Physics and Techniques of B-factories

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- $\Upsilon 4S \to B\bar{B}$ Primer
- CP violation in mixing
- CP violation by mixing-decay interference
- CP violation in decay
- Factorization tests

I. $\Upsilon 4S \to B\bar{B}$ Primer

a. Experimental environment

$$e^+e^- \to \Upsilon 4S \to B\bar{B}$$

$$< \Upsilon 4S >$$

$c\bar{c}$ in spin-1, S-wave, 4th radial excitation.
(probably with some mixing of $2D$ state)

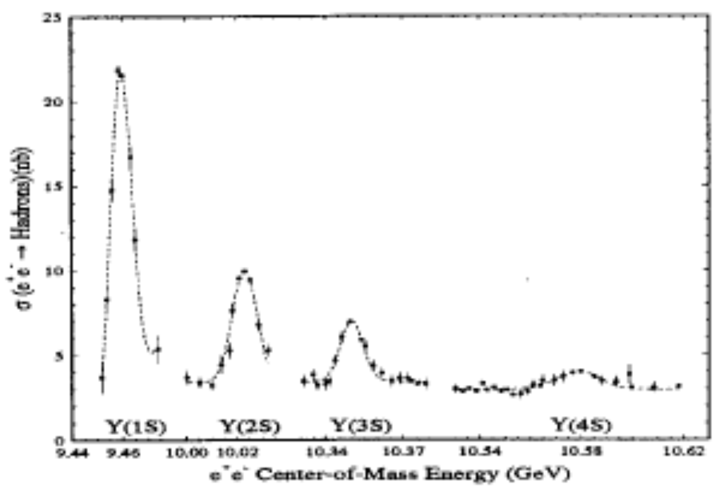
Mass: $10,580.0 \pm 3.5$ MeV

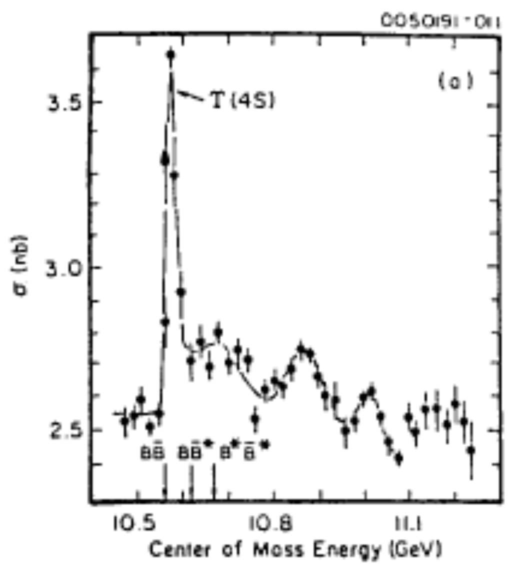
The error dominated by the beam-energy calibration.
(Beam-depolarization resonance:
Sokolov-Ternov effect)

Width: 10.0 ± 3.9 MeV
By energy scan of the $\Upsilon 4S$ resonance.
(Beam energy spread removed)

$\Upsilon 4S$ **energy scan** (CLEO)

Multi-hadron cross section vs C. M. energy





At the $\Upsilon 4S$ peak, ~24% is $B\bar{B}$.

Hadronic cross sections on the $\Upsilon 4S$ peak

channel	$\sigma(nb)$
$\Upsilon 4S$	1.05
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$s\bar{s}$	0.35
$c\bar{c}$	1.30
hadronic total	4.44

~76% is $q\bar{q}$ 2-jet type.
('**continuum** events')

The continuum can be monitored by taking data just below the $\Upsilon 4S$ resonance.

- $\sim$ 55 MeV below the peak.
- **Off-resonance** integrated luminosity:
$\sim$ 1/2 that of **on-resonance** (CLEO).

<B-factory accelerators>

Symmetric energies (CESR)

$$E_{e^-} = E_{e^+} = \frac{M_{\Upsilon 4S}}{2}$$

Asymmetric energies (PEP-II, KEK-B)

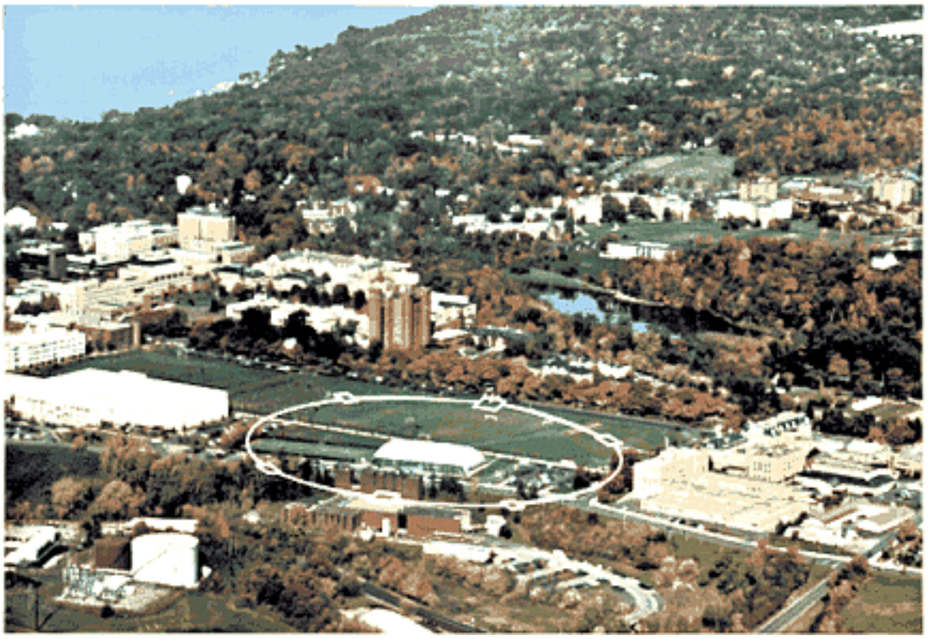
$\Upsilon 4S$ is moving in the lab frame.

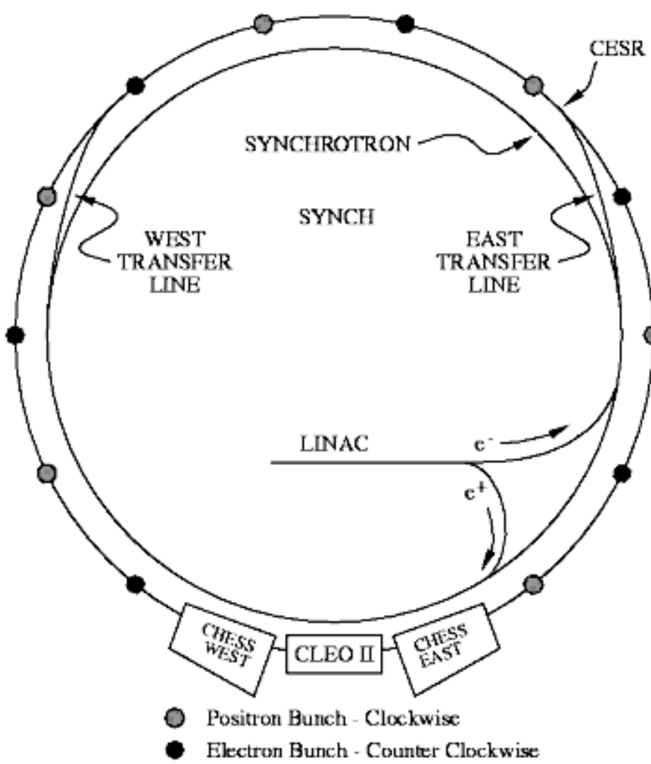
$$E_{\mathrm{CM}} = 2\sqrt{E_{e^+} E_{e^-}} = M_{\Upsilon 4S}$$

$$\begin{cases} E_{\Upsilon 4S} = E_{e^-} + E_{e^+} \\ P_{\Upsilon 4S} = E_{e^-} - E_{e^+} \end{cases}$$

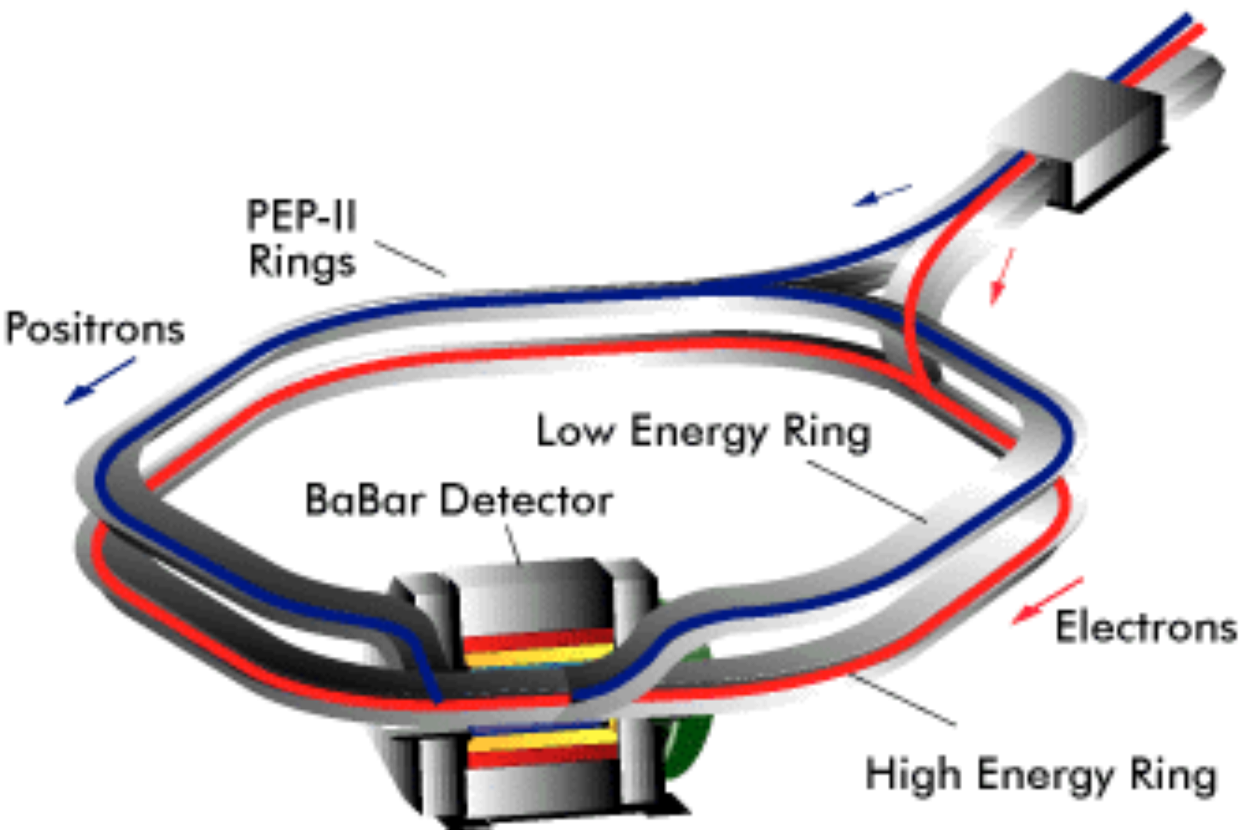
$$\rightarrow \quad \beta_{\Upsilon 4S} = \frac{P_{\Upsilon 4S}}{E_{\Upsilon 4S}} = \frac{E_{e^-} - E_{e^+}}{E_{e^-} + E_{e^+}}$$

CESR (Cornell Electron Strage Ring)

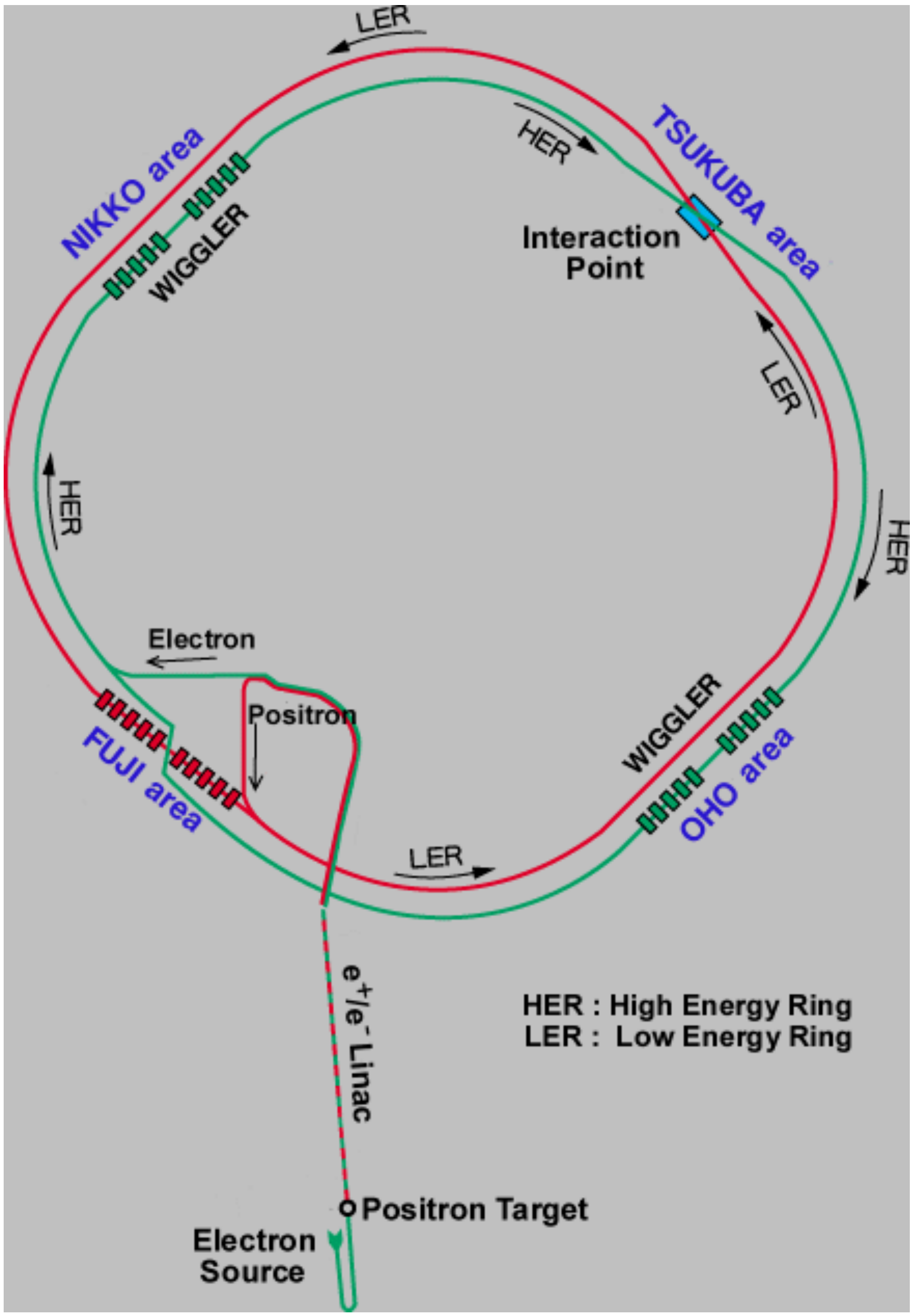




PEP-II (SLAC)


PEP-II
Rings
Positrons
Low Energy Ring
BaBar Detector
Electrons
High Energy Ring

KEK-B (KEK, Japan)



machine	$CESR$	$PEP\text{-}II$	$KEK\text{-}B$
detector	$CLEO$	$BaBar$	$Belle$
circumference (km)	0.768	3.016	2.199
# of rings	1	2	2
E_{e^+}(GeV)	5.3	3.1	3.5
E_{e^-}(GeV)	5.3	9.0	8.0
$\beta_{\Upsilon 4S}$	~ 0	0.49	0.39
$\delta E/E$	6×10^{-4}	7×10^{-4}	7×10^{-4}
Δt_{bunch}	$14ns$	$4.2ns$	$2ns$
bunch size(h)	500μ	181μ	77μ
" (w)	10μ	5.4μ	1.9μ
" (l)	$1.8cm$	$0.4cm$	$1.0cm$
crossing angle(mrad)	± 2.3	0	± 11
Luminosity($cm^{-2}s^{-1}$)	1.5×10^{33}	3×10^{33}	10^{34}
$\#B\bar{B}/s$	1.5	3	10

$$\delta E/E \quad \rightarrow \quad \frac{\delta E_{\text{CM}}}{E_{\text{CM}}} = 4.5 \sim 5\text{MeV}$$

$$(\Gamma_{\Upsilon 4S} \sim 10 \text{ MeV})$$

Beam separation

Want collision to occur only at one location

$\rightarrow$ Need for beam separation
(avoid parasitic crossings)

CESR: Pretzel orbit
Interweaving e^+e^- orbits within a single ring
Crossing angle = ± 2.3 mrad

PEP-II: Separation by bending magnet

$$E_{e^+} \neq E_{e^-}$$

$\rightarrow e^+, e^-$ beams bend differently

Head-on collision

KEK-B: Finite-angle crossing
Crossing angle = ± 11 mrad

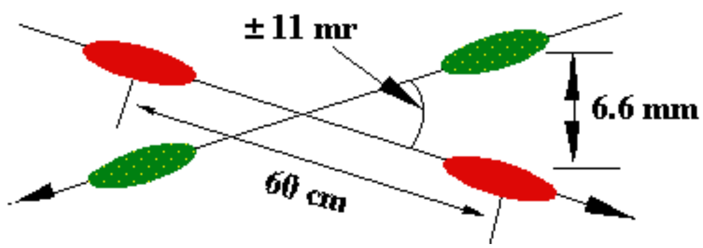
Large crossing angle

$\rightarrow$ Beam instability
(synchro-betatron resonance)
Luminosity reduction
(geometrical)

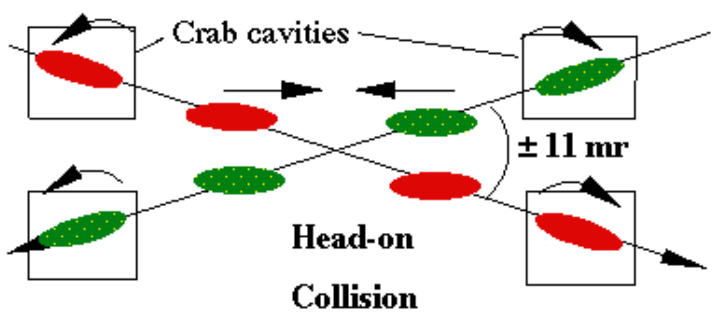
Crab crossing (KEK-B)

In case finite-angle crossing causes problems

□ Without crab cavities



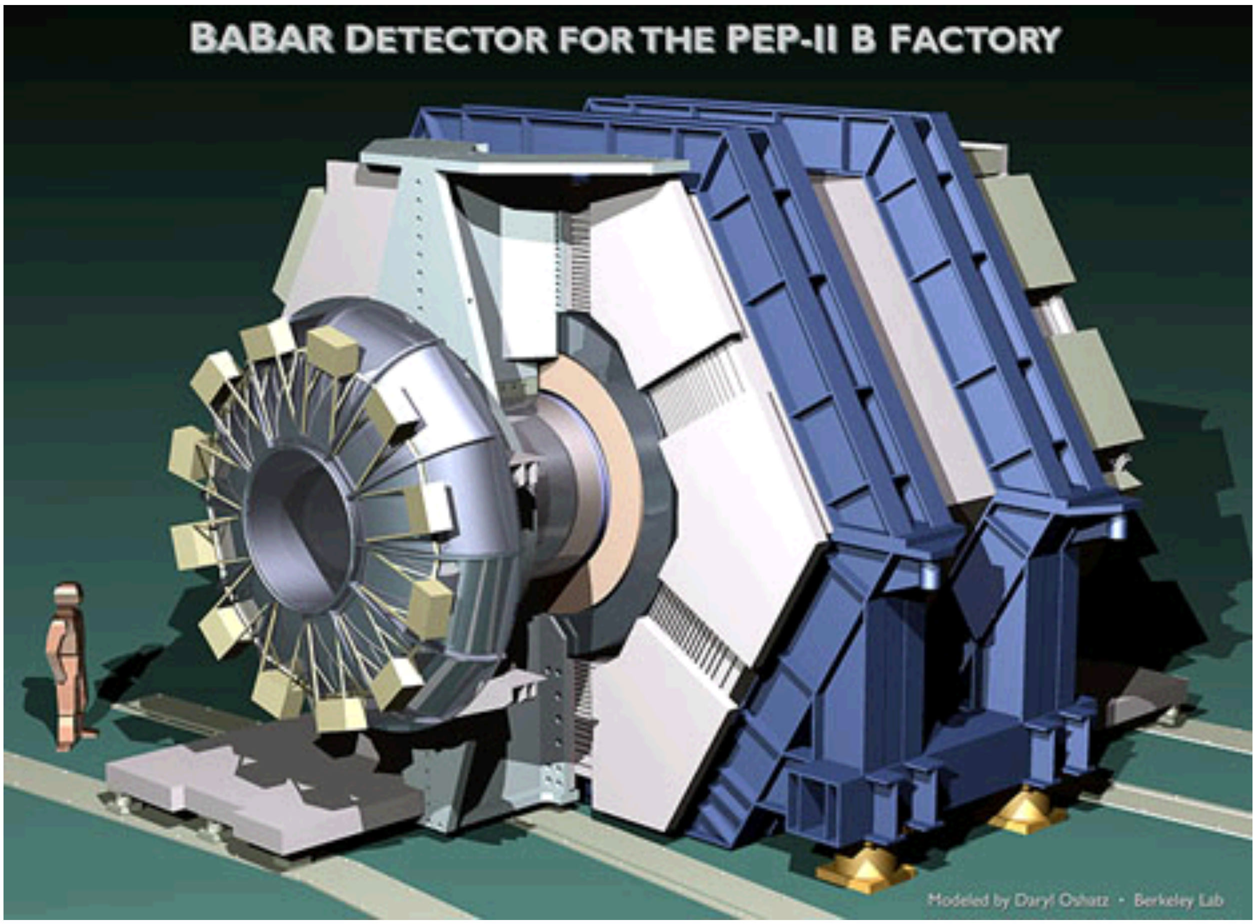
□ With crab cavities



→ complete overlap of beams
(No geometrical luminosity loss.
Suppresses beam instability)

<B-factory detectors>

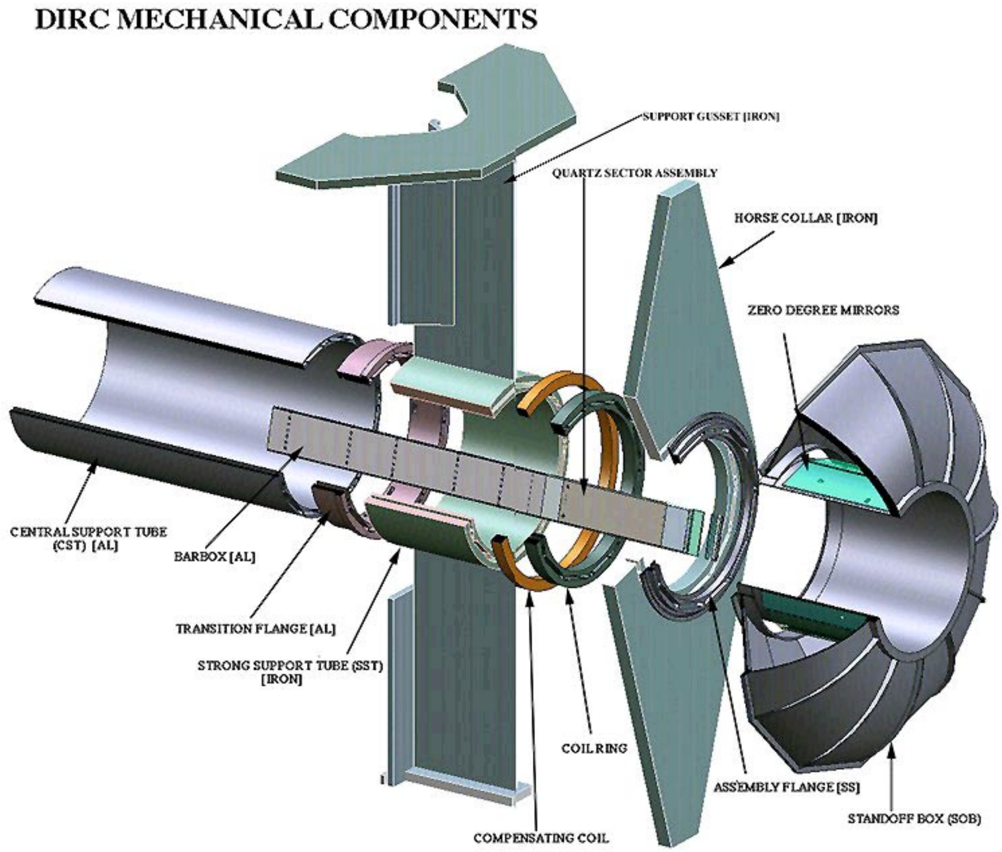
BaBar detector

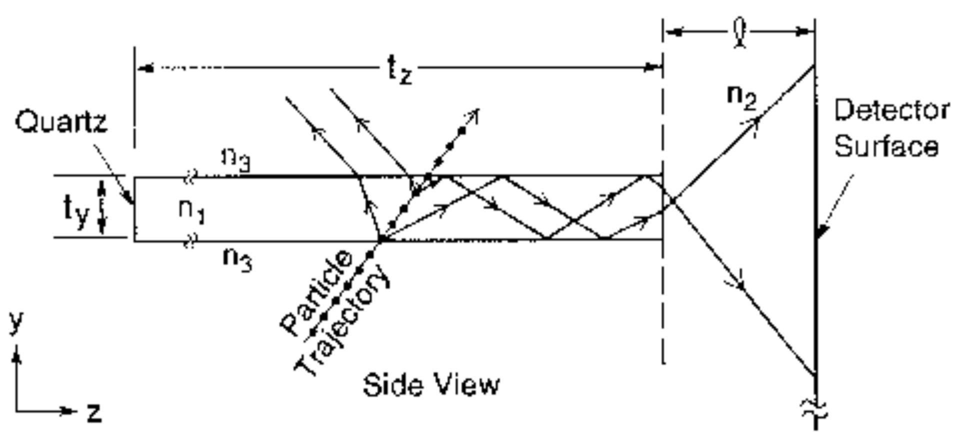


Particle ID:

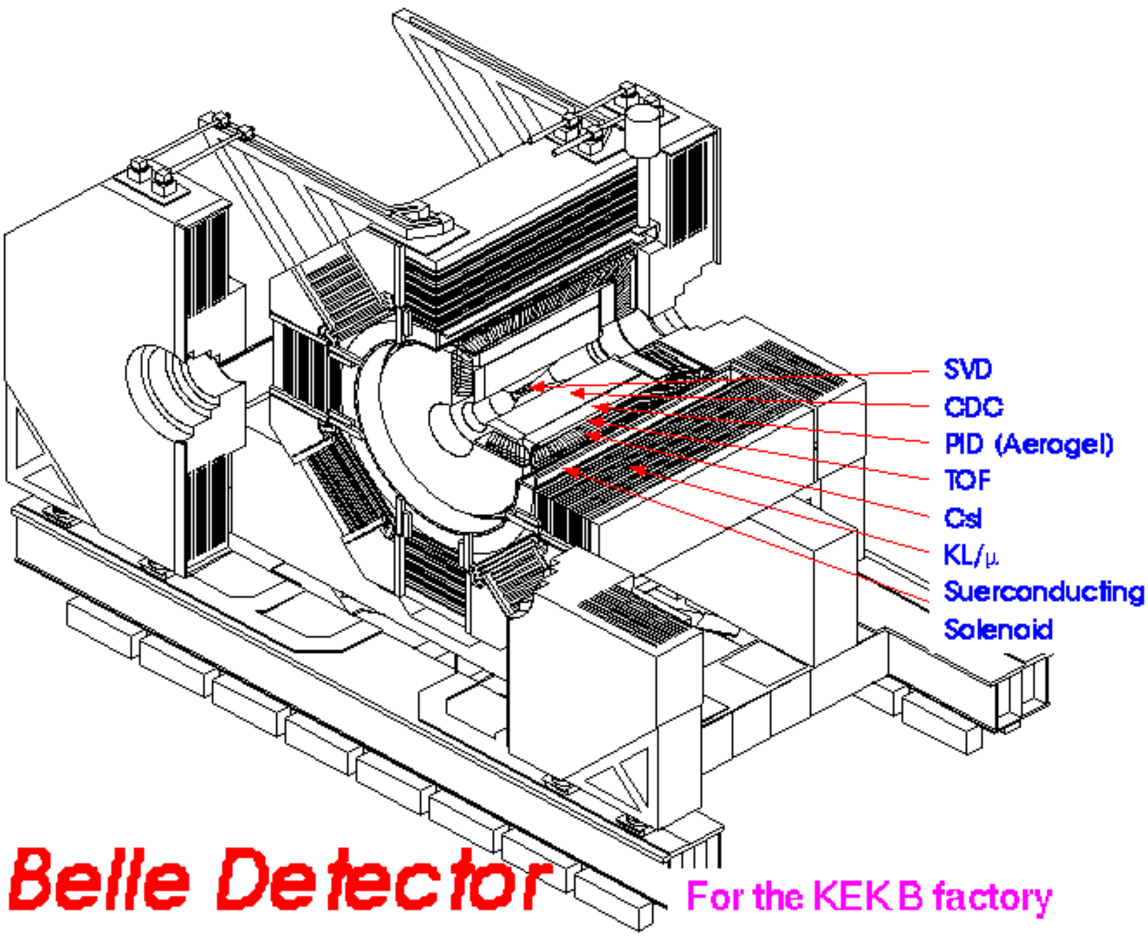
Barrel: DIRC
(Detector of Internally Reflected Cerenkov)
Endcap: ATC
(Aerogel Threshold Cerenkov)

DIRC (Detector of Internally Reflected Cerenkov)



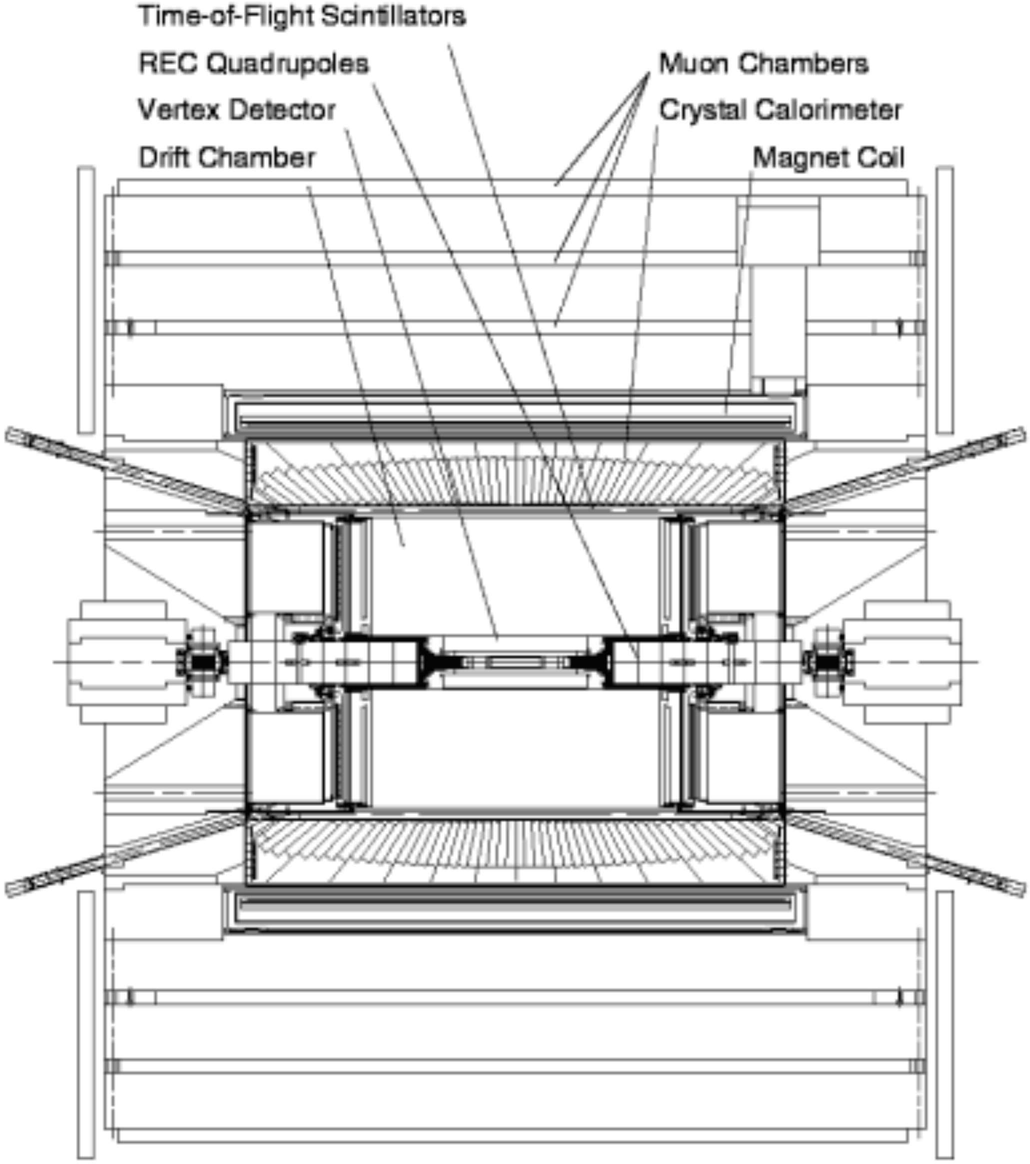


Belle detector



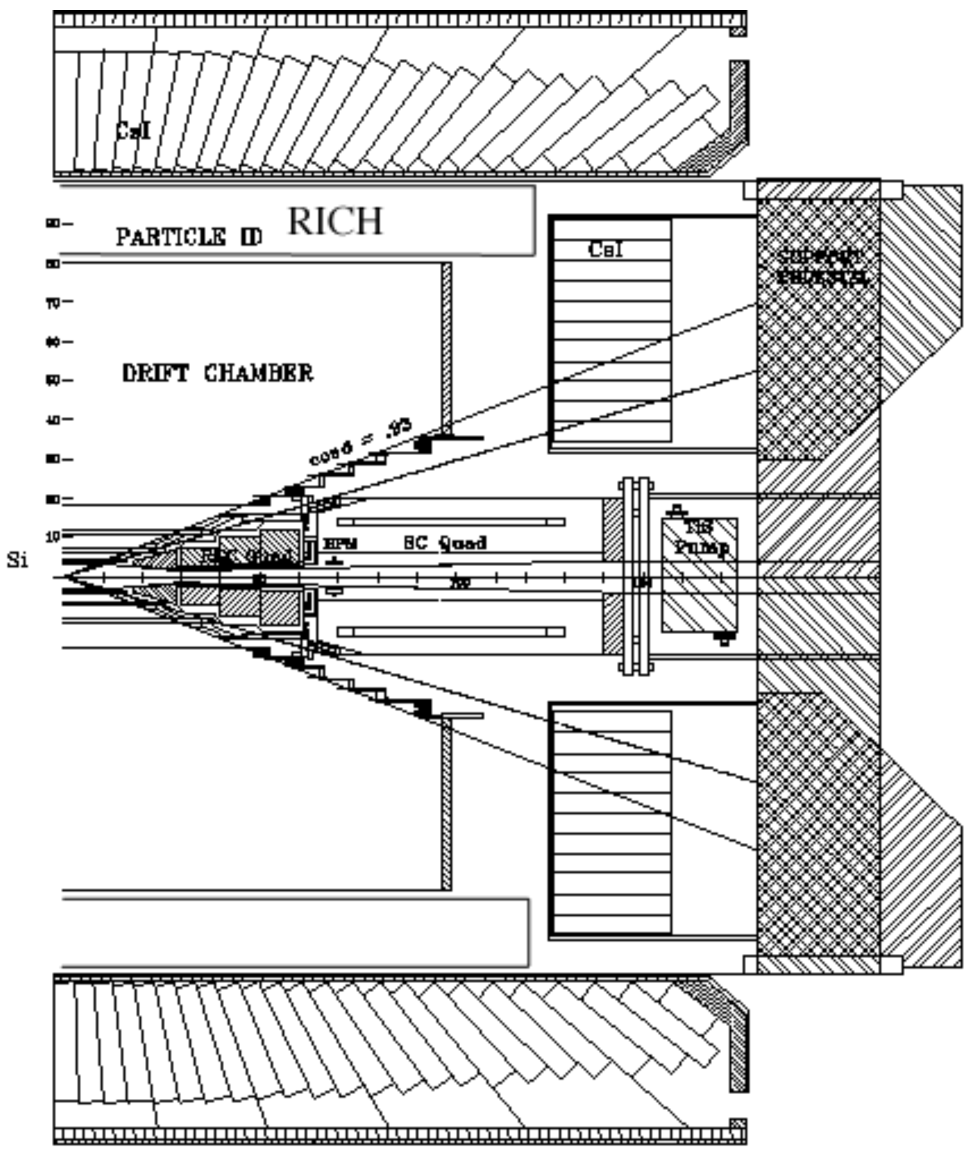
Particle ID: Aerogel Cerenkov Detector
($+dE/dX$, TOF)

CLEO2 detector (current)



No Cerenkov particle identification
(dE/dX, TOF)

CLEO3 detector (1999 fall)



Particle ID: RICH (Ring Imaging Cerenkov)
$(+dE/dX)$

BaBar detector parameters

(1) Tracking

B-field = 1.5 Tesla

- Silicon vertex tracker
- Drift chamber

$$\rightarrow \frac{\sigma_{p_t}}{p_t} = 0.14 p_t(\mathrm{GeV}) + 0.21\ \%$$

Or, $B \rightarrow \pi^+\pi^-$ mass resolution $\sim$ 22 MeV (without beam constraint)

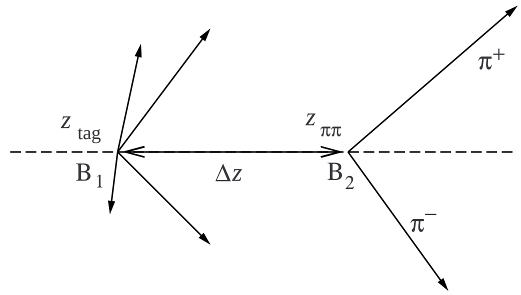
(2) Vertexing

- Silicon vertex tracker

$$\sigma_{xy,z}(\text{imp. param.}) = \frac{50}{p_t} \oplus 15\ \mu m$$

Or, 125μm resolution for

$$\Delta z \equiv z_{\pi^+\pi^-} - z_{\text{tag}}$$



(3) Photon detection

- CsI(Tl) electromagnetic calorimeter

$$\frac{\sigma_E}{E} = \frac{1}{E(\text{GeV})^{1/4}} \oplus 1.2 \quad \%$$

Or, $\pi^0 \to \gamma\gamma$ mass resolution ~ 5 MeV
(for $B \to \rho^+\pi$, $\rho \to \pi^+\pi^0$)

(4) Electron identification

- CsI(Tl) electromagnetic calorimeter

$$p(\text{tracking}) = E(\text{calorimeter})$$

Identification range: $P > 0.5$ GeV/c

(5) Muon identification

- IFR (Instrumented Flux Return)
(i.e. Penetration into iron)
Identification range: $P > 1$ GeV/c

- DIRC can be used for $P < 0.7$ GeV/c
(though the efficiency is low $\sim 60\%$)

(6) π/K separation

- DIRC (quartz radiator)

$$n = 1.46 \quad \rightarrow \quad \beta\gamma_{\text{ thresh}} \sim 1$$

$$P_{\text{thresh.}}(\pi) = 0.14 \text{ GeV/c}$$
$$P_{\text{thresh.}}(K) = 0.5 \text{ GeV/c}$$

Provides ~70% efficiency for K
with $< 5\%$ π misid. for $0.4 < P < 4$ GeV/c

- dE/dX (Drift chamber + silicon tracker)

Effective for $P < 0.7$ GeV/c

(7) K_L identification

- CsI(Tl) electromagnetic calorimeter + IFR

Nuclear interaction → position information only

Identification efficiency:
~50% ($P = 1$ GeV/c)
~70% ($P > 2$ GeV/c)

2. $\Upsilon 4S \to B\bar{B}$ deccay

< B^0 and B^+ mesons>

$$B^+(B_u) : \bar{b}u\,, \quad B^0(B_d) : \bar{b}d$$

Mass: (ARGUS, CLEO, CDF)

$$M(B^+) = 5278.9 \pm 1.8 \text{ MeV}$$
$$M(B^0) = 5279.2 \pm 1.8 \text{ MeV}$$

By full reconstruction of non-leptonic decays:
(back to this later)
Error: energy-scale uncertainty.

$$M(B^0) - M(B^+) = 0.35 \pm 0.29 \text{ MeV}$$

$$\boxed{M(B^+) \sim M(B^0) \sim 5279 \text{ MeV}}$$

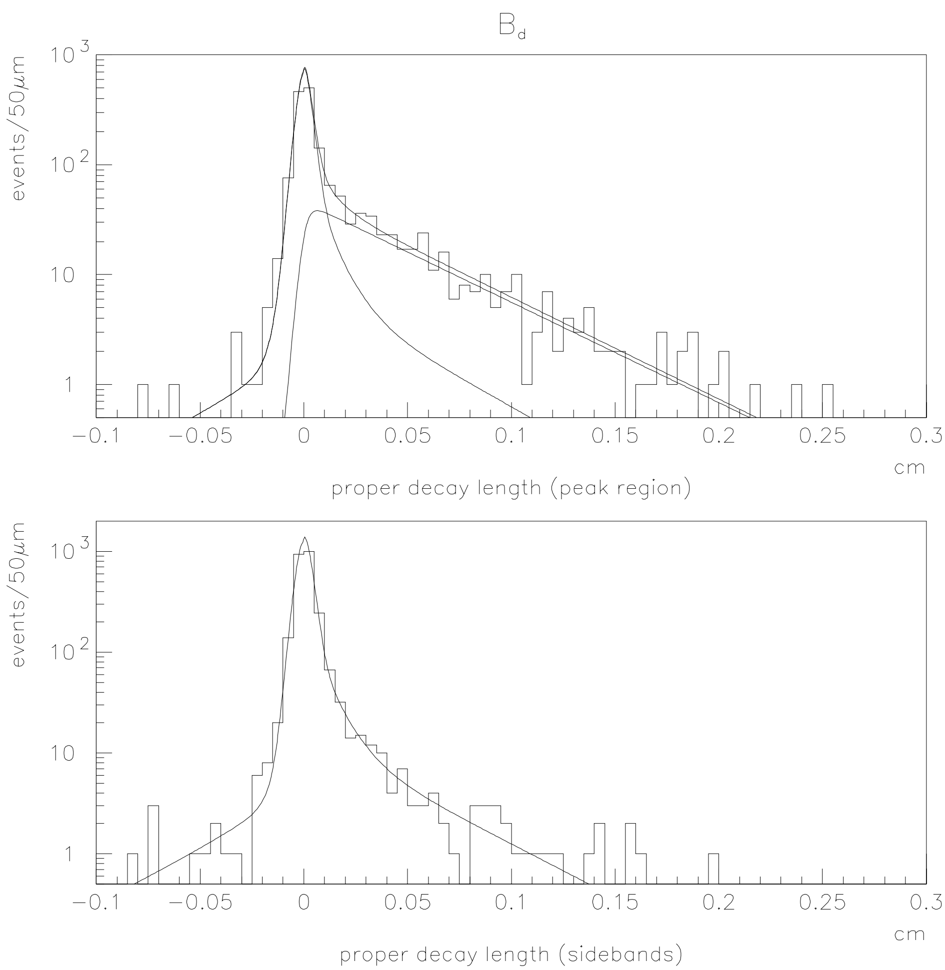
Lifetime: (LEP, CDF)

$$\tau(B^+) = 1.65 \pm 0.04\,\text{ps} \quad (c\tau = 495 \pm 12\,\mu m)$$
$$\tau(B^0) = 1.56 \pm 0.04\,\text{ps} \quad (c\tau = 468 \pm 12\,\mu m)$$

$$\boxed{\tau(B^+) \sim \tau(B^0) \sim 1.6 \text{ ps}}$$
(or $c\tau \sim 480\,\mu m$)

B lifetime measurement (CDF)

$$p\bar{p} \to B^0 X,\ B^0 \to \Psi K^{(*)0}$$



$$\tau(B^+) = 1.68 \pm 0.07 \pm 0.02 \text{ ps}$$
$$\tau(B^0) = 1.58 \pm 0.09 \pm 0.02 \text{ ps}$$

$\square$ $\Upsilon 4S \to B^+B^-$ or $B^0\bar{B}^0$ $\sim 100\%$

By measuring $Br(B \to \ell X)$ in two ways:

- Assuming $Br(\Upsilon 4S \to B\bar{B}) = 100\%$
- Tagging the other B by semileptonic decays

The difference $\to$ $\Upsilon 4S \to$ non-$B\bar{B}$ $< 4\%$

$\square$ $\Upsilon 4S \to B\bar{B}$ kinematics

$P_B = 340$ MeV/c $\quad (\beta = 0.065)$
Nearly at rest.

Angular distribution:
$|Y^1_{\pm 1}(\theta, \phi)|^2 \propto \sin^2\theta$
(θ: angle w.r.t. beam axis)

$\square$ $\Upsilon 4S \to B^0\bar{B}^0$ vs B^+B^-

$$f_0 \equiv \frac{(B^0\bar{B}^0)}{(B^0\bar{B}^0) + (B^+B^-)} \quad f_+ \equiv \frac{(B^+B^-)}{(B^0\bar{B}^0) + (B^+B^-)}$$

f_+/f_0 Theoretical

(1) **Phase space**

$\Upsilon 4S$(spin-1) $\to B\bar{B}$: P-wave, $\to \Gamma \propto P_B^3$:

$$E^2 - M^2 = P^2$$

$$\to \frac{\delta\Gamma}{\Gamma} = 3\frac{\delta P}{P} = 3\left(\frac{M}{P}\right)^2 \frac{\delta M}{M}$$

$$\frac{\delta\Gamma}{\Gamma} \sim 750\frac{\delta M}{M} \sim 0.04$$

So the phase space alone gives

$$\frac{f_+}{f_0} = 0.95 \pm 0.04 \quad (P.S.)$$

(2) **Coulomb effect**

Attractive force of B^+B^-
$\rightarrow$ more overlap of B^+B^- $\rightarrow$ larger rate

$$\frac{f_+}{f_0} = 1.18 \quad \text{(Coulomb, pointlike)}$$

(3) B **form factor,** $\Upsilon 4S$ **wave function**

Strong P_B dependence
($\Upsilon 4S$ wave function in particular)

Coulomb effect also needs corrections.

$$\frac{f_+}{f_0} = 0.97 \sim 1.04 \quad \text{(Overall)}$$

Model-dependent.

f_+/f_0 **Experimental**

If relevant Hamiltonian is <u>isosinglet</u>

$$\rightarrow \Gamma(B^+ \rightarrow F_+) = \Gamma(B^0 \rightarrow F_0)$$

(F_+, F_0: isospin-related final states)

Then,

$$\boxed{\frac{N(F_+)}{N(F_0)} = \frac{f_+}{f_0}\frac{\tau_+}{\tau_0}}$$

$$\tau_+ \equiv \tau(B^+),\ \tau_0 \equiv \tau(B^0)$$

Use the direct lifetime measurement:

$$\frac{\tau_+}{\tau_0} = 1.04 \pm 0.04$$

$$\rightarrow \quad \frac{f_+}{f_0}.$$

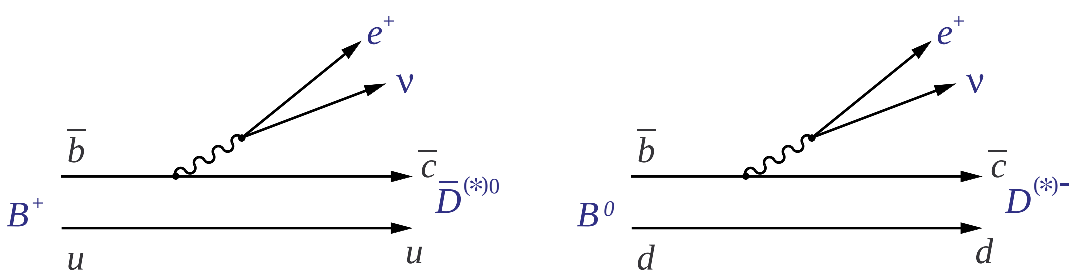
$b \rightarrow c\bar{u}d$ (I=1) $\rightarrow B \rightarrow D^{(*)}\pi^{(*)}$ cannot be used.

□ Semileptonic decays

$\bar{b} \to \bar{c}\ell^+\nu \ (I = 0)$

$$B^+ \to \bar{D}^{*0}\ell^+\nu \quad \leftrightarrow \quad B^0 \to D^{*+}\ell^+\nu$$

$$(\bar{D}^{*0} \to D^0\pi^0) \qquad\qquad (D^{*+} \to D^0\pi^+)$$



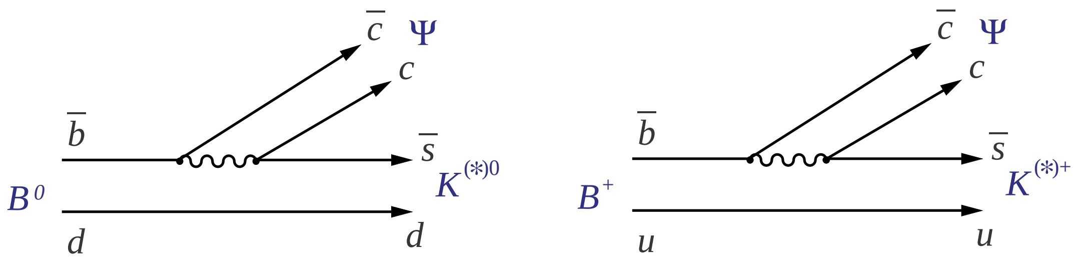
$$\frac{f_+}{f_0}\frac{\tau_+}{\tau_0} = 1.14 \pm 0.14(stat) \pm 0.13(sys)$$

The systematic error is dominated by π^+/π^0 efficiency ratio.

$\square\ B \to \Psi K^{(*)}$

$\bar{b} \to \bar{c}c\bar{s}\ (I=0)$

$$B^+ \to \Psi K^{(*)+} \quad \leftrightarrow \quad B^0 \to \Psi K^{(*)0}$$



$$\frac{f_+}{f_0}\frac{\tau_+}{\tau_0} = 1.15 \pm 0.17(stat) \pm 0.06(sys)$$

Combining $D^*\ell\nu$ and $\Psi K^{(*)}$,

$$\frac{f_+}{f_0}\frac{\tau_+}{\tau_0} = 1.15 \pm 0.13$$

$$\to \quad \frac{f_+}{f_0} = 1.11 \pm 0.13$$

3. B reconstruction techniques

<Full reconstruction>

$$B \to f_1 \cdots f_n$$

Energy and absolute momentum of B known:

$$E_B = E_{\text{beam}} = 5.290 \text{ GeV}$$
$$|\vec{P}_B| = \sqrt{E_{\text{beam}}^2 - M_B^2} = 0.34 \text{ GeV/c}$$

$\to$ require that candidates satisfy

$$E_{\text{tot}} = E_{\text{beam}}\,, \quad |\vec{P}_{\text{tot}}| = |\vec{P}_B|$$

where

$$E_{\text{tot}} \equiv \sum_{i=1}^{n} E_i\,, \quad \vec{P}_{\text{tot}} \equiv \sum_{i=1}^{n} \vec{P}_i$$

Instead of E_{tot} and $|\vec{P}_{\text{tot}}|$, we historically use

$$\Delta E \equiv E_{\text{tot}} - E_B \qquad \text{(energy difference)}$$
$$M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - \vec{P}_{\text{tot}}^2} \quad \text{(beam-constrained mass)}$$

Example of full reconstruction

Require ΔE is near zero and plot $M_{\rm bc}$

$$B \to D^{(*)}\pi^{(*)-}$$

where $\pi^{*-} = \rho^-$ or a_1^-.

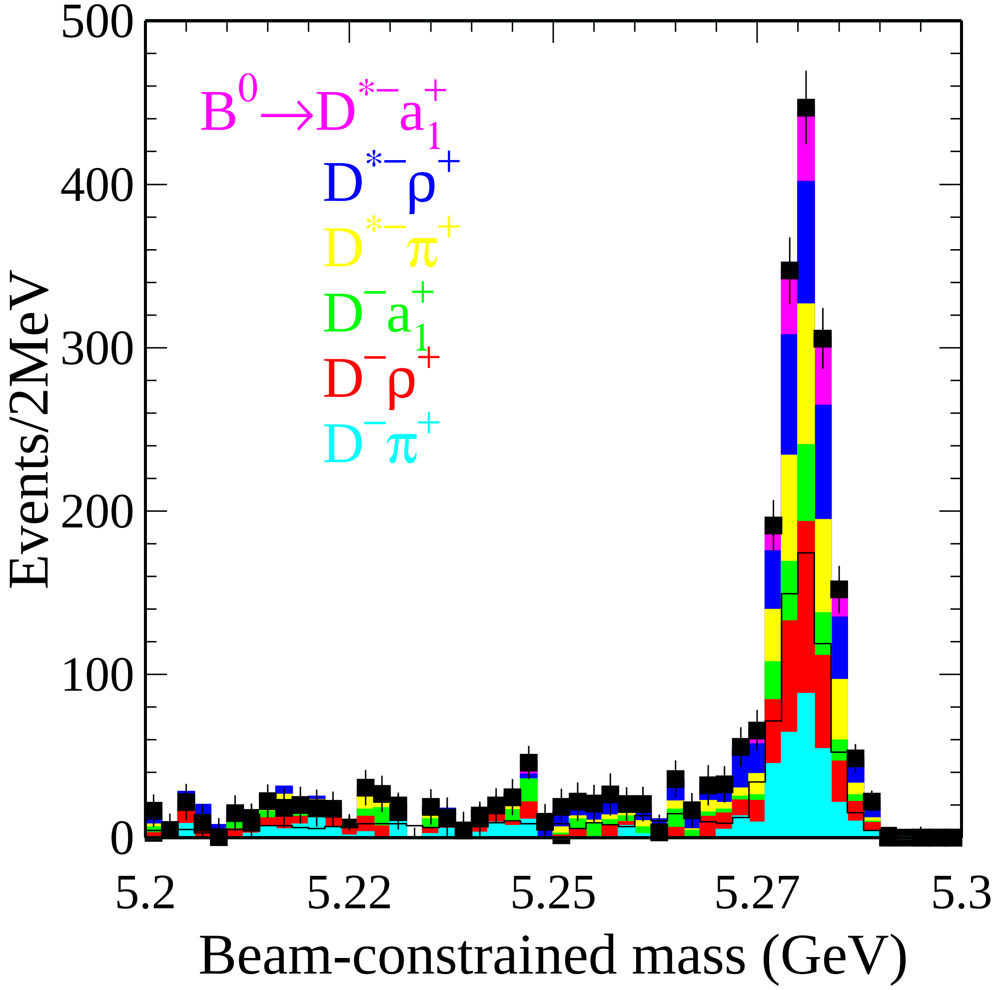
$$D^{*+} \to D^0\pi^+ , \quad D^{*0} \to D^0\pi^0$$

$$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$$

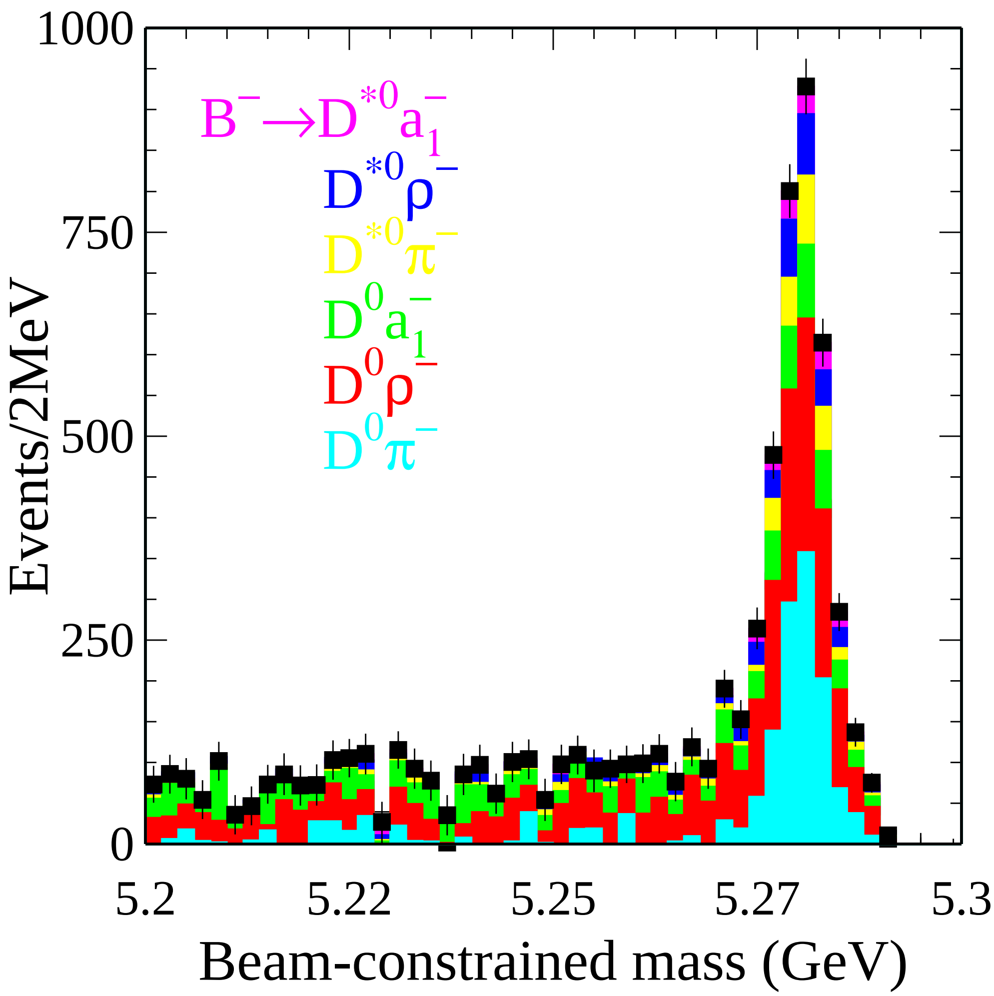
$$a_1 \to \rho^0\pi^-$$

$$\rho^- \to \pi^-\pi^0 , \quad \rho^0 \to \pi^+\pi^-$$

CLEO-2 ($\Upsilon 4S$ rest frame)



CLEO-2 ($\Upsilon 4S$ rest frame)

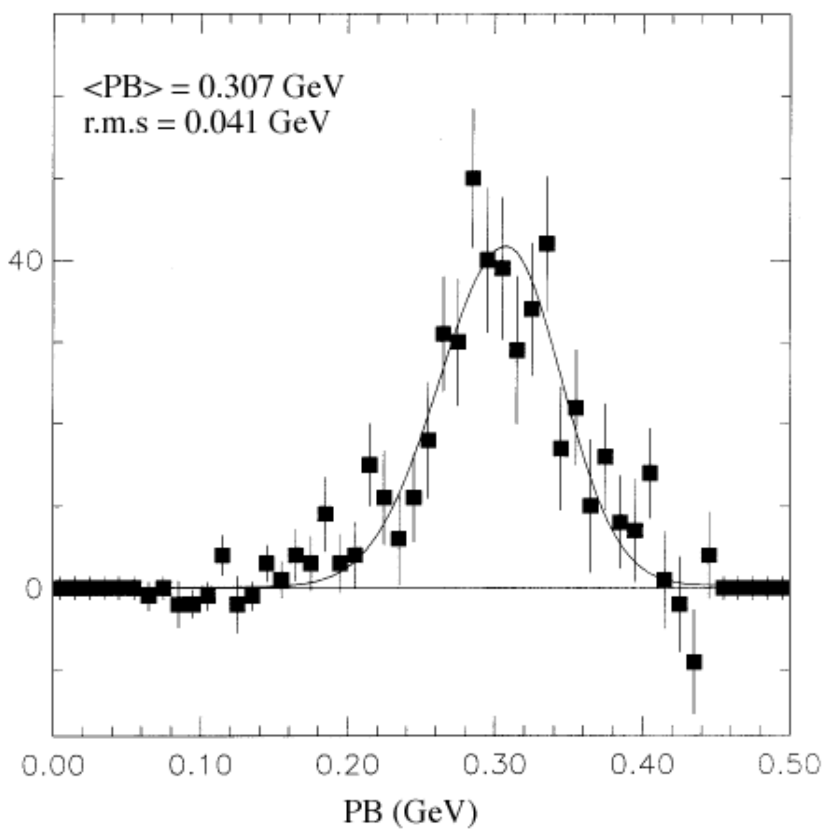


M_{bc} resolution dominated by beam energy spread

($\sigma_{M_{\mathrm{bc}}} \sim \sigma_{E_{\mathrm{beam}}} \sim 3$ MeV)

P_B **distribution of** $B \to D^{(*)}\pi^{(*)}$ (CLEO-2)

For a run block picked randomly,

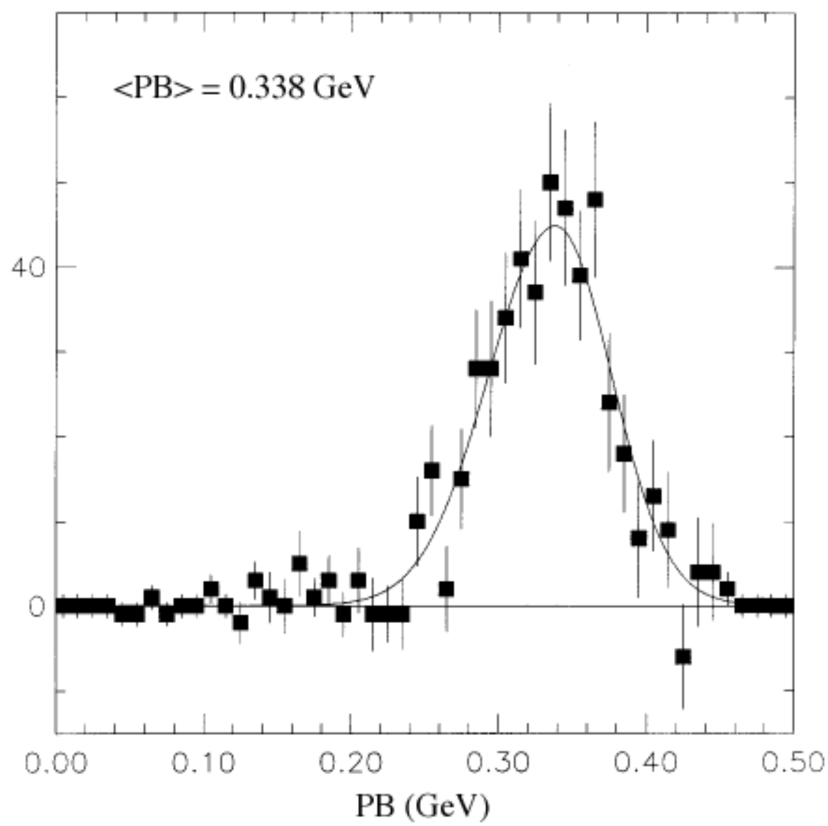


$$\sigma_P = \frac{E}{P}\sigma_E \sim 15\sigma_E$$

$\sigma_{P_B} \sim 40$ MeV/c: consistent with entirely due to $\sigma_{E_{\text{beam}}} = 3$ MeV/c

P_B **distribution of** $B \to D^{(*)}\pi^{(*)}$
(CLEO-2)

For another run block,



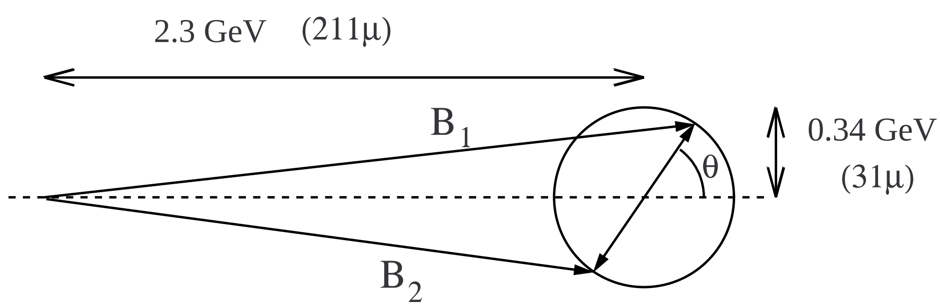
P_B shifted by ~ 30 MeV/c

$\Upsilon 4S$ restframe:

Small shift in $E_{\text{beam}} \rightarrow$ a large shift in P_B

For asymmetric B-factories:

$P_B(\text{lab}) = 2.3(\text{Belle}) \sim 2.8(\text{BaBar})$ GeV/c



(correct scale)

Cannot boost back to the space-time of $\Upsilon 4S$ system
(The time of $\Upsilon 4S$ decay is missing)

Causes errors in
- $\Delta z = (\beta\gamma)_{\Upsilon 4S}\, c\Delta t$
- beam-plane constraint vertex fit

$\rightarrow$ Run on a tad lower side of $\Upsilon 4S$.

Full reconstruction at asymmetric B-factories

(1) Boost all candidates to $\Upsilon 4S$ rest frame
$\rightarrow$ proceed as CLEO

Need mass assignments for each particle. Signal particles (i.e. with correct masses) are boosted correctly, but the rest of tracks in the event may not.

Usually works fine.

(2) Reconstruct B invariant mass from measured E and P in the lab. frame:

$$M_B = \sqrt{E_{\text{tot}}^2 - \vec{P}_{\text{tot}}^2}$$

$$E_{\text{tot}} \equiv \sum_{i=1}^{n} E_i(\text{lab})\,, \qquad \vec{P}_{\text{tot}} \equiv \sum_{i=1}^{n} \vec{P}_i(\text{lab})$$

Separately cut on P_B in $\Upsilon 4S$ rest frame.

<Recoil neutrino mass>

Semileptonic decdays $B \to X\ell\nu$ where
X is fully reconstructed.

Assume B is at rest: $P_B = (M_B, 0, 0, 0)$,
measure 4-momenta of X and lepton.

$$m_\nu^2 = (P_B - P_X - P_\ell)^2$$

m_ν^2 is often called MM^2 (missing mass^2)

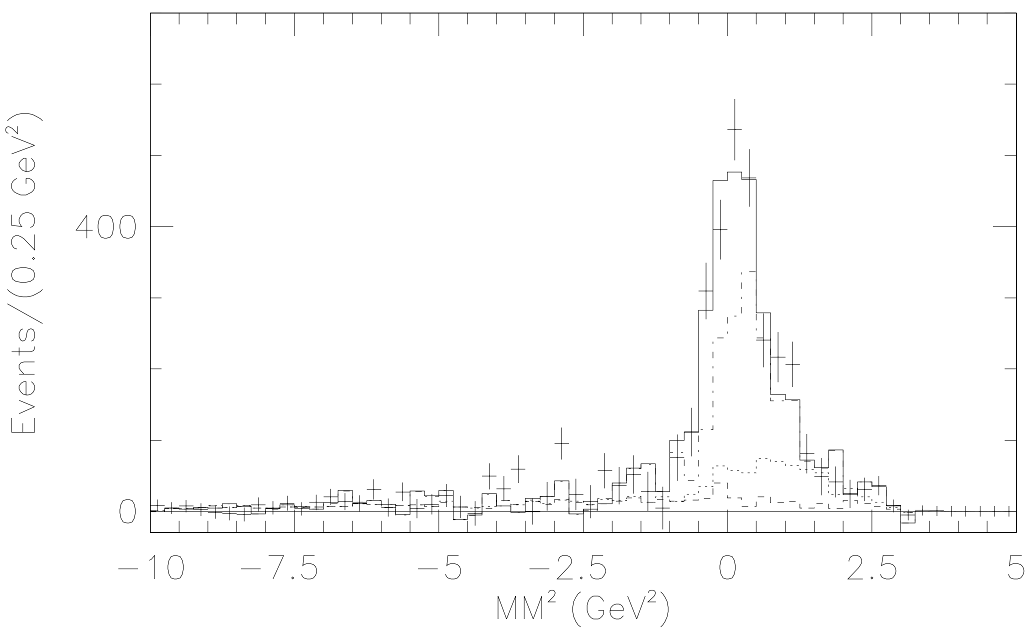
$$q^2 = (P_B - P_X)^2$$

Background:

- Continuum.
  $\to$ Subtract the continuum data.
- $B \to X n\pi\,\ell\nu$ ($n\pi$ lost).
  $\to$ Fit the m_ν^2 shape,
  use MC to subtract (hopefully).

Missing mass analysis of $\bar{B}^0 \to D^+ \ell^- \bar{\nu}$

$(D^+ \to K^- \pi^+ \pi^+)$



Large background from $D^+ n\pi \ell \nu$
(peaks near the signal region)

<Neutrino reconstruction>

Used also for semileptonic decdays $B \to X\ell\nu$ where X is fully reconstructed.

Hermiticity of detector $\to$ $\vec{P}_\nu = \text{missing}\vec{P}$

$$P_\nu = -\sum_i^{\text{all}} \vec{p}_i \,, \quad E_\nu = |\vec{P}_\nu| \,.$$

Combine with X, proceed as the usual full reconstructions.

q^2 is then given directly by

$$q^2 = (P_\nu + P_\ell)^2$$

$\sigma_{P_\nu} \sim 0.11$ GeV/c (CLEO)

Ensure hermiticity by requiring

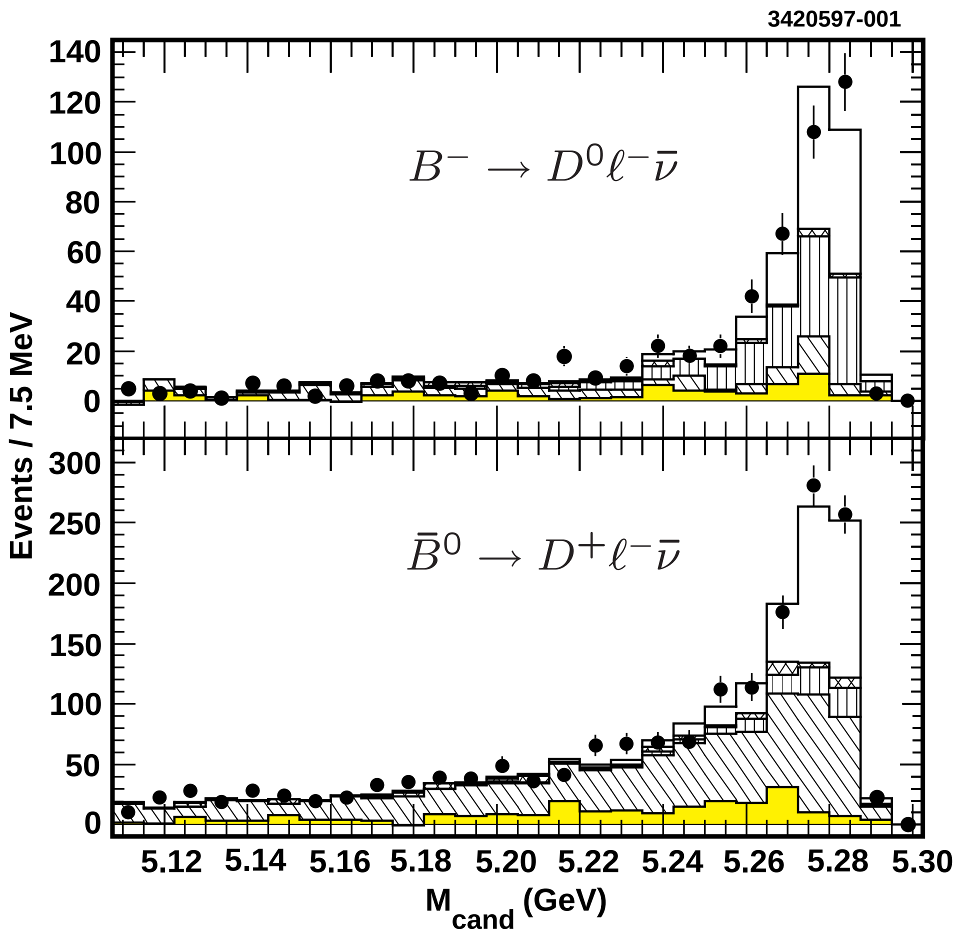
- One lepton per event. (no other ν's).
- $|$Total charge$| < 2$ (missing tracks)

Succesfully used for $B \to \mu\nu$ (1992), $B \to D\ell\nu$, $B \to (\pi/\rho/\omega)\ell\nu$ etc.

Nutrino reconstruction analysis

$(D^+ \to K^-\pi^+\pi^+,\ D^0 \to K^-\pi^+)$

Beam-constrained mass



$D^*\ell\nu$ background is much less than in MM^2 case.

$$Br(B^- \to D^0 \ell^- \bar{\nu}) = 1.94 \pm 0.15 \pm 0.34\%$$
$$Br(\bar{B}^0 \to D^+ \ell^- \bar{\nu}) = 1.87 \pm 0.15 \pm 0.32\%$$

<Partial reconstruction of D^{*+}>

In $D^{*+} \to D^0\pi^+$, $p_{\text{c.m.}}$ is small (39 MeV/c),

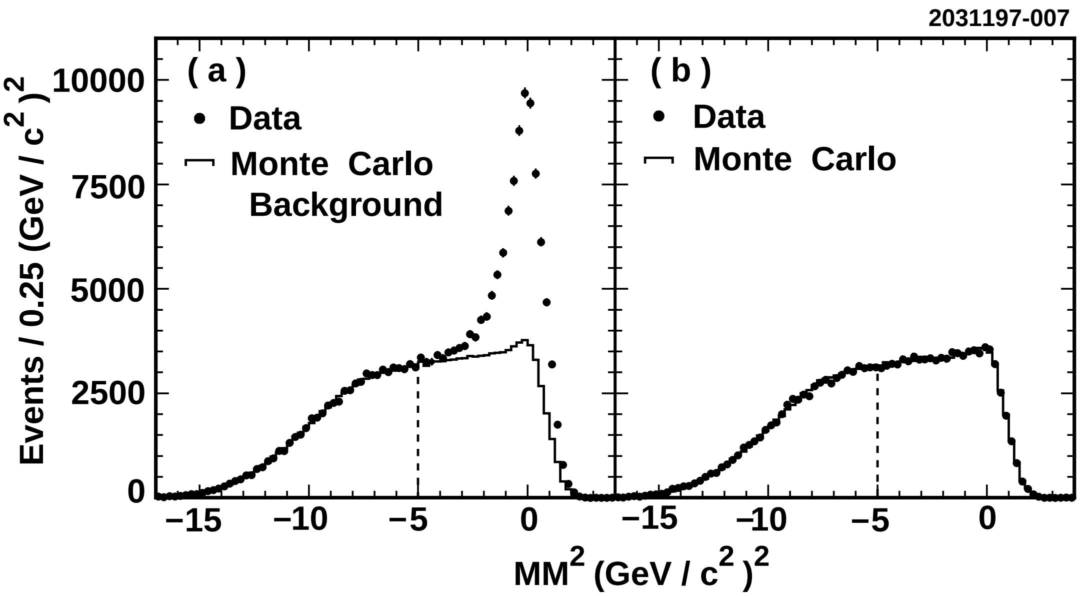
$$\vec{v}_{D^*} \sim \vec{v}_\pi \,.$$

Detect only π^+: $\vec{v}_{D^*} \sim \vec{v}_\pi \to P^\mu_{D^*}$.
(slightly better if make correction depending on p_π(lab))

D^0 is not reconstructed $\to$ high efficiency, high background

Apply it to $B \to D^{*+}\ell^-\bar{\nu}$,
and proceed as the missing mass analysis.
(or, the neutrino reconstruction can be used also)

$B \to D^{*+}\ell^-\bar{\nu}$ partial reconstruction



- $B \to D^{*+}\pi\ell\nu$ cannot be well separated.
- High efficiency tag of B or D^0 (15K tags/fb^{-1})

A sample of $45K$ tagged D^0's was used to obtain

$$Br(D^0 \to K^-\pi^+) = 3.81 \pm 0.15 \pm 0.16\ \%$$

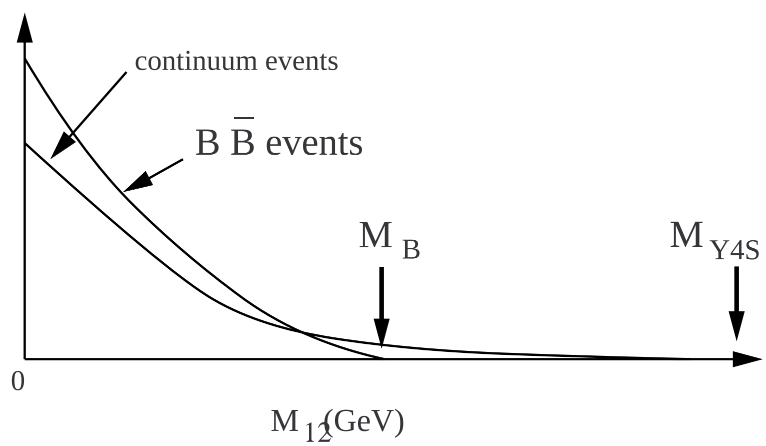
4. Contiuum Background Suppression

Many important rare B decays
($K\pi$, $\pi\pi$, $K^*\gamma$, $\eta' K$, etc.)
are of the type

$B \rightarrow$ 2 light particles

The largest invariant mass 2 final-state particle in a $B\bar{B}$ event can make is $\sim M_B$: the tail end of distribution.

Continuum 2-jet events can generate up to $M_{\Upsilon 4S}$.



$\rightarrow$ Rare decay background is usually dominated by continuum.

<Tools for continuum suppression>

(1) **Event shape variables** (in $\Upsilon 4S$ c.m.)

Thrust, Sphericity, $R2$(Fox-Wolfram), etc.

Measures skinniness of event.

$$\begin{cases} B\bar{B}: & \text{spherical} \\ \text{continuum}: & \text{back-to-back jets (skinny)} \end{cases}$$

(2) **'Sphericity angle'** θ_{sph} (in $\Upsilon 4S$ c.m.)

Angle between the axis of the B candidate and the axis of <u>the rest of the event</u>.

$$\begin{cases} B\bar{B}: & \cos\theta_{\text{sph}} \text{ flat} \\ \text{continuum}: & \cos\theta_{\text{sph}} \text{ peaked at } \pm 1 \end{cases}$$

(3) **Fischer discriminant**

Linearly combine the above variables as well as other variables (typically energy flows inside cones around the event axis etc.)

$$\vec{x} = (x_1 \dots x_n)$$

$$F \equiv \vec{\lambda} \cdot \vec{x}$$

$\vec{\lambda}$: constants to be chosen to maximize separation S between signal and background:

$$S \equiv \frac{(\langle F \rangle_s - \langle F \rangle_b)^2}{\sigma_F^2} = \frac{(\vec{\lambda} \cdot (\langle \vec{x} \rangle_s - \langle \vec{x} \rangle_b))^2}{\vec{\lambda}^T V \vec{\lambda}}$$

$$s : \text{signal}\,, \quad b : \text{bkg}$$

$$V : \text{covariant matrix of } \vec{x}$$

The solution for the optimum coefficients is given by

$$\frac{\partial S}{\partial \lambda_i} = 0$$

$$\rightarrow \quad \vec{\lambda} = V^{-1}(\langle \vec{x} \rangle_s - \langle \vec{x} \rangle_b)$$

(4) **Pseudo B reconstruction**

Used succesfuly for $b \to s\gamma$ and $b \to s\eta'$

To search $b \to s\gamma$, for example, attempt to fully reconstruct

$$B \to (K^- n\pi)\gamma$$

K^-: identified as K^- by dE/dX and TOF
$n \leq 4$ and maximum of one π^0.

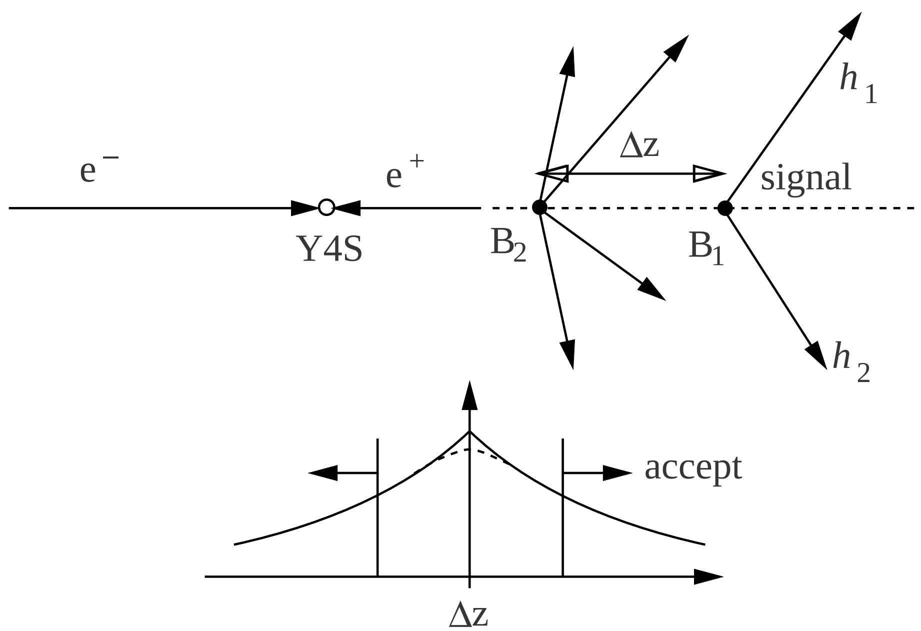
If ΔE and the beam constrained mass falls within signal region, then plot E_γ.

Many times, not all particles of $(K^- n\pi)$ are from B, yet proved very effective in continuum suppression.

Exact mechanism not well understood.
(use with caution)

(4) **Vertex separation in** z

$e^+e^- \rightarrow B_1 B_2$

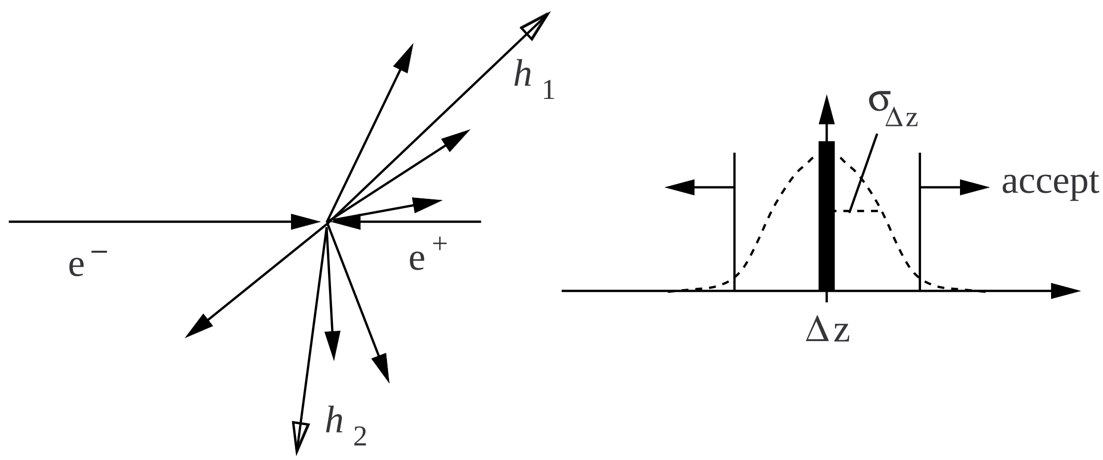


Δz distribution:

$$\propto \exp\left(-\frac{|\Delta z|}{L_0}\right)$$

$L_O(B$ mean decay length$) \sim 211\mu(Belle)$

$e^+e^- \to q\bar{q}$ (continuum)



Δz distribution (assume gaussian):

$$\propto \exp\left(-\frac{\Delta z^2}{2\sigma_{\Delta z}^2}\right)$$

$$\sigma_{\Delta z} \sim 125\mu$$

Discovery sensitivity improvement:

$\#\sigma$ probability of background fluctuate up to the signal.

$$\#\sigma = \frac{N_{\mathsf{sig}}}{\sqrt{N_{\mathsf{bkg}}}}$$

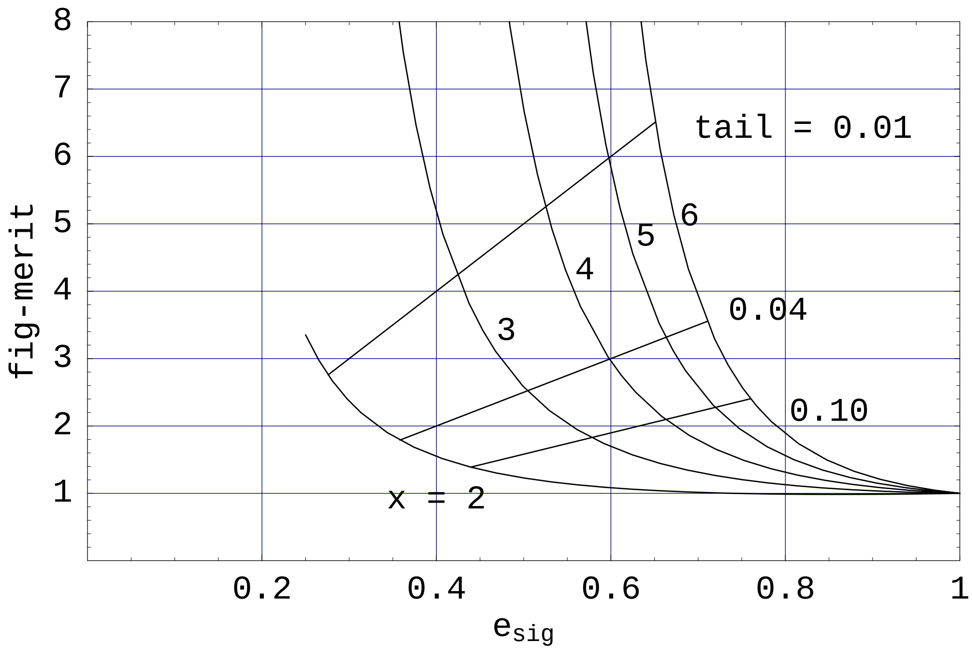
The improvement factor for $\#\sigma$ is then

$$\boxed{\text{fig. merit} = \frac{\epsilon_{\mathsf{sig}}}{\sqrt{\epsilon_{\mathsf{bkg}}}}} \quad \text{(discovery)}$$

Does not depend on $N_{\mathsf{sig}}/N_{\mathsf{bkg}}$ before the vertex separation cut.

Discovery sensitivity improvement:

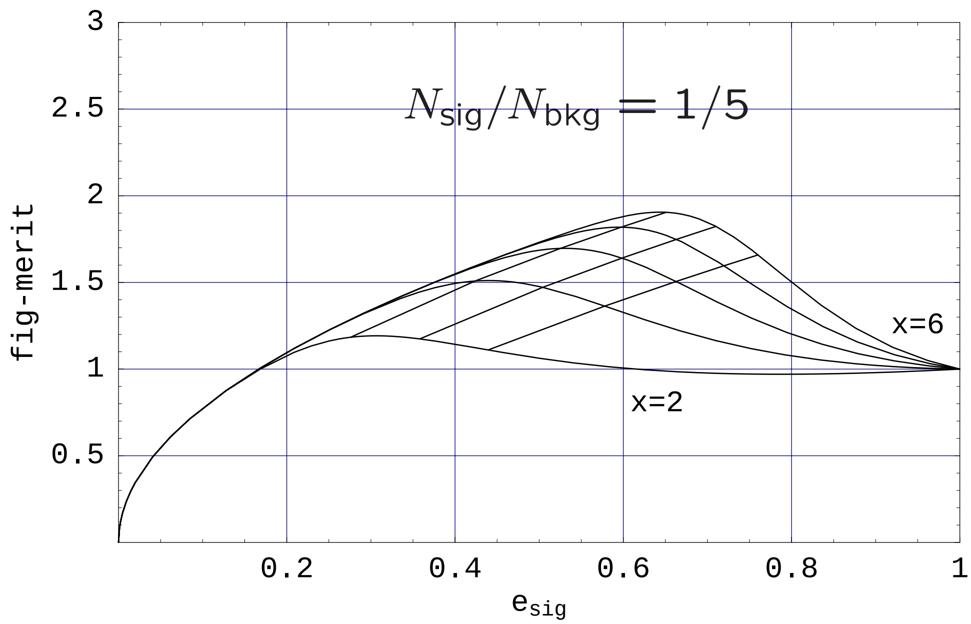
$$x \equiv \frac{L_0}{\sigma_{\Delta z}} \quad \sim 2 \text{ for Belle, BaBar}$$



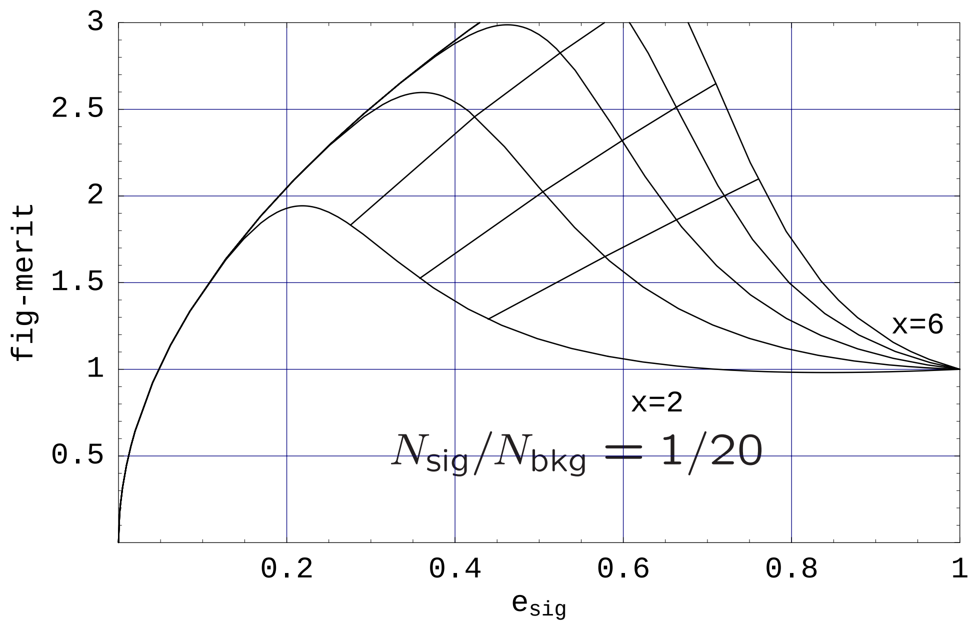
Measurement precision improvement:

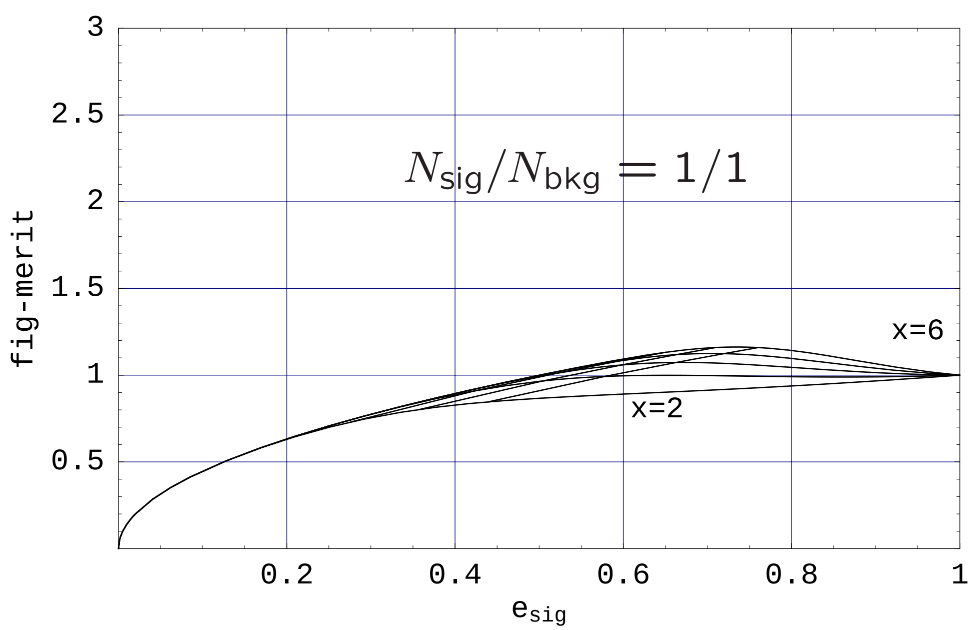
Figure of merit = improvement factor in

$$\frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{bkg}}}}$$



Measurement precision improvement:





Continuum suppression by Δz cut:

- Current $\sigma_{\Delta z}$ is not good enough.
- Factor 2-3 improvement in $\sigma_{\Delta z}$ is effective in accuracy improvement, and increases discovery power dramatically.
- If already $N_{\mathsf{sig}}/N_{\mathsf{bkg}} \sim 1$ before Δz cut, accuracy will not improve. Δz cut is for modes swamped by continuum background.
- Reducing the non-gaussian tail of Δz is critical.

I. K System

K^0-$\bar{K}^0$ system: the only place CPV (CP Violation) have been seen so far.

1964, K_L (as well as K_S) $\rightarrow \pi^+\pi^-(CP+)$

This is CPV because:

$Br(K_S \rightarrow \pi\pi) \sim 1 \Rightarrow$ natural to identify

$$K_S = K_1(CP+), \quad K_L = K_2(CP-)$$

- If $K_L = K_2$,

$$K_2(CP-) \;\rightarrow\; \pi^+\pi^-(CP+)$$

(CPV in decay- or - direct CPV)

- If $K_L \neq K_2$, $\rightarrow CP+$ component in K_L

$$\begin{aligned} K_2(CP-) &= K_L - \epsilon_0 K_S \\ &\xrightarrow{t} c_1 K_L + c_2 K_S \ (CP \text{ mixture }) \end{aligned}$$

(CPV in mixing- or - indirect CPV)

Either case, both $K_L \& K_S \rightarrow \pi^+\pi^-$ is CPV

$$\left(\begin{array}{l}\text{A neutron is a physical state \underline{and} not a } CP \\ \text{eigenstate. But it does not mix (evolve) as} \\ \text{far as we know.} \\ \qquad\qquad\Rightarrow \text{ not } CPV\end{array}\right)$$

All CPV effects so far are consistent with the hypothesis that

CPV in the K^0-$\bar{K}^0$ system is purely indirect (mixing) with

$$\epsilon_0 = (2.26 \times 10^{-3})\, e^{i44^\circ}$$

Intense efforts to search direct CPV are underway:

$$KTeV(Fermilab) \quad NA48(CERN)$$

Hypothetical intereaction that causes indirect CPV: **'Superweak'** (Wolfenstein, 1964)

We now have a 'real' theoretical model of CPV: **the Standard Model**

Standard-Model quark-W Interaction

$$L_{\text{int}} = L_{qW} + L_{qW}^{\dagger}$$

$$L_{qW} = \frac{g}{\sqrt{2}} \int d^3x \; (\bar{u}, \bar{c}, \bar{t})_L \, V_{CKM} \, \gamma_\mu \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W^\mu$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad \begin{pmatrix} \text{CKM matrix} \\ \text{unitary} \end{pmatrix}$$

Actual value of V_{VKM} has a hierarchical structure. Approximately (Wolfenstein parametrization),

$$V_{CKM} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda \sim 0.22$$
$$A \sim 1$$
$$\rho, \eta: \text{ order unity}$$

If there is no non-trivial phase in V_{CKM},
one can adjust CP phases of quarks such that

$$L_{qW} \leftrightarrow L_{qW}^{\dagger} (\text{under } CP)$$

$$\rightarrow \quad (CP) L_{\text{int}} (CP)^{\dagger} = L_{\text{int}}$$

A 3×3 unitary matrix has non-trivial phase
$\rightarrow (CP) L_{\text{int}} (CP)^{\dagger} \neq L_{\text{int}} \quad \rightarrow CPV$.

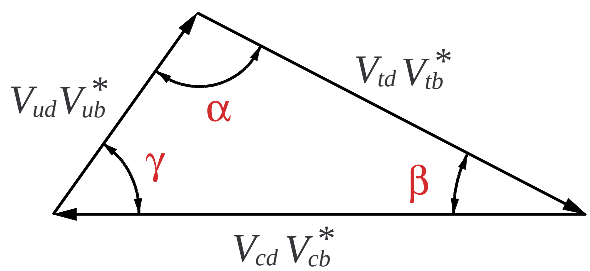
This could explain the CPV in K. If so,

$\Rightarrow$ Large CPV in B decays
Sensitive test of the Standard Model

A Main Question of the CPV Study in B: 'Is V_{CKM} unitary?'

e.g: orthogonality of d-column and b-column:

$$\underbrace{V_{ud}}_{\sim 1} V_{ub}^* + \underbrace{V_{cd}}_{\sim \lambda} V_{cb}^* + V_{td} \underbrace{V_{tb}^*}_{\sim 1} = 0$$



$$\alpha \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{V_{td}V_{tb}^*}\right) \sim \arg(V_{ub}^*/V_{td})$$

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \sim \arg V_{td}^*$$

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \sim \arg V_{ub}^*$$

Note: the definitions of α, β, γ are independent of quark phases.

3 types of CPV in B decays

1. CPV in mixing. (neutral B)
   Particle-antiparticle imbalance in physical neutral B states ($B_{a,b}$):
   $$|\langle B^0|B_{a,b}\rangle|^2 \neq |\langle \bar{B}^0|B_{a,b}\rangle|^2$$

2. CPV by mixing-decay interference. (neutral B)
   When both B^0&$\bar{B}^0$ can decay to the same final state f:
   $$\begin{tikzcd} & \bar{B}^0 \arrow[dr] & \\ B^0 \arrow[ur] \arrow[rr] & & f \end{tikzcd} \qquad \begin{tikzcd} & B^0 \arrow[dr] & \\ \bar{B}^0 \arrow[ur] \arrow[rr] & & \bar{f} \end{tikzcd}$$
   the inteference results in
   $$\Gamma_{B^0\to f}(t) \neq \Gamma_{\bar{B}^0\to \bar{f}}(t)\,.$$
   ($\Gamma_{B^0\to f}(t)$: pure B^0 at $t=0$, decaying to f at t.)

3. CPV in decay. (neutral and charged B)
   Partial decay rate asymmetries.
   $$|Amp(B\to f)| \neq |Amp(\bar{B}\to \bar{f})|$$
   ($Amp(B^0\to f)$: instantaneous decay amplitude.)

II. CPV in mixing

Eigenstates of mass & decay rate (assume CPT):

$$\begin{cases} B_a = pB^0 + q\overline{B}^0 \\ B_b = pB^0 - q\overline{B}^0 \end{cases},$$

B_a (mass: m_a, decay rate: γ_a)
B_b (mass: m_b, decay rate: γ_b)

$\longrightarrow$ Particle-antiparticle asymmetry in $B_{a,b}$:

$$\delta \equiv \frac{|\langle B^0|B_{a,b}\rangle|^2 - |\langle \overline{B}^0|B_{a,b}\rangle|^2}{|\langle B^0|B_{a,b}\rangle|^2 + |\langle \overline{B}^0|B_{a,b}\rangle|^2} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2}$$

$CPT \rightarrow B_a$ and B_b have the same δ (incl. sign)

Use $B^0 \to \ell^+$, $\bar{B}^0 \to \ell^-$ to distinguish B^0 and $\bar{B}^0$.

$$\left(\begin{array}{c} \text{For the neutral } K \text{ system} \\ \\ \delta_K \equiv \dfrac{Br(K_L \to \pi^-\ell^+\nu) - Br(K_L \to \pi^+\ell^-\nu)}{Br(K_L \to \pi^-\ell^+\nu) + Br(K_L \to \pi^+\ell^-\nu)} \\ = (3.27 \pm 0.12) \times 10^{-3} \end{array} \right)$$

$\gamma_a \sim \gamma_b \to B_a$ and B_b cannot be separated easily.
Measure same-sign di-lepton asymmetry in
$\Upsilon 4S \to B^0 \bar{B}^0$ (Okun,Zakharov,Pontecorvo,1975):

$$A_{\ell\ell} \equiv \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = 2\delta$$

CLEO 1993 (by $A_{\ell\ell}$ on $\Upsilon 4S$)

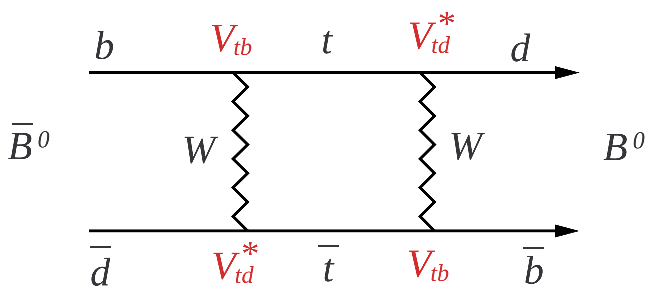
$$\delta = 0.015 \pm 0.048 \pm 0.016$$

OPAL 1997 (by fitting the time dependence of tagged semileptonic decays of B's on Z^0)

$$\delta = -0.012 \pm 0.020 \pm 0.012$$

Standard Model prediction for $\delta (= A_{\ell\ell}/2)$

The dominant diagram for mixing:



$$\rightarrow \begin{cases} p = \frac{1}{\sqrt{2}} e^{i\phi} \\ q = \frac{1}{\sqrt{2}} e^{-i\phi} \end{cases}, \quad \phi = \arg(V_{tb} V_{td}^*)$$

This does not result in $|p| \neq |q|$ (or $A_{\ell\ell} \neq 0$).

The interference of the above diagram with the same one with t replaced by c gives

$$A_{\ell\ell} \sim -4\pi \frac{m_c^2}{m_t^2} \Im \left(\frac{V_{cb} V_{cd}^*}{V_{tb} V_{td}^*} \right) \sim 10^{-3}$$

Long-distance effects may dominate
(hadronic intermediate states)
(Altomari, Wolfenstein, Bjorken, 1988):

$$B^0 \leftrightarrow \begin{pmatrix} D^0 \bar{D}^0 \\ D^+ D^- \\ \text{etc.} \end{pmatrix} \leftrightarrow \bar{B}^0$$

$$|A_{\ell\ell}| = 10^{-3} \sim 10^{-2}.$$

Large theoretical uncertainty.

$\longrightarrow$ Cannot determine CKM phases from $A_{\ell\ell}$.

$\delta (= A_{\ell\ell}/2)$ of 10^{-2} or larger signals **new physics**.

Progress expected in the near future

Single lepton method (H.Y. 1997)

There is also CP asymmetry in single lepton yield, (assuming leptons from $B^{\pm}$ cannot be separated)

$$\boxed{A_\ell \equiv \frac{N_{\Upsilon(4S)\to\ell^+} - N_{\Upsilon(4S)\to\ell^-}}{N_{\Upsilon(4S)\to\ell^+} + N_{\Upsilon(4S)\to\ell^-}} = \chi\,\delta}$$

$$\chi \equiv Br(B^0 \text{ decays as } \bar{B}^0)$$

Comparison of sensitivity on δ

$$\sigma_\delta(\ell\ell) = \frac{1}{2}\frac{1}{\sqrt{N_0\,B_{sl}^2\,\epsilon_\ell^2\,\chi}} \quad (A_{\ell\ell})$$

$$\sigma_\delta(\ell) = \frac{1}{\chi}\frac{1}{\sqrt{4N_0 B_{sl}\,\epsilon_\ell}} \quad (A_\ell)$$

N_0 : #($B^0\bar{B}^0$ pair)
ϵ_ℓ : lepton detection efficiency
B_{sl} : semileptonic branching fraction

CLEO (current data):

$$\begin{aligned} N_0 &= 2\times 10^6 \\ \epsilon_\ell &= 0.4 \\ B_{sl} &= 2\times 0.104 \pm 0.03 \\ \chi &= 0.175 \pm 0.16 \end{aligned}$$

$$\rightarrow \quad \sigma_\delta(\ell) \sim 0.7\%, \qquad \sigma_\delta(\ell\ell) \sim 1\%$$

Two data samples are largely independent; thus, they can be combined:

$$\boxed{\sigma_\delta(\ell + \ell\ell) \sim 0.6\% \ \text{(CLEO current)}}$$

approaching the range of SM predictions.

B-factories: $N_0 \sim 5\times 10^7 \rightarrow \sigma_\delta \sim 0.1\%$

Quite possible that leptonic CP asymmetry will be observed in near future.

III. Mixing-Decay Interference

$\Gamma_{B(\overline{B})\to f}(t)$: the probability that a pure $B^0(\overline{B}^0)$ at $t=0$ decays to a final state f at t is (for $|q\overline{A}/pA|=1$):

$$\boxed{\Gamma_{B(\overline{B})\to f}(t) = e^{-\gamma t}|pA|^2\left[1 \pm \Im\left(\frac{q\overline{A}}{pA}\right)\sin\delta m\, t\right]}$$

$$\begin{cases} B_a = pB^0 + q\overline{B}^0 \\ B_b = pB^0 - q\overline{B}^0 \end{cases},$$

$$\begin{cases} A \equiv Amp(B^0 \to f) \\ \overline{A} \equiv Amp(\overline{B}^0 \to f) \end{cases}, \qquad \begin{cases} \gamma_a = \gamma_b \equiv \gamma \\ \delta m \equiv m_a - m_b \end{cases}$$

Time-integrated asymmetry:

$$A_f \equiv \frac{\Gamma_{B\to f} - \Gamma_{\bar{B}\to f}}{\Gamma_{B\to f} + \Gamma_{\bar{B}\to f}} = \frac{x}{1+x^2}\Im\left(\frac{q\overline{A}}{pA}\right)$$

$$x \equiv \frac{\delta m}{\gamma} \sim 0.71 \pm 0.06 \quad \to \quad \frac{x}{1+x^2} \sim \frac{1}{2}$$

On $\Upsilon 4S \to B^0 \bar{B}^0$

Tag 'the other side' by a lepton:

$$\ell^{\pm} X(t_{tag}) \leftarrow (B^0 \bar{B}^0) \to f(t_{sig})$$

$B^0 \bar{B}^0$ created in a coherent $L = 1$ state.
Quantum correlation:

ℓ^+ tag at t $\to$ Signal side is $\bar{B}^0$ at t
ℓ^- tag at t $\to$ Signal side is B^0 at t

The decay time distribution is nearly identical to the single B case with

$$t \quad \to \quad t_- \equiv t_{sig} - t_{tag}$$

(in fact, esactly identical for $t_- > 0$)

$$\boxed{\Gamma_{4S \to \ell^{\mp} f}(t_-) \propto e^{-\gamma |t_-|} \left[1 \pm \Im \left(\frac{q\overline{A}}{pA} \right) \sin \delta m \, t_- \right]}$$

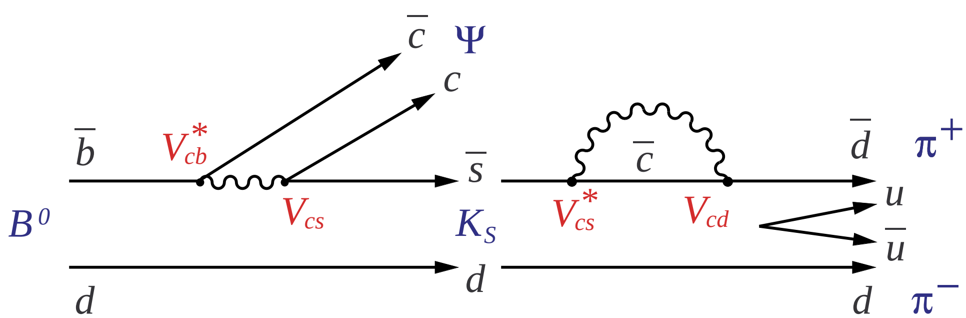
Gold-plated mode $B \to \Psi K_S$

What phases of V_{CKM} do we measure?

Recall $\begin{cases} p = \frac{1}{\sqrt{2}} e^{i\phi} \\ q = \frac{1}{\sqrt{2}} e^{-i\phi} \end{cases}, \qquad \phi = \arg(V_{tb} V_{td}^*)$

$$\Rightarrow \quad \frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$

The interference occurs when $K_S \to \pi^+ \pi^-$:



$$\arg A = \arg(V_{cb}^* V_{cs} V_{cs}^* V_{cd}) = \arg(V_{cb}^* V_{cd})$$

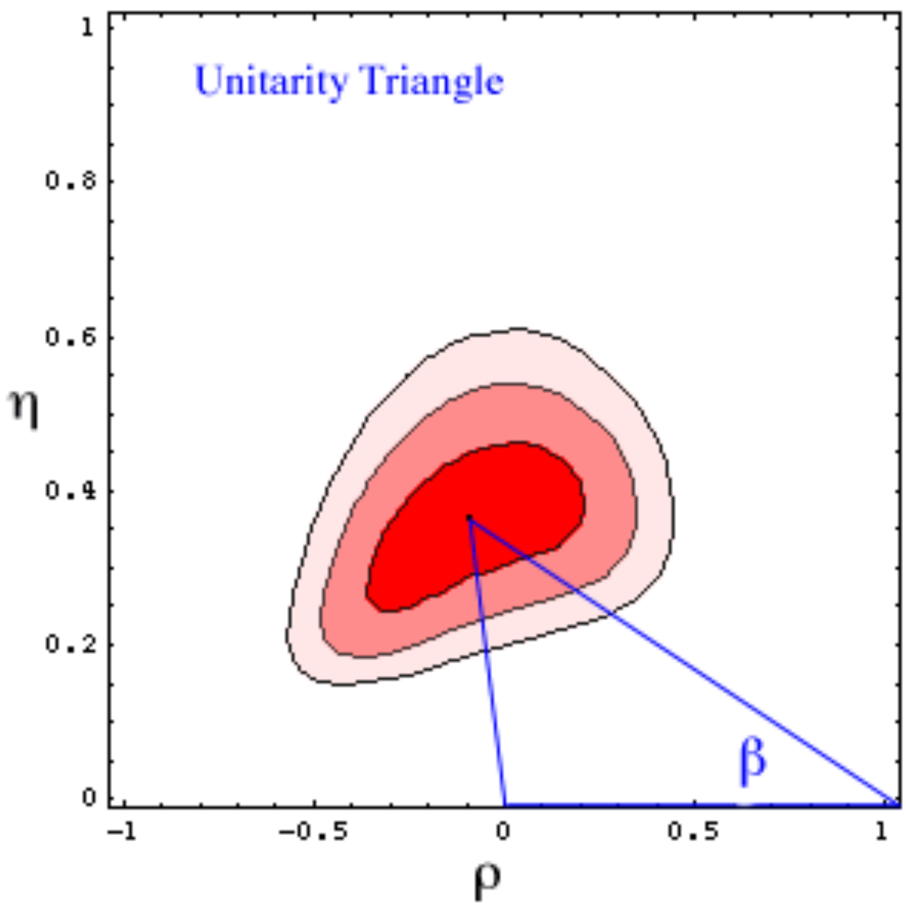
$$\Rightarrow \quad \frac{q\bar{A}}{pA} = \frac{V_{tb}^* V_{td} \; V_{cb} V_{cd}^*}{V_{tb} V_{td}^* \; V_{cb}^* V_{cd}} = \left(- \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)^* \Bigg/ \left(- \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

$$\Rightarrow \quad \Im \left(\frac{q\bar{A}}{pA} \right) = - \sin 2\beta \quad (\Psi K_S)$$

If the Standard Model is correct:

$$\epsilon_K = (2.26 \times 10^{-3})\ e^{i44^\circ}$$

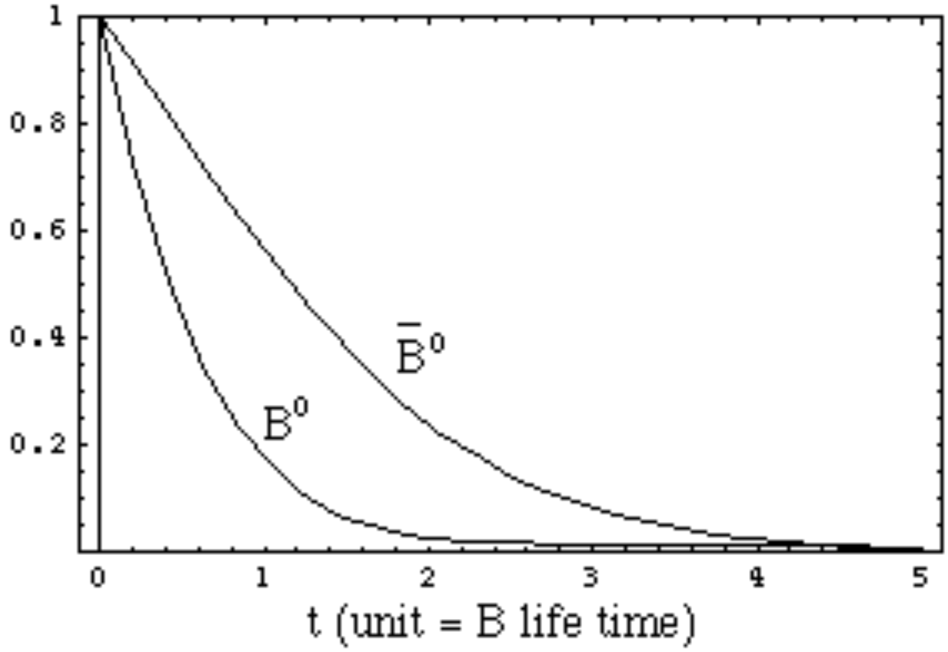
$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.08 \pm 0.02 \quad (\text{from } b \to u\ell\nu)$$



$\sin 2\beta \sim 1$

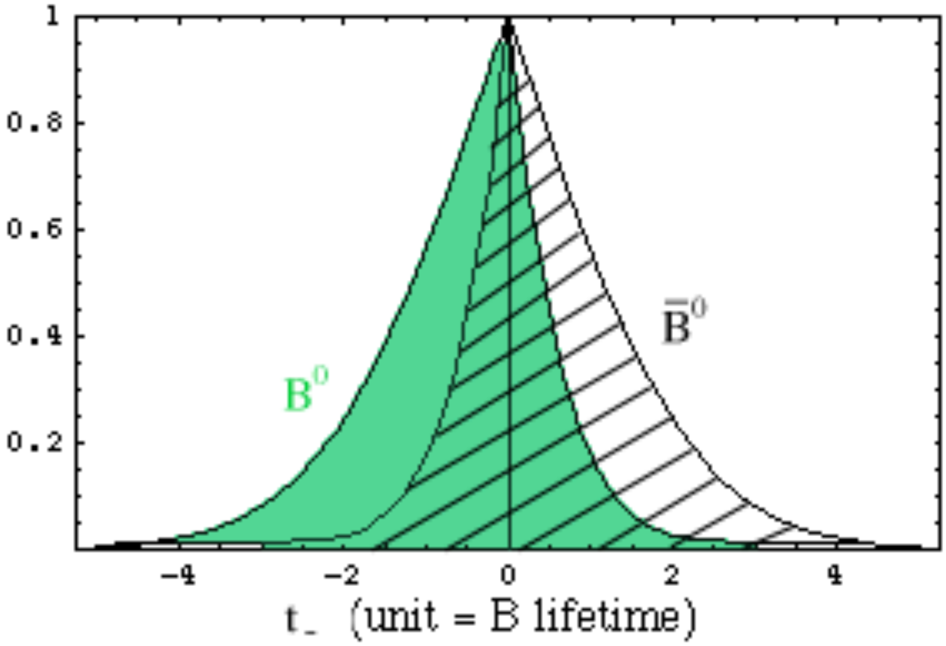
Use $\sin 2\beta = 0.8$.

$$\Gamma_{B^0(\bar{B}^0)\to\Psi K_S}(t)$$



Total rate asymmetry ~ 0.4.

$\Gamma_{4S\to\ell^\mp f}(t_-)$

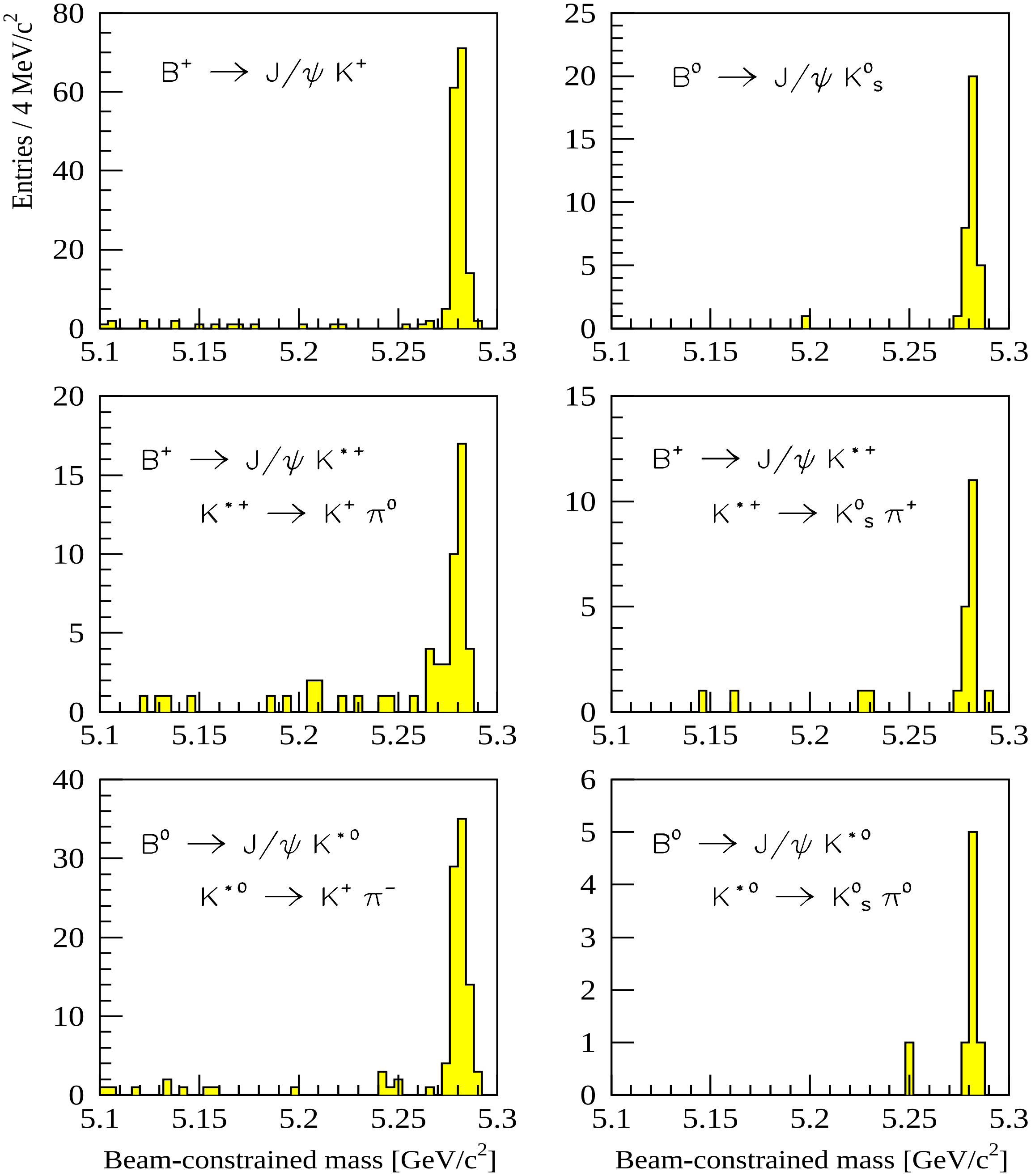


$B^0 \equiv \ell^-$ tag, $\quad \bar{B}^0 \equiv \ell^+$ tag,

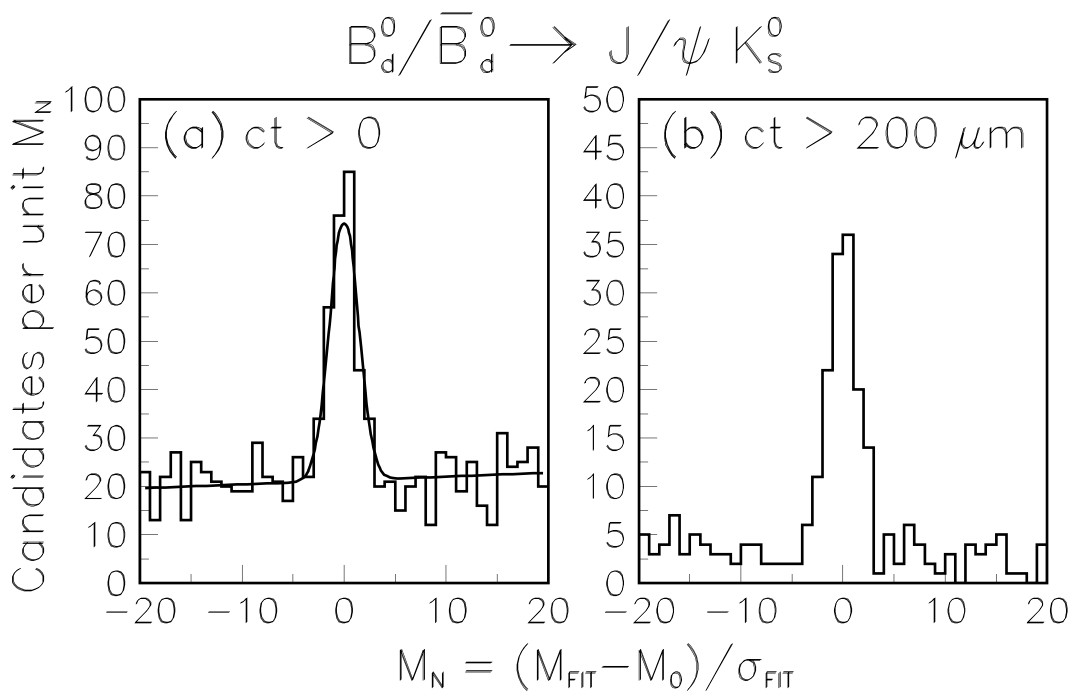
Total rate asymmetry $= 0$
$\rightarrow$ need to measure t_-
($\Rightarrow$ Asymmetric B-factory)

[At CLEO, $B^0\bar{B}^0$ are nearly at rest]

$\psi K^{(*)}$ **(CLEO)** ($\sim$ 1/2 of data)

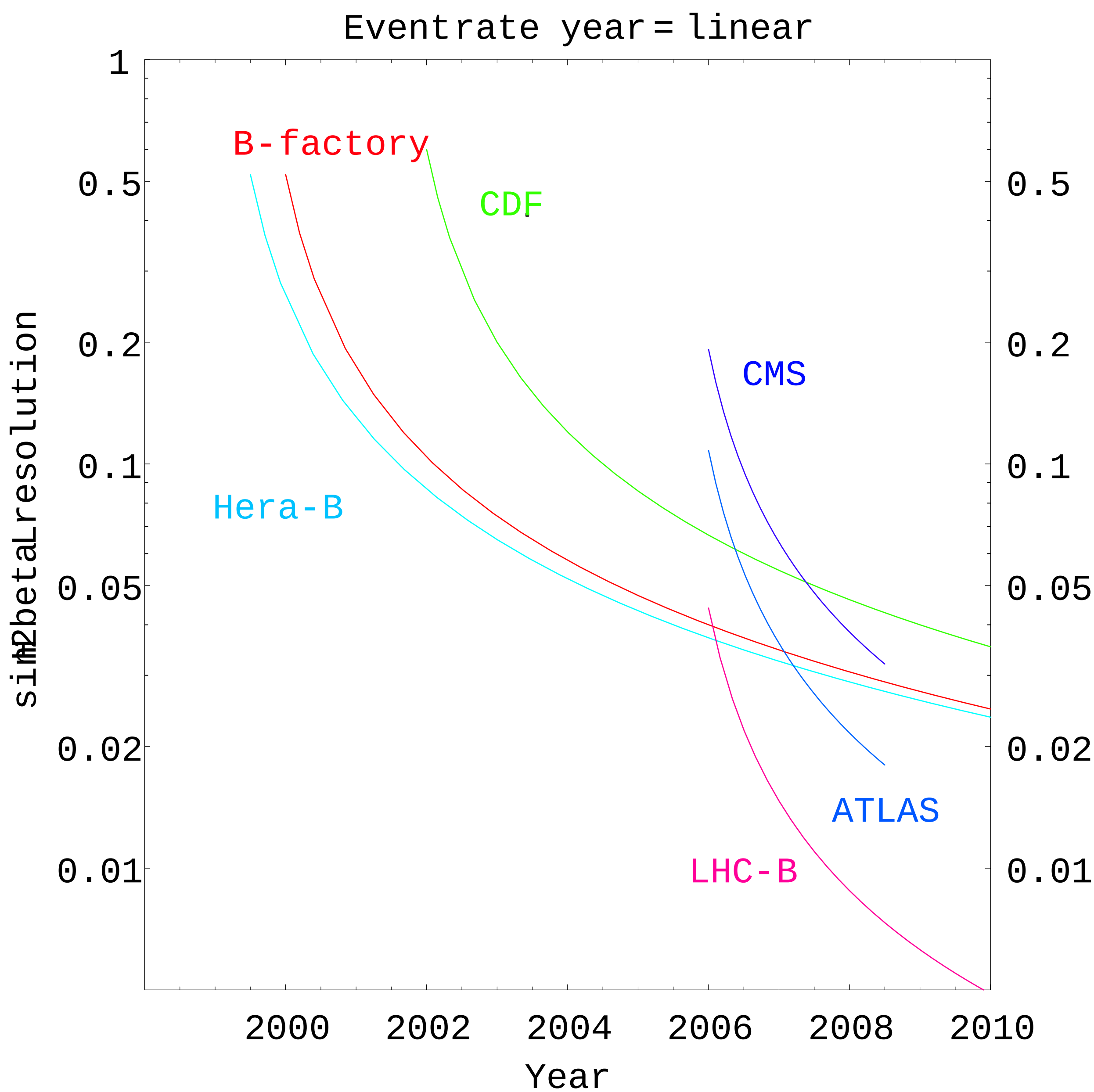


CDF $B \to \Psi K_S$



$\sin 2\beta = 1.8 \pm 1.1 \pm 0.3 \quad (CDF)$

OPAL: $\sin 2\beta = 3.2^{+1.8}_{-2.0} \pm 0.5$



$\sin 2\beta$ **sentivities of B-facilities**

Assume $\begin{cases} \text{Takes 2 yrs to design luminosity} \\ \text{Luminosity increases linearly with time} \end{cases}$

IV. CPV in decays

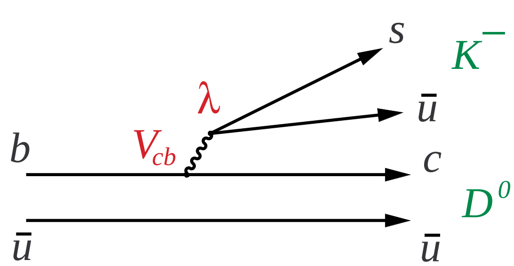
Measurement of γ: $B^- \to D^0 K^{(*)-}$

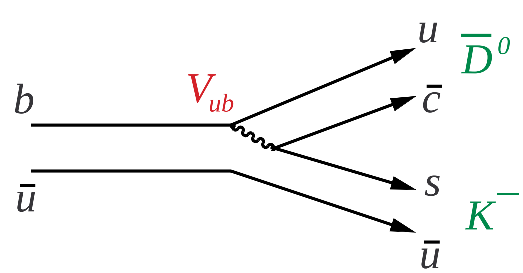
Gronau-London-Wyler (GLW) method:

$$B^- \to D^0_{CP} K^-$$

D^0_{CP} : CP eigenstate. e.g. $K_S\pi^0, K^+K^- \cdots$

Both D^0 and $\bar{D}^0$ decay to a CP eigenstate.
$\to$ 2 diagrams

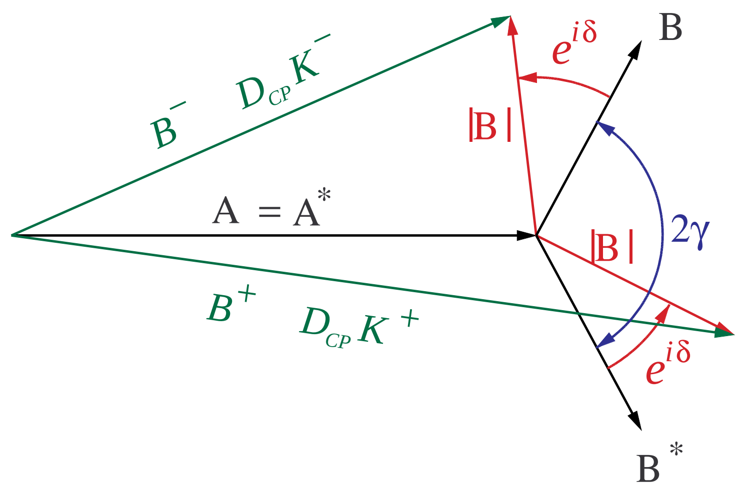




$A \equiv Amp(B^- \to D^0 K^-)$	$B \equiv Amp(B^- \to \bar{D}^0 K^-)$
λV_{cb}	$V_{ub} \sim 0.4\lambda V_{cb}$
Color-favored	Color-suppressed($\sim 1/5$)
$\bar{A} \equiv Amp(B^+ \to \bar{D}^0 K^+)$	$\bar{B} \equiv Amp(B^+ \to D^0 K^+)$
$\bar{A} = A^*$	$\bar{B} = B^*$

Strong final-state-interaction (FSI) phase:
B relative to A : $e^{i\delta}$ (δ could be complex)

(Phase convention: $A = A^*$)



$\gamma = \arg B^* \sim \arg V_{ub}^*$

Measure 4 lengths:

$$\left.\begin{array}{l} (1)\ Amp(B^- \to D^0_{CP}K^-) \\ (2)\ Amp(B^+ \to D^0_{CP}K^+) \end{array}\right\} \text{difference: } CPV$$

(3) $|A|$ by $B^- \to D^0 K^-,\ D^0 \to K^-\pi^+$

(4) $|B|$ by $B^- \to \bar{D}^0 K^-,\ \bar{D}^0 \to K^+\pi^-$

Reconstruct two triangles $\to \gamma$
(2-fold ambiguity)

CP asymmetry expected (e.g. for $D \to K_S\pi^0$):

$$a_{cp} \equiv \frac{\Gamma[B^- \to (K_S\pi^0)K^-] - \Gamma[B^+ \to (K_S\pi^0)K^+]}{\Gamma[B^- \to (K_S\pi^0)K^-] + \Gamma[B^+ \to (K_S\pi^0)K^+]}$$

$$\frac{|B|}{|A|} \sim \underbrace{(\text{color factor})}_{\sim 1/5}\underbrace{(\text{CKM factor})}_{\frac{V_{ub}}{\lambda V_{cb}} \sim 0.4} \sim 0.08$$

$\to a_{cp}$ is of order 8%.

Relevant D^0 decay modes:

CP eigenstates (same $\lvert a_{cp}\rvert$)	$K_S\,\pi^0$	$1.06 \pm 0.11\%$
	$K_S\,\rho^0$	$0.60 \pm 0.09\%$
	$K_S\,\phi$	$0.84 \pm 0.10\%$
	K^+K^-	$0.43 \pm 0.03\%$
	$\pi^+\pi^-$	$0.15 \pm 0.01\%$
calibration	$K^-\pi^+$	$3.83 \pm 0.12\%$

Once $B \to D^0K^-$ is seen in the $K^-\pi^+$ mode is observed, CP asymmetry is not far away (apart from extracting γ)

Problem with the GLW method and Solution
[Atwood, Dunietz, Soni (ADS)]

How to measure $B = Amp(B^- \to \bar{D}^0 K^-)$?

$$B^- \xrightarrow{B} \bar{D}^0\, K^- \quad \text{but also} \quad B^- \xrightarrow{A} D^0\, K^-$$
$$\hookrightarrow K^+\pi^- \qquad\qquad\qquad \hookrightarrow K^+\pi^- \;(DCSD)$$

The ratio of the two amplitudes (R):

$$R = \underbrace{\frac{A}{B}}_{\sim \frac{1}{0.08}} \underbrace{\frac{Amp(D^0 \to K^+\pi^-)}{Amp(\bar{D}^0 \to K^+\pi^-)}}_{\substack{0.088 \pm 0.020 \\ \text{(CLEO 94)}}} \sim 1$$

Phase of R not known $\to$ cannot measure $|B|$.

But: This interference causes CP asymmetry of **order unity** in the wrong-sign $K\pi$ modes:

$$\Gamma[B^- \to (K^+\pi^-)K^-] \quad \text{vs} \quad \Gamma[B^+ \to (K^-\pi^+)K^+]$$

ADS method to extract γ

Measure $B^- \to DK^-$ in two decay modes of D:
wrong-sign flavor-specific modes or CP eigenstates,
say $K^+\pi^-$ and $K_S\,\pi^0$ (and their conjugate modes).

wrong-sign	CP eigen state
$\Gamma[B^- \to (K^+\pi^-)K^-]$	$\Gamma[B^- \to (K_S\,\pi^0)K^-]$
$\Gamma[B^+ \to (K^-\pi^+)K^+]$	$\Gamma[B^+ \to (K_S\,\pi^0)K^+]$

Assume we know $|A|$ and D branching fractions
$\to$ 4 unknowns:

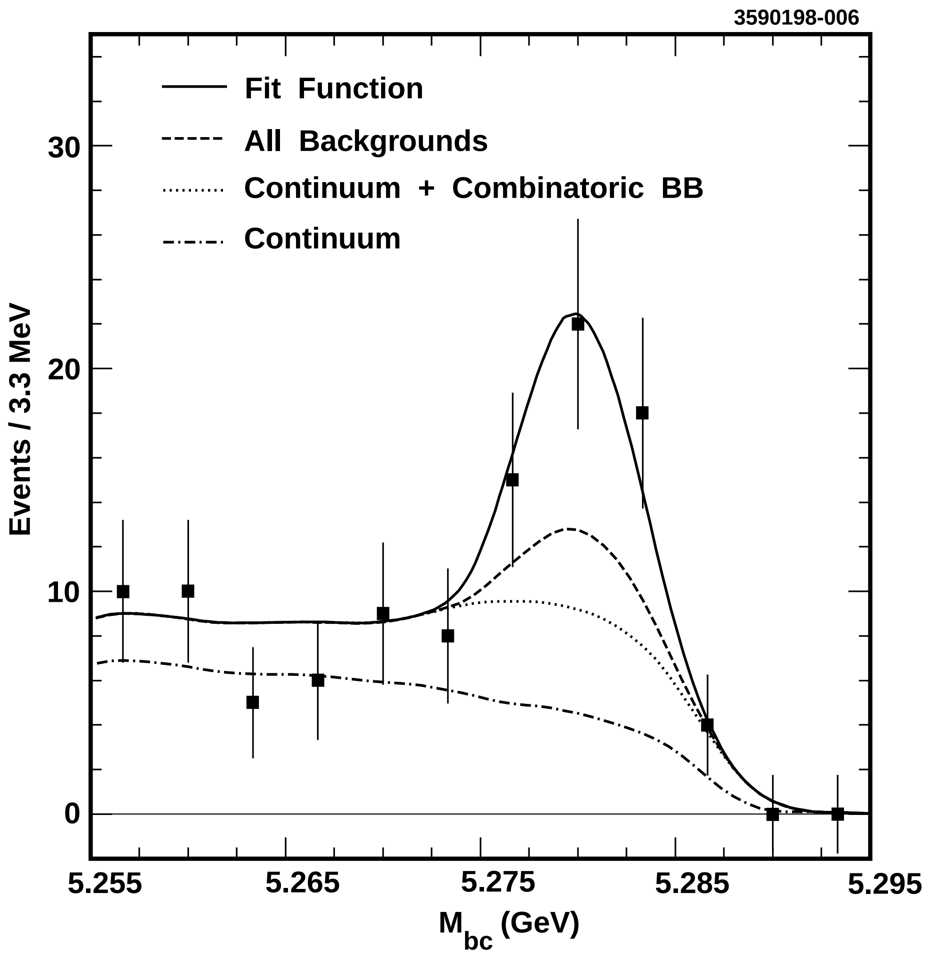
$$\gamma\,, \quad \delta_{K^-\pi^+}\,, \quad \delta_{K_S\pi^0}\,, \quad \frac{|B|}{|A|}$$

$\to$ can be solved.

Statistics: barely possible at B-factories?
(at least 10^8 B's needed)
$\to$ hadron machines

$B^- \to D^0 K^-$ (CLEO)

$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$

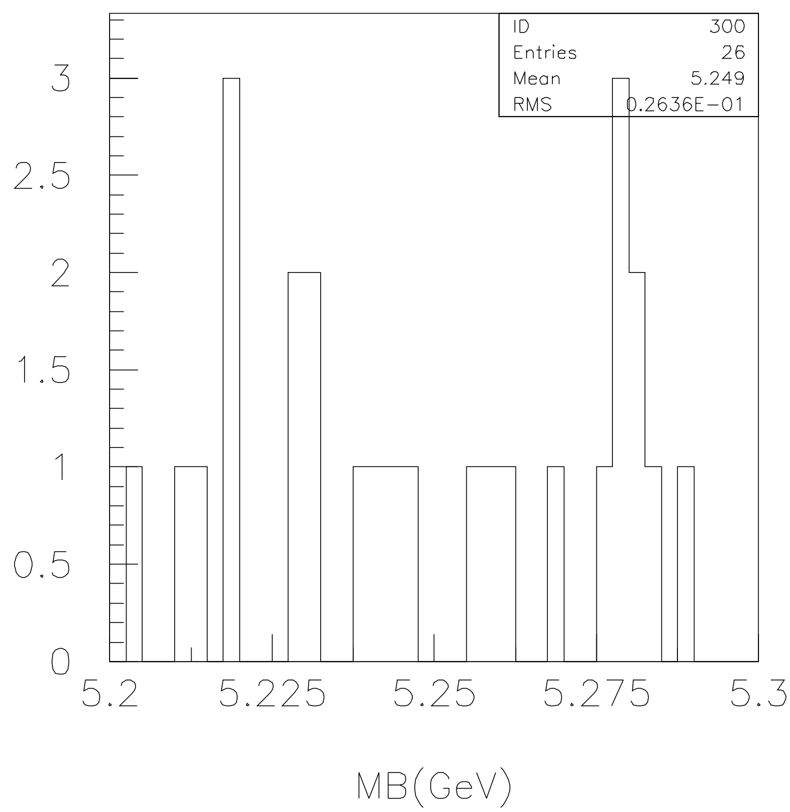


$$\frac{Br(B^- \to D^0 K^-)}{Br(B^- \to D^0 \pi^-)} = 0.055 \pm 0.014 \pm 0.005\,.$$

Large background from $B^- \to D^0 \pi^-$

$B^- \to D^0 K^{*-}$ $(K^{*-} \to K_S\,\pi^-)$

(CLEO) Very Preliminary



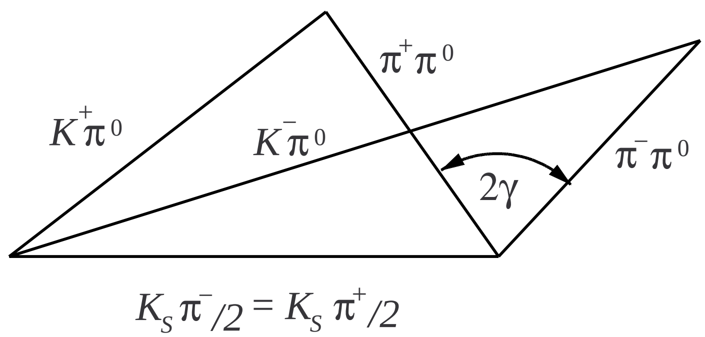
$B \to K\pi, \pi\pi$

Tree-penguin interference
$\to$ large direct CP asymmetries expected.

CP asymmetry requires and depends on FSI phases
(difficult to calculate).

But: Amplitude relations $\to$ α, γ, FSI phases.

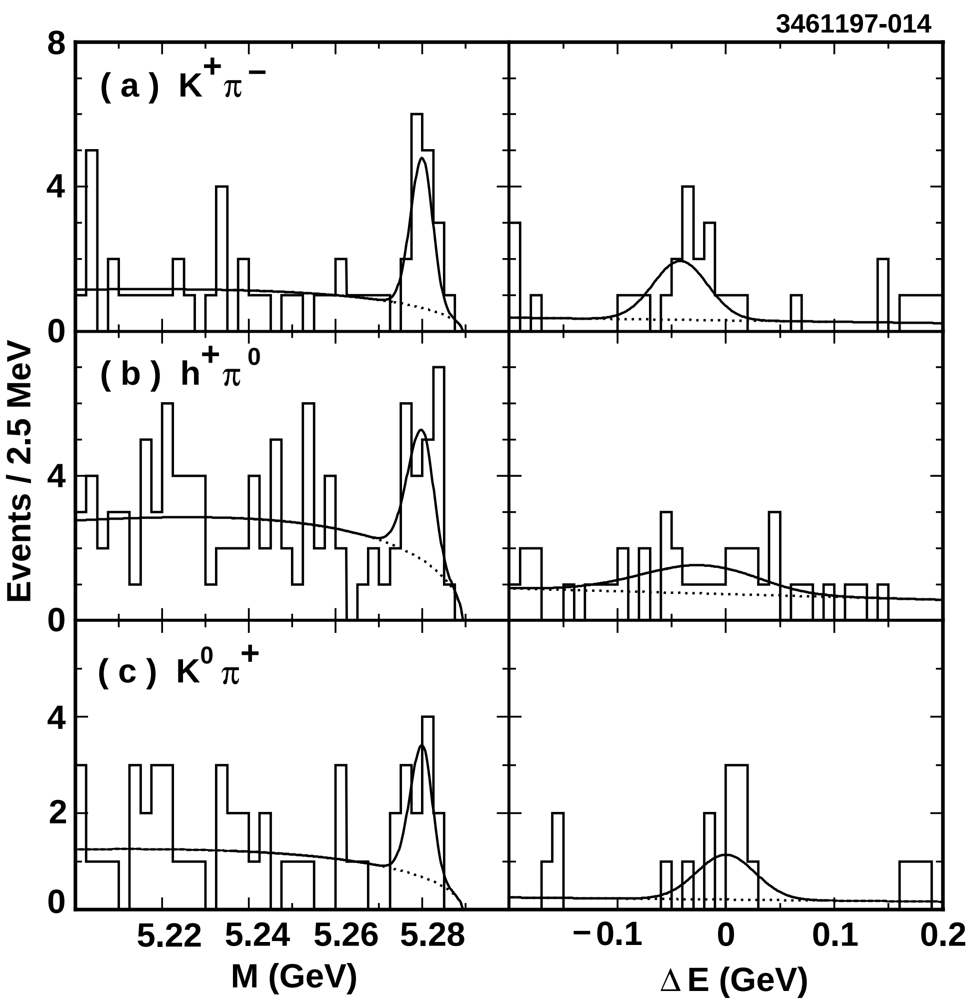
For example:



Note:

- All charged B modes $\to$ self-tagging.
- SU(3) breaking effect and FSI can alter the diagram.

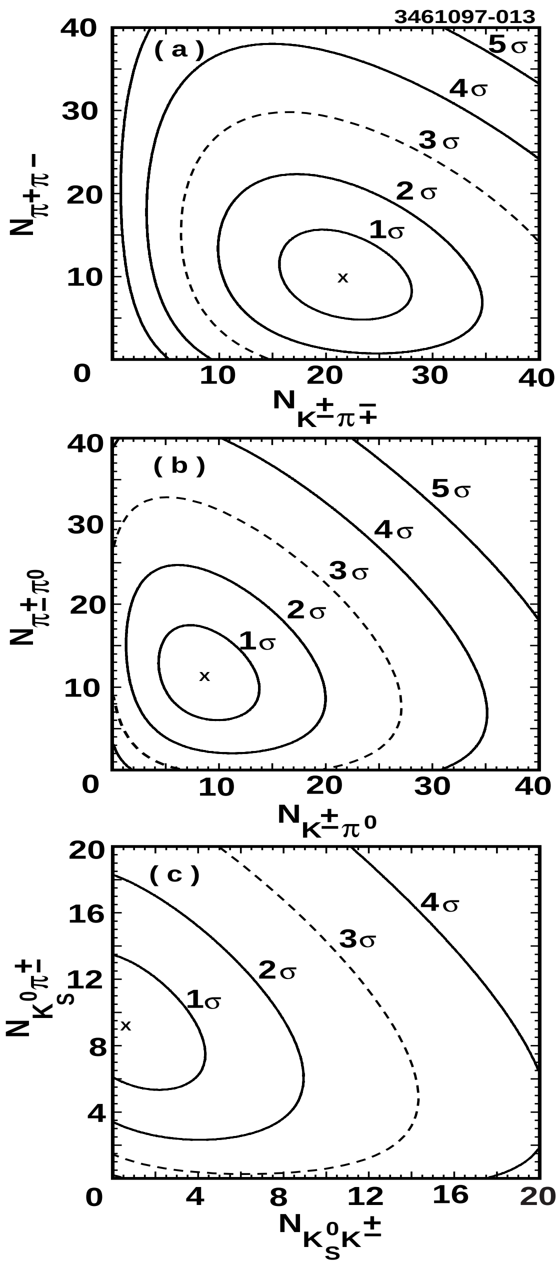
$B \to K\pi, \pi\pi$



$\Delta E \equiv E_{\text{beam}} - E_{\text{cand}}$

Likelihood fit for $K\pi$ modes

($K^{\pm}/\pi^{\pm}$ separation: dE/dx + kinematics)



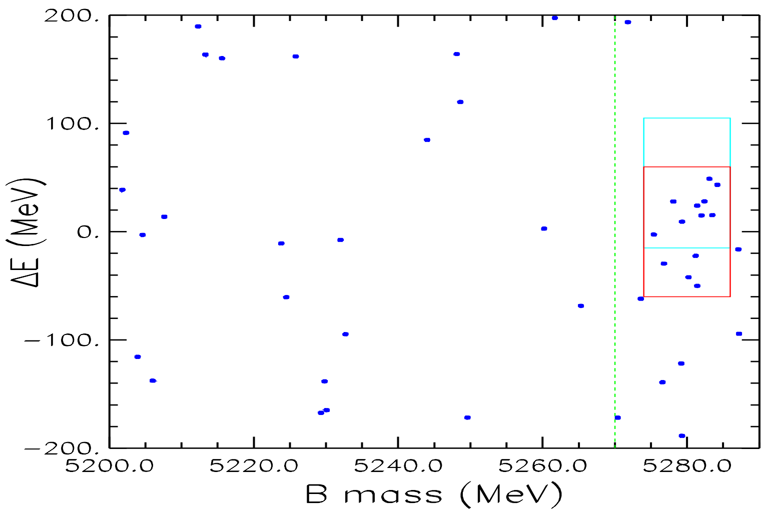
$K\pi$ modes summary

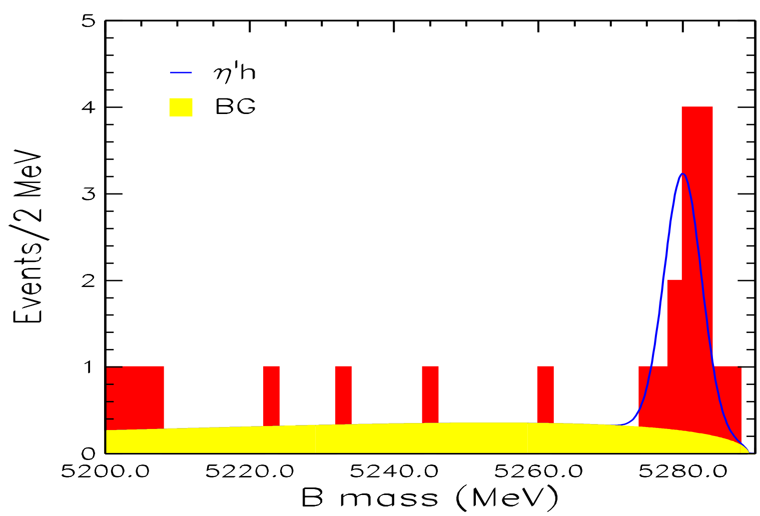
	N(signal)	signif.	$Br(10^{-5})$
$\pi^+\pi^-$	9.9	2.2σ	< 1.5
$\pi^+\pi^0$	11.3	2.8σ	< 2.0
$\pi^0\pi^0$	2.7	2.4σ	< 0.93
$K^+\pi^-$	21.6	5.6σ	$1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.1$
$K^+\pi^0$	8.7	2.7σ	< 1.6
$K^0\pi^+$	9.2	3.2σ	$2.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.2$
$K^0\pi^0$	4.1	2.2σ	< 4.1
K^+K^-	0.0	0.0σ	< 0.43
K^+K^0	0.6	0.2σ	< 2.1
K^0K^0	0	–	< 1.7
$h^+\pi^0$	20.0	5.5σ	$1.6^{+0.6}_{-0.5} \pm 0.3 \pm 0.2$

(h^+ : K^+ or π^+)

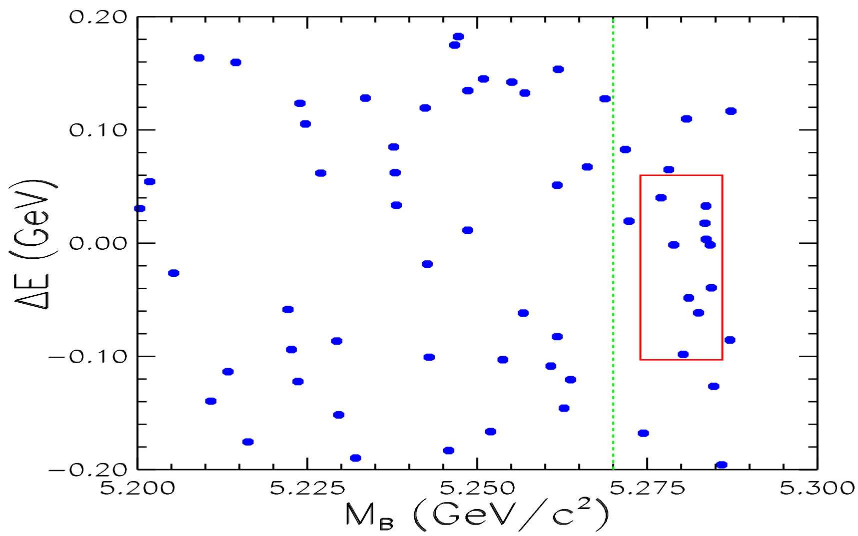
blue: the SU(3) triangle modes.

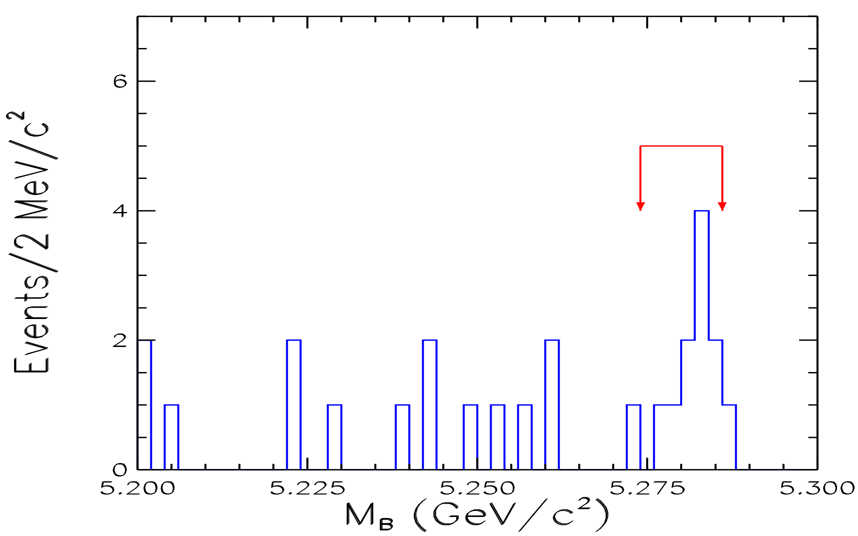
$$B \to \eta' h^- \quad (h^- = K^- \text{ or } \pi^-), \qquad \eta' \to \eta\pi^+\pi^-$$





$B \to \omega h^- \quad (h^- = K^- \text{ or } \pi^-)$





	$Br(\times 10^{-5})$	Signif.
$B \to \eta' K^-$	$6.5^{+1.5}_{-1.4} \pm 0.9$	7.5σ
$B \to \eta' K^0$	$4.7^{+2.7}_{-2.0} \pm 0.9$	3.8σ
$B \to \eta' K^{*0}$	< 3.9	
$B \to \eta K^-$	< 1.4	
$B \to \omega K^-$	$1.5^{+0.7}_{-0.6} \pm 0.2$	3.9σ
$B \to \omega h^-$	$2.5^{+0.8}_{-0.7} \pm 0.3$	5.5σ

Why $\eta' K^-$ so large ?
($\sim$ 5 times larger than pre-CLEO theory)

Why $\eta' K > \eta' K^*$?

QCD anomaly
$c\bar{c}$ content of η'
Strong η' coupling to gluons

Summary

1. Already in currently available data:
   (a) CPV in mixing: $\sigma_\ell \sim 0.6\%$. (0.1 - 1% expected)
   (b) CPV by mixing-decay interference:
   $\sigma_{\sin 2\beta} \sim 1$ (CDF)
   (c) CPV in decay: We already observe:
   $D^0\pi^-$, $K^-\pi^+$, $K_S\pi^+$, $\eta' K^-$, $\eta' K^-$, ωK^-.
   Many other modes are more than 2σ.
   Any of these could have CPV of up to tens of %.
2. Many other channels not discussed here:
   (a) $B \to \pi^+\pi^-$ time-dependent asymmetry (α)
   (b) Inclusive CPV: $B \to K^* X$ etc.
   (c) CPV in B_s.

The era of overwhelmingly rich and diverse CPV in B decays is about to begin. Fasten your seatbelt and enjoy the ride!