Measurement of $\sin(2\alpha)$ at *BABAR*

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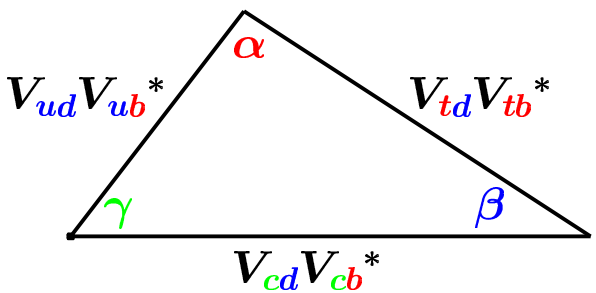
OUTLINE

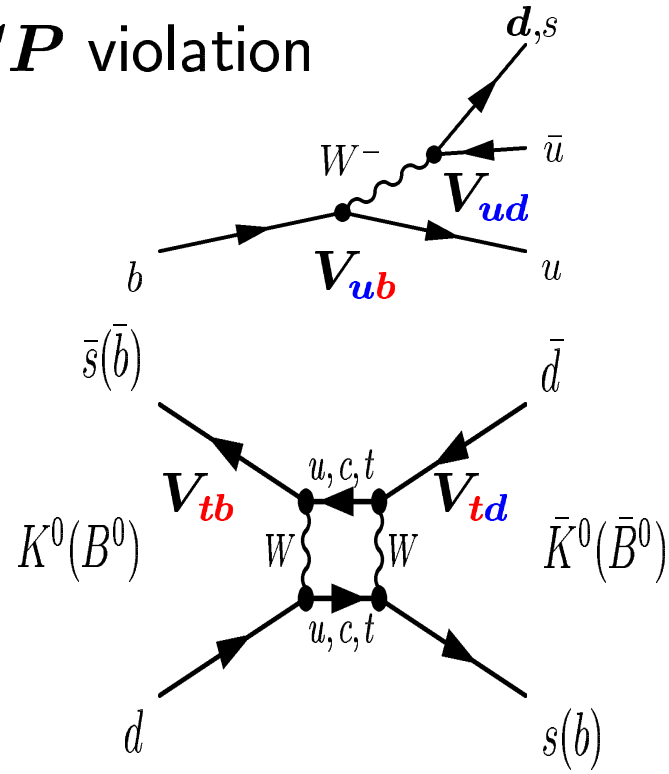
- Introduction
- Experimental Techniques
- Results and Prospects

Why measure sin(2α)

- Study fundamental question of CP violation

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





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

- Is everything limited to CKM matrix (Standard Model)?
  - see if triangle is closed ($\alpha + \beta + \gamma = \pi$)
  - sin(2β) $= 0.78 \pm 0.08$

How to measure $\sin(2\alpha)$

- $\Upsilon(4S) \to B^0{}_{(t_1)}\bar{B}^0{}_{(t_1)}$ coherent P-wave
- Two paths: $B^0{}_{(t_1)} \to B^0{}_{(t_2)} \to f_{CP}$ Ampl$=A_{f_{CP}}$

  $B^0{}_{(t_1)} \to \bar{B}^0{}_{(t_2)} \to f_{CP}$ Ampl$=\bar{A}_{f_{CP}} \times (\frac{q}{p})_{\rm mix}$
- Measure:

$$\Gamma(B^0 \to f, t_2) \propto e^{-|\Delta t|/\tau_B}(1 + C_{f_{CP}}\cos(\Delta m \Delta t) - S_{f_{CP}}\sin(\Delta m \Delta t))$$

$$\Gamma(\bar{B}^0 \to f, t_2) \propto e^{-|\Delta t|/\tau_B}(1 - C_{f_{CP}}\cos(\Delta m \Delta t) + S_{f_{CP}}\sin(\Delta m \Delta t))$$

$$S_{f_{CP}} = \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2} \qquad \lambda_{f_{CP}} = (\frac{q}{p})_{\rm mix} \times \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

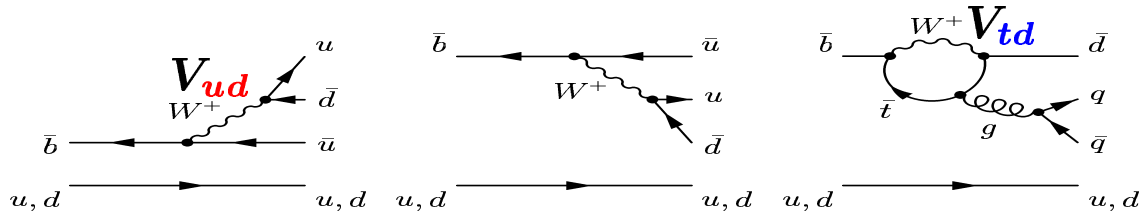
- Have to look at $b \to u$ decays (V_{ub})

Pure tree: $\lambda_{\pi\pi} = (\frac{V_{td}V_{tb}{}^*}{V_{td}{}^*V_{tb}})(\frac{V_{ud}{}^*V_{ub}}{V_{ud}V_{ub}{}^*}) = e^{2i\alpha}$ $\quad S_{\pi\pi} = \sin(2\alpha)$

$B \to \pi^+\pi^-, \pi^+\pi^-\pi^0(\rho\pi), 4\pi(\rho\rho, a_1\pi), ...$ $\quad C_{\pi\pi} = 0$

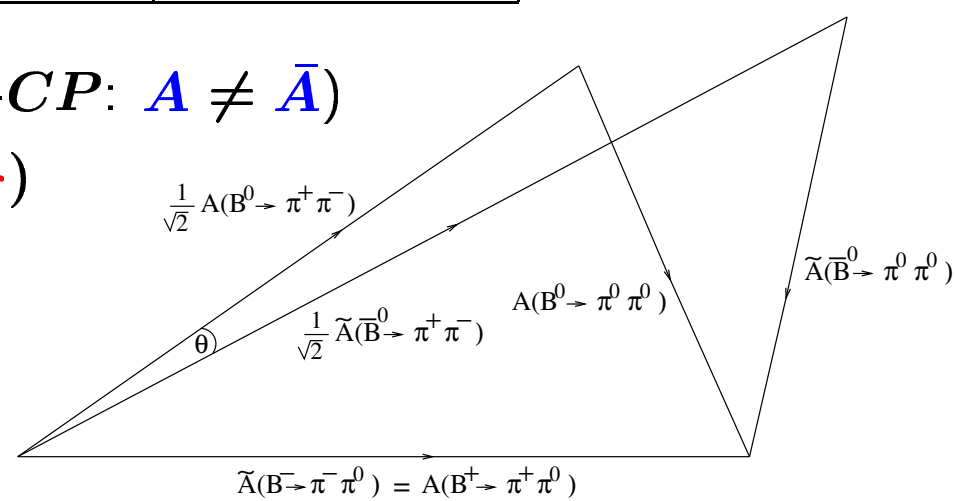
Penguin "pollution" in $\sin(2\alpha)$

$$\alpha_T \cdot T \quad + \quad \alpha_C \cdot C \quad + \quad \alpha_P \cdot P$$



Mode	α_T	α_C	α_P	BABAR $\mathcal{B}(10^{-6})$
$\pi^-\pi^+$	$\sqrt{2}$	0	$\sqrt{2}$	$5.4 \pm 0.7 \pm 0.5$
$\pi^0\pi^+$	1	1	0	$4.1^{+1.1}_{-1.0} \pm 0.8$
$\pi^0\pi^0$	0	1	-1	< 3.4

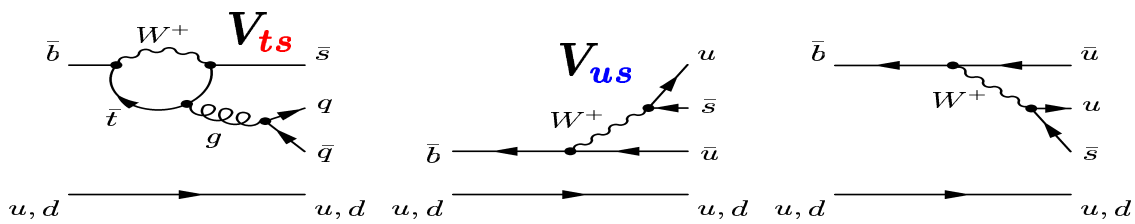
- $C_{\pi\pi} \propto \sin(\delta_{\text{strong}})$ (direct-CP: $A \neq \bar{A}$)
- $S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}{}^2}\,\sin(2\alpha_{\text{eff}})$
- $2\alpha_{\text{eff}} = 2\alpha + \theta$
- θ from Isospin or Model



"Penguin Pollution" from $B \to K\pi$

- Large $B \to K\pi \Rightarrow$ cross-feed in $B \to \pi\pi$ reconstruction
- $B \to K\pi$ interesting by itself:
  e.g. direct CP $\quad \mathcal{A}_{CP} \sim 2(\frac{T'}{P'}) \sin(\gamma) \sin(\delta)$
- SU(3) $\Rightarrow |P/T|_{\pi\pi} \sim 0.28$ (e.g. Gronau/Rosner)

$$\alpha_P \cdot P' \quad + \quad \alpha_T \cdot T' \quad + \quad \alpha_C \cdot C'$$



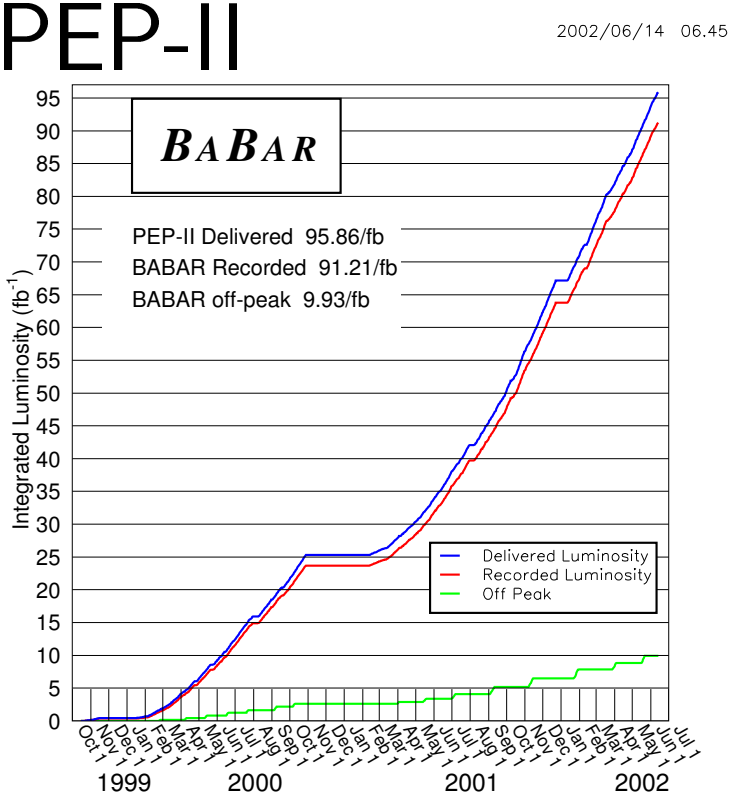
Mode	α_P	α_T	α_C	BABAR $\mathcal{B}(10^{-6})$
$K^+\pi^-$	$\sqrt{2}$	$\sqrt{2}$	0	$17.8 \pm 1.1 \pm 0.8$
$K^0\pi^+$	$-\sqrt{2}$	0	0	$17.5^{+1.8}_{-1.7} \pm 1.3$
$K^+\pi^0$	-1	-1	1	$11.1^{+1.3}_{-1.2} \pm 1.0$
$K^0\pi^0$	-1	0	1	$8.2^{+3.1}_{-2.7} \pm 1.2$

Requirements on $\sin(2\alpha_{\rm eff})$ Analysis

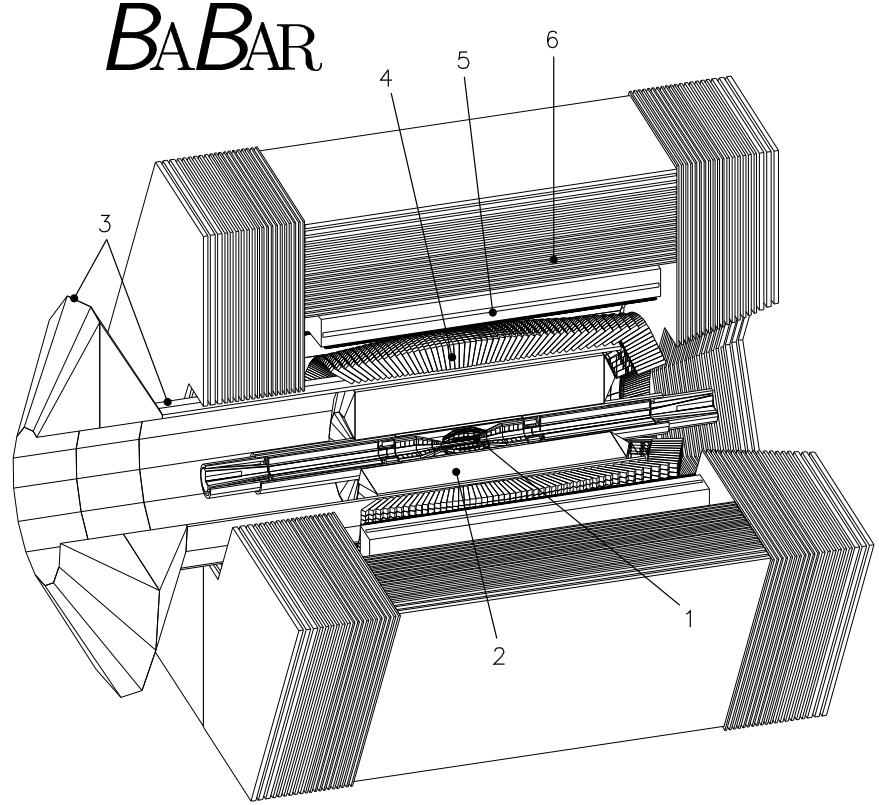
- Features common to $\sin(2\beta)$ and $\sin(2\alpha_{\rm eff})$:
  - exclusive reconstruction of the signal B
  - flavor tagging of the other B
  - precise vertexing for time-dependence
- What is special about $\sin(2\alpha_{\rm eff})$:
  - reconstruct rare decays ($\mathcal{B}$ranching $< 10^{-5}$)
    $\Rightarrow$ need high luminosity, many B's
  - high combinatoric background
    $\Rightarrow$ sophisticated background suppression
  - potential $K\pi/\pi\pi$ cross-feed
    $\Rightarrow$ efficient particle identification, combined fit
  - "penguin pollution"
    $\Rightarrow$ fit for both cos and sin terms

BABAR Experiment

PEP-II



BABAR



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

$e^+e^- \to q\bar{q} \to$ "jets"

This analysis: through Dec.2001

$N_{B\bar{B}} = (60.2 \pm 0.7) \times 10^6$

- Silicon Vertex Tracker (SVT)
- Drift Chamber (DCH)
- Cherenkov Detector (DIRC)
- EM Calorimeter (EMC)
- Instr. Flux Return (IFR)

B-decay Analysis

Fully reconstruct $B \to \pi^+\pi^-$ (or $K^+\pi^-$)

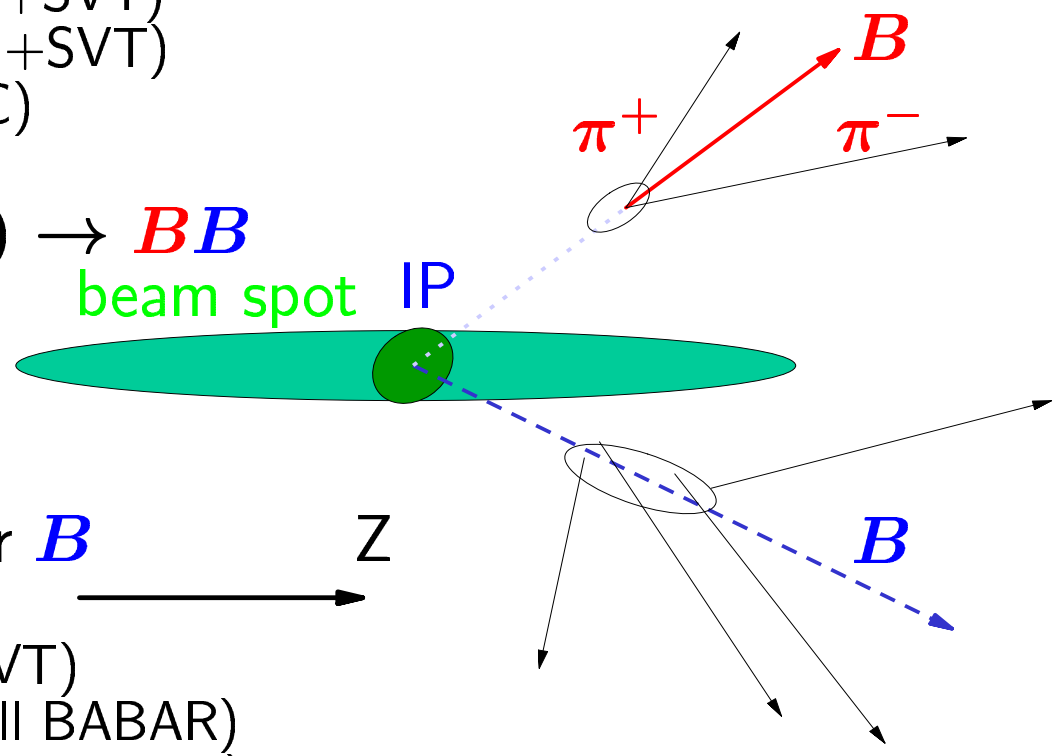
- Vertex (SVT)
- Momentum (DCH+SVT)
- Energy (DCH+SVT)
- Particle ID (DIRC)

Constrain $\Upsilon(4S) \to BB$

- Beam momenta
- Beam spot

Look at the other B

- Vertex (SVT)
- Flavor tagging (full BABAR)
- Event shape (DCH+EMC)



Momentum Constraint

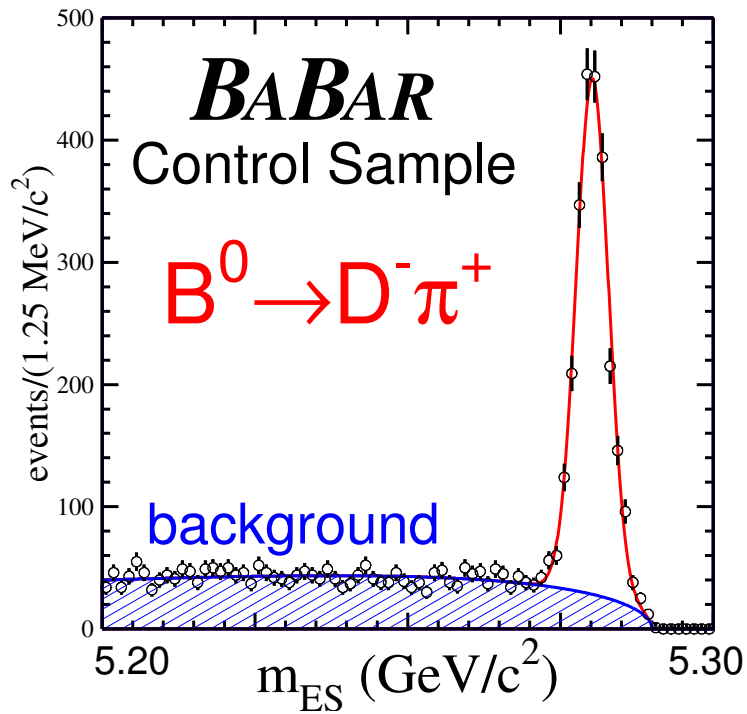
- Energy-substituted mass $(e^+e^- \to \Upsilon(4S) \to B\bar{B})$

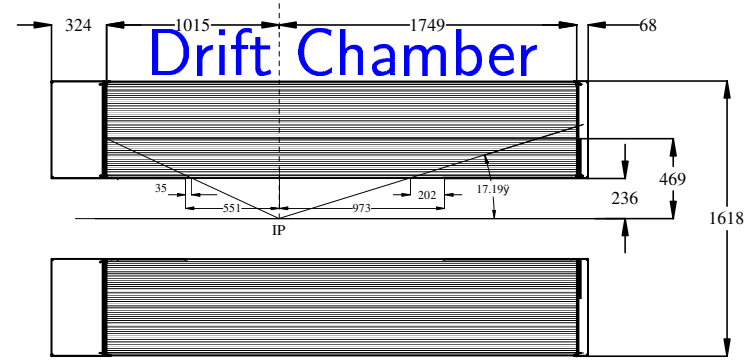
$$m_{\rm ES} = \sqrt{E_{\rm b}^2 - \vec{p}_B^{\,2}}$$

  - $E_{\rm b} = (s/2 + \vec{p}_{ee} \cdot \vec{p}_B)/E_{ee}$
  - $\sigma \sim 2.6$ MeV ($E_{\rm beam}$ dominated)
  - B almost at rest (in $\Upsilon(4S)$ cm)

$$E_{\rm beam}^{\rm cm} = 5.29 \text{ GeV}$$
$$m_B = 5.28 \text{ GeV}$$

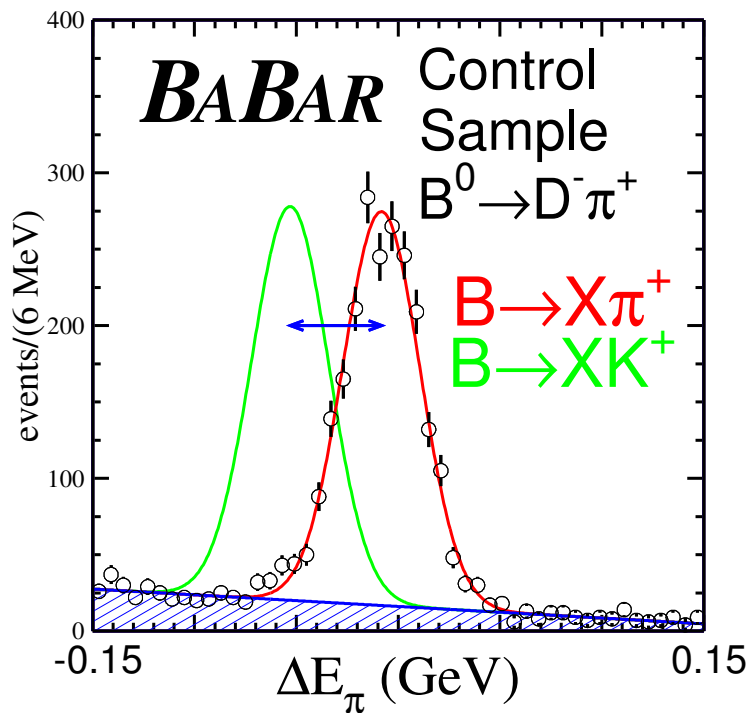
- Signal parameterization:
  - from Monte Carlo
  - and control samples
- Background parameterization
  - from sidebands (float in the fit)

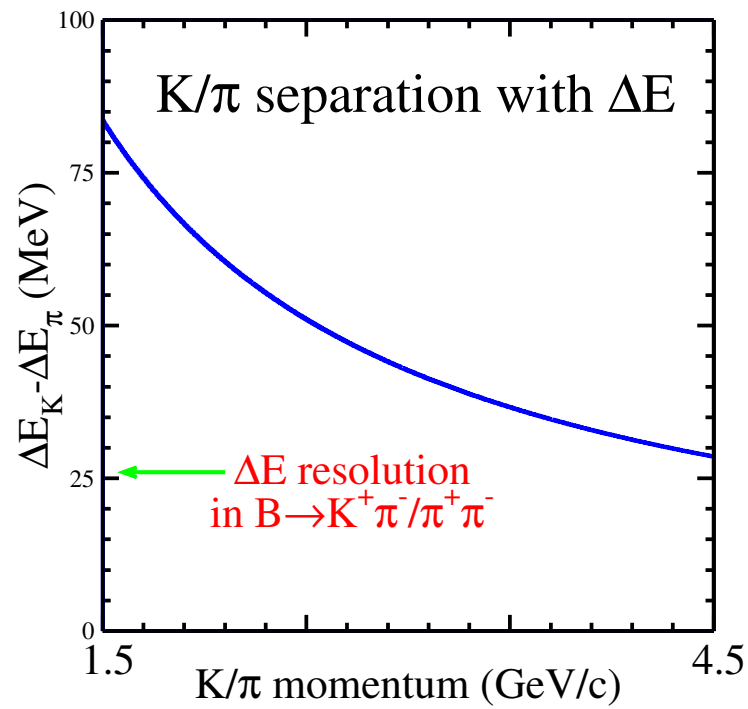




Energy Constraint

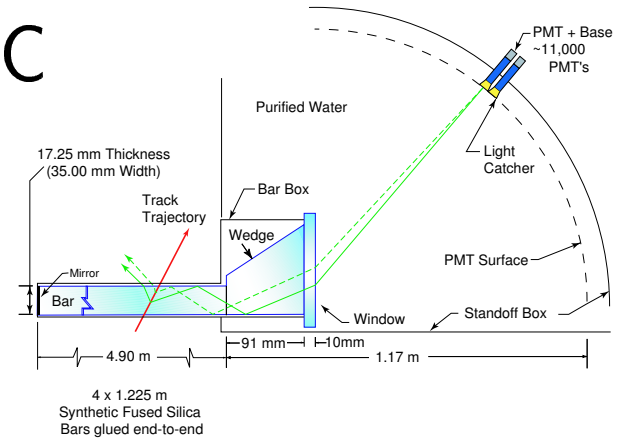
- Energy Constraint: $\Delta E = E_B^{\rm cm} - E_{\rm beam}^{\rm cm}$
  - background suppression; $\sigma \sim 26$ MeV (mom resolution)
  - $K\pi/\pi\pi$ separation: include momentum correlation
  - boost $\Rightarrow$ broad momentum spectrum

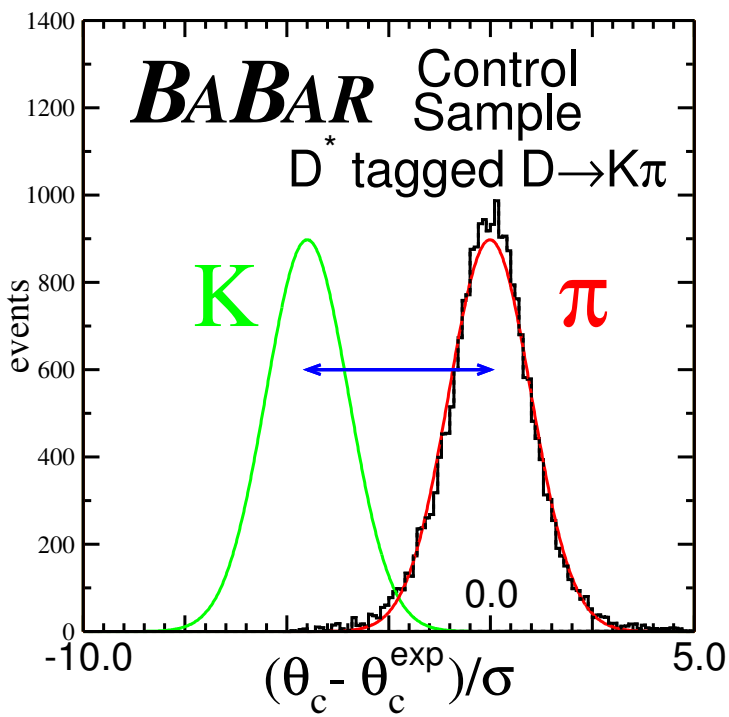


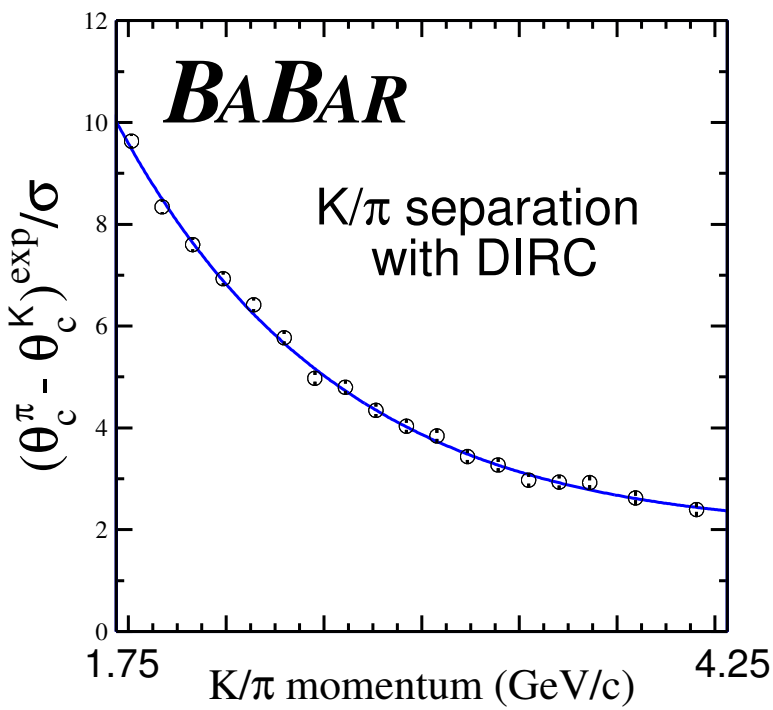


Particle Identification

- Cherenkov angle θ_c from DIRC
  - primary K/π separation
    $\cos(\theta_c) = 1/\beta n$, $\theta_c = f(p, \mathrm{mass})$
  - from 2.5 to $\sim 10\sigma$ separation
  - boost $\Rightarrow$ momentum/angle correlation





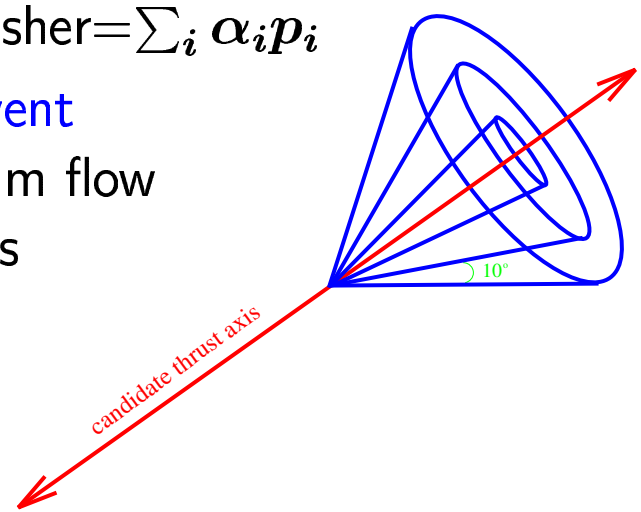


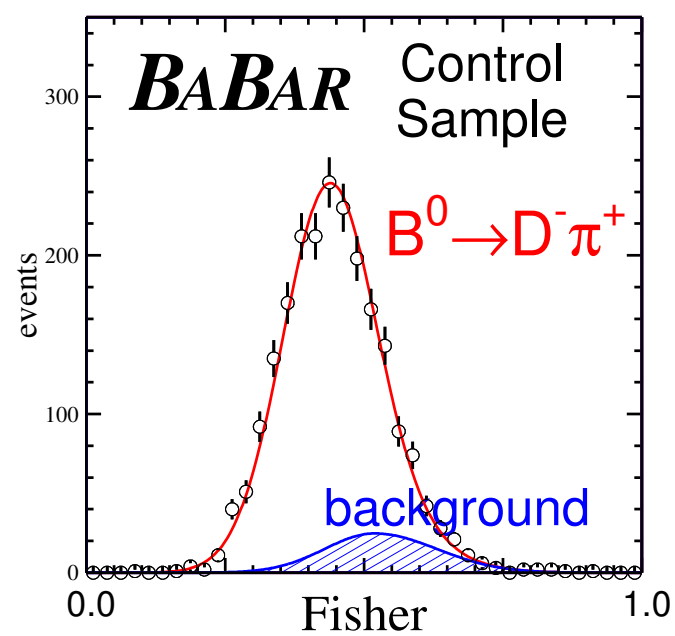
Event Shape

- Suppress background:

$e^+e^- \to q\bar{q} \to$ "jets" (signal "spherical" $e^+e^- \to \Upsilon(4S) \to B\bar{B}$)

- Define in the $\Upsilon(4S)$ cm frame:
  - sphericity axes B/(rest-of-event) angle θ_S
    $\cos(\theta_S) \leq 0.8$; reject $\sim$5/6 background, 1/5 signal
  - CLEO $\mathcal{F}$isher$=\sum_i \alpha_i p_i$
    rest-of-event
    momentum flow
    in 9 cones





Fit for $\mathcal{B}$ranching Fraction

- Unbinned Maximum Likelihood fit

$$\mathcal{L} = \exp\left(-\sum_{i=1}^{8} n_i\right) \prod_{j=1}^{N} \left(\sum_{i=1}^{8} n_i \mathcal{P}_i(\vec{x}_j; \vec{\alpha}) \right) \quad (1)$$

PDF: $\mathcal{P}_i(\vec{x}_j) = \mathcal{P}_{i1}(m_{\rm ES}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{F}) \cdot \mathcal{P}_{i4}(\theta_c^+) \cdot \mathcal{P}_{i5}(\theta_c^-)$

- Fit 4 signal and 4 background yields (n_i):
  - $n_{\pi^+\pi^-}$
  - $n_{K^+\pi^-} = n_{K\pi} \times (1 - \mathcal{A}_{CP})/2$
  - $n_{K^-\pi^+} = n_{K\pi} \times (1 + \mathcal{A}_{CP})/2$
  - $n_{K^+K^-}$

  $(\mathcal{A}_{CP} = \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}})$

- Float 8 background shape parameters
  - $m_{\rm ES}$ (1), ΔE (2), $\mathcal{F}$ (5)
- Reduce systematic uncertainty:
  - no vertexing (Δt) or tagging in $\mathcal{B}$ranching fit

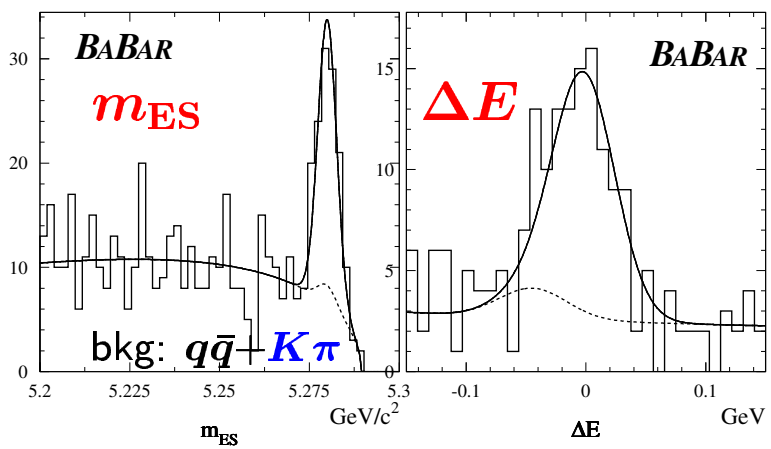
$\mathcal{B}$ranching Fraction Results

- Preliminary: $\sim$60 million $\Upsilon(4S) \to B\bar{B}$, reconstruct $\sim 38\%$ eff

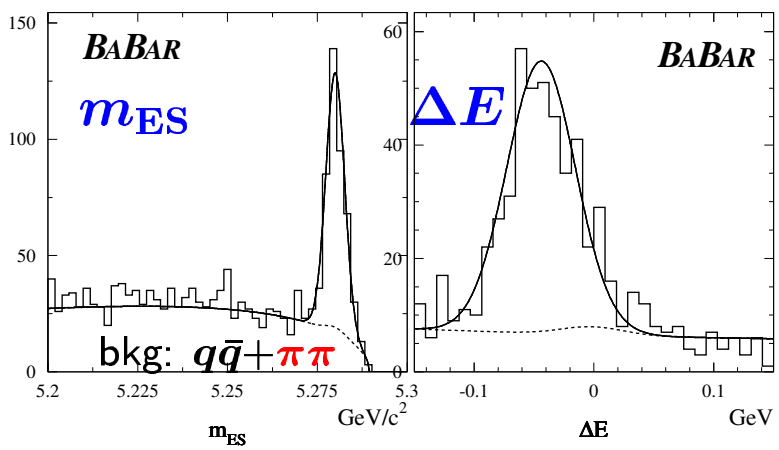
B Decay	Fit Events	BABAR $\mathcal{B}(10^{-6})$	Charge Asymmetry
$\pi^+\pi^-$	124^{+16+7}_{-15-9}	$5.4 \pm 0.7 \pm 0.4$	–
$K^\pm\pi^\mp$	$403 \pm 24 \pm 15$	$17.8 \pm 1.1 \pm 0.8$	$-0.05 \pm 0.06 \pm 0.01$
K^+K^-	$0.6^{+8.0}_{-7.4}$	< 1.1 (90% C.L.)	–

- Projection plots: $\frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm bkg}+\mathcal{P}_{\rm sig}} > \mathcal{C}ut$ ("sphere" in 4D)
  project PDF (total and bkg: $K\pi(\pi\pi)+q\bar{q}$)

$\mathcal{P}$ enhanced $B \to \pi^+\pi^-$



$\mathcal{P}$ enhanced $B \to K^\pm\pi^\mp$



Direct CP in πK and Related Modes

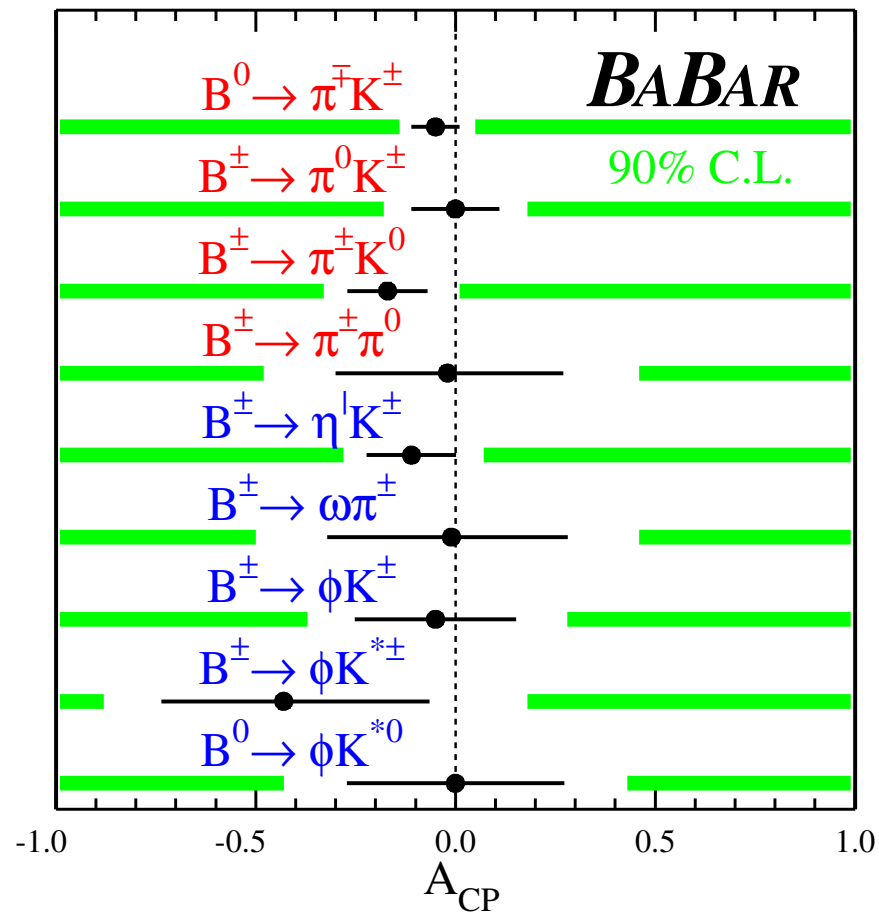
- Penguin+Tree $\Rightarrow$ direct-CP
  - $\pi^+ K^0$, $\phi K^{(*)}$ - "pure" P (New Physics in loops?)
  - $\pi^+ \pi^0$ - pure T

$$\mathcal{A}_{CP} = \frac{2\ |P|\ |T|\ \sin\Delta\phi\ \sin\Delta\delta}{|P|^2+|T|^2+2\ |P|\ |T|\ \cos\Delta\phi\ \cos\Delta\delta}$$

Preliminary with 60×10^6 $B\bar{B}$

B Decay	$\mathcal{A}_{CP}$
$\pi^\mp K^\pm$	$-0.05\pm0.06\pm0.01$
$\pi^0 K^\pm$	$0.00\pm0.11\pm0.02$
$\pi^\pm K^0$	$-0.17\pm0.10\pm0.02$
$\pi^\pm \pi^0$	$-0.05^{+0.27}_{-0.26}\pm0.10$

Published with 23×10^6 $B\bar{B}$
Phys.Rev.D 65, 051101 (2002)



Vertexing (Δt)

- Vertex $B_{\pi\pi} \to \pi^+\pi^-$
- Vertex other B:
  - tracks not from $B_{\pi\pi}$
  - $B_{\pi\pi}$ vertex and momentum
  - $\Upsilon(4S)$ spot and momentum

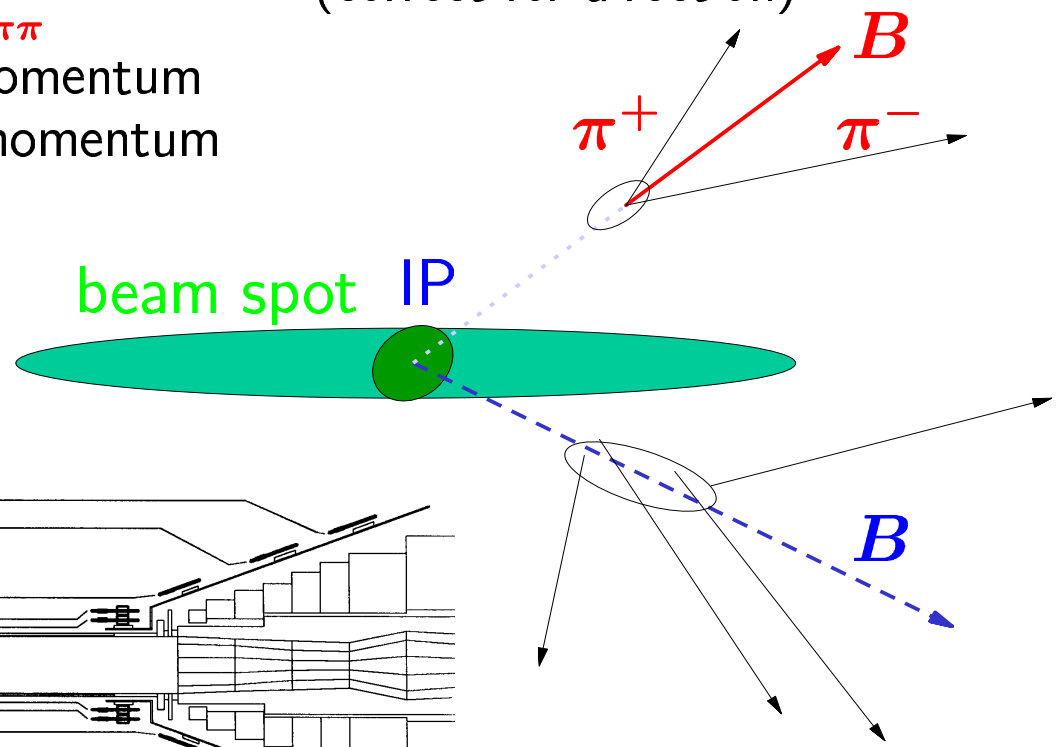
$$\Delta Z = Z_{\pi\pi} - Z_{other}$$

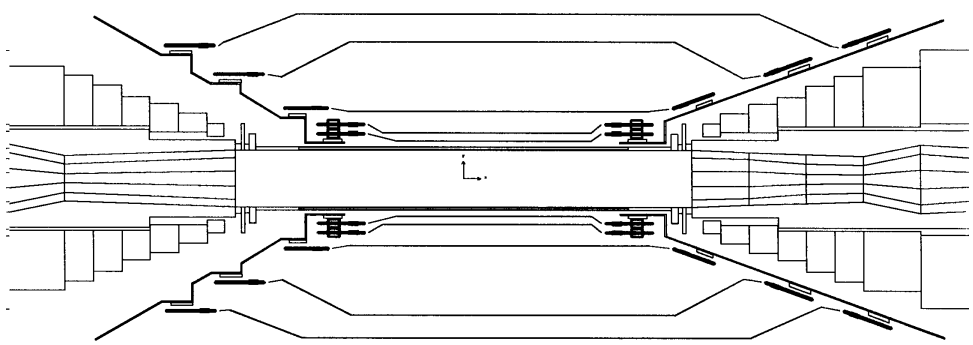
$$\Delta t \approx \Delta Z/(\beta\gamma c)$$

(correct for direction)

$\sigma_{\Delta Z} \sim 180\mu m$

$\beta\gamma c\tau_B \sim 250\mu m$





Silicon Vertex Detector

→ Z

Δt Parameterization

- $B \to \pi^+\pi^-$ (tag other B: $Q_{\rm tag} = \pm 1$ for $B^0/\bar{B}^0$)

$$f_{CP}(\Delta t) = \mathcal{R}_{\rm sig}(\Delta t) \otimes [e^{-|\Delta t|/\tau_B} \times (1 \pm S_{\pi\pi}(1\text{-}2w)\sin(\Delta m_d \Delta t) \mp C_{\pi\pi}(1\text{-}2w)\cos(\Delta m_d \Delta t))]$$

- $B \to K^\pm\pi^\mp$ (kaon charge Q_K)

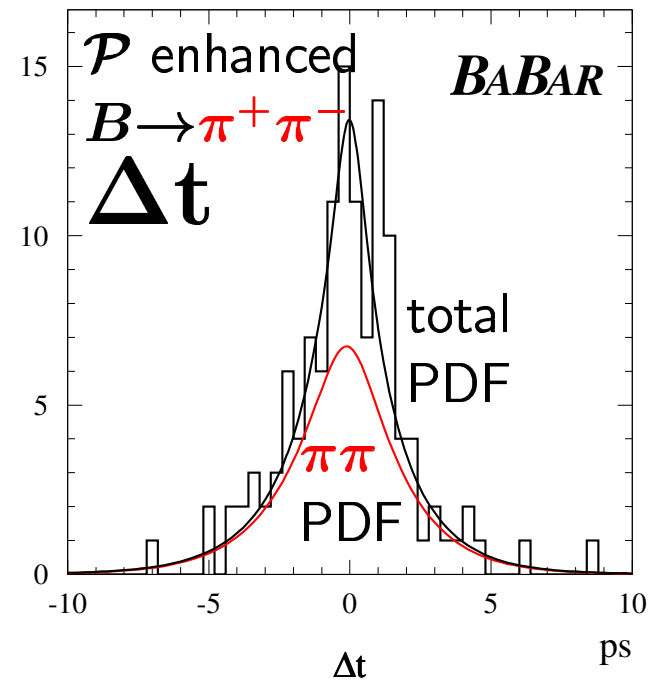
$$f_{\rm self}(\Delta t) = \mathcal{R}_{\rm sig}(\Delta t) \otimes [e^{-|\Delta t|/\tau_B}(1 \pm Q_K(1\text{-}2w)\cos(\Delta m_d \Delta t))]$$

- External info:
  - resolution function $\mathcal{R}_{\rm sig}$ (3 Gaussian)
  - mistag fraction w (next slide)

- Background (empirical):

$$f_{\rm bkg}(\Delta t) = \mathcal{G}_1(\Delta t) \otimes e^{-|\Delta t|/\tau_{\rm bkg}} + \mathcal{G}_2(\Delta t) + \mathcal{G}_3(\Delta t) \quad \text{(Gaussian)}$$

$\tau_{\rm bkg} = 0.56$ ps ($\tau_B = 1.54$ ps)



B Flavor Tagging

- Tagging other B:
  - Lepton charge ($b \to c l^- \nu$)
  - Kaon charge ($b \to c \to s$)
  - Neural Network (p, soft π,..)
    - NT1 (more certain)
    - NT2 (less certain)
  - Untagged

$Q = \Sigma \epsilon_i (1\text{-}2 w_i)^2 = 25.1 \pm 0.8\%$

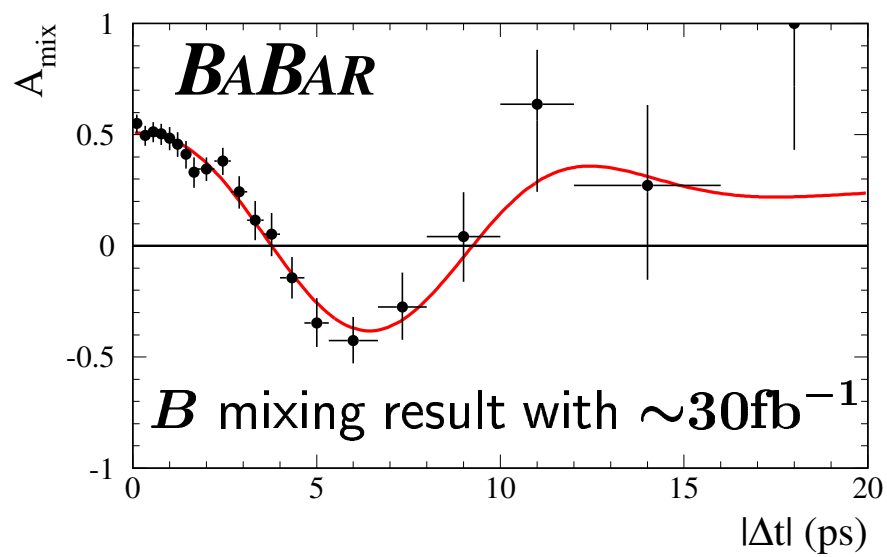
Tag	Mistag w (%)	Signal ϵ (%)	$\pi\pi$ bkg ϵ	$K\pi$ bkg ϵ
Lepton	8.6	11.1	0.9	1.0
Kaon	18.1	34.7	24.9	32.7
NT1	22.0	7.6	6.9	6.1
NT2	37.3	14.0	17.9	15.4
Notag	(50)	32.6	49.4	41.7

- Large sample of

  $B \to D^{(*)-}\pi^+/\rho^+/a_1^+$

  $J/\psi K^{*0}(K^+\pi^-)$

  - determine mistag w_i, ϵ_i
  - resolution function $\mathcal{R}_{\rm sig}$
  - validate vertexing/tagging



Time-dependent Fit

- Add Δt into ML fit:

  $\mathcal{P}_{i1}(m_{\rm ES}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{F}) \cdot \mathcal{P}_{i4}(\theta_c^+) \cdot \mathcal{P}_{i5}(\theta_c^-) \cdot \mathcal{P}_{i6}(\Delta t)$

  – separate PDF, 5 tagging categories: $(n_i \epsilon_{i,c})$, $\mathcal{P}_{i,c}(\vec{x}_j)$

- Fit for: – "sin($2\alpha_{\rm eff}$)": $S_{\pi\pi}$ and $C_{\pi\pi}$

- Fix:
  – yields (n_i) from $\mathcal{B}$ranching fit
  – τ_B and Δm_d
  – signal resolution $\mathcal{R}_{{\rm sig},c}$, mistag w_c, tag ϵff

- Float 32 background shape parameters
  – $m_{\rm ES}$ (5)
  – ΔE (2)
  – $\mathcal{F}$ (5)
  – Δt resolution (8)
  – tagging ϵff $\pi\pi$, $K\pi$, KK (12)

B Lifetime and Mixing with $B \to K\pi$

- Float Δm_d and τ_B in CP fit:

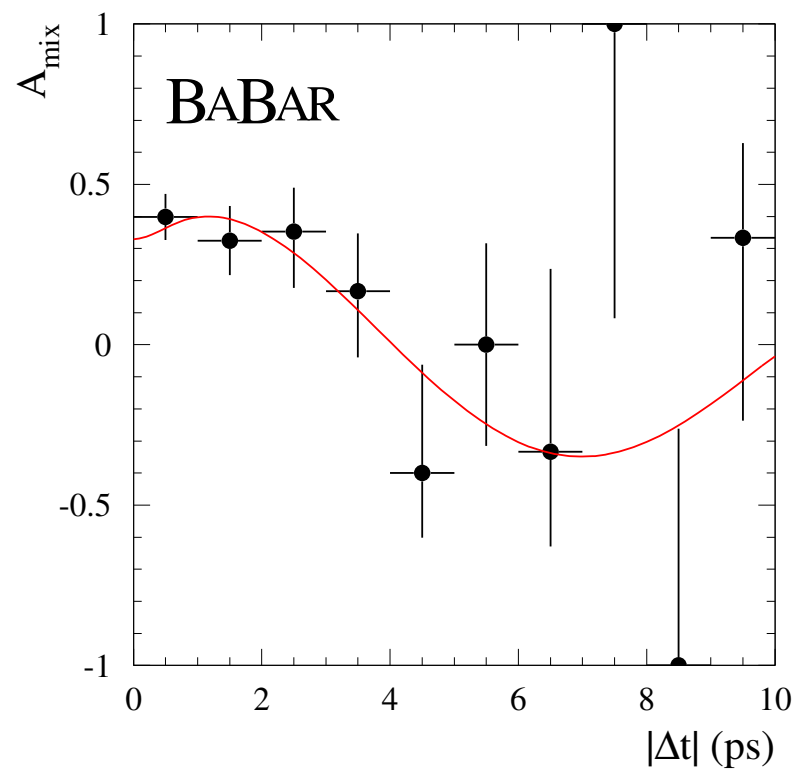
  $\Delta m_d = (0.517 \pm 0.062)$ ps^{-1}

  $\tau_B = (1.66 \pm 0.09)$ ps

- Projection in $B \to K^{\pm}\pi^{\mp}$:

  $$\mathcal{A}_{\rm mix} = \frac{N_{\rm mix} - N_{\rm unmix}}{N_{\rm mix} + N_{\rm unmix}} = (1\text{-}2w)\cos(\Delta m_d \Delta t)$$

- Validation of CP fit



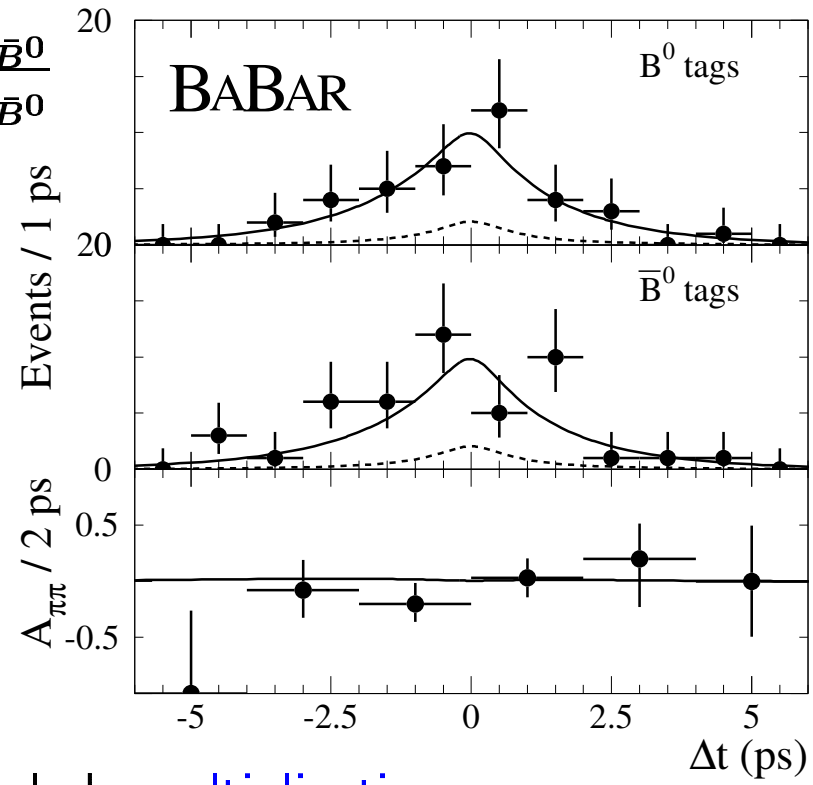
Measurement of $\sin(2\alpha_{\rm eff})$

	BABAR preliminary result	90% C.L.
$S_{\pi\pi}$	$-0.01 \pm 0.37 \pm 0.07$	[-0.66,+0.62]
$C_{\pi\pi}$	$-0.02 \pm 0.29 \pm 0.07$	[-0.54,+0.48]

- Check $\mathcal{A}_{\pi\pi}(\Delta t) = \frac{n_{B^0} - n_{\bar{B}^0}}{n_{B^0} + n_{\bar{B}^0}}$

  $\propto S_{\pi\pi} \sin(\Delta m_d \Delta t)$
  $- C_{\pi\pi} \cos(\Delta m_d \Delta t)$

- Systematics not dominant:
  - θ_c param (0.04-0.06)
  - $\mathcal{R}_{\rm sig}$ (0.01-0.02) ...
  - mistag w_c
  - $\Delta m_d / \tau_B$
  - $\Delta E / m_{\rm ES} / \mathcal{F}$
  - SVT alignment ...



always include multiplicative errors

Cross-Checks

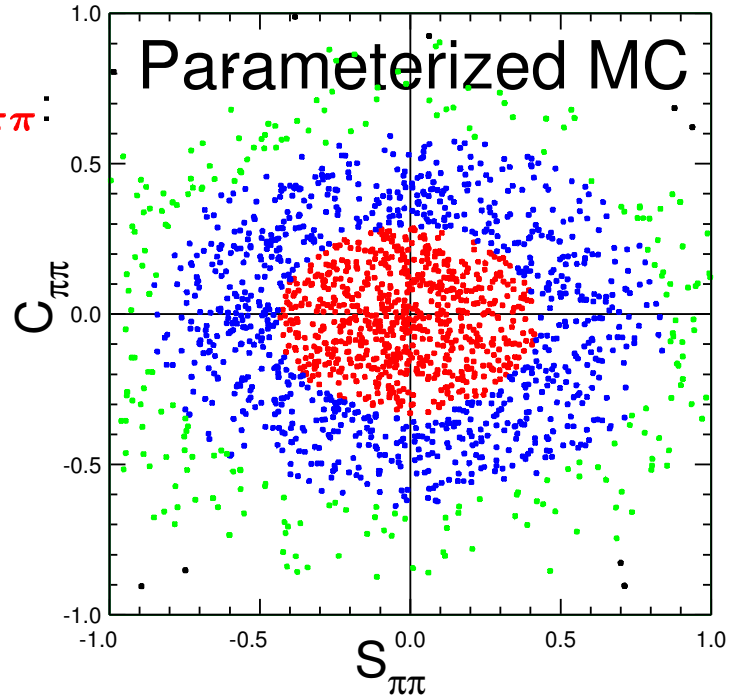
- Parameterized and Simulated Monte Carlo fits:
  - reproduce $\mathcal{L}$ikelihood value
  - reproduce errors ($\pm\sigma$):

    $\sigma_S = 0.37 - 0.48$
    $\sigma_C = 0.28 - 0.34$
  - reproduce generated $S_{\pi\pi}$ and $C_{\pi\pi}$:

    use measured central values (e.g. plot: 1σ, 2σ, 3σ)

    vary non-zero $S_{\pi\pi}$ and $C_{\pi\pi}$ consistent results
  - $S_{\pi\pi}/C_{\pi\pi}$ correlation

    (-13%) in nominal fit



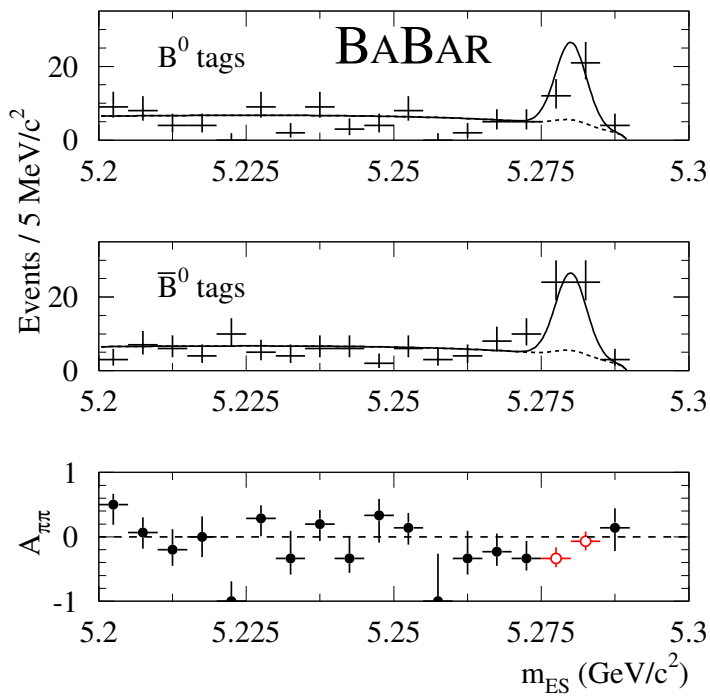
More Cross-Checks

- Simplified analysis:
  - select $\pi\pi$ sample (5D $\mathcal{P}$-based-selection):

    $N_{\pi\pi} = 87.7$
    $N_{K\pi} = 5.4$
    $N_{bkg} = 52.1$

  - 2-parameter fit ($S_{\pi\pi}$ and $C_{\pi\pi}$)
    results consistent
    less accurate
    (should be combined fit with $K\pi$)
  - yield of $B^0 \to \pi\pi$ and $\bar{B}^0 \to \pi\pi$
    no evidence for large $|C_{\pi\pi}|$

$\mathcal{P}$ enhanced $B \to \pi^+\pi^-$



- Of course:
  - tagging/vertexing/reconstruction
    verified in sin(2β), mixing, $\mathcal{B}$ranching analyses

Interpretation of Results

- Constrain α with $C_{\pi\pi}$ and $S_{\pi\pi}$ ($\alpha_{\rm eff}$)

$$S_{\pi\pi}=\frac{2\mathcal{I}m(\lambda_{\pi\pi})}{1+|\lambda_{\pi\pi}|^2}$$

$$C_{\pi\pi}=\frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}$$

$$\lambda_{\pi\pi}=e^{2i\alpha}\left(\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}\right)$$

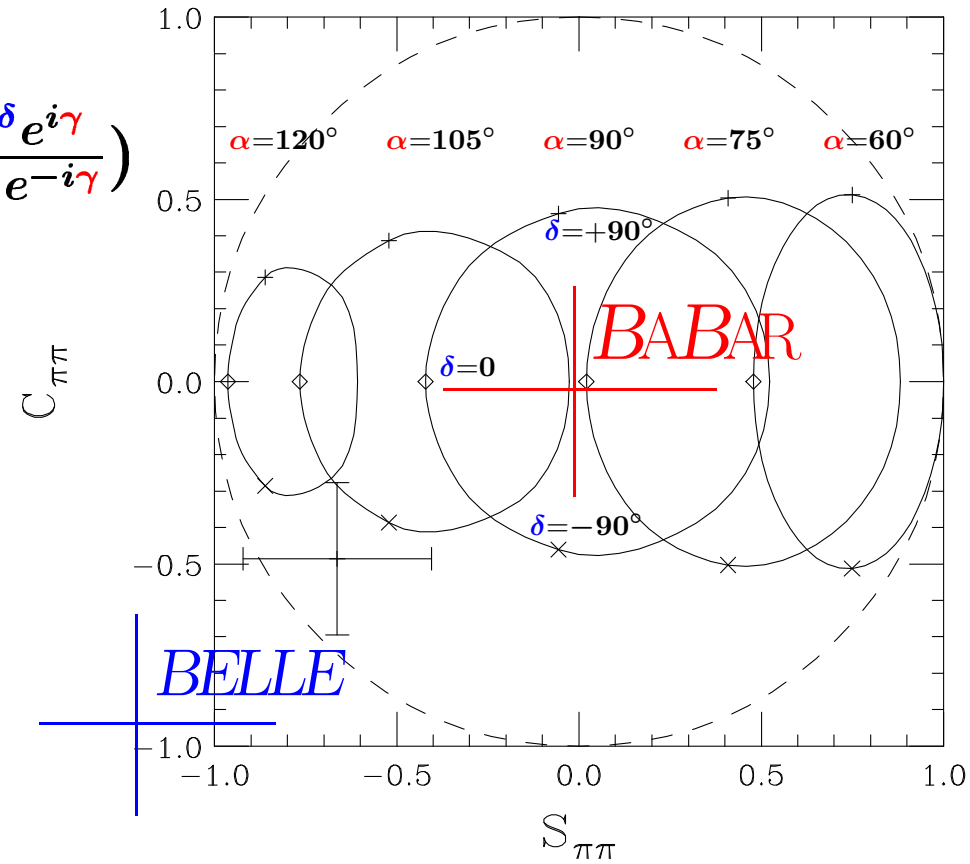
$$S^2+C^2 \leq 1$$

Gronau, Rosner
Phys.Rev.D **65**, 093012 (2002)

- External info:

$$|P/T| \sim 0.28$$
$$\beta = 26^\circ$$
$$-\pi < \delta < \pi$$

$$\alpha = (97^{+30}_{-21})^\circ$$



Summary

- First measurement of $\sin(2\alpha_{\rm eff})$:

  30 million $B\bar{B}$: summer 2001

  BABAR Phys. Rev. D **65**, 051502 (2002)

  $(S_{\pi\pi}=0.03^{+0.53}_{-0.56} \pm 0.11,\ C_{\pi\pi}=-0.25^{+0.45}_{-0.47} \pm 0.14)$

  60 million $B\bar{B}$: this measurement

  $$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$$
  $$C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$$

  90 million $B\bar{B}$: expect this summer

  $$\sigma(S_{\pi\pi}) \sim 0.31, \quad \sigma(C_{\pi\pi}) \sim 0.24$$

- Direct constraints on α

- Extensive *BABAR* program:
  - $\mathcal{B}$ranchings and direct-CP in all $B \to \pi\pi/K\pi$ and other modes
  - $\sin(2\alpha_{\rm eff})$ in other modes