Probing QCD With Rare Charmless *B* Decays

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Outline

Introduction

- The B factories
- Rare charmless B decays

Constraining $\Delta S_f = S_f - \sin 2\beta$

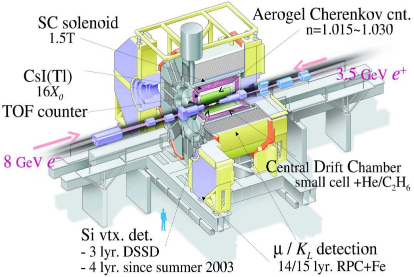
- $\sin 2\beta$ in $b \to q\bar{q}s$ penguins
- Constraining SM pollution

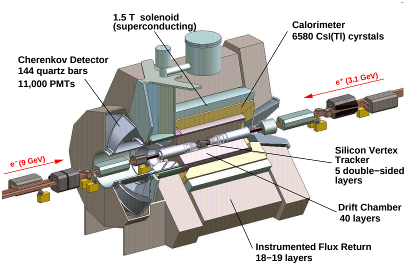
BF, CP And $\mathcal{A}_{ch}$

- Measurements related to α/ϕ_2
- Other charmless B decays

All results preliminary unless journal reference given

The B factories: BELLE and $B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.1em R}$





$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

Asymmetric beam energies

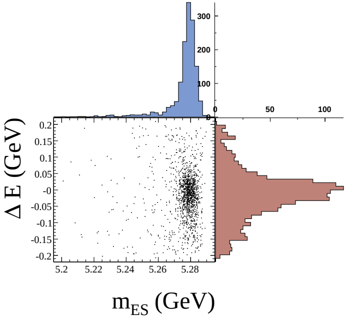
- KEK-B: $8\,\mathrm{GeV}\ e^- \times 3.5\,\mathrm{GeV}\ e^+$
- $\mathcal{L}_{\mathrm{int}} \approx 560\,\mathrm{fb}^{-1}$ so far

- PEP-II: $9\,\mathrm{GeV}\ e^- \times 3.1\,\mathrm{GeV}\ e^+$
- $\mathcal{L}_{\mathrm{int}} \approx 330\,\mathrm{fb}^{-1}$ so far

Detecting a signal

- Largest backgrounds from $e^+e^- \to q\bar{q}$
- Kinematic variables:

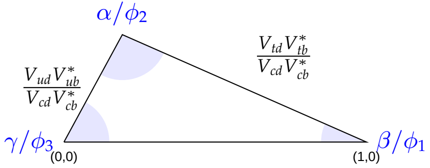
$$\Delta E = E_B^* - E_{\text{beam}}^* \qquad m_{\text{ES}} = \sqrt{E_{\text{beam}}^* - p_B^{*2}}$$



- Event shape for background suppression:

Measuring time-dependent CP asymmetries

Unitarity triangle



Unitarity of the CKM matrix:
$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0$

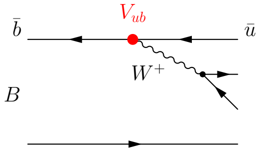
Time-dependent CP asymmetry in B^0-$\bar{B}^0$ mixing

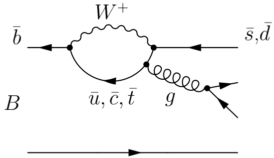
$$\mathcal{A}_{cp}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} = S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t$$

For example $B^0 \to J/\psi\, K_S^0$ ($b \to c\bar{c}s$): $S_{J/\psi\, K_S^0} = \sin 2\beta$, $C_{J/\psi\, K_S^0} = 0$

Rare charmless B decays

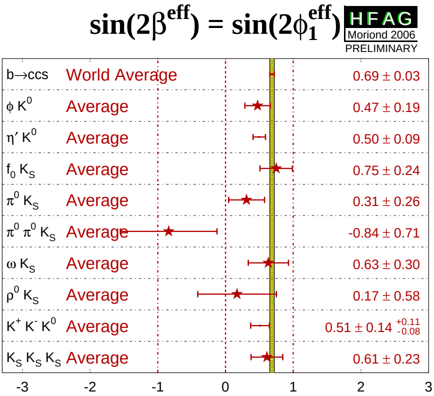
- Contributing amplitudes: CKM suppressed trees, penguins, ...
- Can be used to study
  - Interfering SM amplitudes
  - CP violation
  - Effects of new particles in loops (New Physics?)
- Constrain theoretical models





Constraining $\Delta S_f = S_f - \sin 2\beta$

$\sin 2\beta$ from $b \to q\bar{q}s$ penguins



- New physics can show up in $b \to s$ penguins
- Sub-dominant diagrams introduce additional (weak) phases
- What is SM expectation for $\Delta S_f = S_f - \sin 2\beta$?
- Models prefer $\Delta S_f > 0$
  Beneke, Phys. Lett. B **620**, 143;
  Cheng *et al.*, Phys. Rev. D **72**, 094003
- Measuring related modes helps pin down expected deviations

Constraining SM pollution in $B^0 \to \phi K^0$

- Constrain sub-dominant (V_{ub}) contributions to $B^0 \to \phi K_S^0$ via SU(3) flavour relations Grossman *et al.*, Phys. Rev. D **68**, 015004 (2003)

$$\begin{aligned}\Delta S_{\phi K_S^0} \quad \propto \quad & \frac{1}{4}\mathcal{B}(\rho^0\pi^0) - \frac{1}{4}\mathcal{B}(\omega\pi^0) + \frac{1}{2}\sqrt{\frac{3}{2}}\left[c\mathcal{B}(\phi\eta) - s\mathcal{B}(\phi\eta')\right] \\ & + \frac{\sqrt{3}}{4}\left[c\mathcal{B}(\omega\eta) - s\mathcal{B}(\omega\eta')\right] - \frac{\sqrt{3}}{4}\left[c\mathcal{B}(\rho^0\eta) - s\mathcal{B}(\rho^0\eta')\right] \\ & + \frac{1}{2}\left[\mathcal{B}(\bar{K}^{*0}K^0) - \mathcal{B}(K^{*0}\bar{K}^0)\right] - \frac{1}{2\sqrt{2}}\mathcal{B}(\phi\pi^0)\end{aligned}$$

Search for $B^0 \to K^{*0}K_s^0$

BABAR preliminary, 208 fb^{-1}

Upper limit at 90% C.L.:

$$\mathcal{B}(\bar{K}^{*0}K^0) + \mathcal{B}(K^{*0}\bar{K}^0) < 1.9 \times 10^{-6}$$

SU(3) upper bound $\Delta S_{\phi K^0} < 0.43$

Improved $\mathcal{B}(\phi\pi^0)$

BABAR preliminary, 211 fb^{-1}

Upper limits at 90% C.L.:

$$\begin{aligned}\mathcal{B}(B^0 \to \phi\pi^0) &< 2.8 \times 10^{-7} \\ \mathcal{B}(B^+ \to \phi\pi^+) &< 2.4 \times 10^{-7}\end{aligned}$$

Constraining SM pollution in $B^0 \to \eta' K^0$

- Constrain $\Delta S_{\eta' K_S^0}$ using $B^0 \to \eta^{(\prime)}\pi^0$, $\eta'\eta$.
- Expected $\mathcal{B}$ in the ranges $0.2 - 1 \times 10^{-6} (\eta^{(\prime)}\pi^0)$ and $0.3–2 \times 10^{-6} (\eta'\eta)$.

Upper limits at 90% CL:

$$\begin{aligned} \mathcal{B}(B^0 \to \eta\pi^0) &< 1.3 \times 10^{-6} \\ \mathcal{B}(B^0 \to \eta'\eta) &< 1.7 \times 10^{-6} \\ \mathcal{B}(B^0 \to \eta'\pi^0) &< 2.1 \times 10^{-6} \end{aligned}$$

BABAR preliminary, 211 fb^{-1}

hep-ex/0603013, accepted by PRD-RC

$$\mathcal{B}(\eta'\pi^0) = (2.79^{+1.02+0.25}_{-0.96-0.34}) \times 10^{-6}$$

BELLE hep-ex/0603001

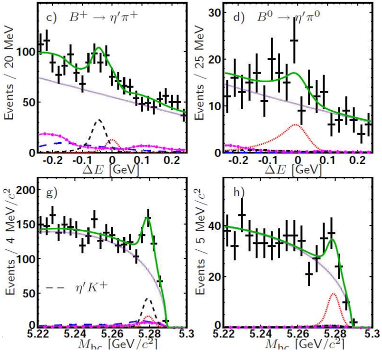
(next slide)

- Estimate 20% improvement in prediction of $\Delta S_{\eta' K_S^0}$

  following Gronau *et al.*, Phys. Lett. B **596**, 107
- Similar improvement for $\sin 2\alpha$ measured in $B^0 \to \pi^+\pi^-$

$B \to \eta'\pi$

BELLE $386 \times 10^6 B\bar{B}$, hep-ex/0603001



- $B^+ \to \eta'\pi^+$

  $\mathcal{B} = (1.76^{+0.67+0.15}_{-0.62-0.14}) \times 10^{-6}$

  $\mathcal{A}_{ch} = 0.20^{+0.37}_{-0.36} \pm 0.04$

  Previous *BABAR*:
  $\mathcal{B} = (4.0 \pm 0.8 \pm 0.4) \times 10^{-6}$
  Phys. Rev. Lett. **95**, 131803

- $B^0 \to \eta'\pi^0$

  $\mathcal{B} = (2.79^{+1.02+0.25}_{-0.96-0.34}) \times 10^{-6}$

  Significance 3.1 σ

  BABAR: $< 2.1 \times 10^{-6}$ hep-ex/0603013

- $\eta'\pi^+$ clearly seen
  $\eta'\pi^0$ not clear

Search for $B \to K^0_S K^0_S K^0_L$

- Pure $b \to s\bar{s}s$ penguin
- Avoids SM pollution:
- CP eigenstate
- Resonant ϕK^0_S contribution small, but non-resonant component may be large:

$$\mathcal{B} = (5.23^{+2.52+6.86+0.05}_{-1.96-2.53-0.06}) \times 10^{-6}$$

Cheng *et al.*, Phys. Rev. D **72**, 094003, using factorisation

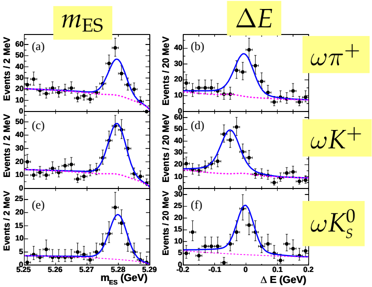
- $\epsilon \times \prod \mathcal{B}_i$ small
- Assuming uniform 3-body phase space, and excluding ϕ: UL at 90% CL:

$$\mathcal{B}(B^0 \to K^0_S K^0_S K^0_L) < 6.4 \times 10^{-6}$$

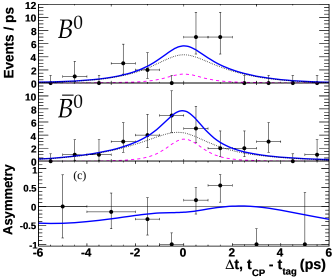
BABAR preliminary, 211 fb^{-1}

- Limited use for understanding CPV in $b \to q\bar{q}s$

CP asymmetries in $B \to \omega\, \pi/K$



BABAR preliminary



- $b \to q\bar{q}s$, dominated by single penguin
- Expect $\Delta S_{\omega K^0} \approx 0.1$ and $\mathcal{A}_{ch} \approx 0$
  [Phys. Lett. B **620**,143; Phys. Rev. D **72**, 014006]
- BABAR:

	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{ch}$
$B^+ \to \omega\pi^+$	$6.1 \pm 0.7 \pm 0.4$	$-0.01 \pm 0.10 \pm 0.01$
$B^+ \to \omega K^+$	$6.1 \pm 0.6 \pm 0.4$	$0.05 \pm 0.09 \pm 0.01$
$B^0 \to \omega K_S^0$	$6.2 \pm 1.0 \pm 0.4$	–

  compatible with BELLE [hep-ex/0508052]

- Time-dependent CPV:

$$S = 0.51^{+0.35}_{-0.39} \pm 0.02$$
$$C = -0.55^{+0.28}_{-0.26} \pm 0.03$$

- Fix $C = 0$ (no direct CPV):

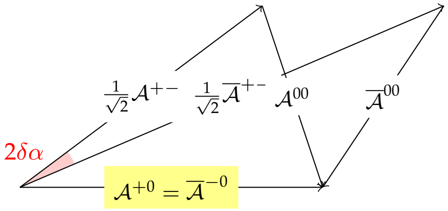
$$S = 0.60^{+0.42}_{-0.38}, \quad \Delta S = 0.12 \pm 0.40$$

  BABAR preliminary, 211 fb^{-1},
  hep-ex/0603040, submitted to PRL

Measurements related to α/ϕ_2

Updates on $B \to \rho\rho$

- Penguin amplitudes $\Rightarrow$ $\alpha_{\text{eff}} \neq \alpha$
- Isospin analysis of $B \to \rho\rho$ to measure shift $2\delta\alpha$ [Gronau & London, Phys. Rev. Lett. **65**, 3381]
- $B^+ \to \rho^+\rho^0$ measures base of isospin triangle for long. polarised amplitudes:



- Previous world averages [HFAG '05]:

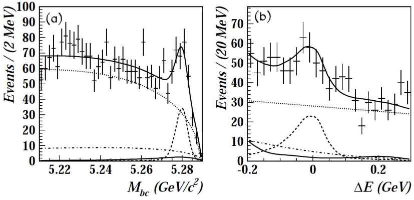
$$\mathcal{B}(\rho^+\rho^-) = (26.2^{+3.6}_{-3.7}) \times 10^{-6}$$

$$\mathcal{B}(\rho^+\rho^0) = (26.4^{+6.1}_{-6.4}) \times 10^{-6}$$

hard to reconcile in isospin triangle

Updates on $B \to \rho\rho$

$B^0 \to \rho^+\rho^-$



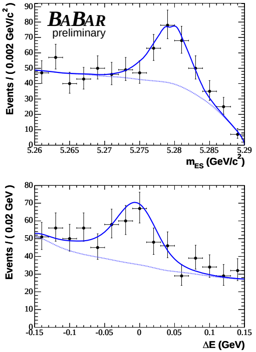
$\mathcal{B} = (22.8 \pm 3.8^{+2.3}_{-2.6}) \times 10^{-6}$
$f_L = 0.941^{+0.034}_{-0.040} \pm 0.030$

BELLE 253 fb^{-1},

hep-ex/0601024 submitted to PRL

- Almost entirely longitudinally polarised
- Isospin triangle closes nicely

$B^+ \to \rho^+\rho^0$



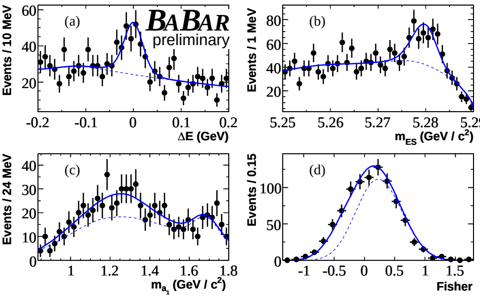
$\mathcal{B} = (17.2 \pm 2.5 \pm 2.8) \times 10^{-6}$
$f_L = 0.96 \pm 0.04 \pm 0.05$
$\mathcal{A}_{ch} = 0.10 \pm 0.14 \pm 0.09$

BABAR preliminary, 211 fb^{-1}

$B^0 \to a_1^\pm(1260)\,\pi^\mp$

- Can be used to extract α/ϕ_2 up to 4-fold ambiguity [Aleksan *et al.*, Nucl. Phys. B **361**, 141]
- Sub-leading penguin amplitude with different weak phase dilutes α
- Can be overcome by exploiting symmetries:
  - Isospin [Gronau & London (1990)]
  - Approximate SU(3) flavour [Dighe, Gronau & Rosner (1998); Gronau & Zupan (2005)]

First step: measure branching fraction



Nice signal seen ($N_{\rm sig} = 421 \pm 48$)

Assume $BR(a_1^+ \to (3\pi)^+) = 100\%$

$$\mathcal{B}(B^0 \to a_1^\pm \pi^\mp) = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$$

BABAR preliminary, 198 fb^{-1}

hep-ex/0603050, submitted to PRL

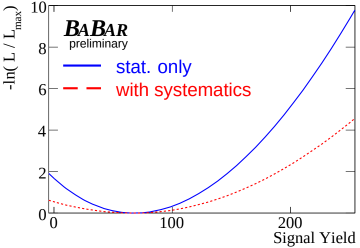
Next step: time dependent analysis

Search for $B^0 \to a_1^+ \rho^-$

- $b \to u\bar{u}d$ transition:
  with sufficient statistics, could be used to measure α/ϕ_2
- $B \to 5\pi$ important background contribution for $B \to \rho\rho$ analyses
- Little known about this decay:

  Theory: $\mathcal{B}(B^0 \to a_1^\pm \rho^\mp)\mathcal{B}(a_1^+ \to (3\pi)^+) = 43 \times 10^{-6}$
  [Bauer *et al.*, Z. Phys. C **34**, 103 (1987)]
  using $|V_{ub}/V_{cb}| = 0.08$

  Experiment: $\mathcal{B}(B^0 \to a_1^\pm \rho^\mp) < 3.4 \times 10^{-3}$
  [ARGUS, Phys. Lett. B **241**, 278 (1990), 214 pb^{-1}]



Assume $f_L = 1$ to get most conservative upper limit (90% C.L.):

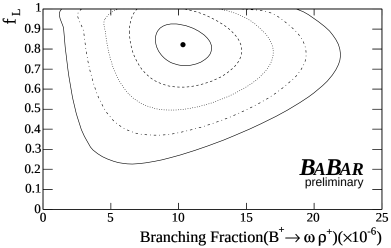
$$\mathcal{B}(B^0 \to a_1^\pm \rho^\mp)\mathcal{B}(a_1^+ \to (3\pi)^+) < 61 \times 10^{-6}$$

BABAR preliminary, 100 fb^{-1},
to be submitted to PRD-RC

Other charmless B decays

Search for $B \to \omega V$ decays

- Expect polarisation in $B \to VV$ to be $\approx 1 - m_V^2/m_B^2$
- $B \to \phi K^*$: $f_L \approx 0.5$
- Penguins?
- Measure related decays $B \to \omega K^*, \omega\phi$



$$
\begin{aligned}
\mathcal{B}(B^+ \to \omega\rho^+) &= (10.6 \pm 2.1^{+1.6}_{-1.0}) \times 10^{-6} \\
f_L(\omega\rho^+) &= 0.82 \pm 0.11 \pm 0.02 \\
\mathcal{A}_{ch}(\omega\rho^+) &= 0.04 \pm 0.18 \pm 0.02 \\
\mathcal{B}(B^0 \to \omega K^{*0}) &< 4.2 \times 10^{-6} \\
\mathcal{B}(B^+ \to \omega K^{*+}) &< 3.4 \times 10^{-6} \\
\mathcal{B}(B^0 \to \omega\rho^0) &< 1.5 \times 10^{-6} \\
\mathcal{B}(B^0 \to \omega\omega) &< 4.0 \times 10^{-6} \\
\mathcal{B}(B^0 \to \omega\phi) &< 1.2 \times 10^{-6} \\
\mathcal{B}(B^0 \to \omega f_0) &< 1.5 \times 10^{-6}
\end{aligned}
$$

BABAR preliminary, 211 fb^{-1}

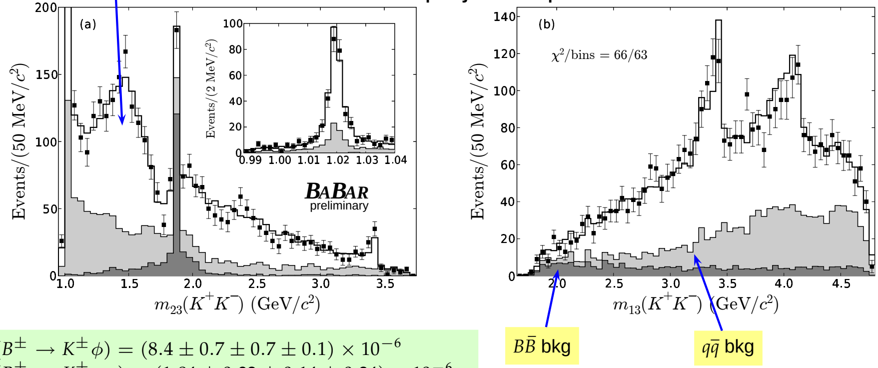
Reasonable agreement with predictions
[e.g. Ali *et al.*, Phys. Rev. D **60**,014005; Cheng & Yang, Phys. Lett. B **511**, 40]

Dalitz plot analysis of $B^+ \to K^+K^+K^-$

BABAR preliminary
$m_0(X_0) = 1.539 \pm 0.020\,\mathrm{GeV}/c^2$
$\Gamma_0(X_0) = 0.257 \pm 0.033\,\mathrm{GeV}/c^2$

BELLE: doublet of solutions
$m_0(X_0) = 1.524 \pm 0.014/1.491 \pm 0.01\,\mathrm{GeV}/c^2$
$\Gamma_0(X_0) = 0.136 \pm 0.023/0.145 \pm 0.029\,\mathrm{GeV}/c^2$
Phys. Rev. D **71**,092003 (2005)

Mass projection plots



$\mathcal{B}(B^\pm \to K^\pm \phi) = (8.4 \pm 0.7 \pm 0.7 \pm 0.1) \times 10^{-6}$
$\mathcal{B}(B^\pm \to K^\pm \chi_{c0}) = (1.84 \pm 0.32 \pm 0.14 \pm 0.24) \times 10^{-6}$

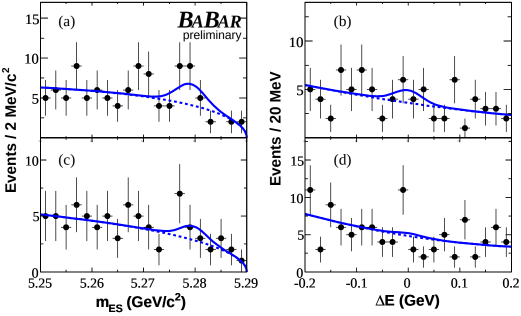
$\mathcal{B}(B^+ \to K^+K^+K^-) = (35.2 \pm 0.9 \pm 1.6) \times 10^{-6}$ *BABAR* preliminary, 205 fb^{-1}

Search for $B \to \eta'\eta' K$

- Motivation:
  - Large $\mathcal{B}(B \to \eta' K)$
  - CP violation in $B \to P^0 P^0 Q^0$ [Gershon & Hazumi, 2004],
    e.g. observation of $B^0 \to K^0_S K^0_S K^0_S$
    [BELLE, Phys. Rev. D **69**, 012001 , BABAR, Phys. Rev. Lett. **95**, 011810]
- Results (@ 90% CL):

$$\mathcal{B}(B^+ \to \eta'\eta' K^+) < 25 \times 10^{-6}$$
$$\mathcal{B}(B^0 \to \eta'\eta' K^0) < 31 \times 10^{-6}$$

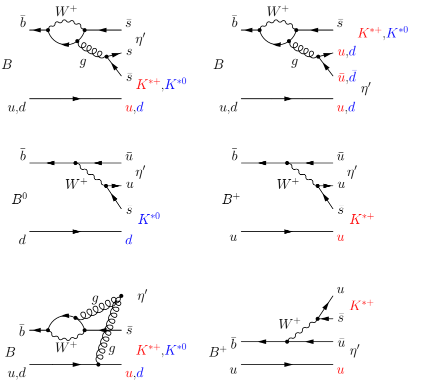
BABAR preliminary, 211 fb^{-1}



$\eta'\ \eta'\ K^+$

$\eta'\ \eta'\ K^0$

$B \to \eta' K^* / \rho$

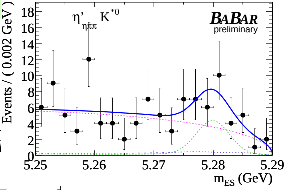


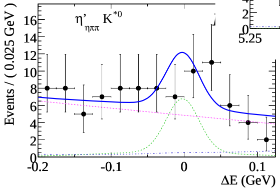
- $B \to \eta' K$ unexpectedly large (CLEO '97), much larger than ηK
  - Understood? Interference between two dominant penguin amplitudes [Lipkin 1991] plus enhancements from m_s, form factors, higher-order in α_s [Beneke & Neubert 2003]
  - Predicts ηK^* large, $\eta' K^*$ small

- Similarly for $\eta' \rho$:
- $b \to u$ colour-suppressed trees dominate
- $\eta' \rho^0$: trees cancel approximately
- $\eta' \rho^+$ small, and $\eta' \rho^0$ very small

$B \to \eta' K^* / \rho$

Decay mode	Branching Fraction (10^{-6}) Theoretical predictions SU(3) flavour	QCD fact.	***BABAR* preliminary 211 fb^{-1}**		
$B^0 \to \eta' K^{*0}$	$3.0^{+1.2}_{-0.3}$	$3.9^{+9.2}_{-5.1}$	$3.8 \pm 1.1 \pm 0.5$	$(4.5\,\sigma)$	
$B^+ \to \eta' K^{*+}$	$2.8^{+1.2}_{-0.3}$	$5.1^{+10.3}_{-\ 5.9}$	$4.9^{+1.9}_{-1.7} \pm 0.8$	$(3.6\,\sigma)$	< 7.9
$B^0 \to \eta' \rho^0$	$0.07^{+0.10}_{-0.05}$	$0.01^{+0.12}_{-0.06}$	$0.4^{+1.2+1.6}_{-0.9-0.6}$	$(0.3\,\sigma)$	< 3.7
$B^+ \to \eta' \rho^+$	$4.9^{+0.7}_{-0.7}$	$6.3^{+4.0}_{-3.3}$	$6.8^{+3.2+3.9}_{-2.9-1.3}$	$(2.3\,\sigma)$	< 14
$B^0 \to \eta' f_0(980) \times \mathcal{B}(f_0 \to \pi^+\pi^-)$			$0.1^{+0.6+0.9}_{-0.4-0.4}$	$(0.2\,\sigma)$	< 1.5
	Phys. Rev. D **68**,074012	Nucl. Phys. B **675**, 333			

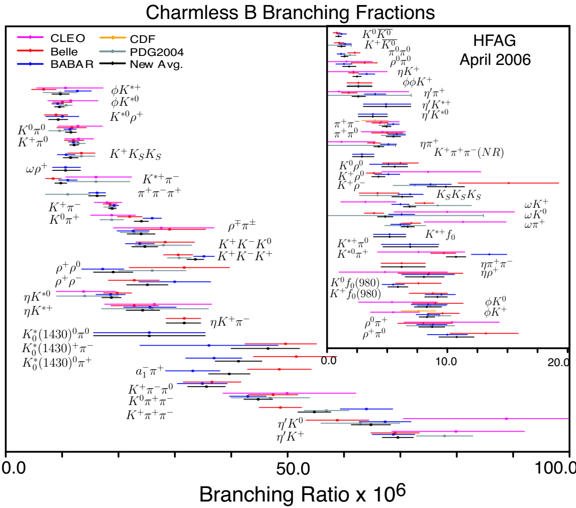




- Predictions have large error, both compatible with measurements
- Predicted pattern in $\eta^{(\prime)} K^{(*)}$ seen
- $\eta' \rho^0$ likely to be very small

Summary

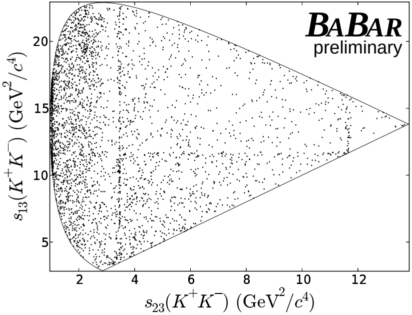
- Many new and updated results from both B factories
- Rare charmless B decays help to improve understanding of Standard Model amplitudes
- More interesting results to come with more data

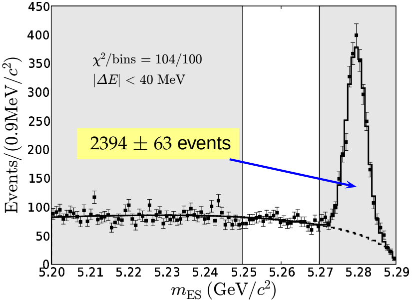


Backup Slides

Dalitz plot analysis of $B^+ \to K^+K^+K^-$

- Full Dalitz plot analysis, measure amplitudes and relative phases
- Fit B^+ and B^- separately for $\mathcal{A}_{ch}$





$$\mathcal{B}(B^+ \to K^+K^+K^-) = (35.2 \pm 0.9 \pm 1.6) \times 10^{-6}$$

Comp.	ρ	ϕ (rad)	F (%)	$F \times \mathcal{B}(B^\pm \to K^\pm K^\pm K^\mp)$	A	$(A_{\min}, A_{\max})_{90\%}$	$\delta\phi$ (rad)
$\phi(1020)$	1.66 ± 0.06	$2.99 \pm 0.20 \pm 0.06$	$11.8 \pm 0.9 \pm 0.8$	$(4.14 \pm 0.32 \pm 0.33)\times10^{-6}$	$0.00 \pm 0.08 \pm 0.02$	$(-0.14, 0.14)$	$-0.67 \pm 0.28 \pm 0.05$
$f_0(980)$	5.2 ± 1.0	$0.48 \pm 0.16 \pm 0.08$	$19 \pm 7 \pm 4$	$(6.5 \pm 2.5 \pm 1.6)\times10^{-6}$	$-0.31 \pm 0.25 \pm 0.08$	$(-0.72, 0.12)$	$-0.20 \pm 0.16 \pm 0.04$
$X_0(1550)$	8.2 ± 1.1	$1.29 \pm 0.10 \pm 0.04$	$121 \pm 19 \pm 6$	$(4.3 \pm 0.6 \pm 0.3)\times10^{-5}$	$-0.04 \pm 0.07 \pm 0.02$	$(-0.17, 0.09)$	$0.02 \pm 0.15 \pm 0.05$
$f_0(1710)$	1.22 ± 0.34	$-0.59 \pm 0.25 \pm 0.11$	$4.8 \pm 2.7 \pm 0.8$	$(1.7 \pm 1.0 \pm 0.3)\times10^{-6}$	$0.0 \pm 0.5 \pm 0.1$	$(-0.66, 0.74)$	$-0.07 \pm 0.38 \pm 0.08$
χ_{c0}^I	0.437 ± 0.039	$-1.02 \pm 0.23 \pm 0.10$	$3.1 \pm 0.6 \pm 0.2$	$(1.10 \pm 0.20 \pm 0.09)\times10^{-6}$	$0.19 \pm 0.18 \pm 0.05$	$(-0.09, 0.47)$	$0.7 \pm 0.5 \pm 0.2$
χ_{c0}^{II}	0.604 ± 0.034	0.29 ± 0.20	6.0 ± 0.7	$(2.10 \pm 0.24) \times 10^{-6}$	-0.03 ± 0.28	-	-0.4 ± 1.3
NR	13.2 ± 1.4	0	$141 \pm 16 \pm 9$	$(5.0 \pm 0.6 \pm 0.4)\times10^{-5}$	$0.02 \pm 0.08 \pm 0.04$	$(-0.14, 0.18)$	0

Non-resonant component not flat across DP