BaBar Purpose: determine the origin of CP violation (CPV) in B-meson decays. The detector and the PEP-II asymmetric $e^+e^-$ collider were designed to study CP violation, especially time-dependent CP violation, in B-meson decays to determine whether the Kobayashi-Maskawa phase as the source of CPV.

SuperB Purpose: study the flavor couplings of New Physics using precise measurements of CPV in B- and D-mesons, lepton flavor violating $\tau$-decays, and very rare decays.
Why BaBar Was Built

• **PEP-II** and **BaBar** were designed to study CP violation (CPV) in B-meson decay, especially time-dependent CPV.

• CPV emerges from the quantum mechanical interference of multiple amplitudes contributing to the same final state; it requires a complex relative phase between the amplitudes.

• In the Standard Model of particle physics, the Kobayashi-Maskawa (KM) phase is responsible for all CPV. Prior to BaBar, CPV had been observed in kaon and hyperon decays.

• CPV naturally probes physics at the electro-weak scale, including physics Beyond the Standard Model (BSM), also called New Physics (NP).

• **Goals:**
  1. test the KM phase as a source of CPV in B-meson decay.
  2. test the KM phase as the source of CPV in B-meson decay.
Some PEP-II Design Goals & Issues

\[ \mathcal{L} = 3 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1} \iff 30 \text{ fb}^{-1} \text{ year}^{-1} \]

Conceptual Design Report [1993]

- Design luminosity driven by physics goal: to determine the origin of CP violation.
- 9.0 GeV \(e^-\times 3.1 \text{ GeV }e^+ \) (\(\beta\gamma \sim 0.55\))
  - \(\beta\gamma\) sufficient to allow time-dependent CP violation measurements
  - Previous e\(^+\)e\(^-\) colliders had been symmetric and beams were stored in the same storage ring.
- 2.14 A \(\times\) 0.99 A
- Beam size is \(\sim\) 150 \(\mu m\) horizontal \(\times\) 6 \(\mu m\) vertical
- 1658 bunches
  - Previous e\(^+\)e\(^-\) colliders had used 10 or fewer bunches
- Total PEP-II power consumption: 43 MW
- Beam lifetimes \(\sim\) 90 minutes
- Circumference 2199 meters (fits onto PEP tunnel)
Weak Charged Current Interactions

As a first approximation, the weak charged current interaction couples fermions of the same generation. The Standard Model explains couplings between quark generations in terms of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.
Weak Phases in the Standard Model

The Cabibbo-Kobayashi-Maskawa (CKM) matrix transforms flavor eigenstates to weak eigenstates at the quark level:

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

The CKM matrix should be unitary:

\[
\begin{pmatrix}
V_{ud}^* & V_{us}^* & V_{ub}^* \\
V_{cd}^* & V_{cs}^* & V_{cb}^* \\
V_{td}^* & V_{ts}^* & V_{tb}^*
\end{pmatrix} \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[e.g., \quad V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0\]

In the Wolfenstein parameterization:

\[
V_W = \begin{pmatrix}
1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{1}{2}\lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} \approx \begin{pmatrix}
\cos \theta_C & \sin \theta_C & 0 \\
-\sin \theta_C & \cos \theta_C & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
Instrumented Flux Return (IFR) (resistive plate chambers)

Superconducting Solenoid (1.5 Tesla)

Electromagnetic Calorimeter (EMC) (Csl crystals)

e⁺ (3.1 GeV)

Cherenkov radiator (DIRC) (quartz bars)

Drift Chamber (DCH) (multiwire gas chamber)

Silicon Vertex Tracker (SVT) (silicon module)

SVT: 97% efficiency, 15 mm z hit resolution (inner layers, transverse tracks)

SVT+DCH: $\sigma(p_T)/p_T = 0.13\% \times p_T + 0.45\%$

DIRC: K⁻π separation $4.2\sigma @ 3.0\text{ GeV}/c \rightarrow 2.5\sigma @ 4.0\text{ GeV}/c$

EMC: $\sigma_E/E = 2.3\% \cdot E^{-1/4} \oplus 1.9\%$

All subsystems crucial for CPV analysis

SLUO Annual Meeting  Michael D Sokoloff
\[ \sin(2\beta) \text{ Fit Results from } J/\Psi K_S, \text{ etc.} \]

\textbf{Summer 2002}

\[ \sin 2\beta = 0.755 \pm 0.074 \]

\[ \sin 2\beta = 0.741 \pm 0.067 \text{ (stat)} \pm 0.034 \text{ (sys) with} \]

\[ |\lambda_f| = 0.948 \pm 0.051 \text{ (stat)} \pm 0.017 \text{ (syst)} \]

\[ S_f = 0.759 \pm 0.074 \text{ (stat)} \pm 0.032 \text{ (syst)} \]

\[ \eta_f = -1 \]
The CKM Matrix Today

SLUO Annual Meeting

Michael D Sokoloff
The 2008 Nobel Prize in Physics

“...The broken symmetries described by Makoto Kobayashi and Toshihide Maskawa ... seem to have existed in nature since the very beginning of the universe and came as a complete surprise when they first appeared in particle experiments in 1964. It is only in recent years that scientists have come to fully confirm the explanations that Kobayashi and Maskawa made in 1972. It is for this work that they are now awarded the Nobel Prize in Physics. They explained broken symmetry within the framework of the Standard Model, but required that the Model be extended to three families of quarks. These predicted, hypothetical new quarks have recently appeared in physics experiments. As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier.”
2010 Dirac Medal

The 2010 Dirac Medal and Prize are awarded to Nicola Cabibbo (University La Sapienza, Rome, Italy) and Ennackal Chandy George Sudarshan (University of Texas, Austin, Texas, USA) in recognition of their fundamental contributions to the understanding of weak interactions and other aspects of theoretical physics.

Cabibbo’s important contributions to theoretical physics include the recognition of the significance of mixing in weak interactions, which has established the existence of a new class of physical constants, whose first example is the Cabibbo angle. This angle determines the mixing of strange quarks with non-strange quarks and has been measured experimentally. With the discovery of a third family of quarks and leptons, quark mixing led to the understanding of the phenomenon of CP violation.
Charm Mixing
Time-Evolution of $D^0 \rightarrow K\pi$ Decays

DCS and mixing amplitudes interfere to give a “quadratic” WS decay rate ($x, y \ll 1$):

$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right) \left(\frac{t}{\tau}\right)^2$$

where \( x' = x \cos \delta + y \sin \delta \)
\( y' = y \cos \delta - x \sin \delta \)
and $\delta$ is the phase difference between DCS and CF decays.
Rate of WS events clearly increases with time:

\[ \frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} \, y' \left( \frac{t}{\tau} \right) + \left( \frac{x'^2 + y'^2}{4} \right) \left( \frac{t}{\tau} \right)^2 \]
Rate of WS events clearly increases with time:

\[ \frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \left( \frac{x'^2 + y'^2}{4} \right) \left( \frac{t}{\tau} \right)^2 \]

\( \chi_2^2 = 24 \)

Inconsistent with no-mixing hypothesis.
Simplified Fit Strategy & Validation (2007)

Rate of WS events clearly increases with time:

\[
\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \left( \frac{x'^2 + y'^2}{4} \right) \left( \frac{t}{\tau} \right)^2
\]

WS/RS (%)

Consistent with prediction from full likelihood fit: \( \chi^2 = 1.5 \)

Inconsistent with no-mixing hypothesis: \( \chi^2 = 24 \)
These plots illustrate the time-integrated PDF and the average decay time as a function of position in the Dalitz plot for \((x,y) = (0.16\%, 0.57\%)\). The sizes of the boxes in the right-hand plot reflect the number of entries, and the colors reflect the average decay time.
Charm Mixing Today
BaBar for Bean-Counters

More than 400 papers published by BaBar in refereed journals.

More than 350 Ph.D. theses from BaBar & another 140 M.S. theses. Compared to CDF/DO average and Belle.
Why SuperB?

• Why build a high luminosity flavor factory in the era of the LHC?
  • What is the nature of electroweak symmetry breaking (EWSB)? Is it a simple Higgs, SUSY, a GUT, ETC, something else? The mass scale is probably somewhere in the 100 GeV - 1 TeV range.
  • What is cold dark matter? How does it couple to flavor? The concordance model of cosmology predicts a mass near that of the EWSB level.
  • Is there a fourth generation of quarks?
  • Is there other, new physics at 100 GeV - 1 TeV in mass?

• With 100 times the integrated luminosity of BaBar, CPV at SuperB will be sensitive to canonical interactions mediated by particles of mass up to about 1 TeV.
• SuperB will also be sensitive to new physics via very rare decays, lepton flavor violation, and lepton non-universality.
SuperB Accelerator Design Goals & Issues

\[ \mathcal{L} = 10^{36} \text{ cm}^{-2} \text{ sec}^{-1}; \quad \int \mathcal{L} \, dt = 75 \text{ ab}^{-1} \quad \text{at the } \Upsilon(4S) \]

\[ \mathcal{L} = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}; \quad \int \mathcal{L} \, dt = 500 \text{ fb}^{-1} \quad \text{at the } \Psi(3770) \]

Baseline Design

- 6.7 GeV $e^+ \times$ 4.18 GeV $e^-$ ($\beta_\gamma \sim 0.24$)
- 1892 mA $\times$ 2410 mA
- 80% polarization of the electron beam
- beam size is $\sim$ 9 $\mu$m horizontal $\times$ 35 nm vertical
- 978 bunches
- total RF power is 17 MW
- luminosity lifetimes are 4.82 & 6.14 minutes
  beam lifetimes $\sim$ 4 minutes
- circumference 1258 meters (fits onto LNF site)
- designed to re-use PEP-II magnets and RF
The Beauty of SuperB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SM Fit today</th>
<th>SM Fit at SuperB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\rho}$</td>
<td>$0.163 \pm 0.028$</td>
<td>$\pm 0.0028$</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>$0.344 \pm 0.016$</td>
<td>$\pm 0.0024$</td>
</tr>
<tr>
<td>$\alpha$ (°)</td>
<td>$92.7 \pm 4.2$</td>
<td>$\pm 0.45$</td>
</tr>
<tr>
<td>$\beta$ (°)</td>
<td>$22.2 \pm 0.9$</td>
<td>$\pm 0.17$</td>
</tr>
<tr>
<td>$\gamma$ (°)</td>
<td>$64.6 \pm 4.2$</td>
<td>$\pm 0.38$</td>
</tr>
</tbody>
</table>

Extracted from the SuperB CDR [2007]
The Charm of SuperB

Based on material found in the SuperB Progress Report: Physics arXiv:1008.1541v1 (August 2010)
LFV in SU(5) SUSY GUT with $\nu_R$

Approximate SuperB sensitivity

Cases I & II, non-degenerate with different Yukawa couplings and PNMS matrix elements

“There are lepton flavor mixings in the slepton sector of the MSSM with right-handed neutrinos and the SU(5) SUSY GUT with right-handed neutrinos. It comes through the running between the right-handed neutrino mass scale and the cut-off scale where the universal soft breaking mass terms are generated. On the other hand, no such slepton flavor mixings exist in the mSUGRA.”

The next generation of high luminosity flavor factories is poised to study the flavor couplings of New Physics.

BaBar verified the KM phase as the origin of CP violation.

SuperB is strongly supported by the Italian Minister of Education and Science and by the Minister of Finance. We are awaiting approval of funding for the project.
back-up material
Time-Dependent CPV at the $\Upsilon(4S)$ Resonance

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

Boost: $\beta_\Upsilon = 0.55$

Coherent L=1 state

$\Delta t \approx \frac{\Delta z}{\langle \beta_\Upsilon \rangle c}$

Start the Clock

Stop the Clock

Flavor tag and vertex reconstruction

Exclusive $B$ meson and vertex reconstruction

---

SLUO Annual Meeting

Michael D Sokoloff
Discovery of Narrow $D_{sJ}$ States (2003) 
[primary decay modes do not conserve isospin]

$D_{s0}^*(2317)^+ \rightarrow D_s^+\pi^0$

$D_{s1}(2460)^+ \rightarrow D_s^{*-}\pi^0$

$D_s^+ \rightarrow K^- K^+\pi^+$

$D_s^+ \rightarrow K^- K^+\pi^+\pi^0$

$\Delta m_{\pi^0}$ [GeV/$c^2$] after $D_s^{*-}\rightarrow D_s\gamma$ mass cut
The $\Upsilon(4260)$: Not Anticipated, Still Not Understood
Discovery of the $\eta_b$ in $\Upsilon(3S)$ running


Search the inclusive $E_{\gamma}$ spectrum for

$$\Upsilon(3S) \rightarrow \gamma \eta_b \text{ in } \Upsilon(3S) \rightarrow \gamma X$$

Understand backgrounds precisely

$$\Upsilon(3S) \rightarrow \gamma \chi_{bJ}(2P) \ ; \ \chi_{bJ}(2P) \rightarrow \gamma \Upsilon(1S)$$

$$J = 1, 2, 3$$

ISR: $e^+ e^- \rightarrow \gamma_{ISR} \Upsilon(1S)$

net signal
\( \pi^0, \eta, \text{ and } \eta' \) transition form factors [2009 & 2010]

\[
|n\rangle = \frac{1}{\sqrt{2}} \left( |\bar{u}u\rangle + |\bar{d}d\rangle \right)
\]
\[
|s\rangle = |\bar{s}s\rangle
\]
\[
|\eta\rangle = \cos \phi |n\rangle - \sin \phi |s\rangle
\]
\[
|\eta'\rangle = \cos \phi |n\rangle + \sin \phi |s\rangle
\]
\[
|\pi^0\rangle = \frac{1}{\sqrt{2}} \left( |\bar{u}u\rangle - |\bar{d}d\rangle \right)
\]

\[
F(Q^2) = \int T(x, \mu^2) \varphi_{\pi}(x, \mu^2) \, dx
\]

Hard scattering amplitude for \( \gamma^* \gamma \rightarrow qq \) transition which is calculable in pQCD

Nonperturbative meson distribution amplitude describing the transition \( P \rightarrow qq \)

\( x \): fraction of the meson momentum carried by one quark in the infinite momentum frame
Possible LFV in the MSSM at SuperB

\[ B(\tau \rightarrow \mu \gamma) \times 10^{-9} \quad 4.2 \quad 7.9 \quad 0.18 \quad 0.26 \quad 97 \quad 0.019 \]
\[ B(\tau \rightarrow \mu \mu \mu) \times 10^{-12} \quad 9.4 \quad 18 \quad 0.41 \quad 0.59 \quad 220 \quad 0.043 \]

Predictions for \( B(\tau \rightarrow \mu \gamma) \) and \( B(\tau \rightarrow \mu \mu \mu) \) corresponding to the SPS points. The values of \( m_{N_i} \) and \( m_{\nu 1} \) are as specified in the Fig. 2 of the SuperB Physics White Paper.

For \( \tau \rightarrow \mu \gamma \), we expect the final efficiency to be \(~7.3\%\) and the final background to be \(~260\) events. This leads to an expected 90% CL upper limit of \( 2.4 \times 10^{-9} \) and a 3\( \sigma \) evidence reach of \( 5.4 \times 10^{-9} \). \( \cdots \) The extrapolation of the \( \tau \rightarrow e \gamma \) search receives benefits from similar improvements, and has a projected 90% CL upper limit of \( 3.0 \times 10^{-9} \) and a 3\( \sigma \) evidence reach of \( 6.8 \times 10^{-9} \).

Material extracted from the SuperB Progress Report: Physics
\textit{arXiv:1008.1541v1} (August 2010)