CP Violation in Decays of B Mesons

CP Symmetry and CP Violation
1964: Discovery in the Decay of K Mesons
37 Years Later the Second Evidence: Decays of B Mesons
Newest Results of BABAR and BELLE
Explanation in the Standard Model of Particle Physics
Consequences for Cosmology and Particle Physics
1. What is CP Symmetry?

One of the discrete symmetries of quantum physics, P = Parity, C = Charge conjugation, T = Time reversal.

\[ P \text{H}(1s) = +\text{H}(1s), \text{Atoms are P eigenstates, } P[H(1s)] = +1. \]

Reason: building blocks are P eigenstates and electric interaction is P-symmetric.

Valid for states and transitions, e.g. \( \text{H}(2p) \rightarrow \text{H}(1s) + \gamma \), P is conserved in all atomic transitions (in very good approximation).

\[ P \pi^0 = -\pi^0, \text{Hadrons} \& \text{nuclei are P eigenstates, } P(\pi^0) = -1. \]

Reason: quarks are P eigenstates and strong interaction is P-symmetric. P is conserved in all nuclear and hadronic reactions.

Caution: \( P \, e^-_L = e^-_R \quad P \quad \text{but } Q(e^-_L) = Q(e^-_R). \)
e^-_L and e^-_R have the same electric charge. Therefore strict P symmetry of the electric interaction.

Equivalently the strong int.: \[ P \ u_L = u_R, \] but \( Q_s(u_L)=Q_s(u_R) \). Strict P symmetry in spite of \( s(q)=1/2 \).

Electric charges Q and strong charges \( Q_s \) are couplings:

Completely different is the weak interaction:

It is not P-symmetric, parity P is not conserved.
P violation seen 1957 in the decay of K mesons:
\( K^+ \to \pi^+ \pi^0, \ P=(-1)^2 \) and \( K^+ \to \pi^+ \pi^+ \pi^-, \ P=(-1)^3. \)
First direct measurement of \( h(\beta^-) = -1: \) Bienlein 1958.

The operator \( C: \ C \ e^- = e^+. \) Positron is antiparticle of
the electron, discovered 1933 by Anderson. \( m(e^+) = m(e^-), \)
\( Q(e^+) = -Q(e^-). \) Electric int. is C-, P- and CP-symmetric:

\[ \begin{align*}
C \ u &= \bar{u}. \ m(\bar{u})=m(u), \ Q(\bar{u})=-Q(u), \ Q_s(\bar{u})=-Q_s(u). \ \text{Strong int.}:
\end{align*} \]
Weak interaction violates C symmetry,
$\Gamma(\mu^- \rightarrow e^-_L \bar{v}_{e_R} \nu_{\mu_L}) = 1/2 \mu s$, $\Gamma(\mu^+ \rightarrow e^+_L \bar{v}_{e_R} \nu_{\mu_L}) = 0$,
violates P and obeys CP symmetry:
$\Gamma(\mu^- \rightarrow e^-_R \bar{v}_{e_L} \nu_{\mu_R}) = 0$, $\Gamma(\mu^+ \rightarrow e^+_R v_{e_L} \bar{v}_{\mu_R}) = 1/2 \mu s$.

CP symmetry of the weak interaction was seen in all experiments... – until 1964.

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>C</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong int.</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Electr. int.</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Weak int.</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

1964: No!

CP symmetry:
All reactions with right-handed antiparticles proceed with the same rate as with left-handed particles.
2. Discovery of CP Violation:

1964 by Christenson, Cronin, Fitch und Turlay in the decay of neutral K mesons. $K^0 = 1^1S_0 \bar{s}d$, $m = 497$ MeV, $\tau = 10^{-10}$s.

Strange particle: Decay law is non-exponential.

Explanation by $K^0\bar{K}^0$ mixing,

$\bar{K}^0 = c K^0 = 1^1S_0 s\bar{d}$

$K^0 \rightarrow$ coherent superposition of $K^0$ and $\bar{K}^0$

2 special superpositions decay exponentially:

$K_S = p K^0 + q \bar{K}^0$,
$K_L = p K^0 - q \bar{K}^0$.

CP conservation: $|p| = |q|$
CP violation: $|p| \neq |q|$
Demonstrating CP violation 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 \( K^0 \) and \( \bar{K}^0 \) as function of time between production and decay.

\[
A(t) = \frac{N(\bar{K}^0 \rightarrow \pi^+\pi^-) - N(K^0 \rightarrow \pi^+\pi^-)}{N(\bar{K}^0 \rightarrow \pi^+\pi^-) + N(K^0 \rightarrow \pi^+\pi^-)}
\]

Described by \( \tau(K_S), \tau(K_L) \),
\( \Delta m_K = m(K_L) - m(K_S) \),

\( \text{Re} \ \varepsilon_K \) and \( \text{Im} \ \varepsilon_K \).

\[
\varepsilon_K = (2.27 \pm 0.02) \cdot 10^{-3} \cdot e^{i(43.3 \pm 0.5)\circ}
\]
Explanation of mixing, $\Delta m_K$ in the St. Model:

The 4x3 couplings are complex numbers. Their interferences lead to

\[ \Gamma(K^0 \rightarrow \bar{K}^0) < \Gamma(\bar{K}^0 \rightarrow K^0) \]

The observed CP violation is also T violation, violation of time reversal invariance.

For 37 years, only $K^0$ mesons (and the Universe) showed CPV. In summer 2001, BABAR and BELLE saw it also in $B^0$ decays.
K → π⁺π⁻

B → J/ψ K_S

K^0

B^0

∆t/τ(K_S)

A

Δt [ps]

A

Δt [ps]
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Discovery of b in $\Upsilon(9.46) = 1^3S_1 b\bar{b}$ at FNAL</td>
</tr>
<tr>
<td>1978</td>
<td>Formation of $\Upsilon(9.46)$ and $\Upsilon(10.01)$ at DESY</td>
</tr>
<tr>
<td>1980</td>
<td>First B mesons $1^1S_0 b\bar{q}$ at Cornell</td>
</tr>
<tr>
<td>1986-89</td>
<td>„B-Meson Factory“ plans at PSI, Switzerland</td>
</tr>
<tr>
<td>1987</td>
<td>ARGUS discovery of $B^0\bar{B}^0$ oscillations</td>
</tr>
<tr>
<td>1988</td>
<td>Start of PEP-II studies at SLAC</td>
</tr>
<tr>
<td>1993</td>
<td>Decisions for PEP-II and KEK-B, TU Dresden participates at SLAC</td>
</tr>
<tr>
<td>1995</td>
<td>BABAR „TDR“ &amp; approval, U Bochum joins</td>
</tr>
<tr>
<td>7/98</td>
<td>First $e^+e^-$ collisions in PEP-II</td>
</tr>
<tr>
<td>5/99</td>
<td>First $e^+e^-$ events in BABAR</td>
</tr>
<tr>
<td>7/00</td>
<td>First BABAR&amp;BELLE results for Osaka conference</td>
</tr>
<tr>
<td>10/00</td>
<td>PEP-II reaches design luminosity of $3 \cdot 10^{33} /\text{cm}^2/\text{s}$</td>
</tr>
<tr>
<td>7/01</td>
<td>BABAR and BELLE find $\sin 2\beta \neq 0$ with $4\sigma$</td>
</tr>
</tbody>
</table>
Search for CPV(B) was not „blind“. There was a clear Standard-Model expectation:

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

Value of $\sin 2\beta$ given by Standard-Model quark mixing; $\sin 2\beta = 0.5 - 0.8$ from CP-conserving B decays and mixing. Nevertheless: About $3 \cdot 10^7$ B mesons necessary!

Best production method:

Alternatives: $Z^0 \rightarrow b\bar{b}$ (LEP only $10^6$), hadronic production (high background).
The B-Meson Factory PEP-II:

<table>
<thead>
<tr>
<th></th>
<th>Plan</th>
<th>reached</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E \ [GeV] \ e^- / e^+$</td>
<td>9.0 / 3.1</td>
<td>yes</td>
</tr>
<tr>
<td>$I \ [A] \ e^- / e^+$</td>
<td>0.6 / 2.1</td>
<td>1.5 / 2.4</td>
</tr>
<tr>
<td>$L \ [cm^{-2} \ s^{-1}]$</td>
<td>$3 \times 10^{33}$</td>
<td>$9.2 \times 10^{33}$</td>
</tr>
<tr>
<td>$L_{int} \ [pb^{-1}/day]$</td>
<td>135</td>
<td>710</td>
</tr>
</tbody>
</table>
Daily and Integrated Luminosity, Oct 1999 - June 2004

Daily Recorded Luminosity (pb⁻¹)

- Design

Integrated Luminosity (fb⁻¹)

- Delivered Luminosity
- Recorded Luminosity
- Off Peak

PEP-II Delivered 228.49/fb
BABAR Recorded 219.82/fb
BABAR off-peak 17.27/fb
From the daily PEP-II protocols:

30 Nov 2003

17 May 2004

„Double Trickle Injection“
The BABAR Collaboration:

Canada [4]
U of British Columbia
McGill U Montreal
U de Montréal
U of Victoria

China [1]
Inst. of High Energy Physics, Beijing

France [5]
LAPP Annecy
LAL Orsay
U Paris 6 et 7
Ecole Polytechnique
DAPNIA CEA Saclay

Germany [4]
RU Bochum
TU Dresden
U Heidelberg
U Rostock

Great Britain [10]
U of Birmingham
U of Bristol
Brunel University
U of Edinburgh
U of Liverpool
Imperial College London
Queen Mary & Westfield College
Royal Holloway U of London
U of Manchester
Rutherford Appleton Laboratory

Italy [12]
INFN Bari
INFN Ferrara
INFN Frascati
INFN Genova
INFN Milano
INFN Napoli

Netherlands [1]
NIKHEF Amsterdam

Norway [1]
U of Bergen

Russia [1]
Budker Inst., Novosibirsk

USA [38]
SUNY Albany
Caltech Pasadena
UC Irvine
UC Los Angeles
UC Riverside
UC San Diego
UC Santa Barbara
UC Santa Cruz
U of Cincinnati
U of Colorado
Colorado State U
Florida A&M
Harvard U
U of Iowa
Iowa State U
LBNL Berkeley
LLNL Livermore
U of Louisville
U of Maryland
U of Massachusetts
MIT Cambridge
U of Mississippi
Mount Holyoke College
U of Notre Dame
Ohio State U
U of Oregon
U of Pennsylvania
Prairie View A&M
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
Vanderbilt
U of Wisconsin
Yale U New Haven

77 Institutes, 10 Countries, ~520 Authors
German Contributions to the BABAR Calorimeter:

- 10% of 6580 CsI(Tl) crystals
- All photodiodes
- Optimisation of crystal light yield
- Mechanics of readout electronics
- Lightpulser system for monitoring
- Bhabha calibration
- $\pi^0$ calibration
- e identification
$B^0 \bar{B}^0$ Mixing with 20M $Y(4S)$:

\[ A(\Delta t) = \frac{N(\ell^+ \ell^-)(\Delta t) - N(\ell^\pm \ell^\pm)(\Delta t)}{N(\ell^+ \ell^-)(\Delta t) + N(\ell^\pm \ell^\pm)(\Delta t)} \]

\[ A(\Delta t) = \frac{e^{-r^0|\Delta t|} \cos(\Delta m_B \Delta t) + R \cdot e^{-r^+|\Delta t|}}{e^{-r^0|\Delta t|} + R \cdot e^{-r^+|\Delta t|}} \]

$\Delta m_B = (0.499 \pm 0.010 \pm 0.012) \text{ps}^{-1}$

This box graph also produces CPV. Expected at o(10^{-3}). Not yet seen.

BABAR from $N(l^+ l^+) - N(l^- l^-)$:

$\text{Re } \varepsilon_B = (1 \pm 4) \times 10^{-3}$. 
A fully reconstructed event:

**CP eigenstate, decay at t₂, either from \( \bar{B}^0 \) or from \( B^0 \), \( \Delta t = t_2 - t_1 \).**

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

**Flavour eigenstate, here from \( \bar{B}^0 \), decay at \( t_1 \) “tags“ the flavour of the other \( B \) at time \( t_1 \).**

Such events are very rare, \( o(10^{-6}) \), therefore we use inclusive tagging for CP asymmetry measurements.
CP Asymmetry:

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

The \( \Upsilon(4S) \) resonance produces a coherent two-particle state \((B^0 \bar{B}^0 - \bar{B}^0 B^0)/\sqrt{2}\).

\((t_{\text{decay}} - t_{\text{prod.}}) \Rightarrow (t_{\text{decay}} - t_{\text{tag}}) = \Delta t\)

Integral of \( A \) over all \( \Delta t \) is zero.
Requires time-dependent measurement.
Measurement of time-dependent CP-Asymmetry:

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

\[\beta \gamma = 0.55\]

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
Newest BABAR results (7/02):

$\bar{c}cK_S$ modes:

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

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

$\chi_{c0} K_S^0 (\rightarrow \pi^+\pi^-)$
- $N_{\text{cond}} = 80$
- Purity = 95%

$J/\psi K_L$:

$J/\psi K_L$
- $N_{\text{cond}} = 988$
- Purity = 55%

$\eta_c(KK\pi)K_S$
- $N_{\text{cond}} = 132$
- Purity = 63%
One more mode: $J/\psi K^{*0}\{\rightarrow K_s^0 \pi^0\}$

$N_{\text{cand}} = 147$

Purity 81%

$D = 0.68 \pm 0.07$

**BABAR**

PRL 87, 241801 (2001)

$R_\perp = (16.0 \pm 3.2_{\text{stat}} \pm 1.4_{\text{syst}})\%$

**BELLE** hep-ex/0205021

$R_\perp = (19.1 \pm 2.3_{\text{stat}} \pm 2.6_{\text{syst}})\%$

Conclude: $J/\psi$ mostly $CP$ even

$D_\perp = 1 - 2 \cdot R_\perp$

$R_\perp \equiv |A_\perp|^2$ fraction of $CP$-odd
<table>
<thead>
<tr>
<th>Tagging Category</th>
<th>Efficiency (%)</th>
<th>Mistag fraction (%)</th>
<th>Q (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>9.1 ± 0.2</td>
<td>3.3 ± 0.6</td>
<td>7.9 ± 0.3</td>
</tr>
<tr>
<td>Kaon and π(soft)</td>
<td>16.7 ± 0.2</td>
<td>9.9 ± 0.7</td>
<td>10.7 ± 0.4</td>
</tr>
<tr>
<td>Kaon II</td>
<td>19.8 ± 0.3</td>
<td>20.9 ± 0.8</td>
<td>6.7 ± 0.4</td>
</tr>
<tr>
<td>Inclusive</td>
<td>20.0 ± 0.3</td>
<td>31.6 ± 0.9</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>total</td>
<td>65.6 ± 0.5</td>
<td></td>
<td>28.1 ± 0.7</td>
</tr>
</tbody>
</table>

Tag quality $Q = \Sigma \varepsilon_i (1-2w_i)^2 \Rightarrow \sigma(\sin 2\beta) \approx \frac{1.9}{\sqrt{N_{\text{sig}}Q}} \cdot \sqrt{1 + \frac{N_{\text{bg}}}{N_{\text{sig}}}}$

Result July 2002 with 90 M $\Upsilon(4S)$, 2641 tagged events:

$\sin 2\beta = 0.741 \pm 0.067 \pm 0.033$
$K \rightarrow \pi^+ \pi^-$

$B \rightarrow J/\psi K_S$

$|\varepsilon_K| = (2.27 \pm 0.02) \times 10^{-3}$

$\sin 2\beta = 0.74 \pm 0.07$
All results for $\sin 2\beta$:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
<th>Error</th>
<th>Error2</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPAL</td>
<td>3.2</td>
<td>± 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALEPH</td>
<td>0.84</td>
<td>± 0.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ 0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 1.04</td>
<td></td>
<td></td>
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<tr>
<td>CDF</td>
<td>0.79</td>
<td>± 0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ 0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BABAR 02</td>
<td>0.741</td>
<td>± 0.067</td>
<td>± 0.033</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td>BELLE 03</td>
<td>0.733</td>
<td>± 0.057</td>
<td>± 0.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mean</td>
<td>0.737</td>
<td>± 0.048</td>
<td></td>
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</table>

(15σ from 0)
5. Explanation of CPV(K) and CPV(B):

Values of $\varepsilon_K$ and $\sin2\beta$ are compatible with each other, and with the hypothesis that they are produced by the charged weak interaction of the Standard Model.

$$d' = V_{ud} \cdot d + V_{us} \cdot s + V_{ub} \cdot b$$

$$s' = V_{cd} \cdot d + V_{cs} \cdot s + V_{cb} \cdot b$$

$$b' = V_{td} \cdot d + V_{ts} \cdot s + V_{tb} \cdot b$$

$$\bar{d}' = V_{ud}^* \cdot \bar{d} + V_{us}^* \cdot \bar{s} + V_{ub}^* \cdot \bar{b}$$

$$\bar{s}' = V_{cd}^* \cdot \bar{d} + V_{cs}^* \cdot \bar{s} + V_{cb}^* \cdot \bar{b}$$

$$\bar{b}' = V_{td}^* \cdot \bar{d} + V_{ts}^* \cdot \bar{s} + V_{tb}^* \cdot \bar{b}$$

CKM matrix $V_{ij}$ describes quark mixing as a consequence of Higgs couplings to quarks. If $V_{ij} \neq V_{ij}^*$, Higgs couples differently to $q$ and $\bar{q}$ and produces CPV.
V is unitary, $V V^+ = 1$. \[ \text{CPV} \Leftrightarrow J = \text{Im} (V_{ik} V_{il}^* V_{jl} V_{jk}^*) \neq 0. \]

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

$A, \lambda, \rho, \eta$ are 4 of 18 “free parameters“ of the St.Model. 6 unitarity conditions may be drawn as triangles, e.g.:

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

$\bar{\rho} = \rho(1-\lambda^2/2), \quad \bar{\eta} = \eta(1-\lambda^2/2).$

Area of this triangle is $J/2$.

Measurements of $\lambda$ and $A$:

$\lambda = 0.2240 \pm 0.0038,$

$A\lambda^2 = 0.0416 \pm 0.0008.$
Measurements of $|V_{ub}|$ and $|V_{td}|$ give, together with $\lambda$ and $A\lambda^2$:
Including the $\bar{\rho}\bar{\eta}$ regions for $\varepsilon_K$ and $\sin 2\beta$:

The regions are in perfect agreement with those from $V_{ub}$ and $V_{td}$

$\Rightarrow$ **Observed CPV is St. Model CPV.**
$\bar{\rho} \bar{\eta}$ fit to measurements of $V_{ub}$, $V_{td}$, $\varepsilon_K$, and $\sin 2\beta$:
Including the 2004 BABAR measurement of $\alpha$,

$\bar{\rho} \bar{\eta}$ fit to measurements of $V_{ub}$, $V_{td}$, $\varepsilon_K$, $\sin2\beta$, and $\alpha$:

\[ \lambda = 0.2240 \pm 0.0038, \quad A\lambda^2 = 0.0416 \pm 0.0008, \]
\[ \bar{\rho} = 0.20 \pm 0.08, \quad \bar{\eta} = 0.35 \pm 0.04. \]
Measurable in decays $B^0, \bar{B}^0 \rightarrow \pi^+\pi^-$ and $\rho^+\rho^-$ with same tagged $\Delta t$-dependent asymmetry as in $B^0, \bar{B}^0 \rightarrow J/\psi K_S$

\[ A(\Delta t) = \sin 2\beta \sin \Delta m \Delta t \]

if tree only: $C=0$, $S=\sin 2\alpha$

if tree + penguin: $C \neq 0$, $S=\sin 2\alpha_{\text{eff}}$, models or Gronau-London for $\alpha-\alpha_{\text{eff}}$. 

$J/\psi K_S$: Tree

$\pi^+\pi^-, \rho^+\rho^-$: Tree plus Penguin
\begin{align*}
\pi^+ \pi^- \\
A(\Delta t) &= C \cos(\Delta m \Delta t) + S \sin(\Delta m \Delta t) \\
S &= \sqrt{1 - C^2} \sin(2(\alpha + \theta))
\end{align*}

There is a 3.5 \sigma CP-violating effect
in this decay, but no model-independent determination of \( \alpha \).
Size of S and C not predictable, but inside St.Model (as \( \varepsilon^'_{K} \))
\( \rho^+ \rho^- : \) No CPV, but \( \alpha \)

vector-vector mode with 3 final states, 2 with \( \eta_{CP} = +1 \), one with -1.

Results:

- \( BF = (30 \pm 4 \pm 5) \times 10^{-6} \)
- \( f_{long} = 0.99 \pm 0.03 \pm 0.04 \pm 0.03 \)
- \( S_{long} = -0.19 \pm 0.33 \pm 0.11 \)
- \( C_{long} = -0.23 \pm 0.24 \pm 0.14 \)

Dominated by \( \eta_{CP} = +1 \)
\begin{align*}
B^0 \rightarrow \rho^+ \rho^- & : \quad \text{BF} = (30 \pm 4 \pm 5) \times 10^{-6} \quad \text{(BABAR)} \\
B^+ \rightarrow \rho^+ \rho^0 & : \quad \text{BF} = (26.4 \pm 6.4) \times 10^{-6} \quad \text{(BABAR & BELLE)} \\
f_{\text{long}} = 0.962^{+0.049}_{-0.065} & \quad \text{(BABAR & BELLE)} \\
B^0 \rightarrow \rho^0 \rho^0 & : \quad \text{BF} = (0.62^{+0.72}_{-0.60} \pm 0.12) \times 10^{-6} \quad \text{(BABAR)}
\end{align*}

\( S_{\text{long}} \) and \( C_{\text{long}}(\rho^+ \rho^-) \), the Gronau-London isospin analysis using these 3 BF, and inclusion of a possible electroweak penguin lead to

\[
\alpha = (96 \pm 10 \pm 4 \pm 13)^0
\]

\[
\sigma_{\text{exp}}(\alpha_{\text{eff}}) \quad \sigma_{\text{th}}(\alpha - \alpha_{\text{eff}}) \quad \text{[and 3 other solutions]}
\]

This solution (and only this one of the 4) is compatible with \( \text{CPV}_{\text{St.Model}} \) and contributes to constrain its fundamental parameters \( \rho \) and \( \eta \):
$\bar{\rho} \bar{\eta}$ fit to measurements of $V_{ub}$, $V_{td}$, $\varepsilon_K$, $\sin 2\beta$, and $\alpha$:

$$\lambda = 0.2240 \pm 0.0038, \ A\lambda^2 = 0.0416 \pm 0.0008,$$

$$\bar{\rho} = 0.20 \pm 0.08, \bar{\eta} = 0.35 \pm 0.04.$$
6. Summary and Consequences:

CPV observed in the laboratory ($\varepsilon_K$, $\sin 2\beta$; $C_{\pi\pi}$, $S_{\pi\pi}$, $\varepsilon'_K$) is a property of Higgs couplings in the Standard Model. This type of CPV is not sufficient for cosmology: Standard-cosmology calculations with this CPV give $N(B)/N(\gamma) \leq 10^{-20}$ instead of, as seen in CMB, $N(B)/N(\gamma) \approx 10^{-9}$.

CPV remains a problem for particle- and cosmo-physics. Majorano neutrinos or supersymmetry could help.

BABAR and BELLE experimentalists are, therefore, further motivated to search for „New Physics“ CPV. BELLE sees a $3\sigma$ non-Standard CPV in $B\rightarrow\phi K_S$, BABAR disagrees.