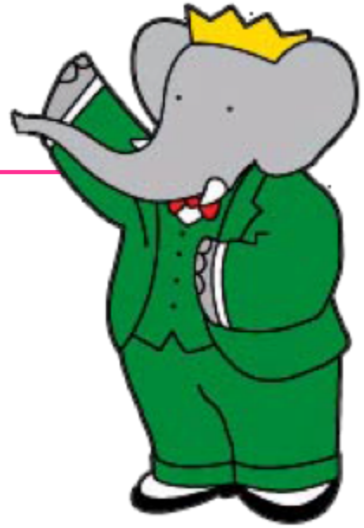
THE UNIVERSITY OF WARWICK

Charmless hadronic B decays with BaBar

Eugenia Maria Teresa Puccio
on behalf of the BaBar collaboration

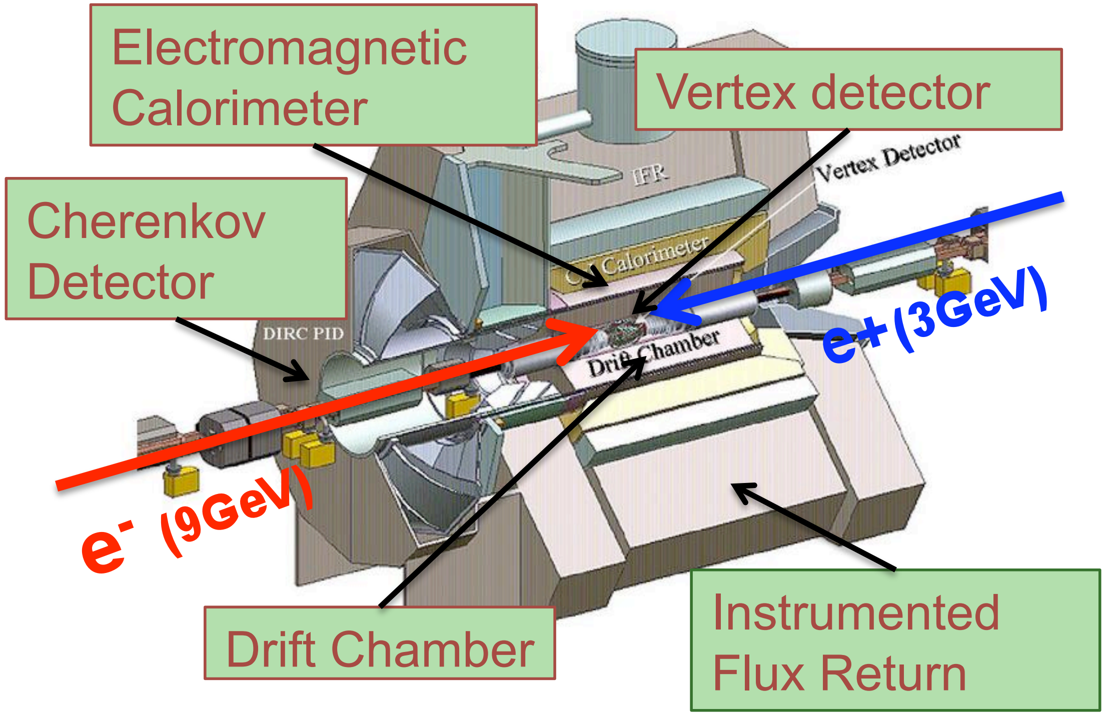


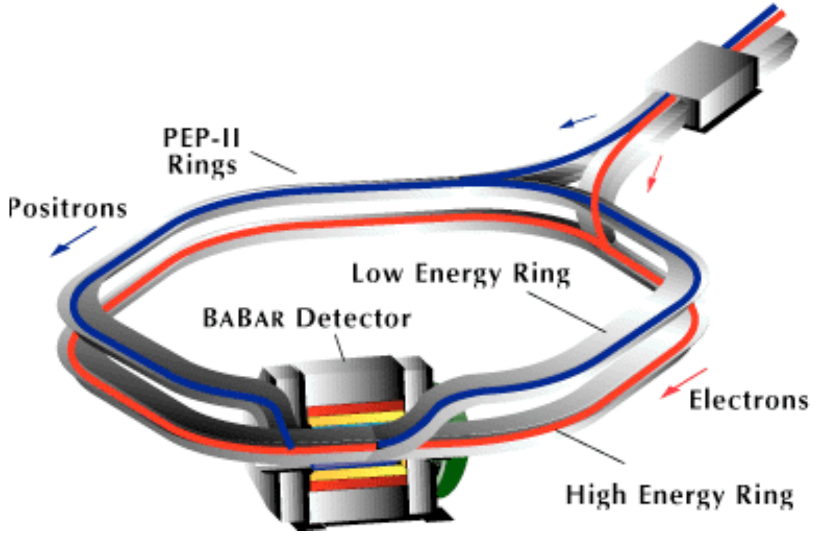
Talk outline

- The experiment
- Analysis techniques
- The results:
  - $B^+ \to \rho^0 K^{*+}$; $B^+ \to f_0 K^{*+}$
  - $B^+ \to \phi\phi K^+$; $B^0 \to \phi\phi K_S$
  - $B^0 \to K^+ \pi^- \pi^0$
  - $B^+ \to K^+ \pi^0 \pi^0$
- Conclusion

PEP-II and BaBar

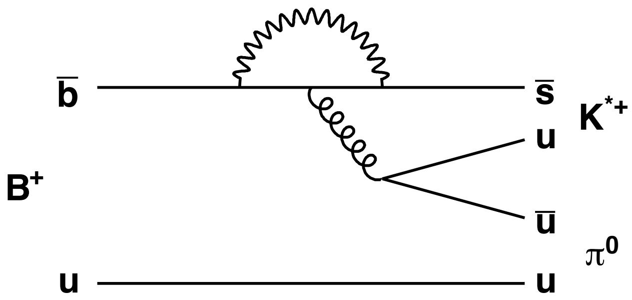
- PEP-II B-Factory collided e^+e^- asymmetric beams at Y(4S) energy threshold

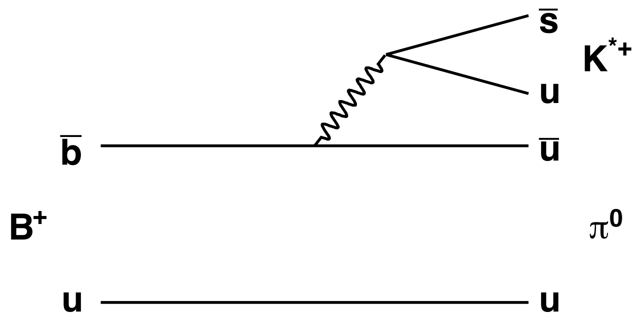




- BaBar in operation from 1999 – 2008
- All analyses presented use full BaBar Y(4S) dataset
  - $432 fb^{-1}$ at the Y(4S)
  - 467M $B\overline{B}$ pairs

Why charmless B decays?



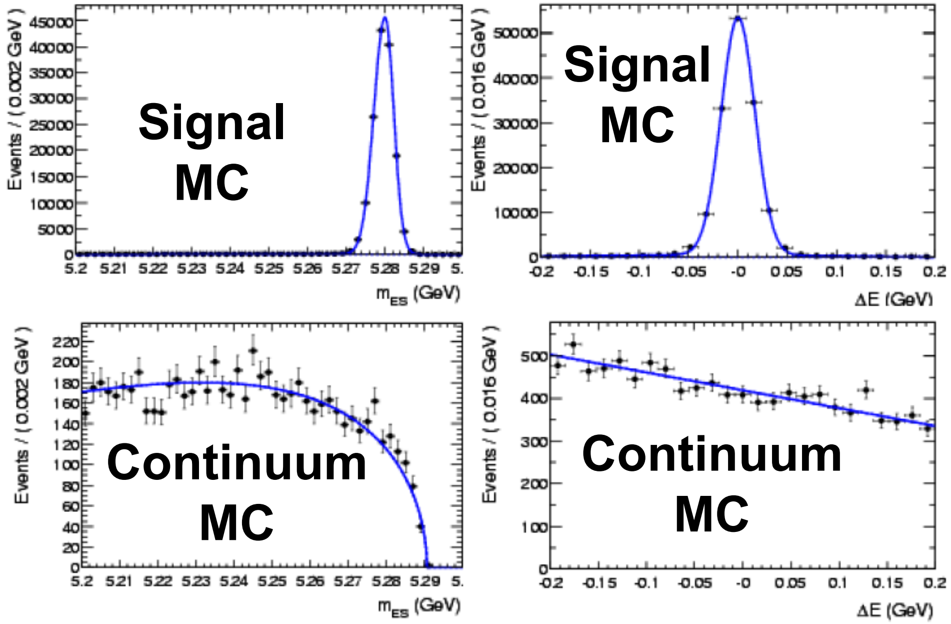


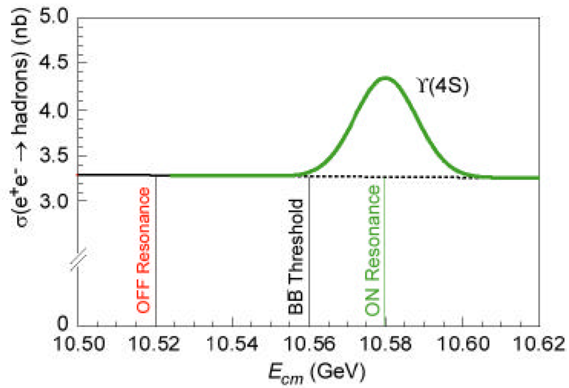
- Charmless B decays probe dynamics of weak and strong interactions
  - Contributions from both penguin and trees can lead to direct CP violation
  - Time dependent measurements and interferences between intermediate states allow to measure all CKM angles
- Allow searching for New Physics from new particles in loops – look for enhanced BF or CP asymmetry (A_{CP})

Analysis techniques

- Use precise kinematical information from beam: m_{ES} and ΔE
- Distinguish light $q\bar{q}$ from $b\bar{b}$ using event topology:
  - B mesons produced almost at rest in the Υ(4S) frame – isotropic event
  - continuum produced with large kinetic energy – jet-like event
- Combine event topology variables in a Neural Network or Fisher discriminant and use output:
  - apply selection to reject continuum
  - as variable in ML fit

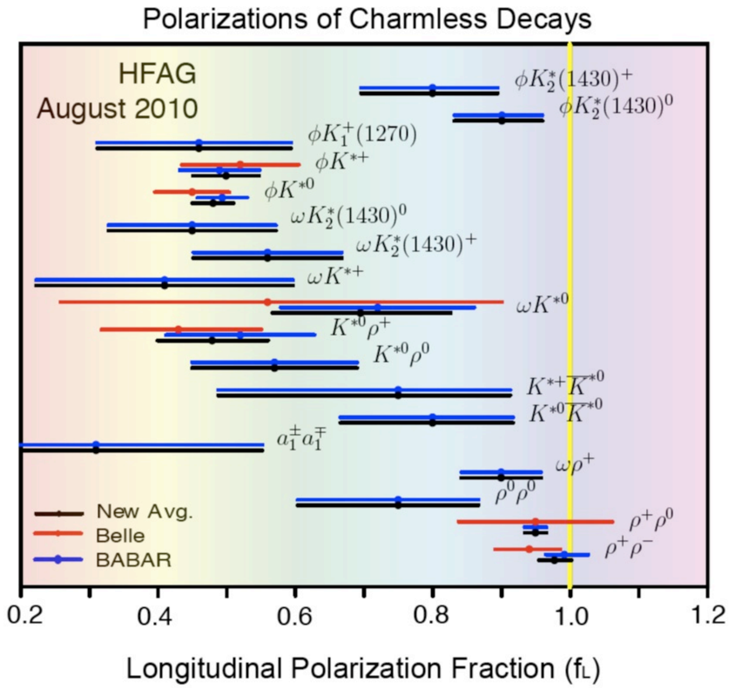
$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}} \qquad \Delta E = E^{*}_{B} - E^{*}_{beam}$$





$B^+ \rightarrow \rho^0 K^{*+}$, $f_0 K^{*+}$: Motivation

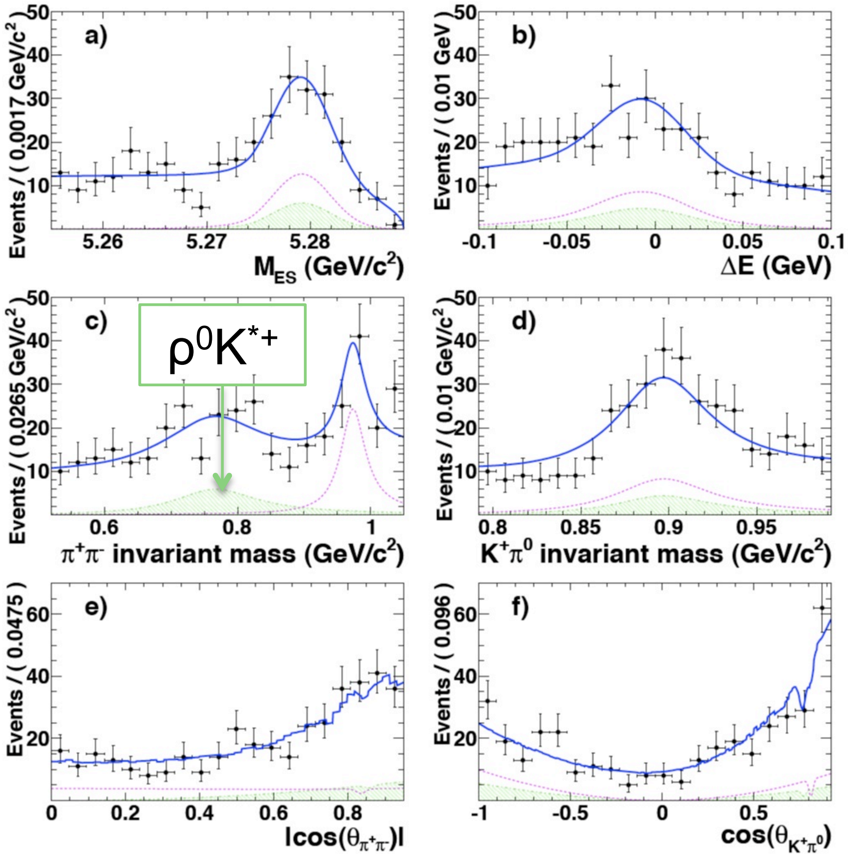
- Model independent predictions give large longitudinal polarisation fractions (f_L) in $B \rightarrow VV$ decays
  - Experimental results give $f_L \approx 0.5$ in penguin dominated $b \rightarrow s$ decays
- $B^+ \rightarrow \rho^0 K^{*+}$ not yet observed
  - Predictions from QCD give BF ≈ (5 ± 1) x 10^{-6}
    - Nucl. Phys. B774, 64 (2007)
    - Phys. Rev. D78, 094001 (2008) [Erratum-ibid. D79, 039903 (2009)]



$B^{+} \rightarrow \rho^{0} K^{*+}$, $f_0 K^{*+}$: Results

Phys.Rev.D83:051101,2011

- Reconstruct ρ^0/f_0 in decay to $\pi^+\pi^-$
- Reconstruct K^{*+} to $K_S\pi^+$ and $K^+\pi^0$
- ML fit with 7 variables
- Results consistent with previous BaBar upper limit
- First observation of $B^+ \rightarrow \rho^0 K^{*+}$ with 5.3σ significance
- f_L compatible with current experimental results in $b \rightarrow s$ decays



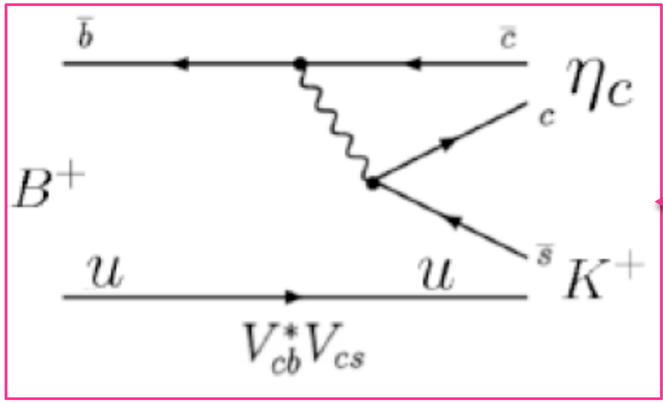
Decay	N_{signal}	BF ($\times 10^{-6}$)	A_{CP} (%)	f_L
$B^+ \rightarrow \rho^0 K^{*+}$	85 ± 24 ($K_S\pi^+$) 67 ± 31 ($K^+\pi^0$)	$4.6 \pm 1.0 \pm 0.4$	$31 \pm 13 \pm 3$	$0.78 \pm 0.12 \pm 0.003$
$B^+ \rightarrow f_0 K^{*+}$	69 ± 14 ($K_S\pi^+$) 91 ± 20 ($K^+\pi^0$)	$4.2 \pm 0.6 \pm 0.3$	$-15 \pm 12 \pm 3$	-

$\rho^0 K^{*+}$ signal

$f_0 K^{*+}$ signal

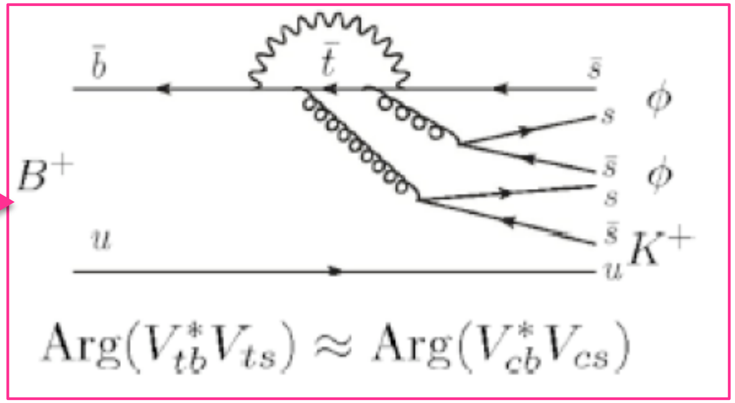
$B \to \phi\phi K$: Motivations

$B \to \eta_c (\to \varphi\varphi) K$ (Tree)



Interference at $m_{\varphi\varphi}$ approx. $m_{\eta c}$

$B \to \varphi\varphi K$ (Penguin)

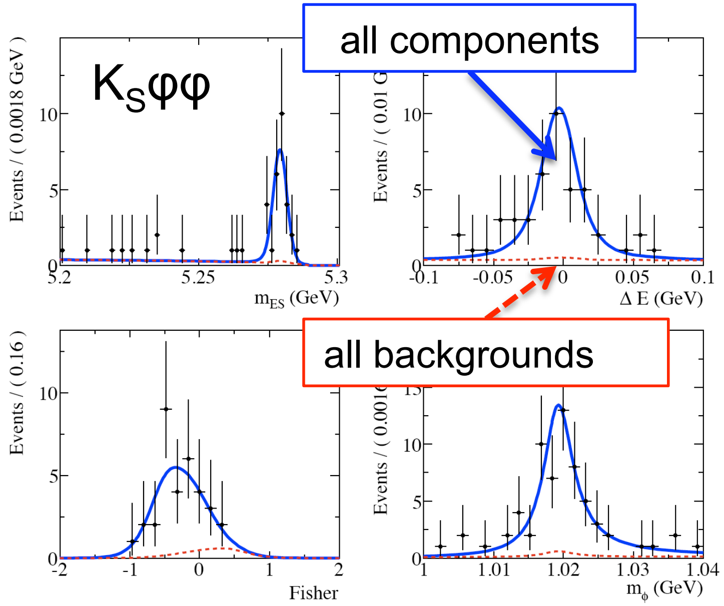


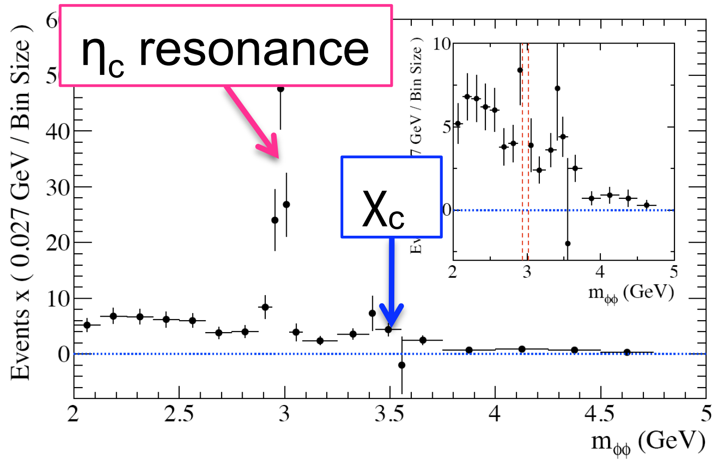
- SM tree and penguin have similar weak phase
  - No direct CP violation expected
- Significant direct CP asymmetry could be produced by a non-zero CP violating phase
  - Sign of New Physics[1]
- Only $J^P = 0^-$ component of $(\varphi\varphi)K$ interferes with η_c
  - Angular analysis is helpful

[1] Phys. Lett. B583, 285 (2004)

$B \rightarrow \phi\phi K$: Results

- ML fit to 5 variables: m_{ES}, ΔE, Fisher, $m_{\varphi 1}$ and $m_{\varphi 2}$
- At $m_{\varphi\varphi}$<2.85 GeV/c^2:
  - $BF(B^+ \rightarrow \phi\phi K^+) = (5.6 \pm 0.5 \pm 0.3) \times 10^{-6}$
  - $A_{CP} = -0.10 \pm 0.08 \pm 0.02$
  - First observation of $BF(B^0 \rightarrow \phi\phi K_S) = (4.5 \pm 0.8 \pm 0.3) \times 10^{-6}$
- In η_c region (2.94<$m_{\varphi\varphi}$<3.02 GeV/c^2)
  - $A_{CP} = -0.09 \pm 0.10 \pm 0.02$ is consistent with SM expectations



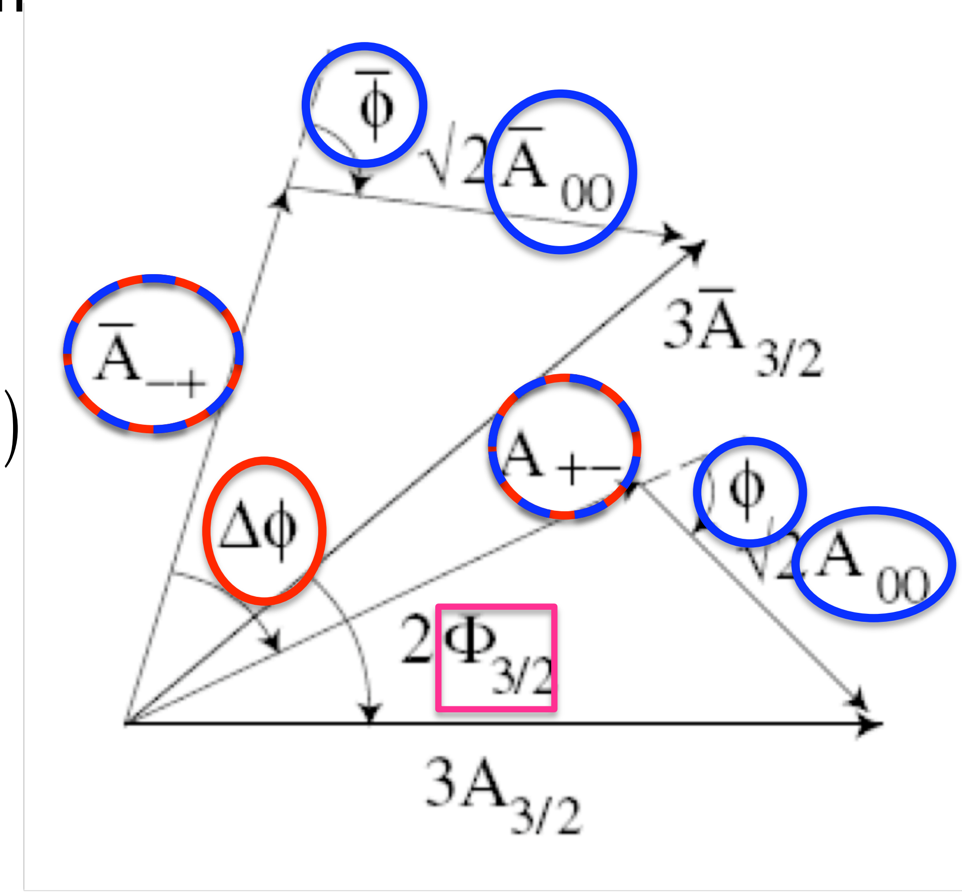


Measuring γ in $B \to K\pi\pi$

- Form isospin triangles from $K^*\pi$ modes: [1]
  - From $B^0 \to K^+\pi^-\pi^0$ [2]
  - From $B^0 \to K_S\pi^+\pi^-$ [3]
- Resultant amplitude:

$$3A_{\frac{3}{2}} = A\left(B^0 \to K^{*+}\pi^-\right) + \sqrt{2}A\left(B^0 \to K^{*0}\pi^0\right)$$

- Phase $\Phi_{3/2}$ determined from combinations of phases and amplitudes
- $\Phi_{3/2}$ is related to γ up to corrections for EW penguins

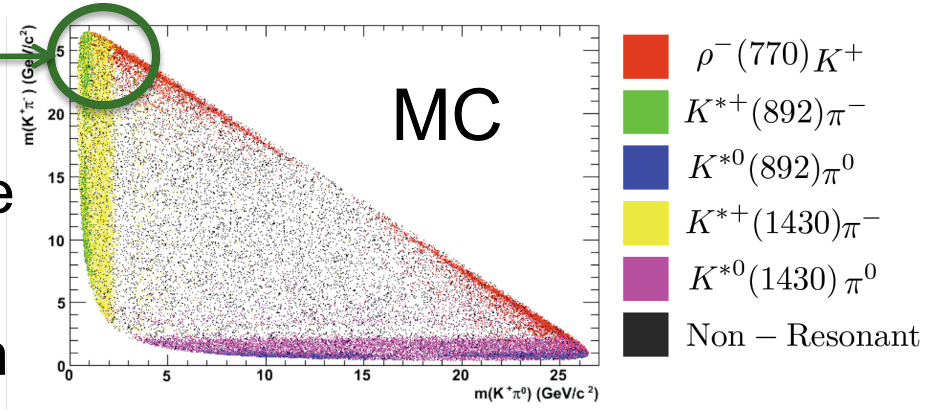


[1] Ciuchini et al., Phys. Rev. D74, 051301 (2006), Gronau et al., Phys. Rev. D81, 094011 (2010)
[2] **Phys.Rev.D83:112010,2011 (results shown here)**
[3] B.Aubert *et al.*, Phys. Rev. D80, 112001

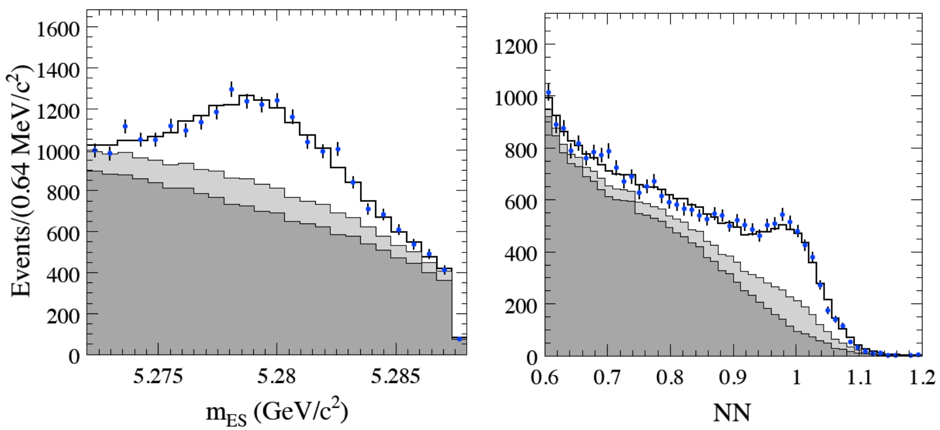
The $K^+\pi^-\pi^0$ Dalitz plot

Phys.Rev.D83:112010,2011

- Overlap region of resonances small
  - Effect on event density is subtle
  - Crucial to understand backgrounds and efficiencies in interference regions.



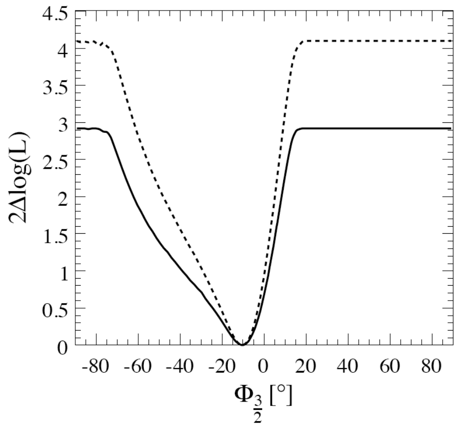
- ML fit with m_{ES}, $\Delta E'$, NN_{out} and DP
  - Maximise separation between signal and background
  - Signal category includes signal from misreconstructed events

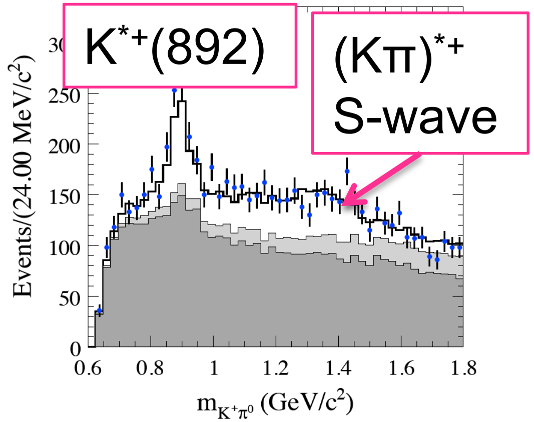


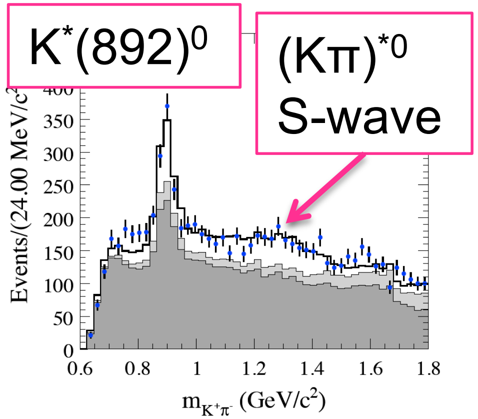
Results from $B^0 \rightarrow K^+\pi^-\pi^0$

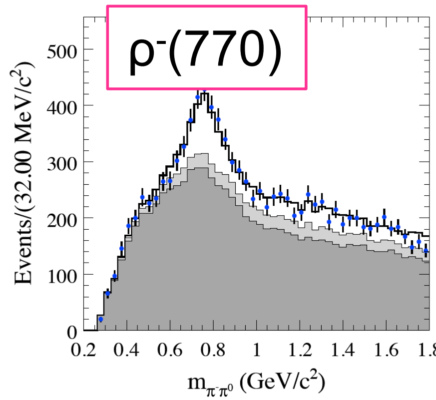
Phys.Rev.D83:112010,2011

- BF($B^0 \rightarrow K^+\pi^-\pi^0$) = $(38.5\pm1.0\pm3.9)\times10^{-6}$
- 3.1σ evidence of direct CP violation in $B^0\rightarrow K^{*+}\pi^-$
- Poor sensitivity to $\Phi_{3/2}$ since $\overline{A}_{3/2}(K^*\pi)$ close to zero.
- $\Phi_{3/2}(\rho K) = (-10^{+10}_{-20}{}^{+7}_{-22})^\circ$





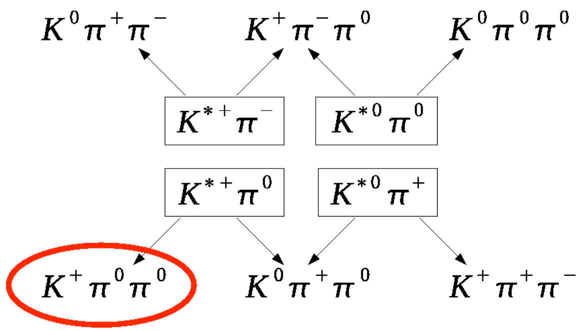




Isobar	$\mathcal{B}$ ($\times10^{-6}$)	$\overline{\Phi}$ [°]	Φ [°]	A_{CP}
$\rho(770)^-K^+$	$6.6\pm0.5\pm0.8$	0 (fixed)	0 (fixed)	$0.20\pm0.09\pm0.08$
$\rho(1450)^-K^+$	$2.4\pm1.0\pm0.6$	$75\pm19\pm9$	$126\pm25\pm26$	$-0.10\pm0.32\pm0.09$
$\rho(1700)^-K^+$	$0.6\pm0.6\pm0.4$	$18\pm36\pm16$	$50\pm38\pm20$	$-0.36\pm0.57\pm0.23$
$K^*(892)^+\pi^-$	$8.0\pm1.1\pm0.8$	$33\pm22\pm20$	$39\pm25\pm20$	$-0.29\pm0.11\pm0.02$
$K^*(892)^0\pi^0$	$3.3\pm0.5\pm0.4$	$29\pm18\pm6$	$17\pm20\pm8$	$-0.15\pm0.12\pm0.04$
$(K\pi)_0^{*+}\pi^-$	$34.2\pm2.4\pm4.1$	$-167\pm16\pm37$	$-130\pm22\pm22$	$0.07\pm0.14\pm0.01$
$(K\pi)_0^{*0}\pi^0$	$8.6\pm1.1\pm1.3$	$13\pm17\pm12$	$10\pm17\pm16$	$-0.15\pm0.10\pm0.04$
NR	$2.8\pm0.5\pm0.4$	$48\pm14\pm6$	$90\pm21\pm15$	$0.10\pm0.16\pm0.08$

Search for $B^+ \to K^+\pi^0\pi^0$: Motivations

- Possible hints of New Physics in measurements of rates and asymmetries in $B \to K\pi$[1,2].
- More precise measurements needed for all observables in $B \to K\pi$ or look at $B \to K^*\pi$ decays[3].



Mode	BF x 10^{-6}	$\mathbf{A_{CP}}$
$K^{*+}\pi^-$	10.3 ± 1.1	-0.23±0.08
$K^{*+}\pi^0$	6.9 ± 2.3	0.04±0.29±0.05[4]
$K^{*0}\pi^+$	9.9 + 0.8 - 0.9	-0.02+0.067-0.061
$K^{*0}\pi^0$	2.4 ± 0.7	-0.15±0.12±0.02

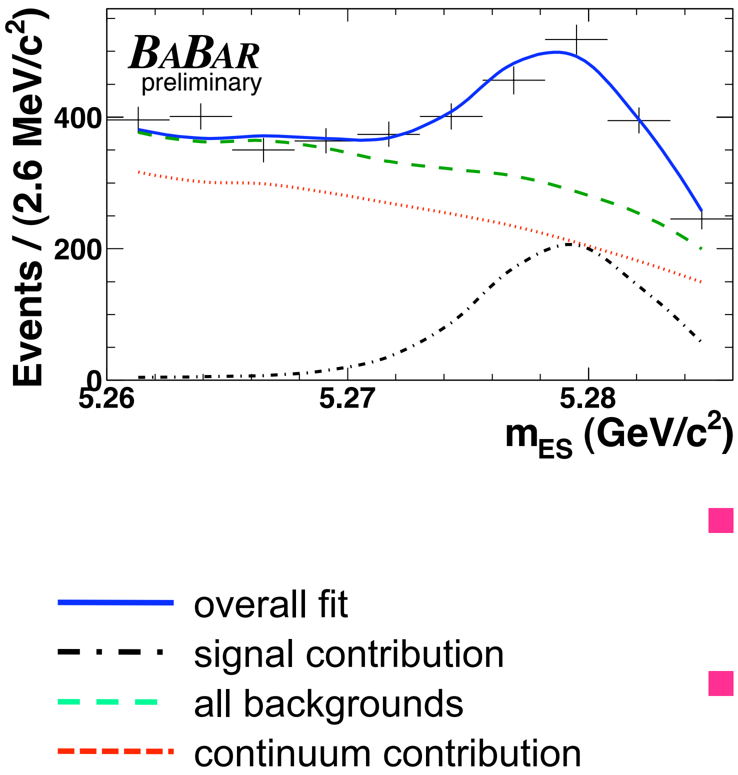
- Improved measurement of $K^{*+}\pi^0$ needed.
- Only 3-body $K\pi\pi$ Dalitz plot not measured.
- Study light mesons in $\pi^0\pi^0$ spectrum eg. $f_0(980)$.

[1] B.Aubert *et al.* (BABAR), *Phys. Rev.* ***D76***, 091102 (2007), 0707.2798
[2] Nature **452,** 332 (2008)
[3] Chiang, C.W. and London, D., *Mod. Phys.Lett.* ***A24***(2009), pp.1983, 0904.2235
[4] B.Aubert *et al.* (BABAR), *Phys. Rev.* ***D71***, 111101 (2005), hep-ex/0504009

Search for $B^+ \to K^+\pi^0\pi^0$: Inclusive results

Preliminary results – To be submitted to Phys. Rev. D

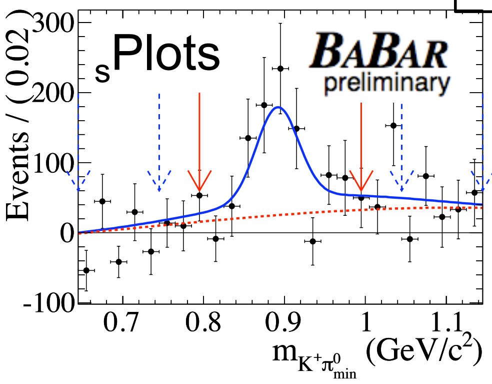
$N_{sig} = 1220 \pm 85$

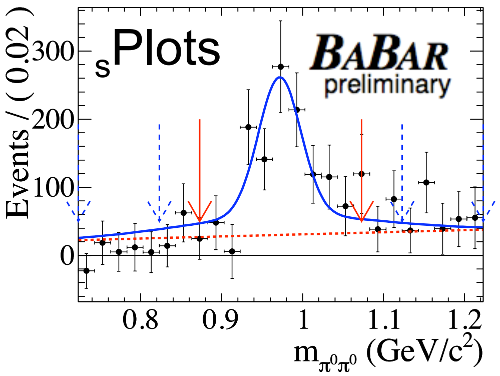


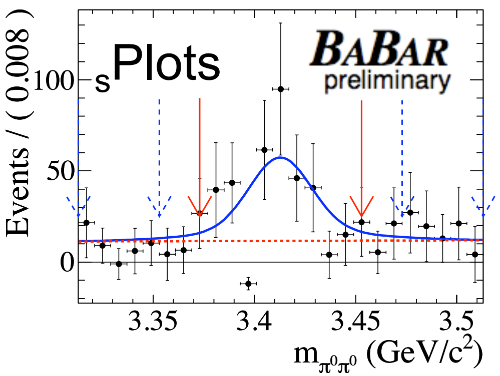
- ML fit to two variables m_{ES} and NN_{out}:
  - DP analysis not possible at present
    - Large fractions of misreconstructed signal events – difficult to model
  - ΔE dependent on DP position, not included in fit to avoid biases
  - Signal component includes also misreconstructed signal events
- $BF(B^+ \to K^+\pi^0\pi^0) = (16.2 \pm 1.2 \pm 1.5) \times 10^{-6}$ with more than 10σ significance
- $A_{CP} = -0.06 \pm 0.06 \pm 0.04$

Search for $B^+ \to K^+\pi^0\pi^0$: resonances

Preliminary results – To be submitted to Phys. Rev. D







- Select resonance signal region in corresponding signal invariant mass reproduced from sWeights
- Yields from nonresonant and other resonances estimated as a normalised average of two sideband regions

Decay mode	**Results**	**Previous world average**
$B^+ \to f_0 (\to \pi^0\pi^0)K^+$	BF= $(2.79 \pm 0.57 \pm 0.51) \times 10^{-6}$ $A_{CP} = (18 \pm 18 \pm 4)\%$	
$B^+ \to K^{*+}(892)\pi^0$	BF = $(8.2 \pm 1.5 \pm 1.1) \times 10^{-6}$ $A_{CP} = (-6 \pm 24 \pm 4)\%$	BF = $(6.9 \pm 2.3) \times 10^{-6}$ $A_{CP} = (4 \pm 29)\%$
$B^+ \to \chi_{c0}K^+$	BF = $(182 \pm 78 \pm 32) \times 10^{-6}$ $A_{CP} = (-96 \pm 37 \pm 4)\%$	BF = $(133^{+19}_{-16}) \times 10^{-6}$ $A_{CP} = (-11 \pm 12)\%$

2.5σ significance

measured from $\chi_c \to \pi^+\pi^-$

Conclusion

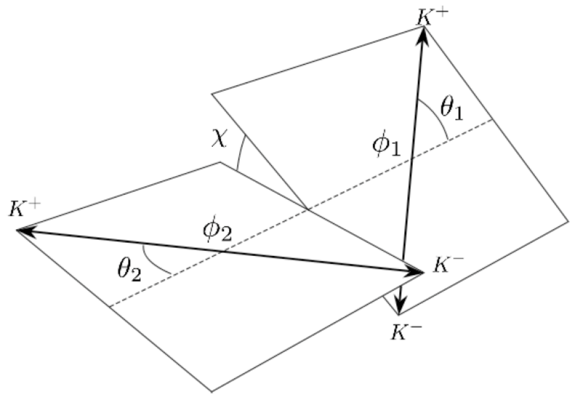
- BaBar continues to produce many new physics results in charmless B decays
- Most of these results agree with Standard Model prediction but some puzzles still remain
  - polarisation puzzle
  - “$K\pi$” puzzle
- More statistics are needed to see if these discrepancies are an indication of New Physics
- Need data from current and future experiments

BACKUP SLIDES

$B \to \phi\phi K$: Angular analysis

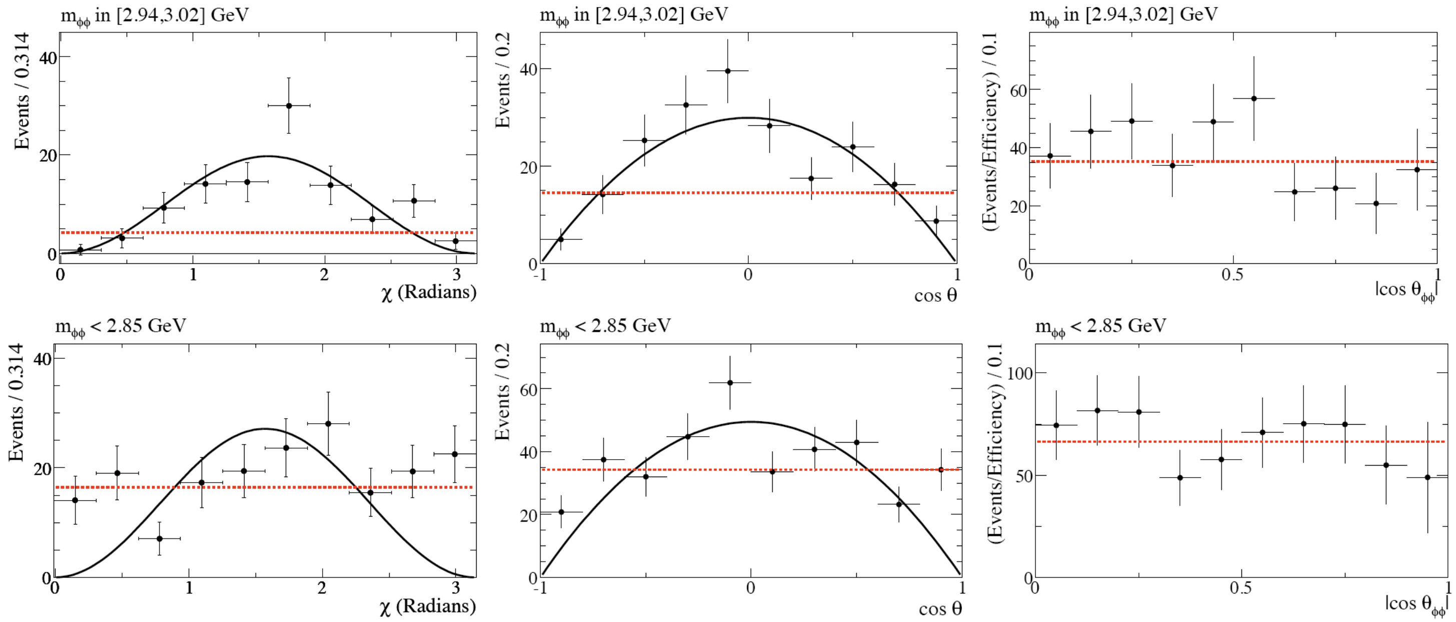
Definition of angles:

- angle between K^+ momentum from φ_i decay wrt to the boost in the $\varphi\varphi$ rest frame
- dihedral angle between φ_1 and φ_2 in $\varphi\varphi$ rest frame
- angle between a φ meson wrt to the boost from B^+ rest frame



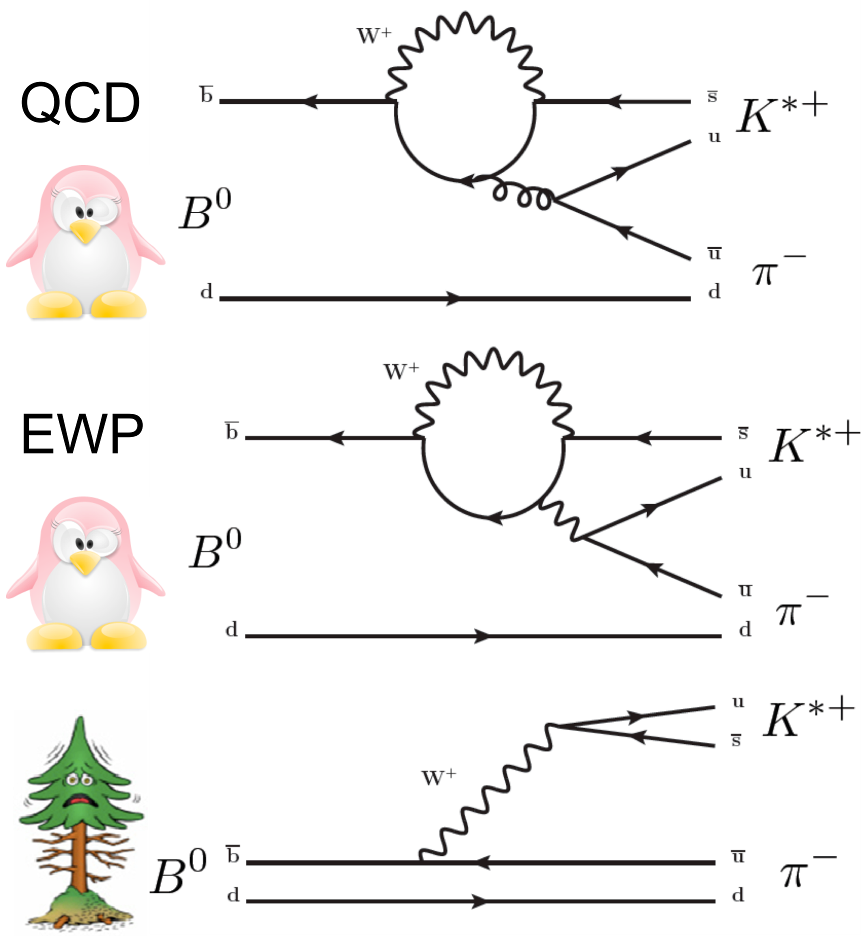
In η_c region consistent with $J^p = 0^-$

Below η_c more consistent with $J^p = 0^+$

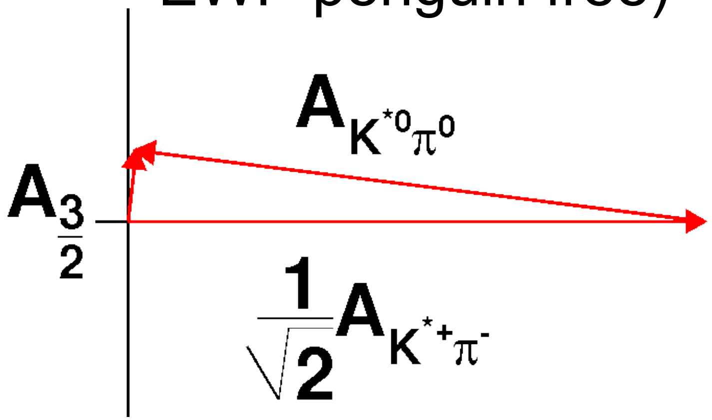


$K^* \pi$ Amplitudes and penguins

$$A_{\frac{3}{2}} = \frac{1}{\sqrt{2}} A\left(B^0 \to K^{*+}\pi^-\right) + A\left(B^0 \to K^{*0}\pi^0\right)$$



- Tree component expected to be small compared to dominant QCD penguin in $K^*\pi$ amplitudes
- QCD penguin contributions cancel in the sum of $A_{K^*\pi}$
  - $A_{3/2}$ is QCD penguins free (not EWP penguin free)



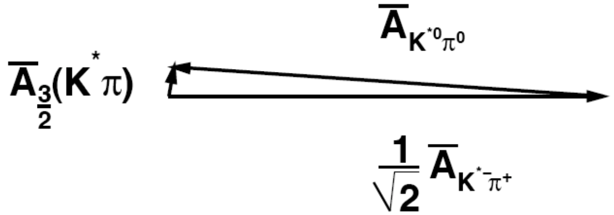
$K^+\pi^-\pi^0$ DP: $K^*\pi$ vs ρK amplitudes

Phys.Rev.D83:112010,2011

- $\bar{A}_{3/2}(K^*\pi)$ found to be consistent with 0:
  - Uncertainties on $\Phi_{3/2}$ too large

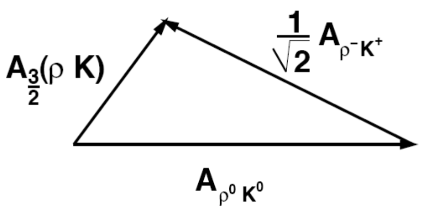
$$\bar{A}_{\frac{3}{2}} = \frac{1}{\sqrt{2}}\bar{A}\left(B^0 \to K^{*-}\pi^+\right) + \bar{A}\left(B^0 \to K^{*0}\pi^0\right)$$

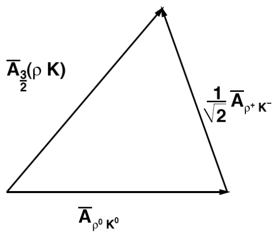
All from $B^0 \to K^+\pi^-\pi^0$ DP



$$\bar{A}_{\frac{3}{2}} = \frac{1}{\sqrt{2}}\bar{A}\left(B^0 \to \rho^+K^-\right) + \bar{A}\left(B^0 \to \rho^0K^0\right)$$

From $B^0 \to K^+\pi^-\pi^0$ DP	From $B^0 \to K_S\pi^+\pi^-$ DP



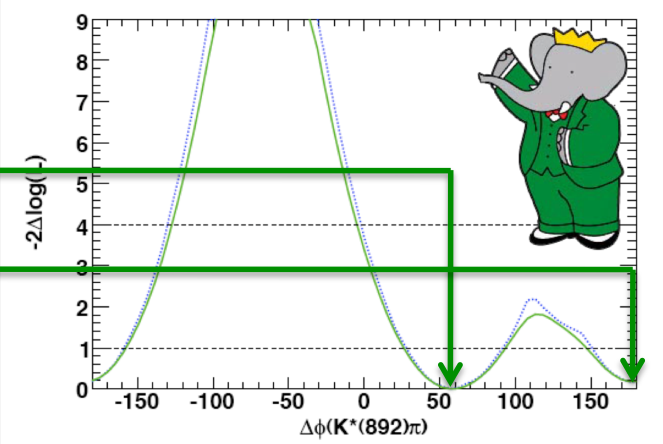


- Situation in ρK decays found to be more favorable.

Results from time dependent $B^0 \rightarrow K_S\pi^+\pi^-$

- BaBar result from 383 million $B\bar{B}$ events gives:
  - $\Delta\phi = (58.3 \pm 32.7 \pm 4.6 \pm 8.1)°$
  - $\Delta\phi = (176.6 \pm 28.8 \pm 4.6 \pm 8.1)°$

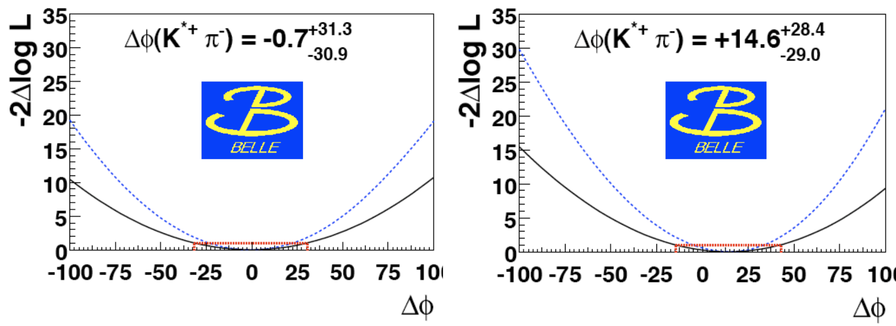
  (errors are stat, syst, model)



B.Aubert *et al.*, Phys. Rev. D80, 112001

- Belle results from 657 million $B\bar{B}$:
  - $\Delta\phi = (-0.7 \pm ^{24}_{23} \pm 11 \pm 18)°$
  - $\Delta\phi = (+14.6 \pm ^{19}_{20} \pm 11 \pm 18)°$

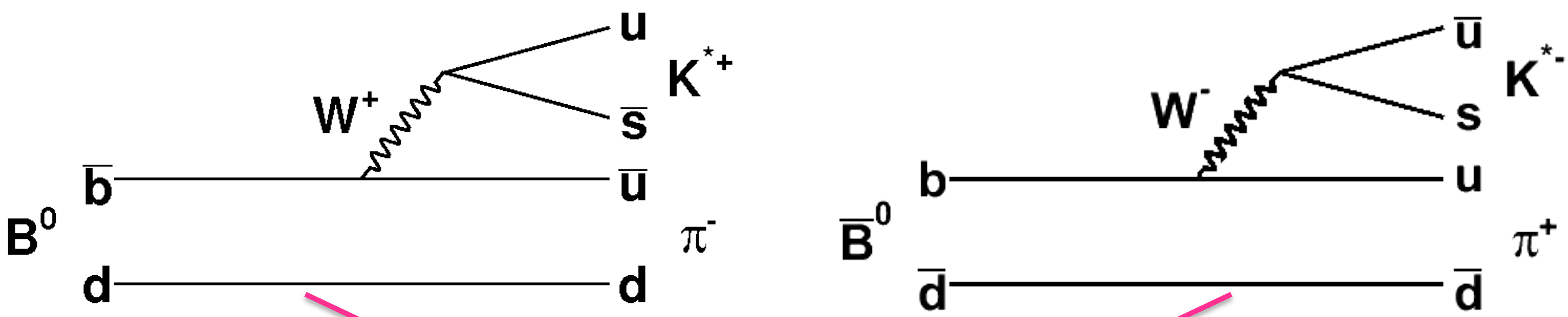
  (errors are stat, syst, model)
- Difference between solutions is interference between $K_0^{*\pm}(1430)$ and NR



J.Dalseno *et al.*, Phys. Rev. D79, 072004

- This phase difference includes the $B^0\bar{B}^0$ mixing phase (-2β)

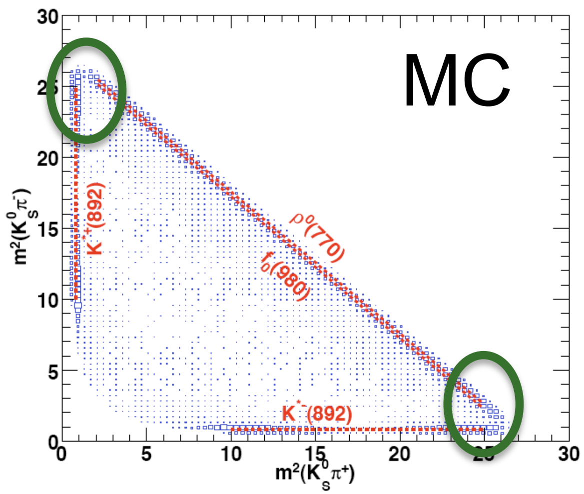
$K^{*+}\pi^-$ and $K^{*-}\pi^+$ phase difference



$$\boxed{B^0 \to K_S\pi^+\pi^-}$$

$$\Delta\phi_{K^*\pi} = \bar{\phi}_{K^{*-}\pi^+} - \phi_{K^{*+}\pi^-}$$

- Measure $K^*\pi$ phases relative to each other due to mixing
  - Additional phase of -2β needs to be accounted for.



Issue 1 - Phase conventions

- Each quasi-two body subsystem of $K\pi\pi$ in the vector meson rest frame contains:
  - Two pseudoscalar decay products with momentum **q** and –**q**
  - The bachelor pseudoscalar with momentum **p**
- Choice of which resonance daughter is defined to have positive momentum defines the phase convention
- Alternative choice induces a 180° flip of the phase
- Whichever choice is made it must be correctly accounted for when combining amplitudes to obtain the constraint on the UT apex
- See Gronau *et al.*, Phys.Rev.D**81**, 094026(2010)

Issue 2 - EWP contributions

$$A_{\frac{3}{2}} = \boxed{Te^{i\gamma}} - \boxed{P_{EWP}}$$

EWP

Gronau *et al.*, Phys.Rev.D75, 014002

$$A_{\frac{3}{2}} \propto \left(\bar{\rho} + i\bar{\eta}\right)\left(1 + \boxed{r_{\frac{3}{2}}}\right) + \boxed{C}\left(1 - r_{\frac{3}{2}}\right)$$

SU(3) decomposition of operators gives good approximation:

Wilson coeff, λ ≈ -0.27

Ratio of hadronic matrix elements

$$\boxed{r_{\frac{3}{2}} = \frac{\left[A_{\rho^+\pi^0} - A_{\rho^0\pi^+}\right] - \sqrt{2}\left[A_{K^{*+}\overline{K}^0} - A_{K^+\overline{K}^{*0}}\right]}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}}}$$

Estimating $r_{3/2}$

Decay Mode	BF(x10^{-6})	A_{CP}
$B^+ \to \rho^0 \pi^+$	$8.3^{+1.2}_{-1.3}$	$0.18^{+0.09}_{-0.17}$
$B^+ \to \rho^+ \pi^0$	$10.9^{+1.4}_{-1.5}$	0.02 ± 0.11
$B^+ \to K^+ \overline{K}^{*0}$	0.68 ± 0.19	-
$B^+ \to K_S K_S \pi^+$	< 0.51	-

BFs are well measured

Amplitudes small but relative phases unknown

Experimental numbers from HFAG Winter 2010, www.slac.stanford.edu/xorg/hfag/

Strategy – Separate into well-measured components and systematic uncertainty

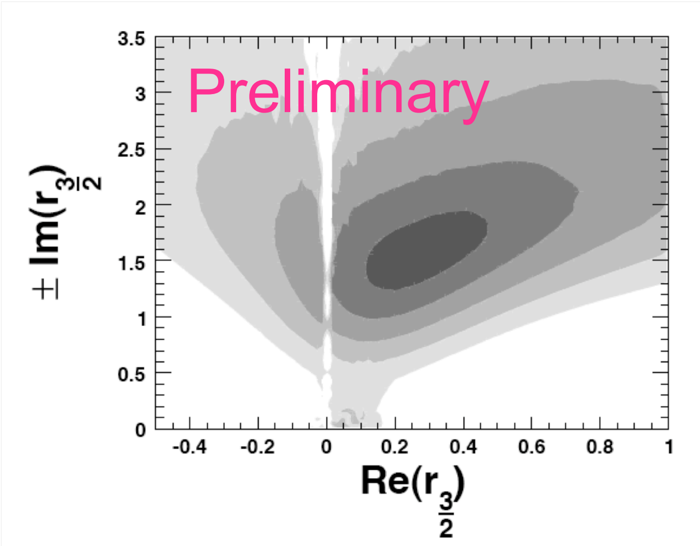
K*K Systematic

$$\frac{m_s}{\Lambda_{QCD}} \approx 30\%$$

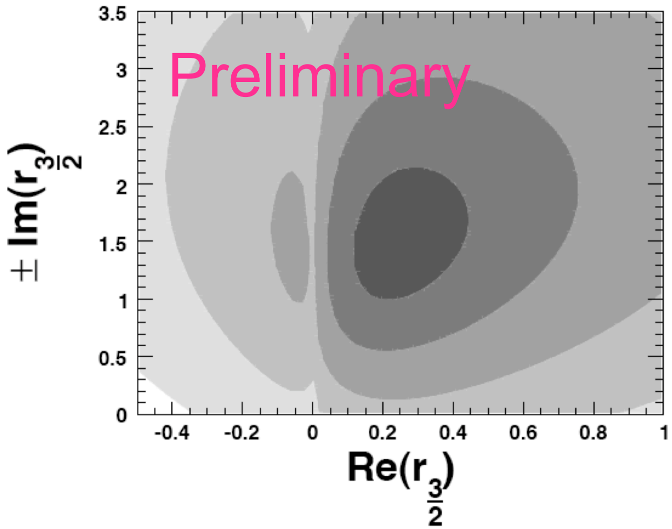
$$r_{\frac{3}{2}} = \frac{A_{\rho^+\pi^0} - A_{\rho^0\pi^+}}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}} \pm \boxed{\sqrt{2}\,\frac{A_{K^{*+}\overline{K}^{*0}} - A_{K^+\overline{K}^{*0}}}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}}} \pm \boxed{30\% SU(3)}$$

Measurement of $r_{3/2}$

3% SU(3) breaking



30% SU(3) breaking



Contours darkest to lightest:
1, 2, 3, 4, 5σ

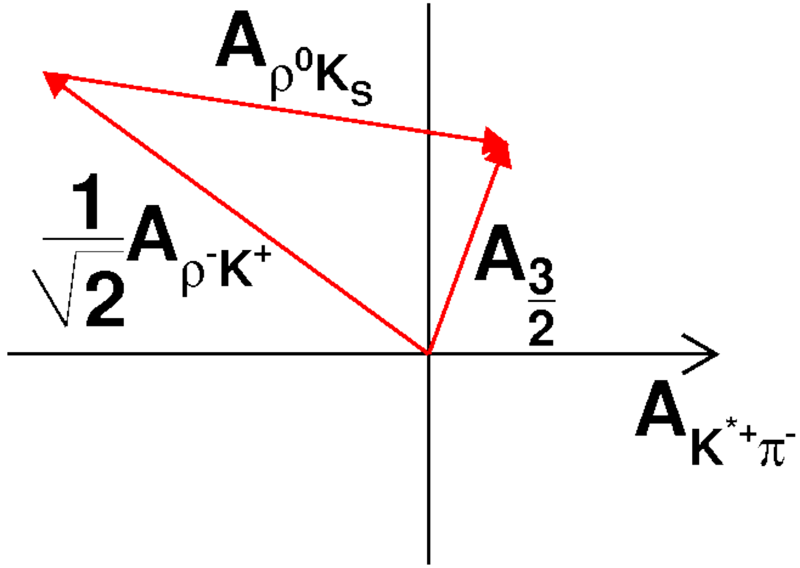
A. Wagner, PhD Thesis, SLAC-R-942

$$r_{\frac{3}{2}} \equiv \frac{A_{\rho^+\pi^0} - A_{\rho^0\pi^+}}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}}$$

- K^*K contribution added as a systematic.

Determining γ from $B \to \rho K$

- Another method involves using $B \to \rho K$ with $K^+\pi^-\pi^0$ and $K_S\pi^+\pi^-$
- Subtle difference with $K^*\pi$: relative phase not measured directly:
  - ρ^+K^- measured from $K^+\pi^-\pi^0$
  - ρ^0K_S measured from $K_S\pi^+\pi^-$
- $A_{3/2}$ determined from difference between the phases relative to $K^{*+}\pi^-$



- EW penguin contributions follow again from $\rho\pi$ like in $K^*(892)\pi$ case

Interference fractions

$$FF_{ij} = \frac{\int_{\mathrm{DP}} 2\,\mathrm{Re}\left[c_i c_j^* F_i(m_+^2, m_-^2) F_j^*(m_+^2, m_-^2)\right] d(m_+^2) d(m_-^2)}{\int_{\mathrm{DP}} \left|\sum_j c_j F_j(m_+^2, m_-^2)\right|^2 d(m_+^2) d(m_-^2)}$$

- Gives the extent of the interference effect between two resonances as measured in the fit.
- It's a convention independent representation of the event population of the DP
  - $+FF_{ij}$ = constructive interference
  - $-FF_{ij}$ = destructive interference