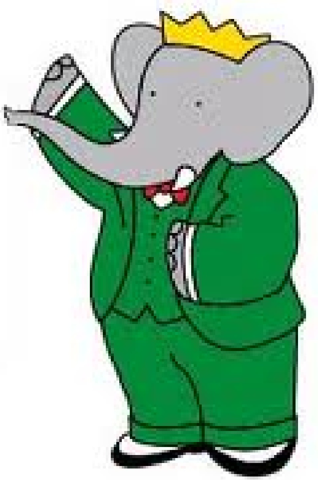
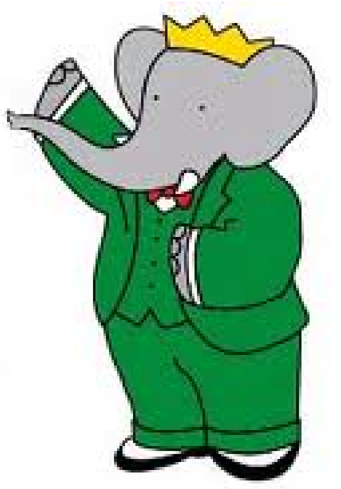


Recent results from the B factories on multi-body charmless B decays

Tim Gershon,
University of Warwick
on behalf of the BaBar & Belle collaborations

CKM2016, 29th November 2016

Selected results from the B factories on multi-body charmless B decays

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CKM2016, 29th November 2016

A potential treasure trove

- Multi-body charmless B decays have (in general)
  - contributions from both tree and penguin diagrams
    - potential for large CP violation effects …
    - … and for new physics contributions
  - various overlapping resonant & nonresonant structures
    - possibility to determine relative phases via amplitude analysis
      - not accessible for 2-body decays
    - need for accurate modelling of lineshapes
  - large samples available, with even more to look forward to soon

- Huge potential … but equally huge challenges

Snyder-Quinn method for α

PHYSICAL REVIEW D VOLUME 48, NUMBER 5 1 SEPTEMBER 1993

Measuring CP asymmetry in $B \to \rho\pi$ decays without ambiguities

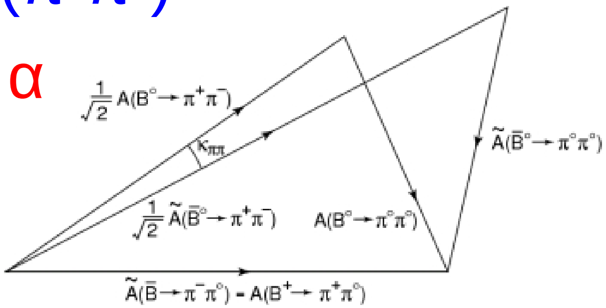
Arthur E. Snyder and Helen R. Quinn
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 24 February 1993)

PRD 48 (1993) 2139

- Methods to measure α exploit time-dependent CP violation in B_d decays via $b \to u$ transitions (eg. $B_d \to \pi^+\pi^-$)

PRL 65 (1990) 3381

- Penguin "pollution" can be subtracted using Gronau-London isospin triangles built from $A(\pi^+\pi^-)$, $A(\pi^+\pi^0)$, $A(\pi^0\pi^0)$
- Expect discrete ambiguities in the solution for α



- Ambiguities can be resolved if you measure both real and imaginary parts of $\lambda = (q/p)(\bar{A}/A)$
  - ie. measure cos(2α) as well as sin(2α)

Toy model for $B \to \pi^+\pi^-\pi^0$ Dalitz plot

Contributions only from $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$

PRD 48 (1993) 2139

Time dependence	Kinematic form	Amplitude measured	α dependence (all $P_i=0$)
1	f^+f^{+*}	$S_3S_3^* + \bar{S}_4\bar{S}_4^*$	1
$\cos(\Delta M t)$	f^+f^{+*}	$S_3S_3^* - \bar{S}_4\bar{S}_4^*$	1
$\sin(\Delta M t)$	f^+f^{+*}	$\mathrm{Im}(q\bar{S}_4S_3^*)$	$\sin(2\alpha)$
1	f^-f^{-*}	$S_4S_4^* + \bar{S}_3\bar{S}_3^*$	1
$\cos(\Delta M t)$	f^-f^{-*}	$S_4S_4^* - \bar{S}_3\bar{S}_3^*$	1
$\sin(\Delta M t)$	f^-f^{-*}	$\mathrm{Im}(q\bar{S}_3S_4^*)$	$\sin(2\alpha)$
1	f^0f^{0*}	$(S_5S_5^* + \bar{S}_5\bar{S}_5^*)/4$	1
$\cos(\Delta M t)$	f^0f^{0*}	$(S_5S_5^* - \bar{S}_5\bar{S}_5^*)/4$	1
$\sin(\Delta M t)$	f^0f^{0*}	$\mathrm{Im}(q\bar{S}_5S_5^*)/4$	$\sin(2\alpha)$
1	$\mathrm{Re}(f^+f^{-*})$	$\mathrm{Re}(S_3S_4^* + \bar{S}_4\bar{S}_3^*)$	1
$\cos(\Delta M t)$	$\mathrm{Re}(f^+f^{-*})$	$\mathrm{Re}(S_3S_4^* - \bar{S}_4\bar{S}_3^*)$	1
$\sin(\Delta M t)$	$\mathrm{Re}(f^+f^{-*})$	$\mathrm{Im}(q\bar{S}_4S_4^* - q^*S_3\bar{S}_3^*)$	$\sin(2\alpha)$
1	$\mathrm{Im}(f^+f^{-*})$	$\mathrm{Im}(S_3S_4^* + \bar{S}_4\bar{S}_3^*)$	1
$\cos(\Delta M t)$	$\mathrm{Im}(f^+f^{-*})$	$\mathrm{Im}(S_3S_4^* - \bar{S}_4\bar{S}_3^*)$	1
$\sin(\Delta M t)$	$\mathrm{Im}(f^+f^{-*})$	$\mathrm{Re}(q\bar{S}_4S_4^* - q^*S_3\bar{S}_3^*)$	$\cos(2\alpha)$
1	$\mathrm{Re}(f^+f^{0*})$	$\mathrm{Re}(S_3S_5^* + \bar{S}_4\bar{S}_5^*)/2$	1
$\cos(\Delta M t)$	$\mathrm{Re}(f^+f^{0*})$	$\mathrm{Re}(S_3S_5^* - \bar{S}_4\bar{S}_5^*)/2$	1
$\sin(\Delta M t)$	$\mathrm{Re}(f^+f^{0*})$	$\mathrm{Im}(q\bar{S}_4S_5^* + q^*S_3\bar{S}_5^*)/2$	$\sin(2\alpha)$
1	$\mathrm{Im}(f^+f^{0*})$	$\mathrm{Im}(S_3S_5^* + \bar{S}_4\bar{S}_5^*)/2$	1
$\cos(\Delta M t)$	$\mathrm{Im}(f^+f^{0*})$	$\mathrm{Im}(S_3S_5^* - \bar{S}_4\bar{S}_5^*)/2$	1
$\sin(\Delta M t)$	$\mathrm{Im}(f^+f^{0*})$	$\mathrm{Re}(q\bar{S}_4S_5^* - q^*S_3\bar{S}_5^*)/2$	$\cos(2\alpha)$
1	$\mathrm{Re}(f^-f^{0*})$	$\mathrm{Re}(S_4S_5^* + \bar{S}_3\bar{S}_5^*)/2$	1
$\cos(\Delta M t)$	$\mathrm{Re}(f^-f^{0*})$	$\mathrm{Re}(S_4S_5^* - \bar{S}_3\bar{S}_5^*)/2$	1
$\sin(\Delta M t)$	$\mathrm{Re}(f^-f^{0*})$	$\mathrm{Im}(q\bar{S}_3S_5^* - q^*S_4\bar{S}_5^*)$	$\sin(2\alpha)$
1	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Im}(S_4S_5^* + \bar{S}_3\bar{S}_5^*)/2$	1
$\cos(\Delta M t)$	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Im}(S_4S_5^* - \bar{S}_3\bar{S}_5^*)/2$	1
$\sin(\Delta M t)$	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Re}(q\bar{S}_3S_5^* - q^*S_4\bar{S}_5^*)/2$	$\cos(2\alpha)$

Note: physical observables depend on either sin(2α) or cos(2α) – never “directly” on α

27 parameters renamed “U” and “I” in commonly used notation

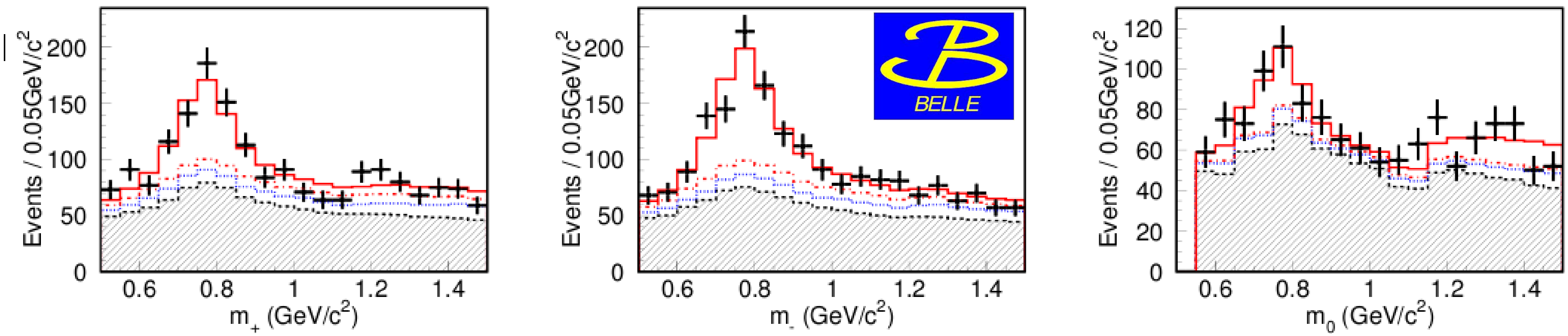
H.Quinn and J.Silva, PRD 62 (2000) 054002

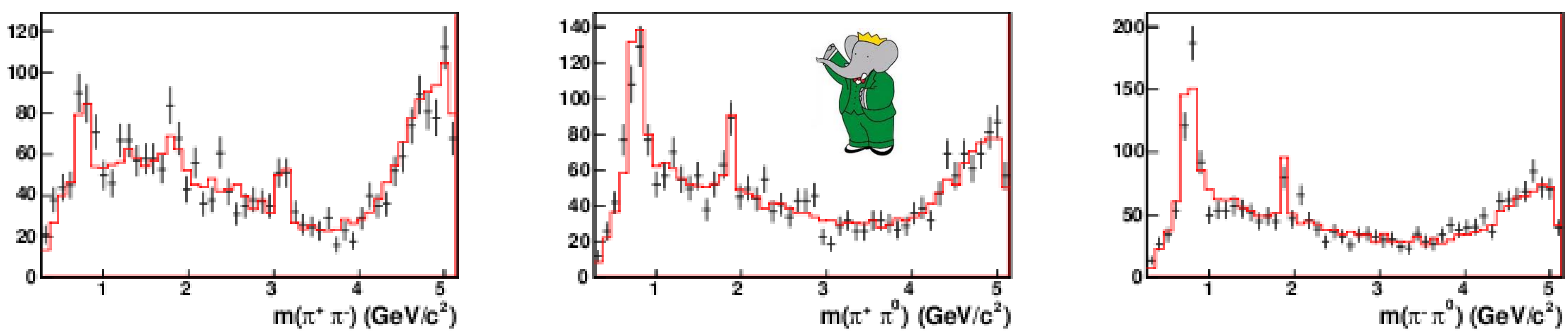
f terms contain hadronic physics (lineshape, spin)

$S_3 = A(\rho^+\pi^-)$, $S_4 = A(\rho^-\pi^+)$, $S_5 = A(\rho^0\pi^0)$,

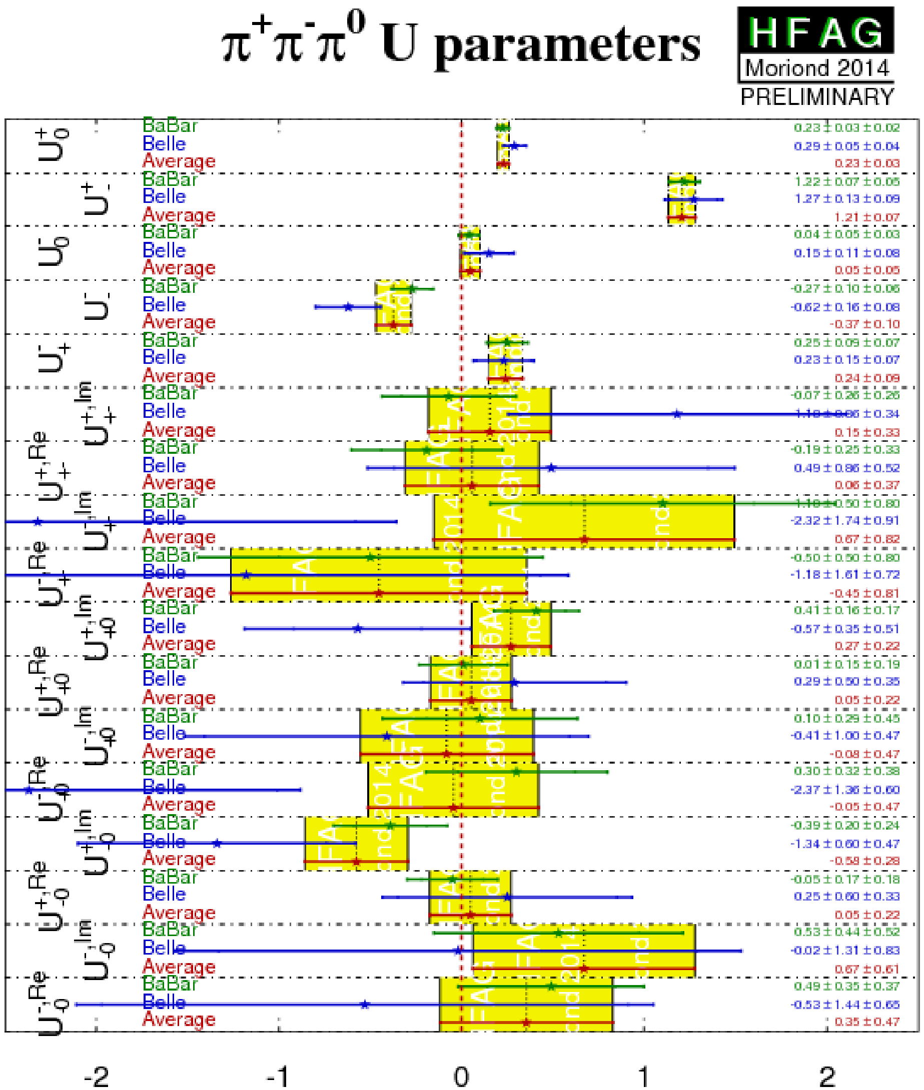
$B \to \pi^+\pi^-\pi^0$ – B factory results

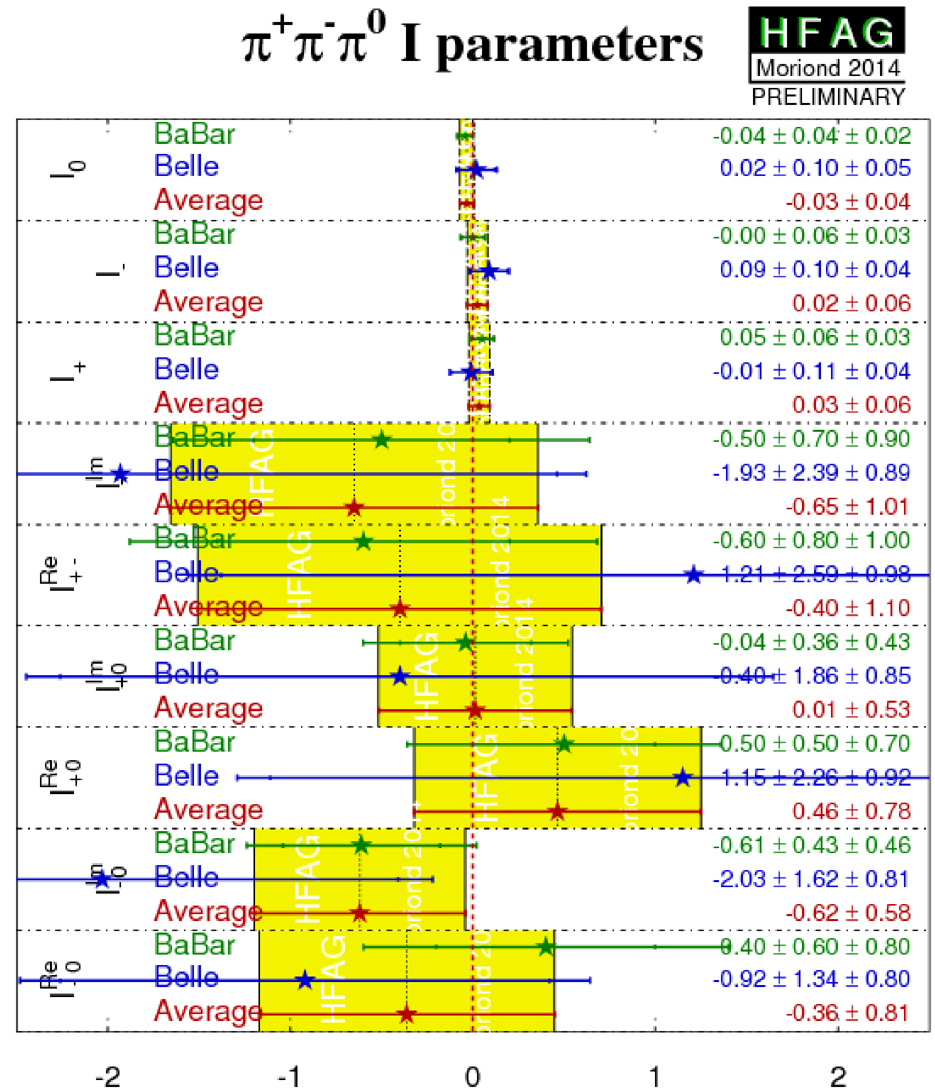
- Belle, 449 M $B\bar{B}$ pairs: PRL 98 (2007) 221602, PR D77 (2008) 072001
- BaBar, 471 M $B\bar{B}$ pairs: PR D88 (2013) 012003





$B \to \pi^+\pi^-\pi^0$ – B factory results





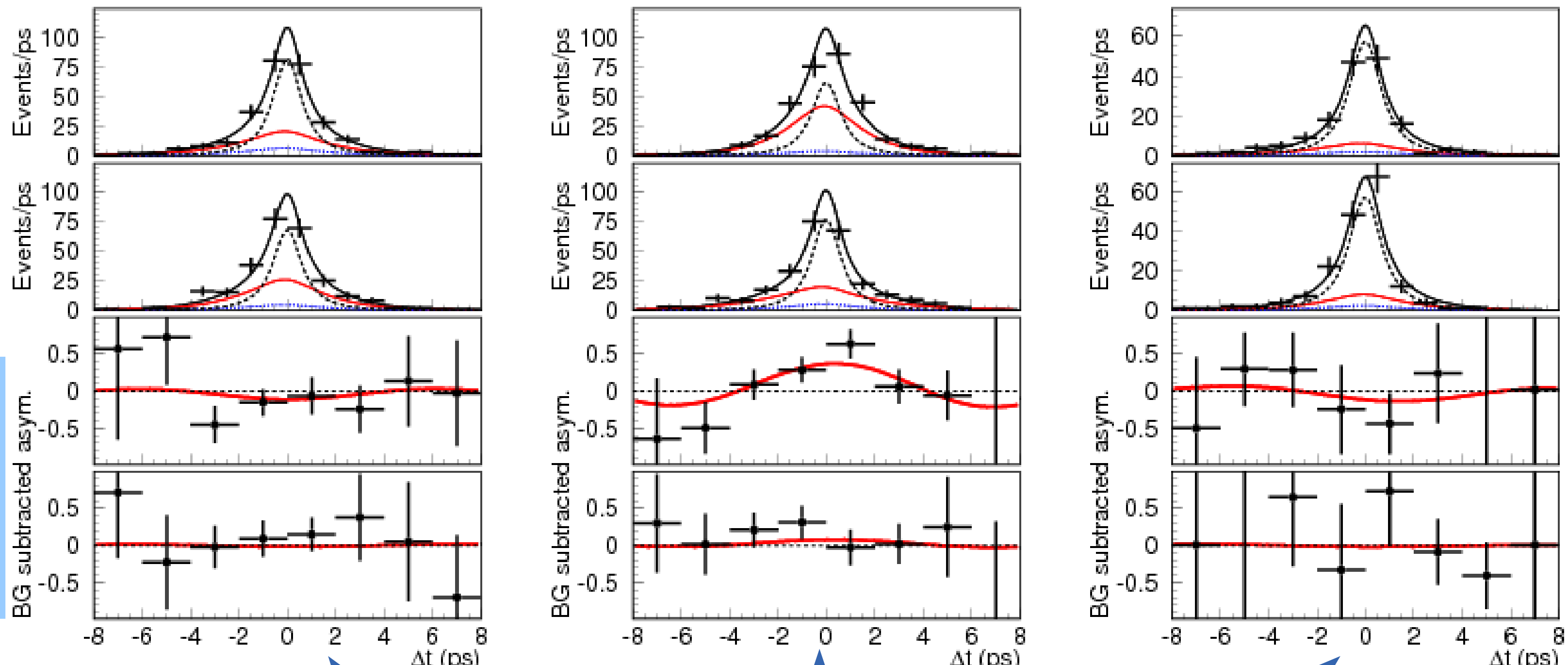
$B \to \pi^+\pi^-\pi^0$ – B factory results

- Belle, 449 M $B\bar{B}$ pairs: PRL 98 (2007) 221602, PR D77 (2008) 072001
- BaBar, 471 M $B\bar{B}$ pairs: PR D88 (2013) 012003

Tagged as $\bar{B}^0$

Tagged as B^0

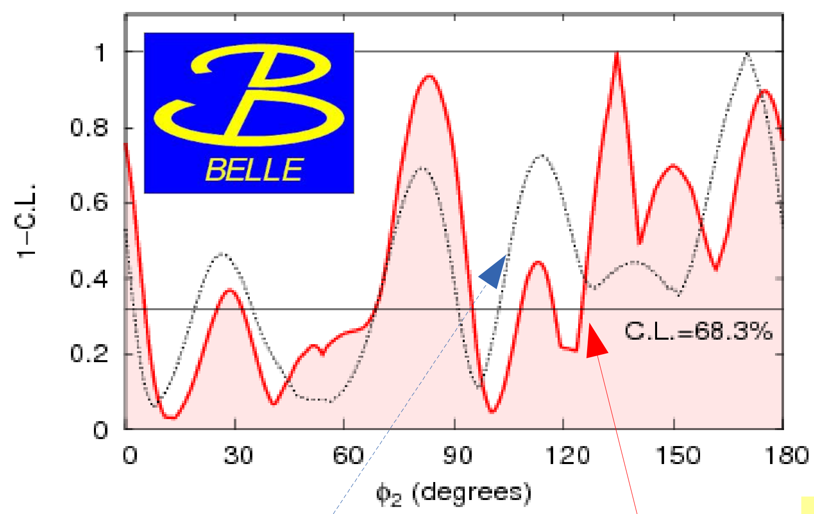
Asymmetry shown separately for (top) good tags and (bottom) less good tags

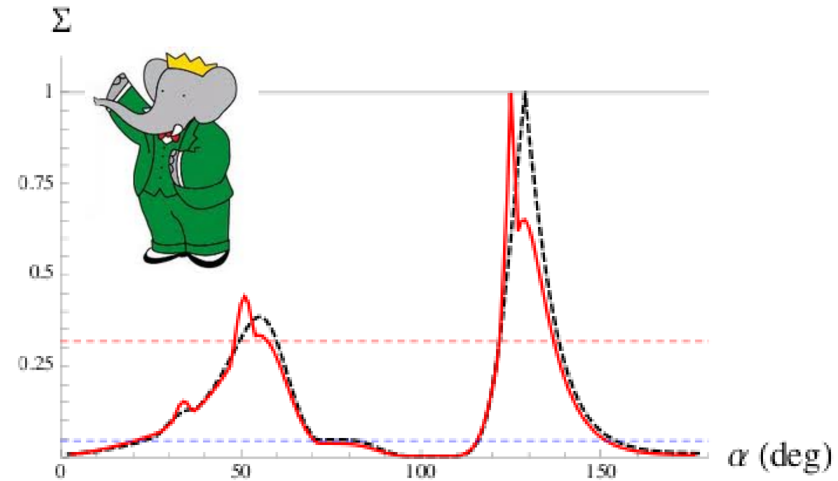


$\rho^+\pi^-$ $\rho^-\pi^+$ $\rho^0\pi^0$

$B \to \pi^+\pi^-\pi^0$ – B factory results

- Results from
  - Belle, 449 M $B\bar{B}$ pairs: PRL 98 (2007) 221602, PR D77 (2008) 072001
  - BaBar, 471 M $B\bar{B}$ pairs: PR D88 (2013) 012003





Contour from $B \to \pi^+\pi^-\pi^0$ only

Including also information on $B^+ \to \rho^+\pi^0$ and $B^+ \to \rho^0\pi^+$

"the extraction of α with our current sample size is not robust"

$B \to K\pi\pi$

- Method to constrain γ from $B \to K\pi\pi$ Dalitz plot (DP) analyses
  - See PRD 74 (2006) 051301, PRD 75 (2007) 014002

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

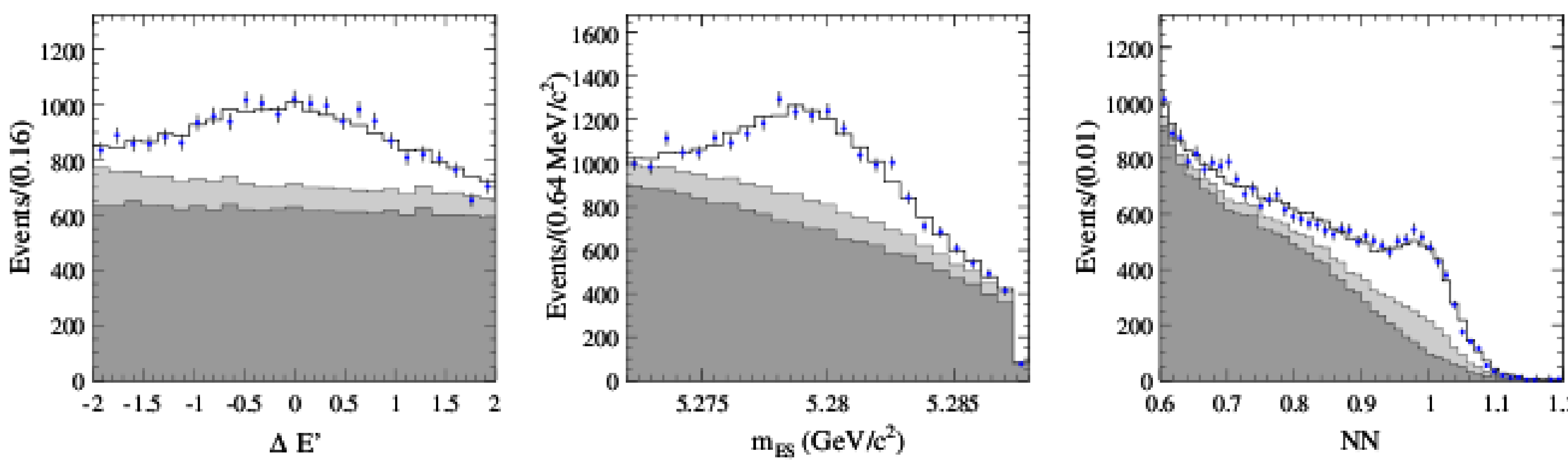
- Construct pure I=3/2 amplitude for B and $\overline{B}$
  - Dalitz plot analysis of $B^0 \to K^+\pi^-\pi^0$
- Relative phase between B and $\overline{B}$ gives γ
  - Dalitz plot analysis of $B^0 \to K_S\pi^+\pi^-$
  - corrections due to electroweak penguins

PR D83 (2011) 112010

454 M $B\bar{B}$ pairs

$B^0 \to K^+\pi^-\pi^0$

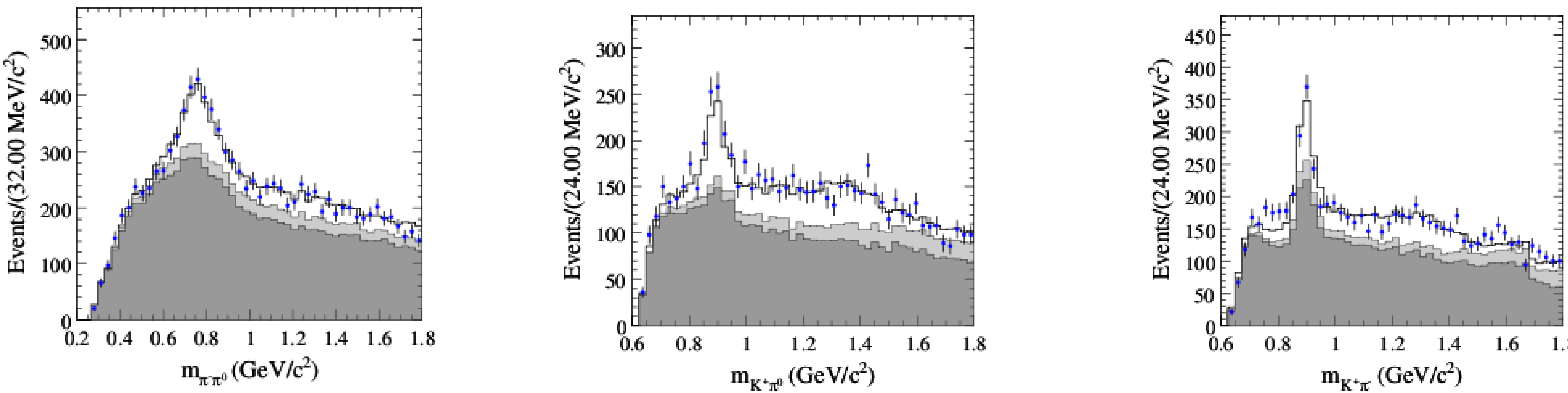
- Signal yield of 3670 ± 96 ± 94 decays
  - separated from background with ΔE', m_{ES} and neural network (NN)
    - n.b.: ΔE' modified version of standard ΔE' variable; removes dependence on π^0 energy & hence DP position
- Branching fraction measured
  - $\mathcal{B}(B^0 \to K^+\pi^-\pi^0) = [38.5 \pm 1.0\ (\text{stat.}) \pm 3.9\ (\text{syst.})] \times 10^{-6}$



$B^0 \to K^+\pi^-\pi^0$

PR D83 (2011) 112010

454 M $B\overline{B}$ pairs



Results need to construct isospin triangles

Isobar	$\mathcal{B}$ $(\times 10^{-6})$	$\overline{\Phi}$ [°]	Φ [°]	A_{CP}
$\rho(770)^- K^+$	$6.6 \pm 0.5 \pm 0.8$	0 (fixed)	0 (fixed)	$0.20 \pm 0.09 \pm 0.08$
$\rho(1450)^- K^+$	$2.4 \pm 1.0 \pm 0.6$	$75 \pm 19 \pm 9$	$126 \pm 25 \pm 26$	$-0.10 \pm 0.32 \pm 0.09$
$\rho(1700)^- K^+$	$0.6 \pm 0.6 \pm 0.4$	$18 \pm 36 \pm 16$	$50 \pm 38 \pm 20$	$-0.36 \pm 0.57 \pm 0.23$
$K^*(892)^+\pi^-$	$8.0 \pm 1.1 \pm 0.8$	$33 \pm 22 \pm 20$	$39 \pm 25 \pm 20$	$-0.29 \pm 0.11 \pm 0.02$
$K^*(892)^0\pi^0$	$3.3 \pm 0.5 \pm 0.4$	$29 \pm 18 \pm 6$	$17 \pm 20 \pm 8$	$-0.15 \pm 0.12 \pm 0.04$
$(K\pi)_0^{*+}\pi^-$	$34.2 \pm 2.4 \pm 4.1$	$-167 \pm 16 \pm 37$	$-130 \pm 22 \pm 22$	$0.07 \pm 0.14 \pm 0.01$
$(K\pi)_0^{*0}\pi^0$	$8.6 \pm 1.1 \pm 1.3$	$13 \pm 17 \pm 12$	$10 \pm 17 \pm 16$	$-0.15 \pm 0.10 \pm 0.04$
NR	$2.8 \pm 0.5 \pm 0.4$	$48 \pm 14 \pm 6$	$90 \pm 21 \pm 15$	$0.10 \pm 0.16 \pm 0.08$

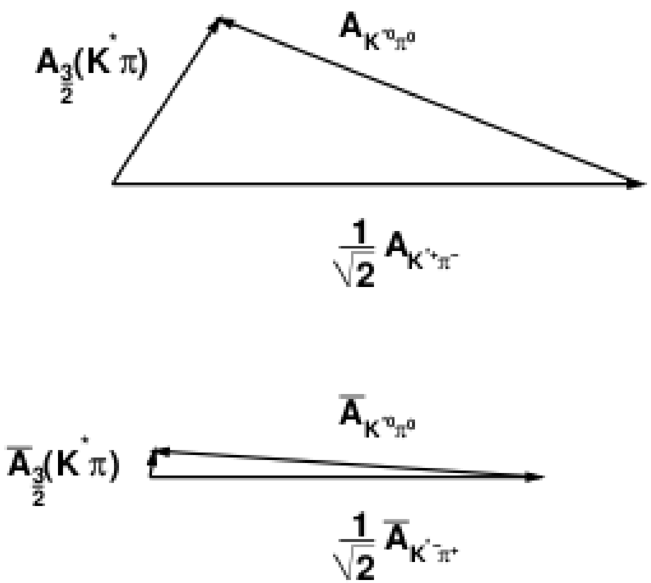
Combined with results from $B^0 \to K_S\pi^+\pi^-$

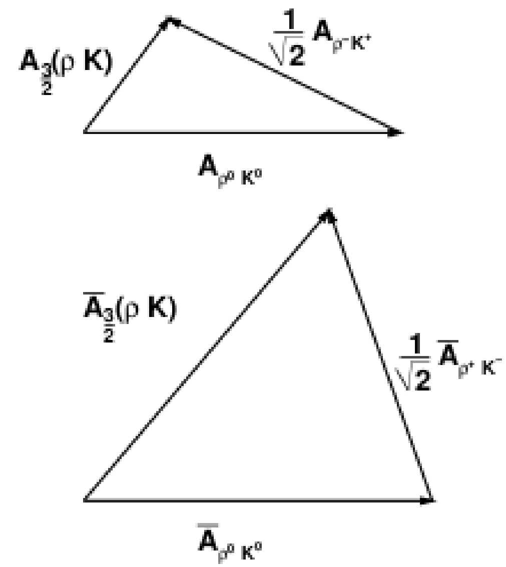
$A_{CP}(K^{*+}\pi^-) = -0.24 \pm 0.07$ (stat.) $\pm$ 0.02 (syst.) [3.1 σ]

PR D83 (2011) 112010
454 M $B\overline{B}$ pairs

$B^0 \to K^+\pi^-\pi^0$

Isospin triangles drawn to scale of experimental results (without uncertainties)





Cancellation makes pure I=3/2 amplitude small – impossible to determine its relative phase

Method may work better for ρK amplitudes – but current uncertainty is large

The $B \to K\pi$ puzzle

- QCD may also be a cause of apparently anomalous CP violation effects

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

	$A_{CP}(K^+\pi^-)$	$A_{CP}(K^+\pi^0)$	
	–0.082 ± 0.006 e.g. LHCb PRL 110 (2013) 221601	+0.040 ± 0.021 e.g. Belle PR D87 (2013) 031103	HFAG averages most precise single measurement

- Look for similar effects in $K^*\pi$ & $K\rho$ systems

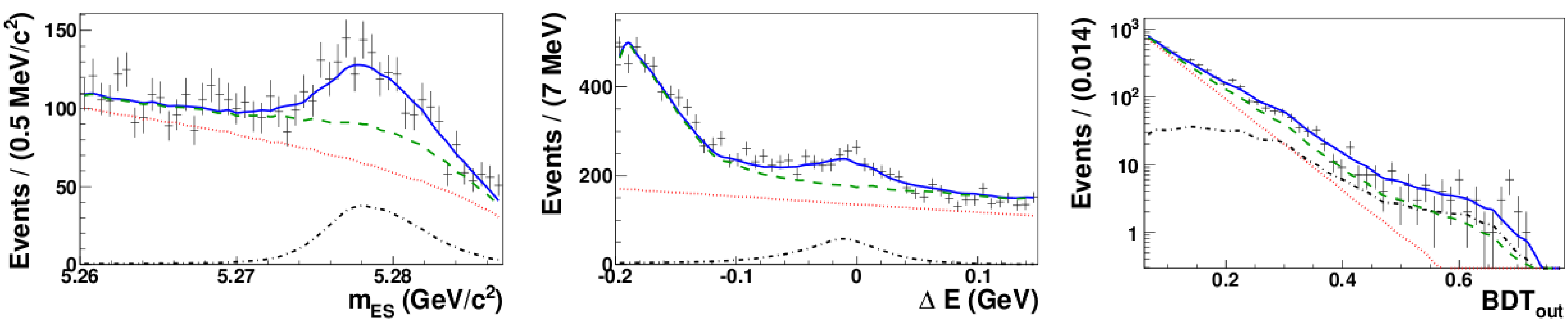
$K^*\pi$	–0.23 ± 0.06 e.g. BaBar PR D83 (2011) 112010	–0.39 ± 0.13 e.g. BaBar arXiv:1501.00705
$K\rho$	+0.20 ± 0.11 e.g. BaBar PR D83 (2011) 112010	+0.37 ± 0.11 BaBar PR D78 (2008) 012004 & Belle PRL 96 (2006) 251803

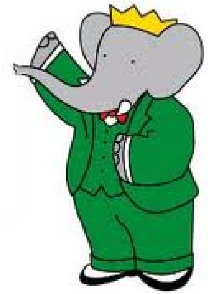
Precision of PV modes often worse as all available data not yet analysed

$B^+ \to K_S \pi^+ \pi^0$

arXiv:1501.00705
471 M $B\overline{B}$ pairs

- Signal yield of 1014 ± 60 decays
  - Separated from background with ΔE, m_{ES} and boosted decision tree (BDT) output
  - Simultaneous fit with Dalitz plot distribution
    - Dependence of ΔE on π^0 energy treated with conditional PDF





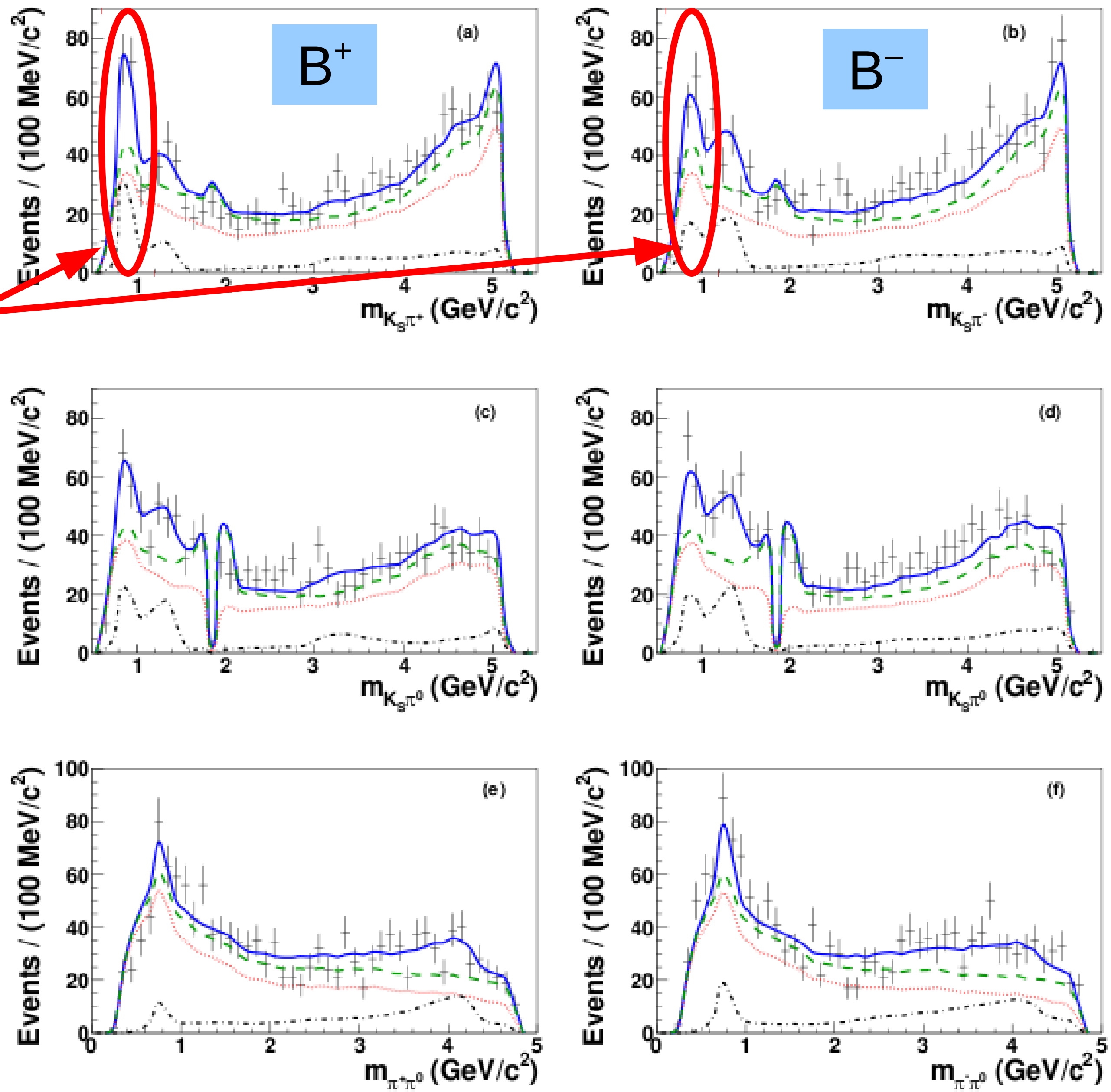
arXiv:1501.00705

471 M $B\bar{B}$ pairs

$B^+ \to K_S \pi^+ \pi^0$

Evidence for CP violation in $B^+ \to K^{*+}\pi^0$

Decay channel	A_{CP}
$K^0\pi^+\pi^0$	$0.07 \pm 0.05 \pm 0.03^{+0.02}_{-0.03}$
$K^*(892)^0\pi^+$	$-0.12 \pm 0.21 \pm 0.08^{+0.0}_{-0.11}$
$K^*(892)^+\pi^0$	$-0.52 \pm 0.14 \pm 0.04^{+0.04}_{-0.02}$
$K_0^*(1430)^0\pi^+$	$0.14 \pm 0.10 \pm 0.04^{+0.13}_{-0.05}$
$K_0^*(1430)^+\pi^0$	$0.26 \pm 0.12 \pm 0.08^{+0.12}_{-0.0}$
$\rho(770)^+K^0$	$0.21 \pm 0.19 \pm 0.07^{+0.23}_{-0.19}$



Summary

- Much physics potential in charmless hadronic decays …
  - and in three-body decays in particular
- Need smart methods to overcome hadronic uncertainties
- These often involve analyses of >1 Dalitz plot
  - cannot rely on only all-charged final states
    - need modes with K_S &/or π^0 too
    - often highly challenging but have been successfully analysed
- Despite many publications, there is still untapped potential in existing data samples
  - even more soon to come with Belle II

B factory
Dalitz plot analyses

$K^+K^+K^-$	PR D85 (2012) 112010	PR D71 (2005) 092003
$K^+K^+K_S$	PR D85 (2012) 112010	PR D82 (2010) 073011
$K^+K_SK_S$	PR D85 (2012) 112010	No amplitude analysis
$K_SK_SK_S$	PR D85 (2012) 054023	No amplitude analysis
$K^+\pi^+\pi^-$	PR D78 (2008) 012004	PRL 96 (2006) 251803
$K_S\pi^+\pi^-$	PR D80 (2009) 112001	PR D79 (2009) 072004
$K^+\pi^-\pi^0$	PR D83 (2011) 112010	No amplitude analysis
$K_S\pi^+\pi^0$	arXiv:1501.00705	No amplitude analysis
$\pi^+\pi^+\pi^-$	PR D79 (2009) 072006	No amplitude analysis
$\pi^+\pi^+\pi^0$	PR D88 (2013) 012003	PR D77 (2008) 072001

All modes with 0, 1 or 3 kaons ($K^\pm$ or K_S) & 0 or 1 π^0

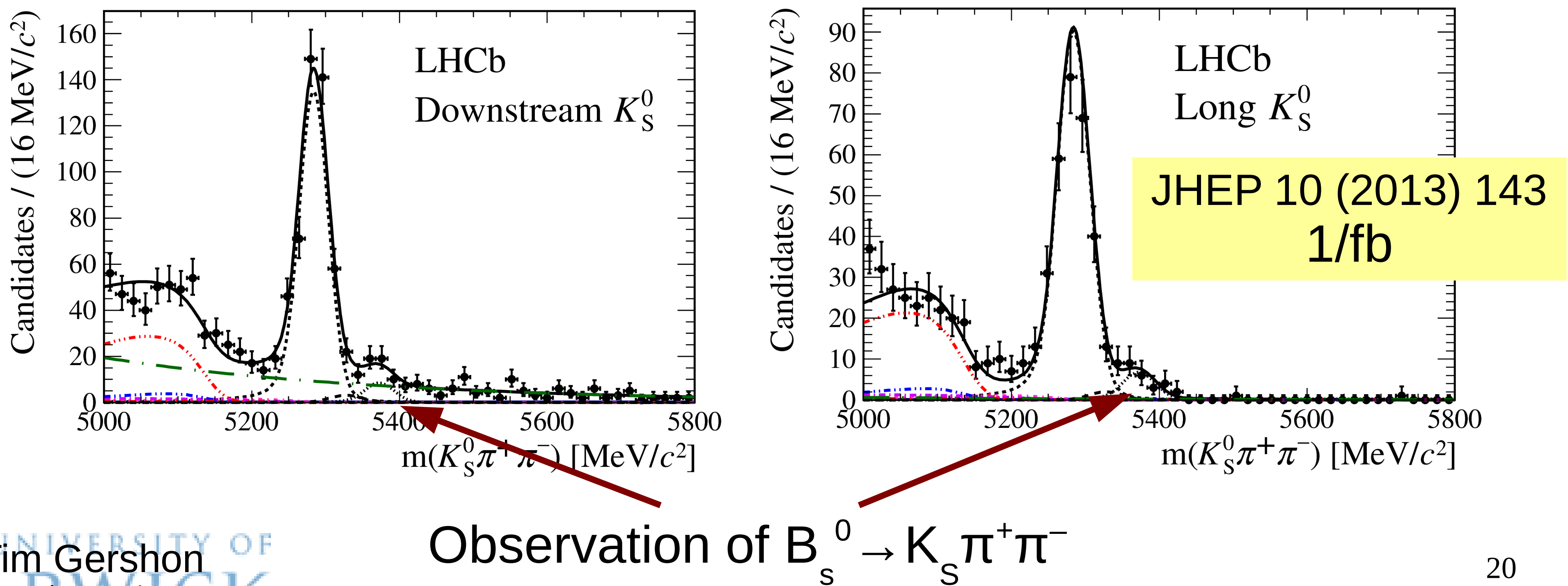

BACK UP!

Aside: $B_s^0 \to K_S\pi^+\pi^-$?

- Similar method works, in principle, for $B_s^0 \to K_S\pi^+\pi^-$
- Tagged time-dependent analysis not possible at B-factories, but could be done at LHCb

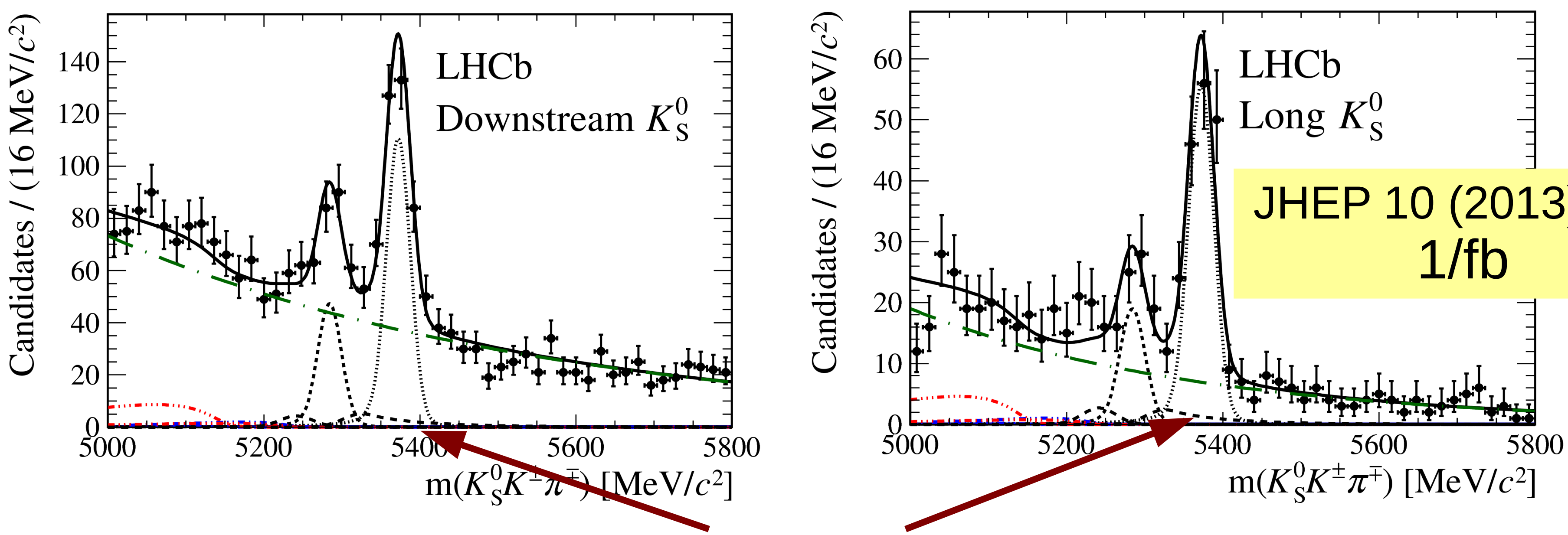
arXiv:1411.2018

- Yields available are, however, small



Aside: $B_s^0 \to KK\pi$?

- Similar method works, in principle, for $B_s^0 \to KK\pi$
- Tagged time-dependent analysis not possible at B-factories, but could be done at LHCb
- Reasonable yields available, but low tagging power
  - $B_s^0 \to K_S K^{+-} \pi^{-+}$ requires double Dalitz plot analysis (two final states)



JHEP 10 (2013) 143
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Observation of $B_s^0 \to K_S K^{+-} \pi^{-+}$