Rare hadronic B decays

Lluïsa-Maria Mir

Lawrence Berkeley National Laboratory

BABAR Collaboration

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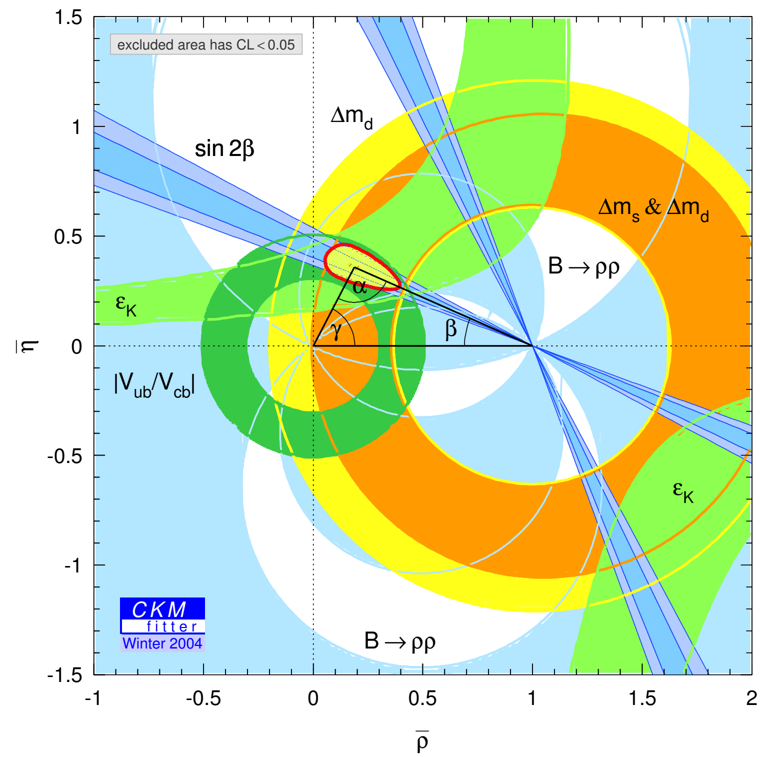
Outline

- Introduction
- Analysis method
- Charmless hadronic B decays
- Decays covered in the talk
  - B^0 decays to two isoscalars
  - $B \to KKK$
  - $B \to \phi K^*$
- Summary

Introduction

- Good agreement between theory (Standard Model) and experimental results up to now

- Look for deviations from S.M. in processes with small rates:
  - CKM-suppressed decays
  - Penguin-loop dominated decays



- What to do? Measure
  - Rates, kinematical distributions
  - Time dependent CP
  - Time integrated (direct) CP

- Disagreements
  - Improved theoretical calculations
  - New Physics

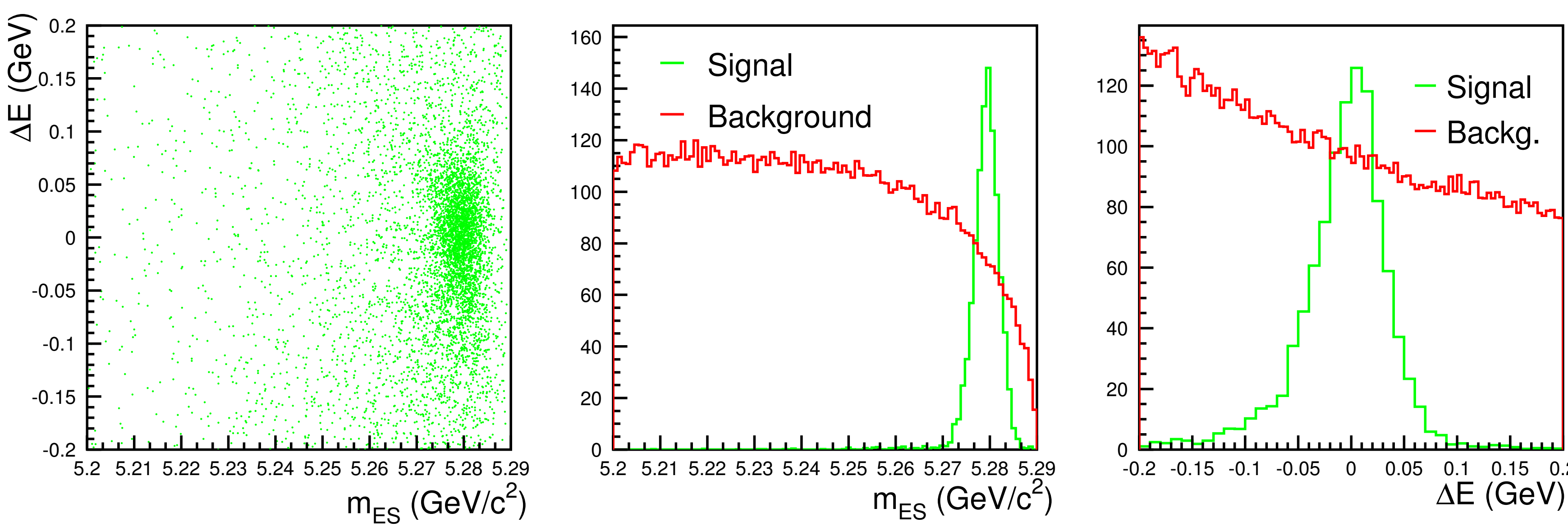
Analysis method

- For fully reconstructed events ($e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$) use E_{beam} to constrain mass and energy of the reconstructed B

For signal

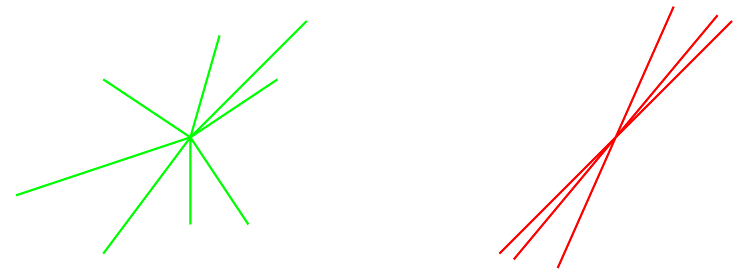
$$\Delta E = E^*_B - E^*_{beam} \qquad = 0$$

$$m_{ES} = \sqrt{E^{*2}_{beam} - |\overrightarrow{p_B}|^2} \qquad = m_B$$

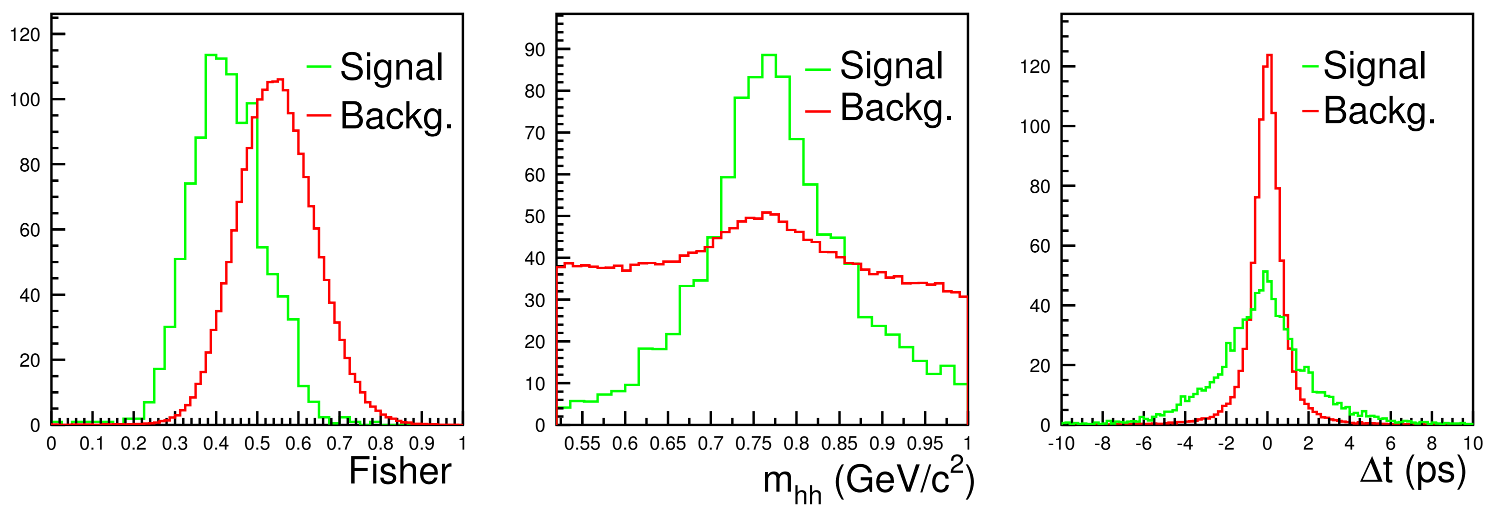


Analysis method

- Event shape:
  - Signal: $\Upsilon(4S) \rightarrow B\bar{B}$ almost at rest
  - Background: "jetty'
  - Use Fisher, Neural Net



- Resonance masses, decay angles, etc.
- Time-dependent measurements: B-flavour, $\Delta t = t_{B_1} - t_{B_2}$



Analysis method

- B^0_d time-dependent asymmetry:

$$f_\pm(\Delta t) = \frac{\exp\frac{-|\Delta t|}{\tau_{B^0}}}{4\,\tau_{B^0}}\left[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)\right]$$

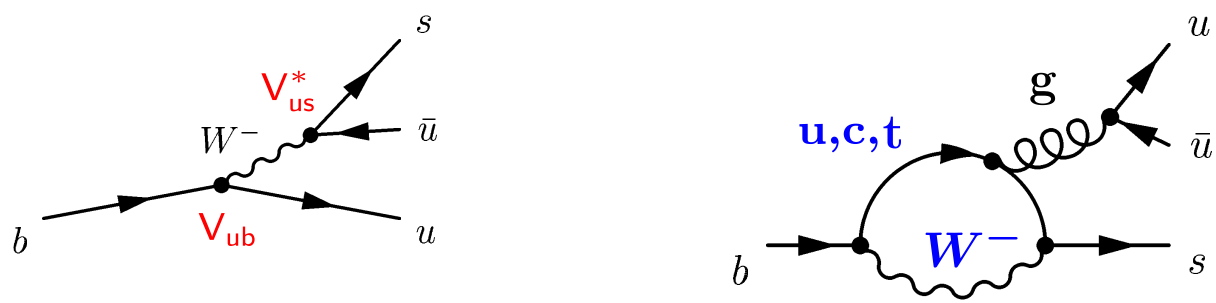
CPV in interference mixing / no-mixing — CPV in decay

  - S depends on CP-content and quark-level amplitudes of final state
  - $C = -\mathcal{A}_{CP} = 0$ (SM)

- Likelihood fit with m_{ES}, ΔE , $\mathcal{F}$, mass and $\cos\theta$ of resonances PDFs
- Add Δt and tagging for time-dependent measurements
- Likelihood fit with signal, continuum, BB background categories

Rare hadronic B decays

- CKM suppressed tree decays and significant penguin contributions



- Decays rare but abundant!
  - Scalar-Pseudoscalar (f_0 , a_0) (π , K)
  - Pseudoscalar-Pseudoscalar (π, K) (π, K)
  - Isoscalar (η , η' , ω , ϕ) (η , η' , ω , ϕ)
  - Pseudoscalar-Vector (π, K, η, η') (ϕ, ρ, ω, K^*)
  - Three-body (Combinations of π and K)
  - Vector-Vector ($\rho\rho$, ρK^* , ϕK^*)

Decay modes covered in this talk

- B^0 decays to two isoscalars

  $\longrightarrow$ Bound on the "tree pollution" on the $B \rightarrow \eta' K^0_S$ decay

- CP-violation in $B \rightarrow KKK$

  $\longrightarrow$ Disagreement in $\sin 2\beta$ between $b \rightarrow s$ penguin and charmonium modes?

- Full angular analysis in $B \rightarrow \phi K^*$

  $\longrightarrow$ A window to new physics?

$B^0 \to$ two isoscalars branching fractions

- Measure $(\eta,\, \eta',\, \omega,\, \phi)$ $(\eta,\, \eta',\, \omega,\, \phi)$ combinations except $\omega\omega$, $\omega\phi$
- Predictions
  - Flavour SU(3)
  - Factorization and specific $B \to$ light-meson form-factors
  - pQCD
- Precise experimental measurements to test accuracy of predictions
- Time evolution of $B^0 \to \phi K^0_S$ and $B^0 \to \eta' K^0_S$:

  $S = \sin 2\beta$ if decays dominated by one single penguin amplitude (SM)

  $\Delta S = (S - \sin 2\beta) \leq 2|\xi_{\eta' K_S}|$
- Grossman-Ligeti-Nir-Quinn bound:

$$|\xi_{\eta' K_S}| < \left|\frac{V_{us}}{V_{ud}}\right| \left[0.59\sqrt{\frac{\mathcal{B}(\eta'\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.33\sqrt{\frac{\mathcal{B}(\eta\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.14\sqrt{\frac{\mathcal{B}(\pi^0\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.53\sqrt{\frac{\mathcal{B}(\eta'\eta')}{\mathcal{B}(\eta' K^0)}} + 0.38\sqrt{\frac{\mathcal{B}(\eta\eta)}{\mathcal{B}(\eta' K^0)}} + 0.96\sqrt{\frac{\mathcal{B}(\eta\eta')}{\mathcal{B}(\eta' K^0)}}\right]$$

$B^0 \to$ two isoscalars branching fractions

- Recall (BaBar) $\begin{cases} S_{\text{charmonium}} = 0.741 \pm 0.067 \pm 0.032 \ (82\ \text{fb}^{-1}) \\ S_{\eta' K_S} = 0.02 \pm 0.34 \pm 0.03 \ (82\ \text{fb}^{-1}) \\ S_{\phi K_S} = 0.47 \pm 0.34^{+0.08}_{-0.06} \ (108\ \text{fb}^{-1}) \end{cases}$

- Results with 82 M $B\bar{B}$:

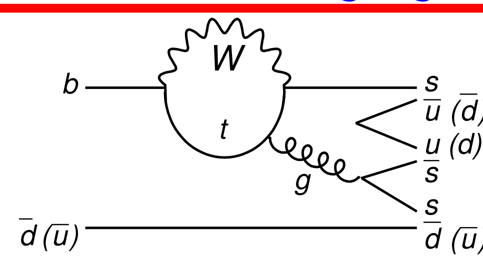
Mode	$S(\sigma)$	$\mathcal{B}(10^{-6})$	UL (10^{-6})	UL (10^{-6}) (CLEO)
$\eta\eta$	0.0	$-0.9^{+1.6}_{-1.4} \pm 0.7$	2.8	18
$\eta\eta'$	0.3	$0.6^{+2.1}_{-1.7} \pm 1.1$	4.6	27
$\eta'\eta'$	0.4	$1.7^{+4.8}_{-3.7} \pm 0.6$	10	47
$\eta\omega$	4.3	$4.0^{+1.3}_{-1.2} \pm 0.4$	6.2	12
$\eta'\omega$	0.0	$-0.2^{+1.3}_{-0.9} \pm 0.4$	2.8	60
$\eta\phi$	0.0	$-1.4^{+0.7}_{-0.4} \pm 0.2$	1.0	9
$\eta'\phi$	0.8	$1.5^{+1.8}_{-1.5} \pm 0.4$	4.5	31
$\phi\phi$	0.3	$0.3^{+0.7}_{-0.4} \pm 0.1$	1.5	12

BABAR, *submitted to Phys. Rev. Lett. hep-ex/0403046*

- GLNQ bound on $|\xi_{\eta' K_S}|$ improved from 0.36 to 0.17

$\mathcal{B}$ and CPV in $B^0 \to K^+K^-K^0_S$ and $B^+ \to K^+K^0_SK^0_S$

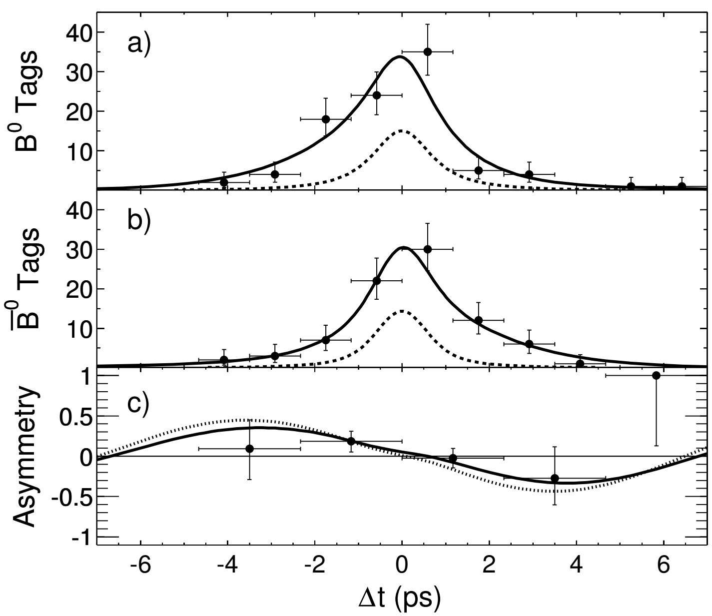
- Dominated by $b \to s\bar{s}s$ gluonic penguin

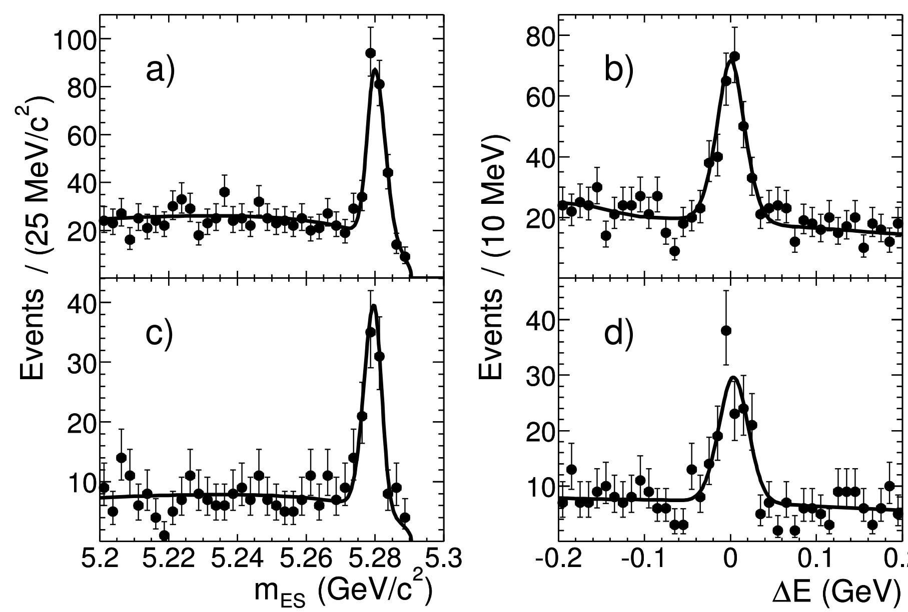


- 2.7 σ discrepancy BaBar/Belle in $S_{\phi K^0_S}$
- $B^0 \to K^+K^-K^0_S$ integrated over all phase-space:
  - Pro: More precise than $B^0 \to \phi K^0_S$ (more statistics)
  - Con: CP-content of final state unknown *a priori*
- Measure
  - $\mathcal{B}(B^0 \to K^+K^-K^0_S)$ and $\mathcal{B}(B^+ \to K^+K^0_SK^0_S)$
  - $B^+ \to K^+K^0_SK^0_S$ charge asymmetry
  - CP-content of $B^0 \to K^+K^-K^0_S$
  - $B^0 \to K^+K^-K^0_S$ time-dependent asymmetry

- Get $\mathcal{B}$ with a likelihood fit using m_{ES}, ΔE and $\mathcal{F}$
- $B^+ \to K^+K^0_SK^0_S$ charge asymmetry: $\mathcal{A}_{CP} = \frac{\Gamma_{K^-K^0_SK^0_S} - \Gamma_{K^+K^0_SK^0_S}}{\Gamma_{K^-K^0_SK^0_S} + \Gamma_{K^+K^0_SK^0_S}}$
- $B^0 \to K^+K^-K^0_S$ CP-content: $f_{even} = \frac{N_{CP}}{N} = 2\frac{\Gamma(B^+ \to K^+K^0_SK^0_S)}{\Gamma(B^0 \to K^+K^-K^0)}$
- Use Δt for CP(t)-asymmetry fit

from isospin symmetry





- Results with 124 M $B\bar{B}$:

CP: This sample has $B^0 \to \phi K^0_S$ removed: $|m_{K^+K^-} - m_\phi| > 15$ MeV/c^2

	$(K^+K^-K^0)^{CP}$	$(K^+K^-K^0)^{all}$	$K^+K^0_SK^0_S$
$\mathcal{B}\,(10^{-6})$	$20.2 \pm 1.9 \pm 1.4$	$23.8 \pm 2.0 \pm 1.6$	$10.7 \pm 1.2 \pm 1.0$
f_{even}	$0.98 \pm 0.15 \pm 0.04$	$0.83 \pm 0.12 \pm 0.03$	–
S	$-0.56 \pm 0.25 \pm 0.04$	-	-0.16 ± 0.35
C	$-0.10 \pm 0.19 \pm 0.10$	-	-0.08 ± 0.22
$\mathcal{A}_{CP}$	-	-	$-0.04 \pm 0.11 \pm 0.02$

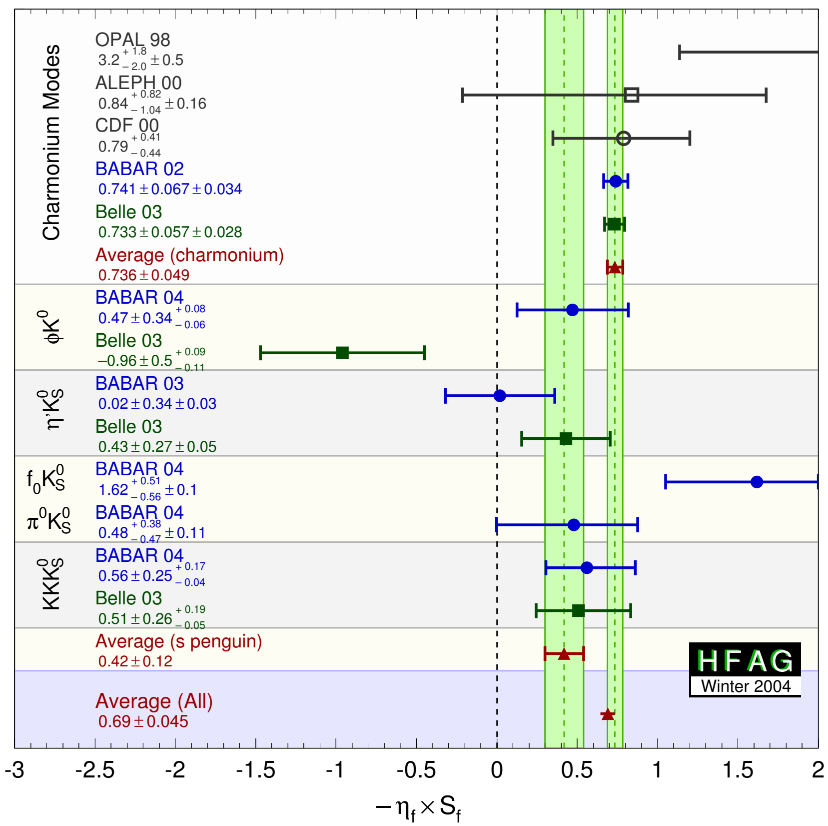
- $C = 0 \to S = -\sin 2\beta = 0.57 \pm 0.26 \pm 0.04^{+0.17}_{-0}$

CP-content

BABAR, *sub. to Phys. Rev. Lett. hep-ex/0406005*

$\mathcal{B}$ and CPV in $B^0 \to K^+K^-K^0_S$ and $B^+ \to K^+K^0_SK^0_S$

$-\eta_f \times S_f$	ϕK^0	KKK^0_S
BABAR	$0.47 \pm 0.34^{+0.08}_{-0.06}$	$0.56 \pm 0.25 \pm 0.04^{+0.17}_{-0.00}$
Belle	$-0.96 \pm 0.50^{+0.09}_{-0.11}$	$0.51 \pm 0.26 \pm 0.05^{+0.18}_{-0.00}$
Average	0.02 ± 0.29 (0.28 stat only)	$0.54 \pm 0.18^{+0.17}_{-0.00}$ (0.18 stat only)



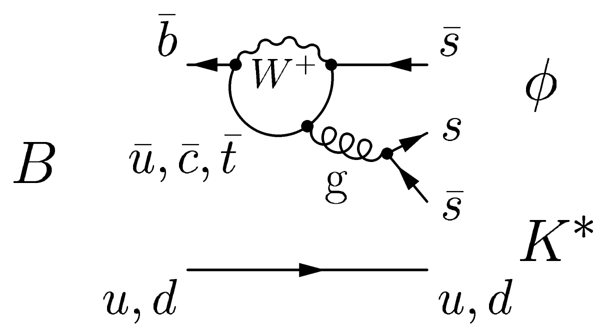
Disagreement between

b → s penguin dominated and

charmonium modes of $\sim 2.4\ \sigma$

Full angular analysis B $\to \phi$K*

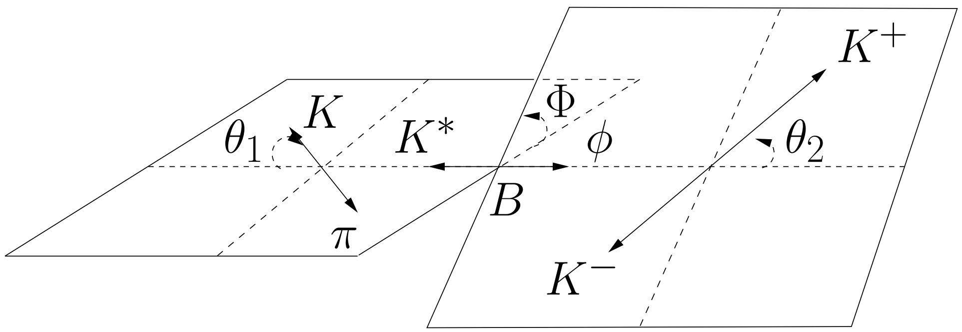
- Decays to two vector mesons reveal fundamental dynamics
  - Successes: $\sin 2\alpha$ from B $\to \rho\rho$
  - Surprises: Longitudinal polarization in B $\to \phi$K* smaller than SM prediction
- Hint of new physics?
  - B $\to \phi$K* is a pure penguin loop



  - Perform full angular analysis

Full angular analysis $B \to \phi K^*$

- Angular distribution of $B \to VV$ unknown *a priori*



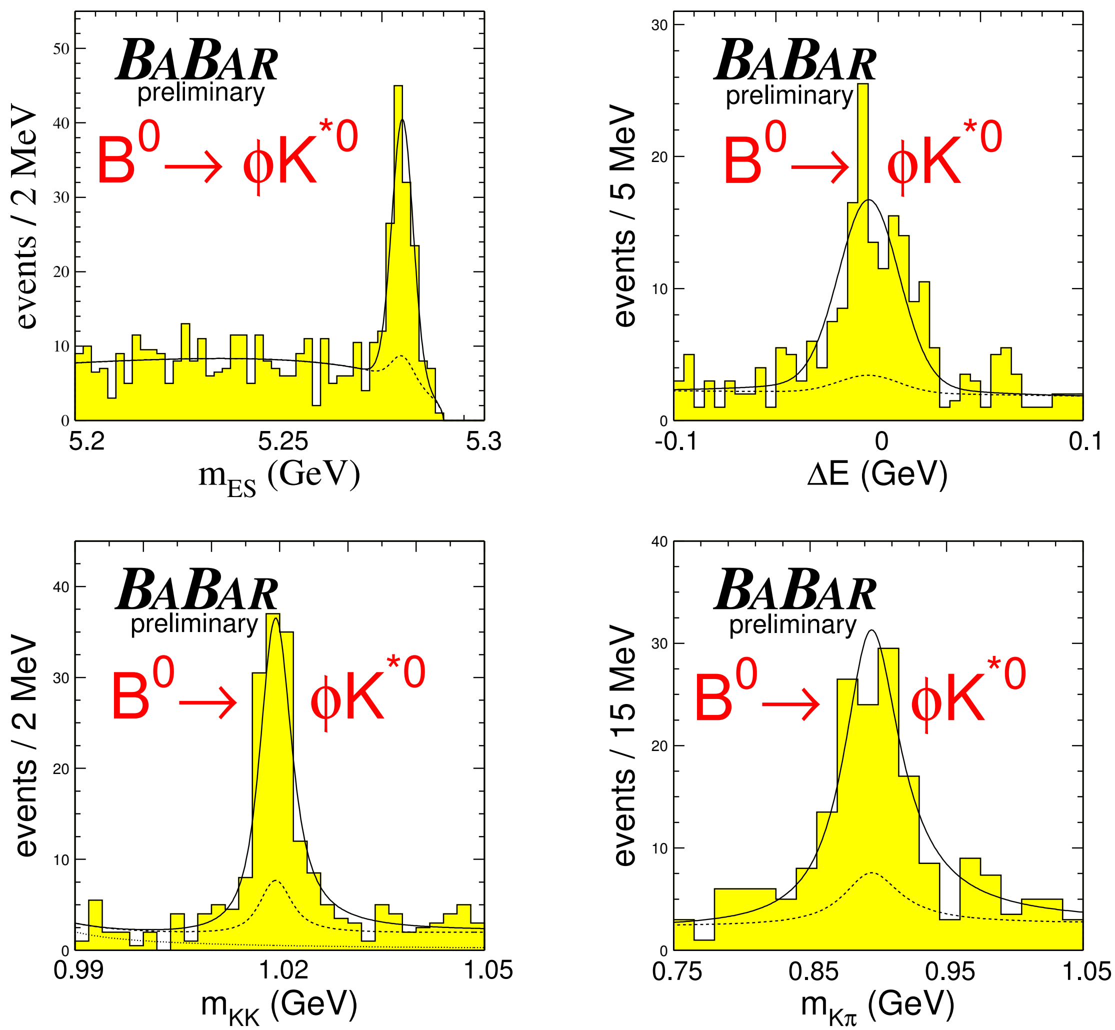
$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} = \frac{9}{8\pi}\frac{1}{|A_0|^2+|A_{+1}|^2+|A_{-1}|^2}\times$$
$$\Big\{\frac{1}{4}\sin^2\theta_1\sin^2\theta_2\left(|A_{+1}|^2+|A_{-1}|^2\right)+\cos^2\theta_1\cos^2\theta_2|A_0|^2+$$
$$\frac{1}{2}\sin^2\theta_1\sin^2\theta_2\left[\cos 2\Phi \mathrm{Re}(A_{+1}A^*_{-1})-\sin 2\Phi \mathrm{Im}(A_{+1}A^*_{-1})\right]-$$
$$\frac{1}{4}\sin 2\theta_1\sin 2\theta_2\left[\cos\Phi \mathrm{Re}\left(A_{+1}A_0^*+A_{-1}A_0^*\right)-\sin\Phi \mathrm{Im}\left(A_{+1}A_0^*-A_{-1}A_0^*\right)\right]\Big\}$$

$A_{\parallel} = \frac{A_{+1}+A_{-1}}{\sqrt{2}}$, CP-even

$A_{\perp} = \frac{A_{+1}-A_{-1}}{\sqrt{2}}$, CP-odd

Full angular analysis $B \to \phi K^*$

- With 124 million $B\bar{B}$: $n_{sig} = 129 \pm 14 \pm 9$



Full angular analysis $B \to \phi K^*$

n_{sig}	$129 \pm 14 \pm 9$
f_L	$0.52 \pm 0.07 \pm 0.02$
$f_\perp$	$0.27 \pm 0.07 \pm 0.02$
$\phi_\parallel$	$2.63^{+0.24}_{-0.23} \pm 0.04$
$\phi_\perp$	$2.71^{+0.22}_{-0.24} \pm 0.03$
$\mathcal{A}_{CP}$	$-0.12 \pm 0.10 \pm 0.03$
$\mathcal{A}^0_{CP}$	$-0.02 \pm 0.12 \pm 0.01$
$\mathcal{A}^\perp_{CP}$	$-0.10^{+0.25}_{-0.27} \pm 0.04$
$\Delta\phi_\parallel$	$0.38^{+0.23}_{-0.24} \pm 0.04$
$\Delta\phi_\perp$	$0.30^{+0.24}_{-0.22} \pm 0.03$
$\mathcal{A}^\parallel_T$	$+0.02 \pm 0.05 \pm 0.01$
$\mathcal{A}^0_T$	$+0.11 \pm 0.07 \pm 0.01$

$\mathcal{A}_T = (q_1 - q_2) \cdot p_1 \times p_2$

n_{sig}: total number of events

$f_l = \frac{|A_0|^2}{\sum_m |A_m|^2}$: longitudinal fraction

$f_\perp = \frac{|A_\perp|^2}{\sum_m |A_m|^2}$: transverse CP-odd fraction

$\phi_\parallel = \arg(A_\parallel) - \arg(A_0)$ (CP-even)

$\phi_\perp = \arg(A_\perp) - \arg(A_0)$: (CP-odd)

$\mathcal{A}_{CP} = \frac{n^+_{sig} - n^-_{sig}}{n^+_{sig} + n^-_{sig}}$: direct CP-asymmetry

$\mathcal{A}^0_{CP} = \frac{f^+_L - f^-_L}{f^+_L + f^-_L}$: longitudinal asymmetry

$\mathcal{A}^\perp_{CP} = \frac{f^+_\perp - f^-_\perp}{f^+_\perp + f^-_\perp}$ (CP-odd)

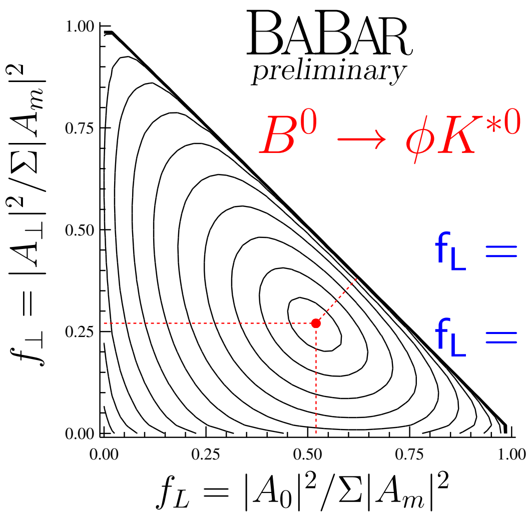
$\Delta\phi_\parallel = \frac{1}{2}(\phi^+_\parallel - \phi^-_\parallel)$ (CP-even)

$\Delta\phi_\perp = \frac{1}{2}(\phi^+_\perp - \phi^-_\perp)$ (CP-odd)

$$\mathcal{A}^{\parallel,0}_T = \frac{1}{2}\left(\frac{\mathrm{Im}(A^+_\perp A^{+*}_{\parallel,0})}{\sum |A^+_m|^2} + \frac{\mathrm{Im}(A^-_\perp A^{-*}_{\parallel,0})}{\sum |A^-_m|^2}\right)$$

$f_L = 1$ up to $\mathcal{O}(1/M_B^2)$ *M. Suzuki Phys. Rev. D* **66** *054018 (2002)*

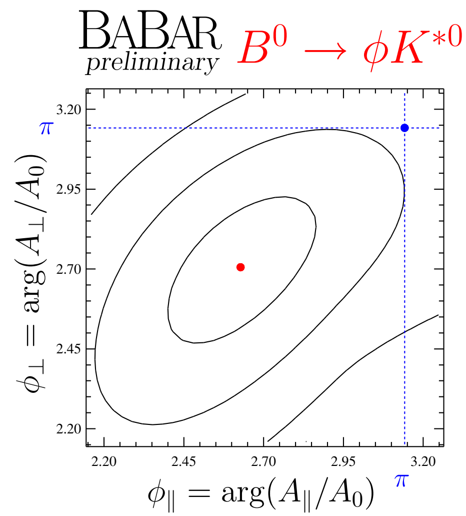
Full angular analysis $B \to \phi K^*$



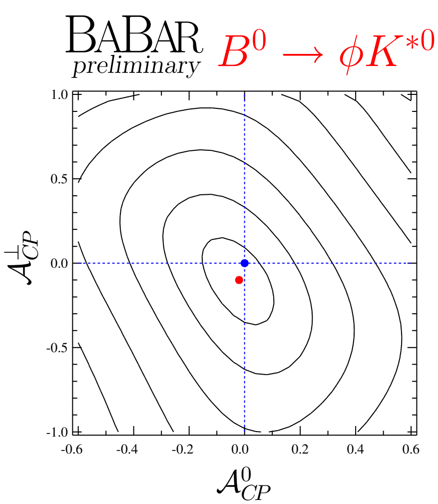
Puzzle:

$f_L = 0.98$ ($B \to \rho\rho$)

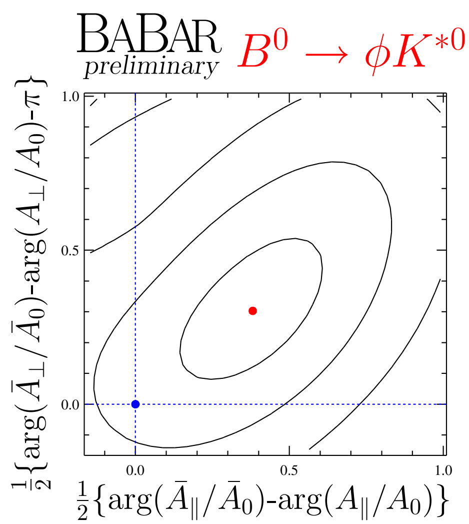
$f_L = 0.50$ ($B \to \phi K^*$)



Weak evidence for FSI (2.3 σ)



No significant direct CP violation



Triple-product asymmetry (1.7 σ)

Summary

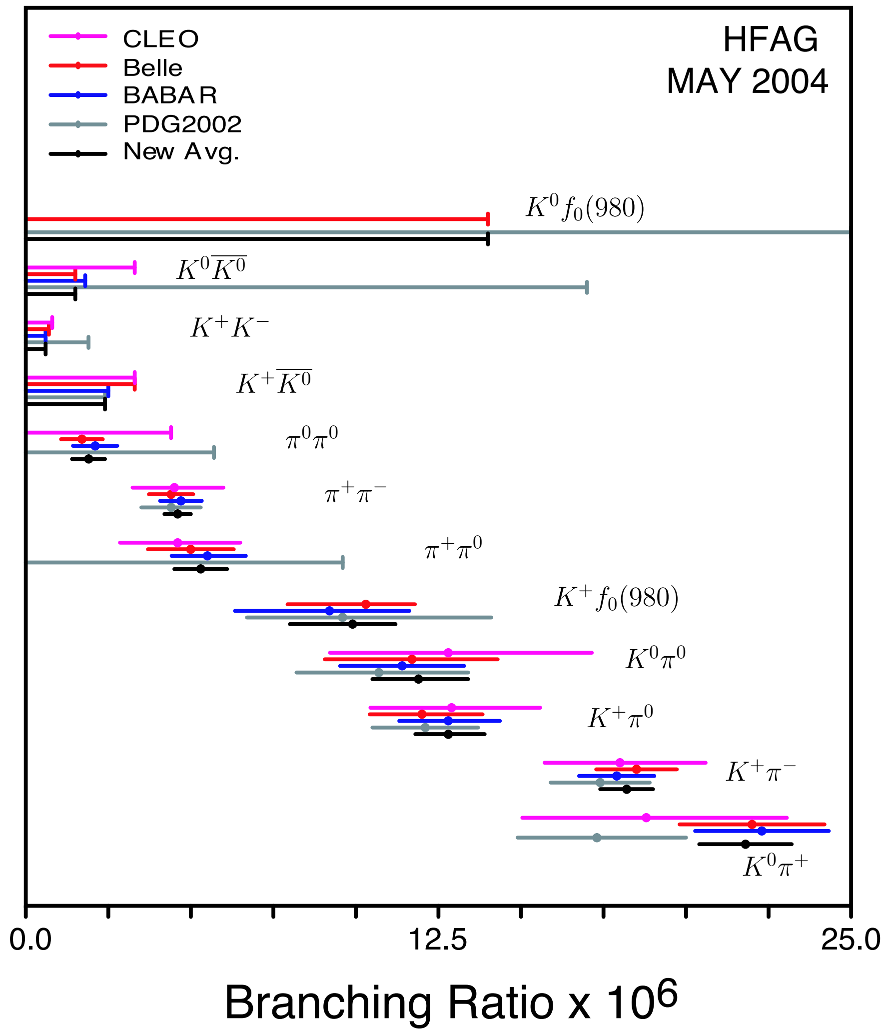
- B-factories provide huge amount of B mesons
  - Many rare-decay first-time observations
  - B.R. measurements more precise
  - Limits on B.R. tightened
- Rare decays are a window for new physics

  $\longrightarrow f_L(\phi K^{*0}) = 0.52 \pm 0.07 \pm 0.02$ (S.M. predicts 1)
- No violation of SM found yet

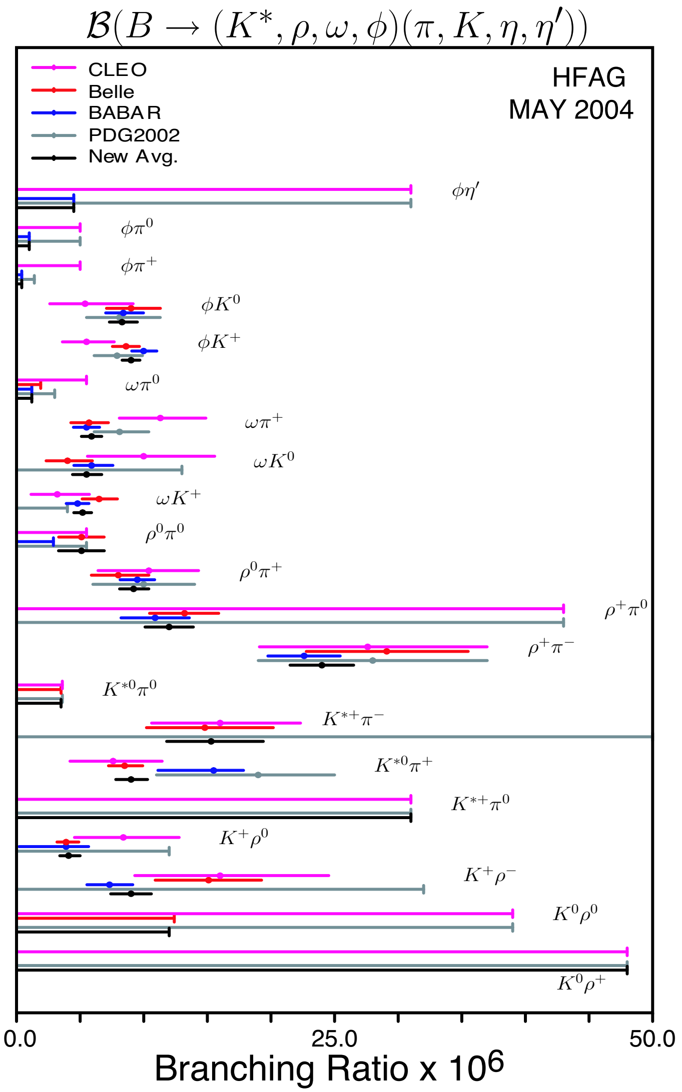
  $\longrightarrow$ Good agreement *BABAR*/Belle in S_{KKK}
- More data to come

Two-body involving pions and kaons

$\mathcal{B}(B \to K\pi,\ \pi\pi,\ KK,\ Kf_0)$

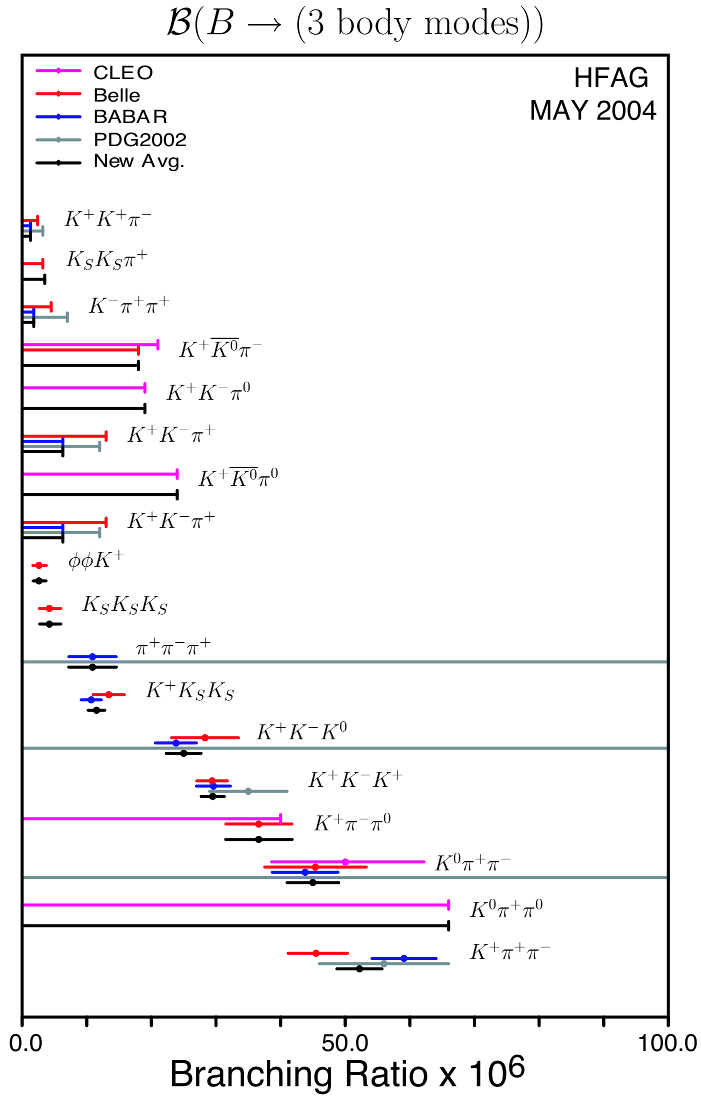


$B \to PV$

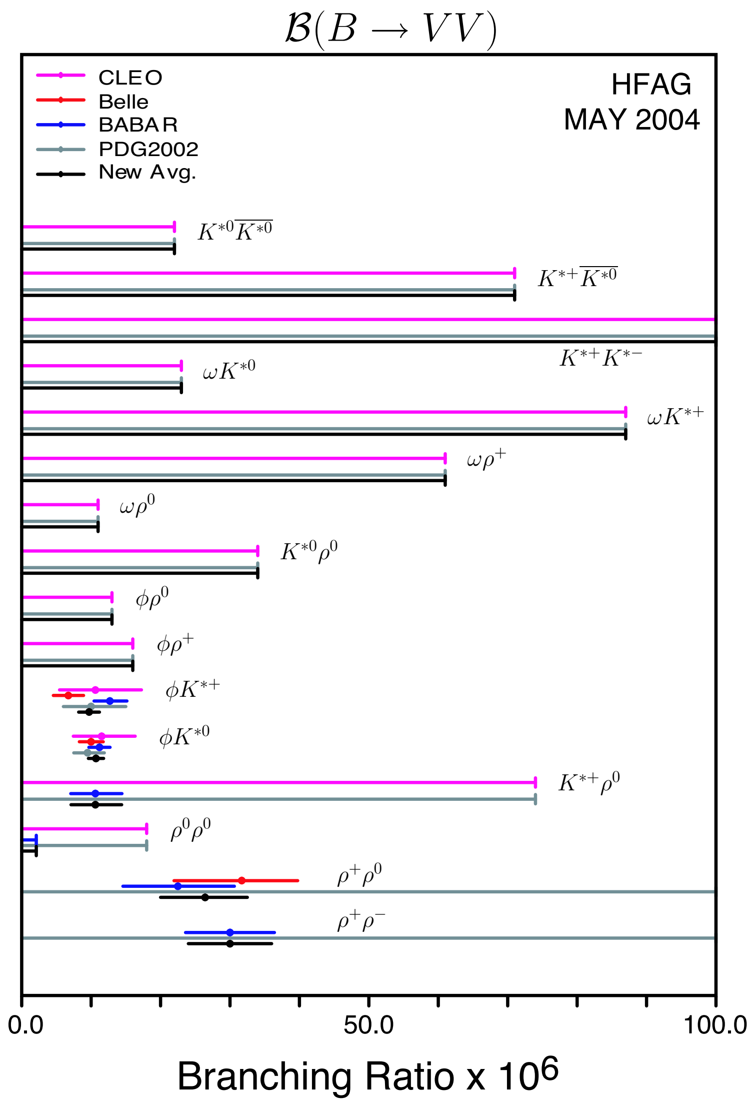


$\mathcal{B}(B \to (K^*, \rho, \omega, \phi)(\pi, K, \eta, \eta'))$
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
MAY 2004
$\phi\eta'$
$\phi\pi^0$
$\phi\pi^+$
ϕK^0
ϕK^+
$\omega\pi^0$
$\omega\pi^+$
ωK^0
ωK^+
$\rho^0\pi^0$
$\rho^0\pi^+$
$\rho^+\pi^0$
$\rho^+\pi^-$
$K^{*0}\pi^0$
$K^{*+}\pi^-$
$K^{*0}\pi^+$
$K^{*+}\pi^0$
$K^+\rho^0$
$K^+\rho^-$
$K^0\rho^0$
$K^0\rho^+$
0.0
25.0
50.0
Branching Ratio x 10^6

Three-body decays



B → VV



$\mathcal{B}(B \to VV)$
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
MAY 2004
$K^{*0}\overline{K^{*0}}$
$K^{*+}\overline{K^{*0}}$
$K^{*+}K^{*-}$
ωK^{*0}
ωK^{*+}
$\omega\rho^{+}$
$\omega\rho^{0}$
$K^{*0}\rho^{0}$
$\phi\rho^{0}$
$\phi\rho^{+}$
ϕK^{*+}
ϕK^{*0}
$K^{*+}\rho^{0}$
$\rho^{0}\rho^{0}$
$\rho^{+}\rho^{0}$
$\rho^{+}\rho^{-}$
0.0
50.0
100.0
Branching Ratio x 10^6