Recent CP Violation Results from the B Factories and their Implications on the CKM Paradigm

Taming(*) the Penguin to Determine $\alpha$

Andreas Höcker
LAL - Orsay

DESY Seminar
November 19, 2002

Determining the *CP*-Violating CKM Phase

**CP Violation (CPV) in B and K Systems:**
- CPV in interference of decays with and without mixing
- CPV in mixing
- CPV in interference between decay amplitudes

**Neutral $B_d$ and $B_s$ Mixing**

**Precise Determination of the Matrix Elements $|V_{ub}|$ and $|V_{cb}|$**

**Detection of Rare Decays:**
- Determination of weak phases
- Search for new physics and direct CPV
CP Violation in the Standard Model

- Local SU(2) invariance of $\mathcal{L}_{SM}$ with doublets $(\nu_{iL}, l_{iL}), (u_{iL}, d_{iL}), i=1..3$ gives rise to charged weak currents

- Mass terms: $m_i \left( f_L f_R + f_R f_L \right)$ require scalar doublet $(\phi_1, \phi_2)$

- Spontaneous symmetry breaking leads to $3 \times 3$ quark mass matrices

$$M_{u(d)} = \frac{v}{\sqrt{2}} \frac{g_{u(d)}}{\sqrt{2}}$$

- Unitary rotation from mass to flavour eigenstates via

$$U_{u(d,e)} M_{u(d,e)} U_{u(d,e)}^+ = \text{diag} \left( m_{u(d,e)}, m_{c(s,\mu)}, m_{t(b,\tau)} \right)$$

- Modifies $\mathcal{L}_{SM}$ for charged weak currents:

$$V_{CKM} = U_u U_d^+ \quad (V_{CKM} V_{CKM}^\dagger = \text{Id})$$

CKM Matrix

Kobayashi, Maskawa 1973
The Cabibbo-Kobayashi-Maskawa Matrix

Mass eigenstates ≠ Flavor eigenstates → Quark mixing

**B and K mesons decay weakly**

→ modified couplings for charged weak currents:

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

\[V_{\text{CKM}}\text{ unitary and complex} \Rightarrow 4 \text{ real parameters (3 angles and 1 phase)}\]

Kobayashi, Maskawa 1973

**Wolfenstein Parameterization** (expansion in \(\lambda \sim 0.2\)):

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

CPV phase

“Explicit” CPV in SM, if:

\[
J = \text{Im} \left( V_{ij} V_{k\ell} V_{i\ell}^* V_{kj}^* \right) \neq 0
\]

(phrase invariant!)

Jarlskog 1985

\[J \approx A^2 \lambda^6 \eta \rightarrow \eta = 0 \Rightarrow \text{no CPV in SM}\]
The Unitarity Triangle

**B sector:**

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
\[ \propto A\lambda^3 \propto -A\lambda^3 \propto A\lambda^3 \]

**K sector:**

\[ V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \]
\[ \propto \lambda \propto -\lambda \propto -A^2\lambda^5 \]

Expect large CP-violating effects in B-System

\[ R_t = \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \approx -\sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2} e^{-i\beta} \]

\[ R_u = \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \approx -\sqrt{\rho^2 + \eta^2} e^{i\gamma} \]

\[ \gamma = \arg V_{ub}^* , \quad \alpha = \pi - \gamma - \beta \]
Many Ways Lead to the Unitarity Triangle

Point of Knowledge:
SM or new phases (fields)?

What is the value of \( J \) in our world?

Wolfenstein-Parameters:
\[
\lambda = |V_{us}| \approx 0.2200 \pm 0.0025 \\
A = |V_{cb}| / \lambda^2 \approx 0.83 \pm 0.05 \\
(\rho, \eta) \text{ not well known}
\]

"\( \rho, \eta \)"-plane

Can we describe all observables with one unique set of \( \lambda, A, \rho, \eta \)?
Experimental and Theoretical Input to the Standard CKM Analysis
### The CKM Matrix: Impact of non-$B$ Physics

<table>
<thead>
<tr>
<th>Observables</th>
<th>CKM Parameters(*)</th>
<th>Experimental Sources</th>
<th>Theoretical Uncertainties</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{ud}</td>
<td>$</td>
<td>$\lambda$</td>
<td>nuclear $\beta$ decay</td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>$</td>
<td></td>
<td>$K^{+(0)} \rightarrow \pi^{+(0)} e^+\nu$</td>
</tr>
<tr>
<td>$\varepsilon_K$</td>
<td></td>
<td>$\eta \propto (1-\rho)^{-1}$</td>
<td>$B_K$, $\eta_{cc}$</td>
<td>*</td>
</tr>
<tr>
<td>$\varepsilon'/\varepsilon_K$</td>
<td>$\eta$</td>
<td>$K^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$</td>
<td>$B_6$, $B_8$</td>
<td>?</td>
</tr>
<tr>
<td>$\text{Im}^2[V_{ts}^* V_{td} \ldots]$</td>
<td>$\propto (\lambda^2 A)^4 \eta^2$</td>
<td>$K^0_L \rightarrow \pi^0\nu\bar{\nu}$</td>
<td>small (but: $(\lambda^2 A)^4$)</td>
<td>** (*)</td>
</tr>
<tr>
<td>$</td>
<td>V_{td}</td>
<td>$</td>
<td>$(1-\rho)^2 + \eta^2$</td>
<td>$K^* \rightarrow \pi^+\nu\bar{\nu}$</td>
</tr>
</tbody>
</table>

(*) Observables may also depend on $\lambda$ and $A$ - not always explicitly noted.
A Worldwide Effort - Testing the Standard Model:

The Quest for CP Violation in the $B$ System
### The CKM Matrix: Impact of $B$ Physics

<table>
<thead>
<tr>
<th>Observables</th>
<th>CKM Parameters(*)</th>
<th>Experimental Sources</th>
<th>Theoretical Uncertainties</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_d (</td>
<td>V_{td}</td>
<td>)$</td>
<td>$(1-\rho)^2 + \eta^2$</td>
<td>$B_d \bar{B}<em>d \to f^+ f^- + X, X</em>{RECO}$</td>
</tr>
<tr>
<td>$\Delta m_s (</td>
<td>V_{ts}</td>
<td>)$</td>
<td>$A$</td>
<td>$B_s \to f^+ + X$</td>
</tr>
<tr>
<td>$\sin^2 \beta$</td>
<td>$\rho, \eta$</td>
<td>$B_d \to c\bar{c} s\bar{d}, s\bar{s} s\bar{d}$</td>
<td>small</td>
<td>** **</td>
</tr>
<tr>
<td>$\sin^2 \alpha$</td>
<td>$\rho, \eta$</td>
<td>$B_d \to \pi^+ (\rho^+) \pi^-$</td>
<td>Strong phases, penguins</td>
<td>?</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$\rho, \eta$</td>
<td>$b \to u$, Direct CPV</td>
<td>Strong phases, penguins</td>
<td>?</td>
</tr>
<tr>
<td>$</td>
<td>V_{cbl}</td>
<td>$</td>
<td>$A$</td>
<td>$b \to c l \nu$ (excl. / incl.)</td>
</tr>
<tr>
<td>$</td>
<td>V_{ubl}</td>
<td>$</td>
<td>$\rho^2 + \eta^2$</td>
<td>$b \to u l \nu$ (excl. / incl.)</td>
</tr>
<tr>
<td>$</td>
<td>V_{tdl}</td>
<td>$</td>
<td>$(1-\rho)^2 + \eta^2$</td>
<td>$B_d \to \rho \gamma$</td>
</tr>
<tr>
<td>$</td>
<td>V_{tsl}</td>
<td>$</td>
<td>NP</td>
<td>$B_d \to X_s (K^<em>) \gamma, K^</em> l^+ l^-(FCNC)$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ubl}</td>
<td>, f_{Bd}$</td>
<td>$\rho^2 + \eta^2$</td>
<td>$B^+ \to \tau^+ \nu$</td>
</tr>
</tbody>
</table>

(*) Observables may also depend on $\lambda$ and $A$ - not always explicitly noted
The Asymmetric $B$-Meson Factory PEP-II:

9 GeV $e^-$ on 3.1 GeV $e^+$:

$$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B}$$

- coherent neutral $B$ pair production and decay (p-wave)
- boost of $\Upsilon(4S)$ in lab frame: $\beta \gamma = 0.56$
BABAR and Belle: Integrated Luminosity

Belle just passed 100 fb$^{-1}$ ~ 113 million $BB$ pairs
**BABAR Detector**

- **Muon/Hadron Detector**
- **Magnet Coil**
- **Electron/Photon Detector**
- **Cherenkov Detector**
- **Tracking Chamber**
- **Support Tube**
- **Vertex Detector**

**SVT**
- 97% efficiency, 70 - 180 μm Δz resolution

**Tracking**
- $\sigma(p_T)/p_T = 0.13\% + 0.45\%$

**DIRC**
- K-π separation > 3.4σ for $p < 3.5$ GeV/c

**EMC**
- $\sigma_E/E = 1.3\% E^{-1/4} + 2.1\%$
Schrödinger equation governs time evolution of $B^0 - \bar{B}^0$ System:

$$i \frac{d}{dt} \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

with mass eigenstates:

$$| B_L \rangle \propto p | B^0 \rangle + q | \bar{B}^0 \rangle$$

$$| B_H \rangle \propto p | B^0 \rangle - q | \bar{B}^0 \rangle$$

Defining:

$$\Delta m_B \equiv M_H - M_L \approx 2 | M_{12} |$$

$$\Delta \Gamma_B \equiv \Gamma_H - \Gamma_L = 2 \text{Re} \left( M_{12} \Gamma_{12}^* \right) / | M_{12} |$$

One obtains for the time-dependent asymmetry:

$$A_{\text{mixing}}(\Delta t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} = \cos (\Delta m_B \Delta t)$$

where:

unmixed: $e^+ e^- \rightarrow B^0(\Delta t) \bar{B}^0(\Delta t)$

mixed: $e^+ e^- \rightarrow B^0(\Delta t) B^0(\Delta t)$

and: $A_{\text{mixing}}(\Delta t = 0) = 1$
$B^0\bar{B}^0$ Mixing (Theory)

Effective FCNC Processes ($CP$ conserving):

whose oscillation frequencies $\Delta m_{d/s}$ are computed by:

$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \eta_B S(x_t) f_{B_q}^2 B_q |V_{tq}V_{tb}^*|^2 \approx 0.5 \text{ ps}^{-1}$ (for $q = d$)

Important theoretical uncertainties:

$\sigma_{rel} \left( \frac{f_{B_{d/s}}^2 B_{d/s}}{f_{B_d}^2 B_d} \right) \approx 36\%$

Improved error from $\Delta m_s$ measurement:

$\sigma_{rel} \left( \frac{\xi^2 = f_{B_s}^2 B_s / f_{B_d}^2 B_d}{f_{B_d}^2 B_d} \right) \approx 10\%$
$B^0 \bar{B}^0$ Mixing (Experiment)

Experimental Technique:

\[ \Upsilon(4S) \rightarrow e^+ e^- \]
\[ \bar{B}^0 \rightarrow \text{anti } B \]

$B^0_{\text{rec}} = B^0_{\text{flav}}$ (flavor eigenstates)

$B^0_{\text{rec}} = B^0_{\text{CP}}$ (CP eigenstates)

$\langle \Delta z \rangle \approx 250 \mu m$

Exclusive $B$ Reconstruction

$B$-Flavor Tagging

$\Delta t \approx \Delta z/\langle \beta \gamma \rangle c$

Lifetime, mixing analyses

$CP$ analysis
$B^0 \bar{B}^0$ Mixing using Flavour Eigenstates

\[
A_{\text{mixing}}(\Delta t') = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} = (1 - 2\omega)\cos(\Delta m_{B_d}\Delta t) \otimes \text{Res}(\Delta t, \Delta t')
\]

\[
\Delta m_{B_d} = (0.516 \pm 0.016_{\text{stat}} \pm 0.010_{\text{syst}}) \text{ps}^{-1}
\]

BABAR PRD 66 (2002) 032003
$B_S^0 \bar{B}_S^0$ Mixing

$\Delta m_s$ not yet measured. How to use the available experimental inform.?

Following a presentation of F. Le Diberder at the CERN CKM workshop (Feb. 02)

- compute the expected PDF for the current preferred value
- compute the CL
- infer an equivalent $\chi^2$

Preferred value is 17.2 ps$^{-1}$, but only limit exploitable in CKM fit
Constraints from $\Delta m_d$ and $\Delta m_s$

Waiting for a $\Delta m_s$ measurement at Tevatron...
**Time-dependent \( CP \) Asymmetry**

\( CP \) violation arises from interference between decays with and without mixing:

\[
\lambda_{t_{CP}} = \eta_{t_{CP}} \frac{q}{p} \frac{\bar{A}_{t_{CP}}}{A_{t_{CP}}} \approx e^{-2i\beta}
\]

\( CP \) eigenvalue

\[
\lambda_{t_{CP}} \neq \pm \text{Prob}(\bar{B}^0(t) \rightarrow f_{CP}) \neq \text{Prob}(B^0(t) \rightarrow f_{CP})
\]

**Time-dependent \( CP \) Observables:**

\[
A_{t_{CP}}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) - \Gamma(B^0(t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) + \Gamma(B^0(t) \rightarrow f_{CP})}
\]

\[
= -\eta_{t_{CP}} \left( S_{t_{CP}} \sin(\Delta m_d t) - C_{t_{CP}} \cos(\Delta m_d t) \right)
\]

with: \( = \sin(2\beta) \) and \( = 0 \) for \( b \rightarrow c\bar{c}s, s\bar{s}s \)

\( C_{t_{CP}} = \frac{1 - |\lambda_{t_{CP}}|^2}{1 + |\lambda_{t_{CP}}|^2} \)

\( S_{t_{CP}} = \frac{2 \text{ Im } \lambda_{t_{CP}}}{1 + |\lambda_{t_{CP}}|^2} \)
**The Golden Channel:** \( B^0, \bar{B}^0 \rightarrow J/\psi K_{S,L} \)

**Tree Diagram**

\[ \bar{b} \rightarrow V_{cb}^* V_{cs} \quad \bar{c} \quad \bar{c} \]
\[ d \quad V_{td} \quad V_{cb}^* \quad V_{cs} \quad c \quad s \]
\[ q \bar{A} = -V_{tb}^* V_{td} V_{cb} V_{cs}^* \]
\[ \frac{p A}{\rho} = -e^{-2i\beta} \]

**Single weak phase:**

- clean extraction of CP phase
- no direct CPV: \( \lambda_{J/\psi K_{S,L}} = 1 \)

\[ A_{J/\psi K_{S,L}}(t) = -\eta_{J/\psi K_{S,L}} \cdot \sin(2\beta) \cdot \sin(\Delta m_{B_d} t) \]
Time-dependent \( CP \) Asymmetries

\[ \sin 2\beta = 0.741 \pm 0.067_{\text{stat}} \pm 0.033_{\text{syst}} \]

CP Violation established in the \( B \) system!

null measurement for comparison: using \( B_{\text{flav}} \) sample in fit

more on time-dependent CP asymmetries later...
World Average:

Results improved by more than just the luminosity gain

World average
Determinant of the Matrix Elements $|V_{cb}|$ and $|V_{ub}|$

Symmetry of heavy quarks [=SU(2n_Q)]:

- in the limit $m_Q \to \infty$ of a $Qq$ system, the heavy quark represents a static color source with fixed 4-momentum
- the light degrees of freedom become insensitive to spin and flavor of the heavy quark

For both, $|V_{cb}|$ and $|V_{ub}|$, exist exclusive and inclusive semileptonic approaches.

The theoretical tools are Heavy Quark Effective Theory (HQET) and the Operator Product Expansion (OPE), respectively.

- $|V_{ub}|$ ($\to \rho^2 + i\eta^2$) is crucial for the SM prediction of $\sin(2\beta)$
- $|V_{cb}|$ ($\to A$) is important for the interpret. of kaon physics ($\varepsilon_K$, BR($K \to \pi\nu\nu$), ...)
**Exclusive Semileptonic** **$B \rightarrow D^* l \nu$ Decays**

- Measurement of $B \rightarrow D^* \ell \bar{\nu}$ rate as fct. of $B \rightarrow \ell \nu$ momentum transition $\omega$
- Determination of $|V_{cb}|$ from extrapolation to $\omega \rightarrow 1$ (theory is most restrictive)

\[
\frac{d\Gamma(B \rightarrow D^* \ell \bar{\nu})}{d\omega} \propto F^2_*(\omega)|V_{cb}|^2
\]

HQ Symmetry:

\[F_*(1) \approx 0.9 \ (\pm 5\%)
\]

Bigi; Uraltsev; Neubert; ...
Lattice QCD: Hashimoto et al. [hep-ph/0110253]

In $B$ rest system is $\omega = \gamma(D^*)$

![Graph showing measurement of $|V_{cb}|$](image)

**Belle**

\[F_*(1)|V_{cb}| = 10^{-3} \times \begin{cases} 
35.6 \pm 1.7 \ (LEP) \\
42.2 \pm 2.2 \ (CLEO) \\
36.2 \pm 2.3 \ (Belle)
\end{cases}
\]

Belle, PLB 526, 247 (2002)
OPE shows that for $\Lambda_{QCD} \ll m_b$, inclusive $B$ decay rates are equal to $b$ quark decay rates. Corrections are suppressed by $\Lambda_{QCD}/m_b$ and $\alpha_s(m_b)$.

\[ |V_{cb}| \approx 0.0411 \sqrt{\frac{\text{BR}(B \rightarrow X_c \ell \bar{\nu})}{0.105}} \frac{1.6 \text{ ps}}{\tau_B} \left( 1 \pm 0.015_{\text{pQCD}} \pm 0.010_{m_b} \pm 0.012_{1/m_b^3} \right) \]

A promising approach for a theoretically improved analysis is the combined fit of the HQET parameters $\Lambda$ und $\Lambda_1$ (CLEO) to $B \rightarrow X_u \ell \bar{\nu}$ mass and lepton moments or to $b \rightarrow s \gamma$. Allows to directly probe Quark-Hadron Duality → successful in $\tau$ decays

| $V_{cb}$ | $(40.9 \pm 0.9) \times 10^{-3}$

Bauer et al., hep-ex/0210027 [BABAR, CLEO, DELPHI data]
\( |V_{ub}| \) from exclusive Decays (I)

- Pure tree decay.
- Decay rate is proportional to CKM element \( |V_{ub}|^2 \)

\[
\text{BR}\left( B^0 \rightarrow h^- \ell^+ \nu \right) \propto |V_{ub}|^2 F_B^2(q^2)
\]

**Problem:**

form factor is model dependent!

Would need unquenched lattice calculation to become model-independent...

\[
|V_{ub}| = (3.25 \pm 0.14 \pm 0.29 \pm 0.55) \times 10^{-3} \quad \text{(CLEO)}
\]

\[
|V_{ub}| = (3.69 \pm 0.23 \pm 0.27 \pm 0.40 \pm 0.59) \times 10^{-3} \quad \text{(BABAR)}
\]

**CLEO, Phys.Rev.D61:052001,2000; BABAR hep-ex/0207080**
**$|V_{ub}|$ from inclusive Decays**

$$ \frac{d\Gamma}{d(PS)} \approx \text{parton model} \pm \sum_n C_n \left( \frac{\Lambda_{QCD}}{m_b} \right)^n $$

**Good:** relation between $\sum_{X_u} \Gamma(B \rightarrow X_u \ell \nu)$ & $|V_{ub}|$ known to ~5%

**Bad:** cannot be measured fully inclusively, since $\frac{\Gamma(B \rightarrow X_c \ell \nu)}{\Gamma(B \rightarrow X_u \ell \nu)} \sim 100$

need to impose stringent cuts to eliminate charm background …

“… and here the troubles begin” (M. Luke, FPCP’02)
\[ |V_{ub}| \text{ from inclusive Decays} \]

Suppression of the dominant charm background by cutting on the \( B \to X_u l \nu \) lepton momentum beyond the kinematic limit of \( B \to X_c l \nu \)

**Problem:** strong model dependence of \( |V_{ub}| \)

Reduction of model dependence by using HQE and the “shape function“ measured in \( B \to X_s \gamma \)

\[
|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3} \\
\text{(stat)} \quad \text{(fu)} \quad \text{(1/m}_b\text{)} \quad \text{(HQE)}
\]

Validity of quark-hadron duality? CLEO, hep-ex/0202019

Measurement of the whole spectrum (\( \text{Theorie under control} \) \( B \to X_u l \nu \) (Neural Net for Signal)

\[
|V_{ub}| = \left(4.09 \pm 0.36 \pm 0.42 \pm 0.24 \pm 0.01 \pm 0.17\right) \times 10^{-3} \\
\text{(exp)} \quad \text{(b \to c)} \quad \text{(b \to u)} \quad \tau_b \quad \text{(HQE)}
\]

Knowledge of \( b \to c \) background; inclusive measurement? LEP \( |V_{ub}/| \) Working group
The Standard CKM Analysis

- $|\epsilon'/\epsilon_K|$
- $|\epsilon_K|$,
- $K^0 \rightarrow \pi^0 \nu\nu$
- $|V_{ub}/V_{cb}|$
- $\sin 2\alpha$
- $K^+ \rightarrow \pi^+ \nu\nu$
- $\Delta m_d$
- $K^0 \rightarrow \pi^0 \nu\nu$
- $\sin 2\beta$
- $\sin \gamma$
Extracting the CKM Parameters

- Measurement
  - \( x_{\text{exp}} \)

- Constraints on theoretical parameters
  - \( y_{\text{theo}} = (A, \lambda, \rho, \eta, m_t \ldots) \)

- Theoretical predictions
  - \( x_{\text{theo}}(y_{\text{model}} = y_{\text{theo}}, y_{\text{QCD}}) \)
    - \( y_{\text{QCD}} = (B_K, f_B, B_{Bd} \ldots) \)

- Assumed to be Gaussian

- \( \chi^2 = -2 \ln \mathcal{L}(y_{\text{model}}) \)
  - \( \mathcal{L}(y_{\text{model}}) = \mathcal{L}_{\text{exp}} \left[ x_{\text{exp}} - x_{\text{theo}}(y_{\text{model}}) \right] \times \mathcal{L}_{\text{theo}}(y_{\text{QCD}}) \)

- Uniform likelihoods: “allowed ranges”

- Frequentist: Rfit

- Bayesian

- « Guesstimates »
Probing the SM
Test: “Goodness-of-fit”

- Evaluate global minimum
  \( \chi^2_{\text{min}; y_{\text{mod}}(y_{\text{mod-opt}})} \)
- Fake perfect agreement:
  \( x_{\text{exp-opt}} = x_{\text{theo}}(y_{\text{mod-opt}}) \)
  generate \( x_{\text{exp}} \) using \( L_{\text{exp}} \)
- Perform many toy fits:
  \( \chi^2_{\text{min-toy}(y_{\text{mod-opt}})} \rightarrow F(\chi^2_{\text{min-toy}}) \)

\[ \text{CL}(\text{SM}) \leq \int_{\chi^2 \geq \chi^2_{\text{min}; y_{\text{mod}}}} F(\chi^2) d\chi^2 \]

Metrology

- Define:
  \( y_{\text{mod}} = \{ a; \mu \} = \{ \rho, \eta, A, \lambda, y_{\text{QCD}}, \ldots \} \)
- Set Confidence Levels in \( \{ a \} \) space, irrespective of the \( \mu \) values
- Fit with respect to \( \{ \mu \} \)
  \( \chi^2_{\text{min} ; \mu(a)} = \min_{\mu} \{ \chi^2(a, \mu) \} \)
- \( \Delta \chi^2(a) = \chi^2_{\text{min} ; \mu(a)} - \chi^2_{\text{min}; y_{\text{mod}}} \)
- \( \text{CL}(a) = \text{Prob}(\Delta \chi^2(a), N_{\text{dof}}) \)

Test New Physics

- If CL(SM) good
  Obtain limits on New Physics parameters
- If CL(SM) bad
  Hint for New Physics ?!

AH, H. Lacker, S. Laplace, F. Le Diberder
Standard Inputs

| $|V_{ud}|$ | 0.97394 ± 0.00089 | neutron & nuclear $\beta$ decay |
| $|V_{us}|$ | 0.2200 ± 0.0025 | $K \rightarrow \pi l\nu$ |
| $|V_{cd}|$ | 0.224 ± 0.014 | dimuon production: $\nu N$ (DIS) |
| $|V_{cs}|$ | 0.969 ± 0.058 | $W \rightarrow XcX$ (OPAL) |
| $|V_{ub}|$ | (4.09 ± 0.61 ± 0.42) × 10^-3 | LEP inclusive |
| $|V_{ub}|$ | (4.08 ± 0.56 ± 0.40) × 10^-3 | CLEO inclusive & moments $b \rightarrow s\gamma$ |
| $|V_{ub}|$ | (3.25 ± 0.29 ± 0.55) × 10^-3 | CLEO exclusive |

$\mathcal{E}_K$ | (2.271 ± 0.017) × 10^-3 | PDG 2000 |
$\Delta m_d$ | (0.496 ± 0.007) ps^-1 | BABAR, Belle, CDF, LEP, SLD (2002) |
$\Delta m_s$ | Amplitude Spectrum’02 | LEP, SLD, CDF (2002) |
$\sin 2\beta$ | 0.734 ± 0.055 | WA, Updates Moriond’02 BABAR and Belle included |

$m(t(\overline{\text{MS}}))$ | (166 ± 5) GeV/c^2 | CDF, D0, PDG 2000 |
$f_{B_d} \sqrt{B_d}$ | (230 ± 28 ± 28) MeV | Lattice 2000 |
$\xi$ | 1.16 ± 0.03 ± 0.05 | Lattice 2000 |
$B_K$ | 0.87 ± 0.06 ± 0.13 | Lattice 2000 |

+ other parameters with less relevant errors...
Standard Constraints
(not including $\sin 2\beta$)

Region of $> 5\%$ CL

$\Delta m_d$

$\Delta m_s$ & $\Delta m_d$

$|\varepsilon_k|$

$|V_{ub}/V_{cb}|$

$|\rho|$

Metrology (I)

status: ICHEP'02
A TRIUMPH FOR THE STANDARD MODEL AND THE KM PARADigm!

KM mechanism most probably the dominant source of CPV at EW scale

Still true???
Both decays dominated by single weak phase

\[
\text{"sin2}\beta" = \begin{cases} 
\phi K_s^0 & -0.19^{+0.52}_{-0.50} \pm 0.09_{\text{syst}} \\
\phi K_s^0 & -0.73 \pm 0.64 \pm 0.18_{\text{syst}} \\
\eta' K_s^0 & +0.76 \pm 0.64^{+0.05}_{-0.06}_{\text{syst}} 
\end{cases} = -0.39 \pm 0.40
\]

New CP Results from complementary modes:

BABAR, hep-ex/0207078

Belle, hep-ex/0207098

New Physics?
Standard Constraints (including sin2\(\beta\))

\[\sin 2\beta/G69\]

already provides one of the most precise and robust constraints.

How to improve these constraints?
How to measure the missing angles?

status: ICHEP’02
Metrology (II): the sin(2\(\alpha\)) - sin(2\(\beta\)) Plane

**Standard Constraints (not including sin2\(\beta\))**

Be aware of ambiguities!

status: FPCP'02
Metrology (II): the $\sin(2\beta)$ - $\gamma$ Plane
New Constraints

\[ |\varepsilon /\varepsilon_K|, K^0 \rightarrow \pi^0 \nu\nu \]

\[ |\varepsilon_K| \]

\[ K^0 \rightarrow \pi^0 \nu\nu \]

\[ \sin 2\alpha \]

\[ |V_{ub}/V_{cb}| \]

\[ \sin 2\beta \]

\[ \sin \gamma \]

\[ K^+ \rightarrow \pi^+ \nu\nu \]

\[ \Delta m_d \]
Rare Charmless $B$ Decays

We distinguish two Categories:

- **Semileptonic (FCNC) and radiative decays**
  - $(G_F)^2\alpha$ increased compared to loop-induced non-radiative decays $\propto (G_F\alpha)^2$
  - Sensitive sondes for new physics (SUSY, right-handed couplings, ...)
  - Determination of $|V_{td}|$ and $|V_{ts}|$
  - Determination of HQET parameters
  - Search for direct CP asymmetry

- **Hadronic $b \rightarrow u(d)$ decays**
  - Measurement of CPV
  - Determination of UT angles $\alpha$ and $\gamma$
  - Test der $B$ decay dynamics (Factorization)
Charmless $B$ Decays into two Pseudoscalars

[ Constraining $\alpha$ and $\gamma$ ?! ]
\( B \rightarrow K\pi \) and the Determination of \( \gamma \)

**Theoretical analysis deals with:**
- SU(3) breaking
- Rescattering (FSI)
- EW penguins

**The tool is:** QCD Factorization...

... based on Color Transparancy
- Large energy release
- soft gluons do not interact with small qq-bar color dipole of emitted mesons
- non-fact. contributions are calculable in pQCD perfect for \( m_b \rightarrow \infty \).
  But, \( m_b \) finite \( \rightarrow \) corrections: \( O(\Lambda_{QCD}/m_b) \)

Potential for significant direct CPV

\( CP \) averaged BRs and measurements of direct CPV determine the angle \( \gamma \)

Interfering contributions of tree and penguin amplitudes:

\[
A_{K\pi} \propto Pe^{-i\beta} + \lambda^2 e^{i\gamma T}
\]

Fleischer, Mannel (98)
Gronau, Rosner, London (94, 98)
Neubert, Rosner (98)
Buras, Fleischer (98)
Beneke, Buchalla, Neubert, Sachrajda (01)
Keum, Li, Sanda (01)
Ciuchini et al. (01)
...list by far not exhaustive!
### Agreement among experiments. Most rare decay channels discovered

<table>
<thead>
<tr>
<th>Mode</th>
<th>BABAR (×10⁻⁶)</th>
<th>Belle</th>
<th>CLEO (×10⁻⁶)</th>
<th>World average (×10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \pi^+\pi^-$</td>
<td>4.7 ± 0.6 ± 0.2</td>
<td>5.4 ± 1.2 ± 0.5</td>
<td>4.3 ± 1.6 ± 0.5</td>
<td>4.78 ± 0.54</td>
</tr>
<tr>
<td>$B^+ \to \pi^+\pi^0$</td>
<td>5.5 ± 1.0 ± 0.6</td>
<td>7.4 ± 2.3 ± 0.9</td>
<td>5.6 ± 2.1 ± 1.5</td>
<td>5.83 ± 0.96</td>
</tr>
<tr>
<td>$B^0 \to \pi^0\pi^0$</td>
<td>$(1.6^{+0.7}_{-0.6}^{+0.6})$</td>
<td>$(3.2 ± 1.5 ± 0.7)$</td>
<td>$(2.2^{+1.7}_{-1.3} ± 0.7)$</td>
<td>$(2.01^{+0.70}_{-0.67})$</td>
</tr>
<tr>
<td>$B^0 \to K^+\pi^-$</td>
<td>17.9 ± 0.9 ± 0.7</td>
<td>22.5 ± 1.9 ± 1.8</td>
<td>17.2 ± 2.5 ± 1.2</td>
<td>18.46 ± 0.98</td>
</tr>
<tr>
<td>$B^+ \to K^+\pi^0$</td>
<td>12.8 ± 1.2 ± 1.0</td>
<td>13.0 ± 2.5 ± 1.3</td>
<td>11.6 ± 3.0 ± 1.4</td>
<td>12.68 ± 1.23</td>
</tr>
<tr>
<td>$B^+ \to K^0\pi^+$</td>
<td>17.5 ± 1.8 ± 1.3</td>
<td>19.4 ± 3.1 ± 1.6</td>
<td>18.2 ± 4.6 ± 1.6</td>
<td>18.09 ± 1.69</td>
</tr>
<tr>
<td>$B^0 \to K^0\pi^0$</td>
<td>10.4 ± 1.5 ± 0.8</td>
<td>8.0 ± 3.3 ± 1.6</td>
<td>14.6 ± 5.9 ± 2.4</td>
<td>10.34 ± 1.48</td>
</tr>
<tr>
<td>$B^0 \to K^+K^-$</td>
<td>&lt; 0.6</td>
<td>&lt; 0.9</td>
<td>&lt; 1.9</td>
<td></td>
</tr>
<tr>
<td>$B^+ \to K^+\bar{K}^0$</td>
<td>&lt; 1.3</td>
<td>&lt; 2.0</td>
<td>&lt; 5.1</td>
<td></td>
</tr>
<tr>
<td>$B^0 \to K^0\bar{K}^0$</td>
<td>&lt; 0.6</td>
<td>&lt; 4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{CP}(\pi^+\pi^-)$</td>
<td>$-0.03^{+0.18}_{-0.17} ± 0.02$</td>
<td>$0.30 ± 0.30^{+0.06}_{-0.04}$</td>
<td>$-$</td>
<td>$+0.06 ± 0.16$</td>
</tr>
<tr>
<td>$A_{CP}(K^+\pi^-)$</td>
<td>$-0.102 ± 0.050 ± 0.016$</td>
<td>$-0.06 ± 0.09^{+0.01}_{-0.02}$</td>
<td>$-0.04 ± 0.16$</td>
<td>$-0.088 ± 0.044$</td>
</tr>
<tr>
<td>$A_{CP}(K^+\pi^0)$</td>
<td>$-0.09 ± 0.09 ± 0.01$</td>
<td>$0.02 ± 0.09 ± 0.01$</td>
<td>$-0.29 ± 0.23$</td>
<td>$\Box 0.05 ± 0.07$</td>
</tr>
<tr>
<td>$A_{CP}(K^0\pi^+)$</td>
<td>$-0.17 ± 0.10 ± 0.02$</td>
<td>$+0.46 ± 0.15 ± 0.02$</td>
<td>$+0.18 ± 0.24$</td>
<td>$+0.04 ± 0.08$</td>
</tr>
<tr>
<td>$A_{CP}(K^0\pi^0)$</td>
<td>$0.03 ± 0.36 ± 0.09$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.03 ± 0.36 ± 0.09$</td>
</tr>
</tbody>
</table>
Bounds on $\gamma$

Ratios of CP averaged branching fractions can lead to bounds on $\gamma$:

<table>
<thead>
<tr>
<th>Bound</th>
<th>Expression</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM bound</td>
<td>$R = \frac{\tau(B^+) \cdot BR(K^{\pm} \pi^\mp)}{\tau(B^0) \cdot BR(K^0 \pi^\pm)}$</td>
<td>$1.09^{+0.13}_{-0.11} &lt; 1 \ ? \ \Rightarrow$ no constraint</td>
<td>Fleischer, Mannel PRD D57 (1998) 2752</td>
</tr>
<tr>
<td>BF bound</td>
<td>$R_{n} = \frac{1}{2} \frac{BR(K^{\pm} \pi^\mp)}{BR(K^{0} \pi^{\pm})}$</td>
<td>$0.89^{+0.16}_{-0.12} \neq 1 \ ? \ \Rightarrow$ no constraint</td>
<td>Buras, Fleischer EPJ C11 (1998) 93</td>
</tr>
<tr>
<td>NR bound</td>
<td>$R_{c} = 2 \frac{BR(K^{\pm} \pi^{0})}{BR(K^{0} \pi^{\pm})}$</td>
<td>$1.40^{+0.20}_{-0.18} \neq 1 \ ? \ \Rightarrow$ some constraint</td>
<td>Neubert, Rosner PL B441 (1998) 403</td>
</tr>
</tbody>
</table>
Neubert-Rosner Bound

\( a) \quad \frac{T}{P} \rightarrow \bar{\varepsilon}_{3/2} = R_{th} \cdot \tan \theta_c \frac{f_K}{f_\pi} \sqrt{\frac{2 \cdot BR(\pi^\pm \pi^0)}{BR(K^0\pi^\pm)}} = R_{th}(SU(3), BBNS) \cdot (0.221 \pm 0.028) \)

\( b) \quad \text{QCD FA: small relative strong phases} \)

status: FPCP’02
CP Violation in $B^0 \rightarrow \pi^+\pi^-$ Decays

\[ \lambda_{t_{CP}} = \eta_{t_{CP}} \frac{q}{p} \frac{\overline{A}_{t_{CP}}}{A_{t_{CP}}} \]

ratio of amplitudes

\[ \lambda = q \frac{\overline{A}_f}{p A_f} = \eta_f e^{-2i(\beta + \gamma)} = \eta_f e^{2i\alpha} \]

\[ C_{\pi\pi} = 0, \quad S_{\pi\pi} = \sin(2\alpha) \]

For a single weak phase (tree):

For additional phases:

\[ |\lambda| \neq 1 \Rightarrow \text{must fit for direct CP} \]

\[ \text{Im} (\lambda) \neq \sin(2\alpha) \Rightarrow \text{need to relate asymmetry to } \alpha \]

\[ C_{\pi\pi} \neq 0, \quad S_{\pi\pi} \sim \sin(2\alpha_{\text{eff}}) \]
Bounds/Predictions on $|\alpha - \alpha_{\text{eff}}|$

\[
S_{\pi\pi} = \frac{2\Im \lambda_{\pi\pi}}{1 + |\lambda_{\pi\pi}|^2},\quad C_{\pi\pi} = \frac{1 - |\lambda_{\pi\pi}|^2}{1 + |\lambda_{\pi\pi}|^2},
\]

\[
\lambda_{\pi\pi} = e^{-2i\beta} \frac{e^{-i\gamma}}{e^{+i\gamma}} + \frac{P_{\pi\pi}/T_{\pi\pi}}{P_{\pi\pi}/T_{\pi\pi}}
\]

to be “tamed”... (Charles)

Different Strategies:

■ Determination of $P/T$ by virtue of flavour symmetries (mild theoretical assumptions, eg, $P_{\text{EW}}=0$)

• SU(2):
  Gronau-London Isospin Analysis
  Grossmann-Quinn bound (also Charles, Gonau et al.)

• SU(3):
  Fleischer-Buras, Charles
  ($P_{\pi\pi} \sim P_{K\pi}$)

■ Using theoretical predictions for $P/T$

• “naive” Factorization ($|P/T|^2 \sim \text{BR}(B^+ \rightarrow \pi^+ K^0)/\text{BR}(B^+ \rightarrow \pi^+ \pi^0)$)

• $|P/T|$ and phase from QCD Factorization (Beneke et al.) and pQCD (Lee et al.)
Using the BRs: $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\pi^0$ (limit)

and the CP asymmetries: $A_{CP}(\pi^0\pi^0)$, $S_{\pi\pi}$, $C_{\pi\pi}$

and the amplitude relations: $A^+ / \sqrt{2} + A^{00} = A^{+0}$, 

$(A \leftrightarrow \overline{A})$ and $|A^{+0}| = |\overline{A}^{+0}|$
How about More Statistics?

Isospin analysis for present central values, but 500 fb$^{-1}$

If central value of BR($\pi^0\pi^0$) stays large, isospin analysis cannot be performed by first generation B factories
\[ \sin(2\alpha_{\text{eff}}) & \text{SU}(3) \text{ or "naive" FA} \]

Need to make more assumptions ... achieve better constraints

**Input: \text{SU}(2) + \text{BR}(K^+\pi^-)**

**Input: \lvert P \rvert \text{ from BR}(K^0\pi^+)**
\[ \sin(2\alpha_{\text{eff}}) & \text{QCD FA} \]

\[ |P/T| \text{ and } \arg(P/T) \text{ predicted by QCD FA (BBNS'01)} \]

Input: \( S_{\pi\pi} \& C_{\pi\pi} \)

Input: \( S_{\pi\pi} \& C_{\pi\pi} \& \sin(2\beta_{\text{WA}}) \)

Constraint from \( \sin(2\alpha) \) and \( \sin(2\beta) \)
$\sin(2\alpha_{\text{eff}})$ & QCD FA

Belle:
(Moriond’02)

<table>
<thead>
<tr>
<th>$S_{\pi\pi}$</th>
<th>$C_{\pi\pi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1.21^{+0.41}_{-0.30}$</td>
<td>$-0.94^{+0.32}_{-0.27}$</td>
</tr>
</tbody>
</table>

no update since Moriond’02

Input: $S_{\pi\pi}$ & $C_{\pi\pi}$
Predicting the Experimental Observables

Only predictive approach: QCD FA...it works...yet!

Using $\rho$, $\eta$ from standard CKM fit

$C_{\pi\pi}$

$S_{\pi\pi}$
Where are we today?
What brings the future?
PEP-II Luminosity Projections

Similar scenario expected for Belle
Conclusions

- Global CKM fit (CKMfitter) gives consistent picture of Standard Model

- \(\sin(2\beta)\) now most accurate constraint
  
  \[ J/\psi K_S \leftrightarrow \phi K_S \]

  future consistencies: BABAR \(\leftrightarrow\) Belle ?

- \(\Delta m_s\): constraint on UT angle \(\gamma\) from LEP/SLD/CDF limit
  
  expect measurement from TEVATRON soon: sensitive to new physics!

- Rare \(K\) decays enter the game, but more statistics needed
  
  also: keep an eye on improving \(|V_{cb}|\)!

Need more constraints on CKM phase:

- Charmless \(B\) decays and \(CP\) violation: best fits (in BBNS) around \(\gamma \approx 80^\circ\)
  
  - Conventional isospin analysis potentially unfruitful to extract \(\sin(2\alpha)\)
  
  - Significant theoretical input needed
  
  - Requires detailed study of relevant theoretical uncertainties

- The race for \(\gamma\): high statistics needed for \(B \rightarrow DK(\pi)\) – low theoretical input

Many more results to come from the \(B\)-factories
We know the center already quite well…but there is not enough redundancy.

A better understanding/prediction of long distance QCD (lattice!) opens the shrine to a full exploitation of the huge data samples currently produced at KEKB and PEPII.

...and the immense data quantities that will be produced at the Tevatron & LHC.