European Research Council

THE UNIVERSITY OF WARWICK

Charmless *B* decays at BaBar

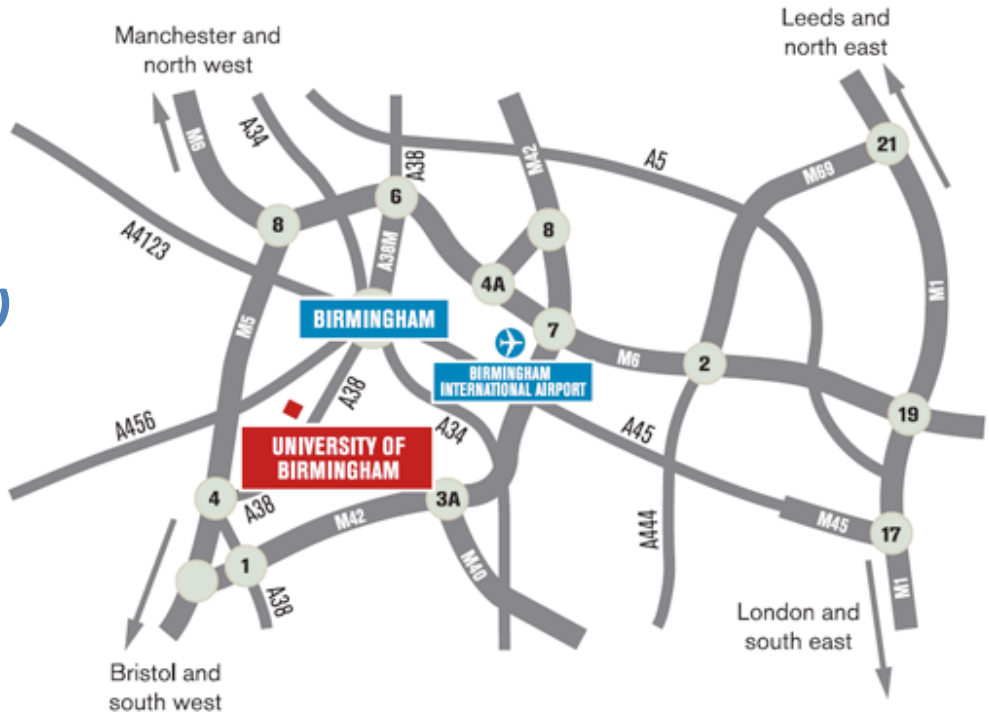
Thomas Latham

(on behalf of the BaBar experiment)

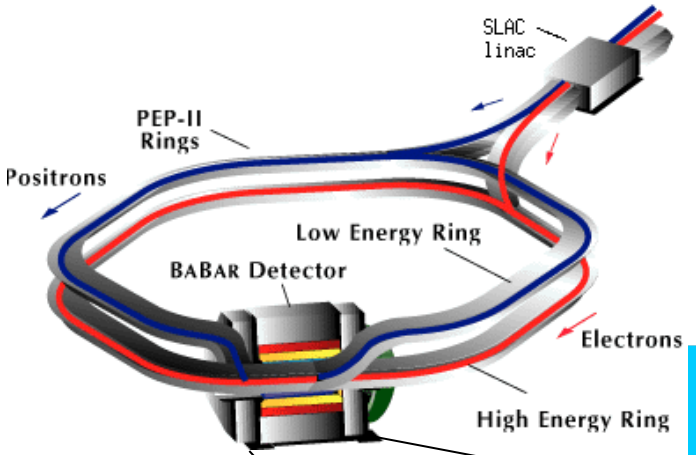
23rd July 2014

Overview

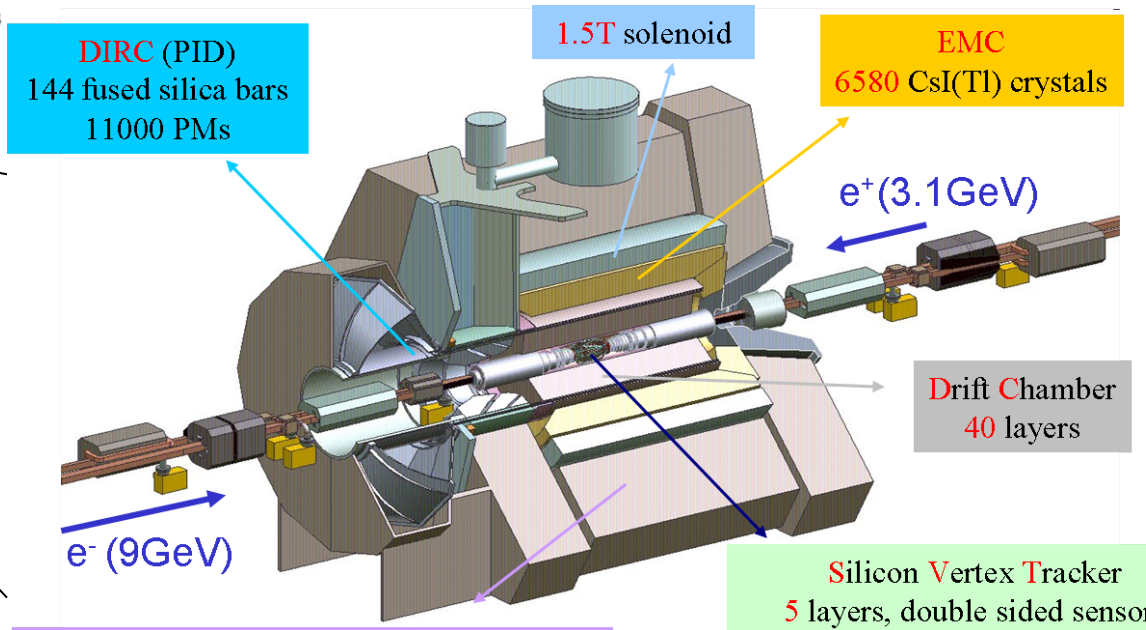
- Introduction
- Search for $B^0 \longrightarrow \omega\omega$ and $B^0 \longrightarrow \omega\phi$
- Amplitude analysis of $B^+ \longrightarrow K_S\pi^+\pi^0$



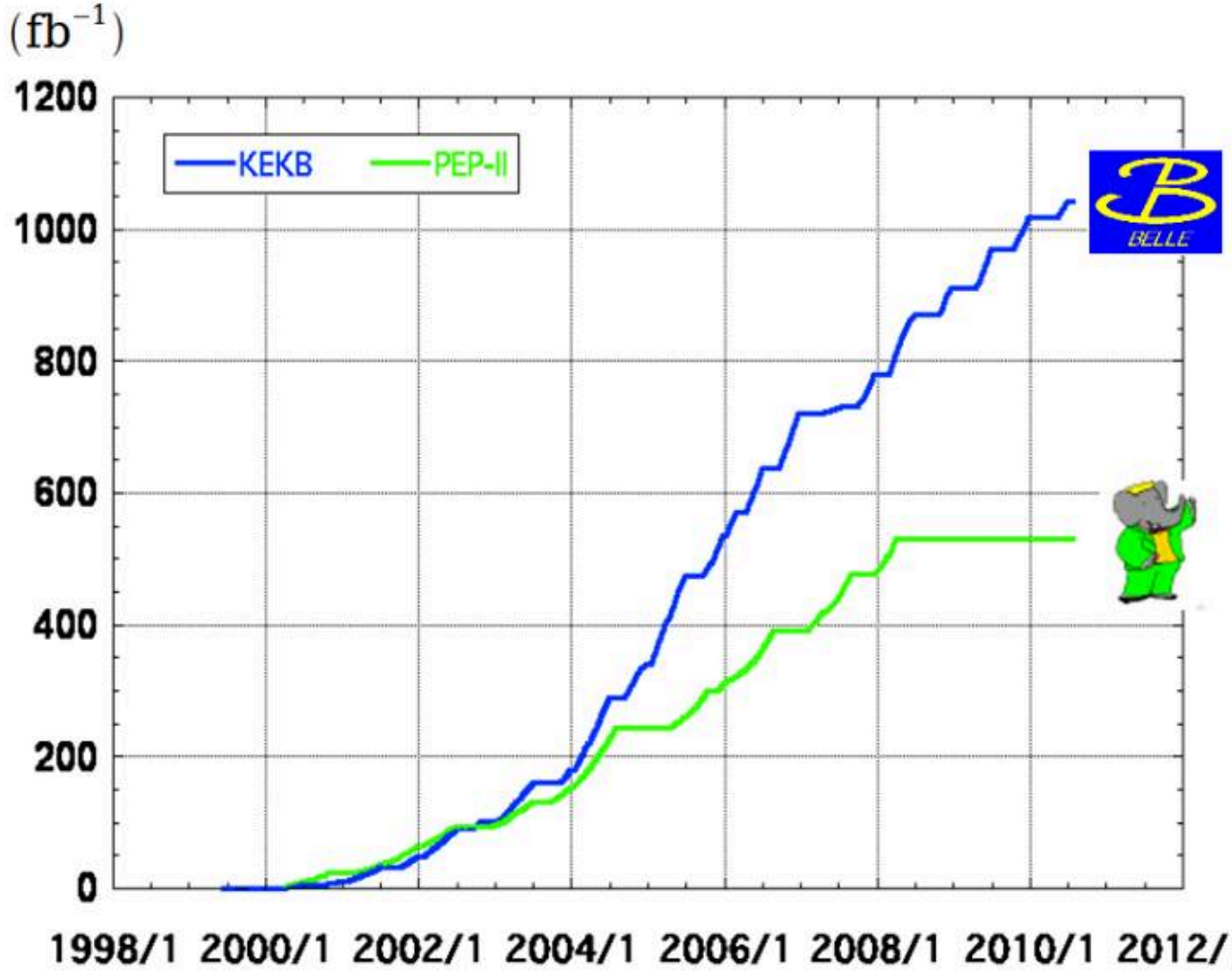
PEP-II and BaBar



- PEP II/BaBar *B*-Factory located at SLAC National Accelerator Laboratory
- Collided beams of electrons and positrons with asymmetric energies



Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

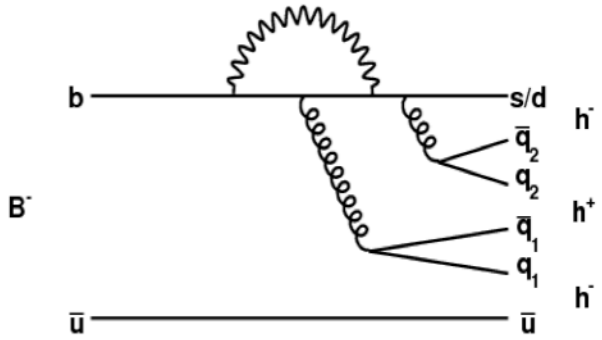
$\Upsilon(3S)$: 30 fb^{-1}

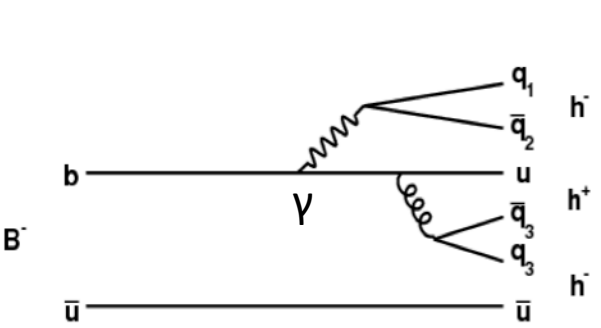
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Why charmless decays?

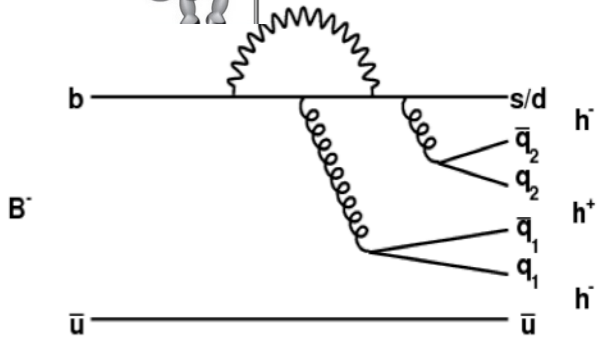


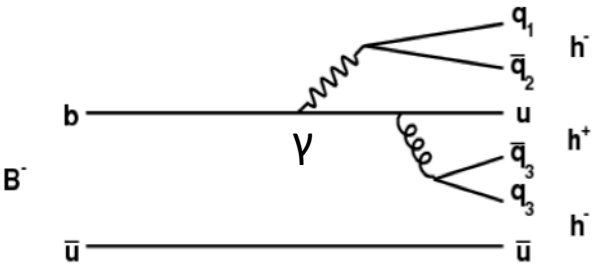


- Contributions from both loop (penguin) and tree decay diagrams
- These diagrams have a relative weak phase (= γ in SM)
- Interference can therefore give rise to CP violation in decay
- In neutral *B* decays can make time-dependent measurements, allowing measurements of mixing-induced CP asymmetries
- These can be compared with measurements from, e.g. $B^0 \longrightarrow J/\psi\, K_S$, to search for signs of new physics

Why charmless decays?

New physics contributions in loops?

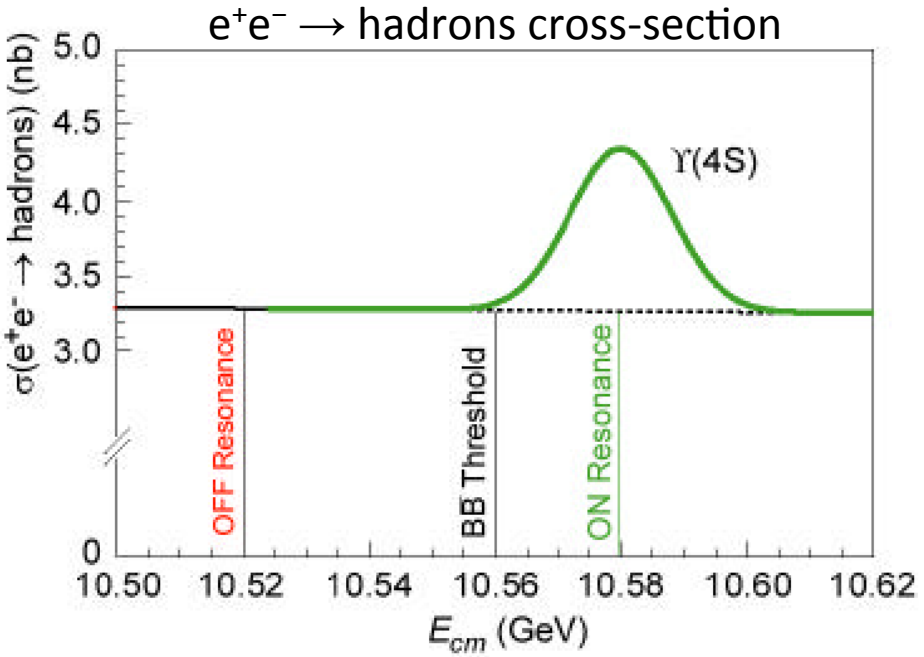


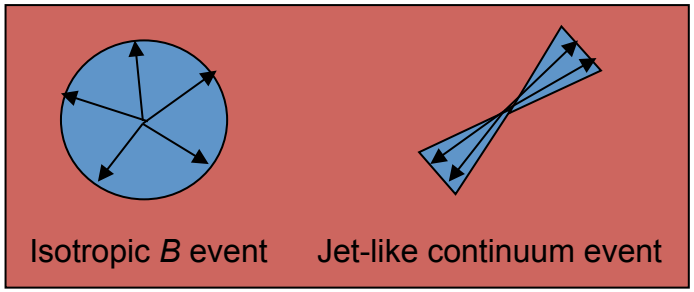


- Contributions from both loop (penguin) and tree decay diagrams
- These diagrams have a relative weak phase (= γ in SM)
- Interference can therefore give rise to CP violation in decay
- In neutral *B* decays can make time-dependent measurements, allowing measurements of mixing-induced CP asymmetries
- These can be compared with measurements from, e.g. $B^0 \longrightarrow J/\psi\, K_S$, to search for signs of new physics

Analysis Variables – Topological

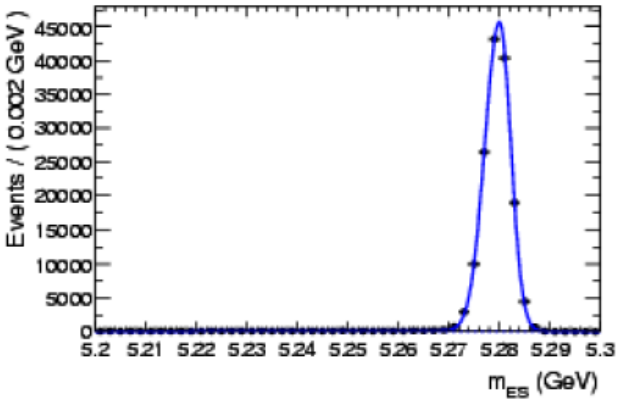
- Light quark continuum cross section ~3x $\sigma\left(b\bar{b}\right)$
- *B* mesons produced almost at rest since just above threshold
- Use event topology to discriminate
- Combine variables in an MVA, e.g. Fisher, Neural Network or Decision Tree



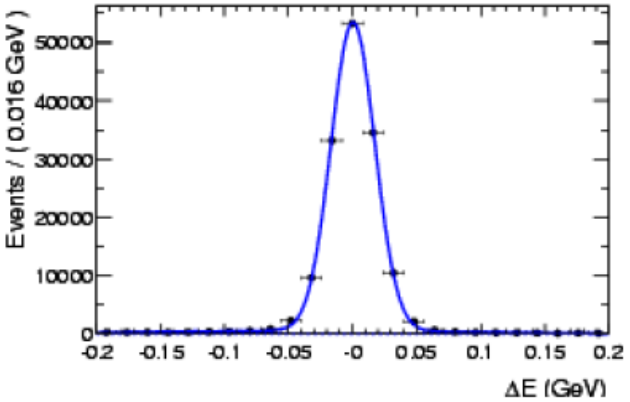


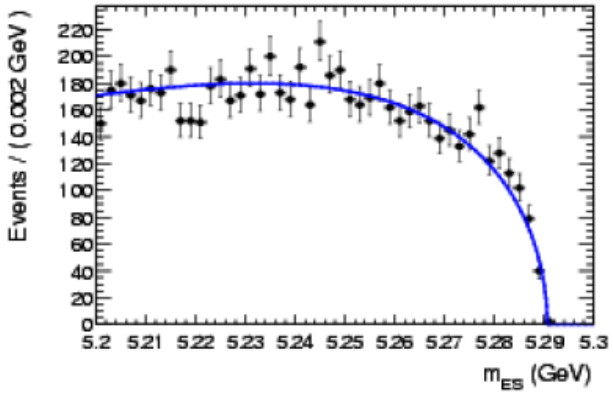
Analysis Variables – Kinematic

Make use of precision kinematic information from the beams.

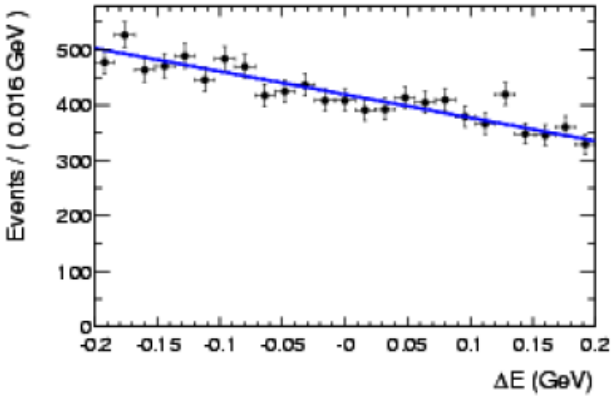


Characteristic Signal Distributions





Characteristic Continuum Distributions



$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

Plots show simulation

$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

Evidence for $B^0 \longrightarrow \omega\omega$ and search for $B^0 \longrightarrow \omega\varphi$

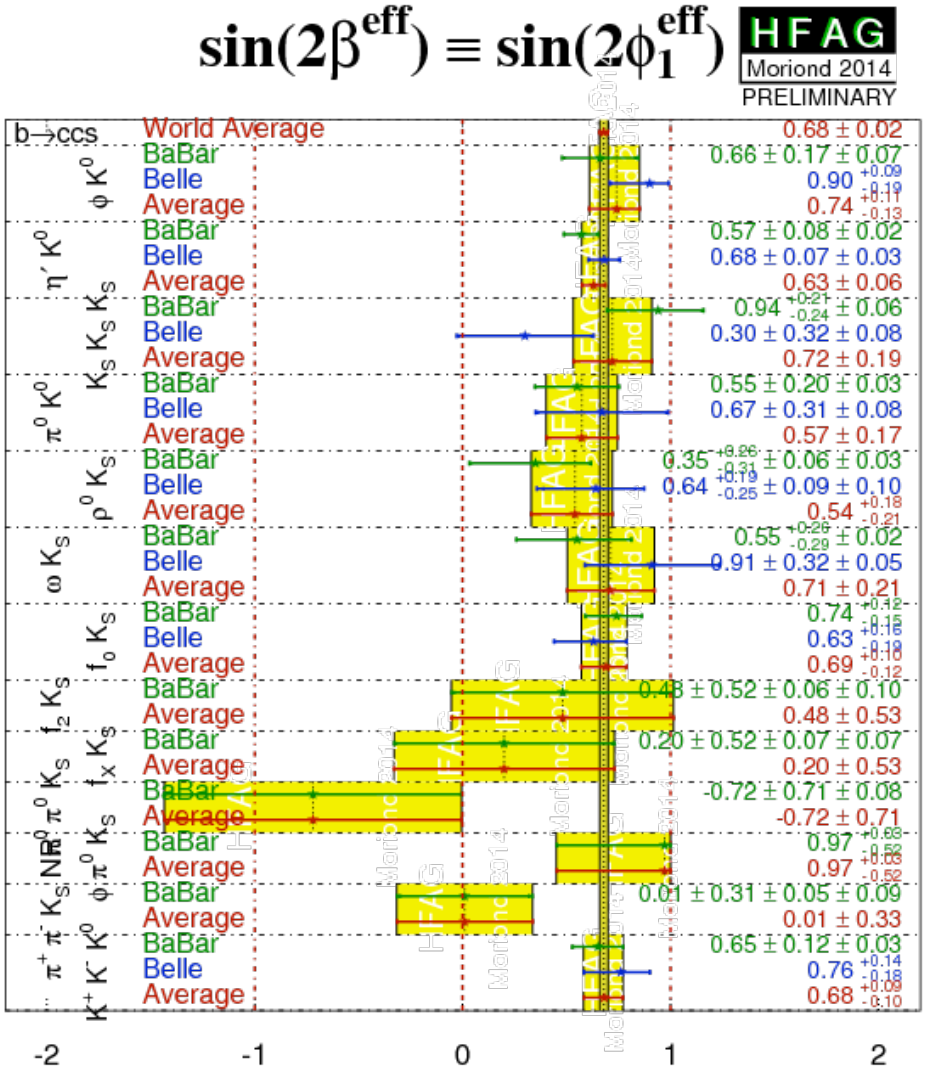
Recently published

Phys. Rev. D89, 051101 (2014)

SM expected BFs:
$B^0 \to \omega\omega$: O(1 x 10^{-6})
$B^0 \to \omega\phi$: O(1 x 10^{-7})

Motivation

- Some hints of anomalies in loop-dominated charmless B decays
- Smaller than expected longitudinal polarisation fraction (f_L) in $B^0 \to \phi K^*$ (World avg. = 0.48 ± 0.03)
- Trend of time-dependent CP asymmetries is smaller than value from $b \to c\bar{c}s$
- Hints of new physics?



Phys. Rev. D89, 051101 (2014)

Reconstruction & Fit

- Full reconstruction of *B* candidates
- $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-$

State	Inv. mass (MeV)
ω	$740 < m_{\pi\pi\pi} < 820$
ϕ	$1009 < m_{KK} < 1029$
π^0	$120 < m_{\gamma\gamma} < 150$

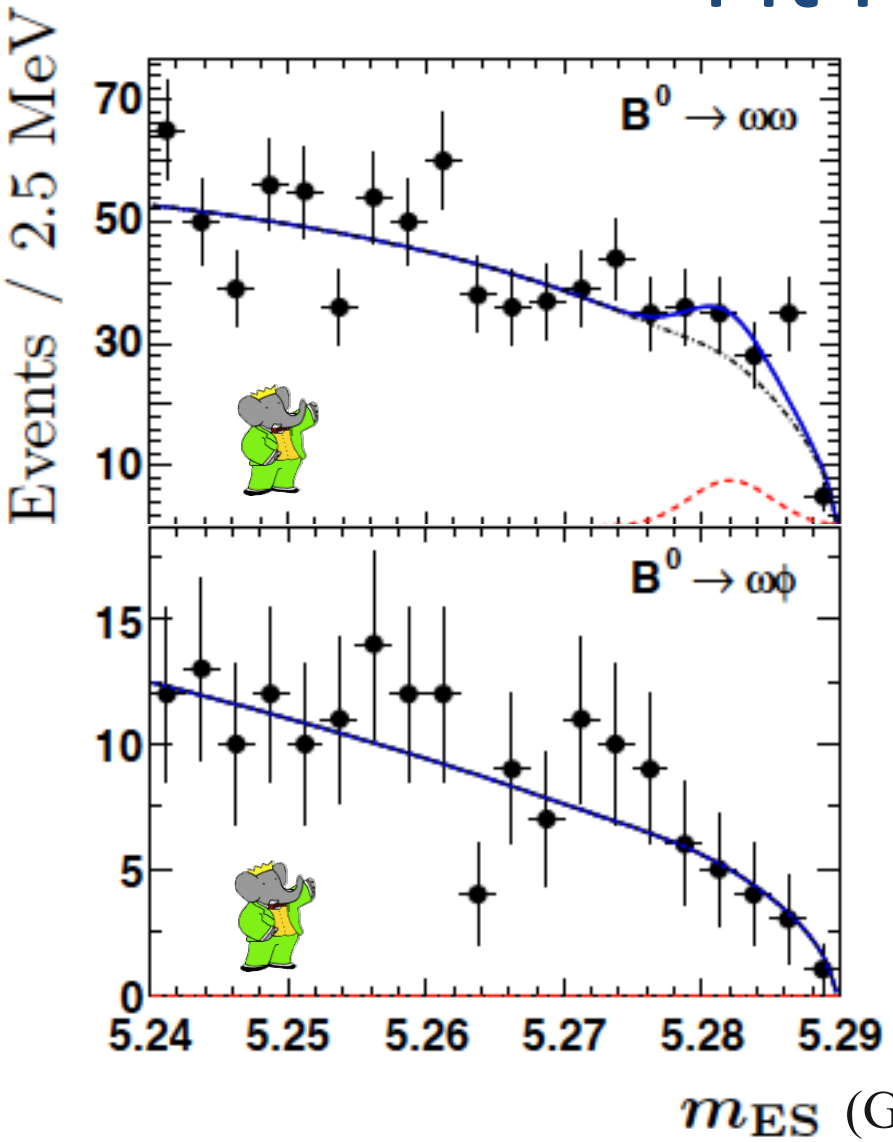
- Two background categories:
  - Combinatorial (continuum + *B* events)
  - Peaking (*B* events)

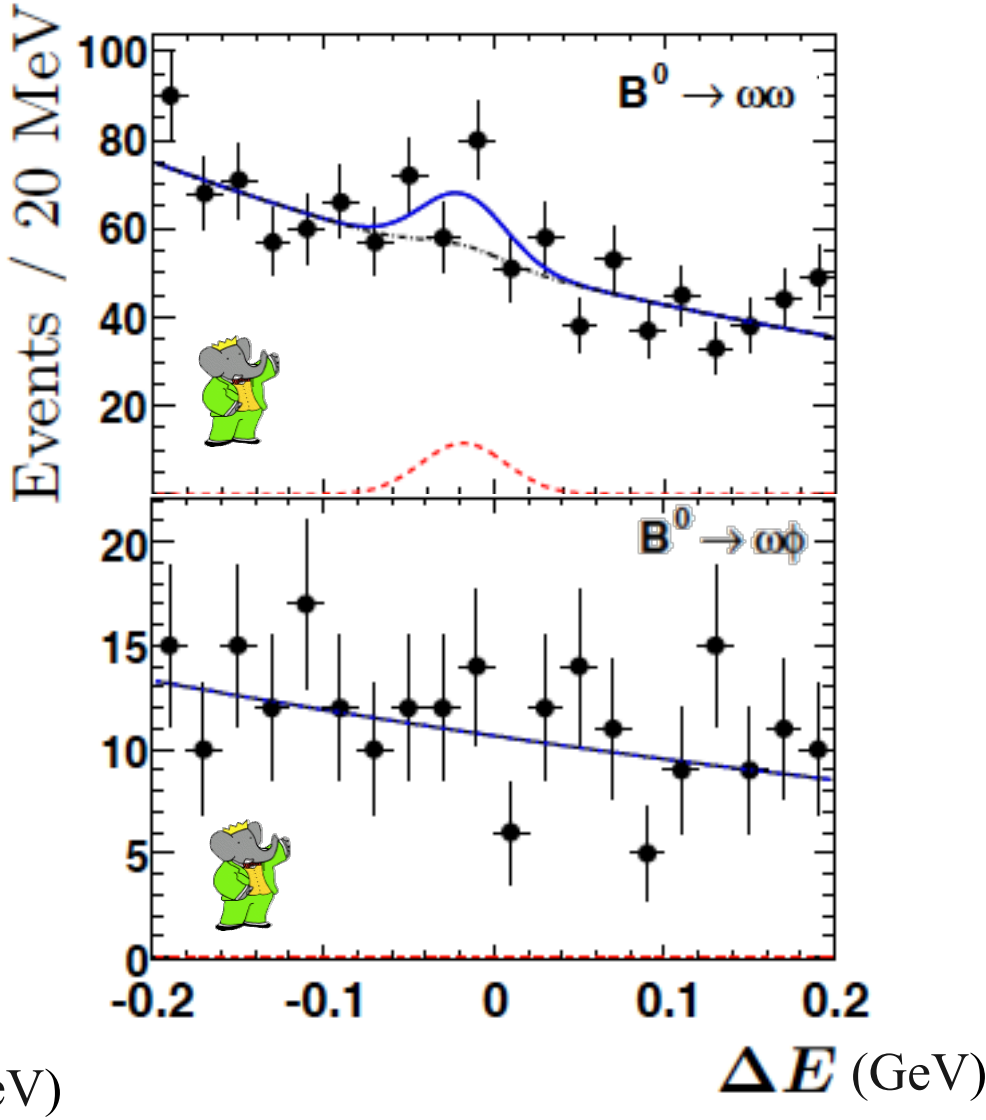
- Maximum likelihood fit to 8 ($\omega\omega$) or 9 ($\omega\phi$) variables
  - m_{ES}
  - ΔE
  - Fisher discriminant (event topology)
  - 2x resonance masses
  - 2x resonance helicity angles
  - ω "internal" helicity (polar angle of π^0 wrt ω flight direction in $\pi^+\pi^-$ rest frame)

- Event yields of signal and background categories + continuum PDF parameters floated

Phys. Rev. D89, 051101 (2014)

Fit Results



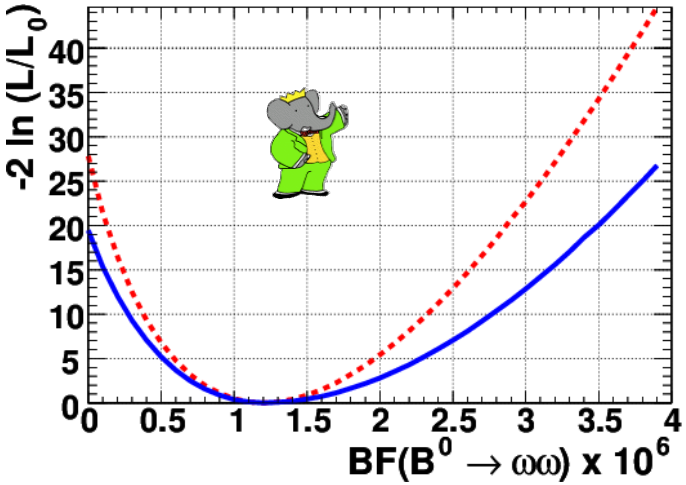


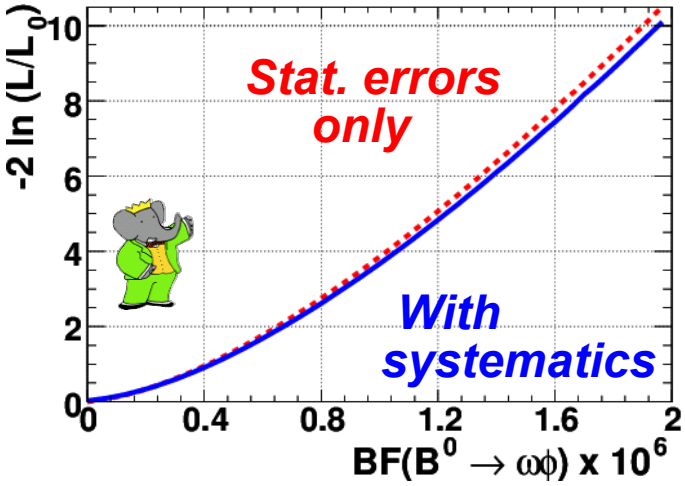
Phys. Rev. D89, 051101 (2014)

Fit Results

- BF($\omega\omega$) = $(1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6}$ (4.4σ significance)
- BF($\omega\phi$) < 0.7×10^{-6} (90% CL)
- Results consistent with theoretical expectations

- Largest systematic contributions from:
  - fit bias ($\lesssim$ 10% for $\omega\omega$)
  - uncertainty on longitudinal fraction (0.88 is used as nominal central value)





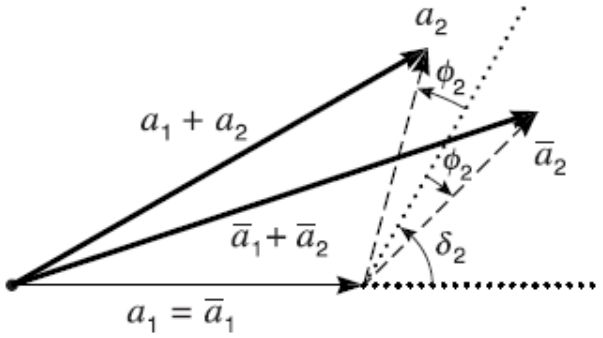
Amplitude analysis of $B^+ \longrightarrow K_S\pi^+\pi^0$

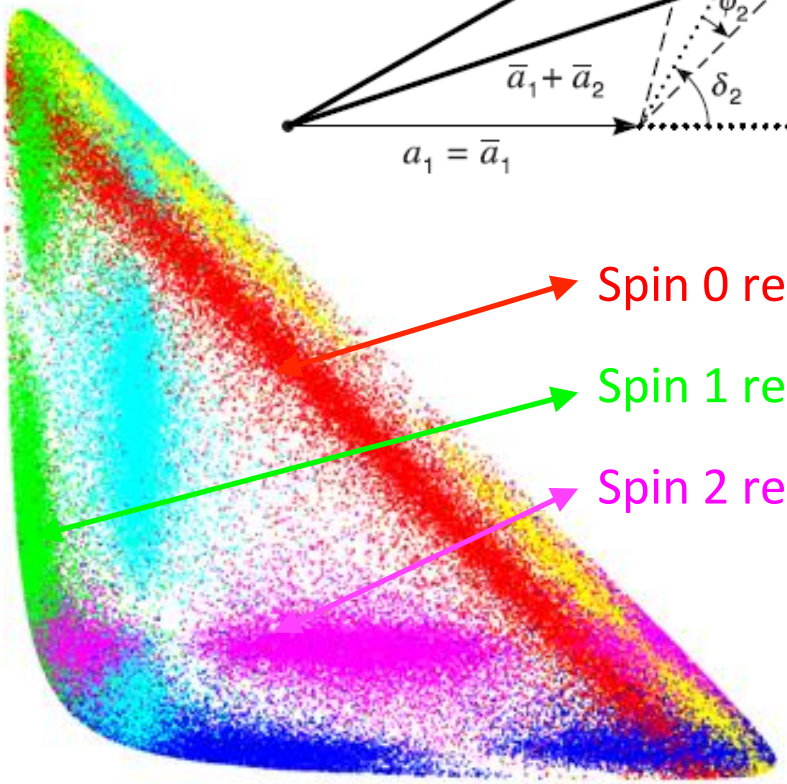
Preliminary Results

To be submitted to Phys. Rev. D

Dalitz plot analysis formalism

- Intermediate resonances appear as structures in Dalitz plot, characterised by their mass, width and spin
- Overlapping resonant contributions lead to interference effects
- Hence the sensitivity to relative phases





Simulated data

Motivation

- Only upper limit exists on inclusive branching fraction, from CLEO collaboration

$$\mathcal{B}\left(B^+ \to K^0\pi^+\pi^0\right) < 66 \times 10^{-6}$$

Phys. Rev. Lett. **89**, 251801 (2002)

- Improved measurements of direct CP violation in $B^+ \to K^{*+}\pi^0$ can shed light onto equivalent of "$K\pi$ puzzle" in $K^*\pi$ system [Phys. Rev. **D81**, 094011 (2010)]
- ΔA_{CP} predicted to be zero
- $A_{CP}(K^{*+}\pi^-)$ quite precisely measured by BaBar & Belle
- Only previous measurement of $A_{CP}(K^{*+}\pi^0)$ by BaBar, using final state $B^+ \to K^+\pi^0\pi^0$

$$\Delta A_{\rm CP} = A_{\rm CP}(K^{*+}\pi^0) - A_{\rm CP}(K^{*+}\pi^-)$$

$$A_{\rm CP}(B^0 \to K^{*+}\pi^-) = -0.23 \pm 0.06$$

HFAG Average

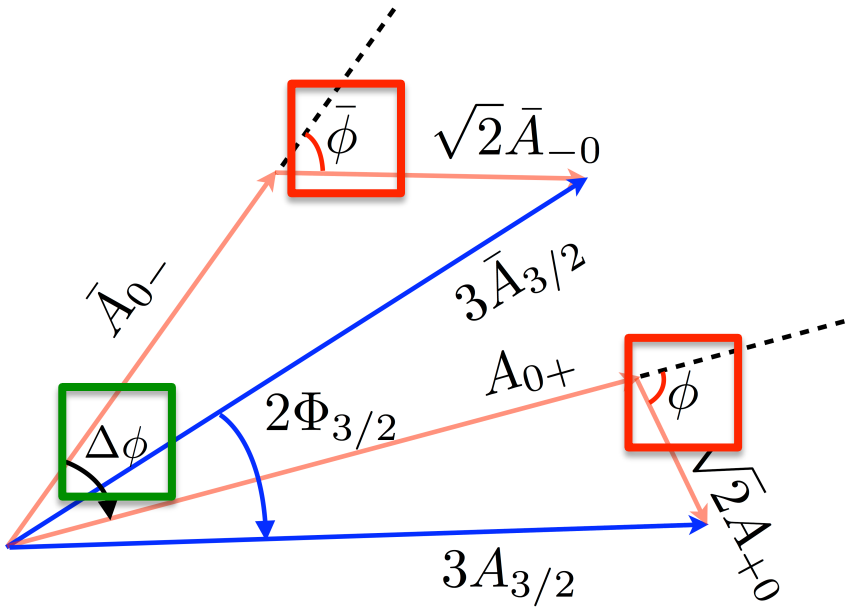
$$A_{\rm CP}(B^+ \to K^{*+}\pi^0) = -0.06 \pm 0.24$$

Phys. Rev. **D84**, 092007 (2011)

Motivation

- Relative phases between the two $K^*\pi$ intermediate states can be used to measure CKM angle γ
- Uses the fact that $K^{*0}\pi^+$ is a pure penguin decay
  - Hence $\Delta\phi$ is approximately zero
- In absence of EW penguins $\Phi_{3/2} = \gamma$

Isospin relations



Phys. Rev. D74, 051301 (2006)
Phys. Rev. D75, 014002 (2007)

Dalitz plot analysis formalism

- Resonance parameterisation (isobar model):

$$\overline{\mathrm{A}} = \sum \overline{\mathrm{A}}_i = \sum \overline{\mathrm{c}}_i F\left(m^2_{K_S\pi^+}, m^2_{\pi^0\pi^+}\right)$$

Complex coefficients

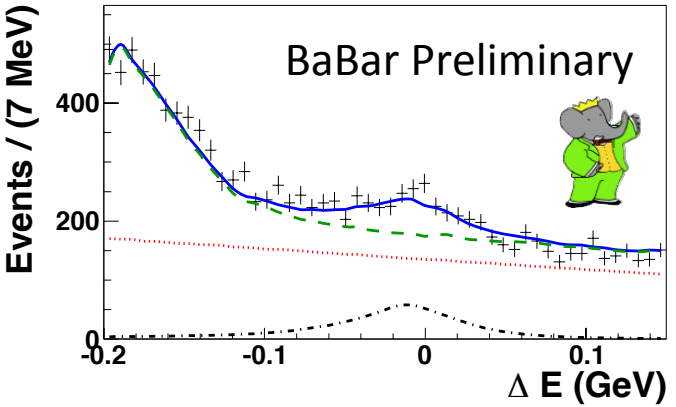
Decay dynamics

- Directly extracted parameters: $\mathrm{Re}(c_i)$ & $\mathrm{Im}(c_i)$
- Other quantities (relative phases, BF, A_{CP}) are derived from these

Selection and fit

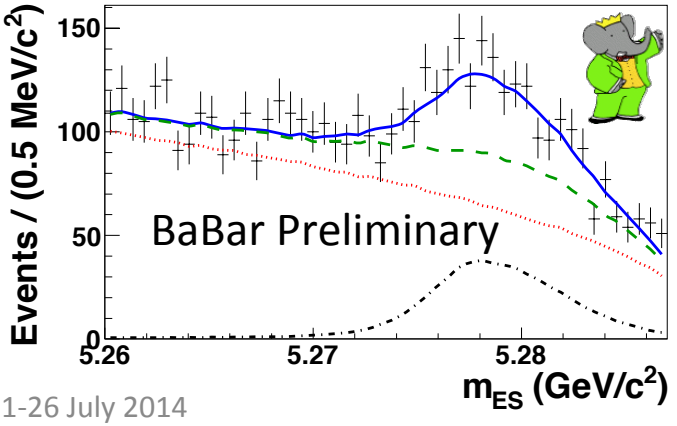
- K_S candidates reconstructed in decay to $\pi^+\pi^-$
- Largest B backgrounds removed by vetoing $D^0 \longrightarrow K_S\pi^0$
- Approx. 32,000 candidates after all selection

- Maximum likelihood fit to m_{ES}, ΔE, Boosted Decision Tree (event topology) and DP
- Large correlations between DP position and kinematic variables
- Signal PDFs parameterised as function of DP position
- Signal yield of 1014 ± 63 (statistical uncertainty only)



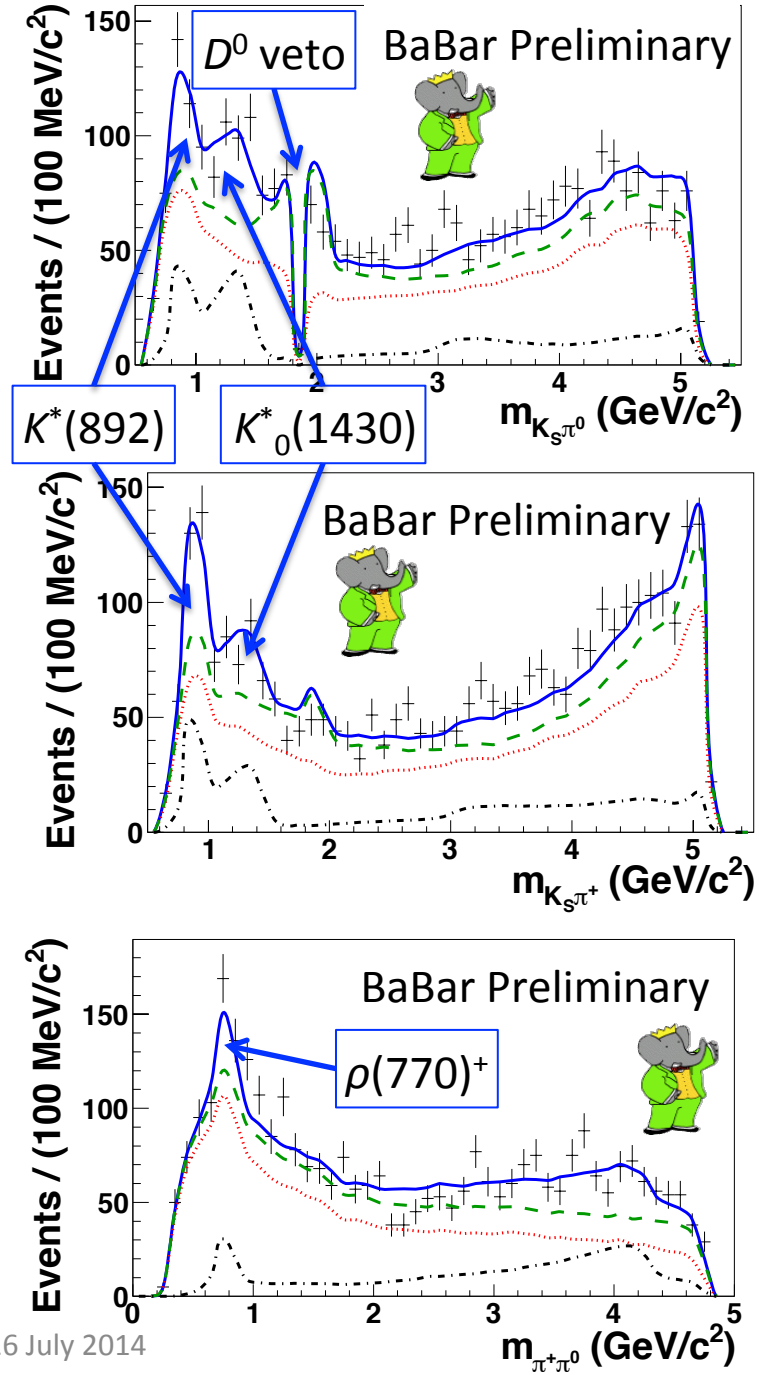
Total fit | Total background

Continuum background | Signal

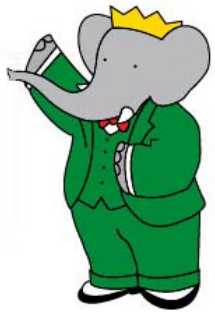


DP fit results

- Model contains $K^*(892)$, $K\pi$ S-wave and $\rho(770)$ contributions
- Both charged and neutral K^*'s included
- $K\pi$ S-wave modelled using LASS parameterisation (coherent sum of $K^*_0(1430)$ resonance and effective range nonresonant terms)
  [Nucl. Phys. **B296**, 493 (1988)]



BFs and Phases

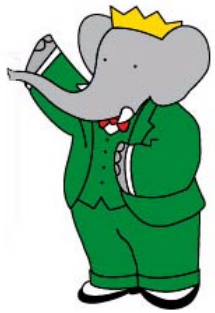


Decay channel	$\mathcal{B}\,(10^{-6})$
$K^0\pi^+\pi^0$	$45.9 \pm 2.6 \pm 3.0 \pm 8.6$
$K^{*0}(892)\pi^+$	$14.6 \pm 2.4 \pm 1.3 \pm 0.5$
$K^{*+}(892)\pi^0$	$9.2 \pm 1.3 \pm 0.6 \pm 0.5$
$K_0^{*0}(1430)\pi^+$	$50.0 \pm 4.8 \pm 6.0 \pm 4.0$
$K_0^{*+}(1430)\pi^0$	$17.2 \pm 2.4 \pm 1.5 \pm 1.8$
$\rho^+(770)K^0$	$9.4 \pm 1.6 \pm 1.0 \pm 2.6$

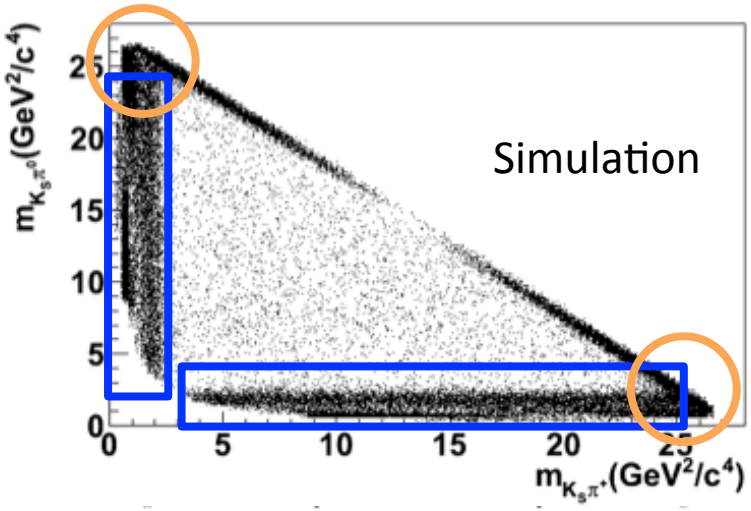
- First measurement of inclusive $K^0\pi^+\pi^0$ and $K^{*+}_0(1430)\pi^0$ BFs
- First uncertainty is statistical, second systematic, and third due to the signal model
- Sensitivity to relative phases depends strongly on overlap in DP and effects of mis-reconstruction in the corners
- Smaller uncertainties for pairs of parallel resonances

Reference amplitude \ Resonances	Relative phases (°) $K^{*0}(892)\pi^+$	$K^{*+}(892)\pi^0$	$(K\pi)_0^{*0}\pi^+$	$(K\pi)_0^{*+}\pi^0$	$\rho^+(770)K_S^0$
$B^+ \to K^{*0}(892)\pi^+$	0	-96 ± 44	174 ± 11	-91 ± 43	-122 ± 38
$B^+ \to K^{*+}(892)\pi^0$	–	0	-90 ± 42	6 ± 10	-27 ± 26
$B^+ \to (K\pi)_0^{*0}\pi^+$	–	–	0	95 ± 42	64 ± 37
$B^+ \to (K\pi)_0^{*+}\pi^0$	–	–	–	0	-32 ± 25
$B^+ \to \rho^+(770)K_S^0$	–	–	–	–	0

BFs and Phases



Decay channel	$\mathcal{B}\,(10^{-6})$
$K^0\pi^+\pi^0$	$45.9 \pm 2.6 \pm 3.0 \pm 8.6$
$K^{*0}(892)\pi^+$	$14.6 \pm 2.4 \pm 1.3 \pm 0.5$
$K^{*+}(892)\pi^0$	$9.2 \pm 1.3 \pm 0.6 \pm 0.5$
$K_0^{*0}(1430)\pi^+$	$50.0 \pm 4.8 \pm 6.0 \pm 4.0$
$K_0^{*+}(1430)\pi^0$	$17.2 \pm 2.4 \pm 1.5 \pm 1.8$
$\rho^+(770)K^0$	$9.4 \pm 1.6 \pm 1.0 \pm 2.6$

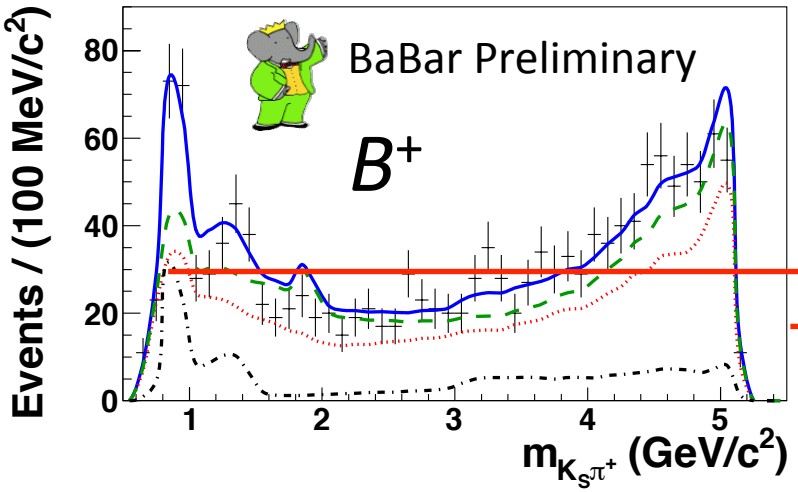


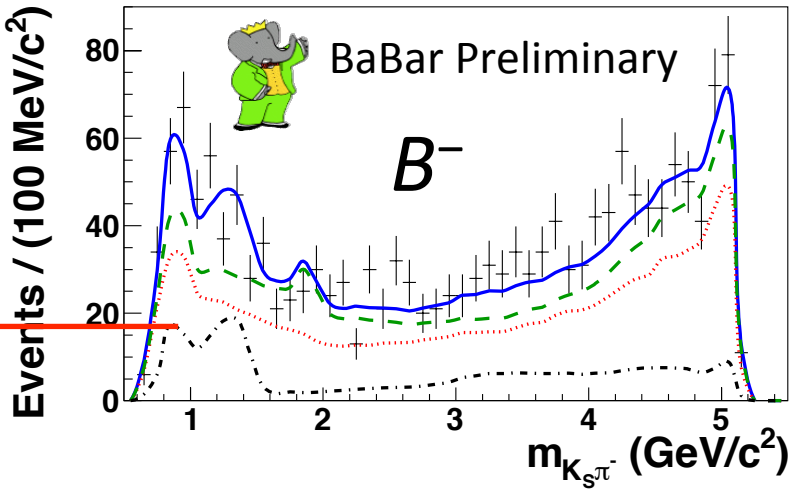
Reference amplitude \ Resonances	Relative phases (°) $K^{*0}(892)\pi^+$	$K^{*+}(892)\pi^0$	$(K\pi)_0^{*0}\pi^+$	$(K\pi)_0^{*+}\pi^0$	$\rho^+(770)K_S^0$
$B^+ \to K^{*0}(892)\pi^+$	0	-96 ± 44	174 ± 11	-91 ± 43	-122 ± 38
$B^+ \to K^{*+}(892)\pi^0$	–	0	-90 ± 42	6 ± 10	-27 ± 26
$B^+ \to (K\pi)_0^{*0}\pi^+$	–	–	0	95 ± 42	64 ± 37
$B^+ \to (K\pi)_0^{*+}\pi^0$	–	–	–	0	-32 ± 25
$B^+ \to \rho^+(770)K_S^0$	–	–	–	–	0

Direct CP Violation

- First evidence of direct CP violation in $B^+ \to K^{*+}\pi^0$
- 3.4σ significance estimated including statistical, systematic and model uncertainties
- A_{CP} for $B^+ \to K^{*0}\pi^+$ consistent with zero (as expected)

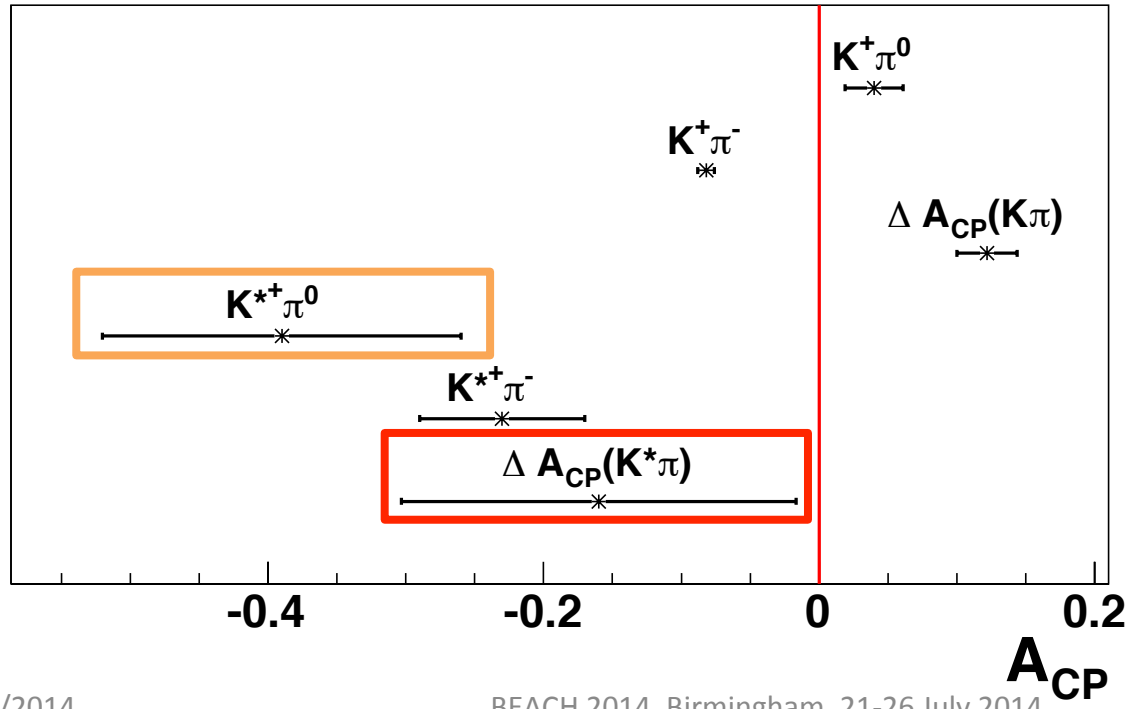
Decay channel	A_{CP}
$K^0\pi^+\pi^0$	$0.07 \pm 0.05 \pm 0.03 \pm 0.04$
$K^{*0}(892)\pi^+$	$-0.12 \pm 0.21 \pm 0.08 \pm 0.11$
$K^{*+}(892)\pi^0$	$-0.52 \pm 0.14 \pm 0.04 \pm 0.04$
$K_0^{*0}(1430)\pi^+$	$0.14 \pm 0.10 \pm 0.04 \pm 0.14$
$K_0^{*+}(1430)\pi^0$	$0.26 \pm 0.12 \pm 0.08 \pm 0.12$
$\rho^+(770)K^0$	$0.21 \pm 0.19 \pm 0.07 \pm 0.30$





Effect on $K\pi$ puzzle

- Plot uses world average values for $K\pi$ and $K^{*+}\pi^-$ asymmetries and personal average of the two BaBar results for $K^{*+}\pi^0$
- Gives $\Delta A_{CP}(K^*\pi) \equiv A_{CP}(K^{*+}\pi^0) - A_{CP}(K^{*+}\pi^-) = -0.16 \pm 0.14$
  - Consistent with zero
- Uncertainty much improved but still too large to be conclusive

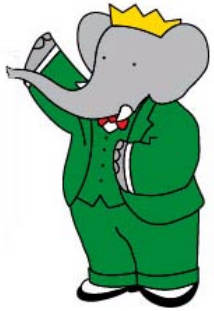


BaBar, Belle

BaBar, Belle, CDF, LHCb

BaBar only!

BaBar, Belle

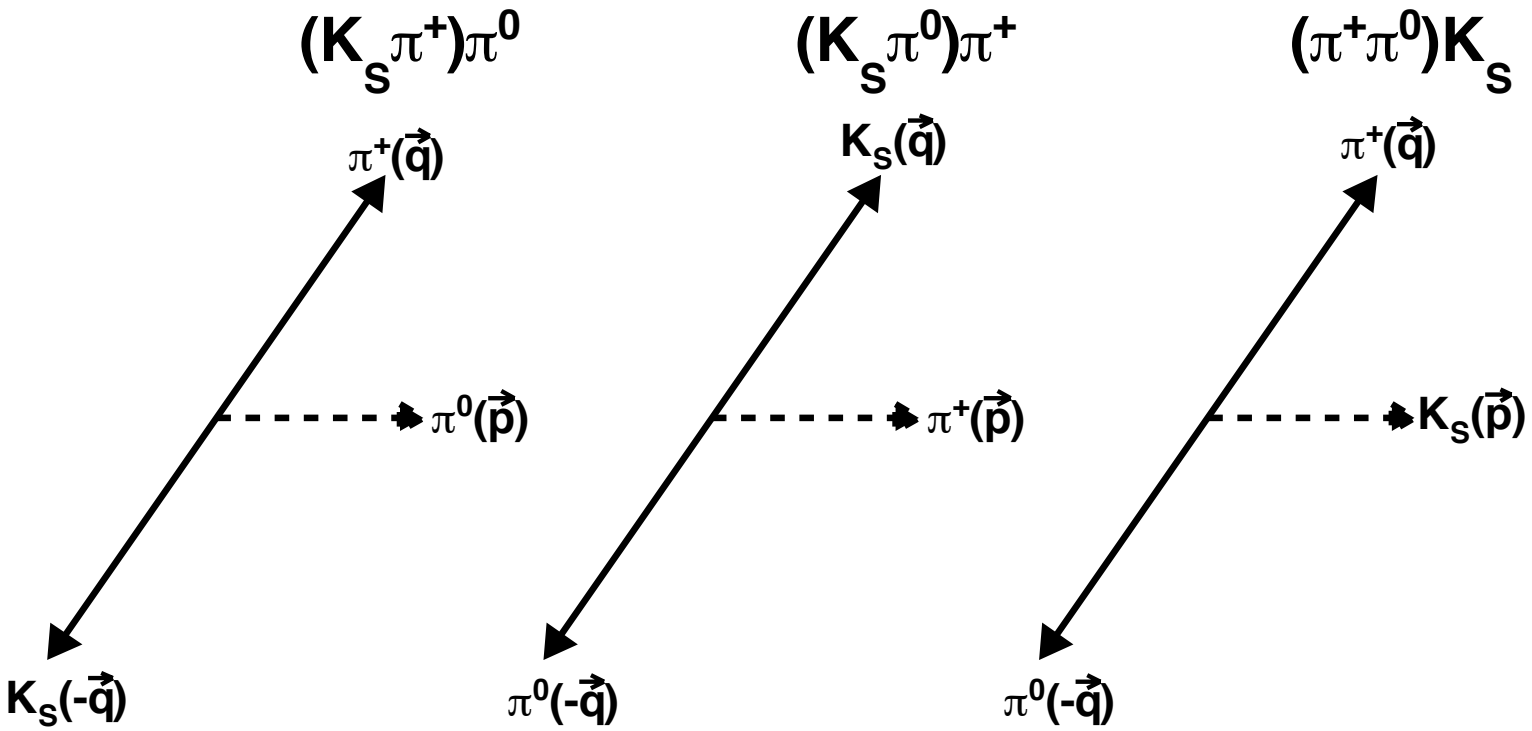


Summary

- Evidence (at the 4.4σ level) for $B^0 \to \omega\omega$, and improved limit for $B^0 \to \omega\phi$
- BF($\omega\omega$) = $\mathbf{(1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6}}$
- BF($\omega\phi$) < $\mathbf{0.7 \times 10^{-6}}$ (90% CL)
- First amplitude analysis of $B^+ \to K_S\pi^+\pi^0$
  - Measurements of intermediate BFs, phases and CP asymmetries
- First evidence (3.4σ) of direct CP violation in intermediate decay $B^+ \to K^{*+}(892)\pi^0$
- Greater precision required to resolve the puzzles in charmless *B* decays – look forward to results from LHCb and Belle II

Backup Slides

Phase convention



LASS parameterisation

- Parametrising the $J^P = 0^+$ component of the $K\pi$ spectrum with LASS parametrisation
- Integrating separately for the different contributions in the parametrisation gives:
  - 88% resonance $K^{*0/+}_0(1430)$
  - 49% effective range nonresonant component (describes slowly increasing phase as a function of $K\pi$ mass)
  - extra 37% from destructive interference
- Effective range part of the amplitude has a cut-off at 1800 MeV/c^2

$$R_j^{\mathrm{LASS}} = \frac{m}{q\cot\delta_B - iq} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{(m_0^2 - m^2) - im_0\Gamma_0\frac{qm_0}{mq_0}}$$