a 5σ-effect, as a function of βs

Assumptions

✓ ∆Γ_s = 0.1 ps^{-1}
✓ Constant data-taking efficiency
✓ No analysis improvements.
✓ No external constraints (A_{SL}, lifetimes) used.

CDF future will probably be better than that.
And DØ will contribute too.

\[
\sin 2\Phi_{Bs} = -\sin \beta_s = \sin \phi_s
\]

Observation by 2010 if Central Value Stays!

--- 8/fb (~2010)
--- 6/fb (~2009)
IV. Soaring to the Heavens: Enough CPV for BAU?

If ... KM4
\[
\frac{n_{\overline{B}}}{n_{\gamma}} \approx 0 \quad \frac{n_{\overline{B}}}{n_{\gamma}} = (6.2 \pm 0.2) \times 10^{-10}
\]

**WMAP**

**KM \sim 10^{-20}**

Too Small in SM

(need 3 generation in KM)

**Why? Jarlskog Invariant in SM3**

\[
J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) A
\]

Normalize by \( T \sim 100 \text{ GeV} \)

\[
\frac{J}{T^{12}} \sim 10^{-20}
\]

masses too small!

\( A \sim 3 \times 10^{-5} \) in SM

is common (unique) area of triangle

**CPV Phase**
\[
\frac{n_{\bar{B}}}{n_{\gamma}} \approx 0
\]
\[
\frac{n_{\bar{B}}}{n_{\gamma}} = (6.2 \pm 0.2) \times 10^{-10}
\]

\[\text{WMAP}\]

\[\text{Too Small in SM}\]

\[\text{KM } \sim \text{Enough CPV?}\]

\[\text{If shift by One Generation in SM}^4 \text{ (need 3 generation in KM)}\]

\[J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2) (m_s^2 - m_t^2) A\]

\[\text{Providence}\]

\[\text{WSH, arXiv:0803.1234 [hep/ph]}\]

\[\text{Moriond QCD}\]

\[J_{(2,3,4)}^{sb} \approx (m_u^2 - m_c^2)(m_u^2 - m_t^2)(m_t^2 - m_c^2)(m_b^2 - m_s^2)(m_b^2 - m_t^2) A_{234}^{sb}\]

\[\approx \frac{m_t^2}{m_c^2} \left( \frac{m_t^2}{m_c^2} - 1 \right) \frac{m_b^4}{m_b^2 m_s^2} A_{234}^{sb} \]

\[\sim 10^{+15} \text{ Gain}\]

\[\text{Order 1 } \sim 30\]

\[\text{CPV Phase}\]

\[\text{Gain mostly in Large Yukawa Couplings!}\]
The Abyss between CPV in SM3 vs BAU bridged in SM4 by *Heaviness of t' and b'*

Why wasn't this clearly pointed out in past 20 years?
4th Generation Still?

- \( N_\nu \) counting? 4th “neutrino” heavy
  Massive neutrinos call for new Physics

- Disfavored by EW Precision  (see e.g. J. Erler hep-ph/0604035; PDG06

  An extra generation of ordinary fermions is excluded at the 99.999% CL on the basis
  parameter alone, corresponding to \( N_F = 2.81 \pm 0.24 \) for the number of families
  assumes that there are no new contributions to \( T \) or \( U \) and the first three families are degenerate. In principle this restricts
  to a non-degenerate extra family. However, \( T < 0 \), thus strengthening the exclusion limits. A more detailed
  required if the extra neutrino (or the extra down-type quark) is close to
  the mass limit [208]. This can drive \( S \) to small or even negative values but at
  the expense of too-large contributions to \( T \). These results are in agreement with a fit
  to the number of light neutrinos, \( N_\nu = 2.986 \pm 0.007 \) (which favors a larger value for
  \( \alpha_s(M_Z) = 0.1231 \pm 0.0020 \) mainly from \( R_t \) and \( \tau \)). However, the \( S \) parameter fits are
  valid even for a very heavy fourth family neutrino.

- 4th generation not in such great conflict with EWPrt
  Kribs, Plehn, Spannowsky, Tait, PRD'07

(To Me) CPV Source for BAU Overrides These Concerns!
Gain mostly in Large Yukawa Couplings!

\[ J^{sb}_{(2,3,4)} \simeq (m_{\nu}^2 - m_c^2)(m_{\nu}^2 - m_t^2)(m_u^2 - m_c^2)(m_{\nu}^2 - m_s^2)(m_b^2 - m_t^2)(m_b^2 - m_s^2) A^{sb}_{234} \]

\[ \simeq \frac{m_{\nu}^2}{m_c^2} \left( \frac{m_{\nu}^2}{m_t^2} - 1 \right) \frac{m_u^4}{m_b^2 m_s^2} \frac{A^{sb}_{234}}{A} J \]

~ 10^{+15} Gain

\[ m_{b'} \approx 300 \text{ GeV} \quad \text{10}^{+13} \]
\[ m_{t'} \approx 600 \text{ GeV} \quad \text{10}^{+15} \]

Only fac. 30 in CPV per se

This part will shrink a bit.
CPV for BAU: 2-3-4 Dominance

Jarlskog'85, 3 generations
\[ \text{Im} \, \text{det} \left[ m_u m^\dagger_u, \ m_d m^\dagger_d \right] \]
\[ S , \quad S' \]
4 generations: 3 indep. phases

long and short
d-s degenerate
(on v.e.v. scale)

2-3-4 generation only!

Effectively 3 generations

\[ J^{sb}_{(2,3,4)} \approx (m^2_{\nu} - m^2_c)(m^2_{\nu} - m^2_t)(m^2_t - m^2_c)(m^2_{\nu} - m^2_s)(m^2_s - m^2_{\nu})(m^2_{\nu} - m^2_s)A^{sb}_{234} \]
\[ \approx \frac{m^2_{\nu}}{m^2_c} \left( \frac{m^2_{\nu}}{m^2_t} - 1 \right) \frac{m^4_{\nu}}{m^2_{\nu} m^2_s} \frac{A^{sb}_{234}(J)}{A} \]

\[ J^{(1,2,3)} \text{ very small} \]
suppressed by \( m_s, m_c \)
Ran out of time, and knowledge ...

(perturbative)

- Fok & Kribs: Not possible in 4th generation
- Conjecture: Could Strong Yukawa’s do it ?

Beyond Unitarity Limit

Not quite conclusive (?)
Thoughts on the other 1/2 Nobel Prize

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

\[ \langle \bar{Q}Q \rangle \text{ can Condense by Large Yukawa!} \]

Could EWSB be due to b' and t' above unitarity bound ~ 500-600 GeV?

Bob Holdom: N–J–L
[Bardeen, Hill, Lindner]

V. Direct Sighting @ Tevatron vs LHC

the Experimentalist
Tevatron

\(\sin 2\Phi_{BS}\) "Evidence" by 2009? "Observe" by 2010?

- \(t'\) Search Ongoing:
  - \(m_{t'} > 311\) GeV @ 95% CL

LHC

- \(\sin 2\Phi_{BS}\) "Confirmation" — "Easy" for LHCb
- \(b', t'\) Discovery — Straightforward/full terrain

Agenda of Taiwan-CMS

**Caveat:**

- **Tevatron** Unequivocal BSM... if true

- **LHC** but when?
4th generation? — The jury is out ...

In era of LHC, can **Directly Search for b', t'**
**Once and For All!**

**Find b', t', or Rule Out @ LHC**

It's a Duty.

**Strategy Considerations** (漢中策略)

- **Well shielded** — All Tools
  - Move on to Greener Pastures ~ in 2 years

- **Publish early** — Large Cross Section
  - If “Limits”, then easy to publish
  - If “Signal”, Lucked Out!
For $m_{b'} < m_t + M_W = 255$ GeV

- $b' \rightarrow cW$ dominance for sizable $V_{cb'}$
- $b' \rightarrow tW^*$ dominance for suppressed $V_{cb'}$

- Kinematic suppressed for $m_{b'} \lesssim 230$ GeV

Initial discovery should consider

- $b' \rightarrow cW \sim b' \rightarrow bZ, bH \sim b' \rightarrow tW^*$

For $m_{b'} > m_t + M_W = 255$ GeV

- $b' \rightarrow tW$ dominance; FCNC searchable

- Rich Signature: $cc(\bar{c}c)WW; cWbZ; cWbH; ct(\bar{c}t)WW^*; tt(\bar{t}t)W^*W^*; tW^*bZ; tW^*bH$; $tt(\bar{t}t)WW \rightarrow bb(\bar{b}b)W^+W^-W^+W^-$

- Bonus!!

- Heavy Q related
- To EWSB?

- 4 $W$'s + 2 $b$'s
CMS PAS EXO-08-09

CMS Physics Analysis Summary

Search for Heavy Bottom-like Fourth Generation Quark Pair at CMS in $pp$ Collisions at $\sqrt{s} = 14$ TeV

The CMS collaboration
same-sign dilepton and trilepton

<table>
<thead>
<tr>
<th>$b'$ Mass</th>
<th>300 GeV/$c^2$</th>
<th>400 GeV/$c^2$</th>
<th>500 GeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b'b'$ LO cross section</td>
<td>34.9 pb</td>
<td>8.05 pb</td>
<td>2.45 pb</td>
</tr>
<tr>
<td>Expected signal yield</td>
<td>68.2</td>
<td>22.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Expected background yield</td>
<td>7.3$^{+10.5}_{-4.8}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>7.5$\sigma$</td>
<td>2.0$\sigma$</td>
<td>0.0$\sigma$</td>
</tr>
<tr>
<td>$S_{cP}$</td>
<td>N/A</td>
<td>2.1$\sigma$</td>
<td>0.0$\sigma$</td>
</tr>
</tbody>
</table>

Limit to 480 GeV w/ 100 pb$^{-1}$
VI. Conclusion: Know in 3-5 Years

\[ J^{sb}_{(2,3,4)} \simeq (m_{t}^{2} - m_{c}^{2})(m_{t}^{2} - m_{t'}^{2})(m_{t}^{2} - m_{s}^{2})(m_{t}^{2} - m_{b}^{2})(m_{b}^{2} - m_{s}^{2}) A^{sb}_{234} \]

\[ \sim \frac{m_{t}^{2}}{m_{t'}^{2}} \left( \frac{m_{t}^{2}}{m_{t'}^{2}} - 1 \right) \frac{m_{b}^{2}}{m_{b}^{2} m_{s}^{2}} \left( \frac{A^{sb}}{A} \right) J \]

\[ \sim 10^{15} \text{ Gain} \]

\[ m_{b'}, m_{t'} \approx 300 \text{ GeV} \quad 10^{13} \]

\[ \sim 600 \text{ GeV} \quad 10^{15} \]

Even if \( O(1) \)

Enough CPV for B.A.U.

Maybe there is a 4th Generation!

Will Really Know in \( \sim 3-5 \) years!

\( \sin^{2}\Phi_{bs} \)

@ Tevatron by 2010

@ LHC

Heaven on Earth?
Backup
Matter (and More !!) Universe: No Antimatter

Composition of the Cosmos

- Dark Matter: ~25%
- Antimatter: 0%
- Dark Energy: ~70%
- Heavy elements: 0.03%
- Neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: ~25%
- Dark energy: ~70%
“Affleck-Dine”, SUSY etc.:

Extra $\textit{Scalars}$ (strongly) coupled to $H^0$

More Scalars!

Let’s first find One Scalar.

Leptogenesis:

Heavy $\textit{Majorana Neutrinos}$

⊕ $\text{LFV/CPV Decay}$

⊕ $\text{B/L Violation (“EW Baryogenesis”)}$

Popular! Driving $\theta_{13}$ study for neutrinos.

But, “Heavenly” — Could be(come) Metaphysics
ElectroMagnetism:

Charge $e$ is **Real**.

"We" Understand:  **Gauge** Charge is Real.

*Imagine* *a Complex Coupling*:

True, or, Possible, for Yukawa (湯川) Coupling of quarks/leptons to Higgs boson(s)...

**Quantum Interference** in **Amplitude** More Interesting

→ How CP Violation Appears
CP Violation Primer

Particle Process $A_{1} + A_{2}$

AntiParticle Process $\bar{A}_{1} + \bar{A}_{2}$

\[ A = A_{1} + A_{2} = a_{1} + a_{2}e^{i\delta_{2}}e^{i\phi_{2}} \]

\[ \bar{A} = \bar{A}_{1} + \bar{A}_{2} = a_{1} + a_{2}e^{i\delta_{2}}e^{-i\phi_{2}} \]

\[ A^{CP} = \frac{\Gamma(\bar{B}^{0} \to f) - \Gamma(B^{0} \to f)}{\Gamma(\bar{B}^{0} \to f) + \Gamma(B^{0} \to f)} = \frac{2a_{1}a_{2}\sin\phi_{2}\sin\delta_{2}}{a_{1}^{2} + a_{2}^{2} + 2a_{1}a_{2} + 2a_{1}a_{2}\cos\phi_{2}\cos\delta_{2}} \]

CP Asymmetry needs both CP Conserving/Violating Phase $i_{QM}$ $i_{dyn}$
\[ \Delta A_{K\pi} = A_{B \rightarrow K^+\pi^0} - A_{B \rightarrow K^+\pi^-} \neq 0 \]

\[ = +0.147 \pm 0.028 > 5\sigma \]

Experiment is Firm

\[ \Delta A_{K\pi} \sim 0 \text{ expected} \]

\[ \mathcal{M}(B^0 \rightarrow K^+\pi^-) \propto (T + P) = r e^{i\phi_3} + e^{i\delta} \]

\[ \sqrt{2}\mathcal{M}_{K^+\pi^0} - \mathcal{M}_{K^+\pi^-} \propto (P_{EW} + C)? \]

Large C?

Large EW Penguin?

\[ \rightarrow \text{A lot of (hadronic) finesse} \]


\[ P_{EW} \text{ has practically no weak phase in SM} \]

\[ \text{Need NP CPV Phase} \]
\[ \Delta A_{K\pi} = A_{B \to K^+\pi^0} - A_{B \to K^+\pi^-} \neq 0 \]

\[ \Delta A_{K\pi} = +0.147 \pm 0.028 > 5\sigma \]

Why a Puzzle?

\[ \mathcal{M}(B^0 \to K^+\pi^-) \propto (T + P) = r e^{i\phi_3} + e^{i\delta} \]

\[ \sqrt{2}\mathcal{M}_{K^+\pi^0} - \mathcal{M}_{K^+\pi^-} \propto (P_{EW} + C) \]

Large C?

Large EWPenguin?

A lot of (hadronic) finesse


Need NP CPV Phase

\[ P_{EW} \text{ has practically no weak phase in SM} \]

4th Gen. in EWP Natural

nondecoupling
On Boxes and Z Penguins

- GIM, charm, $\varepsilon_K$
- small $\varepsilon'/\varepsilon$, $K \rightarrow \pi\nu\nu$ (still waiting)
- heavy top, $\sin2\phi_1/\beta$
- $Z$ dominance for heavy top

Most Flavor/CPV learned from these diagrams/processes

1986 $\rightarrow$ 2002
On Boxes and Z Penguins

GIM, charm, $\varepsilon_K$

Nondecoupling

$\therefore$ Large Yukawa!

small $\varepsilon'/\varepsilon$, $K \to \pi\nu\nu$ (still waiting)

heavy top, $\sin 2\phi_1/\beta$

$A_{FB}$

Z dominance for heavy top

1986 $\rightarrow$ 2002

All w/ 3-generations, Just wait if there's a 4th

$B_s$

$D!$

$b', t' @ LHC$
4×4 Unitarity ⇒ Constraints

\[
\begin{align*}
  u &\equiv \begin{pmatrix}
  c_{12} & c_{13} & c_{14} \\
  -c_{12}^2 c_{13} & c_{12} c_{14} & s_{12} \\
  -c_{12} c_{13} & -c_{14} & -s_{12}
  \end{pmatrix} \\
  s &\equiv \begin{pmatrix}
  s_{24} \\
  -s_{13} s_{24} \\
  -s_{13} s_{24} e^{i\phi_{sb} + i\phi_{ub}}
  \end{pmatrix} \\
  b &\equiv \begin{pmatrix}
  c_{24} \\
  s_{13} s_{24} e^{-i\phi_{ub}} \\
  -s_{13} s_{24} e^{-i\phi_{ub}}
  \end{pmatrix} \\
  b' &\equiv \begin{pmatrix}
  c_{12} c_{14} s_{14} e^{i\phi_{ub}} \\
  c_{13} c_{24} s_{14} e^{i\phi_{ub}} \\
  c_{13} c_{14} s_{14} e^{i\phi_{ub}}
  \end{pmatrix}
\end{align*}
\]

We need to deal with mixing matrix in detail to keep **Unitarity**

\[
V_{t's} V_{t'd} = c_{24} s_{24} 14 8 24 \exp \left(i(\phi_{sb} - \phi_{db})\right)
\]

**Kaon**

\[
V_{l's} V_{l'b} = c_{34} s_{24} 34 \exp i\phi_{sb}
\]

\[b \rightarrow s \quad \equiv r_{sb}
\]

**Cross Check!**

\[
\Gamma(Z \rightarrow \text{hadrons})
\]

\[
|V_{t'b}|^2 + 3.4|V_{t'd}|^2 < 1.14 \quad \text{for} \quad m_t = 300 \text{GeV} \Rightarrow s_{34} < 0.25
\]

From **b → s** study

\[
r_{sb} e^{i\phi_{sb}} \simeq 0.025 e^{i70^\circ}
\]

**Impose**

\[
s_{34} = 0.22 \simeq V_{us}
\]

\[
\Delta m_{B_s}/\Delta m_D A_{B_s/\bar{B}_s}
\]

George W.S. Hou (NTU)  
ICHEP'06, 7/29/06 83
**Constrain s ↔ d from K Physics**

\[ BR(K^+ \to \pi^+\nu\bar{\nu}) = (14.7^{+13.0}_{-8.9}) \cdot 10^{-11} \]

\[ BR(K_L \to \mu^+\mu^-)_{SD} < 3.75 \cdot 10^{-9} \]

\[ \epsilon_K = (2.284 \pm 2 \times 0.014) \cdot 10^{-3} \]

\[ \frac{\epsilon'}{\epsilon} = (16.6 \pm 2 \times 1.6) \cdot 10^{-4} \]

- \( R_6 = 1.2 \) (E. Pallante et al.)
- \( R_8 = 0.7 - 1.3 \) “Standard”
- \( R_6 = 2.2 \) (J. Bijnens et al.)
- \( R_8 = 0.8 - 1.4 \) No SM3 solution

Therefore…

\[ r_{ds} \sim 5 \times 10^{-4}, \quad \phi_{ds} \sim -60^\circ \text{ or } +35^\circ \]

well-satisfy \( \Delta m_{B_d} \) and \( \sin 2\phi_1 \)!
$r_{ds} \sim 5 \times 10^{-4}, \quad \phi_{ds} \sim -60^\circ$ or $+35^\circ$

$r_{db} \sim 1 \times 10^{-3}, \quad \phi_{db} \sim 10^\circ$ ($105^\circ$)

well-satisfy $\Delta m_{B_d}$ and $\sin 2\phi_1$ vs $V_{ub} \sim 0.01 e^{-i\gamma}$

Hard to tell apart (non-trivial) with present precision

$\Delta m_{B_s}/\Delta m_{B_d}/A_{K}\bar{K}$

George W.S. Hou (NTU)
$A_{FB}(B \to K^*\ell^+\ell^-)$ and Other Predictions
Quoted by Tsybychev at FPCP08

Fourth Generation
PRD 77, 014016 (2008)

data: LHCb MC (2 fb⁻¹)

 Favor the “opposite-sign C₇ model”

Eigen at FPCP08

349 fb⁻¹
Instead flipped $C_7$

\[
\frac{dA_{FB}}{d\hat{s}} \propto \text{Re}(C_6^{\text{eff}} C_7) H_7 \left( \frac{\hat{s}}{m_{K^*}^2} \right) + A_{T_1} \left( 1 + \frac{\hat{m}_{K^*}^2}{m_{K^*}^2} \right).
\]


- complex wilson coefficients
- SM
- 4th generation (SM4)
- 2fb\(^{-1}\) MC study of LHCb
  (~7000 K*\(\pi\) events)

Belle 657M

J.-T. Wei

2008/07/31 ICHEP2008
$f_D \sqrt{B_D} = 200 \text{ MeV}$

$V_{t'd} V_{t'b} \equiv r_{db} e^{i\phi_{db}}$

From 4 x 4 Unitarity

$V_{ub'} V_{cb'}$

$x = \Delta m/\Gamma \sim 1 - 3 \text{ plausible}$

w/ Sizable (but not huge)
CPV in Mixing $\sim -15\%$

N.B. SM LD could generate
$y \sim 1\%, x \approx y$

[Falk, Grossman, Ligeti, (Nir,) Petrov]
Implication for $B(K_L \to \pi^0 \nu \bar{\nu})$

Nontrivial (phase) $V_{td}^* V_{ts}$

Current E391A U.L.
$2.86 \times 10^{-7}$ (90% c.l.)
Very hard to measure

$B(K_L \to \pi^0 \nu \bar{\nu}) \simeq 3 \times 10^{-11}$

Rate could be enhanced by up to almost two orders !!

$K_L \to \pi^0 \nu \bar{\nu}$ enhanced to $5 \times 10^{-10}$ or even higher !!
In general larger than $K^+ \to \pi^+ \nu \bar{\nu}$ ($2 - 3 \times 10^{-10}$)

:: Large CPV Phase
$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* + V_{t'd}V_{t'b}^* = 0$

$\sim$ SM3

$V_{us}V_{ub}^*$

$b \rightarrow d$

$V_{cs}V_{cb}^*$

$V_{ts}V_{tb}^*$

$-V_{cd}V_{cb}^*$

$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* + V_{t's}V_{t'b}^* \approx 0$

$b \rightarrow s$

$b \rightarrow s$ Quadrangle (almost Triangle)

Area $\sim (-)30 \times b \rightarrow d$ Triangle

Strength and Size of $\sin 2\Phi_{B_s}$
Consistency and $b \rightarrow s\gamma$ Predictions

$\beta(b \rightarrow s\gamma) \times 10^{-4}$

$A_{CP}(b \rightarrow s\gamma)$

BR OK

Heavy $t'$ effect
decoupled for $b \rightarrow s\gamma$

$A_{CP} \sim 0$ far away

beyond SuperB

$C_{t}^{i} - C_{t'}^{i} \propto x_{t} - x_{t'}$

$i=9$

$i=4$

$i=6$

$i=7$

$m_{t'}$ [GeV]

Georges W.S. Hou (NTU)
The Eureka Moment

Large $t$, $t'$ Yukawa

ca. late summer 2007  ...

Large Yukawa!

YuReKawa!
4 generations: 3 indep. phases

If $V_{us}V_{ub}$ shrinks to a point

Difference in area for $b \rightarrow s$ Small

If $V_{us}V_{ub}$ shrinks to a point

4 generations: 3 indep. phases

Emergent $b \rightarrow s$

$b \rightarrow s$ Quadrangle (almost Triangle)
Area $\sim (-30 \times b \rightarrow d)$ Triangle

2nd argument that $J_{(2,3,4)}^{sb}$ is predominant CPV