Recent progress in CP violation:
New Physics under siege

High Energy Seminar
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Alexandre Telnov
Princeton University

SLAC, Mail Stop 35
2575 Sand Hill Road
Menlo Park, CA 94025
AVTELNOV@PRINCETON.EDU
Matter-Antimatter Asymmetry the Universe

We are survivors of the post-Big Bang mutual annihilation of matter and antimatter

Baryonic asymmetry of the Universe: \[ \frac{N_B - N_{\bar{B}}}{N_y} \approx \frac{N_B}{N_y} \approx 5 \times 10^{-10} \]
Sakharov’s three conditions

The three conditions necessary to produce the baryonic asymmetry of the Universe:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Through the CPT Theorem, CP violation implies the existence of T violation

A. D. Sakharov, Письма в ЖЭТФ, 5, № 1, 32-35, 1 января 1967
A. D. Sakharov, Soviet Journal of Experimental and Theoretical Physics, Letters to the Editor, 5, No. 1, 24-27, 1st January 1967
The Quark Mixing Matrix

The only Standard-Model source of CP violation in the quark sector

The Cabibbo-Kobayashi-Maskawa matrix relates the electroweak ($q'$) and the mass ($q$) quark eigenstates:

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

$$
V^\dagger V = 1 \Rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0
$$

$$
V_{\text{CKM}} = \begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4) + iO(\lambda^6)
$$

In Kobayashi-Maskawa theory, a single phase is responsible for all CP violation in meson decays, making it testable.


Supersymmetry (SUSY): dozens of independent phases, mostly in flavor-changing couplings; effects could be seen in loops
Current knowledge of the Unitarity Triangle

Important: all measurements are still statistics-limited

A frequentist interpretation

from angle measurements

A Bayesian interpretation, with model-dependent choices of priors

from angle measurements

from all other sources


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The time-dependent rate for $B^0 (f_+)$ or $B^0 (f_-)$ decays to a final state $f$ (neglecting the lifetime difference between the mass eigenstates $B_H$ and $B_L$):

$$f_{\pm} (\Delta t) = e^{-|\Delta t|/\tau_B} \left[ 1 \mp C_f \cos (\Delta m \Delta t) \mp S_f \sin (\Delta m \Delta t) \right]$$

where

$S$ and $C$ is what we measure

| $B_{L/H} > = p | B^0 > \mp q | B^0 >$ | $A_f = \frac{q}{p} A_f$, $\lambda_f = \frac{q}{p} \overline{A_f}$ | $S_f = -2 \text{Im} \lambda_f \over 1 + |\lambda_f|^2$, $C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$ |
|---|---|---|

$a_f$ is the time-evolution asymmetry:

$$a_f (\Delta t) = \frac{f_+ (\Delta t) - f_- (\Delta t)}{f_+ (\Delta t) + f_- (\Delta t)}$$

If $f$ is a $CP$ eigenstate, $f_{CP}$, we have $CP$ violation if $\lambda_f \neq \pm 1$:

- $|q/p| \neq 1$ ($CP$ violation in mixing, very small)
- $|\overline{A_f}/A_f| \neq 1$ (direct $CP$ violation, small in $b \to c\bar{c}s$)
- $\text{Im}(\lambda_f) \neq 0$ (interference between mixing and decay)

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Example of a $B$-decay event in data:

$$B^0 \rightarrow \phi K_S$$ at BaBar

only the hits that correspond to reconstructed tracks and neutral candidates are shown (noise hits are removed)

$K_S \rightarrow \pi^+ \pi^-$

$\phi \rightarrow K^+K^-$

Run 29368, event hexID 249a4b/d610dd73 (June 27, 2002)
From the dataset used in Phys.Rev.D 69:011102, 2004
Common discriminating variables: kinematics

A pair of weakly correlated variables that reflect energy and momentum conservation: peaking for fully reconstructed $B$ decays, smooth for combinatorial background

$$m_{ES} \equiv \sqrt{E_{CM\ beam}^2 - P_{CM\ B}^2} = m_B$$

$$\Delta E \equiv E_{CM\ B} - E_{CM\ beam} = 0$$

resolution $\sim 2.6$ MeV/c$^2$

determined by the beam energy spread

continuum background in the Grand Side Band

resolution $\sim 15-80$ MeV

depending on the number of tracks and presence of neutrals in the final state
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**Common discriminating variables: event shape**

- The principal source of background to rare $B$ decays: random track/neutral combinations from quark-pair ($udsc$) production in the continuum:
  - total $udsc$ cross section $\sim 3.4$ nb, compared to $\sim 1.1$ nb for $Y(4S)$
  - $udsc$ events have jet-like topology, while $B$ decays are nearly spherical in CM
  - several topological variables are employed to suppress this background

- Backgrounds from $\tau^+\tau^-$ production and two-photon physics are usually negligible

- Backgrounds from other $B$ decays tend to be small

Analyses are **blind** until the methodology has been finalized and frozen
**sin2β in “golden” modes:**

The highest-precision test of the KM mechanism of CP violation in meson decays

```
 branching fractions $O(10^{-3})$

 $\bar{B}^0, B^-$  $W^-$  $\bar{K}, K^*, \pi^0$

 $\bar{d}, \bar{u}$

$J/\psi, \psi(2S), \chi_{c1}$

$u,c,t$

$g$

$B^0, B^-$  $W^-$  $\pi^0, K, K^*$

$n, \bar{n}$

“Golden” modes: color-suppressed tree dominates; the $t$-quark penguin has the same weak phase as the tree. In SM, therefore,

$$S_{\text{golden}} = \eta_{CP} \times \sin2\beta, \quad C_{\text{golden}} = 0 \quad (\eta_{CP} = \pm1)$$

Theoretical uncertainties:

- *an example* of a model-independent, data-driven calculation:
  - assuming $SU(3)_{\text{flavor}}$ invariance, use $B^0 \rightarrow J/\psi \pi^0$ data to constrain penguin pollution in $J/\psi K^0 \Rightarrow \Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin2\beta = 0.000 \pm 0.012$

- theoretical estimates of the biases due to $u$- and $c$-quark penguins, etc.:
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin2\beta \sim O(10^{-3})$
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin2\beta \sim O(10^{-4})$


H. Li, S. Mishima, hep-ph/0610120

**Recent progress in CP violation: New Physics under siege**

**BaBar with 384x10^6 BB pairs:**
\[ \sin 2\beta = 0.714 \pm 0.032 \text{ (stat)} \pm 0.018 \text{ (syst)} \]

**Belle with 535x10^6 BB pairs:**
\[ \sin 2\beta = 0.642 \pm 0.031 \text{ (stat)} \pm 0.017 \text{ (syst)} \]

**CP violation in Standard Model is not small, it is O(1).**
Smaller of CPV in kaon decays is due to flavor suppression.

**CP-violating phases in New Physics can also be O(1).**

---

**sin2β in “golden” modes: latest from BaBar and Belle**


\[ \sin^2 \beta = 0.714 \pm 0.032 \text{ (stat)} \pm 0.018 \text{ (syst)} \]

In **“golden” modes:**

BaBar and Belle

PRL 98, 031802 (2007)

\[ \sin^2 \sin^2 \beta = 0.642 \pm 0.031 \text{ (stat)} \pm 0.017 \text{ (syst)} \]

---

**CP violation in Standard Model is not small, it is O(1).**
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---

**Recent progress in CP violation: New Physics under siege**

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Measuring $\alpha$ with $B^0 \rightarrow \pi^+ \pi^-$

$A_{CP}(t)$ in $b \rightarrow u\bar{u}d$ decay to a $CP$ eigenstate \textit{at the tree level}:

\[
\text{Measure } 180^\circ - \beta - \gamma = \alpha \equiv \arg \left[ -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right] \quad \text{(in SM)}
\]

\textbf{Penguins:} $A_{CP}(t) \Rightarrow \sin(2\alpha_{\text{eff}})$; $\alpha_{\text{eff}} = \alpha - \Delta\alpha$; direct $A_{CP} \neq 0$

Tree and penguin amplitudes have different weak and strong phases

Recent progress in CP violation: New Physics under siege

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Isospin analysis in $B \to \pi\pi, \rho\rho$

Determines relative phase between $B$ mixing and the tree, independent of the EW model

$$S = \sin(2\alpha + 2\Delta \alpha) \sqrt{1 - C^2}$$

In $B \to \rho\rho$, there are 3 such relations (one for each polarization)

6 unknowns, 6 observables in $\pi\pi$ (there is no vertex to measure $S_{\pi^0 \pi^0}$)
5 observables in $\rho\rho$ (or 7, when both $C_{\rho^0 \rho^0}$ and $S_{\rho^0 \rho^0}$ are measured)

4-fold ambiguity in $2\Delta \alpha$: either triangle can flip up or down

Neglecting EW penguins, $\pm 0$ is a pure tree mode, and so the two triangles share a common side:

$$A_{hh} = e^{i\gamma_T} T + e^{-i\beta} P$$

$$\tilde{A}_{hh} = e^{-i\gamma_T} T + e^{i\beta} P$$

$$A(B^+ \to h^+ h^0) = \tilde{A}(B^- \to h^- h^0)$$
The “classic” $B^0 \rightarrow h^+h^-$ analysis

Simultaneous ML fit to $B^0 \rightarrow \pi^+\pi^-, K^+\pi^-, \pi^+K^-, K^+K^-$

Using DIRC Cherenkov angle to identify pions and kaons

Additional $\pi\pi/K\pi/KK$ separation from energy difference $\Delta E$

Belle: $\pi/K$ separation with aerogel (threshold Cherenkov) and $dE/dx; \Delta E$

Due to higher particle ID acceptance, Belle had $\times 1.4$ more $h^+h^-$ per fb$^{-1}$ than BaBar

CDF: $dE/dx$ and $B$ mass; $A_{K^+\pi^-}$ only

Recent progress in CP violation: New Physics under siege

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In the **barrel** ($\theta > 0.445$), the DIRC is ~9.3% inefficient ($\varphi$ cracks, etc.)

Another ~12% of high-momentum tracks are outside the DIRC acceptance in $\theta$.

We use **DCH tracks down to $\theta = 0.35$ rad**

($J/\psi \rightarrow \mu^+\mu^-$ in $\sin 2\beta$ analysis: down to 0.30 rad)

→ 16% event-yield increase for $B \rightarrow X h^{\pm}$, 35% for $B^0 \rightarrow h^+ h^-$
Ionization energy loss for $B \rightarrow Xh^{\pm}$

$dE/dx$ is usually used for particle ID at $p < m$

Particle Data Group
In the forward region, DCH dE/dx is not much worse than the DIRC—and is 100% efficient!

0.4 < θ < 0.7, 3.8 < p < 4.2 GeV/c
1999-2006 data
There were many reasons DCH $dE/dx$ failed to work in likelihood-based $B \rightarrow Xh^\pm$ analyses in the past.
**dE/dx in DCH**

This is what DCH dE/dx looks like **after the new calibration**

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**DCH dE/dx for various particle types, Run 3, data**

![Graph showing corrected DCH dE/dx for various particle types](image)

- 0.9 < θ < 1.1
- protons
- kaons
- pions
- muons
- electrons

DCH dE/dx mean and resolution also depend on the number of dE/dx samples

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**Recent progress in CP violation: New Physics under siege**
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New, detailed DCH $dE/dx$ parametrization: $\pi, K, p$ pulls for $B \to Xh^\pm$ track momenta

Pulls are controlled at a <1% level; non-Gaussian tails are absent by construction
DCH dE/dx K-π separation in $B \rightarrow Xh^{\pm}$
complementary to DIRC

(for tracks that have good DIRC information, we use both DIRC and dE/dx)
**Our new result:** $B^0 \rightarrow \pi^+ \pi^-$

$N_{\pi^+ \pi^-} = 1139 \pm 49$

52% overall increase in signal reconstruction efficiency:

- 35% from DCH $dE/dx$,
- 13% mainly from reoptimizing the event-shape $|\cos \theta_{\text{spher}}|$ cut

$sPlot$: Builds a histogram of $x$ excluding it from the Maximum-Likelihood fit, assigning a weight to each event, keeping all signal events, getting rid of all background events, and keeping track of the statistical errors in each $x$ bin.

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Observation of CP Violation in $B^0 \rightarrow K^+\pi^-$ and $B^0 \rightarrow \pi^+\pi^-$

**BaBar** has made a $5.4\sigma$ observation of CP violation in $B^0 \rightarrow \pi^+\pi^-$

$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03$ ($5.1\sigma$)

$C_{\pi\pi} = -0.21 \pm 0.09 \pm 0.02$ ($2.3\sigma$)

**BaBar**: 383 million $B\bar{B}$ pairs, 1139 $\pm$ 49 $\pi^+\pi^-$

**Belle**: 535 million $B\bar{B}$ pairs, 1464 $\pm$ 65 $\pi^+\pi^-$

**BaBar** now has 9% more $\pi^+\pi^-$ per fb$^{-1}$ than **Belle**

**Belle** PRL 98, 211801 (2007)

$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$ ($5.3\sigma$)

$C_{\pi\pi} = -0.55 \pm 0.08 \pm 0.05$ ($5.5\sigma$)

**BaBar** has made a 5.4$\sigma$ observation of CP violation in $B^0 \rightarrow \pi^+\pi^-$

also:

$\mathcal{A}_{K^+\pi^-} = -0.107 \pm 0.018^{+0.007}_{-0.004}$ ($5.5\sigma$)
History of $B^0 \rightarrow \pi^+ \pi^-$ results

There exists a history of disagreement between Belle and $BaBar$ on $B^0 \rightarrow \pi^+ \pi^-$. A 2.6$\sigma$ difference is still present, in $C_{\pi\pi}$

$C_{\pi\pi} \equiv -A_{\pi\pi}$

There exists a history of disagreement between Belle and $BaBar$ on $B^0 \rightarrow \pi^+ \pi^-$. A 2.6$\sigma$ difference is still present, in $C_{\pi\pi}$

$C_{\pi\pi} \equiv -A_{\pi\pi}$

$S_{\pi\pi}$ regresses to mean

$S_{\pi\pi}$ regresses to mean

early Belle results were unphysical

H. Ishino

Recent progress in CP violation: New Physics under siege

Alexandre Telnov (Princeton), January 29, 2008
The $B \rightarrow \pi^{\pm} \pi^{0}, \pi^{0} \pi^{0}$ analysis

Simultaneous fit to $B^{0} \rightarrow \pi^{+} \pi^{0}, K^{+} \pi^{0}$ (using DIRC Cherenkov angle to separate pions and kaons)

$B^{0} \rightarrow \pi^{0} \pi^{0}$: branching fraction and time-integrated direct CP asymmetry

**new:** in addition to $\pi^{0} \rightarrow \gamma \gamma$, we use merged $\pi^{0}$ and $\gamma \rightarrow e^{+}e^{-}$ conversions

⇒ 10% efficiency increase per $\pi^{0}$ (4% from merged $\pi^{0}$, 6% from $\gamma$ conversions)

At a Super B-meson factory, $\gamma \rightarrow e^{+}e^{-}$ conversions would make $S_{\pi^{0}\pi^{0}}$ determination possible!

**merged $\pi^{0}$:**

the two photons are too close to one another in the EMC to be reconstructed individually; can be recovered using

$$M_{\pi^{0}}^{2} \approx E_{\pi^{0}}^{2}(S_{\pi^{0}} - S_{\gamma})$$

where $S$ is the second EMC moment of the merged $\pi^{0} \rightarrow \gamma \gamma$

The control sample: $\tau \rightarrow \rho \nu$

**$\gamma \rightarrow e^{+}e^{-}$ conversions:**

result from interactions with detector elements

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Recent progress in CP violation: New Physics under siege  
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An interpretation of our new $B \rightarrow \pi\pi$ results

This is a frequentist interpretation: we use only the $B \rightarrow \pi\pi$ isospin-triangle relations in arriving at these constraints on $\Delta \alpha = \alpha - \alpha_{\text{eff}}$ and on $\alpha$ itself.

Here is one of the possible solutions to the Gronau-London isospin triangle in $B \rightarrow \pi\pi$ according to the central values of the Summer 2006 BaBar results:

$$|\Delta \alpha| < 39^\circ \text{ at } 90\% \text{ C.L.}$$

$\pi^0\pi^0$ is doing increasingly better job at separating isospin-triangle solutions.

$\alpha$ near 0 can be disfavored by additional experimental information.

with limits on penguins from $B_s \rightarrow K^+K^-$.

$\Delta \alpha = \alpha - \alpha_{\text{eff}}$
Global fits for the value of \( \alpha \)

The second-highest-precision test of the KM mechanism of CP violation in meson decays

Two interpretations currently exist that convert the \( B \rightarrow \pi\pi, \rho\pi, \rho\rho \) measurements to constraints on \( \alpha \):

- A frequentist interpretation
- A Bayesian interpretation, with model-dependent choices of priors

\( \alpha \in [82.2, 93.7]^\circ \) at 68.3\% C.L.

CKM fit no \( \alpha \) meas. in fit

A frequentist interpretation

A Bayesian interpretation, with model-dependent choices of priors


Our new result: \( B^0 \rightarrow K^+ \pi^- \)

the first \( >5\sigma \) observation of \( \mathcal{A}_{K^+\pi^-} \) (direct CP violation)

\begin{align*}
\mathcal{A}_{K^+\pi^-} &= -0.107 \pm 0.018 +0.007 -0.004 \\
\text{BaBar:} & \\
\mathcal{A}_{K^+\pi^-} &= -0.093 \pm 0.018 \pm 0.008 \\
\text{Belle:} & \\
\mathcal{A}_{K^+\pi^-} &= -0.086 \pm 0.023 \pm 0.009 \\
\text{CDF:} & \\
\mathcal{A}_{K^+\pi^-} &= -0.097 \pm 0.012 \ (8\sigma \text{ from 0})
\end{align*}

Predicted to be \( \approx \mathcal{A}_{K^+\pi}^{(\text{WA})} = +0.051 \pm 0.025 \)

5.4\( \sigma \) difference: an \textit{“}\( \mathcal{A}_{K\pi} \) puzzle”

\begin{align*}
\text{assuming unbroken } SU(3)_{\text{flavor}}: \\
C_{\pi\pi} &= 3 \times \mathcal{A}_{K^+\pi^-} \\
with \text{factorizable } SU(3)_{\text{flavor}}-\text{breaking corrections:} \\
C_{\pi\pi} &= 2.5 \times \mathcal{A}_{K^+\pi^-} = -0.24
\end{align*}

- Could be due to hadronic effects, not New Physics
  (e.g., see R. Fleischer, hep-ph/0608010, hep-ph/0701217)
AK+π bias due to material interactions determined and cross-checked using several independent approaches

1) Detailed GEANT4 v7.1-based simulation: bias of \(-0.005\)
2) From material accounting and material properties + cross sections tabulated in PDG-RPP

<table>
<thead>
<tr>
<th>Material type</th>
<th>comment</th>
<th>density</th>
<th>(\lambda_T)</th>
<th>thickness</th>
<th>in (\lambda_T)</th>
<th>(\int \lambda_T) from IP</th>
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<tr>
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<td>beam pipe</td>
<td>19.3</td>
<td>113.9</td>
<td>4 (\mu)m</td>
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<td>(2.46 \times 10^{-3})</td>
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<td>Si</td>
<td>SVT modules</td>
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<td>70.6</td>
<td>1.7 mm</td>
<td>(5.61 \times 10^{-3})</td>
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<td>Kapton + glue</td>
<td>SVT fanouts</td>
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<td>60.3</td>
<td>0.50 mm</td>
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<td>Cu + Cr</td>
<td>SVT fanouts</td>
<td>9.0</td>
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<td>24 (\mu)m</td>
<td>(0.25 \times 10^{-3})</td>
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<td>Au</td>
<td>SVT fanouts</td>
<td>19.3</td>
<td>113.9</td>
<td>5 (\mu)m</td>
<td>(0.09 \times 10^{-3})</td>
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<td>Air</td>
<td>SVT</td>
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<td>62.0</td>
<td>20 cm</td>
<td>(0.39 \times 10^{-3})</td>
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<td>C</td>
<td>support tube</td>
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<td>1.5 mm</td>
<td>(5.57 \times 10^{-3})</td>
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<tr>
<td>Be</td>
<td>inner DCH wall</td>
<td>1.848</td>
<td>55.8</td>
<td>1.00 mm</td>
<td>(3.31 \times 10^{-3})</td>
<td>(2.34%)</td>
</tr>
<tr>
<td>80% He, 20% C₄H₁₀</td>
<td>25 cm of DCH</td>
<td>0.000615</td>
<td>51.2</td>
<td>25 cm</td>
<td>(0.30 \times 10^{-3})</td>
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<td>Total (IP to DCH)</td>
<td>90° GTL track</td>
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<td></td>
<td></td>
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<td>(2.37% \lambda_T)</td>
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<tr>
<td>80% He, 20% C₄H₁₀</td>
<td>the rest of DCH</td>
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<td>51.2</td>
<td>32 cm</td>
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<td>C</td>
<td>DCH outer wall</td>
<td>2.265</td>
<td>60.2</td>
<td>3.8 mm</td>
<td>(14.3 \times 10^{-3})</td>
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<tr>
<td>Al</td>
<td>DCH outer wall</td>
<td>2.70</td>
<td>70.6</td>
<td>125 (\mu)m</td>
<td>(0.48 \times 10^{-3})</td>
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<td>Al</td>
<td>DRC before SiO₂</td>
<td>2.70</td>
<td>70.6</td>
<td>3.2 mm</td>
<td>(12.3 \times 10^{-3})</td>
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<tr>
<td>Total IP to DIRC</td>
<td>90° track</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(5.1% \lambda_T)</td>
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3) Asymmetry in the continuum background (uncorrected): \(-0.011 \pm 0.004\) (stat)

\(\mathcal{A}_{K+\pi}\) bias correction: \(+0.005^{+0.006}_{-0.003}\)

conservative

bias cannot be zero
Summary and outlook

By gaining a better, more detailed and precise understanding of BaBar detector performance, we have:

- Found ways to increase the $B^0 \rightarrow h^+ h^-$ reconstruction efficiency by 52%
- Observed CP violation the time distribution of $B^0 \rightarrow \pi^+ \pi^-$ decays
- Observed CP violation the charge asymmetry of $B^0 \rightarrow K^+ \pi^-$ decays

The first single-experiment 5-sigma observation of direct CP violation in a process where direct CP violation is not tightly coupled to another type of CP violation (as in $\epsilon'$ or $C_{\pi\pi}$). CPV in decay rules out “superweak” models.

The Kobayashi-Maskawa phase has been demonstrated to be the dominant source of CP violation in meson decays.

Constraints on the CKM Unitarity Triangle from angle measurements are comparable with constraints from all other sources – and mutually consistent.

The absence of a statistically significant incompatibility between them contains a wealth of information about the New Physics that we can be expected at the TeV scale. In particular, it pushes up the scale of new CP-violating physics in most models.
We continue to improve *BaBar*!
The only major problem with the *BaBar* detector, known since 1999: RPC efficiency deteriorating at ~10-20%/year.

Good muon and $K_L$ identification efficiency essential in many searches for New Physics at *BaBar*.

Forward End Cap upgraded in 2002:

The Barrel has $5.1 \lambda_{\text{int}}$ with Layer 19 RPCs (dying, inaccessible), $4.5 \lambda_{\text{int}}$ without – marginal for a muon system.

Adding six 2.2 cm layers of brass increases barrel thickness to $5.3 \lambda_{\text{int}}$.

The technology chosen for Barrel RPC replacement is the **Limited Streamer Tube** (LST). Installed in 2004-06.
LST technology

- LST is a wire chamber operating in the self-limiting streamer mode, so
- Signal does not depend on the amount of initial ionization.
- Non-flammable gas (CO$_2$/i-C$_4$H$_{10}$/Ar).
- 17x15 mm cells with three walls covered with conductive paint (graphite/PVAC).
- Tubes with 7 or 8 cell, 13 to 20 tubes per layer.
- phi position read off the wires (4 channels per tube), 94% eff., multiplicity mostly 1.
- Z strips span the entire width of a layer.
LST performance

First cosmics: run 50769, event 50170, Sep 28, 2004

Example of single-layer efficiency, May 2005

Upgrade of entire barrel completed in October 2006
**Muons ID with LSTs**
before many further improvements

*LSTs were immediately doing better than RPCs ever did!*

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**Recent progress in CP violation: New Physics under siege**  
Alexandre Telnov (Princeton), January 29, 2008  
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Muon ID idea: Neural Net vs. Bagged Decision Trees

First try, some time in 2005... (Ilya Narsky, Caltech, CMS)

The more heterogeneous the inputs and/or the number of discriminating variables, the greater the advantage of Decision Trees over Neural Nets.

Recent progress in CP violation: New Physics under siege

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Where does the room for improvement come from?

1) Better parameterization of detector response:
   - DCH $dE/dx$ significantly improved
   - SVT $dE/dx$ greatly improved

Existing likelihood-based selectors will benefit “automatically” from the new $dE/dx$

First physics publications to use the new $dE/dx$ parameterizations:

“Observation of CP Violation in $B^0 \rightarrow K^+ \pi^-$ and $B^0 \rightarrow \pi^+ \pi^-$”, PRL 99, 021603 (2007)

“Evidence for $D^0$-anti-$D^0$ Mixing”, PRL 98, 211802 (2007)

“Search for $D^0$-anti-$D^0$ mixing using doubly flavor tagged semileptonic decay modes”, PRD 76, 014018 (2007)

More analyses in the pipeline: all $\tau \rightarrow KX$, all charm-mixing with a $D^{*+}$, $B^+ \rightarrow K_S h^+$, ...
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**dE/dx in BaBar Silicon Vertex Tracker:**

π/e, K/e separation; stand-alone SVT tracking

This is what SVT dE/dx looks like after the new detailed calibration

Suffers from the same systematics as DCH dE/dx, only worse

**SVT dE/dx for various particle types, Run 3, data**

- **protons**
- **kaons**
- **pions**
- **muons**
- **electrons**

**LAB momentum, GeV/c**

<table>
<thead>
<tr>
<th>LAB momentum, GeV/c</th>
<th>corrected SVT dE/dx</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
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<tr>
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<td>12</td>
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**θ**

- 0 0.5 1 1.5 2 2.5 3

**SVT dE/dx**

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<th>SVT dE/dx</th>
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**phi**

- -3 -2 -1 0 1 2 3

**minimum-ionizing SVT dE/dx, Run 2+4 data, by charge**

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 3</th>
<th>Run 5</th>
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<tbody>
<tr>
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</table>

**minimum-ionizing SVT dE/dx, Runs 1, 3 and 5, data**

<table>
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</table>

**Need momentum at each SVT wafer**

will aid PID at low momenta

Suffers from the same systematics as DCH dE/dx, only worse
Where does the room for improvement come from?

2) previously unused quantities (“weak classifiers”), e.g.:
   • number of signal and background photons in the DIRC (in a non-”binary” fashion)
   • last layer hit in DCH (for kaon and pion decays in flight)
   • DIRC and DCH dE/dx for muon ID
   • full set of EMC quantities for all particle types
   • SVT dE/dx for electron ID
   • Flattening of the training-sample spectra in theta, phi and charge allows the use of these variables as input parameters

3) new quantities:
   • longitudinal EMC shower depth
   • using geometry to predict “dead spots” in detector acceptance

4) advanced statistical techniques from StatPatternRecognition
   • SPR developed by Ilya Narsky (Caltech), SourceForge SPR V06-00-02
   • we use SPR Boosted Decision Trees (muonBDT and kaonBDT selectors)
   • and SPR multi-class learner (electron/pion/kaon/proton “KM” selectors)
EMC longitudinal shower depth

Shower Depth, 0.00<Track P< 0.40 GeV:cm

Shower Depth, 0.40<Track P< 0.60 GeV:cm

~1σ µ/π separation at low momentum

Shower Depth, 0.60<Track P< 1.25 GeV:cm

Shower Depth, 1.25<Track P< 10.00 GeV:cm

a NIM paper is planned

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DCH $dE/dx \pi,\mu/e$ separation

**DIRC and DCH mu/e separation**

Data, Run 1-5

DCH $dE/dx$

0% efficiency cut-off

LAB momentum, GeV/c

Recent progress in CP violation: New Physics under siege

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Muons below ~0.9 GeV/c do not have enough energy to punch through the IFR; Until now, neither the DIRC nor the DCH were used in the muon selectors, nor a full set of EMC quantities.
SVT $dE/dx \pi/e$ separation

SVT $dE/dx$ pi/e separation, Run 3 data

helps deal with electron background to slow pions ($D^*, D^{**}$, non-$B$ $Y(4S)$ decays)
SVT dE/dx K/e separation

DCH and SVT dE/dx K/e separation, data

will help fight the kaon fake rate in the electron selectors around 0.65 GeV/c
“Ultimate” muon ID now:
30 discriminating variables used

- p
- theta
- charge
- ifrns
- ifrmatchchi2
- ifrfitchi2
- ifrcnt
- ifrsigmum
- ifrmeasintlen
- ecal
- l1mom
- zmom20
- zmom42
- ncry
- s1s9
- s9s25
- seccmom
- dEdxchpullmu
- drcmuprob
- smsdrcmuprob
- emcdcm
- date
- drcpiprob
- drckprob
- nphoton
- ndch
- lhit
- Ifrcrackphi
- deltalamda
- ecaldepth
- date
- drcpiprob
- drckprob
- nphot
- ndch
- lhit
- Ifrcrackphi
- deltalamda
- ecaldepth

BaBar preliminary new eff

BaBar preliminary old eff

π NN (blue) and BDT (red) eff and μ misID rate (LooseFakeRate)
kaonBDT selector: replacement for kaonNN

Plot made for $D^*$ pion and kaon spectra, relevant to $B^0$ flavor tagging

To be presented on February 11 at Caltech workshop on multivariate analysis

Recent progress in CP violation: New Physics under siege

Alexandre Telnov (Princeton), January 29, 2008
How much would you pay for 6% more electrons? 😊
The Motto

Make impossible measurements possible
and make the possible measurements first
(or the best)
by gaining detailed understanding
of your detector;
Make it in a way the entire Collaboration would benefit
The future: physics at the Large Hadron Collider

There is little doubt that previously unseen phenomena will be observed at LHC.

My primary goal for the next several years is to make important contributions to measurements that are key to establishing a pattern among these new phenomena.

So, we see something that could be a Higgs. What is it that we see?

• Is it responsible for the Electro-Weak Symmetry Breaking? Are the $WWh$ and $ZZh$ couplings SM-like, $\sim O(1)$? Important: $h \rightarrow \gamma \gamma$, $bb$, $WW^*$. 

• Are there other particles (Higgses?) responsible for the large top-quark mass? Does the $tth$ coupling agree with SM? Important: $h \rightarrow \gamma \gamma$, $bb$. 

• Are there other Higgses? $H/A \rightarrow \tau^+ \tau^-$? $H^+ \rightarrow tb$?

How can we use constraints on New Physics from $B$, $B_s$, $K$, $D$ decays to be smart about the searches we focus on?
Answering these questions will be a challenge
Excellent understanding of the detector and sophisticated tools will be required

alignment
tracking
muons
electrons
\(b\) jets
\(\tau\) jets
momentum scale
etc.
Muons at ATLAS: not merely a discovery tool!

\[ H \rightarrow ZZ(\ast) \rightarrow e^+e^-\mu^+\mu^- \]

If Nature is kind, LHC may be able to make a precision measurement of Higgs mass, and perhaps even width

Excellent muon isolation/identification and momentum determination will be essential:

- alignment
- magnetic field map
- unbiased momentum determination
- multivariate “particle ID” (suppression of fakes)?

Calibration sample:

\[ Z \rightarrow \mu^+\mu^- \]

Not to mention scenarios with a \( Z' \) or other dimuon resonances…