



Branching fractions and CP asymmetries in charmless 2-body B decays at $BABAR$ $[B \rightarrow \pi\pi, K\pi, KK]$

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for the BABAR collaboration

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Outline

- some phenomenology of 2-body B decays
- analysis method
- experimental results

Charmless two-body decays: $B \rightarrow [\pi\pi], [\pi K], [KK]$



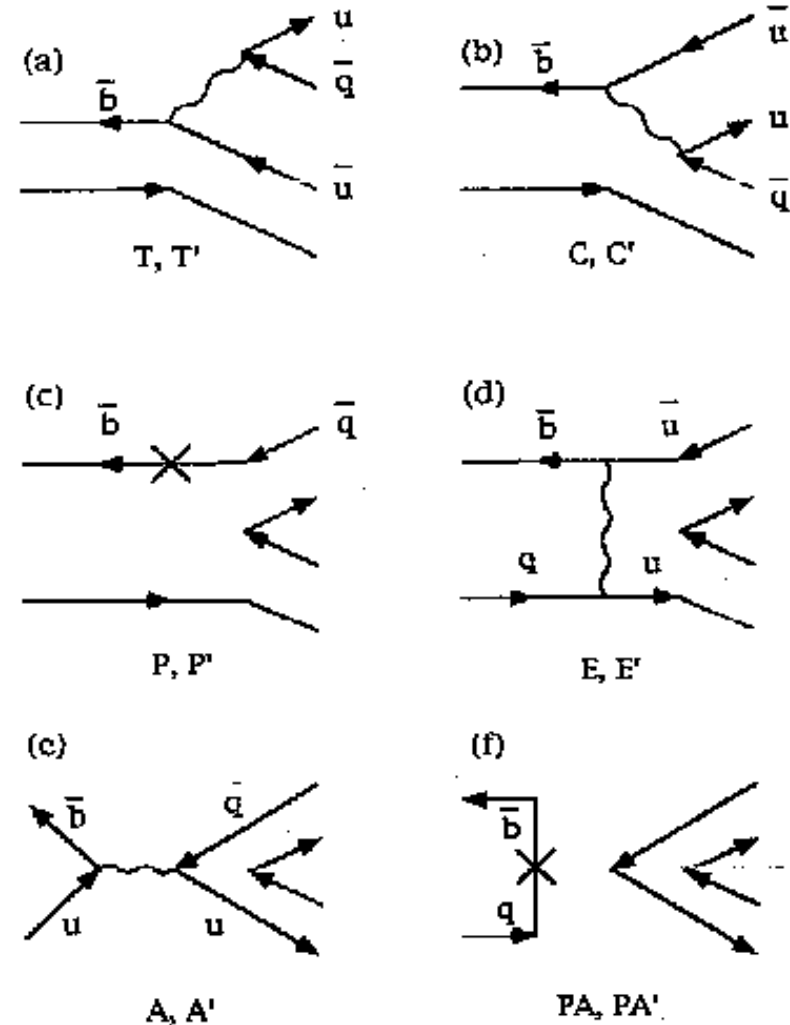
Why?

- many topologies: not just 'trees' and 'penguins'
 - rich source for understanding B decays
- large expected CPV effects
 - sensitive to weak phases
- several decays dominated by loops
 - sensitive to new physics

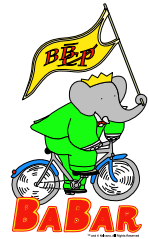
How?

- amplitudes related by isospin and SU(3)
 - use to extract weak phases
- α from isospin in $\pi\pi$ (G&L PRL65, 3381 (1990))
- γ from isospin in $K\pi$ (G&R&L PRL73, 21 (1994))
- amplitude computation
 - QCD FA (Beneke, Neubert)
 - pQCD (Li *et.al.*)
 - SCET (Bauer, Pirjol, Fleming *et.al.*)
 - charming penguins (Ciuchini *et.al.*)

common: use symmetries to extract certain non-perturbative parameters from data



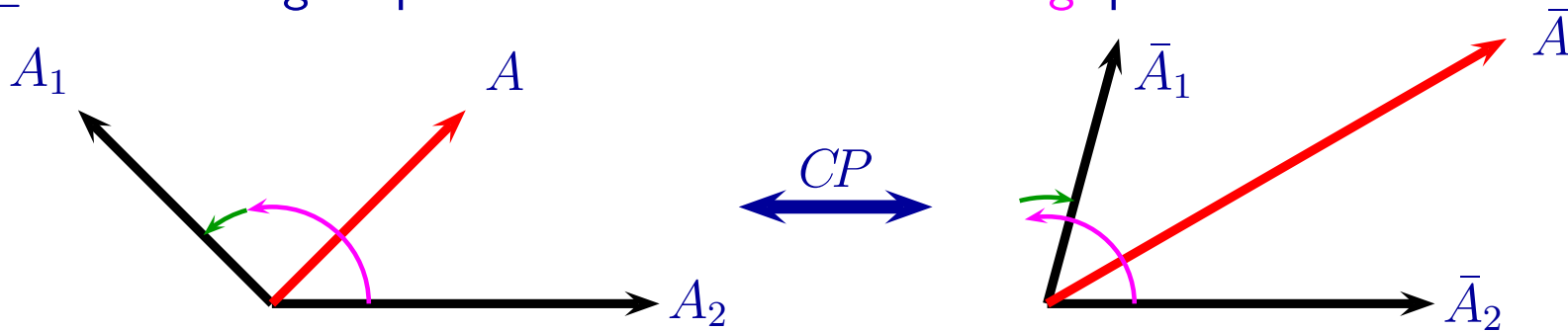
Charge or direct asymmetry



CP violation observed in charge asymmetry:

$$\mathcal{A}_f \equiv \frac{N(\bar{B} \rightarrow \bar{f}) - N(B \rightarrow f)}{N(\bar{B} \rightarrow \bar{f}) + N(B \rightarrow f)} = \frac{|A(\bar{B} \rightarrow \bar{f})|^2 - |A(B \rightarrow f)|^2}{|A(\bar{B} \rightarrow \bar{f})|^2 + |A(B \rightarrow f)|^2}$$

≥ 2 interfering amplitudes with **weak** and **'strong'** phase difference



For two amplitudes:

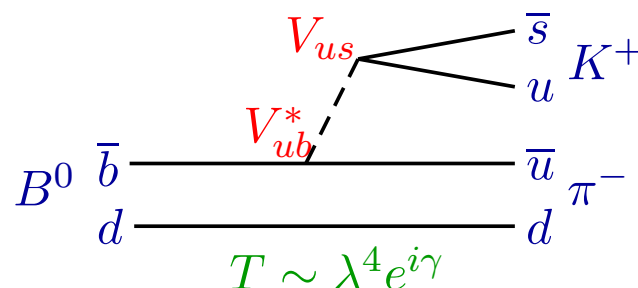
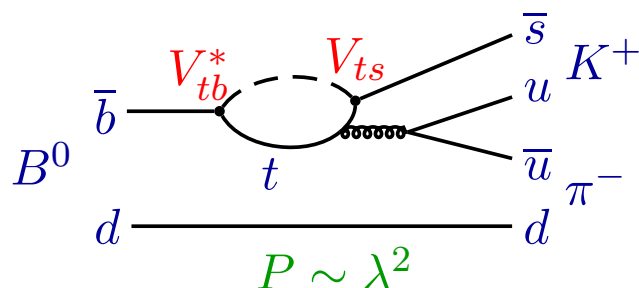
$$\mathcal{A} = \frac{2 \sin \Delta\phi_w \sin \Delta\phi_s}{|A_1/A_2| + |A_2/A_1| + 2 \cos \Delta\phi_w \cos \Delta\phi_s}$$

- sizable only if $\Delta\phi_s \neq 0$ and $|A_2/A_1| \approx 1$
- expect large effects in $B \rightarrow \pi K$ decays
- extraction of fundamental parameters non-trivial



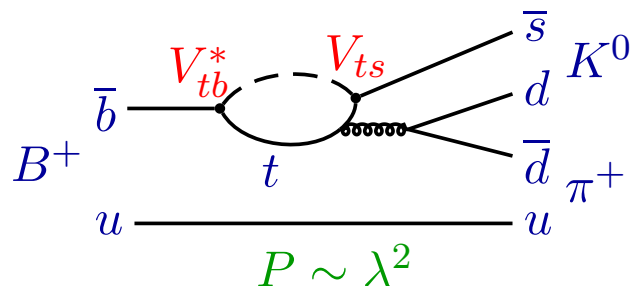
Example: $B^0 \rightarrow K^\pm \pi^\mp$ and $B^+ \rightarrow K^0 \pi^+$

- $B^0 \rightarrow K^\pm \pi^\mp$: color-suppressed penguin and CKM suppressed tree



- weak phase difference γ : $\mathcal{A} = \frac{2r \sin \delta \sin \gamma}{1 - 2r \cos \delta \cos \gamma + r^2} \stackrel{\text{SM}}{\approx} -0.1$

- $B^+ \rightarrow K^0 \pi^+$: one dominant penguin amplitude

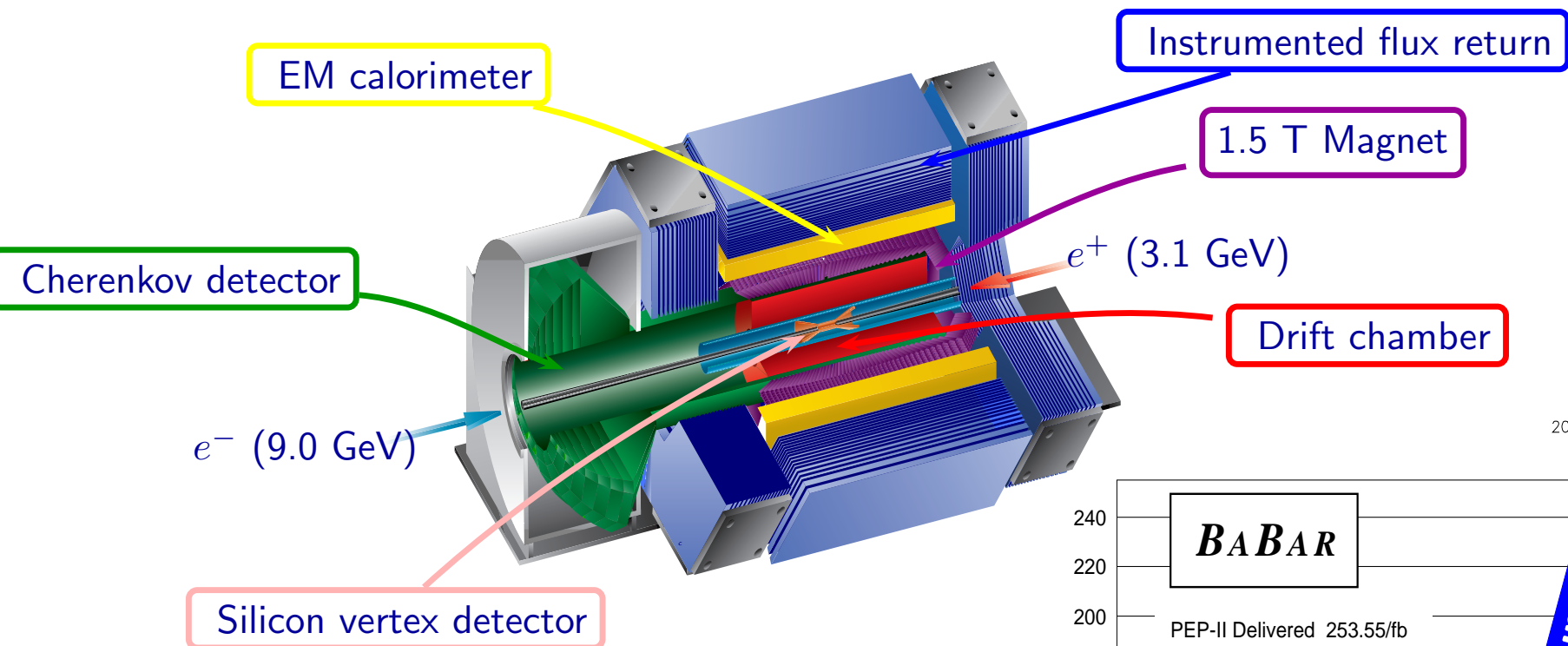


no tree amplitude, small P_{ew} and annihilation contributions
 expect small asymmetry ($\mathcal{A}_{\text{SM}} \approx 0$)

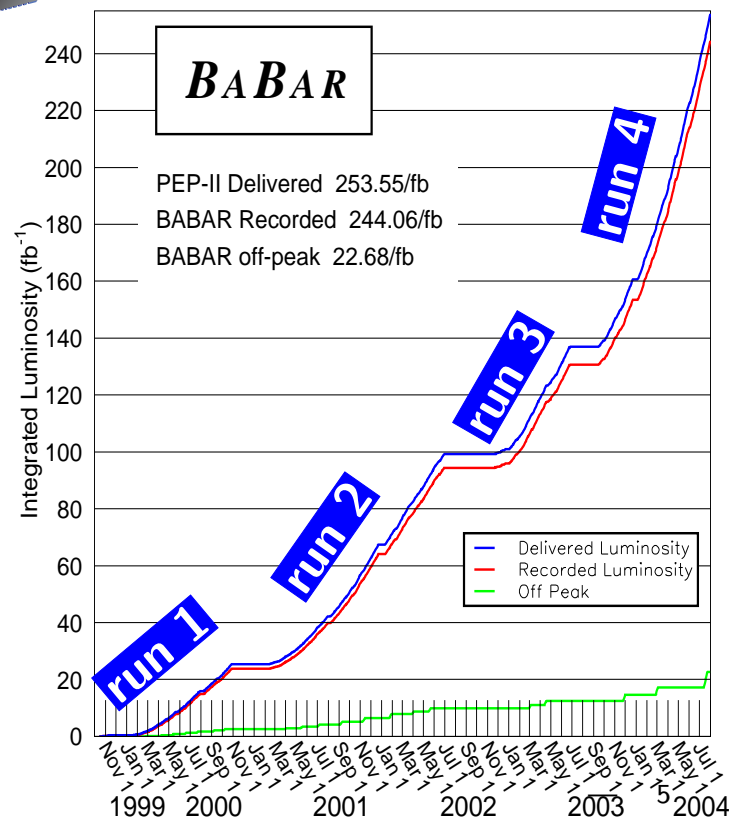
- ratio of branching ratios also sensitive to γ (e.g. Buras et.al., 2004)

$$R \equiv \frac{\Gamma(B^0 \rightarrow \pi^- K^+) + \Gamma(\bar{B}^0 \rightarrow \pi^+ K^-)}{\Gamma(B^+ \rightarrow \pi^+ K^0) + \Gamma(B^- \rightarrow \pi^- K^0)} = 1 - 2r \cos \delta \cos \gamma + r^2$$

The BABAR Experiment



2004/08/09 09.21

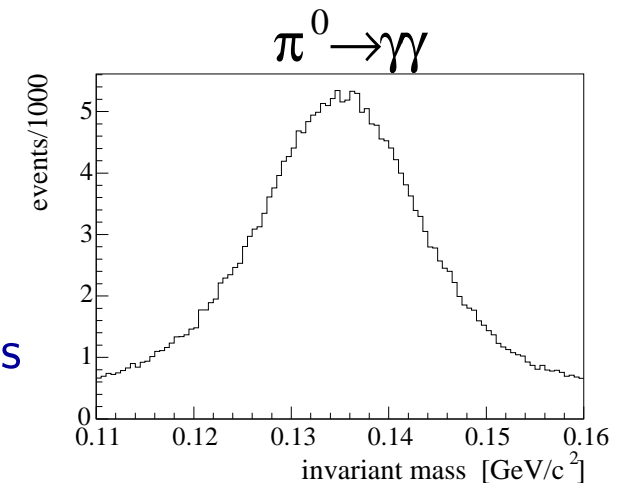
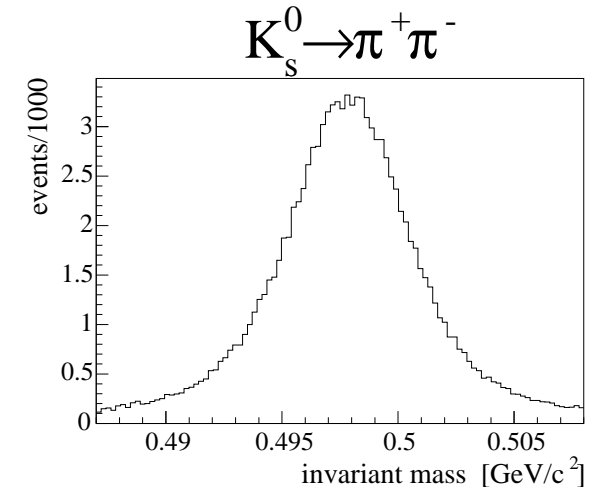


Results in this talk based on
 ~ 227 M $B\bar{B}$ events
 ~ 205 fb⁻¹
(Practically) all results preliminary

Reconstruction, efficiencies, backgrounds



- 'two body': $B \rightarrow XY$ with X, Y any two from
 - tracks reconstruction in SVT and DCH
 - $K_S^0 \rightarrow \pi^+ \pi^-$, selected by $m_{\pi^+ \pi^-}$ and decay length
 - $\pi^0 \rightarrow \gamma\gamma$, selected by $m_{\gamma\gamma}$ and EMC shower shape
- small branching fraction: $1 - 25 \cdot 10^{-6}$
- high efficiency, typically 30 %
- large background from $e^+ e^- \rightarrow q\bar{q}$ ($q \in \{u, d, s, c\}$)
 - 'continuum background'
 - $S : B$ from 1 : 1 to 1 : 5 ($\pi^0 \pi^0$)
 - separated by event kinematics and event 'shape'
- additional background from 'quasi' two-body B decays
 - $B \rightarrow \rho\pi, B \rightarrow K^* \pi$ etc.
 - like signal if missing particle has small momentum
 - separated by event kinematics, subtracted using known \mathcal{B}



Analysis method



- unbinned maximum likelihood fits to (typically 5) observables: event shape, B kinematics (ΔE , m_{ES}), PID, flavor tag, ...
- modes with π^\pm and K^\pm are background to one another
 - combined in one analyses, e.g. $B^+ \rightarrow h^+ \pi^0$
 - π/K separation with DIRC and B kinematics
 - one fit to event sample extracts both yields
- 10 modes, 6 analyses, 20 measurements

81/fb – no update yet

- | | | |
|----|-------------------------------------|--|
| 1. | $B^0 \rightarrow h^+ h^-$ | $\mathcal{B}_{\pi^+ \pi^-}, \mathcal{B}_{K^+ \pi^-}, \mathcal{B}_{K^+ K^-}, \mathcal{A}_{K^+ \pi^-}, \mathcal{C}_{\pi^+ \pi^-}, \mathcal{S}_{\pi^+ \pi^-}$ |
| 2. | $B^0 \rightarrow \pi^0 \pi^0$ | $\mathcal{B}_{\pi^0 \pi^0}, \mathcal{C}_{\pi^0 \pi^0}$ |
| 3. | $B^+ \rightarrow h^+ \pi^0$ | $\mathcal{B}_{\pi^+ \pi^0}, \mathcal{B}_{K^+ \pi^0}, \mathcal{A}_{K^+ \pi^0}, \mathcal{A}_{\pi^+ \pi^0}$ |
| 4. | $B^+ \rightarrow h^+ K_S^0$ | $\mathcal{B}_{K^+ K^0}, \mathcal{B}_{\pi^+ K^0}, \mathcal{A}_{K^+ K^0}, \mathcal{A}_{\pi^+ K^0}$ |
| 5. | $B^0 \rightarrow K_S^0 \pi^0$ | $\mathcal{B}_{K_S^0 \pi^0}, \mathcal{C}_{K_S^0 \pi^0}, \mathcal{S}_{K_S^0 \pi^0}$ |
| 6. | $B^0 \rightarrow K_S^0 \bar{K}_S^0$ | $\mathcal{B}_{K^0 \bar{K}^0}$ |

talk by N. Danielson

talk by F. Blanc

(few remaining measurements not yet possible because of statistics)

Kinematic variables for B selection



Two kinematic invariants characterize $e^+e^- \rightarrow B\bar{B}$ event:

- reconstructed particle is $B \rightarrow |p_B^4| \equiv m_B$
- other particle is also a $B \rightarrow |p_{e^+e^-}^4 - p_B^4| \equiv m_B$

Two mass variables correlated \rightarrow use instead:

- 'beam-energy substituted mass':

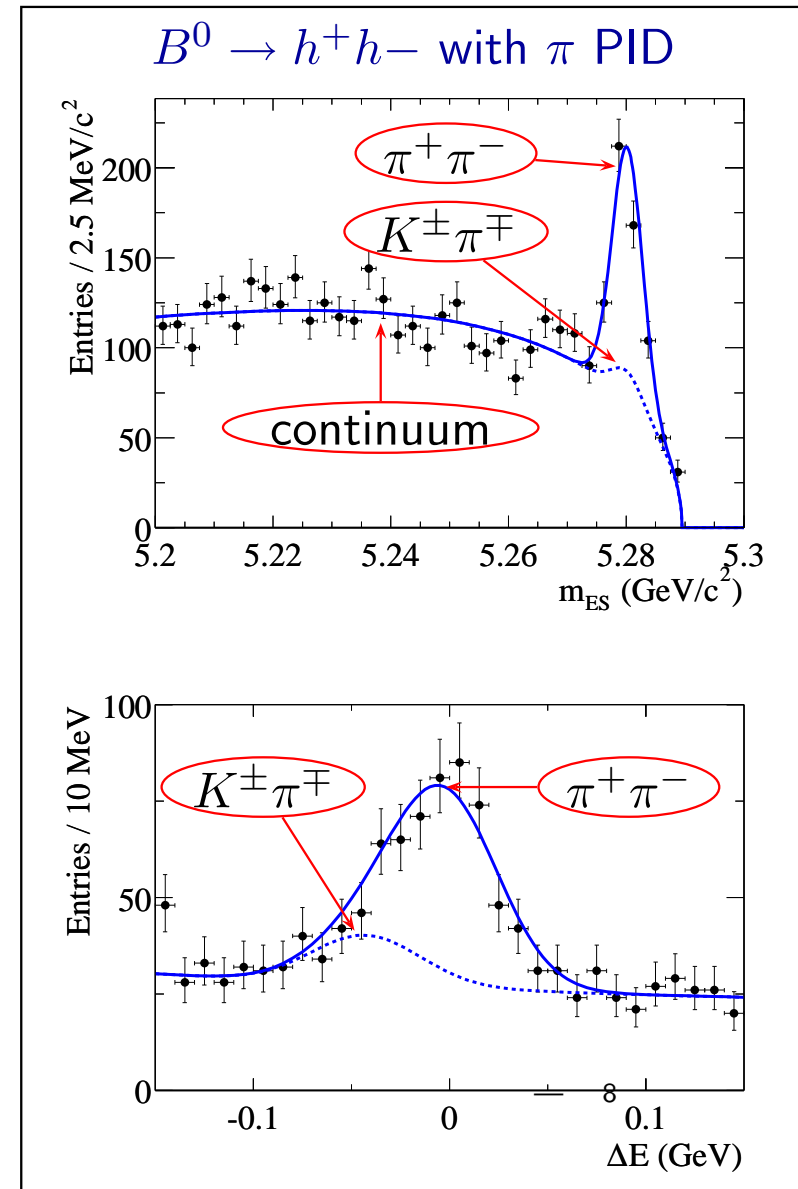
$$m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_{e^+e^-} \cdot \mathbf{p}_B)^2 / E_{e^+e^-}^2 - p_B^2}$$

- precise definition depends on analysis:
this choice: equal for K and π hypothesis
- resolution ~ 3 MeV, dominated by \sqrt{s}

- B energy in the CMS:

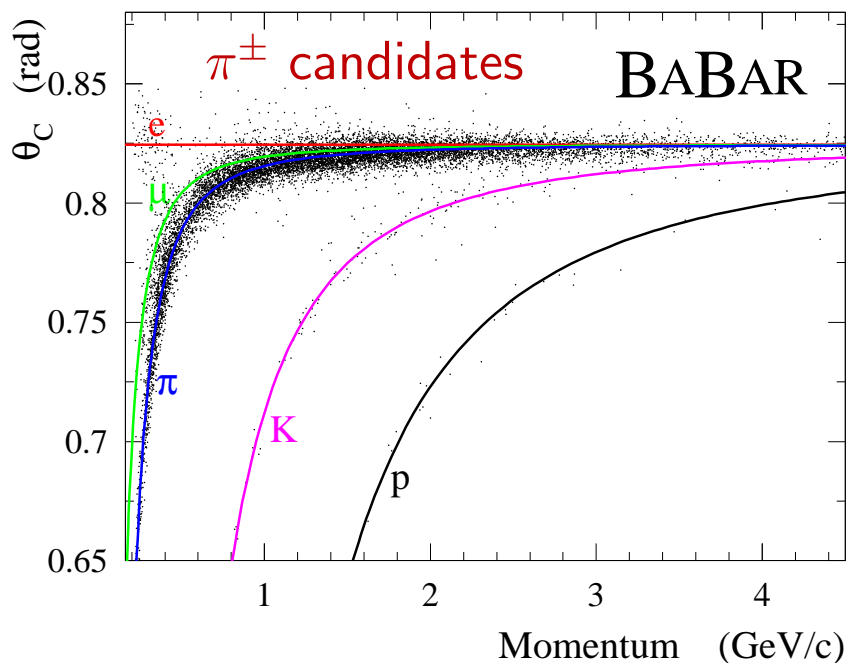
$$\Delta E = E_B^* - \sqrt{s}/2$$

- typical resolution 10 – 50 MeV
- use π hypothesis for tracks
 $\rightarrow K$ distribution shifted



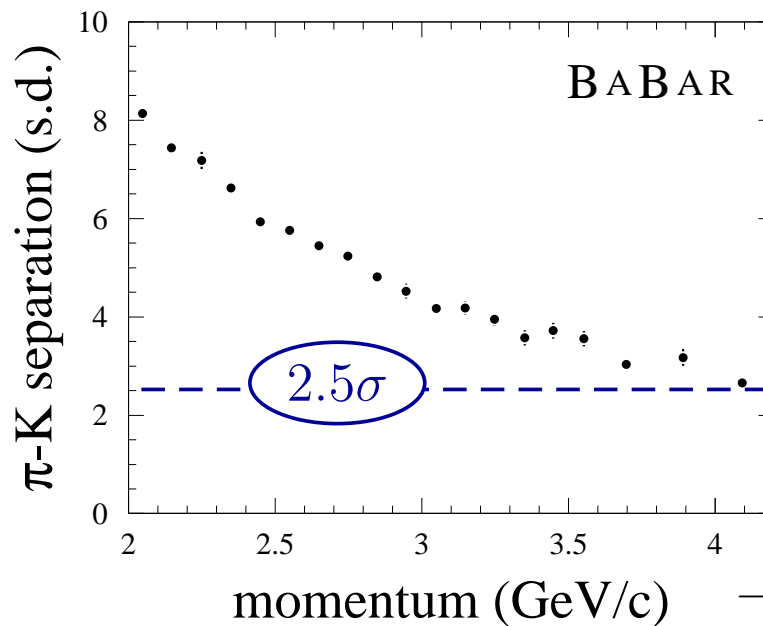
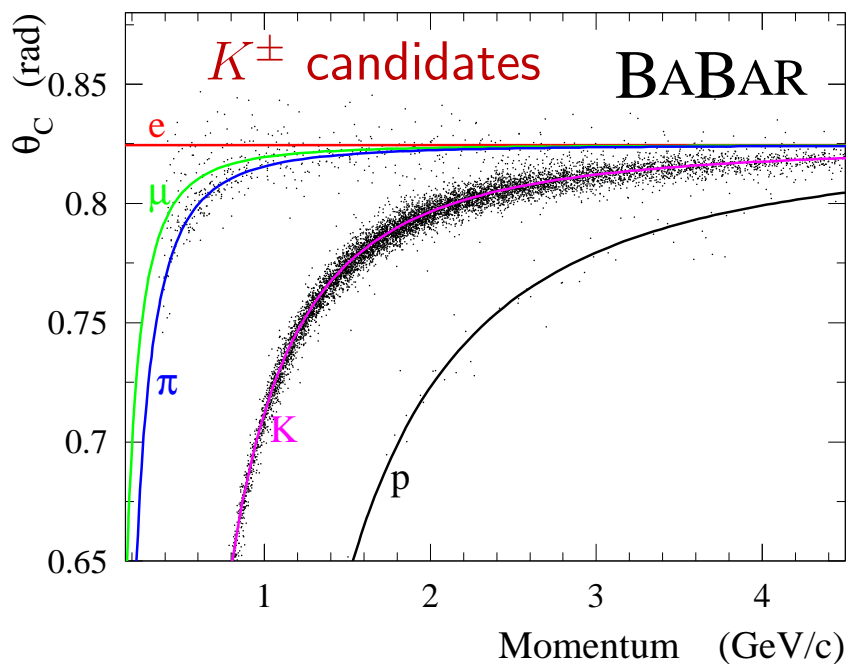


K/π separation with the DIRC



- DIRC cherenkov cone angle θ_c
- used in ML fit to separate h^\pm
- separate PDFs for K^+, K^-, π^+, π^-
- calibrated with control sample

$D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+$ (plots)



Common systematic uncertainties



For asymmetries:

- detection/PID asymmetries
estimated from control samples, MC and data sidebands
- background from 'quasi' two body B decays, e.g. $B \rightarrow \rho\pi$, $B \rightarrow K^*\pi$ etc.
 - contribution estimated from known BRs
 - CP content not always known

For branching fractions:

- efficiencies: π^0 , tracking
use control samples, e.g. $\tau^+ \rightarrow \pi^+\pi^0\nu_\tau$
- energy resolution: enters signal PDFs
- B background

Direct asymmetry in $B^0 \rightarrow K^+ \pi^-$



- fit to $\sim 68k$ $B^0 \rightarrow h^+ h^-$ 'candidates'
- input: m_{ES} , ΔE , \mathcal{F} , θ_c^+ , θ_c^- , tagging

Results (hep-ex/0407057, submitted to PRL)

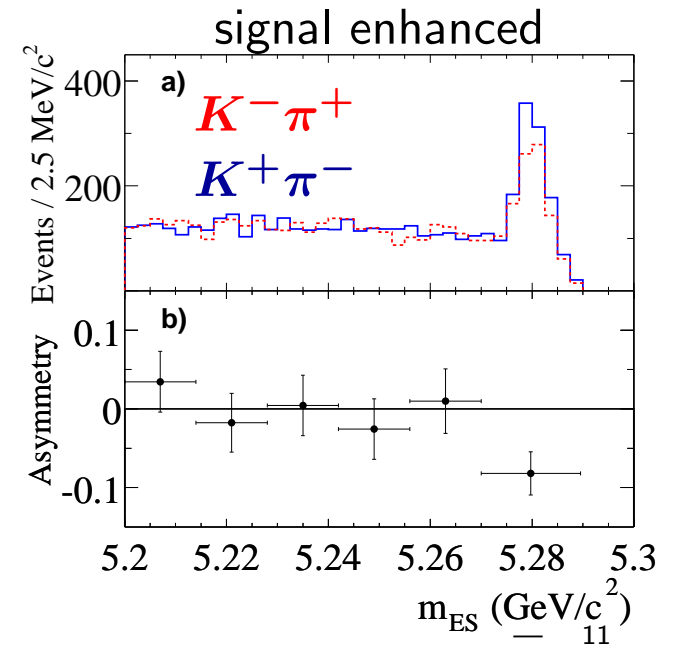
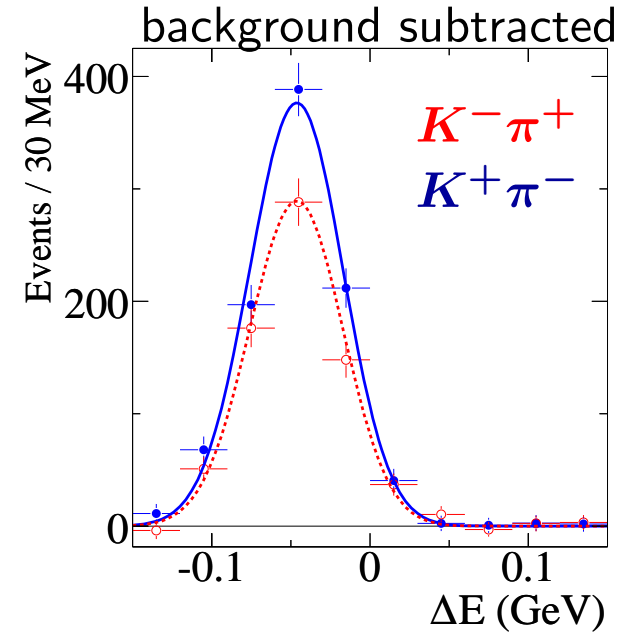
$n_{\pi\pi}$	$=$	467 ± 33
$n_{K\pi}$	$=$	1606 ± 51
n_{KK}	$=$	3 ± 12
$\mathcal{A}_{K\pi}$	$=$	$-0.133 \pm 0.030^{\text{stat}} \pm 0.009^{\text{syst}}$ (4.2σ , incl. syst.)

Observation of direct CPV in B system!

Most convincing 'cross check':

$\mathcal{A}_{K\pi}^{\text{bkg}}$	$=$	0.001 ± 0.008
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→ no asymmetry in background



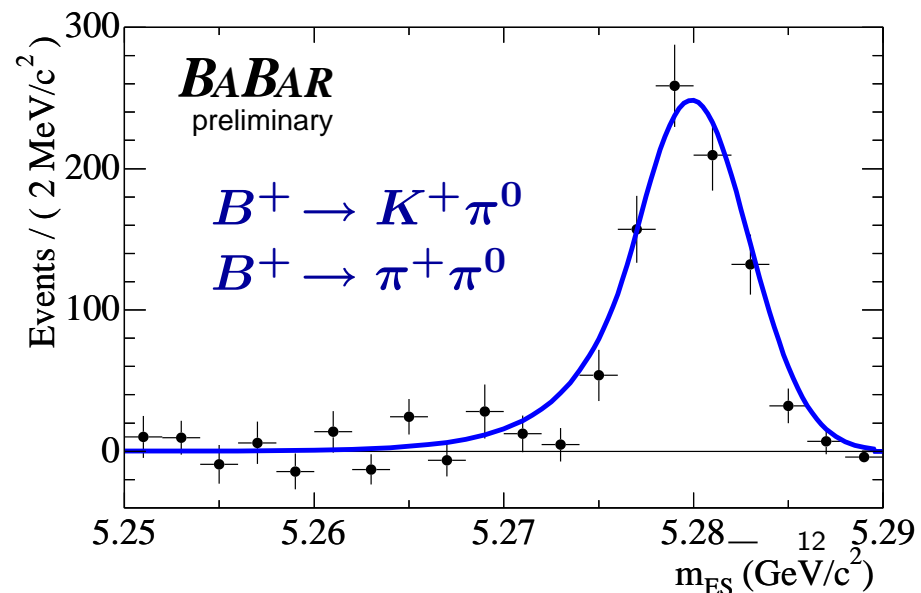
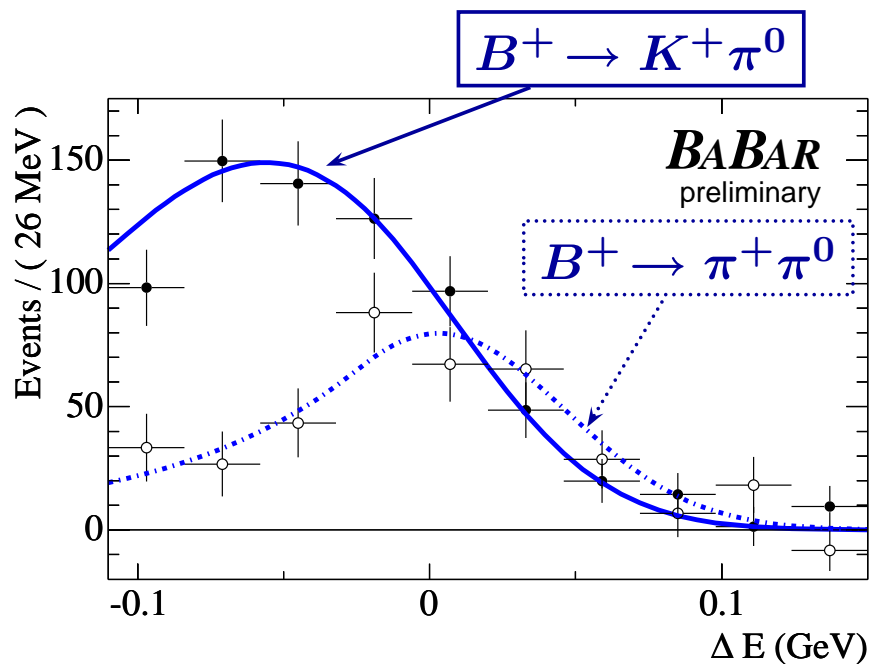


$B^+ \rightarrow \pi^+ \pi^0$ and $B^+ \rightarrow K^+ \pi^0$

- extended ML fit to $\sim 41k$ $B^\pm \rightarrow h^\pm \pi^0$ candidates
- input: m_{ES} , ΔE , \mathcal{F} , θ_c^+ ,
expected $B \rightarrow \rho\pi$, $B \rightarrow \rho K$ and $B \rightarrow K^* \pi$ yields and asymmetries

Preliminary results (hep-ex/0408081)

	$B^+ \rightarrow \pi^+ \pi^0$	$B^+ \rightarrow K^+ \pi^0$
n	379 ± 41	672 ± 39
\mathcal{B}	$5.8 \pm 0.6 \pm 0.4$	$12.0 \pm 0.7 \pm 0.6$
\mathcal{A}	$0.01 \pm 0.10 \pm 0.02$	$0.06 \pm 0.06 \pm 0.01$



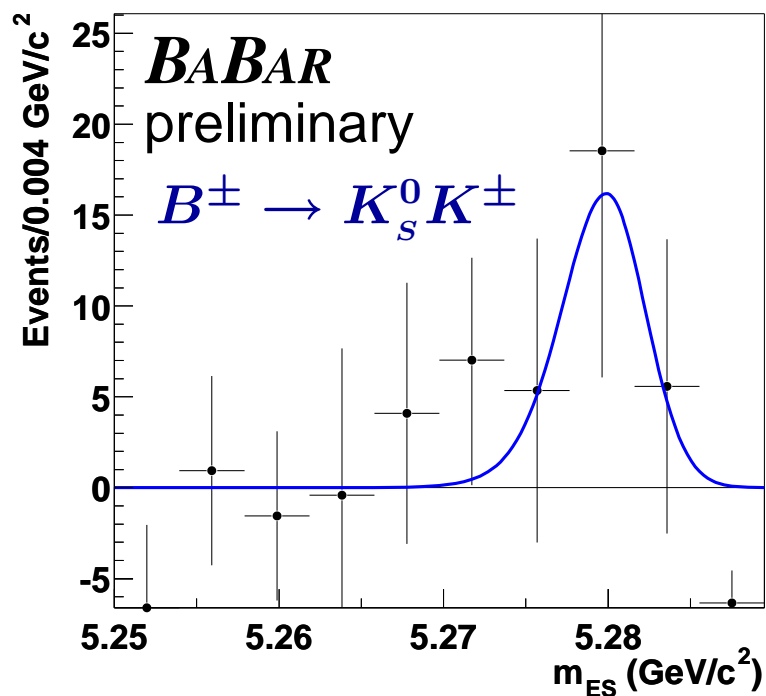


$$B^\pm \rightarrow h^\pm K_S^0 \text{ and } B^0 \rightarrow K_S^0 K_S^0$$

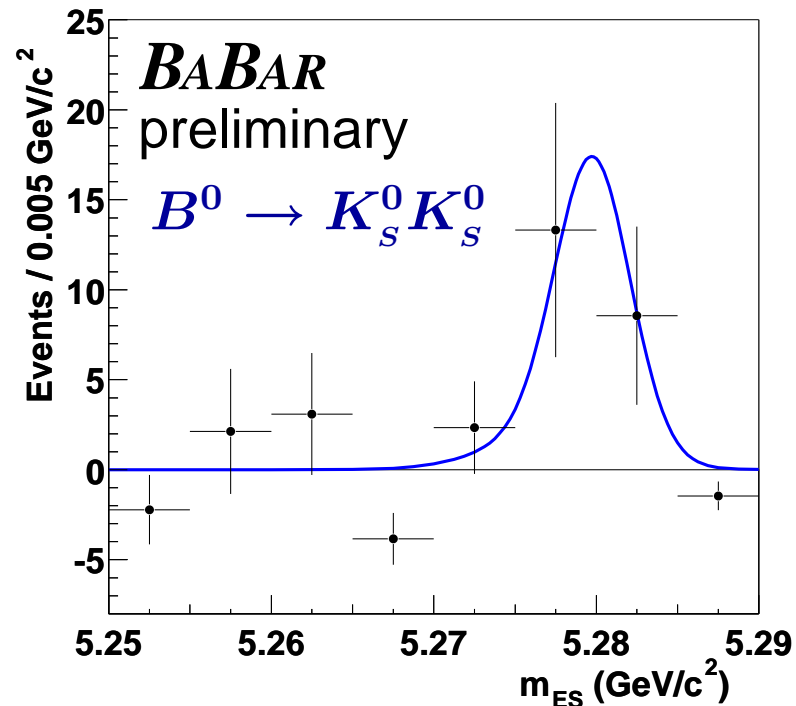
- fit to $\sim 20k$ $B^\pm \rightarrow h^\pm K_S^0$ and $\sim 1.9k$ $B^0 \rightarrow K_S^0 K_S^0$ candidates
- input: m_{ES} , ΔE , \mathcal{F}

Preliminary results (hep-ex/0408080)

	$B^\pm \rightarrow K^0 \pi^\pm$	$B^\pm \rightarrow K^0 K^\pm$	$B^0 \rightarrow K^0 K^0$
n	743 ± 36	41 ± 14	23 ± 7
\mathcal{B}	$26.0 \pm 1.3 \pm 1.0$	$1.45_{-0.46}^{+0.53} \pm 0.11$	$1.19_{-0.35}^{+0.40} \pm 0.13$
\mathcal{A}	$-0.087 \pm 0.046 \pm 0.010$	$0.15_{-0.35}^{+0.33} \pm 0.03$	— — —



First evidence (3.5σ) !



First observation (4.5σ)!

Summary of measured yields and branching fractions



Note: results preliminary!

	events/205 fb ⁻¹	$\mathcal{B} \times 10^6$
$B^0 \rightarrow \pi^+ \pi^-$	467 ± 33	$4.7 \pm 0.6 \pm 0.2$
$B^0 \rightarrow \pi^0 \pi^0$	61 ± 17	$1.2 \pm 0.3 \pm 0.1$
$B^+ \rightarrow \pi^+ \pi^0$	379 ± 41	$5.8 \pm 0.6 \pm 0.4$
$B^0 \rightarrow K^+ \pi^-$	1606 ± 51	$17.9 \pm 0.9 \pm 0.7$
$B^+ \rightarrow K^+ \pi^0$	672 ± 39	$12.0 \pm 0.7 \pm 0.6$
$B^0 \rightarrow K^0 \pi^0$	300 ± 23	$11.4 \pm 0.9 \pm 0.6$
$B^+ \rightarrow K^0 \pi^+$	743 ± 36	$26.0 \pm 1.3 \pm 1.0$
$B^0 \rightarrow K^+ K^-$	3 ± 12	< 0.6
$B^+ \rightarrow K^0 K^+$	41 ± 14	$1.45^{+0.53}_{-0.47} \pm 0.12$
$B^0 \rightarrow K^0 \bar{K}^0$	23 ± 7	$1.19^{+0.40}_{-0.35} \pm 0.13$

(results on 81/fb)

One test of isospin conservation: Lipkin sum rule

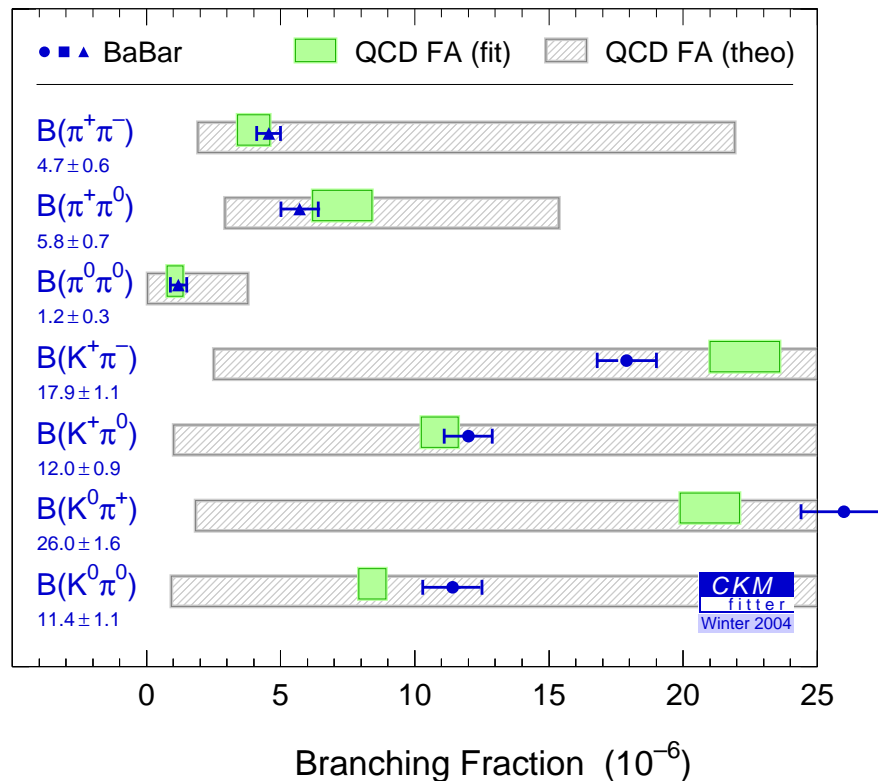
$$R_L \equiv \frac{2\Gamma(B^+ \rightarrow K^+ \pi^0) + 2\Gamma(B^0 \rightarrow K^0 \pi^0)}{\Gamma(B^+ \rightarrow K^0 \pi^+) + \Gamma(B^0 \rightarrow K^+ \pi^-)} = 1 + O\left(\frac{P_{EW} + T}{P}\right)^2$$

BABAR measurements: $R_L = 1.07 \pm 0.08$

Comparison to global fit by Charles et al (hep-ph/0406184)



- global fit to 'all' CKM data: branching fractions, CP asymmetries
- 'prediction': remove observable and fit again
- note: these predictions were made with 'Winter 2004 World-Average'



pattern of $K\pi$ BF's slightly at odds with prediction \longrightarrow *the $K\pi$ puzzle*

Branching fraction ratios, sensitive to γ



$K\pi$ BF ratios are functions of weak phase γ , strong phases and T/P ratios (see for example Buras *et.al.*, hep-ph/0402112):

$$R \equiv \frac{\Gamma(B^0 \rightarrow \pi^- K^+) + \Gamma(\bar{B}^0 \rightarrow \pi^+ K^-)}{\Gamma(B^+ \rightarrow \pi^+ K^0) + \Gamma(B^- \rightarrow \pi^- K^0)} = 1 - 2r \cos \delta \cos \gamma + r^2$$

$$R_c \equiv 2 \frac{\Gamma(B^+ \rightarrow \pi^0 K^+) + \Gamma(B^- \rightarrow \pi^0 K^-)}{\Gamma(B^+ \rightarrow \pi^+ K^0) + \Gamma(B^- \rightarrow \pi^- \bar{K}^0)} = \dots$$

$$R_n \equiv \frac{1}{2} \frac{\Gamma(B^0 \rightarrow \pi^- K^+) + \Gamma(\bar{B}^0 \rightarrow \pi^+ K^-)}{\Gamma(B^0 \rightarrow \pi^0 K^0) + \Gamma(\bar{B}^0 \rightarrow \pi^0 \bar{K}^0)} = \dots$$

Can give meaningful bound on γ if smaller than 1, e.g. $\gamma < \arccos \sqrt{1 - R}$.

Using SU(3), 'plausible' dynamical assumptions and γ_{SM} :

	SM (Buras <i>et.al.</i>)	BABAR (ICHEP 2004)
R	0.94 ± 0.03	0.75 ± 0.07
R_c	1.14 ± 0.08	0.92 ± 0.09
R_n	1.11 ± 0.07	0.79 ± 0.09



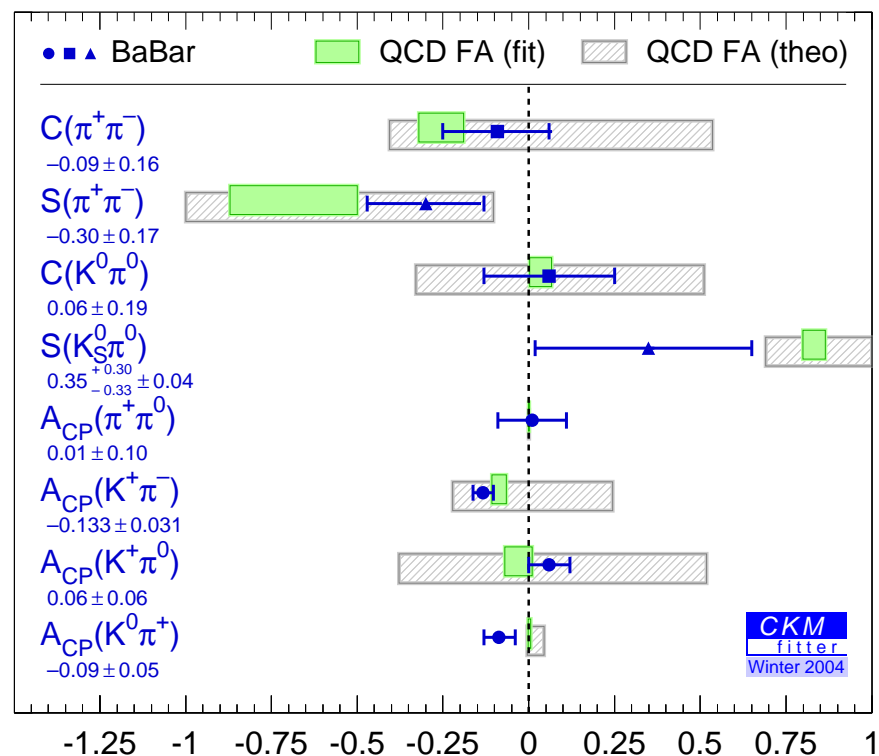
Summary of CPV asymmetries

Time-dependent CPV asymmetries:

	C	S
$B^0 \rightarrow \pi^0 \pi^0$	$-0.12 \pm 0.56 \pm 0.06$	—
$B^0 \rightarrow \pi^+ \pi^-$	$-0.09 \pm 0.15 \pm 0.04$	$-0.30 \pm 0.17 \pm 0.03$
$B^0 \rightarrow K_S^0 \pi^0$	$0.06 \pm 0.18 \pm 0.06$	$0.35^{+0.30}_{-0.33} \pm 0.04$

Direct CPV asymmetries:

	A
$B^+ \rightarrow \pi^+ \pi^0$	$0.01 \pm 0.10 \pm 0.02$
$B^+ \rightarrow K^+ \pi^0$	$0.06 \pm 0.06 \pm 0.01$
$B^0 \rightarrow K^+ \pi^-$	$-0.133 \pm 0.030 \pm 0.009$
$B^+ \rightarrow K^0 \pi^+$	$-0.087 \pm 0.046 \pm 0.010$
$B^+ \rightarrow K^0 K^+$	$0.15^{+0.33}_{-0.35} \pm 0.03$





Many interesting new results from *BABAR*

- family of charmless two-body B decays is almost complete
→ important input for understanding B decays
- first observations of direct CPV in the B system
- puzzling pattern in $K\pi$ branching fractions remains