B Physics and CP Violation

Matthias Neubert – Cornell University
(neubert@mail.lns.cornell.edu)

I. Introduction

II. Charmless Hadronic Decays

III. CP Violation in Mixing

IV. Looking Ahead... Beyond the Standard Model

V. Summary


(SLAC Summer Institute – Topical Conference – 23 August 2000)
Part I: Introduction
The Role of Flavor Physics

* flavor sector contains most of the undetermined parameters of the SM: Yukawa couplings
  → determine quark masses and mixings, lepton and neutrino masses and mixings, CP violation
* not as well tested as the gauge sector of the SM
  • quark mixings correctly described by CKM model?
  • CKM phase only source of CP violation?
  • hierarchical patterns caused by new symmetries?
* CP violation in SM is not sufficient to explain baryon asymmetry in Universe
* need New Physics, but many possibilities:
  • TeV scale physics? GUT scale physics? Physics at an intermediate scale?
  • CP violation in lepton sector?
* complementarity between new particle searches and measurements of flavor parameters
Lessons from Kaons

* observation of CP violation in $K - \bar{K}$ mixing (parameter $\epsilon_K$) in 1964 showed that CP is not a symmetry of Nature, but left open the question whether the pattern of CP violation predicted by the Standard Model is correct (e.g., “superweak” interactions?)

* confirmation of CP violation in $K \rightarrow \pi \pi$ decays (“direct CP violation”, parameter $\epsilon'$) in 1999 proved that CP is violated in flavor-changing charged-current interactions, as predicted by the Standard Model:

\[ \delta_{\text{CKM}} = \gamma \text{ in CKM matrix} \]

\[ \Rightarrow \text{CP violation in mixing and weak decays} \]
\[
\text{Re}\left(\frac{\epsilon'}{\epsilon}\right) \approx 13 \left[ (1 - \Omega_{\eta\eta'}) B_6^{(1/2)} - 0.4 B_8^{(3/2)} + \ldots \right] \\
\text{hadronic matrix elements}
\]

\[
\times \frac{\text{Im}(V_{td}V_{ts}^*)}{|V_{ub}| |V_{cb}| \sin \gamma}
\]

* ideally, would determine \( \sin \gamma \)...

... if we only knew how to compute the \textit{hadronic matrix elements}!

* \textbf{but}: order of magnitude is as predicted by the \textit{Standard Model}!
* CKM mechanism relates all CP-violating observables to a single parameter $\delta_{\text{CKM}}$

  • very predictive!

  • in particular, expect large CP asymmetries in some $B$ decays

* important: $B$ system is more accessible to a solid theoretical analysis, since $m_b \gg \Lambda_{\text{QCD}}$

  • strong-interaction effects can be dealt with using heavy-quark expansions, i.e., expansions in powers of $\alpha_s(m_b) \ll 1$ and $\Lambda_{\text{QCD}}/m_b \ll 1$

  • systematic, model-independent framework with controlled theoretical uncertainties
The CKM Paradigm

Cabibbo–Kobayashi–Maskawa matrix:

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

3 × 3 unitary matrix connecting mass eigenstates of down-type quarks with interaction eigenstates

→ described by 4 real parameters

Wolfenstein parameterization:

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

• accurately known: \( |V_{us}| \) and \( |V_{cb}| \) (\( \lambda \) and \( A \))

• more uncertain: \( |V_{ub}| \) and \( |V_{td}| \) (\( \rho \) and \( \eta \))
* in past 15 years, strong combined efforts of several complementary experiments \((e^+e^- \text{ at } \Upsilon(4S), e^+e^- \text{ at } Z^0, \text{ hadron colliders})\), accompanied by significant progress in theory, has led to tremendous advances in our knowledge of the CKM matrix

**Example 1:** \(|V_{cb}|(1990) = 0.043 \pm 0.010\), whereas 
\(|V_{cb}|(1999) = 0.040 \pm 0.002\) has a precision not much worse than that in the Cabibbo angle

**Example 2:** \(|V_{ub}|(1990) \equiv 0\) still possible since \(b \rightarrow u\) decays were not yet observed, whereas 
\(|V_{ub}|(1999) = (3.4 \pm 0.7) \cdot 10^{-3}\) is known with 20\% accuracy despite its smallness
Example 3: exploring the ($\rho, \eta$)-plane

(F. Caravaglions et al., 2000)
Unitarity triangle:

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

* combining the measurements of \( |V_{ub}| \) in semi-leptonic decays, \( |V_{td}| \) in \( B_{d,s} - \bar{B}_{d,s} \) mixing, and \( \epsilon_K \) in \( K - \bar{K} \) mixing, the parameters of the unitarity triangle are determined already with great accuracy:

(F. Caravagllos et al., 2000)

- \( \bar{\rho} = 0.240^{+0.057}_{-0.047} \) and \( \bar{\eta} = 0.335 \pm 0.042 \)
- \( \sin 2\beta = 0.750^{+0.058}_{-0.064} \), \( \sin 2\alpha = -0.38^{+0.24}_{-0.28} \)
  
  and \( \gamma = (55.5^{+6.0}_{-8.5})^\circ \)
**Key feature:**

* in SM, all CP violation results from a single complex phase $\delta_{\text{CKM}} = \gamma = \arg(V_{ub}^*)$ in the CKM matrix

→ beginning to be tested by confronting measurements of $\epsilon_K$ (from $K-\bar{K}$ mixing) and $\sin 2\beta$ (from $B \to J/\psi K_S$ decays) with information obtained from measurements of CP-conserving quantities ($|V_{ub}|$, $\Delta m_d$, $\Delta m_s$)
Where Do We Go from Here?

* precise determination of $\rho$ and $\eta$ in itself is only one of many goals

* focus has now shifted towards testing the consistency of the entire CKM picture

  $\rightarrow$ 4 parameters, unitarity relations, 1 phase
  (not just checking “whether the triangle closes”)

* in addition, $B$ factories are now in focus for having a realistic chance of finding deviations from the SM

* to this end:

  - need many different, independent measurements of the unitarity triangle using $B_d$, $B_s$ and $K$ decays, and based on CP-conserving and CP-violating processes

  - need many manifestations of CP violation, in mixing (“indirect”), decay (“direct”), and their interference

  - need to test for New Physics in rare processes (penguins and boxes)
The Tools

* several existing and approved facilities, as well as proposed new experiments, will help us to explore the quark sector with unprecedented precision

**B factories:**

* Existing $e^+e^-$ colliders at $\Upsilon(4S)$:
  - BaBar (SLAC), Belle (KEK), CLEO-3 (Cornell), HERA-B (DESY)

→ BaBar and Belle plan luminosity upgrades in several stages

→ PEP-II as an example (similar for KEK-B):

<table>
<thead>
<tr>
<th>Year</th>
<th>$\mathcal{L}$ (cm$^{-2}$ s$^{-1}$)</th>
<th>$B\bar{B}$ (yr$^{-1}$)</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000–2002</td>
<td>$3 \times 10^{33}$</td>
<td>$20 \times 10^6$</td>
<td>$60 \times 10^6$</td>
</tr>
<tr>
<td>Phase 2:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003–2005</td>
<td>$1 \times 10^{34}$</td>
<td>$67 \times 10^6$</td>
<td>$260 \times 10^6$</td>
</tr>
<tr>
<td>Phase 3:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006–2008</td>
<td>$3 \times 10^{34}$</td>
<td>$200 \times 10^6$</td>
<td>$860 \times 10^6$</td>
</tr>
</tbody>
</table>
→ will have about $2.5 \times 10^8 \, B \bar{B}$ pairs per experiment at end of phase 2, and about $10^9 \, B \bar{B}$ pairs per experiment at end of phase 3

* Existing hadron collider:

  • CDF and D0 (Fermilab) at Tevatron Run-II

* Approved hadron colliders:

  • BTeV (Fermilab), LHC-b (CERN)

→ will produce about $4 \times 10^{11} \, B \bar{B}$ pairs per year at luminosity $\mathcal{L} = 2 \times 10^{32} \, \text{cm}^{-2} \, \text{s}^{-1}$

→ trigger and particle reconstruction are big issues!

* Future possibilities:

  • High-luminosity $e^+e^-$ collider
    $(\mathcal{L} \sim 10^{35-36} \, \text{cm}^{-2} \, \text{s}^{-1})$ at $\Upsilon(4S)$

  • High-luminosity $e^+e^-$ collider
    $(\mathcal{L} \sim 10^{33-34} \, \text{cm}^{-2} \, \text{s}^{-1})$ at $Z^0$ ("Giga-$Z$")
Rare kaon experiments:

* measurements of $K \rightarrow \pi \nu \bar{\nu}$ provide direct information on the Wolfenstien parameters $\rho$ and $\eta$, and are theoretically very clean:

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \Rightarrow |V_{td} V_{ts}^*| \sim |1 - \rho - i\eta| \]
\[ K^0_L \rightarrow \pi^0 \nu \bar{\nu} \Rightarrow \text{Im}(V_{td} V_{ts}^*) \sim \eta \]

Existing and approved experiments:

- E787 (BNL) has reported 1 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ event, corresponding to a branching ratio of $(1.5^{+3.5}_{-1.3}) \times 10^{-10}$ — about twice the SM prediction

- modestly upgraded experiment E949 (BNL) expects about 10 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events in SM

Proposed experiments:

- CKM (Fermilab) expects about 100 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events in SM

“Contemplated” experiments:

- K0PI0 (BNL) and KAMI (Fermilab) expect about 65 $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ events in SM
Part II:
Charmless Hadronic $B$ Decays
**Reason for Excitement**

* recent experimental data on charmless hadronic $B$ decays from CLEO, BaBar and Belle have caused a lot of excitement in the theory community

→ here focus on $B \to \pi K$ and $B \to \pi\pi$ decays, which at present are best understood theoretically

* in general, sensitivity to CP-violating “weak” phases requires sizable interference of decay topologies which differ in their CKM parameters

* in charmless hadronic $B$ decays, there is significant interference of tree and penguin topologies!

<table>
<thead>
<tr>
<th>Tree</th>
<th>Penguin</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{ub} V_{us}^* \sim \lambda^4 e^{-i\gamma}$</td>
<td>$V_{tb} V_{ts}^* \sim \lambda^2$</td>
<td>$</td>
</tr>
<tr>
<td>$V_{ub} V_{ud}^* \sim \lambda^3 e^{-i\gamma}$</td>
<td>$V_{tb} V_{td}^* \sim \lambda^3 e^{i\beta}$</td>
<td>$</td>
</tr>
</tbody>
</table>
* implies potentially large CP asymmetries, e.g.:
\[
A_{CP}(B^\pm \to \pi^0 K^\pm) \approx 2 \left| \frac{T}{P} \right| \sin \gamma \quad \sin \delta_{st}
\]

\approx 0.5

strong phase

* sensitivity to \( \gamma \) also in CP-averaged rates, e.g.:
\[
\frac{\Gamma(B \to \pi^+ K^{\pm})}{\Gamma(B \to \pi^{\pm} K_S)} \approx 1 + 2 \left| \frac{T}{P} \right| \cos \gamma \cos \delta_{st}
\]

* varying \(-1 \leq \cos \delta_{st} \leq 1\) yields bounds on \( \cos \gamma \):

→ Fleischer–Mannel bound, Neubert–Rosner bound

→ see lectures by Helen Quinn at last year’s SSI

* in some cases, one can use symmetries (isospin, Fierz relations, SU(3)) to eliminate hadronic uncertainties

* to do better, need a theory of hadronic \( B \) decays

→ recent progress using the heavy-quark expansion
The Challenge

* theoretical description of hadronic weak decays is difficult due to non-perturbative hadronic dynamics
* this affects interpretation of $B$ factory data, studies of CP violation, and searches for New Physics
* the problem:

\[ \begin{align*}
\mathcal{H}_{\text{eff}} &= \frac{G_F}{\sqrt{2}} \sum_i \lambda_i^{\text{CKM}} C_i(\mu) O_i(\mu) \\
\end{align*} \]

* difficulty is to calculate hadronic matrix elements of local operators $O_i(\mu)$
“Naive” factorization:

* consider $\bar{B}^0 \rightarrow D^+ \pi^-$ as an example:

$$A_{\bar{B}^0 \rightarrow D^+ \pi^-} \sim \left( C_1 + \frac{C_2}{N_c} \right) \langle D^+ \pi^- | (\bar{d}u)(\bar{c}b) | \bar{B}^0 \rangle$$

$$+ 2C_2 \langle D^+ \pi^- | (\bar{d}t\bar{u})(\bar{c}t\bar{b}) | \bar{B}^0 \rangle$$

$$\xrightarrow{\text{fact.}} \left( C_1 + \frac{C_2}{N_c} \right) \langle \pi^- | (\bar{d}u) | 0 \rangle \langle D^+ | (\bar{c}b) | \bar{B}^0 \rangle$$

$$\sim f_\pi \sim F_0^{B \rightarrow D}$$

hence:

$$A_{\bar{B}^0 \rightarrow D^+ \pi^-} \sim G_F V_{cb} V_{ud}^* f_\pi F_0^{B \rightarrow D} (m_\pi^2) a_1$$

with

$$a_1 = C_1(\mu) + \frac{C_2(\mu)}{N_c}$$

* similarly, define parameter $a_2 = C_2 + C_1/N_c$, and further parameters $a_3, \ldots, a_{10}$ for more complicated decays

Problem: $a_i$ are renormalization-scale and -scheme dependent in “naive” factorization!
**QCD Factorization Formula**

\[
\langle M_1 M_2 | O_i | B \rangle = F^B_{j \rightarrow M_1} f_{M_2} T^I_{ij} \otimes \Phi_{M_2} \\
+ T^I_{ij} \otimes \Phi_B \otimes \Phi_{M_1} \otimes \Phi_{M_2} \\
+ \text{power suppressed contributions}
\]

(M. Beneke et al., 1999–2000)

* if \( M_1 \) is heavy, the second term is power suppressed and should be dropped

* factorization does not hold if \( M_2 \) is a heavy-light meson, but it works for an onium state such as \( J/\psi \)

* validity of factorization formula demonstrated by explicit 1-loop (and 2-loop) calculation; general arguments support factorization to all orders in perturbation theory
Implications:

* obtain approach that allows for a systematic, model-independent calculation of corrections to “naive” factorization, which emerges as leading term in heavy-quark limit

* possibility to compute systematically logarithmic corrections to “naive” factorization solves problem of scale and scheme dependences (scale and scheme dependences of hard scattering kernels compensate those of Wilson coefficients)

* non-factorizable corrections are process dependent and hence non-universal, in contrast with basic assumption of “generalized” factorization models

* strong FSI and rescattering phases are calculable and are perturbative or power suppressed (soft rescattering vanishes in the heavy-quark limit)
**\( \bar{B}^0 \to D^{(*)+} L^- \) Decays**

* useful to define “transition operator”:

\[
\mathcal{T} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{cb} \left[ a_1^{D_L} \bar{c} \gamma_\mu b \otimes \bar{d} \gamma^\mu (1 - \gamma_5) u \\
- a_1^{D^*_L} \bar{c} \gamma_\mu \gamma_5 b \otimes \bar{d} \gamma^\mu (1 - \gamma_5) u \right]
\]

* obtain explicit, renormalization-scheme invariant expression for parameters \( a_1 \) at next-to-leading order in \( \alpha_s \) and leading power in \( \Lambda_{QCD}/m_b \):

\[
a_1 = C_1(\mu) + \frac{C_2(\mu)}{N_c} + \frac{C_2(\mu)}{N_c} \frac{C_F \alpha_s}{4 \pi} \left[ 12 \ln \frac{m_b}{\mu} - B + \Delta_{D^{(*)}} \left( \frac{m_c}{m_b} \right) \right]
\]

with

\[
\Delta_{D^{(*)}}(z) = \int_0^1 dx \Phi_L(x) T_{D^{(*)}}(x, z)
\]

process-dependent, non-universal correction

* however, for these decays \( |a_1^{D^{(*)+}L}| = 1.05 \pm 0.02 \)
Predictions for class-I decay amplitudes:

Model-independent predictions for the branching ratios (in units of $10^{-3}$) of $\bar{B}_d \to D(\ast)^+ L^-$ decays in the heavy-quark limit. Theory numbers are $\times (|V_{cb}|/0.04)^2 \times (|a_1|/1.05)^2 \times (\tau_{B_d} / 1.56 \text{ ps})$.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Theory (HQL)</th>
<th>PDG98</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B}_d \to D^+ \pi^-$</td>
<td>$3.27 \times [F_+(0)/0.6]^2$</td>
<td>$3.0 \pm 0.4$</td>
</tr>
<tr>
<td>$\bar{B}_d \to D^+ K^-$</td>
<td>$0.25 \times [F_+(0)/0.6]^2$</td>
<td>$7.9 \pm 1.4$</td>
</tr>
<tr>
<td>$\bar{B}_d \to D^+ \rho^-$</td>
<td>$7.64 \times [F_+(0)/0.6]^2$</td>
<td></td>
</tr>
<tr>
<td>$\bar{B}_d \to D^+ K^{*-}$</td>
<td>$0.39 \times [F_+(0)/0.6]^2$</td>
<td>$6.0 \pm 3.3$</td>
</tr>
<tr>
<td>$\bar{B}_d \to D^+ a_1^-$</td>
<td>$7.76 \times [F_+(0)/0.6]^2$</td>
<td></td>
</tr>
<tr>
<td>$\bar{B}_d \to D^{*+} \pi^-$</td>
<td>$3.05 \times [A_0(0)/0.6]^2$</td>
<td>$2.8 \pm 0.2$</td>
</tr>
<tr>
<td>$\bar{B}_d \to D^{*+} K^-$</td>
<td>$0.22 \times [A_0(0)/0.6]^2$</td>
<td>$6.7 \pm 3.3$</td>
</tr>
<tr>
<td>$\bar{B}_d \to D^{*+} \rho^-$</td>
<td>$7.59 \times [A_0(0)/0.6]^2$</td>
<td></td>
</tr>
<tr>
<td>$\bar{B}_d \to D^{<em>+} K^{</em>-}$</td>
<td>$0.40 \times [A_0(0)/0.6]^2$</td>
<td></td>
</tr>
<tr>
<td>$\bar{B}_d \to D^{*+} a_1^-$</td>
<td>$8.53 \times [A_0(0)/0.6]^2$</td>
<td>$13.0 \pm 2.7$</td>
</tr>
</tbody>
</table>

* good agreement may be taken as indication that in these decays there are no unexpectedly large power corrections

$\rightarrow$ confirmed by explicit estimates!
**Extraction of \( \cos \gamma \) in \( B \to \pi K, \pi\pi \)**

* applying the QCD factorization formula to the present case gives

\[
\langle \pi K | H_{\text{eff}} | B \rangle = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb}^* V_{ps} \langle \pi K | T_p | B \rangle
\]

with the “transition “operator”:

\[
T_p = a_1^{\pi K} \delta_{pu} (\bar{b}u)_{V-A} \otimes (\bar{u}s)_{V-A} \\
+ a_2^{\pi K} \delta_{pu} (\bar{b}s)_{V-A} \otimes (\bar{u}u)_{V-A} \\
+ a_3^{\pi K} \sum_q (\bar{b}s)_{V-A} \otimes (\bar{q}q)_{V-A} \\
+ a_4^{\pi K} \sum_q (\bar{b}q)_{V-A} \otimes (\bar{q}s)_{V-A} \\
+ a_5^{\pi K} \sum_q (\bar{b}s)_{V-A} \otimes (\bar{q}q)_{V+A} \\
+ a_6^{\pi K} (\mu) \sum_q (-2)(\bar{b}q)_{S-P} \otimes (\bar{q}s)_{S+P} \\
+ a_7^{\pi K} \sum_q (\bar{b}s)_{V-A} \otimes \frac{3}{2} e_q (\bar{q}q)_{V+A} \\
+ a_8^{\pi K} (\mu) \sum_q (-2)(\bar{b}q)_{S-P} \otimes \frac{3}{2} e_q (\bar{q}s)_{S+P} \\
+ a_9^{\pi K} \sum_q (\bar{b}s)_{V-A} \otimes \frac{3}{2} e_q (\bar{q}q)_{V-A} \\
+ a_{10}^{\pi K} \sum_q (\bar{b}q)_{V-A} \otimes \frac{3}{2} e_q (\bar{q}s)_{V-A}
\]
* contributions of \((S - P) \otimes (S + P)\) penguin operators are multiplied by a factor:

\[
\frac{2\mu_K}{m_b} = \frac{2m_K^2}{(m_s + m_d)m_b} \sim \frac{\Lambda_{QCD}}{m_b} \quad [\approx 0.8]
\]

→ include all such “chirally enhanced” power corrections, since they are numerically important

* terms proportional to the same factor also appear at twist-3 order in the collinear expansion

* these terms involve the logarithmically IR-divergent integral:

\[
X = \int_0^1 \frac{du}{1-u}
\]

indicating the dominance of soft gluon exchange (violation of factorization at next-to-leading power)

* set \(X = \ln(m_B/\Lambda) + r\) with \(r\) a complex random number such that \(|r| < 3\) (“realistic” \(\rightarrow\) blue dots) or \(|r| < 6\) (“conservative” \(\rightarrow\) green dots)

* vary all theory parameters over conservative ranges: renormalization scale, quark masses, wave function parameters, \(X\) parameters, etc.
* focus on ratios of decay rates, which are independent of semi-leptonic form factors:

(M. Beneke et al., hep-ph/0007256)

* with more data, comparison with these predictions will provide a crucial test of the approach
* this will determine $\gamma$ up to a sign ambiguity

* at present, experimental errors are too large to obtain a meaningful determination:

* in future, this will be a powerful analysis

* sign of $\gamma$ can be determined by comparing direct CP asymmetries with theoretical predictions

$\rightarrow$ ultimately, will obtain $\gamma$ without any discrete ambiguities!
Some modes to keep an eye on:

* branching ratios with $\gamma = (60 \pm 20) \degree$ and $|V_{ub}/V_{cb}| = 0.085$:

\[
\text{Br}(B \rightarrow \pi^+\pi^-) = (9 \pm 2) \cdot 10^{-6} \times (F_{B \rightarrow \pi}^+/0.3)^2
\]

\[
\text{Br}(B \rightarrow \pi^0K^0) = (4.5 \pm 2.5) \cdot 10^{-6} \times (F_{B \rightarrow \pi}^+/0.3)^2
\]

* first result is larger than CLEO $(4.3 \pm 1.6)$, but in good agreement with BaBar $(9.3 \pm 2.8)$ and Belle $(6.3 \pm 4.0)$

* second result is smaller than CLEO $(14.6 \pm 6.2)$ and Belle $(21.0 \pm 8.9)$
Direct CP Asymmetries

* generic theoretical prediction:
  strong phases are suppressed (subleading in the heavy-quark expansion), except for very rare decays such as $B \rightarrow \pi^0 \pi^0$

* implies that direct CP asymmetries will be much below the present CLEO bounds:

* observing these asymmetries is an important long-term goal!
Part III:
Mixing-Induced CP Violation
**Strong Phases from Quantum Mechanics**

* in $B$ decays into a CP eigenstate $f_{CP}$, observable CP asymmetries can arise from interference of weak phases in the amplitudes for $B - \bar{B}$ mixing and decay:

$$
B^0 \rightarrow f_{CP} \quad \text{mixing} \sim e^{-2i\beta} \quad \bar{B}^0 \rightarrow f_{CP}
$$

* resulting time-dependent CP asymmetry:

$$
A_{CP}(t) = \frac{\Gamma(B^0 \rightarrow f_{CP}) - \Gamma(\bar{B}^0 \rightarrow f_{CP})}{\Gamma(B^0 \rightarrow f_{CP}) + \Gamma(\bar{B}^0 \rightarrow f_{CP})} \approx -\frac{2 \text{Im}\lambda}{1 + |\lambda|^2} \sin(\Delta m_B t) + \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos(\Delta m_B t)
$$

where:

$$
\lambda = e^{-2i\beta} \frac{\bar{A}}{A} = \eta_{f_{CP}} e^{-2i\beta} \sum_i \frac{A_i e^{i\delta_i} e^{-i\phi_i}}{\sum_i A_i e^{i\delta_i} e^{i\phi_i}}
$$
* if the decay amplitude is dominated by a single weak phase $\phi_A$, then $|\lambda| \simeq 1$ and

$$\text{Im}(\lambda) \simeq -\eta_{f_{\text{CP}}} \sin 2(\beta + \phi_A)$$

**Example 1:**

$\sin 2\beta$ from $B \to J/\psi K_S$ decays

$(b \to c\bar{c}s$ transitions, $\eta_{J/\psi K_S} = -1)$

<table>
<thead>
<tr>
<th>Tree</th>
<th>Penguin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{cb}V_{cs}^* \sim \lambda^2$</td>
<td>$V_{tb}V_{ts}^* \sim \lambda^2, \lambda^4 e^{-i\gamma}$</td>
</tr>
</tbody>
</table>

hence: $\phi_A \simeq 0 \Rightarrow \text{Im}(\lambda) \simeq \sin 2\beta$

* above discussion relies on Standard Model

* it could be upset if there existed a New Physics contribution to $b \to c\bar{c}s$ transitions with $\phi_{\text{NP}} \neq 0$
* but such a contribution would also yield 

\[ A_{CP}(B^\pm \rightarrow J/\psi K^\pm) \sim \sin \delta_{st} \sin \phi_{NP} \neq 0 \]

* unless strong phase \( \delta_{st} \) vanishes accidentally, there is not much room given the CLEO result:

\[ A_{CP}(B^\pm \rightarrow J/\psi K^\pm) = (1.8 \pm 4.3 \pm 0.4)\% \]

**Example 2:**

\( \sin 2\alpha \) from \( B \rightarrow \pi^+ \pi^- \) decays

\( (b \rightarrow u\bar{u}d \ transitions, \ \eta_{\pi^+\pi^-} = 1) \)

\[
\begin{array}{ccc}
  b & \rightarrow & u \\
  \downarrow W & & \downarrow W \\
  u & \rightarrow & u, d \\
  \downarrow & & \downarrow \\
  W & \rightarrow & d \\
  \downarrow & & \downarrow \\
  & \rightarrow & u, d
\end{array}
\]

<table>
<thead>
<tr>
<th>Tree</th>
<th>Penguin</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{ub}V_{ud}^* \sim \lambda^3 e^{-i\gamma} )</td>
<td>( V_{tb}V_{td}^* \sim \lambda^3 e^{i\beta} )</td>
</tr>
</tbody>
</table>

hence: \( \phi_A \simeq \gamma + \text{“penguin pollution”} \)

\( \Rightarrow \text{Im}(\lambda) \simeq \sin 2\alpha \times [1 + O(P/T)] \)

* conventional way to circumvent this problem is to perform an isospin analysis, using measurements of \( B \rightarrow \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0 \) and their CP conjugates (nearly impractical)
**Extraction of \( \sin 2\alpha \) in \( B \to \pi^+\pi^- \)**

* QCD factorization approach can be used to calculate the “penguin pollution” in \( B \to \pi^+\pi^- \), thereby allowing a determination of \( \alpha \) without isospin analysis

* time-dependent, mixing-induced CP asymmetry in \( B_d \to \pi^+\pi^- \) decays:

\[
A_{\text{CP}}(t) = \frac{\Gamma(B^0(t) \to \pi^+\pi^-) - \Gamma(\bar{B}^0(t) \to \pi^+\pi^-)}{\Gamma(B^0(t) \to \pi^+\pi^-) + \Gamma(\bar{B}^0(t) \to \pi^+\pi^-)}
\]

\[
= - S \cdot \sin(\Delta m_B t) + C \cdot \cos(\Delta m_B t)
\]

* without “penguin pollution”:

\[
S = \sin 2\alpha \ , \quad C' = 0
\]

free of hadronic uncertainties

* interference of tree and (subdominant) penguin topologies introduces hadronic uncertainties, which can be controlled by applying the QCD factorization theorem to the \( B \to \pi\pi \) decay amplitudes
we can calculate this effect with small theoretical uncertainty: (M. Beneke et al., hep-ph/0007256)

\[ \sin(2\beta) = 0.75 \]

consistency check is provided by the calculation of the direct CP asymmetry (= C):

\[ A_{CP} \]
Part IV:
Looking Ahead... Beyond the Standard Model
Many Determinations of the UT

* generalize discussion presented by Peskin at LP99, indicating precision that could be achieved 10 years from now:

* pursue different strategies, the most important ones being as follows...
(a) **Non-CP triangle:**

determine the triangle by measuring the length of the two sides in semi-leptonic $B$ decays ($|V_{ub}|$ from exclusive and inclusive $B \to X_u \ell \nu$ decays) and $B_{d,s} - \bar{B}_{d,s}$ mixing ($|V_{td}|$ from $\Delta m_d$ and $\Delta m_s$)

$\to$ no CP violation involved

$\to$ main sensitivity to New Physics via magnitude of $B - \bar{B}$ mixing amplitude
(b) $B$ triangle:

determine the angles $\beta$, $2\beta + \gamma$, and $\beta + \gamma$ by measuring time-dependent CP violation in $B \rightarrow J/\psi K_S$, $B \rightarrow D(\ast)^{\pm} \pi^{\mp}$, and $B \rightarrow \pi \rho$

$\rightarrow$ CP violation in interference of mixing and decay

$\rightarrow$ main sensitivity to New Physics via mixing

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Tree</th>
<th>Mix + Tree</th>
<th>$e^+e^-$</th>
<th>hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow J/\psi K_S$ $(b \rightarrow c\bar{c}s, \bar{b} \rightarrow \bar{c}c\bar{s})$</td>
<td>1</td>
<td>$e^{2i\beta}$</td>
<td>P1,P2</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$B \rightarrow D(\ast)^{\pm} \pi^{\mp}$ $(b \rightarrow c\bar{u}d, \bar{b} \rightarrow \bar{u}c\bar{d})$</td>
<td>1</td>
<td>$\lambda^2 e^{i(2\beta + \gamma)}$</td>
<td>P2,P3</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$B \rightarrow \pi \rho$ $(b \rightarrow u\bar{u}d, \bar{b} \rightarrow \bar{u}u\bar{d})$</td>
<td></td>
<td>$e^{-i\gamma}$ $e^{i(2\beta + \gamma)}$</td>
<td>P2,P3</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>
(b’) \( B \) triangle:

determine the angle \( \gamma \) using isospin analysis in 
\( B^\pm \rightarrow DK^\pm \) decays

\( \rightarrow \) only tree amplitudes involved

\( \rightarrow \) lowest sensitivity to New Physics of all weak phase determinations!

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Tree</th>
<th>Tree</th>
<th>( e^\pm e^- )</th>
<th>hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^\pm \rightarrow DK^\pm ) ( (b \rightarrow c\bar{u}s, \ b \rightarrow u\bar{c}s) )</td>
<td>1</td>
<td>( e^{i\gamma} )</td>
<td>P2?, P3</td>
<td>?</td>
</tr>
</tbody>
</table>
(c) $B_s$ triangle:

determine the angle $\gamma - 2\chi$ and the $B_s$ mixing phase $-\chi$ (SM predicts $\chi = O(\lambda^2 \eta)$ of order 1%) by measuring CP asymmetries in $B_s$ decays, such as $B_s \to D_s^\pm K^\mp$, and $B_s \to J/\psi \phi$ or $B_s \to J/\psi \eta^{(i)}$

→ CP violation in interference of mixing and decay

→ main sensitivity to New Physics via mixing

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Tree</th>
<th>Mix + Tree</th>
<th>$e^+e^-$</th>
<th>hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to J/\psi \phi$ or $\eta^{(i)}$ ($b \to c\bar{c}s$, $\bar{b} \to \bar{c}cs$)</td>
<td>1</td>
<td>$e^{-2i\chi}$</td>
<td>-</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$B_s \to D_s^\pm K^\mp$ ($b \to c\bar{u}s$, $\bar{b} \to \bar{u}cs$)</td>
<td>1</td>
<td>$e^{i(-2\chi + \gamma)}$</td>
<td>-</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>
(d) $K$ triangle:

determine the coordinates $(\rho, \eta)$ from measurements of rare $K$ decays ($K^+ \to \pi^+ \nu \bar{\nu}$ and $K^0_L \to \pi^0 \nu \bar{\nu}$) and $K-\bar{K}$ mixing ($\epsilon_K$)

$\rightarrow$ CP violation in mixing and decay

$\rightarrow$ sensitivity to New Physics in mixing and decay

* performing these measurements is of comparable importance as the $B_s$ physics program at hadron $B$ factories!
**Strategy for Exploring New Flavor Physics**

Q: What if $\sin 2\beta_{\psi K}$ is low?

Q: More generally, what if there is New Physics affecting the particle–antiparticle mixing amplitudes of $B_d$, $B_s$ and $K$ mesons?


* then none of the triangle constructions discussed above should really close!

* need a reference triangle constructed independently of any information from mixing

  • $B$ system: extract $|V_{ub}|$ from semi-leptonic $B$ decays, and $\gamma = \arg(V_{ub}^*)$ using a variety of methods (e.g., charmless hadronic decays, $B \rightarrow DK$ decays, $B_s$ decays)

  • $K$ system: extract $|V_{td}|$ and $\text{Im}(V_{td})$ from $K \rightarrow \pi \nu \bar{\nu}$ decays
Reference triangle in the near and long-term future:

(a) $B$-decay triangle with two-fold ambiguity, assuming uncertainties of 20\% in $|V_{ub}/V_{cb}|$ and $\pm 25^\circ$ in $\gamma$ (near-term).

(b) $B$-decay triangle (pink) with no ambiguity, assuming uncertainties of 10\% in $|V_{ub}/V_{cb}|$ and $\pm 10^\circ$ in $\gamma$, and $K$-decay triangle (gold) with four-fold ambiguity, assuming 15\% uncertainties in $R_t$ and $|\eta|$ (long-term).
* once the reference triangle is known, one can explore separately potential New Physics contributions to mixing in the $B_d$, $B_s$ and $K$ systems

* knowledge of $\gamma$ is the key ingredient that makes this strategy feasible and powerful!

**New Physics in $K-\bar{K}$ mixing:**

![Diagram showing the dependence of $|\epsilon_K|$ on $\gamma$](image)

New Physics contribution to $|\epsilon_K|$ in units of $10^{-3}$, assuming present day uncertainties (region bounded by blue curves, using $B_K = 0.86 \pm 0.10$ and $|V_{ub}/V_{cb}| = 0.085 \pm 0.018$) and future smaller errors (region bounded by green curves, using $B_K = 0.86 \pm 0.05$ and $|V_{ub}/V_{cb}| = 0.085 \pm 0.009$).
**New Physics in $B_d$–$\bar{B}_d$ mixing:**

![Diagrams](image)

Determination of the $B_d$–$\bar{B}_d$ mixing amplitude $M_{12}$ with present day (left) and future (right) uncertainties on the input parameters.

(a) **Standard Model contribution** $M_{12}^{\text{SM}}$ (region bounded by dashed circles) with marks indicating fixed values of $\gamma$. The experimentally determined regions for $M_{12}$ are shown for $\sin 2\phi_d = 0.26 \pm 0.29$.

(b) **New Physics contribution** $M_{12}^{\text{NP}}$ corresponding to the four different solutions for $\gamma$ and $2\phi_d$. 
New Physics in Penguins

* above strategies are sensitive to New Physics mainly via the $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing amplitudes (box diagrams)

![](image1)

* there is, in addition, a large class of loop-dominated processes sensitive to New Physics in the decay amplitude (penguins)

![](image2)

* consider some examples of how to explore this type of New Physics...
1. determine $\beta$ from interference of mixing and decay in the penguin-mediated mode $B \to \phi K_S$, and compare with $\beta$ from $B \to J/\psi K_S$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Peng.</th>
<th>Mix + Peng.</th>
<th>$e^\pm e^-$</th>
<th>hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to \phi K$</td>
<td>1</td>
<td>$e^{2i\beta}$</td>
<td>P2, P3</td>
<td>✓</td>
</tr>
<tr>
<td>($b \to s\bar{s}s, \bar{b} \to \bar{s}s\bar{s}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. certain observables are particularly sensitive to New Physics contributions to chromo-magnetic or chromo-electric dipole operators

→ direct CP asymmetry in inclusive radiative decays $B^\pm \to X_s \gamma$ is a clean probe of such effects, with basically no SM background

3. certain observables are particularly sensitive to isospin-violating New Physics contributions in \( b \to s(d) + \bar{q}q \) transitions (with \( q = u \) or \( d \))

→ potentially large effect on \( \gamma \) determined from \( B \to \pi K \) decays, which would show up if \( \gamma_{\pi K} \) is compared with \( \gamma_{\text{tree}} = \gamma_{DK} \) or \( \gamma_{\pi \rho} \):

(Y. Grossman et al., 1999)

| New Physics Model                        | \(| \gamma_{\pi K} - \gamma_{\text{tree}} | \) | \(| \gamma_{\pi K} - \gamma_{\text{tree}} | \) |
|------------------------------------------|---------------------------------|---------------------------------|
|                                          | isospin-cons. | isospin-viol. |
| FCNC \( Z \) exchange                    | 3°               | 180°            |
| Extra \( Z' \) boson                     | 180°             | 180°             |
| SUSY without R-parity                    | 180°             | 180°             |
| SUSY with R-parity:
  max. \( \tilde{s}_R - \tilde{b}_R \) mixing | 7°               | 25°              |
  max. \( \tilde{s}_L - \tilde{b}_L \) mixing | 7°               | 180°             |
| 2-Higgs-doublet model
  \((m_{H^+} > 100 \text{ GeV}, \tan\beta > 1)\)
  anom. gauge-boson couplings | 0°               | 10°              |

|                                           | 0°               | 20°              |
Instead of a Summary...
Four Reasons Why B Physics is Cooler than String Theory

1. \textit{B} theorists look forward to confronting experiment.
   String theorists look forward to \textit{not} confronting experiment.

2. \textit{B} theorists make effective theories:
   heavy-quark effective theory, large-energy effective theory, non-relativistic effective theory...
   String theorists make:
   \textit{A} theory (of the Universe) ... \textit{K} theory ... \textit{M} theory ...
   1-branes ... 5-branes ... \textit{d}-branes ... \textit{p}-branes ...

3. String theorists dream of a \textit{Theory of Everything}.
   \textit{B} theorists have a \textit{Theory of Something}.

4. We know what we are talking about...