Hadronic uncertainties in flavour physics

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MAMI and beyond
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Motivation

- Understand **flavour structure** of Standard Model
- Test Standard Model predictions
- Search for New Physics

- Want to access **quark-level** quantities, but only can measure hadron decays:

- Need handle on QCD dynamics to understand flavour physics
This talk

Flavour physics

\( \sin 2\beta \) in \( s \)-penguin decays

\( |V_{cb}| \) from semileptonic \( B \) decays

Side of unitarity triangle from \( B \) mixing

Future experiments

Summary
Mixing of mass- to flavour-eigenstates described by Cabbibo-Kobayashi-Maskawa matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\approx
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

For 3 quark families: 3 mixing angles, 1 irreducible phase
Practical: Wolfenstein-parametrisation: $\lambda$, $A$, $\rho$, $\eta$

$\lambda \approx \sin \theta_C \approx 0.2257$ (Cabbibo angle) $\Rightarrow$ hierarchy
Unitarity Triangle and \( CP \) violation

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

- \( V_{\text{CKM}} \) is unitary (universality of weak interaction):
  \[
  V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0
  \]
- triangle in complex \((\bar{\rho}, \bar{\eta})\) plane
  \[
  \bar{\rho} \approx (1 - \lambda^2/2 + \ldots)\rho
  \]
- apex at
  \[
  \bar{\rho} + i\bar{\eta} \equiv (V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)
  \]

- Kobayashi & Maskawa 1973:
  Non-zero phase in CKM matrix generates \( CP \) violation:
  \[\eta \neq 0 \iff \text{Unitarity triangle is not flat} \]
  (Nobel Price 2008)

\[\eta \neq 0 \iff \text{Unitarity triangle is not flat}\]
Constraining the CKM matrix

- Goal: over-constrain Unitarity Triangle to validate three-generation SM (or find New Physics!)
- Measure observables $\mathcal{O}$ (branching fractions, $CP$ asymmetries . . .)
- Translate measurements into constraints in $(\bar{\rho}, \bar{\eta})$ plane
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'Clean observables'

- Hadronic uncertainties cancel or expected small
- $\sin 2\beta$, $\alpha$
- $\gamma$ (but very large experimental uncertainty)

Large hadronic uncertainties

- $|\varepsilon_K|$ — Mixing and $CP$ violation in $K^0-\bar{K}^0$
- $|V_{cb}|$, $|V_{ub}|$ — CKM matrix elements
- $\Delta m_d$, $\Delta m_s$ — mass difference in $B^0$ mass eigenstates
- $\mathcal{B}(B \to \tau \nu)$
Constraints as of Winter 2009

\[ \sin 2\beta \quad \alpha \quad \gamma \quad \cos 2\beta \quad \sin(2\beta + \gamma) \]

\[ \epsilon_K \quad V_{ub}/V_{cb} \quad \Delta m_d \quad \Delta m_d/\Delta m_s \quad B(B \rightarrow \tau\nu) \]

UTfit collaboration (M. Bona et al.), http://www.utfit.org
The Unitarity Triangle as of Winter 2009

\[ \bar{\rho} = 0.154 \pm 0.022 \]
\[ \bar{\eta} = 0.342 \pm 0.014 \]
\[ \sin 2\beta = 0.695 \pm 0.020 \]

http://www.utfit.org

Theoreticians’ toolbox

Need theoretical tools to
- make predictions for branching fractions, $CP$ asymmetries . . .
- compute hadronic corrections

- Effective Hamiltonian: integrate out $W$ and $t$
- $m_b \gg \Lambda_{\text{QCD}}$
  - factorisation: form factors, distribution amplitudes, . . .
  - heavy quark expansion (powers of $\Lambda_{\text{QCD}}/m_b$)
  - perturbation theory: expansion in $\alpha_s(m_b)$
- $\Lambda_{\text{QCD}} \gg m_u, m_d, m_s$: $SU(2)$ or $SU(3)$ global symmetries
- Lattice gauge theory (LQCD)
  difficult to deal with light energetic particles
QCD factorisation at work

Hard, but not without success:
Predictions of QCDF ▲ (Beneke & Neubert, 2003),
compared to experiment □ (as of 2006)

M. Beneke, HQL 2006

CP-averaged $B \to PP$ branching fractions.
Time-dependent CP asymmetries

- Neutral $B$ mesons oscillate between $B^0$ and $\bar{B}^0$.

$$\langle \bar{B}^0 | \mathcal{H} | B^0 \rangle = \frac{B^0}{d} \xrightarrow{W} \frac{B^0}{b} \xrightarrow{W} \frac{B^0}{t} \xrightarrow{d} \frac{B^0}{t} \xrightarrow{b} \frac{B^0}{d} + \text{long distance}$$

- Mass eigenstates $|B^0_{H,L}\rangle = p |B^0\rangle \pm q |\bar{B}^0\rangle$; $q/p \approx e^{-2i\beta}$
  \[ \Delta m = m_H - m_L = 2|\mathcal{M}_{12}| \]

- Decay into common final state $f$:
  - If $f$ is CP eigenstate: interference between two decay paths
  - $V_{\text{CKM}}$ complex
    - $B^0$ and $\bar{B}^0$ decays have different weak phase
  - Leads to lifetime dependent differences
    \[ \Gamma( B^0 \xrightarrow{t=0} f |_t ) \neq \Gamma( \bar{B}^0 \xrightarrow{t=0} f |_t ) \]
Time-dependent CP asymmetries

Time evolution of $B_{\text{tag}} = B^0(\bar{B}^0)$ is

$$f_{\pm}(\Delta t) = e^{-|\Delta t|/\tau_{B^0}} \left\{ 1 \pm \left[ -\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t) \right] \right\}$$

$\Delta m_d = m_H - m_L = 0.507 \pm 0.005 \, \hbar/\text{ps}$
$\tau_B$: $B^0$ lifetime $(1.530 \pm 0.009 \, \text{ps})$
$\eta_f$: CP eigenvalue of final state $f$

- $S_f, C_f$ encode information about CP violation
- Construct asymmetry as a function of $\Delta t$:

$$A_{\text{cp}}(\Delta t) = \frac{\Gamma(\Delta t) - \bar{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \bar{\Gamma}(\Delta t)} = S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t$$
\[ \sin 2\beta \] from time-dependent \( CP \) violation in \( b \to c\bar{c}s \)

- ‘Golden mode’ \( B^0 \to J/\psi K^0 \): tree amplitude dominates, sub-leading amplitude small and with the same weak phase.

\[ S_{J/\psi} K^0_s = \sin 2\beta \]

- Very small corrections \( \mathcal{O}(10^{-3}) \)
- Measured in \( B \to (c\bar{c})K^0 \) decays to 3% accuracy

- Exploit precision to search for effects of new physics at TeV scale
Searching for new physics in $CP$ violation

- Measure CPV in $b \to s$ loop (‘penguin’) dominated decays: $S_f$

- Standard model & penguin only

  \[ S_f = -\eta_f \sin 2\beta \]

- ‘Golden mode’ $B^0 \to \phi K_S^0$

- New Physics (NP) can show up in loops and modify $S_f$

- Sensitive to masses

  $\sim \mathcal{O}(10 \text{ TeV})$

- But: sub-leading SM amplitudes not negligible, and have different weak phases

- In order to see NP in

  \[ 0 \neq \Delta S_{NP} \equiv S_f - S_{c\bar{c}s} - \Delta S_{SM} \]

  need to control ‘SM pollution’
sin $2\beta$ from $b \rightarrow q\bar{q}s$ penguins

$\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1\text{eff}})$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>World Average</th>
<th>Average</th>
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<tbody>
<tr>
<td>$b \rightarrow c\bar{c}s$</td>
<td>0.67 ± 0.02</td>
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<tr>
<td>$\phi K^0$</td>
<td>0.44 ± 0.17</td>
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</tr>
<tr>
<td>$\eta' K^0$</td>
<td>0.59 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>$K_s K_s K_s$</td>
<td>0.74 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 K^0$</td>
<td>0.57 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>$\rho^0 K_s$</td>
<td>0.63 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>$\omega K_s$</td>
<td>0.45 ± 0.24</td>
<td></td>
</tr>
<tr>
<td>$f_0 K_s$</td>
<td>0.62 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \pi^0 K_s$</td>
<td>-0.52 ± 0.41</td>
<td></td>
</tr>
<tr>
<td>$\phi \pi^0 K_s$</td>
<td>0.97 ± 0.52</td>
<td></td>
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<tr>
<td>$K^+ K^0 K^0$</td>
<td>0.82 ± 0.07</td>
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- Experiments seem to favour $\Delta S < 0$
- Was more exciting 2 years ago

- $\Delta S_{\text{SM}}$ tend to be small and positive
- Neither experimental nor theoretical precision high enough to confirm or rule out New Physics
Unitarity triangle side from semileptonic $B$ decays

$$\frac{|V_{ub}|}{|V_{cb}|} = \frac{\lambda}{1 - \lambda^2/2} \sqrt{\rho^2 + \bar{\eta}^2}$$
Semileptonic $b \rightarrow c$ decays

- $|V_{cb}|$ (and $|V_{ub}|$) determined from semileptonic $B$ decays
- Tree-level process: free from new physics!
- Everything nice and clean at quark-level:
  \[ \Gamma \propto |V_{cb}|^2 \]

Need to include QCD corrections

- Inclusive measurements
  ($\bar{B} \rightarrow X_c \ell \bar{\nu}$)
  Operator Product Expansion
- Exclusive measurements:
  Form factors from Lattice QCD
- Complementarity between incl. and excl.
Inclusive semileptonic decay width

\[ \mathcal{B}(B \to X_c e\nu) = 10.08 \pm 0.30 \pm 0.22 \]


\[ \Gamma(\bar{B} \to X_c \ell\bar{\nu}) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \left[ f(\rho) + k(\rho) \frac{\mu_\pi^2}{2m_b^2} + g(\rho) \frac{\mu_G^2}{2m_b^2} \right. \\
\left. + d(\rho) \frac{\rho_D^3}{m_b^3} + l(\rho) \frac{\rho_{LS}^3}{m_b^3} + O(m_b^{-4}) \right] \quad \rho = \frac{m_c^2}{m_b^2} \]

Wilson coefficients \( f, k, g, d, l \) calculable in perturbation theory

Non-perturbative parameters \( \mu_\pi, \mu_G, \rho_D, \rho_{LS} \) matrix elements of local operators in HQET

Same matrix elements (but different Wilson coefficients) appear in OPE for moments of

- lepton energy spectrum \( E_\ell \) in \( B \to X_c \ell\bar{\nu} \)
- hadronic mass spectrum \( M_X \) in \( B \to X_c \ell\bar{\nu} \)
- photon energy spectrum \( E_\gamma \) in \( B \to X_s \gamma \)
Inclusive $|V_{cb}|$ — moment analysis

Moment measurements

OPE Expressions

Ext. input: $\alpha_s$, $\tau_B$, QED ...

Fit

$|V_{cb}|$, $m_b$, $m_c$, $\mu_\pi$, $\mu_G$, $\rho_D$, $\rho_{LS}$

Quark masses? Kinetic mass scheme; 1S mass scheme

World average (HFAG; kinetic scheme)

$$|V_{cb}| = (41.67 \pm 0.43_{\text{fit}} \pm 0.08_{\tau_B} \pm 0.58_{\text{th}}) \times 10^{-3}$$

$$m_b = (4.601 \pm 0.034) \text{ GeV}$$

$$\mu_\pi^2 = (0.440 \pm 0.040) \text{ GeV}^2$$
Exclusive $|V_{cb}|$ measurements

\[ \frac{d\Gamma(B \to D^*\ell\nu)}{dw} = G_F^2 |V_{cb}|^2 \frac{\mathcal{K}(w) F(w)^2}{48\pi^3} \]

- $w$: four-velocity transfer from $b$ to $\ell\nu$
- $\mathcal{K}$: known phase-space factor, vanishes as $w \to 1$
- $F$: form factor; in limit of infinite quark mass: $F(w = 1) = 1$
  LQCD: $F(1)^{B\to D^*\ell\nu} = 0.924 \pm 0.022$\(^{\text{FNAL, arXiv:0710.1111}}\)
- Typically, experiments measure $d\Gamma/dw$ and extrapolate to $w \to 1$ to determine $|F(1)V_{cb}|$

\begin{align*}
F(w)|V_{cb}| &\times 10^3 \\
\begin{array}{c|c}
1 & 34.4 \\
1.1 & 33.7 \\
1.2 & 33.0 \\
1.3 & 32.2 \\
1.4 & 31.4 \\
1.5 & 30.6 \\
\end{array}
\end{align*}

$F(1)|V_{cb}| = (34.4 \pm 0.3 \pm 1.1) \times 10^{-3}$

$\text{BaBar, Phys. Rev. D 77 032002 (2008)}$
Exclusive \left| V_{cb} \right| results

\textbf{B} \rightarrow \textbf{D}^* \ell \nu

ALEPH (excl)
31.6 \pm 1.8 \pm 1.3

CLEO
41.3 \pm 1.3 \pm 1.8

OPAL (excl)
36.9 \pm 1.6 \pm 1.5

OPAL (partial reco)
37.6 \pm 1.2 \pm 2.4

DELPHI (partial reco)
35.8 \pm 1.4 \pm 2.3

BELLE (excl)
34.7 \pm 0.2 \pm 1.0

DELPHI (excl)
36.3 \pm 1.8 \pm 1.9

BABAR (excl)
33.9 \pm 0.3 \pm 1.1

BABAR (D^*)
34.9 \pm 0.8 \pm 1.4

BABAR (Global Fit)
35.7 \pm 0.2 \pm 1.2

Average
35.4 \pm 0.5

\chi^2/\text{dof} = 39/21 (\text{CL} = 0.01 \%)
Unitarity triangle side from $\Delta m_d, \Delta m_s$
Constrain side with $\Delta m_d$

- $\Delta m_d$ related to $B^0 - \bar{B}^0$ oscillations
- In Standard Model:
  \[
  \begin{array}{c}
  b \xrightarrow{W} t \xrightarrow{W} d \\
  \bar{d} \xrightarrow{t} \bar{b}
  \end{array}
  \]
  
  $t$ box dominated
- Experiment:
  \[
  \Delta m_d = 0.507 \pm 0.005 \, \text{ps}^{-1}
  \]

\[
\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 B_{B_d} |V_{cb}|^2 \lambda^2 ((1 - \bar{\rho})^2 + \bar{\eta}^2)
\]

$f_{B_d}^2 B_{B_d}$: non-perturbative contribution, uncertainty $\approx 10\%$
\( \Delta m_d / \Delta m_s \)

- \( B_s \) also oscillates \( \Rightarrow \Delta m_s \)
- Precisely measured at Tevatron
  
  \[
  \Delta m_s = 17.31^{+0.33}_{-0.18} \text{(stat)} \pm 0.07 \text{(sys)} \ h \text{ps}^{-1}
  \]

- \( f_{B_s}^2 B_{B_s} \) easier to calculate in LQCD: larger mass of \( s \) quark
  \( \Rightarrow \) smaller uncertainties than \( f_{B_d}^2 B_{B_d} \)

- Ratio \( \xi = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} \) can be calculated even better

\[
\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 B_{B_d}}{m_{B_s} f_{B_s}^2 B_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2} \propto \frac{1}{\xi^2}((1 - \bar{\rho})^2 + \bar{\eta}^2)
\]
Turning the tables

- Use overconstrained UT to fit for $B_K$, $f_{B_s} \sqrt{B_{B_s}}$, $\xi$
- Include angles and $|V_{ub}|/|V_{cb}|$ information in fit, exclude $\Delta m_d$, $\Delta m_s$, $\varepsilon_K$
- Compare to Lattice QCD Lubitz & Tarantino, arXiv:0807.4605v1 [hep-lat]

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<thead>
<tr>
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<th>UT</th>
<th>LQCD</th>
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<tbody>
<tr>
<td>$B_K$</td>
<td>0.75 ± 0.07</td>
<td>0.75 ± 0.07</td>
</tr>
<tr>
<td>$f_{B_s} \sqrt{B_{B_s}}$ (MeV)</td>
<td>264.7 ± 3.6</td>
<td>270 ± 30</td>
</tr>
<tr>
<td>$\xi$</td>
<td>1.26 ± 0.05</td>
<td>1.21 ± 0.04</td>
</tr>
<tr>
<td>$f_{B_d}$ (MeV)</td>
<td>191 ± 13</td>
<td>200 ± 20</td>
</tr>
</tbody>
</table>

- Remarkable agreement
- Precision from UT fit comparable to current LQCD
Experimental outlook

- Current $B$ Factories at or near the end of data taking
- Some tensions in several parameters, but currently not significant
- Most promising channels to look for New Physics still limited by statistics

 elders: LHCb, Super-Flavour-Factory
Near future: LHCb

- $pp \rightarrow b\bar{b}X$ at $\sqrt{s} = 14$ TeV
  Start of data taking: Sept. ‘09?
- First data sample: 10 fb$^{-1}$ in $\sim 5$ years
- Measure angles with precision of $\approx 1^\circ$
- Definitive measurements in $B_s$ system
- Large samples of certain types of decays
  (high-$p$ leptons or hadrons (trigger!), $\leq 1$ neutral)
  $B_{d,s} \rightarrow \mu\mu$, $B_s \rightarrow \phi\gamma$, $B \rightarrow K^*\mu\mu$, . . .
- But: no chance for $B$ decays with lots of neutrals, neutrinos, . . .

- LHCb upgrade: 100 fb$^{-1}$?
Mid-term future: Super-Flavour-Factory

Asymmetric $e^+e^-$ collider on $\Upsilon(4S)$, with $\mathcal{L} \gtrsim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$

- Two proposals under consideration:
  - Super-KEKB (KEK, Japan), reusing KEK-B and much of Belle detector ($\mathcal{L} \sim 0.8 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$)
  - SuperB (Tor Vergata, near Frascati): new site, reuse PEP-II and BABAR components ($\mathcal{L} \sim 1–4 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$)

- Will collect huge charm, $\tau$, $q\bar{q}$ samples, too.

- Physics topics:
  - $CP$ violation in charm
  - Lepton Flavour violation: $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$
  - (Very) rare FCNC $B$ decays, $b \to s\gamma$, $b \to s\ell^+\ell^-$, $b \to d\gamma$
  - leptonic $B \to \ell\nu$: $\ell = \tau, \mu$
  - ...

Highly complementary to LHCb
New rare decays accessible $\Rightarrow$ increased physics reach
And there’s more physics . . .

No time today to talk about

- Spectroscopy (BABAR, Belle, CDF); complementary to PANDA
- Precision measurements of $\sigma(e^+e^- \to \text{hadrons}) \Rightarrow (g - 2)_\mu$, $\alpha_{\text{em}}$
- Spin-dependent fragmentation functions (Belle)
- Time-like baryon form factors: $e^+e^- \to p\bar{p}, \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$ ($\text{BABAR}$)
- . . .

Benefit from statistics at a Super-Flavour Factory
Summary

- $B$ Factory programme very successful in establishing CKM theory
- CKM dynamics provides at least lion’s share of observed $CP$ violation [I. Bigi]
- Works beautifully at current precision
- Some (hints of) tensions exist, but effects of New Physics likely to be subtle
- Good control of QCD essential for precision flavour physics

Need to acquire high precision data and interpret it with high precision:
Progress in experiment and theory needed

Next generation Flavour factories:
LHCb starting soon
Super Flavour Factory under consideration
The B-factories \textit{BABAR} at SLAC and Belle at KEK

- $e^+e^-$-colliders running at $\sqrt{s} = m(\Upsilon(4S)) = 10.58 \text{ GeV}$
- Asymmetric beam energies
- High luminosity ($\mathcal{O}(10^{34}) \text{ cm}^{-2}\text{s}^{-1}$) $\rightarrow$ data samples of $\mathcal{O}(10^{10})$ $B$ decays

- Data taking stopped a year ago
- $\mathcal{L}_{\text{int}} = 531 \text{ fb}^{-1}$
  - 465 million $B\bar{B}$ pairs on-$\Upsilon(4S)$

- Current data sample $> 900 \text{ fb}^{-1}$
- Approved to collect 1000 fb$^{-1}$
The **BABar** experiment

- **PEP-II**: $e^+e^-$ collider, $3.1 \times 9 \text{ GeV}^2$  
  $\sqrt{s} = 10.58 \text{ GeV} \ [\Upsilon(4S)]$

- Asymmetric beam energies
  - c.m. lab boost $\beta\gamma = 0.56$

- Asymmetric detector
  - acceptance in c.m.  
    $-0.9 \lesssim \cos \theta^* \lesssim 0.85$

- excellent performance
  - Good tracking, mass resolution
  - Good $\gamma$, $\pi^0$ reco.
  - Full PID for $e, \mu, \pi, K, p$

- **High luminosity**
  - $\approx 530 \text{ fb}^{-1}$ accumulated
  - 465 million $B\bar{B}$ pairs on-$\Upsilon(4S)$
  - 120 million $\Upsilon(3S)$
  - 100 million $\Upsilon(2S)$
  - 1.7 billion $e^+e^- \rightarrow q\bar{q}$ events
PEP-II performance and the *BABAR* data sample

- Peak luminosity
  \[12.069 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\]

- Data taking stopped 8 April 2008

- Integrated luminosity 531 fb$^{-1}$

As of 2008/04/11 00:00

*PEP II Delivered Luminosity: 553.48/fb*
*BaBar Recorded Luminosity: 531.43/fb*
*BaBar Recorded Y(4s): 432.89/fb*
*BaBar Recorded Y(3s): 30.23/fb*
*BaBar Recorded Y(2s): 14.45/fb*
*Off Peak Luminosity: 53.85/fb*
'The other $B$ factory' at KEK-B in Tsukuba, Japan

Friendly competition over the last decade

Very similar setup of accelerator and detector

Larger data sample: $\approx 900 \, fb^{-1}$ so far

Scheduled to run until $1,000 \, fb^{-1}$
Measuring $\Delta t$

$\beta\gamma = 0.56$

$\Delta z \approx 250 \mu m$

$\Gamma_{\Delta t} \approx 1.1 \text{ ps}$

$\tau_B \approx 1.5 \text{ ps}$

$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c} \frac{1}{\langle \beta\gamma \rangle c}$

CP tag $\varepsilon \approx 0.1$

Flavour tag $Q \approx 0.3$
Detecting a signal

- Largest backgrounds from $e^+ e^- \rightarrow q\bar{q}$
- Use event shape for background suppression:
  - jet-like $q\bar{q}$
  - spherical $b\bar{b}$
- Kinematic variables identify $B$:

\[
\Delta E = E^*_B - E^*_\text{beam} \sim 0
\]

\[
m_{ES} = \sqrt{E^*_\text{beam}^2 - p^*_B^2} \sim m_B
\]