Extracting weak phases from Dalitz plots

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University of Warwick

Workshop on Amplitude Analysis
in Hadron Spectroscopy

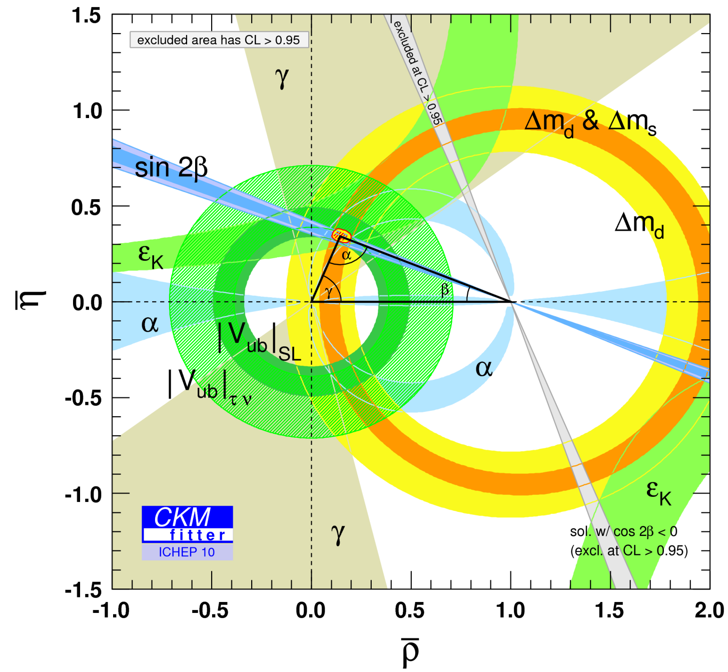
ECT* Trento

26th January 2011

Current status of CP violation and the CKM matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

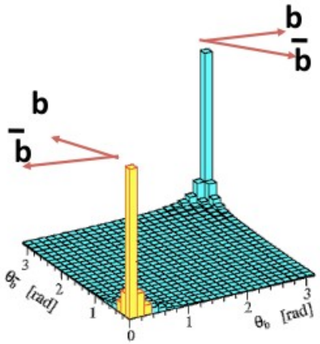


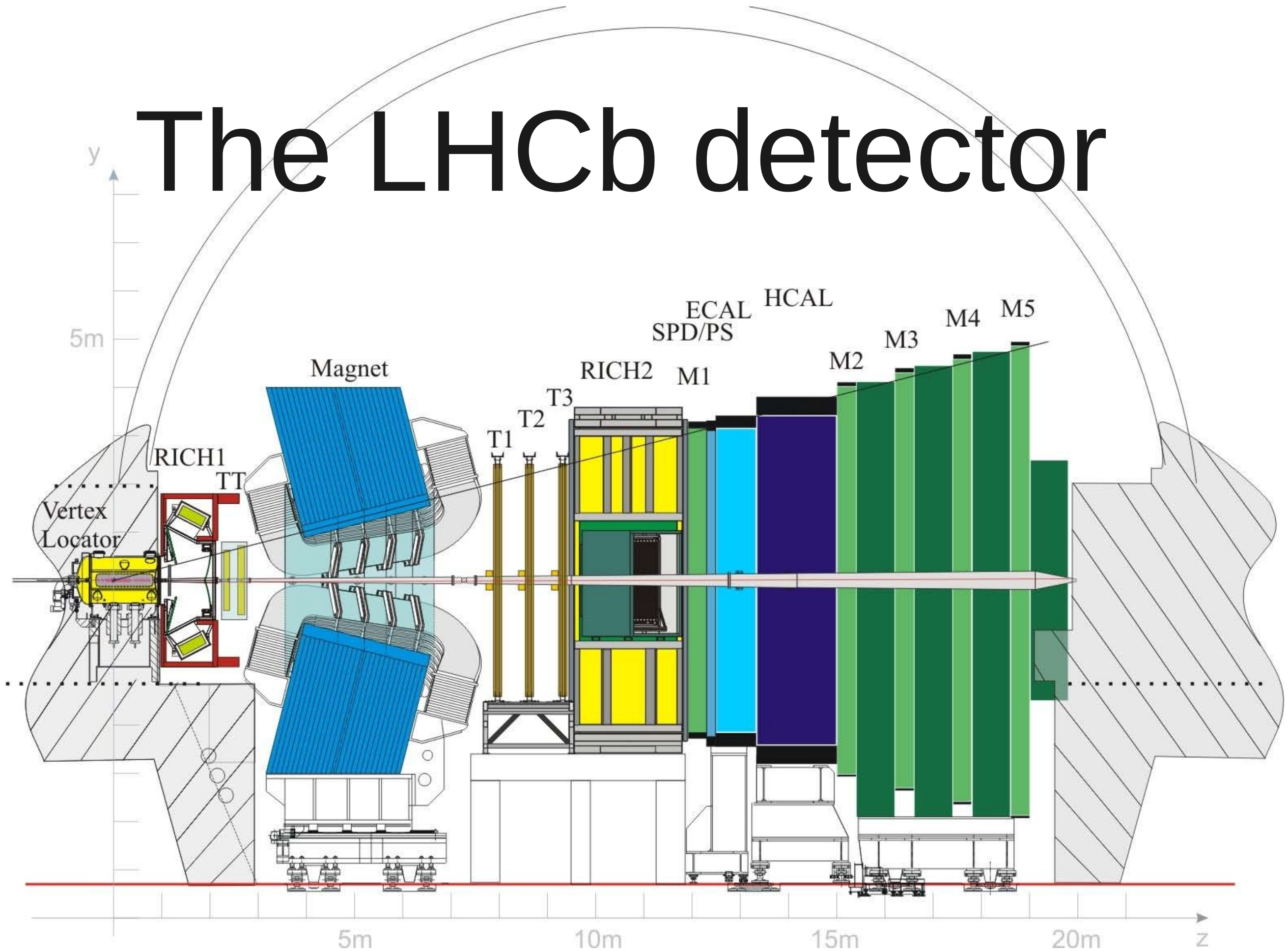
- CKM mechanism confirmed
  - All measurements of quark mixing & CP violation consistent with CKM paradigm
  - Several possible hints for effects of physics beyond the SM (A_{SL}, β_s, $K^*l^+l^-$, $B\rightarrow\tau\nu$)
  - Large contributions from new physics not excluded

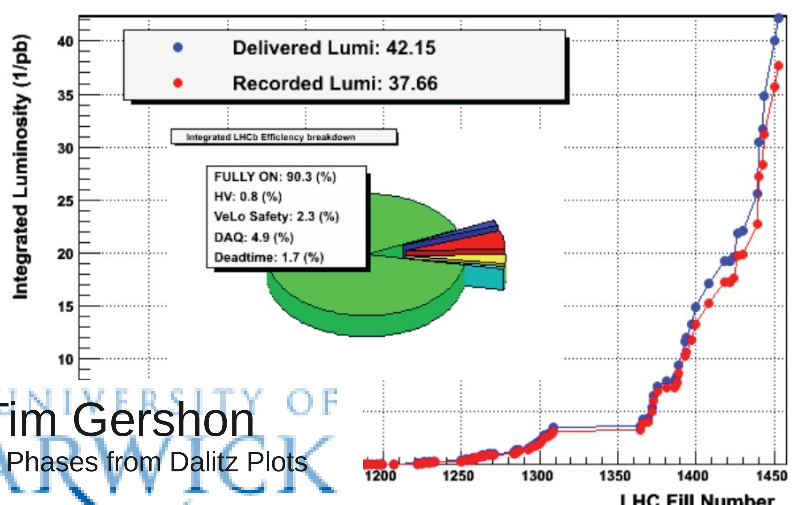
Experimental situation

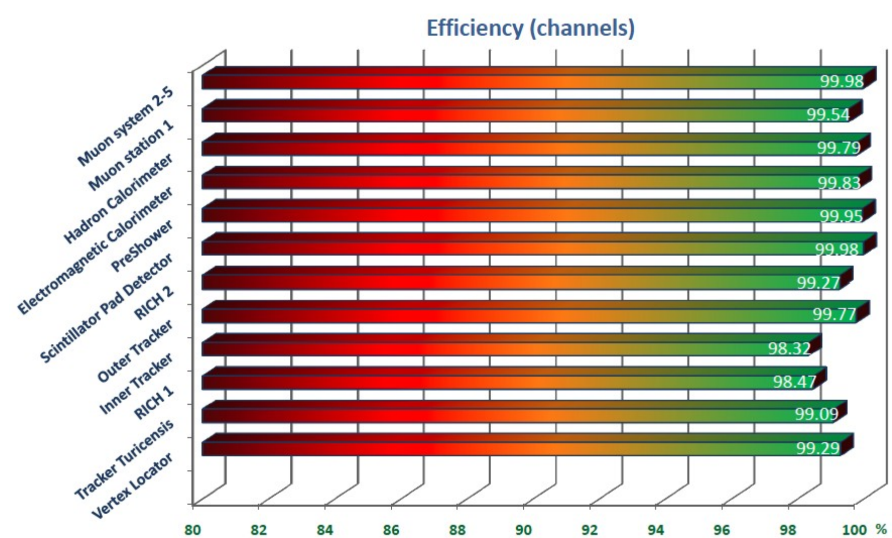
- B factories have completed data taking
  - publication rate still impressive
- Next generation experiments will provide much larger data samples of b and c hadrons
  - exciting new possibilities for analysis
- LHCb (CERN) – taking data since 2009
  - main focus of this talk
- Super B factories – data taking anticipated ~2015+
  - SuperKEKB/Belle2 (KEK, Japan)
  - SuperB (LNF, Frascati)

The LHCb detector



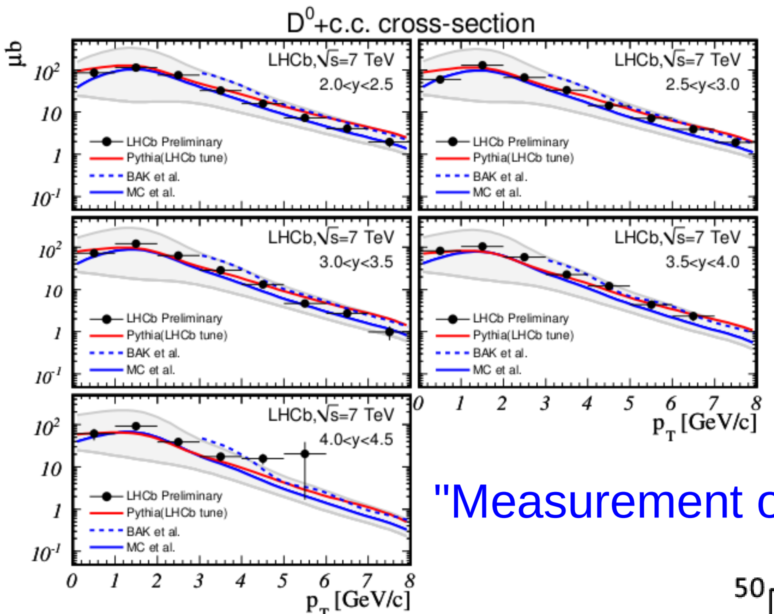




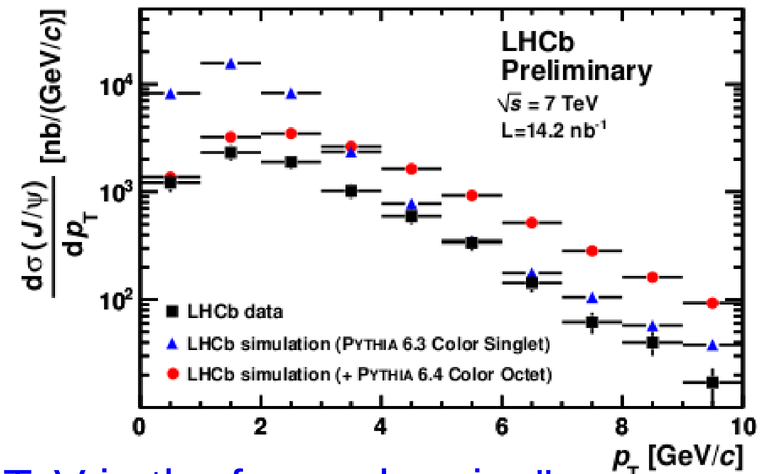


LHCb first physics

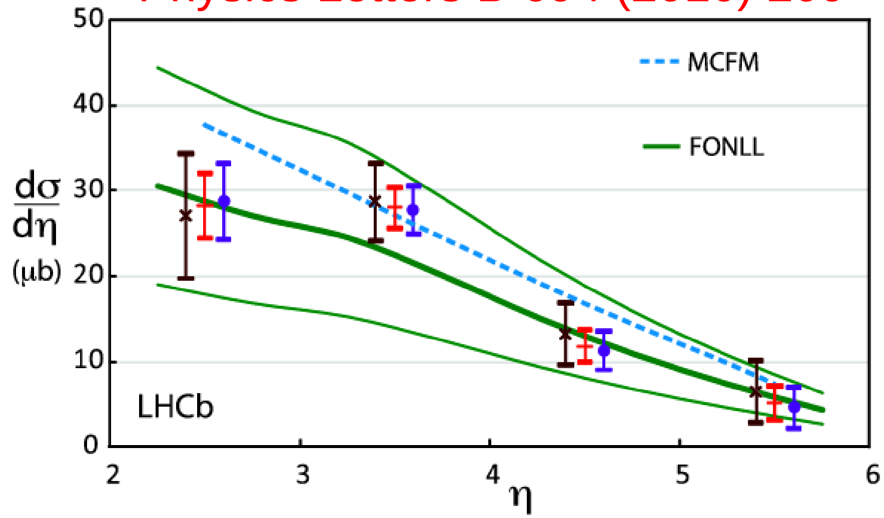
“Prompt charm production in pp collisions at √s = 7 TeV”
LHCb-CONF-2010-013



“Measurement of the J/ψ production cross-section at √s = 7 TeV in LHCb”
LHCb-CONF-2010-010

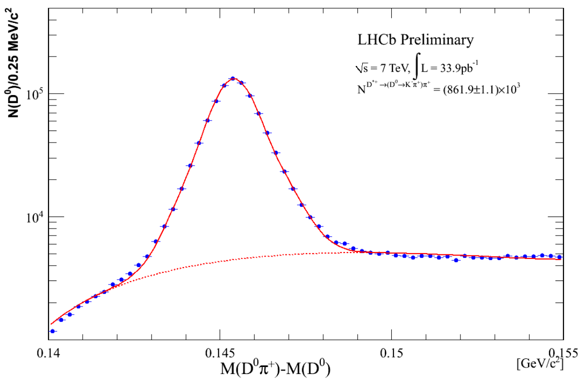


"Measurement of σ(pp→bb̄X) at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209

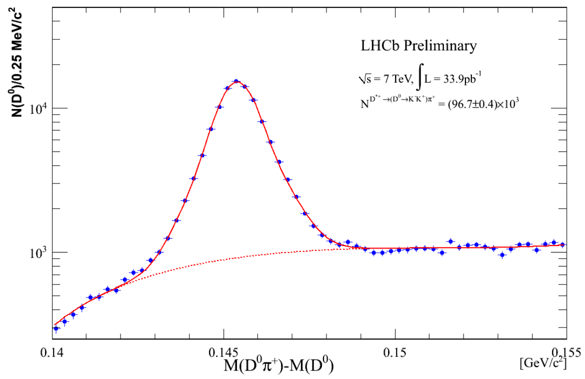


Copious yields at LHCb (e.g. in charm)

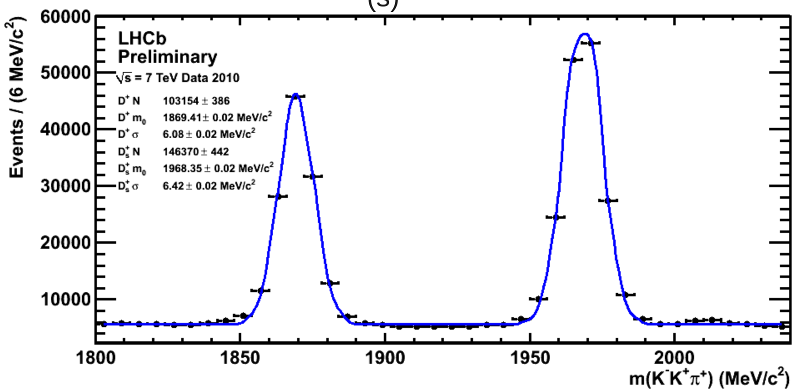
$D^{*\pm} \rightarrow D\pi^{\pm}$; $D \rightarrow K\pi$



$D^{*\pm} \rightarrow D\pi^{\pm}$; $D \rightarrow KK$



$D_{(s)}^{\pm} \rightarrow KK\pi^{\pm}$



Copious samples of charm already available

- e.g. 10^5 $D^{*\pm} \rightarrow D\pi^{\pm}$; $D \rightarrow KK$ events in 34/pb
- c.f. Belle: ~3×10^5 in 384/fb

Challenge is to control systematics to necessary level

- work in progress – expect world's best results in 2011

Introduction

- Dalitz plot analyses have been around for a long time
  - "On the analysis of tau-meson data and the nature of the tau-meson."
    - R.H. Dalitz, Phil. Mag. 44 (1953) 1068
- Only more recently have they been used to obtain information about weak phases (CP violation)
  - No observation (5σ) of direct CPV in any Dalitz plot analysis yet
- I will distinguish between methods that provide "qualitative" measures of CP violation and those that allow "quantitative" extraction of weak phases
  - ie. Unitarity Triangle angles α, β, γ as well as β_s and φ_D
  - I will focus mainly on the "quantitative" approaches and on B physics

Qualitative measures of CP violation in Dalitz plots

An incomplete bibliography (more literature outside B physics)

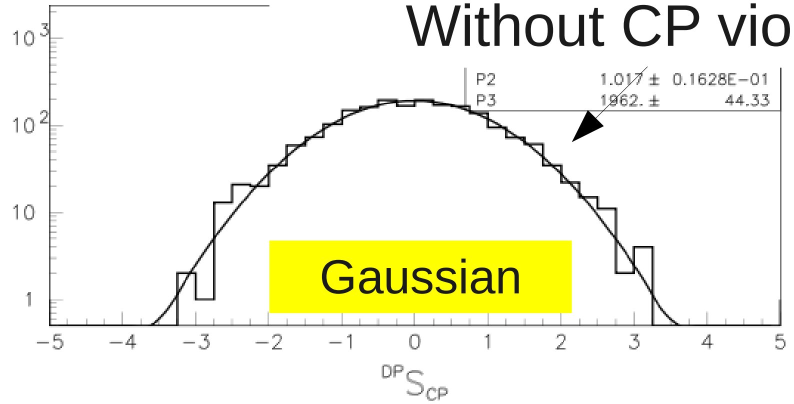
- “B meson CP violation without flavor identification”
  - G.Burdman and J.Donoghue, PRD 45 (1992) 187
- “CP violation in B mesons using Dalitz plot asymmetries”
  - R.Sinha, hep-ph/9608314
- “Direct CP violation in untagged B meson decays”
  - S.Gardner, PLB 553 (2003) 261
- “Observing direct CP violation in untagged B meson decays”
  - S.Gardner and J.Tandean, PRD 69 (2004) 034011
- “A New 'Miranda' Procedure for Dalitz CP Studies”
  - I.Bediaga et al., PRD 80 (2009) 096006

"Miranda" procedure a.k.a. Dalitz plot anisotropy

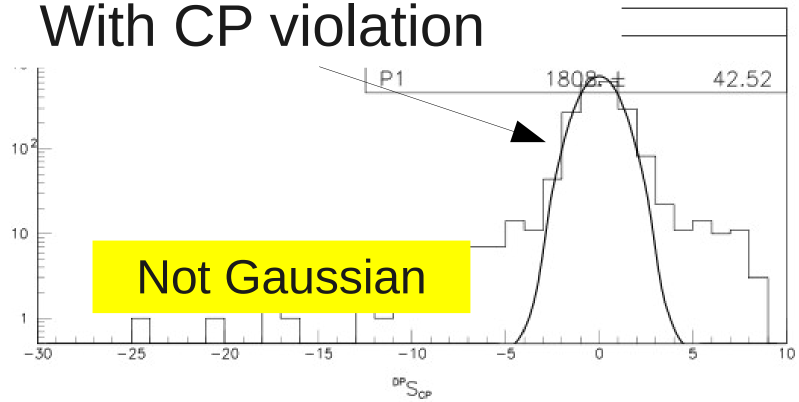
$$^{\mathrm{Dp}}S_{CP} \equiv \frac{N(i) - \bar{N}(i)}{\sqrt{N(i) + \bar{N}(i)}}$$

Toy model (using $B^+ \to K^+\pi^+\pi^-$)

Without CP violation



With CP violation



- Good model-independent way to identify CP violation
  - could be sufficient to identify non-SM physics in, e.g., charm decays
- Constant (DP independent) systematic asymmetries can be accounted for
- Can isolate region of the Dalitz plot where CP violation effects occur

But does not provide quantitative measure of weak phase

Quantitative methods –

Time-dependent Dalitz plot analyses

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

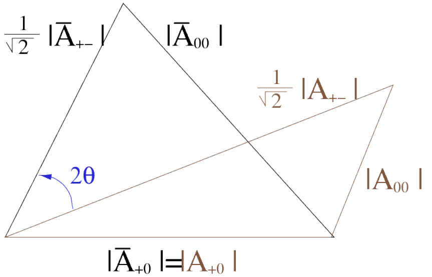
PRD 48 (1993) 2139

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

- 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)

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

- Results from
  - Belle, 449 M BB pairs: PRL 98 (2007) 221602, PRD 77 (2008) 072001
  - BaBar, 375 M BB pairs: PRD 76 (2007) 012004

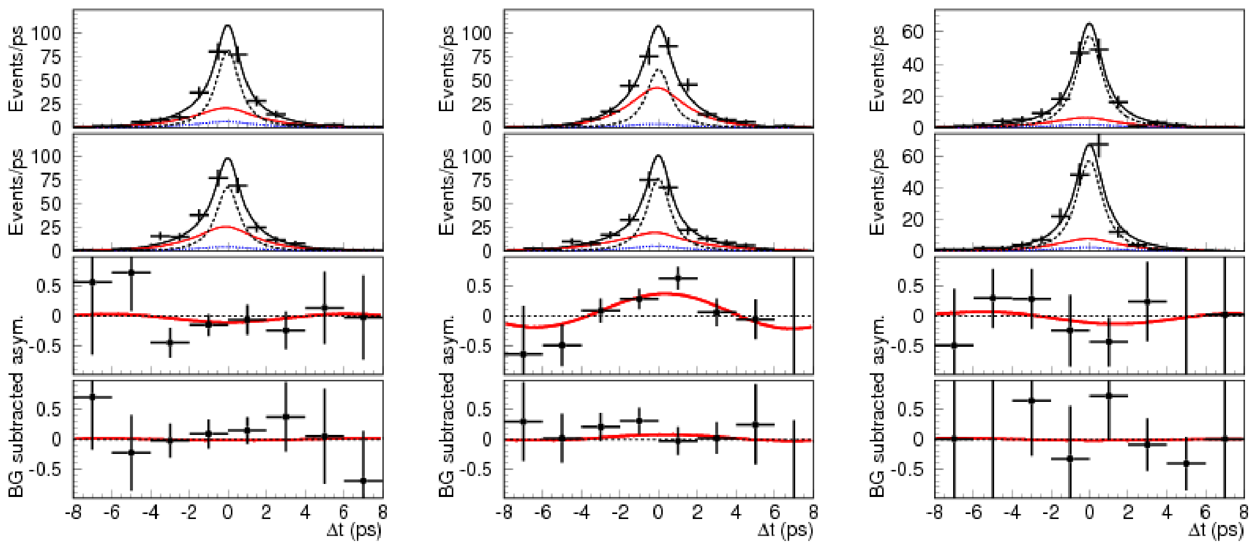


FIG. 10: Proper time distributions of good tag ($r > 0.5$) regions for $f_{\rm tag} = B^0$ (upper) and $f_{\rm tag} = \overline{B}^0$ (middle upper), in $\rho^+\pi^-$ (left), $\rho^-\pi^+$ (middle), $\rho^0\pi^0$ (right) enhanced regions, where solid (red), dotted, and dashed curves correspond to signal, continuum, and $B\overline{B}$ PDFs. The middle lower and lower plots show the background-subtracted asymmetries in the good tag ($r > 0.5$) and poor tag ($r < 0.5$) regions, respectively. The significant asymmetry in the $\rho^-\pi^+$ enhanced region (middle) corresponds to a non-zero value of U^-_-.

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

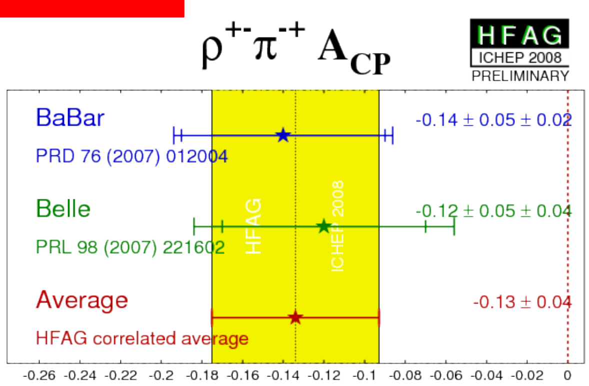
$B \to \pi^+\pi^-\pi^0$ – B factory results

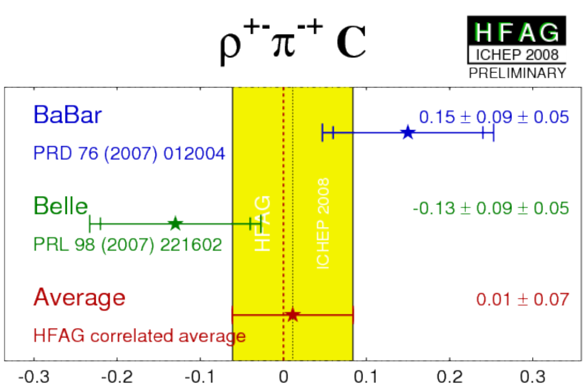
- Results from
  - Belle, 449 M BB pairs: PRL 98 (2007) 221602, PRD 77 (2008) 072001
  - BaBar, 375 M BB pairs: PRD 76 (2007) 012004

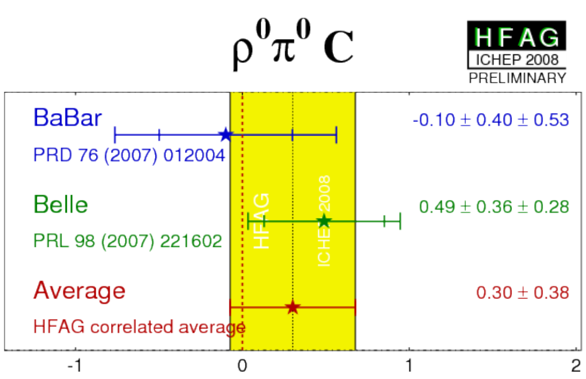
Experiment	A_{CP} ($\rho^{+-}\pi^{-+}$)	C ($\rho^{+-}\pi^{-+}$)	S ($\rho^{+-}\pi^{-+}$)	ΔC ($\rho^{+-}\pi^{-+}$)	ΔS ($\rho^{+-}\pi^{-+}$)	Correlations	Reference
BaBar N(BB)=375M	−0.14 ± 0.05 ± 0.02	0.15 ± 0.09 ± 0.05	−0.03 ± 0.11 ± 0.04	0.39 ± 0.09 ± 0.09	−0.01 ± 0.14 ± 0.06	(stat)	PRD 76 (2007) 012004
Belle N(BB)=449M	−0.12 ± 0.05 ± 0.04	−0.13 ± 0.09 ± 0.05	0.06 ± 0.13 ± 0.05	0.36 ± 0.10 ± 0.05	−0.08 ± 0.13 ± 0.05	(stat)	PRL 98 (2007) 221602
Average	−0.13 ± 0.04	0.01 ± 0.07	0.01 ± 0.09	0.37 ± 0.08	−0.04 ± 0.10	(stat)	HFAG correlated average χ^2 = 4.2/5 dof (CL=0.52 ⇒ 0.6σ)

Experiment	C ($\rho^0\pi^0$)	S ($\rho^0\pi^0$)	Correlation	Reference
BaBar N(BB)=375M	−0.10 ± 0.40 ± 0.53	0.04 ± 0.44 ± 0.18	0.35	PRD 76 (2007) 012004
Belle N(BB)=449M	0.49 ± 0.36 ± 0.28	0.17 ± 0.57 ± 0.35	0.08	PRL 98 (2007) 221602
Average	0.30 ± 0.38	0.12 ± 0.38	0.12	HFAG correlated average χ^2 = 0.5/2 dof (CL=0.76 ⇒ 0.3σ)

≠0 at 3σ



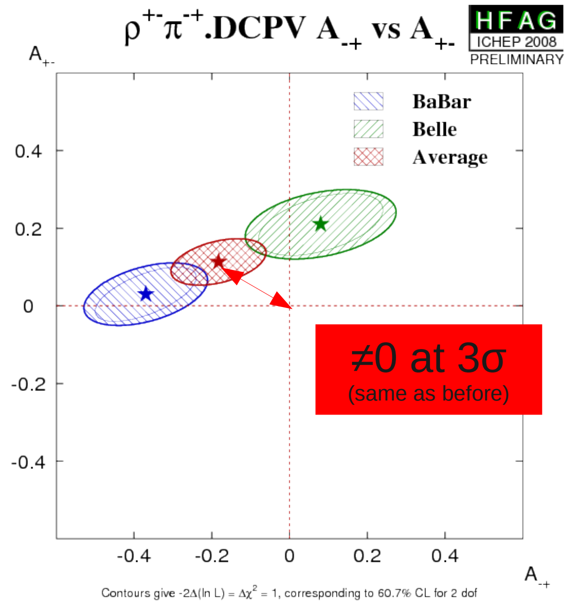




$B \to \pi^+\pi^-\pi^0$ – B factory results

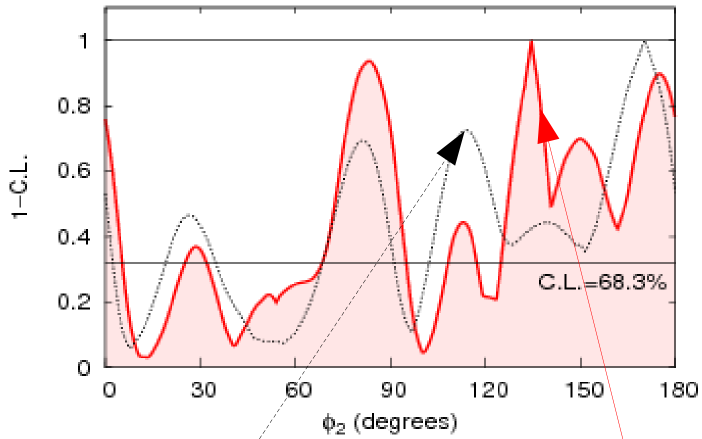
- Results from
  - Belle, 449 M BB pairs: PRL 98 (2007) 221602, PRD 77 (2008) 072001
  - BaBar, 375 M BB pairs: PRD 76 (2007) 012004

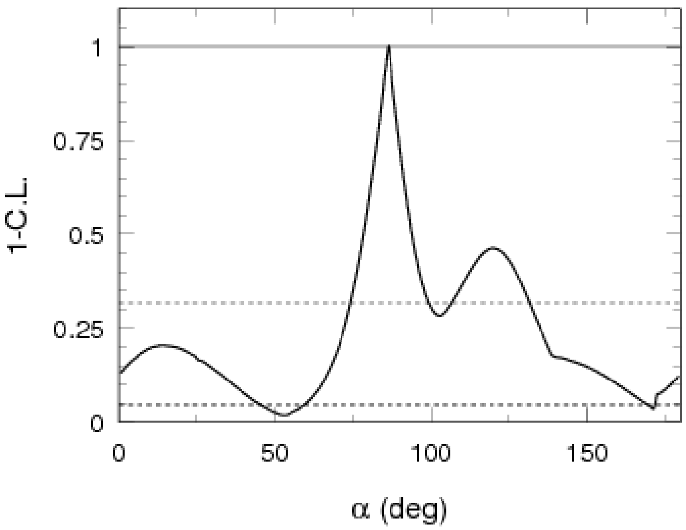
Experiment	A_{-+} ($\rho^{+-}\pi^{-+}$)	A_{+-} ($\rho^{+-}\pi^{-+}$)	Correlation	Reference
BaBar N(BB)=375M	$-0.37\ ^{+0.16}_{-0.10} \pm 0.09$	$0.03 \pm 0.07 \pm 0.04$	0.62	PRD 76 (2007) 012004
Belle N(BB)=449M	$0.08 \pm 0.16 \pm 0.11$	$0.21 \pm 0.08 \pm 0.04$	0.47	PRL 98 (2007) 221602
Average	-0.18 ± 0.12	0.11 ± 0.06	0.40	HFAG correlated average χ^2 = 4.0/2 dof (CL=0.14 ⇒ 1.5σ)



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

- Results from
  - Belle, 449 M BB pairs: PRL 98 (2007) 221602, PRD 77 (2008) 072001
  - BaBar, 375 M BB pairs: PRD 76 (2007) 012004



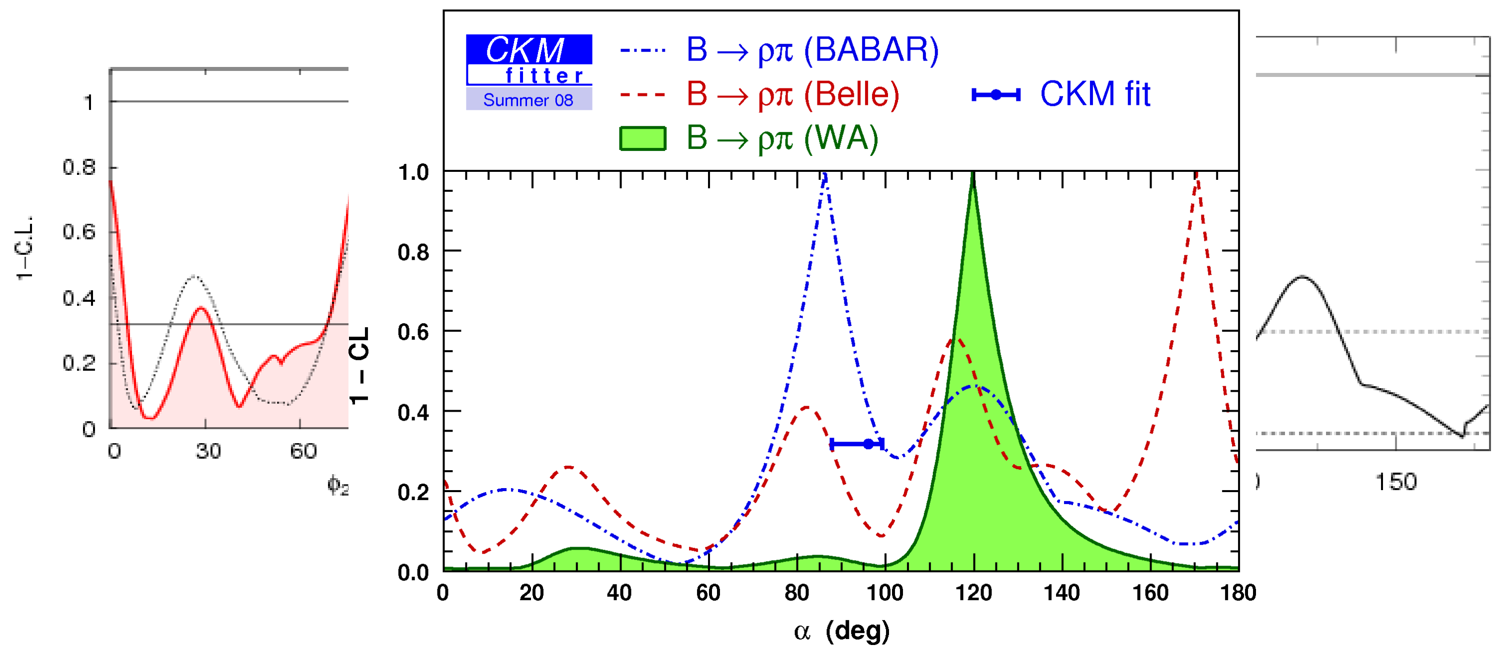


Contour from $B \to \pi^+\pi^-\pi^0$ only

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

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

- Results from
  - Belle, 449 M BB pairs: PRL 98 (2007) 221602, PRD 77 (2008) 072001
  - BaBar, 375 M BB pairs: PRD 76 (2007) 012004



$B \to \pi^+\pi^-\pi^0$ – model dependence

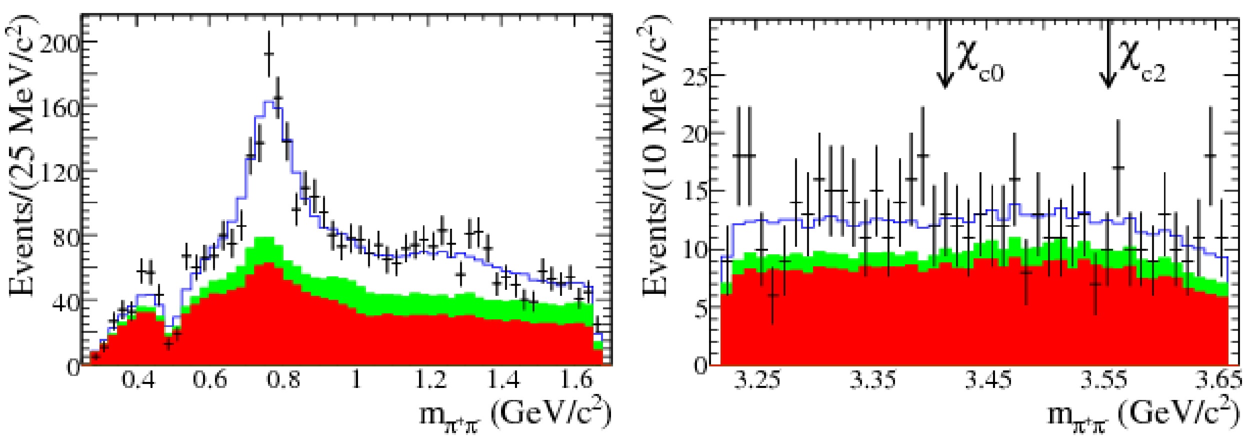
- Nominal model
  - includes ($\rho(770)$, $\rho(1450)$, $\rho(1450)$) x (+,–,0)
  - Gounaris-Sakurai lineshape
  - largest source of model dependence from varying parameters of ρ' & ρ''
- Possible contributions from $\pi^+\pi^-$ S-wave (σ or nonresonant)?
  - U.-G. Meissner & S. Gardner, EPJA 18 (2003) 543
  - J. Tandean & S. Gardner, PRD 66 (2002) 034019
  - S. Gardner, U.-G. Meissner, PRD 65 (2002) 094004
- Not apparent in the ($\pi^+\pi^-\pi^0$) data so far

Cross-check model (and extract γ?) from $B^+ \to \pi^+\pi^+\pi^-$

- Exploit interference between $b \to ccd$ and $b \to uud$
  - $B^+ \to \chi_{c0}\pi^+$ and charmless $B^+ \to \pi^+\pi^+\pi^-$ (eg. $B^+ \to \rho^0\pi^+$)

Eilam et al., PRL 74 (1995) 4984, Deshpande et al., PRD 52 (1995) 5354,
Bediaga et al., PRL 81 (1998) 4067, Bajc et al., PLB 447 (1999) 313

- Most recent analysis – no signal for $\chi_{c0}\pi^+$ → no sensitivity



BaBar PRD 79 (2009) 072006

- But significant S-wave contribution (NR + $f_0(1370)$) seen

Cross-check model (and extract γ?) from $B^+ \to \pi^+\pi^+\pi^-$

TABLE III: Summary of measurements of branching fractions (averaged over charge conjugate states) and CP asymmetries. The first error is statistical, the second is systematic and the third represents the model dependence. Also included are 90% CL upper limits of the branching fractions of the components that do not have statistically significant fit fractions.

Mode	Fit Fraction (%)	$\mathcal{B}(B^\pm \to \text{Mode})(10^{-6})$	$\mathcal{A}_{CP}$ (%)
$\pi^\pm\pi^\pm\pi^\mp$ Total		$15.2 \pm 0.6 \pm 1.2\,^{+0.4}_{-0.3}$	$+3.2 \pm 4.4 \pm 3.1\,^{+2.5}_{-2.0}$
$\rho^0(770)\pi^\pm$; $\rho^0(770) \to \pi^+\pi^-$	$53.2 \pm 3.7 \pm 2.5\,^{+1.5}_{-7.4}$	$8.1 \pm 0.7 \pm 1.2\,^{+0.4}_{-1.1}$	$+18 \pm 7 \pm 5\,^{+2}_{-14}$
$\rho^0(1450)\pi^\pm$; $\rho^0(1450) \to \pi^+\pi^-$	$9.1 \pm 2.3 \pm 2.4\,^{+1.9}_{-4.5}$	$1.4 \pm 0.4 \pm 0.4\,^{+0.3}_{-0.7}$	$-6 \pm 28 \pm 20\,^{+12}_{-35}$
$f_2(1270)\pi^\pm$; $f_2(1270) \to \pi^+\pi^-$	$5.9 \pm 1.6 \pm 0.4\,^{+2.0}_{-0.7}$	$0.9 \pm 0.2 \pm 0.1\,^{+0.3}_{-0.1}$	$+41 \pm 25 \pm 13\,^{+12}_{-8}$
$f_0(1370)\pi^\pm$; $f_0(1370) \to \pi^+\pi^-$	$18.9 \pm 3.3 \pm 2.6\,^{+4.3}_{-3.5}$	$2.9 \pm 0.5 \pm 0.5\,^{+0.7}_{-0.5}$ (< 4.0)	$+72 \pm 15 \pm 14\,^{+7}_{-8}$
$\pi^\pm\pi^\pm\pi^\mp$ nonresonant	$34.9 \pm 4.2 \pm 2.9\,^{+7.5}_{-3.4}$	$5.3 \pm 0.7 \pm 0.6\,^{+1.1}_{-0.5}$	$-14 \pm 14 \pm 7\,^{+17}_{-3}$
$f_0(980)\pi^\pm$; $f_0(980) \to \pi^+\pi^-$	-	< 1.5	-
$\chi_{c0}\pi^\pm$; $\chi_{c0} \to \pi^+\pi^-$	-	< 0.1	-
$\chi_{c2}\pi^\pm$; $\chi_{c2} \to \pi^+\pi^-$	-	< 0.1	-

BaBar PRD 79 (2009) 072006

- But significant S-wave contribution (NR + $f_0(1370)$) seen

More time-dependent Dalitz plot analyses

$B_d^0(t) \rightarrow DPP$ time-dependent Dalitz plots,
CP-violating angles 2β, $2\beta+\gamma$, and discrete ambiguities

J. Charles [1], A. Le Yaouanc [2], L. Oliver [3], O. Pène, J.-C. Raynal

Laboratoire de Physique Théorique et Hautes Énergies [4] Université de Paris XI, Bâtiment 211, 91405 Orsay Cedex, France

PLB 425 (1998) 375

- $B_d \rightarrow D^+D^-\pi^0$ (b→ccd transition)
  - measures 2β, never done yet
- $B_d \rightarrow D^+D^-K_S$ (b→ccs transition)
  - measures 2β, never done yet (but note $B_d \rightarrow D^{*+}D^{*-}K_S$ analyses by both B factories)

T.Browder et al., PRD 61 (2000) 054009;
BaBar PRD 74 (2006) 091101, Belle PRD 76, 072004 (2007)

- $B_d \rightarrow D_{CP}\pi^+\pi^-$ (b→cud transition)
  - measures 2β, never done yet

T.Latham and T.Gershon, JPG 36 (2009) 025006

- $B_d \rightarrow D^+\pi^-K_S$ (b→cus transition)
  - measures 2β+γ, done by BaBar

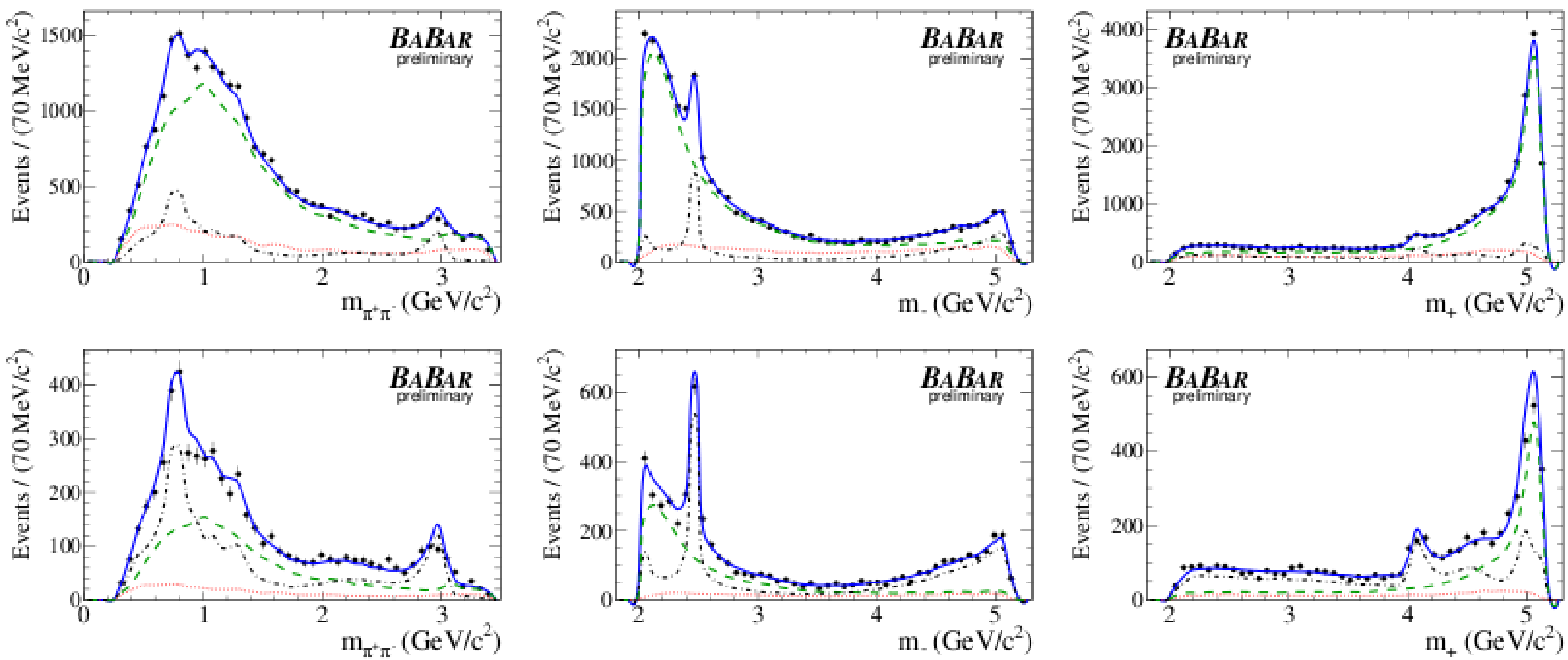
R.Aleksan and T.Petersen, hep-ph/0307371;
F.Polci et al., hep-ph/0605129; BaBar PRD 77 (2008) 071102

$B_d \to D\pi^+\pi^-$

- Neutral D mesons conveniently reconstructed as either
  - $D \to K\pi$ (quasi-flavour-specific); $D \to KK$, $\pi\pi$ (CP-eigenstate)

All data

Signal enhanced



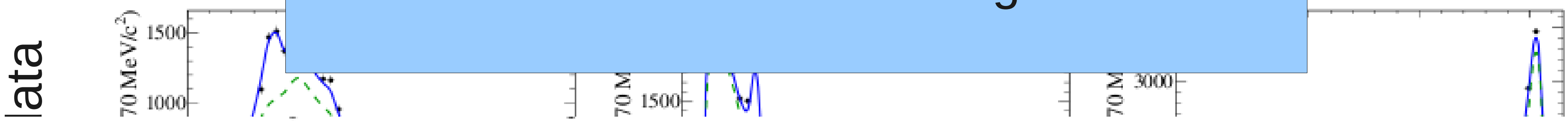
Green dashed – background
Black dotted – signal

BABAR-CONF-10/004, arXiv:1007.4464 (see also Belle PRD 76 (2007) 012006 & related analyses of $B^+ \to D^-\pi^+\pi^+$)

$B_d \rightarrow D\pi^+\pi^-$

- Neutral ... either
  - $D \rightarrow K$ ... genstate)

Model agrees well with data but contains some interesting features



Resonance	Fit Fraction (%)	$\mathcal{B}(B^0 \to \text{Mode}) \times \mathcal{B}(R \to hh)$ (10^{-4})	$\mathcal{B}(B^0 \to \text{Mode})$ (10^{-4})
Inclusive $B^0 \to \overline{D}^0\pi^+\pi^-$	...	...	8.81±0.18±0.76±0.78±0.11
$D_2^*(2460)^-\pi^+$	20.5±0.9±1.3±3.7	1.80±0.09±0.19±0.37±0.02	...
$D_0^*(2400)^-\pi^+$	24.8±2.5±3.0±12.9	2.18±0.23±0.33±1.15±0.03	...
$\rho(770)^0\overline{D}^0$	33.4±2.0±5.2±10.0	2.94±0.19±0.53±0.92±0.04	2.98±0.19±0.53±0.93±0.04
$f_2(1270)\overline{D}^0$	9.8±1.1±1.6±3.4	0.86±0.10±0.16±0.31±0.01	1.02±0.12±0.18±0.36±0.03
$D_v^*(2010)^-\pi^+$	15.8±0.9±1.2±3.7	1.39±0.08±0.16±0.35±0.02	...
$D\pi$ nonresonant	18.4±2.3±4.3±13.6	1.62±0.21±0.41±1.21±0.02	...
K matrix total	25.6±2.5±3.2±6.1	2.26±0.22±0.34±0.58±0.03	...

First use of K matrix in B decays

BABAR-CONF-10/004, arXiv:1007.4464
(see also Belle PRD 76 (2007) 012006)

Time-dependent Dalitz plot analyses of charmless hadronic B decays

- $B_d \to K_S K^+ K^-$ (mainly $b \to sss$)
  - $\sin(2\beta^{eff})$ ambiguity for φK_S broken by interference with K^+K^- S-wave

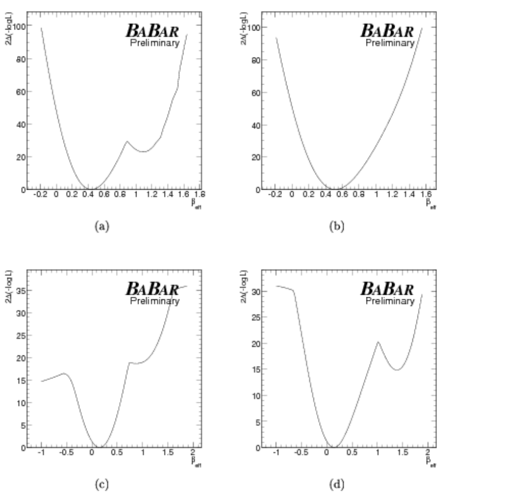
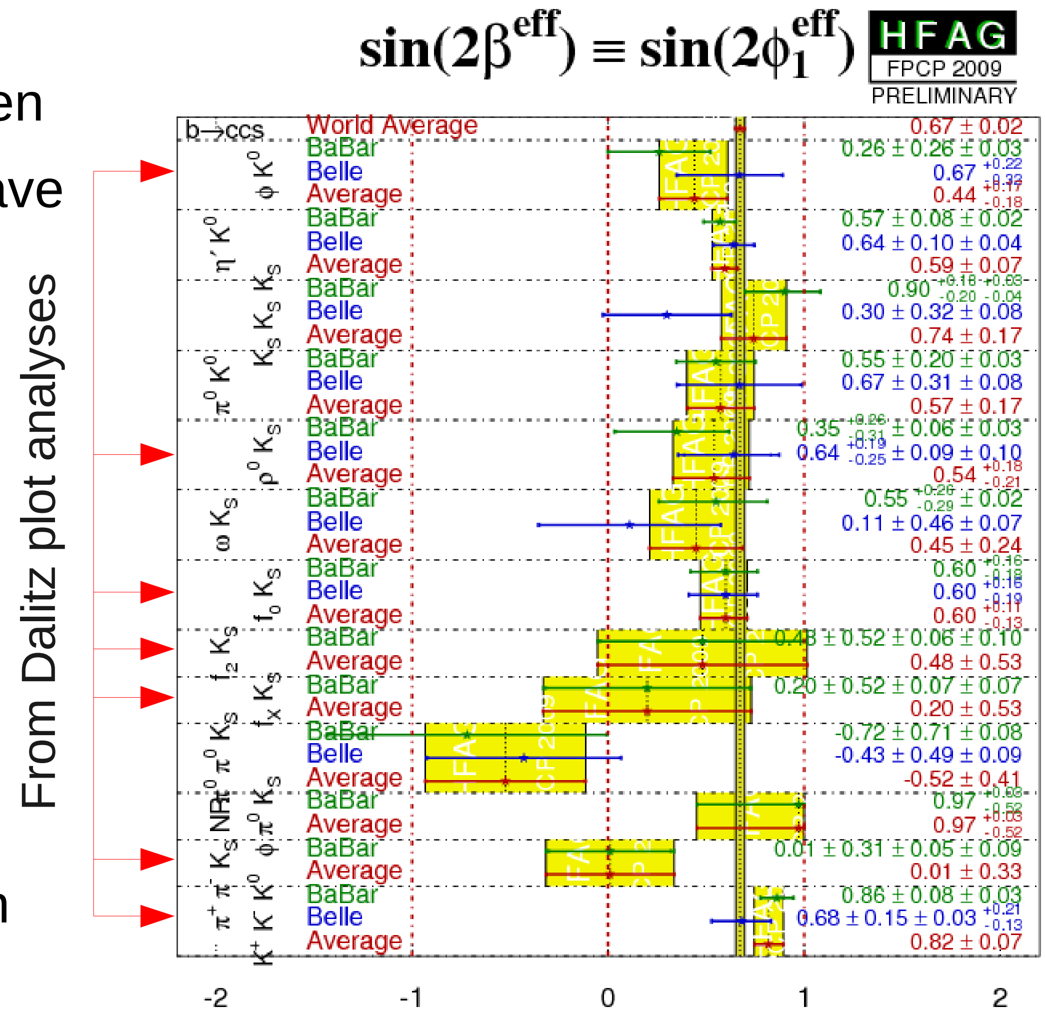


Figure 6: The change in the value of $-2\log(\mathcal{L})$ as a function of β_{eff}, for (a) the whole DP, (b) the High-mass region, (c) $f_0(980)$, and (d) $\phi(1020)$.

- $B_d \to K_S \pi^+\pi^-$
  - $b \to uus$ tree and $b \to sqq$ penguin
  - also useful for γ measurement



BaBar arXiv:0808.0700, Belle PRD 82 (2010) 073011;
BaBar PRD 80 (2009) 112001, Belle PRD 79 (2009) 072004

Quantitative methods –

Weak phases from direct CP violation in Dalitz plot analyses

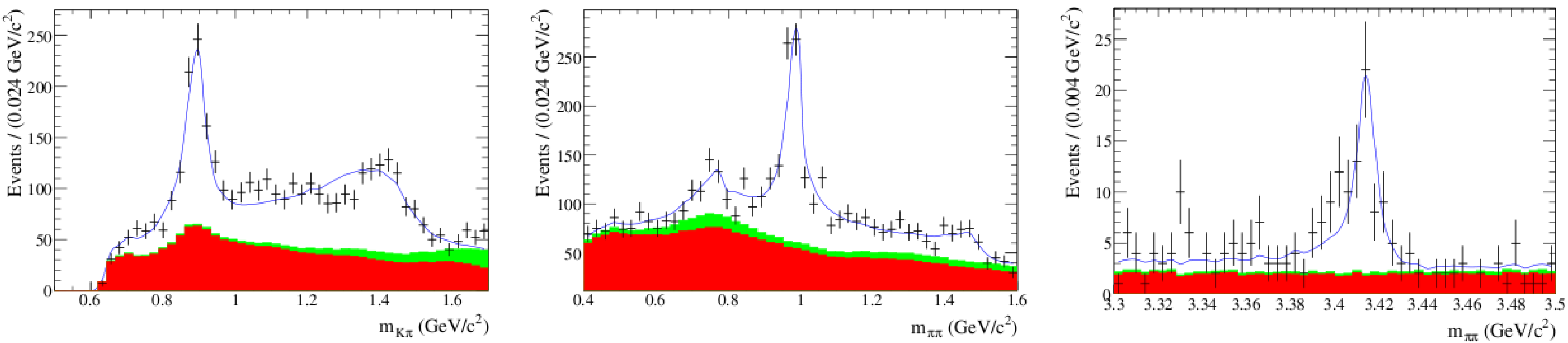
γ from $B^+ \to K^+\pi^+\pi^-$

- Can apply same argument as for $B^+ \to \pi^+\pi^+\pi^-$, but now interference is between $b \to ccs$ and $b \to uus$
  - $B^+ \to \chi_{c0}K^+$ and charmless $B^+ \to K^+\pi^+\pi^-$ (eg. $B^+ \to \rho^0K^+$)

Lipkin et al., PRD 44 (1991) 1454, Deshpande et al., PRL 90 (2003) 061802, Blanco et al., PRL 86 (2001) 2720

- Large penguin contribution with different weak phase
  - method is not theoretically clean
  - use flavour symmetries to reduce uncertainties

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



BaBar PRD 78 (2008) 012004
See also Belle PRL 96 (2006) 251803

Model includes:

- $K^{*0}(892)\pi^+$, $K_2^{*0}(1430)\pi^+$
- $(K\pi)_0^*\pi^+$ (LASS lineshape)
- $\rho^0(770)K^+$, $\omega(782)K^+$, $f_0(980)K^+$, $f_2(1270)K^+$, $\chi_{c0}K^+$
- $f_X(1300)K^+$, phase-space nonresonant

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

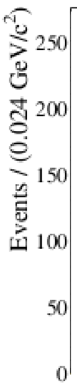
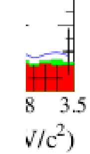


TABLE II: Summary of measurements of branching fractions (averaged over charge conjugate states) and *CP* asymmetries. Note that these results are not corrected for secondary branching fractions. The first uncertainty is statistical, the second is systematic, and the third represents the model dependence. The final column is the statistical significance of direct *CP* violation determined as described in the text.

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	$4.5 \pm 0.9 \pm 2.4\,^{+0.6}_{-1.5}$	$2.4 \pm 0.5 \pm 1.3\,^{+0.3}_{-0.8}$	—	—
$K^{*0}_2(1430)\pi^+;\ K^{*0}_2(1430) \to K^+\pi^-$	$3.40 \pm 0.75 \pm 0.42\,^{+0.99}_{-0.13}$	$1.85 \pm 0.41 \pm 0.28\,^{+0.54}_{-0.08}$	$+5 \pm 23 \pm 4\,^{+18}_{-7}$	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



- $f_X(1300)K^+$, phase-space nonresonant

BaBar PRD 78 (2008) 012004
See also Belle PRL 96 (2006) 251803

Evidence for direct CP violation
But significant model dependence

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

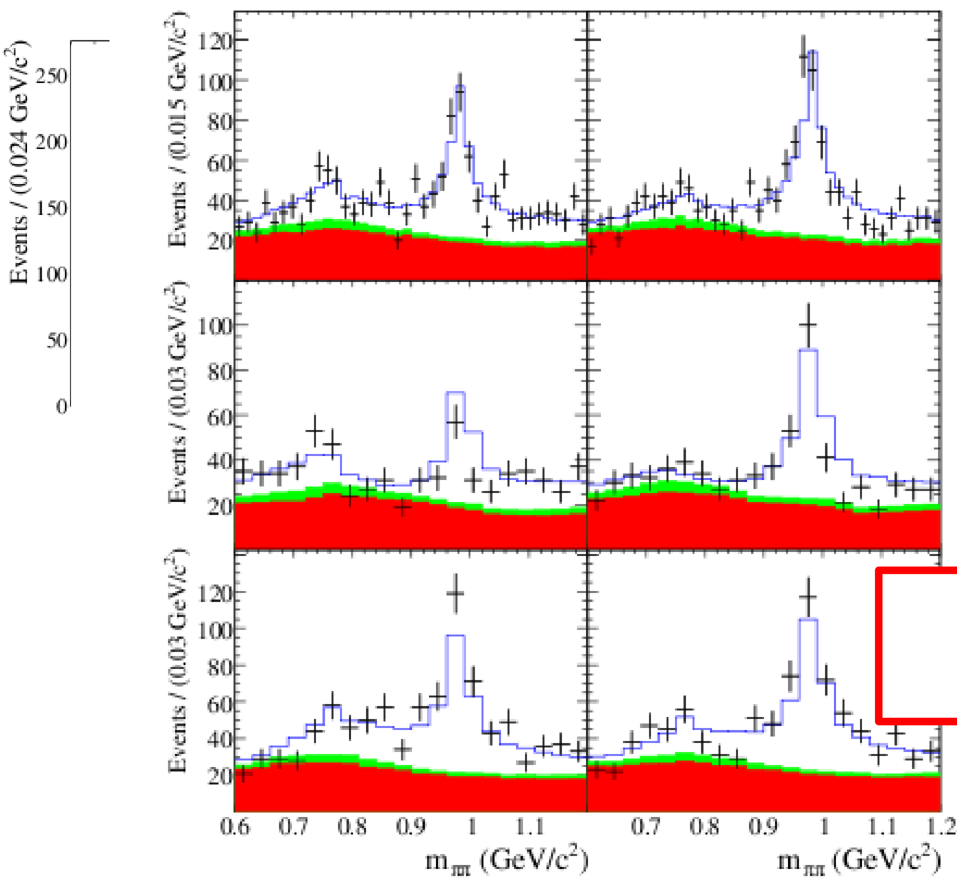


FIG. 4: Projection plots of the $\pi^+\pi^-$ invariant mass in the region of the $\rho^0(770)$ and $f_0(980)$ resonances. The left (right) plots are for B^- (B^+) candidates. The top row shows all candidates, the middle row shows those where $\cos\theta_H > 0$, and the bottom row shows those where $\cos\theta_H < 0$. The data are the black points with statistical error bars, the lower solid (red/dark) histogram is the $q\overline{q}$ component, the middle solid (green/light) histogram is the $B\overline{B}$ background contribution, while the blue open histogram shows the total fit result.

veraged over charge conjugate states) and CP asymmetries. ng fractions. The first uncertainty is statistical, the second The final column is the statistical significance of direct CP

$\mathcal{B}(B^+ \to \text{Mode})(10^{-6})$	A_{CP} (%)	DCPV sig.
$54.4 \pm 1.1 \pm 4.5 \pm 0.7$	$2.8 \pm 2.0 \pm 2.0 \pm 1.2$	
$7.2 \pm 0.4 \pm 0.7\,^{+0.3}_{-0.5}$	$+3.2 \pm 5.2 \pm 1.1\,^{+1.2}_{-0.7}$	0.9σ
$24.5 \pm 0.9 \pm 2.1\,^{+7.0}_{-1.1}$	$+3.2 \pm 3.5 \pm 2.0\,^{+2.7}_{-1.9}$	1.2σ
$.56 \pm 0.45 \pm 0.43\,^{+0.38}_{-0.15}$	$+44 \pm 10 \pm 4\,^{+5}_{-13}$	3.7σ
$10.3 \pm 0.5 \pm 1.3\,^{+1.5}$	$-10.6 \pm 5.0 \pm 1.1\,^{+3.4}$	1.8σ
$.85 \pm 0.41 \pm 0.28\,_{-0.08}$	$+5 \pm 23 \pm 4\,_{-7}$	0.2σ
$.09 \pm 0.13 \pm 0.02\,^{+0.03}_{-0.04}$	—	—
$.50 \pm 0.15 \pm 0.07\,^{+0.13}_{-0.09}$	$-85 \pm 22 \pm 13\,^{+22}_{-2}$	3.5σ
$.73 \pm 0.21 \pm 0.47\,^{+0.02}_{-0.08}$	$+28 \pm 26 \pm 13\,^{+7}_{-5}$	0.6σ

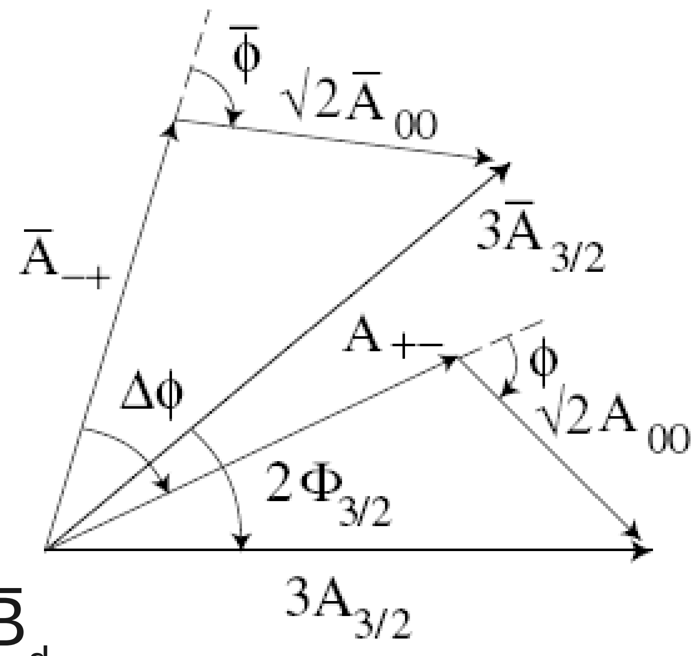
Evidence for direct CP violation
But significant model dependence

onant

BaBar PRD 78 (2008) 012004
See also Belle PRL 96 (2006) 251803

γ from $B^0 \to K\pi\pi$

Ciuchini et al., PRD 74 (2006) 051301, Gronau et al., PRD 75 (2007) 014002, PRD 77 (2008) 057504



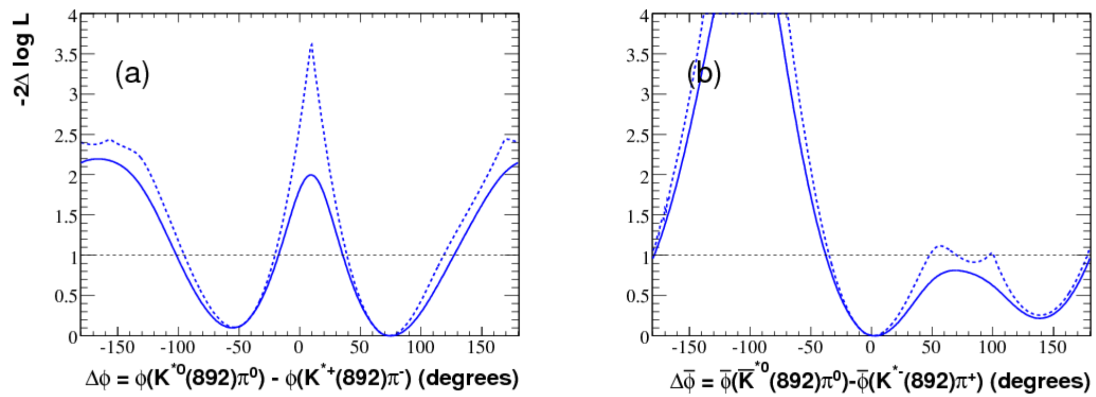
- Use $B_d \to K^{*+}\pi^-$ and $B_d \to K^{*0}\pi^0$
  - form isospin triangles
  - $A_{ij} = A(B^0 \to K^{*i}\pi^j)$
- Both contribute to $B_d \to K^+\pi^-\pi^0$
  - determine $\varphi = \arg(A_{00}/A_{+-})$
- Need relative phase between B_d and $\bar{B}_d$
  - determine $\Delta\varphi = \arg(A_{+-}/\bar{A}_{+-})$ from time-dependent analysis of $B_d \to K_S\pi^+\pi^-$
- Can now extract $\Phi_{3/2} \approx \gamma$ (with corrections due to EW penguins)

γ from $B^0 \to K\pi\pi$ – B factory results

- $B_d \to K^+\pi^-\pi^0$ results

BaBar PRD 78 (2008) 052005

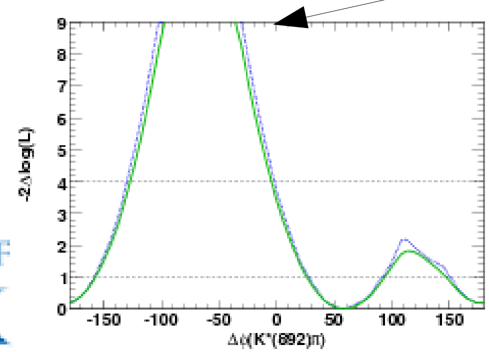
  - multiple solutions reduce precision
  - improvement expected with updated analysis (arXiv:0807.4567)

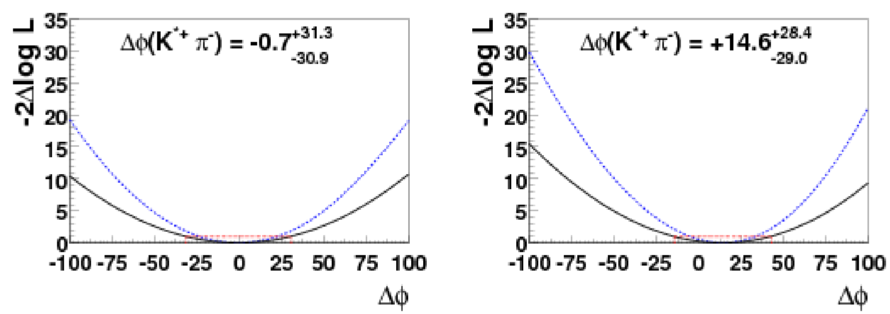


- $B_d \to K_S\pi^+\pi^-$ results

BaBar arXiv:0905.3615, Belle PRD 79 (2009) 072004

(two solutions)





γ from $B^0 \to K\pi\pi$ – B factory results

- $B_d \to K^+\pi^-\pi^0$ results

BaBar PRD 78 (2008) 052005

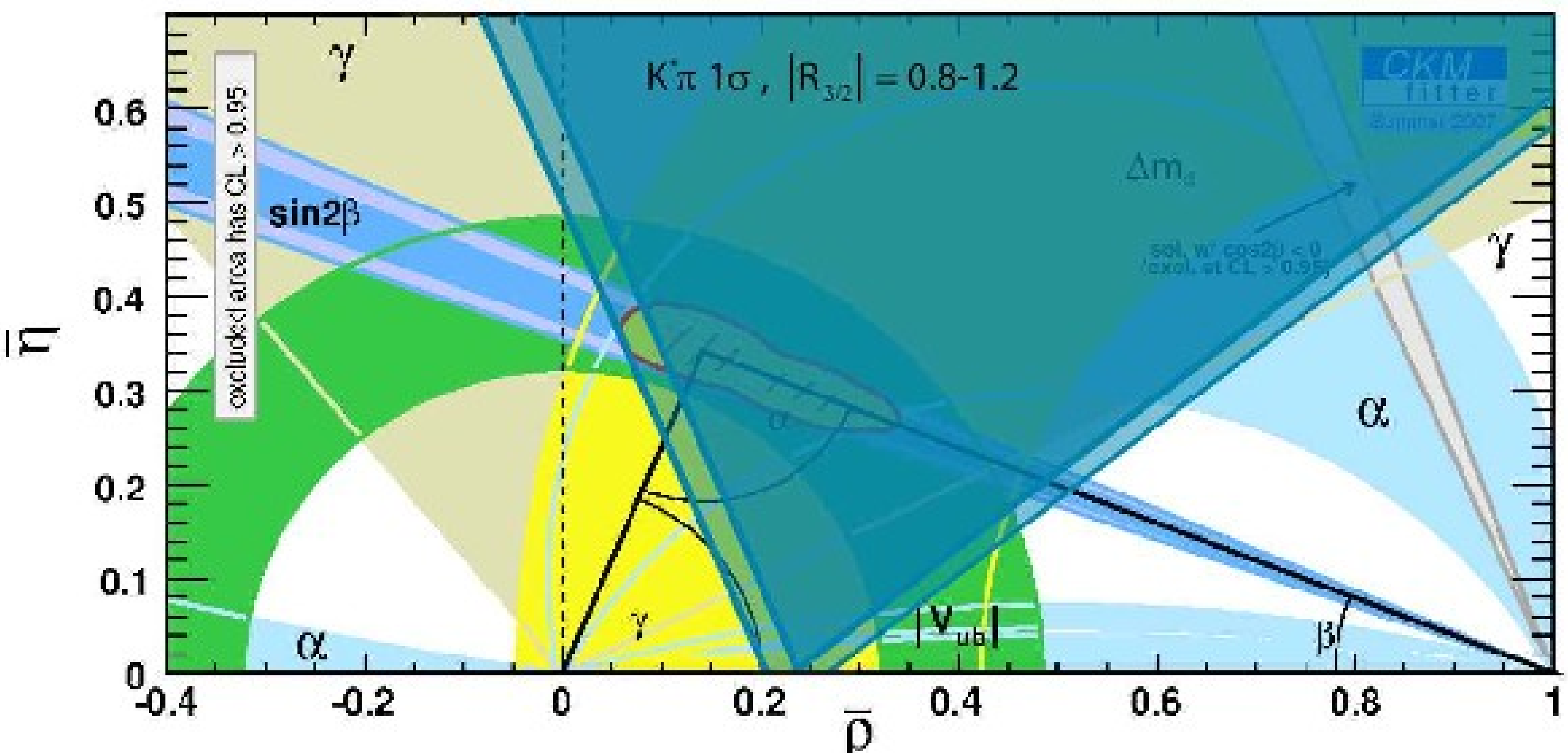
$$\bar{\eta} = \tan\Phi_{3/2}\left[\bar{\rho} - 0.24 \pm 0.03\right]$$

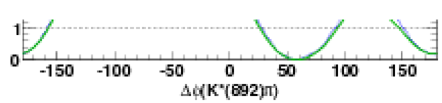
  - multiple s
  - improvement expected with updated analysis (arXiv:0807.4567)

- B_d

072004

ions)





Does not include all latest data

Other Related Ideas

Ciuchini et al., PLB 645 (2007) 201

- Exactly the same thing but with $B_s \to K^{*+}\pi^-$ and $B_s \to K^{*0}\pi^0$
  - analysis then similar to the Snyder-Quinn method for α

Never done yet

Ciuchini et al., hep-ph/0602207v1

- A similar idea with $B_s \to K^{*+}K^-$ and $B_s \to K^{*0}K_S$
  - some complications since $K^+\pi^-K_S$ not flavour-specific

Never done yet

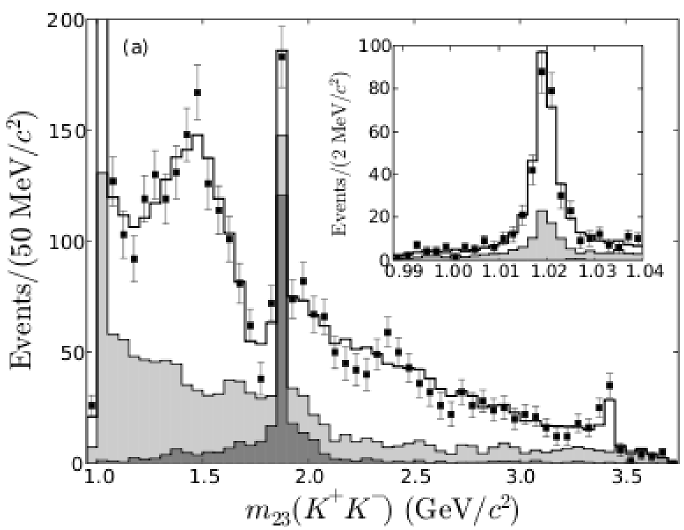
Bediaga et al., PRD 76 (2007) 073011

- Use isospin to relate $B^+ \to K^+\pi^+\pi^-$ to $B_d \to K_S\pi^+\pi^-$
  - don't need π^0 – good for LHCb
  - untagged analysis also possible

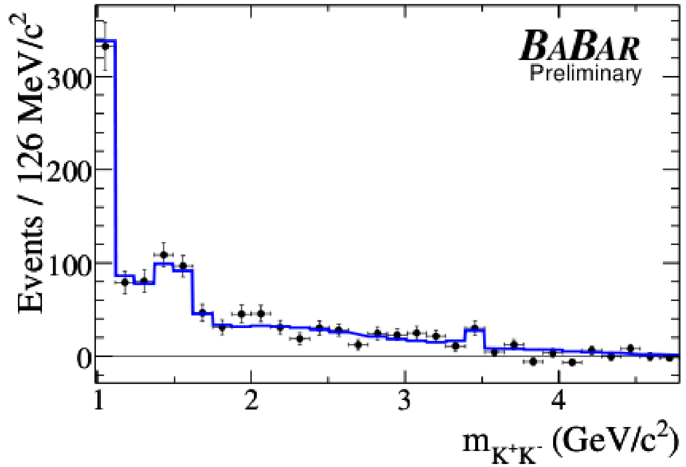
All good opportunities for LHCb

$B \to KKK$

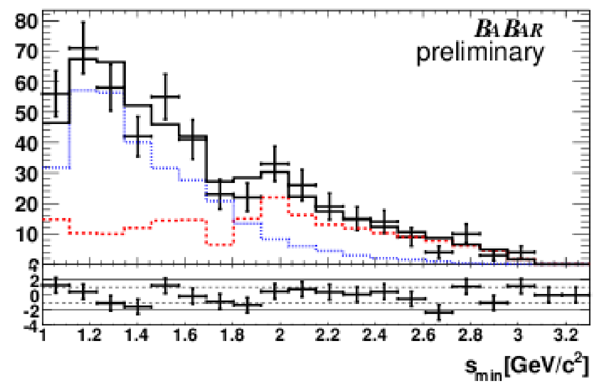
BaBar $B \to K^+K^-K^+$
PRD 74 (2006) 032003
(also Belle PRD 71 (2005) 092003)



BaBar $B \to K^+K^-K_S$
arXiv:0808.0700
(also Belle PRD 82 (2010) 073011)



BaBar $B \to K_SK_SK_S$
CKM2008 preliminary

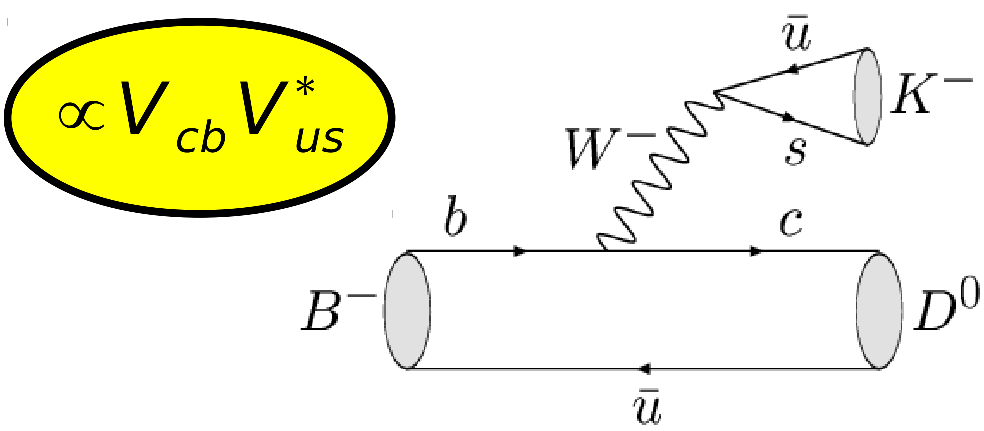


Large nonresonant components
Poorly understood scalar (?) contributions

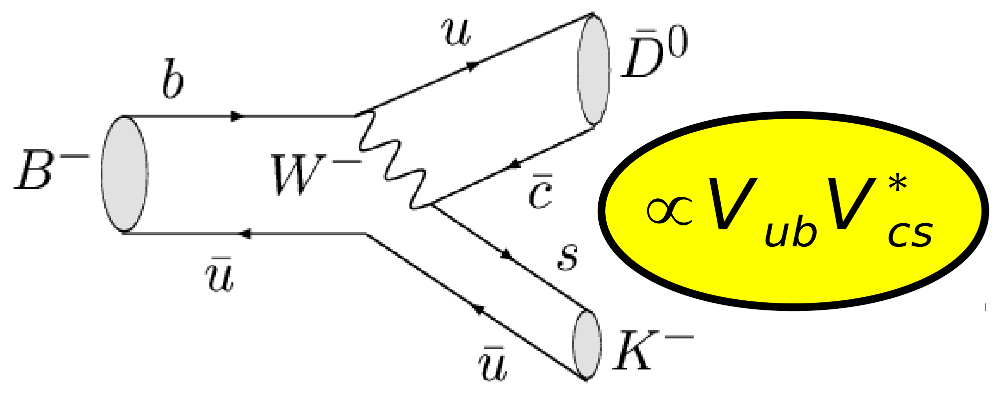
γ from $B\to DK$ type decays involving Dalitz plots

How To Measure γ

- Focus on theoretically pristine measurement
  - Interference between



- colour allowed
- final state contains D^0



- colour suppressed
- final state contains $\bar{D}^0$

Relative magnitude of suppressed amplitude is r_B

Relative weak phase is –γ, relative strong phase is δ_B

Use of Dalitz plots in γ measurement

- Problems of conventional (GLW/ADS) $B \to DK$ analyses
  - ambiguities
  - unknown hadronic parameters
  - lack of statistics
- Good way to address all these: study D decay Dalitz plot (typically $K_s\pi^+\pi^-$)
  - Dalitz plot analysis can disentangle relative amounts, and relative phases, of D^0 and $\bar{D}^0$ contributions

Giri et al., PRD 68 (2003) 054018; Bondar @ BINP Belle Dalitz plot workshop

  - Very successfully applied by the B factories

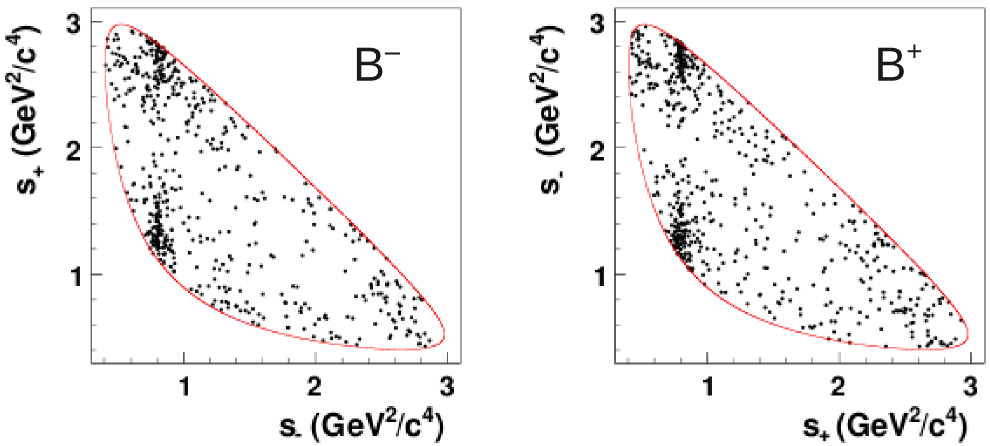
BaBar PRL PRL 105 (2010) 121801, PRD 78 (2008) 034023;
Belle PRD 81 (2010) 112002, PRD 73, 112009 (2006)

  - Similar idea: $B \to Dh^0$ (time-dependent) → determination of cos(2β)

Bondar et al., PLB 624 (2005) 1;
BaBar PRL 99 (2007) 231802, Belle PRL 97 (2006) 081801

$B \to DK$, $D \to K_S \pi^+ \pi^-$ results

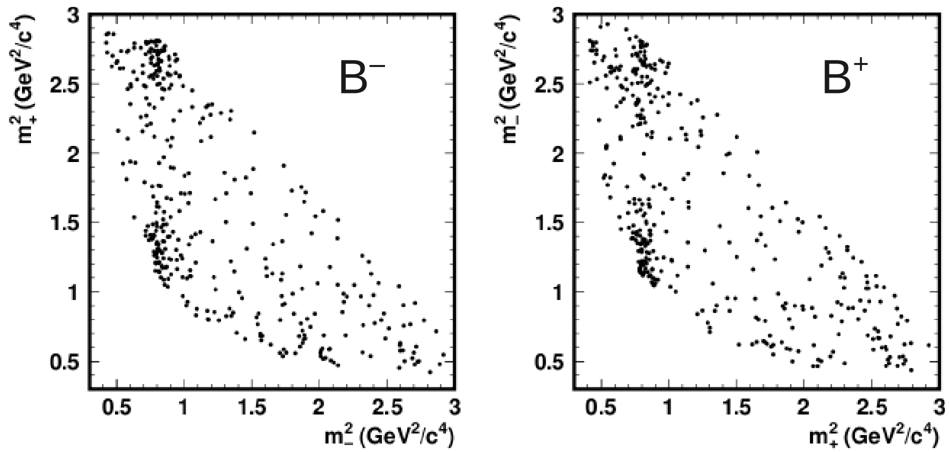
BaBar PRL 105 (2010) 121801



Model: NR + 8 resonant component + LASS $(K\pi)_0$ + K matrix $(\pi\pi)_0$

$\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$

Belle PRD 81 (2010) 112002



Model: NR + 18 resonant components

$\gamma = (78.4\,^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$

Model dependence

How to resolve model dependence

- Use CP-tagged D mesons to provide model-independent information about phase variation

$$A(D_{CP}\rightarrow f)=\frac{1}{\sqrt{2}}\left(A(D^0\rightarrow f)\pm A(\overline{D^0}\rightarrow f)\right)$$

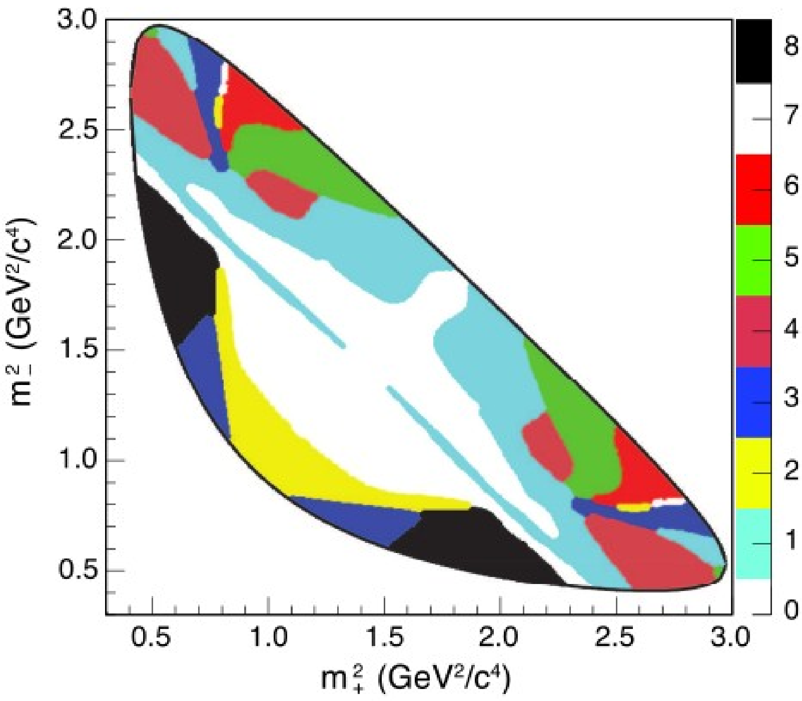
$$\left|A(D_{CP}\rightarrow f)\right|^2=\frac{1}{2}\left(\left|A(D^0\rightarrow f)\right|^2+\left|A(\overline{D^0}\rightarrow f)\right|^2\pm 2\left|A(D^0\rightarrow f)\right|\left|A(\overline{D^0}\rightarrow f)\right|\cos(\delta)\right)$$

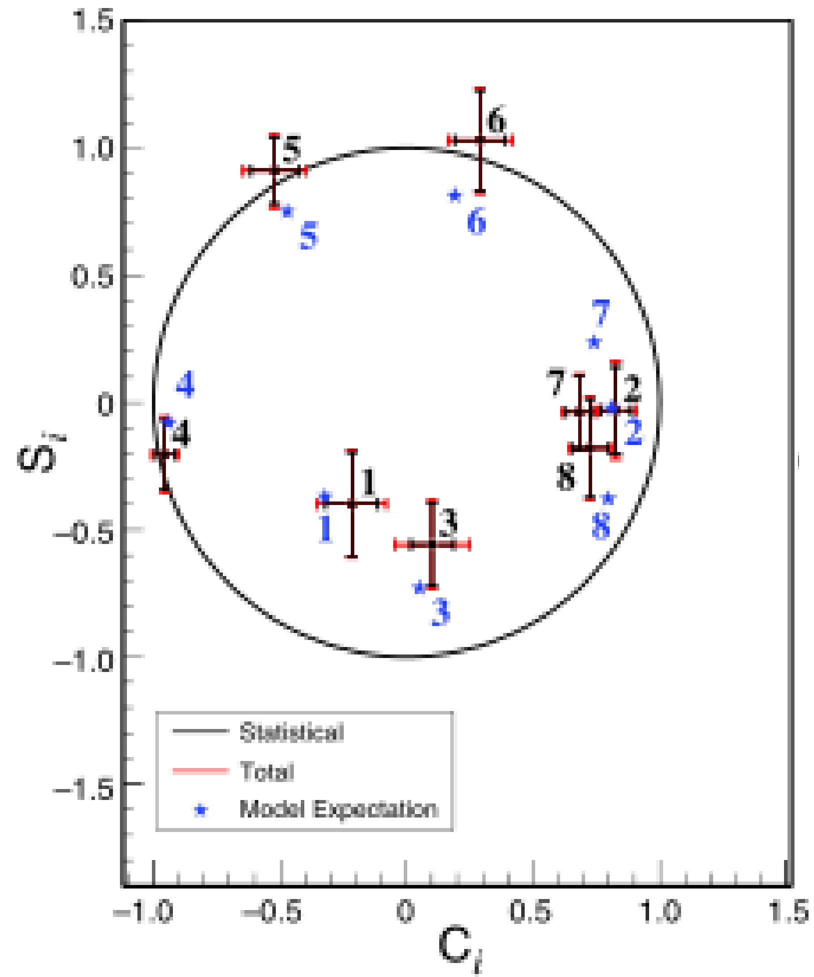
- Can be done by charm factory ($\Psi(3770)\rightarrow DD$)
  - CLEOc / BES / SuperB
- First measurements from CLEOc
  - $D\rightarrow K\pi$ PRL 100 (2008) 221801, PRD 78 (2008) 012001
  - $D\rightarrow K\pi\pi$, $K3\pi$ PRD 80 (2009) 031105
  - $D\rightarrow K_S\pi\pi$, K_SKK PRD 80 (2009) 032002, PRD 82 (2010) 112006

Model-independent results on $D \to K_S \pi\pi$

PRD 82 (2010) 112006

Binning





$(C_i, S_i) \equiv$ weighted average of $(\cos\delta, \sin\delta)$ across bin i

γ from $B^0 \to DK^{*0}$

- $B^0 \to DK^{*0}$ has many attractive features
  - large CP violation expected → good sensitivity to γ
  - flavour specific → time-dependent analysis not required
  - all charged final state
- But finite width of K^{*0} could be a problem
  - other contributions dilute sensitivity
- Turn problem into advantage:
  - Dalitz plot analysis
  - Exploit interference with D_2^*K, where D flavour is fixed

T.G, PRD 79 (2009) 051301; T.G and M.Williams PRD 80 (2009) 092002

- But now suffer $B \to DK\pi$ model dependence
  - Can be removed in $B \to DK\pi$, $D \to K_S\pi\pi$ double Dalitz plot analysis

T.G and A. Poluektov, PRD 81 (2010) 014025

Very exciting prospects for LHCb

Other possibilities

- I have of course mentioned only a small subset of the interesting B decay Dalitz plot analyses
- In the unlikely event that I have any time left by now, I would like to mention
  - $B_{d,s} \to J/\psi \pi^+ \pi^-$
  - $B_{d,s} \to J/\psi K^+ \pi^-$
  - $B_{d,s} \to J/\psi K^+ K^-$

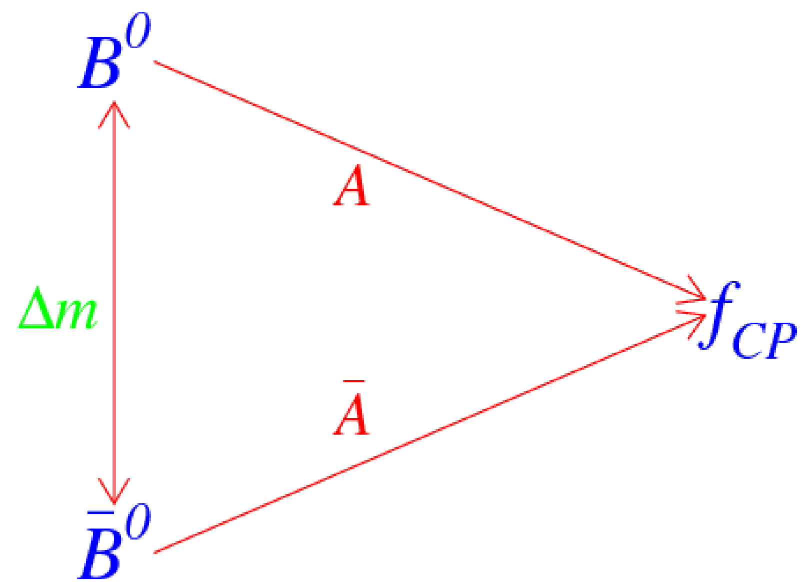
Summary

- Dalitz plot analyses provide promising methods to measure weak phases and CP violation
- Many attractive features …
- … but significant complications due to model dependence
- Need progress on several fronts
  - Understand better ($\pi\pi$), ($K\pi$), (KK), ($D\pi$), (DK) systems
  - “Nonresonant” contributions and 3-body unitarity
  - Methods to combat model-dependence
  - Nabis initiative set up to try to address this
- Many new possibilities opening up with LHCb

Reminder – CP violation formalism

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



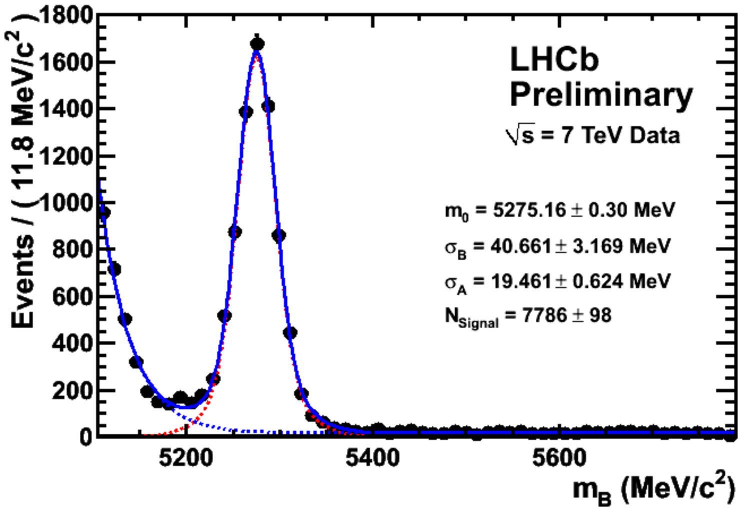
$$|\frac{q}{p}| \neq 1$$ CP violation in mixing

$$|\frac{\bar{A}}{A}| \neq 1$$ CP violation in decay (direct CPV)

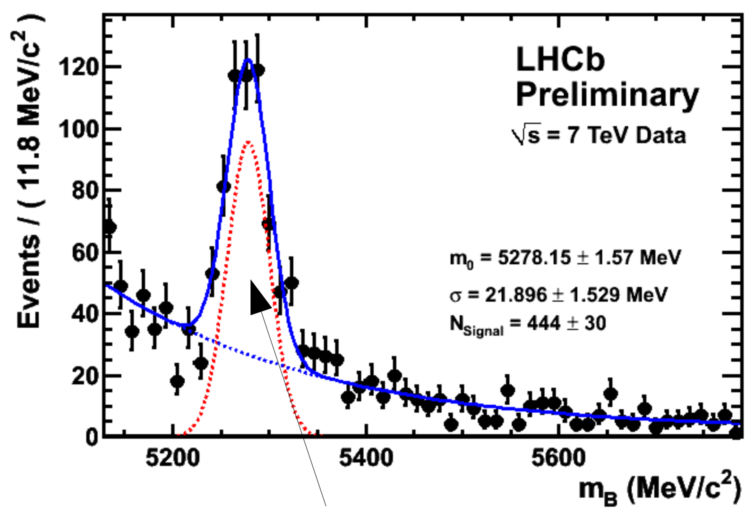
$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$ CP violation in interference between mixing and decay

LHCb yields in $B^\pm \to D\pi^\pm$ & $B^\pm \to DK^\pm$

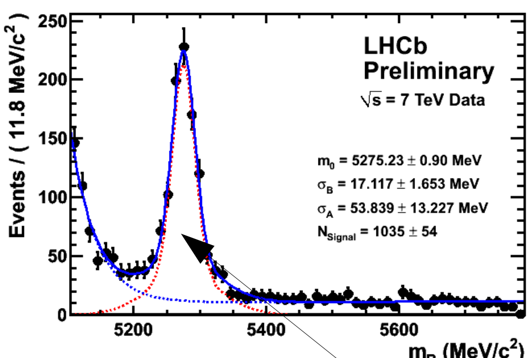
$B^\pm \to D\pi^\pm$ with $D \to \pi K$



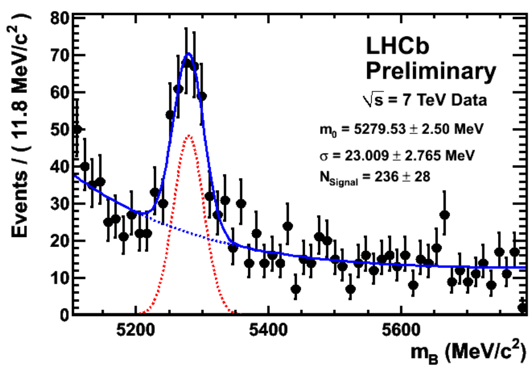
$B^\pm \to DK^\pm$ with $D \to \pi K$



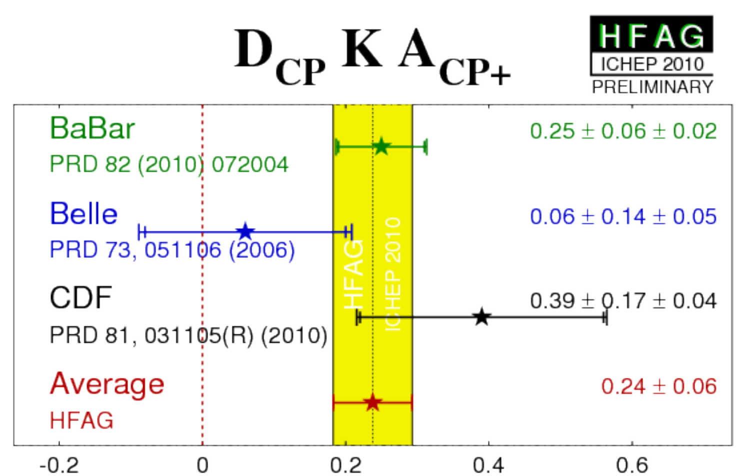
$B^\pm \to D\pi^\pm$ with $D \to KK$



$B^\pm \to D\pi^\pm$ with $D \to \pi\pi$



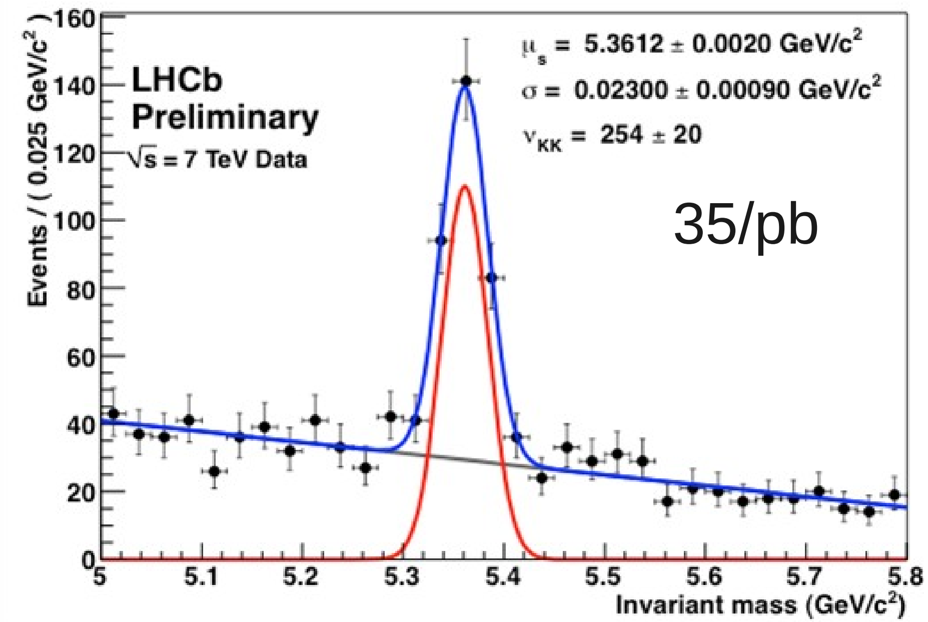
LHCb yield with ~34/pb : 444 ± 30
c.f. CDF with 1/fb : 516 ± 37



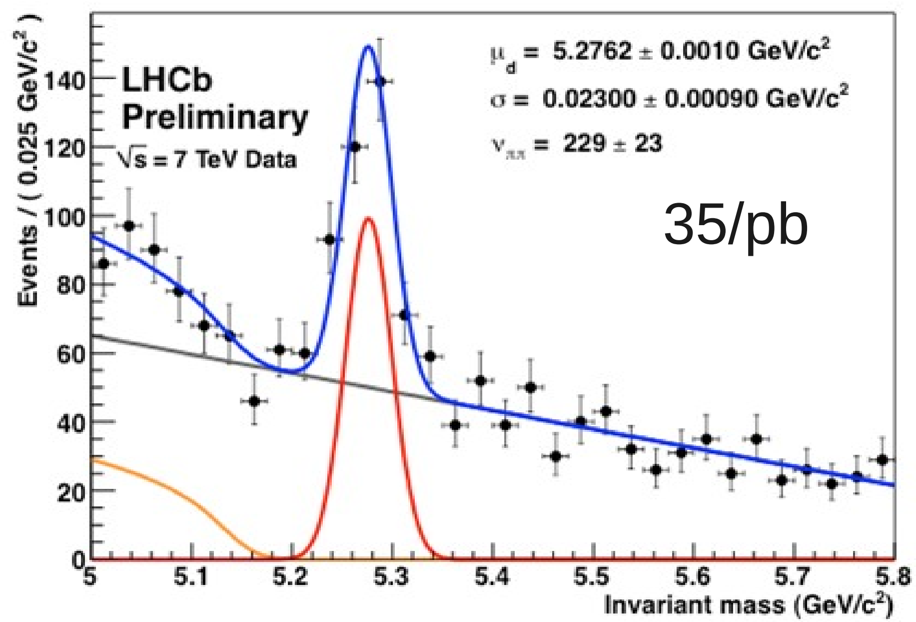
LHCb yield with ~34/pb : 1035 ± 54
c.f. CDF with 1/fb : 780 ± 36

Prospects for γ measurement from $B_s \to K^+K^-$

$B_s \to K^+K^-$



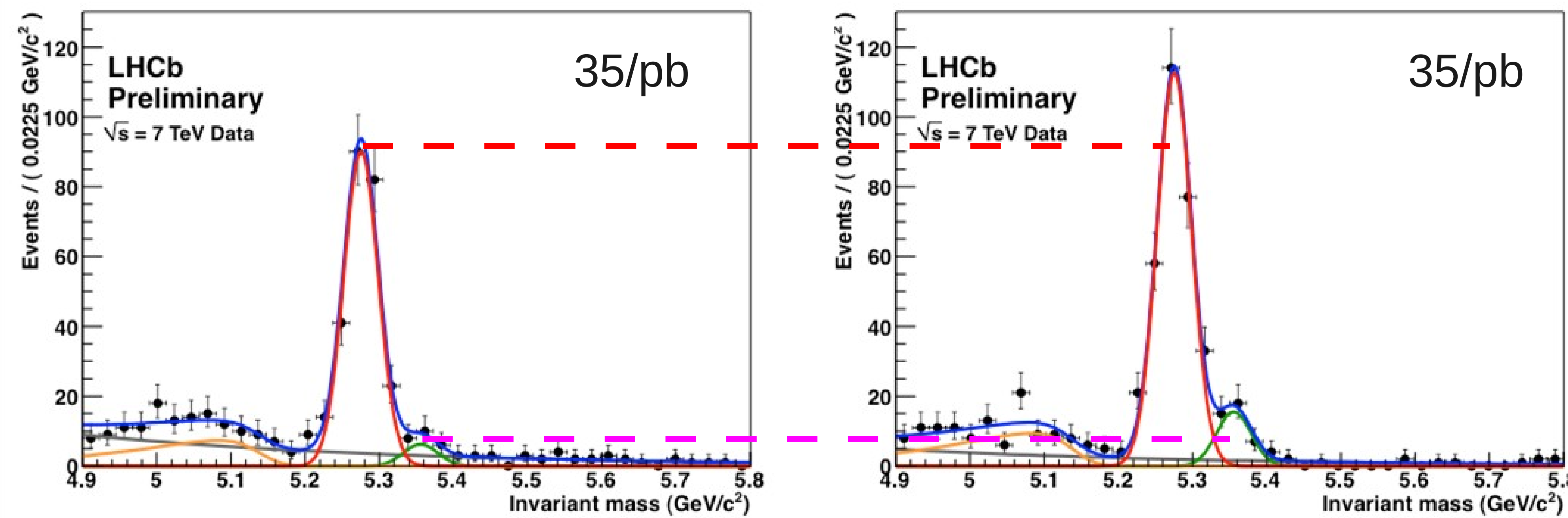
$B_d \to \pi^+\pi^-$



- LHCb yields in ~35/pb: 254±20 $B_s \to K^+K^-$ & 229±23 $B_d \to \pi^+\pi^-$
  - c.f. CDF in 1/fb: 1307±64 $B_s \to K^+K^-$ & 1121±63 $B_d \to \pi^+\pi^-$
- Expect first time-dependent measurements in 2011
  - (including measurement of B_s lifetime in CP-even K^+K^- final state)

Prospects for direct CP violation in $B_{d/s} \to K^+\pi^-$

$\overline{B}^0_{d/s} \to K^-\pi^+$ $\qquad$ $B^0_{d/s} \to K^+\pi^-$



- Raw asymmetries clearly visible in existing data
- Central values consistent with expectations & previous measurements
- Calibration and evaluation of systematic uncertainties in progress

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

27 parameters renamed "U" and "I" in commonly used notation

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

TABLE I. The time and kinematic dependence of contributions to the distribution of events.

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
$\sin(\Delta M t)$	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Re}(q\bar{S}_3S_5^* - q^*S_4\bar{S}_5^*)/2$	$\cos(2\alpha)$

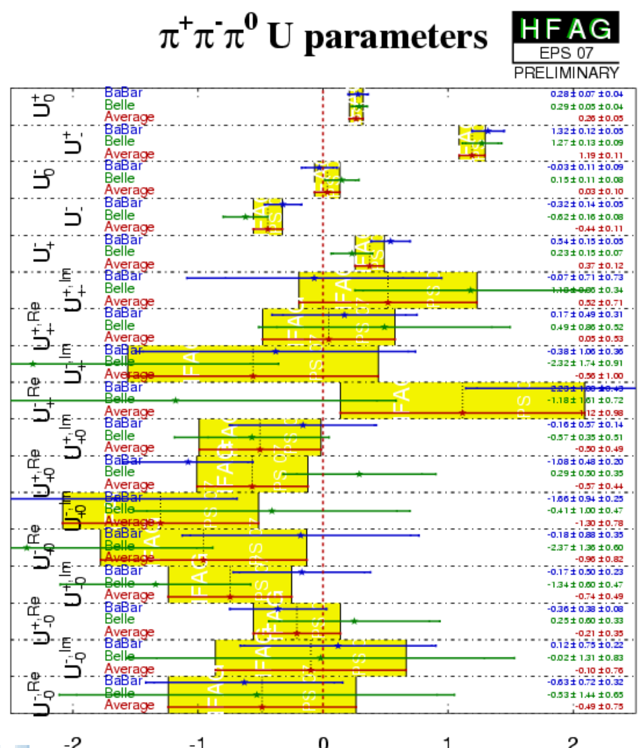
Note: physical observables depend on either sin(2α) or cos(2α) – never "directly" on α

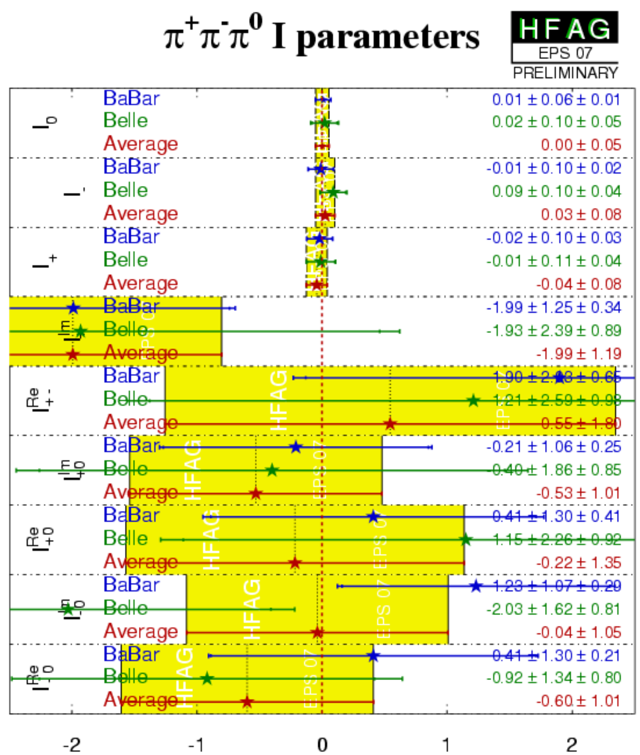
f terms contain hadronic physics (lineshape, spin)

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

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

- Results from
  - Belle, 449 M BB pairs: PRL 98 (2007) 221602, PRD 77 (2008) 072001
  - BaBar, 375 M BB pairs: PRD 76 (2007) 012004





Resolving the sin(2β) ambiguity

- The Dunwoodie method

BaBar PRD 71 (2005) 032005, Belle PRL 95 (2005) 091601

  – $B_d \to J/\psi K_S \pi^0$ ($b \to ccs$ transition)
  – Exploit interference between K*(892) and $K^*_0(1430)$
    - NB. ambiguity otherwise unbroken in B→VV analysis

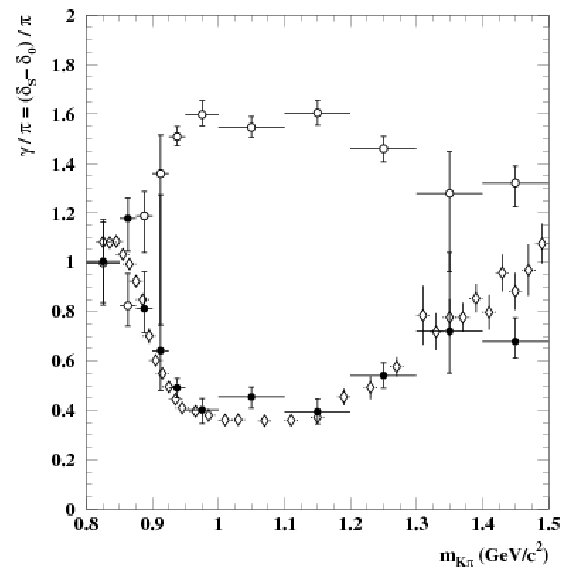


FIG. 9: Comparison of the variation of $\gamma = \delta_S - \delta_0$ with $m_{K\pi}$ for the $J/\psi K^{\pm}\pi^{\mp}$ events, for "Solution I" (open points, Eq. (29)) and "Solution II" (full points, Eq. (30)), with that measured by the LASS experiment [22, 39, 40] (diamond markers).

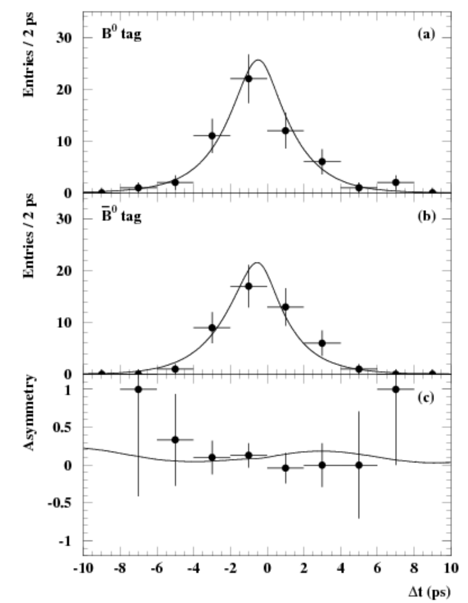


FIG. 11: The distribution of Δt for events in the signal region, for (a) B^0 and (b) $\overline{B}^0$ tags with the fit result (full curve) overlaid. In (c) we show the raw asymmetry in the number of B^0 and $\overline{B}^0$ tags in the signal region, $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, for data, with the fit result (full curve) overlaid. Note that above distributions are not sensitive to $\cos 2\beta$ since this dependence vanishes when integrated over the angular variables.

Prospects for LHCb

- Dalitz plot analyses are not something that we will do with first data
  - and, be warned, they are hard work
- But longer term there are many possibilities
  - many channels that are well suited for LHCb
    - all charged (or nearly all charged) final states
  - some have been looked at before
  - many have not
  - still room for new ideas