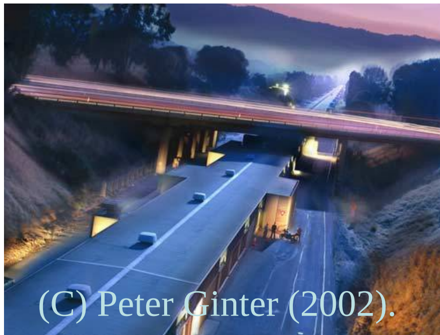
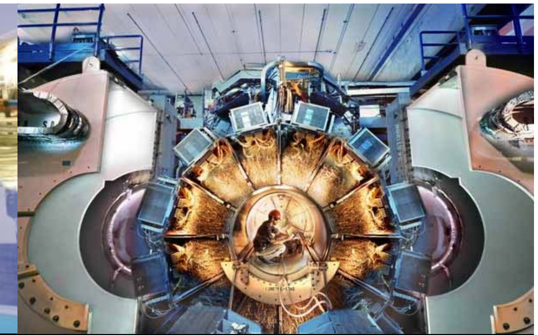






# Rare Hadronic B decays

Adrian Bevan

Flavour physics in the LHC Era

10th October 2006

Queen Mary
University of London

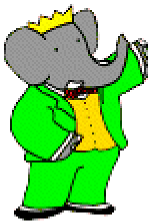
# Overview

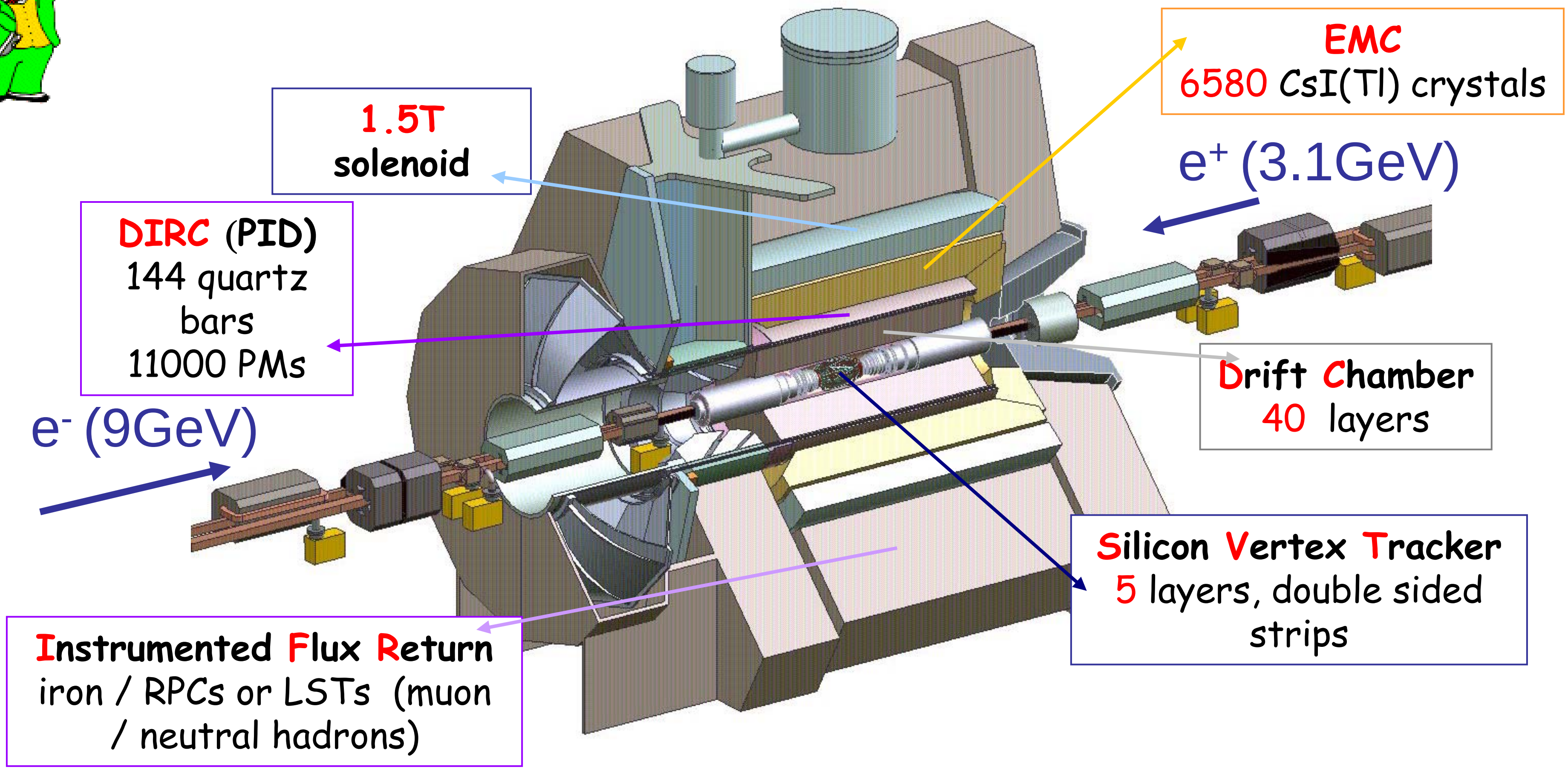
- Motivation
- The BaBar Detector
- Isolating Signal Decays
- Results
  - Direct CPV
  - $B \to VV$ Results
    - $K^*\rho$
    - Constraining penguins in $B \to \rho\rho$
    - $B \to \phi K^*$
    - Building a bigger picture
  - Constraining $\Delta S$ with $B \to PP$ decays
  - $B \to a_1 \pi$
  - $B \to \eta' V$
- Summary

# Motivation

- Rare hadronic B decays to PP, PV, VV final states provide a complicated and rich test bed for B physics theory calculations.
  - Branching Fractions.
  - Direct CP violation.
  - TDCPV (not covered – see G. Cavoto's talk)
  - Unitarity Triangle angles.
  - VV: polarisation, amplitude hierarchy, T-odd asymmetries, NP searches.
  - + much more...
- This is a small selection of results: BaBar sent O(40) papers on this subject to ICHEP '06.

# BaBar detector



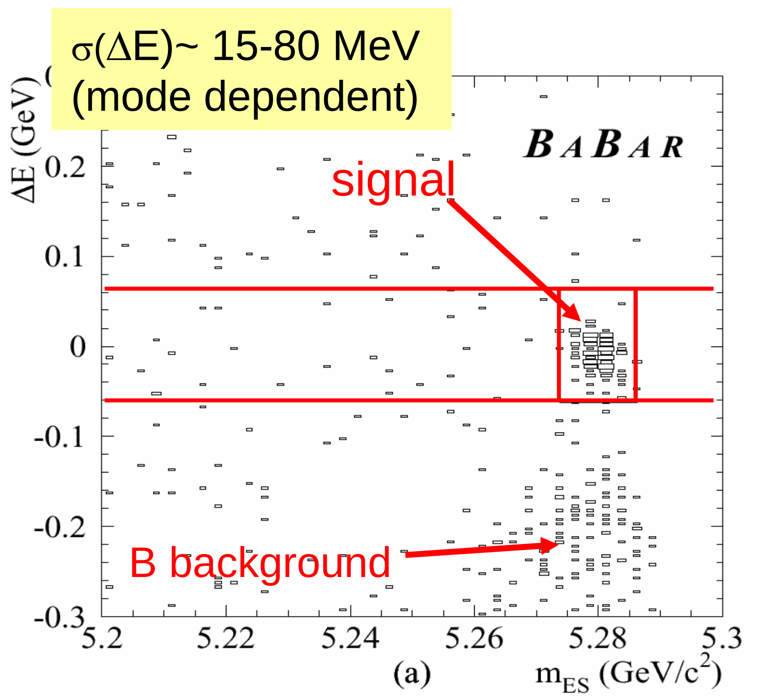


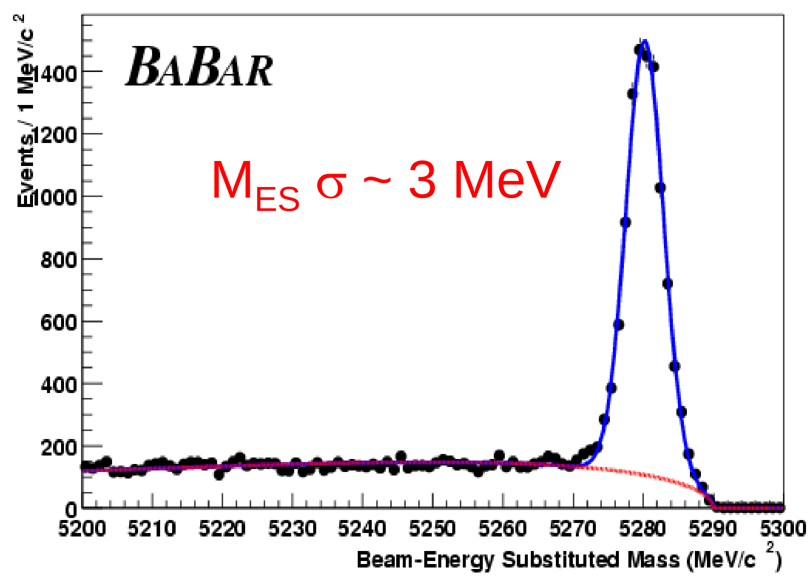

- Upgrading muon system to replace all remaining RPCs with LSTs for run 6.

# Isolating signal events

- Beam energy is known very well at an $e^+e^-$ collider like PEP-II.
  - use an energy difference and effective mass to select events:

$$\Delta E = E_B - E^*_{beam} \qquad m_{ES} = \sqrt{(E^*_{beam})^2 - P_B^2}$$

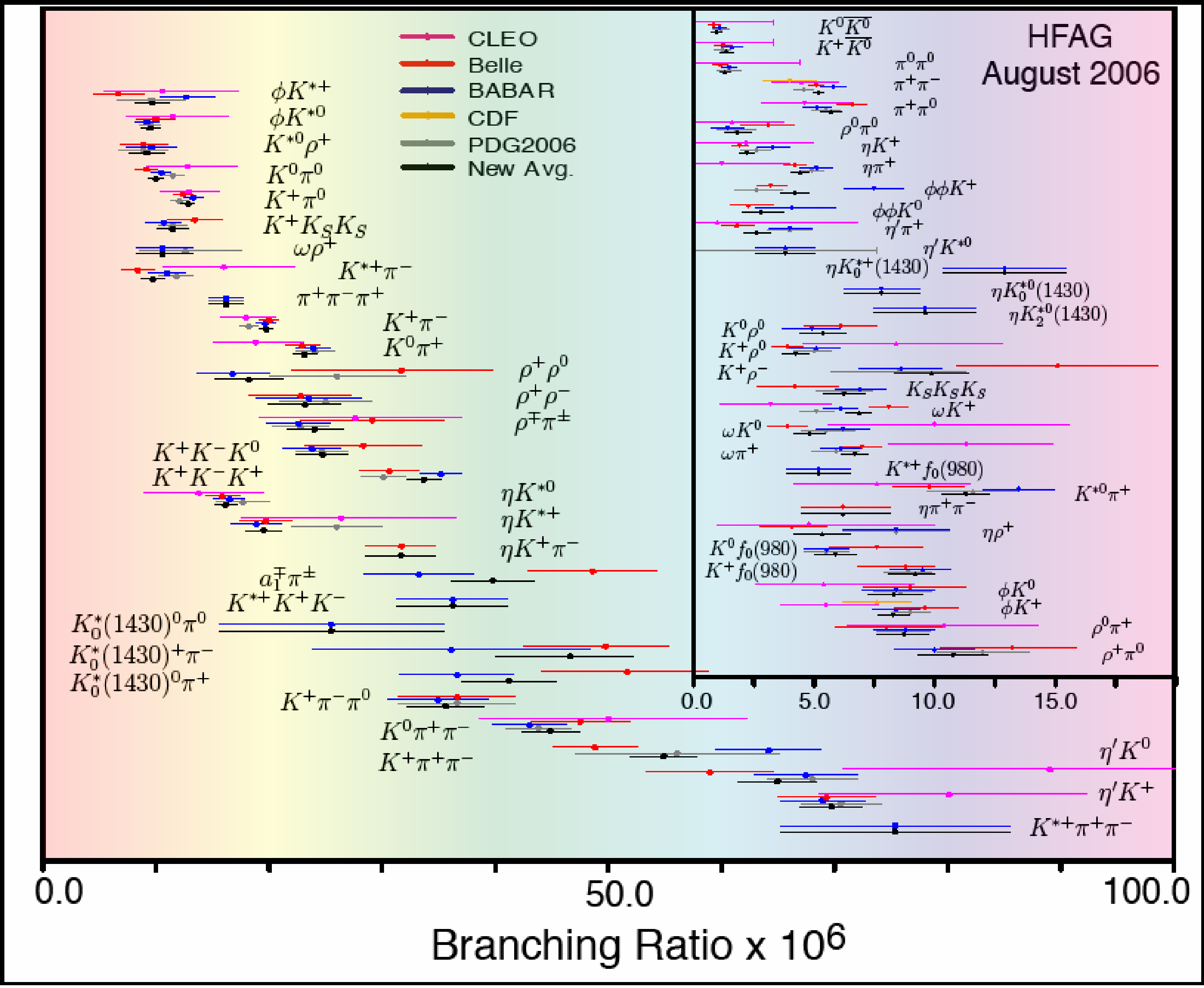


# Results

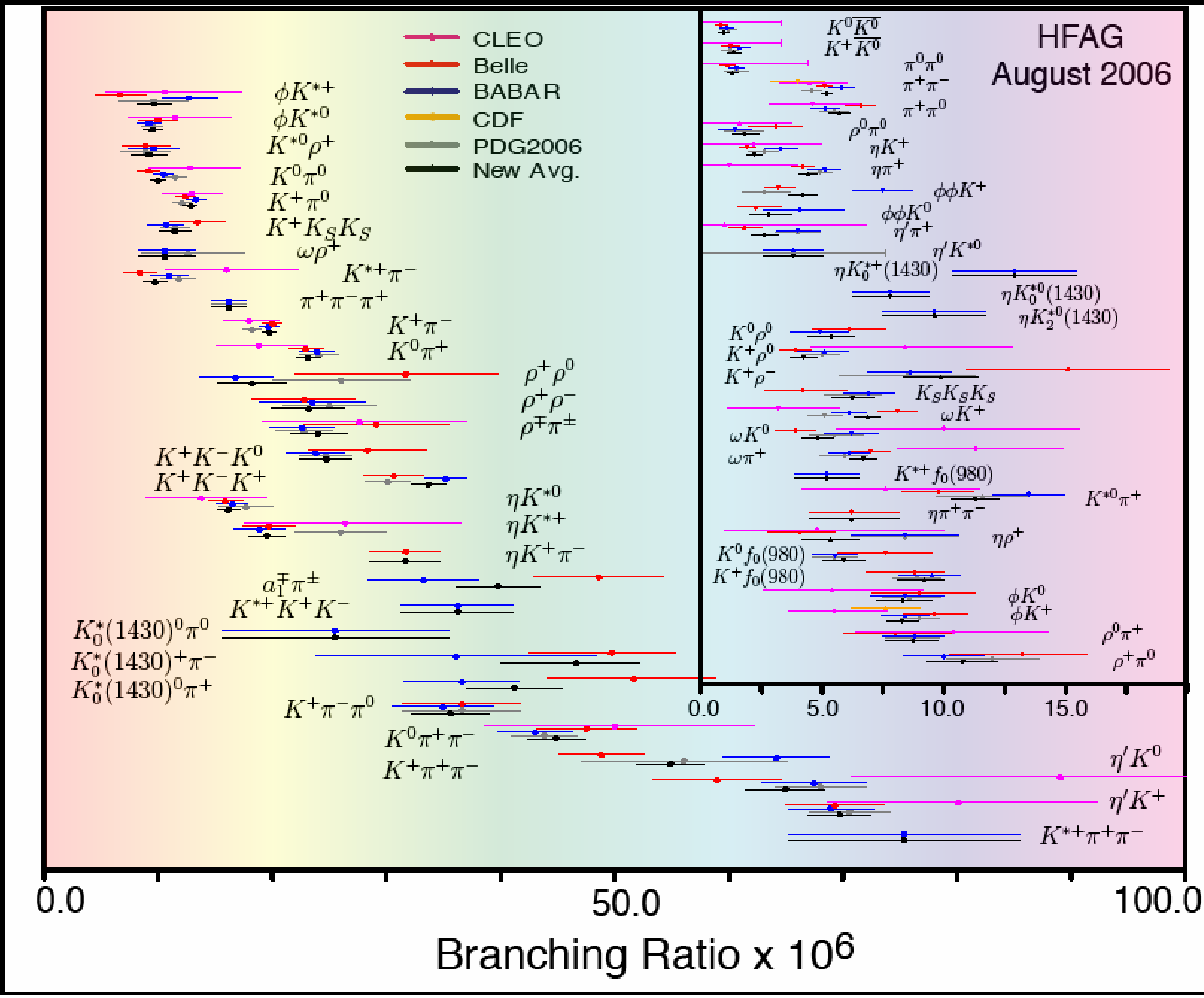
**Searching for needles in a haystack**

# The full range of measurements...
# is far too much to cover!



# Direct CP Violation searches

summarise only two of many results: $K\pi$ and $\pi^+\pi^-\pi^0$.



# Direct CP violation

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

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

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

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

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

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

# Direct CPV in B→Kπ

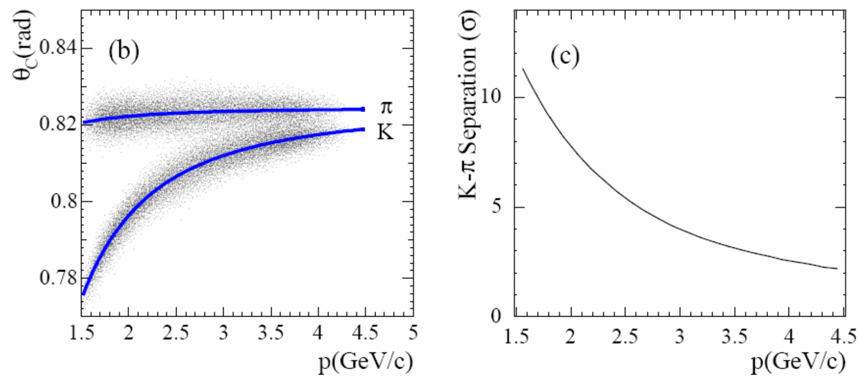
hep-ex/0607106

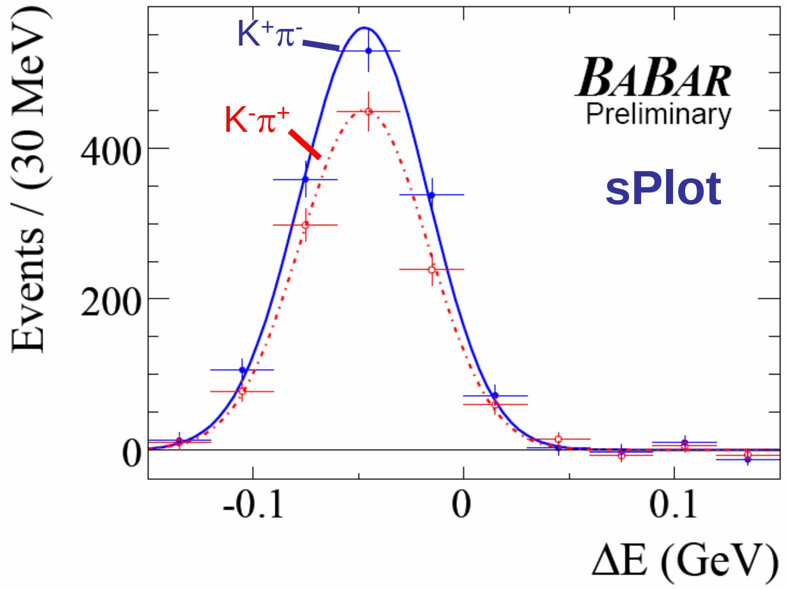
- $347 \times 10^6$ B pairs
- Charge of K in the final state tags the flavor of the B-meson.
- Use particle ID to separate K and π mesons.
- Calculate asymmetry:

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

$$\mathcal{A}_{K\pi} = -0.108 \pm 0.024 \pm 0.008$$

- 2nd Manifestation of direct CPV observed (after ε').

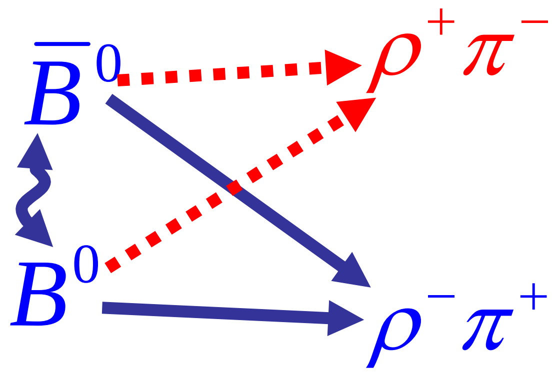


# $B^0 \to \rho^{\pm}\pi^{\mp}$

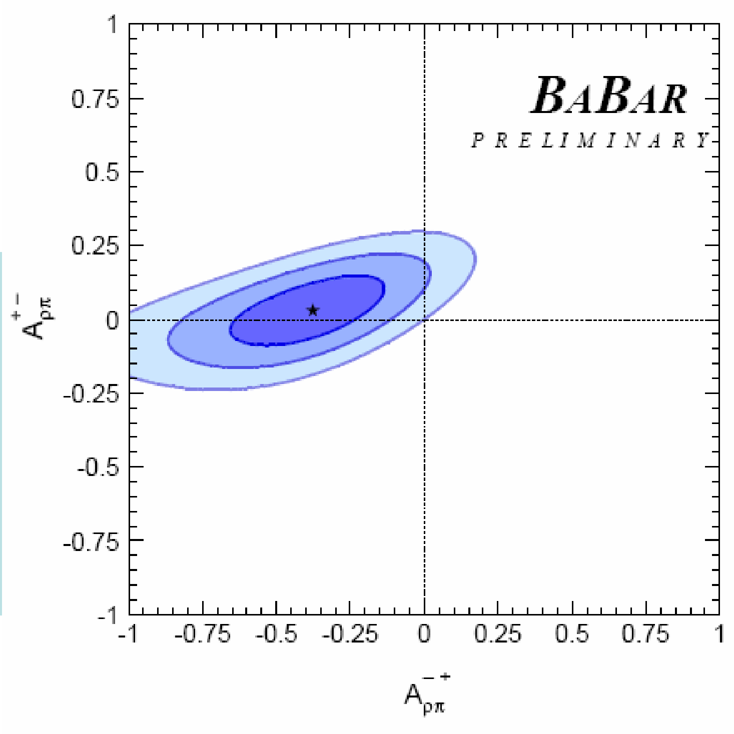
hep-ex/0608002

- Not a CP eigenstate.
- Can measure $A_{CP}$ for both $\rho^+\pi^-$ and $\rho^-\pi^+$ final states.
- Results obtained from the TD Dalitz analysis for $\alpha$.
- Good channel to continue searching for direct CPV.

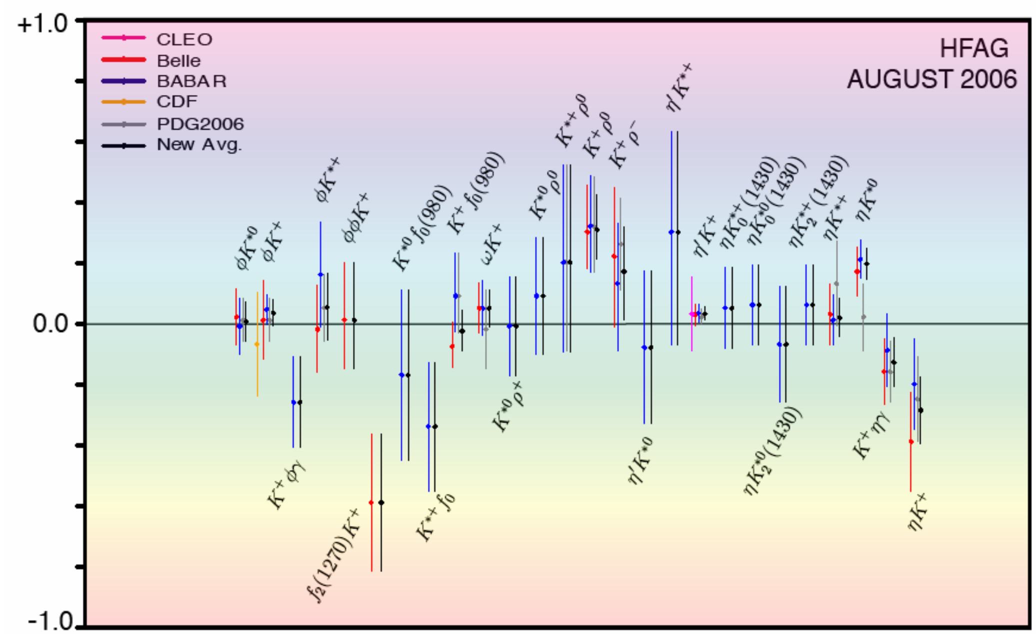


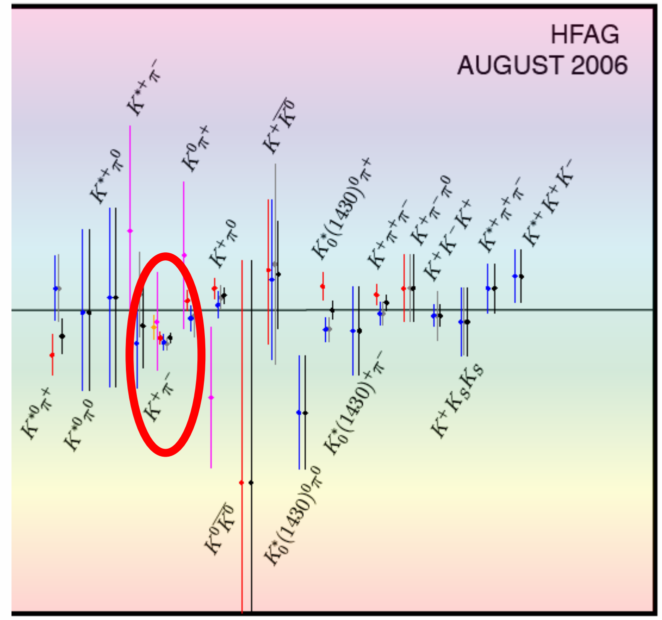

$$A_{\rho\pi}^{-+} = \frac{A_{\rho\pi} - C - A_{\rho\pi}\Delta C}{1 - C - A_{\rho\pi}\Delta C} = 0.03 \pm 0.07 \pm 0.03$$

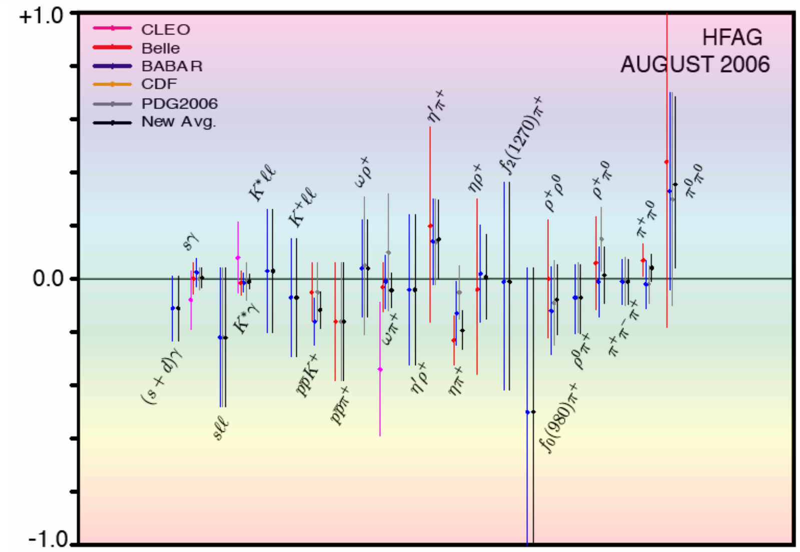
$$A_{\rho\pi}^{+-} = \frac{A_{\rho\pi} + C + A_{\rho\pi}\Delta C}{1 + C + A_{\rho\pi}\Delta C} = -0.38^{+0.15}_{-0.16} \pm 0.07$$



# Searches for Direct CP Violation in B decay

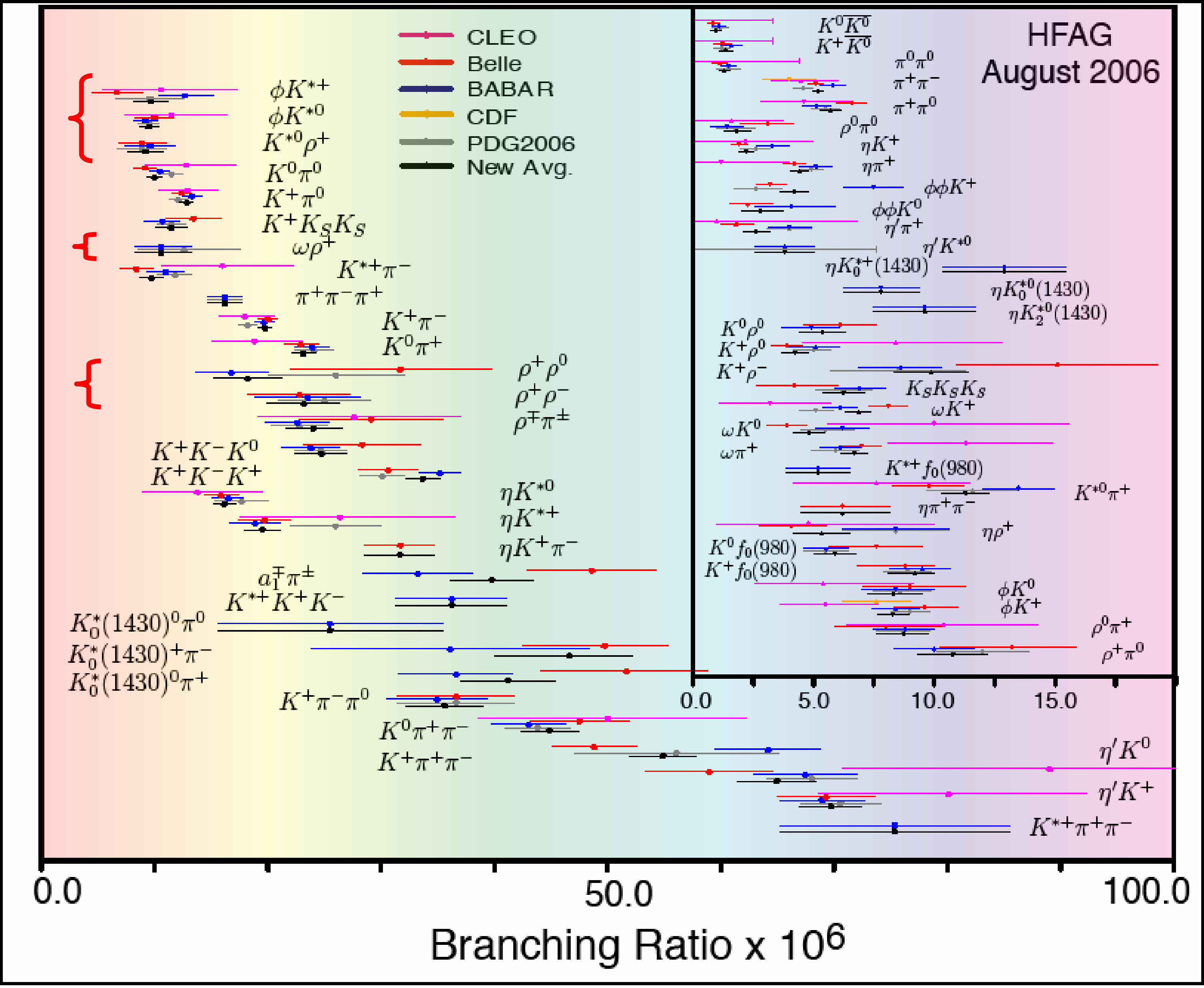


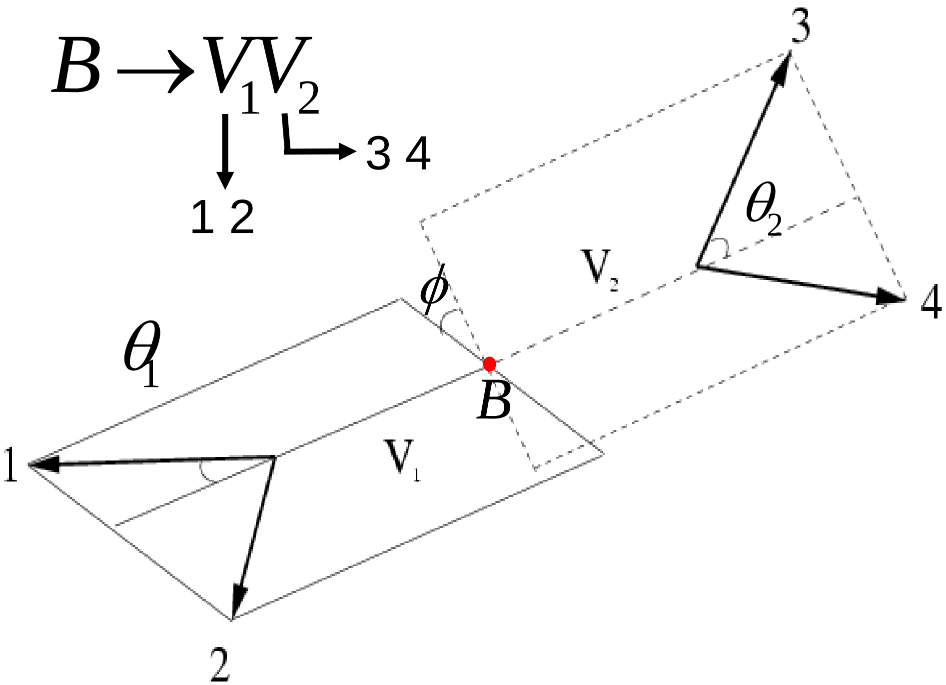

- The B-factories observed direct CPV in $B \to K\pi$ decays in 2004.
- There are other modes with evidence for direct CPV
  - $B^+ \to \rho(770)^0 K^+$
  - $B^0 \to \pi^+\pi^-$
  - $B^0 \to \pi^+\pi^-\pi^0$
- and a massive effort to uncover more signals.

# B→VV final states.



# Angular analysis of B→VV decays

- 11 observables
  - 6 amplitudes, $A_0$, $A_{+1}$, $A_{-1}$ + C.C.
  - 5 phases
- Simplify analysis to separating transverse and longitudinal events when have low statistics.
  - Measure polarisation: $f_L$
- Analogous to $H \to ZZ \to l^+l^-l^+l^-$




$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_{m=-1,0,1} A_m Y_{1,m}(\theta_1,\Phi) Y_{1,-m}(\theta_2,\Phi) \right|^2$$

$$\propto \begin{cases} \frac{1}{4}\sin^2\theta_1 \sin^2\theta_2 (|A_{+1}|^2 + |A_{-1}|^2) + \cos^2\theta_1 \cos^2\theta_2 |A_0|^2 \\ +\frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 [\cos 2\Phi \Re(A_{+1}A_{-1}^*) - \sin 2\Phi \Im(A_{+1}A_{-1}^*)] \\ +\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 [\cos\Phi \Re(A_{+1}A_0^* + A_{-1}A_0^*) - \sin\Phi \Im(A_{+1}A_0^* - A_{-1}A_0^*)] \end{cases}$$

$$f_L = \frac{|A_0|^2}{\sum_{m=-1,0,1} |A_m|^2}$$

# Angular analysis of B→VV decays

- For low statistics / when $A_0$ dominates:

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

- Longitudinal and transverse polarisations generally have different efficiencies.
- Naive factorisation prediction is

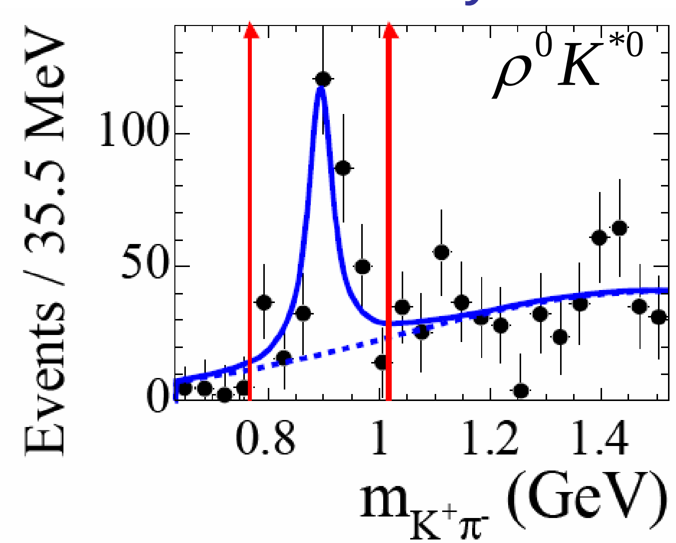
$$f_L \approx 1 - \left(\frac{m_v}{m_b}\right)^2 \approx O(1)$$

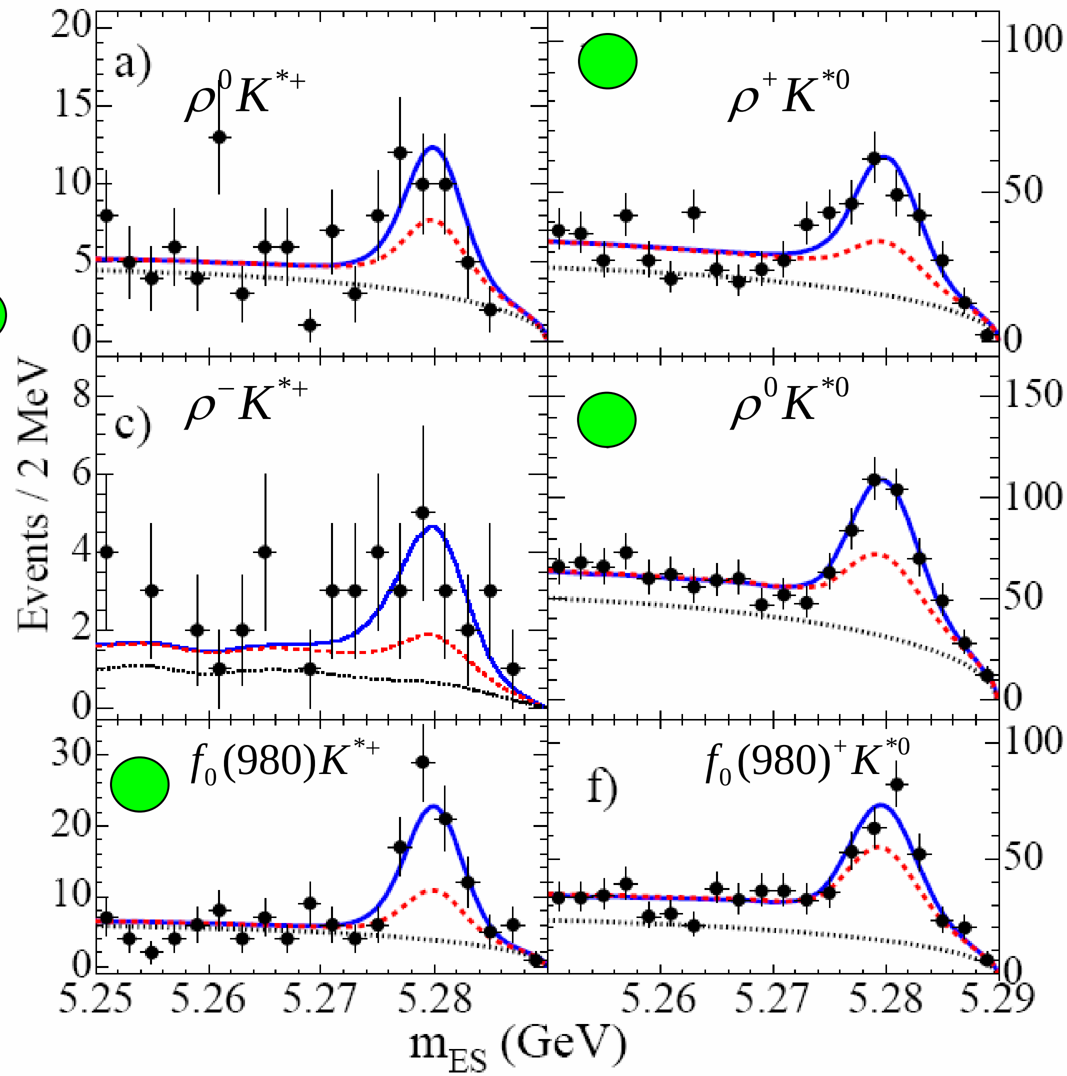
- Can also search T-odd (CP violating) asymmetries using triple products and new physics signatures. Easy to do if no single amplitude dominates the final state.
- Hierarchy of amplitudes predicted in SM.

# $B \to K^{*}\rho$

hep-ex/0607057

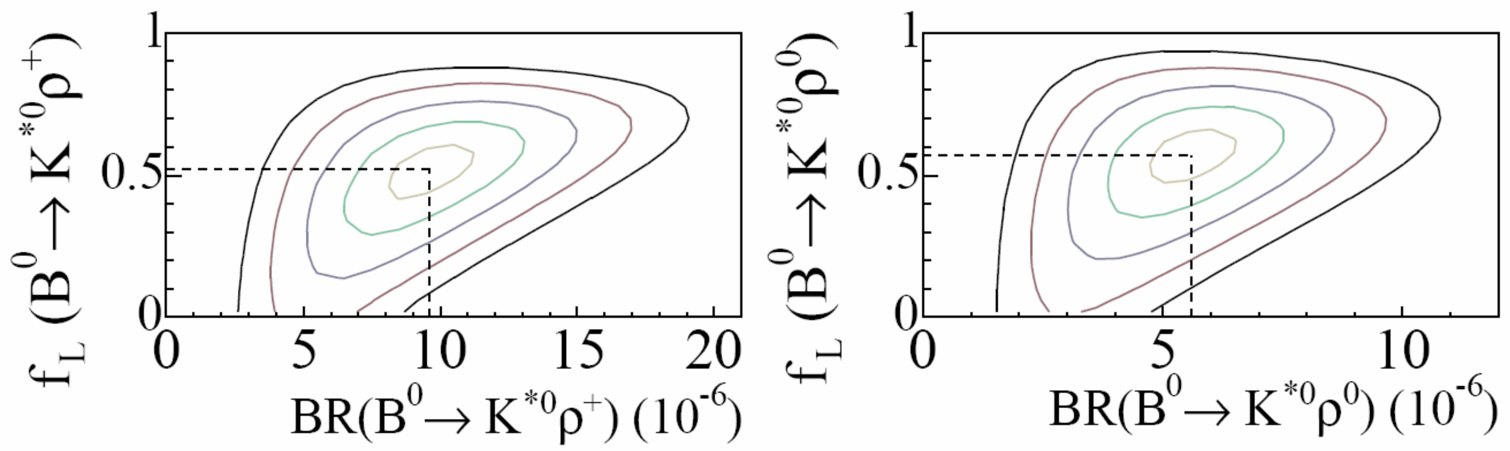
- $232 \times 10^6$ B Pairs
- BF~few $10^{-6}$.
- 2 VV modes and $f_0K^{*+}$ have been observed.
- Understanding non-resonant $K\pi$ background is critical for these analyses.



# B→K*ρ

hep-ex/0607057




| Mode | $n_{sig}$ | $S(\sigma)$ | $\mathcal{B}(10^{-6})$ | $f_L$ | $\mathcal{A}_{CP}$ |
|---|---|---|---|---|---|
| $\rho^0 K^{*+}$ | | 2.5 | $3.6^{+1.7}_{-1.6} \pm 0.8\ (6.1)$ | $[0.9 \pm 0.2]$ | – |
| $\to \rho^0 K^{*+}_{K^+\pi^0}$ | $19^{+16}_{-15}$ | 1.3 | $3.2^{+2.7}_{-2.4} \pm 0.9$ | $[0.8^{+0.3}_{-0.5}]$ | – |
| $\to \rho^0 K^{*+}_{K^0_S\pi^+}$ | $32^{+19}_{-17}$ | 2.1 | $3.8^{+2.2}_{-2.1} \pm 0.9$ | $[1.0 \pm 0.3]$ | – |
| $\rho^+ K^{*0}$ | $194 \pm 29$ | 7.1 | $9.6 \pm 1.7 \pm 1.5$ | $0.52 \pm 0.10 \pm 0.04$ | $-0.01 \pm 0.16 \pm 0.02$ |
| $\rho^- K^{*+}_{K^+\pi^0}$ | $60^{+25}_{-22}$ | 1.6 | $5.4^{+3.8}_{-3.4} \pm 1.6\ (12.0)$ | $[-0.18^{+0.52}_{-1.74}]$ | – |
| $\rho^0 K^{*0}$ | $185 \pm 30$ | 5.3 | $5.6 \pm 0.9 \pm 1.3$ | $0.57 \pm 0.09 \pm 0.08$ | $0.09 \pm 0.19 \pm 0.02$ |
| $f_0(980) K^{*+}$ | | 5.0 | $5.2 \pm 1.2 \pm 0.5$ | – | $-0.34 \pm 0.21 \pm 0.03$ |
| $\to f_0(980) K^{*+}_{K^+\pi^0}$ | $40^{+13}_{-12}$ | 3.8 | $6.2^{+2.1}_{-1.9} \pm 0.7$ | – | $-0.50 \pm 0.29 \pm 0.03$ |
| $\to f_0(980) K^{*+}_{K^0_S\pi^+}$ | $37^{+14}_{-12}$ | 3.2 | $4.2^{+1.5}_{-1.4} \pm 0.5$ | – | $-0.13 \pm 0.30 \pm 0.01$ |
| $f_0(980) K^{*0}$ | $83 \pm 19$ | 3.5 | $2.6 \pm 0.6 \pm 0.9\ (4.3)$ | – | $-0.17 \pm 0.28 \pm 0.02$ |

# Constraining Penguins in $B^0 \to \rho^+\rho^-$

Beneke et al., Phys.Lett. B638 (2006) 68-73

- Relate the penguin contribution in $\rho^+\rho^-$ to $K^{*0}\rho^+$ using SU(3) symmetry:

$$
\begin{aligned}
C_{\mathrm{long}} &= \frac{2r\sin\delta\sin(\beta+\alpha)}{1-2r\cos\delta\cos(\beta+\alpha)+r^2}, \\
S_{\mathrm{long}} &= \frac{\sin 2\alpha + 2r\cos\delta\sin(\beta-\alpha) - r^2\sin 2\beta}{1-2r\cos\delta\cos(\beta+\alpha)+r^2},
\end{aligned}
$$

$$
\begin{aligned}
R &= \left(\frac{|V_{cd}|f_\rho}{|V_{cs}|f_{K^*}}\right)^2 \cdot \frac{\Gamma_{L,CP-averaged}(B^\pm \to K^{*0}\rho^+)}{\Gamma_{L,CP-averaged}(B^0 \to \rho^+\rho^-)}, \\
&= \frac{Fr^2}{1-2r\cos\delta\cos(\beta+\alpha)+r^2}.
\end{aligned}
$$

r=|P/T|

δ=strong phase difference between P and T

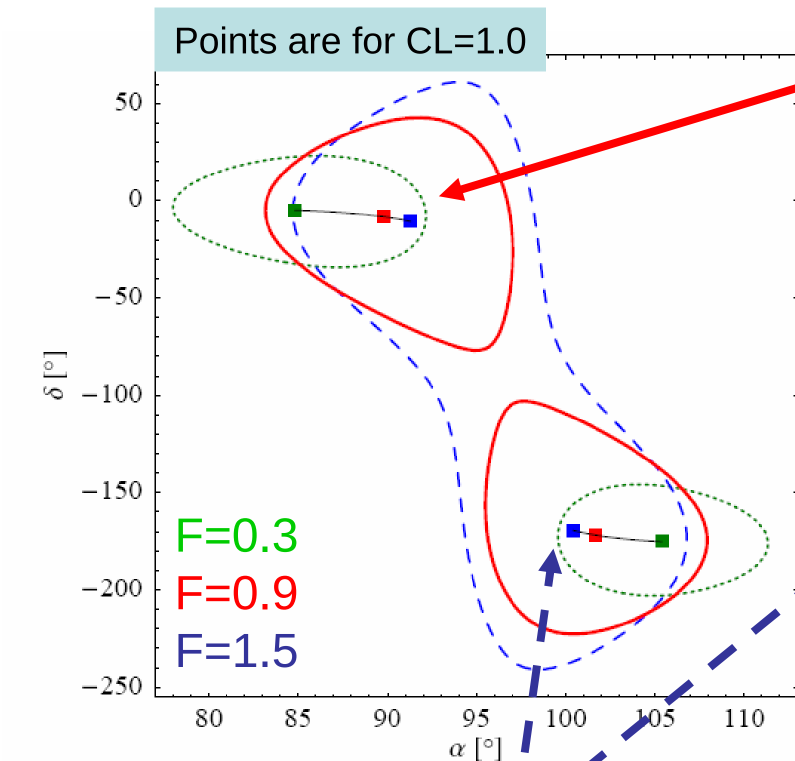
F=Correction for SU(3) breaking effects not included in the decay constants

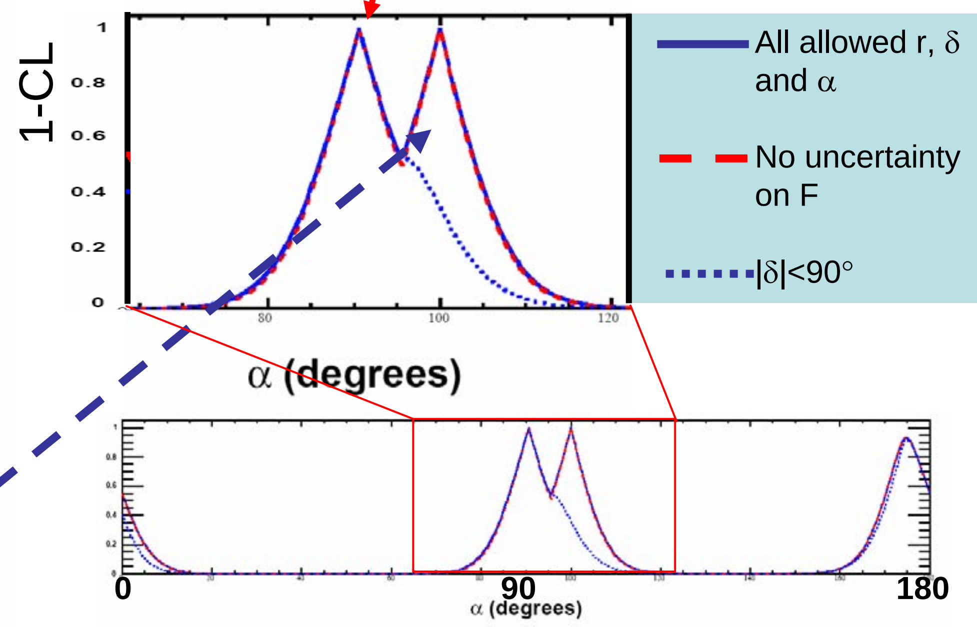
- The error on α and δ don't depend strongly on F and σ(F): Variance always suppressed by a factor of $r^2$.
- Produces usual ambiguities in 0-180°.
- Also get 2 fold ambiguities in δ.
- Remove one ambiguity in δ by assuming |δ|<90°.

# Constraints using the Beneke et al. model

- For the standard model solution of $\alpha$:

α~90° is preferred for |δ|<90°




α~100° is preferred for |δ|>90°

$\sigma(\alpha)$~7°(expt.)±1.5 °(th.)

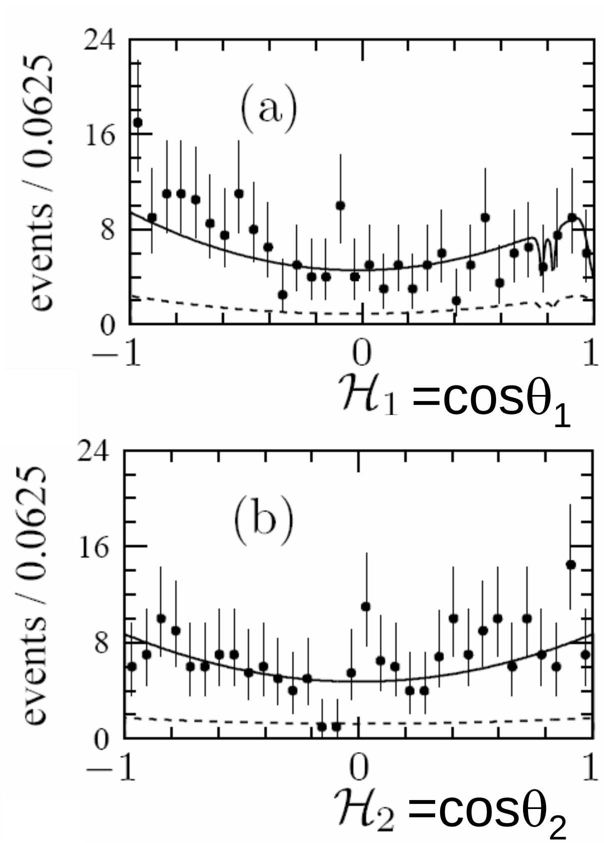
- c.f. Isospin constraint on $\alpha$~18°.
- Error predominantly from measurement of S and C ($\alpha_{eff}$).

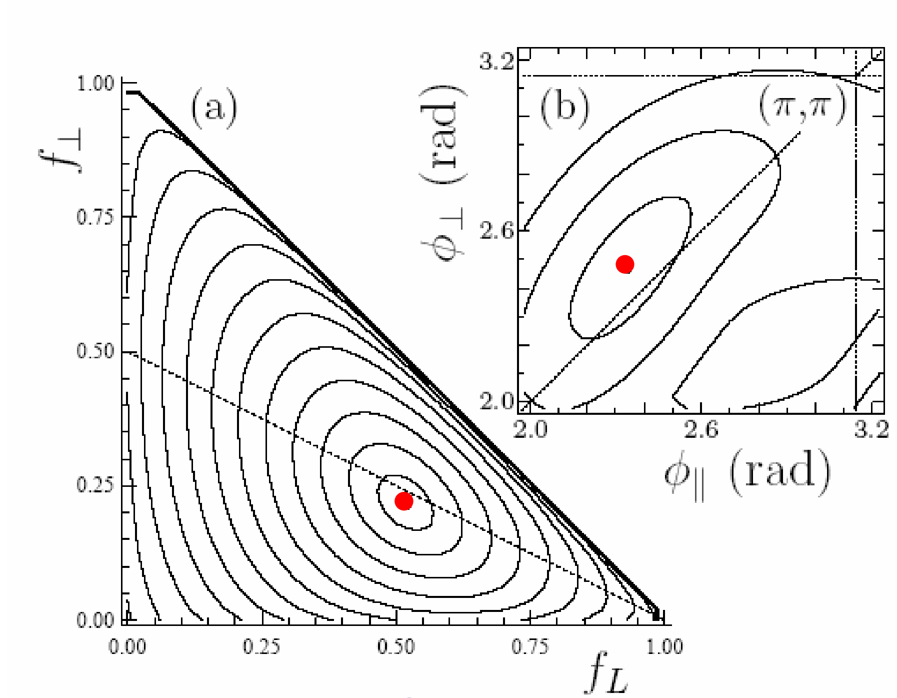
# $B \to \phi K^*$

PRL **93** (2004) 231804

- $227 \times 10^6$ B pairs
- Transversity analysis
- Obtain 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% |
| $f_\perp$ | $0.22 \pm 0.05 \pm 0.02$ | |

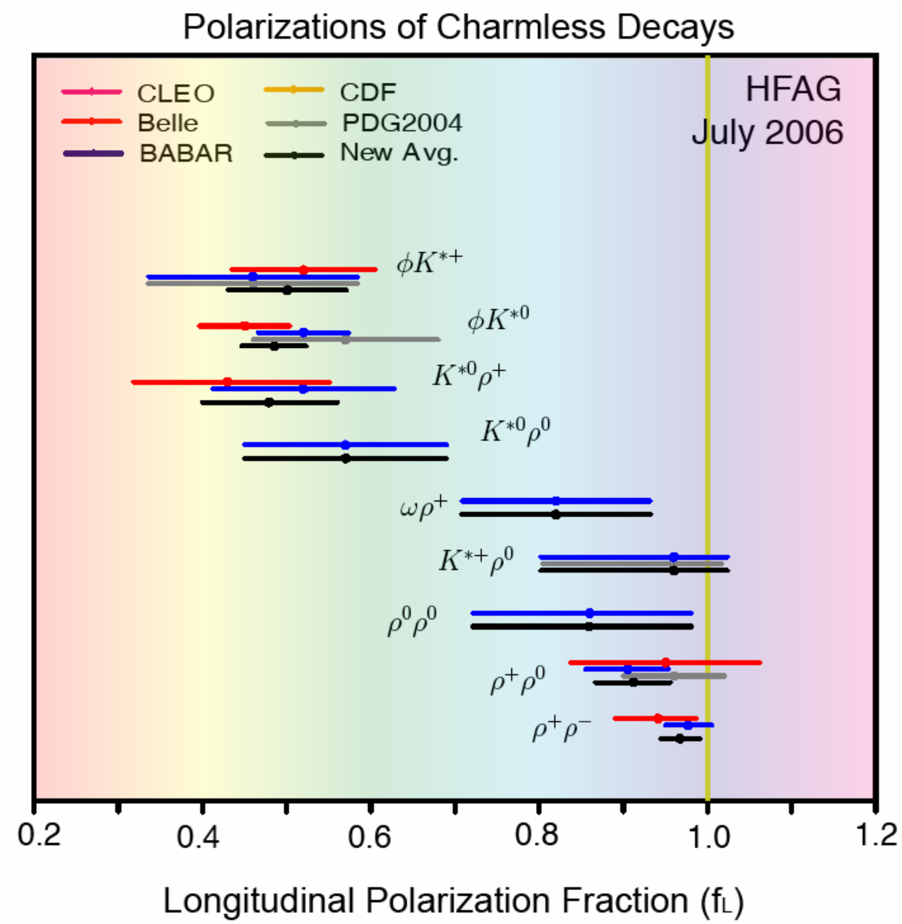



1 $\sigma$ contours
● central value

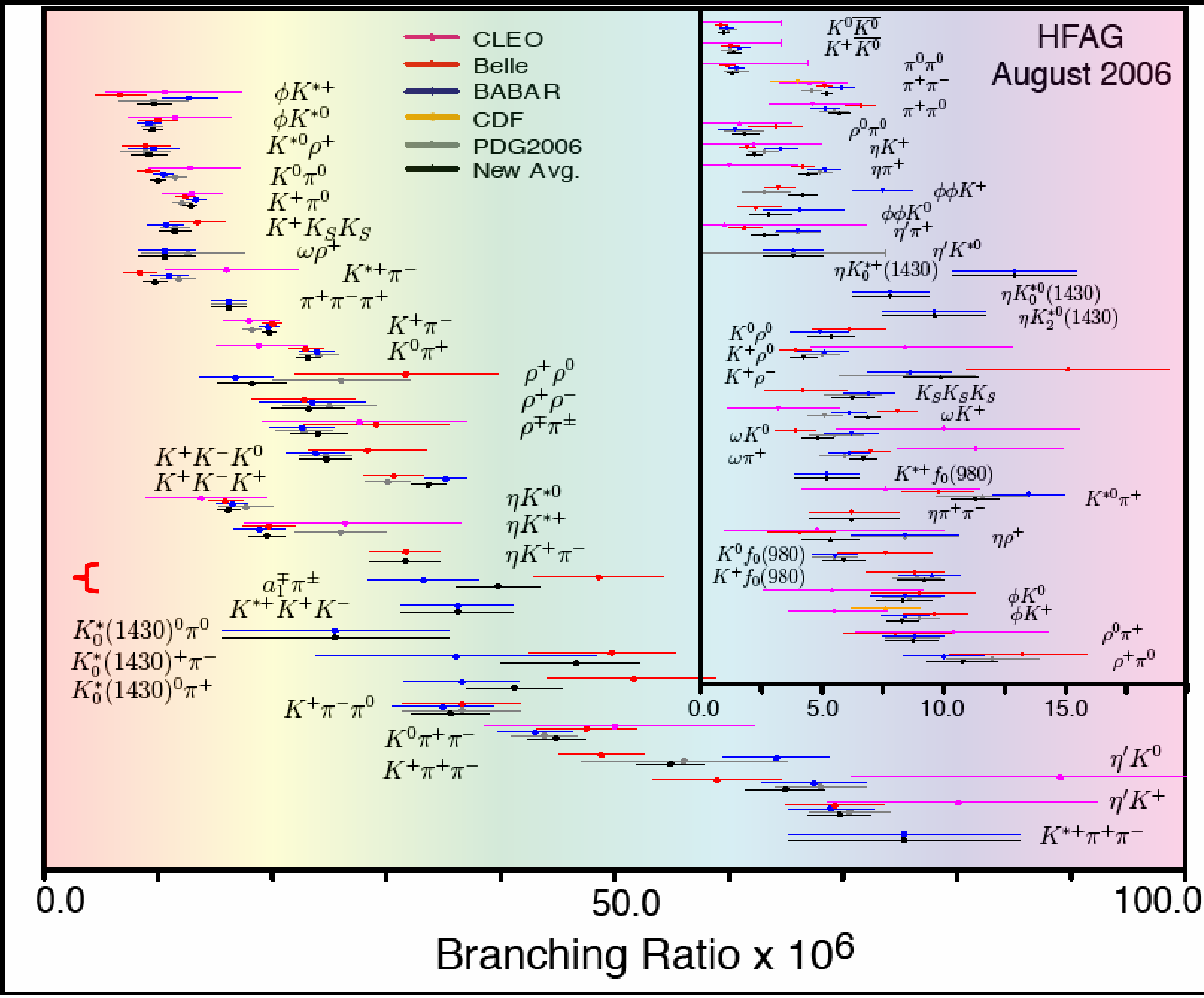
# Overview of $f_L$ in B→VV decays

- Some decays follow naive expectations with large $f_L$.
- Some dont!
  - $\phi K^*$
  - some of the $\rho K^*$ modes
- Important to finish building the picture:
  - What is $f_L$ for other B→VV modes?
  - What is $f_L$ for AV modes?
    - Searched for $a_1\rho$.
  - What additional contributions can explain this pattern?
- Can use $K^{*0}\rho^+$ obtain model dependent constraints on $\alpha$.
- Also have performed searches for other VV final states (e.g. $\omega\omega$ etc).




$K^*\rho$ hep-ex/0607057
$\phi K^*$ PRL **93** (2004) 231804
$a_1\rho$ PRD **74** (2006) 031104
$\rho\rho$ hep-ex/0607098, 0607097, 0607092
$\omega X$ PRD **74** (2006) 051102

# B→PP,PV, PA.



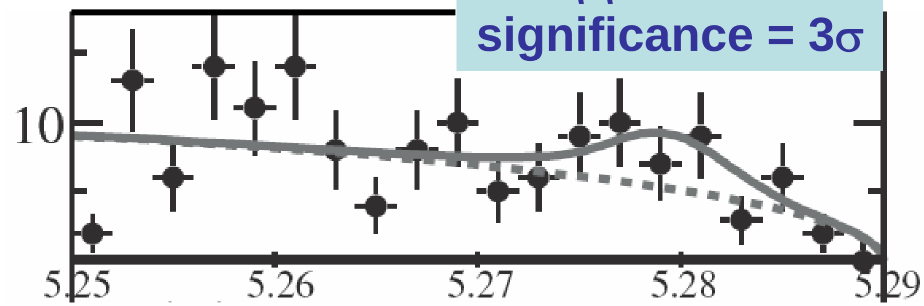
CLEO
Belle
BABAR
CDF
PDG2006
New Avg.
HFAG
August 2006
$\phi K^{*+}$
$\phi K^{*0}$
$K^{*0}\rho^+$
$K^0\pi^0$
$K^+\pi^0$
$K^+K_SK_S$
$\omega\rho^+$
$K^{*+}\pi^-$
$\pi^+\pi^-\pi^+$
$K^+\pi^-$
$K^0\pi^+$
$\rho^+\rho^0$
$\rho^+\rho^-$
$\rho^\mp\pi^\pm$
$K^+K^-K^0$
$K^+K^-K^+$
$\eta K^{*0}$
$\eta K^{*+}$
$\eta K^+\pi^-$
$a_1^\mp\pi^\pm$
$K^{*+}K^+K^-$
$K_0^*(1430)^0\pi^0$
$K_0^*(1430)^+\pi^-$
$K_0^*(1430)^0\pi^+$
$K^+\pi^-\pi^0$
$K^0\pi^+\pi^-$
$K^+\pi^+\pi^-$
$\eta' K^0$
$\eta' K^+$
$K^{*+}\pi^+\pi^-$
$K^0\overline{K^0}$
$K^+\overline{K^0}$
$\pi^0\pi^0$
$\pi^+\pi^-$
$\pi^+\pi^0$
$\rho^0\pi^0$
$\eta K^+$
$\eta\pi^+$
$\phi\phi K^+$
$\phi\phi K^0$
$\eta'\pi^+$
$\eta' K^{*0}$
$\eta K_0^{*+}(1430)$
$\eta K_0^{*0}(1430)$
$\eta K_2^{*0}(1430)$
$K^0\rho^0$
$K^+\rho^0$
$K^+\rho^-$
$K_SK_SK_S$
$\omega K^+$
$\omega K^0$
$\omega\pi^+$
$K^{*+}f_0(980)$
$K^{*0}\pi^+$
$\eta\pi^+\pi^-$
$\eta\rho^+$
$K^0 f_0(980)$
$K^+ f_0(980)$
$\phi K^0$
$\phi K^+$
$\rho^0\pi^+$
$\rho^+\pi^0$
0.0
5.0
10.0
15.0
0.0
50.0
100.0
Branching Ratio x $10^6$

# $B \to PP$

PRD **73** 071102 (2006)
PRD **74** 051106 (2006)

- Can use $B\to\eta\eta$, $\eta'\eta'$, $\eta'\eta$, $\eta'\pi^0$, $\eta\pi^0$ to bound $\Delta S = \sin2\beta - \sin2\beta_{eff}$ in the golden s-penguin modes $B\to\eta' K^0$ and $\phi K^0$.
- All final states have neutrals to reconstruct.

$$B(\eta\eta) = (1.1^{+0.5}_{-0.4} \pm 0.1)\times 10^{-6}$$
$$B(\eta'\eta') < 2.4\times 10^{-6}$$
$$B(\eta'\eta) < 1.7\times 10^{-6}$$
$$B(\eta\pi^0) < 1.3\times 10^{-6}$$
$$B(\eta'\pi^0) < 2.1\times 10^{-6}$$



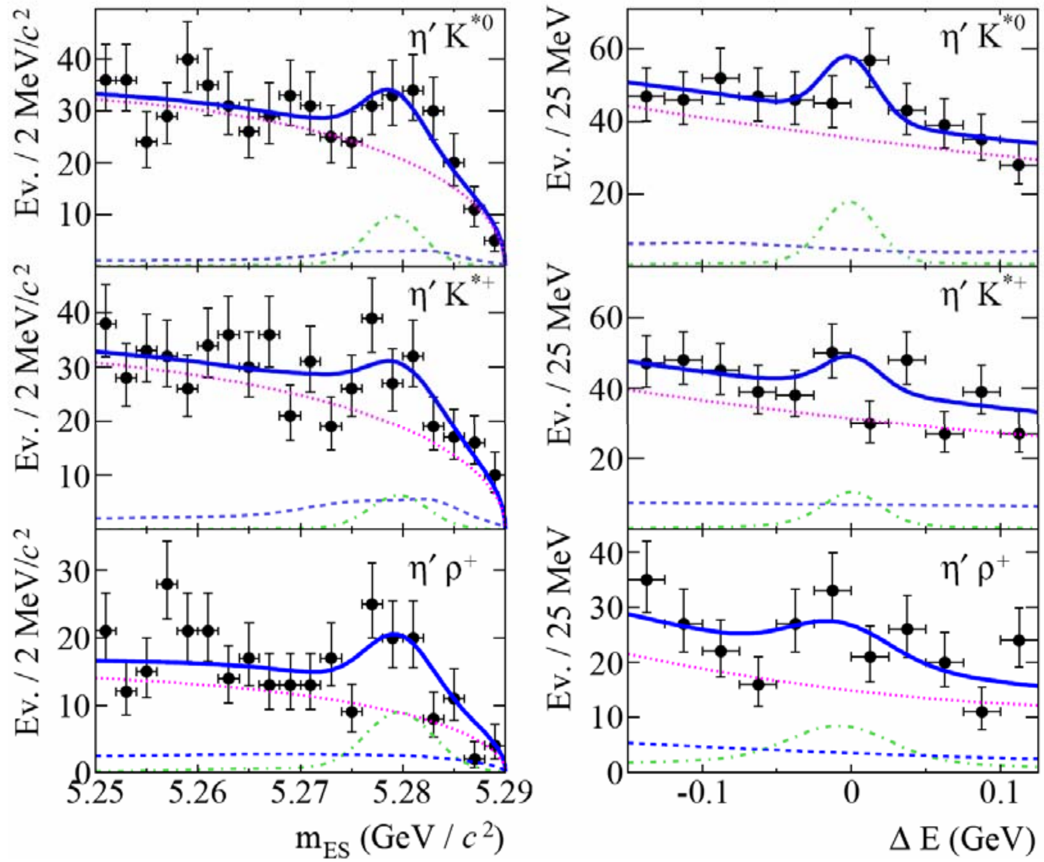

**$B\to\eta\eta$**
**significance = $3\sigma$**

$$|\Delta S(\eta' K^0)| < 0.15$$
$$|\Delta S(\phi K^0)| < 0.38$$

# $B \to \eta' V$

hep-ex/0607109

- Useful in understanding the decay $\eta' K^0$.
- both $\eta' K^*$ and $\eta' \rho$ provide additional tests of theoretical calculations.

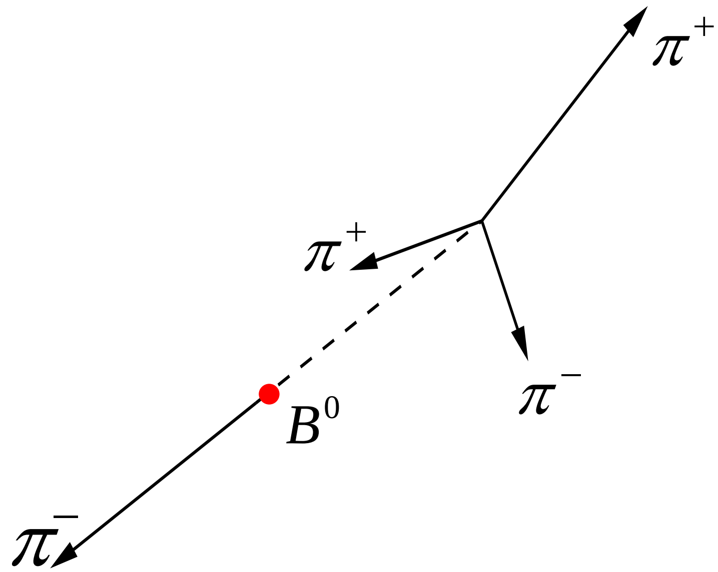



| Mode | $n$ (ev.) | Bias (ev.) | $\varepsilon(\%)$ | $\prod \mathcal{B}_i(\%)$ | $S(\sigma)$ | $\mathcal{B}(10^{-6})$ | $\mathcal{A}_{ch}$ |
|---|---|---|---|---|---|---|---|
| $B \to \eta' K^*$ | | | | | **5.6** | $4.1^{+1.0}_{-0.9} \pm 0.5$ | |
| $B^0 \to \eta' K^{*0}$ | | | | | **4.3** | $3.8 \pm 1.1 \pm 0.5$ | $-0.08 \pm 0.25 \pm 0.02$ |
| $B^+ \to \eta' K^{*+}$ | | | | | **3.6** | $4.9^{+1.9}_{-1.7} \pm 0.8 (< 7.9)$ | $0.30^{+0.33}_{-0.37} \pm 0.02$ |
| $B^0 \to \eta' \rho^0$ | $15^{+11}_{-8}$ | $+11.2 \pm 5.7$ | $22.8 \pm 1.4$ | 17.5 | **0.3** | $0.4^{+1.2+1.6}_{-0.9-0.6} (< 3.7)$ | |
| $B^0 \to \eta' f_0(980) (f_0 \to \pi^+ \pi^-)$ | $-3^{+6.0}_{-4.0}$ | $-3.8 \pm 2.0$ | $25.4 \pm 1.6$ | 17.5 | **0.2** | $0.1^{+0.6+0.9}_{-0.4-0.4} (< 1.5)$ | |
| $B^+ \to \eta' \rho^+$ | $57^{+16}_{-15}$ | $+11.5 \pm 5.8$ | $13.0 \pm 1.0$ | 17.5 | **3.2** | $8.7^{+3.1+2.3}_{-2.8-1.3} (< 14)$ | $-0.04 \pm 0.28 \pm 0.02$ |

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

- First seen in 2004
- Difficult analysis
  - $a_1$ 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 $a_2(1320)\pi$, $\pi(1300)\pi$.
- Interesting prospects for model dependent CKM constraints
  - Can be used to measure $\alpha$.
  - Not yet clear how effective a measurement will be.
    - need $a_1K$, $K_1\pi$ decays as well.

PRD **73** (2006) 057502



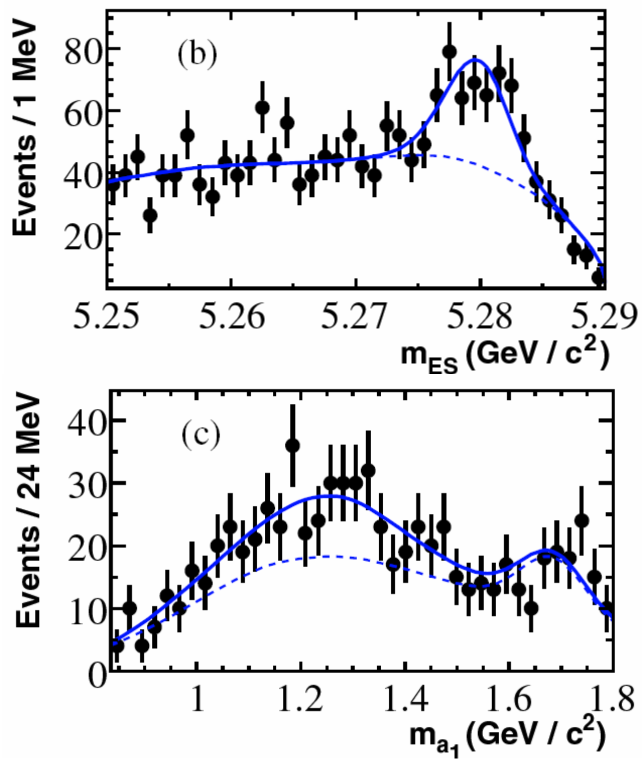

Angular correlations discriminate between signal and background

- BaBar uses the angle between the bachelor $\pi$ and the normal to the $a_1 \rightarrow 3\pi$ decay plane: (cosA).

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

PRL **71**, 051082 (2006)

- Fit $m_{ES}$, $\Delta E$, Fisher, $m_{a1}$, cosA.
- backgrounds from
  - $e^+e^- \to qq$
  - inclusive B background
  - $B^0 \to a_2^+(1320)\pi^-$
- $B^0 \to \pi^+(1300)\pi^-$ negligible
- Reconstruction efficiency:
  - $\varepsilon$=11.7%
- Dominant systematic errors:
  - PDF shape (6.2%)
  - $\rho^0\rho^0$, $\rho\pi\pi$, $4\pi$ background.
- Assume $BF(a_1 \to \rho^0\pi)$=0.5, and $B(a_1 \to \pi^+\pi^-\pi^+) = B(a_1 \to \pi^+\pi^0\pi^0)$.




$$BF = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$$

$$N_{signal} = 421 \pm 48 \text{ events}$$

218 million $B\overline{B}$ pairs

# Summary

- Lots of results on rare hadronic B decays.
  - The spectrum of branching fractions provides theorists reference points to tune calculations.
  - Observation of direct CPV was a triumph of B-physics and we need to continue this effort to see other signals in $B^0$ decays and find direct CP violation in $B^+$ decay.
  - $B \rightarrow VV$ decays have provided an interesting polarisation puzzle to solve.
  - Also obtain interesting model dependent constraints on UT.
  - Starting to produce interesting bounds on SM pollution in $\eta' K^0$ and $\phi K^0$ using PP decays.
- Much more not discussed ... Dalitz analyses, TDCPV, CPV in $\eta' K^0$ etc.
- Lots more work to do in this exciting area into the multi-$ab^{-1}$ realm!