CP Violation in B-Meson Decays

CP Violation in the Standard Model
Expectations for B-Meson Experiments
PEP-II and KEK-B, BABAR and BELLE
Results and Interpretation
Particle physicists know three systems without particle-antiparticle symmetry:

The Universe
More matter than antimatter. \( n(N)/n(\gamma) \approx 10^{-9} \) points to \( N\bar{N} \) annihilation at the end of the „massive-quark gluon“ era; \( q/\bar{q} \approx 1+10^{-9} \) requires CP. Standard Model offers this at the end of the „massless“ era, but with \( q/\bar{q} \approx 1+10^{-20} \). Extra CP?

The Neutral K Meson
Discovery of \( K_L \rightarrow \pi^+\pi^- \) by Cronin et al 1964 \( \Rightarrow \text{Re}(\varepsilon) \approx 10^{-3} \), \( \pi^0\pi^0 \neq \pi^+\pi^- \) by NA31/48, E731/KTeV 1988/99 \( \Rightarrow |\varepsilon'| \approx 3\cdot10^{-6} \). Only CP values till 2001.

The Neutral B Meson
2002: Measurements of BABAR (90 M \( \bar{B}\bar{B} \)) and BELLE (85 M \( \bar{B}\bar{B} \)) in \( e^+e^- \) annihilation at 10.6 GeV show \( \sin2\beta = 0.73 \pm 0.06 \) in agreement with Standard Model CP for \( K^0 \) and \( B^0 \) mesons.
Standard Model of Elementary Particle Physics
= Extension of Dirac equation by gauge principle and „zoology“.

Dirac 1928:
\[ L = \bar{e} \gamma^\mu i \partial_\mu e - m \bar{e} e \]
\[ e = e(x) = (e_L^-, e_R^-, e_L^+, e_R^+) \]
Dirac’s eq. is C- and P-symmetric.

Weyl 1929:
\[ e(x) \rightarrow e(x) \cdot e^{i \alpha(x)} \]
\[ \Rightarrow \quad i \partial_\mu \rightarrow i \partial_\mu - q A_\mu \]
With electricity, Dirac’s eq. remains C- and P-symmetric.

Paul Adrien Maurice Dirac (1902 – 1984)
Glashow 1961:

\[
\begin{pmatrix}
    v_L(x) \\
    e_L(x)
\end{pmatrix}
\text{and } e_R \text{ instead of } e, \quad e_R \rightarrow e_R e^{i\alpha(x)}
\]

\[
\begin{pmatrix}
    v_L(x) \\
    e_L(x)
\end{pmatrix}
\rightarrow U(x) \begin{pmatrix}
    v_L(x) \\
    e_L(x)
\end{pmatrix} e^{i\alpha(x)}
\]

\[\Rightarrow \quad i\partial_\mu \rightarrow i\partial_\mu - g W_\mu^a \frac{\sigma_a}{2} - g' y B_\mu\]

Invariance of Dirac’s eq. under local SU(2) + U(1) produces weak and electric interaction by \(W^+, W^-, Z^0, \gamma\) exchange.

P- and C- symmetry are maximally broken; CP symmetry remains.

SU(2) invariance requires, because of

\[m \bar{e}e = m (\bar{e}_L e_R + \bar{e}_R e_L) \leftrightarrow m \bar{e}e:\]

\[m(\gamma) = m(W) = m(Z) = m(e) = m(\nu) = 0.\]
Higgs 1964: Introduction of a spin-0-doublet $\Phi$ and spontaneous symmetry breaking

\[ L \rightarrow L - c \left[ \bar{e}_R \left( \Phi_1^* \Phi_2^* \right) \left( \nu_L e_L \right) + (\bar{\nu}_L \bar{e}_L) \left( \Phi_1 \Phi_2 \right) e_R \right] \]

\[ \left( \Phi_1(x) \right) \rightarrow \left( \begin{array}{c} 0 \\ \nu + h(x) \end{array} \right) \Rightarrow L \rightarrow L - cv (\bar{e}_R e_L + \bar{e}_L e_R) + L_{\text{int}} (h, e) \]

\[ cv (\bar{e}_R e_L + \bar{e}_L e_R) = m \bar{e}e \]

Higgs gives back Dirac's electron mass which was taken away by Glashow.

Glashow, Weinberg, Salam 1968:
Same Higgs mechanism produces masses for $\mu$ and quarks $u d c s$, and gives quark mixing in $W$ exchange.
Kobayashi, Maskawa 1973: Extension 2 → 3 families
(discovery of τ-lepton 1975, c-quark 1974, b 1977)

\[ L = L_{\text{Dirac,kin}} (3l, 3\nu, 3u, 3d) + L_{U1 \otimes SU2 \otimes SU3} + L_{\text{bosons}} \]

\[ -[C^{(l)}_{\alpha\beta} \bar{l}_R \Phi + (\nu \beta_L) + C^{(d)}_{\alpha\beta} \bar{d}_L \Phi + (u \beta_L)] \]

\[ + C^{(u)}_{\alpha\beta} \bar{u}_L \Phi T + (u \beta_L) + (d \beta_L) + h.c. \]

For gauge invariance, the complex matrices \( C \) arbitrary. \( C^{(u)} \) can be diagonalized by rotations in family space:

\[
\begin{pmatrix}
 u_1 \\
 u_2 \\
 u_3
\end{pmatrix} \rightarrow \begin{pmatrix} u \\ c \\ t \end{pmatrix}; \quad \nu C^{(u)} \rightarrow \begin{pmatrix} m_u & 0 & 0 \\
 0 & m_c & 0 \\
 0 & 0 & m_t \end{pmatrix}; \quad \text{Doubletts} \rightarrow \\
\begin{pmatrix} u_L \\ c_L \\ t_L \\
 d'_L \\ s'_L \\ b'_L \end{pmatrix}
W exchange: \[ u_L \leftrightarrow W^+ d'_L, \quad c_L \leftrightarrow W^+ s'_L, \quad t_L \leftrightarrow W^+ b'_L. \]

Dublet partners of u c t are not mass eigenstates. Since \((u_\alpha \ d_\alpha)\) is one object to be rotated in family space, \(C(u)\) and \(C(d)\) cannot be diagonalised simultaneously.

\[
\begin{pmatrix}
d' \\
s' \\
b'
\end{pmatrix}
= V
\begin{pmatrix}
d \\
s \\
b
\end{pmatrix}; \quad V = V_{\text{CKM}} \quad \text{with} \quad VV^+ = 1.
\]

V was introduced into the Standard Model by Kobayashi and Maskawa 1973. Phenomenology for 2 families already by Cabibbo 1963.

**Properties of the CKM matrix:**
The matrix $V_{ik}$ is complex. CPT symmetry requires:

\[
\begin{align*}
    \bar{d}' &= V_{ud}^* \cdot \bar{d} + V_{us}^* \cdot \bar{s} + V_{ub}^* \cdot \bar{b} \\
    \bar{s}' &= V_{cd}^* \cdot \bar{d} + V_{cs}^* \cdot \bar{s} + V_{cb}^* \cdot \bar{b} \\
    \bar{b}' &= V_{td}^* \cdot \bar{d} + V_{ts}^* \cdot \bar{s} + V_{tb}^* \cdot \bar{b}
\end{align*}
\]

Higgs mixes antiquarks in a different way than quarks. This is the origin of CP violation in the Standard Model. $V_{ik}^* \neq V_{ik}$ is necessary, but not sufficient. Because of unobservable quark phases, we must have:

\[
J = \text{Im} \left( V_{ik}^* V_{il}^* V_{jl}^* V_{jk}^* \right) \neq 0.
\]
Wolfenstein 1984:

\[
V \approx \begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} ; \quad J \approx A^2 \lambda^6 \eta.
\]

A, \(\lambda\), \(\rho\), \(\eta\) are 4 of 18 „free parameters“ of the St. Model.

6 unitarity conditions of \(V\) can be drawn as triangles, e.g.:

\[
V_{ud} V_{ub}^* - A\lambda^3 + V_{td} V_{tb}^* = 0, \\
V_{ub}^* / A\lambda^3 + V_{td} / A\lambda^3 \approx 1.
\]

Area of this triangle is \(J/2\).

Measurements of \(\lambda\), \(A\), \(\rho^2 + \eta^2\) and \((1 - \rho)^2 + \eta^2\) give

\[
\lambda = 0.223 \pm 1\% , \quad A = 0.82 \pm 4\% , \quad |J| \approx 3 \cdot 10^{-5} . \quad \text{Standard Model violates CP symmetry.}
\]
There is $\mathcal{CP}$ in the Standard Model, concluded from only $\mathcal{CP}$-symmetric observations!

1. Does this $J$ explain $\varepsilon(K^0)$?  
2. What prediction for $\mathcal{CP}(B^0)$?
Demonstration of $\mathcal{CP}(K)$ in a more recent experiment:

CPLEAR 1999, $p\bar{p} \rightarrow K^+\pi^-\bar{K}^0, K^-\pi^+K^0$; $K^0,\bar{K}^0 \rightarrow \pi^+\pi^-$

Asymmetry between $\pi^+\pi^-$ decays of tagged $K^0$ und $\bar{K}^0$ as function of time between production and decay:

$$a(t) = \frac{N(\bar{K}^0 \rightarrow \pi^+\pi^-) - N(K^0 \rightarrow \pi^+\pi^-)}{N(\bar{K}^0 \rightarrow \pi^+\pi^-) + N(K^0 \rightarrow \pi^+\pi^-)}$$

$$= \frac{-2|\eta_{+-}| e^{-\left(\Gamma_s + \Gamma_t\right)t/2} \cos(\Delta m_K \cdot \Delta t - \varphi_{+-})}{e^{-\Gamma_s t} + |\eta_{+-}|^2 e^{-\Gamma_t t}}$$

$$\eta_{+-} = (2.27 \pm 0.02) \cdot 10^{-3} \cdot e^{i(43.3 \pm 0.5)}$$
1. Yes!
2. Prediction for $\mathcal{CP}(B^0)$:

$$A = \frac{N(B^0 \to J/\Psi K^0_S) - N(B^0 \to J/\Psi K_S^0)}{N(B^0 \to J/\Psi K^0_S) + N(B^0 \to J/\Psi K_S^0)} = \sin 2\beta \cdot \sin[\Delta m(B^0)\Delta t]$$

where $\Delta t$ is the time between $\bar{B}^0(B^0)$ production and decay.
Short History:

1977   Discovery of b in \( Y(9.46) = 1^3S_1 b\bar{b} \) at FNAL
1978   Formation of \( Y(9.46) \) and \( Y(10.01) \) at DESY
1980   First B mesons \( 1^1S_0 b\bar{q} \) at Cornell
1986-89 „B-Meson Factory“ plans at PSI
1987   ARGUS discovery of \( B^0\bar{B}^0 \) oscillations
1988   Start of PEP-II studies at SLAC
1993   Decisions for PEP-II and KEK-B
1995   BABAR „TDR“ & approval
7/98    First e⁺e⁻ collisions in PEP-II
5/99    First e⁺e⁻ events in BABAR
7/00    First BABAR & BELLE results at Osaka
10/00   PEP-II reaches design luminosity of \( 3 \cdot 10^{33}/\text{cm}^2/\text{s} \)
3/01    BABAR and BELLE publish \( \sin 2\beta \) in PRL
The B-Meson Factory PEP-II:

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>Reached</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E \ [\text{GeV}] \ e^- / e^+$</td>
<td>9.0 / 3.1</td>
<td>yes</td>
</tr>
<tr>
<td>$I \ [\text{mA}] \ e^- / e^+$</td>
<td>610 / 2140</td>
<td>980 / 1680</td>
</tr>
<tr>
<td>$L \ [\text{cm}^{-2} \text{ s}^{-1}]$</td>
<td>$3 \times 10^{33}$</td>
<td>$4.5 \times 10^{33}$</td>
</tr>
<tr>
<td>$L_{\text{int}} \ [\text{pb}^{-1} / \text{day}]$</td>
<td>135</td>
<td>308</td>
</tr>
</tbody>
</table>
KEKB

asymmetric $e^+e^-$ collider

- Two separate rings
  - $e^+$ (LER) : 3.5 GeV
  - $e^-$ (HER) : 8.0 GeV
- $E_{CM}$ : 10.58 GeV at $\Upsilon(4S)$
- Luminosity
  - target: $10^{34}$/cm$^2$/s
  - achieved: $7.35 \times 10^{33}$/cm$^2$/s
- Small beam sizes:
  - $\sigma_\gamma \approx 3$ $\mu$m; $\sigma_x \approx 100$ $\mu$m
- $\pm 11$ mrad crossing angle
Daily and Integrated Luminosity,

October 1999 to February 2003

BABAR

BELLE

Recorded 107.79/fb

Design

PEP-II Delivered 106.08/fb
BABAR Recorded 100.90/fb
BABAR off-peak 9.93/fb

13 Feb 2003

K. R. Schubert (TU Dresden), Colloquium U Edinburgh
The BABAR Detector:

(1) Silicon Vertex Detector

(2) Drift Chamber

(3) Cerenkov-Detector

(4) Electromagnetic Calorimeter

(5) 1.5 T Solenoid

(6) Instrumented Iron Yoke
BABAR Collaboration: 10 Countries, 74 Institutes

China
Inst. of High Energy Physics, Beijing

Germany
RU Bochum
TU Dresden
U Rostock

France
LAPP Annecy
LAL Orsay
U Paris 6 et 7
Ecole Polytechnique
CEA Saclay

United Kingdom
U of Birmingham
U of Bristol
Brunel University
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary & Westfield College
Royal Holloway, University of London
U of Manchester
Rutherford Appleton Laboratory

Italy
INFN Bari
INFN Ferrara
INFN Frascati
INFN Genova
INFN Milano
INFN Napoli

Canada
U of British Columbia
McGill U
U de Montréal
U of Victoria

Netherlands
NIKHEF Amsterdam

Norway
U of Bergen

Russia
Budker Inst., Novosibirsk

≈500 physicists

13 Feb 2003
K. R. Schubert (TU Dresden), Colloquium U Edinburgh
Dresden Contributions to Calorimeter:

10 % of 6580 CsI(Tl) crystals, and all photodiodes

Optimisation of crystal light yield

Mechanics of readout electronics

Lightpulser system for monitoring (with Edinburgh and Bochum)

Bhabha calibration

$\pi^0$ calibration
e identification
**Silicon Vertex Tracker:**

\[ \sigma_z \approx 70 \, \mu m \] for fully reconstructed B mesons

\[ \sigma_z \approx 180 \, \mu m \] for \( B^0 \) meson tags

\[ \beta \gamma = 0.55, \beta \gamma c \tau(B) = 260 \, \mu m, \]

\[ \pi \beta \gamma c / \Delta m(B^0) = 1 \, mm, \]

R = 14 cm
≈ 300 physicists, 49 institutes, 14 countries: Australia, Austria, China, Germany, India, Korea, Japan, Philippines, Poland, Russia, Slovenia, Switzerland, Taiwan, USA

- SVD $\sigma \sim 55\mu m$ for 1GeV/c @ 90°
- CDC $\sigma_p/p \sim 0.35\%$ @ 1GeV/c; $\sigma_\pi (dE/dx) \sim 7\%$
- $K^\pm$ id: TOF ($\sigma \sim 100$ ps); Aerogel ($n = 1.01 \sim 1.03$)
- CsI $\sigma_E/E_\gamma \sim 1.5\%$ @ 1GeV
- KLM (RPCs) $\mu^\pm$: effic. $> 90\%$; $\sim 2\%$ fakes
A fully reconstructed event in BABAR:

\[ e^+ e^- \rightarrow (4S) \rightarrow \bar{B}^0 B^0 \rightarrow \mu^+ \mu^- \rightarrow \psi(2S) K^0_s \rightarrow D^{*+} \pi^- \rightarrow \pi^+ \pi^- \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \]
CP asymmetries in $B^0$ decays:

$$A = \frac{\Gamma(B^0 \rightarrow J/\psi K^0_S) - \Gamma(B^0 \rightarrow J/\psi K^0_S)}{\Gamma(B^0 \rightarrow J/\psi K^0_S) + \Gamma(B^0 \rightarrow J/\psi K^0_S)} = \sin 2\beta \cdot \sin[\Delta m(t_{\text{decay}} - t_{\text{prod}})]$$

Decay of $\Upsilon(4S)$ produces coherent 2-particle state $(B^0\bar{B}^0 - B^0\bar{B}^0)/\sqrt{2}$:

$$(t_{\text{dec}} - t_{\text{prod}}) \Rightarrow (t_{\text{dec}} - t_{\text{tag}}) = \Delta t$$

Integral of $A$ over all $\Delta t$ is zero

$\Rightarrow$ time dependent and boosted measurement necessary.

Tagging by partially reconstructed, but flavour-specific decays of the second $B$. 

13 Feb 2003  
K. R. Schubert (TU Dresden), Colloquium U Edinburgh  
26
Measurement of time-dependent CP asymmetry:

\[
\tilde{A} (\Delta t) = \frac{\Gamma (B^0 \rightarrow J/\psi K^0_S) - \Gamma (B^0 \rightarrow J/\psi K^0_S)}{\Gamma (B^0 \rightarrow J/\psi K^0_S) + \Gamma (B^0 \rightarrow J/\psi K^0_S)} = D \cdot \sin 2\beta \cdot \int \sin (\Delta m \Delta t) \cdot r (\Delta \tilde{t} - \Delta t) \, d\Delta t
\]

1. 2. 3: B Reconstruction into CP Eigenstate

4: Flavour Determination of the other B Meson ("tag")

5: Determination of the fraction \( w \) of mistags

Dilution \( D = (1 - 2w) \) reduces observed Asymmetry.

6: Determination of \( \Delta t = \Delta z / \beta \gamma c \)

7: Determination of the \( \Delta z \) resolution function

8: \( \sin 2\beta \) Fit to both Time Distributions

\( \beta \gamma = 0.55 \)
Event Selection in $B \rightarrow J/\psi K_S$

1. $J/\psi$ Reconstruktion

$J/\psi \rightarrow e^+e^-$

$J/\psi \rightarrow \mu^+\mu^-$

2. $K^0$ Reconstruktion

$\pi^+\pi^-$

$\pi^0\pi^0$
3. $B^0$ Reconstruction:

- More CP Modes in addition to $B^0 \rightarrow J/\psi K_S$:
  - $B^0 \rightarrow \psi(2S) K_S$
  - $B^0 \rightarrow \chi_{c1} K_S$
  - $B^0 \rightarrow \eta_c K_S$
  - All with CP = -1 and

$$\Delta E = E^*(J/\psi) + E^*(K^0) - E_{CMS}/2$$

$$m_{ES}^2 = (E_{CMS}/2)^2 - [p(J/\psi) + p(K^0)]^2$$

- $B^0 \rightarrow J/\psi K_L$ CP = +1
- $B^0 \rightarrow J/\psi K^0*(K_S\pi^0)$
- $CP_{eff} = +0.65 \pm 0.07$
Data 1999-2002: 81/fb on the $\Upsilon(4S)$, 90 M $\overline{B}B$

$\psi(2S)K^0_S(\rightarrow \pi^{-}\pi^+)$
$N_{\text{cond}} = 150$
Purity = 97%

$\psi(2S)K^0_S(\rightarrow \pi^{-}\pi^+)$
$N_{\text{cond}} = 80$
Purity = 95%

$J/\psi K^0_S(\rightarrow \pi^{-}\pi^+)$
$N_{\text{cond}} = 170$
Purity = 89%

$J/\psi K^0_S(\rightarrow \pi^{-}\pi^+)$
$N_{\text{cond}} = 974$
Purity = 97%

$\eta_c(KK\pi)K_S$
$N_{\text{cand}} = 132$
Purity = 63%

CP = -1. N = 1506 after tagging. Purity = $S/(S+B) = 94%$

$B^0 \rightarrow J/\psi K^0_L$: Only $K^0_L$ direction measured. Energy from $m(B^0)$.

$N_{\text{tot}} = 2641$ (incl. $J/\psi K^{0*}_L$)
78% purity.
4. Flavour-Tagging of the CP eigenstate by flavour-specific decays of the other B: Electrons, myons, charged Kaons, or Combi.

5. Fraction $w$ of mistags determined from the „Flavour Sample“

$$B^0 \rightarrow J/\psi K^0(K^+\pi^-), D^{(*)-}\pi^+, D^{(*)-}\rho^+...$$

6. Determination of $\Delta t = \Delta z/\beta\gamma c$

$\Delta z = z_{\text{decay}} - z_{\text{tag}}$, with $z_{\text{tag}}$ from vertex fit with two or more tracks with small $\chi^2$ contribution.
7. $R(\Delta z)$

Flavour samples with $1 \pm \cos \Delta m t$

$CP$ samples with $1 \pm \sin 2\beta \sin \Delta m t$

Perfect resolution vs real resolution

$B^0$ and $\bar{B}^0$ distributions for mixed and unmixed samples.
8. $\sin 2\beta$ fit to the $\Delta t$ distributions

$\sin 2\beta = 0.741 \pm 0.067 \pm 0.033$

220 lepton-tagged $\eta_f = -1$ events

98% purity
3.3% mistag rate
20% better $\Delta t$ resolution
July 2002
Results
with 78/ fb, 85 M γ(4S)

\[ \sin 2\beta = 0.719 \pm 0.074^{(stat)} \pm 0.035^{(syst)} \]
All results for $\sin2\beta$:

- **OPAL**: $3.2 \pm 1.8 \pm 0.5$
- **ALEPH**: $0.84 \pm 0.82 \pm 0.16$
- **CDF**: $0.79 \pm 0.41 \pm 0.44$
- **BABAR**: $0.741 \pm 0.067 \pm 0.033$
- **Belle**: $0.719 \pm 0.074 \pm 0.035$
- **Mean**: $0.732 \pm 0.055$ (13σ)
A new triumph for the Standard Model!

CP violation in K and B decays has its origin in quark mixing produced by Higgs coupling to $\bar{6}q$. 

Fit with $|V_{ub}|$, $|V_{td}|$, and $\eta_{+-}$. 

$\text{sin}2\beta$ 

Max L, $1\sigma$, $2\sigma$ 

13 Feb 2003 K. R. Schubert (TU Dresden), Colloquium U Edinburgh
Fit to all observations:

CKM quark mixing matrix parameters:
$A = 0.82 \pm 0.03$, $\lambda = 0.223 \pm 0.002$,
$\rho = 0.20 \pm 0.10$, $\eta = 0.36 \pm 0.06$, $J = (2.9 \pm 0.6) \times 10^{-5}$. 
Conclusions and Prospects:

BABAR from 90 M $B\bar{B}$ events: $\sin^2\beta = 0.74 \pm 0.07 \pm 0.03$.
BELLE from 85 M $B\bar{B}$ events: $\sin^2\beta = 0.72 \pm 0.07 \pm 0.04$.
World average $\sin^2\beta = 0.732 \pm 0.055$ agrees with St. Model.

No hint for New Physics CP, which could help cosmology.

PEP-II & KEK-B work well, both plan to increase $B\bar{B}$ rates.
Next years: Increase significance on $\sin^2\beta$
  Precision measurements on $\Delta m(B^0)$, $|V_{ub}|$, $V_{cb}$
  Search for rare decays like $B \rightarrow K l^+l^-$, $B \rightarrow \rho \gamma$
  Search for CP in other B decay modes ...
Check and overconstrain the description of the
Charged Weak Interaction in the St. Model.

2003 CDF,D0; 2007 ATLAS,CMS,LHCb; BTeV.