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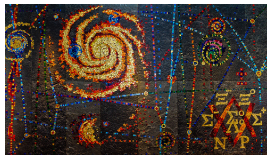
# CP violation: Recent Results from BABAR

Presented at SUSY2014

Roger Barlow  
representing the BaBar collaboration

Huddersfield University

25th July 2014



# A brief history of CP violation

in particle physics

## Discovery 1964

Fitch and Cronin (PRL **13**:138, 1964; Nobel Prize 1980)

Small effect (0.3%) for s quark:  $K_L^0 \rightarrow \pi^+ \pi^-$

Nothing much happened for almost 40 years:  $K_L^0 \rightarrow \ell^\pm \pi^\mp \nu$ ,  $K_L^0 \rightarrow \pi^0 \pi^0$

Seen in B mesons (b quark): BaBar and Belle

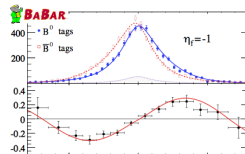
PRL **81** 091801, 2001, Nobel prize 2008 <sup>1</sup>

Large effects (several %). Many measurements.

Mainstream  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$

1st decays to CP eigenstate, 2nd tagged as  $b$  or  $\bar{b}$

Plot decay time dependences.



BaBar: PRD79:072009,2009

Reported in D mesons (c quark)

<sup>1</sup>For Kobayashi and Maskawa

# Overview

Talk covers 7 non-mainstream beauty results and 3 charm results

Caused by complex weak phase in:

## Mixing

Indirect CP violation

Violation of CP quantum number conservation

## Decays

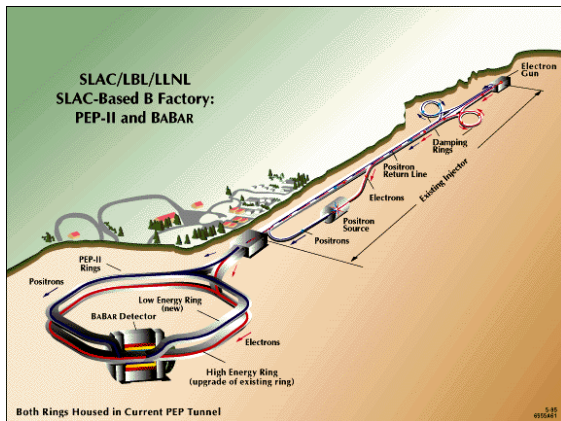
Direct CP violation

E.g. asymmetry in  $B^0 \rightarrow K^+\pi^- / \bar{B}^0 \rightarrow K^-\pi^+$  is  $9.8 \pm 1.2\%$

## Interference between mixing and decays

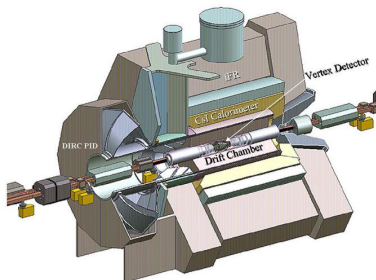
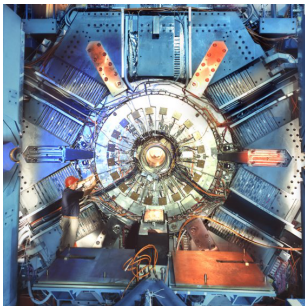
Different time dependence

# PEP-II: a 'B factory'



Results from  $471 \times 10^6 \Upsilon(4S)$  decays produced with speed  $0.5c$  in the lab  
Luminosity  $1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$       Currents 2-3 amps  
Technical triumph. Design goals greatly exceeded.

# The BABAR detector



Precision vertex chamber, charged particle tracking, PID using DIRC, precision EM calorimeter, muon detector.

# Direct CP violation in $B^\pm \rightarrow K^{*\pm}(892)\pi^0$

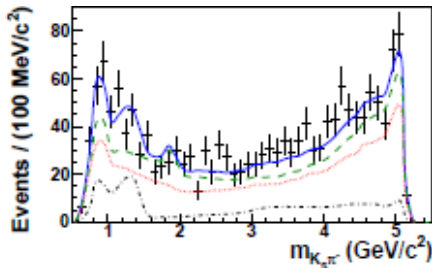
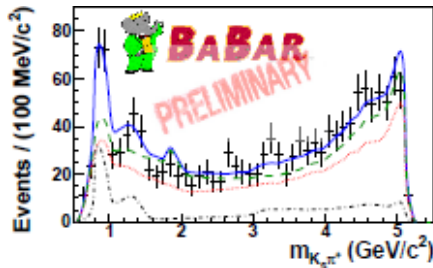
new result - preliminary

Select  $B^\pm \rightarrow K_s^0 \pi^\pm \pi^0$ . BR  $(45.9 \pm 2.6 \pm 3.0 \pm 8.6) \times 10^{-6}$

First measurement! Final error uncertainty due to signal model

Overall  $A_{CP} = \frac{N^+ - N^-}{N^+ + N^-} = 0.07 \pm 0.05 \pm 0.03 \pm 0.04$

Fit Dalitz plot using isobar model:  $K^{*0}(892)\pi^+$ ,  $K^{*+}(892)\pi^0$ ,  $K_s^0 \rho^+$ , etc



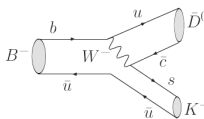
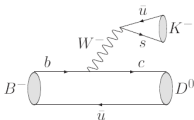
$A_{CP} = -0.52 \pm 0.14 \pm 0.04 \pm 0.04$  : Significant at  $3.4\sigma$

Difference between  $B^+ \rightarrow K^{*+}\pi^0$  and  $B^- \rightarrow K^{*-}\pi^0$

# Direct CP violation in $B^\pm \rightarrow K^{(*)\pm} D^{(*)0}$ : global fit to $\gamma$

Phys Rev D **87** 052015 (2013)

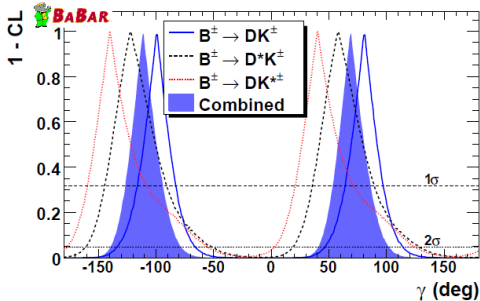
Interference between 2 diagrams in final states accessible through  $D$  or  $\bar{D}$



GGSZ:  $K\pi\pi$  etc

GL:  $K^+K^-$  etc

ADS:  $K^+\pi^-$  doubly-Cabibbo-suppressed states



$$\gamma = (69^{+17}_{-16})^\circ$$

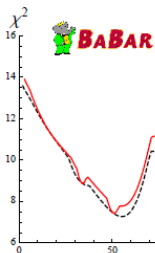
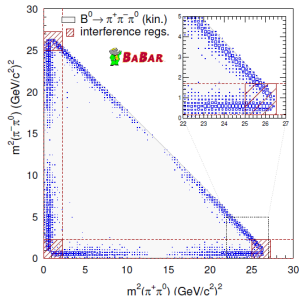
Significant at  $5.9\sigma$



# $B^0 \rightarrow \pi^+ \pi^- \pi^0$ : fit to $\alpha$

Phys. Rev. D **88** 012003 (2013)

Dalitz plot: fit  
 $\rho^\pm \pi^\mp$  and  $\rho^0 \pi^0$ .  
Transform to  
square plot to  
include efficiencies



Time dependent fit  
 $\propto 1 + C \cos(\Delta_m t) + S \sin(\Delta_m t)$   
 $C$  terms are direct CP,  
 $S$  terms are interference  
Results interpretable in terms  
of CKM angle  $\alpha$

# $B \rightarrow X_S \ell^+ \ell^-$ Direct CPV

Phys. Rev. Lett. 112, 211802 (2014)

10 different exclusive  $X_S$   
modes ( $K^+$ ,  $K^+\pi^0$ ,  $K^+\pi^-$ ,  
 $K^+\pi^-\pi^0$ ,  $K^+\pi^-\pi^+$ ,  $K_S^0$ ,  $K_S^0\pi^0$ ,  
 $K_S^0\pi^+$ ,  $K_S^0\pi^+\pi^0$ ,  $K_S^0\pi^+\pi^-$ )

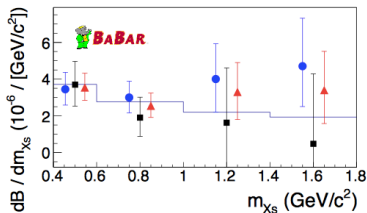
Extrapolation gives

branching ratio

$$(6.73^{+0.70+0.34}_{-0.64-0.25} \pm 0.50) \times 10^{-6}$$

for  $m_{\ell\ell}^2 > 0.1$

$$A_{CP} = 0.04 \pm 0.11 \pm 0.01$$



blue=electrons,

black=muons,

red=average

# $B \rightarrow X_s \gamma$ Direct CPV

New result - preliminary

Use charged  $B$  mesons and self-tagging neutral  $B$  meson decays

Sum over exclusive  $X_s$  states  
Reconstruct 38 (x2) different final states - use 16 with good statistics.

$$A_{CP} = \frac{\Gamma(B^-/\bar{B}^0) - \Gamma(B^+/B^0)}{\Gamma(B^-/\bar{B}^0) + \Gamma(B^+/B^0)}$$

$$A_{CP} = (1.7 \pm 1.9 \pm 1.0)\%$$

consistent with SM prediction

#	Final State	#	Final State
1*	$B^+ \rightarrow K_S \pi^+ \gamma$	20	$B^0 \rightarrow K_S \pi^+ \pi^- \pi^+ \pi^- \gamma$
2*	$B^+ \rightarrow K^+ \pi^0 \gamma$	21	$B^0 \rightarrow K^+ \pi^+ \pi^- \pi^- \pi^0 \gamma$
3*	$B^0 \rightarrow K^+ \pi^- \gamma$	22	$B^0 \rightarrow K_S \pi^+ \pi^- \pi^0 \pi^0 \gamma$
4	$B^0 \rightarrow K_S \pi^0 \gamma$	23*	$B^+ \rightarrow K^+ \eta \gamma$
5*	$B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$	24	$B^0 \rightarrow K_S \eta \gamma$
6*	$B^+ \rightarrow K_S \pi^+ \pi^0 \gamma$	25	$B^+ \rightarrow K_S \eta \pi^+ \gamma$
7*	$B^+ \rightarrow K^+ \pi^0 \pi^0 \gamma$	26	$B^+ \rightarrow K^+ \eta \pi^0 \gamma$
8	$B^0 \rightarrow K_S \pi^+ \pi^- \gamma$	27*	$B^0 \rightarrow K^+ \eta \pi^- \gamma$
9*	$B^0 \rightarrow K^+ \pi^- \pi^0 \gamma$	28	$B^0 \rightarrow K_S \eta \pi^0 \gamma$
10	$B^0 \rightarrow K_S \pi^0 \pi^0 \gamma$	29	$B^+ \rightarrow K^+ \eta \pi^+ \pi^- \gamma$
11*	$B^+ \rightarrow K_S \pi^+ \pi^- \pi^+ \gamma$	30	$B^+ \rightarrow K_S \eta \pi^+ \pi^0 \gamma$
12*	$B^+ \rightarrow K^+ \pi^+ \pi^- \pi^0 \gamma$	31	$B^0 \rightarrow K_S \eta \pi^+ \pi^- \gamma$
13*	$B^+ \rightarrow K_S \pi^+ \pi^0 \pi^0 \gamma$	32	$B^0 \rightarrow K^+ \eta \pi^- \pi^0 \gamma$
14*	$B^0 \rightarrow K^+ \pi^+ \pi^- \pi^- \gamma$	33*	$B^+ \rightarrow K^+ K^- K^+ \gamma$
15	$B^0 \rightarrow K_S \pi^0 \pi^+ \pi^- \gamma$	34	$B^0 \rightarrow K^+ K^- K_S \gamma$
16*	$B^0 \rightarrow K^+ \pi^- \pi^0 \pi^0 \gamma$	35	$B^+ \rightarrow K^+ K^- K_S \pi^+ \gamma$
17	$B^+ \rightarrow K^+ \pi^+ \pi^- \pi^+ \pi^- \gamma$	36	$B^+ \rightarrow K^+ K^- K^+ \pi^0 \gamma$
18	$B^+ \rightarrow K_S \pi^+ \pi^- \pi^+ \pi^0 \gamma$	37*	$B^0 \rightarrow K^+ K^- K^+ \pi^- \gamma$
19	$B^+ \rightarrow K^+ \pi^+ \pi^- \pi^0 \pi^0 \gamma$	38	$B^0 \rightarrow K^+ K^- K_S \pi^0 \gamma$

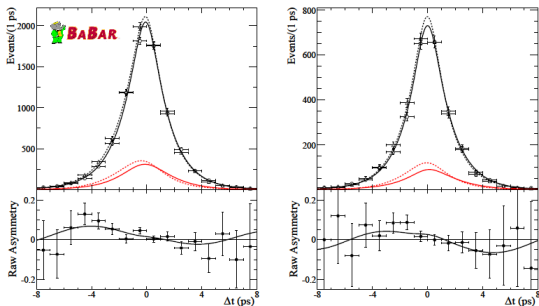
# $B^0 \rightarrow D^{*+} D^{*-}$ Time dependent asymmetry

Phys. Rev. D **86** 112006 (2012)

One  $D^*$  reconstructed fully from  $D^0\pi$  with  $D^0 \rightarrow K\pi, K\pi\pi, K\pi\pi\pi, K_S^0\pi\pi$

Second reconstructed partially: combine first with slow pion and requiring missing mass consistent with  $M_D$ .

Flavour of other  $B^0$  from identified kaon or lepton.



$$C = 0.15 \pm 0.09 \pm 0.04 \quad S = -0.34 \pm 0.12 \pm 0.05$$

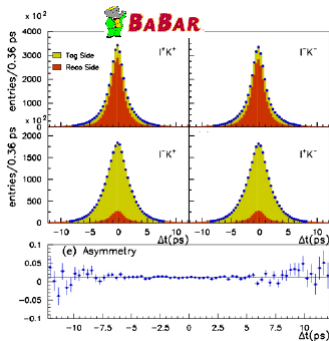
Consistent with  $\sin 2\beta$  determined from  $B^0 \rightarrow \text{charmonium}$

# CP violation in mixing: $B^0 \rightarrow D^{*-} X \ell \nu_\ell$ and a kaon tag

Phys. Rev. Lett. **111** 101802 (2013)

Reminder: CPV in mixing not seen by BaBar: dilepton asymmetry ( PRL **96** 251802 (2006) )  $A_{CP} = (1.6 \pm 5.4 \pm 3.8) \times 10^{-3}$  Consistent with SM( $\approx 0$ ). Means the  $D\bar{D}$  result must be due to  $B_s$  decays.

Partial  
reconstruction  
technique for  $D^*$   
Tag the other  $B$   
through kaon  
(avoids lepton  
identification  
systematics)



$$A_{CP} = \frac{N(B^0 B^0) - N(\bar{B}^0 \bar{B}^0)}{N(B^0 B^0) + N(\bar{B}^0 \bar{B}^0)} = (0.6 \pm 1.7^{+3.8}_{-3.2}) \times 10^{-3}$$

Charm:  $D^0 \rightarrow K^+ K^-, K^\pm \pi^\mp, \pi^+ \pi^-$

Phys. Rev. D **87** 012004 (2012)

Compare lifetimes to CP even  $K^+ K^-$  and  $\pi^+ \pi^-$  with CP mixed  $K^\pm \pi^\mp$

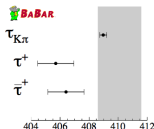
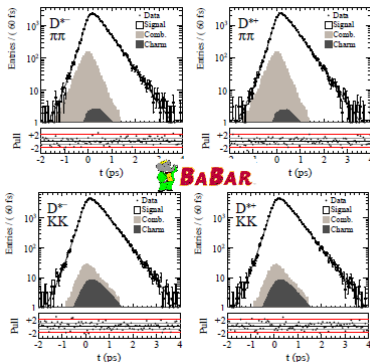
Rate  $\Gamma^+$  for  $D^0 \rightarrow CP_{\text{even}}$ ,

$\bar{\Gamma}^+$  for  $\bar{D}^0 \rightarrow CP_{\text{even}}$ ,

$\Gamma$  for  $D^0 \rightarrow CP_{\text{mixed}}$

$$y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1 = (0.72 \pm 0.18 \pm 0.12)\%$$

$$\Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma} = (0.09 \pm 0.26 \pm 0.06)\%$$



So  $3.3\sigma$  evidence for mixing, no evidence for CP violation

# Charm: Singly Cabibbo Suppressed $D^\pm \rightarrow K^+ K^- \pi^\pm$

Phys. Rev. D **87** 05210 (2013)

Evaluate charge asymmetry:

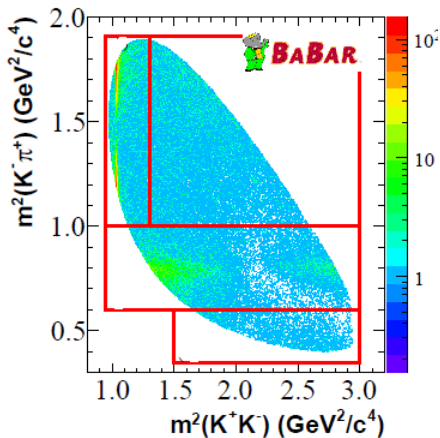
$$A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%$$

Also no sign in any of the subregions

(low  $M_{K\pi}$ ,  $K^*$ ,  $\phi$ , high  $M_{K\pi}$ )

or in isobar-model fits

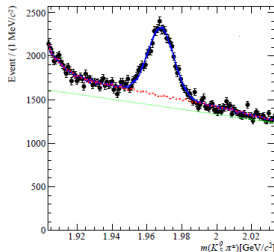
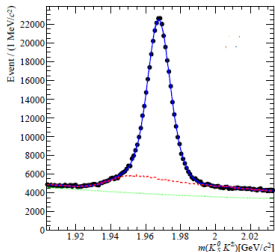
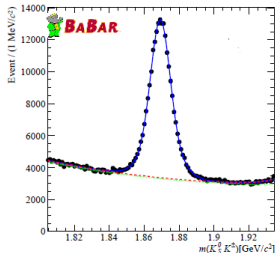
( $KK^*$ ,  $\pi\phi$ , etc)



Charm:  $D^\pm \rightarrow K_S^0 K^\pm$ ,  $D_S^\pm \rightarrow K_S^0 K^\pm$ ,  $D_S^\pm \rightarrow K_S^0 \pi^\pm$

Phys. Rev. D87 052012 (2013)

## Detector charge bias determined from data



$$A_{CP}(D^\pm \rightarrow K_S^0 K^\pm) = (0.13 \pm 0.36 \pm 0.25)\%$$

$$A_{CP}(D_S^\pm \rightarrow K_S^0 K^\pm) = (-0.05 \pm 0.23 \pm 0.24)\%$$

$$A_{CP}(D_S^\pm \rightarrow K_S^0 \pi^\pm) = (0.6 \pm 2.0 \pm 0.3)\%$$

All consistent with zero and small SM prediction (0.33 %).



# Conclusions

Measurements of CP violation  
in B mesons continue

No sign of CP violation in  
charm

No sign of charge asymmetry  
as reported by DØ

Results give consistent values  
of CKM matrix  $\alpha, \beta, \gamma$  angles.

Powerful constraints on New  
Physics models

