Determination of the CKM angle γ from $B \to K\pi\pi$ Dalitz plots

Thomas Latham

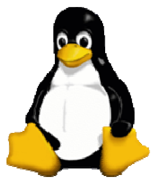
THE UNIVERSITY OF WARWICK

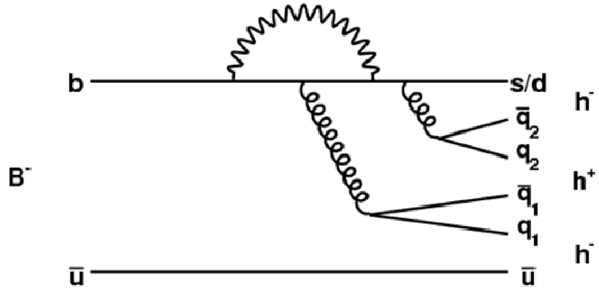
BaBar Collaboration

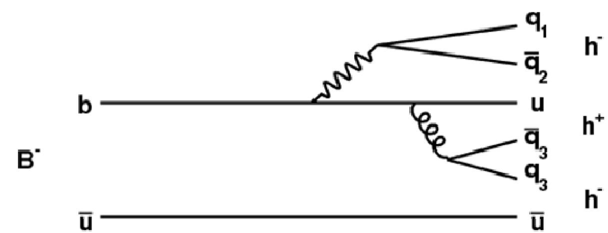
Overview

- Introduction
- Motivation
- Recent results:
  - $B^+ \to K^+\pi^+\pi^-$
  - $B^0 \to K_S\pi^+\pi^-$
  - $B^0 \to K^+\pi^-\pi^0$
- Implications for γ
- Conclusion

Introduction to $B \to K\pi\pi$ Decays







- Rich Dalitz-plot structure – interference between intermediate resonant states, e.g. K^*, ρ
  - Gives rise to both $\sin(2\beta_{\mathrm{eff}})$ and to $\cos(2\beta_{\mathrm{eff}})$ terms in B^0 decays to CP eigenstates, e.g. $\rho^0 K_S$
- Both $b \to u$ (tree) and $b \to s$ (penguin) processes
  - Possible direct CP violation
- Relative weak phase of tree and penguin = γ

Introduction to $B \to K\pi\pi$ Decays

- Additional contributions possible in some cases from $b \to c$ (tree) diagrams, e.g. via the χ_{c0} resonance
- Interference between the χ_{c0} and the nonresonant or other resonant states in $B^+ \to \pi^+\pi^+\pi^-$ or $K^+\pi^+\pi^-$ could, in principle, allow a determination of γ
  - Eilam et al., Phys. Rev. Lett. 74, 4984 (1995)
  - Bediaga et al., Phys. Rev. Lett. 81, 4067 (1998)
  - Blanco et al., Phys. Rev. Lett. 86, 2720 (2001)
- However, the rather small BF of $B \to \chi_{c0}K/\pi$ seems to preclude this, at least at current luminosities

Summary of $K^*\pi$ and ρK experimental measurements and theory predictions

	Branching Fraction (10^{-6})		A_{CP} (%)	
Mode	Exp.	QCDF	Exp.	QCDF
$K^{*0}\pi^+$	10.0 ± 0.8	8.9 ± 1.6	-2 ± 7	0.16 ± 0.16
$K^{*+}\pi^0$	6.9 ± 2.3	5.3 ± 0.8	4 ± 29	-41 ± 7
$K^{*+}\pi^-$	10.3 ± 1.1	9.1 ± 1.7	-25 ± 11	-48 ± 8
$K^{*0}\pi^0$	2.4 ± 0.7	3.9 ± 0.8	-15 ± 12	4.7 ± 1.1
ρ^+K^0	$8.0 \pm^{1.5}_{1.4}$	10.3 ± 2.0	-12 ± 17	0.53 ± 0.21
ρ^0K^+	3.8 ± 0.5	4.8 ± 0.9	$42 \pm^{8}_{10}$	46 ± 6
ρ^+K^-	$8.6 \pm^{0.9}_{1.1}$	13.4 ± 2.3	15 ± 6	31.4 ± 4.6
ρ^0K^0	$5.4 \pm^{0.9}_{1.0}$	7.5 ± 1.3	1 ± 20	-3.3 ± 1.3

Experimental numbers from HFAG Summer 2008, QCDF predictions from Chang et al., arXiv:0807.4295v3

Summary of $K^{*}\pi$ and ρK experimental measurements and theory predictions

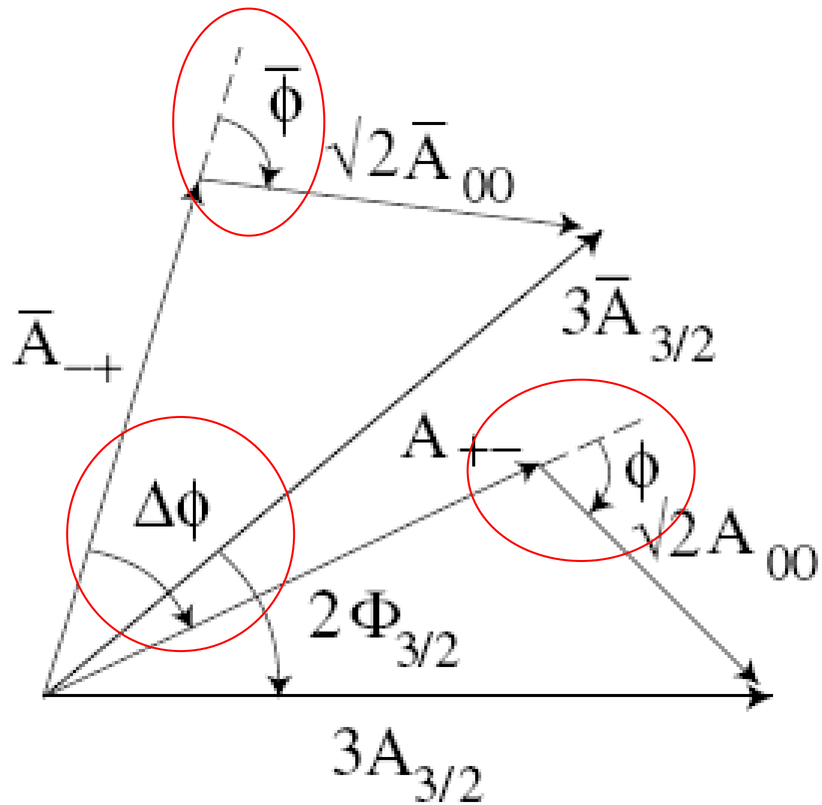
- Agreement between experiment and theory is generally good
- Experimental precision on *CP* asymmetries much worse than theory errors
- Would be nice to have (updated) results from $K_S\pi^+\pi^0$ and $K^+\pi^0\pi^0$, particularly given large A_{CP} prediction in $K^{*+}\pi^0$
- Most results now coming from Dalitz-plot analyses
  - Additional information in the phases can be used to reduce the model dependence in extracting γ

Determining γ from $K\pi\pi$ DPs

- Much recent theoretical activity in this area
  - See first talk in session by Pierini and Zupan for more detail
- Main method involves $K^+\pi^-\pi^0$ and $K_S\pi^+\pi^-$ DPs
  - Ciuchini et al., Phys. Rev. D74, 051301 (2006)
  - Gronau et al., Phys. Rev. D75, 014002 (2007)
  - Gronau et al., Phys. Rev. D77, 057504 (2008) and D78, 017505 (2008)
- Other methods use $K_S\pi^+\pi^0$; $K^+\pi^+\pi^-$ & $K_S\pi^+\pi^-$; and B_s decays to $K^+\pi^-\pi^0$ & $K_S\pi^+\pi^-$
  - Ciuchini et al., Phys. Rev. D74, 051301 (2006)
  - Bediaga et al., Phys. Rev. D76, 073011 (2007)
  - Ciuchini et al., Phys. Lett. B645, 201 (2007)

Determining γ from $K\pi\pi$ DPs

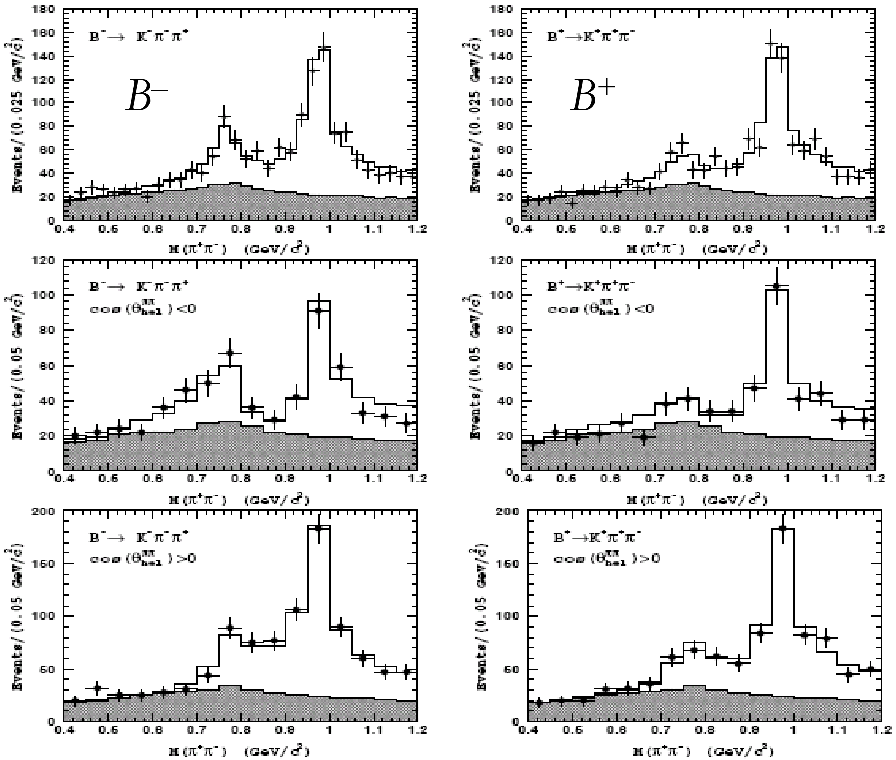
- Method from Ciuchini et al. and Gronau et al.
- Use $B \rightarrow K^*\pi$ modes to form isospin triangles
- $A_{ij} = A(B^0 \rightarrow K^{*i}\pi^j)$
- $\Phi_{3/2} = \gamma$ up to correction from EW penguins
- The amplitude magnitudes as well as ϕ, $\bar{\phi}$ and $\Delta\phi$ can be measured from Dalitz-plot analyses of $K^+\pi^-\pi^0$ and $K_s\pi^+\pi^-$



Recent Results – $B^+ \to K^+\pi^+\pi^-$

- Results not directly used in main γ method
- But, highest (BF x ε) of all $K\pi\pi$ modes
  - Help determine signal DP model for other modes
- Possible large A_{CP} in $\rho^0 K^+$
  - Establishes that tree and penguin magnitudes are comparable and hence sensitivity to γ
- Another method uses this mode and $K_S\pi^+\pi^-$ – useful for LHCb since no neutral particles
  - See last talk in the session by Guerrer

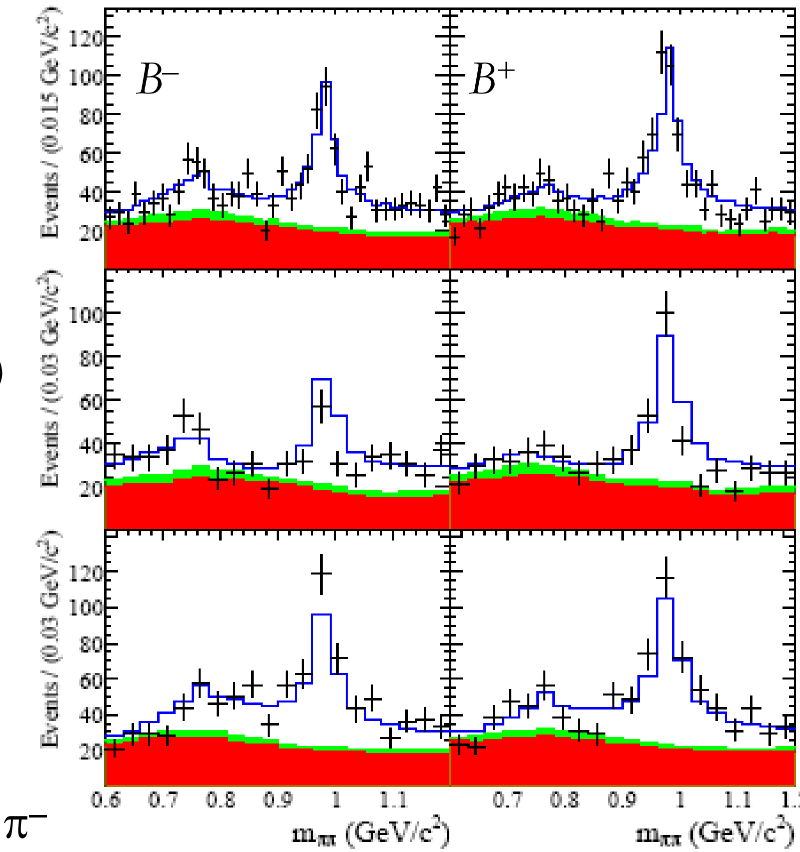
Recent Results – $B^+ \to K^+\pi^+\pi^-$

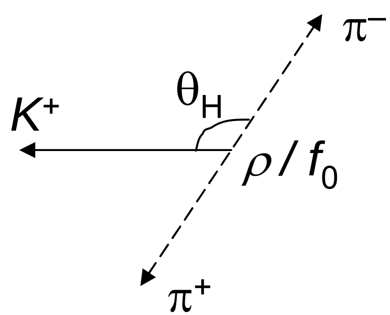


All

$\cos(\theta_H) > 0$

$\cos(\theta_H) < 0$

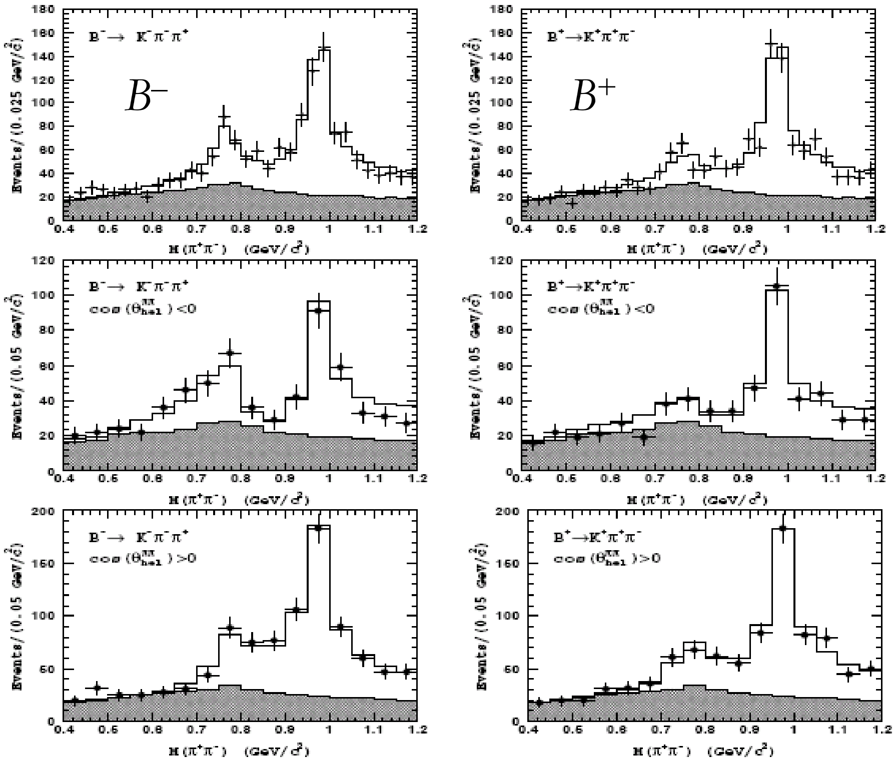




BELLE-CONF-0827

PRD 78, 012004 (2008)

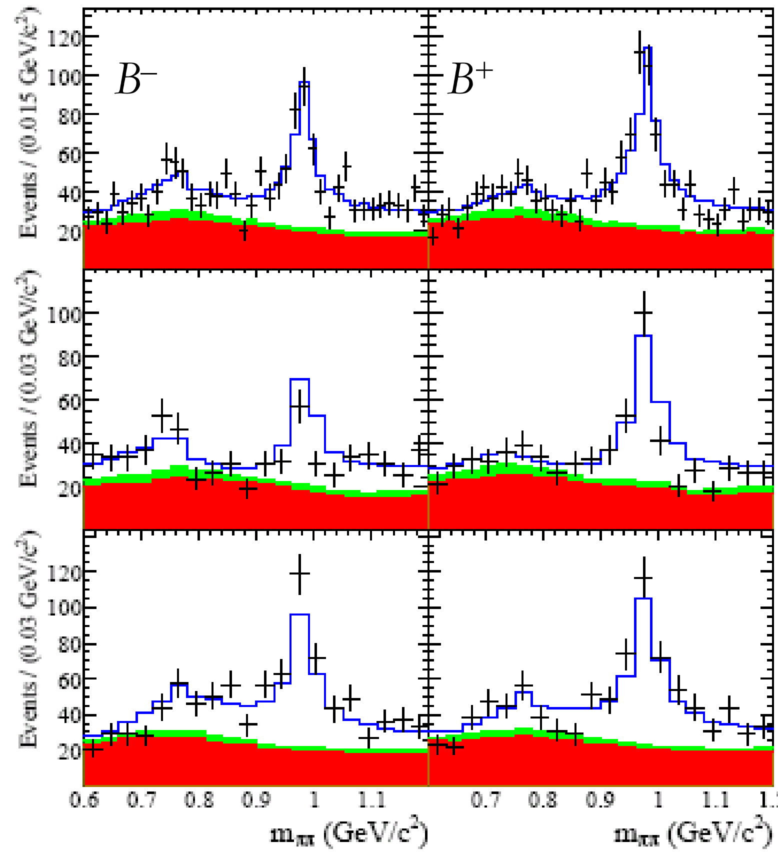
Recent Results – $B^+ \to K^+\pi^+\pi^-$



All

$\cos(\theta_H) > 0$

$\cos(\theta_H) < 0$



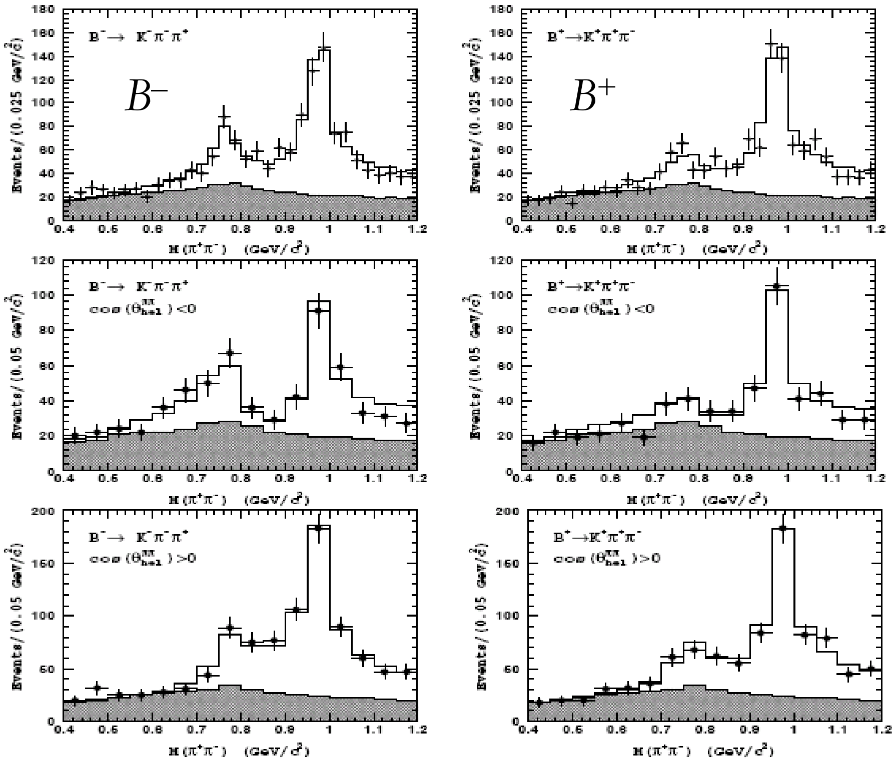
BELLE-CONF-0827 – 657 million BB

PRD 78, 012004 (2008) – 383 million BB

$\mathbf{A_{CP}(\rho^0 K^+) = (+41 \pm 10 \pm 3 \pm {}^{3}_{7})\%}$

$\mathbf{A_{CP}(\rho^0 K^+) = (+44 \pm 10 \pm 4 \pm {}^{5}_{13})\%}$

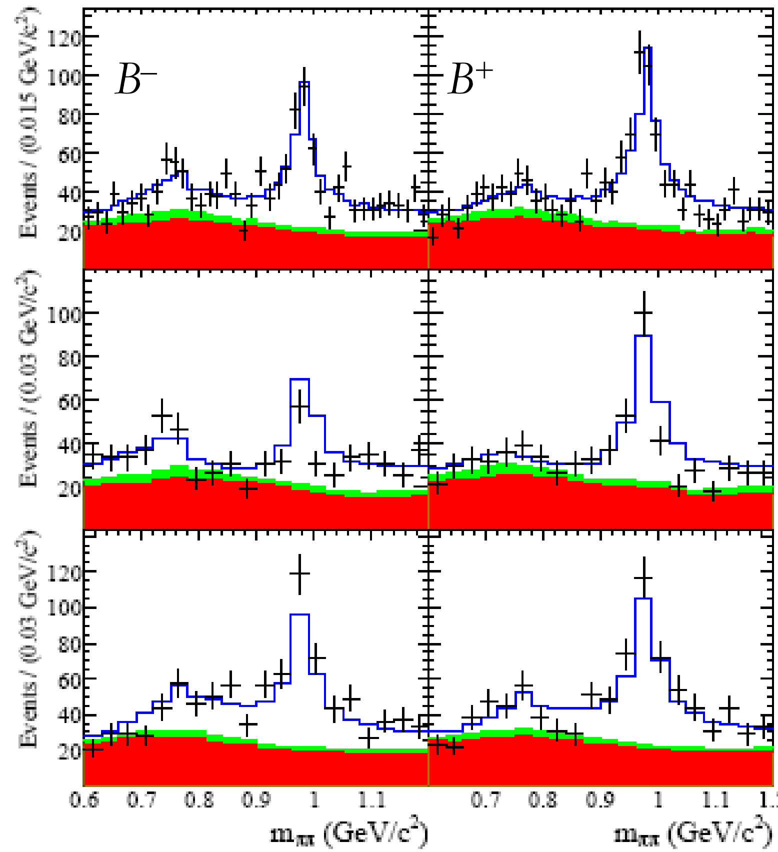
Recent Results – $B^+ \to K^+\pi^+\pi^-$



All

$\cos(\theta_H) > 0$

$\cos(\theta_H) < 0$



HFAG Average

$A_{CP}(\rho^0 K^+) = (+42 \pm {}^{8}_{10})\%$

~ 4 σ significance

(including systematic and model dependent uncertainties)

Recent Results – $B^0 \to K_S\pi^+\pi^-$

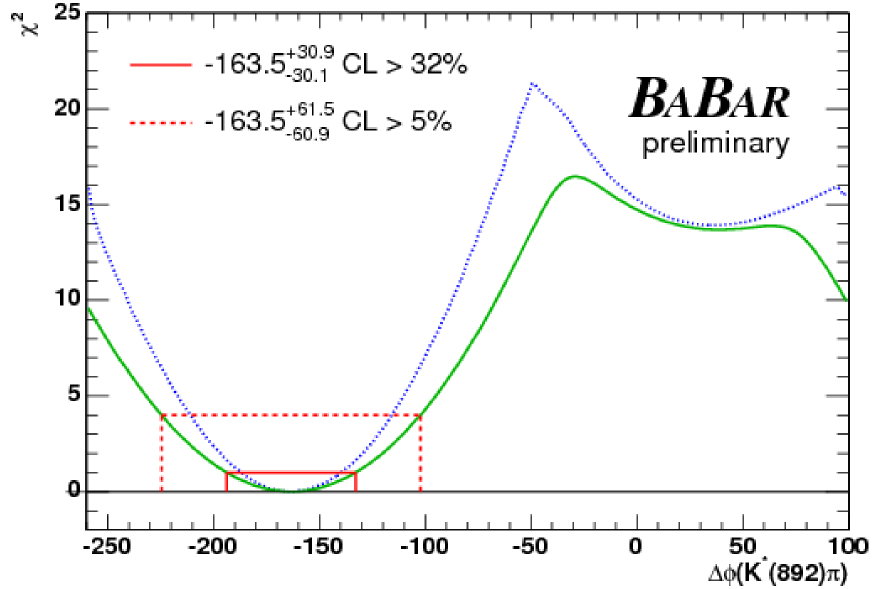
- Phase $\Delta\phi$ can be determined from this DP from interference between:
  - $K^{*+}\pi^-$ and $\rho^0 K_S$ in the B^0 decay
  - $K^{*-}\pi^+$ and $\rho^0 K_S$ in the $\bar{B}^0$ decay
- Does not require tagging or time-dependent analysis
- However, both BABAR (Lepton-Photon '07) and Belle (ICHEP '08) have performed time-dependent analyses of this mode
- Time-dependent analyses also allow measurement of β_{eff} from $\rho^0 K_S$, $f_0 K_S$ etc.
  - See talk in tomorrow's session by Dalseno on β

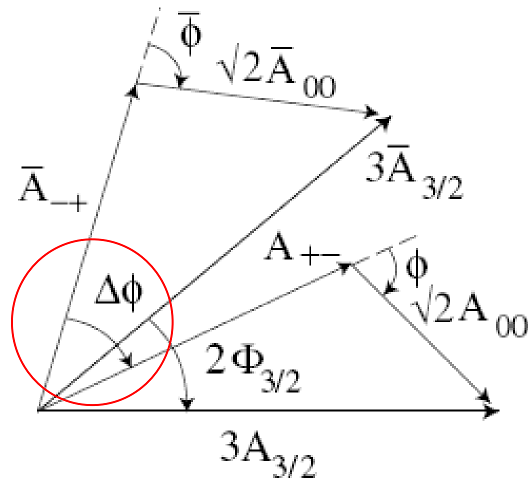
Recent Results – $B^0 \rightarrow K_S \pi^+ \pi^-$

- BABAR preliminary result from 383 million BB gives:

  $\Delta\phi = (-164 \pm 24 \pm 12 \pm 15)°$

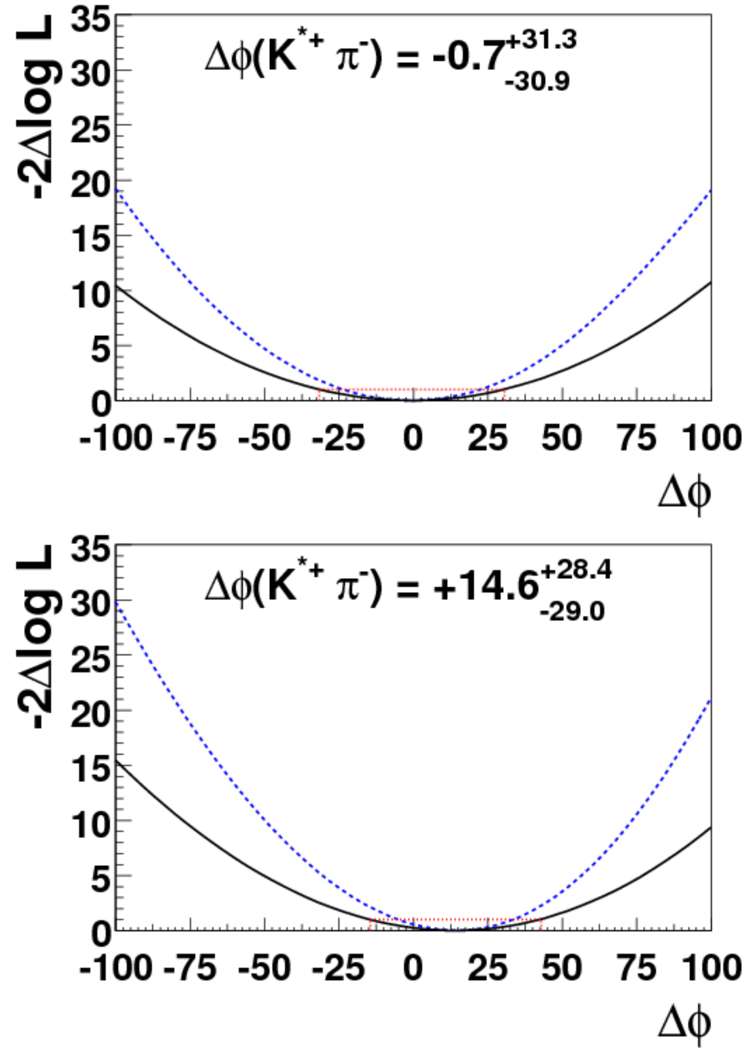
  (errors are stat, syst, model)
- This phase difference includes the $B^0\bar{B}^0$ mixing phase (-2β)
- Secondary solution excluded at $>3\sigma$
- Conference paper:
  - arXiv:0708.2097 [hep-ex]





Recent Results – $B^0 \rightarrow K_S\pi^+\pi^-$

- A new Belle preliminary result from 657 million BB:
  $\Delta\phi = (-1 \pm ^{24}_{23} \pm 11 \pm 18)°$
  (errors are stat, syst, model)
- A second, almost degenerate, solution:
  $\Delta\phi = (+15 \pm ^{19}_{20} \pm 11 \pm 18)°$
- Difference between solutions is interference between $K_0^{*\pm}(1430)$ and NR
- These again include the $B^0\bar{B}^0$ mixing phase (-2β)
- Apparent disagreement with the BABAR results

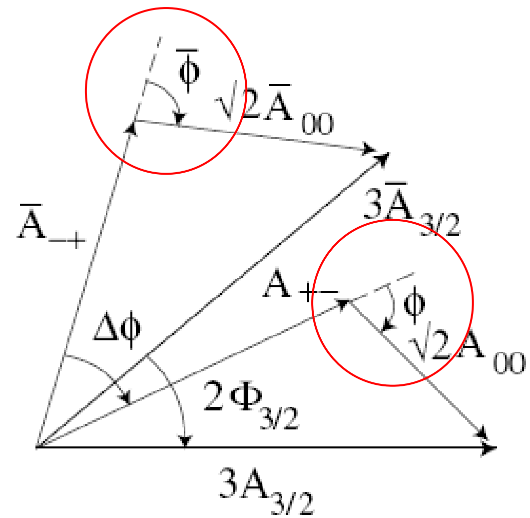


Recent Results – $B^0 \rightarrow K^+\pi^-\pi^0$

- Can determine the phases ϕ and $\bar{\phi}$ from this Dalitz plot
- Mode is self-tagging (from charge of kaon) so analysis does not involve flavour tagging or time-dependence
- Analysis not yet performed by Belle
- BABAR have results from 232 million BB
- Also preliminary results from 454 million BB

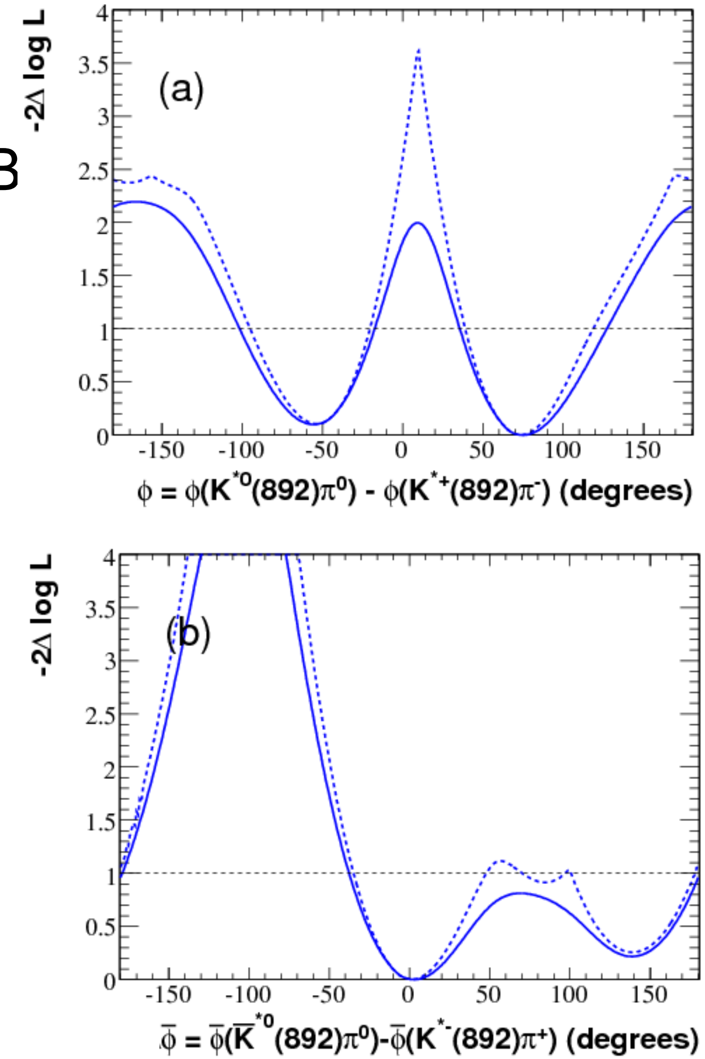
Recent Results – $B^0 \to K^+\pi^-\pi^0$

- BABAR results from 232 million BB
- Accepted by PRD
  - arXiv:0711.4417 [hep-ex]
- Scans opposite show the results for ϕ and $\bar{\phi}$
- Presence of multiple solutions reduces precision of constraint
- Preliminary BABAR results on 454 million BB indicate much better separation between solutions
  - Likelihood scans of phase differences not yet completed
  - arXiv:0807.4567 [hep-ex]



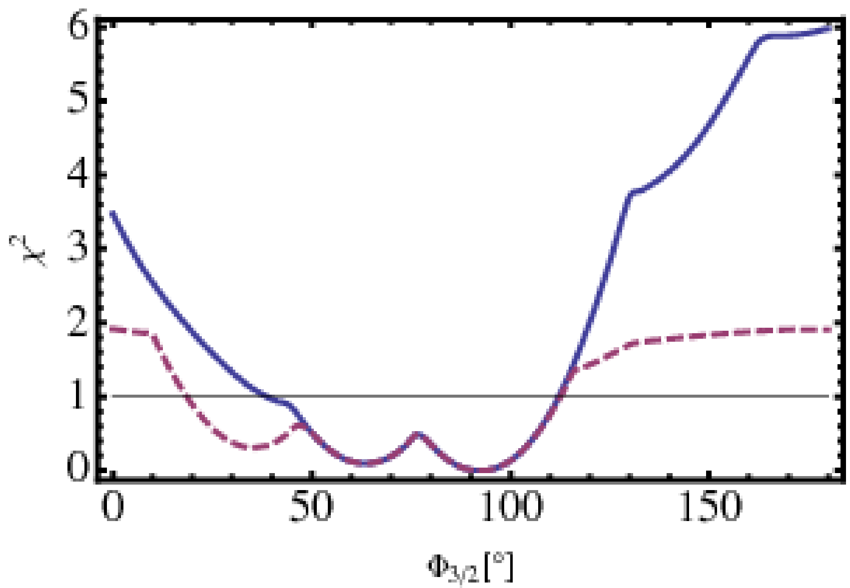
Recent Results – $B^0 \rightarrow K^+\pi^-\pi^0$

- BABAR results from 232 million BB
- Accepted by PRD
  - arXiv:0711.4417 [hep-ex]
- Scans opposite show the results for ϕ and $\bar{\phi}$
- Presence of multiple solutions reduces precision of constraint
- Preliminary BABAR results on 454 million BB indicate much better separation between solutions
  - Likelihood scans of phase differences not yet completed
  - arXiv:0807.4567 [hep-ex]



Putting it all together

- BABAR results from $K_S\pi^+\pi^-$ (arXiv:0708.2097) and $K^+\pi^-\pi^0$ (arXiv:0711.4417) combined together
  - Gronau et al., Phys. Rev. D77, 057504 (2008) and D78, 017505 (2008)



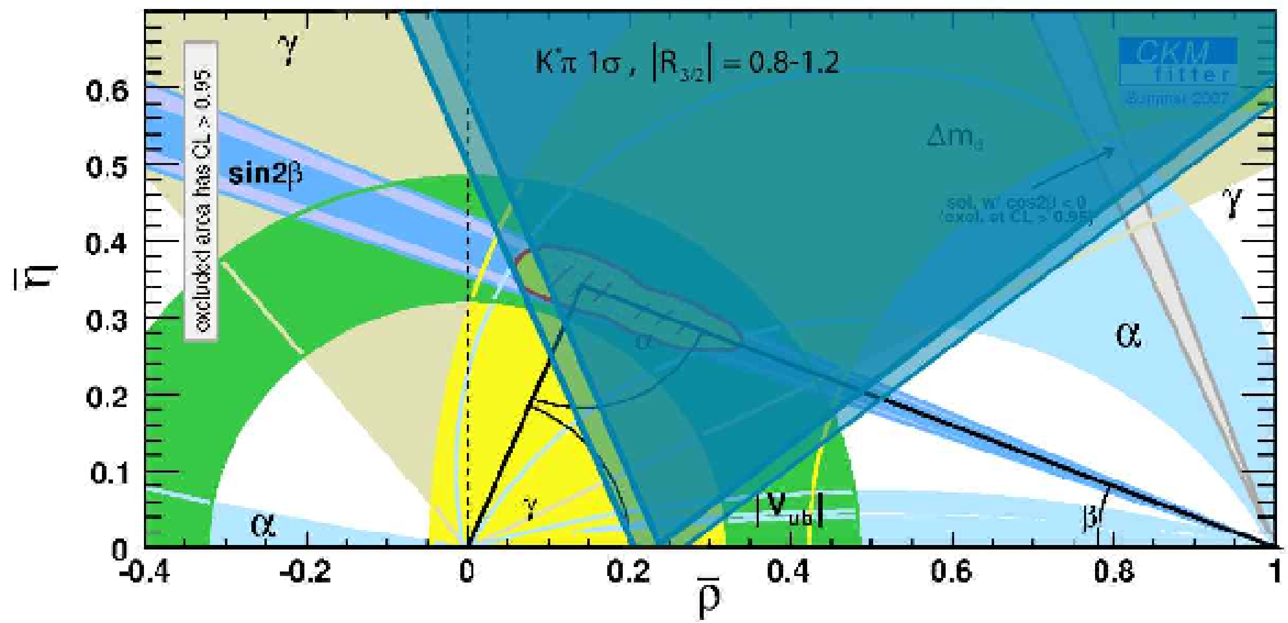
Dotted purple line – unconstrained $|R_{3/2}|$
Solid blue line – $0.8 < |R_{3/2}| < 1.2$

$39° < \Phi_{3/2} < 112°$ (68% CL)

Putting it all together

- CKM constraint in presence of EW penguins is:

$$\bar{\eta} = \tan\Phi_{3/2}\left[\bar{\rho} - 0.24 \pm 0.03\right]$$



Conclusion

- The B-factories have reacted quickly to the theoretical developments in this area
- Results available allow CKM constraint to be formed
- Updated results on ϕ and $\bar{\phi}$ from $K^{+}\pi^{-}\pi^{0}$ expected soon from BABAR
  - Should help to resolve ambiguities
- Measurements from other $K\pi\pi$ modes, such as $K_S\pi^{+}\pi^{0}$, could help improve the precision
- Also a very promising method for future experiments

Backup Material

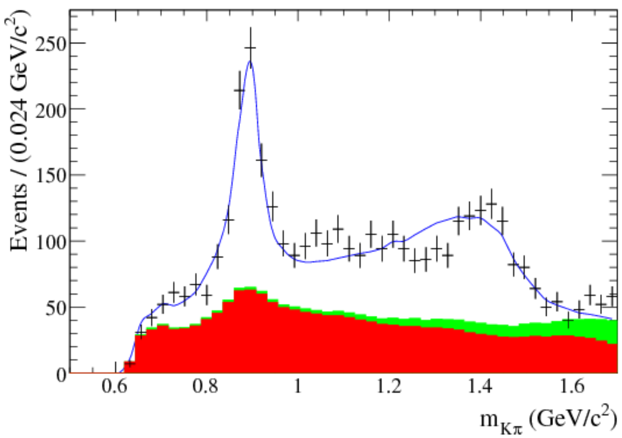
General differences between BABAR and Belle $B \to K\pi\pi$ analyses

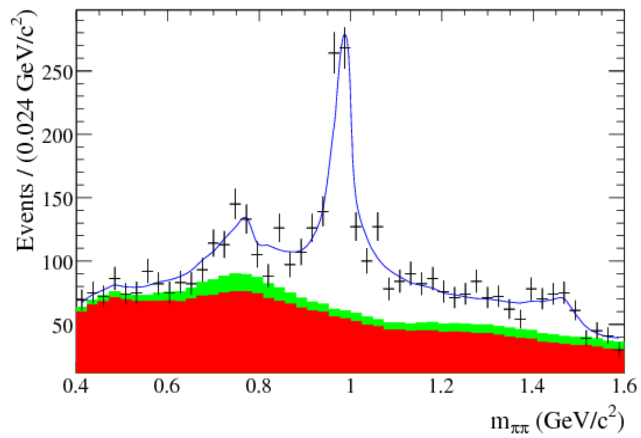
- Main difference is in approach to low mass $K\pi$ S-wave
- BABAR use the LASS parameterisation
  - Coherent sum of $K_0^*(1430)$ and effective range nonresonant that is constrained to be unitary
- BABAR analyses also have to include a phase-space NR term to account for NR events above LASS cut-off (~1.8 GeV/c^2)
- Belle use $K_0^*(1430)$ as RBW and exponential shaped NR
- Belle parameterisation often suffers from multiple solutions where the fractions of the $K_0^*(1430)$ are very different
  - Preferred solution can often depend on which other terms are included in the DP model, e.g. $K_2^*(1430)$
- Neither approach is perfect but both seem to allow a pretty good fit to the data
- Does make comparison of results rather tricky
- However, different approaches don't seem to significantly affect results for other modes in the DP, e.g. $\rho^0 K^+$ A_{CP}

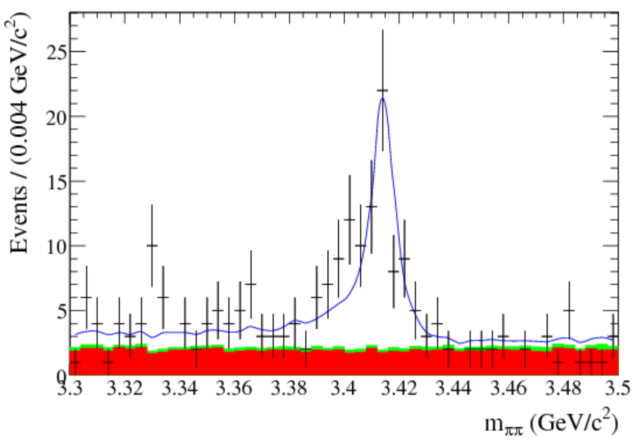
Details of BaBar $K^+\pi^+\pi^-$ Analysis

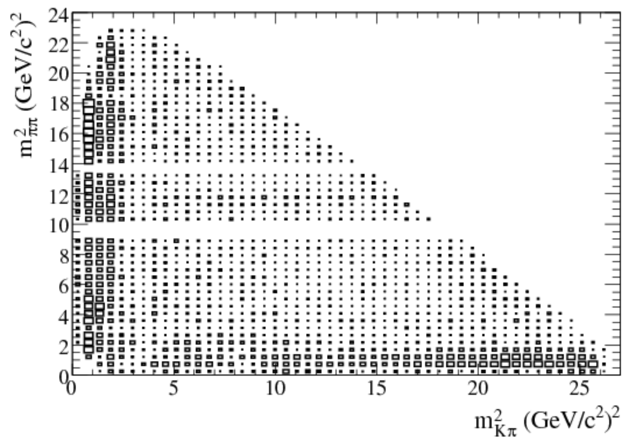
- Signal model contains:
  - $K^{*0}(892)$ – Relativistic Breit-Wigner
  - $K\pi$ S-wave – LASS
  - $K_2^{*0}(1430)$ – RBW
  - $\rho^0(770)$ – RBW
  - $\omega(782)$ – RBW
  - $f_0(980)$ – Flatté
  - $f_2(1270)$ – RBW
  - $f_X(1300)$ – RBW (m and Γ consistent $f_0(1500)$)
  - χ_{c0} – RBW
  - Phase-space nonresonant

Details of BaBar $K^+\pi^+\pi^-$ Analysis









Details of BABAR $K^+\pi^+\pi^-$ Analysis

Mode	Fit Fraction (%)	$\mathcal{B}(B^+ \to \text{Mode})(10^{-6})$	A_{CP} (%)	DCPV Sig.
$K^+\pi^-\pi^+$ Total		$54.4 \pm 1.1 \pm 4.5 \pm 0.7$	$2.8 \pm 2.0 \pm 2.0 \pm 1.2$	
$K^{*0}(892)\pi^+$; $K^{*0}(892) \to K^+\pi^-$	$13.3 \pm 0.7 \pm 0.7\,^{+0.4}_{-0.9}$	$7.2 \pm 0.4 \pm 0.7\,^{+0.3}_{-0.5}$	$+3.2 \pm 5.2 \pm 1.1\,^{+1.2}_{-0.7}$	0.9σ
$(K\pi)^{*0}_0\pi^+$; $(K\pi)^{*0}_0 \to K^+\pi^-$	$45.0 \pm 1.4 \pm 1.2\,^{+12.9}_{-0.2}$	$24.5 \pm 0.9 \pm 2.1\,^{+7.0}_{-1.1}$	$+3.2 \pm 3.5 \pm 2.0\,^{+2.7}_{-1.9}$	1.2σ
$\rho^0(770)K^+$; $\rho^0(770) \to \pi^+\pi^-$	$6.54 \pm 0.81 \pm 0.58\,^{+0.69}_{-0.26}$	$3.56 \pm 0.45 \pm 0.43\,^{+0.38}_{-0.15}$	$+44 \pm 10 \pm 4\,^{+5}_{-13}$	3.7σ
$f_0(980)K^+$; $f_0(980) \to \pi^+\pi^-$	$18.9 \pm 0.9 \pm 1.7\,^{+2.8}_{-0.6}$	$10.3 \pm 0.5 \pm 1.3\,^{+1.5}_{-0.4}$	$-10.6 \pm 5.0 \pm 1.1\,^{+3.4}_{-1.0}$	1.8σ
$\chi_{c0}K^+$; $\chi_{c0} \to \pi^+\pi^-$	$1.29 \pm 0.19 \pm 0.15\,^{+0.12}_{-0.03}$	$0.70 \pm 0.10 \pm 0.10\,^{+0.06}_{-0.02}$	$-14 \pm 15 \pm 3\,^{+1}_{-5}$	0.5σ
$K^+\pi^-\pi^+$ nonresonant	$4.5 \pm 0.9 \pm 2.4\,^{+0.6}_{-1.5}$	$2.4 \pm 0.5 \pm 1.3\,^{+0.3}_{-0.8}$	—	—
$K_2^{*0}(1430)\pi^+$; $K_2^{*0}(1430) \to K^+\pi^-$	$3.40 \pm 0.75 \pm 0.42\,^{+0.99}_{-0.13}$	$1.85 \pm 0.41 \pm 0.28\,^{+0.54}_{-0.08}$	$+5 \pm 23 \pm 4\,^{+18}_{-7}$	0.2σ
$\omega(782)K^+$; $\omega(782) \to \pi^+\pi^-$	$0.17 \pm 0.24 \pm 0.03\,^{+0.05}_{-0.08}$	$0.09 \pm 0.13 \pm 0.02\,^{+0.03}_{-0.04}$	—	—
$f_2(1270)K^+$; $f_2(1270) \to \pi^+\pi^-$	$0.91 \pm 0.27 \pm 0.11\,^{+0.24}_{-0.17}$	$0.50 \pm 0.15 \pm 0.07\,^{+0.13}_{-0.09}$	$-85 \pm 22 \pm 13\,^{+22}_{-2}$	3.5σ
$f_X(1300)K^+$; $f_X(1300) \to \pi^+\pi^-$	$1.33 \pm 0.38 \pm 0.86\,^{+0.04}_{-0.14}$	$0.73 \pm 0.21 \pm 0.47\,^{+0.02}_{-0.08}$	$+28 \pm 26 \pm 13\,^{+7}_{-5}$	0.6σ

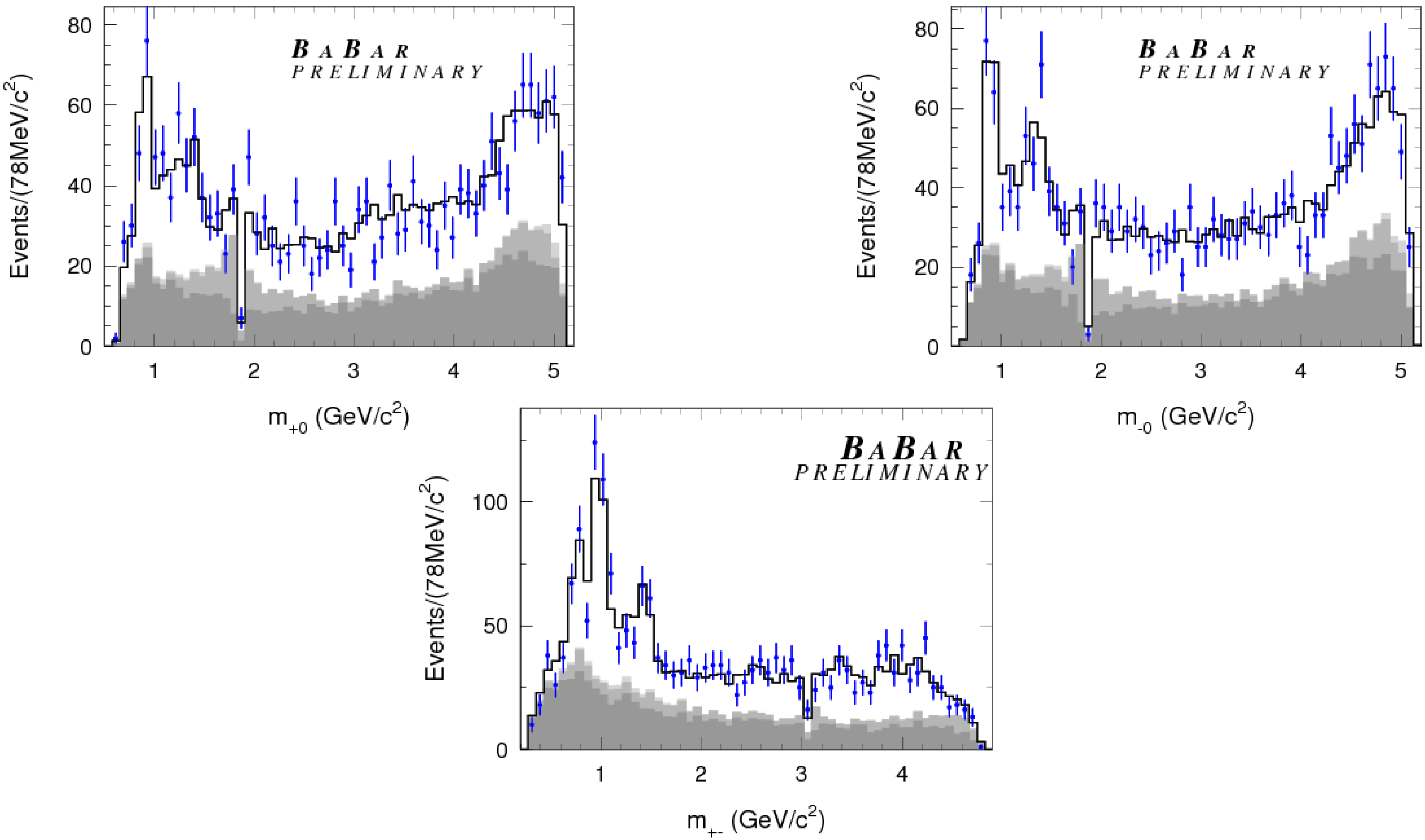
First error is statistical, second systematic and third model-dependent. Significance of DCPV is statistical only.

Total NR branching fraction = $(9.3 \pm 1.0 \pm 1.2\,^{+6.7}_{-0.4} \pm 1.2) \times 10^{-6}$

Details of BaBar $K_S\pi^+\pi^-$ Analysis

- Signal model contains:
  - $K^{*+}(892)$ – Relativistic Breit-Wigner
  - $K\pi$ S-wave – LASS
  - $\rho^0(770)$ – Gounaris-Sakurai
  - $f_0(980)$ – Flatté
  - $f_2(1270)$ – RBW
  - $f_X(1300)$ – RBW (m and Γ consistent $f_0(1500)$)
  - χ_{c0} – RBW
  - Phase-space nonresonant

Details of BABAR $K_S\pi^+\pi^-$ Analysis



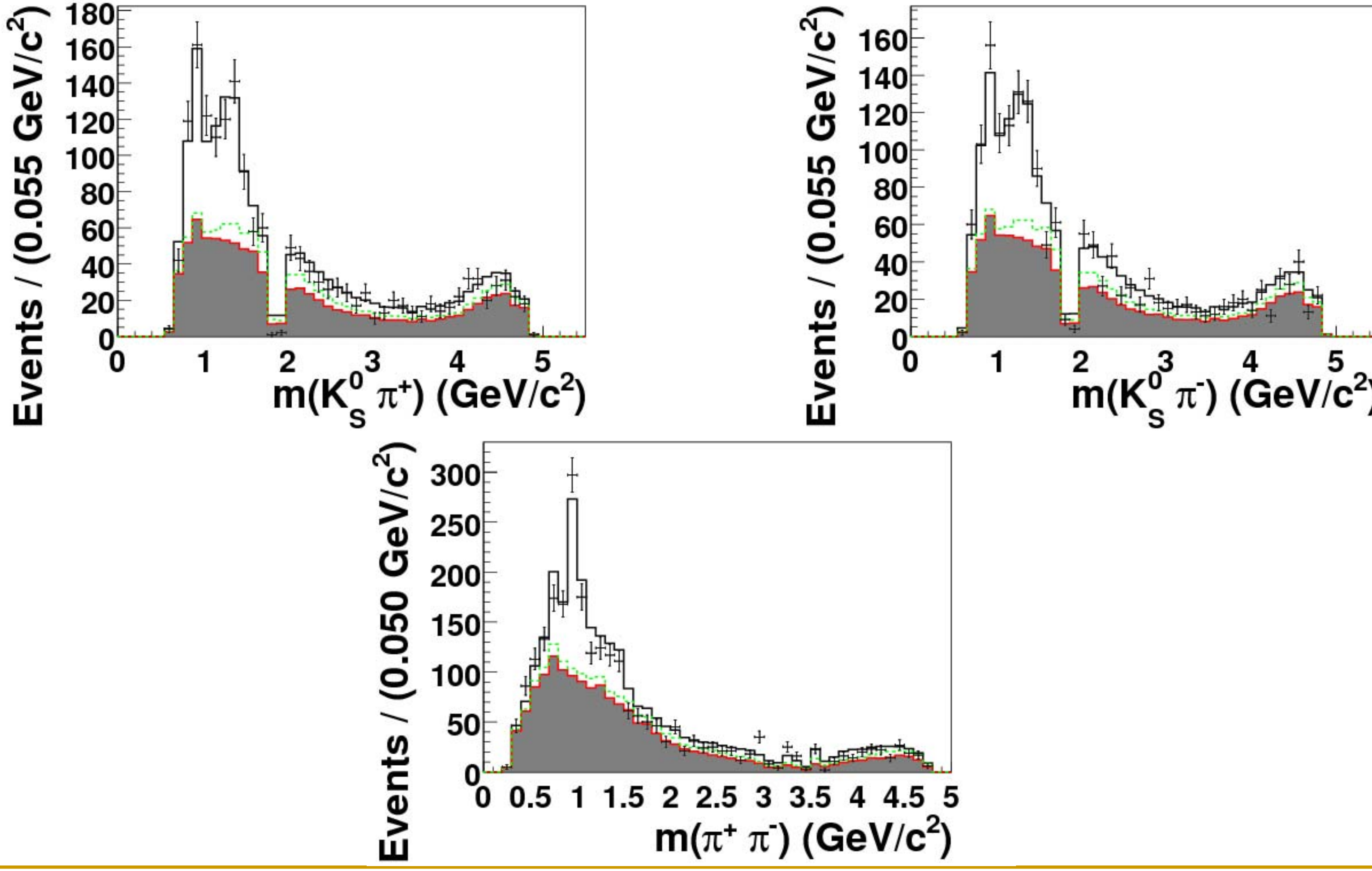
Details of BABAR $K_S\pi^+\pi^-$ Analysis

Resonance Name	$\|c_\sigma\|$	ϕ[degrees]	$\|\overline{c}_\sigma\|$ ($\|\overline{c}_{\overline{\sigma}}\|$)	$\overline{\phi}$[degrees]
$f_0(980)K_S^0$	4.0	0.0	2.8 ± 0.7	-88.6 ± 21.3
$\rho^0(770)K_S^0$	0.10 ± 0.02	58.6 ± 16.4	0.09 ± 0.02	21.3 ± 21.2
$f_0(1300)K_S^0$	1.9 ± 0.4	117.6 ± 22.6	1.1 ± 0.3	-15.2 ± 23.8
Nonresonant	3.0 ± 0.6	13.8 ± 14.3	3.7 ± 0.5	-16.2 ± 17.3
$K^{*+}(892)\pi^-$	0.136 ± 0.021	-60.7 ± 18.5	0.113 ± 0.018	102.6 ± 22.9
$K^{*+}(1430)\pi^-$	4.9 ± 0.7	-82.4 ± 16.8	7.1 ± 0.9	79.2 ± 20.5
$f_2(1270)K_S^0$	0.011 ± 0.004	62.9 ± 23.3	0.010 ± 0.003	-73.9 ± 27.8
$\chi_{c0}(1P)K_S^0$	0.34 ± 0.15	68.7 ± 31.1	0.40 ± 0.11	154.5 ± 28.6

Details of Belle $K_S\pi^+\pi^-$ Analysis

- Signal model contains:
  - $K^{*+}(892)$ – Relativistic Breit-Wigner
  - $K_0^{*+}(1430)$ – RBW
  - $\rho^0(770)$ – Gounaris-Sakurai
  - $f_0(980)$ – Flatté
  - $f_2(1270)$ – RBW
  - $f_X(1300)$ – RBW (m and Γ consistent $f_0(1500)$)
  - Three exponential shaped NR terms

Details of Belle $K_S\pi^+\pi^-$ Analysis



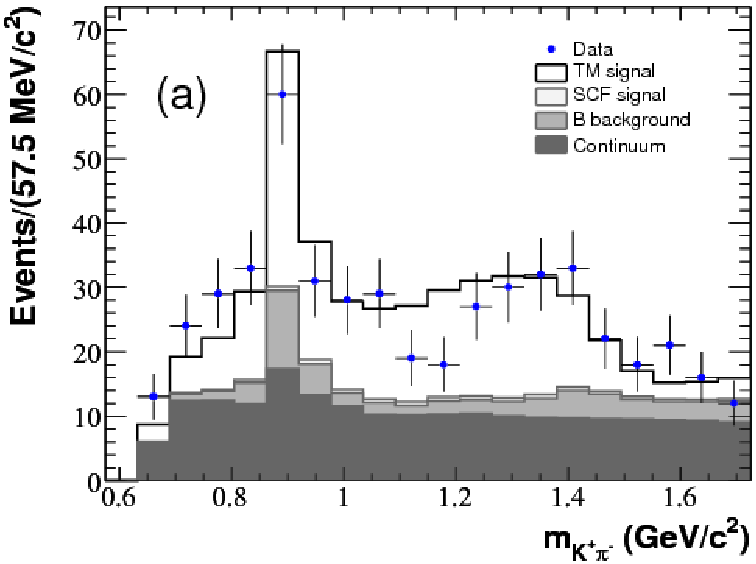
Details of Belle $K_S\pi^+\pi^-$ Analysis

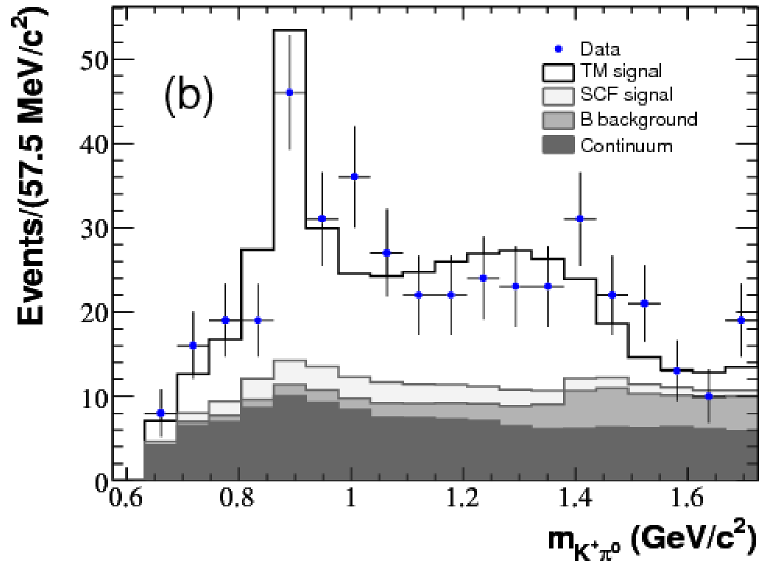
Decay channel	Sol. 1 Fraction (%)	Sol. 2 Fraction (%)
$K^{*+}(892)\pi^-$	9.3 ± 0.8	9.0 ± 1.3
$K_0^{*+}(1430)\pi^-$	61.7 ± 10.4	17.4 ± 5.0
$\rho^0(770)K_S^0$	6.1 ± 1.5	8.5 ± 2.6
$f_0(980)K_S^0$	14.3 ± 2.7	14.9 ± 3.3
$f_2(1270)K_S^0$	2.6 ± 0.9	3.2 ± 1.2
$f_X(1300)K_S^0$	2.3 ± 0.8	6.0 ± 1.6
$(K_S^0\pi^+)_{\rm NR}\pi^-$	57.2 ± 11.4	55.9 ± 13.3
$(K_S^0\pi^-)_{\rm NR}\pi^+$	2.9 ± 4.7	6.4 ± 3.7
$(\pi^+\pi^-)_{\rm NR}K_S^0$	10.7 ± 3.5	7.7 ± 4.1
Total	167.1 ± 0.2	129.0 ± 0.2

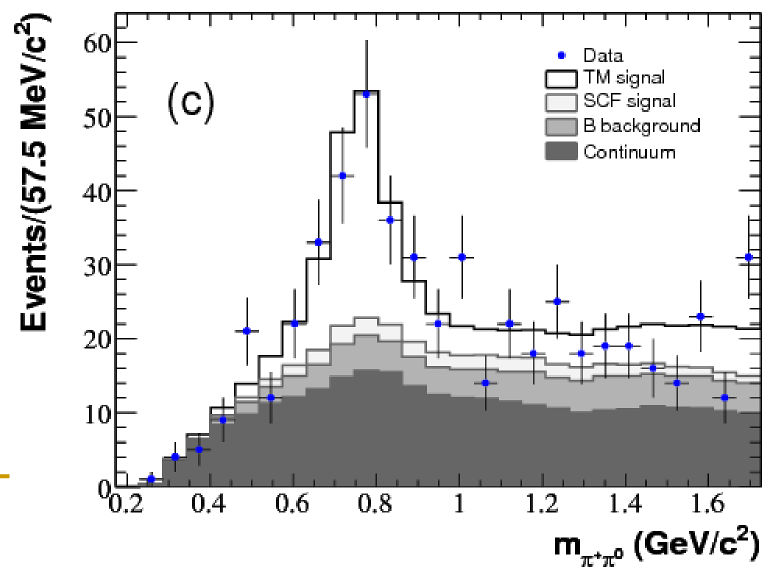
Details of BABAR $K^+\pi^-\pi^0$ Analysis

- Signal model contains:
  - $K^{*+}(892)$ – Relativistic Breit-Wigner
  - $K^{*0}(892)$ – Relativistic Breit-Wigner
  - $(K\pi)^+$ S-wave – LASS
  - $(K\pi)^0$ S-wave – LASS
  - $\rho^-(770)$ – Gounaris-Sakurai
  - Phase-space nonresonant

Details of BABAR $K^+\pi^-\pi^0$ Analysis







Details of BABAR $K^+\pi^-\pi^0$ Analysis

isobar j	FF_j (%)	$\mathcal{B}_j$ (10^{-6})	A^j_{CP}
$K^{*+}(892)\pi^-$	$11.8^{+2.5}_{-1.5} \pm 0.6$	$4.2^{+0.9}_{-0.5} \pm 0.3$	$-0.19^{+0.20}_{-0.15} \pm 0.04$
$K^{*0}(892)\pi^0$	$6.7^{+1.3}_{-1.5}{}^{+0.7}_{-0.6}$	$2.4 \pm 0.5 \pm 0.3$	$-0.09^{+0.21}_{-0.24} \pm 0.09$
$(K\pi)^{*+}_0\pi^-$	$26.3^{+3.1}_{-3.8}{}^{+2.1}_{-2.0} \pm 4.9$	$9.4^{+1.1}_{-1.3}{}^{+1.4}_{-1.1} \pm 1.8$	$+0.17^{+0.11}_{-0.16} \pm 0.09 \pm 0.20$
$(K\pi)^{*0}_0\pi^0$	$24.3^{+3.0}_{-2.6}{}^{+3.7}_{-3.0} \pm 6.7$	$8.7^{+1.1}_{-0.9}{}^{+1.8}_{-1.3} \pm 2.2$	$-0.22 \pm 0.12^{+0.13}_{-0.11} \pm 0.27$
$\rho^-(770)K^+$	$22.5^{+2.2}_{-3.7} \pm 1.2$	$8.0^{+0.8}_{-1.3} \pm 0.6$	$+0.11^{+0.14}_{-0.15} \pm 0.07$
N.R.	$12.4 \pm 2.6^{+1.3}_{-1.2}$	$4.4 \pm 0.9 \pm 0.5$	$+0.23^{+0.19}_{-0.27}{}^{+0.11}_{-0.10}$
Total	$102.3^{+7.1}_{-4.0} \pm 4.1$	$35.7^{+2.6}_{-1.5} \pm 2.2$	$-0.030^{+0.045}_{-0.051} \pm 0.055$