CP Violation at Asymmetric e^+e^- B-Factories

Anders Ryd

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Outline:

- Introduction to CP-violation
- Asymmetric B-factories
  - BaBar and BELLE
- First CP violation studies:
  - $\sin(2\beta)$
  - $\sin(2\alpha)$
- Beyond the first measurements
- Conclusions

CP violation in the standard model

In the standard model of particle physics CP-violation is generated through the complex phases of the CKM matrix. It is convenient to use the Wolfenstein parameterization:

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$\approx \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

where

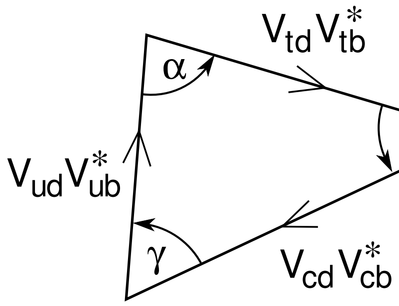
$$\lambda = V_{us} = 0.2205 \pm 0.0018$$

$$A = V_{cb}/\lambda^2 = 0.83 \pm 0.06$$

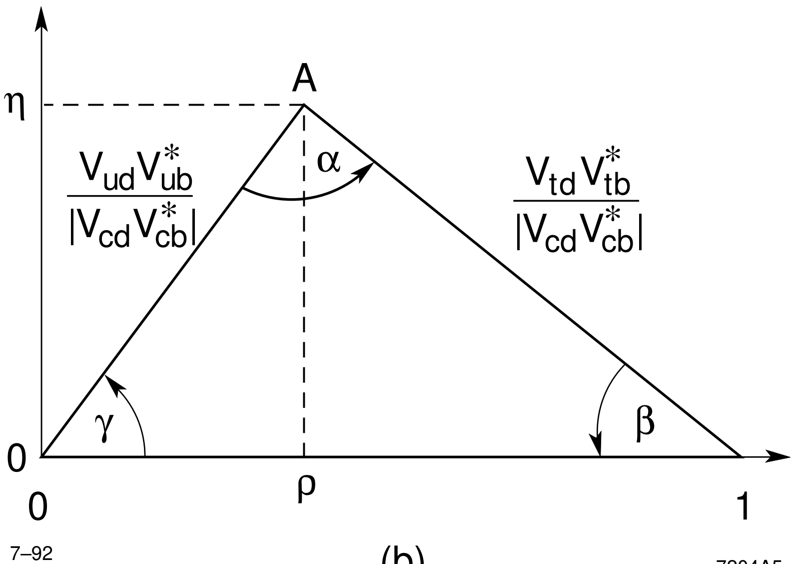
The Unitarity Triangle.

Orthogonality of the CKM matrix allows construction unitarity triangles:

$$0 = V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^*$$



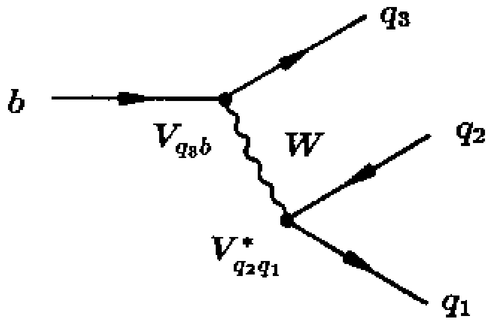
(a)



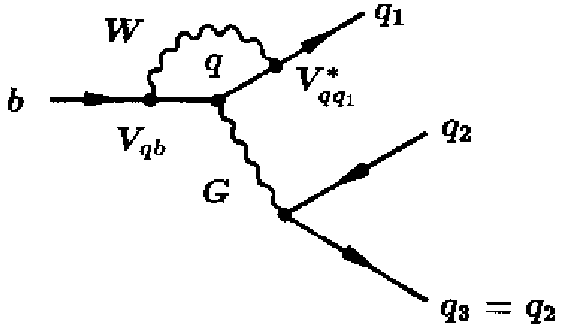
(b)

Quark Diagrams in b Decays.

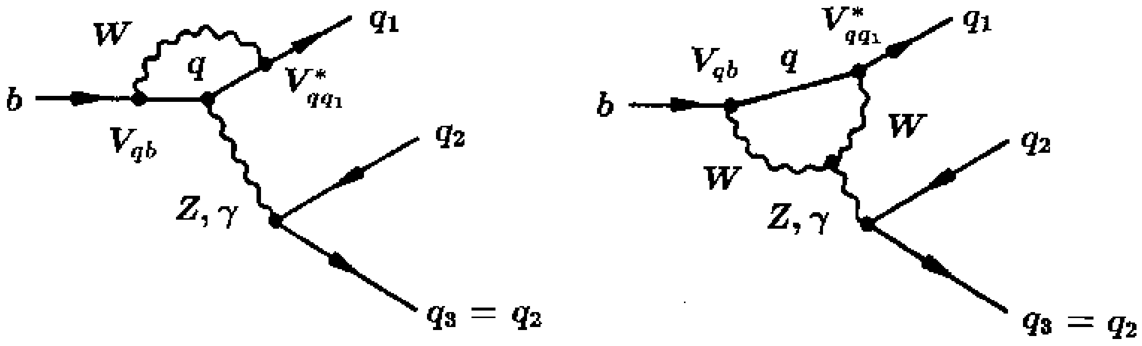
Tree Diagrams:



QCD Penguin Diagrams:



EW Penguin Diagrams:



Quark subprocesses and CP-violating asymmetries.

$B \to q\bar{q}s$ Decay Modes

Quark Process	Leading Term	Secondary Term	Sample B_d Modes	B_d Angle	Sample B_s Modes	B_s Angle
$b \to c\bar{c}s$	$V_{cb}V_{cs}^* = A\lambda^2$ tree + penguin $(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ penguin only $(u-t)$	$J/\psi\ K_S$	β	$\psi\eta'$ $D_s\overline{D}_s$	β_S
$b \to s\bar{s}s$	$V_{cb}V_{cs}^* = A\lambda^2$ penguin only $(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ penguin only $(u-t)$	ϕK_S	β	$\phi\eta'$	0
$b \to u\bar{u}s$ $b \to d\bar{d}s$	$V_{cb}V_{cs}^* = A\lambda^2$ penguin only $(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ tree + penguin $(u-t)$	$\pi^0\ K_S$ ρK_S	competing terms	$\phi\pi^0$ K_SK_S	competing terms
$b \to c\bar{u}s$ $b \to u\bar{c}s$	$V_{cb}V_{us}^* = A\lambda^3$ $V_{ub}V_{cs}^* = A\lambda^3(\rho - i\eta)$	0	$D^0K \searrow$ common $\overline{D}^0K \nearrow$ modes	γ	$D^0\phi \searrow$ common $\overline{D}^0\phi \nearrow$ modes	γ

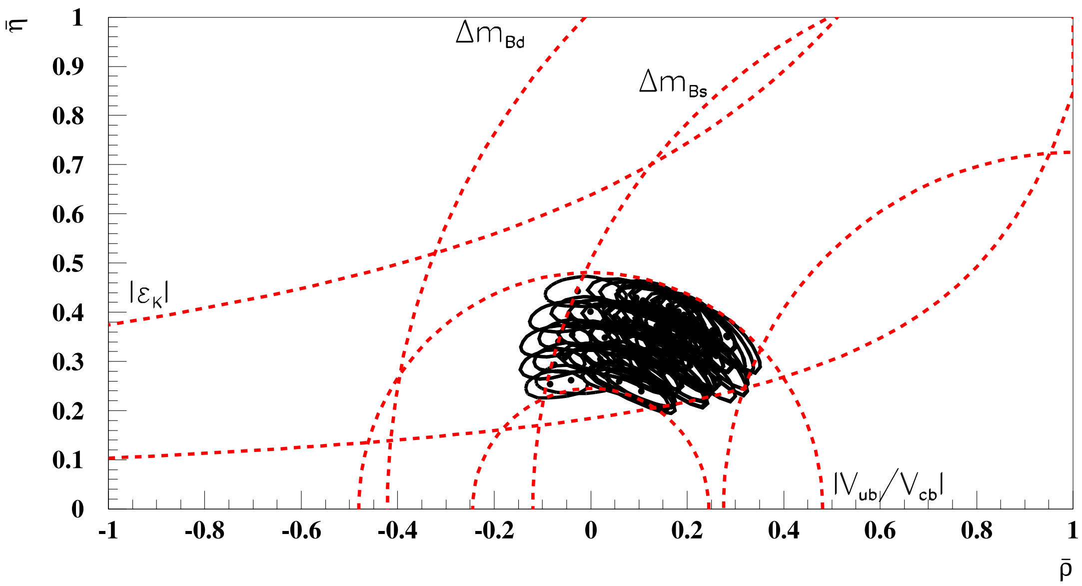
$b \to q\bar{q}d$ Decay Modes

Quark Process	Leading Term	Secondary Term	Sample B_d Modes	B_d Angle * (leading terms only)	Sample B_s Modes	B_s Angle * (leading term)
$b \to c\bar{c}d$	$V_{cb}V_{cd}^* = -A\lambda^3$ tree + penguin $(c-u)$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only $(t-u)$	D^+D^-	$^*\beta$	ψK_S	β_S
$b \to s\bar{s}d$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only $(t-u)$	$V_{cb}V_{cd}^* = A\lambda^3$ penguin only $(c-u)$	$\phi\pi$ $K_S\overline{K}_S$	competing terms	ϕK_S	competing terms
$b \to u\bar{u}d$ $b \to d\bar{d}d$	$V_{ub}V_{ud}^* = A\lambda^3(\rho - i\eta)$ tree + penguin (uc)	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only $(t-c)$	$\pi\pi$; $\pi\rho$ $\pi\, a_1$	$^*\alpha$	π^0K_S ρ^0K_S	competing terms
$b \to c\bar{u}d$ $b \to u\bar{c}d$	$V_{cb}V_{ud}^* = A\lambda^2$ $V_{ub}V_{cd}^* = -A\lambda^4(\rho - i\eta)$	0	$D^0\pi^0 \searrow$ common $\overline{D}^0\pi^0 \nearrow$ modes	γ	$D^0K_S \searrow$ common $\overline{D}^0K_S \nearrow$ modes	γ

ρ and η Constrains

Non B-CP violating ρ and η constraints

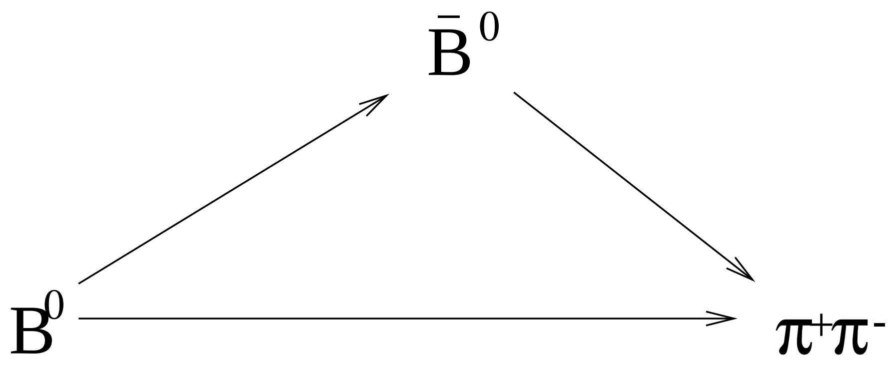
- $|V_{ub}/V_{cb}|$ from $B \to u\ell\nu$.
- $|\epsilon_K|$ from CP violation in the neutral Kaon system.
- Δm_{B_d} from B_d mixing.
- Δm_{B_s} from B_s mixing.



Measuring Phases of CKM Elements

To measure the phases of the CKM matrix we need interference between different amplitudes that allows us to measure the phase.

This talk will focus on the CP violation in interference between B decays with and without mixing:



CP Asymmetries

The observable asymmetry

$$a_{f_{CP}} = \frac{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) - \Gamma(\bar{B}^0_{\rm phys}(t) \to f_{CP})}{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) + \Gamma(\bar{B}^0_{\rm phys}(t) \to f_{CP})}$$

is related to the amplitudes

$$a_{f_{CP}} = \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m_B t) - 2\Im\lambda_{f_{CP}}\sin(\Delta m_B t)}{1 + |\lambda_{f_{CP}}|^2}$$

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

p and q are defined by the time evolution of the B:

$$|B^0_{\rm phys}(t)\rangle = g_+(t)|B^0\rangle + (q/p)g_-(t)|\bar{B}^0\rangle,$$

$$|\bar{B}^0_{\rm phys}(t)\rangle = (p/q)g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle,$$

where

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m_B\ t/2),$$

$$g_-(t) = e^{-iMt}e^{-\Gamma t/2} i\sin(\Delta m_B\ t/2).$$

A Word About the $\Upsilon(4S)$ System

- The $\Upsilon(4S)$ system produces B mesons only in the modes $\Upsilon(4S) \to B^0\bar{B}^0$ and $\Upsilon(4S) \to B^+B^-$

- The produced $B^0\bar{B}^0$ system is in a coherent $L = 1$ state. The two mesons are evolving in phase, this means that when one of the B mesons decays the other B is at that time of the opposite flavor. After the decay of one of the B's the other B evolves independently, hence final states with decays of two B or $\bar{B}$ are possible.

- Since the uncorrelated time evolution starts with the decay of one of the B mesons the relevant quantity for the time evolutions of a B meson produced in an $\Upsilon(4S)$ decay is Δt, the time difference between the two B decays.

Asymmetric B-factories

The idea of an asymmetric collision was proposed to allow a measurement of Δt by simply measuring the vertex displacement in z of the two B meson decays.

Since the B mesons are almost at rest in the $\Upsilon(4S)$ frame we have:

$$\Delta z = \beta\gamma c \Delta t$$

In BaBar $\beta\gamma \approx 0.56$ which gives a typical vertex separation of 250 μm.

Excellent vertexing in z is required for this measurement.

KEK-B and PEP-II

	PEP-II	KEK-B
Bunches	1658	5000
Current (I^+/I^-) (A)	1.0/2.1	1.1/2.6
$\beta\gamma$ $\Upsilon(4S)$	0.56	0.43
Design luminosity	3×10^{33}	10^{34}

- KEK-B is operating with 25 mr crossing angle.
- Both machines collided beams with detectors installed in the last week of May 1999.
- KEK-B is currently down for machine upgrades but will continue running in October.
- PEP-II has delivered record luminosities of 10^{33}, which is 1/3 of the design luminosity.

BELLE and BaBar

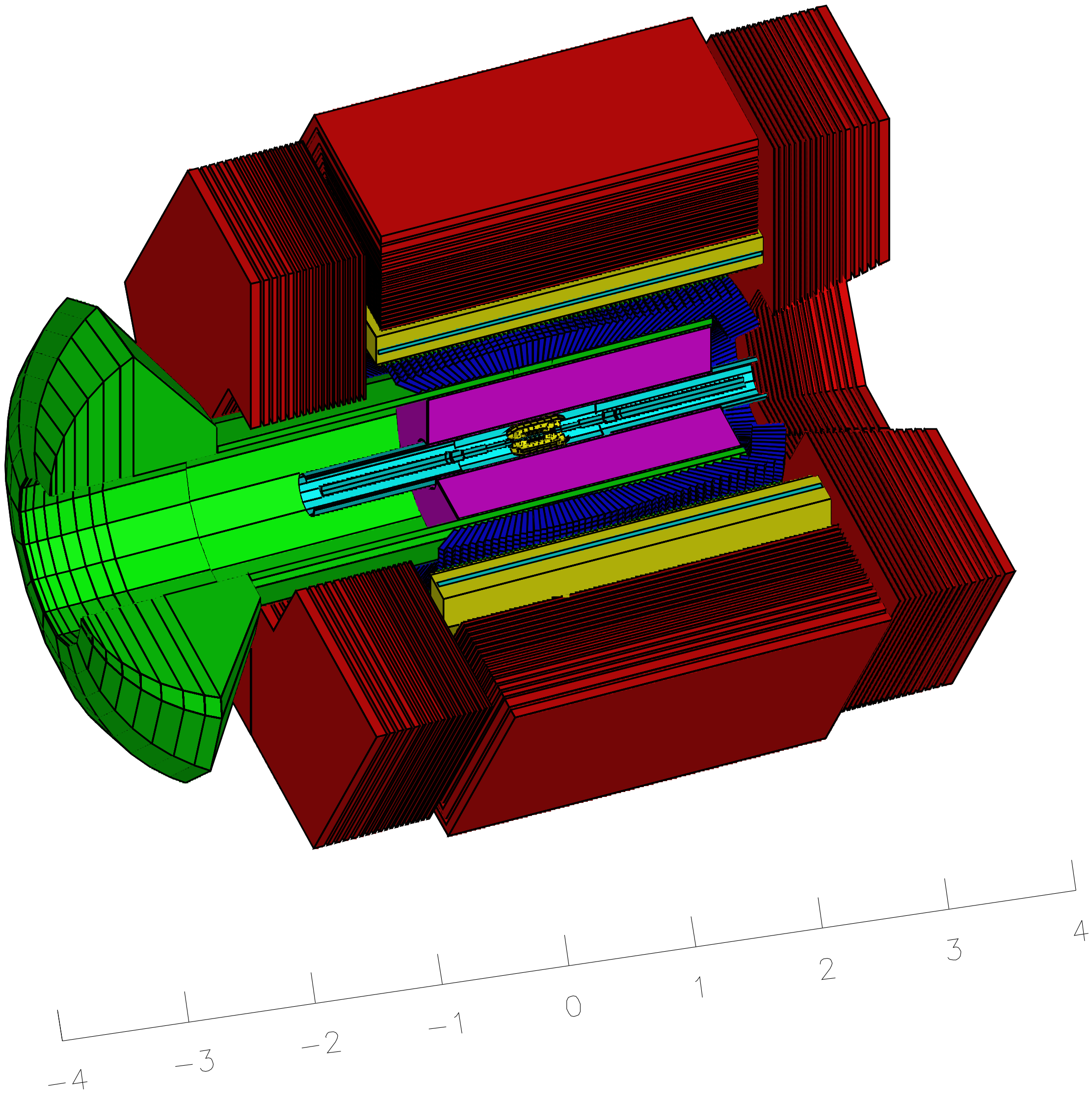
BELLE and BaBar are similar detectors:

- Silicon Vertex detectors for vertex reconstruction. (BELLE 3 layers and BaBar 5 layers.)
- Drift chambers with low Z-gas for optimal momentum resolution and 1.5 T field.
- CsI electro-magnetic calorimeter for optimal energy resolution down to a few 10's of MeV for photon detection and electron ID.
- Instrumented flux return for muon identification and K_L detection.

For charged hadron identification (K/π separation) BaBar uses the DIRC (Detection of Internally Reflected Cherenkov photons) and BELLE uses aerogel counters.

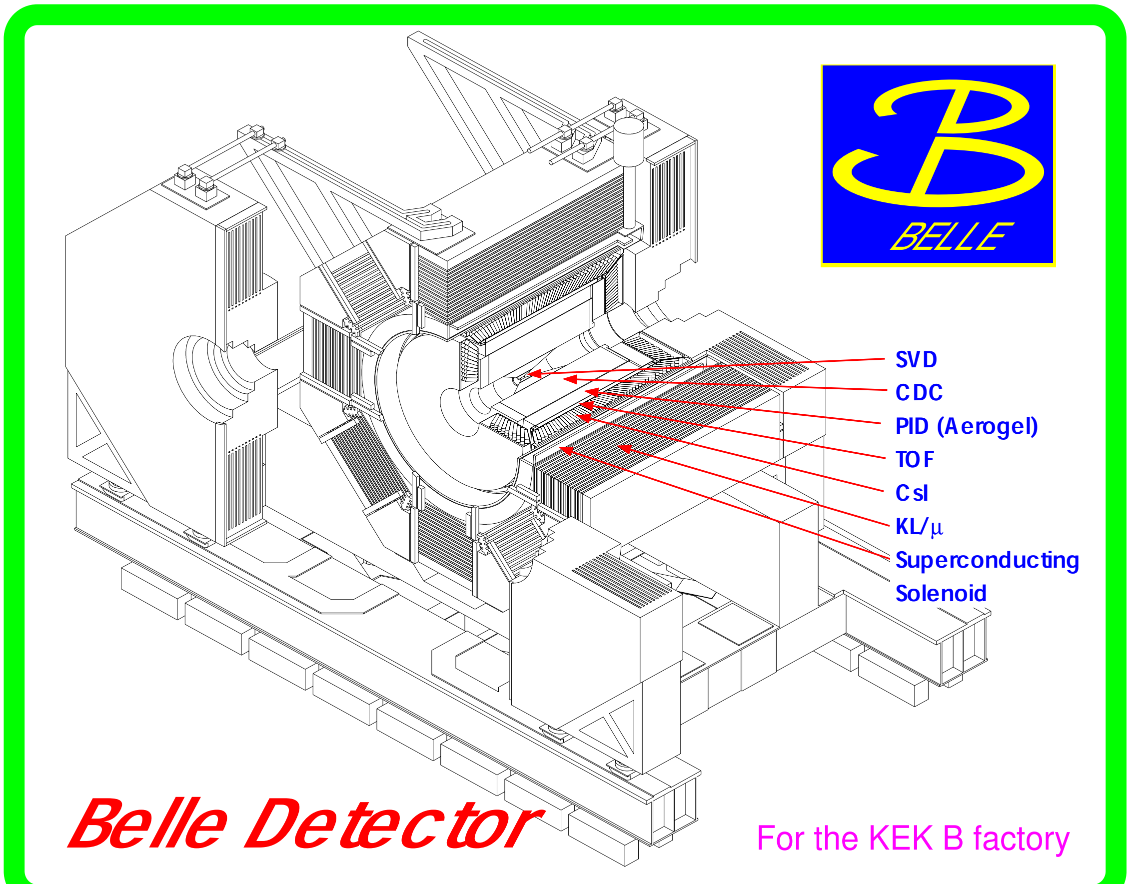
BELLE also have a ToF system.

BaBar Detector



BELLE Detector

High precision magnetic spectrometer



SVD: Three layers of DSSD

Readout chip : VA1 (not rad hard)

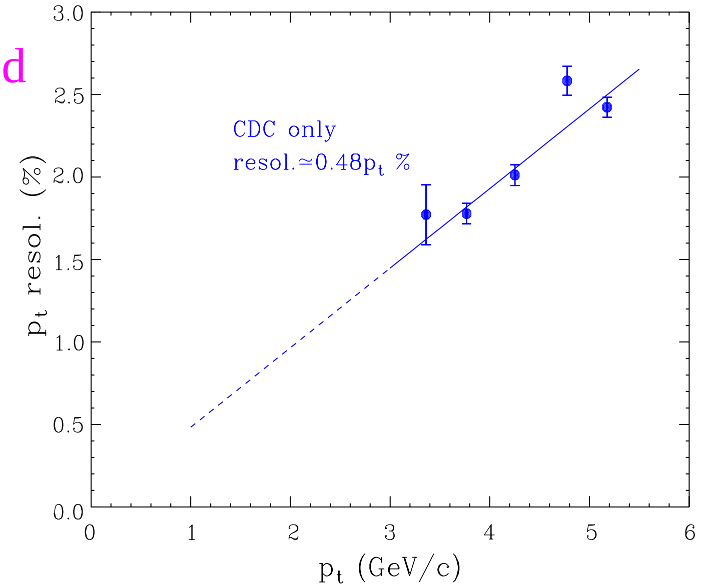
KID : ACC + dE/dx + TOF

(We are making SVD1.1, SVD1.5 (semi R.-hard), and SVD2 (R.-hard) to replace SVD, if needed.)

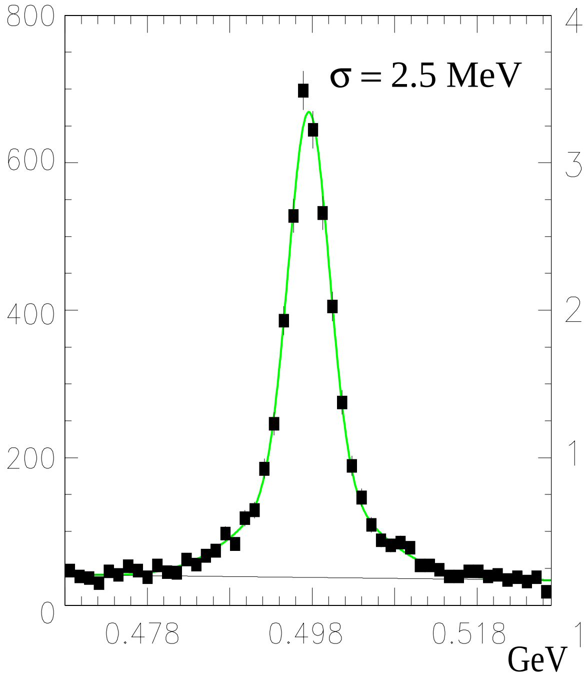
BELLE Performance (3) - Tracking

P_T resolution measured by $\mu^+\mu^-$ events.

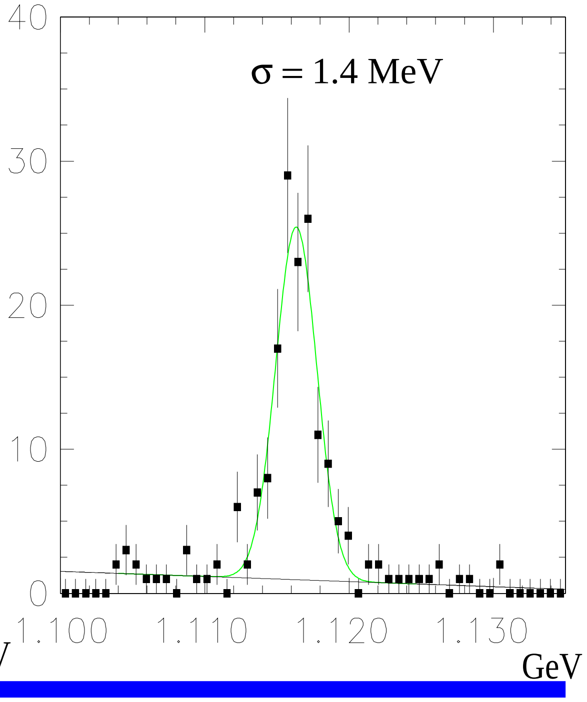
Spatial resolution per point = 160 μm



K_S reconstruction

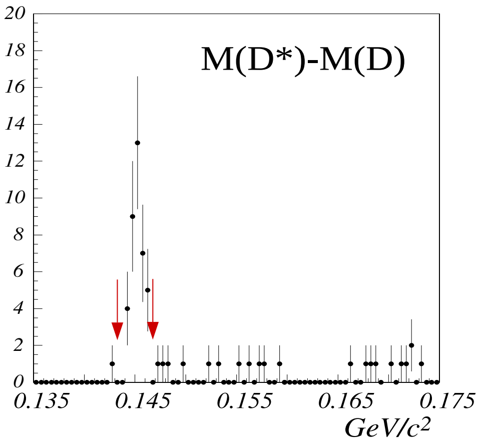


Λ reconstruction



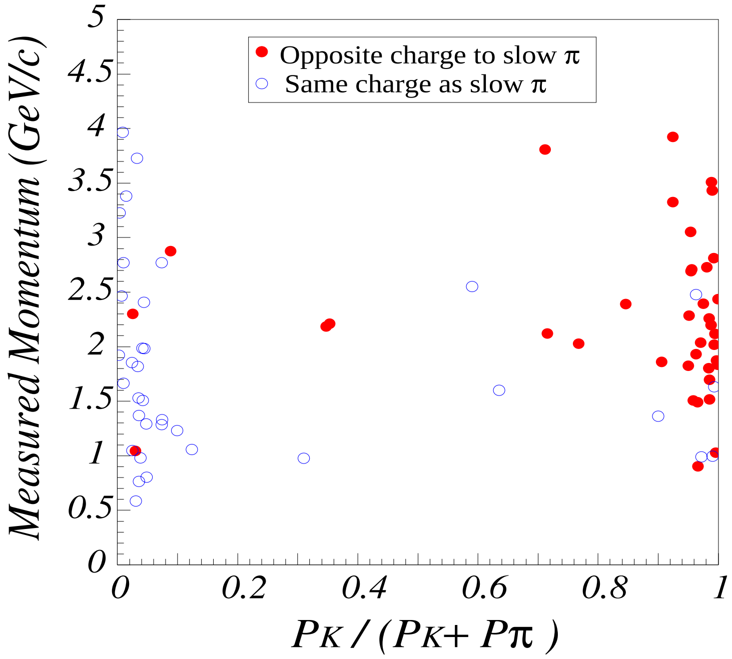
BELLE Performance (4') - πK ID

Test of KID w/ $D^{*+} \rightarrow D^0\pi^+$
$\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow K^-\pi^+$

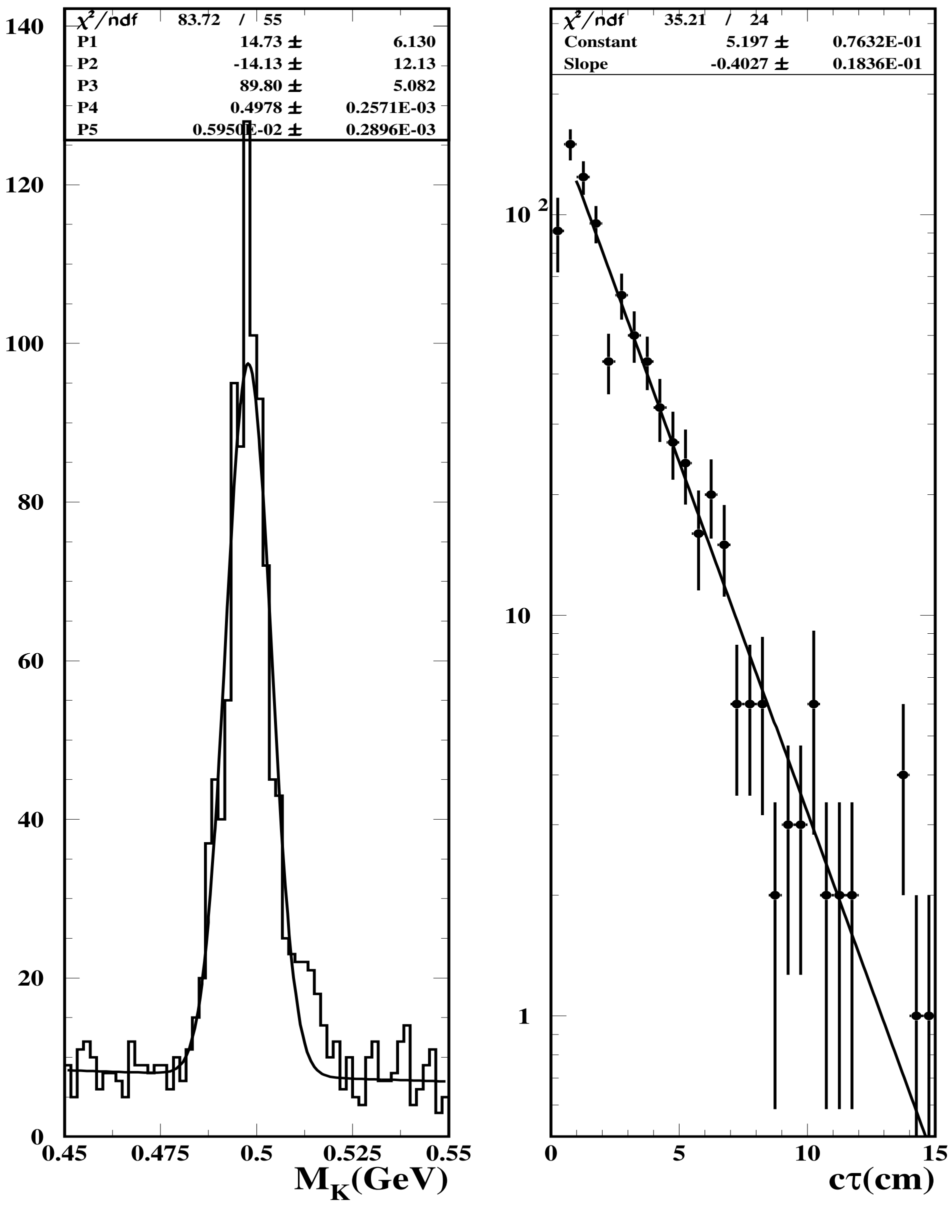


- $|M(D)-1.865| \leq 0.030$
- $P(D^*)/Eb(CM) > 0.5$
- $|\cos\theta k| \leq 0.8$

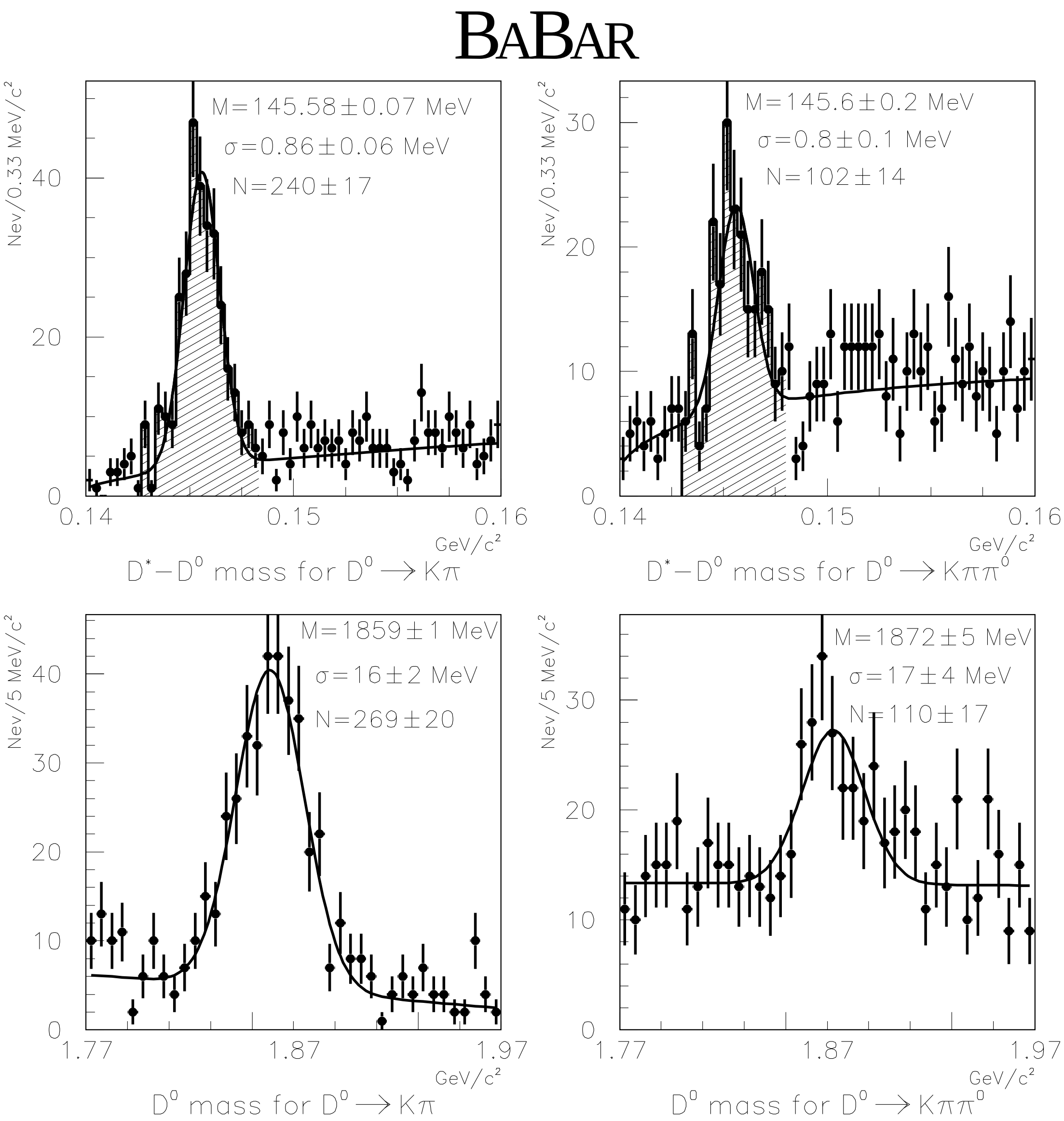
$\Rightarrow$ Estimated purity ~ 95%



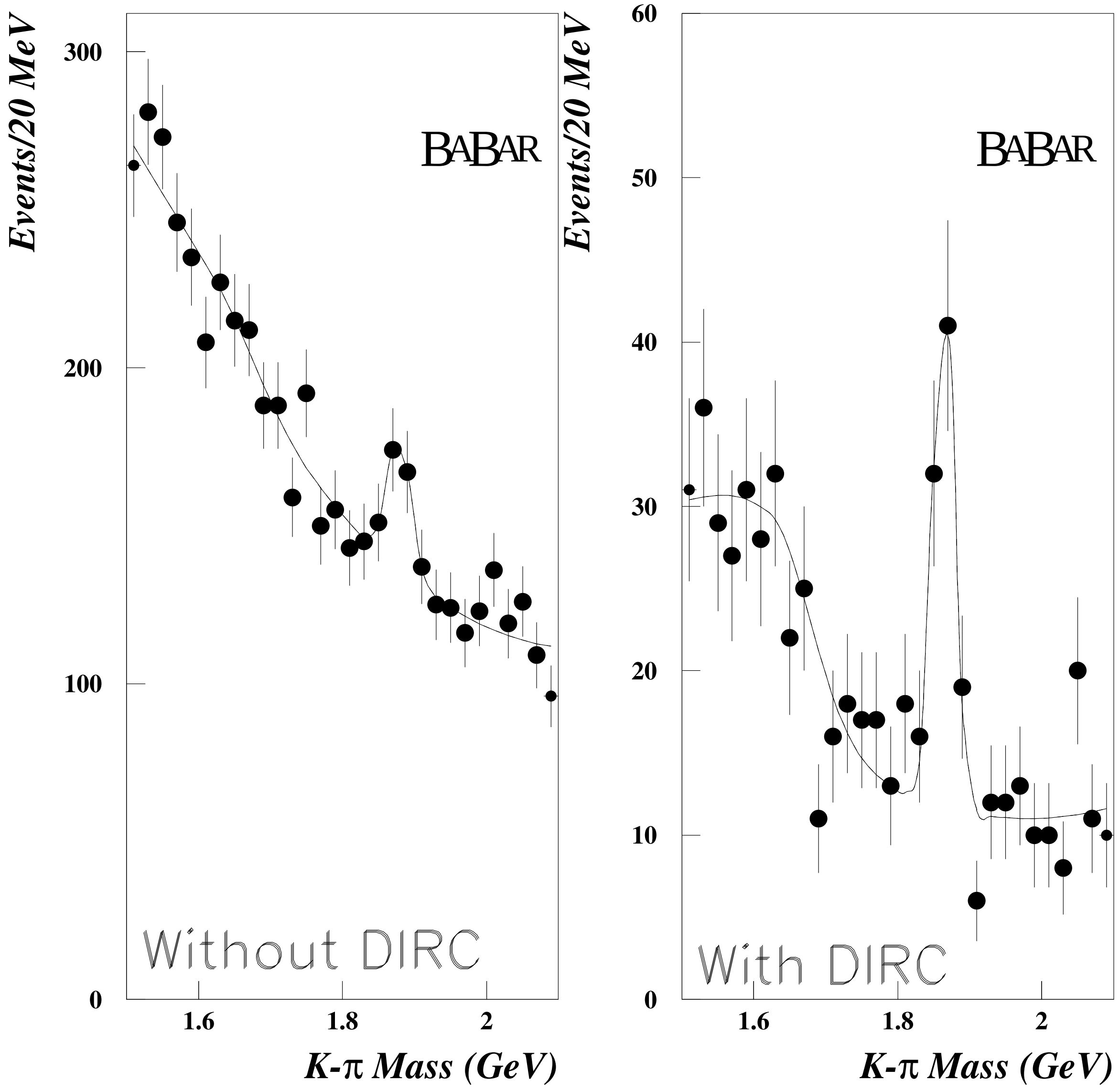
BaBar K_S Reconstruction



BaBar D^* Reconstruction



BaBar Kaon Identification



Measuring $\sin 2\beta$

The precision on the $\sin 2\beta$ measurement can be estimated from

$$\sigma_{\sin 2\beta} = \frac{\sigma(\sin 2\beta, \Delta m/\Lambda, \sigma_z)}{\sqrt{N_s}\sqrt{\epsilon_{\rm tag}(1-2w)^2}} \frac{\sqrt{1+N_B/N_S}}{1+(A_B/A_S)(N_B/N_S)}$$

- $\sigma(\sin 2\beta, \Delta m/\Lambda, \sigma_z)$ represents the error on one event.
- $\epsilon_{\rm tag}$ is the tagging efficiency.
- w misstag fraction.
- N_S is the number of signal events.
- N_B is the number of background events.
- A_S is the CP asymmetry for the signal.
- A_B is the CP asymmetry for the background.

Flavor Tagging

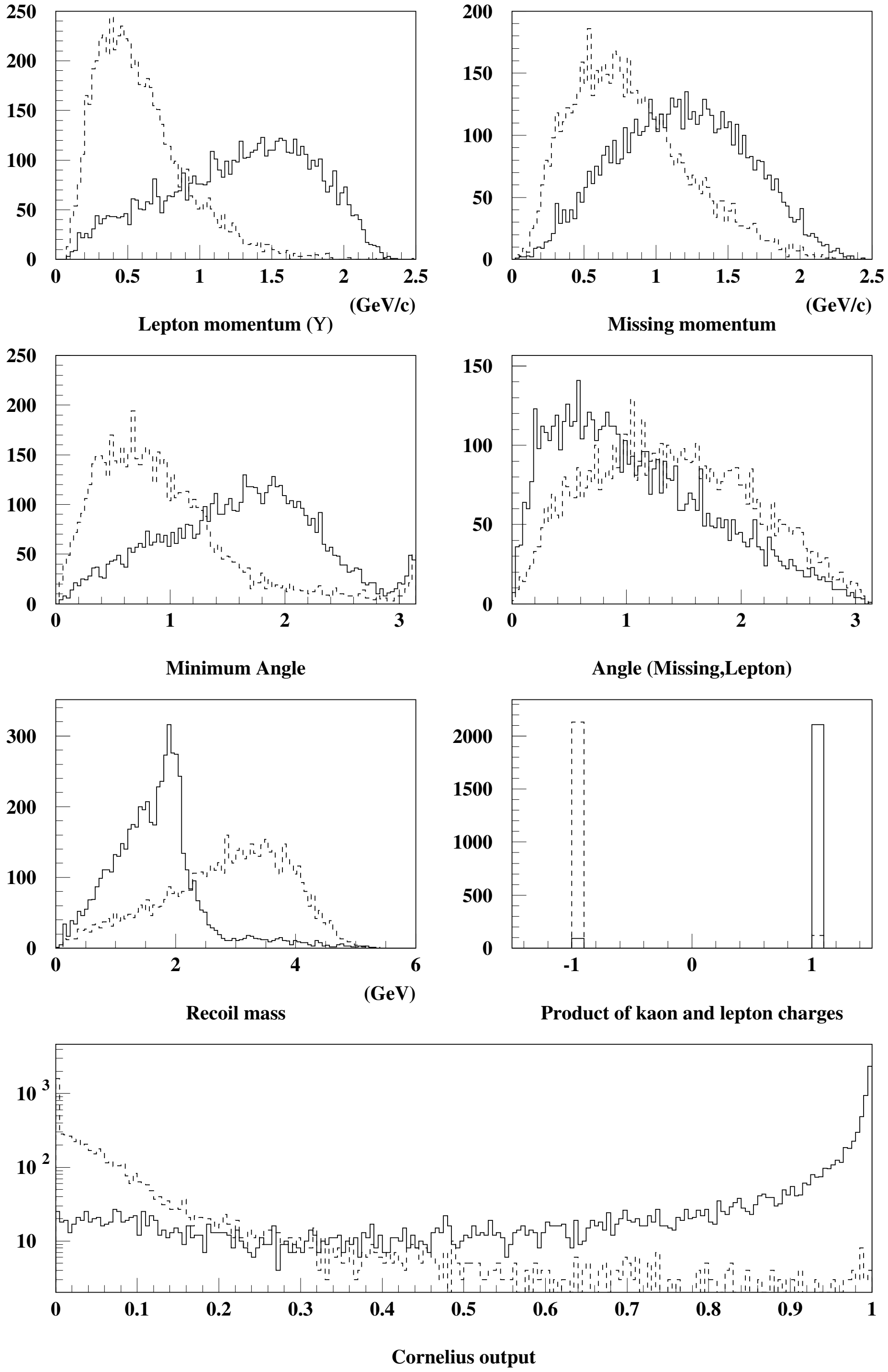
Tagging refers to the task of determining the flavor of the other B in the $\Upsilon(4S)$ decay. This is done by combining many different observables to optimize the efficiency and purity.

In particular the following variables are useful

- Lepton momentum.
- Lepton recoil mass.
- Kaon momentum.
- Plus many other kinematic quantities.

This information is combined using, e.g., a neural network to optimize the separation.

Tagging Variables



Tagging Performance

Tagging Category	Separation $\langle s^2 \rangle$ (%)	Tagging Efficiency ϵ_{tag} (%)	Absolute Separation $\epsilon_{tag}\langle s^2 \rangle$ (%)
Electron **(1)**	36.0	12.9	4.6
Electron + Kaon **(2)**	60.6	6.0	3.6
Muon **(3)**	34.6	7.9	2.7
Muon + Kaon **(4)**	57.5	4.6	2.6
Electron **(5)**	44.4	18.9	8.4
Muon **(6)**	42.9	12.5	5.4
Kaon **(7)**	39.5	24.2	9.6
TOTAL (1)+(2) (3)+(4)+(7)		55.6	23.1
TOTAL (5)+(6)+(7)		55.6	23.4

z Resolution

The selected events are fit as a function of the time difference distributions to determine the CP-asymmetry.

The time difference Δt is measured by

$$\Delta t = \frac{\Delta z}{\beta\gamma c}$$

where $\beta\gamma$ is known from the asymmetry in the machine because the B mesons are essentially at rest in the $\Upsilon(4S)$ rest frame.

To measure Δz the vertex of both the CP- and tagging- B mesons must be reconstructed.

This is straight forward for the CP-B but more complicated for the tagging-B as all tracks are not from the primary vertex position.

Measurement of β: $B \to J/\psi K_S$

The first measurement of CP violation is likely to be done in the decay $B \to J/\psi K_s$

- Large branching fraction, $\approx 4.25 \times 10^{-4}$.
- Easy to reconstruct in $J/\psi \to \ell^+\ell^-$ and $K_S \to \pi^+\pi^-$ modes.
- Hadronic uncertainties are small, penguins have same weak phase:

$$a_{f_{CP}} = -sin(2\beta)sin(\Delta m_B t)$$

CDF:

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}$$

Other Modes for Measuring β

- $B \to J/\psi K_L$

Will provide an important check of systematic errors as it has the opposite CP.

- $D^{(*)}D^{(*)}$
- "Pure penguin" modes, e.g., $B \to \pi^0 K_S^0$, $B \to \eta' K_S^0$, $B \to \phi K_S^0$ etc.

These modes will likely contribute information on the measurement of $\sin 2\beta$, however they are not as clean as the Charmonium-Kaon modes as they either have penguin or tree pollution.

Summary of β modes from BaBar.

Estimated statistical error on $\sin 2\beta$ for a 30 fb^{-1} sample.

Mode	B (10^{-4})	Rec. eff.	N_S	N_B/N_S	$\sigma_{\Delta z}$ (μm)	σ_0	error
$J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$	4.25	0.60	660	0.06	130	1.59	0.12
$J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$	4.25	0.21	110	0.06	130	1.59	0.30
$J/\psi(\ell^+\ell^-)K_L$	4.25	0.41	650	0.59	130	1.59	0.15^*
$\psi'(\pi^+\pi^-\ell^+\ell^-)K_L$	3.5	0.27	120	0.83	130	1.59	0.34^*
$\chi_{c1}(\gamma\ell^+\ell^-)K_L$	5.0	0.28	143	0.78	130	1.59	0.28^*
$J/\psi(\ell^+\ell^-)K^{*0}(\pi^+\pi^0\pi^0)$	13.2	0.09	51	0.18	130	1.79	0.50
D^+D^- (6 D Modes)	4.5	0.24	140	2.80	130	1.59	0.48^*
$D^{*+}D^{*-}$ (4 D Modes)	9.7	0.05	60	0.23	150	1.70	0.44
$\phi(K^+K^-)K_L$	0.065	0.22	22	0.10	130	1.59	0.66^*
$\phi(K^+K^-)K^{*0}(\pi^+\pi^-\pi^0)$	0.1	0.20	5	0.10	150	1.70	1.40^*
$\eta'(\eta\pi^+\pi^-)K_S(\pi^+\pi^-)$	0.24	0.23	20	0.10	150	1.70	0.73
$\eta'(\rho\gamma)K_S(\pi^+\pi^-)$	0.24	0.35	55	0.90	130	1.59	0.56
$\eta'(\eta\pi^+\pi^-)K_L$	0.24	0.21	44	0.10	150	1.70	0.49^*

Systematic errors on $\sin 2\beta$ modes from BELLE.

BELLE has investigated the systematic errors based on 100 fb^{-1}.

Source	$J/\psi K_S$	$\psi(2S)K_S$	$\chi_{c1}K_S$	$\eta_c K_S$	Combined
B lifetime	± 0.016	${}^{+0.013}_{-0.017}$	${}^{+0.008}_{-0.009}$	± 0.020	${}^{+0.016}_{-0.014}$
Wrong tag	± 0.025	± 0.024	± 0.007	± 0.034	± 0.025
Response	± 0.035	${}^{+0.019}_{-0.017}$	± 0.016	± 0.036	${}^{+0.031}_{-0.029}$
Background	${}^{+0.007}_{-0.003}$	${}^{+0.061}_{-0.018}$	${}^{+0.091}_{-0.038}$	${}^{+0.054}_{-0.019}$	${}^{+0.054}_{-0.018}$
Total	± 0.046	${}^{+0.069}_{-0.037}$	${}^{+0.047}_{-0.035}$	${}^{+0.076}_{-0.057}$	${}^{+0.069}_{-0.044}$

$$\sin 2\beta = 0.637^{+0.081}_{-0.082}(stat.)^{+0.069}_{-0.044}(syst.)$$

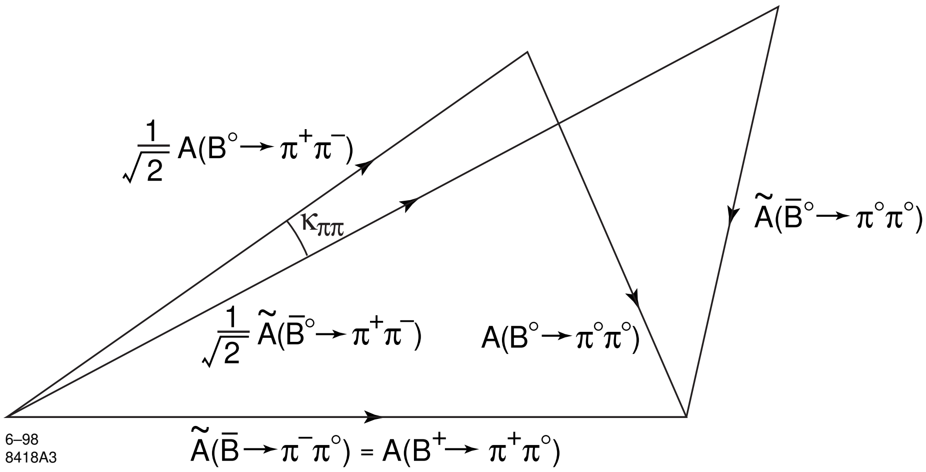
Measurements of α

The original proposal was to measure α in the decay $B \to \pi^+\pi^-$ similar to how β is measured.

However, it was realized that there is a significant complication by the presence of strong penguins. In fact the CLEO measurements of a large $B \to K\pi$ shows that the penguin amplitudes are significant.

Isosopin Analysis for $B \to \pi\pi$

Using isospin relations between $B^0 \to \pi^0\pi^0$, $B^0 \to \pi^+\pi^-$, and $B^\pm \to \pi^\pm\pi^0$ decays the magnitudes of the isospin amplitudes can be determined (Gronau and London).



- Measuring $B \to \pi^0\pi^0$ is hard.
- Many discrete solutions.

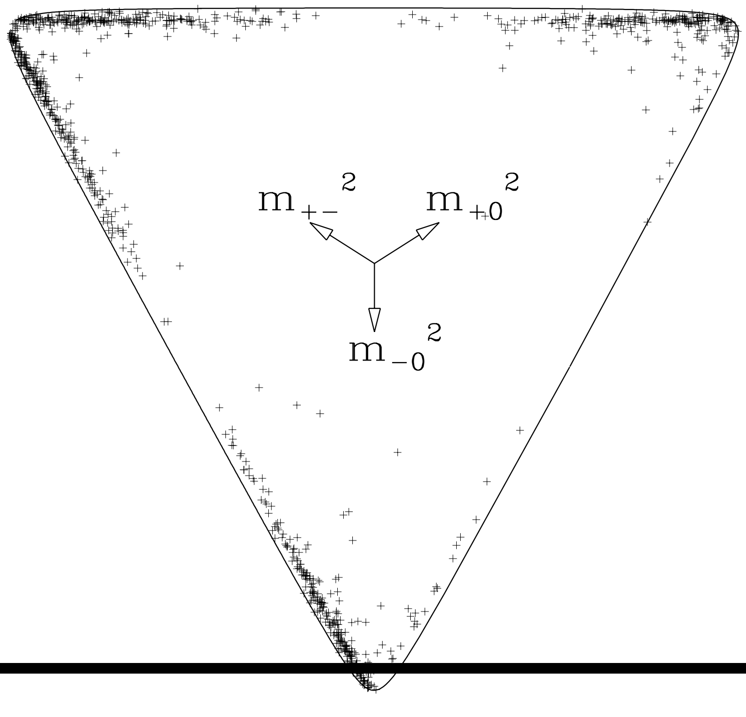
Modes with 3 Pions

This mode is also subject to significant penguin pollution, but a Dalitz plot analysis is possible to deconvolute the tree and penguin contributions (Snyder and Quinn).

$$
\begin{array}{lclclcl}
A(B^0 \to \rho^+\pi^-) & \equiv & A^{+-} & = & e^{-i\alpha}T^{+-} & + & P^{+-} \\
A(B^0 \to \rho^-\pi^+) & \equiv & A^{-+} & = & e^{-i\alpha}T^{-+} & + & P^{-+} \\
A(B^0 \to \rho^0\pi^0) & \equiv & A^{00} & = & e^{-i\alpha}T^{00} & + & P^{00} \\
q/pA(\bar{B}^0 \to \rho^+\pi^-) & \equiv & q/p\bar{A}^{+-} & = & e^{+i\alpha}T^{-+} & + & P^{-+} \\
q/pA(\bar{B}^0 \to \rho^-\pi^+) & \equiv & q/p\bar{A}^{-+} & = & e^{+i\alpha}T^{+-} & + & P^{+-} \\
q/pA(\bar{B}^0 \to \rho^0\pi^0) & \equiv & q/p\bar{A}^{00} & = & e^{+i\alpha}T^{00} & + & P^{00}
\end{array}
$$

$$P^{00} = -\frac{1}{2}(P^{+-} + P^{-+}).$$

- 10 parameters.
- Significant backgrounds.



Determining α from $B \to \pi^+\pi^-\pi^0$

Pick a set of amplitudes:

Mode	Large Penguins
$\rho + i\eta$	0.05+i0.36
α	1.35
T^{+-}	1.00
T^{-+}	0.47
T^{00}	0.14
T^{+0}	1.09
P^{+-}	-0.20 $e^{-0.5i}$
P^{-+}	0.15 $e^{2.0i}$

Fit for α including penguin contributions:

# events	Generated	Penguins		
	sin 2α	$\langle$sin $2\alpha\rangle$	σ(sin 2α)	%
300	0.432	0.34	0.27	73
600	0.432	0.38	0.20	89
1200	0.432	0.39	0.11	95

Fit for α excluding penguin contributions:

# events	Generated	No penguins		
	sin 2α	$\langle$sin 2αeff$\rangle$	σ(sin $2\alpha_{\rm eff}$)	%
300	0.432	0.19	0.16	76
600	0.432	0.20	0.12	81
1200	0.432	0.19	0.06	90

Summary of α measurements

- There are significant complications in the measurement of α from the combination of small branching fractions and large penguin contributions.
- Initial measurements are expected to establish CP violation but will not provide a model independent determination of α.
- The three pion modes are expected to eventually provide the cleanest determination of α.

Asymmetric e^+e^- B-factories in the future

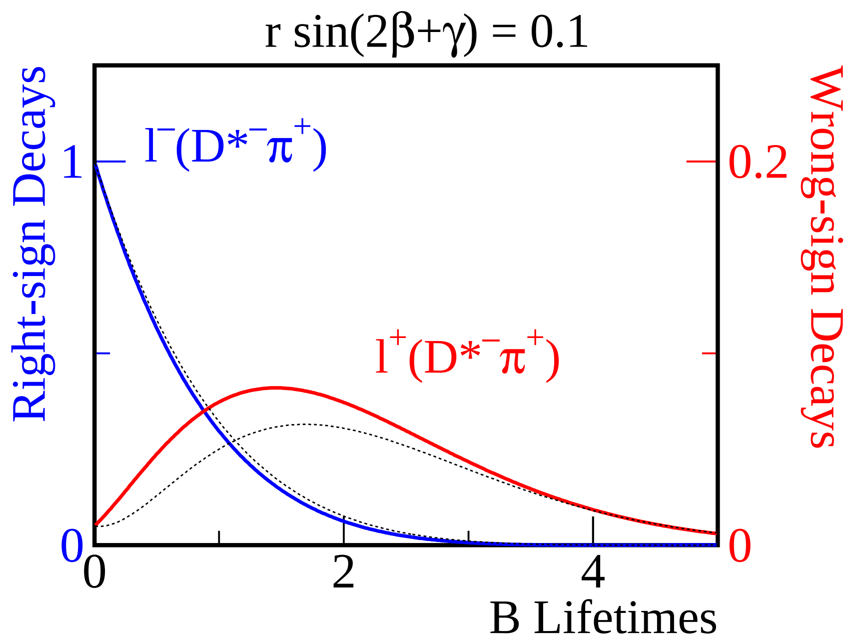
- On the time scale of 5 years it is likely that we will see B factories operating at luminosities up to 3×10^{34}.
- BaBar, e.g., should be able to upgrade beyond the current design by, first, installing more RF to allow smaller bunches and eventually by rebuilding the interaction region to allow filling every bunch and have collisions every 2ns.
- At these luminosities samples of 3×10^8 neutral B-mesons would be produced per year. This makes several proposed measurements interesting.

$\sin(2\beta+\gamma)$ from $B \to D^{*\pm}\pi^{\mp}$

The decays $B \to D^{*\pm}\pi^{\mp}$ provides an interesting possibility for measuring $\sin(2\beta+\gamma)$ or equivalently $\sin(\beta-\alpha)$.

In these decays

$$\lambda(B_d \to f)\lambda(B_d \to \bar{f}) = e^{-2i(2\beta+\gamma)}$$



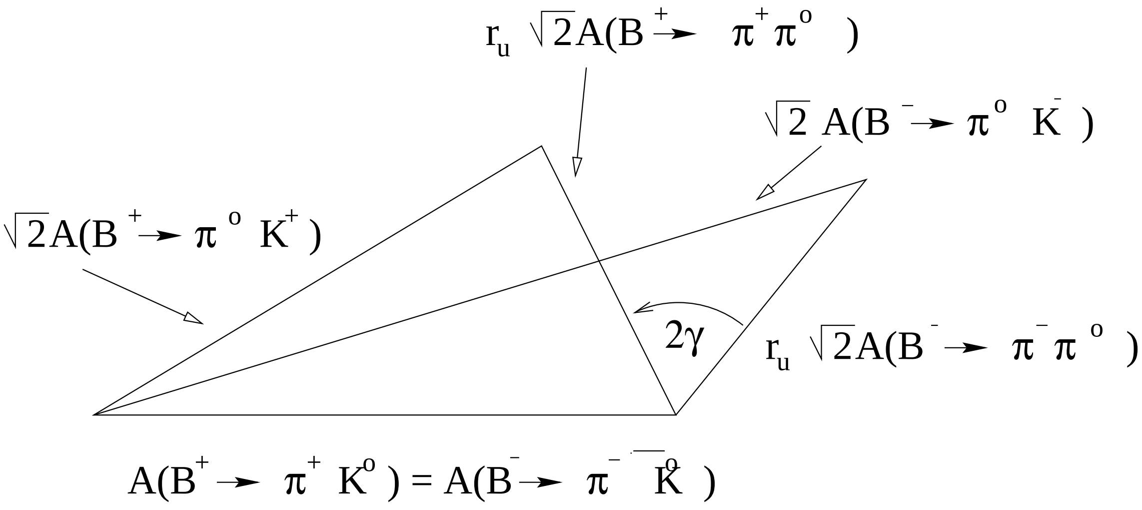
To gain statistical power the $D^{*\pm}\pi^{\mp}$ decay can be partially reconstructed using the "slow" and "fast" pions.

An estimated precision for 30 fb^{-1} gave

$$\sigma_{\sin(2\beta+\gamma)} = 0.22$$

γ Measurements

- Approximate methods, e.g.,



  suffers from problems with final state interactions and SU(3) breaking.

- Exact methods using interference through common modes of the neutral D meson suffers from very small branching fractions and backgrounds.

CLEO combines information from several measurements and theory and quotes: $\gamma = 113^\circ\,{}^{+25^\circ}_{-23^\circ}$

Running at the $\Upsilon(5S)$

- $\Upsilon(5S)$ running would allow B_s production.
- However γ measurements at the $\Upsilon(5S)$ are very hard:
  - $B_s \to \rho^0 K_S$ has branching fractions of order 10^{-7} and will have substantial penguin pollution.
  - $B_s \to D_s K$ and $B_s \to D\phi$ are pure tree, similar to $B_d \to D^* \pi$. But is very hard to to the need of resolving the rapid $\Delta m_{B_s} t$ oscillations.
- BaBar is unlikely to run at the $\Upsilon(5S)$ soon.

Conclusions

- The construction of the B-factories, BELLE and BaBar, have been completed on a very tight schedule and commissioning well underway.
- The measurement of β from $B \to J/\psi K_S$ decays and other Charmonium+Kaon final state will provide the first measurements of CP violation.
- Both experiments hope to be able to show the first measurements of CP violation by the summer of 2000.
- Initial measurements of α will ignore penguin contributions or not be model independent. With data sample of a few hundred fb^{-1} a true α measurement can be done.