

# Rare hadronic B decays



Recent results from the Belle and  
BaBar experiments.

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# Overview

- Motivation
- Analysis Methods
  - Selecting events.
  - Extracting information about the signal.
- Results
  - Direct CP Violation studies
  - $B \rightarrow hh$  and  $a_1\pi$  branching fractions
  - $B \rightarrow VV$  decays
  - $B \rightarrow K\pi\pi$
- Summary and Conclusions

All results quoted are preliminary unless published

# Motivation

- Rare Hadronic B-decays are rich sources of information
  - Indirect CP Violation: measuring Unitarity Triangle Angles. (See talks by S. Ganzhur, M. Hazumi)
  - Direct CP violation.
  - Branching fractions and angular correlations: inputs to allow theorists to test and fine tune models.
  - Search for potential new physics effects
    - look for deviations from expected behaviour

# Direct CP violation

- Study difference between number of B (N) and anti-B ( $\bar{N}$ ) mesons decaying into the same final state.

$P(B \rightarrow f)$  compared to  $P(\bar{B} \rightarrow \bar{f})$

$$A_{CP} = \frac{\bar{N} - N}{\bar{N} + N}$$

- Quantum interference effect.
- Need different weak ( $\phi$ ) and strong ( $\delta$ ) phases in the decay amplitudes of the B( $\bar{B}$ ) to the final state.

$$A_{CP} \propto - \sum_{i,j} A_i A_j (\sin[\phi_1 - \phi_2] \sin[\delta_1 - \delta_2])$$

- Expect large direct CP Violation when interfering amplitudes are of a similar magnitude.

# Analysis methods (selecting signal)

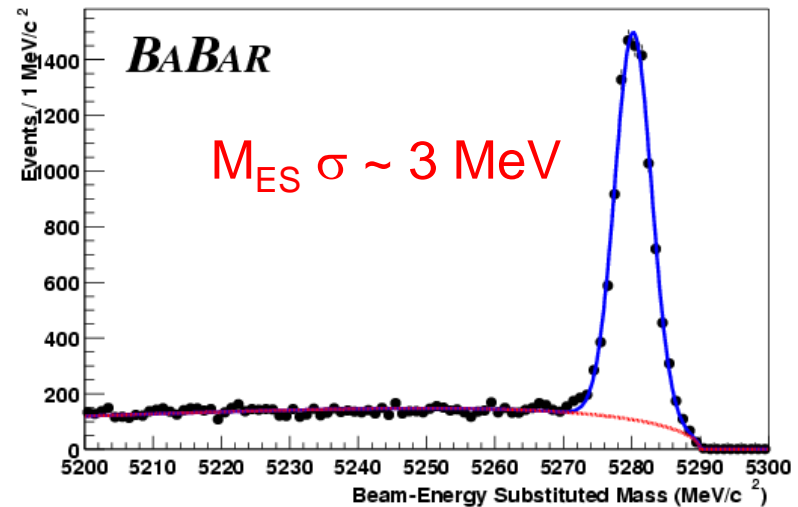
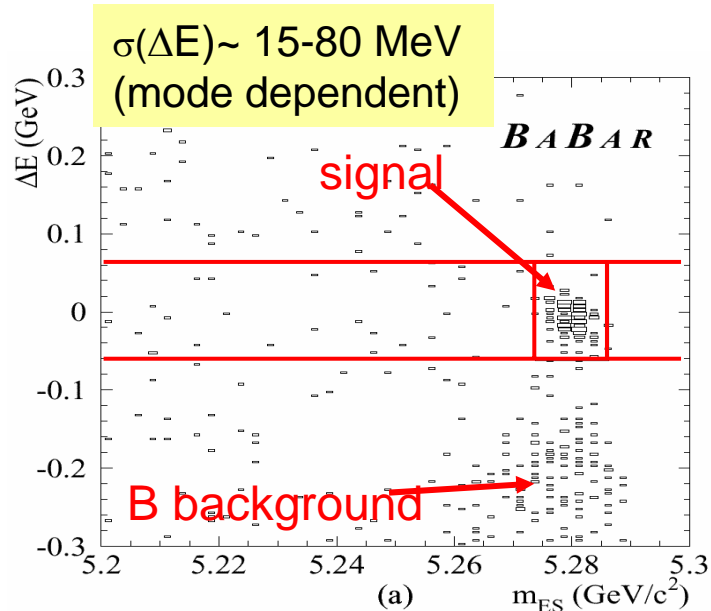
- Beam energy is known very well at an  $e^+e^-$  collider like PEP-II / KEK-B:

$$e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$$

- use an energy difference and effective mass to select events:

$$\Delta E = E_B - E_{beam}^*$$

$$m_{ES} = \sqrt{(E_{beam}^*)^2 - P_B^2}$$



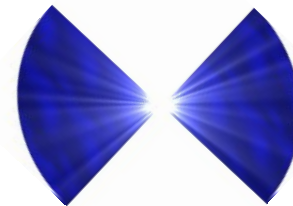
# Analysis methods

## (selecting signal)

- Use the shape of an event to distinguish between  $Y(4S) \rightarrow B\bar{B}$  and  $e^+e^- \rightarrow q\bar{q}$  background.



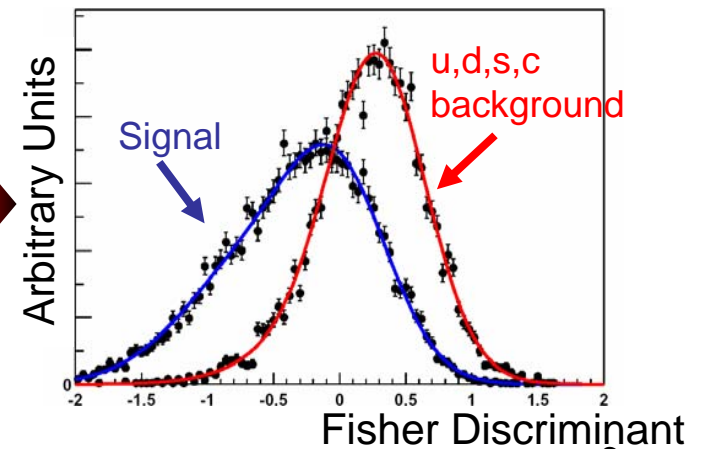
B events tend to be spherical



continuum ( $ee \rightarrow q\bar{q}$ ) events are 'jetty'

Combine several event shape variables in a single discriminating variable: *MVA*  
Fisher, Neural Network or likelihood ratio.

This gives discrimination between B and continuum events.



# Analysis methods (selecting signal)

- **Pros** and Cons of different approaches:

- Fisher Discriminant:  $F = \sum_i \alpha_i x_i$ 
  - retain all events for fit
  - simple to understand and study

- Neural Network:
  - retain all events for fit (or apply a loose cut)
  - not necessarily intuitive

- Likelihood ratio:
  - cut on ratio → lower signal efficiency
  - usually have a simpler fit to data



Show fit result  
on a “signal  
enhanced”  
data sample

sPlots  
(physics/0402083)



Show all events  
that are in the fit  
when plotting signal

# Analysis methods

(Extracting information about the signal)

- These decays are rare:  $BF \sim 10^{-6}$ 
  - There is a lot of background from  $e^+e^- \rightarrow q\bar{q}$  events as well as from other B decays.
  - Discriminating information is generally available in more than one dimension.
  - Often perform multi-dimensional unbinned maximum-likelihood fits to extract and study signal events.

$$L = \text{Poisson term} \times \prod_{\text{events}} \left( N_{\text{signal}} P_{\text{signal}} + \sum_{\text{backgrounds}} N_{\text{background}} P_{\text{background}} \right)$$

# Results



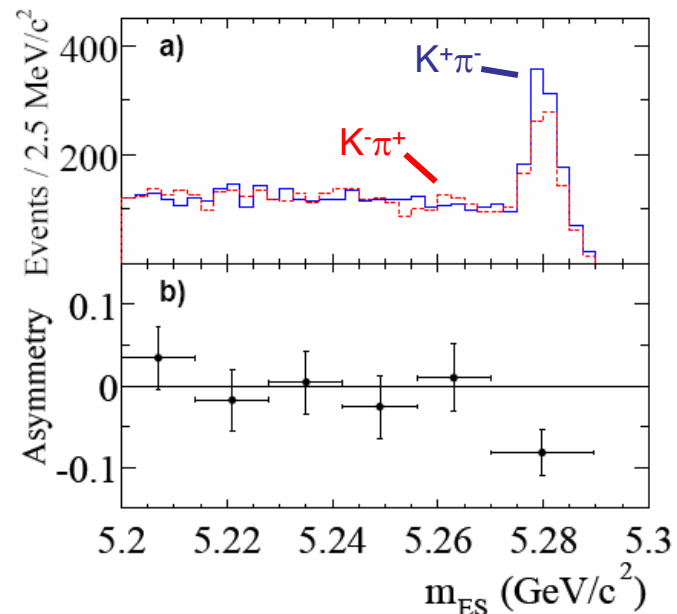
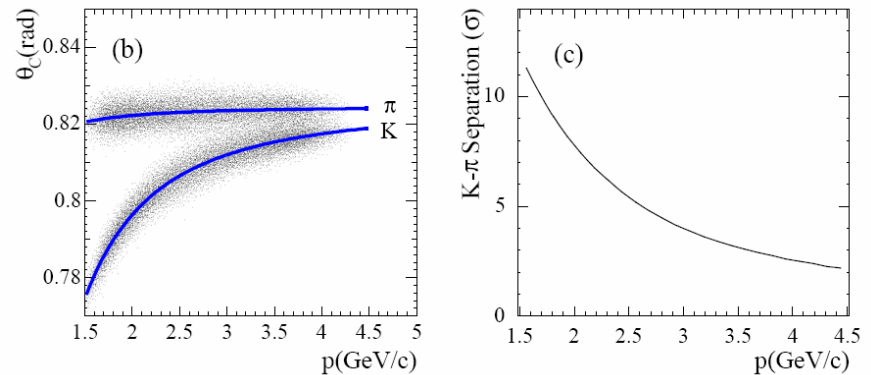
# Direct CPV in $B \rightarrow K\pi$



- $227 \times 10^6$  B pairs
- Charge of K in the final state tags the flavor of the B-meson.
- Use particle ID to separate K and  $\pi$  mesons.
- Calculate asymmetry:

$$\mathcal{A}_{K\pi} \equiv \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}}$$

$$\mathcal{A}_{K\pi} = -0.133 \pm 0.030 \text{ (stat)} \pm 0.009 \text{ (syst)}$$

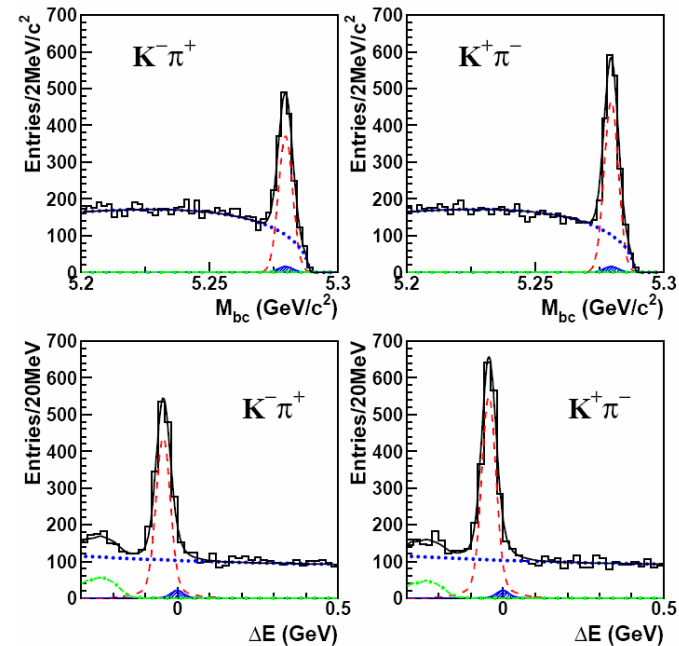


# Direct CPV in $B \rightarrow K\pi$



- $386 \times 10^6$  B pairs
- Use  $dE/dx$  and cherenkov counters for particle identification.

	Set I		Set II	
	Eff. (%)	Fake rate (%)	Eff. (%)	Fake rate (%)
$K^+$	$83.76 \pm 0.18$	$5.10 \pm 0.12$	$81.92 \pm 0.15$	$6.29 \pm 0.10$
$K^-$	$84.76 \pm 0.18$	$5.69 \pm 0.12$	$82.79 \pm 0.14$	$6.71 \pm 0.10$
$\pi^+$	$91.24 \pm 0.15$	$10.72 \pm 0.15$	$89.88 \pm 0.12$	$12.28 \pm 0.12$
$\pi^-$	$90.53 \pm 0.15$	$10.08 \pm 0.15$	$89.08 \pm 0.13$	$11.83 \pm 0.12$



- Combining both experiments gives:

$$A_{CP} = -0.115 \pm 0.018$$

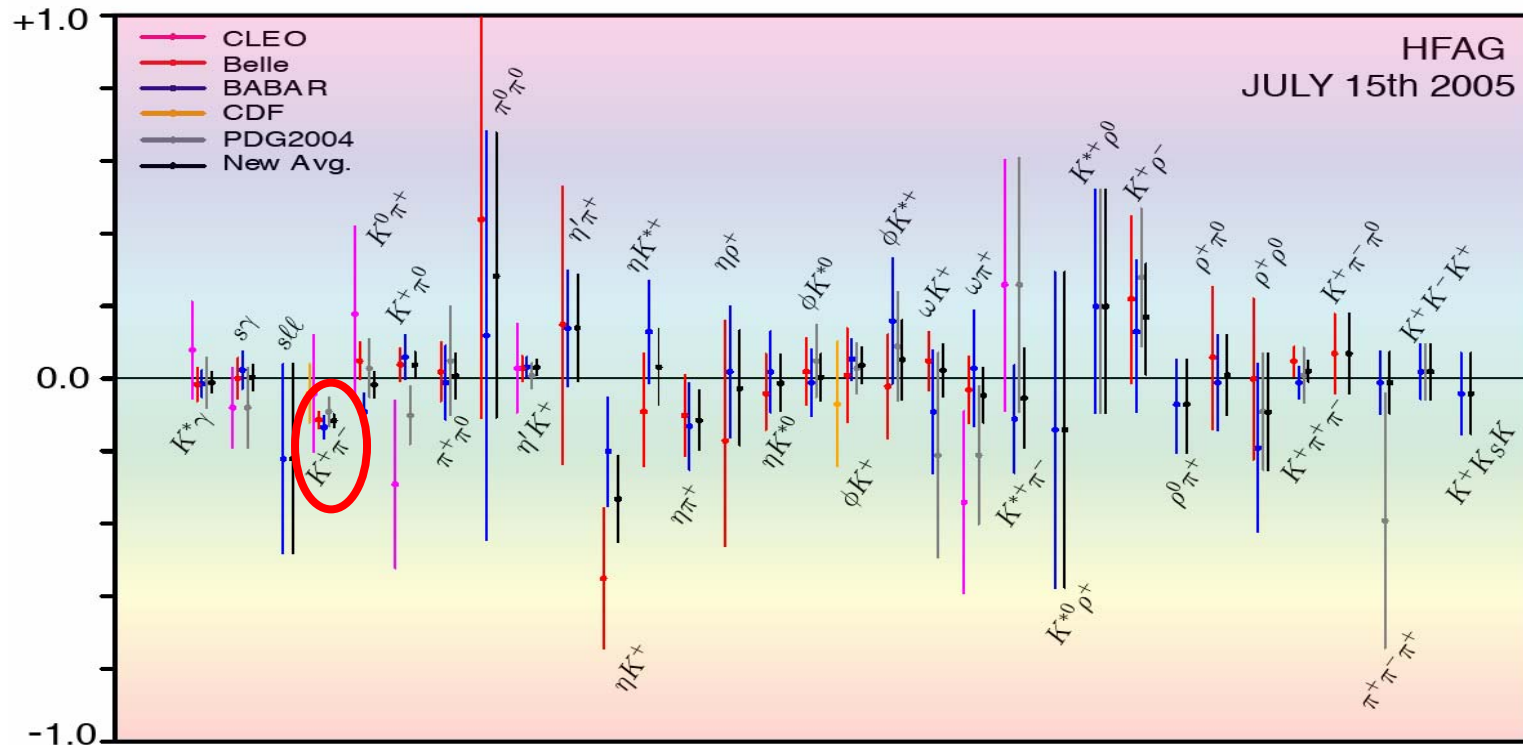
Establishing direct CP Violation in B-meson decay!

Mode	Signal Yield	$A_{CP}$	Bkg $A_{CP}$
$K^\mp \pi^\pm$	$3026 \pm 63$	$-0.113 \pm 0.022 \pm 0.008$	$-0.001 \pm 0.004$
$K^\mp \pi^0$	$1084 \pm 45$	$+0.04 \pm 0.04 \pm 0.02$	$-0.02 \pm 0.01$
$\pi^\mp \pi^0$	$454 \pm 36$	$+0.02 \pm 0.08 \pm 0.01$	$-0.01 \pm 0.01$

- large asymmetry in  $K^+\pi^-$  decays
- other modes consistent with no asymmetry.

# $A_{CP}$ measurements

## CP Asymmetry in Charmless B Decays

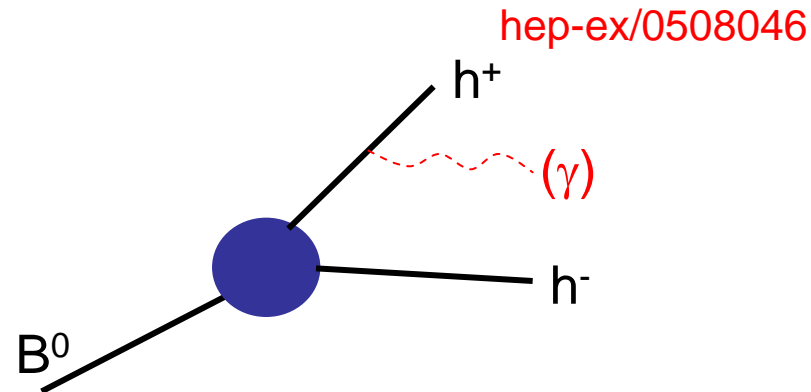


- B-factories observed direct CPV in  $B \rightarrow K\pi$  decays
- There are other modes with evidence for direct CPV
  - $B^+ \rightarrow \rho(770)^0 K^+$  (see later)
  - $B \rightarrow \pi^+ \pi^-$

# B → hh branching fractions



- $227 \times 10^6$  B pairs
- Update of  $\pi^+\pi^-$ ,  $K^+\pi^-$  and  $K^+K^-$  branching fractions.
- $\pi^+\pi^-$  result is important for the isospin analysis.
- Includes the effects of final state radiation: This is important for:
  - yield extraction.
  - and efficiency calculation.
- Used QED calculation to  $O(\alpha)$  to account for this effect.
- PHOTOS crosscheck gives systematic uncertainty.



Parameter	Nominal Fit	Ignoring FSR
$N_{\pi\pi}$	$491 \pm 35$	$469 \pm 34$
$N_{K\pi}$	$1674 \pm 53$	$1634 \pm 52$
$N_{KK}$	$3.0 \pm 13.1$	$5.3 \pm 12.6$

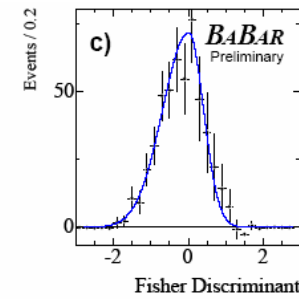
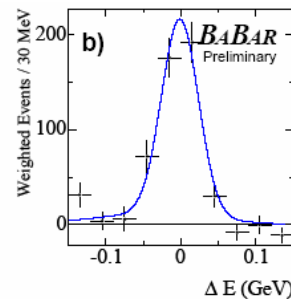
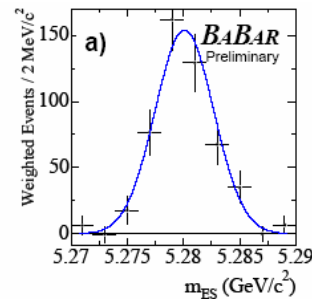
2.4% more  $K\pi$  events fitted.  
4.7% more  $\pi\pi$  events fitted.

# B → hh branching fractions



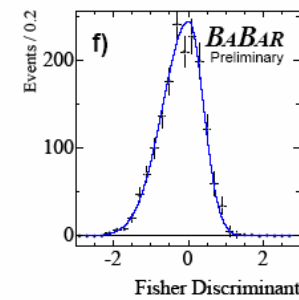
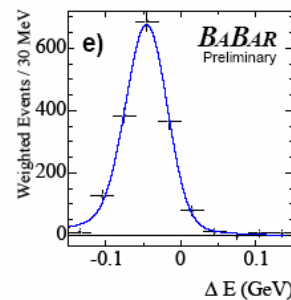
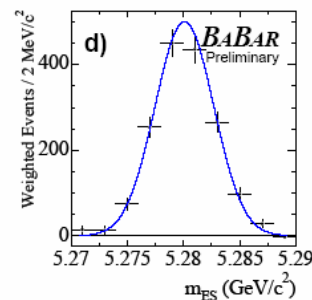
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$$B^0 \rightarrow \pi^+ \pi^-$$



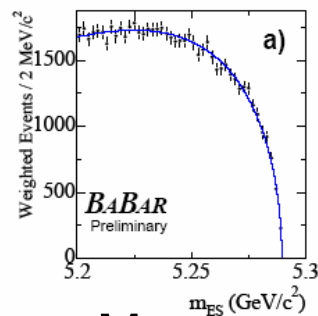
Signal Distribution

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

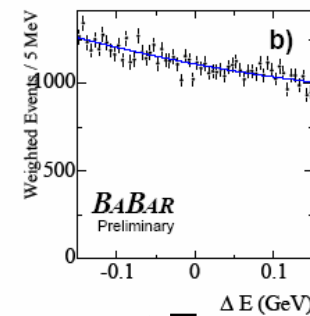


Signal Distribution

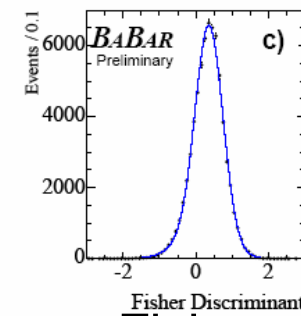
continuum background



$M_{ES}$



$\Delta E$



Fisher

Background Distribution

# B→hh branching fractions

- Comparison with previous results

Mode	$N_S$	New Results	$\epsilon$ (%)	$\mathcal{B}(10^{-6})$
$\pi^+\pi^-$	$491 \pm 35 \pm 11$	$39.4 \pm 0.2 \pm 0.9$		$5.5 \pm 0.4 \pm 0.3$
$K^+\pi^-$	$1674 \pm 53 \pm 15$	$38.4 \pm 0.2 \pm 0.8$		$19.2 \pm 0.6 \pm 0.6$
$K^+K^-$	$3.0 \pm 13.1 \pm 6.8$ ( $< 25.9$ )	$37.6 \pm 0.3 \pm 0.8$		$< 0.40$ (90% C.L.)

## Previous Results

Mode	$\mathcal{B}(BABAR)$ [9]	$\mathcal{B}(Belle)$ [10]	$\mathcal{B}(CLEO)$ [11]	Theory
$\pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$4.4 \pm 0.6 \pm 0.3$	$4.5^{+1.4}_{-1.2} {}^{+0.5}_{-0.4}$	4.6-11.0
$K^+\pi^-$	$17.9 \pm 0.9 \pm 0.7$	$18.5 \pm 1.0 \pm 0.7$	$18.0^{+2.3}_{-2.1} {}^{-1.2}_{-0.9}$	12.7-21.0
$K^+K^-$	$< 0.6$	$< 0.7$	$< 0.8$	0.007-0.080

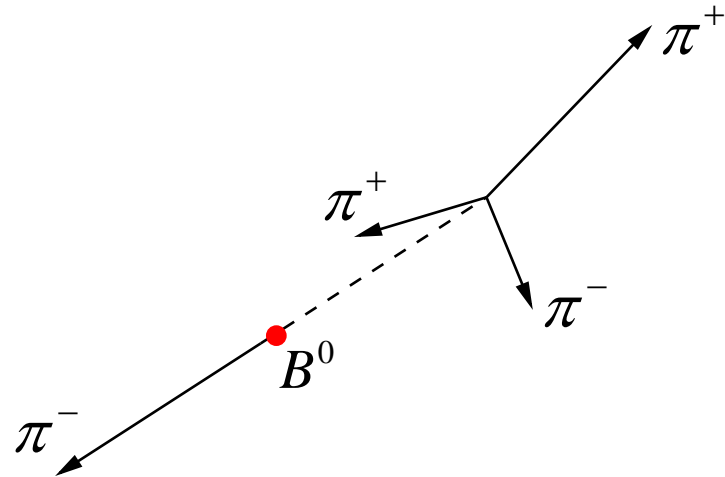
$\mathcal{B}(\pi\pi) = 5.5 \pm 0.4 \pm 0.3 \quad \rightarrow 17\% \text{ higher}$

$\mathcal{B}(K\pi) = 19.2 \pm 0.6 \pm 0.6 \quad \rightarrow 7\% \text{ higher}$

BFs in units of  $10^{-6}$

# $B^0 \rightarrow a_1(1260)\pi$

- First seen in 2004
  - $a_1$  not well known.
  - Some disagreement on its width in PDG.
  - Decays to  $\rho\pi$  and  $\sigma\pi$  final states have been reported.
  - $\tau$  data from CLEO give the most information on this.
  - Possible backgrounds include  $a_2(1320)\pi$ ,  $\pi(1300)\pi$ .
  - Can be used to measure  $\alpha$ .
  - Not yet clear how effective a measurement will be.



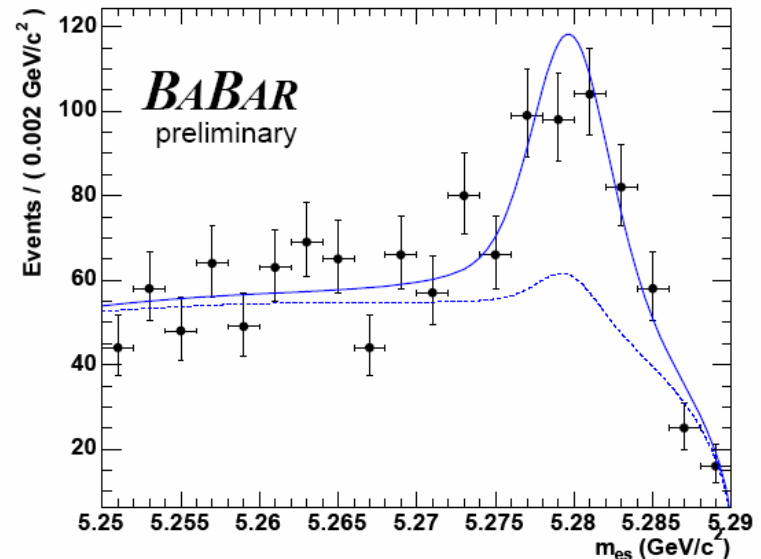
Angular correlations discriminate between signal and background

- BaBar uses the angle between the bachelor  $\pi$  and the normal to the  $a_1 \rightarrow 3\pi$  decay plane:  $(\cos A)$ .
- Belle use the angle between the  $\rho^0$  and B flight direction in the  $a_1$  frame:  $(\cos\theta_{\text{HEL}})$

# $B^0 \rightarrow a_1(1260)\pi$



- Fit  $m_{ES}$ ,  $\Delta E$ , Fisher,  $m_{a_1}$ ,  $\cos A$  a sample of 49529 events.
- backgrounds from
  - $e^+e^- \rightarrow qq$
  - inclusive B background
  - $B^0 \rightarrow a_2^+(1320)\pi^-$
  - $B^0 \rightarrow \pi^+(1300)\pi^-$
- Reconstruction efficiency:
  - $\varepsilon=19.8\%$
- Dominant systematic errors:
  - PDF shape (6.2%)
  - Interference between  $a_1$  and  $a_2$
- Assume  $BF(a_1 \rightarrow \rho^0\pi)=0.5$ .



$$BF = (40.2 \pm 3.9 \pm 3.9) \times 10^{-6}$$

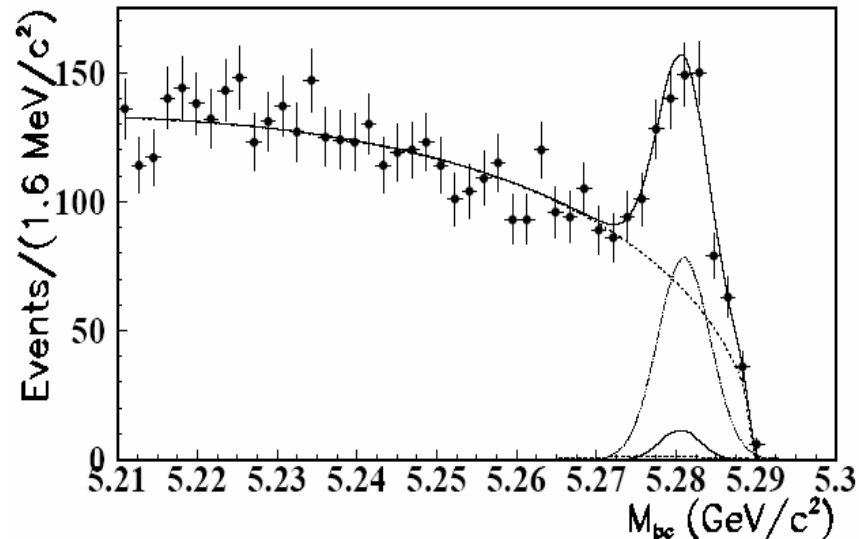
$$N_{signal} = 867 \pm 85 \text{ events}$$

218 million  $B\bar{B}$  pairs

# $B^0 \rightarrow a_1(1260)\pi$



- Fit  $m_{ES}$ ,  $\Delta E$ ,  $\cos\theta_{HEL}$  in a sample of 13541 events.
- Same background model as Babar.
- Reconstruction efficiency:
  - $\varepsilon=6.1\%$
- Dominant Systematic Errors:
  - tracking
  - $\Delta E$  cut selection
- Assume  $BF(a_1 \rightarrow \rho^0\pi)=0.5$ .



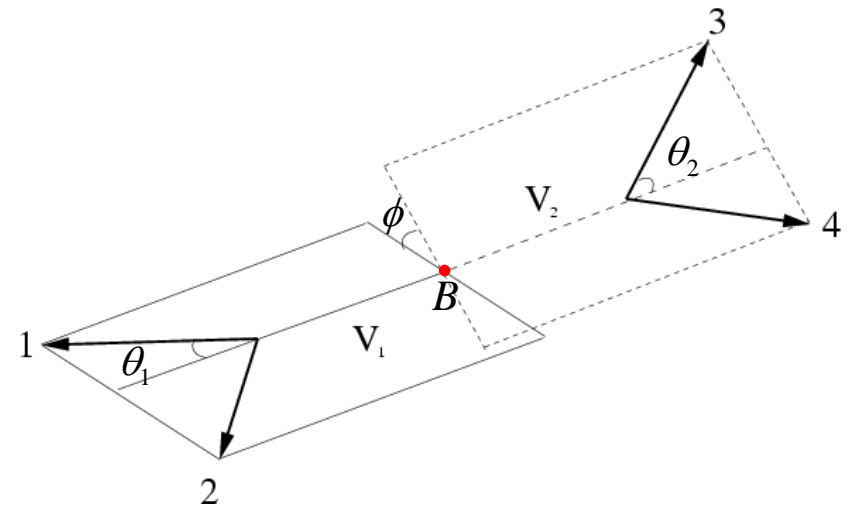
$$BF = (48.6 \pm 4.1 \pm 3.9) \times 10^{-6}$$

$$N_{signal} = 394 \pm 33 \text{ events}$$

$$275 \times 10^6 B\bar{B} \text{ pairs}$$

# B → VV decays

- $0^+ \rightarrow 1^- 1^-$
- These decays usually require full angular analysis.
- Simplify analysis to separating transverse and longitudinal events when have low statistics.
- Measure polarisation:  $f_L$



$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4} \left( \underbrace{f_L \cos^2\theta_1 \cos^2\theta_2}_{\text{Longitudinal}} + \frac{1}{4}(1 - f_L) \underbrace{\sin^2\theta_1 \sin^2\theta_2}_{\text{Transverse}} \right)$$

- From early calculations, expected  $f_L \approx 1 - \left(\frac{m_v}{m_b}\right)^2$   
 $\approx O(1)$

Also: See the talks yesterday and scheduled for the parallel session Thursday on this subject.

# $B \rightarrow K^* \rho$

- $K^{*+}\rho^-$ ,  $K^{*+}\rho^0$ ,  $K^{*0}\rho^+$ ,  $K^{*0}\rho^0$  have been studied.
- Only an upper limit on  $K^{*+}\rho^-$  and  $K^{*0}\rho^0$

$$f_L(B^+ \rightarrow \rho^+ K^{*0})$$

$$\text{BELLE} \quad 0.43 \pm 0.11(\text{stat})_{-0.02}^{+0.05}(\text{syst}).$$



$$0.79 \pm 0.08(\text{stat}) \pm 0.04(\text{syst}) \pm 0.02(\text{NR})$$

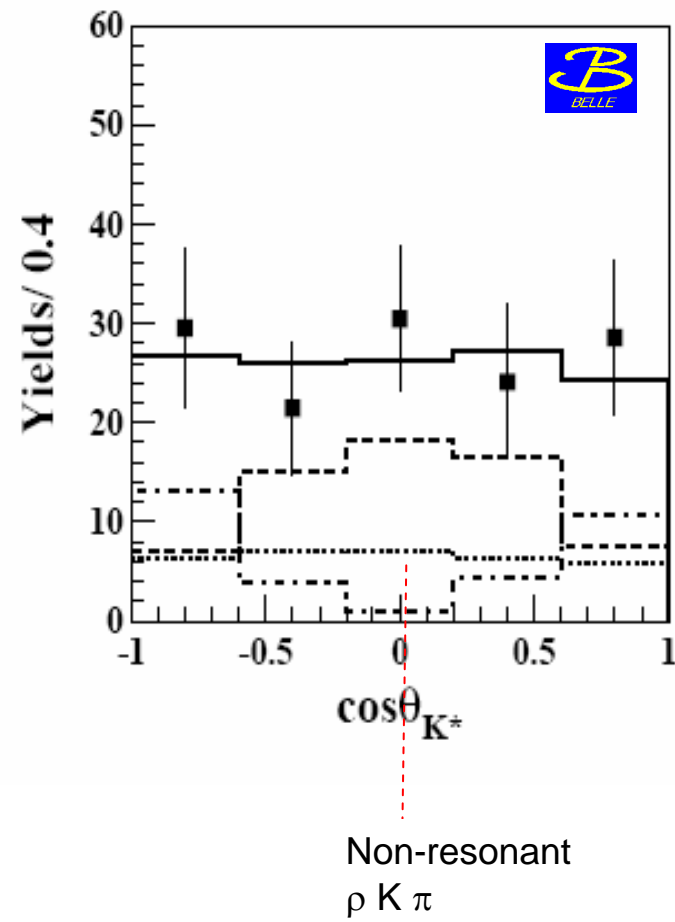
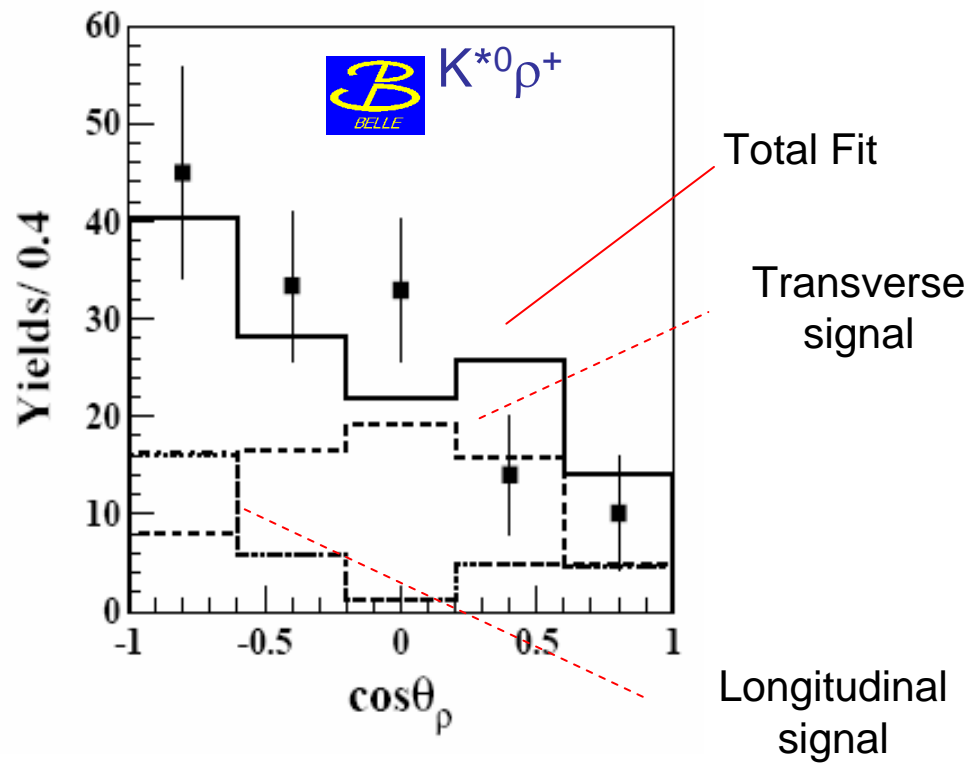
$$f_L(B^+ \rightarrow K^{*+} \rho^0)$$



$$0.96_{-0.15}^{+0.04}(\text{stat}) \pm 0.04(\text{syst})$$

- An indication of a deviation from expectation for  $K^{*0}\rho^+$ .

# $B \rightarrow K^* \rho$



# $B \rightarrow \phi K^*$

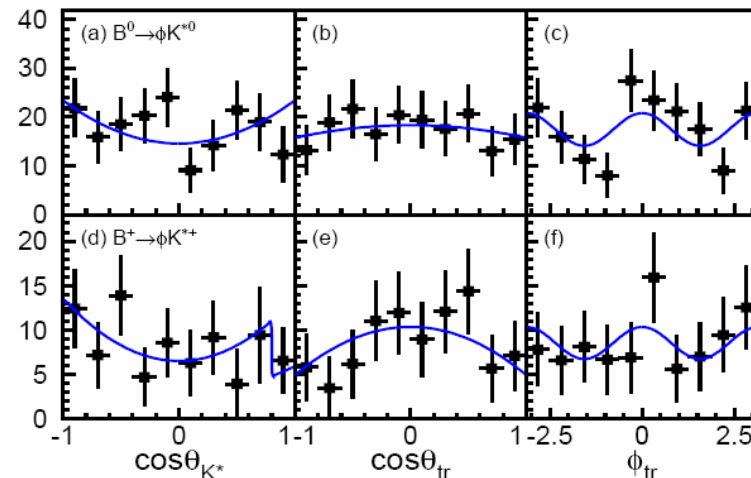


- $275 \times 10^6$  B pairs
- $f_L$ : Clear deviation from expectation

- Perform transversity analysis on  $\phi K^*$ .

Mode	$\phi K^{*0}$	$\phi K^{*+}$
$f_L,  A_0 ^2$	$0.45 \pm 0.05 \pm 0.02$	$0.52 \pm 0.08 \pm 0.03$
$ A_\perp ^2$	$0.30 \pm 0.06 \pm 0.02$	$0.19 \pm 0.08 \pm 0.02$
$\arg(A_\parallel)$ (rad)	$2.39 \pm 0.24 \pm 0.04$	$2.10 \pm 0.28 \pm 0.04$
$\arg(A_\perp)$ (rad)	$2.51 \pm 0.23 \pm 0.04$	$2.31 \pm 0.30 \pm 0.07$

- Fit for  $A_0, A_\perp, A_\parallel$   
and  $\theta_{tr}, \phi_{tr}$ .

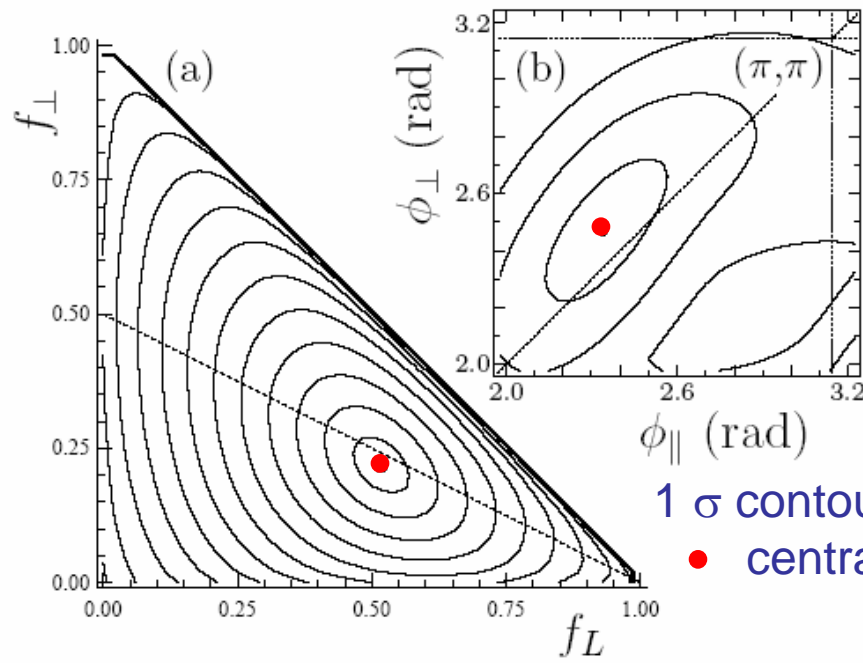
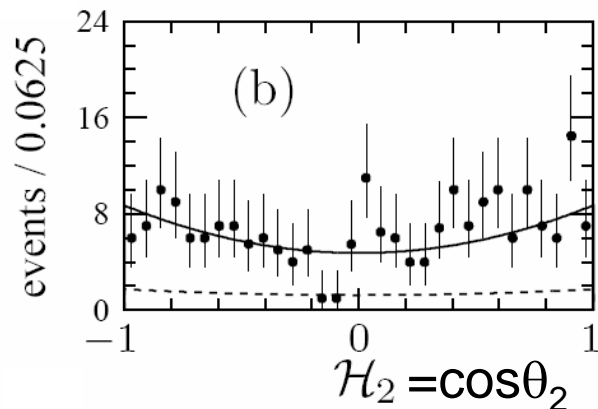
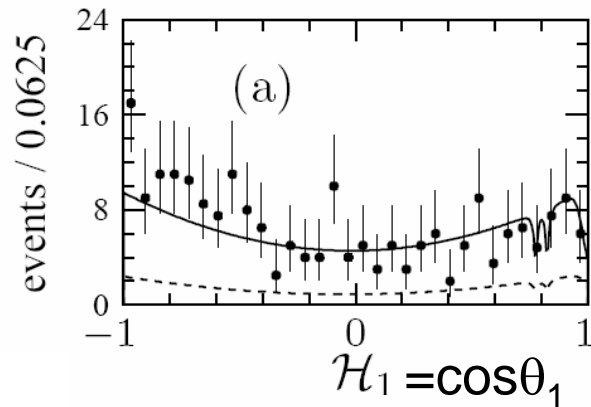


# $B \rightarrow \phi K^*$



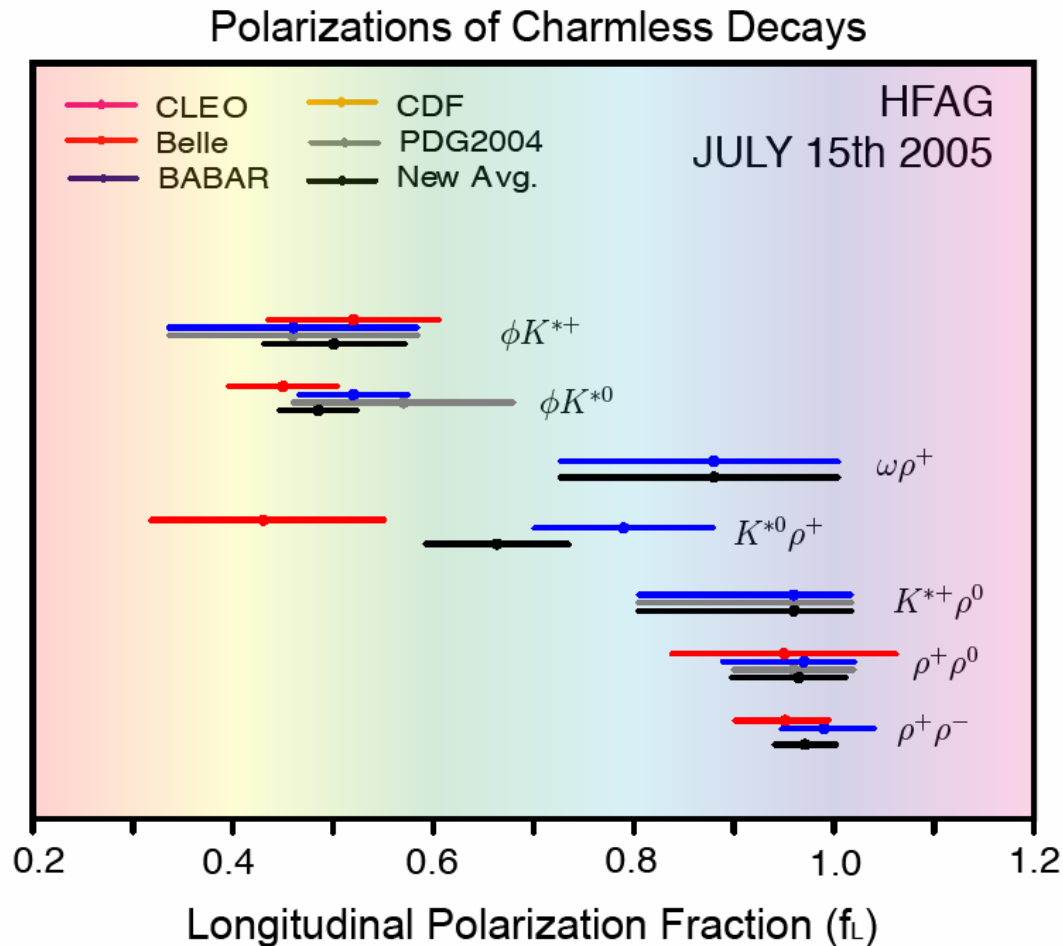
- $227 \times 10^6$  B pairs
- Transversity analysis
- Also see a small  $f_L$

Fit parameter	Fit result	Correlation
$n_{\text{sig}}$ (events)	$201 \pm 20 \pm 6$	
$f_L$	$0.52 \pm 0.05 \pm 0.02$	} -46%
$f_{\perp}$	$0.22 \pm 0.05 \pm 0.02$	



1  $\sigma$  contours  
 • central value

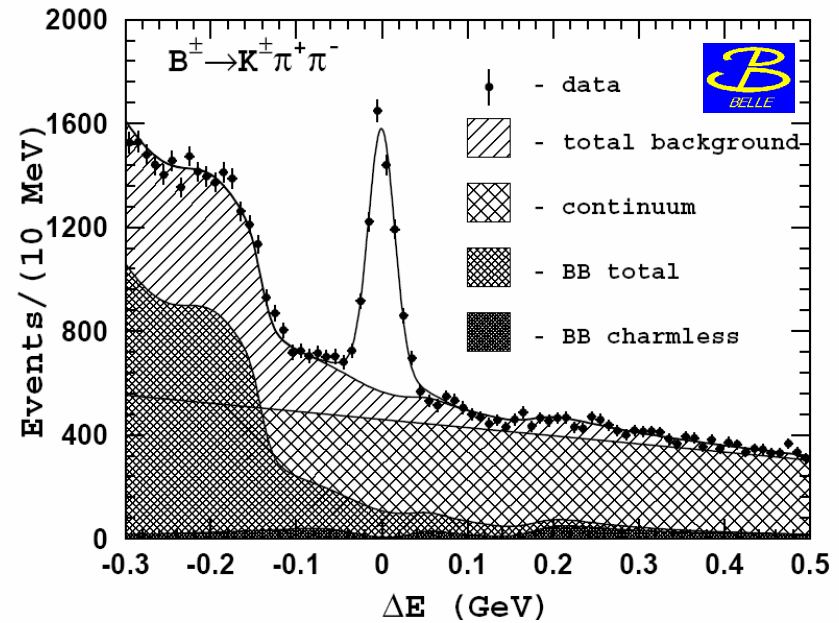
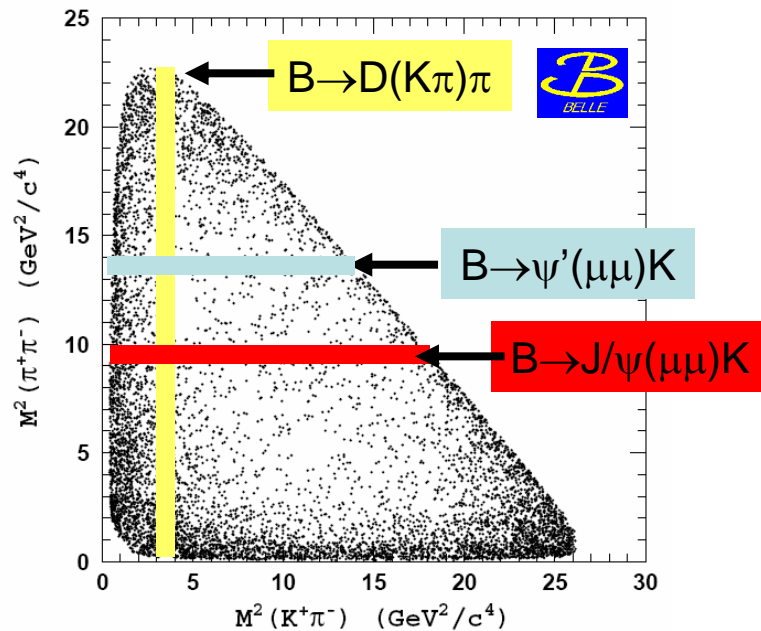
# Overview of VV decays



- Some decays don't follow naive expectations.
- Important to finish building the picture:
  - What is  $f_L$  for other  $K^* \rho$  modes?
  - What is  $f_L$  for other VV modes?
  - What additional contributions can explain these observations?

# Dalitz plot analysis of $B^+ \rightarrow K\pi\pi$

- Dalitz plot (DP) analysis of the  $K\pi\pi$  final state
- Select events in  $m_{ES}$  and  $\Delta E$
- Veto charm in the DP

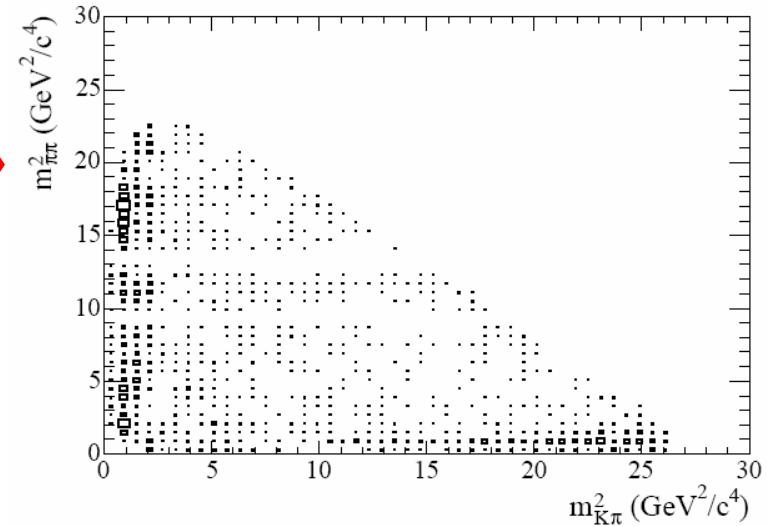


- Estimate the background from sideband data.
- Model the matrix element for the amplitudes in the DP.
- Fit the DP.

# Dalitz plot analysis of $B \rightarrow K\pi\pi$



- $226 \times 10^6$  B pairs
- background subtracted DP  $\rightarrow$
- 2125 signal events
- 13 amplitudes fitted
- $A_{CP}$  consistent with zero

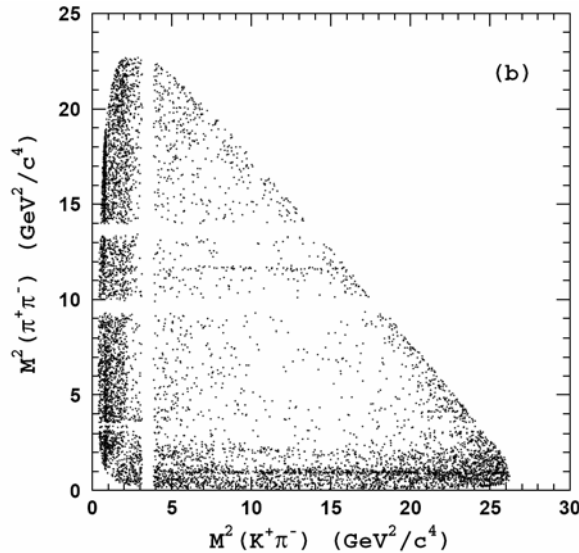


Mode	$\mathcal{B}(B^+ \rightarrow \text{Mode})(10^{-6})$	90% CL UL ( $10^{-6}$ )	$A_{CP}$ (%)
$K^+\pi^-\pi^+$ Total	$64.1 \pm 2.4 \pm 4.0$	—	$-1.3 \pm 3.7 \pm 1.1$
$K^{*0}(892)\pi^+; K^{*0}(892) \rightarrow K^+\pi^-$	$8.99 \pm 0.78 \pm 0.48^{+0.28}_{-0.39}$	—	$6.8 \pm 7.8 \pm 5.7^{+4.0}_{-3.5}$
$(K\pi)^*_{0^+}\pi^+; (K\pi)^*_{0^+} \rightarrow K^+\pi^-$	$34.0 \pm 1.7 \pm 1.5^{+1.2}_{-1.6}$	—	$-6.4 \pm 3.2 \pm 2.0^{+1.1}_{-1.7}$
$\rho^0(770)K^+; \rho^0(770) \rightarrow \pi^+\pi^-$	$5.07 \pm 0.75 \pm 0.35^{+0.42}_{-0.68}$	—	$32 \pm 13 \pm 6^{+8}_{-5}$
$f_0(980)K^+; f_0(980) \rightarrow \pi^+\pi^-$	$9.47 \pm 0.97 \pm 0.46^{+0.42}_{-0.75}$	—	$8.8 \pm 9.5 \pm 2.6^{+9.3}_{-5.0}$
$\chi_{c0}K^+; \chi_{c0} \rightarrow \pi^+\pi^-$	$0.66 \pm 0.22 \pm 0.07 \pm 0.03$	$< 1.1$	—
$K^+\pi^-\pi^+$ nonresonant	$2.85 \pm 0.64 \pm 0.41^{+0.70}_{-0.34}$	$< 6.5$	—
$K_2^{*0}(1430)\pi^+; K_2^{*0}(1430) \rightarrow K^+\pi^-$	—	$< 7.7$	—
$K^{*0}(1680)\pi^+; K^{*0}(1680) \rightarrow K^+\pi^-$	—	$< 3.8$	—
$f_2(1270)K^+; f_2(1270) \rightarrow \pi^+\pi^-$	—	$< 8.9$	—
$f_0(1370)K^+; f_0(1370) \rightarrow \pi^+\pi^-$	—	$< 10.7$	—
$\rho^0(1450)K^+; \rho^0(1450) \rightarrow \pi^+\pi^-$	—	$< 11.7$	—
$f_0(1500)K^+; f_0(1500) \rightarrow \pi^+\pi^-$	—	$< 4.4$	—
$f'_2(1525)K^+; f'_2(1525) \rightarrow \pi^+\pi^-$	—	$< 3.4$	—

$A_{CP}$ : only  $2.5\sigma$

hep-ex/0507004  
(submitted to PRD-RC)

# Dalitz plot analysis of $B \rightarrow K\pi\pi$



- $386 \times 10^6$  B pairs
- 7757 events in signal region
- 7 amplitudes fitted
- $3.9\sigma$  evidence for direct CPV in  $B^+ \rightarrow \rho(770)^0 K^+$

Mode	$B(B^+ \rightarrow Rh^+ \rightarrow K^+\pi^+\pi^-)$ $\times 10^6$	$B(B^+ \rightarrow Rh^+)$ $\times 10^6$	$A_{CP},$ %
$K^\pm\pi^\pm\pi^\mp$ Charmless	—	$48.8 \pm 1.1 \pm 3.6$	$4.9 \pm 2.6 \pm 3.0$
$K^*(892)^0[K^+\pi^-]\pi^+$	$6.45 \pm 0.43 \pm 0.48^{+0.25}_{-0.35}$	$9.67 \pm 0.64 \pm 0.72^{+0.37}_{-0.52}$	$-14.9 \pm 6.4 \pm 3.0^{+0.8}_{-0.8}$
$K_0^*(1430)[K^+\pi^-]\pi^+$	$32.0 \pm 1.0 \pm 2.4^{+1.1}_{-1.9}$	$51.6 \pm 1.7 \pm 6.8^{+1.8}_{-3.1}$	$+7.6 \pm 3.8 \pm 3.0^{+2.0}_{-0.9}$
$\rho(770)^0[\pi^+\pi^-]K^+$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$+30 \pm 11 \pm 3.0^{+11}_{-4}$
$f_0(980)[\pi^+\pi^-]K^+$	$8.78 \pm 0.82 \pm 0.65^{+0.55}_{-1.64}$	—	$-7.7 \pm 6.5 \pm 3.0^{+4.1}_{-1.6}$
$f_2(1270)[\pi^+\pi^-]K^+$	$0.75 \pm 0.17 \pm 0.06^{+0.11}_{-0.18}$	$1.78 \pm 0.41 \pm 0.14^{+0.26}_{-0.43}$	$-59 \pm 22 \pm 3.0^{+3}_{-3}$
Non-resonant	—	$16.9 \pm 1.3 \pm 1.3^{+1.1}_{-0.9}$	—
$\chi_{c0}[\pi^+\pi^-]K^+$	$0.56 \pm 0.06 \pm 0.04^{+0.12}_{-0.04}$	$112 \pm 12 \pm 18^{+24}_{-8}$	$-6.5 \pm 19.6 \pm 3.0^{+2.9}_{-1.4}$

←  $A_{CP}: 3.9\sigma$

# Conclusions

- Rare Hadronic B-decays provide many observables that can be used to increase our understanding.
  - direct CP asymmetries probe  $\Delta b=1$  transitions.
  - The potential to constrain Unitarity Triangle angles continues to be pushed.
  - $f_L$  measurements and study of angular correlations in  $B \rightarrow VV$  decays are potential probes for new physics effects.
  - Reproducibility of the spectrum of observed branching fractions are vital tests of the validity of available models.

# Conclusions

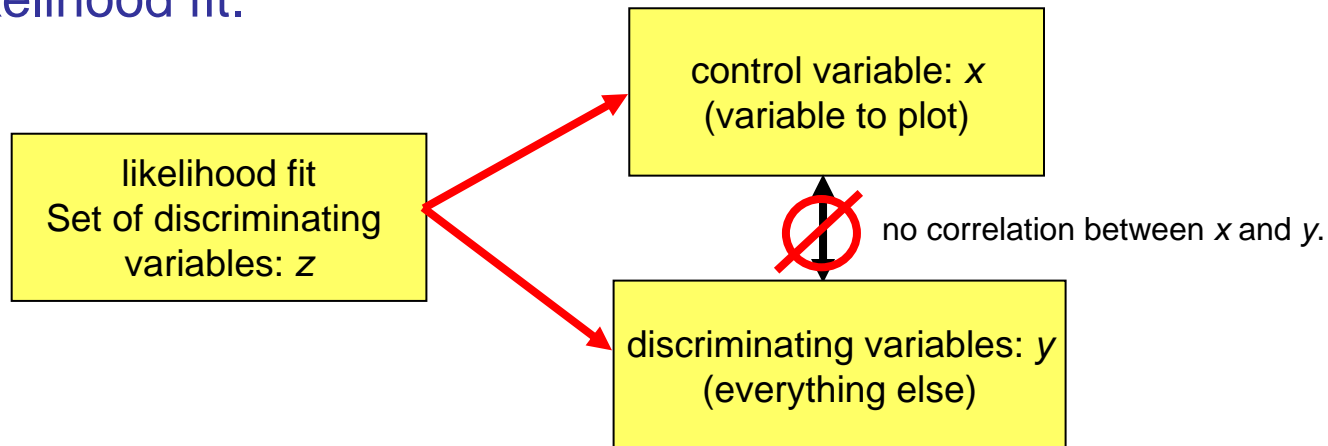
- The study of rare hadronic B-decays has come of age:
  - The B-factories have observed direct CP violation in B-meson decay. More hints are appearing in the data
  - Final state radiation corrections are becoming increasingly important for some branching fraction measurements.
  - Will  $B \rightarrow a_1 \pi$  decays provide a competitive measurement of  $\alpha$ ?
  - Measuring different  $B \rightarrow VV$  decays will help pin down deviations from expected behaviour that are observed in some modes.
- But there is still a lot of physics to understand.

# Backup Slides

# sPlots

physics/0402083  
(accepted for  
publication in NIM)

- Technique for visually representing fit species in a maximum likelihood fit.



- Calculate an sWeight for each event
  - based on PDFs for variables,  $y$
  - summed over set of species,  $k$

$$\text{sWeight} \rightarrow {}_s\mathcal{P}_n(y_e) = \frac{\sum_{j=1}^{N_s} \mathbf{V}_n f_j(y_e)}{\sum_{k=1}^{N_s} N_k f_k(y_e)}$$

covariance matrix

PDF for variables,  $y$

Number of species,  $k$