The Mirror Crack’d*: History and Status of CP Violation Studies

*apologies to Agatha Christie

*Eric Prebys (UR ‘90*), Fermi National Accelerator Laboratory
Representing the
BELLE Collaboration

September 26, 2001

University of Rochester
The BELLE Collaboration

≈300 people from 49 Institutions in 11 Countries:

Australia, China, India, Korea, Japan, Philippines, Poland, Russia, Taiwan, Ukraine, and USA

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Dear Eric,

I just returned to Rochester and I am happy to know that Tom has invited you for a colloquium on Sep 26. Can you send me a title of your talk at the earliest. I would like to tell you a few things that Tom may not have mentioned. First, you will be the first speaker of the semester and, therefore, you carry a great responsibility for presenting a very good colloquium. Second, since our colloquium attendance has thinned over the years (because of bad talks, specialized talks), I have assured the students that I will only invite extraordinary speakers who can give a very general talk to graduate students across all disciplines. So, I would like you to prepare your talk keeping this in mind. In particular, what this means is that please do not make it a talk on experimental physics, rather on physics. Remember the time when you were a student and the kinds of things you hated in colloquia, please avoid them. Not all the students will be from high energy physics. In fact, many are from optics, astronomy and so a talk with less display of detectors etc and with a greater balance of theoretical motivation and the explanation of results would be highly appreciated.

Why am I telling you all this? Well, first of all, you were our former student and as such I have a right to ask you for things. Second, you will be the first speaker and if the students are not thrilled with your talk, the attendance may shrink in the subsequent talks. On the other hand, if your talk is superb, which I hope it will be, more people will show up for the later talks (people have a tendency to extrapolate). In any case, please keep in mind that you will be talking to a general audience and not to a group of experimentalists.

Let me know when your itinerary is complete, but please send me a title in a couple of days.

With very best regards,

Ashok.
Outline

• Why do we care?

• History
  – Parity Violation
  – V-A Currents and CP (almost) Conservation
  – CP Violation in the Neutral K System
  – The Cabbibo-Kobayashi-Maskowa Mechanism
  – “The” Unitarity Triangle

• The Present
  – Direct CP Violation in the Neutral K System ($\epsilon'/\epsilon$)
  – Indirect CP Violation in the B meson System (B-Factories)

• The Future?
Why do We Care?

- Dirac first predicted antimatter in 1930 as a consequence of the “extra” solutions to his relativistic formulation of quantum mechanics - and was widely ridiculed.
- The positron (anti-electron) was discovered by Anderson in 1932 and the anti-proton was discovered by Segre and Chamberlain in 1955.
- Now we are all quite comfortable with the idea of antimatter as “equal and opposite” to matter, e.g.

> “Of course, there is only one correct mixing ratio of matter and antimatter: **one to one**!” – Star Trek, The Next Generation

- …but why does the universe seem to be made entirely of matter?
- Why do there seem to be *tiny* differences in the physics of matter and antimatter?
- These legitimately qualify as ‘**big questions**’.
Parity Violation

- The “parity” operation transforms the universe into its mirror image (*goes from right-handed to left-handed*).
- Maxwell’s equations are totally parity invariant.
- BUT, in the 50’s huge parity violation was observed in weak decays…

Example: β decay of polarized Co...

- Electron preferentially emitted opposite spin direction
Weak Currents and Parity Violation

Review: QED

\[ j_{\mu}^{EM} = \gamma^* \]

\[ j_{\mu}^{EM,\mu} = \gamma^* \]

\[ A \propto j_{\mu}^{CA} j_{DB,\mu} = (\overline{u}_C \gamma^\mu u_A) (\overline{u}_D \gamma_\mu u_B) \]

Transform like vectors

For weak interactions, try (“four fermion interaction”)

\[ j_{\mu}^{weak} = \overline{u}_C (c_v \gamma^\mu + c_A \gamma^5 \gamma^\mu) u_A \]

Manifestly Violates Parity!!
“V-A” Current

Experimentally, it was found that data were best described by

\[ j_{weak}^\mu = \overline{u}_C (\gamma^\mu - \gamma^5 \gamma^\mu) u_A \]

Maximum Parity Violation!!!!

Recall that for Direct Spinors, the left handed projection operator is

\[ u_L = P_L u = \left( \frac{1 - \gamma^5}{2} \right) u \Rightarrow j_{weak}^\mu \propto \overline{u}_L \gamma^\mu u_L \]

“Left-handed” current

For massless particles, spinor state = helicity state

Only Left-handed Neutrinos
When we apply the usual Dirac gymnastics, we find that for \textit{anti-particles}:

\[
j_{\text{weak}}^\mu = \bar{\nu}_C (\gamma^\mu + \gamma^5 \gamma^\mu) \nu_A \propto \bar{\nu}_R \gamma^\mu \nu_R \quad \text{Right-handed current}
\]

\[
\text{Only Right-handed anti-Neutrinos}
\]

Overall symmetry restored under the combined operations of \textit{C(harge conjugation)} and \textit{P(arity)}.

\[
\text{CP Conservation}!!!
\]

well, maybe not....
The Neutral Kaon System

In experiments in the 1950s, it was found that there were two types of neutral strange particles, of indistinguishable mass (498 MeV), but with different decay properties.

\[ K_{L(\text{long})} \Rightarrow 3\pi \quad \text{CP} = -1 \]

\[ K_{S(\text{short})} \Rightarrow 2\pi \quad \text{CP} = +1 \]

Because \( 3m_\pi \approx m_K \), the \( K_L \) lives about 600 times longer than the \( K_S \), hence the names.

Possible explanation:

\[ |K_S\rangle = \frac{1}{\sqrt{2}} \left( |K_0\rangle + |\overline{K}_0\rangle \right) \]

\[ |K_L\rangle = \frac{1}{\sqrt{2}} \left( |K_0\rangle - |\overline{K}_0\rangle \right) \]

Strangeness eigenstates

close, but not quite correct…
In 1964, Fitch, Cronin, *etal*, showed that in fact $K_L \Rightarrow 2\pi$ with a branching ratio on the order of $10^{-3}$.

Interpretation:

**CP Eigenstates**

$$|K_1\rangle = \frac{1}{\sqrt{2}} \left( |K_0\rangle + |\overline{K}_0\rangle \right)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}} \left( |K_0\rangle - |\overline{K}_0\rangle \right)$$

**Mass Eigenstates**

$$|K_S\rangle \approx |K_1\rangle + \varepsilon |K_2\rangle$$

$$|K_L\rangle \approx |K_2\rangle + \varepsilon |K_1\rangle$$

$$\varepsilon = 2.3 \times 10^{-3}$$
The Significance

In other words…

\[ |K_{L,S} \rangle \equiv a_{L,S} |K^0 \rangle + b_{L,S} |\bar{K}^0 \rangle \]

where \( |a_{L,S}| \neq |b_{L,S}| \)

This generated great interest (not to mention a Nobel Prize), and has been studied in great detail ever since, but until recently had only been conclusively observed in the kaon system.

Unlike parity violation, it is not trivial to incorporate CP violation into the standard model. To understand how it is done, we must now digress a bit into some details of fundamental particle interactions….
In the Standard Model, the fundamental particles are **leptons** and **quarks**.

Quarks combine as $qqq$, $qqq$, or $qq$ to form hadrons.

Leptons exist independently.

In this model, weak interactions are analogous to QED.

\[
\begin{align*}
\text{Leptons:} & \quad \nu_e, \mu, \tau \\
\text{Quarks:} & \quad u, c, t, d, s, b
\end{align*}
\]

\[
\begin{align*}
\text{Force Carriers:} & \quad \gamma, Z, W, W^-
\end{align*}
\]
Quark Mixing

In the Standard Model, leptons can only transition within a generation (NOTE: probably not true!)

Although the rate is suppressed, quarks can transition between generations.
The CKM Matrix (1973)

- The weak quark eigenstates are related to the strong (or mass) eigenstates through a unitary transformation.

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

\[
\begin{pmatrix}
    u \\
    d' \\
    s' \\
    b'
\end{pmatrix}
\]

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- The only straightforward way to accommodate CP violation in the SM is by means of an irreducible phase in this matrix.
- This requires at least three generations and led to prediction of t and b quarks … a year before the discovery of the c quark!
The CKM matrix is an SU(3) transformation, which has four free parameters. Because of the scale of the elements, this is often represented with the “Wolfenstein Parameterization”

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

First two generations *almost* unitary. \(\lambda = \text{sine of “Cabbibo Angle”}

CP Violating phase
“The” Unitarity Triangle

- Unitarity imposes several constraints on the matrix, but one (product first and third columns)... 

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

results in a triangle in the complex plane with sides of similar length \( \left( \approx A\lambda^3 \right) \), and appears the most interesting for study

(Note! in US: \( \phi_1 \equiv \beta, \ \phi_2 \equiv \alpha, \ \phi_3 \equiv \gamma \))
The \( \rho-\eta \) Plane

- Remembering the Wolfenstein Parameterization

\[
\begin{bmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{bmatrix}
\]

we can divide through by the magnitude of the base \((A\lambda^3)\)....

\[
\begin{align*}
&\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \\
&\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}
\end{align*}
\]

\((\rho, \eta)\)

\((0,0)\)

\((1,0)\)

CP violation is generally discussed in terms of this plane
Direct CP Violation

- CP Violation is manifested as a difference between the physics of matter and anti-matter

\[ \Gamma(i \rightarrow f) \neq \Gamma(i \rightarrow f') \]

- Direct CP Violation is the observation of a difference between two such decay rates; however, the amplitude for one process can in general be written

\[ A = |A| e^{i\phi_w} e^{i\phi_s} \Rightarrow \bar{A} = |A| e^{-i\phi_w} e^{i\phi_s} \]

  Weak phase changes sign  Strong phase does not

- Since the observed rate is only proportional to the amplitude, a difference would only be observed if there were an interference between two diagrams with different weak \emph{and} strong phase.

  \[ \Rightarrow \text{Rare and hard to interpret} \]
Direct CP Violation in the Neutral Kaon System

(\varepsilon'/\varepsilon\ Measurement)

Recall...

\[ K_S = K_1 + \varepsilon K_2 \]
\[ K_L = K_2 + \varepsilon K_1 \]

If there is only indirect CP violation, then ALL 2\pi decays really come from \( K_L \), and we expect (among other things)

\[ \frac{Br(K_L \Rightarrow \pi^+\pi^-)}{Br(K_L \Rightarrow \pi^0\pi^0)} = \frac{Br(K_1 \Rightarrow \pi^+\pi^-)}{Br(K_1 \Rightarrow \pi^0\pi^0)} = \frac{Br(K_S \Rightarrow \pi^+\pi^-)}{Br(K_S \Rightarrow \pi^0\pi^0)} \]

But the Standard Model allows

\[ Br(K^0 \rightarrow 2\pi) \neq Br(\bar{K}^0 \rightarrow 2\pi) \]

\[ \Rightarrow K_2 \rightarrow 2\pi \quad \leftarrow \text{Direct CP Violation} \]
Direct CP Violation in the Neutral Kaon System (cont’d)

Formalism:

\[
|K_L\rangle = |K_2\rangle + \varepsilon |K_1\rangle
\]

\(\varepsilon'\)

\[
\eta_{+-} \equiv \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \varepsilon + \varepsilon'
\]

\[
\eta_{00} \equiv \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = \varepsilon - 2\varepsilon'
\]

\[
\frac{Br(K_L \rightarrow \pi^+\pi^-) / Br(K_S \rightarrow \pi^+\pi^-)}{Br(K_L \rightarrow \pi^0\pi^0) / Br(K_S \rightarrow \pi^0\pi^0)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \approx 1 + 6 \text{Re}(\varepsilon' / \varepsilon)
\]

Theoretical estimates for \(\varepsilon'/\varepsilon\) range from 4-30 \(\times 10^{-4}\)
Easy to Measure….NOT!

\[ \begin{align*}
K_L & \quad \pi^+ \quad \pi^- \\
K_S & \quad \pi^+ \quad \pi^- \\
\end{align*} \]

Must take great steps to understand acceptances and systematic errors!!
KTeV Experiment (Fermilab)

(Images from Jim Graham’s Fermilab “Wine and Cheese” Talk)

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At this point, the accuracy of this measurement is better than that of the theoretical prediction:

\[(4 \times 30 \times 10^{-4})\]

This bothered people.
Indirect CP Violation in the B Meson System

Let’s Look at B-mixing…

\[
B^0(t) = e^{-i(m-i\Gamma)/2} \times \left[ \cos\left(\frac{\Delta m t}{2}\right) B^0 + i \sin\left(\frac{\Delta m t}{2}\right) e^{-2i\phi_m} \bar{B}^0 \right]
\]

Mixing phase = \arg(V_{td} V_{tb}^*) = \phi_1
Indirect CP Violation (cont’d)

- If both $B$ and $\bar{B}$ can decay to the same CP eigenstate $f$, there will be an interference.

$$
B^0 \xrightarrow{\text{Decay phase}} f
$$

And the time-dependent decay probability will be

$$
P(t) = e^{-\Gamma|t|}\left[1 - \eta_{CP} \sin(\phi_M + \phi_D) \sin(\Delta m^* t)\right]
$$

Difference between B mass eigenstates

- CP state of $f$
- Decay phase
- Mixing phase
At the right energies, electrons and positrons can produce a spectrum of bound resonant states of $b$ and \textit{anti-$b$} quarks.

The $1^-$ states are called the “ϒ (‘Upsilon’) resonances”

Starting with the \(\Upsilon(4S)\), they can decay strongly to \textit{pairs of B-mesons}.

The lighter states must decay through quark-antiquark annihilation.
The Basic Idea

- We can create $B^0 \bar{B}^0$ pairs at the $\Upsilon(4S)$ resonance.
- Even though both $B$’s are mixing, if we tag the decay of one of them, the other must be the CP conjugate at that time. We therefore measure the time dependent decay of one $B$ relative to the time that the first one was tagged (EPR “paradox”).
- **PROBLEM:** At the $\Upsilon(4S)$ resonance, $B$’s only go about 30 $\mu$m in the center of mass, making it difficult to measure time-dependent mixing.
If the collider is *asymmetric*, then the entire system is Lorentz boosted.

In the Belle Experiment, 8 GeV e⁻’s are collided with 3.5 GeV e⁺’s so

\[ \mu \approx 30 \mu m \]

So now the time measurement becomes a *z position measurement*.
“Gold-Plated” Decay

\[ B^0 \rightarrow J / \psi \quad (\psi \rightarrow e^+ e^-, \mu^+ \mu^- , \text{etc}) \]

Total state CP

\[ K_S (CP = -1), \quad K_L (CP = +1) \]

\[ \pi^+ \pi^-, \pi^0 \pi^0 \]

\[ \phi_D = \arg(V_{cs} V_{cb}^*) \approx 0 \]

probes \[ \phi_M = \phi_1 \quad (= \beta) \]
Predicted Signature

\[ \sin 2\phi_1 = +0.8 \]

\[ t = \text{Time of tagged decays} \]
“Tin-Plated” Decay

\[ \phi_D = \arg(V_{ud} V_{ub}^*) \approx -(\phi_1 + \phi_2) \]

probes \( \phi_M + \phi_D = \phi_1 - (\phi_2 + \phi_1) = -\phi_2 \) (\( = -\alpha \))

Complicated by “penguin pollution”, but still promising
Make **LOTS** of \( b\bar{b} \) pairs at the \( \Upsilon(4S) \) resonance in an asymmetric collider.

- Detect the decay of one \( B \) to a CP eigenstate.
- **Tag** the flavor of the other \( B \).
- Reconstruct the position of the two vertices.
- Measure the \( z \) separation between them and calculate proper time separation as \( t = \Delta z / (\beta_{CM} \gamma_{CM} c) \).
- Fit to the functional form

\[
e^{-\Gamma|t|} \left[ \left\{ 1 - \eta_{CP} \sin 2\phi_1 \sin \Delta m \Delta t \right\} \right]
\]

- **Write papers.**
- Over the last ~8 years, there have been two dedicated experiments under way to do this – BaBar (SLAC) and Belle (KEK)
Motivations for Accelerator Parameters

- Must be asymmetric to take advantage of Lorentz boost.
- The decays of interest all have branching ratios on the order of $10^{-5}$ or lower.
  - Need lots and lots of data!
    - Physics projections assume $100 \text{ fb}^{-1} = 1\text{ yr} @ 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
    - Would have been pointless if less than $10^{33} \text{ cm}^{-2}\text{s}^{-1}$
The KEKB Collider (KEK)

- Asymmetric Rings
  - 8.0GeV(HER)
  - 3.5GeV(LER)
- \( E_{cm} = 10.58 \text{GeV} = M(\Upsilon(4S)) \)
- Target Luminosity: \( 10^{34} \text{s}^{-1} \text{cm}^{-2} \)
- Circumference: 3016m
- Crossing angle: \( \pm 11 \text{mr} \)
- RF Buckets: 5120
- \( \Rightarrow 2 \text{ns crossing time} \)
The PEP-II Collider (SLAC)

- Asymmetric Rings
  - 9.0GeV (HER)
  - 3.1GeV (LER)
- \(E_{cm} = 10.58 \text{GeV} = M(\Upsilon(4S))\)
- Target Luminosity: \(3 \times 10^{33} \text{s}^{-1} \text{cm}^{-2}\)
- Crossing angle: 0 mr
- 4ns crossing time
Motivation for Detector Parameters

- **Vertex Measurement**
  - Need to measure decay vertices to <100µm to get proper time distribution.

- **Tracking…**
  - Would like $\Delta p/p \approx 0.5-1\%$ to help distinguish $B \rightarrow \pi\pi$ decays from $B \rightarrow K\pi$ and $B \rightarrow KK$ decays.
  - Provide $dE/dx$ for particle ID.

- **EM calorimetry**
  - Detect $\gamma$’s from slow, asymmetric $\pi^0$’s → need efficiency down to 20 MeV.

- **Hadronic Calorimetry**
  - Tag muons.
  - Tag direction of $K_L$’s from decay $B \rightarrow \psi K_L$.

- **Particle ID**
  - Tag strangeness to distinguish $B$ decays from Bbar decays (low p).
  - Tag $\pi$’s to distinguish $B \rightarrow \pi\pi$ decays from $B \rightarrow K\pi$ and $B \rightarrow KK$ decays (high p).

*Rely on mature, robust technologies whenever possible!!!*
BaBar Detector (SLAC)
The Accelerator is Key!!!

STOP Run
+HV Down
+Fill HER
+Fill LER
+HV Up
+START Run
= 8 Minutes!
Luminosity

Our Records:
- Instantaneous: $4.49 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- Per (0-24h) day: $229.1$ pb$^{-1}$
- Per (24 hr) day: $241.3$ pb$^{-1}$
- Per week: $1478$ pb$^{-1}$
- To date: $\approx 29.9$ fb$^{-1}$ (on peak)

World Records!!

Total integrated luminosity

Note: integrated numbers are accumulated!

Total for these Results: $29.1$ fb$^{-1}$

Total for first CP Results (Osaka): $6.2$ fb$^{-1}$

September 26, 2001

University of Rochester
The Pieces of the Analysis

- Event reconstruction and selection
- Flavor Tagging
- Vertex reconstruction
- CP fitting
J/ψ and K_S Reconstruction

\[ J/\psi \rightarrow \mu^+ \mu^- \]

\[ K_S \rightarrow \pi^+ \pi^- \]

\[ \sigma = 4 \text{ Mev} \]

Require mass within 4\( \sigma \) of PDG.
In the CM, both energy and momentum of a real $B^0$ are constrained.

Use “Beam-constrained Mass”:

$$M_{BC}^2 = E_{beam}^2 - \left( \sum p \right)^2$$

123 Events

3.7 Background
All Fully Reconstructed Modes (i.e. all but $\psi K_L$)

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<th>Mode</th>
<th>Events</th>
<th>Background</th>
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<td>$B \rightarrow \psi K_s$</td>
<td>457</td>
<td>12</td>
</tr>
<tr>
<td>All Others</td>
<td>290</td>
<td>46</td>
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<tr>
<td>Total</td>
<td>747</td>
<td>58</td>
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$B \rightarrow \psi K_L$ Reconstruction

- Measure direction (only) of $K_L$ in lab frame
- Scale momentum so that $M(K_L + \psi) = M(B^0)$
- Transform to CM frame and look at $p(B^0)$. 
$B \rightarrow \psi K_L$ Signal

$N_{\text{sig}} = 346$ events

$N_{\text{bkg}} = 223$ events

$0 < p_B^* < 2$ GeV/c

Biases spectrum!

346 Events

223 Background
Flavor Tagging

Statistically, $B^0$'s will tend to produce high momentum $e^+, \mu^+$, and/or $K^+$, while $\bar{B}^0$'s will produce the opposites.
Flavor Tagging (Slow Pion)

\[ \text{Very slow pion.} \]

\[ B^0 \text{'s will tend to produce slow } \pi^- \text{.} \]

Combined effective efficiency \( \epsilon_{\text{eff}} = \epsilon_t (1-2w)^2 = 27.0 \pm 2\% \)
Overall efficiency = $\sim 85\%$. In total 1137 events for the CP fit.
CP Fit (Probability Density Function)

\[ f(\Delta t; \sin 2\phi_1) = e^{-\frac{|\Delta t|}{\tau_B}} \left( 1 \pm \sin 2\phi_1 \sin x_d \frac{\Delta t}{\tau_B} \right) \]

\[ PDF = \int (1 - f_{BG}) f(t') R(t' - \Delta t) \, dt' + f_{BG} PDF_{BG}(\Delta t) \]

- \( f_{BG} = \) background fraction. Determined from a 2D fit of \( E \) vs \( M \).
- \( R(\Delta t) = \) resolution function. Determined from \( D^* \)’s and MC.
- \( PDF_{BG}(\Delta t) = \) probability density function of background. Determined from \( \psi K \) sideband.
Resolution Function

Fit with a double-Gaussian…

\[ f_{\text{main}} = \frac{1}{\sqrt{2\pi}\sigma_{\text{main}}} \exp\left(-\frac{(t-\mu_{\text{main}})^2}{2\sigma_{\text{main}}^2}\right) \]

\[ f_{\text{tail}} = \frac{1}{\sqrt{2\pi}\sigma_{\text{tail}}} \exp\left(-\frac{(t-\mu_{\text{tail}})^2}{2\sigma_{\text{tail}}^2}\right) \]

- \( \mu_{\text{main}} = -0.09 \text{ ps} \)
- \( \sigma_{\text{main}} = 1.54 \text{ ps} \)
- \( \mu_{\text{tail}} = -0.78 \text{ ps} \)
- \( \sigma_{\text{tail}} = 3.78 \text{ ps} \)
- \( f_{\text{tail}} = 0.018 \)
Test of Vertexing – B Lifetime

$\tau_{B^0} = 1.55 \pm 0.02 \text{ ps (PDG : } 1.55 \pm 0.03 \text{ ps)}$

$\tau_{B^\pm} = 1.64 \pm 0.03 \text{ ps (PDG : } 1.65 \pm 0.03 \text{ ps)}$
The Combined Fit (All Charmonium States)
Sources of Systematic Error

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex Algorithm</td>
<td>.04</td>
</tr>
<tr>
<td>Flavor Tagging</td>
<td>.03</td>
</tr>
<tr>
<td>Resolution Function</td>
<td>.02</td>
</tr>
<tr>
<td>$K_L$ Background Fraction</td>
<td>.02</td>
</tr>
<tr>
<td>Background Shapes</td>
<td>.01</td>
</tr>
<tr>
<td>$\Delta m_d$ and $\tau_B$ Errors</td>
<td>.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>.06</strong></td>
</tr>
</tbody>
</table>

- **Bottom Line**

$$\sin 2\phi_1 = .99 \pm .14(\text{stat}) \pm .06(\text{syst.})$$

Published in *Phys.Rev.Lett.* 87, 091802 (2001)
The BaBar Measurement

Based on 32 million B-Bbar pairs

$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05$$

Summary of $2\phi_1$ Measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (2000)</td>
<td>0.79 +0.41 -0.44</td>
</tr>
<tr>
<td>ALEPH (2000)</td>
<td>0.84 +0.82 -1.04 ±0.16</td>
</tr>
<tr>
<td>Belle (Osaka,6.2/fb)</td>
<td>0.45 +0.43 +0.07 -0.44 - 0.09</td>
</tr>
<tr>
<td>BaBar (Osaka,9/fb)</td>
<td>0.12 ± 0.37 ±0.09</td>
</tr>
<tr>
<td>Belle (11.2M BB)</td>
<td>0.58 +0.32 +0.09 -0.34 -0.10</td>
</tr>
<tr>
<td>BaBar (23M BB)</td>
<td>0.34 ± 0.20 ±0.05</td>
</tr>
<tr>
<td>Belle (31.3M BB)</td>
<td>0.99 ± 0.14 ±0.06</td>
</tr>
<tr>
<td>BaBar (32M BB)</td>
<td>0.59 ± 0.14 ±0.05</td>
</tr>
<tr>
<td>Average (4 exp.)</td>
<td>0.79 ± 0.10</td>
</tr>
</tbody>
</table>
How About That $\rho-\eta$ Plane?

World Average $\sin^2 \phi_1$ ($\pm 1\sigma$)

Constraints of Everything but $\sin^2 \phi_1$

Looks good for the Standard Model, but a little *dull* for experimenters!
Current Status

- The study of CP Violation has been going on for almost 40 years!
- A number of experiments are currently taking data which seem to be confirming the Standard Model (CKM) explanation of CP Violation, and thereby constraining that model
  - Direct CP violation is observed in the neutral K system!
  - CP is violated in the B-Meson system!
- Over the next several years, the existing B-Factories will continue to take data, providing tighter and tighter constraints.
- New players are also coming on the scene:
  - Fermilab Run II (CDF and D0) - now
  - BTeV (dedicated B Experiment at Fermilab) - ~2005
  - LHC (Atlas and CMS) - 2006
  - LHC-B (dedicated B Experiment at LHC) - ?
More “Out There”

- CP Violation in the $\nu$ sector? (probably there, hard to study)
- CPT Violation?
  - CPT Conservation is a direct consequence of the Lorentz invariance of the Lagrangian.
  - Evidence of its violation would be observation (direct or indirect) of
    $$m(p) \neq m(\bar{p}) \text{ or } \Gamma(p) \neq \Gamma(\bar{p})$$
    and would be big news.
- We still can’t answer why the universe is all matter. Maybe it isn’t!
  - The AMS experiment, set to fly on the ISS, will look for massive anti-nuclei to test the hypothesis that distant parts of the universe might be antimatter (!!)
Are Two B-Factories Too Many?

- These are not discovery machines!
- Any interesting physics would manifest itself as small deviations from SM predictions.
- People would be very skeptical about such claims without independent confirmation.
- Therefore, the answer is NO (two is not one too many, anyway).
Differences Between PEP-II (BaBar) and KEKB (Belle)

- PEP-II has complex IR optics to force beams to collide head-on.
  - Pros: Interaction of head-on beams well understood.
  - Cons: Complicates IR design.
  - More synchrotron radiation.
  - Can’t populate every RF bucket.

- In KEK-B, the beams cross at ±11 mr.
  - Pros: Simple IR design.
  - Can populate every RF bucket.
  - Lower (but not zero!!) synchrotron radiation.
  - Cons: Crossing can potentially couple longitudinal and transverse instabilities.

At present, both designs seem to be working.
Readout:

- BaBar uses an SLD-inspired system, based on a continuous digitization. The entire detector is pipelined into a software-based trigger.
  
  **Pros:** Extremely versatile trigger.  
  Less worry about hardware-based trigger systematics.  
  Can go to very high luminosities.  
  
  **Cons:** Required development of lots of custom hardware.

- Belle’s readout is based on converting signals to time-pulses. The trigger is an “old-fashioned” hardware-based level one. Events satisfying level one are read out after a 2 µs latency.
  
  **Pros:** Simple.  
  Readout relies largely on “off-the-shelf” electronics.  
  
  **Cons:** Potential for hardware-based trigger systematics.  
  Possible problems with high luminosity.
Particle ID needs

<table>
<thead>
<tr>
<th>Technology</th>
<th>Pros</th>
<th>Cons</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF</td>
<td>Simple.</td>
<td>Only for low momentum.</td>
<td>Included in Belle</td>
</tr>
<tr>
<td>dE/dx</td>
<td>Proven. Comes for free.</td>
<td>Only for low momentum</td>
<td>Included in Belle.</td>
</tr>
<tr>
<td>TMAE based RICH</td>
<td>Proven in SLD and DELPHI</td>
<td>Universally despised.</td>
<td>Rejected.</td>
</tr>
<tr>
<td>CSI RICH</td>
<td>Once seemed promising.</td>
<td>No one could build a working prototype.</td>
<td>Rejected.</td>
</tr>
<tr>
<td>DIRC</td>
<td>Rugged. Excellent separation.</td>
<td>New. Contstrants on detector geometry</td>
<td>Babar choice</td>
</tr>
<tr>
<td>Aerogel threshold Cerenkov</td>
<td>Simple.</td>
<td>Barely adequate</td>
<td>Belle choice</td>
</tr>
</tbody>
</table>