Progress in Heavy-Quark Physics from BABAR, Belle, and CLEO

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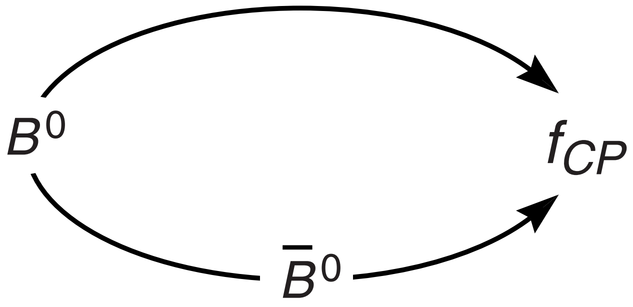
Outline

1. **Why is heavy-quark physics interesting?**
2. **New experiments and accelerators running at the** $\Upsilon(4S)$
3. **Measurements and what they tell us:**
   - The simplest processes: semileptonic and leptonic decays and the magnitudes of CKM elements
   - Rare B decays, penguins, and searches for direct CP violation
   - Mixing in the neutral D and B meson systems
   - Time-dependent CP asymmetries from the interference between mixing and decay
4. **Conclusions and prospects**

Why Is Heavy Quark Physics Interesting?

1. What is the origin of CP violation?

   - SM predicts potentially *very large* CP asymmetries in the B meson system arising from the interference between $B^0 - \bar{B}^0$ mixing and decay. Because we can extract interference information from asymmetries as opposed to rates, in certain cases all of the uncertainties due to hadronic effects cancel out in the ratio.
   - New experiments will perform a comprehensive set of measurements to determine whether CP asymmetries in the B-meson system are consistent with Standard-Model predictions, or whether new physics is required to explain the observations.



The Legacy of Kaon Physics

...the effect [of CP violation] is telling us that at some tiny level there is a fundamental asymmetry between matter and antimatter, and it is telling us that at some tiny level interactions will show an asymmetry under the reversal of time. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in coming decades. We are hopeful, then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered.

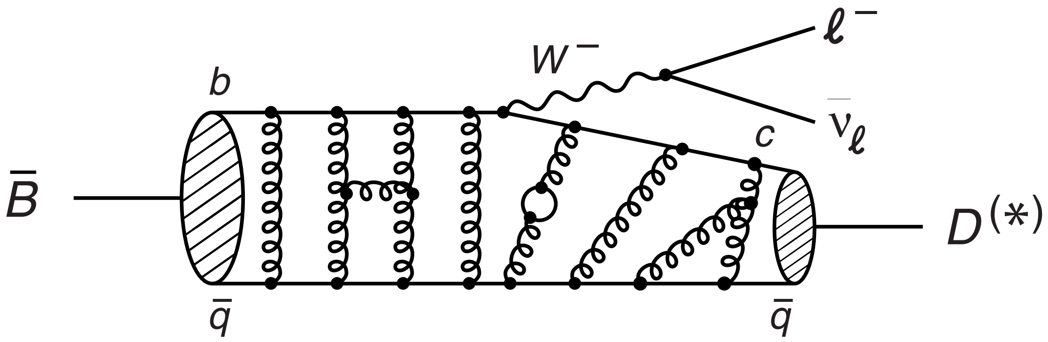
...J. W. Cronin, Rev. Mod. Phys. **53**, *373 (1981). (Nobel Prize lecture on the discovery of CP violation in $K^0 - \bar{K}^0$ system.)*

Both K and D studies still have large a large role to play in advancing our understanding of issues related to quark-flavor physics.

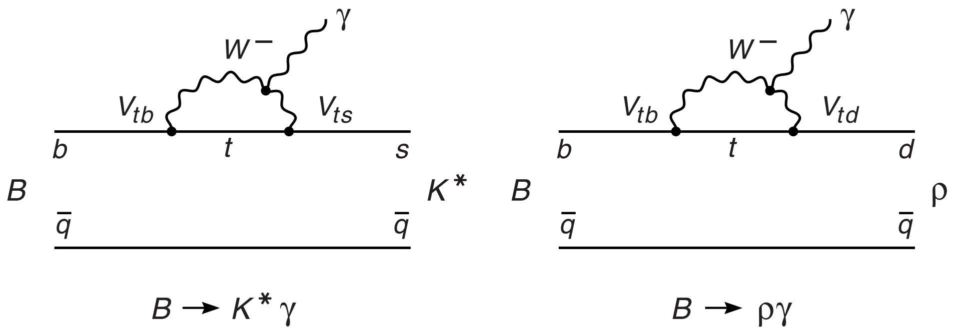
2. Measure the *rates* for relatively simple processes to extract the *magnitudes* CKM matrix elements. In the standard model, semileptonic decays are simple tree diagrams with no interference effects.

   - $|V_{cb}|$ and $|V_{ub}|$ are determined from semileptonic decays; while $|V_{td}|$ and $|V_{ts}|$ can be determined from $B^0 - \bar{B}^0$ and $B_s - \bar{B}_s$ mixing, as well as $b \to t \to s(d)$ penguin processes.
   - Measurement of the magnitude of a CKM element requires significant theoretical input based on an understanding of the decay dynamics:

$$B(M_{Q\bar{q}} \to X_{q'\bar{q}} \ell \nu) = \gamma_{\text{theory}} |V_{q'Q}|^2 \tau_M .$$



3. Search for the effects of new physics in a variety of sensitive processes with loops.
   - Electroweak- and hadronic-penguin decays; $D^0 - \bar{D}^0$ mixing, etc.

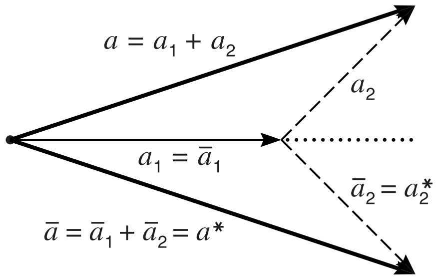


4. Understand the complicated interplay between the underlying weak processes and strong interaction effects.
   - Measure and understand meson decay constants, semileptonic decay form factors, patterns of hadronic decays
   - Impressive theoretical developments: heavy-quark effective theory (HQET), lattice QCD calculations, etc.

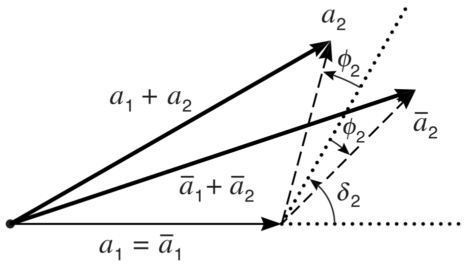
All of these goals are closely related!

Weak Phases and CP Violation

Graphical Representation



(a)



(b)

- Need processes in which the CP conserving phase δ_2 is well understood!

CP Violating Phase (ϕ_2) without CP Asymmetry

$$
\begin{aligned}
a &= a_1 + a_2 \\
&= |a_1| + |a_2| e^{i\phi_2} \\
\bar{a} &= |a_1| + |a_2| e^{-i\phi_2} \\
|\bar{a}| &= |a|
\end{aligned}
$$

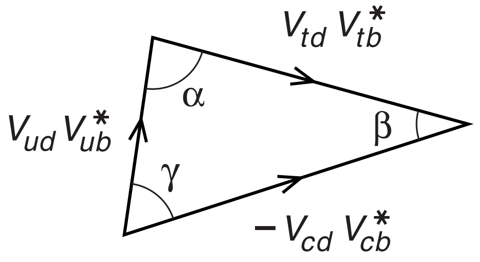
CP Violating Phase with CP Asymmetry

$$
\begin{aligned}
a &= a_1 + a_2 \\
&= |a_1| + |a_2| e^{i(\phi_2+\delta_2)} \\
\bar{a} &= |a_1| + |a_2| e^{i(-\phi_2+\delta_2)} \\
|\bar{a}| &\neq |a|
\end{aligned}
$$

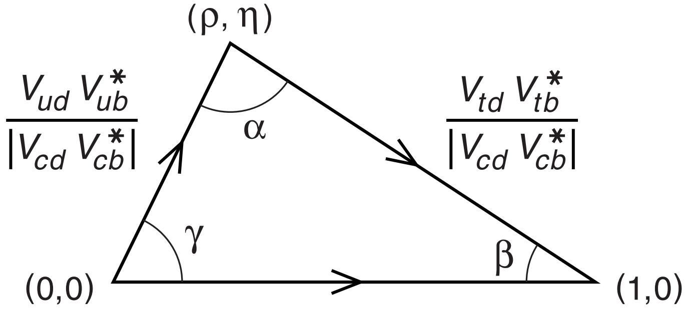
The CKM Matrix and Unitarity Triangle

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

- Unitarity + remove unphysical quark phases $\Rightarrow$ 4 independent parameters in standard model with 3 generations
- Wolfenstein: A, λ, ρ, η
- 6 unitarity triangles: all have same area proportional to $J_{CP} \simeq A^2\eta\lambda^6$ but the CP asym.'s aren't the same!
- Col 1$\times$ (Col 3)* gives standard triangle; all sides $\mathcal{O}(\lambda^3)$.

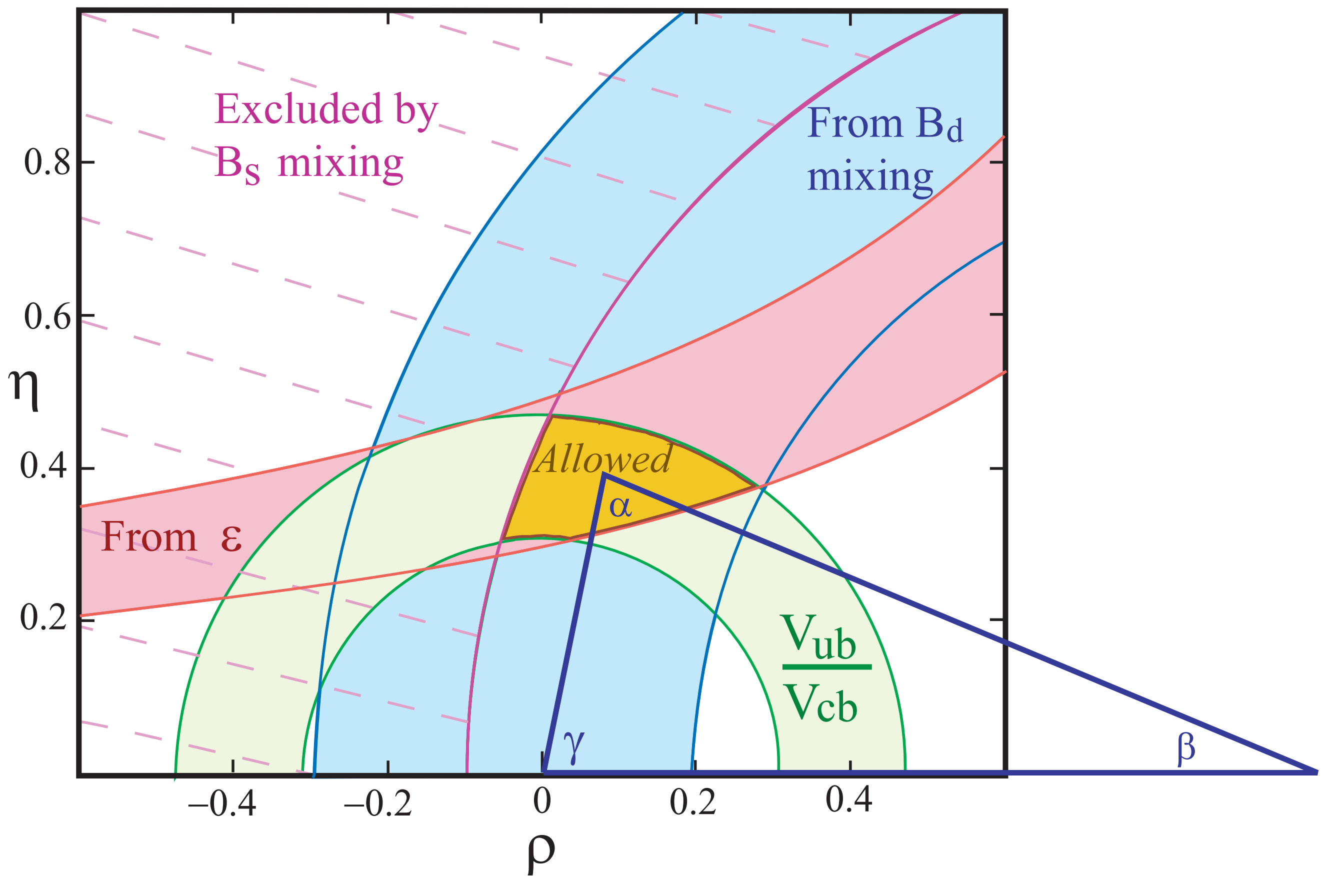


(a)



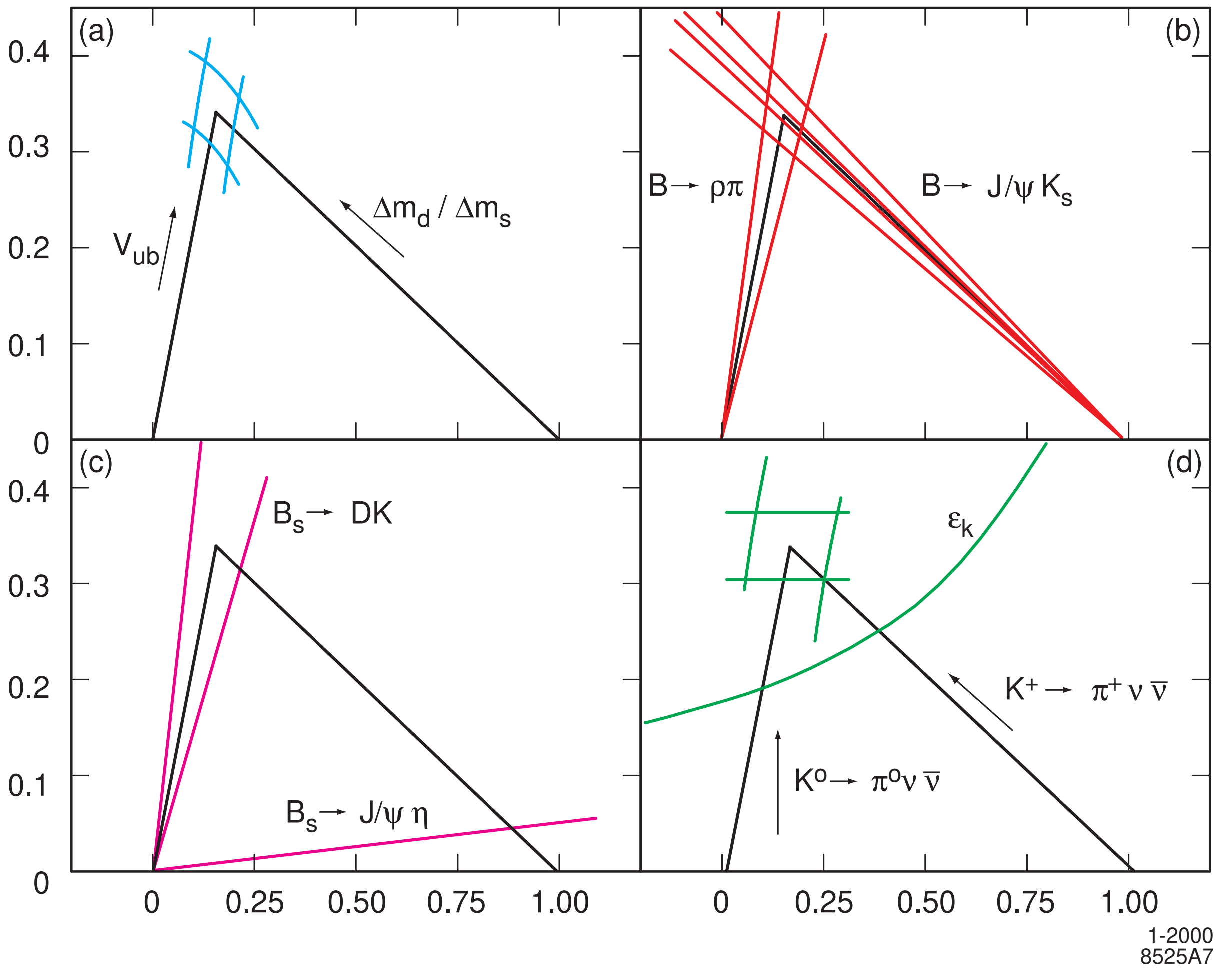
(b)

Individual Constraints on the Unitarity Triangle



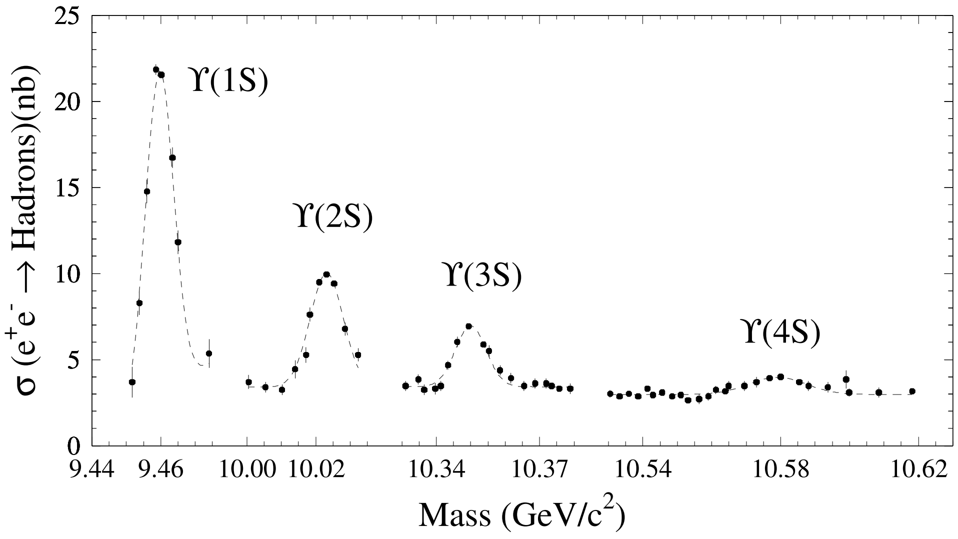
(Figure used with permission of Sheldon Stone.)

Another View of the Constraints



(Figure used with permission of Michael Peskin.)

Producing B Mesons Using $e^+e^- \to \Upsilon(4S)$



- The $\Upsilon(4S)$ is just above threshold for producing $B\bar{B}$ pairs, so there are no accompanying particles in the same event.

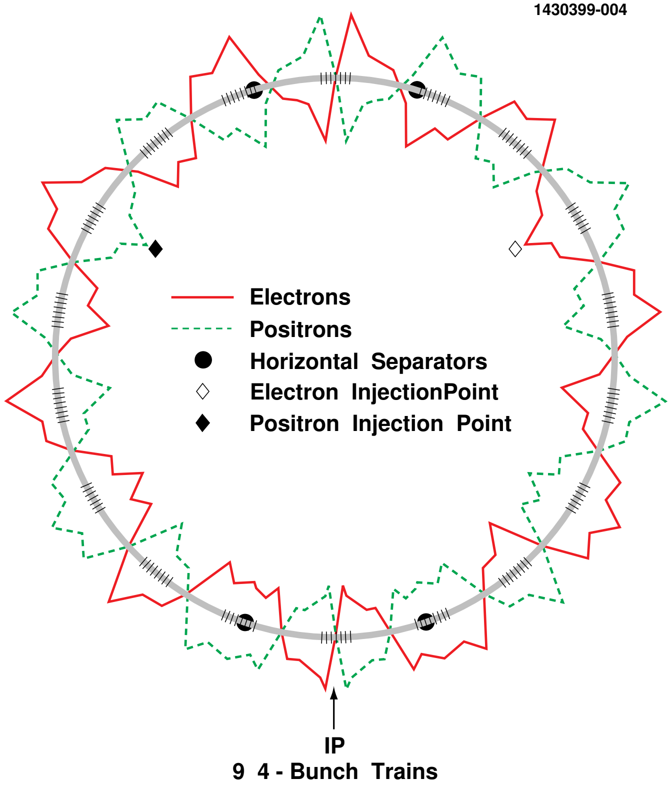
$$\begin{aligned} \Upsilon(4S) &\to B^0\bar{B}^0 \ (\approx 50\%), \\ &\to B^+B^- \ (\approx 50\%) \end{aligned}$$

- $\sigma(e^+e^- \to \Upsilon(4S) \approx 1.05$ nb
- $\sigma(e^+e^- \to q\bar{q}) \approx 3$ nb; $(q = \Sigma u, d, s, c)$

- $B\bar{B}$ production is a substantial fraction of the total hadronic cross section. Hadron machines have a much higher $b\bar{b}$ cross section ($\approx 50\ \mu$b), but this is a tiny fraction ($\approx 10^{-3}$) of the total hadronic rate.
- $p_B \approx 325$ MeV in $\Upsilon(4S)$ rest frame.
- $B\bar{B}$ events have spherical topology (unlike $Z \to b\bar{b}$); continuum events are jet-like.

The New B Factories

- The success of PEP-II (SLAC), KEK-B (Japan), and CESR (Cornell) has been a remarkable achievement. These are the highest luminosity colliding-beam machines in the world!
- Major issues:
  - very high-current, multibunch operation
  - avoid beam instabilities
  - avoid parasitic bunch crossings (not at IP)
  - high-quality vacuum to keep backgrounds tolerable for the experiments
  - extensive RF and vacuum system development

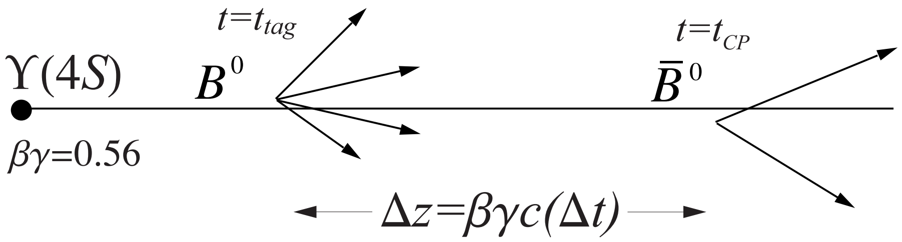


Pretzel orbits in the CESR storage ring. The maximum horizontal displacement of the beams from the center of the vacuum chamber is about 20 mm. Tic marks indicate parasitic crossing points for operation with 9 bunches and 4 bunches/train (14 ns separation).

MACHINE PARAMETERS

Machine	CESR	PEP-II	KEK-B
Detector	CLEO	BABAR	Belle
Date 1st events recorded	1979	May ’99	June ’99
Circumference (km)	0.768	2.199	3.016
# of Rings	1	2	2
E_{e^+} (GeV)	5.3	3.1	3.5
E_{e^-} (GeV)	5.3	9.0	8.0
$\beta\gamma$	0.06 (B)	0.56 ($\Upsilon(4S)$)	0.42 ($\Upsilon(4S)$)
# Beam bunches (design)	$9 \times 4 \rightarrow 9 \times 6$	1658	5000
$I_{\rm beam}$ (A)	$0.26 \rightarrow 0.5$	2.16 (e^+), 1.0 (e^-)	2.6 (e^+), 1.1 (e^-)
$\Delta s_{\rm bunch}$ (m)	4.2	1.26	0.6
$\Delta t_{\rm bunch}$ (ns)	14	4.2	2
Beam crossing angle (mrad)	± 2.1	0 (magnetic sep.)	± 11
Achieved Luminosity cm^{-2}s^{-1}	8.3×10^{32}	$\sim 2 \times 10^{33}$	$\sim 2 \times 10^{33}$
Integrated Luminosity (fb^{-1})	13	≈ 7.5	≈ 3.5

$B^0\bar{B}^0$ Production at Asymmetric-Energy Colliders

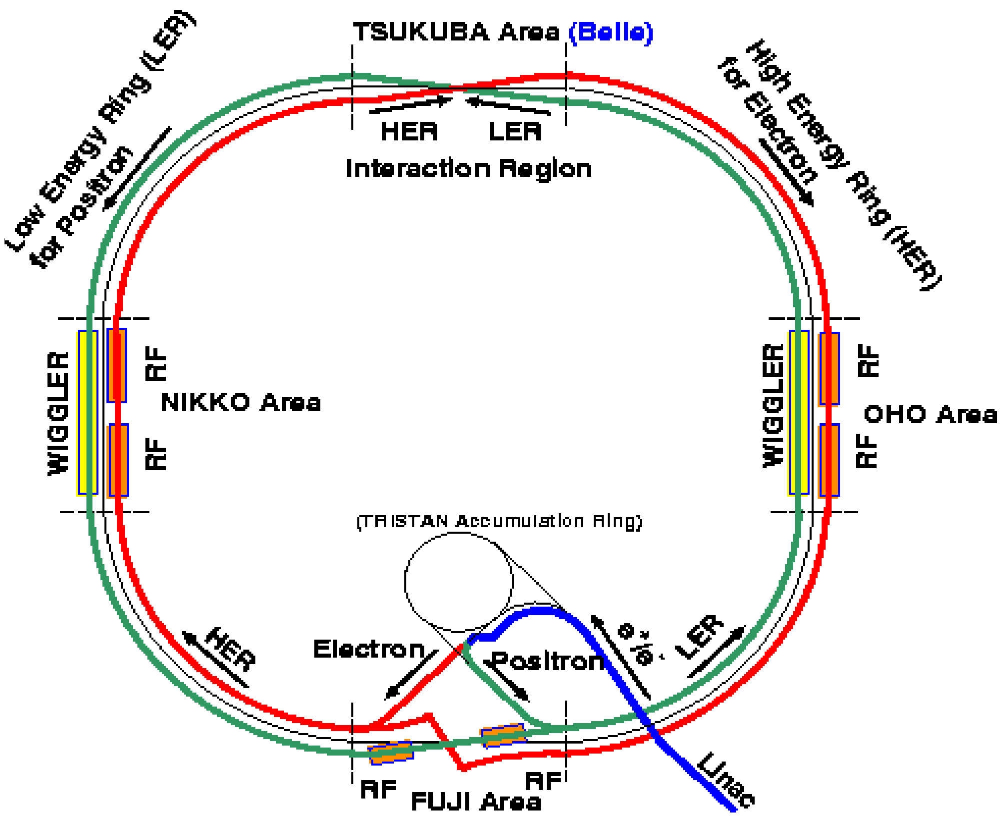


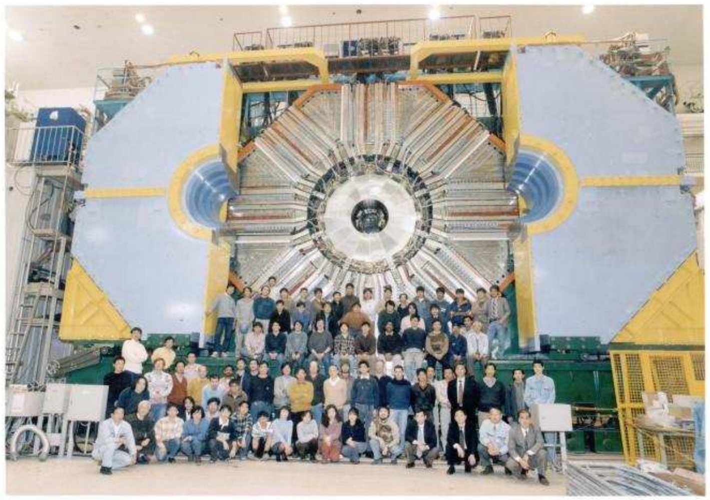
- The purpose of having asymmetric beam energies is to boost the $B^0\bar{B}^0$ system relative to the lab frame. $<\Delta t>=\tau_B=1.6$ ps

$$\begin{aligned} p_{\rm cm}=p_{\Upsilon(4S)} &= (E_{e^-}+E_{e^+},(E_{e^-}-E_{e^+})\hat{\mathbf{z}}) \\ E_{\rm cm}=\sqrt{4E_{e^-}E_{e^+}} &= M(\Upsilon(4S)) \\ \beta &= \frac{E_{e^-}-E_{e^+}}{E_{e^-}+E_{e^+}} \qquad \beta\gamma=\frac{E_{e^-}-E_{e^+}}{2E_{e^-}E_{e^+}} \\ \Rightarrow<\Delta z> &= \beta\gamma c\tau_B \approx 260\ \mu\text{m} \end{aligned}$$

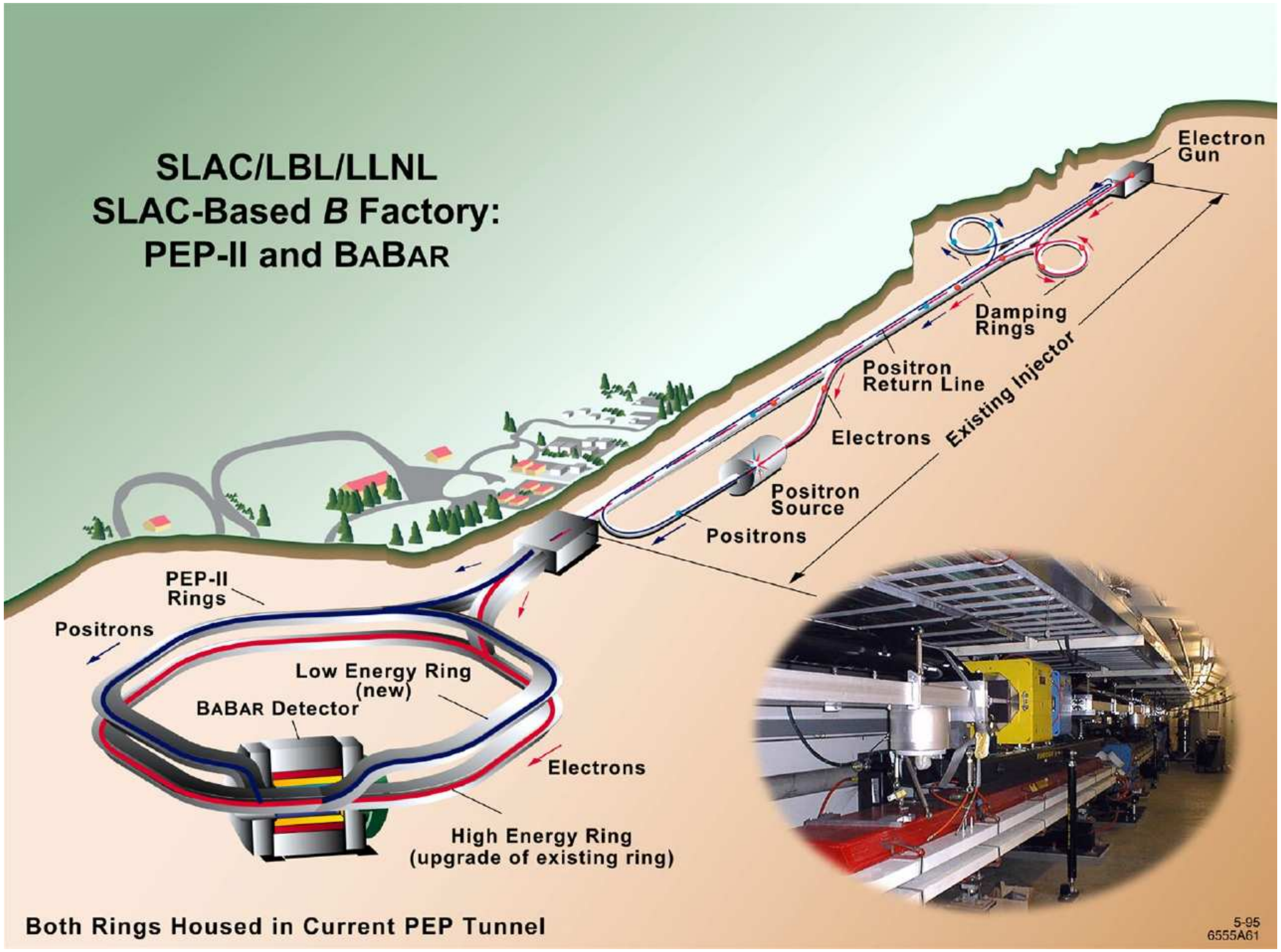
- By measuring Δz, we can follow time-dependent effects in B decays.
- The distance scale is much smaller than in kaon physics!

KEK-B and Belle

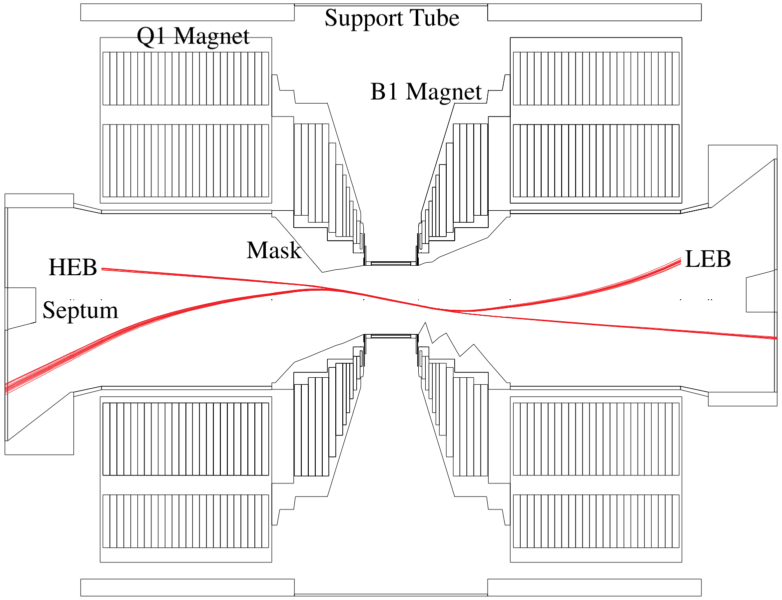


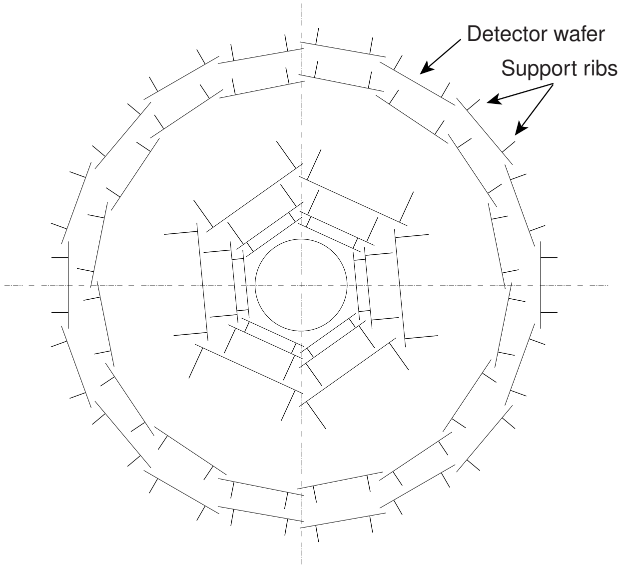


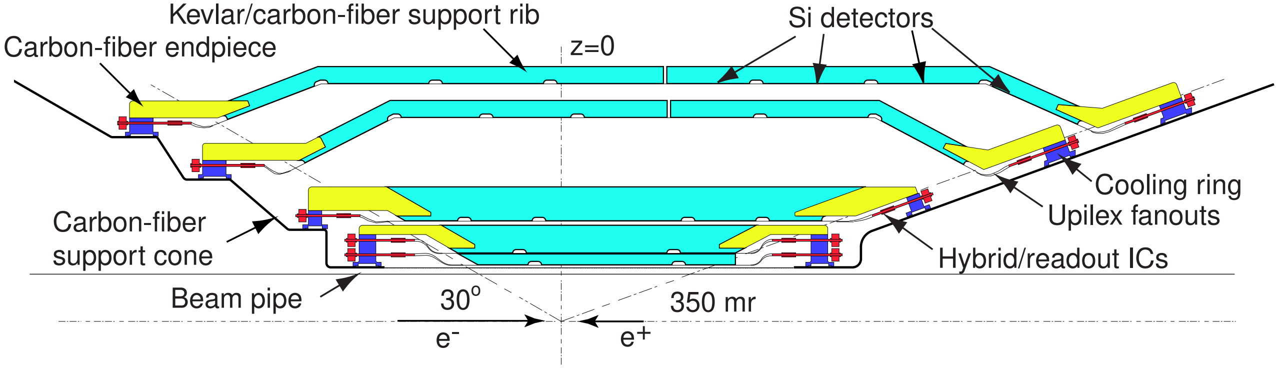
The PEP-II Project



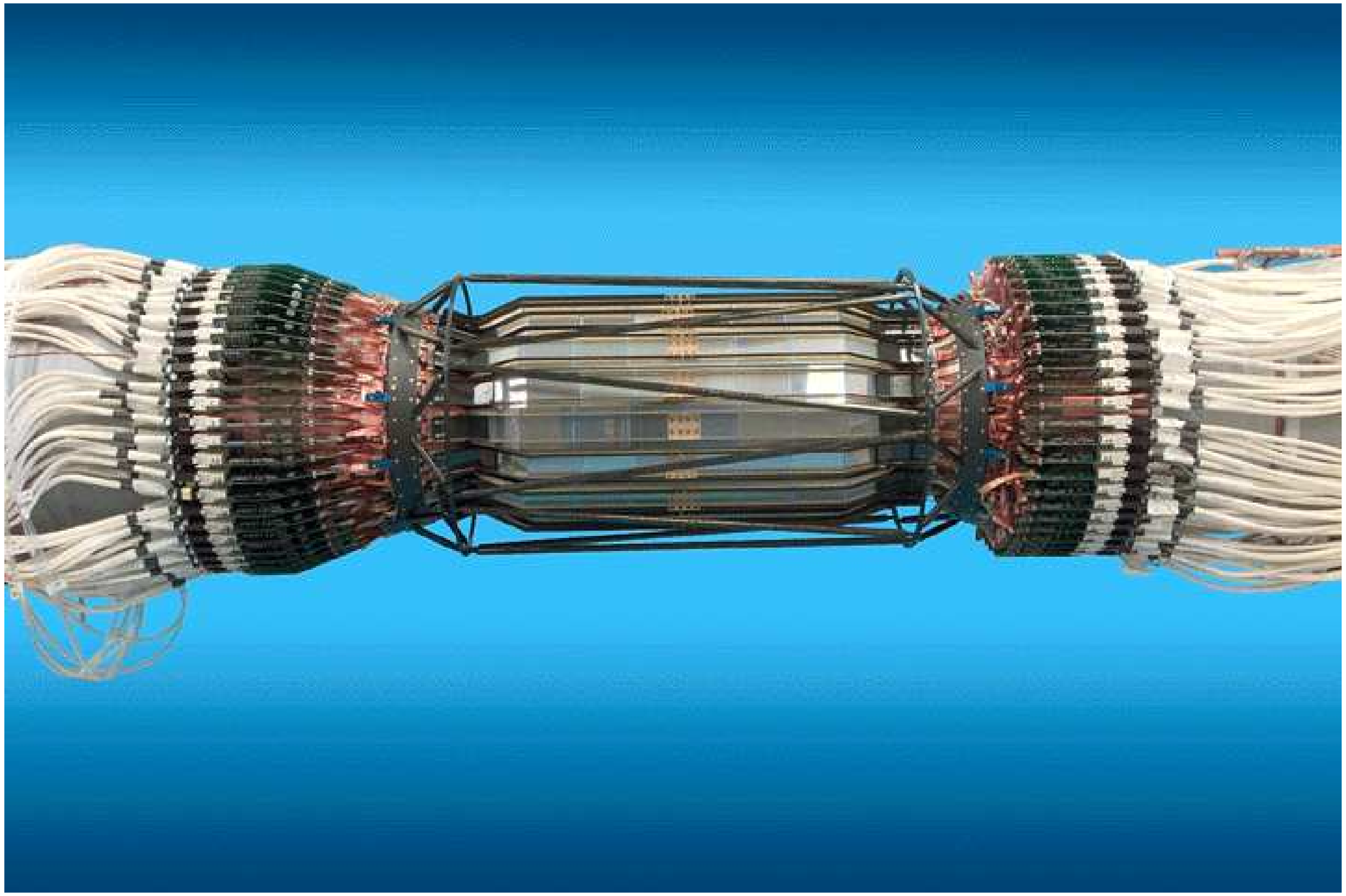
BABAR Interaction Region and Silicon Vertex Tracker



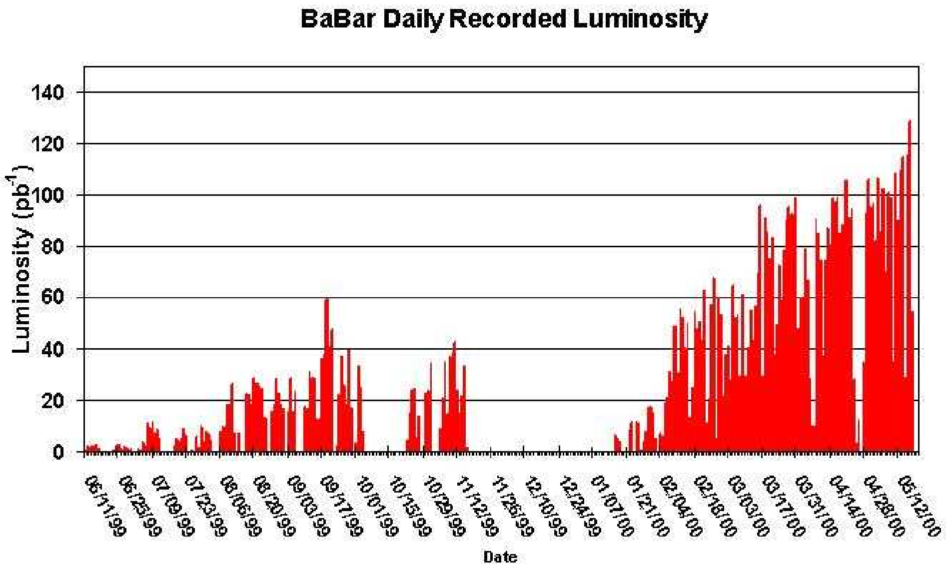


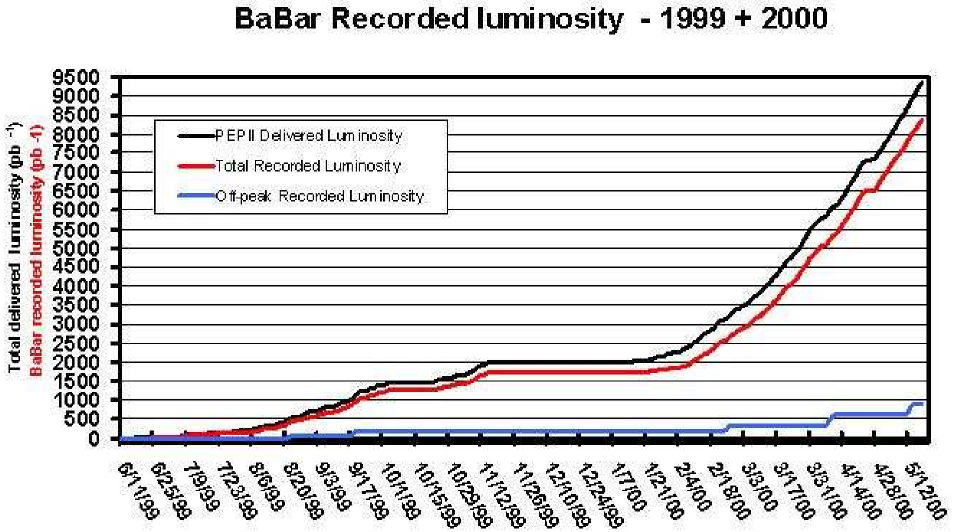


The BABAR Silicon Vertex Tracker



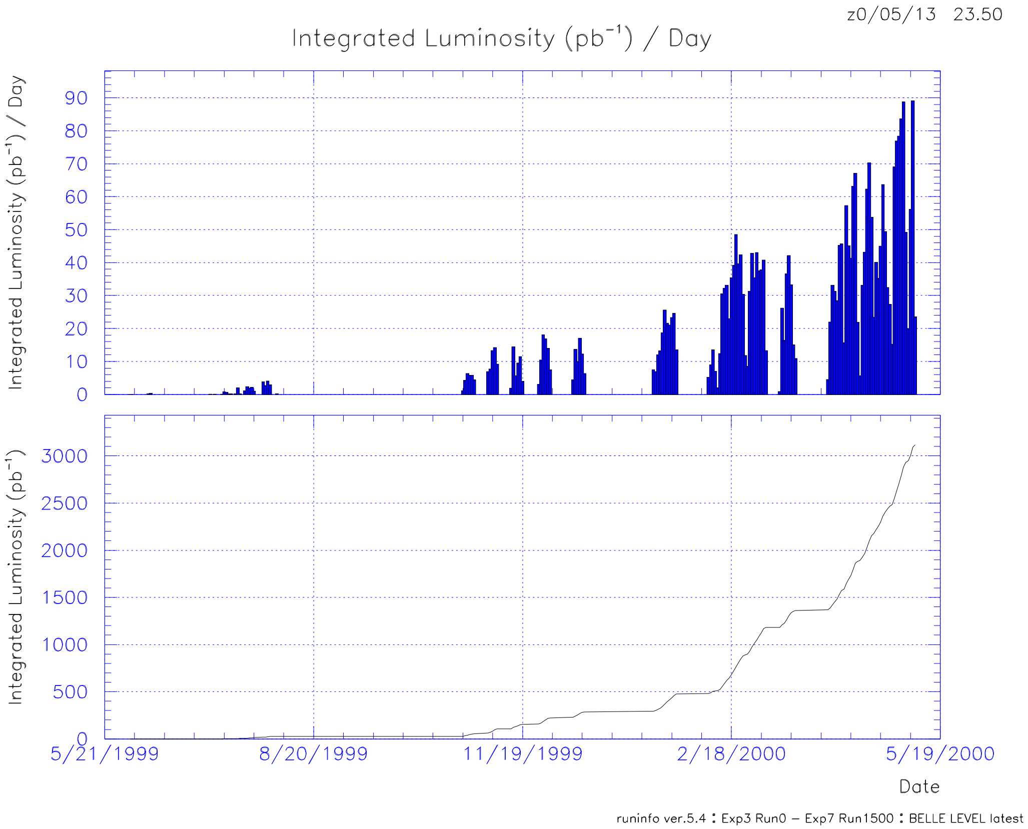
PEP-II/BABAR Running





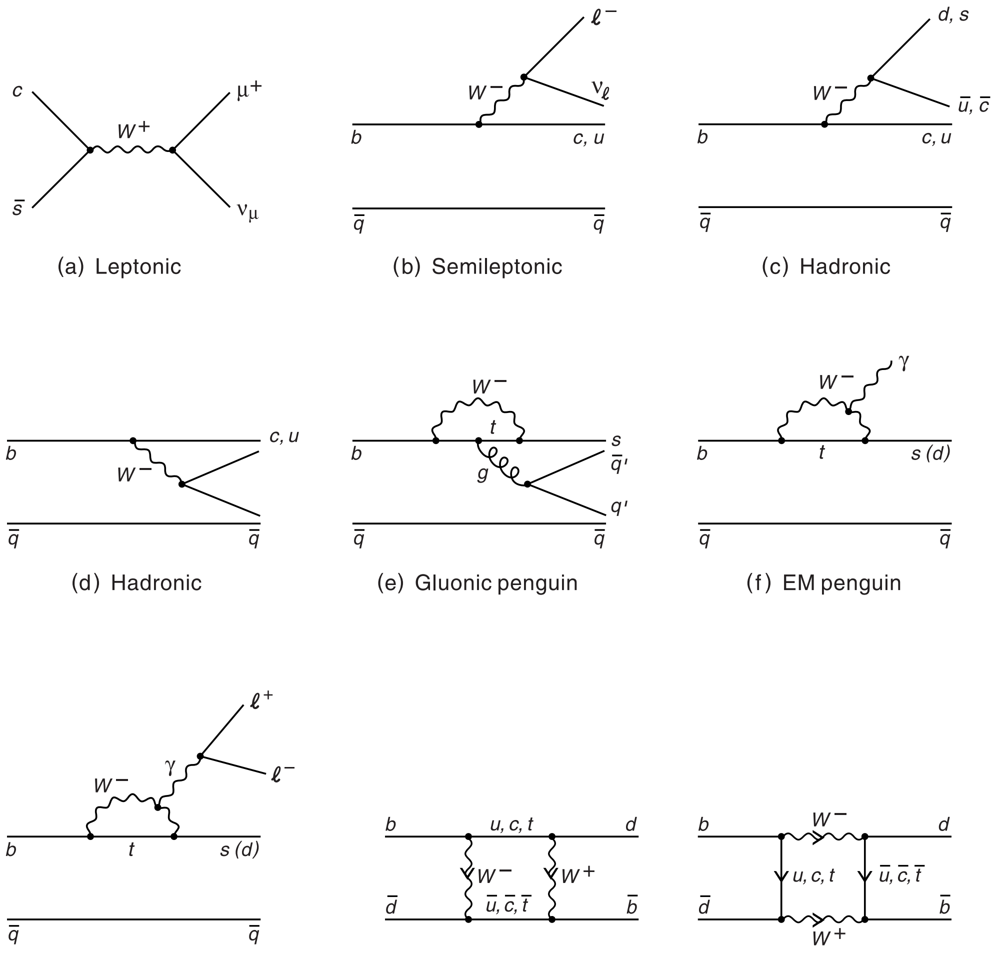
- PEP-II can now deliver 130 pb^{-1}/day.
- 100 $\mathrm{pb}^{-1} = 10^5 B\bar{B}$ events!
- In two days, BABAR gets more than the entire ARGUS $\Upsilon(4S)$ data sample.
- ARGUS, a very successful experiment, discovered $B^0\bar{B}$ mixing with 103 pb^{-1} on the $\Upsilon(4S)$ in 1987 at DESY in Hamburg.

KEK-B and Belle Running



Although there is clearly a race between BABAR and Belle to discover CP violation in B decays, these physics programs are broad, long-term programs that will extend for many years.

Overview of B and D Decays and Oscillations



(a) Leptonic (b) Semileptonic (c) Hadronic

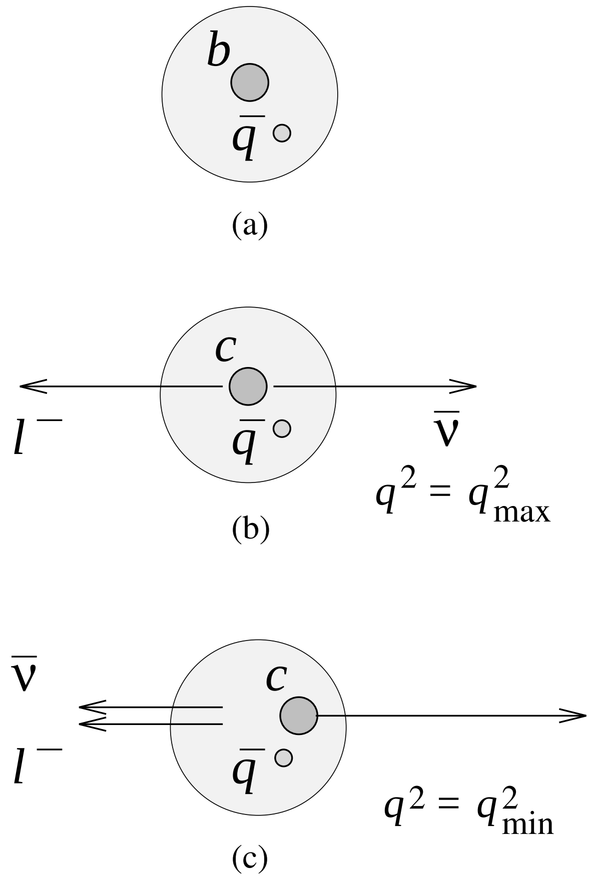
(d) Hadronic (e) Gluonic penguin (f) EM penguin

(g) EM penguin (h) Oscillation

- In B decay, $b \to c$ transitions are dominant, but even these are suppressed by the small value of $|V_{cb}| \approx 0.04$.
- Leptonic decay branching fractions are much lower for B, D than π, K because $\Gamma_{\rm tot} \propto m_b^5$.
- Largest B branching fraction: $B(B \to D^* \ell^- \bar{\nu}) \approx 5\%$
- Hadronic decays: interference between internal and external W diagrams makes $\tau(D^+) \gg \tau(D^0)$.
- In hadronic B decays, the interference has opposite sign, but there is very little effect on the lifetimes: $\tau_{B^+} \approx \tau_{B^0}$.

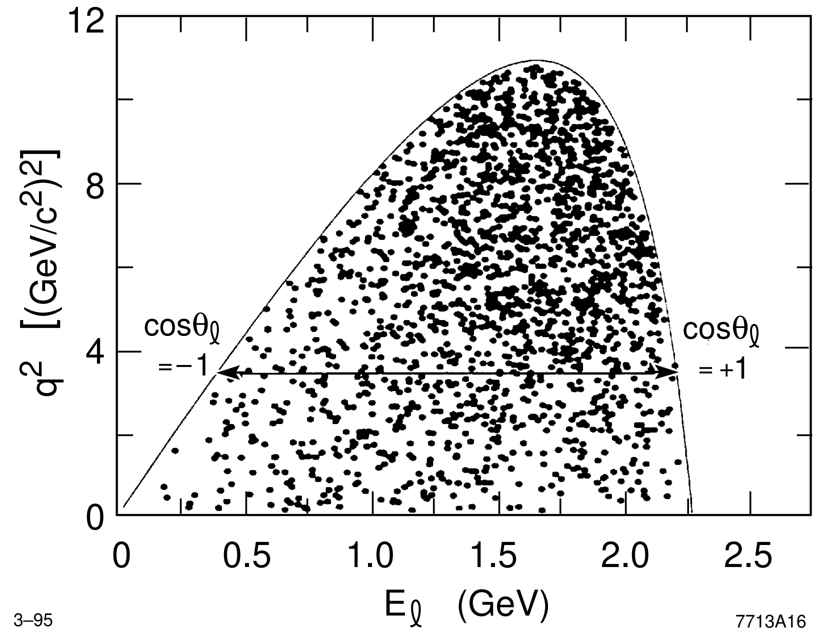
Semileptonic B Decays, Form Factors, V_{cb}, and V_{ub}

- Semileptonic decays are much simpler than hadronic decays. Strong interaction effects are important, but
  - they are isolated to the hadronic current
  - their effects can be rigorously parametrized by form factors (Lorentz-invariant functions of q^2).
- $b \to c\ell^-\bar{\nu}$ processes are dominant and are much easier to understand than $b \to u\ell^-\bar{\nu}$ decays:
  - reliable theoretical normalization for $b \to c\ell^-\bar{\nu}$ at zero recoil (Heavy-Quark Symmetry/Heavy-Quark Effective Theory)
  - Rates for $b \to u\ell^-\bar{\nu}$ processes are much harder to predict, even at small recoil of the daughter hadron, and they have a much large range of hadronic recoil velocities.

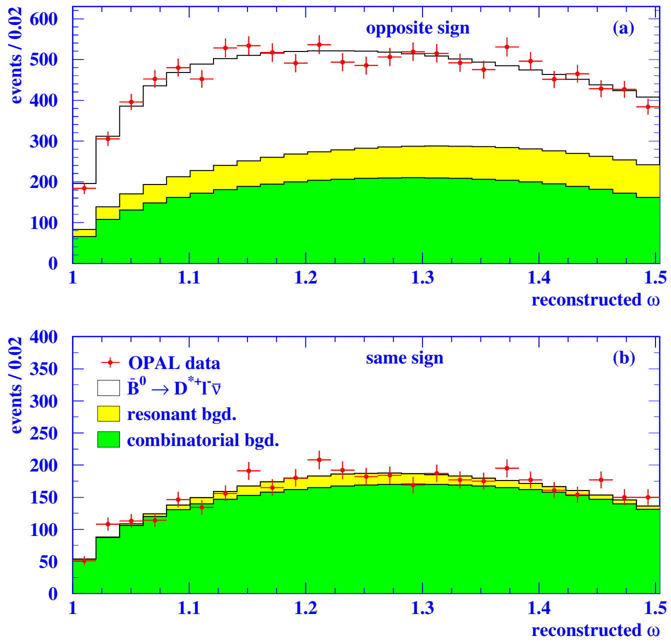


Measuring $|V_{cb}|$ from $B \to D^* \ell^- \bar{\nu}$ at "Zero Recoil"

Monte Carlo simulation of $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ based on CLEO measurement of all three form factors.



OPAL measurement of $|V_{cb}|$ by extrap. to rate at zero recoil (CERN-EP-2000-032).



$$\frac{d\Gamma(B \to D^{*+} \ell^- \bar{\nu})}{dw} = \frac{G_F^2 M_B^5}{48\pi^3} K(w) |V_{cb}|^2 \mathcal{F}^2(w)$$

$$\mathcal{F}(w=1) = 0.92 \pm 0.05 \text{ (PDG Rev.)}$$
$$\mathcal{F}(w=1) = 0.91 \pm 0.03 \text{ (M.Neubert)}$$

Results on $b \to c\ell^-\bar{\nu}$ Decays and $|V_{cb}|$

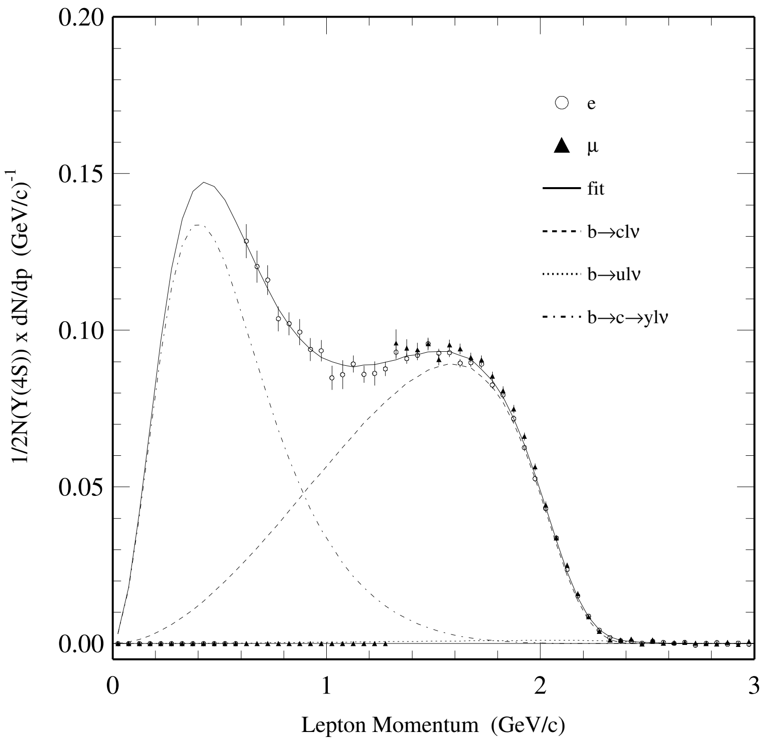
Mode	$\|V_{cb}\|$	Comment
$\bar{B} \to D^{*+}\ell^-\bar{\nu}$ (from $Z \to b\bar{b}$)	$0.0367 \pm 0.0023 \pm 0.0018$	$\mathcal{F}(w)$ param. from dispersion relations
$\bar{B} \to D^{*+}\ell^-\bar{\nu}$ (from $\Upsilon(4S)^*$)	$0.0392 \pm 0.0030 \pm 0.0019$	Linear $\mathcal{F}(w)$ param. + correction
$\Gamma(b \to c\ell^-\bar{\nu})$ (Z)	$0.0408 \pm 0.0005 \pm 0.0025$	B^0, B^+, B_s, b-baryons
$\Gamma(B \to X_c\ell^-\bar{\nu})$ $(\Upsilon(4S))$	$0.0400 \pm 0.0010 \pm 0.0024$	B^0, B^+ admixture

- Uncertainties are experimental and theoretical; both are the result of enormous effort. There remain some controversional aspects to these measurements.
- Reference: L. Gibbons and K. Honscheid, "Production and Decay of b-Flavored Hadrons," Minireview in 2000 edition of Reviews of Particle Properties.
- The $\bar{B} \to D^{*+}\ell^-\bar{\nu}$ result indicated by the asterisk above is based on only 3 fb^{-1} of CLEO data and an update is expected very soon.

The Struggle to Measure $|V_{ub}|$

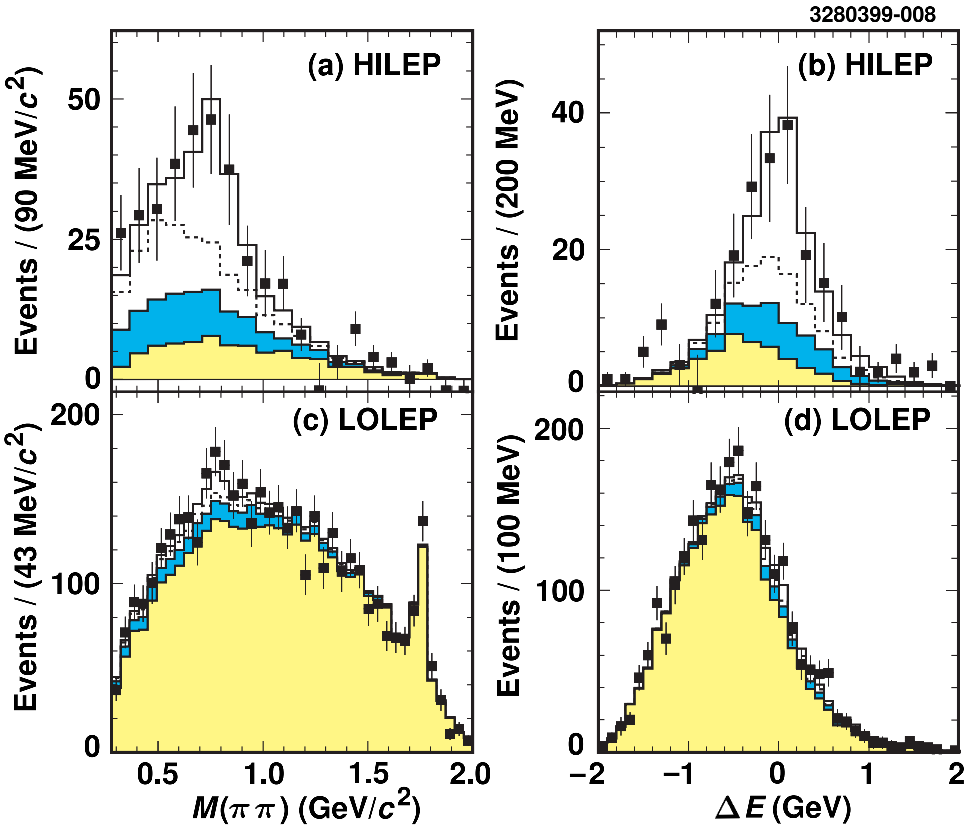
- First evidence for $|V_{ub}| \neq 0$ came from an excess of events beyond the $B \to X_c \ell^- \bar{\nu}$ endpoint.
- That "endpoint" measurement probed a tiny region of phase space, and the extraction of $|V_{ub}|$ suffered from very large model dependence.
- Basic tradeoff: tight cuts give less background but more model dependence in extracting $|V_{ub}|$.
- Inclusive endpoint: $|V_{ub}| = (3.1 \pm 0.8) \times 10^{-3}$ (CLEO 1993).

Inclusive Single Lepton Spectrum from CLEO



Study of the $b \to u$ Decay $B \to \rho\ell^-\bar{\nu}$ from CLEO

$M(\pi\pi)$ and ΔE Distributions



B.H. Behrens *et al.* (CLEO), PRD **61**, 052001 (2000).

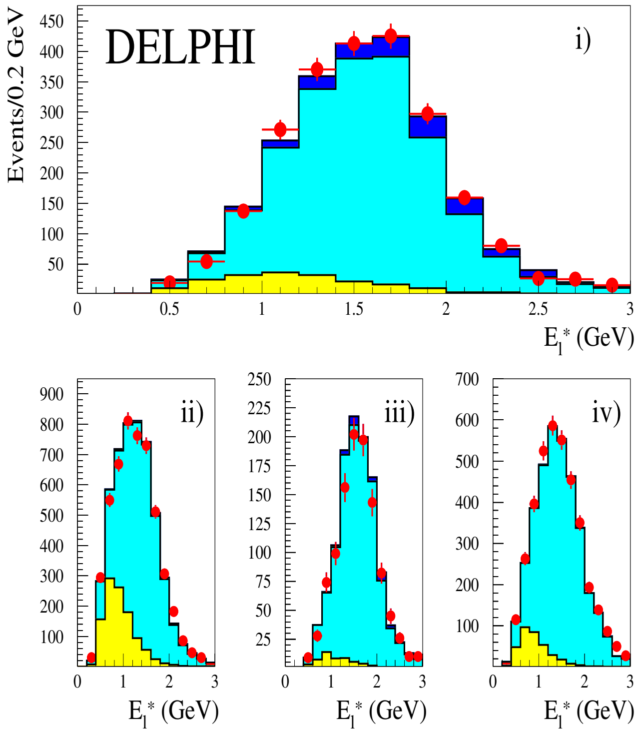
- Modes: $\bar{B}^0 \to \rho^+\ell^-\bar{\nu}$ and $B^- \to \rho^0\ell^-\bar{\nu}$
- Two lepton energy regions:
  - HILEP: $E_\ell > 2.3$ GeV
  - LOLEP: $2.0 < E_\ell < 2.3$ GeV

Models: HILEP is 24% – 35% of rate; LOLEP is 28% – 34%.

- Signal: 7σ.
- Yellow region: $b \to c\ell^-\bar{\nu}$ background.
- Blue region: $b \to u\ell^-\bar{\nu}$ background.
- White regions: direct and crossfeed signal.
- Shows can measure Γ at high q^2.

DELPHI Results on Inclusive $b \to u\ell^-\bar{\nu}$

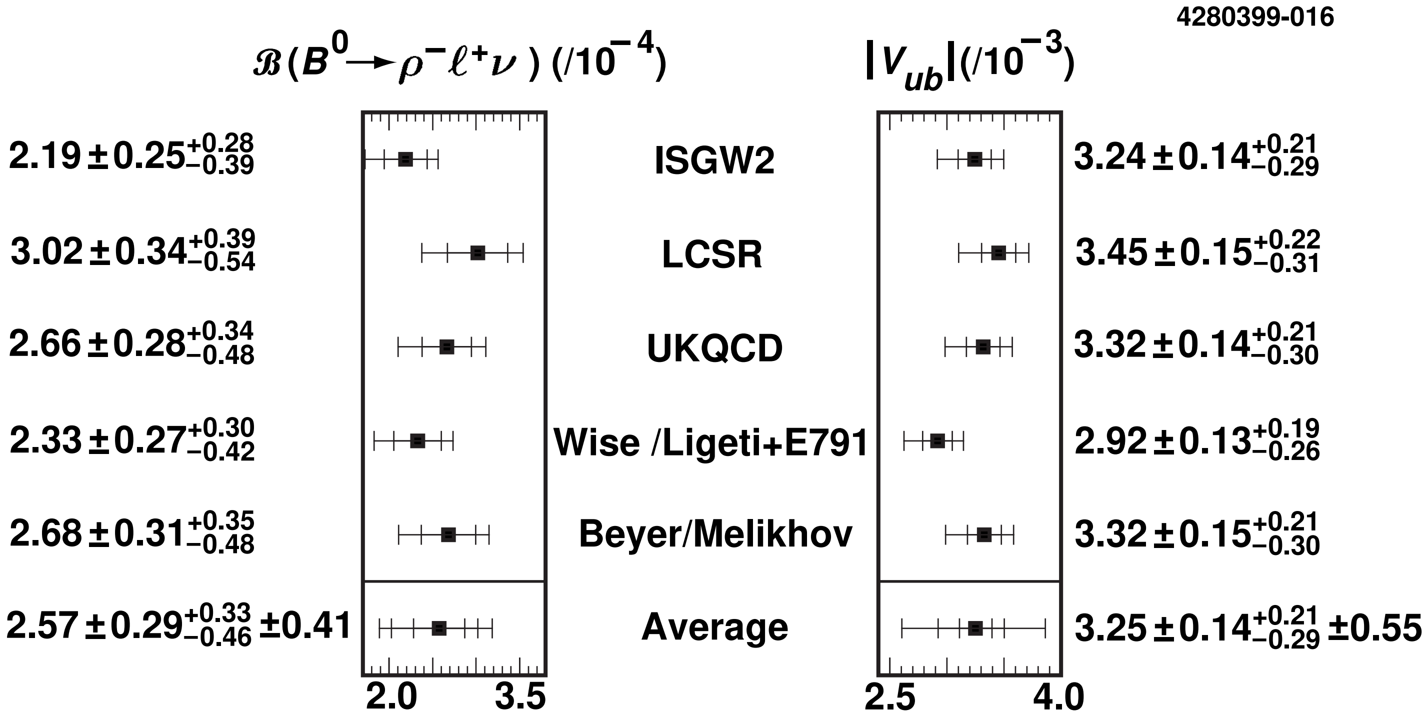
- Idea: reduce theory uncertainty by measuring inclusive $b \to u\ell\bar{\nu}$ rate.
- Estimate mass M_X of hadronic recoil system: $B \to X_u \ell^- \bar{\nu}$ can give $M_X < M_D$
- Enhance $B \to X_u \ell^- \bar{\nu}$ with cuts on lepton impact param. rel. to secondary vtx. and with π/K cuts.
- 214 ± 56 $b \to u\ell^-\bar{\nu}$ events
- CERN-EP-2000-030



- $\mathcal{B}(B \to X_u \ell^- \bar{\nu}) = (1.57 \pm 0.35 \pm 0.48 \pm 0.27) \times 10^{-3}$
- $|V_{ub}/V_{cb}| = 0.103^{+0.011}_{-0.012} \pm 0.016 \pm 0.010$ (model dep.)

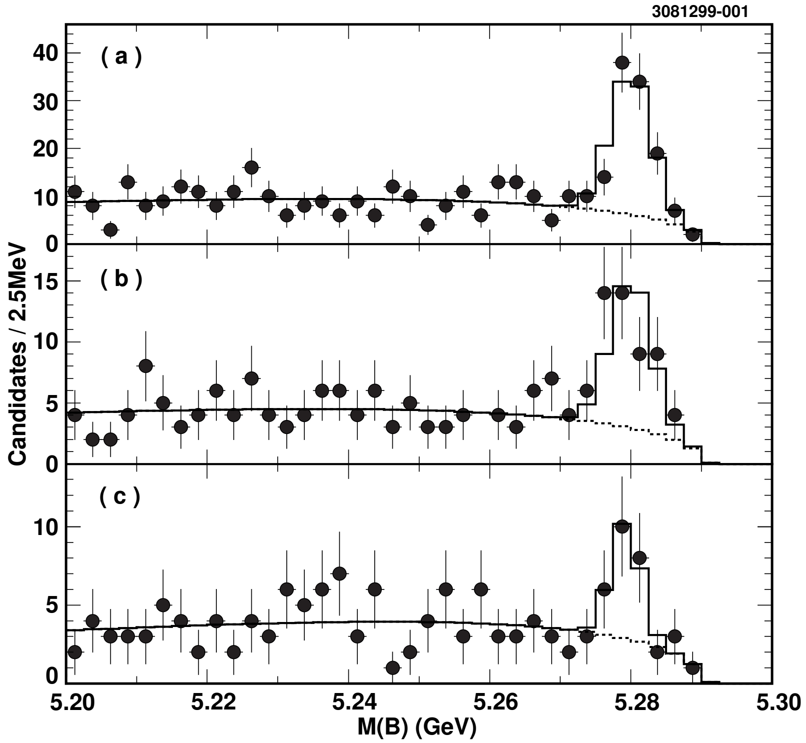
Results on $B(B \to \rho \ell^- \bar{\nu})$ and $|V_{ub}|$

CLEO (combined 1996+2000 results):



- The largest error on $|V_{ub}|$ (± 0.55) is due to the theoretical uncertainty; it is larger than the full spread among the models.
- LEP avg.: $|V_{ub}|/10^{-3} = 4.04^{+0.41}_{-0.46}(\text{expt})^{+0.43}_{-0.48}(b \to c)^{+0.24}_{-0.25}(b \to u) \pm 0.02(\tau_b) \pm 0.19(\text{HQS})$

Exclusive Radiative-Penguin Decays: $B \to K^*\gamma$



$$B(B^0 \to K^{*0}\gamma) = (4.55^{+0.72}_{-0.68} \pm 0.34) \times 10^{-5}$$

$$B(B^+ \to K^{*+}\gamma) = (3.76^{+0.89}_{-0.83} \pm 0.28) \times 10^{-5}$$

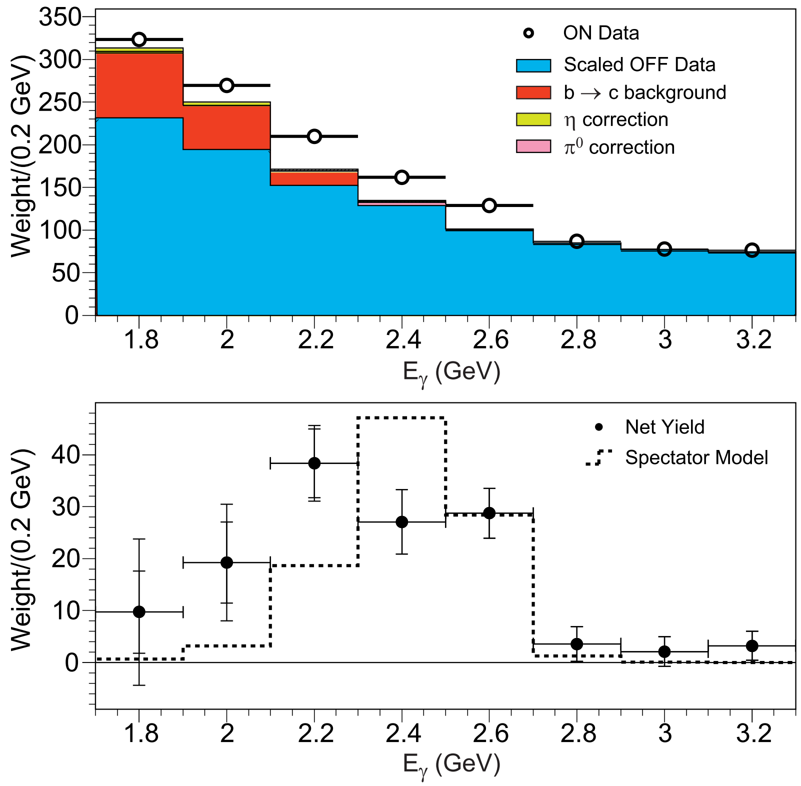
$$B(B \to K_2^*(1430)\gamma) = (1.66^{+0.59}_{-0.53} \pm 0.13) \times 10^{-5}$$

CLEO: hep-ex/9912057, submitted to PRL.

- The observation of $B \to K^*\gamma$ by CLEO in 1993 was the first evidence for the effective FCNC one-loop penguin process. Because these processes contain a loop, the rates can be substantially affected by heavy particles outside the standard model.
- With new data, the signal yields have increased substantially.
- Theoretical predictions for these exclusive final states are very difficult, but the values are within the expected range.

Inclusive Radiative-Penguin Decays: $b \to s\gamma$

CLEO Inclusive Photon Spectrum from $B \to X_s\gamma$



CLEO: hep-ex/9908022.

After a huge theoretical effort, the rate for $b \to s\gamma$ has been calculated including all next-to-leading order terms:

$$B(b \to s\gamma) = (3.28 \pm 0.33) \times 10^{-4},$$

consistent with measurements from CLEO and ALEPH:

$$B(b \to s\gamma) = (3.15 \pm 0.35 \pm 0.41) \times 10^{-4}$$

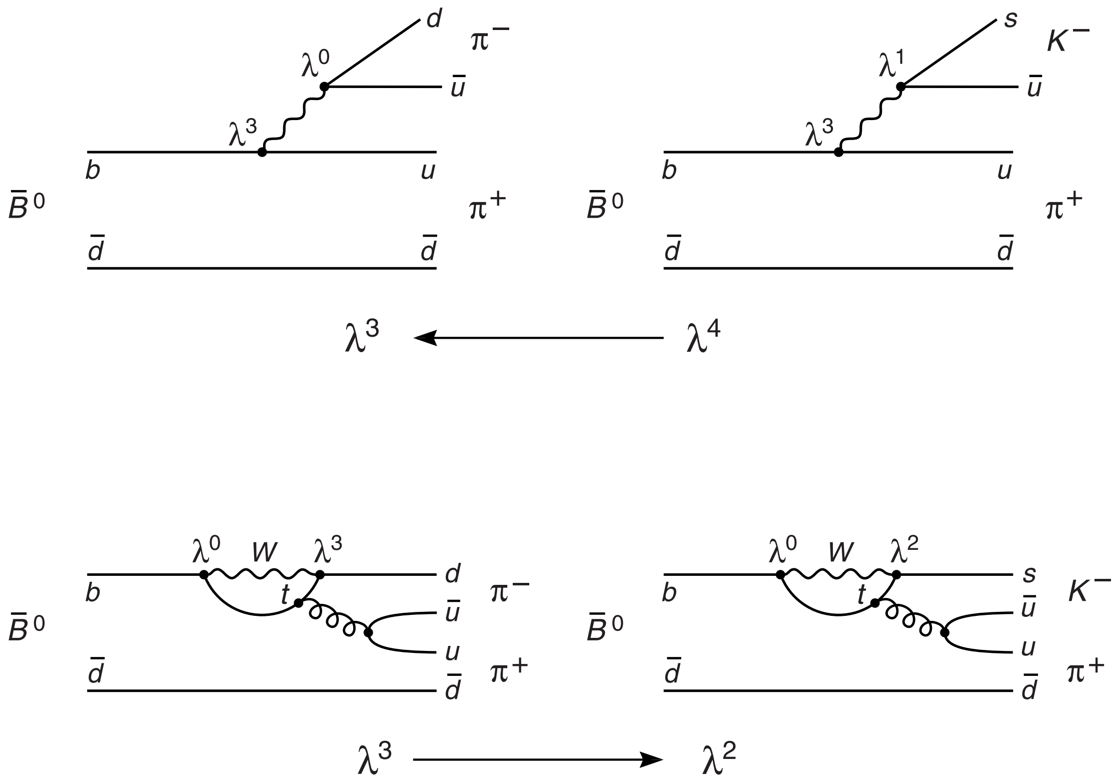
$$B(b \to s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$$

(CLEO value based on 3.3×10^6 $B\bar{B}$ events.) New physics could also produce a sizable ($\sim 40\%$) CP asymmetry:

$$\mathcal{A}^0 \equiv \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)}$$

CLEO:
$-0.09 < \mathcal{A}^{\mathrm{meas}} < 0.42$ 90% C.L.

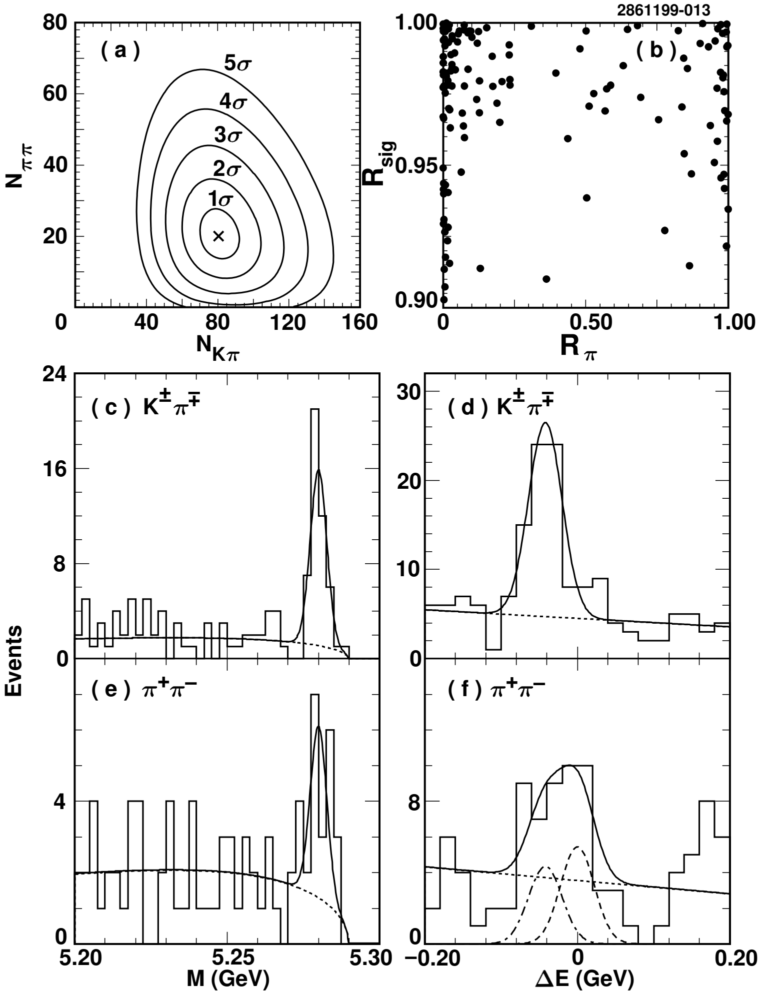
Rare B decays: $B \to K\pi$ and $B \to \pi\pi$



Expectations:

- $B \to \pi\pi$ dominated by $b \to u$ transition.
- $B \to K\pi$ dominated by gluonic penguin.
- If tree only

Exclusive Rare B Decays from CLEO: $B \to K\pi$ and $B \to \pi\pi$

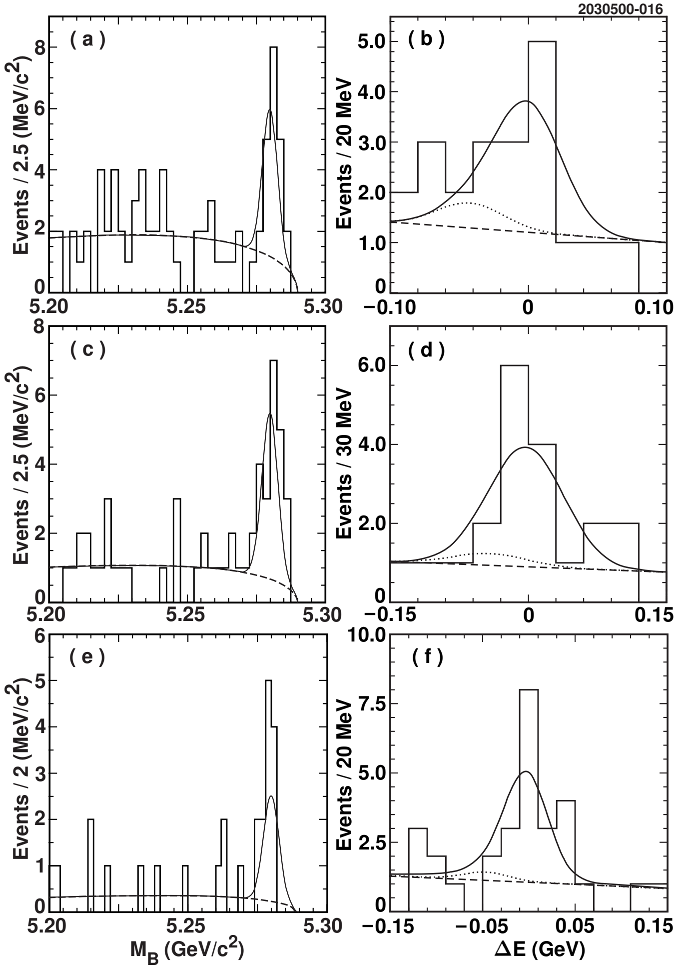


Mode	$N_{\rm SIG}$	Signif.	$\mathcal{B}/10^{-6}$
$\pi^+\pi^-$	$20.0^{+7.7}_{-6.5}$	4.2σ	$4.3^{+1.6}_{-1.4} \pm 0.5$
$K^\pm\pi^\mp$	$80.2^{+11.8}_{-11.0}$	11.7σ	$17.2^{+2.5}_{-2.4} \pm 1.2$
$K^\pm\pi^0$	$42.1^{+10.9}_{-9.9}$	6.1σ	$11.6^{+3.0+1.4}_{-2.7-1.3}$
$K^0\pi^\pm$	$25.2^{+6.4}_{-5.6}$	7.6σ	$18.2^{+4.6}_{-4.0} \pm 1.6$
$K^0\pi^0$	$16.1^{+5.9}_{-5.0}$	4.9σ	$14.6^{+5.9+2.4}_{-5.1-3.3}$

- Because $K^+\pi^- \gg \pi^+\pi-$, there may be a substantial penguin contribution to $B^0 \to \pi^+\pi^-$. (An unwelcome surprise!)

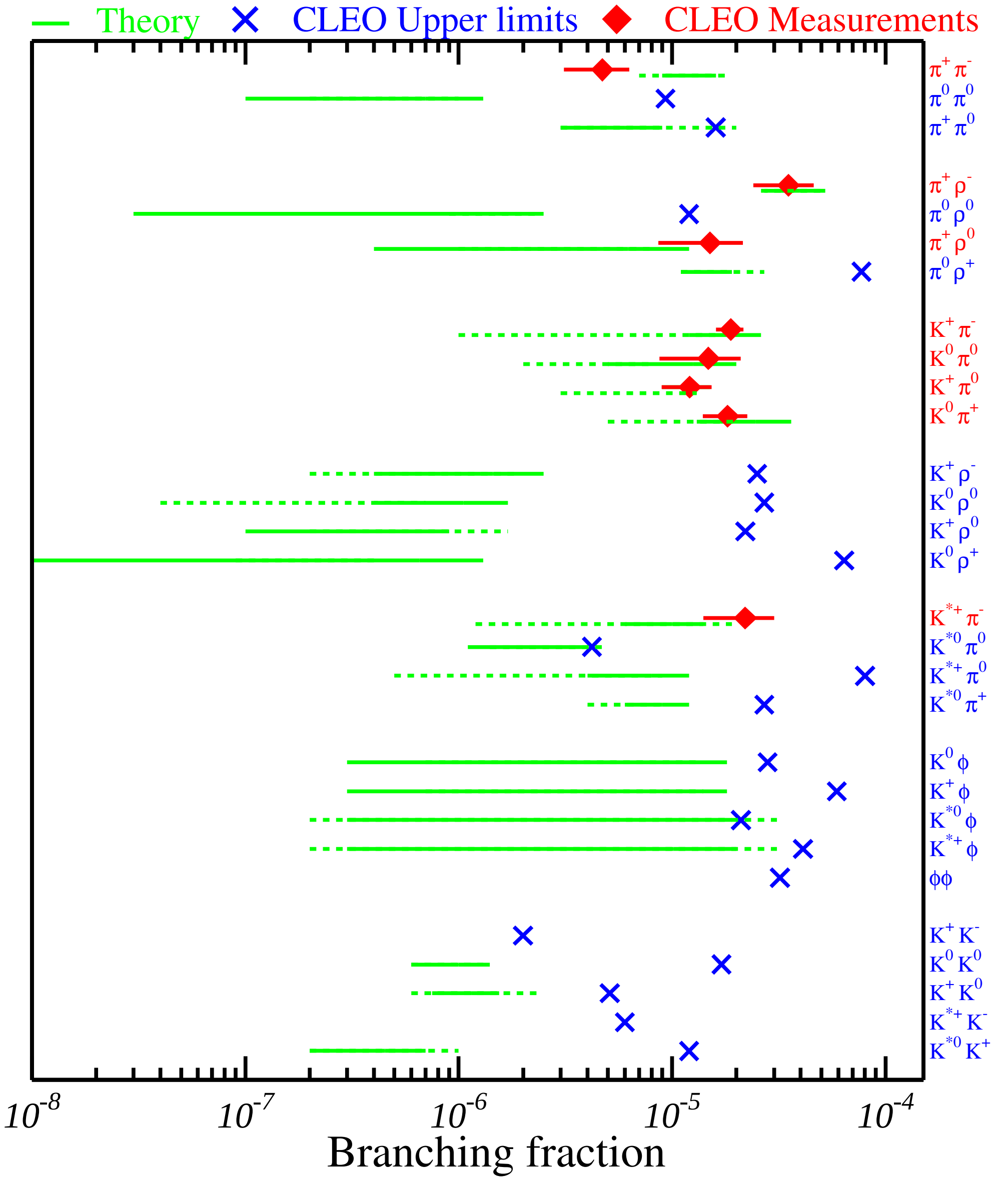
- If $B^0 \to \pi^+\pi^-$ were purely $b \to u$, interference with mixing would allow one to measure $\sin 2\alpha$. "Penguin pollution" greatly complicates the interpretation of this measurement.

CLEO $B \to \rho\pi$



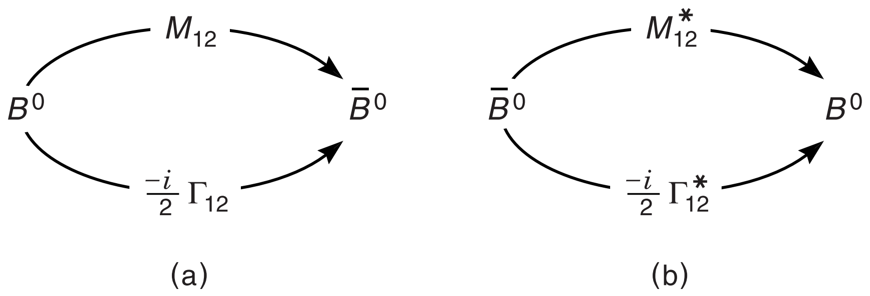
Mode	N_{SIG}	Signif.	$\mathcal{B}/10^{-6}$
$B^- \to \pi^- \rho^0$	$29.8^{+9.3}_{-9.6}$	5.4σ	$10.4^{+3.3}_{-3.4} \pm 2.1$
$\bar{B}^0 \to \pi^\pm \rho^\mp$	$31.0^{+9.4}_{-8.3}$	5.6σ	$27.6^{+8.4}_{-7.4} \pm 4.2$
$B^- \to \pi^- \omega$	$28.5^{+8.2}_{-7.3}$	6.2σ	$11.3^{+3.3}_{-2.9} \pm 1.4$
$B^- \to K^- \rho^0$			< 17.3
$B^- \to \pi^- \bar{K}^{*0}$			< 15.9
$\bar{B}^0 \to K^\pm \rho^\mp$			< 32.3
$\bar{B}^0 \to \pi^0 \bar{K}^{*0}$			< 3.6

- Indicates that penguins may play a smaller role in Vector+Pseudoscalar decays than PP modes.
- With a very large amount of data, it may be possible to perform a Dalitz-plot analysis of the $B \to \rho\pi$ mode that would allow extraction of $\sin 2\alpha$ (A. Snyder, H. Quinn)



Rare B Decays from CLEO

Mixing in the $K^0\bar{K}^0$, $D^0\bar{D}^0$, and $B^0\bar{B}^0$ Systems

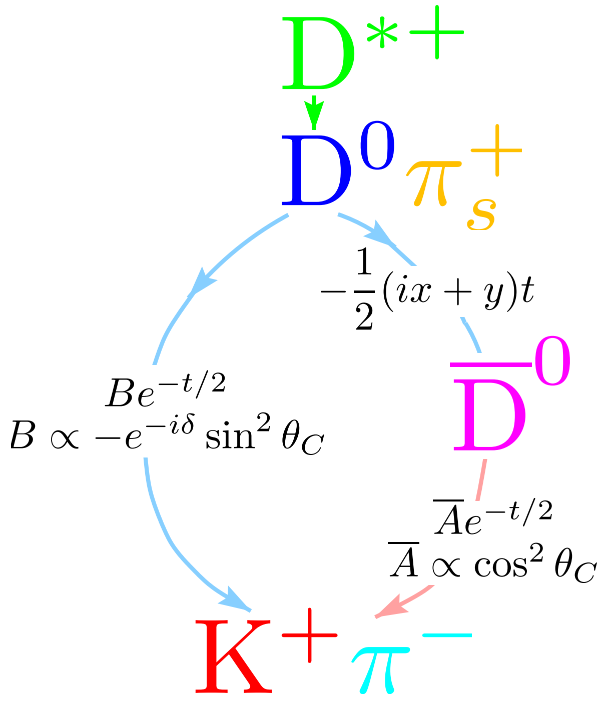


- Mixing between a pseudoscalar meson P^0 and its antiparticle $\bar{P}^0$ can be described in terms of an effective hamiltonian matrix

$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- Diagonalizing $\mathbf{H}$ gives mass eigenstates as linear combinations of P^0 and $\bar{P}^0$.
- Γ_{12} describes $\bar{P}^0 \to f \to P^0$ via on-shell intermediate states.
- M_{12} describes $\bar{P}^0 \to f \to P^0$ via off-shell intermediate states.
- CP violation in mixing can arise from interference between on-shell and off-shell amplitudes. This leads to $\Gamma(P^0 \to \bar{P}^0) \neq \Gamma(\bar{P}^0 \to P^0)$.
- In the B system Γ_{12} is very small; mixing is dominated by $\Delta M = 2M_{12}$.

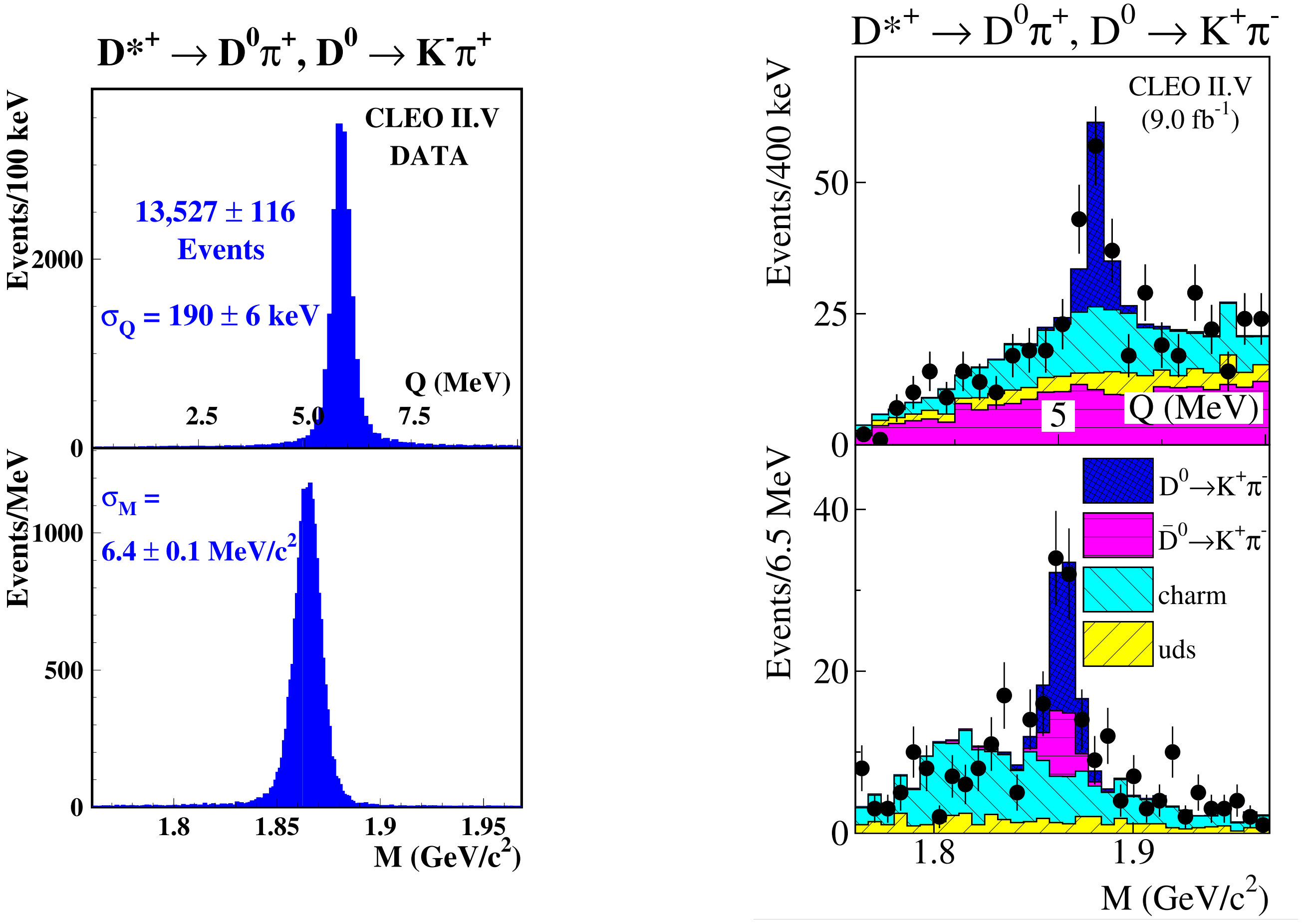
$D^0\bar{D}^0$ Mixing from CLEO



- $D^0\bar{D}^0$ mixing is expected to be highly suppressed in the standard model. It has excellent sensitivity to new physics via ΔM (off-shell intermediate states).
- Production: $e^+e^- \to c\bar{c}$; $c \to D^{*+} \to D^0\pi_s^+$. Charge of the "soft pion" tags whether the initial state was D^0 or $\bar{D}^0$.
- Cabibbo favored decay: $D^0 \to K^-\pi^+$ (4%) gives "right-sign" charge correlation ($\pi_s^+K^-$)
- Mixing is a potential source of wrong-sign decays: $D^0 \to \bar{D}^0 \to K^+\pi^-$
- Doubly Cabibbo suppressed decay $D^0 \to K^+\pi^-$ also gives wrong-sign ($\pi_s^+K^+$) charge correlation.
- Use time dependence to distinguish:

$$r_{ws}(t) = (R_D + \sqrt{R_D}y't + \frac{1}{4}[x'^2 + y'^2]t^2)e^{-t}$$

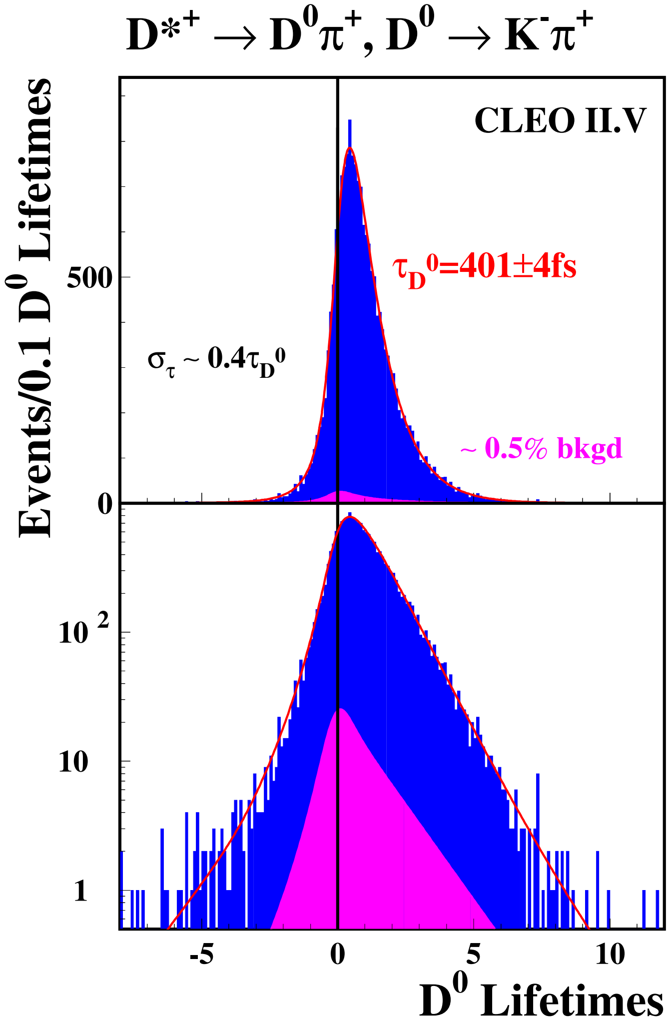
Right-Sign and Wrong-Sign Decay Signals (Time-Integrated)

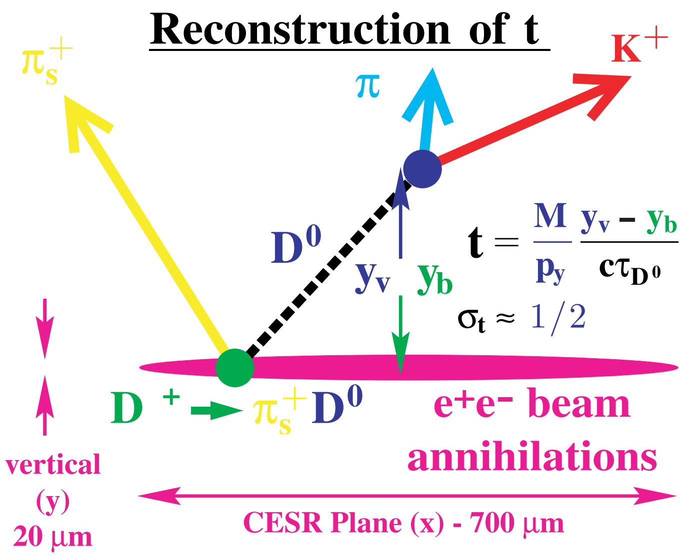


Under assumption of no-mixing: $R = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (0.332^{+0.063}_{-0.065} \pm 0.040)\%$

Compare with previous measurements: PDG (CLEO II + E791) $R = (0.72 \pm 0.25)\%$

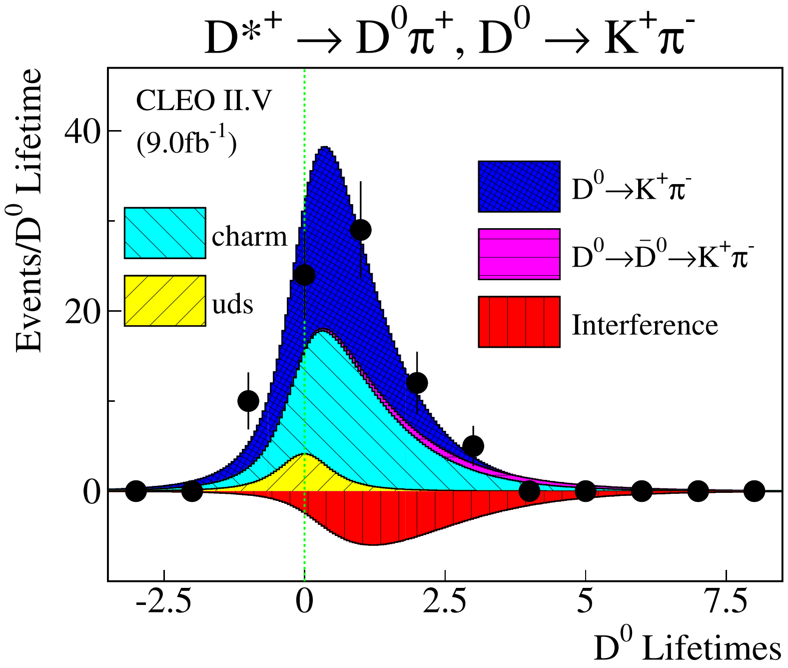
Reconstruction of $D \to K\pi$ in CLEO





- Trajectory of the $K\pi$ system + position of the CESR luminous region determine the 3-D D^0 production point.
- Constrain π_s^+ trajectory to the D^0 production point. Improved Q resolution.

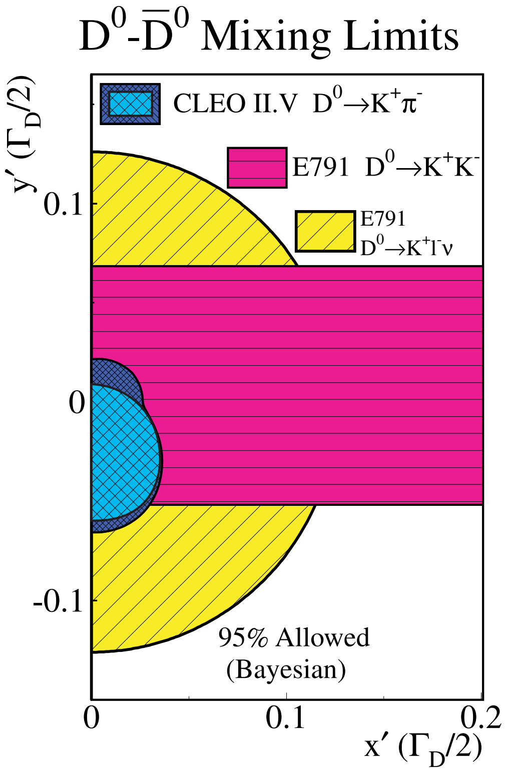
Decay-Time Dependence of $D^0 \to K^+\pi^-$

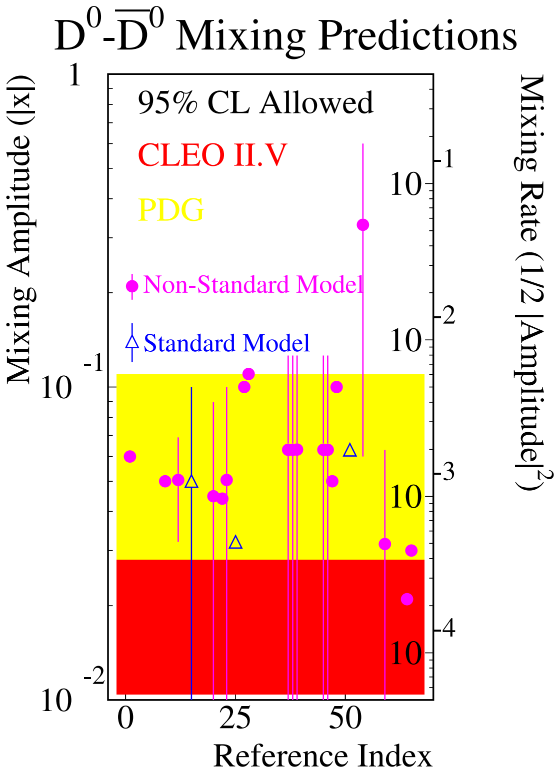


- Distribution shows all $D^0 \to K^+\pi^-$ with 2σ of RS signal value in $Q-M$.
- Likelihood fit in bins that are 1/20 of the D^0 lifetime.
- Background levels are deduced from fit to the $Q-M$ plane.
- WS signal distribution, $(R_D + \sqrt{R_D}y' t + \frac{1}{4}[x'^2 + y'^2]t^2)e^{-t}$, is folded with the resolution function.
- x' is new physics amplitude if $\delta = 0$.

Parameter	**Best Fit**	**95% C.L.**
R_D	$(0.48 \pm 0.12 \pm 0.04)\%$	$0.24\% < R_D < 0.71\%$
y'	$(-2.5^{+1.4}_{-1.6} \pm 0.3)\%$	$-5.8\% < y' < 1.0\%$
x'	$(0 \pm 1.5 \pm 0.2)\%$	$\lvert x'\rvert < 2.9\%$
$(1/2)x'^2$		$< 0.041\%$

Mixing Limits and Theory Comparison

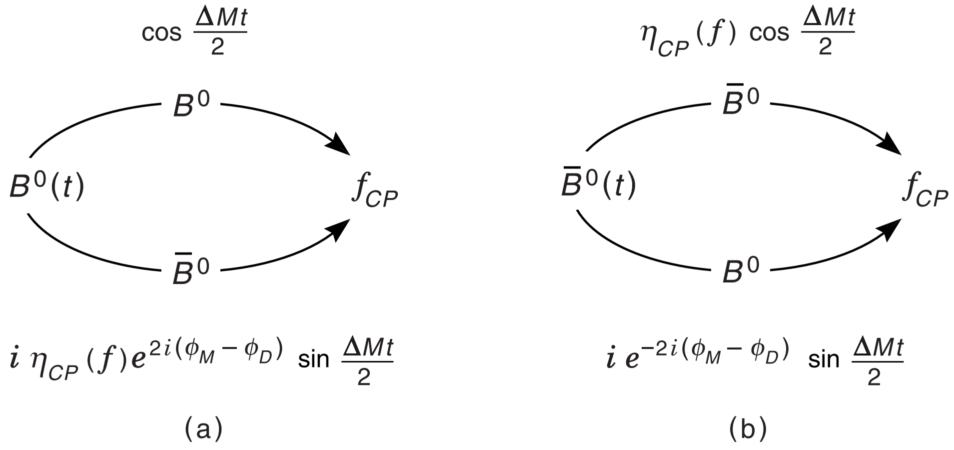




Reference: H.N. Nelson, hep-ex/9908021.

- Most Standard Model Predictions for $D^0 - \overline{D}^0$ Mixing rate $(10^{-6} - 10^{-10})$ are beyond current experimental sensitivity.
- Non-Standard Model physics enhances x relative to y.

CP Violation in Neutral B Meson Decay

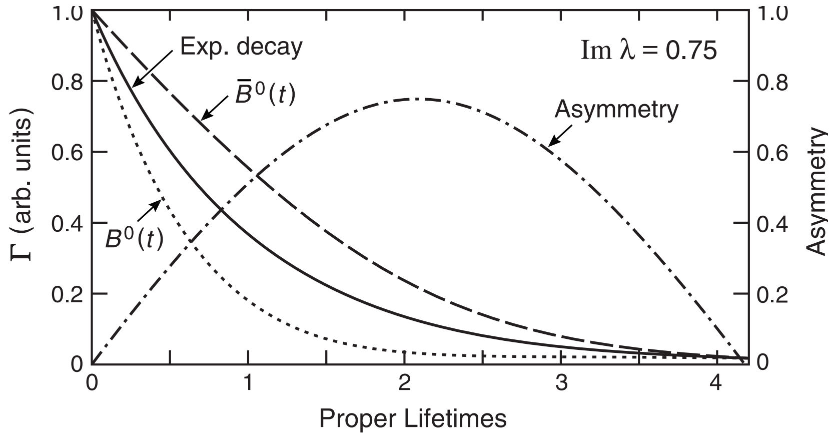


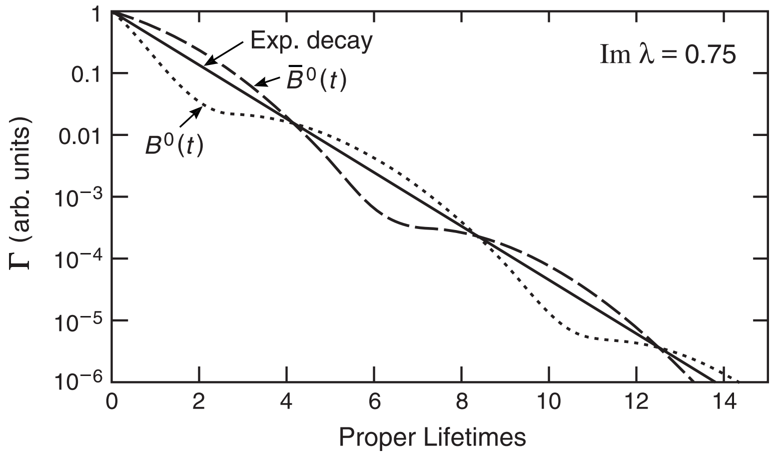
- $B^0\bar{B}^0$ mixing is dominated by off-shell intermediate states: gives single weak phase.
- To measure CP asymmetry need common final state. Measure

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)}$$

- Although CP asymmetries are large, useful modes, *e.g.*, $B^0 \to J/\psi K^0_s$, have relatively small branching fractions. Need very large data samples: 30 M to 50 M $B\bar{B}$ events or more. For $B^0 \to J/\psi K^0_s$,

$$\mathcal{A}_{CP}(t) = -\sin 2\beta \sin \Delta M t$$



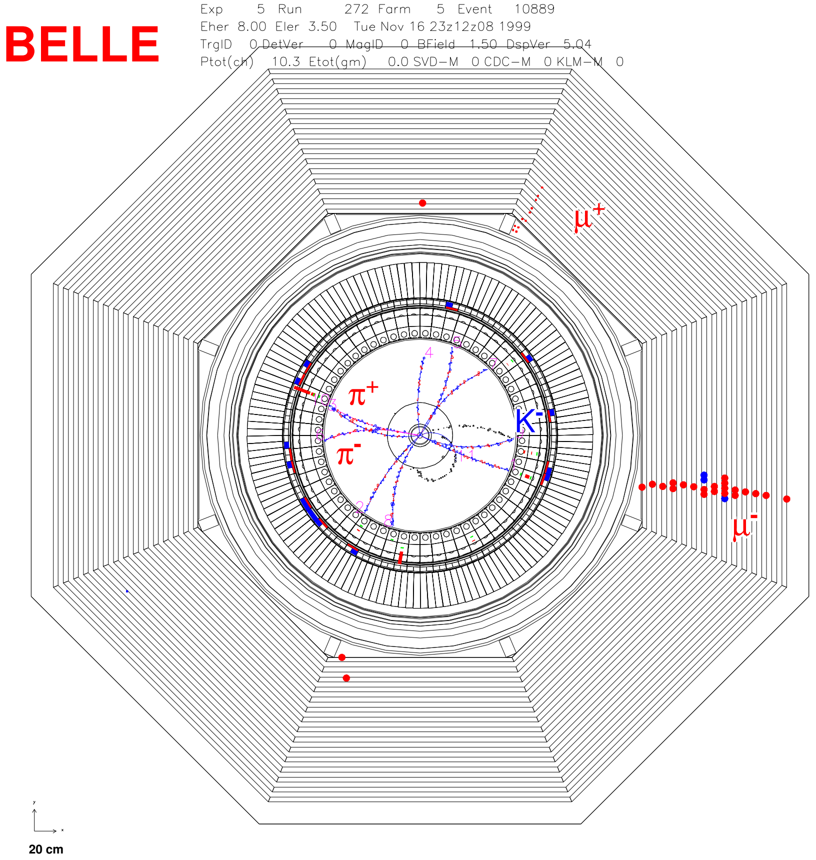


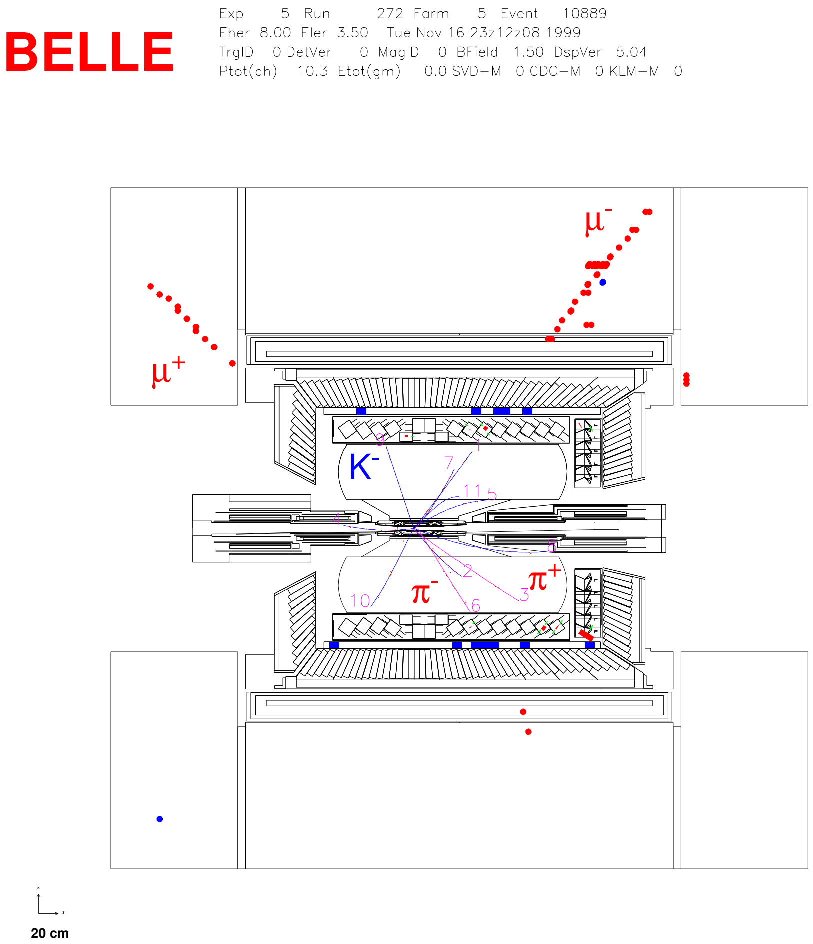
- Due to correlated time evolution in $\Upsilon(4S) \to B^0\bar{B}^0$, the asymmetry reverses sign when $t_{CP} - t_{\text{tag}}$ reverses sign. This forces the time-integrated CP asymmetry to be zero. Must measure time-dependent CP asymmetry. Vertexing is critical!
- Tagging of initial state: use lepton and kaons from other B meson:

  $$b \to \ell^- \qquad b \to c \to s$$

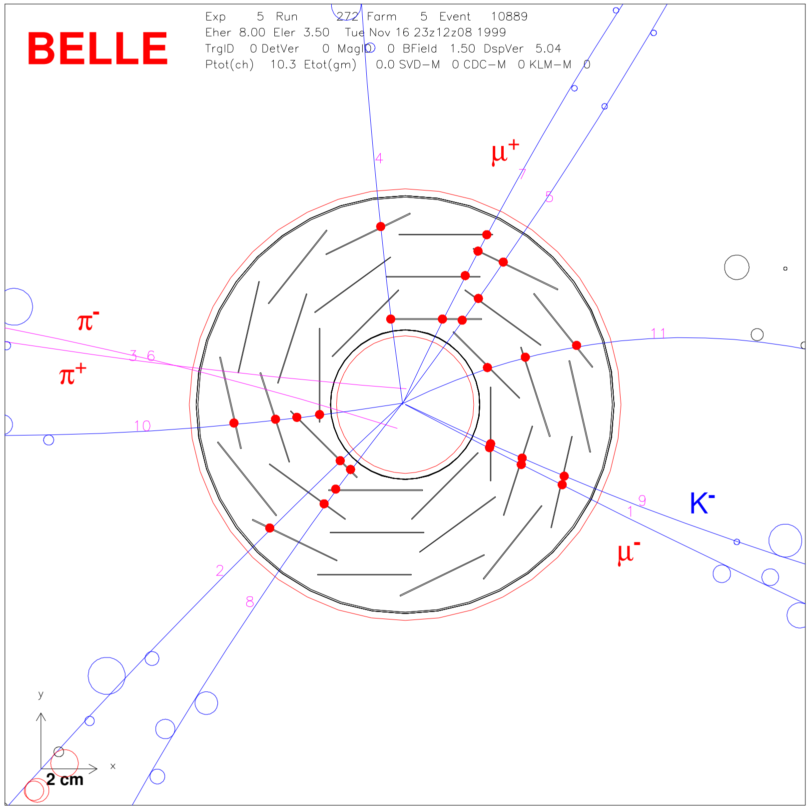
  Should get relatively high effective tagging efficiency ($\sim 20\%$).
- Excellent particle identification: e, μ, K, π, both for tagging and reconstruction of CP final state.
- The mode $B^0 \to J/\psi K^0_s$ is a "golden mode" because of its theoretical simplicity and strong experimental signature. It will be used to measure $\sin 2\beta$.

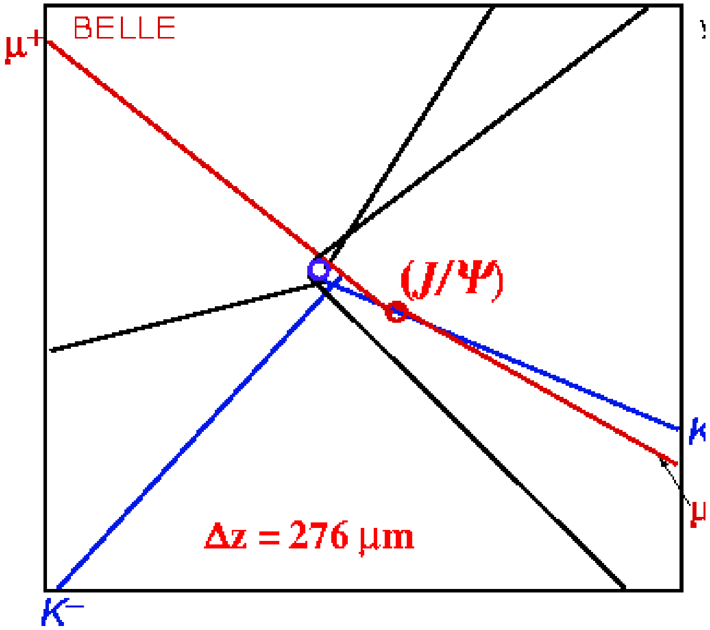
Belle $J/\psi K_s^0$ Candidate Event



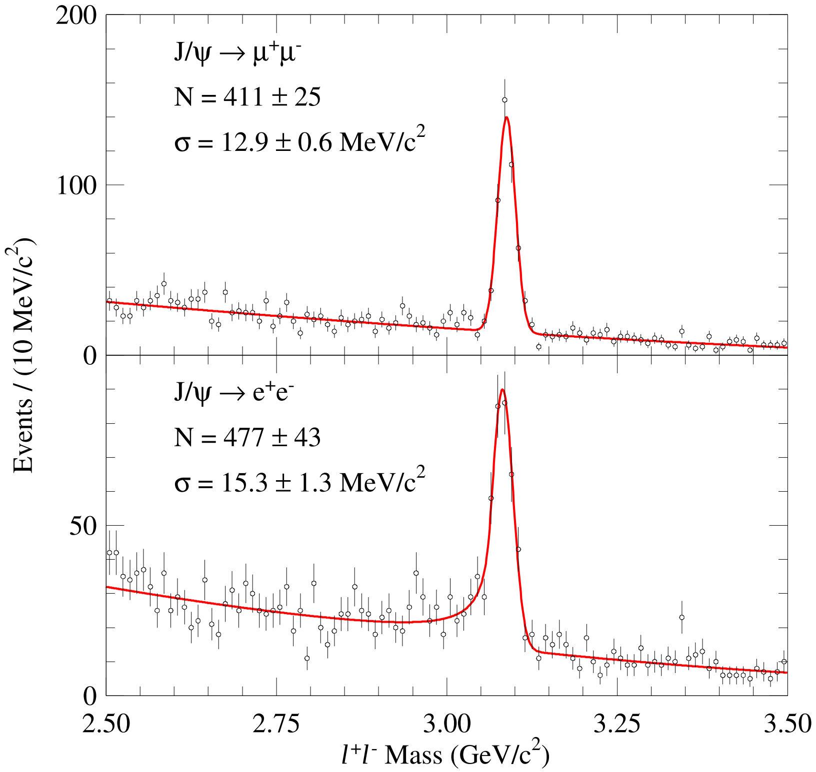


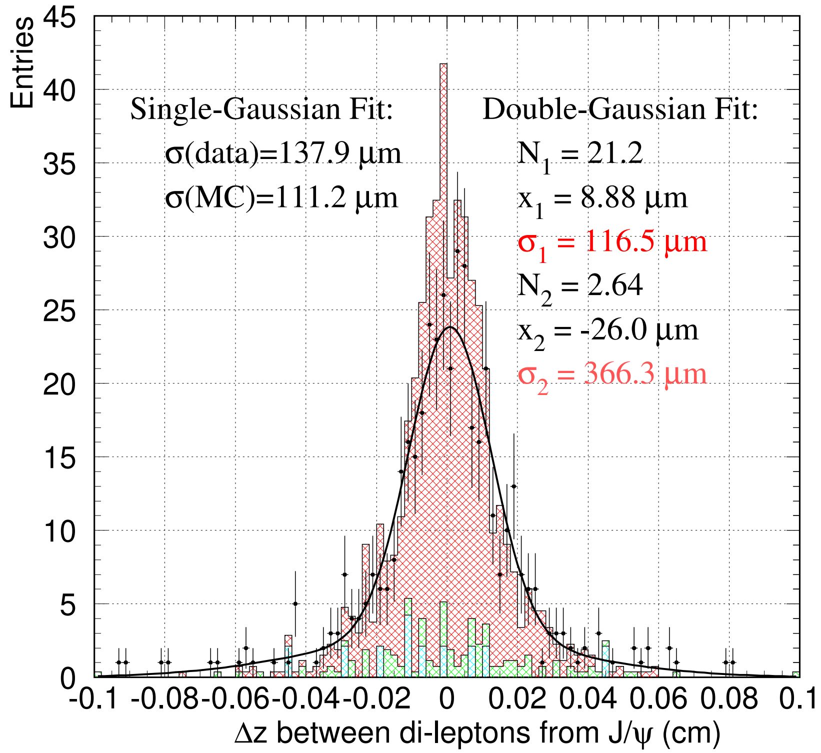
Belle $J/\psi K_s^0$ Candidate Event

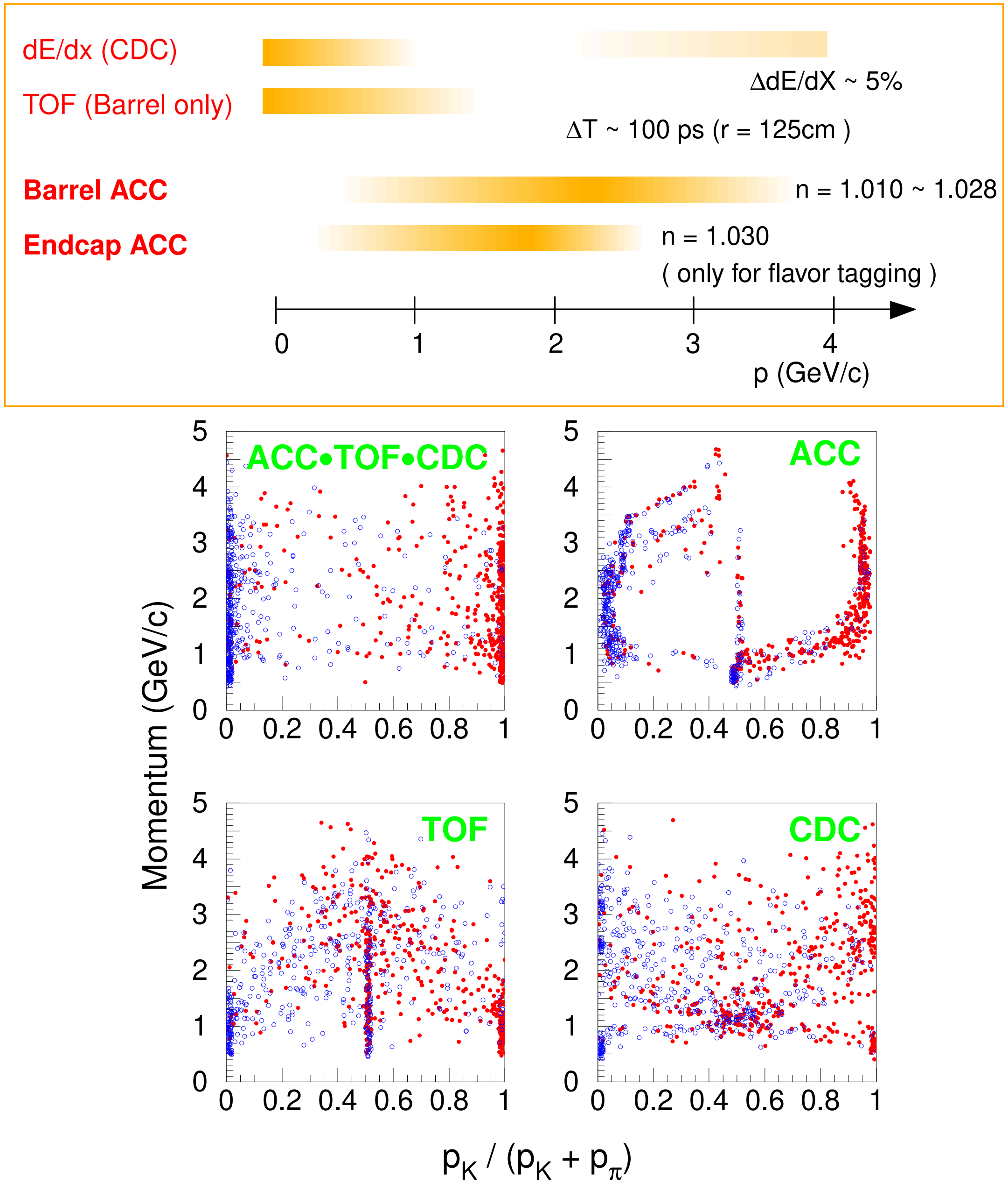




Belle J/ψ Inclusive Signals and Dilepton Δz



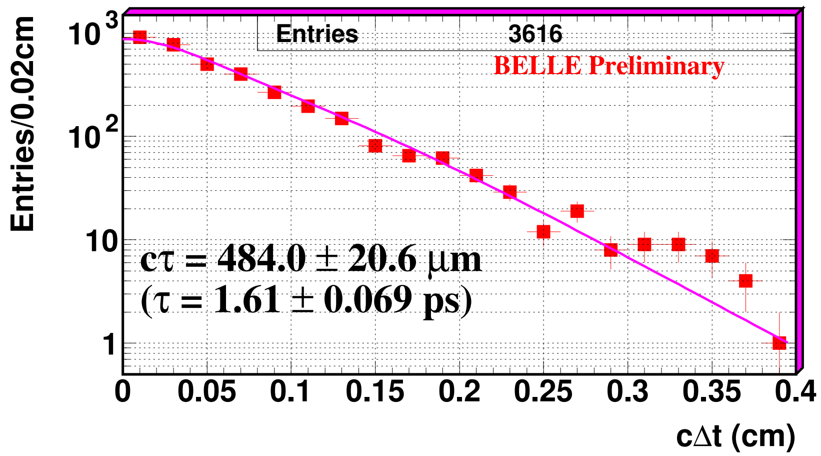




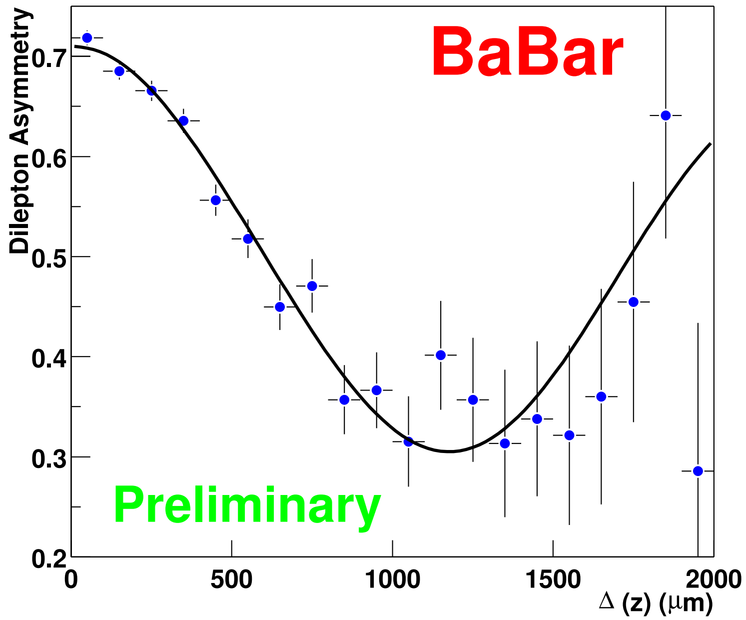
Belle K/π Separation

Time-Dependent Measurements from BABAR and Belle

B lifetime measurement using $B \to \ell^+$, $\bar{B} \to \ell^-$ events.



B mixing measurement using $B \to \ell^+$, $\bar{B} \to \ell^-$ events.



Conclusions and Prospects

- Leptonic decays are barely seen (D_s only).
- We are just beginning to map out $b \to u\ell^-\bar{\nu}$ decays, to understand their dynamics, and to measure $|V_{ub}|$.
- New hadronic rare decays are rapidly being found. We may well observe direct CP violation in such modes and even obtain useful constraints on CKM angles.
- Much remains to be learned about radiative penguin modes. We need to observe and understand $B \to K^*\ell^+\ell^-$.
- Charm physics still has much to teach us. We have seen an order-of-magnitude improvement in our limits on $D^0\bar{D}^0$ mixing. We need to continue focusing on this process with new data samples.
- There will be many CP asymmetry measurements in the B system over the next 10 years.

Conclusions and Prospects

- The new asymmetric B factories are working extremely well, delivering high luminosities with tolerable backgrounds.
- We can expect incisive tests of standard-model predictions for CP violation in the B meson system in the relatively near future. Precise measurements will come both from B-factories and from hadron-collider experiments.
- The B and D physics program is extremely broad; there is an enormous amount of territory yet to be explored.
- In the next 3-5 years, our understanding of heavy-quark physics will advance dramatically.