Review of Rare Two-Body B Decays

FPCP

Flavor Physics and CP Violation

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May 17, 2002

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$B \to \pi\pi \quad B \to K\pi \quad B \to KK$

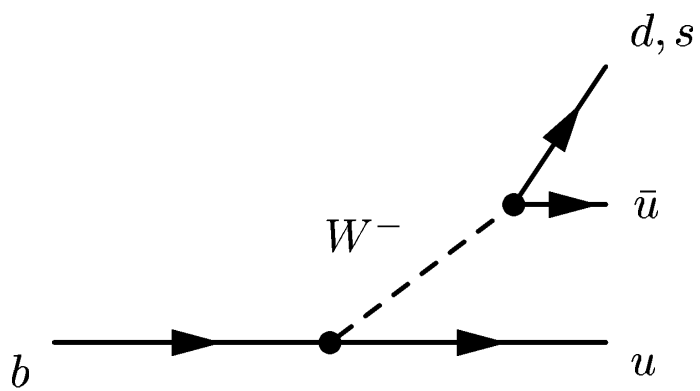
Overview

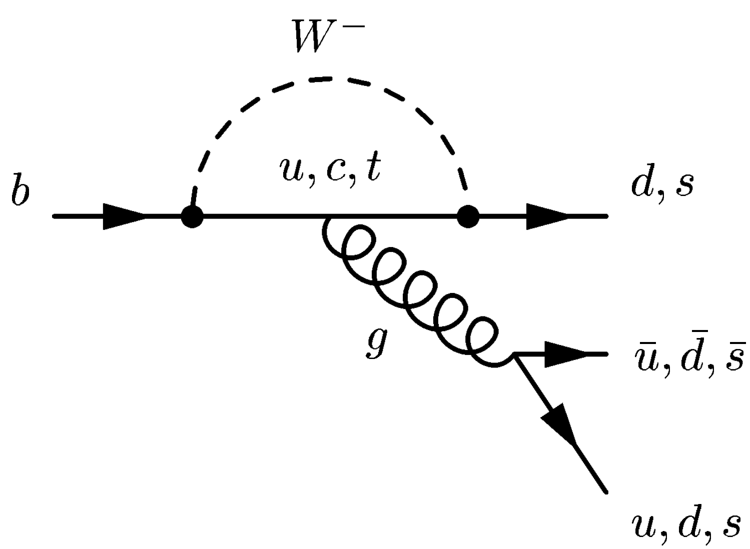
- *Belle* and *BABAR* have now looked at all charge combinations of the rare decays $B \to \pi\pi$, $B \to K\pi$ and $B \to KK$
- No new data from CLEO, but will include previous results in comparisons and averages

Outline

- Introduction
- *Belle* and *BABAR* Analyses
- Results and Averages
- Conclusions

Trees and Penguins





- Many $B \rightarrow h'h$ modes are dominated by V_{ub} tree (T) or gluonic penguin (P) diagrams
- Other topologies can contribute (such as W-Exchange, Annihilation)
- P/T interference can lead to direct CPV
- Possibility to measure CKM angles
- Probe for New Physics

Decay Dynamics

Final state	Diagrams
$B^0 \to K^+\pi^-$	*P dominated + T*
$B^+ \to K^+\pi^0$	*P dominated + T*
$B^+ \to K^0\pi^+$	*P*
$B^0 \to K^0\pi^0$	*P + T_C*
$B^0 \to \pi^+\pi^-$	*T dominated + P "polluted"*
$B^+ \to \pi^+\pi^0$	*T (+ P_{EW})*
$B^0 \to \pi^0\pi^0$	*T_{C} + P*
$B^0 \to K^+K^-$	*W-Exchange*
$B^+ \to K^+\overline{K}^0$	*P + Annihilation*
$B^0 \to K^0\overline{K}^0$	*P + W-Exchange*

- In $K\pi$ modes, penguins are Cabibbo enhanced
- $\pi\pi$ modes favor trees
- The K^+K^- mode is strongly suppressed

Isospin Analysis

- Isospin relations allow to set bounds on the strong phase difference δ, *e.g.*,

$$B^{00} \equiv \frac{\mathcal{B}(B^0 \to \pi^0\pi^0)}{\mathcal{B}(B^+ \to \pi^+\pi^0)}$$

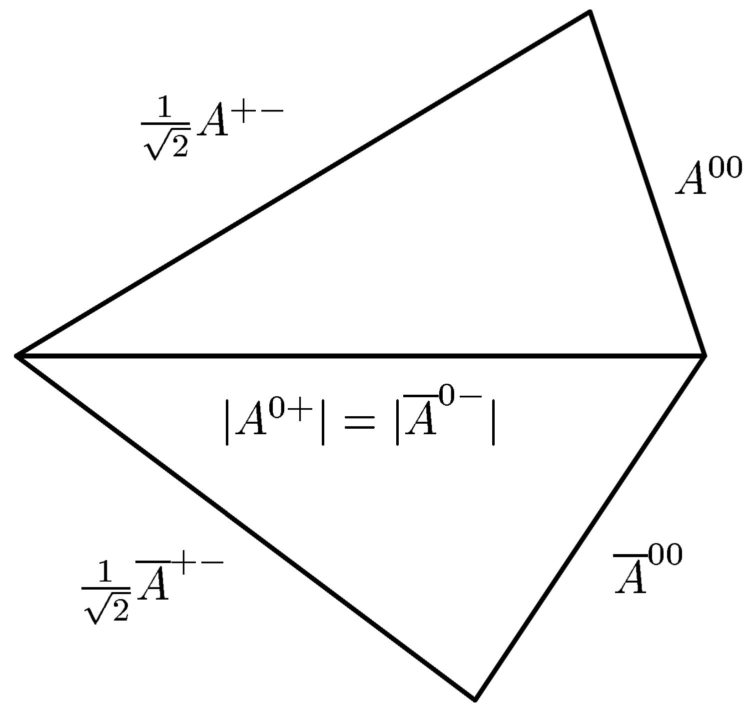
$$B^{+-} \equiv \frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B^+ \to \pi^+\pi^-)}$$

constrain δ in $B^0 \to \pi^+\pi^-$ via:

$$\sin^2\delta \leq B^{00,+-}$$

$$\delta = \alpha - \alpha_{\text{eff}}$$

(Grossman, Quinn) [hep-hp/9712306]
(Charles) [hep-hp/9806568]



- Will show an example application at the end

Data Sets Used

CLEO / CESR

- $E_{e^\pm} = 5.29\,\mathrm{GeV}$
- $9.1\ \mathrm{fb}^{-1}$

Belle / KEKB

- $E_{e^-} = 8\,\mathrm{GeV}$, $E_{e^+} = 3.5\,\mathrm{GeV}$, $\beta\gamma = 0.43$
- $29.1\ \mathrm{fb}^{-1}$, corresponding to 31.7 ± 0.3 million $B\overline{B}$ events

BABAR / PEP-II

- $E_{e^-} = 9\,\mathrm{GeV}$, $E_{e^+} = 3.1\,\mathrm{GeV}$, $\beta\gamma = 0.55$
- $55.6\ \mathrm{fb}^{-1}$, corresponding to 60.2 ± 0.7 million $B\overline{B}$ events

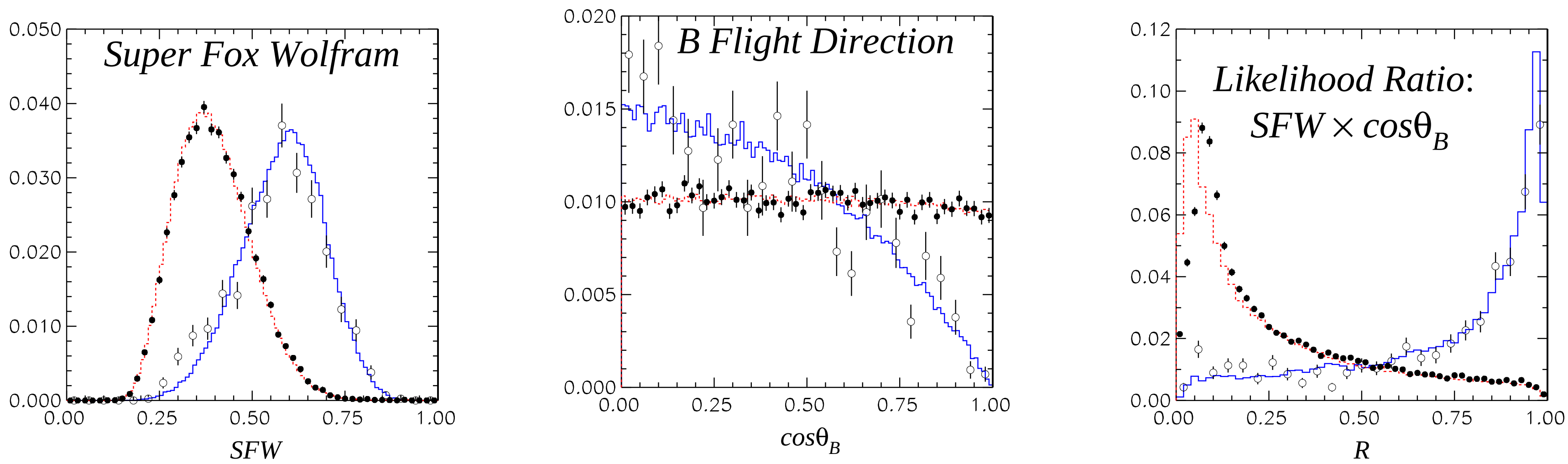
Analysis Overview

- Select B candidates using invariant mass and energy difference
- Suppress (jetlike) continuum background with event shape variables
- Separate modes with particle identification (PID) ($\pi^{\pm}$,$K^{\pm}$), reconstruct $\pi^0 \rightarrow \gamma\gamma$ and $K_S^0 \rightarrow \pi^+\pi^-$
- Obtain probability density functions (PDFs) from sideband data and Monte Carlo simulation
- Perform maximum likelihood fit of signal and background yields and CP asymmetries to preselected data sample

Continuum Suppression

Belle

- Create a six-variable Fisher discriminant called "Super Fox-Wolfram'
  - $SFW = \sum_{l=2,4} \alpha_l (\frac{h_l^{so}}{h_0^{so}}) + \sum_{l=1}^{4} \beta_l (\frac{h_l^{oo}}{h_0^{oo}})$, with $h_l = \sum_{i,j} p_i p_j P_l(\cos\theta_{ij})$
  - h_l^{so} iterate over B candidate and remaining particles, h_l^{oo} over remaining particles
- Cut on likelihood ratio of SFW and B flight direction $\cos\theta_{B,z}$
- Signal PDF derived from MC, continuum PDF from sideband data
  - Compare to $B^+ \to D^0(K^-\pi^+)\pi^+$ control sample (○) and off-resonance data (●)



Continuum Suppression (cont)

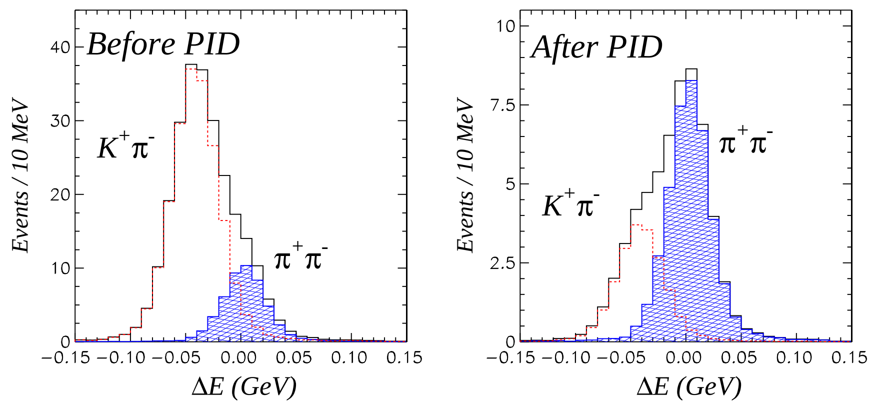
BABAR

- Cut on Fox-Wolfram $R_2 < 0.95$, Sphericity $S > 0.01$
- Cut on angle between sphericity axes of B candidate and rest of event, $|\cos\theta_{\rm S}| < 0.9$
- Construct Fisher discriminant $\mathcal{F} = \sum_i \alpha_i x_i$ counting energy/momentum flow into 9 concentric 10° cones around B candidate thrust axis (as introduced by CLEO)

Particle Identification

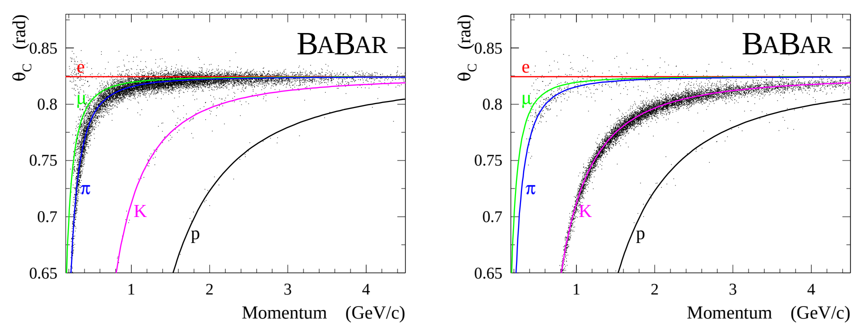
Belle

- Array of Silica Aerogel Čerenkov counters (ACC)
  - Measurement of light yield in ACC
- Barrel of 128 time-of-flight plastic scintillating modules (TOF)



BABAR

- Detection of Internally Reflected Čerenkov light (DIRC)
  - Čerenkov angle measurement θ_c
  - $4\,\sigma$ K/π separation up to $3\,\mathrm{GeV}$, $2.5\,\sigma$ at kin. endpoint $4.3\,\mathrm{GeV}$



$D^{*+} \to D^0(K^-\pi^+)\,\pi^+$ sample

Kinematic Variables

$$\Delta E = E_B^* - \sqrt{s}/2$$

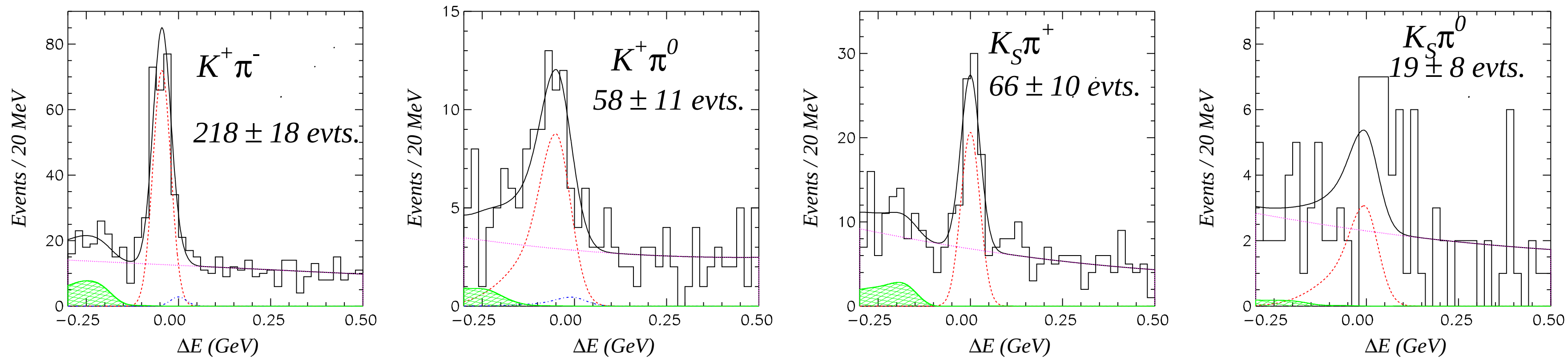
$$m_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_B^2} \quad (\textit{Belle})$$

$$m_{\rm ES} = \sqrt{(s/2 + \mathbf{p_0}\,\mathbf{p_B})^2/E_0^2 - p_B^2} \quad (\textit{BABAR})$$

- Energy of charged particles calculated using π mass hypothesis
  - ΔE shifts by $-45\,\mathrm{MeV}$ for each charged K
- Use beam constrained or energy substituted mass, respectively
  - Improves mass resolution by an order of magnitude
  - dominated by beam energy spread (*e.g.* $2.5\,\mathrm{MeV}$ at PEP-II when folded with $\Upsilon(4S)$ line shape)

$B \to K\pi$

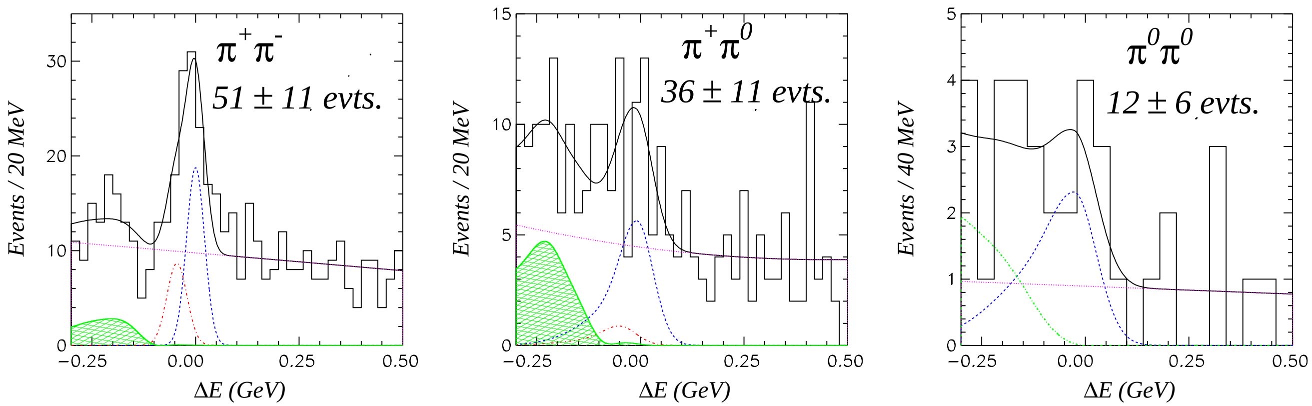
Belle



- Dashed line represents signal component
- Dotted line is continuum background
- Hatched histogram shows rare (charmless) B background

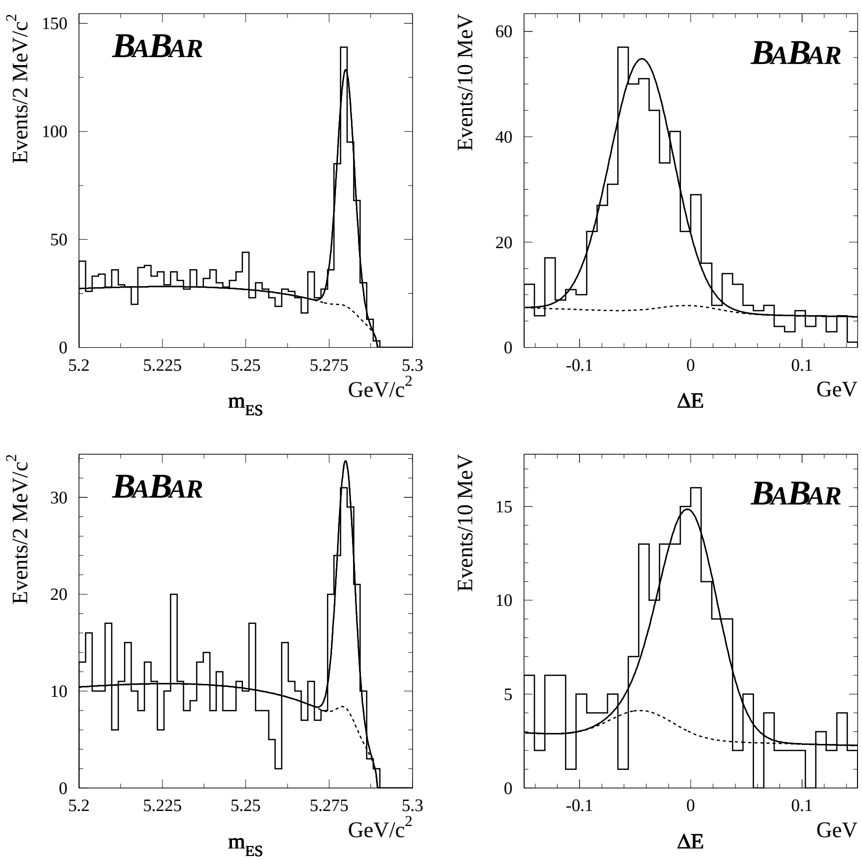
$B \to \pi\pi$

Belle



$B^0 \to K^+\pi^- \quad B^0 \to \pi^+\pi^-$

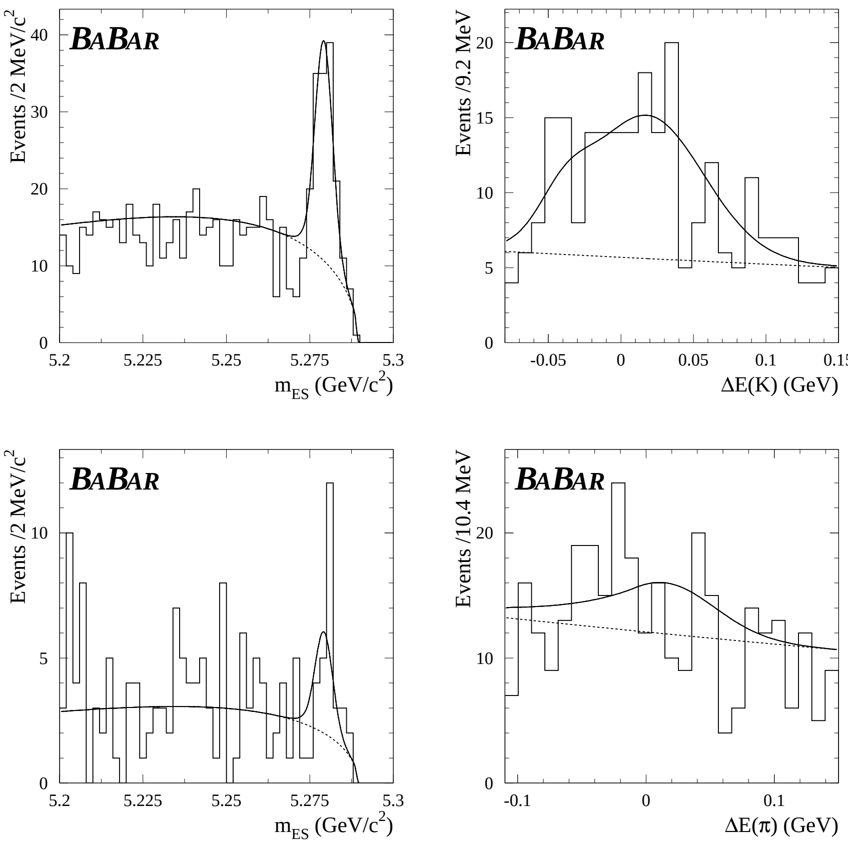
BABAR



- Charged kaon/pion modes measured simultaneously
- Solid curve represents projection of ML fit result
- Dashed curve shows sum of $q\overline{q}$ and cross-feed background

$B^+ \to K^+\pi^0 \quad B^+ \to \pi^+\pi^0$

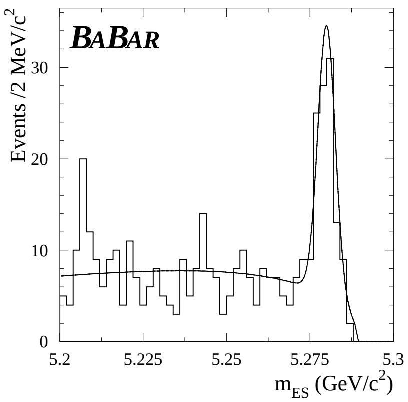
BABAR

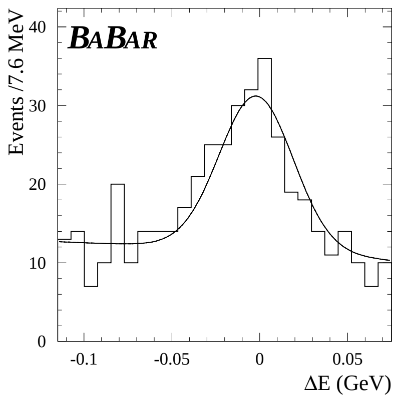


- Reconstructed $\pi^0 \to \gamma\gamma$

$B^+ \to K^0\pi^+$

BABAR





- Reconstructed $K^0_S \to \pi^+\pi^-$

Systematics

- Uncertainty in shape/parameterization of PDFs
- Charmless three-body decay feed-down
  - *e.g.*, $B^0 \to \rho^+\pi^-$ ($\mathcal{B} \approx 25 \cdot 10^{-6}$) and $B^+ \to \rho^+\pi^0$ (not yet observed) background in $\pi^+\pi^0$ channel
  - Similarly, $B^0 \to \rho^+\pi^0$ background in $\pi^0\pi^0$
  - Assume CLEO central value of $24 \cdot 10^{-6}$ for $\rho^+\pi^0$ and vary within $\pm 1\,\sigma$
  - ΔE most discriminating variable for this background

Belle Branching Fractions

Final state	Efficiency	Yield	Significance	$\mathcal{B}\,[10^{-6}]$
$K^+\pi^-$	31 %	218 ± 18	16.4	$21.8 \pm 1.8 \pm 1.5$
$K^+\pi^0$	15 %	58 ± 11	6.3	$12.5 \pm 2.4 \pm 1.2$
$K^0\pi^+$	11 %	66 ± 10	8.2	$18.8 \pm 3.0 \pm 1.5$
$K^0\pi^0$	8 %	19 ± 8	2.7	$7.7 \pm 3.2 \pm 1.6$
$\pi^+\pi^-$	31 %	51 ± 11	5.4	$5.1 \pm 1.1 \pm 0.4$
$\pi^+\pi^0$	16 %	36 ± 11	3.5	$7.0 \pm 2.2 \pm 0.8$
$\pi^0\pi^0$	13 %	12 ± 6	2.2	< 5.6
K^+K^-	26 %	0 ± 2	0	< 0.5
$K^+\overline{K}^0$	6 %	0 ± 2	0	< 3.8
$K^0\overline{K}^0$	2 %	1 ± 3	0	< 13

BABAR **Branching Fractions**

Final state	Efficiency	Yield	Significance	$\mathcal{B}\,[10^{-6}]$
$K^+\pi^-$		403 ± 24		$17.8 \pm 1.1 \pm 0.8$
$K^+\pi^0$	22 %	$149\,^{+17}_{-17}\,^{+8}_{-7}$		$11.1\,^{+1.3}_{-1.2} \pm 1.0$
$K^0\pi^+$	16 %	$172\,^{+17}_{-17} \pm 9$	17.8	$17.5\,^{+1.8}_{-1.7} \pm 1.8$
$K^0\pi^0$	10 %	$17.9\,^{+6.8}_{-5.8} \pm 1.9$	4.5	$8.2\,^{+3.1}_{-2.7} \pm 1.2$ *
$\pi^+\pi^-$		$124\,^{+16}_{-15}$		$5.4 \pm 0.7 \pm 0.4$
$\pi^+\pi^0$	25 %	$62\,^{+17}_{-16}\,^{+10}_{-11}$	5.2	$4.1\,^{+1.1}_{-1.0}\,^{+0.8}_{-0.7}$
$\pi^0\pi^0$		9.8 ± 8.7	1.3	< 3.4
K^+K^-		$0.6\,^{+8.0}_{-7.4}$		< 1.1
$K^+\overline{K}^0$	16 %	$-5.6\,^{+2.8}_{-5.5} \pm 2.5$		< 1.3
$K^0\overline{K}^0$		$3.4\,^{+3.4}_{-2.4}$	1.5	< 7.3 *

*) Based on a data sample of $20.6\,\mathrm{fb}^{-1}$

Partial Rate Asymmetries

- Asymmetries

$$\mathcal{A}_{\rm CP}(f) = \frac{N(\overline{B} \to \overline{f}) - N(B \to f)}{N(\overline{B} \to \overline{f}) + N(B \to f)}$$

can be measured for B^0 or B^+ and their charge conjugates. (f represents $h'h$ final state)

  – For CP eigenstates, parent B flavor must be tagged from other B

  – In other modes, flavor is given by charge of final state K or π (self-tagging)

Charge Asymmetry Results

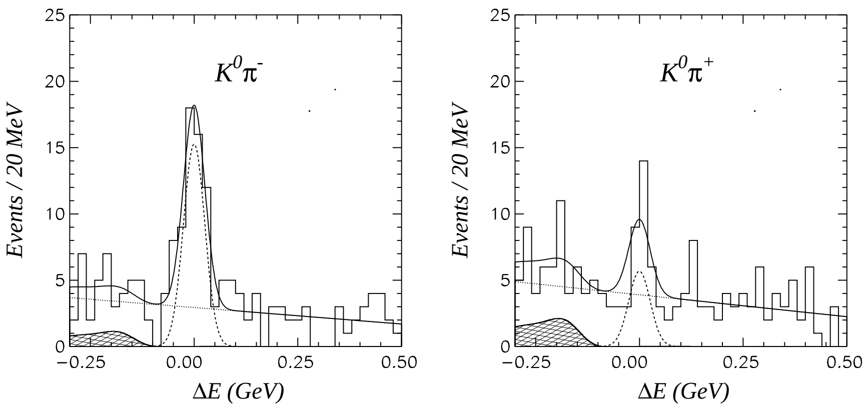
Belle

Final state	$N(\overline{B})$	$N(B)$	$\mathcal{A}_{\rm CP}$	
$K^{\mp}\pi^{\pm}$	103 ± 12	115 ± 14	$-0.06 \pm 0.08 \pm 0.01$	
$K^{\mp}\pi^{0}$	28 ± 8	30 ± 8	$-0.04 \pm 0.19 \pm 0.03$	
$K^{0}\pi^{\mp}$	49 ± 8	18 ± 6	$0.46 \pm 0.15 \pm 0.02$	$\leftarrow$
$\pi^{\mp}\pi^{0}$	24 ± 8	13 ± 7	$0.31 \pm 0.31 \pm 0.05$	

- *Belle* sees a $3\,\sigma$ direct CP asymmetry in $B^+ \to K^0\pi^+$
- No tree diagram: $\mathcal{A}_{\rm CP}(K^0\pi^\pm) \neq 0$ implies a significant annihilation or rescattering contribution

BABAR

Final state	$\mathcal{A}_{\rm CP}$
$K^{0}\pi^{\mp}$	$-0.17^{+0.10}_{-0.10} \pm 0.02$



- *BABAR* data do not confirm this

Summary of BF Results

Mode	9.1 fb^{-1} CLEO	29.1 fb^{-1} Belle	55.6 fb^{-1} BABAR	**Average**	χ^2
$K^+\pi^-$	$17.2^{+2.5}_{-2.4}\pm1.2$	$21.8\pm1.8\pm1.5$	$17.8\pm1.1\pm0.8$	$\mathbf{18.6^{+1.1}_{-1.1}}$	2.5
$K^+\pi^0$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	$12.5\pm2.4\pm1.2$	$11.1^{+1.3}_{-1.2}\pm1.0$	$\mathbf{11.5^{+1.3}_{-1.3}}$	0.2
$K^0\pi^+$	$18.2^{+4.6}_{-4.0}\pm1.6$	$18.8\pm3.0\pm1.5$	$17.5^{+1.8}_{-1.7}\pm1.3$	$\mathbf{17.9^{+1.7}_{-1.7}}$	0.1
$K^0\pi^0$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	$7.7\pm3.2\pm1.6$	$8.2^{+3.1}_{-2.7}\pm1.2$ *	$\mathbf{8.9^{+2.3}_{-2.2}}$	1.0
$\pi^+\pi^-$	$4.3^{+1.6}_{-1.4}\pm0.5$	$5.1\pm1.1\pm0.4$	$5.4\pm0.7\pm0.4$	$\mathbf{5.2^{+0.6}_{-0.6}}$	0.4
$\pi^+\pi^0$	$5.4^{+2.1}_{-2.0}\pm1.5\ (<13)$	$7.0\pm2.2\pm0.8$	$4.1^{+1.1}_{-1.0}{}^{+0.8}_{-0.7}$	$\mathbf{4.9^{+1.1}_{-1.1}}$	1.2
$\pi^0\pi^0$	<5.2	<5.6	<3.4		
K^+K^-	<1.9	<0.5	<1.1		
$K^+\overline{K}^0$	<5.1	<3.8	<1.3		
$K^0\overline{K}^0$	<13	<13	<7.3 *		

*) Based on a data sample of 20.6 fb^{-1}

Example Application

- Bound of the relative strong phase $\delta = \alpha - \alpha_{\text{eff}}$ in $B \to \pi^+\pi^-$, inferred from isospin relations

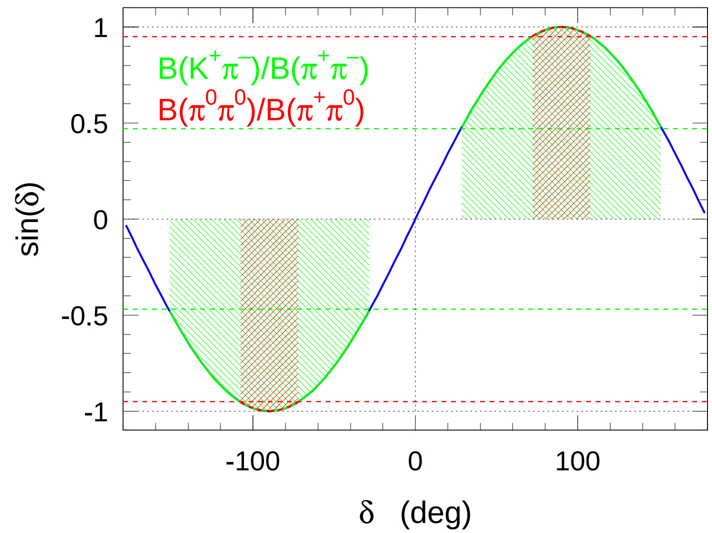
- Using the world average for $\mathcal{B}(B^+ \to \pi^+\pi^0)$, and the best upper limit on $\mathcal{B}(B^0 \to \pi^0\pi^0)$ or the measured $\mathcal{B}(B^0 \to K^+\pi^-)$, respectively, one obtains:

$$\sin^2\delta[B^{00}] \leq 0.91 \quad @\,90\,\%\,\text{C.L.} \qquad \sin^2\delta[B^{+-}] \leq 0.22 \quad @\,90\,\%\,\text{C.L.}$$

- With the following allowed regions for the phase difference:

$$\delta[B^{00}\ ]\ \epsilon\ \pm[0° - 72°, 108° - 180°]$$

$$\delta[B^{+-}]\ \epsilon\ \pm[0° - 28°, 152° - 180°]$$



Conclusions

- The complete set of $B \rightarrow h'h$ modes (with h',h= (π,K)) has been investigated by CLEO, *Belle* and *BABAR*.
- Branching fractions are generally in good agreement between the experiments
- We have the first measurement(s) of the decay $B^+ \rightarrow \pi^+\pi^0$
  - Together with $B^+ \rightarrow K^0\pi^+$, necessary ingredient to assess P/T ratio
- The $B^0 \rightarrow \pi^0\pi^0$ upper limit has been pushed down
- No KK signals have been observed yet in 55 (29) fb^{-1}